NLO Unitarity Fits of the THDM

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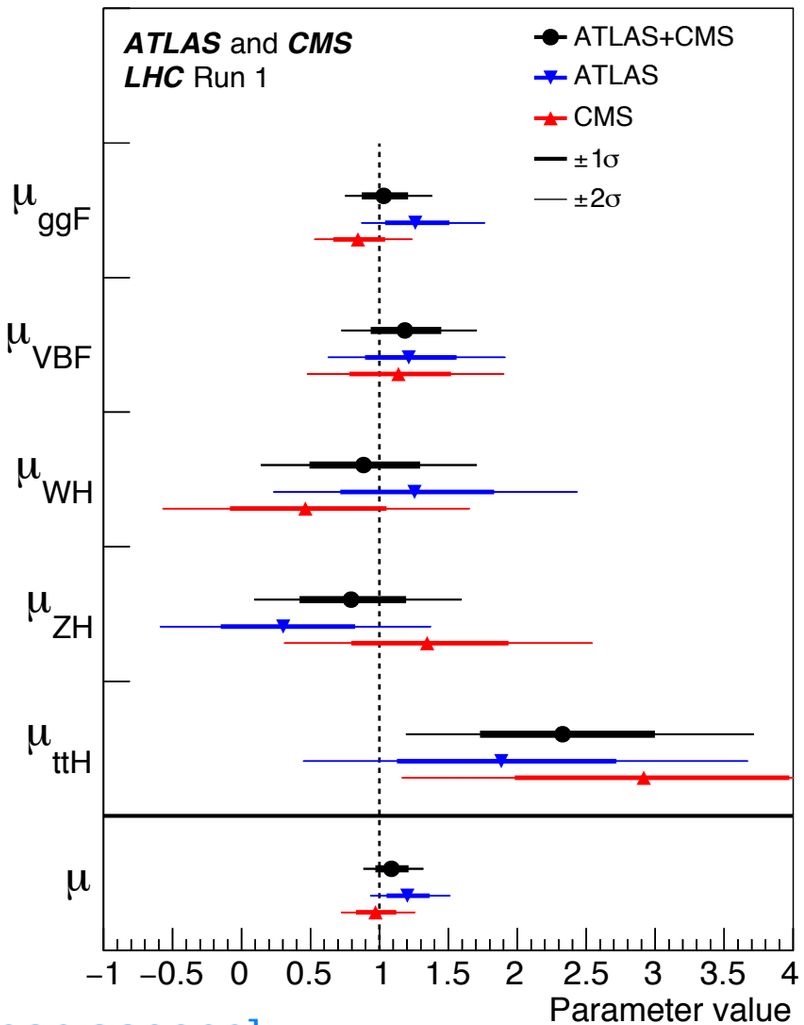
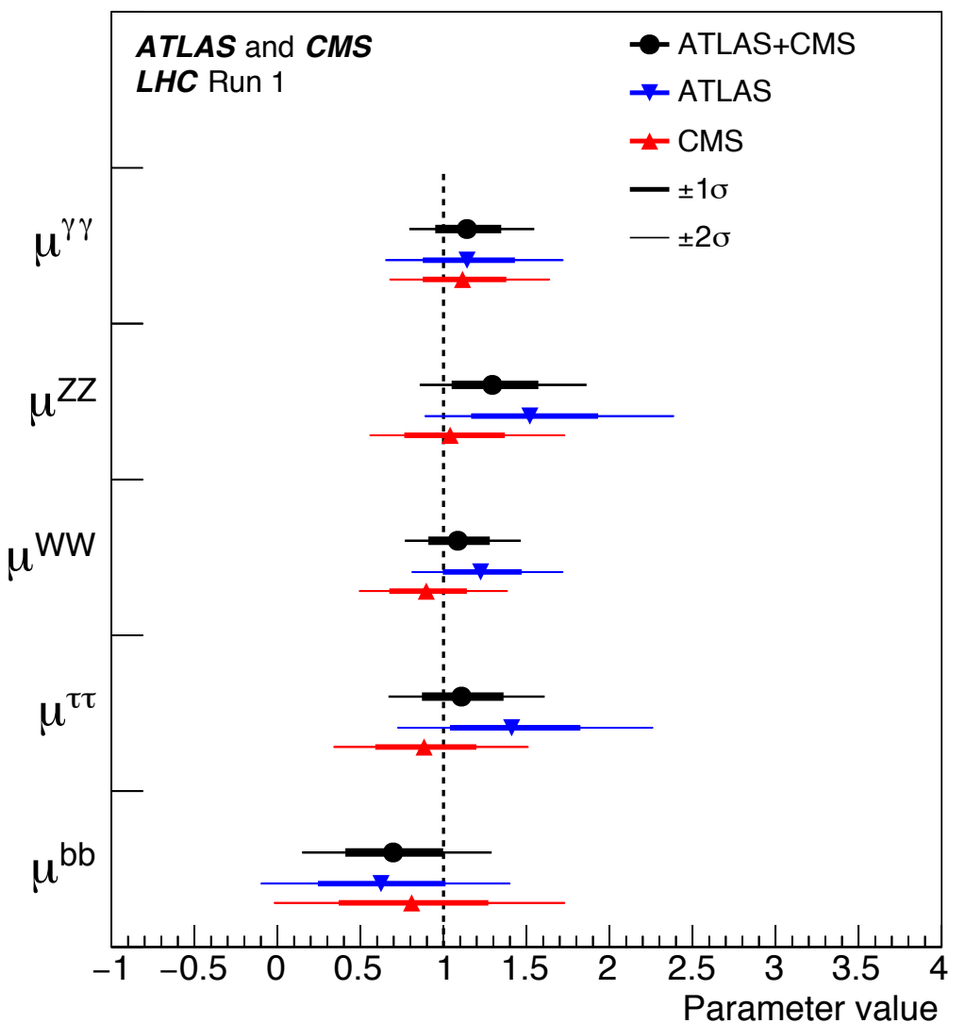
[arXiv:1607.0XXXX]

SUSY 2016
Melbourne
July 7, 2016

Higgs Discovery at LHC

* Mass of the Higgs is around 125 GeV
* Higgs is parity even and spin-0
* Measurements are in reasonable agreement with SM-predictions.





[arXiv:1606.002266]

Motivation

- All couplings of the 125 GeV Higgs seem to be like SM, but :
  - Why spin-0 content is minimal while spin-1/2 is not?
  - No evidence of any degrees of freedom which could ensure the naturalness of the Higgs mass.
  - Dark Matter
  - Vacuum Meta-stability

Model

We consider two-Higgs-doublet-model to address these issues.

2HDM: SM supplemented by a second Y=+1 complex scalar.

$$V_H^{\text{2HDM}} = m_{11}^2 \Phi_1^\dagger \Phi_1 + m_{22}^2 \Phi_2^\dagger \Phi_2 - m_{12}^2 \left(\Phi_1^\dagger \Phi_2^\dagger + \Phi_2^\dagger \Phi_1 \right)$$
$$+ \frac{\lambda_1}{2} \left(\Phi_1^\dagger \Phi_1 \right)^2 + \frac{\lambda_2}{2} \left(\Phi_2^\dagger \Phi_2 \right)^2 + \lambda_3 \left(\Phi_1^\dagger \Phi_1 \right) \left(\Phi_2^\dagger \Phi_2 \right)$$
$$+ \lambda_4 \left(\Phi_1^\dagger \Phi_2 \right) \left(\Phi_2^\dagger \Phi_1 \right) + \frac{\lambda_5}{2} \left[\left(\Phi_1^\dagger \Phi_2 \right)^2 + \left(\Phi_2^\dagger \Phi_1 \right)^2 \right]$$

We impose a softly broken Z_2 symmetry ($\Phi_1 \to -\Phi_1$ and $\Phi_2 \to -\Phi_2$) to avoid tree-level flavor changing neutral currents.

We consider CP-conserving 2HDM i.e. $m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \ldots, \lambda_5 \in \mathcal{R}$

Yukawa sector

t couples to Φ_2,

- b couples to Φ_2,
  - τ couples to Φ_2 — **Type I**
  - τ couples to Φ_1 — **Type X**
- b couples to Φ_1,
  - τ couples to Φ_2 — **Type Y**
  - τ couples to Φ_1 — **Type II**

Parameters

$$\langle \Phi_i \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_i \end{pmatrix} \qquad \tan\beta = \frac{v_2}{v_1} \qquad v^2 = v_1^2 + v_2^2$$

The 8 potential parameters ($m_{11}^2, m_{22}^2, m_{12}^2, \lambda_1, \ldots, \lambda_5$) can be translated into 8 physical parameters

$$v \approx 246 \text{ GeV}, \qquad m_h = 125 \text{ GeV}$$

$$m_H\,,\ m_A\,,\ m_{H^+}\,,\ m^2_{12}\,,\ \tan\beta\,,\ \beta\text{-}\alpha$$

The Higgs Basis and Alignment

Linear Transformation to go to the Higgs basis:

$$\begin{pmatrix} H_1 \\ H_2 \end{pmatrix} = \begin{pmatrix} c_\beta & s_\beta \\ -s_\beta & c_\beta \end{pmatrix} \begin{pmatrix} \Phi_1 \\ \Phi_2 \end{pmatrix} \quad \Rightarrow \quad \langle H_1^0 \rangle = \frac{v}{\sqrt{2}}, \langle H_2^0 \rangle = 0$$

$$\begin{aligned} V =& Y_1 H_1^\dagger H_1 + Y_2 H_2^\dagger H_2 + Y_3 (H_1^\dagger H_2 + \text{h.c.}) + \frac{1}{2} Z_1 (H_1^\dagger H_1)^2 \\ & Z_3 (H_1^\dagger H_1)(H_2^\dagger H_2) + Z_4 (H_1^\dagger H_2)(H_2^\dagger H_1) + \\ & \left[\frac{1}{2} Z_5 (H_1^\dagger H_2)^2 + \left\{ Z_6 (H_1^\dagger H_1) + Z_7 (H_2^\dagger H_2) \right\} H_1^\dagger H_2 + \text{h.c.} \right] \end{aligned}$$

$$\mathcal{M}_H^2 = \begin{pmatrix} Z_1 v^2 & Z_6 v^2 \\ Z_6 v^2 & m_A^2 + Z_5 v^2 \end{pmatrix}$$

$$m_A^2 = m_{H^\pm}^2 - \frac{1}{2} v^2 (Z_5 - Z_4)$$

$$m_{H^\pm}^2 = Y_2 + \frac{1}{2} v^2 Z_3$$

One of the two CP-even mass eigenstates will be SM-like if aligned with the direction of the vacuum expectation value

$$h = (\sqrt{2}\text{Re}H_1^0 - v) s_{\beta-\alpha} + \sqrt{2}\text{Re}H_2^0 c_{\beta-\alpha}$$

$$H = (\sqrt{2}\text{Re}H_1^0 - v) c_{\beta-\alpha} - \sqrt{2}\text{Re}H_2^0 s_{\beta-\alpha}$$

Alignment in h is SM-like scenario

$$h \simeq (\sqrt{2}\mathrm{Re}H_1^0 - v)$$

$$c_{\beta-\alpha} = \frac{-Z_6 v^2}{\sqrt{(m_H^2 - m_h^2)(m_H^2 - Z_1 v^2)}} \simeq 0$$

$m_H^2 \gg v^2$: **Decoupling limit**

New states will be difficult to discover at the LHC

$|Z_6| \ll 1$: **Alignment limit**

New states could be well in the reach of the LHC

[Gunion, Haber '02, Craig et al. '13, Carena et al. '13]

[See also the talk by Howard Haber]

Theoretical Constraints

* **Positivity of the scalar potential:** [Deshpande, Ma '78]

$$\lambda_1 > 0, \qquad \lambda_2 > 0,$$
$$\lambda_3 > -\sqrt{\lambda_1 \lambda_2}, \quad \lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}$$

* **Avoiding an unstable vacuum:** [Barroso, Ferreira, Ivanov, Santos '13]

$$m_{12}^2 \left(m_{11}^2 - \sqrt{\lambda_1/\lambda_2}\, m_{22}^2 \right) \left(\tan\beta - \sqrt[4]{\lambda_1/\lambda_2} \right) > 0$$

* **Perturbativity of the quartic couplings:**

Perturbativity in SM: $\lambda = \dfrac{m_h^2}{2v^2} \approx 0.13 \ll 1$

Prior to Higgs discovery, there were upper limits from RGE and Unitarity.

Using LO RGE: $\lambda(M_Z) \lesssim 5$ **Using NLO RGE:** $\lambda(M_Z) \lesssim 2.2$

[Nierste, Riesselmann '97]

* Unitarity constraint

Imposing the S-matrix to be unitary, i.e. $SS^\dagger=\mathbb{1}$, constrains partial wave amplitudes:

$$\left|a_\ell^{2\to 2}-\frac{i}{2}\right|^2+\sum_{n>2}\left|a_\ell^{2\to n}\right|^2=\frac{1}{4}$$

For large $s\equiv(p_1+p_2)^2$, we can neglect $a_\ell^{2\to n}$ part and set $\ell=0$

$$\Rightarrow\ \left|\Re\left(a_0^{2\to 2}\right)\right|\leq\frac{1}{2}\quad\textbf{and}\quad a_0^{2\to 2}=\frac{1}{16\pi s}\int_{-s}^{0}dt\mathcal{M}(s,t)$$

In SM, at LO: $a_0^{2\to 2}=-\dfrac{3\lambda}{8\pi}\Rightarrow\lambda\lesssim 4$ [Lee, Quigg, Thacker '77]

In SM, at NLO: $\lambda\lesssim 2.2$ [Dawson, Willenbrock '89; Durand, Johnson, Lopez '92]

* Unitarity in THDM

$\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ instead of λ in THDM $\Rightarrow$ a_0 to be a matrix

Tree-level unitarity matrix after imposing Z_2 symmetry

$$\frac{1}{8\pi}\begin{pmatrix}
\lambda_1 & \lambda_5 & & & & & & & & & & \\
\lambda_5 & \lambda_2 & & & & & & & & & & \\
 & & \lambda_3+\lambda_4 & & & & & & & & & \\
 & & & \lambda_3-\lambda_4 & & & & & & & & \\
 & & & & \lambda_1 & \lambda_4 & & & & & & \\
 & & & & \lambda_4 & \lambda_2 & & & & & & \\
 & & & & & & \lambda_3 & \lambda_5 & & & & \\
 & & & & & & \lambda_5 & \lambda_3 & & & & \\
 & & & & & & & & 3\lambda_1 & 2\lambda_3+\lambda_4 & & \\
 & & & & & & & & 2\lambda_3+\lambda_4 & 3\lambda_2 & & \\
 & & & & & & & & & & \lambda_3+2\lambda_4 & 3\lambda_5 \\
 & & & & & & & & & & 3\lambda_5 & \lambda_3+2\lambda_4
\end{pmatrix}$$

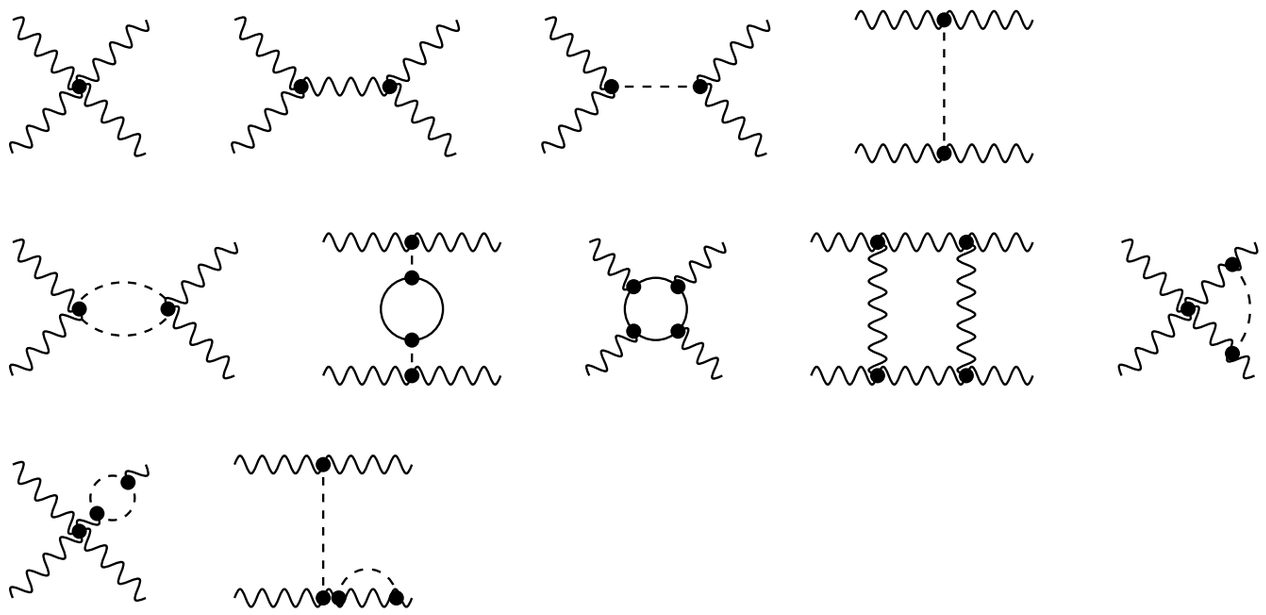
Tree-level eigenvalues of the unitarity matrix

$$\begin{aligned}
a_0^{(1,2)} &= \frac{1}{16\pi}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_5^2}\right)\\
a_0^{(3,4)} &= \frac{1}{16\pi}\left(\lambda_1+\lambda_2 \pm \sqrt{(\lambda_1-\lambda_2)^2+4\lambda_4^2}\right)\\
a_0^{(5,6)} &= \frac{1}{16\pi}\left(3(\lambda_1+\lambda_2) \pm \sqrt{9(\lambda_1-\lambda_2)^2+4(2\lambda_3+\lambda_4)^2}\right)\\
a_0^{(7,8)} &= \frac{1}{8\pi}\left(\lambda_3 \pm \lambda_4\right)\\
a_0^{(9,10)} &= \frac{1}{8\pi}\left(\lambda_3 \pm \lambda_5\right)\\
a_0^{(11,12)} &= \frac{1}{8\pi}\left(\lambda_3+2\lambda_4 \pm 3\lambda_5\right)
\end{aligned}$$

[Ginzburg, Ivanov '05]

* NLO Unitarity in THDM

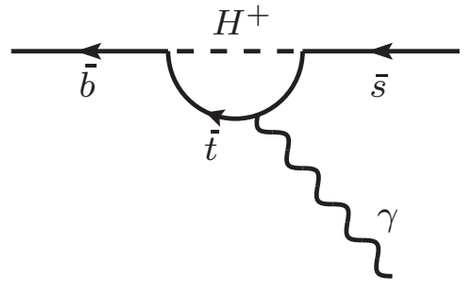
[Grinstein, Murphy, Uttayarat '15]



* **Perturbativity of the NLO Contribution:** $R_1' = \dfrac{\left|a_0^{\rm NLO}\right|}{\left|a_0^{\rm LO}\right|} \leq 1$

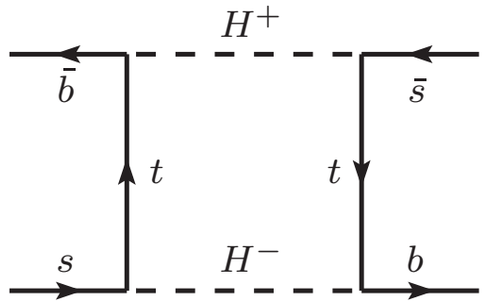
Experimental Constraints

Flavor and Electroweak Observables



$\mathcal{B}(b \to s\gamma)$

[Hermann, Misiak, Steinhauser '12; Misiak et al. '15; HFAG '14]



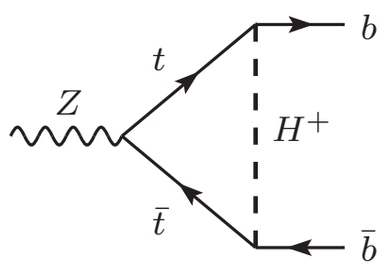
Δm_{B_s}

[Deschamps et al. '09; LHCb '13]

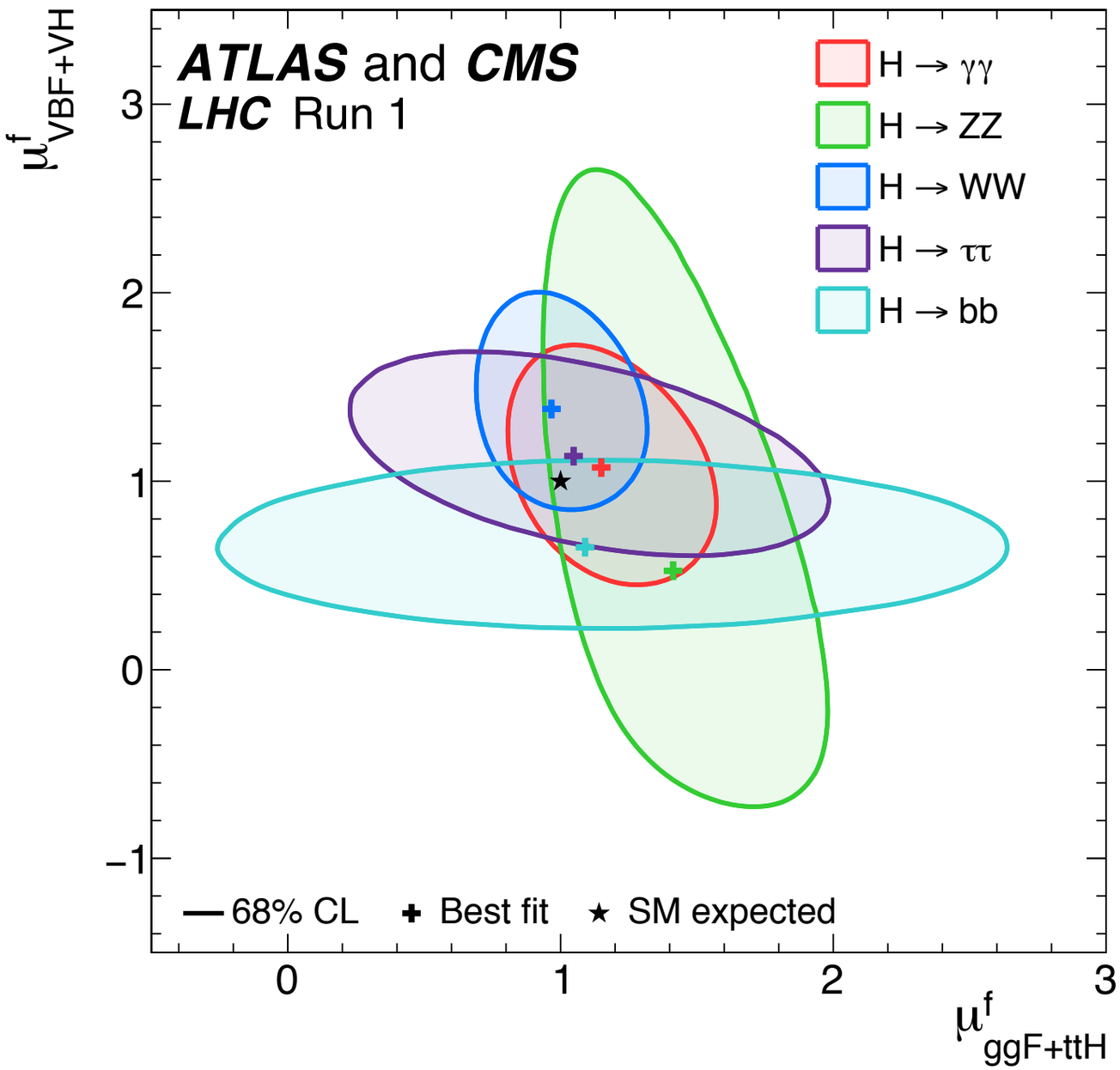
$M_W,\ \Gamma_W,\ \Gamma_Z,\ \sin^2\theta_l^{\text{eff}},\ \sigma^0_{\text{had}},\ A^{0,l}_{\text{FB}},\ A^{0,c}_{\text{FB}},\ A^{0,b}_{\text{FB}},\ A_l,\ A_c,\ A_b,\ R^0_l,\ R^0_c,\ R^0_b$

[Zfitter '90,'01,'06; LEP & SLD '06]

[HEPfit '16]

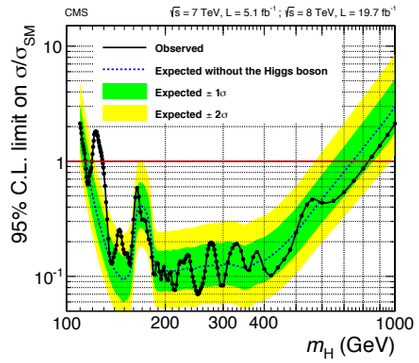


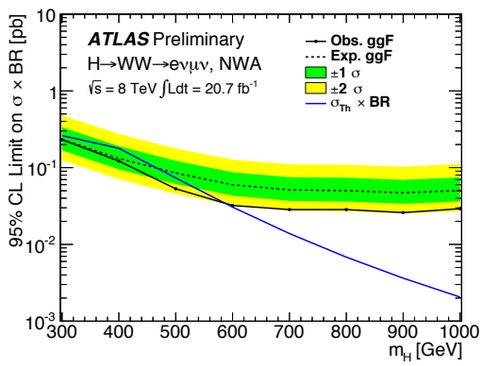
Light Higgs Signal Strengths

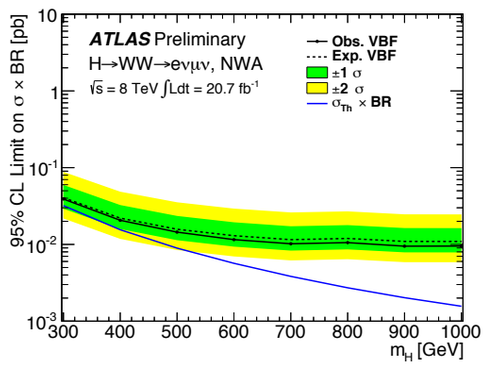


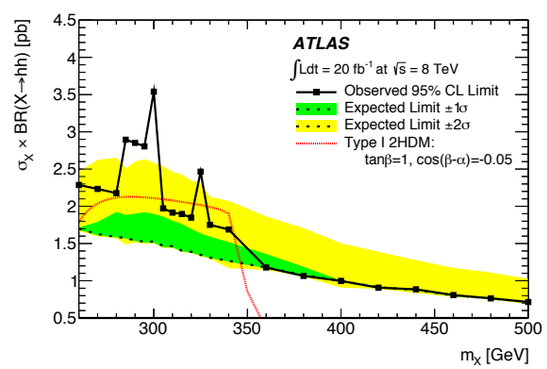
[arXiv:1606.002266]

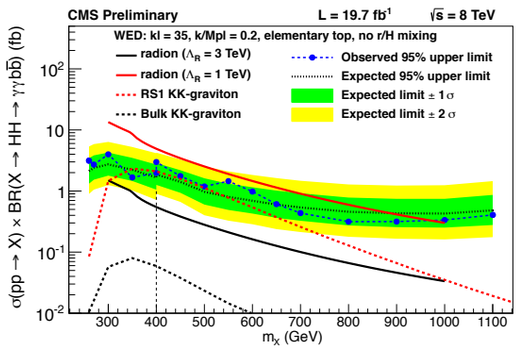
Heavy Higgs Searches at LHC

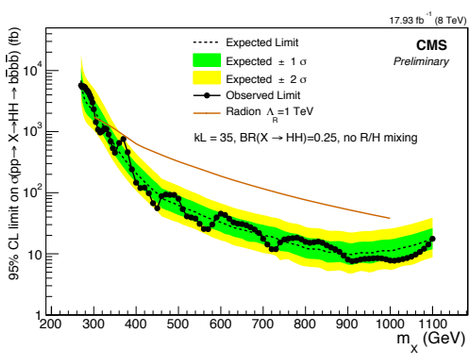


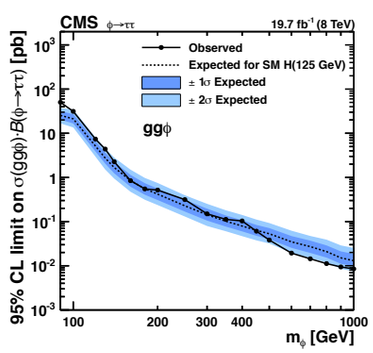


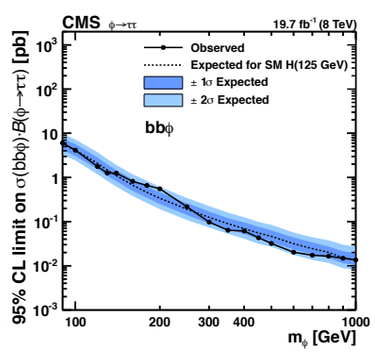


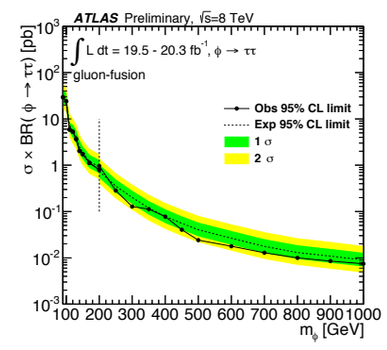


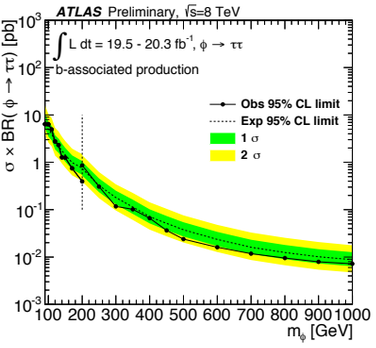


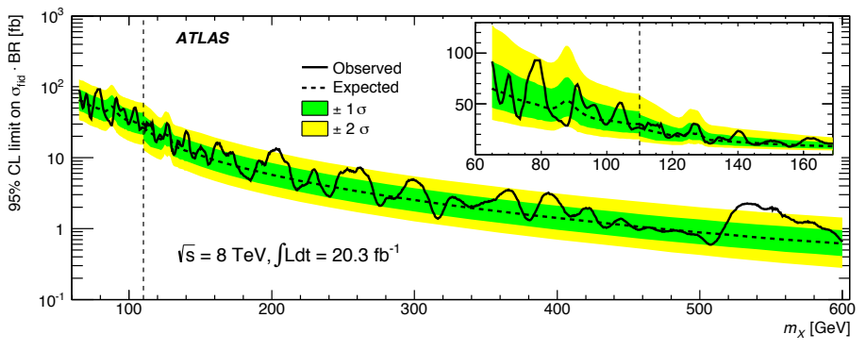


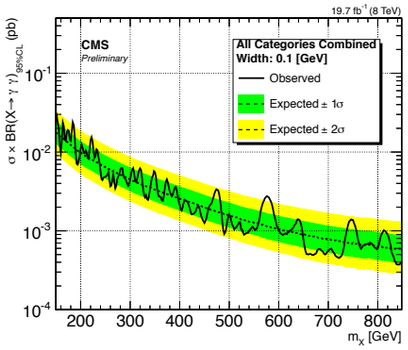


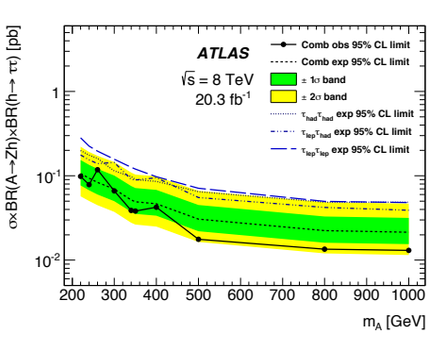




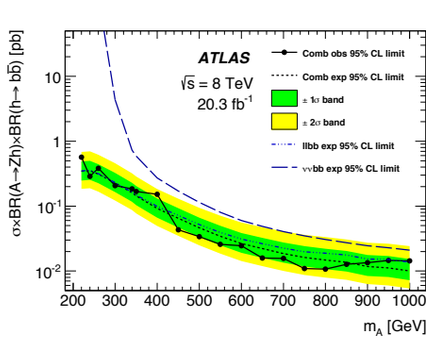




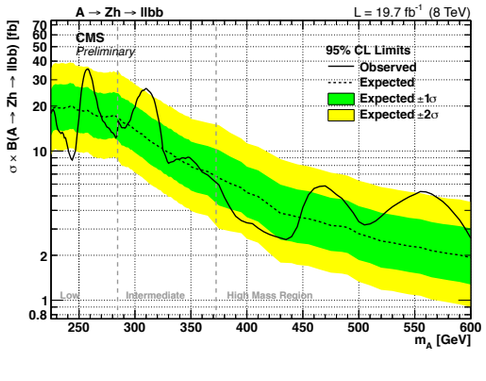


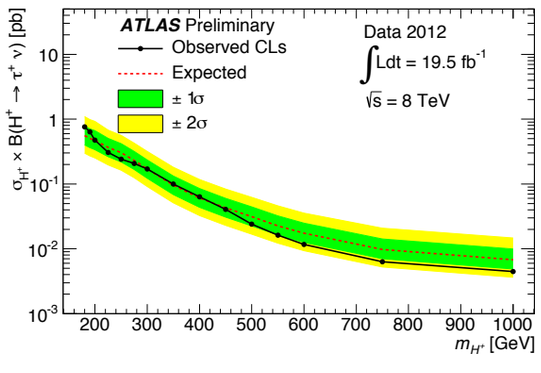


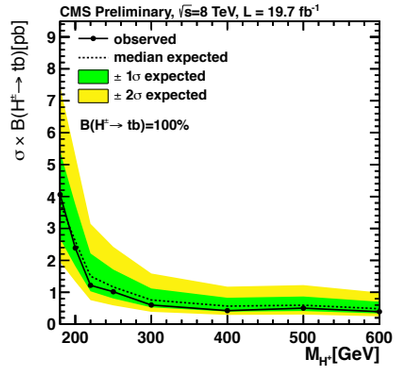
(a) $A \to Zh,\ h \to \tau\tau$

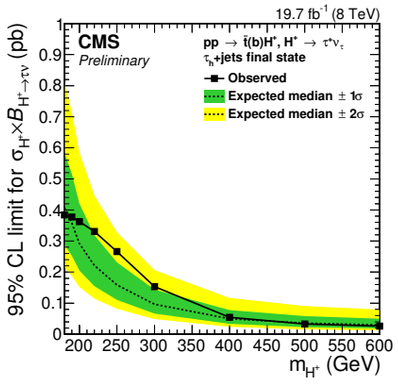


(b) $A \to Zh,\ h \to bb$



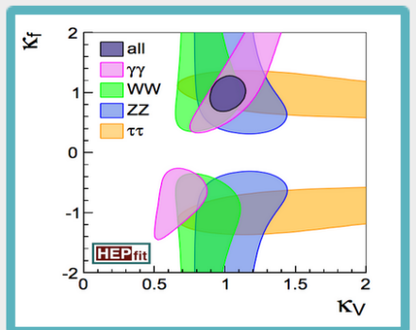






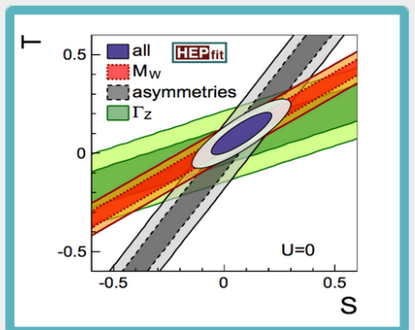
[LHC '15]

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.



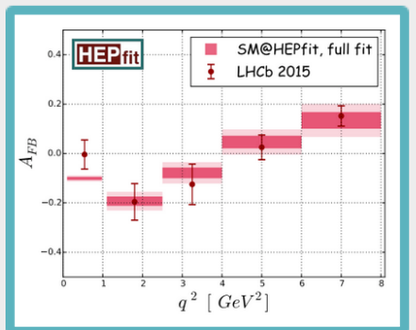
Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



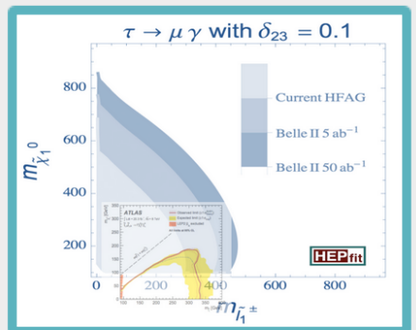
Precision Electroweak

Electroweak precision observables are included in HEPfit



Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.



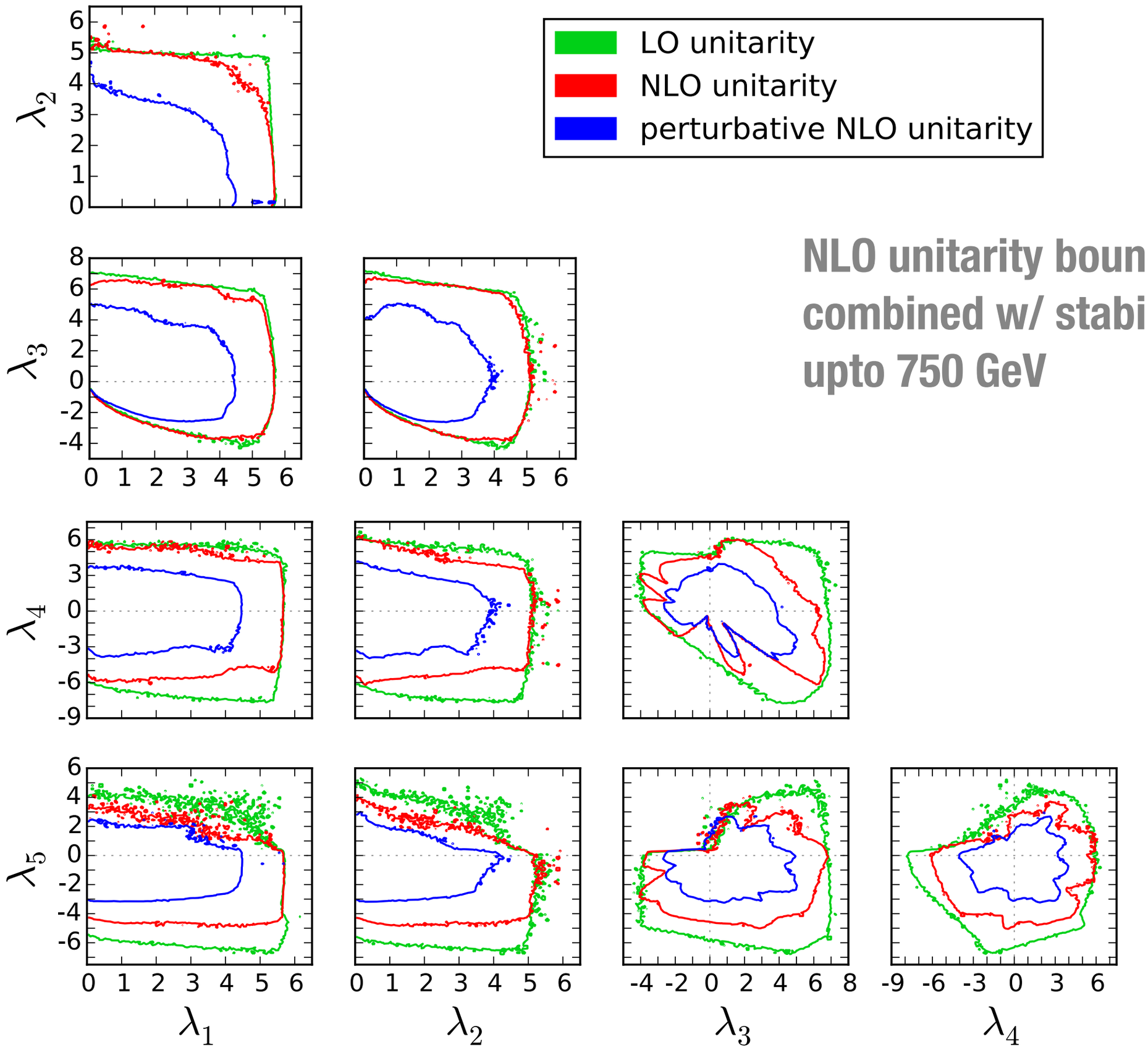
BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

- **Flexible open-source C++ code to do calculations with various observables in the SM and beyond:**
  - **Simple user-defined models and/or observables**
  - **Stand-alone or library modes to compute single observables.**
  - **Optional Bayesian fitting framework to do global statistical analyses (run-time optimized, parallelized; can be replaced by a different one)**

For more details, look at the talk by J. de Blas on Monday afternoon

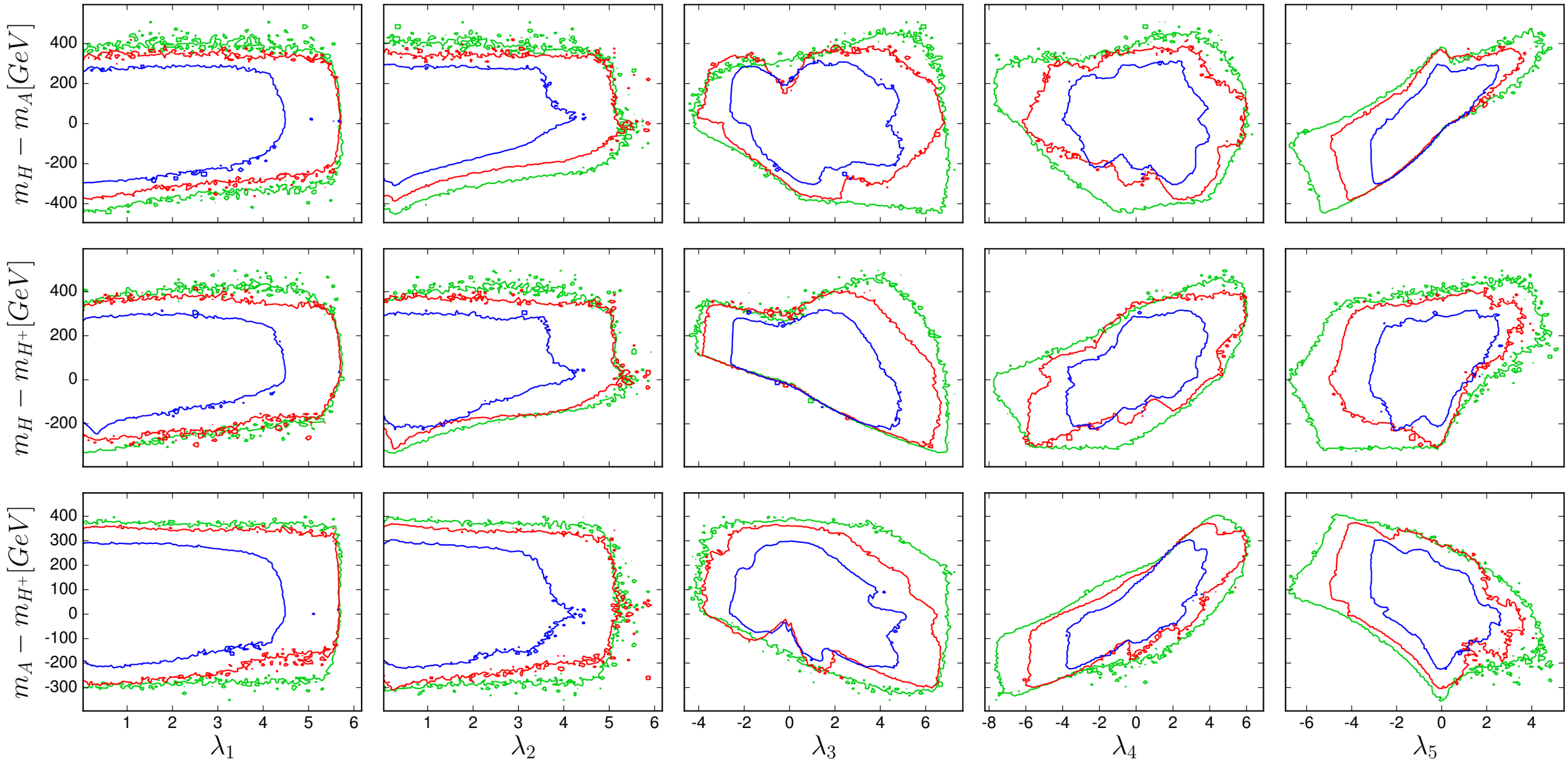
Quartic Couplings



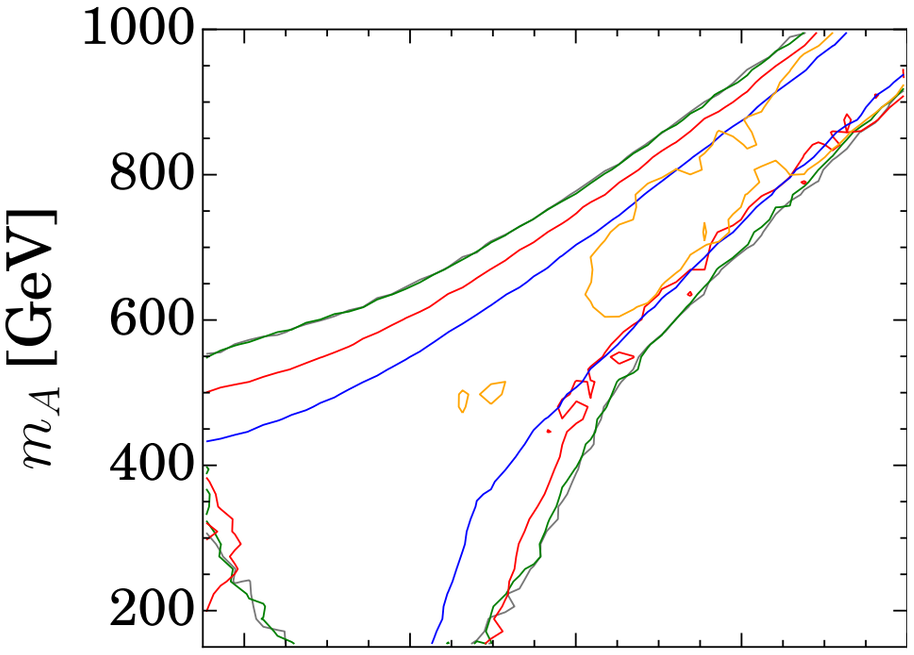
NLO unitarity bounds combined w/ stability upto 750 GeV

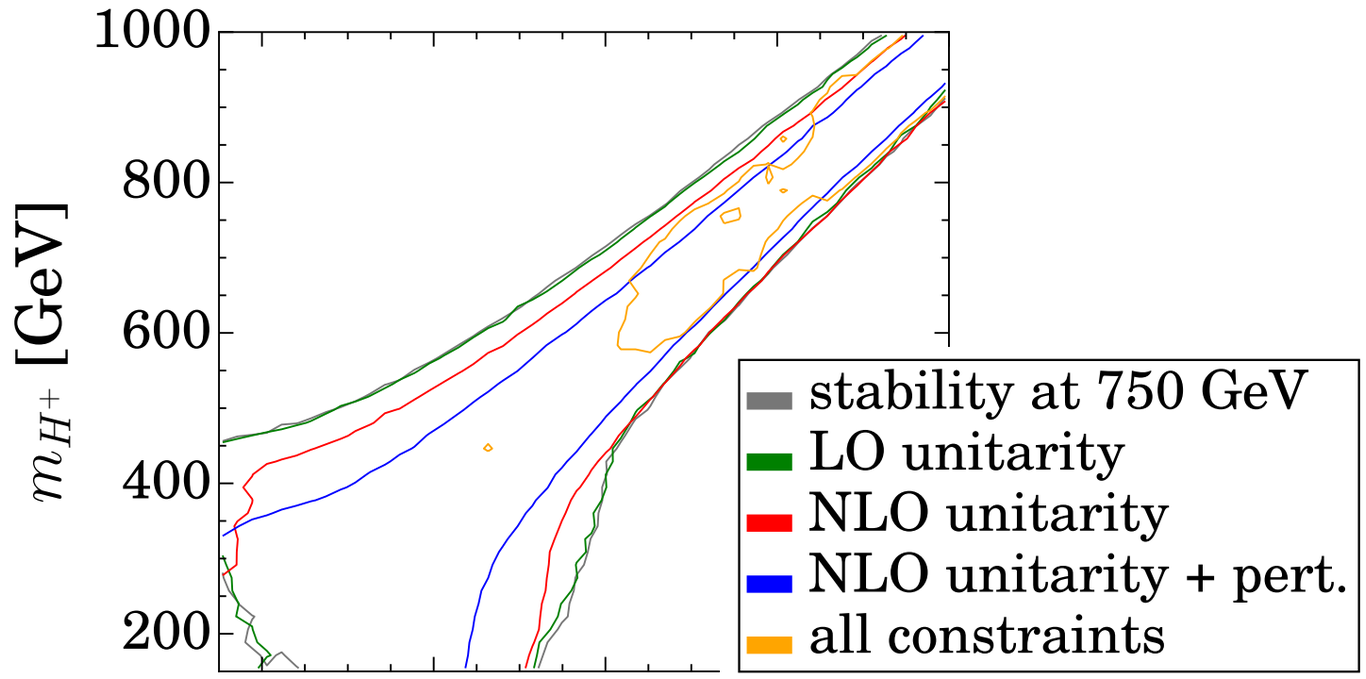
Light Higgs Signal Strengths

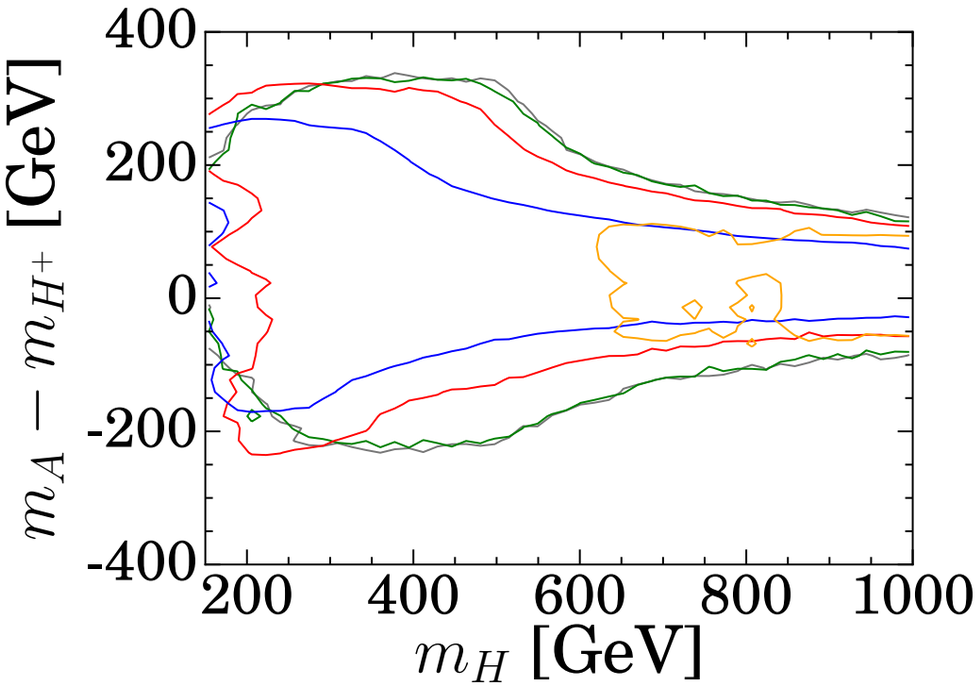
NLO unitarity bounds combined w/ stability upto 750 GeV

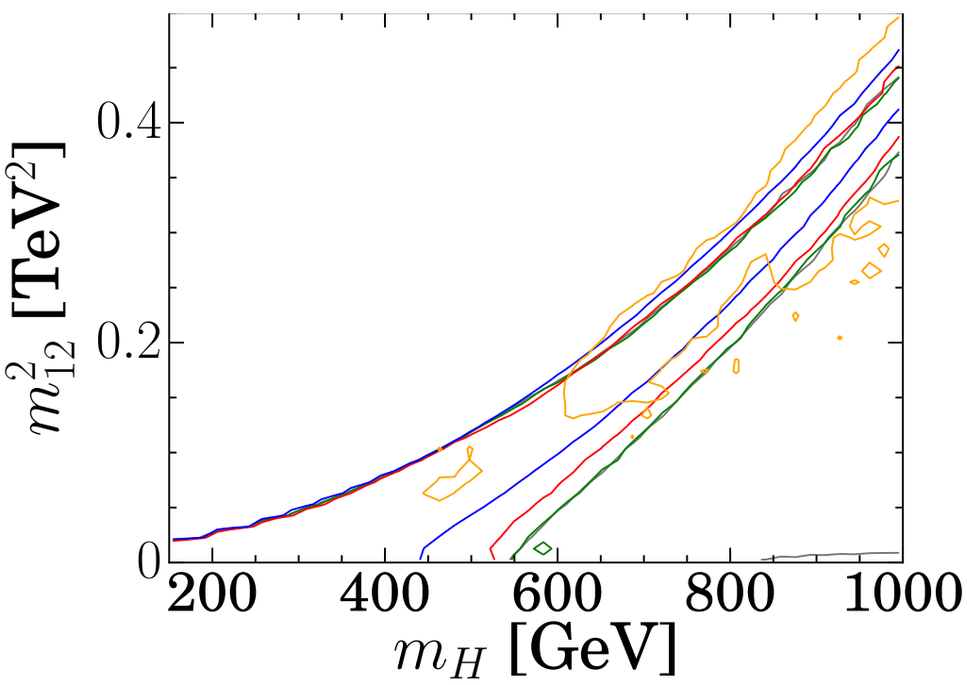


Physical Parameters I



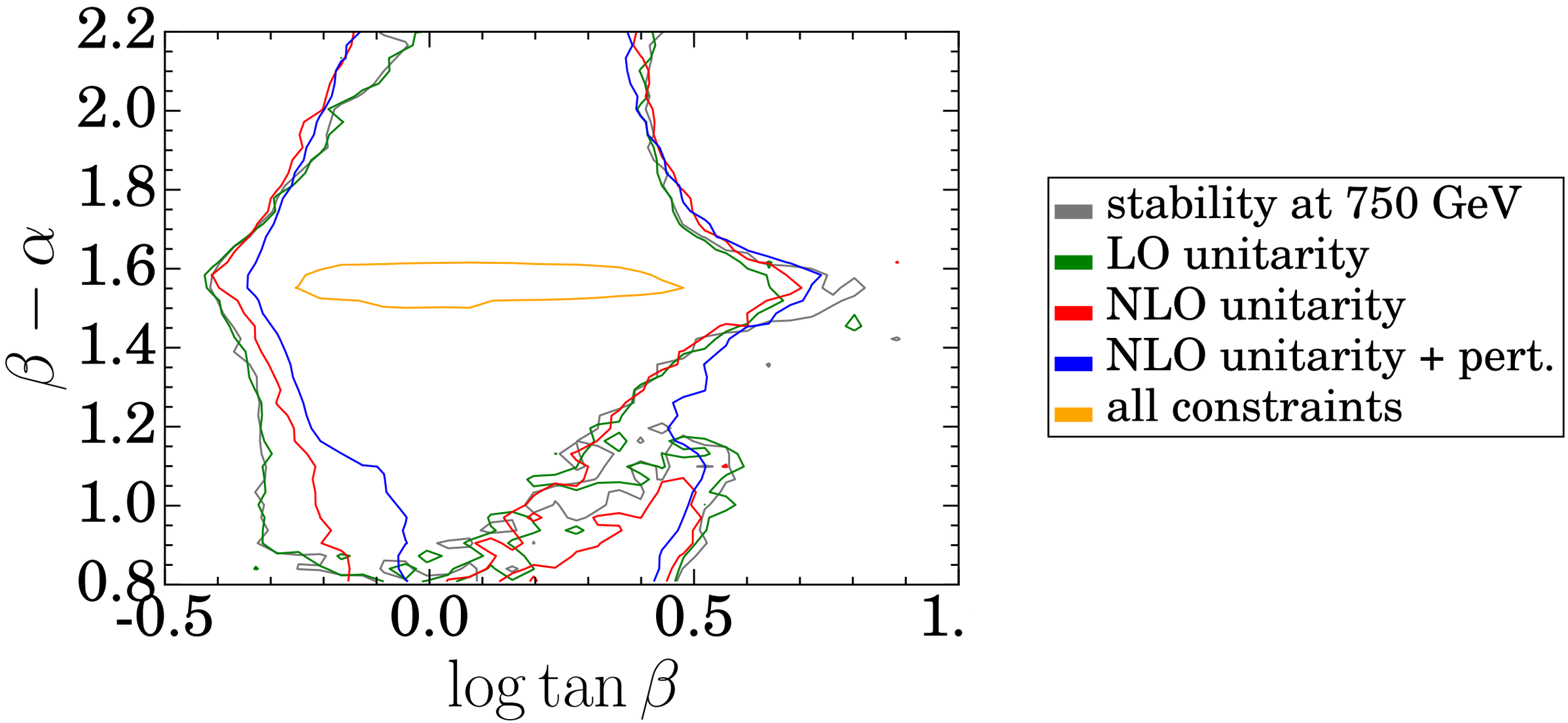






Preliminary

Physical Parameters II



Preliminary

Conclusions

* Quartic couplings of the 2HDM with a softly broken Z_2 get strongly constrained by NLO unitarity.

* Heavy Higgs mass differences as well as λ's gets even more constrained if perturbativity of the NLO contributions are imposed in addition to NLO unitarity.

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Stay tuned!

Thank You!!

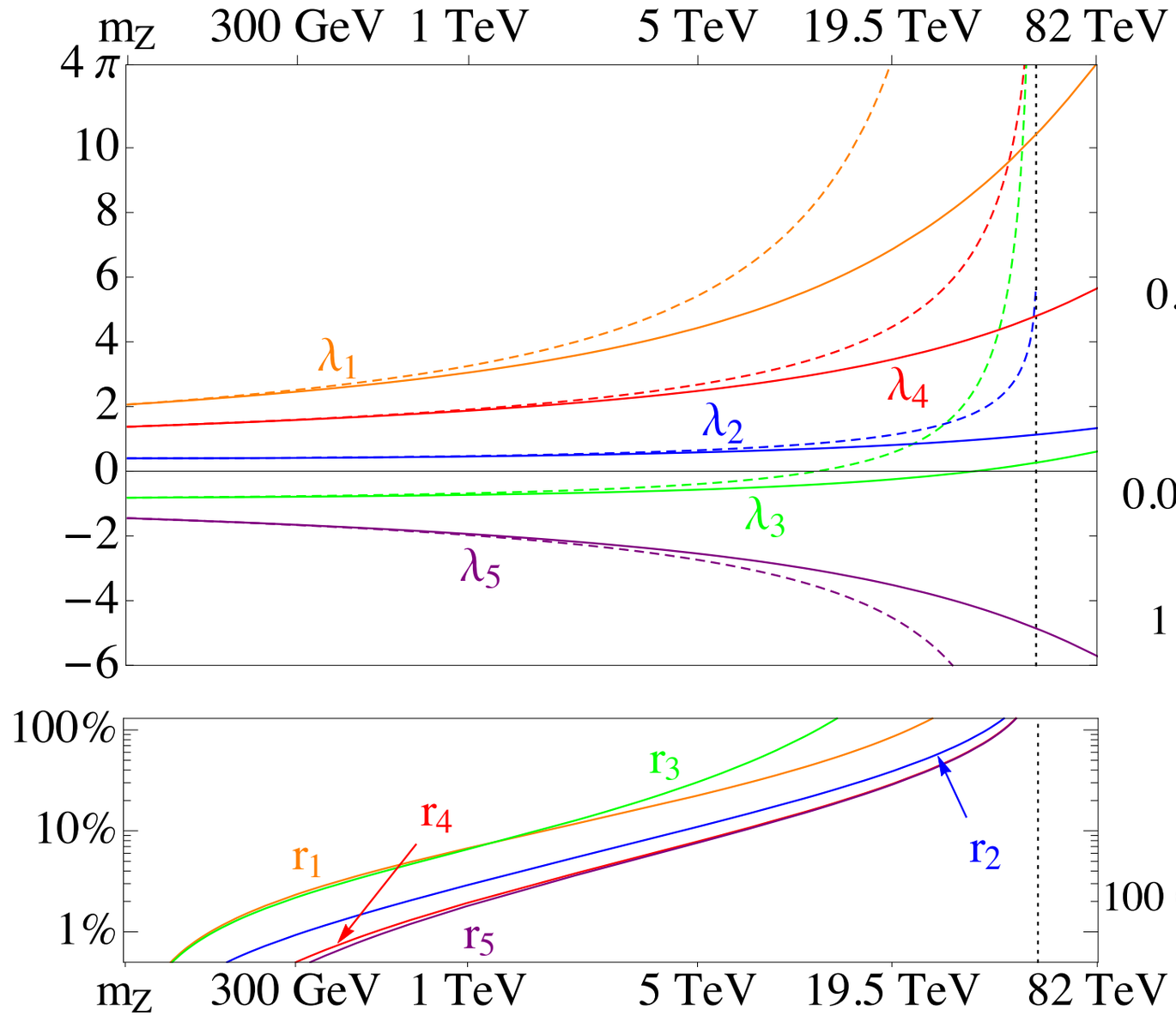
Y	τ	$\mathbb{Z}_2$-even	$\mathbb{Z}_2$-odd
0	0	$\frac{1}{\sqrt{2}}(\Phi_1^\dagger \Phi_1)$ $\frac{1}{\sqrt{2}}(\Phi_2^\dagger \Phi_2)$	$\frac{1}{\sqrt{2}}(\Phi_1^\dagger \Phi_2)$ $\frac{1}{\sqrt{2}}(\Phi_2^\dagger \Phi_1)$
0	1	$\frac{1}{\sqrt{2}}(\Phi_1^\dagger \tau^k \Phi_1)$ $\frac{1}{\sqrt{2}}(\Phi_2^\dagger \tau^k \Phi_2)$	$\frac{1}{\sqrt{2}}(\Phi_1^\dagger \tau^k \Phi_2)$ $\frac{1}{\sqrt{2}}(\Phi_2^\dagger \tau^k \Phi_1)$
1	0	—	$\frac{1}{\sqrt{2}}(\tilde{\Phi}_1 \Phi_2)$
1	1	$\frac{1}{2}(\tilde{\Phi}_1 \tau^k \Phi_1)$ $\frac{1}{2}(\tilde{\Phi}_2 \tau^k \Phi_2)$	$\frac{1}{\sqrt{2}}(\tilde{\Phi}_1 \tau^k \Phi_2)$

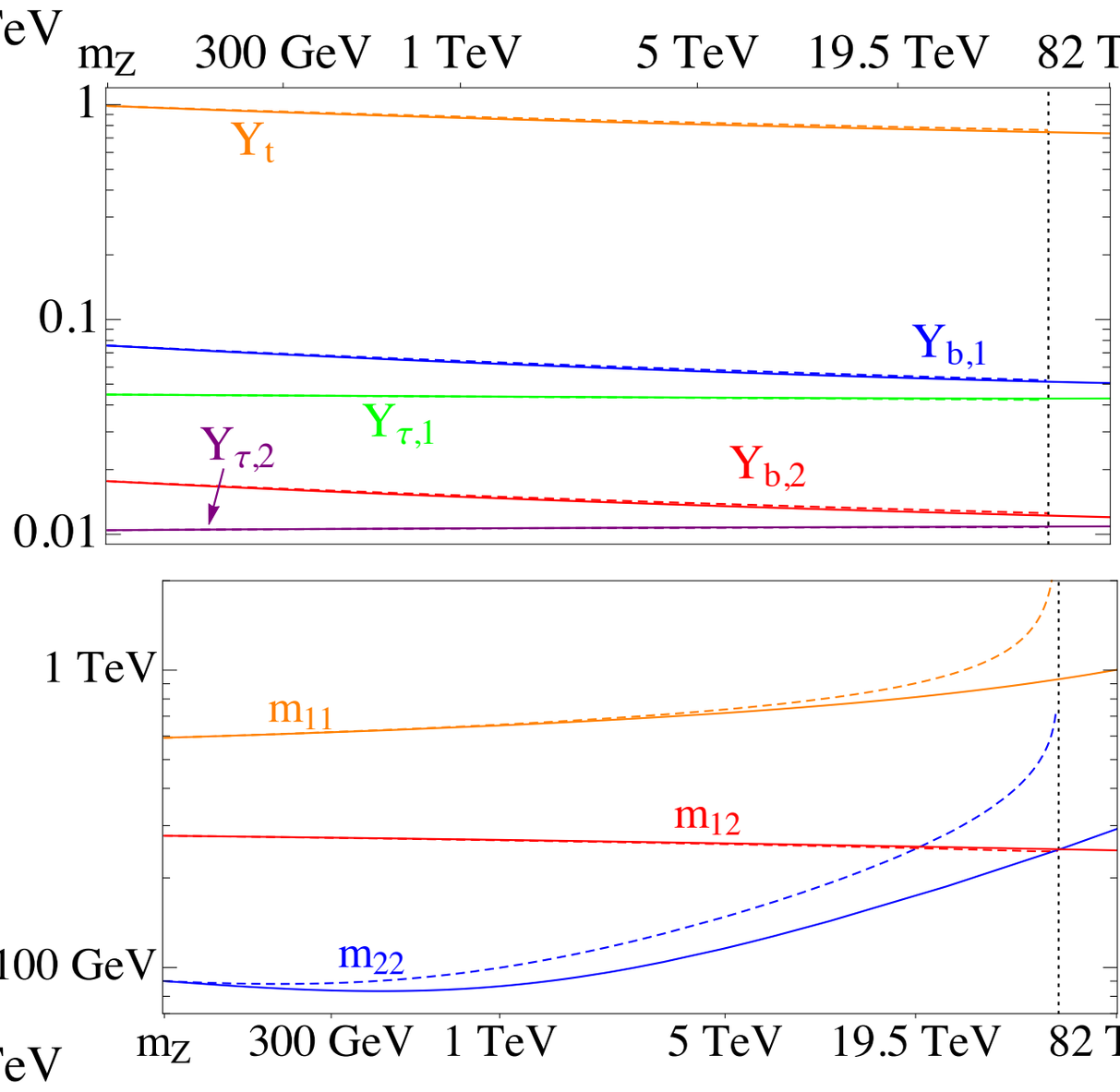
Higgs signal strengths

$$\mu^{\mathrm{f}}_{\mathrm{ggF+tth}} = \frac{[(\sigma_{\mathrm{ggF}} + \sigma_{\mathrm{tth}}) \cdot B(h \to f)]_{\mathrm{2HDM}}}{[(\sigma_{\mathrm{ggF}} + \sigma_{\mathrm{tth}}) \cdot B(h \to f)]_{\mathrm{SM}}}$$

$$\mu^{\mathrm{f}}_{\mathrm{VBF+Vh}} = \sin^2(\beta - \alpha) \cdot \frac{[B(h \to f)]_{\mathrm{2HDM}}}{[B(h \to f)]_{\mathrm{SM}}}$$

Benchmark point - potential parameters





$$r_i = \left| \frac{\lambda_i^{\text{LO}} - \lambda_i^{\text{NLO}}}{\lambda_i^{\text{NLO}}} \right|$$

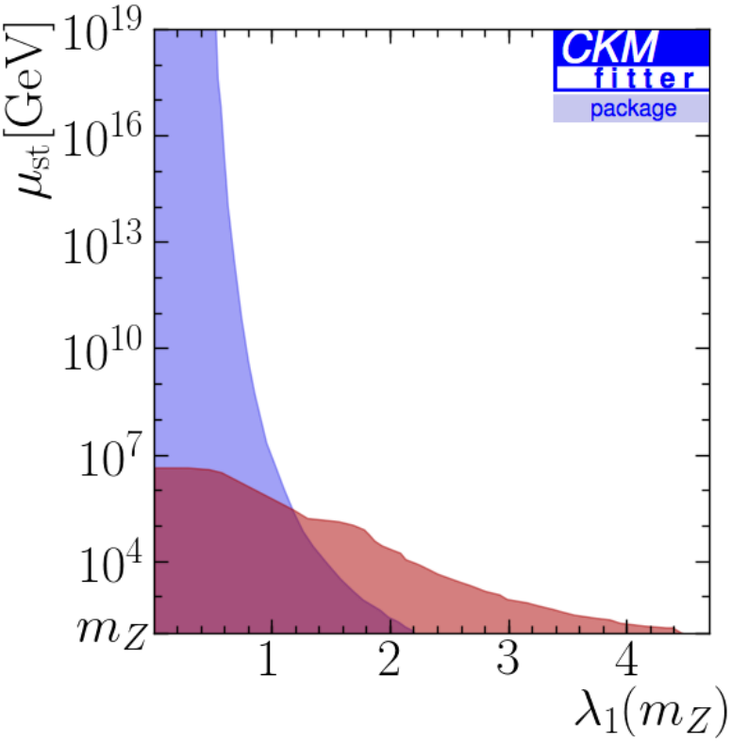
LO RGE

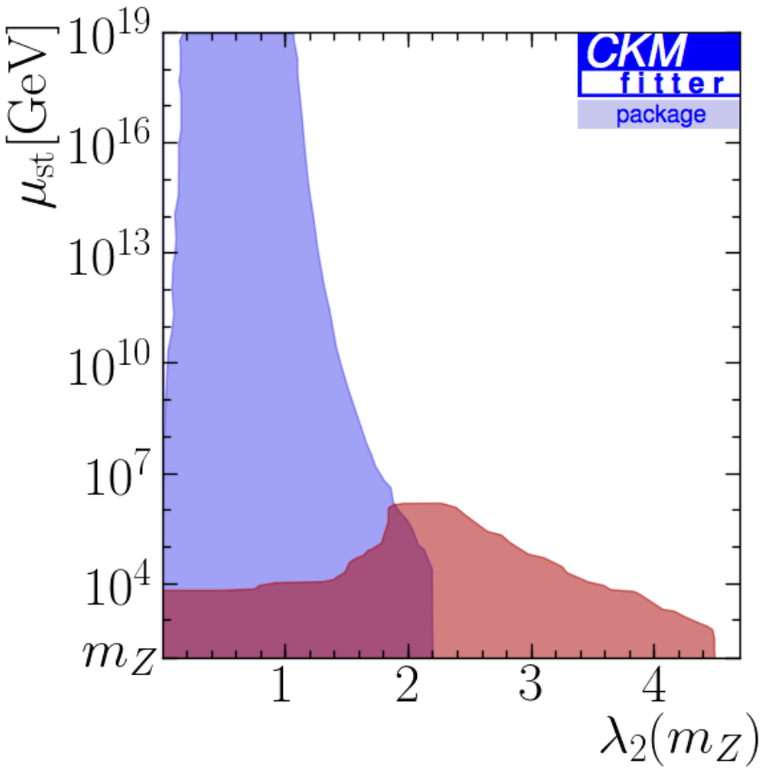
NLO RGE

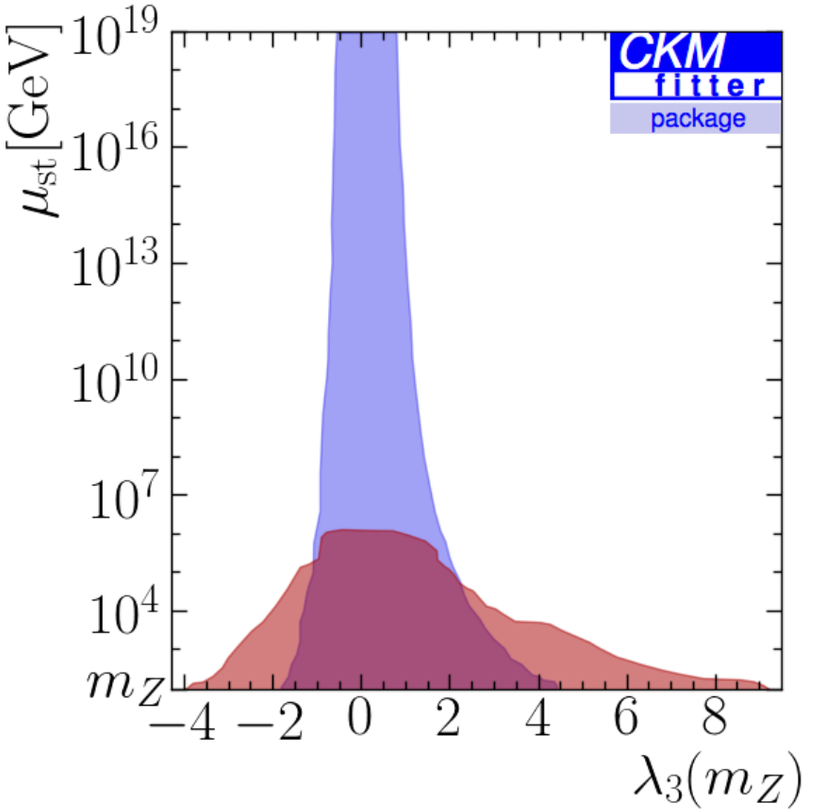
- 2-loop RGE softens the running.
- Cut-off scales pushed to higher values with 2-loop RGEs.

[DC, Eberhardt '15]

Results with Theoretical Constraints



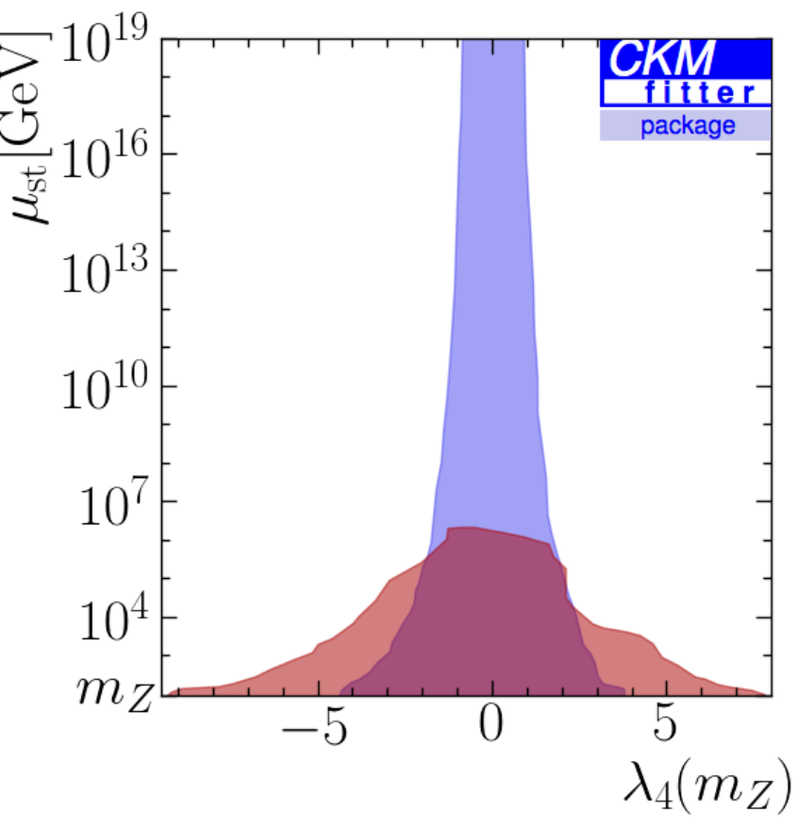


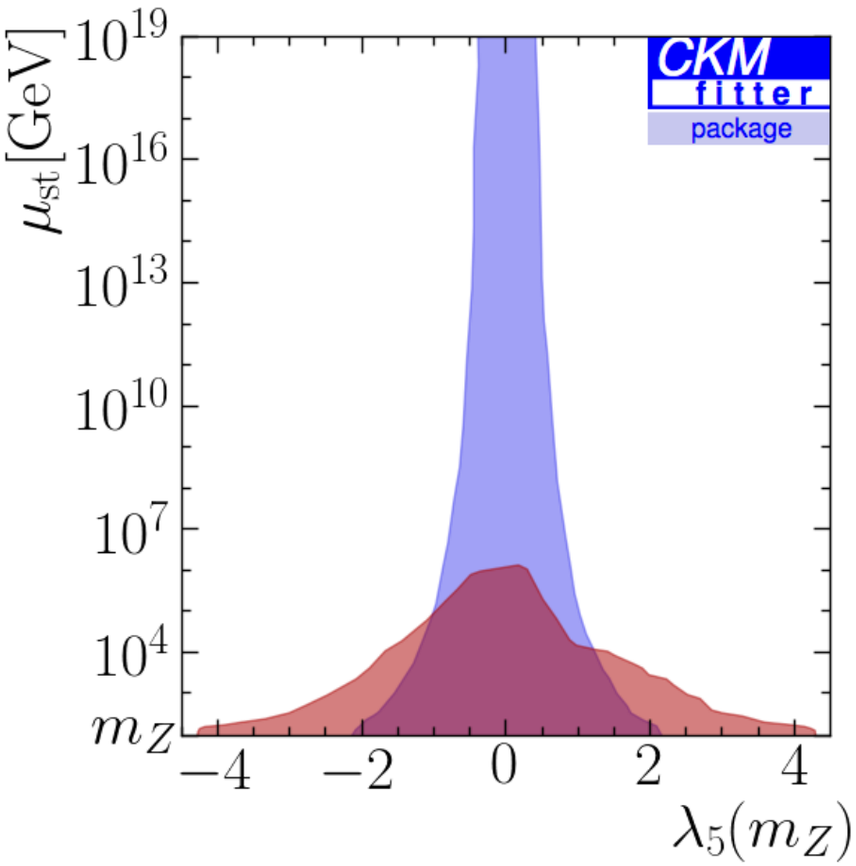


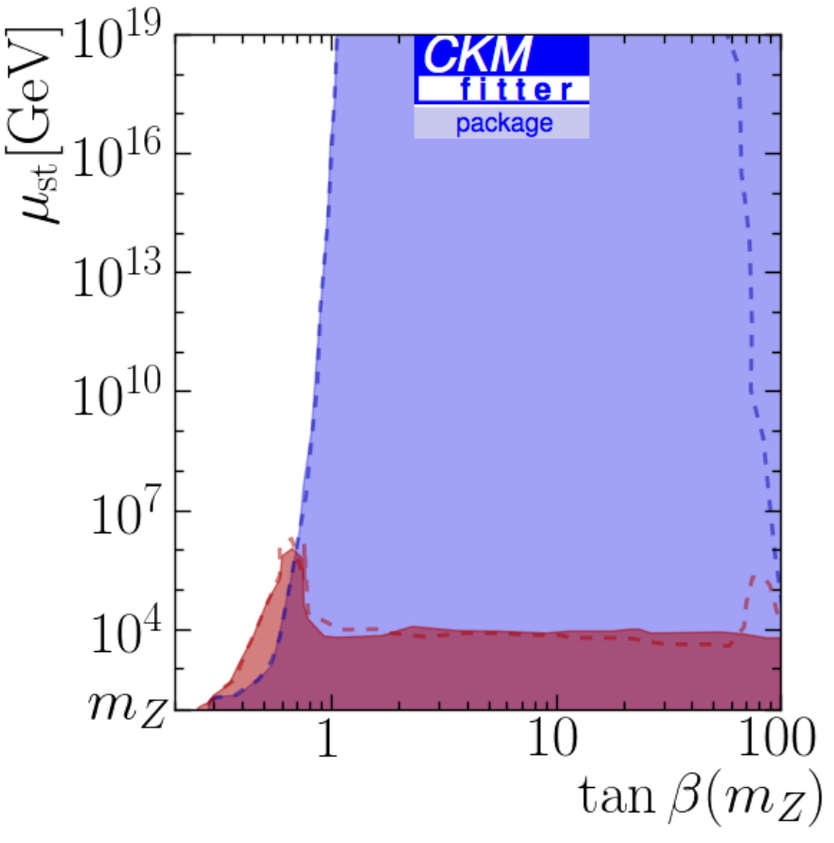
$\max(\|S_{\phi_i\phi_j\to\phi_i\phi_j}\|) < \frac{1}{8}$

$\frac{1}{8} < \max(\|S_{\phi_i\phi_j\to\phi_i\phi_j}\|) < \frac{1}{4}$

[DC, Eberhardt '15]

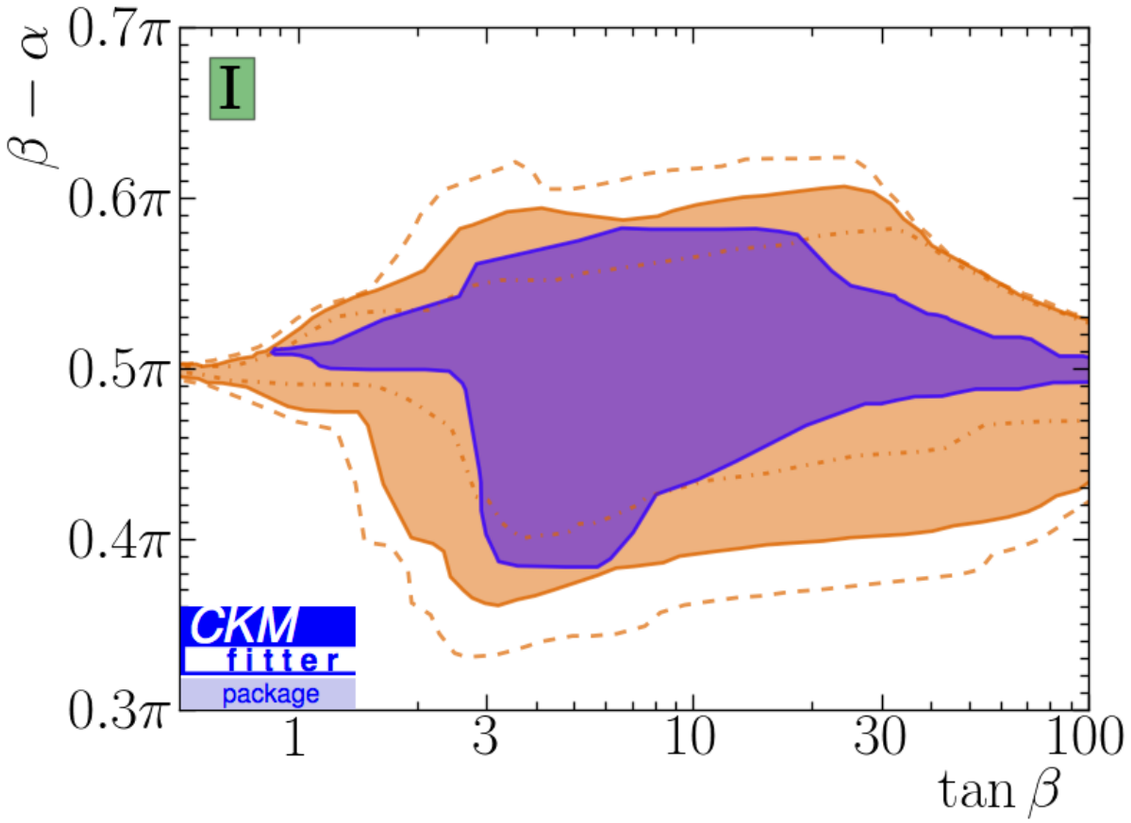


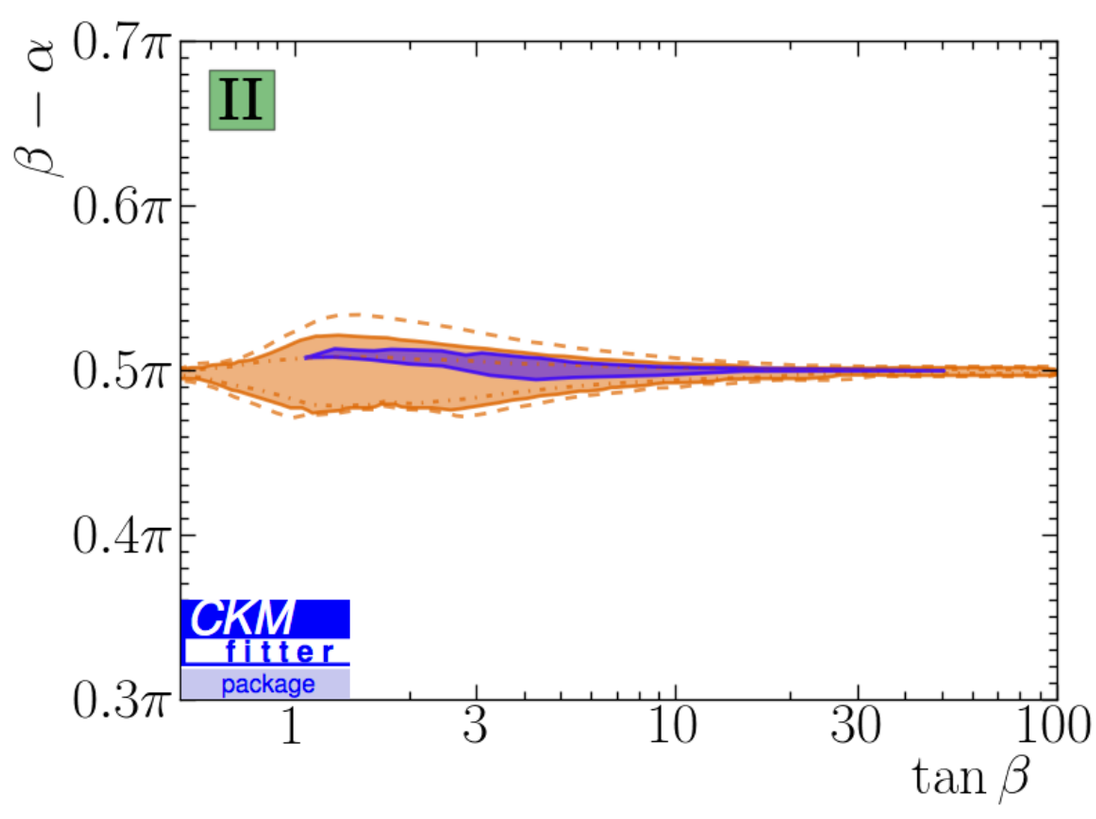




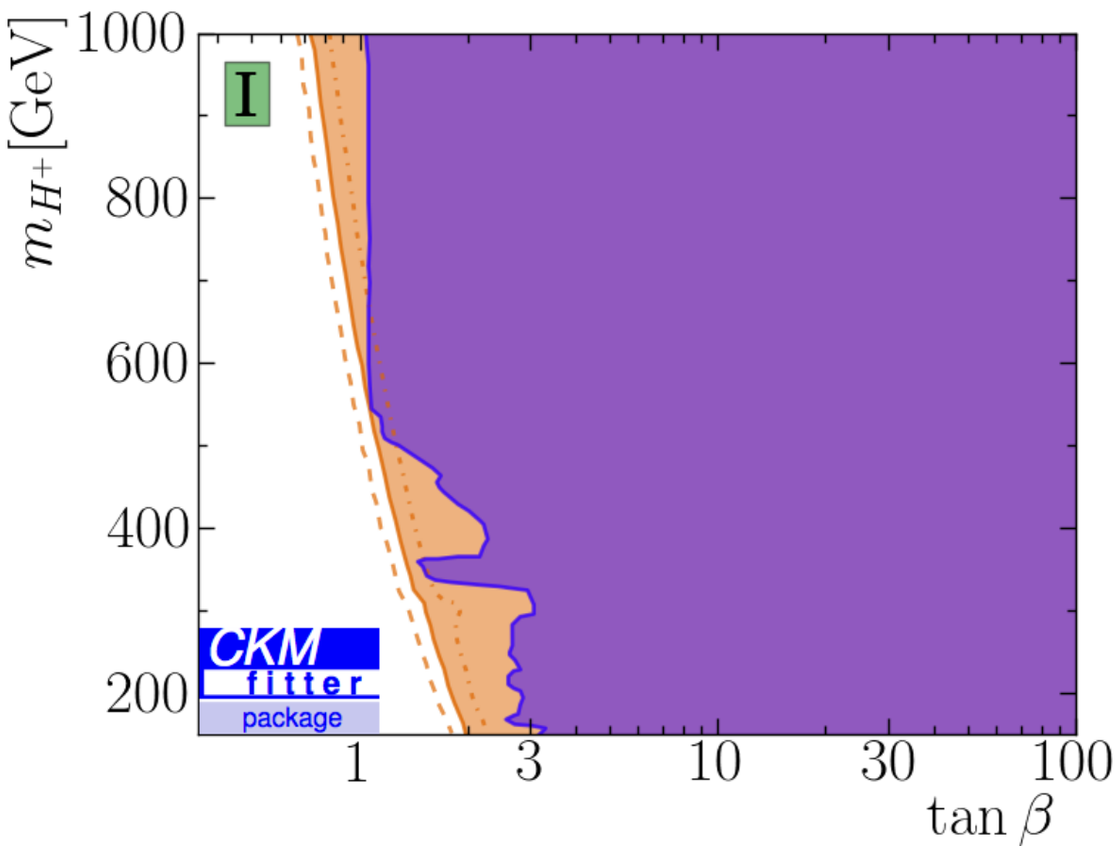
Results with Experimental Data

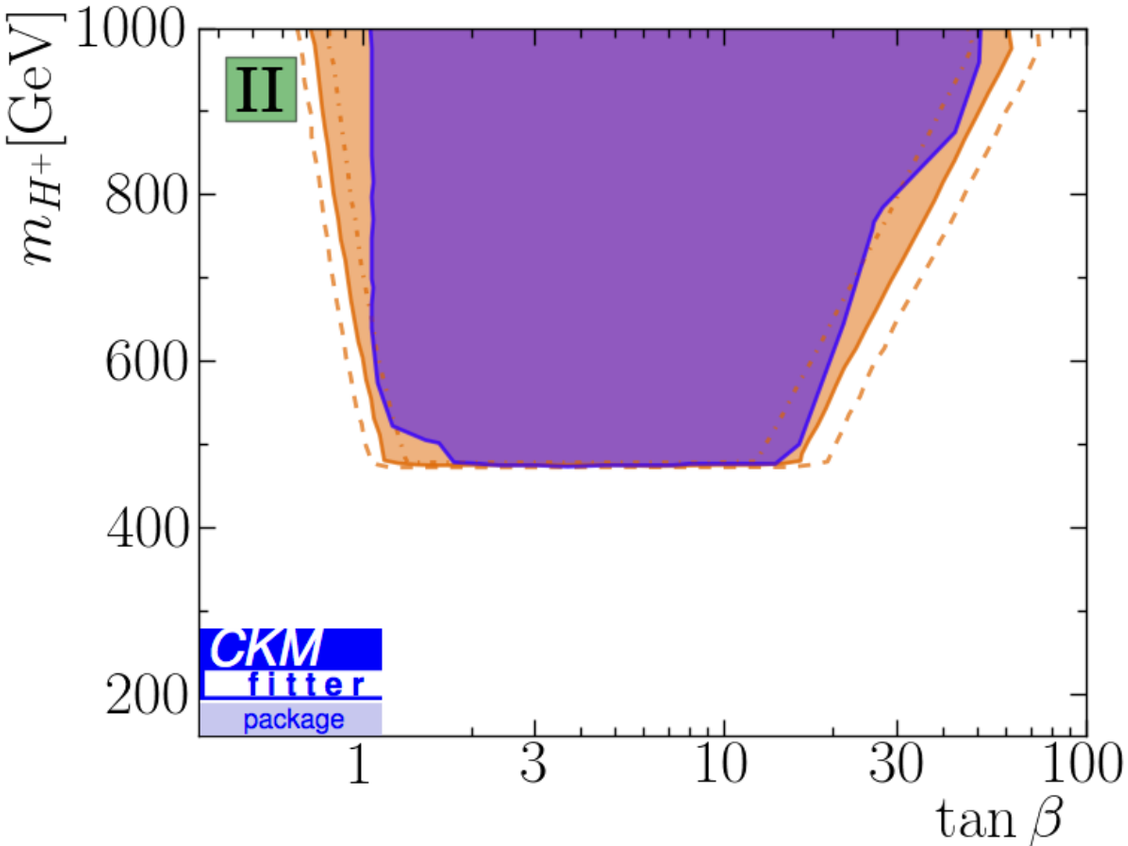
[DC, Eberhardt '15]





Stable up to μ_{ew} M_{Planck}





Limits on β-α, Sin(β-α), Cos(β-α)

		Type I	Type II
$\mu_{\text{st}} = \mu_{\text{ew}}$	$\beta - \alpha$	$[1.136; 1.909]$	$[1.491; 1.640]$
		$[0.362\pi; 0.608\pi]$	$[0.475\pi; 0.522\pi]$
	$\cos(\beta - \alpha)$	$[-0.332; 0.421]$	$[-0.069; 0.080]$
	$\sin(\beta - \alpha)$	$[0.907; 1]$	$[0.997; 1]$
$\mu_{\text{st}} = \mu_{\text{PI}}$	$\beta - \alpha$	$[1.207; 1.87]$	$[1.555; 1.614]$
		$[0.384\pi; 0.595\pi]$	$[0.495\pi; 0.514\pi]$
	$\cos(\beta - \alpha)$	$[-0.258; 0.36]$	$[-0.043; 0.016]$
	$\sin(\beta - \alpha)$	$[0.935; 1]$	$[0.999; 1]$

[DC, Eberhardt '15]