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STANDARD MODEL EFT AND EXTENDED SCALAR SECTORS

based on 1704.07851 w/ Sally Dawson

GOALS OF THIS WORK

- ▶ Are there any simple models where whose first signal might be double Higgs production? Are significant deviations from the SM possible?
- ▶ How well does the SMEFT describe the kinematic distributions of double Higgs production in these models?

STANDARD MODEL EFFECTIVE FIELD THEORY

- ▶ expansion in E^2 / Λ^2 , $v^2 < \Lambda^2$

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \mathcal{L}^{(5)} + \mathcal{L}^{(6)} + \dots$$

- ▶ a subset of dimension-6 operator affect double Higgs production in models under consideration

$$\begin{aligned} \mathcal{L}_H^{(6)} = & \frac{c_H}{2v^2} \partial_\mu (H^\dagger H) \partial^\mu (H^\dagger H) + \frac{c_T}{2v^2} \left| H^\dagger \overleftrightarrow{D}_\mu H \right|^2 - \frac{c_6 \lambda}{v^2} (H^\dagger H)^3 \\ & + \frac{(H^\dagger H)}{v^2} \left[c_b y_b (\bar{q}_L b_R H) + c_t y_t (\bar{q}_L t_R \tilde{H}) + c_\tau y_\tau (\bar{l}_L \tau_R H) + \text{h.c.} \right] \end{aligned}$$

in models we consider:

$$c_t = c_b = c_\tau \equiv c_f$$

EXTENDED SCALAR SECTORS

- ▶ $SU(2)_L$ singlets, triplets, quartets
- ▶ complete set of models (+2HDM) w/ renormalizable Z_2 breaking interaction

$$V(H, \phi) = V_{SM}(H) + V_{Z_2}(H, \phi) + V_{\cancel{Z_2}}(H, \phi)$$

(real ϕ) \rightarrow

$$V_{Z_2}(H, \phi) = \frac{1}{2}M^2\phi^a\phi^a + \lambda_\alpha H^\dagger H\phi^a\phi^a + \lambda_\beta (\phi^a\phi^a)^2$$

$$V_{\cancel{Z_2}} \sim m_1 H^2 \phi \quad \text{or} \quad V_{\cancel{Z_2}} \sim \lambda_1 H^3 \phi$$

(additional ϕ terms in singlet model)

TREE LEVEL DIMENSION-6 OPERATORS

single Higgs production

double Higgs production

ρ/T parameter

Model	c_H	$c_6 \lambda_{SM}$	c_T	c_f
Real Singlet w/ explicit \mathbb{Z}_2	$\frac{m_1^2 v^2}{M^4}$	$\frac{m_1^2 v^2}{M^4} \left(\lambda_\alpha - \frac{m_1 m_2}{M^2} \right)$	0	0
Real Singlet w/ spontaneous \mathbb{Z}_2	$\left(\frac{\lambda_\alpha v}{4\lambda_\beta v_\phi} \right)^2$	0	0	0
2HDM	0	✓	0	✓
Real Triplet	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2 \lambda_\alpha}{4M^4}$	$\frac{m_1^2 v^2}{4M^4}$	$\frac{m_1^2 v^2}{4M^4}$
Complex Triplet	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2}{2M^4} \left(\lambda_{\alpha 1} - \frac{\lambda_{\alpha 2}}{2} \right)$	$-\frac{m_1^2 v^2}{2M^4}$	$\frac{m_1^2 v^2}{2M^4}$
Quartet ₁	0	$-\frac{\lambda_1^2 v^2}{M^2}$	$\frac{\lambda_1^2 v^4}{2M^4}$	0
Quartet ₃	0	$-\frac{\lambda_1^2 v^2}{M^2}$	$-\frac{3\lambda_1^2 v^4}{2M^4}$	0

see e.g. 1201.4383, 1412.1837, 1412.8480, 1502.07352

THE RHO PARAMETER

- ▶ ratio of neutral to charged currents at zero momentum
 - ▶ experimentally close to 1

$$\rho_{\text{exp.}} = 1 + (3.6 \pm 1.9) \cdot 10^{-4} \quad \text{Erler, Moriond 2017}$$

- ▶ SMEFT: tree level, dimension-6

$$\rho = 1 + c_T$$

- ▶ extra $SU(2)_L$ multiplets: tree level

$$\rho = \frac{\sum_i [t(i)(t(i)+1) - t_3(i)^2] v_i^2}{2 \sum_i t_3(i)^2 v_i^2}$$

THE RHO PARAMETER

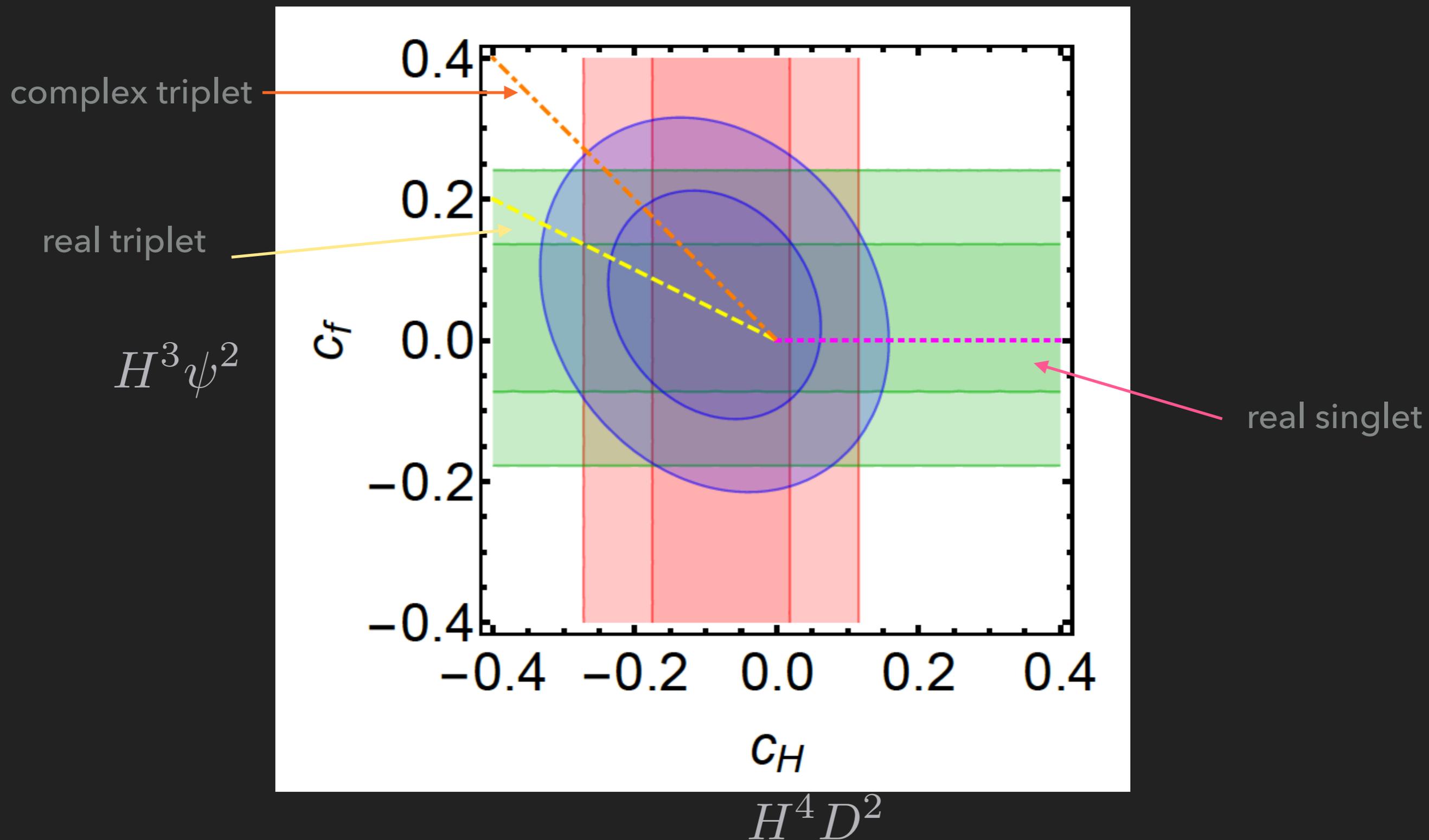
- ▶ consider 2 $SU(2)_L$ multiplets w/ vevs

$$v_h = v \cos \beta, \quad v_\phi = v \sin \beta / \sqrt{2 [t(\phi) (t(\phi) + 1) - t_3(\phi)^2]}$$

$$\tan \beta \propto \frac{v_\phi}{v_h}$$

Model	ρ	3σ upper limit on β
Singlet	1	none
2HDM	1	none
Real Triplet	$\sec^2 \beta$	0.030
Complex Triplet	$2 (3 - \cos 2\beta)^{-1}$	0.014
Quartet ₁	$7 (4 + 3 \cos 2\beta)^{-1}$	0.033
Quartet ₃	$(2 - \cos 2\beta)^{-1}$	0.010

CONSTRAINTS FROM SINGLE HIGGS PRODUCTION



PERTURBATIVE UNITARITY

$$S^\dagger S = \mathbf{1} \rightarrow |\operatorname{Re}(a_0)| \leq \frac{1}{2} \quad (a_0)_{i,f} = \frac{1}{16\pi s} \int_{-s}^0 dt \mathcal{M}_{i \rightarrow f}(s, t)$$

▶ Unitarity Bound on SMEFT

$$E_{\text{crit.}} \approx \sqrt{\frac{16\pi}{3c_H}} v \approx \frac{1 \text{ TeV}}{\sqrt{c_H}} \quad c_T \approx 0$$

▶ Perturbativity Bounds on Extended Scalar Sectors

▶ e.g.

$$m_H^2 < \frac{16\pi v^2}{\tan^2 \beta_s}$$

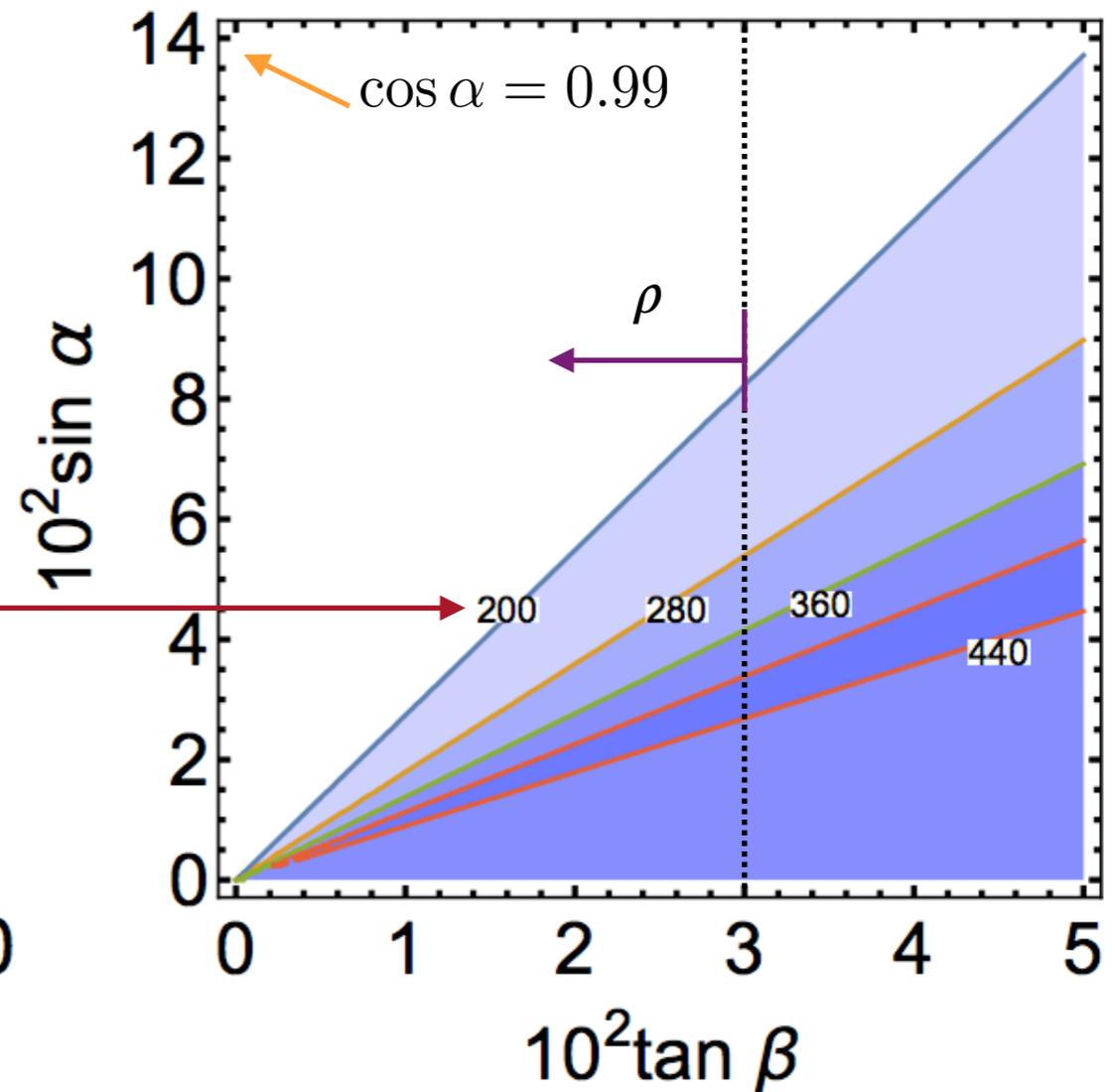
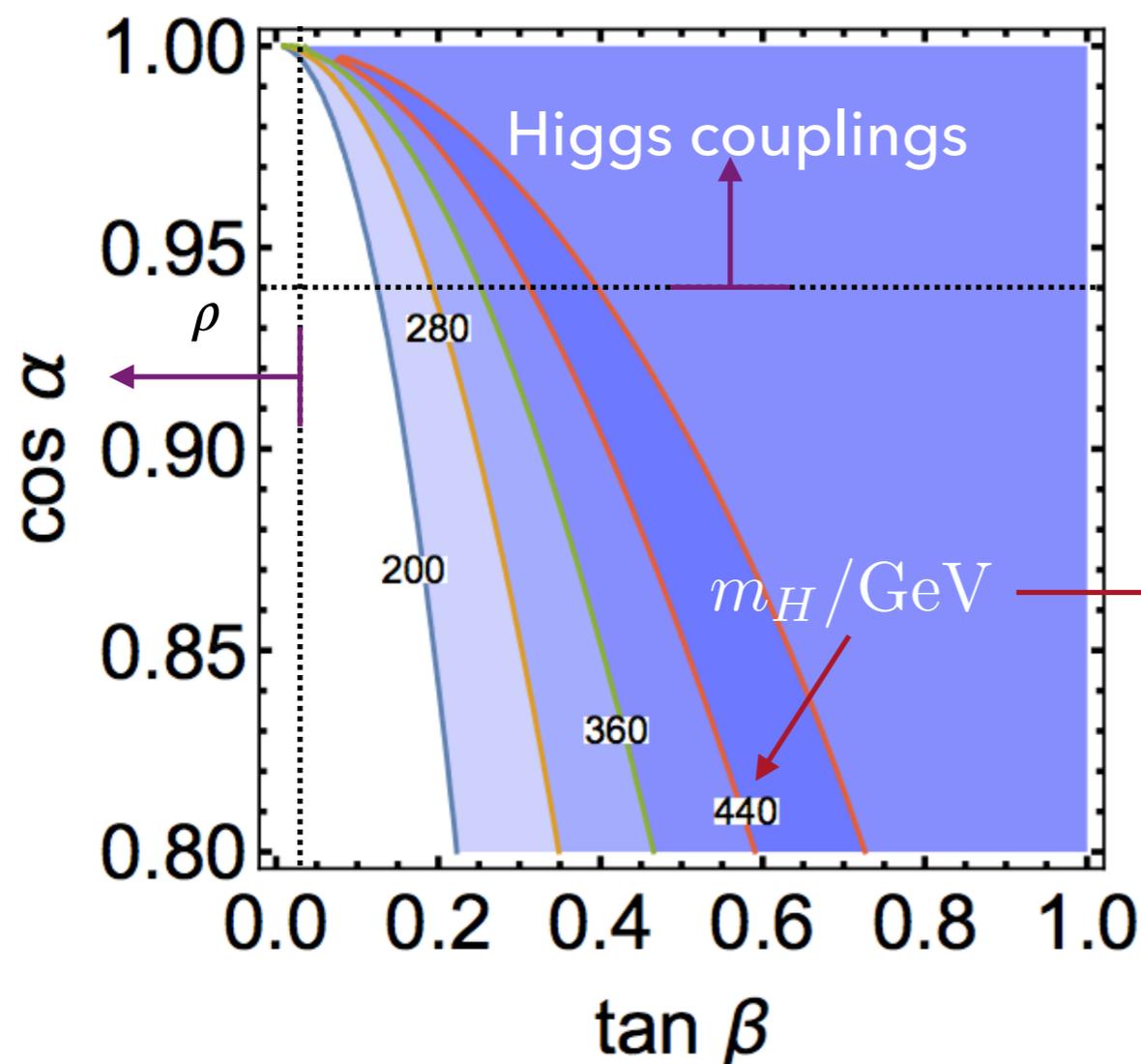
singlet model: opposite convention

$$\tan \beta_s = \frac{v_h}{v_\phi}$$

$$\begin{pmatrix} h \\ \mathcal{H} \end{pmatrix} = \begin{pmatrix} \cos \alpha & -\sin \alpha \\ \sin \alpha & \cos \alpha \end{pmatrix} \begin{pmatrix} h' \\ \varphi \end{pmatrix}$$

PERTURBATIVITY BOUNDS

- ▶ require all eigenvalues to satisfy $|\text{Re}(a_0)| \leq \frac{1}{2}$
- ▶ take $m_H = m_{H^+}$



PERTURBATIVITY BOUNDS

- ▶ Triplets and Quartets qualitatively similar
 - ▶ perturbativity and the ρ parameter force α to be much closer to 0 than Higgs measurements require

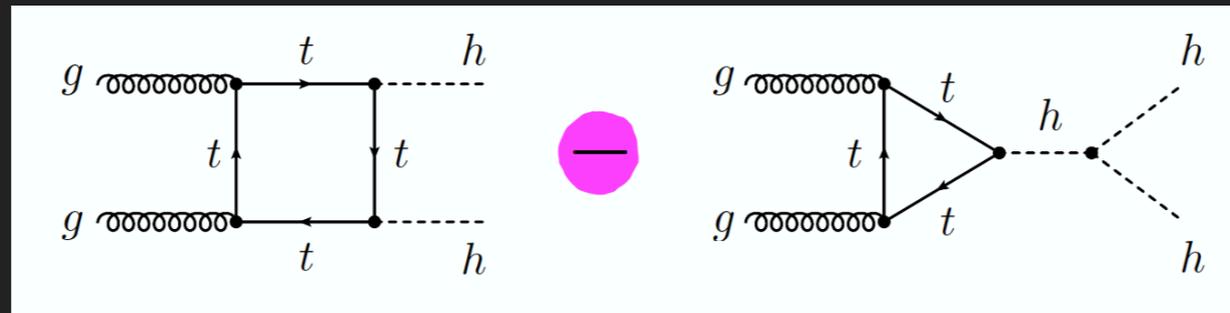
- ▶ real triplet w/ $\alpha \approx \beta \approx 0$

$$469 \text{ GeV} > m_H,$$
$$\left(\frac{\beta}{0.03}\right)^2 (11.7 \text{ GeV})^2 > |m_{H^+}^2 - m_H^2|$$

- ▶ both single and double Higgs production look SM-like,
models are strongly interacting,
or have new scalars w/ $m < 200 \text{ GeV}$

DOUBLE HIGGS PRODUCTION

- ▶ SM: destructive interference between box and triangle diagrams



graphic by U. Haisch

- ▶ SMEFT: box and triangle coefficients modified

$$C_{\Delta} \approx \frac{3m_h^2}{s - m_h^2 + im_h\Gamma_h} (1 + c_6 - 2c_H - c_t) - (c_H + 3c_t),$$

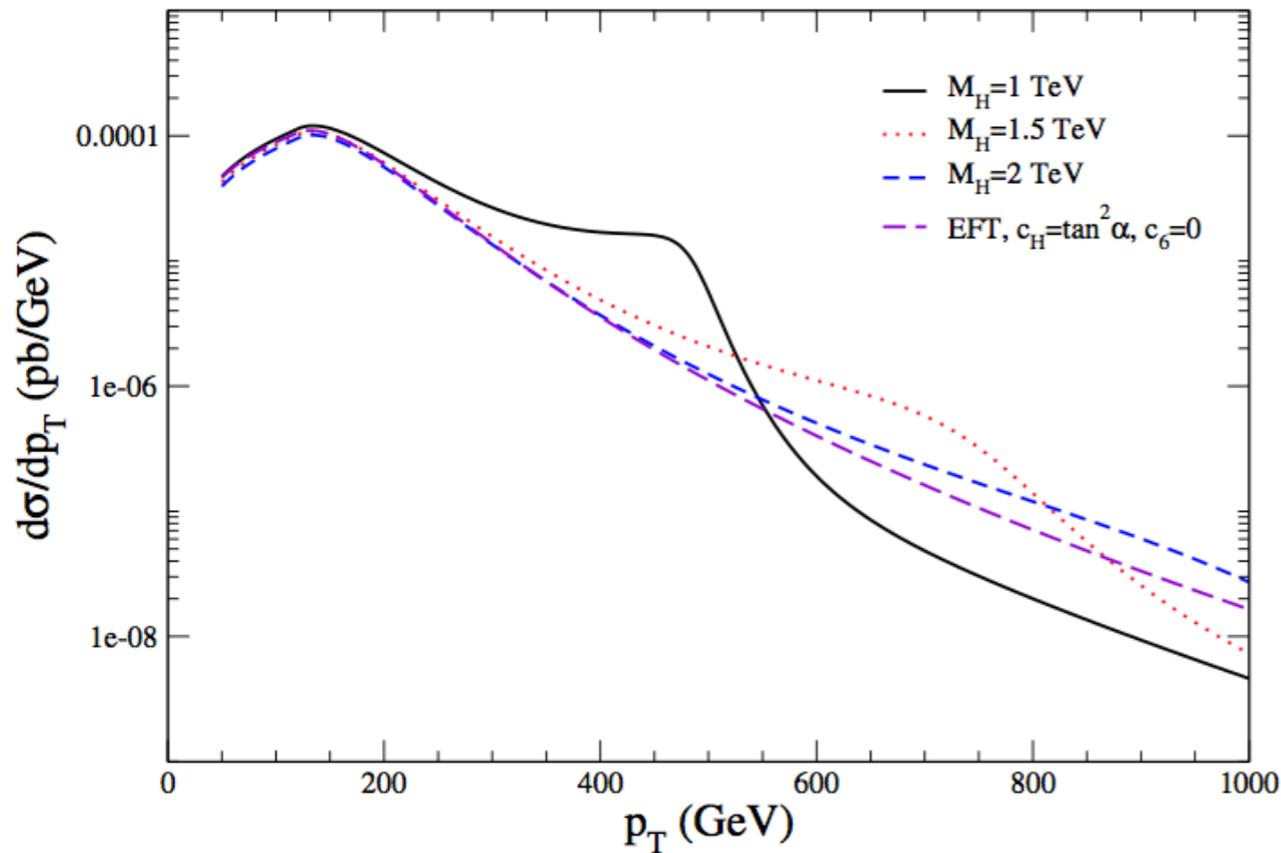
$$C_{\square} \approx 1 - c_H - 2c_t,$$

- ▶ Extended scalar sectors: resonant enhancement possible when $m_H > 2m_h$

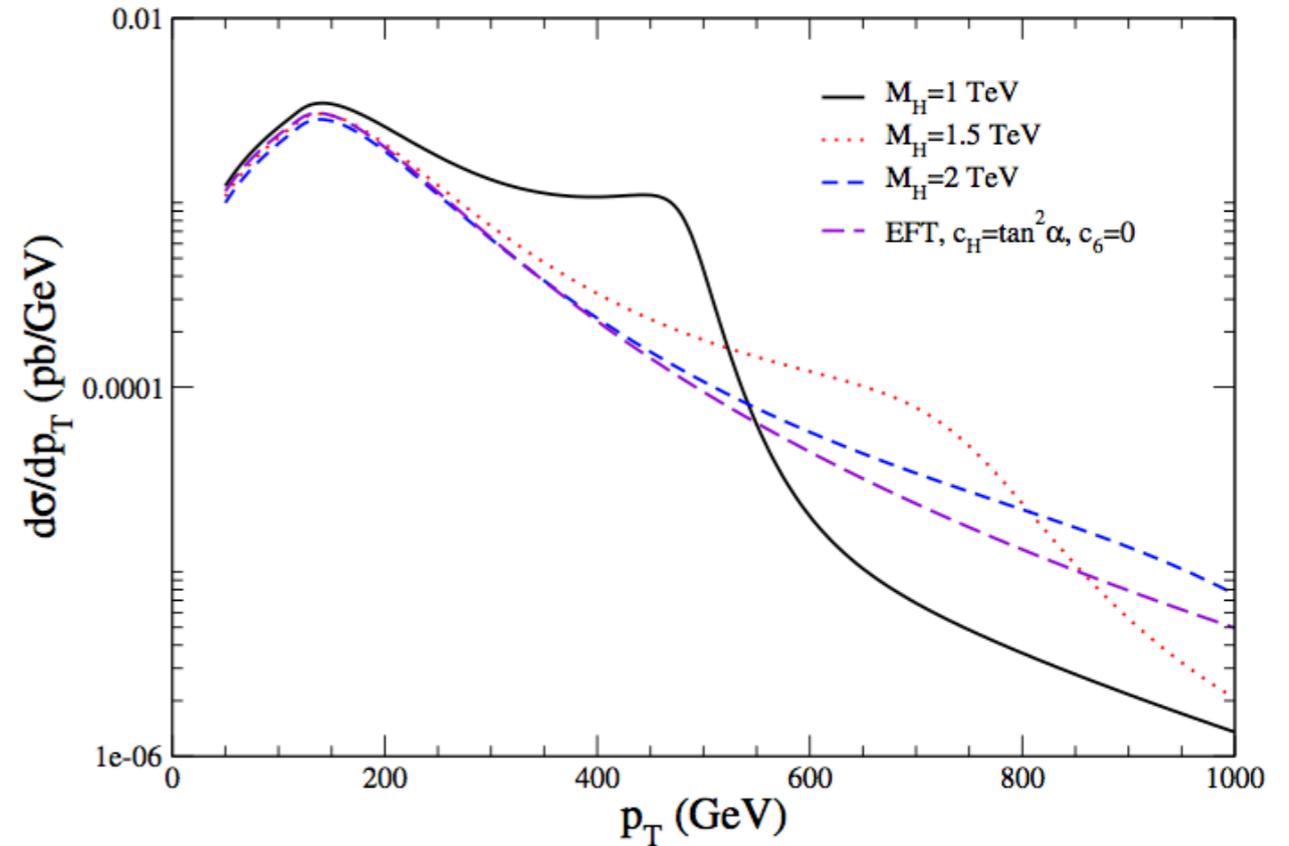
DOUBLE HIGGS PRODUCTION: SMEFT VS. SINGLET MODEL

► Unexpectedly good agreement!

Spontaneously Broken Z_2 Symmetric Singlet Model, $\sqrt{s}=13$ TeV
 $\mu^2=s$, CT12PDFs, $\cos\alpha=0.94$, $\tan\beta=0.5$



Spontaneously Broken Z_2 Symmetric Singlet Model, $\sqrt{s}=100$ TeV
 $\mu^2=s$, CT12PDFs, $\cos\alpha=0.94$, $\tan\beta=0.5$



CONCLUSIONS

- ▶ SMEFT vs. Singlet model
 - ▶ excellent agreement in p_T and M_{hh} distributions for $m_H \gtrsim 2$ TeV
 - ▶ good agreement for $p_T, M_{hh} \lesssim 400$ GeV w/ $m_H \gtrsim 600$ GeV
 - ▶ find resonance, best hope for BSM discovery in double Higgs production
- ▶ Triplet & Quartet models
 - ▶ SM-like signal in single & double Higgs production
 - ▶ $m_{\text{heavy}} \lesssim 500$ GeV: discover through charged Higgs pair production?
- ▶ to do: 2HDM, (generalized) Georgi-Machacek

THE OTHER SLIDES



SM HIGGS PRODUCTION AT LHC

$$m_h \approx 125 \text{ GeV}$$



$$V_{SM} = \frac{1}{2} m_h^2 h^2 + \lambda_{SM} v h^3 + \frac{\lambda_{SM}}{4} h^4$$

$$v \approx 246 \text{ GeV}$$



$$\lambda_{SM} = \frac{m_h^2}{2v^2} \approx 0.13$$

$$\sigma(pp \rightarrow h)_{SM} \sim 45 \text{ pb}$$

discovered

$$\sigma(pp \rightarrow hh)_{SM} \sim 35 \text{ fb}$$

challenging

$$\sigma(pp \rightarrow hhh)_{SM} \sim 0.1 \text{ fb}$$

not going to happen

SMEFT BASES

Operator	Relation to [36] References: Coefficients, \bar{C}_i :	Operators, O_i			
		[36] C_i	[10] a_i	[35] $\frac{\bar{c}_i}{v^2}$	[3] c_i
$ D^2 H ^2$	$ EoM ^2$				\mathcal{O}_D
$(H^\dagger H) (D_\mu H^\dagger D^\mu H)$	$\frac{1}{2} Q_{H\Box} - \frac{1}{2} (H^\dagger H) (H^\dagger EoM + \text{h.c.})$		O_2		\mathcal{O}_R
$(\partial_\mu (H^\dagger H))^2$	$-Q_{H\Box}$			$2O_H$	$2\mathcal{O}_H$
$ H^\dagger \overleftrightarrow{D}_\mu H ^2$	$-Q_{H\Box} - 4Q_{HD}$			$2O_T$	$2\mathcal{O}_T$
$(H^\dagger H) \Box (H^\dagger H)$		$Q_{H\Box}$	$2O_1$		
$ H^\dagger D_\mu H ^2$		Q_{HD}	O_T		
$(H^\dagger H)^3$		Q_H	\checkmark	$\frac{1}{\lambda} O_6$	\mathcal{O}_6

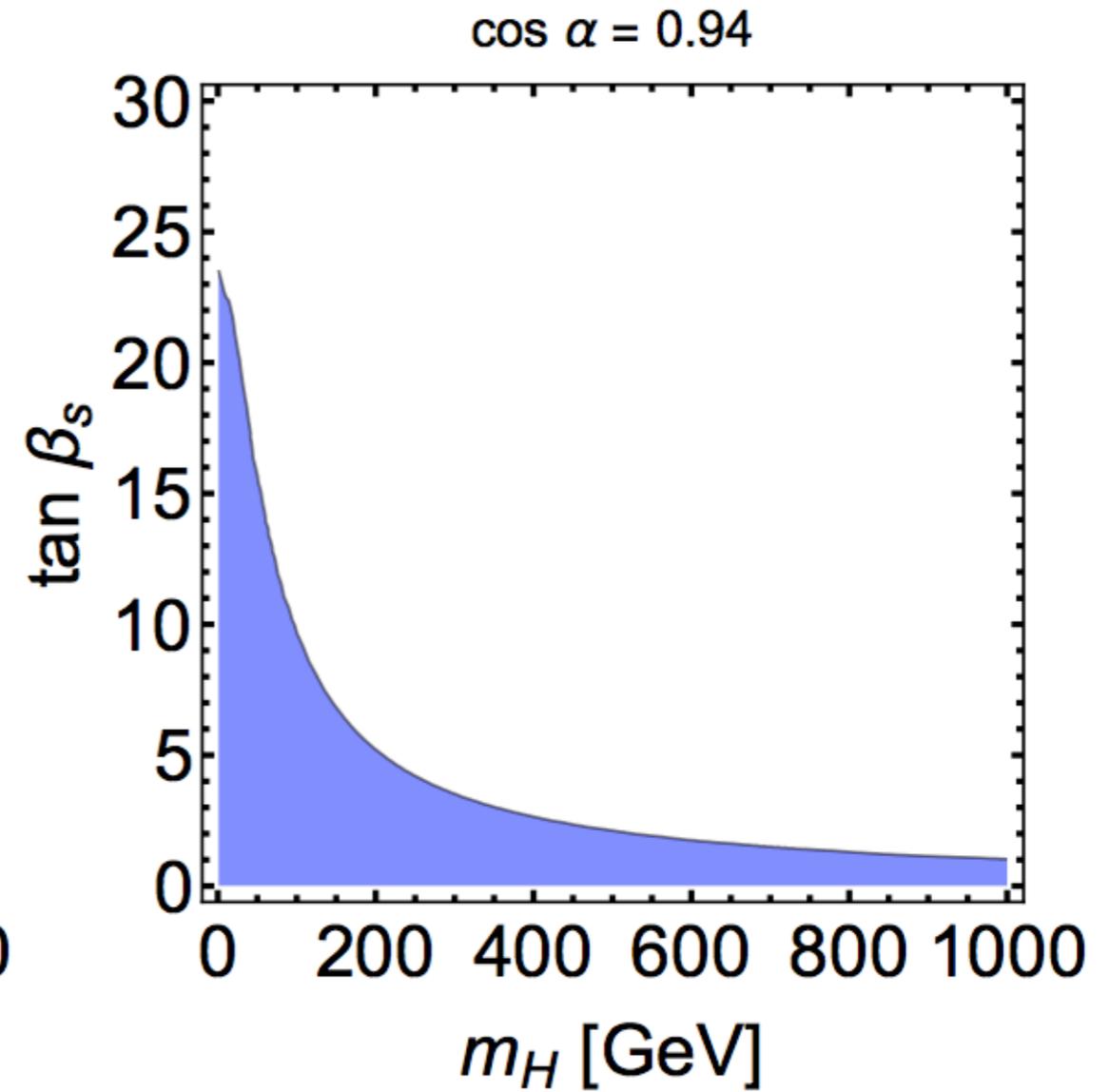
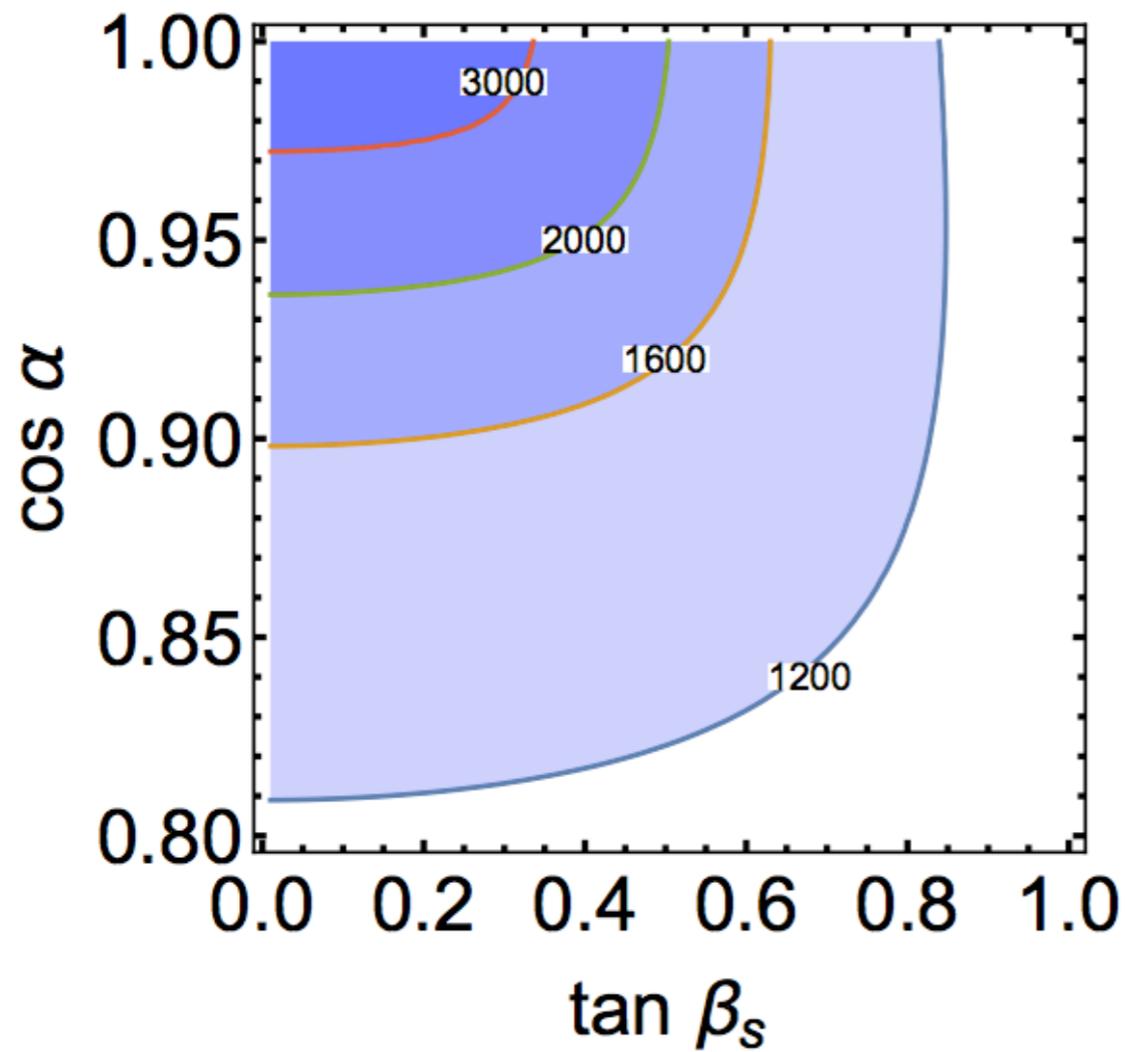
TREE LEVEL DIMENSION-6 OPERATORS

Model	\mathbf{c}_H	$\mathbf{c}_6 \lambda_{SM}$	\mathbf{c}_T	\mathbf{c}_f
Real Singlet w/ explicit \mathbb{Z}_2	$\tan^2 \alpha$	$\tan^2 \alpha \left(\lambda_\alpha - \frac{m_2}{v} \tan \alpha \right)$	0	0
Real Singlet w/ spontaneous \mathbb{Z}_2	$\tan^2 \alpha$	0	0	0
Real Triplet	$-\frac{8 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^6}{m_H^4 v^2}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_{H+}^4}{m_H^4}$
Complex Triplet	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{8 \sin^2 \beta m_A^6}{m_H^4 v^2}$	$-\frac{4 \sin^2 \beta m_A^4}{m_H^4}$	$\frac{4 \sin^2 \beta m_A^4}{m_H^4}$
Quartet ₁	0	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^2 v^2}$	$\frac{24 \tan^2 \beta m_A^4}{7 m_H^4}$	0
Quartet ₃	0	$\frac{8 \tan^2 \beta m_A^4}{3 m_H^2 v^2}$	$-\frac{8 \tan^2 \beta m_A^4}{m_H^4}$	0

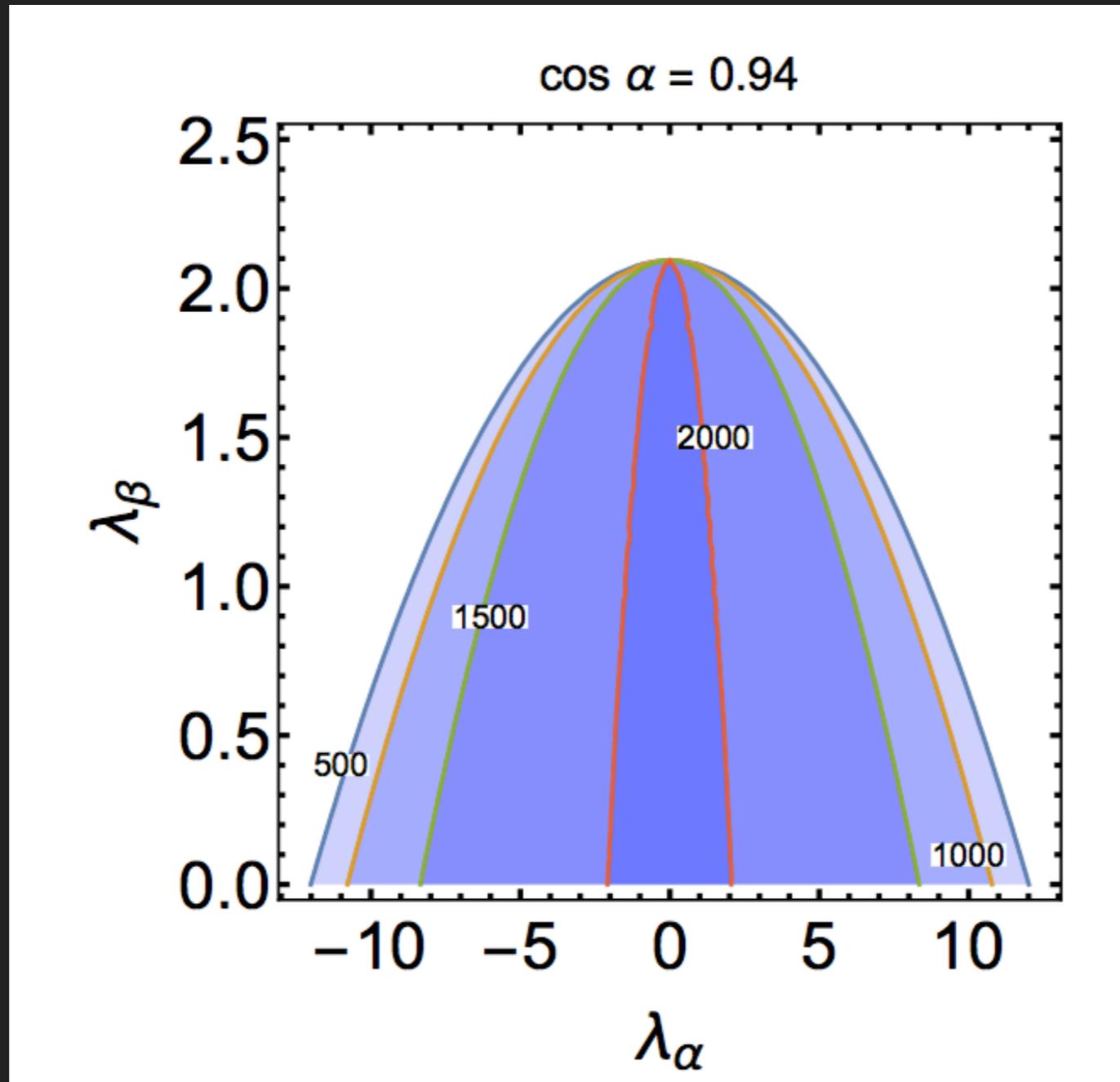
HIGGS SIGNAL STRENGTH RESULTS

Signal strength	Value	Correlation matrix		μ_{SMEFT}
$\mu_{\text{ggF}+\text{tth}}^{\gamma\gamma}$	1.16 ± 0.26	1	-0.30	$1 - c_H + 0.01c_f$
$\mu_{\text{VBF}+\text{Vh}}^{\gamma\gamma}$	1.05 ± 0.43	-0.30	1	$1 - c_H + 2.01c_f$
$\mu_{\text{ggF}+\text{tth}}^{bb}$	1.15 ± 0.97	1	$4.5 \cdot 10^{-3}$	$1 - c_H + 2.55c_f$
$\mu_{\text{VBF}+\text{Vh}}^{bb}$	0.65 ± 0.30	$4.5 \cdot 10^{-3}$	1	$1 - c_H + 0.55c_f$
$\mu_{\text{ggF}+\text{tth}}^{\tau\tau}$	1.06 ± 0.58	1	-0.43	$1 - c_H + 2.55c_f$
$\mu_{\text{VBF}+\text{Vh}}^{\tau\tau}$	1.12 ± 0.36	-0.43	1	$1 - c_H + 0.55c_f$
$\mu_{\text{ggF}+\text{tth}}^{WW}$	0.98 ± 0.21	1	-0.14	$1 - c_H + 0.55c_f$
$\mu_{\text{VBF}+\text{Vh}}^{WW}$	1.38 ± 0.39	-0.14	1	$1 - c_H + 1.45c_f$
$\mu_{\text{ggF}+\text{tth}}^{ZZ}$	1.42 ± 0.35	1	-0.49	$1 - c_H + 0.55c_f$
$\mu_{\text{VBF}+\text{Vh}}^{ZZ}$	0.47 ± 1.37	-0.49	1	$1 - c_H + 1.45c_f$

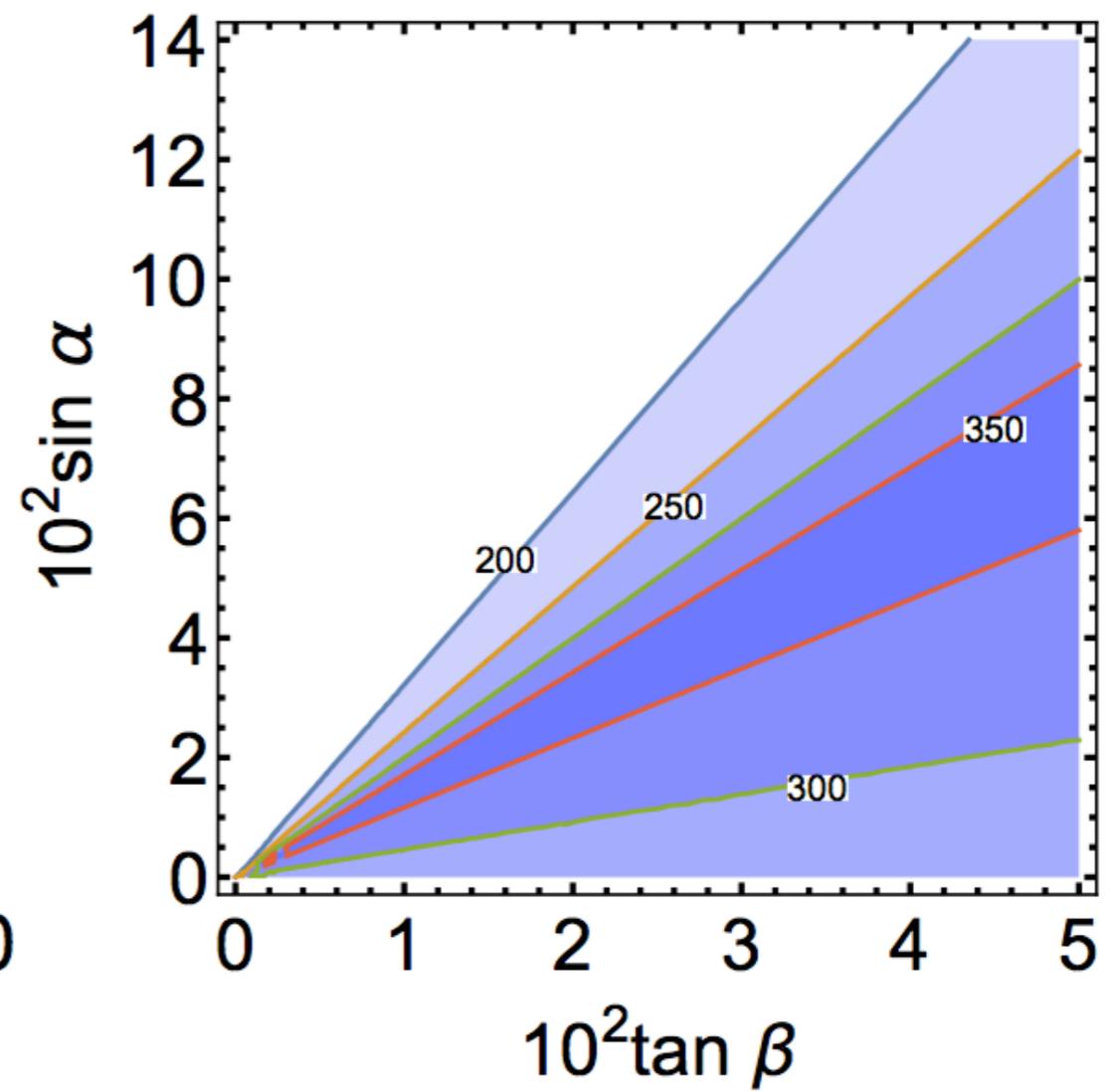
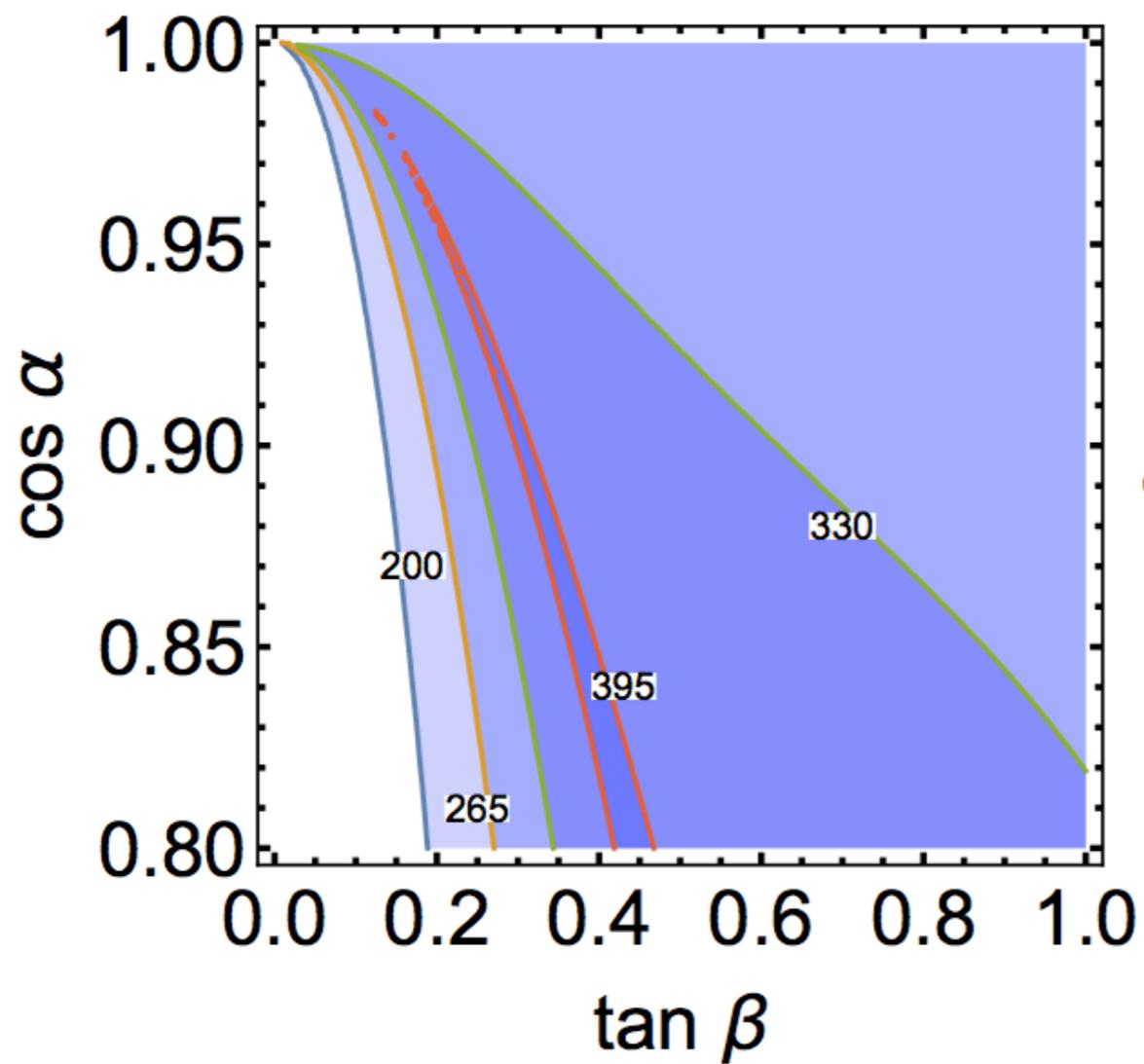
PERTURBATIVITY BOUNDS



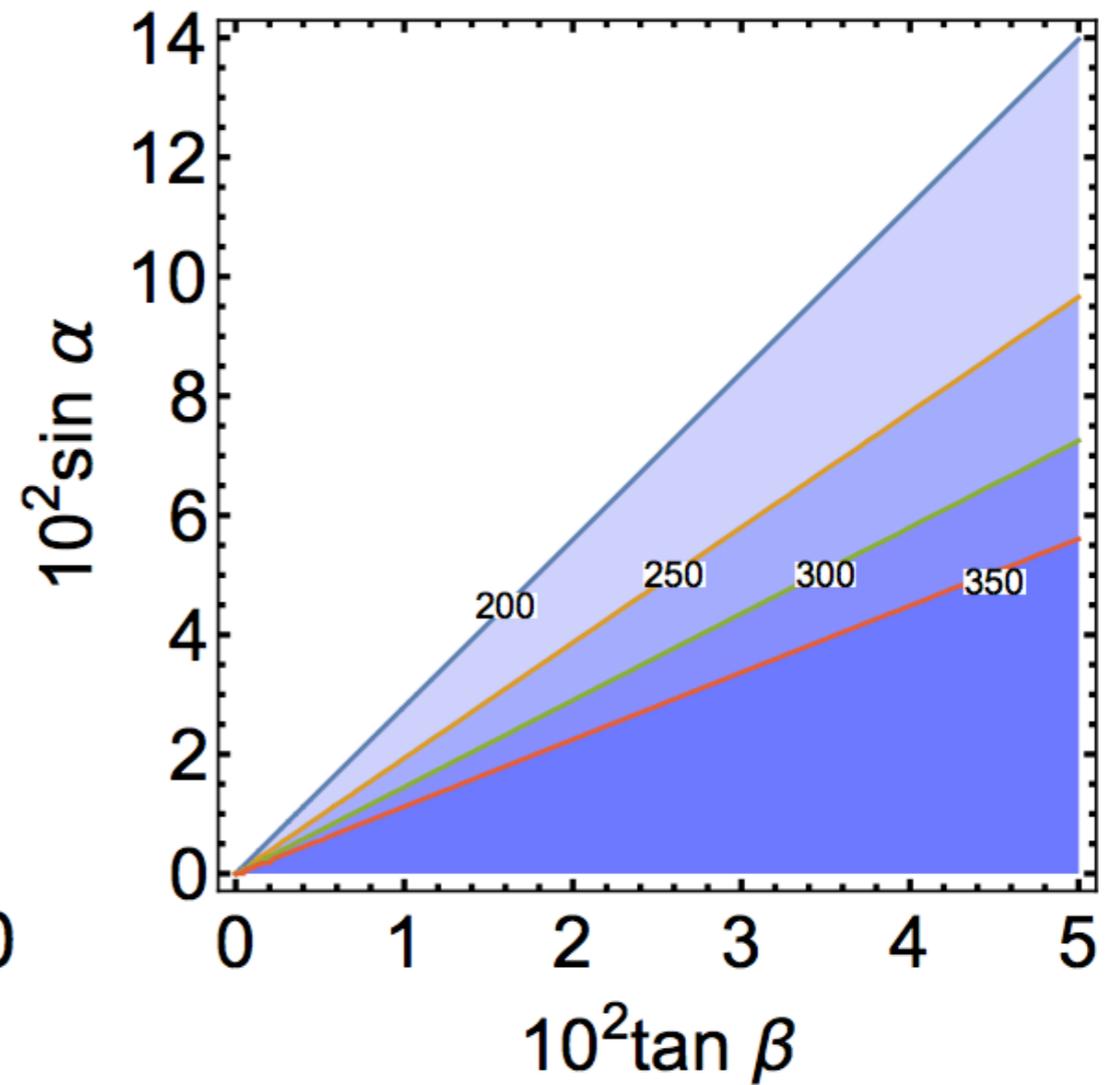
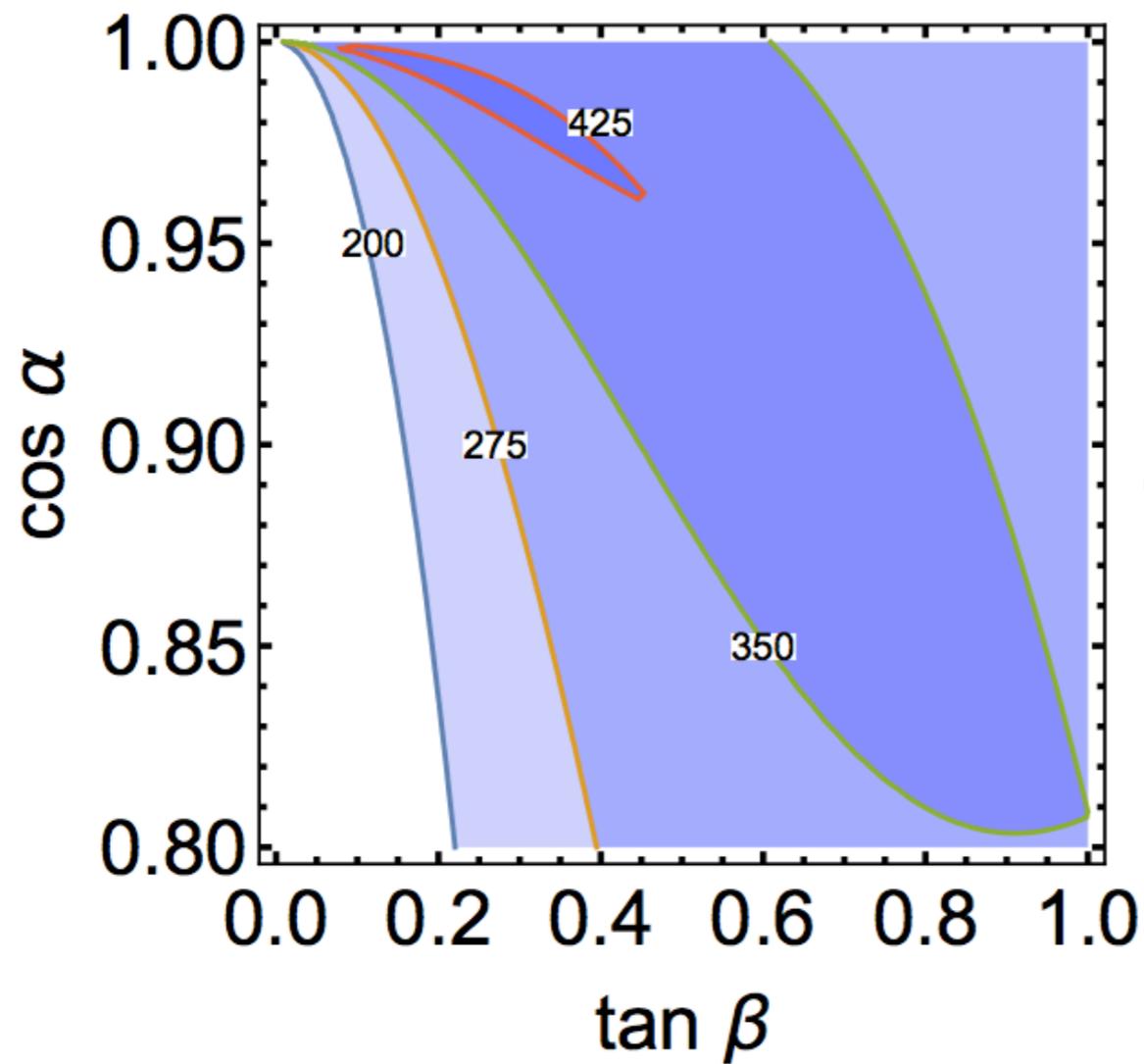
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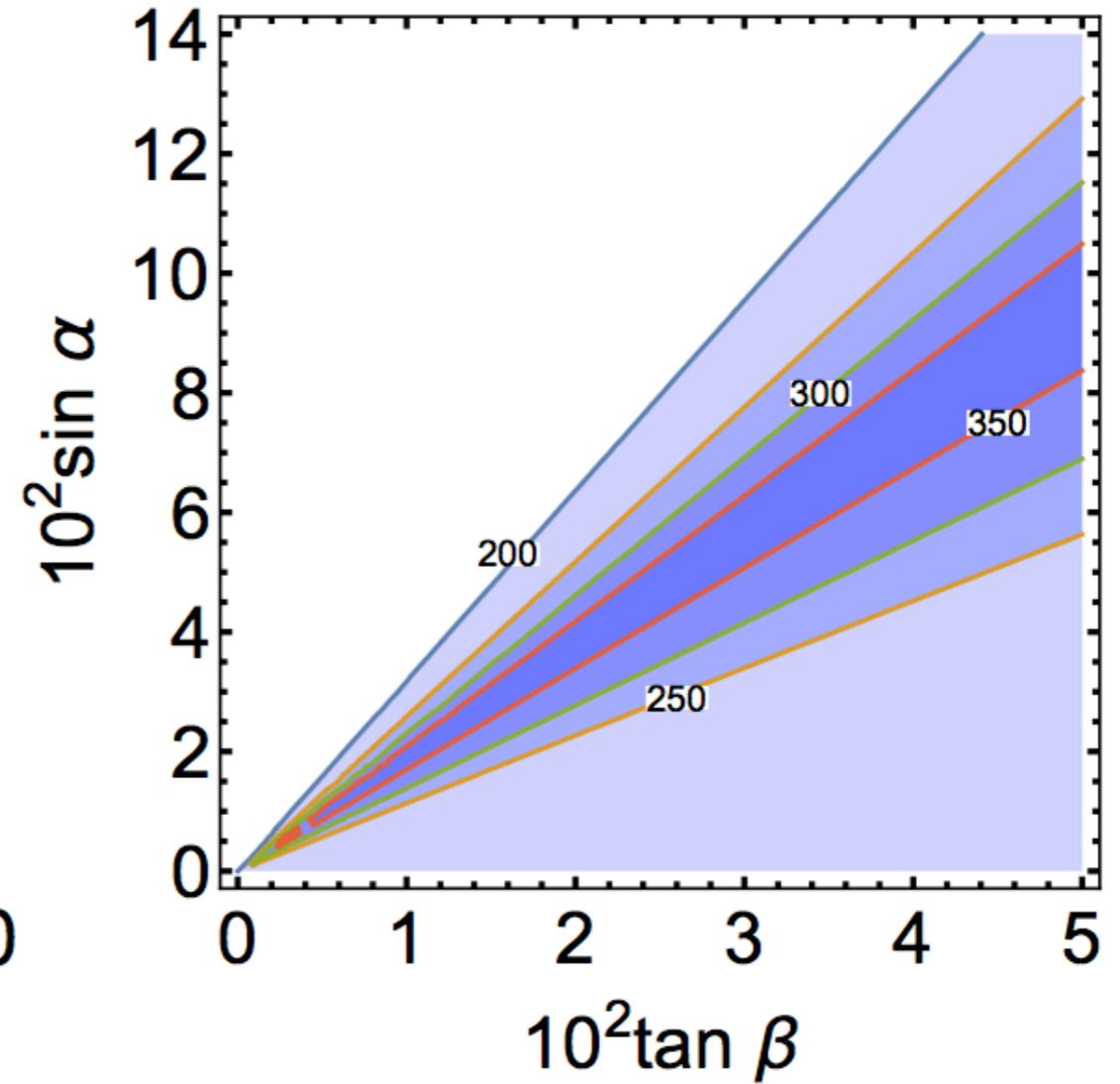
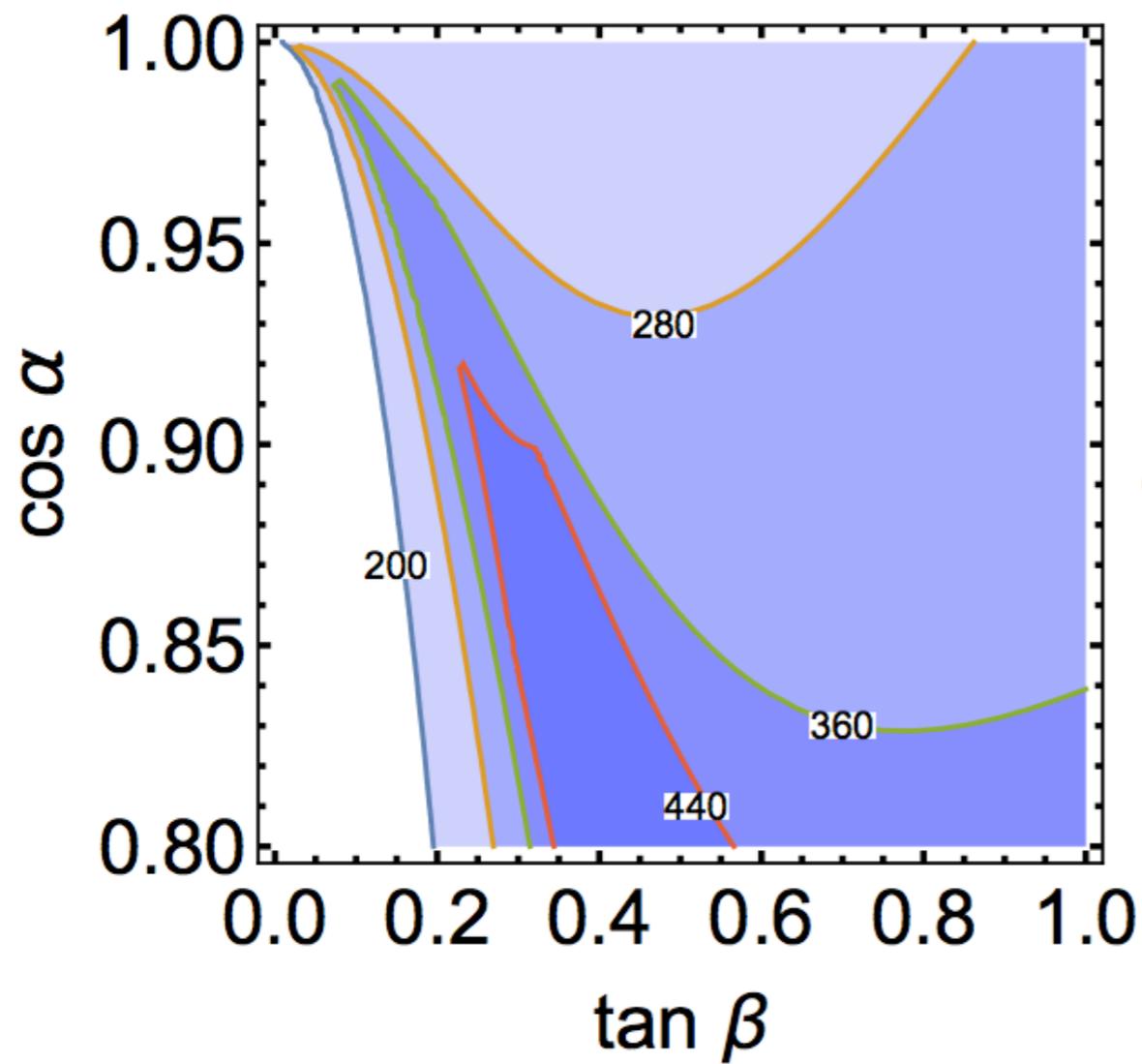
PERTURBATIVITY BOUNDS



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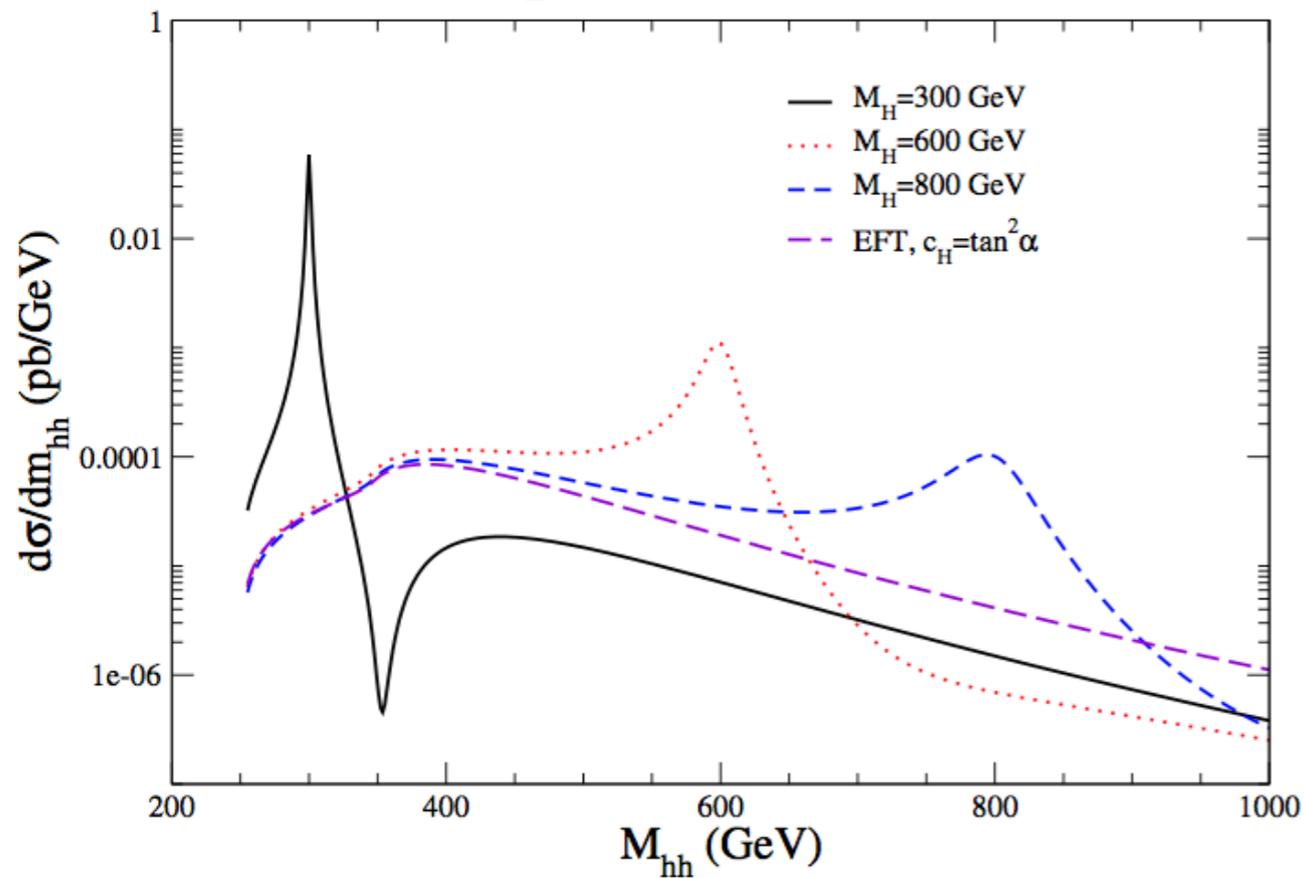
PERTURBATIVITY BOUNDS



DOUBLE HIGGS PRODUCTION: SMEFT VS. SINGLET MODEL

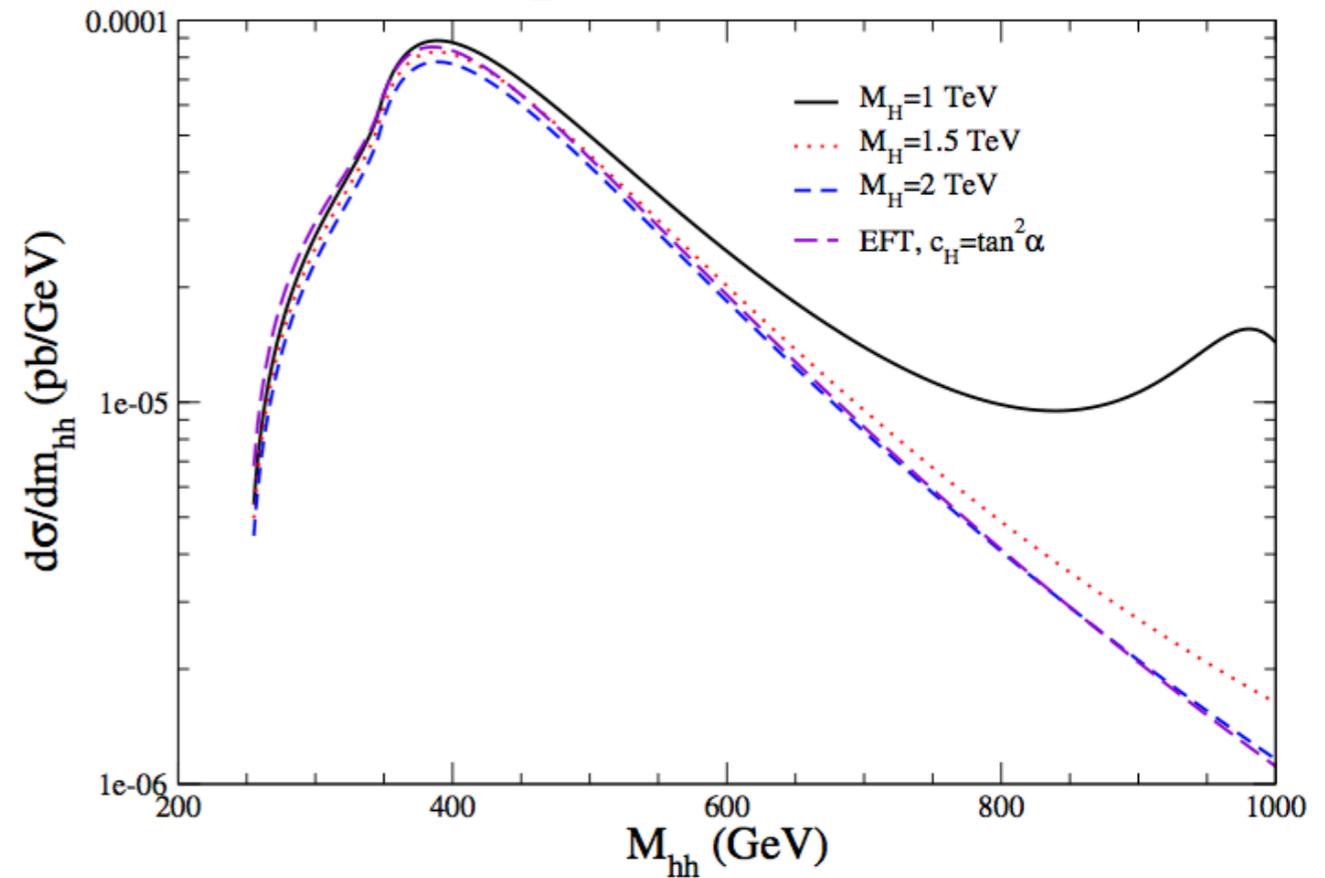
Spontaneously Broken Z_2 Symmetric Singlet Model, $\sqrt{S}=13$ TeV

$\mu=M_{hh}$, CT12 PDFs, $\cos\alpha=0.94$, $\tan\beta=0.5$



Spontaneously Broken Z_2 Symmetric Singlet Model, $\sqrt{S}=13$ TeV

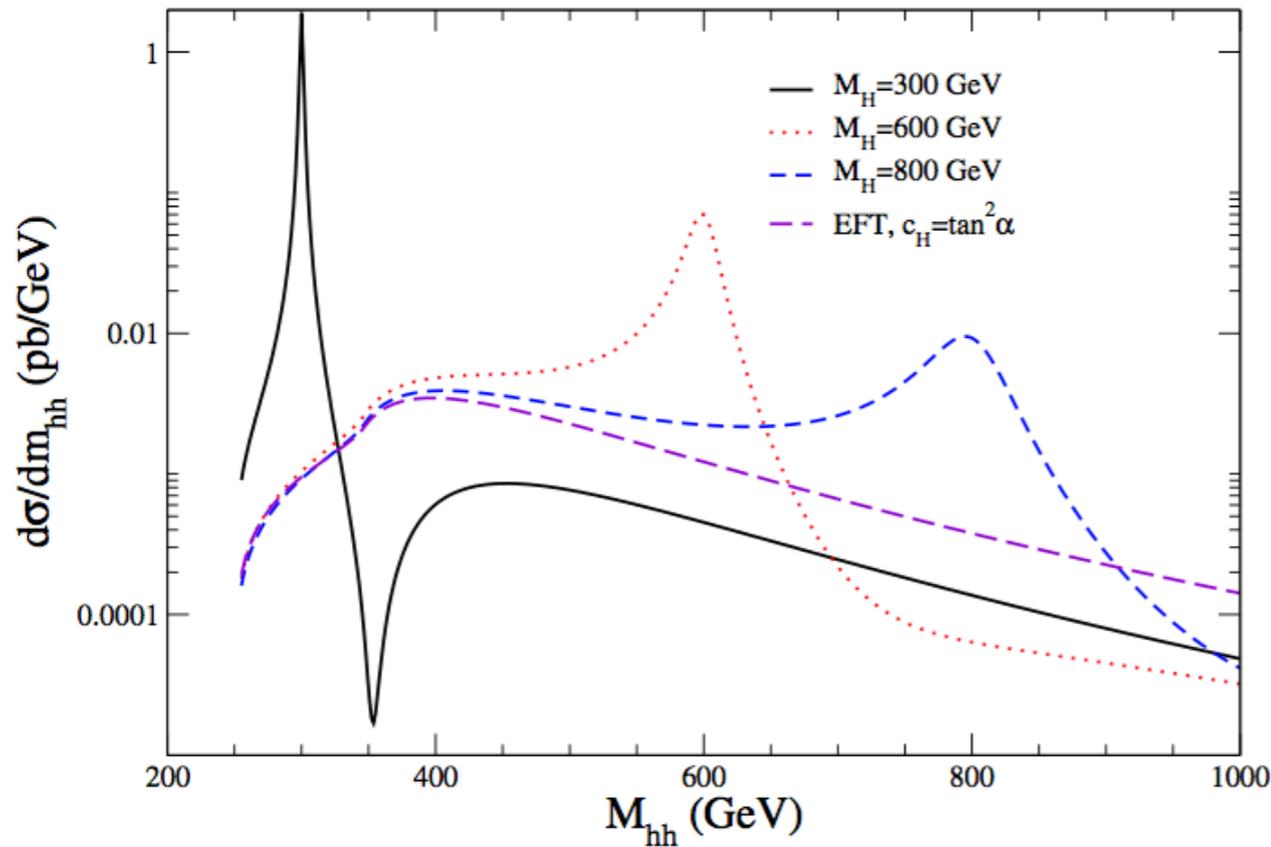
$\mu=M_{hh}$, CT12 PDFs, $\cos\alpha=0.94$, $\tan\beta=0.5$



DOUBLE HIGGS PRODUCTION @ 100TEV: EFT VS. SINGLET MODEL

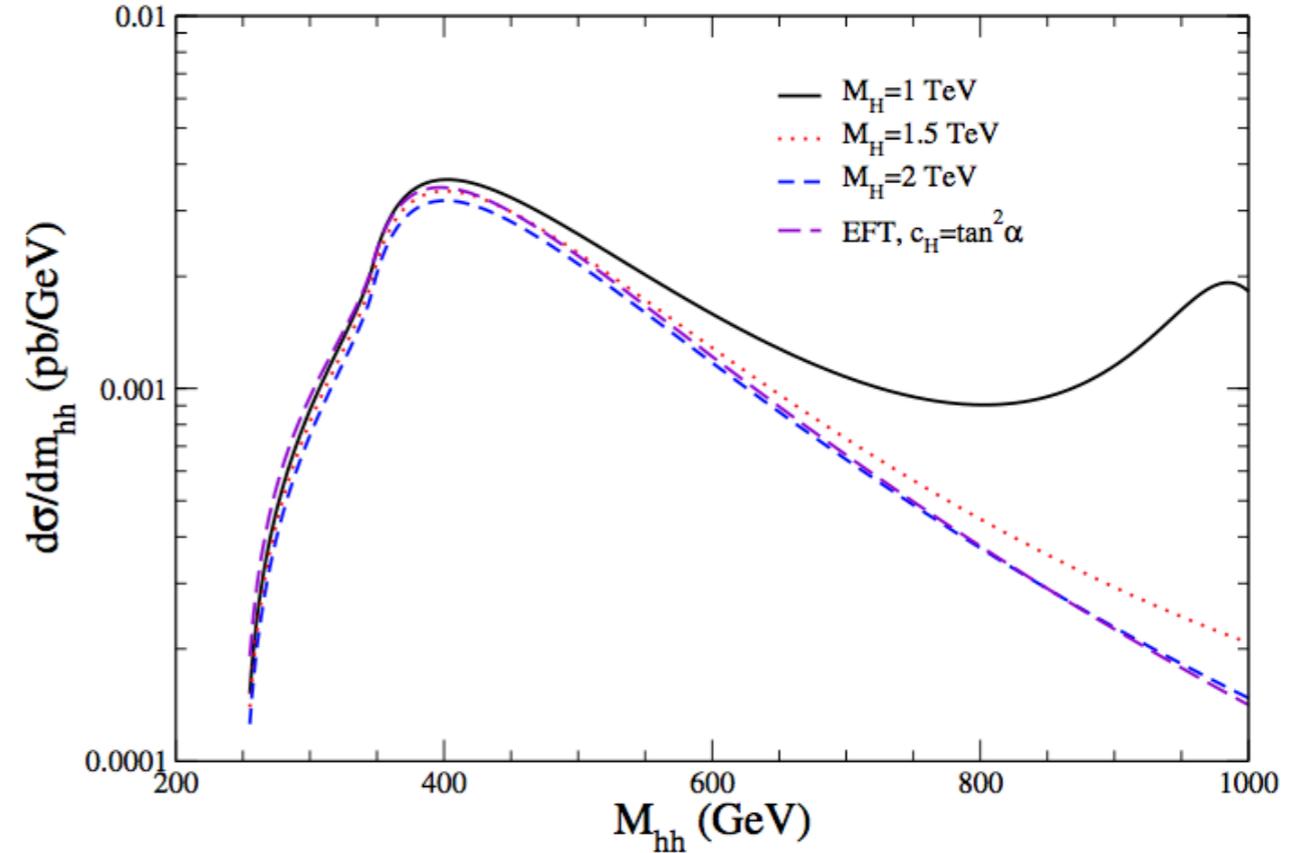
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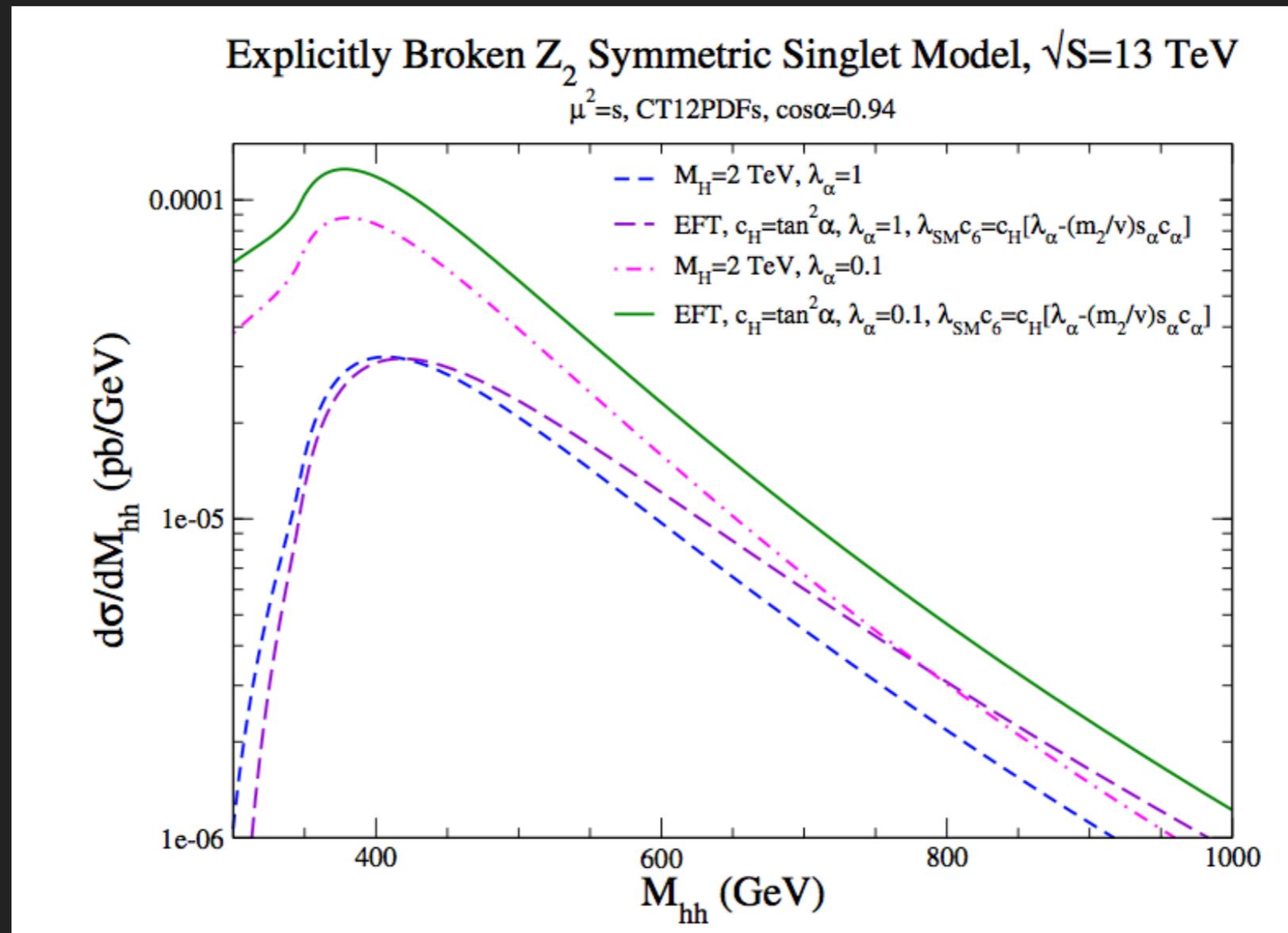


Spontaneously Broken Z_2 Symmetric Singlet Model, $\sqrt{S}=100$ TeV

$\mu=M_{hh}$, CT12 PDFs, $\cos\alpha=0.94$, $\tan\beta=0.5$



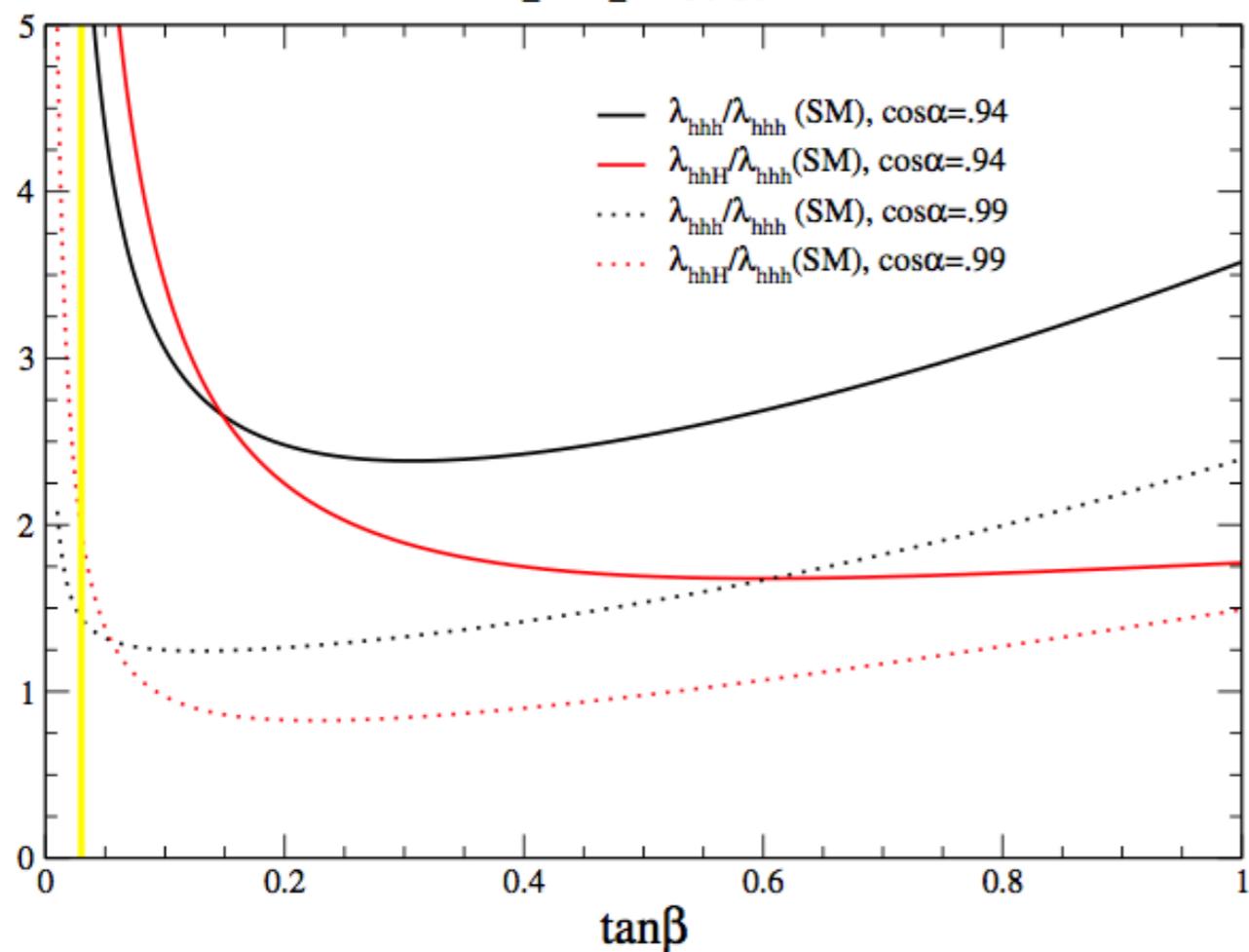
DOUBLE HIGGS PRODUCTION: EFT VS. SINGLET MODEL W/ EXPLICIT Z₂ BREAKING



QUARTET MODEL

Y=1/2 Quartet Model

$m_H=m_A=190$ GeV



Y=1/2 Quartet Model. $\sqrt{S}=13$ TeV

$m_H=m_A=190$ GeV, $\tan\beta=.03$

