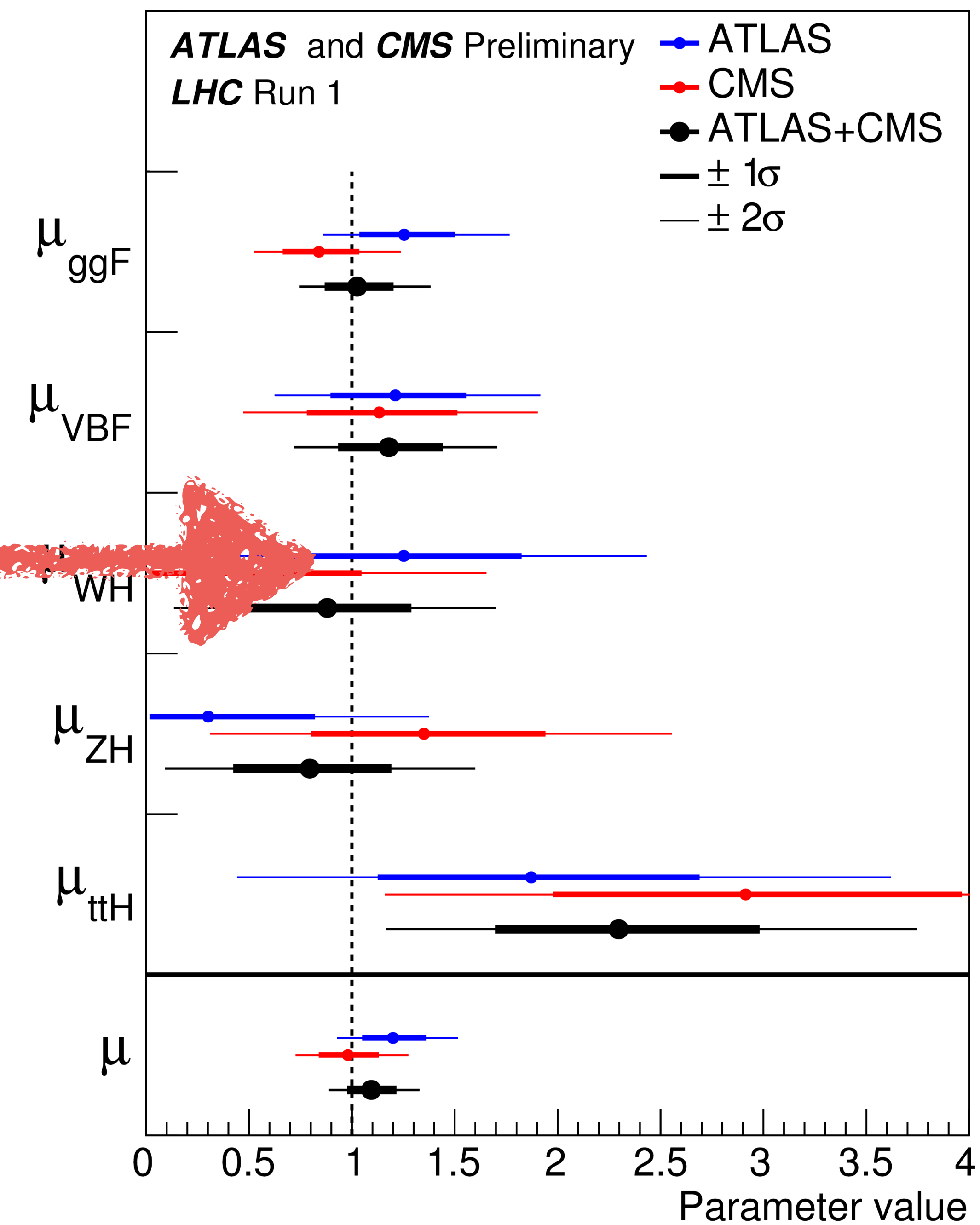
HEPKIT 2015

Simplified models for Higgs physics

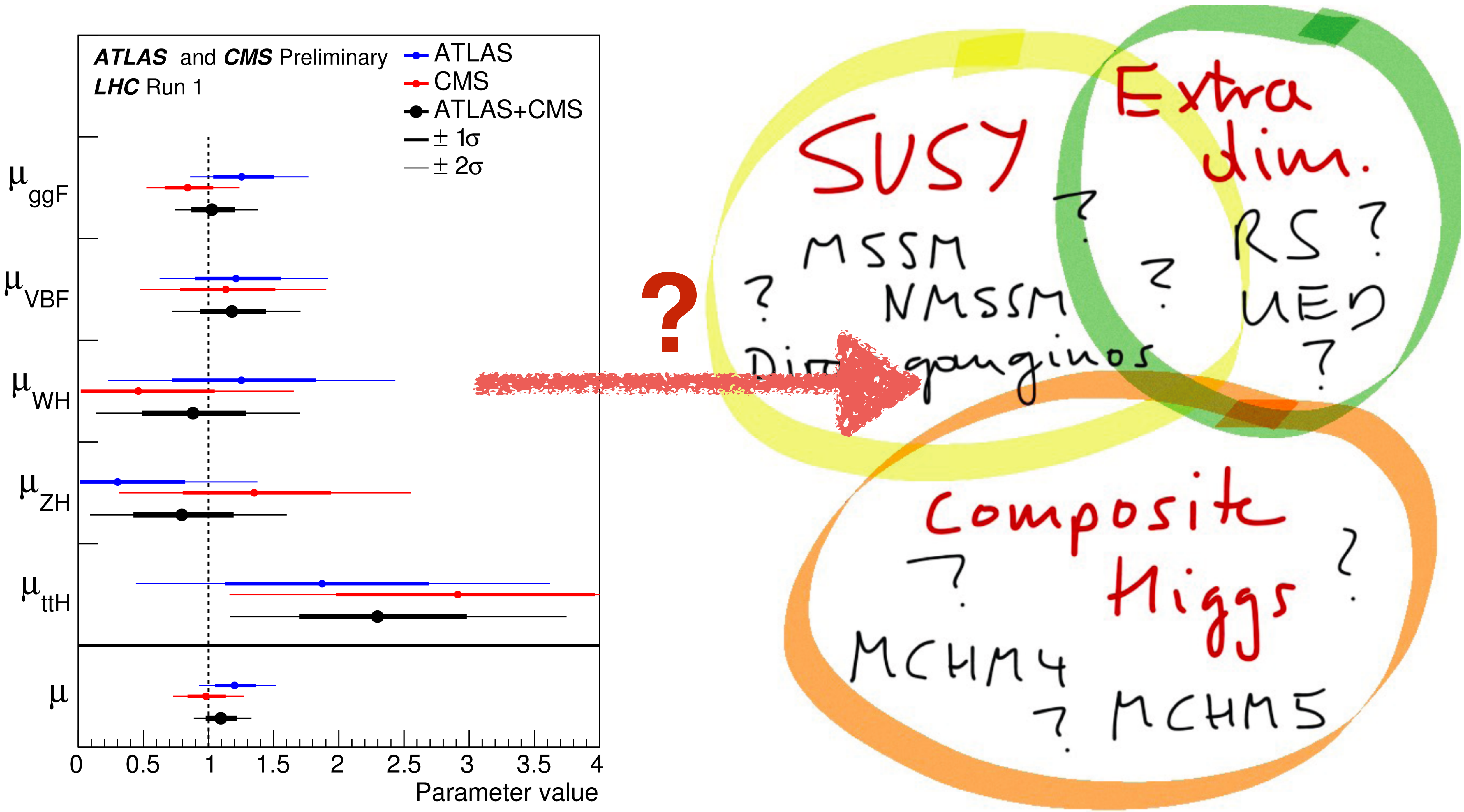
Michael Krämer (RWTH Aachen University)

with Matt Dolan, JoAnne Hewett and Tom Rizzo

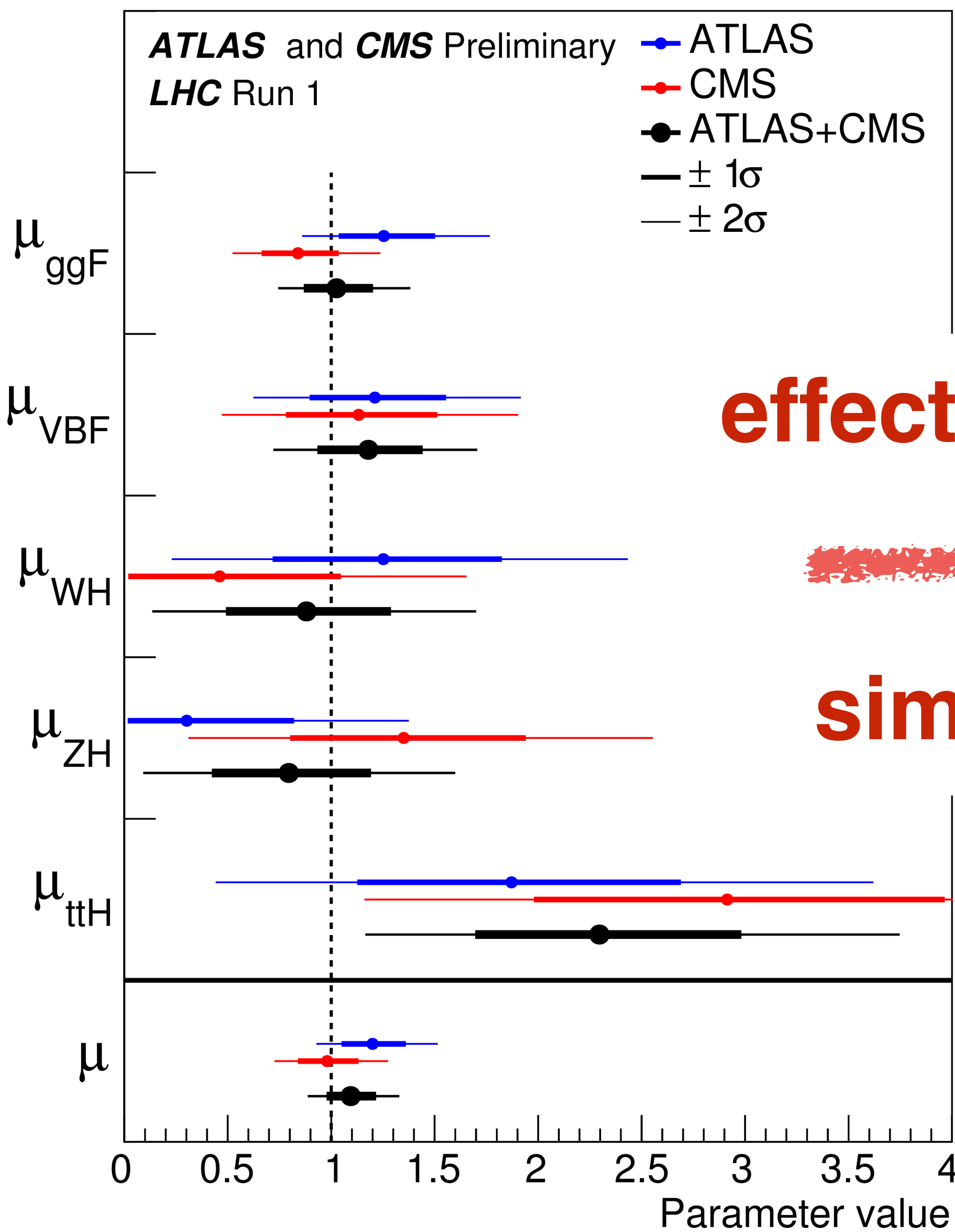
BSM models for Higgs physics: top-down



BSM models for Higgs physics: bottom-up

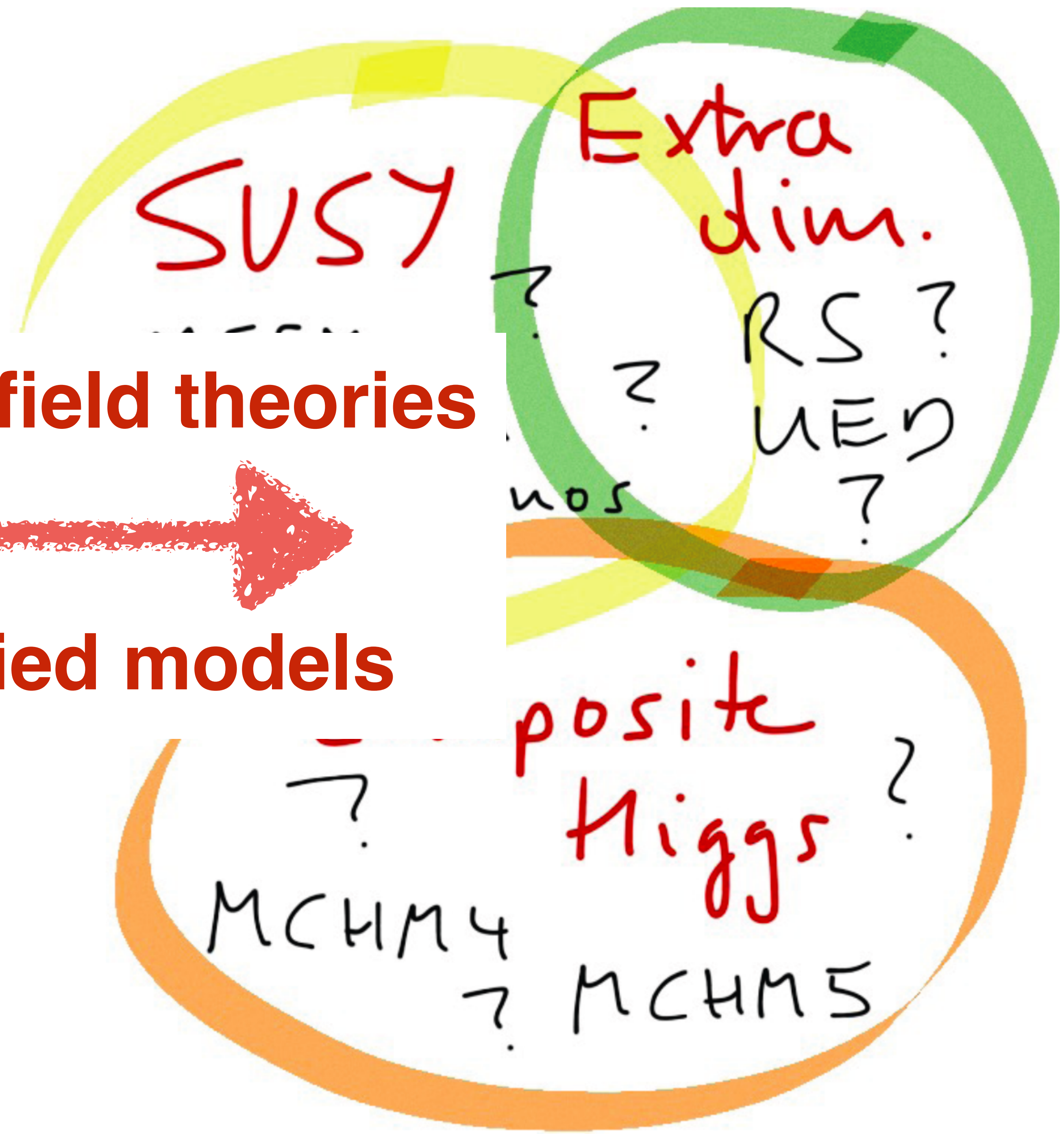


BSM models for Higgs physics: bottom-up



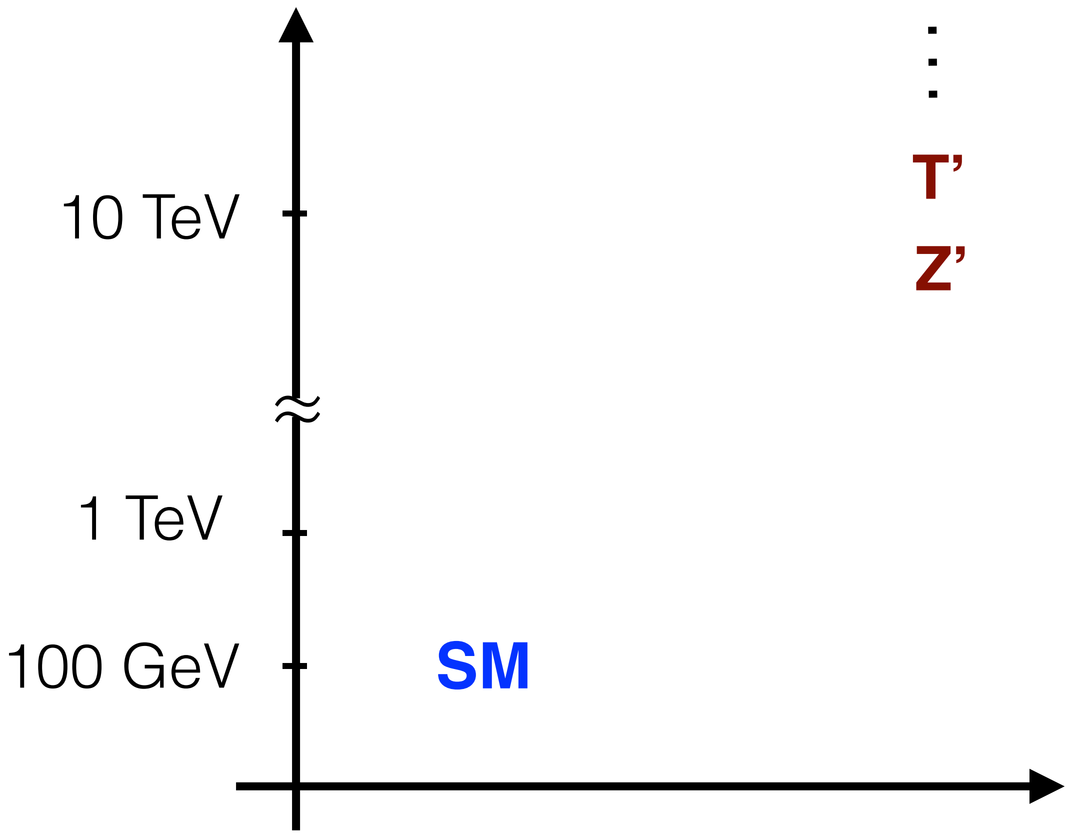
effective field theories

simplified models



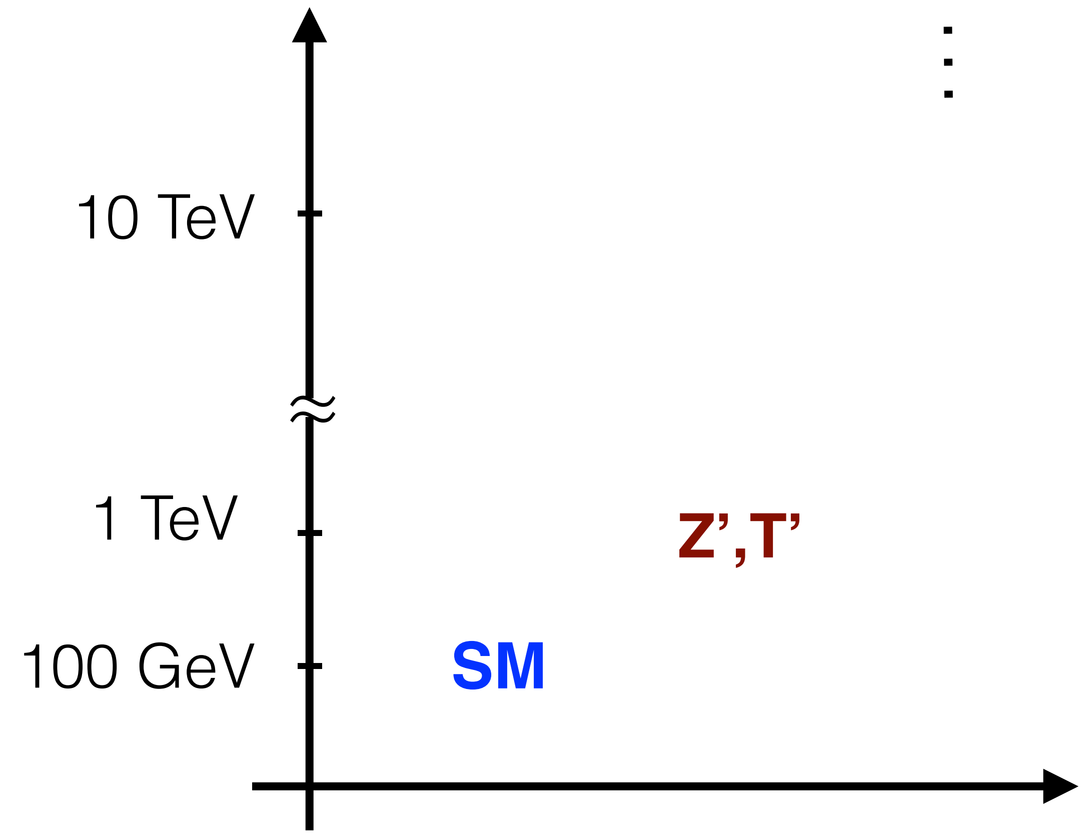
BSM models for Higgs physics: bottom-up

effective field theories



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_6 + \ldots$$

simplified models



$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{T',Z'} + \mathcal{L}_6 + \ldots$$

Simplified models

- mediate between theory and data
- allow to explore the space of theories and signatures
- connect direct and indirect searches for new physics

Simplified models have become standard for SUSY and dark matter searches at the LHC. We want to construct simplified models for Higgs physics to

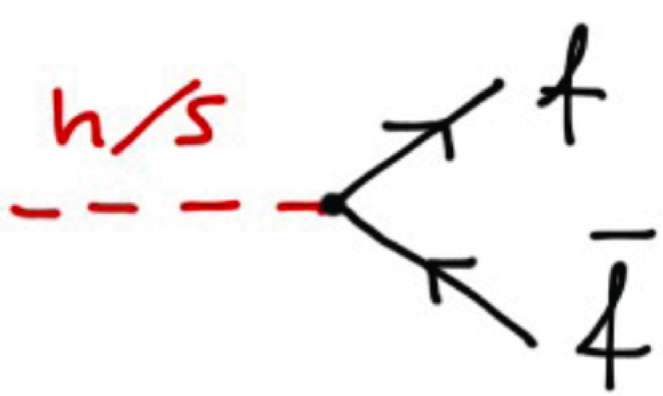
- explore BSM theories that affect the Higgs sector;
- connect measurements of Higgs properties and direct searches for new physics.

A simplified model for Higgs physics

We take the SM and add

- a scalar singlet S
- a vector-like fermion representation F

S aquires a vev, $S = (s + v_S)$, and provides mass for the fermion, $m_F = y_F\, v_S$. The Higgs and new scalar fields mix, $\lambda_{HS}\, H^\dagger H\, S^2$, and thus we generate new physics effects in all SM Higgs couplings:



A simplified model for Higgs physics

Different representations for the new fermion result in different patterns for Higgs cross sections and branching ratios.

Consider the Higgs gauge boson coupling ~ h $V_{\mu\nu}V^{\mu\nu}$

$$\gamma\gamma: \quad \epsilon_\gamma \frac{\alpha}{\pi}\frac{1}{v}\left(\frac{\lambda_{\rm HS} v^2}{m_S^2}\right)$$

$$G_a G^a: \quad \epsilon_g \frac{\alpha_s}{\pi}\frac{1}{v}\left(\frac{\lambda_{\rm HS} v^2}{m_S^2}\right)$$

$$BB: \quad \epsilon_B \frac{g'^2}{\pi^2}\frac{1}{v}\left(\frac{\lambda_{\rm HS} v^2}{m_S^2}\right)$$

$$W_i W^i: \quad \epsilon_W \frac{g^2}{\pi^2}\frac{1}{v}\left(\frac{\lambda_{\rm HS} v^2}{m_S^2}\right)$$

F	ϵ_γ	ϵ_g	ϵ_B	ϵ_W
$\begin{pmatrix} T' \\ B' \end{pmatrix}_{L+R}$	$\frac{5}{18}$	$-\frac{1}{6}$	$\frac{1}{144}$	$\frac{1}{16}$
Q_{L+R}	$\frac{1}{2}Q^2$	$-\frac{1}{12}$	$\frac{1}{8}Q^2$	0
$\begin{pmatrix} N \\ E \end{pmatrix}_{L+R}$	$\frac{1}{6}$	0	$\frac{1}{48}$	$\frac{1}{48}$
L_{L+R}	$\frac{1}{16}Q^2$	0	$\frac{1}{24}$	0

A simplified model for Higgs physics

$$\mathcal{L} \supset \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{gauge}} - V(H,S)$$

We chose **F = T**, colour-triplet, SU(2) singlet, Q = 2/3:

$$\mathcal{L}_{\text{Yukawa}} = y_T S \overline{T}_L^{\text{int}} T_R^{\text{int}} + y_t \overline{Q}_L^{\text{int}} \widetilde{H} t_R^{\text{int}} + y_b \overline{Q}_L^{\text{int}} H b_R + \lambda_T \overline{Q}_L^{\text{int}} \widetilde{H} T_R^{\text{int}}$$

After SSB the SM top quark $\mathbf{t^{int}}$ and the vector quark $\mathbf{T^{int}}$ mix to form the mass eigenstates **t** and **T**:

$$m_t^2 = \frac{1}{2} v_H^2 y_t^2 \left(1 - \frac{\lambda_T^2}{2y_T^2} \frac{v_H^2}{v_S^2}\right) \qquad m_T^2 = v_S^2 y_T^2 \left(1 + \frac{\lambda_T^2}{2y_T^2} \frac{v_H^2}{v_S^2}\right)$$

$$\tan(2\theta_L) = \frac{2}{\sqrt{2}} \frac{\lambda_T}{y_T} \frac{v_H}{v_S}$$

A simplified model for Higgs physics

$$\mathcal{L} \supset \mathcal{L}_{\text{Yukawa}} + \mathcal{L}_{\text{gauge}} - V(H,S)$$

$$V(H,S) = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + \frac{a_1}{2} H^\dagger H\, S$$
$$+ \frac{a_2}{2} H^\dagger H\, S^2 \;\; + b_1 S + \frac{b_2}{2} S^2 + \frac{b_3}{3} S^3 + \frac{b_4}{4} S^4$$

with $\quad H = \begin{pmatrix} i\phi^+ \\ \frac{1}{\sqrt{2}}(h + v_H + i\phi^0) \end{pmatrix} \quad$ and $\quad S = (s + v_S)$

For simplicity, we assume a Z_2-symmetry and set $a_1 = b_1 = b_3 = 0$.

H and **S** mix, to form mass eigenstates $\mathbf{h_1}$ and $\mathbf{h_2}$:

$$m_1^2 = 2\lambda v_H^2 \left(1 - \frac{a_2^2}{4\lambda b_4}\right) \qquad m_2^2 = 2 b_4 v_S^2 \left(1 + \frac{a_2^2}{4 b_4^2} \frac{v_H^2}{v_S^2}\right)$$

$$\tan(2\theta) = \frac{a_2}{b_4} \frac{v_H}{v_S}$$

A simplified model for Higgs physics

The model has 5 free and 3 fixed parameters. We choose:

m_2, θ, v_S, m_T and **θ_L**

and set m_1= 125 GeV, v_H = 246 GeV and m_t = 173 GeV.

The parameters are constrained by

- perturbative unitary
- precision EW data: S, T and U
- Higgs cross sections and branching ratios

A simplified model for Higgs physics

It is straightforward to calculate the couplings of the 125-Higgs to SM particles:

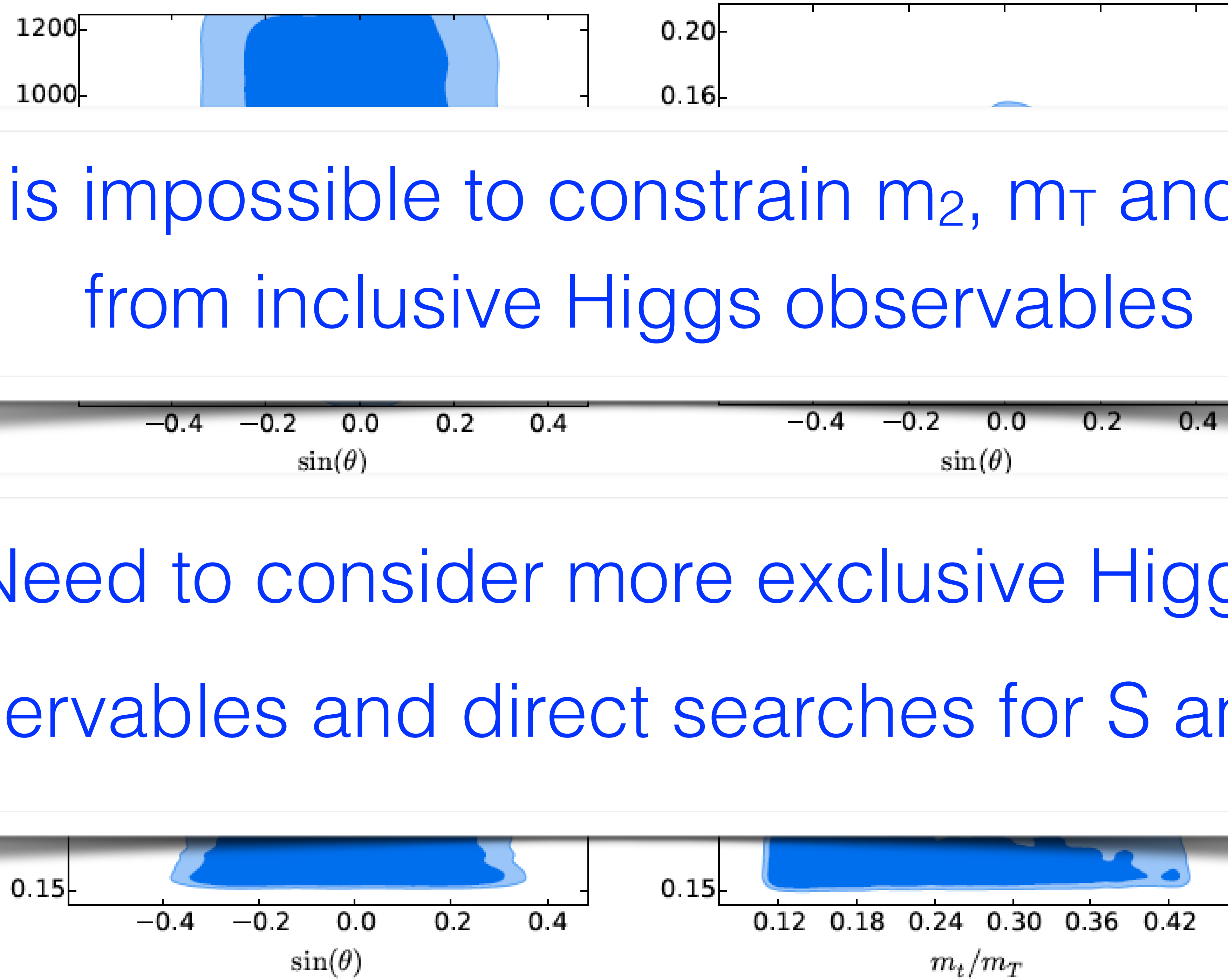
$$\kappa_W = \kappa_Z = \kappa_b = \kappa_\tau = \cos\theta \quad \text{and} \quad \kappa_t = c_L^2 c_\theta - s_L^2 s_\theta \frac{v_H}{v_S}$$

For the loop-induced couplings one has

$$g_{hgg} = \frac{g_s^2}{4\pi^2}\left(\sum_f \frac{g_{hff}}{m_f} A_{1/2}(\tau_f) + \frac{g_{hTT}}{m_T} A_{1/2}(\tau_T)\right) \approx g_{hgg}^{\rm SM}\left(c_\theta - s_\theta \frac{v_H}{v_S}\right)$$

$$g_{h\gamma\gamma} = \frac{e^2}{4\pi^2}\left(\frac{g_{hWW}}{m_W^2} A_1(\tau_W) + \sum_f 2N_C^f Q_f^2 \frac{g_{hff}}{m_f} A_{1/2}(\tau_f) + \frac{8}{3}\frac{g_{hTT}}{m_T} A_{1/2}(\tau_T)\right)$$

A fit to the Higgs cross sections and BRs



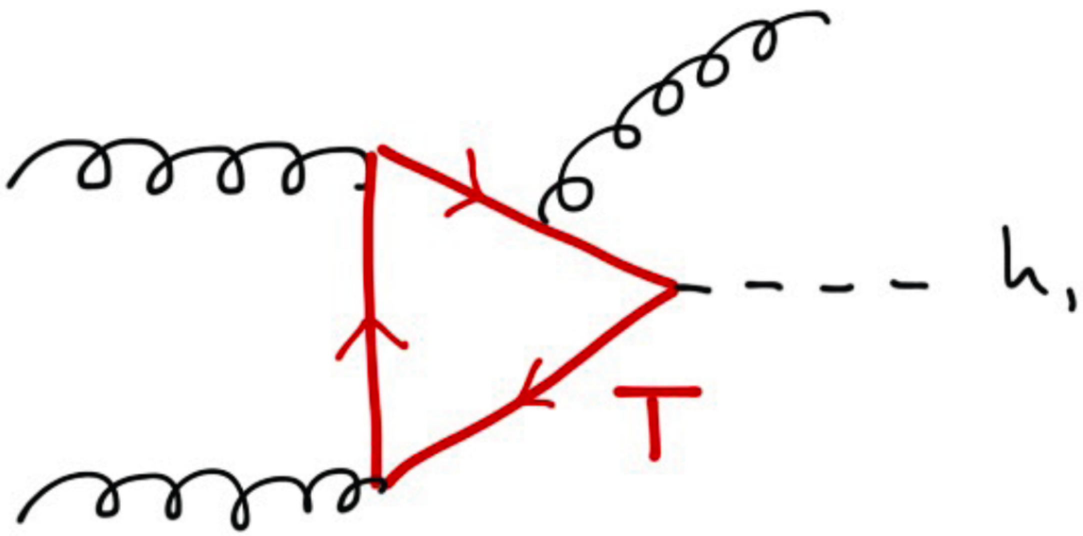
It is impossible to constrain m_2, m_T and v_S from inclusive Higgs observables

Need to consider more exclusive Higgs observables and direct searches for S and T.

HiggsSignals/HiggsBounds

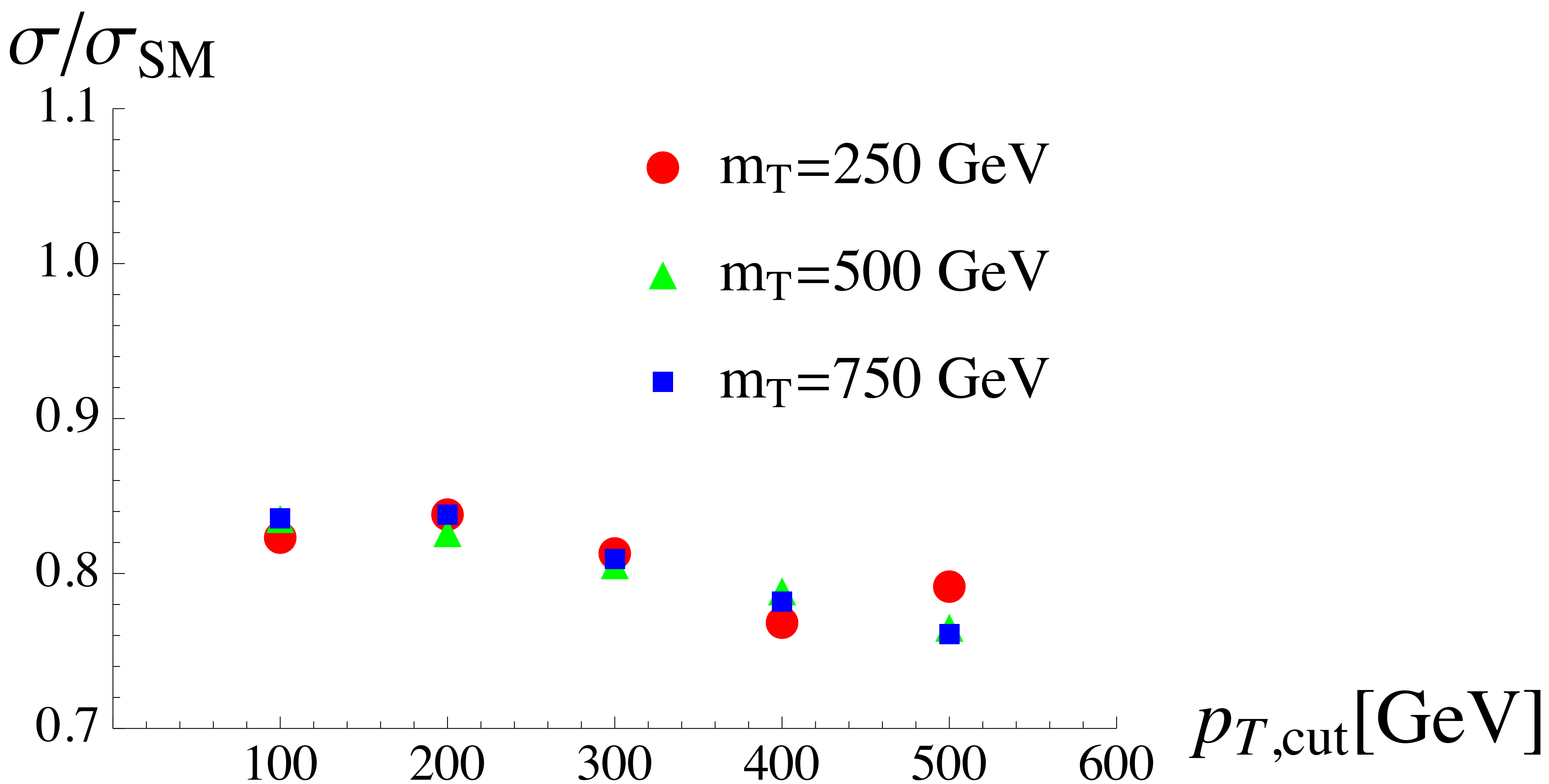
The Higgs P_T distribution

One can try to resolve the heavy new fermion in the loop through Higgs + jet production:



The Higgs P_T distribution

One can try to resolve the heavy new fermion in the loop through Higgs + jet production:

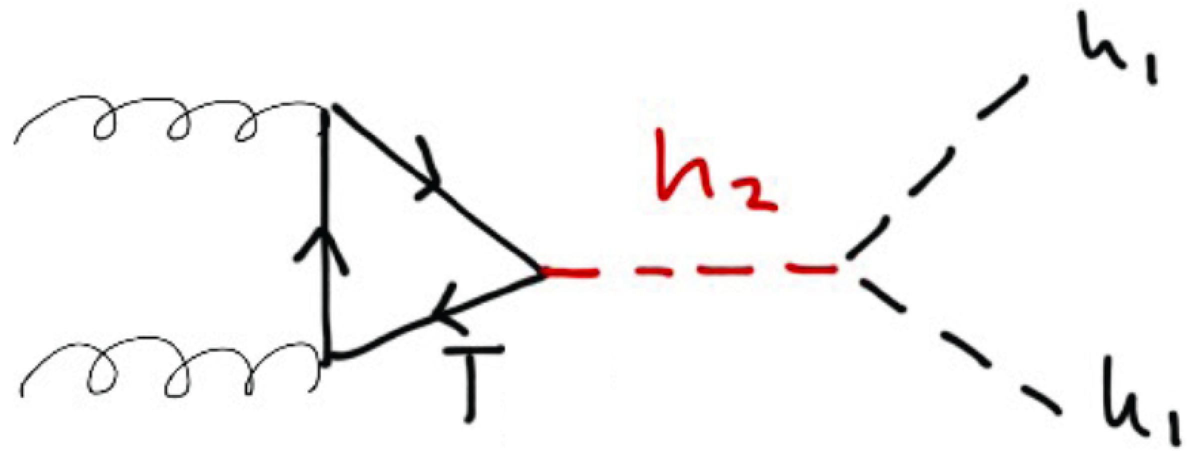


$\sin\theta = \sin\theta_L = 0.15$, $v_S = 500$ GeV

Madgraph5@NLO

Higgs pair production

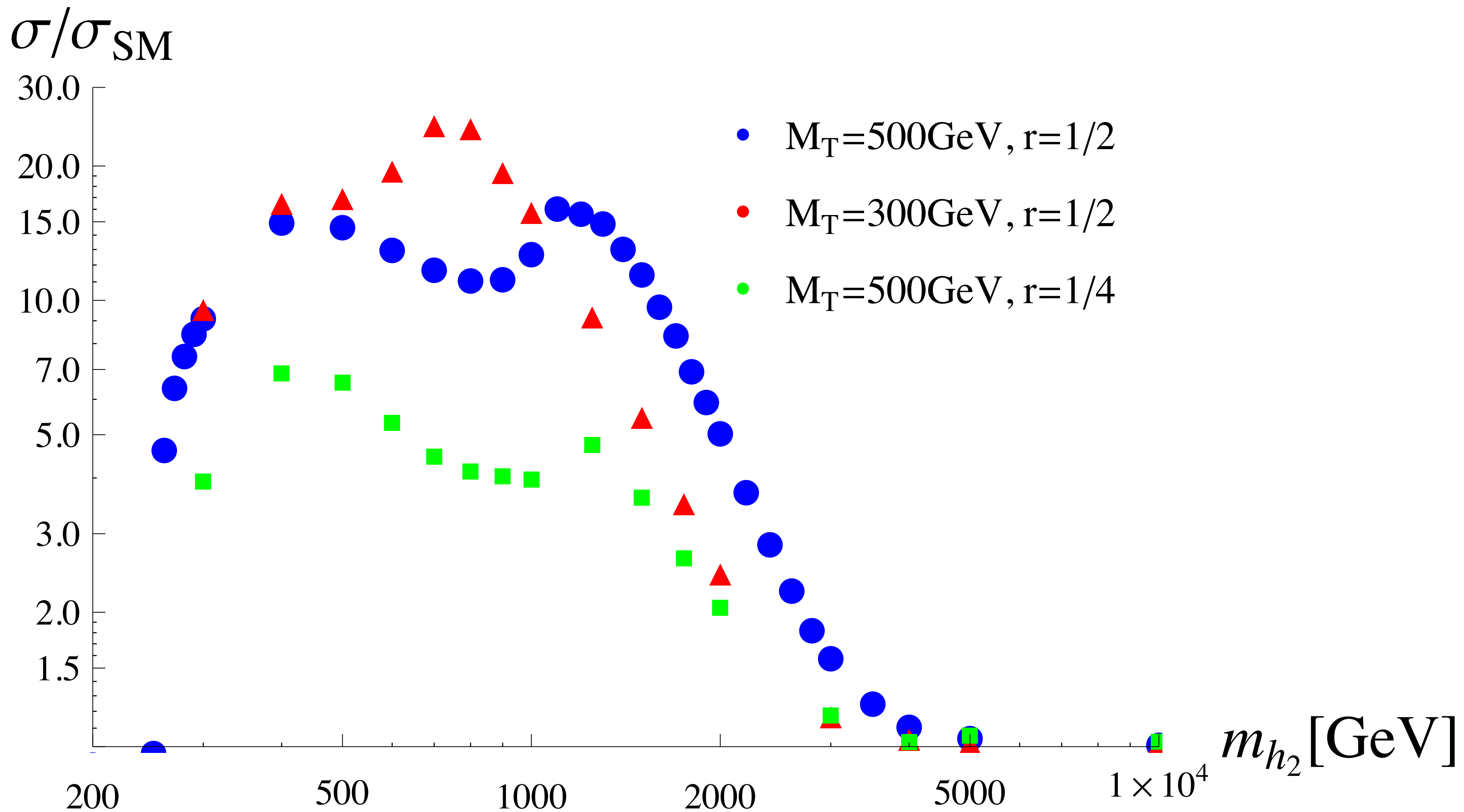
One can try to learn something about the new scalar sector through Higgs pair production:



$$\mathcal{L} \supset g_{tty}^{\rm SM} \left(\bar{t} t h_1 + \frac{m_T}{m_t} \frac{v_H}{v_S} \bar{T} T h_2 \right)$$ for $\sin\theta = \sin\theta_L = 0$

Higgs pair production

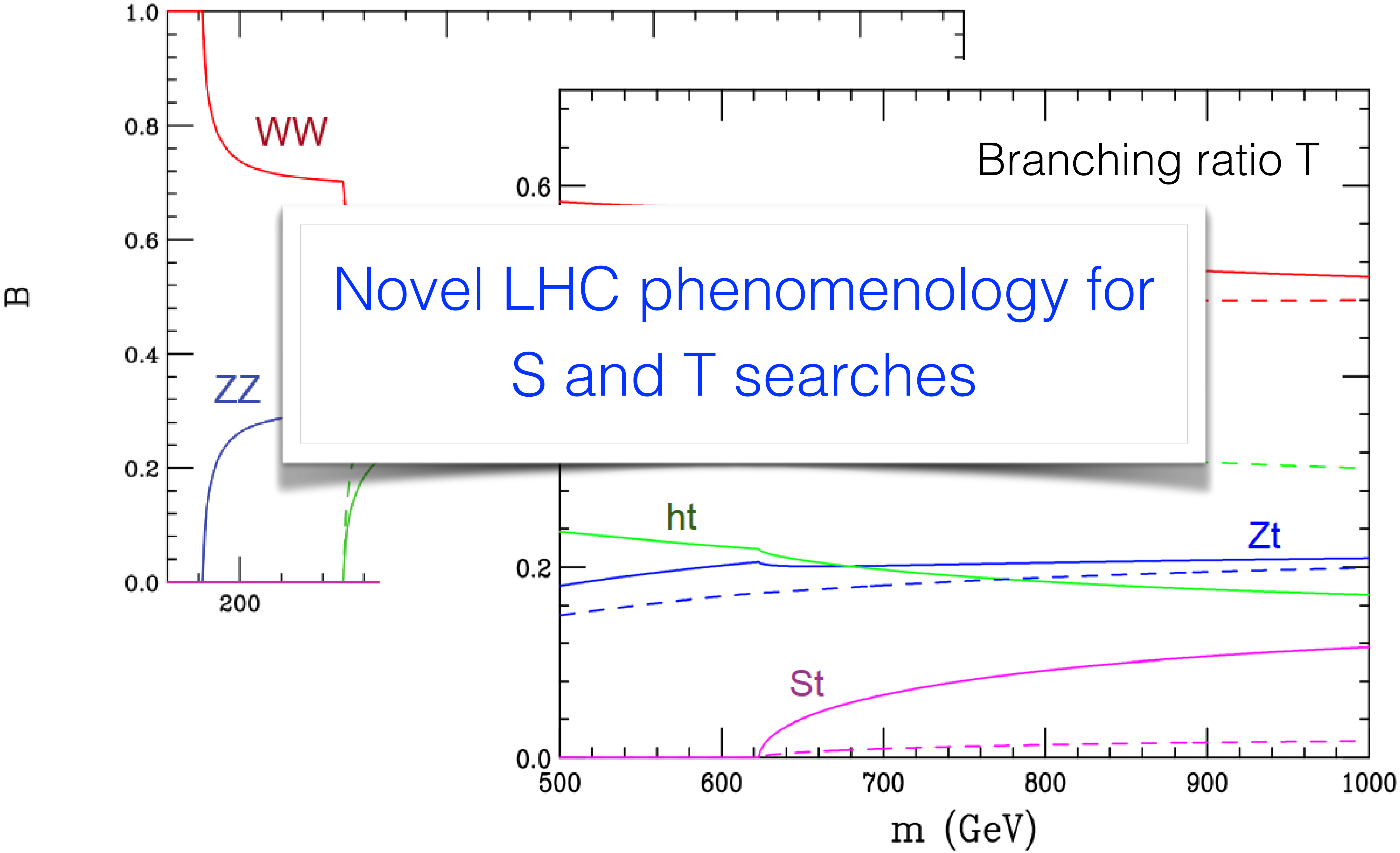
One can try to learn something about the new scalar sector through Higgs pair production:



$\sin\theta = \sin\theta_L = 0.15$

Madgraph5@NLO

Direct searches for S and T



Novel LHC phenomenology for S and T searches

Simplified models for Higgs physics

- mediate between theory and data;
- allow to explore the space of theories and signatures;
- connect direct and indirect searches for new physics.

We have performed a phenomenological study of the simplest simplified Higgs model with a new scalar and vector-like T quark:

- inclusive Higgs observables are only sensitive to part of the parameter space;
- Higgs p_T distributions and Higgs-pair production may provide additional information;
- Need direct searches to fully explore the model.

Thank you!