BSM AT COLLIDERS

NEUTRINO MASSES

DARK MATTER

BARYOGENESSIS

NATURALNESS, NOBODY TALKS ABOUT THAT ANY MORE

TWO WAYS TO SEE THE PROBLEM:

- IS THE VEV AND THE HIGGS MASS CALCULABLE?(PREDICTING THE W AND HIGGS MASS?)

- **WHY THE RATIO** $\frac{M_W^2}{M_{PL}^2} = 10^{-34}$ **IS UV STABLE?**

THOSE QUESTIONS ARE RELEVANT BECAUSE GRAVITY IS THERE AND PROVIDES A CUT-OFF TO THE SM!

WITHOUT GRAVITY, THE SM IS A MATHEMATICALLY CONSITENT THEORY WITH FREE PARAMETRS

SUPPOSE WE CAN PREDICT THE HIGGS MASS IN TERMS OF MORE FUNDAMENTAL PARAMETERS

FEASIBLE? YES (SUSY, COMPOSITE HIGGS…)

$$V = (m_H^2 + \Sigma\ \delta m_H^2)|H|^2 + (\lambda + \Sigma\ \delta\lambda)|H|^4 + \ldots$$

$$m_h^2 = -2(m_H^2 + \delta m_H^2) \ = 2(\lambda + \delta\lambda)v^2$$

FINE-TUNING

$$\Delta = \frac{2\delta m_H^2|_{max}}{m_h^2}$$

$$\delta m_H^2 \sim \frac{1}{16\pi^2}(g_2^2\Lambda_w^2 + \lambda^2\Lambda_h^2 - y_t^2\Lambda_t^2 + ...)$$

THEN JUST ON THE DIMENSIONAL GROUND

$$\delta m_H^2 = \Sigma_i g_i^2 \Lambda_i^2 \qquad \Lambda_i = M_{PL} \ \ ?$$

(UP TO LOGARITHMIC FACTORS)

WE NEED SOME „PARTNERS" TO THE SM PARTICLES THAT WOULD CUT-OFF THE SM LOOPS AND PROVIDE THE SCALES LIKE

$$\Lambda_t = M_T, \ \Lambda_w, \ \Lambda_h \ldots\ldots$$

Hierachical mass scales in particle physics and naturalness

Proton mass and Planck scale

In QCD, the proton mass is determined by the confinement scale = the scale of quark-antiquark condensate = the scale of spontaneous chiral symmetry breaking

Examples of other “natural’ hierarchies of scales

- **ELECTRON MASS VS ANY CUT-OFF (BJORKEN&DRELL p.165, refers to Weiskopf)**

SELF-ENERGY CORRECTION. TO THE ELECTRON MASS

$$\Delta E = \frac{e^2}{r} \rightarrow e^2\Lambda$$

”Saved” by the existence of the positronium

$m_{K_L} - m_{K_S}$ CHARM AND GIM

$m^2_{\pi^+} - m^2_{\pi_0}$ ρ MESON

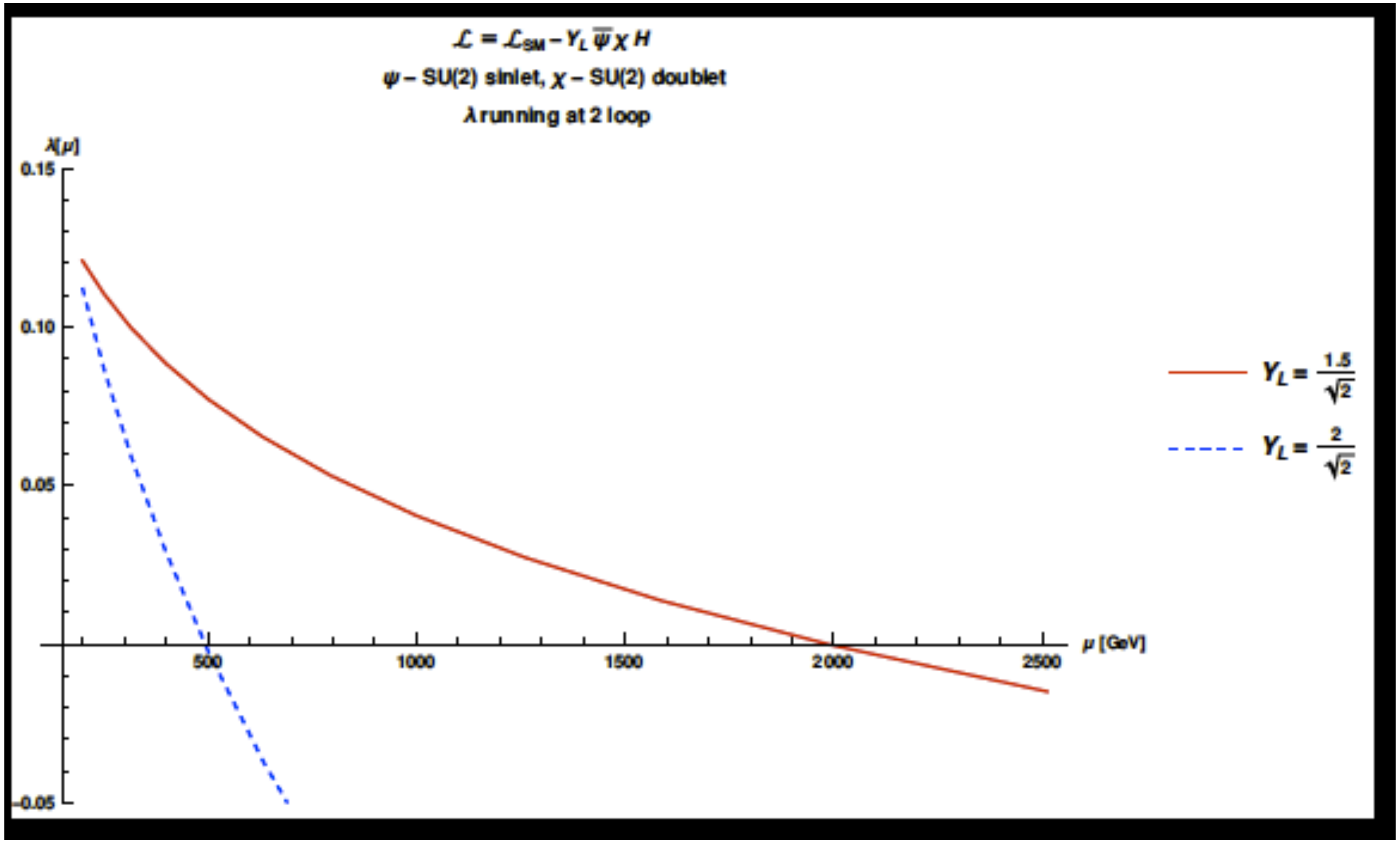
Quadratic sensitivity of the higgs stimulates the search for new states “naturalness ” guide to new physics

- New physics around the TeV scale...

....coupled to the Higgs

Beyond-the-Standard Model physics connected to Higgs!
Supersymmetry: Relates Higgs to a sfermion via SM fermion
Compositeness: Higgs is a
composite particle (a (pseudo) Goldstone boson)

More sophisticated scenarios possible (NEUTRAL NATURALNESS, a pseudo-Goldstone in perturbative models,
LOW CUT-OFF TO THE SM WITH ADDITIONAL VECTOR-LIKE FERMIONS)



$\mathcal{L} = \mathcal{L}_{SM} - Y_L \overline{\psi} \chi H$
ψ – SU(2) sinlet, χ – SU(2) doublet
λ running at 2 loop
$\lambda[\mu]$
0.15
0.10
0.05
-0.05
500
1000
1500
2000
2500
μ [GeV]
$Y_L = \frac{1.5}{\sqrt{2}}$
$Y_L = \frac{2}{\sqrt{2}}$

ANOTHER PUZZLE OF THE SM:

A RENORMALISABLE THEORY!

RENORMALISABLE BUT EFFECTIVE (LIKE QED)?

Renormalisable effective QFT : UV sensitivity hidden in a finite number of free parameters, to be taken from experiment

QED --→ SM (useful for a large separation of scales)

Why renormalisability useful in case of the SM if one expects UV completion, with new physical „low" mass scales, because of „naturalness"?

No real benefit from a renormalisable effective electroweak theory?

BUT WHY THEN CHIRAL GAUGE ANOMALY CANCELLATION IN THE SM (A NECESSARY CONDITION FOR RENORMALISABILITY)?

It depends on its extension…e.g. for minimal supersymmetric extension anomaly cancellation and renormalisability of the SM are relevant.

That fuzzy picture is behind various different attempts to go beyond the electroweak scale

ONE THING IN COMMON: MODIFICATION OF THE HIGGS BOSON PROPERTIES!!!

THE TOP PARTNERS MUST COUPLE TO THE HIGGS FIELD BUT NEED NOT TO BE COLORED. THEY CAN BE SCALARS AND /OR FERMIONS. PERTURBATIVE AND NON-PERTURBATIVE SCENARIOS. SUSY, GOLDSTONE BOSON, COMBINATION OF BOTH

	COLORED	UNCOLORED
SCALARS	SUSY	FOLDED SUSY
FERMIONS (HIGGS AS A PSEUDO -GOLDSTONE)	COMPOSITE HIGGS	TWIN HIGGS

DIRECT SEARCHES OF NEW STATES DIFFICULT TO BE SYSTEMATIC, MANY LOOPHOLES.

FOR SUSY SEARCHES, SEE E.G.

LHC constraints on electroweakino dark matter revisited
T. Buanes, I. Lara, K.Rolbiecki, K. Sakurai,e-Print: 2208.04342

Monojet signatures from gluino and squark decays
I.Lara, T. Buanes, R.Masełek, M. M. Nojiri, K.Rolbiecki, K.Sakurai
JHEP 10 (2022) 150, e-Print: 2208.01651 [hep-ph]

NEW PHYSICS COUPLED TO THE SM HIGGS (IN PARTICULAR TO AMELIORATE NATURALNESS).

NEW SCALARS, NEW VECTOR-LIKE FERMIONS …..

TAKE NEAR THE DECOUPLING LIMIT AND CARE ABOUT POSSIBLE FLAVOUR STRUCTURES OF THEIR CONTRIBUTIONS TO THE EFFECTIVE THEORY

Javier Alonso Gonzales, Arturo de Giorgi, Fotis Koutroulis, Luca Merlo, SP

IN THE SMEFT FRAMEWORK, INCLUDING DIM 6 OPERATORS:

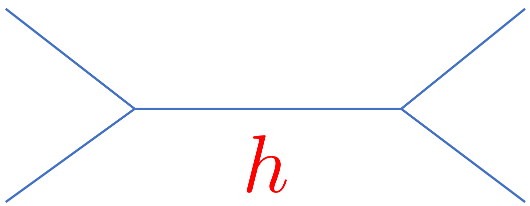
$$-(\bar{Q}_L^J \bar{H} C_u'^{JK} u_R^K - \bar{Q}_L^J H C_d'^{JK} d_R^K - \bar{L}_L^J H C_e'^{JK} e_R^K)\frac{H^\dagger H}{\Lambda^2} + h.c$$

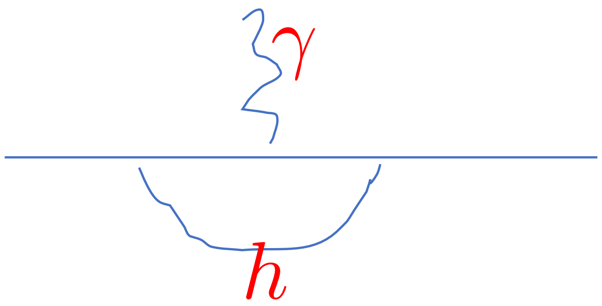
Y', C' ARE 3x3 COMPLEX MATRICES IN THE FLAVOUR SPACE

$(H^+ H)^3$ TRIPLE HIGGS COUPLING

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





FLAVOUR STRUCTURE OF THE WILSON COEFFICIENTS- EXAMPLES:

- MINIMAL FLAVOUR VIOLATION
- U(1) SYMMETRY FROGGATT-NIELSEN MODELS

OR, EFT DERIVED FROM "COMPLETE" EXTENSIONS: Z2 SYMMETRIC 2HDM (TO AVOID TREE-LEVEL FCNC) NEAR THE DECOUPLING LIMIT

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

2HDMs

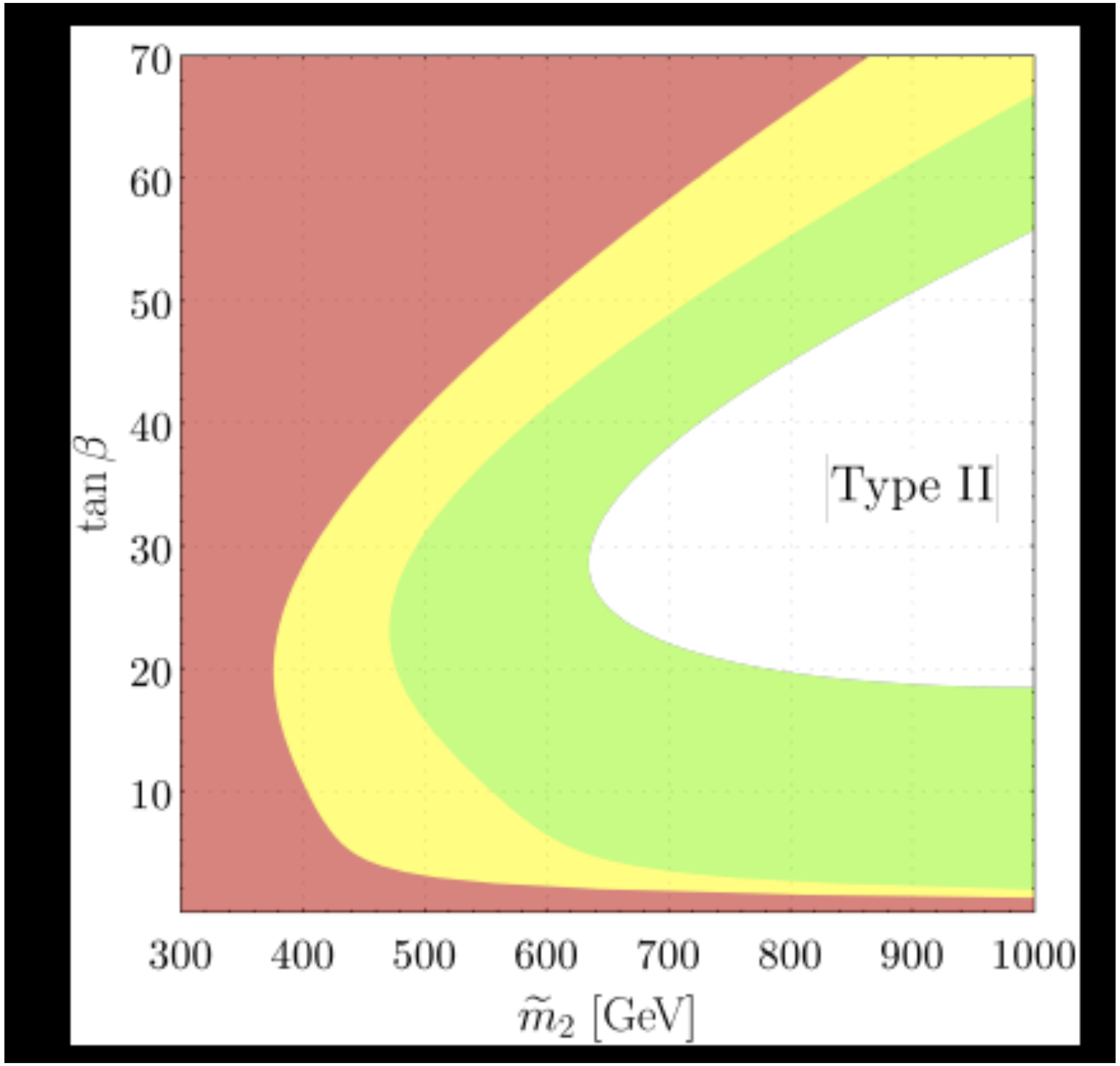
$$-\mathscr{L}_Y^{\text{eff}} \supset M_f \overline{f} f + \frac{M_f}{v} h \left(\kappa_f \overline{f} f + \widetilde{\kappa}_f \overline{f} i\gamma_5 f\right) + \dots ,$$

$$\kappa_u = \kappa_d = \kappa_e = 1 - \zeta_f \,\mathrm{Re}\left[\widetilde{\lambda}_6^* e^{-i\xi/2}\right] \frac{v^2}{\widetilde{m}_2^2} \equiv 1 - \zeta_f \left|\widetilde{\lambda}_6\right| \cos(\rho) \frac{v^2}{\widetilde{m}_2^2} ,$$

$$\widetilde{\kappa}_u = \widetilde{\kappa}_d = \widetilde{\kappa}_e = -\zeta_f \,\mathrm{Im}\left[\widetilde{\lambda}_6^* e^{-i\xi/2}\right] \frac{v^2}{\widetilde{m}_2^2} \equiv -\zeta_f \left|\widetilde{\lambda}_6\right| \sin(\rho) \frac{v^2}{\widetilde{m}_2^2} ,$$

	Type I	Type II	Type III (X)	Type IV (Y)
ζ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ζ_d	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
ζ_e	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

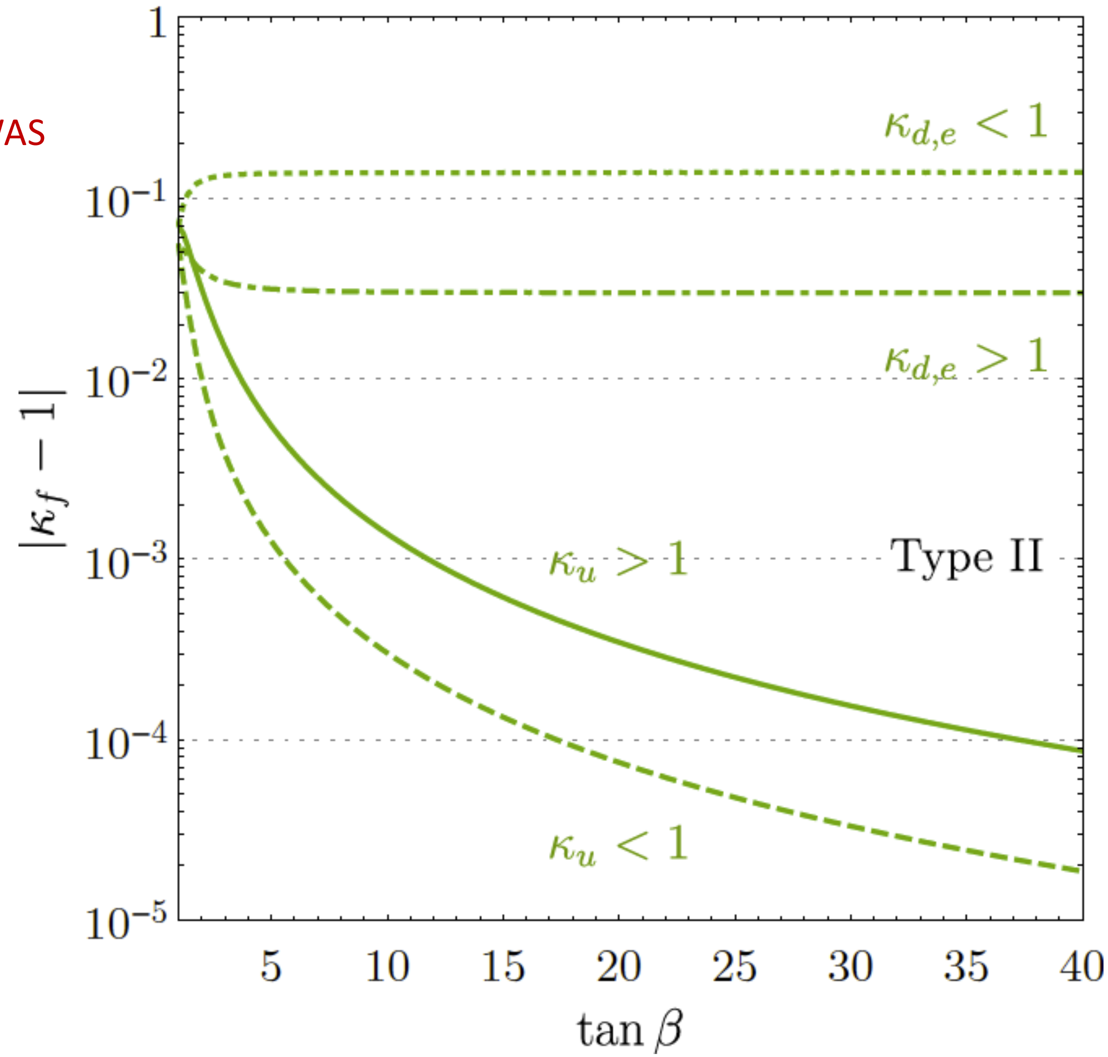
$\tilde{m}_2$ IS THE APPROXIMATELY DEGENERATE MASS OF HEAVY NEUTRAL AND CHARGED HIGGSES

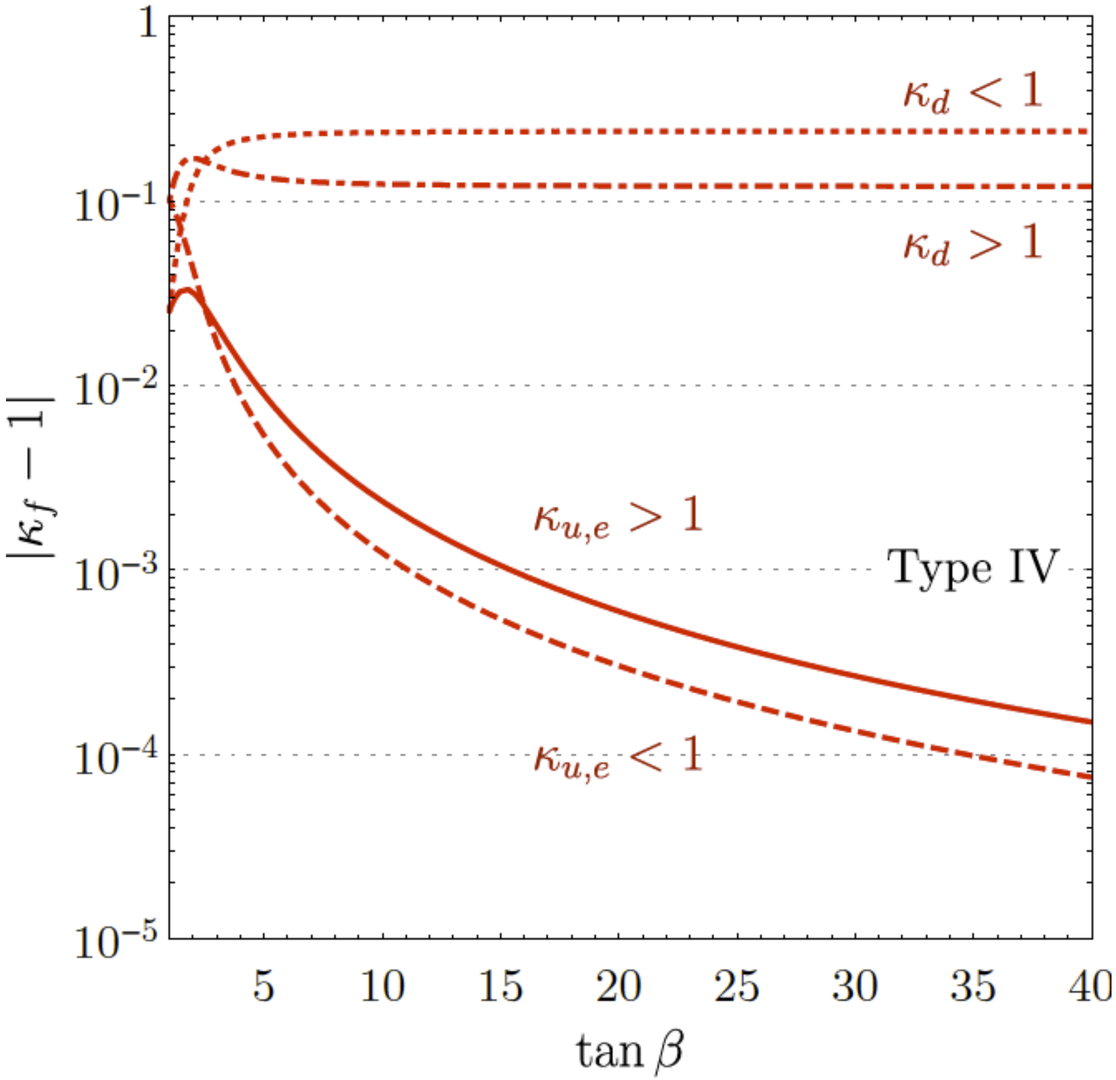


BOUNDS FROM FLAVOUR PHYSICS

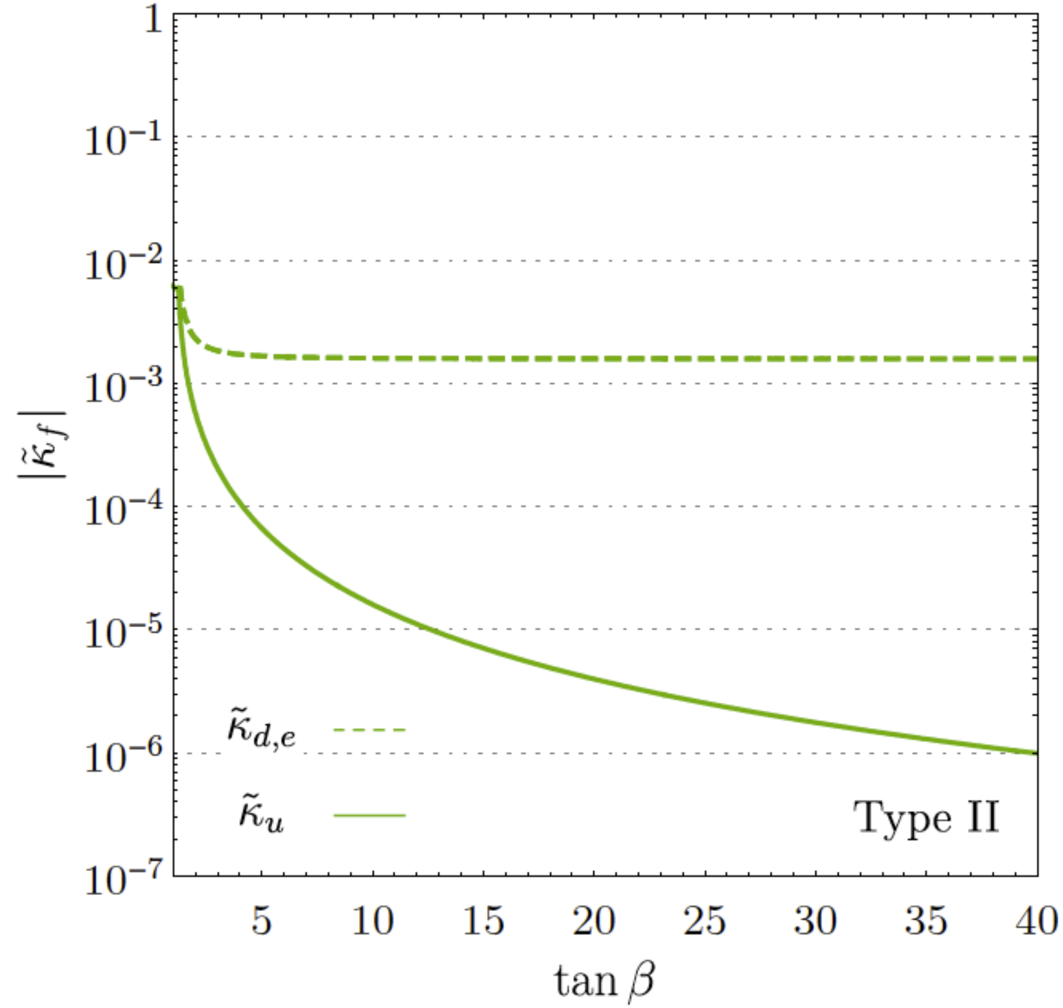
WEAK LOWER BOUNDS BECAUSE FLAVOUR SYMMETRY ELIMINATES TREE-LEVEL CONTRIBUTIONS TO FCNC

A GLOBAL FIT TO YUKAWAS
IN HIGGS PRODUCTION
AND DECAYS





1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
5
10
15
20
25
30
35
40
$\tan\beta$
$|\kappa_f - 1|$
$\kappa_d < 1$
$\kappa_d > 1$
$\kappa_{u,e} > 1$
Type IV
$\kappa_{u,e} < 1$



ELECTRON EDM BOUNDS

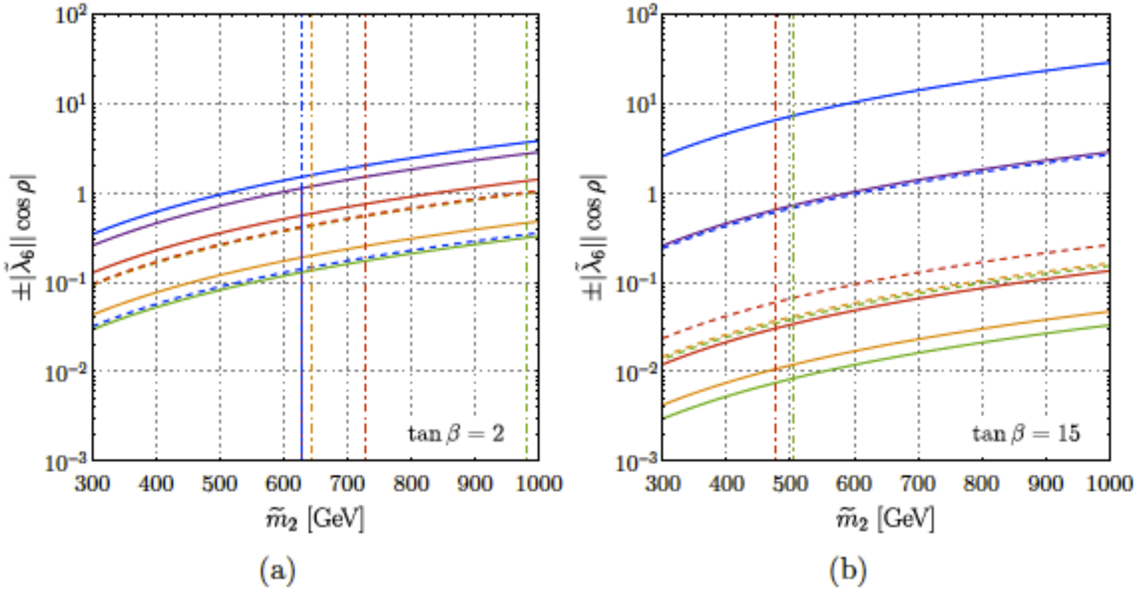
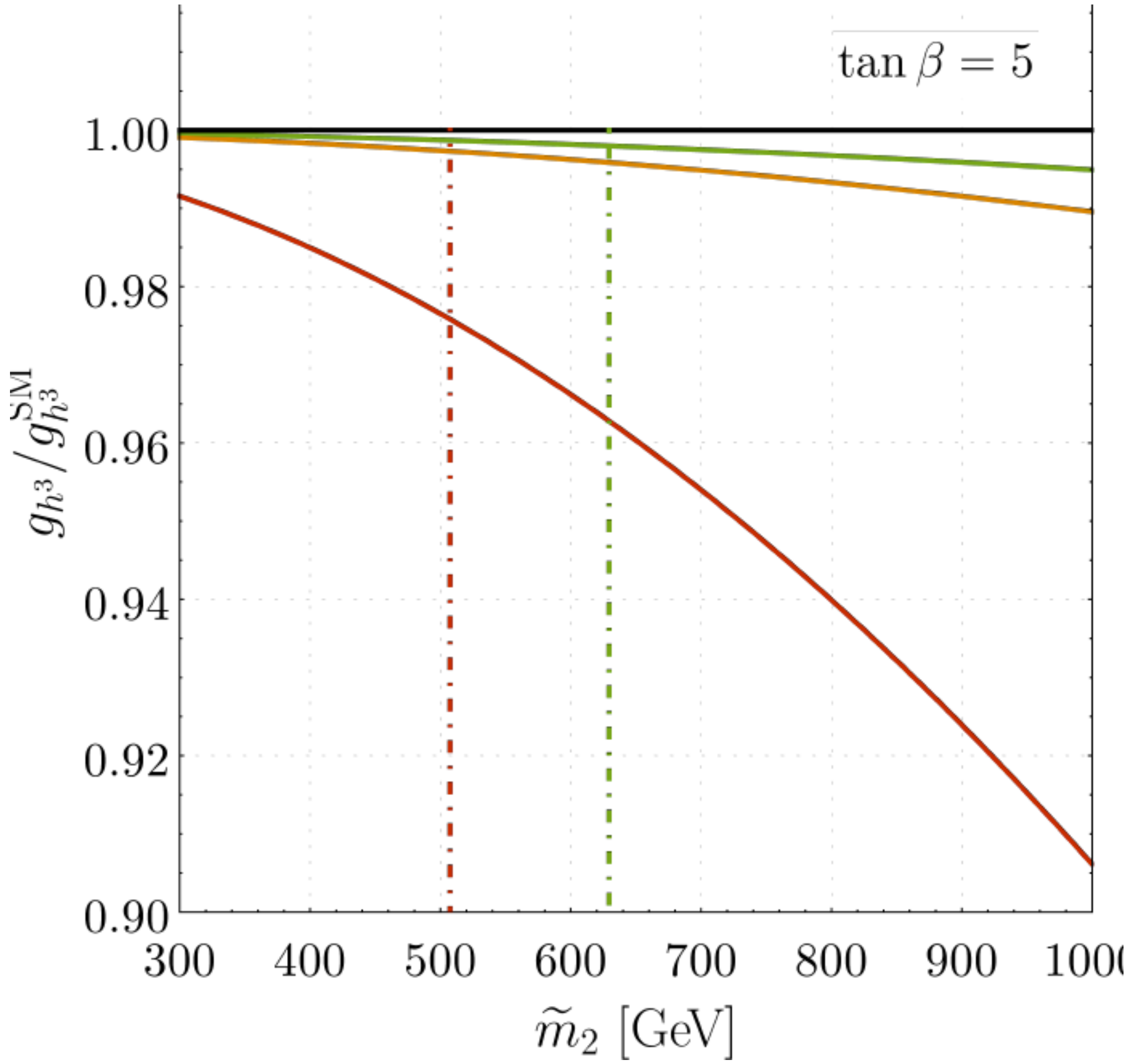


Figure 5: *Upper bounds at 2σ from collider observables for different types of 2HDM and values of $\tan\beta$. Each colour corresponds to a specific realization of 2HDM: Type I-blue, Type II-green, Type III-orange, Type IV-red. The case with $\cos\rho > 0$ (< 0) corresponds to solid (dashed) lines. The area on the left-side of the vertical dot-dashed lines is excluded at 2σ by flavour observables. The purple line corresponds to the limit in Eq. (3.9) and it applies to the case $|| \, |\cos\rho| = 1$.*



$$V^{\rm eff} = \frac{1}{2} m_h^2 h^2 + \frac{g_{h^3}}{3!}\, v\, h^3 + \frac{g_{h^4}}{4!} h^4 + \ldots$$

$$g_{h^3} = \frac{3\, m_h^2}{v^2} - 6 \left|\widetilde{\lambda}_6\right|^2 \frac{v^2}{\widetilde{m}_2^2} -$$

$$g_{h^4} = \frac{3\, m_h^2}{v^2} - 36 \left|\widetilde{\lambda}_6\right|^2 \frac{v^2}{\widetilde{m}_2^2} -$$

SUMMARY

DON'T FORGET ABOUT THE NATURALNESS ISSUE:

- DIRECT SEARCHES STILL HAVE MANY LOOPHOLES IN THE "LOW" MASS REGIONS AND THERE ARE MANY QUALITATIVELY DIFFERENT SCENARIOS

- THE HIGGS SECTOR IS AFFECTED IN ANY SCENARIO

  - HIGGS DECAYS VS FLAVOUR PHYSICS WITH SOME FLAVOUR "SYMMETRIES"- SIMILAR SENSITIVITY TO NEW MASS SCALES

  - TRIPLE HIGGS COUPLING VERSUS HIGGS DECAYS, e.g. 2HDM vs HIGGS AS A PSEUDO-GOLDSTONE (NOT DISCUSSED)

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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