SMEFT TO 2HDM MATCHING WITHIN ATLAS

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INTRODUCTION

Recently published interpretation of Higgs combined measurements within ATLAS

First SMEFT to UV matching results in ATLAS for 2HDM included in the CONF note

This talk:

- ✦ Provide a summary of 2HDM matching within the Higgs group in ATLAS
- ✦ Comparison with κ formalism
- ✦ Feedback on SMEFT to UV matching

Two Higgs Doublet Model (2HDM):

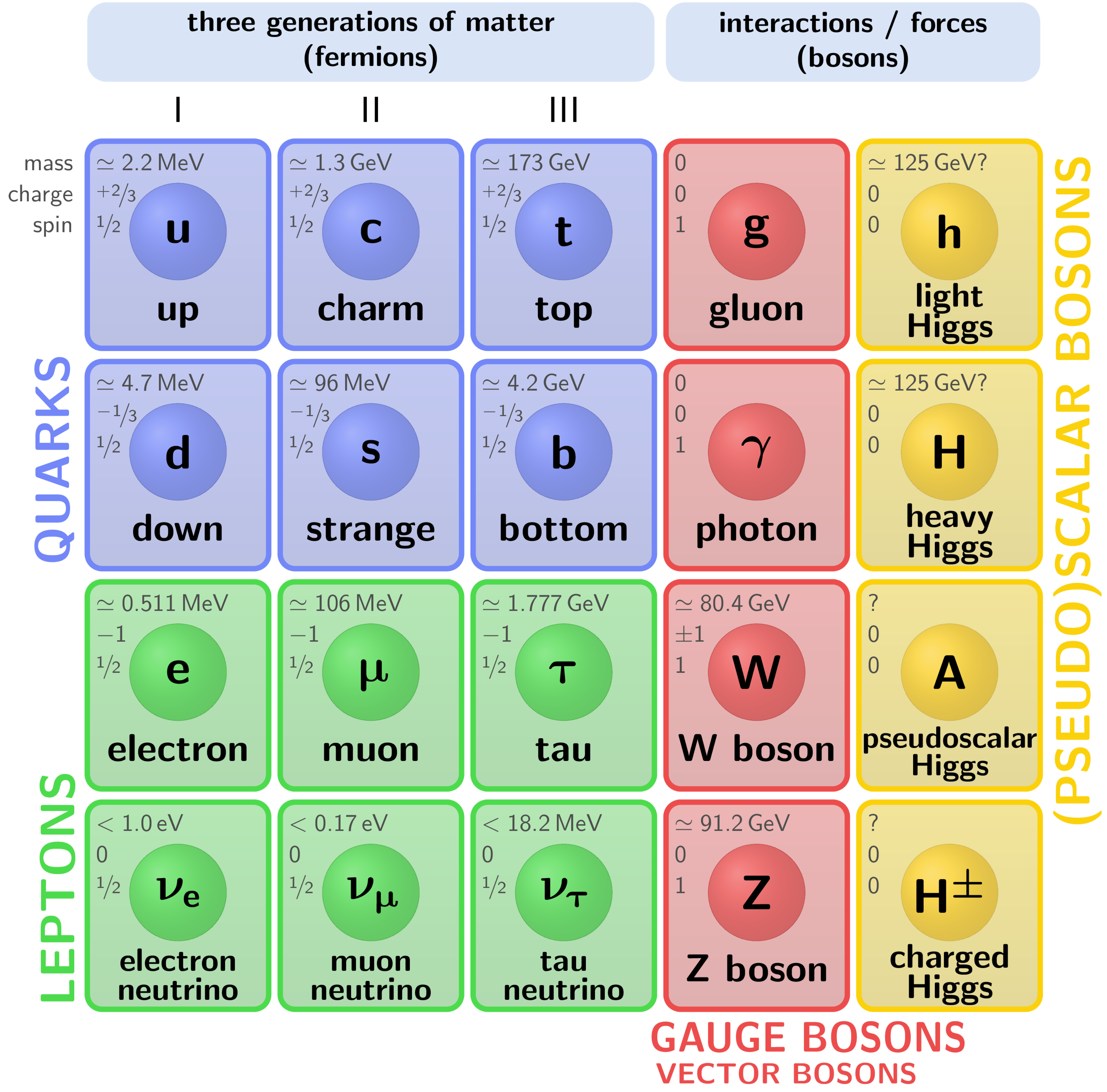
- ✦ Popular model where one additional doublet is included wrt SM
- ✦5 Higgs bosons are predicted, two of them neutral CP-even, one of them being the discovered one at LHC
- ✦Model described by six parameters: the masses of the bosons, the ratio of expectation values $\tan(\beta) = \frac{v_1}{v_2}$ and α the mixing angle between the two neutral CP-even states):

Type I : one Higgs doublet couples to vector bosons, the other to fermions

Type II: one doublet couples to up type quarks the other to down type quarks and leptons

Type LS: coupling to quarks as in as in type I, coupling to charged leptons as in type II

Flipped: coupling to quarks as in as in type II, coupling to charged leptons as in type I



THE κ FRAMEWORK

Run-I style Higgs interpretations for 2HDM model results based on reparameterising couplings in the κ framework:

- A set of dedicated modifiers κ_i for Higgs couplings, defined for inclusive observables and BR
- In this framework, the $\sigma \times BR$ for the various Higgs production and decay modes are expressed in the narrow-width approximation as :

$$\sigma_i \times B(H \to f) = \frac{\kappa_i^2 \kappa_f^2}{\kappa_H^2} \sigma_i^{SM} \times B^{SM}(H \to f)$$

where κ_i and κ_f are multiplicative factors applied on SM production and decay respectively

Production cross section	Resolved modifier
$\sigma(\text{ggF})$	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\text{VBF})$	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	κ_Z^2
$\sigma(gg \to ZH)$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	κ_W^2
$\sigma(t\bar{t}H)$	κ_t^2
$\sigma(tHW)$	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	κ_b^2
Partial decay width	
Γ^{bb}	κ_b^2
Γ^{WW}	κ_W^2
Γ^{gg}	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	κ_τ^2
Γ^{ZZ}	κ_Z^2
Γ^{cc}	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_t$
Γ^{ss}	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	κ_μ^2
Total width	
Γ_H	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

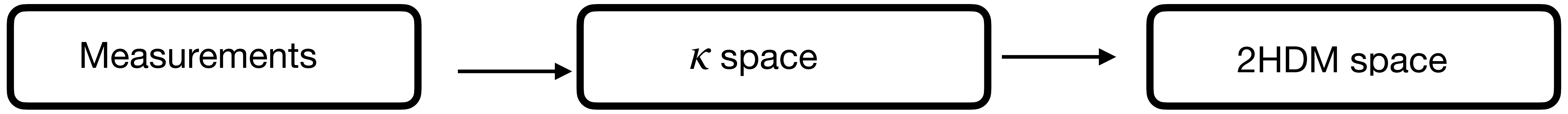
FROM κ TO 2HDM

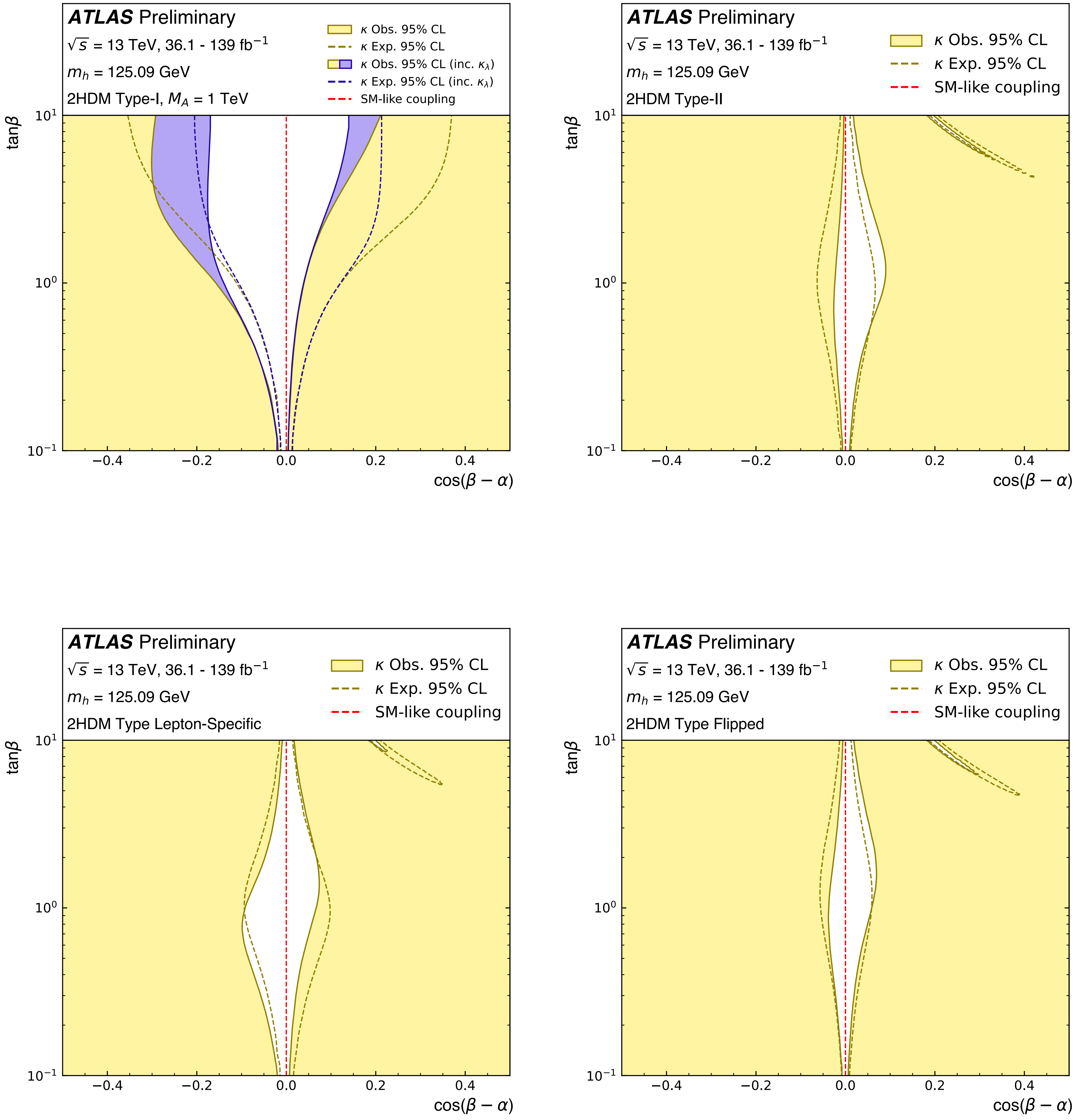
Constraints on coupling modifiers can be rotated into the 2HDM space in terms of 2D limits in the $\cos(\beta-\alpha), \tan(\beta)$ plane:

Coupling	Type I	Type II	Lepton-specific	Flipped
u, c, t	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$			
d, s, b	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$
e, μ, τ	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} - c_{\beta-\alpha} \times \tan\beta$	$s_{\beta-\alpha} + c_{\beta-\alpha}/\tan\beta$
W, Z	$s_{\beta-\alpha}$			
H	$s^3_{\beta-\alpha} + \left(3 - 2\frac{\bar{m}^2}{m_h^2}\right) c^2_{\beta-\alpha} s_{\beta-\alpha} + 2\cot(2\beta)\left(1 - \frac{\bar{m}^2}{m_h^2}\right) c^3_{\beta-\alpha}$			

$s_{\beta-\alpha} = \sin(\beta-\alpha)$
$c_{\beta-\alpha} = \cos(\beta-\alpha)$

- Interpretation using full experimental likelihood of inclusive cross-sections in different decay channels
- Parameterisation from κ framework to 2HDM as in the previous slide
- Petal structures appear due to "opposite sign" solutions not being completely excluded by data
- Effect of Higgs self-coupling κ_λ shown for Type I





SMEFT

SMEFT Lagrangian:

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \sum_{i,n} \frac{c_i^n \mathcal{O}_i^n}{\Lambda^{n-4}}$$

with n the dimension, and i running on all possible operators for a given dimension

- "top" flavour scheme: considering the third generation of quarks independently from the other two and dropping lepton flavour universality
- Inputs from the theory community exist for a large class of new physics models where SMEFT parameter is mapped out to new physics model parameters
- For this talk I'll consider the SMEFT to 2HDM parameterisation in Phy. Rev. D 102, 055012 (2020) - S.Dawson, S.Homiller, & S.D. Lane

- Relevant C_i (top flavour scheme) parametrised as function of the 2HDM parameters:

Phy. Rev. D 102, 055012 (2020) - S.Dawson, S.Homiller, & S.D. Lane

SMEFT parameters	Type I	Type II	Lepton-specific	Flipped
$\frac{v^2 c_{tH}}{\Lambda^2}$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$	$-Y_t c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{bH}}{\Lambda^2}$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$	$-Y_b c_{\beta-\alpha}/\tan\beta$	$Y_b c_{\beta-\alpha}\tan\beta$
$\frac{v^2 c_{eH,22}}{\Lambda^2}$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$Y_\mu c_{\beta-\alpha}\tan\beta$	$-Y_\mu c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_{eH,33}}{\Lambda^2}$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$	$-Y_\tau c_{\beta-\alpha}\tan\beta$	$Y_\tau c_{\beta-\alpha}\tan\beta$	$-Y_\tau c_{\beta-\alpha}/\tan\beta$
$\frac{v^2 c_H}{\Lambda^2}$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$	$c^2_{\beta-\alpha}M_A^2/v^2$

with Λ the SMEFT energy scale , v the VEV, Y_i the Yukawa-couplings ($Y_i = \sqrt{2}m_i/v$) and M_A is the common mass of the heavy decoupled scalars

SMEFT TO 2HDM PROCEDURE

Measurements → EFT space → 2HDM space

All measurements are rotated in the EFT space, info on nuisance parameters (NP) maintained

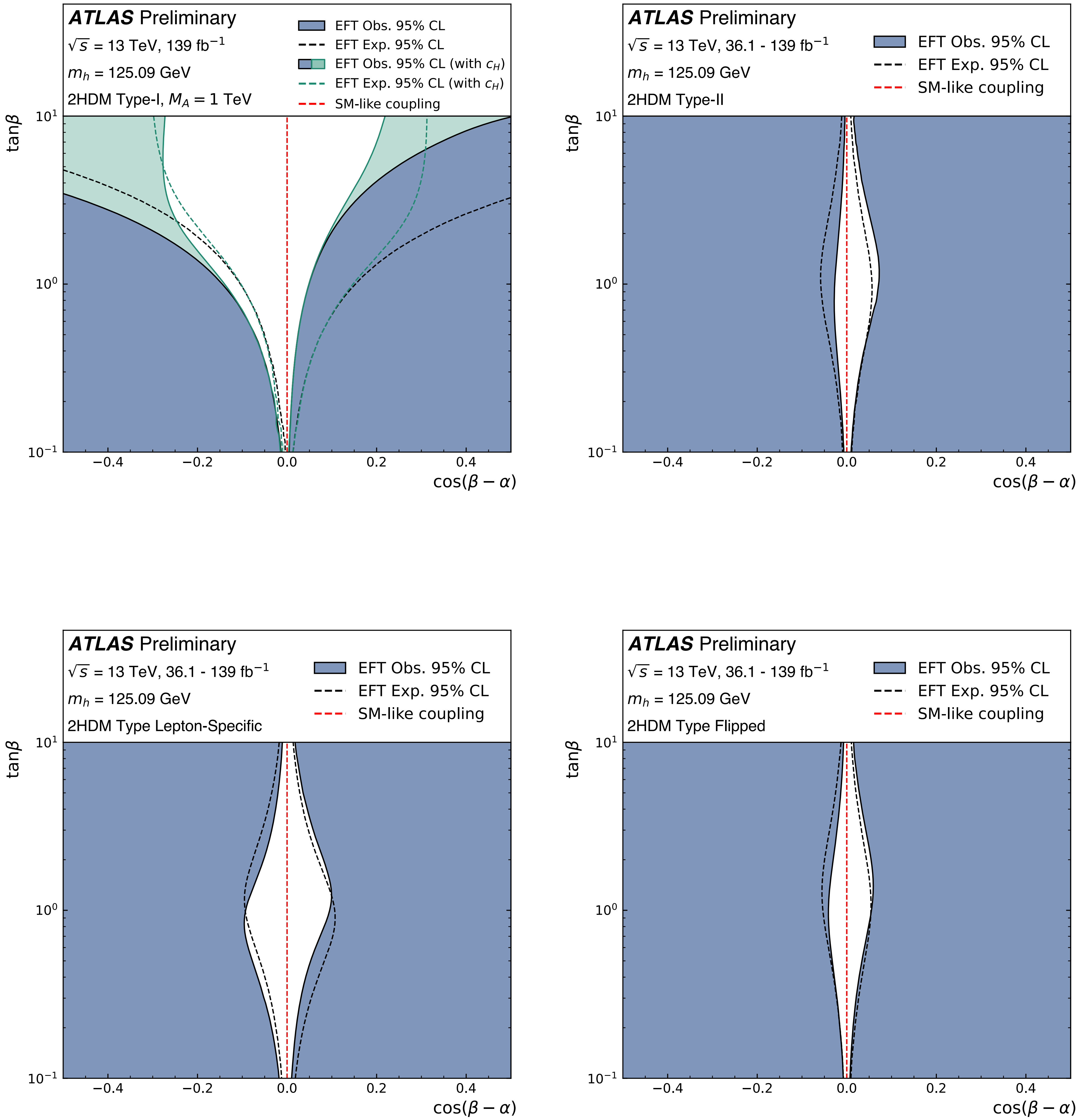
Relevant c_i re-parametrised as function of $\cos(\beta - \alpha), \tan(\beta)$, the rest fixed to SM

- Results obtained considering the systematics effect of experimental and theoretical uncertainties for the four types of 2HDM (combined likelihood from different Higgs channels has large complexity, O(3000) parameters)

- Formulas valid in the limit of $\cos(\beta - \alpha) \to 0$ (alignment limit), in agreement with EFT assumptions

Measurements → EFT space → 2HDM space

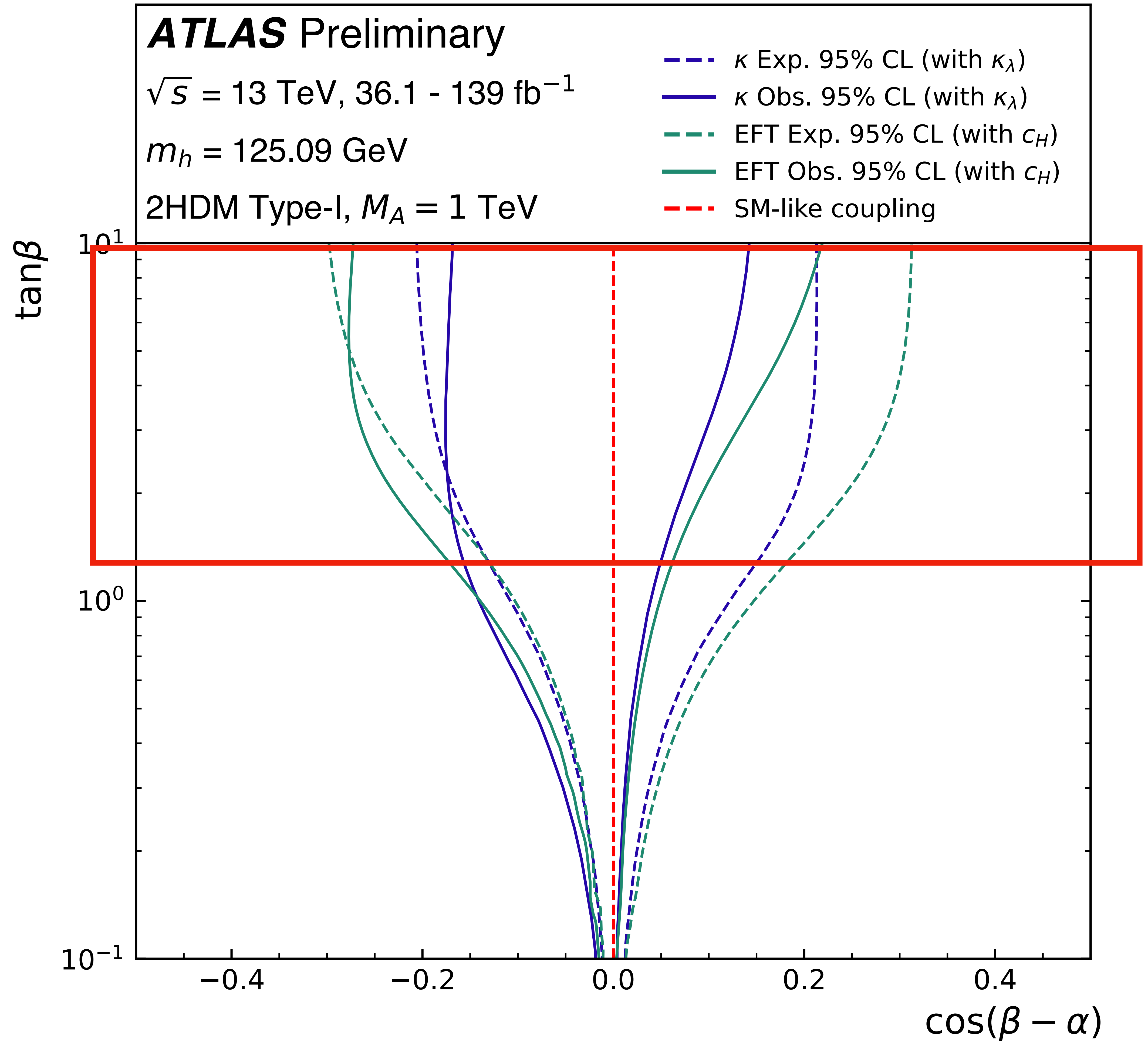
- Interpretation using full experimental likelihood of inclusive cross-sections in different decay channels (same measurements as the ones used for results in Slide 6)
- Parameterisation from EFT to 2HDM as in Slide 8
- Effect of c_H operator included for Type I
- Differences with κ constraints:
  - Petal structures are missing
  - Type I constraints at high $\tan\beta$
  - Linearisation differences



SMEFT VS κ FRAMEWORK: TYPE I CONSTRAINTS

Dimension six results are known not to reproduce full model results (PhysRevD.106.055012 - S.Dawson, D. Fontes, S. Homiller, M. Sullivan):

- Type I constraints are driven at high $\tan(\beta)$ by the effect of Higgs Boson couplings to vector bosons
- These effects are captured by EFT only at dimension eight

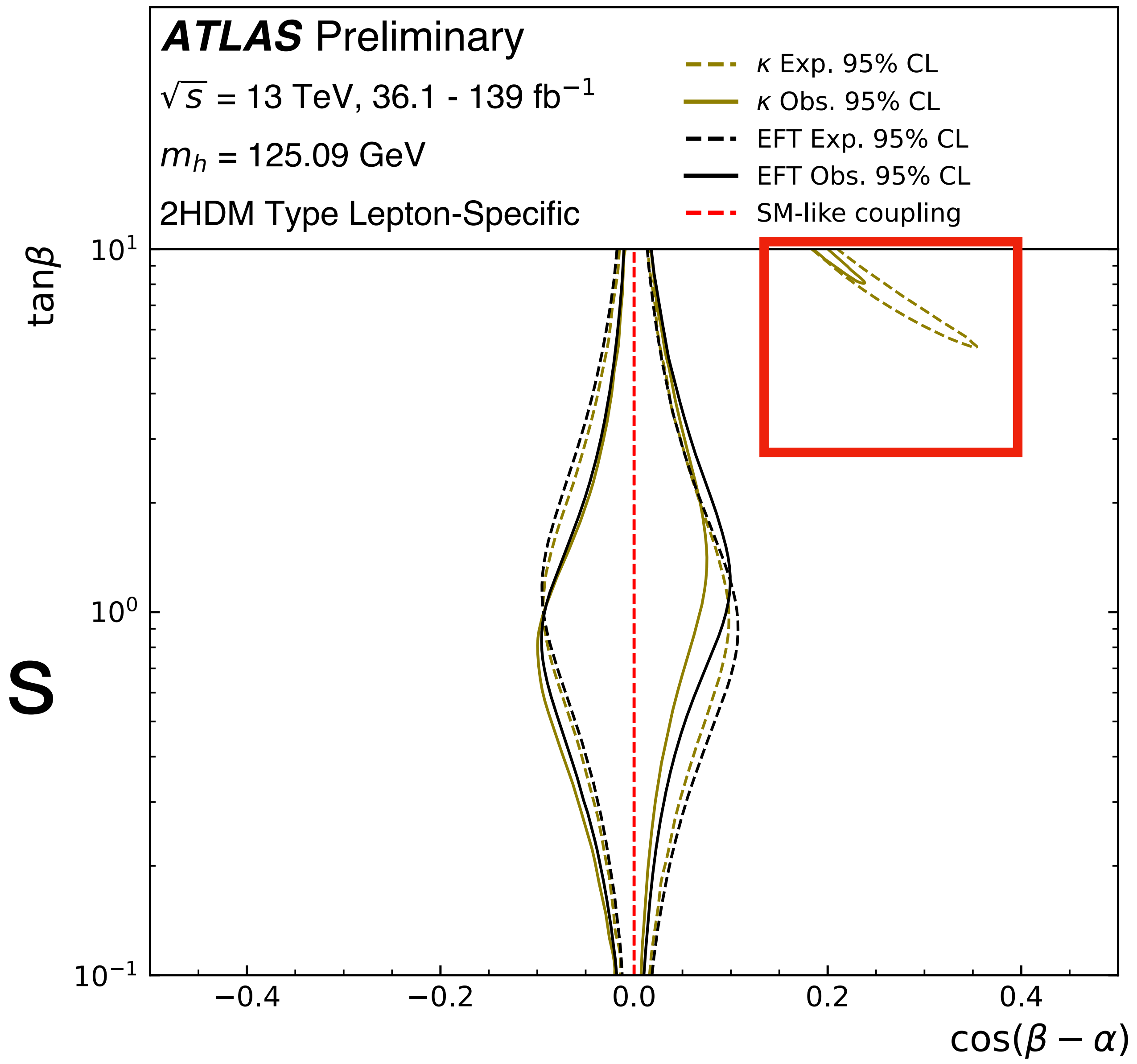


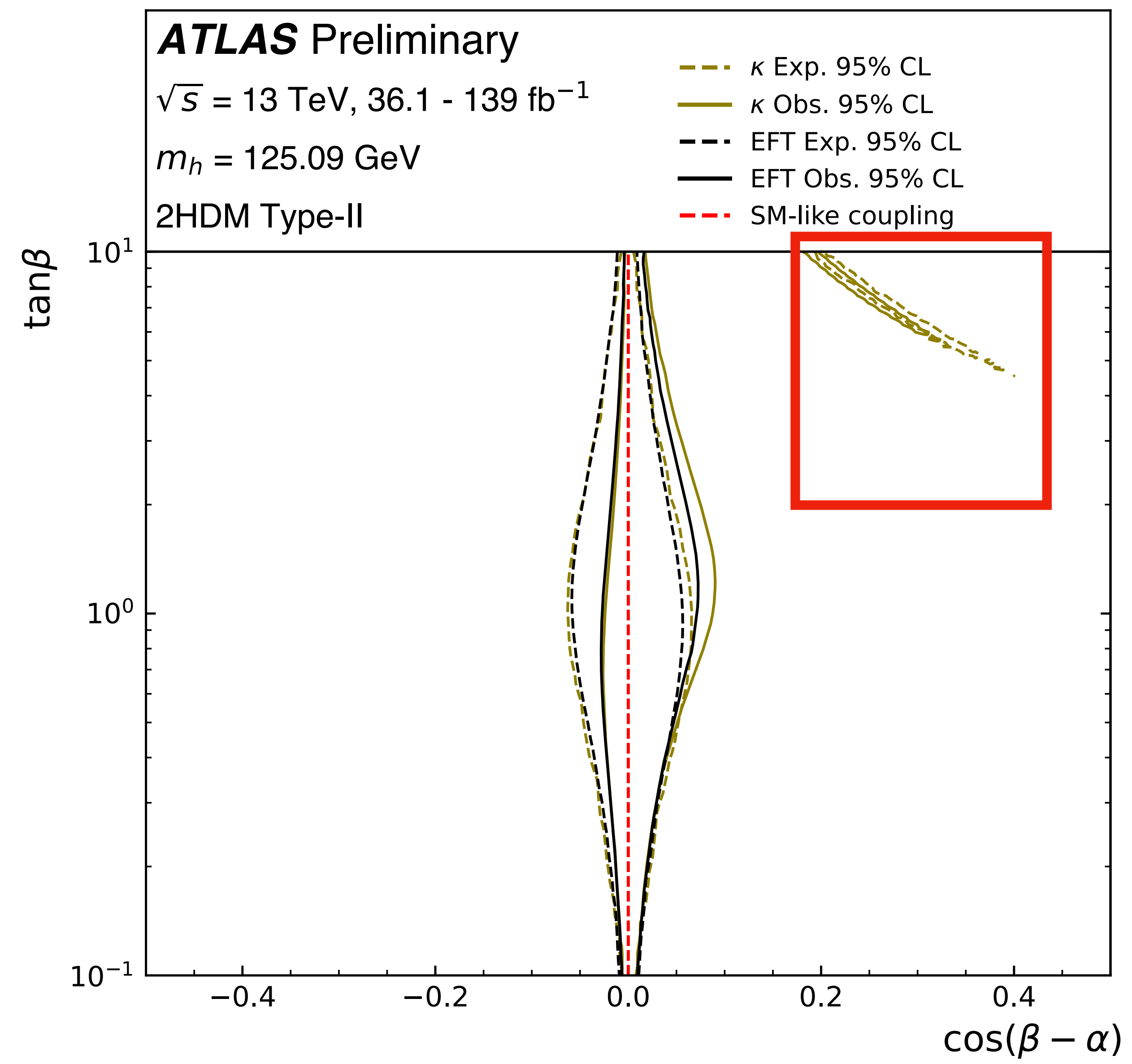
SMEFT VS κ FRAMEWORK: PETALS

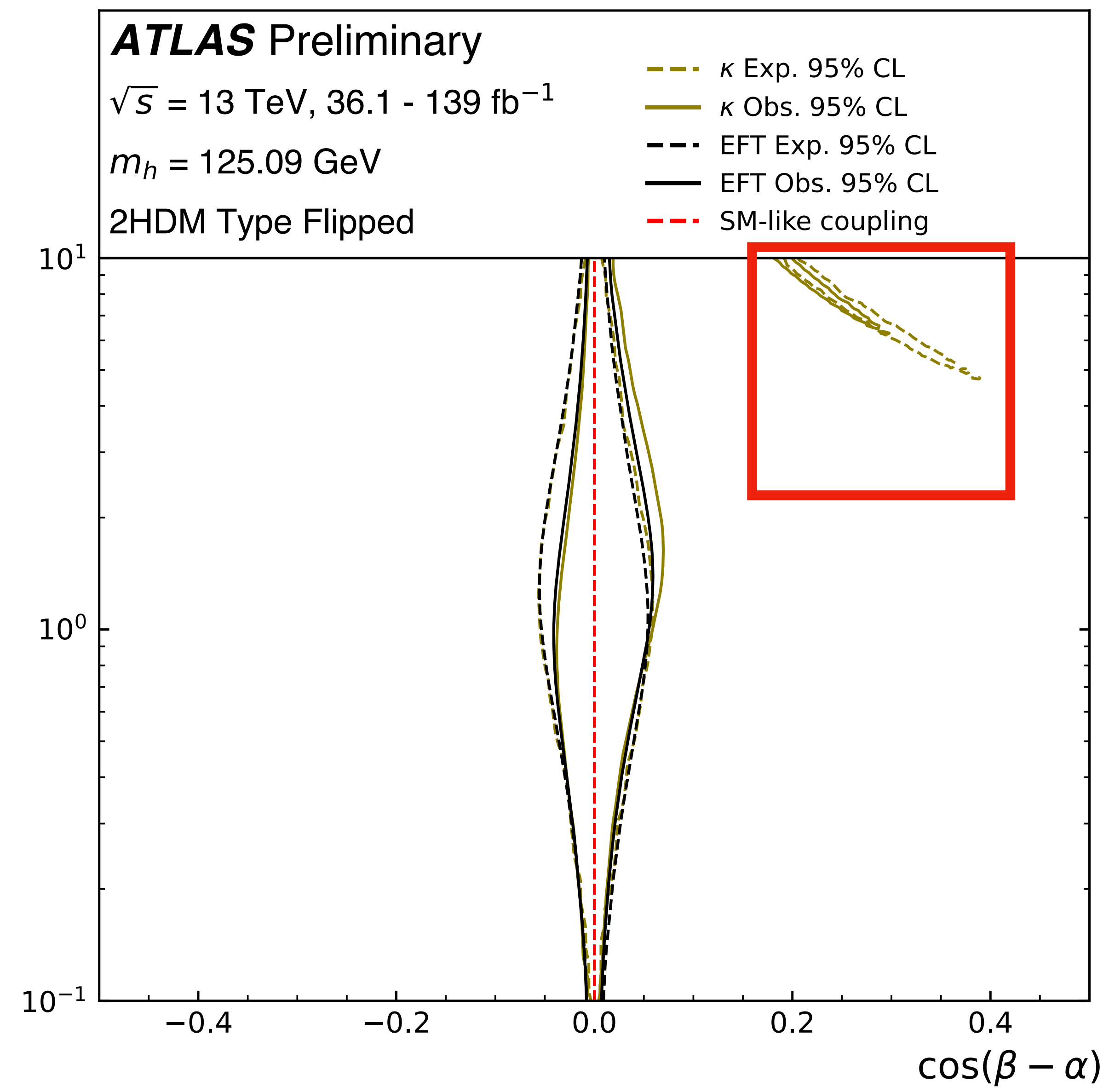
Dimension six results are known not to reproduce full model results ([PhysRevD.106.055012 - S.Dawson, D. Fontes, S. Homiller, M. Sullivan]):

- For type L,F and II dimension six is unable to capture the “opposite sign” solution, i.e. the classical petal structure found in the full model is not present (only one minimum possible).

- Quadratic effects can capture this to a certain extent







Additional differences come from the parametrisation of the measurements in terms of 2HDM parameters:

$$\frac{\kappa_{prod}^2 \, \kappa_{decay}^2}{\kappa_H^2}$$

$$\kappa_i \approx 1 + c_i$$

$$\sigma \times \Gamma^{H\to X} / \Gamma^H$$

used for published results!

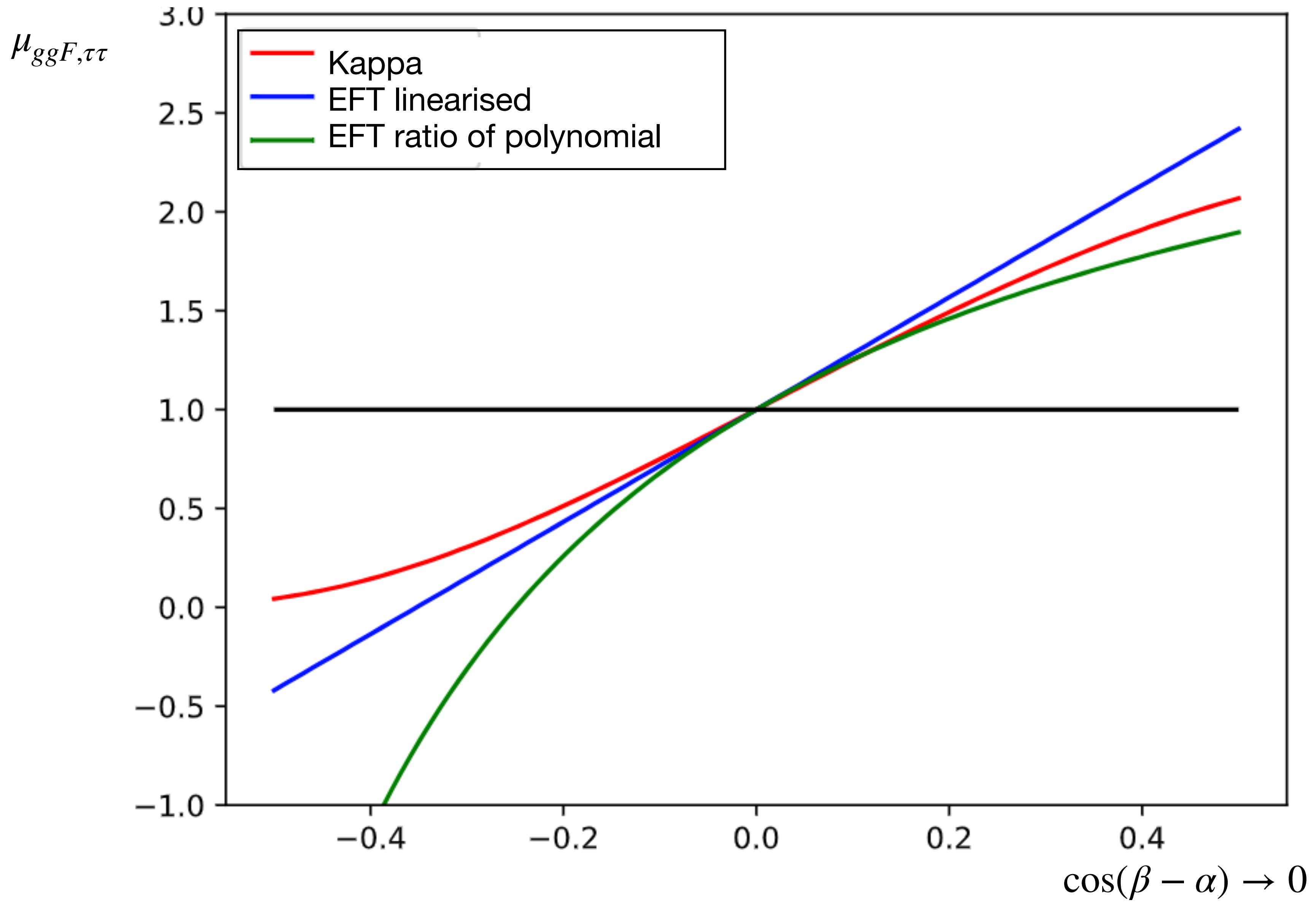
$$\frac{1 + \sum_i \left(A_i^{\sigma} + A_i^{\Gamma^{H\to X}}\right) c_i}{1 + \sum_i A_i^{\Gamma^H} c_i}$$

Ratio of polynomials

$$1 + \sum_j \left(A_j^{\sigma} + A_j^{\Gamma^{H\to X}} - A_j^{\Gamma^H}\right) c_j$$

Taylor expanded

Example of EFT modification to an input measurement

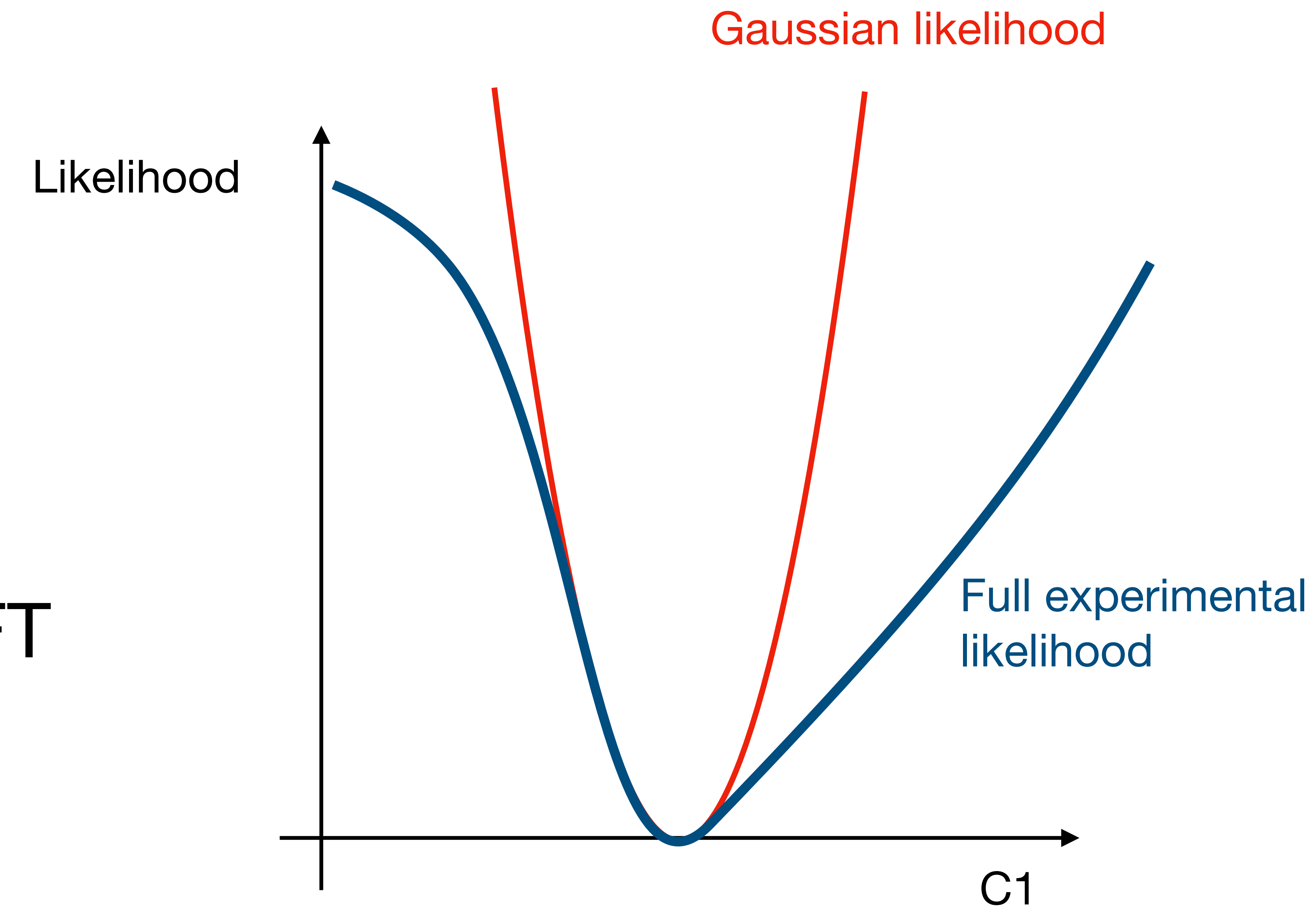


All three parameterisations are equivalent for $\cos(\beta - \alpha) \to 0$, difference is in terms of higher powers of $1/\Lambda$

EFT AS A INTERFACE

Can EFT be used as the interface between experiment and theory?

- Experimental likelihood not necessarily gaussian, mainly due to handling of Taylor expansion in the parameterisation
- Full likelihood results can be different than results obtained constructing χ^2 fits around published results
- Publishing EFT results requires information on underlying measurements and how to parametrised them in terms of EFT operators



CONCLUSIONS

Conclusions:

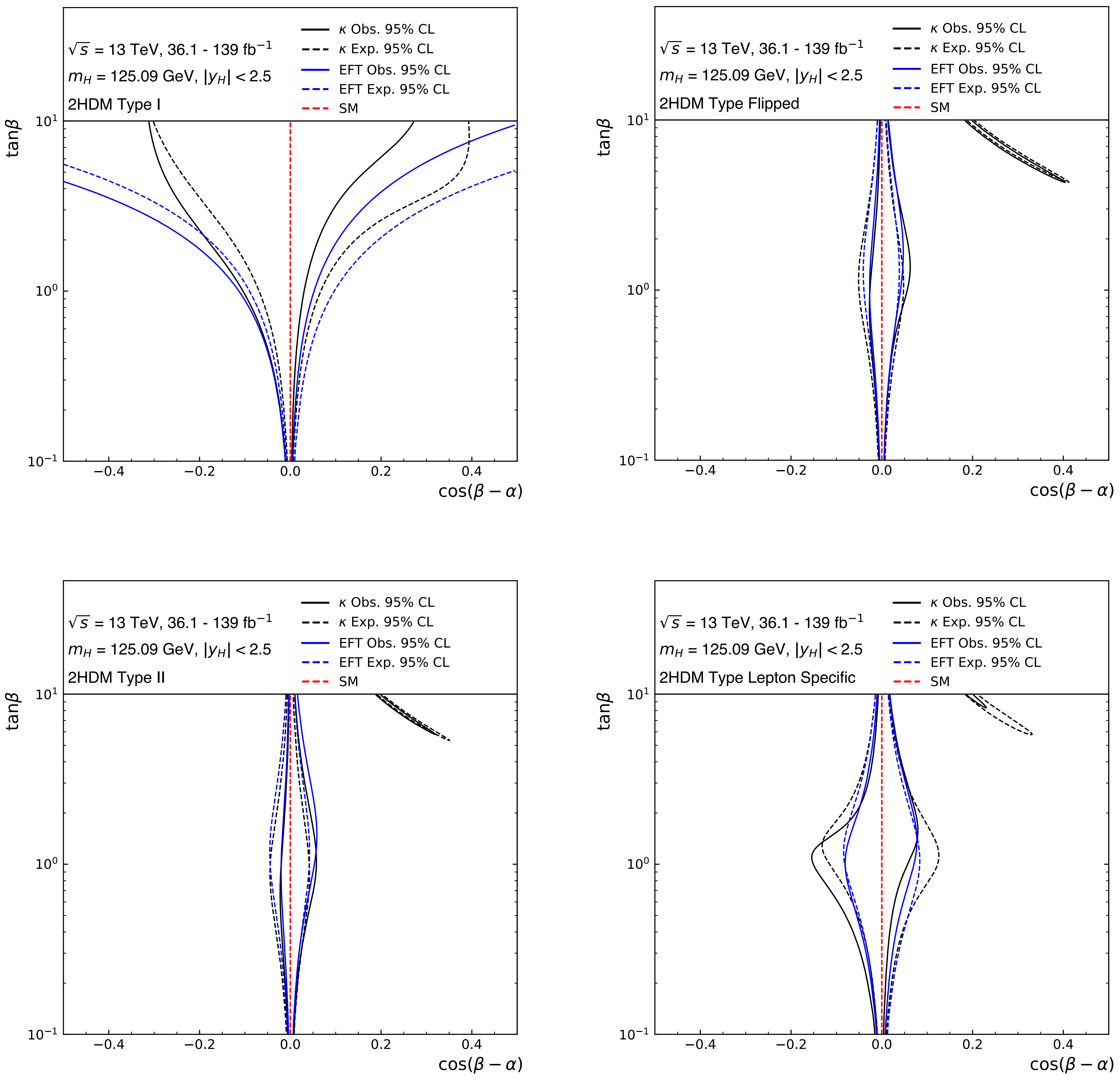
- SMEFT to UV has been included for the first time in the most recent interpretation of Higgs combined results
- EFT to 2HDM procedure in ATLAS and comparison with κ-derived results shown today

Discussion:

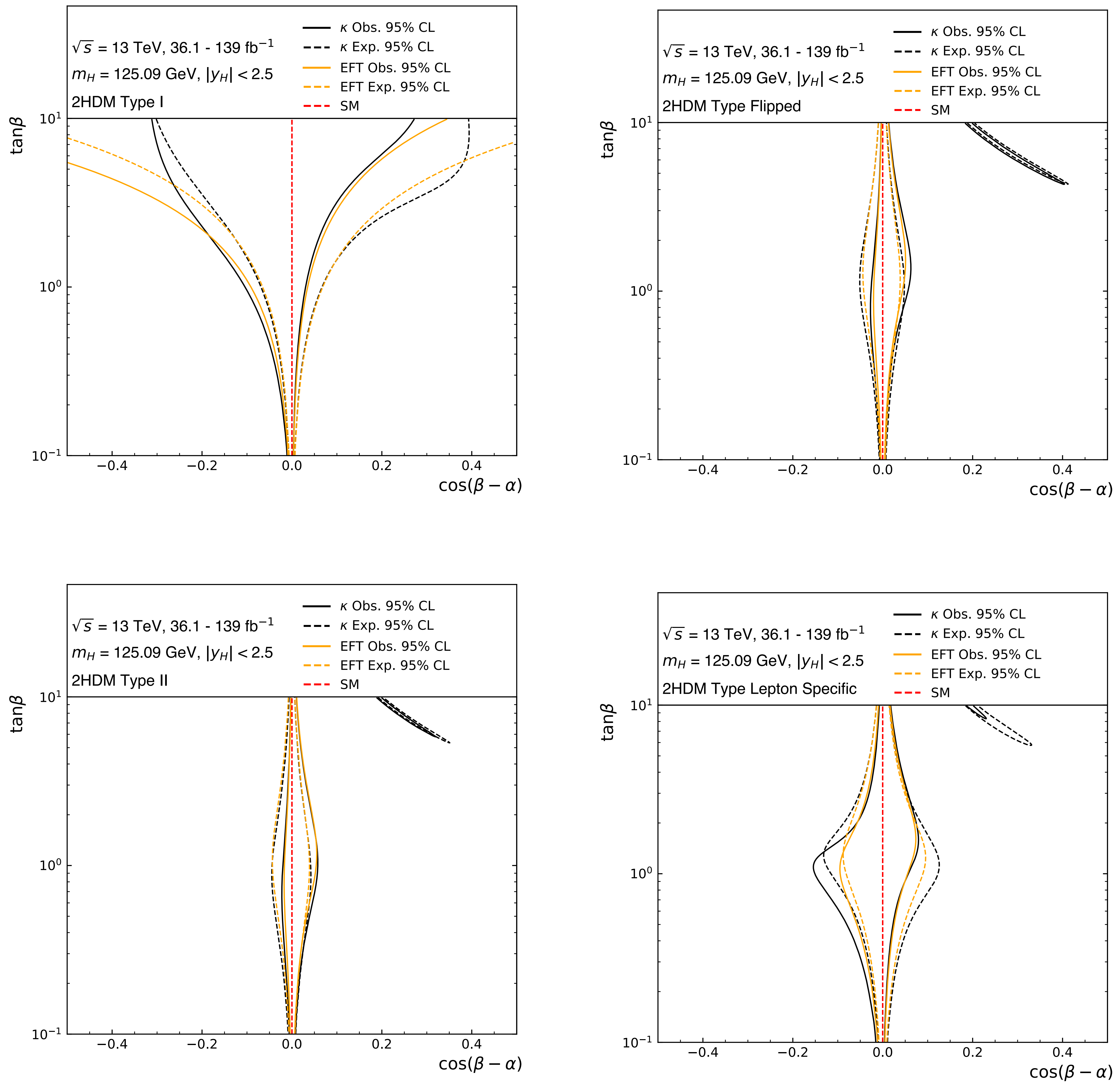
- Limitations of these procedures in the context of Higgs combinations and global EFT fits (effect of linearisation and choice of parameterisation, dim. 8 …)
- Extending UV matching in ATLAS to different models?
- Bridge between experimental results and theory: can EFT be the interface for this? (Advantages and disadvantages?)

BACK -UP

EFFECT OF LINEARISATION



Taylor expanded



Ratio of polynomials

SMEFT VS κ FRAMEWORK: LINEARISATION

Dimension six results are known not to reproduce full model results ([S.Dawson, D. Fontes, S. Homiller, M. Sullivan]):

- Effect of linearisation in EFT procedure is cause for more differences between κ and EFT derived constraints (effect also known and discussed in paper above)

$$\sigma \times \Gamma^{H\to X}/\Gamma^{H}$$

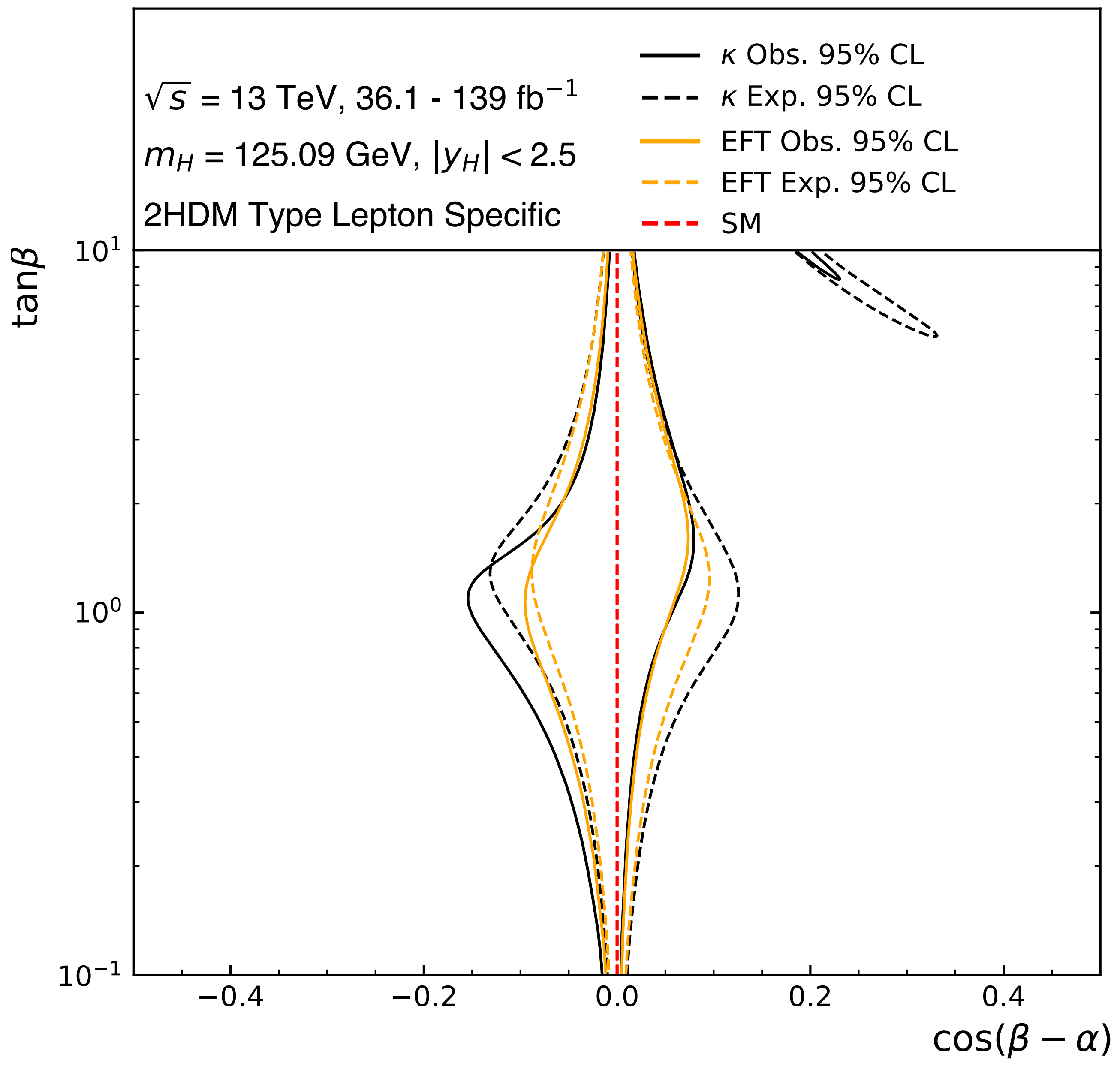
$$\frac{1+\sum_i \left(A_i^{\sigma}+A_i^{\Gamma^{H\to X}}\right)c_i}{1+\sum_i A_i^{\Gamma^H}c_i}$$

Ratio of polynomials

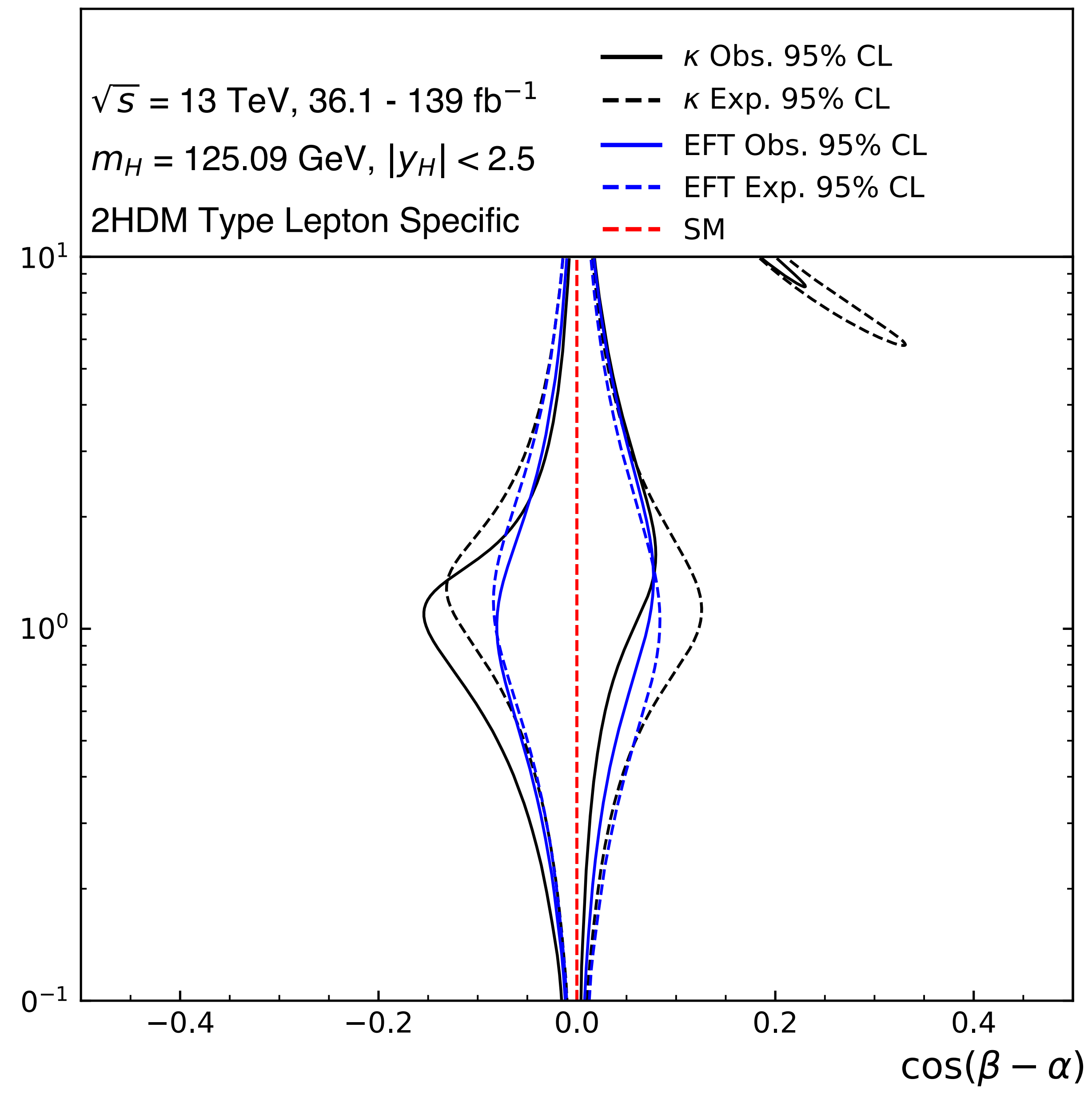
$$1+\sum_j \left(A_j^{\sigma}+A_j^{\Gamma^{H\to X}}-A_j^{\Gamma^H}\right)c_j$$

Taylor expanded

Study with simplified likelihood



EFT: Ratio of polynomials



EFT: Taylor expanded

EFFECT OF LINEARISATION