RWTH AACHEN UNIVERSITY

HiggsDays 2016

Simplified models for Higgs physics

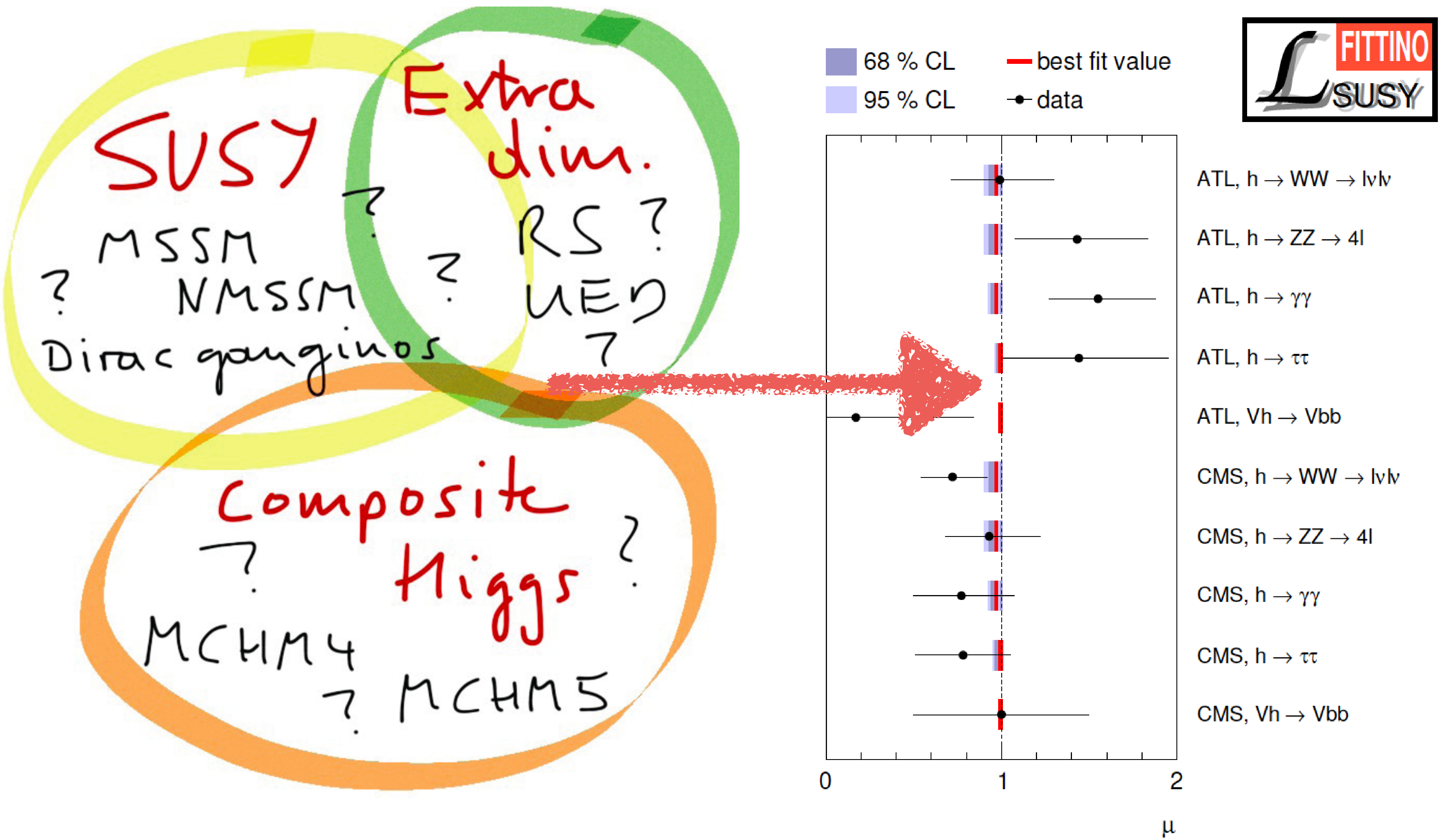
Michael Krämer (RWTH Aachen University)

with Matt Dolan, JoAnne Hewett and Tom Rizzo (JHEP 1607 (2016) 039)

Aachen Bonn Heidelberg Mainz

DFG Deutsche Forschungsgemeinschaft

BSM models for Higgs physics: top-down



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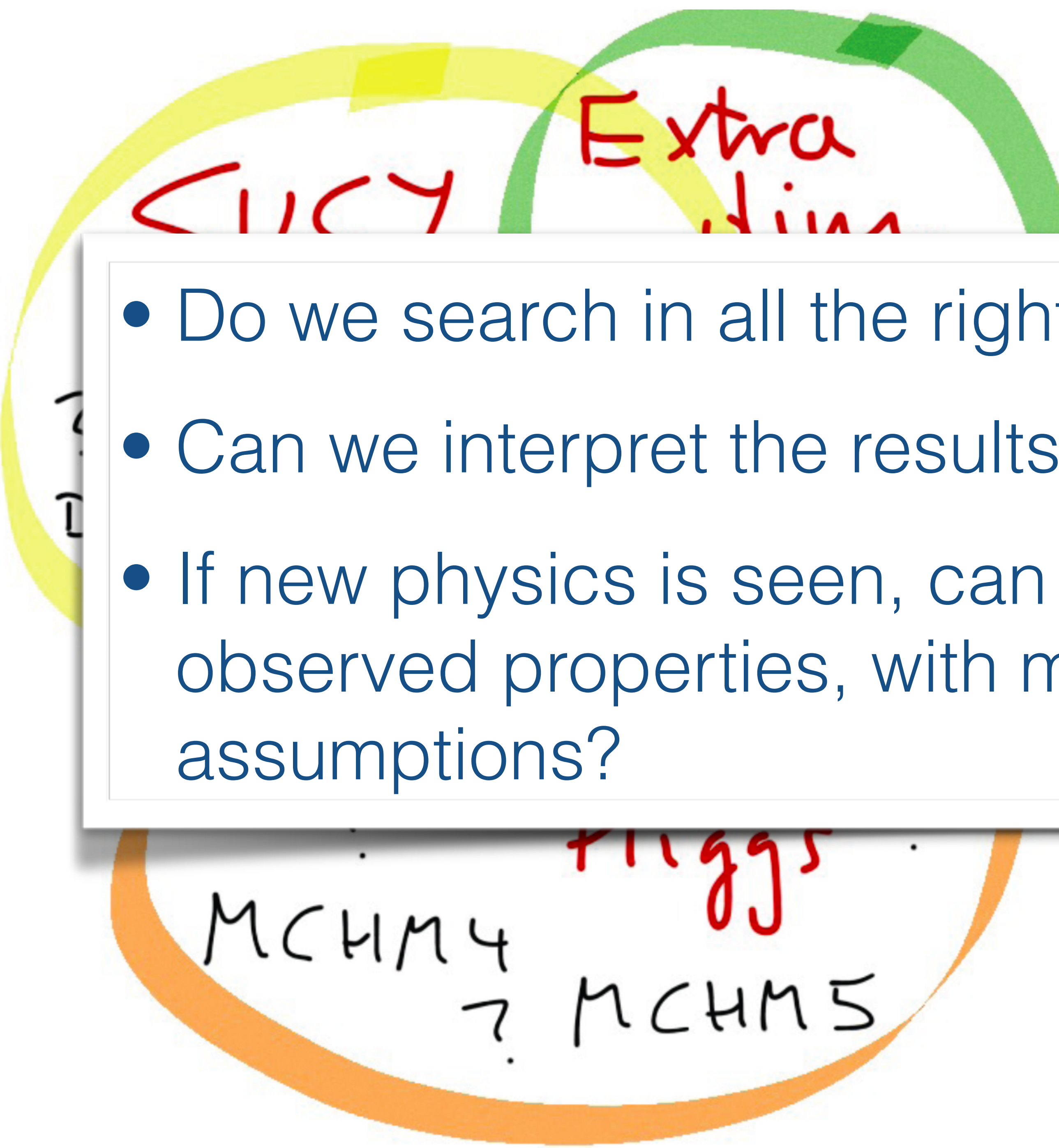
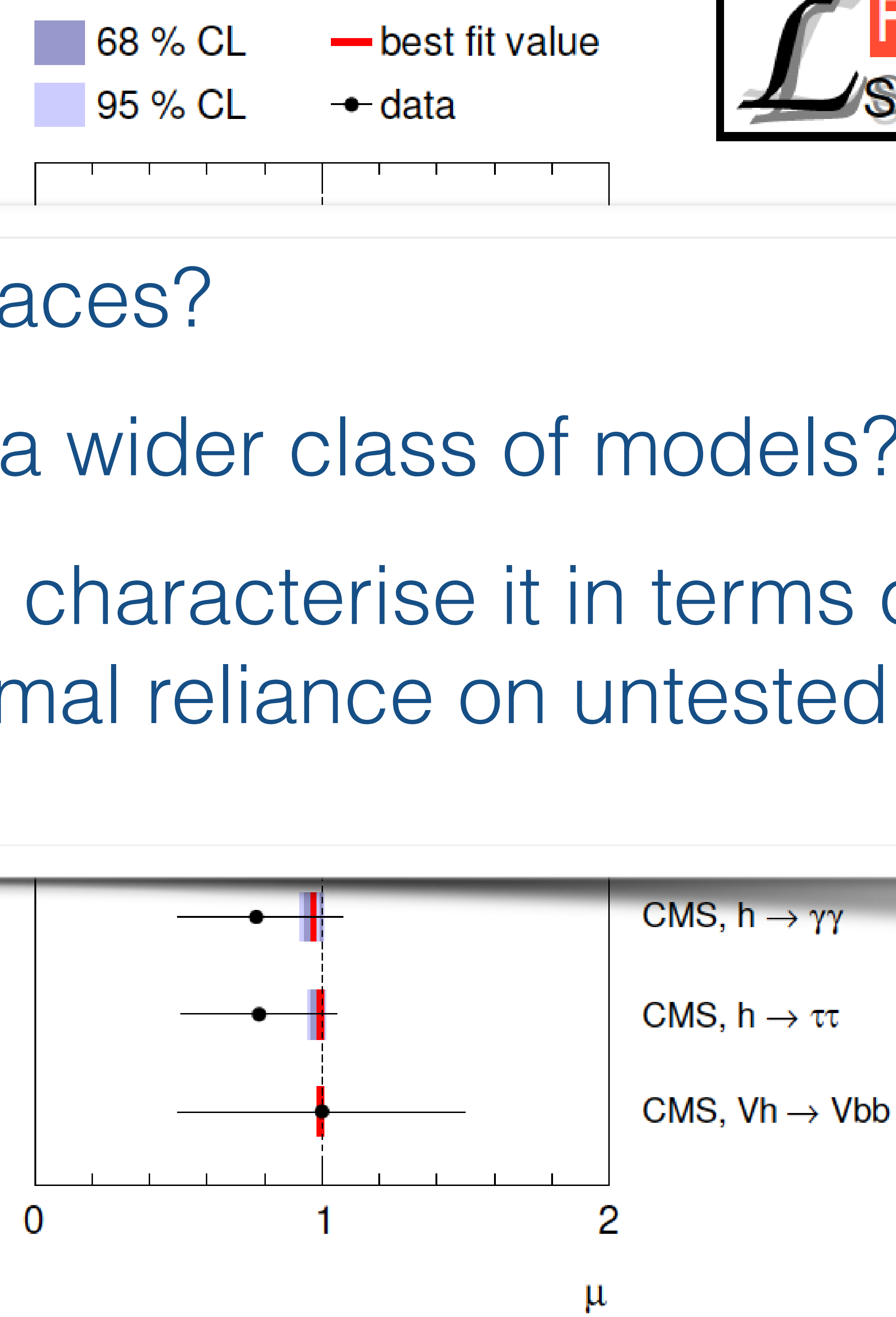
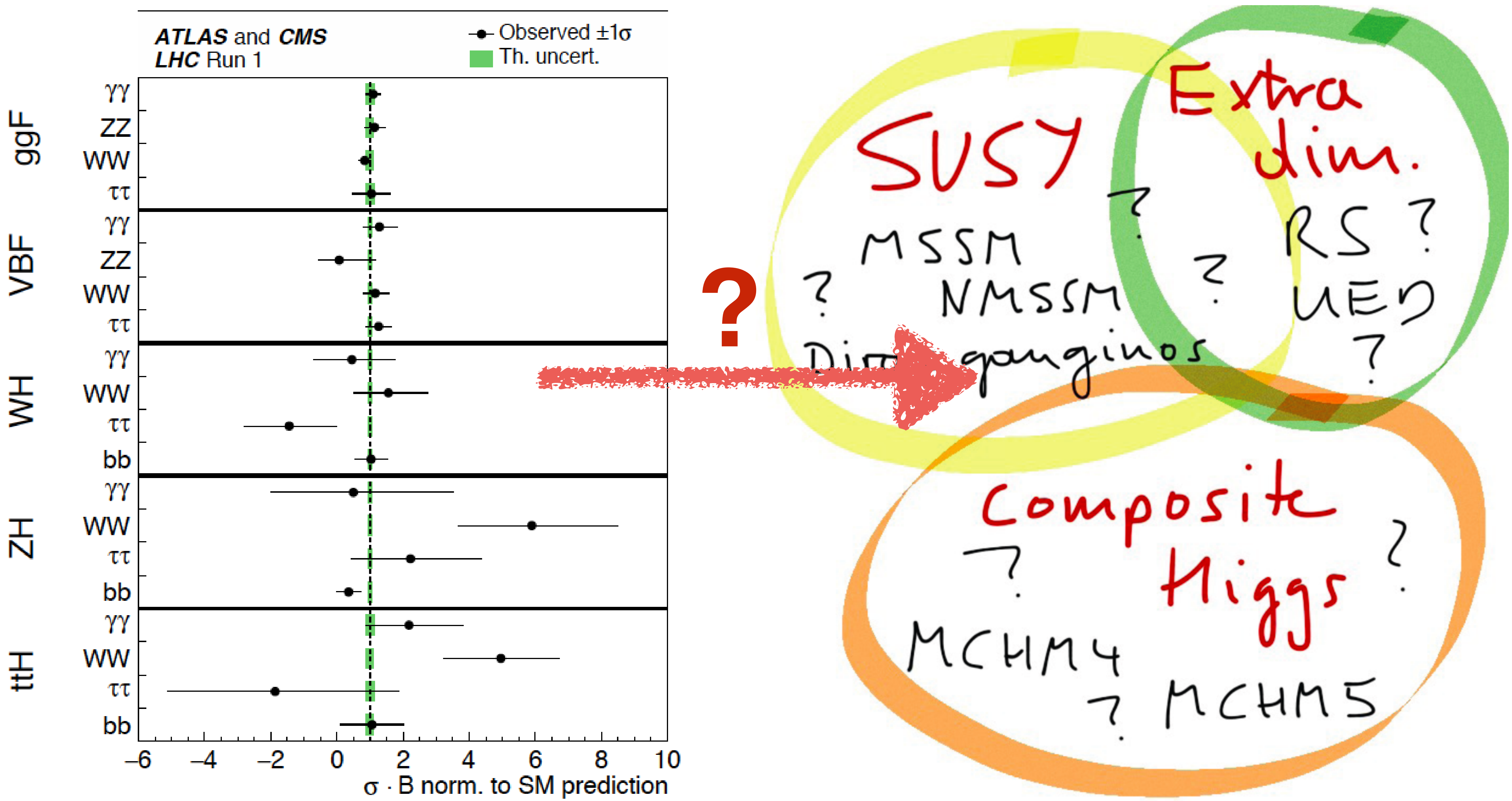




- Do we search in all the right places?
- Can we interpret the results in a wider class of models?
- If new physics is seen, can we characterise it in terms of observed properties, with minimal reliance on untested assumptions?

BSM models for Higgs physics: bottom-up



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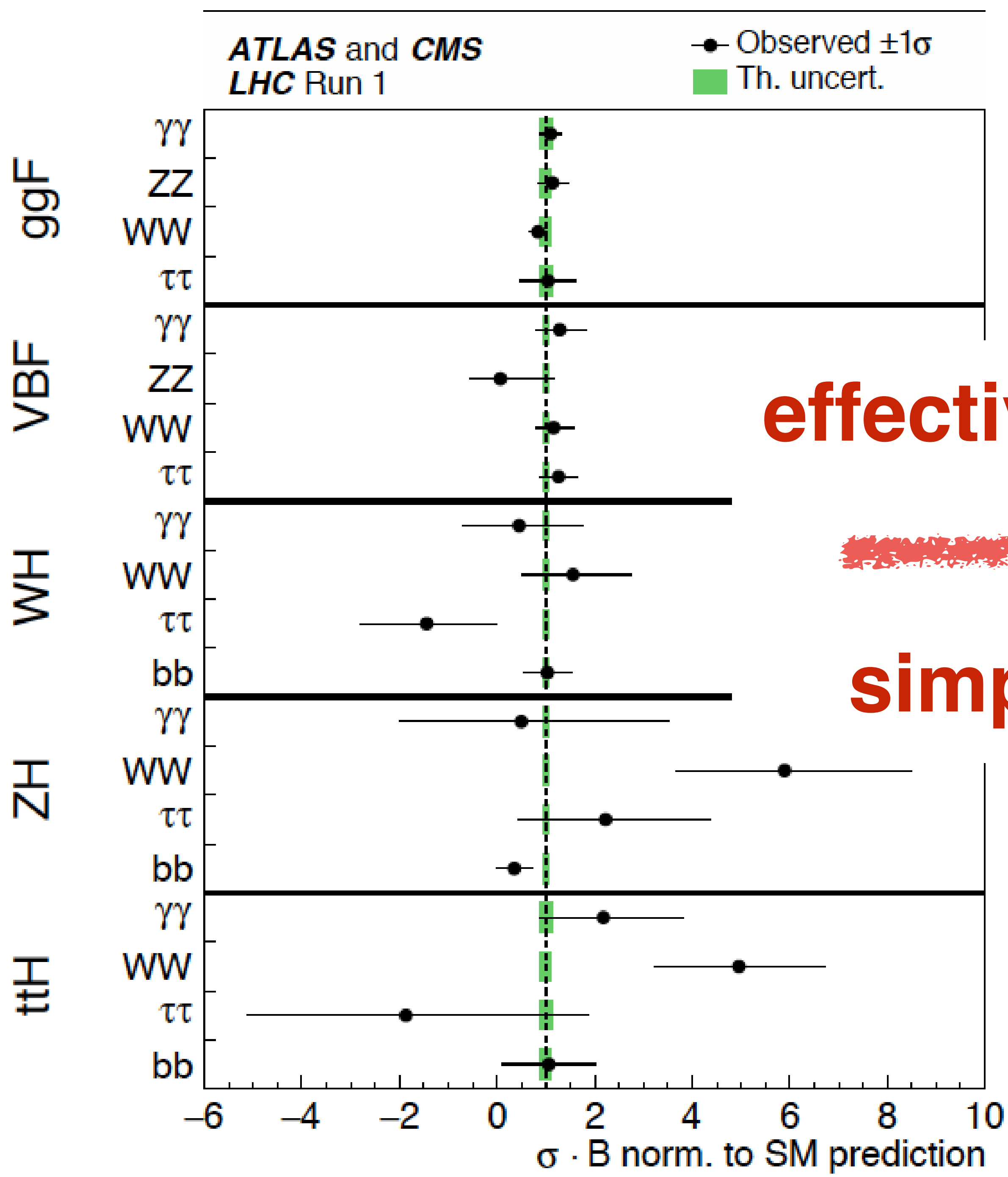
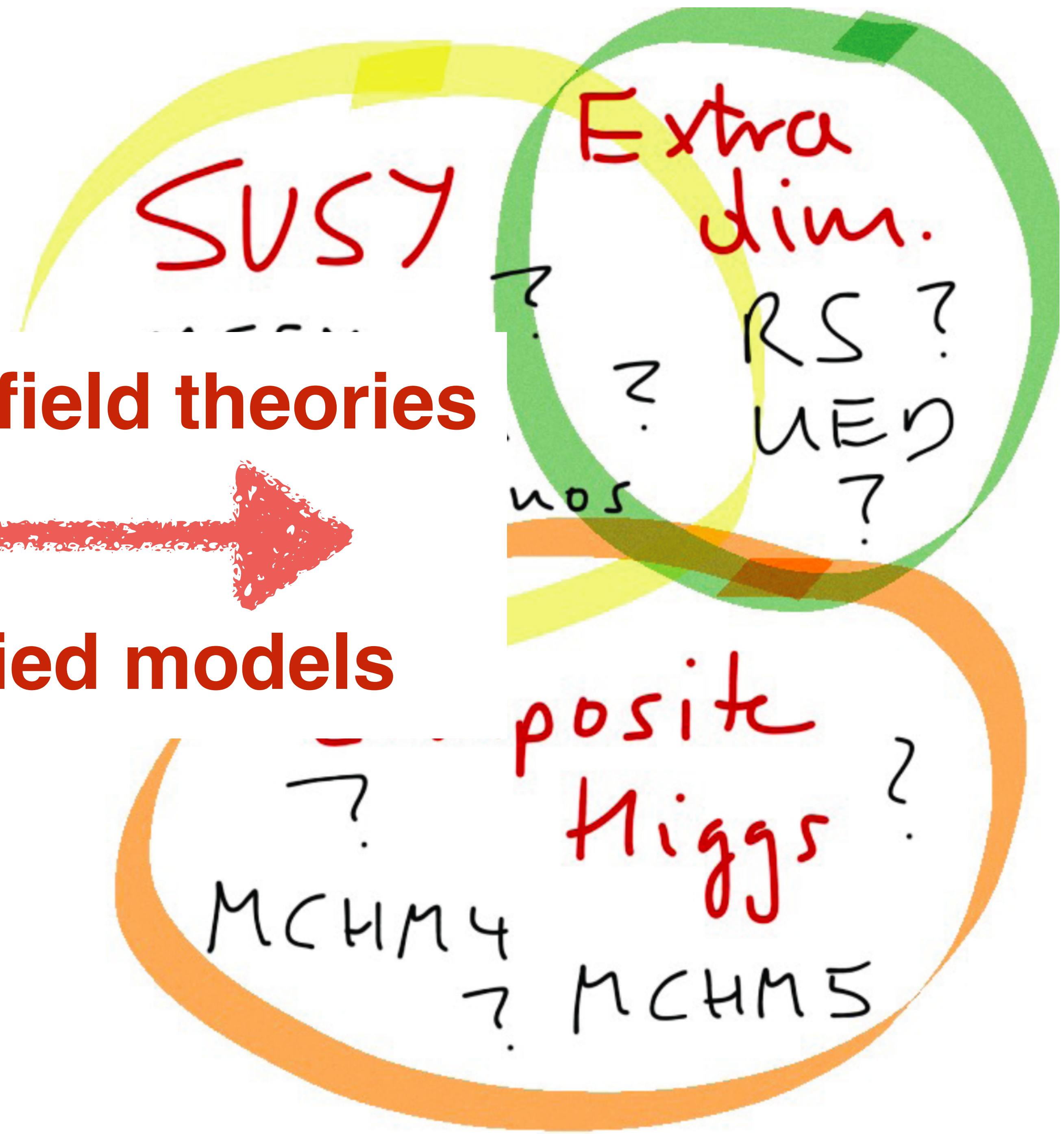


effective field theories

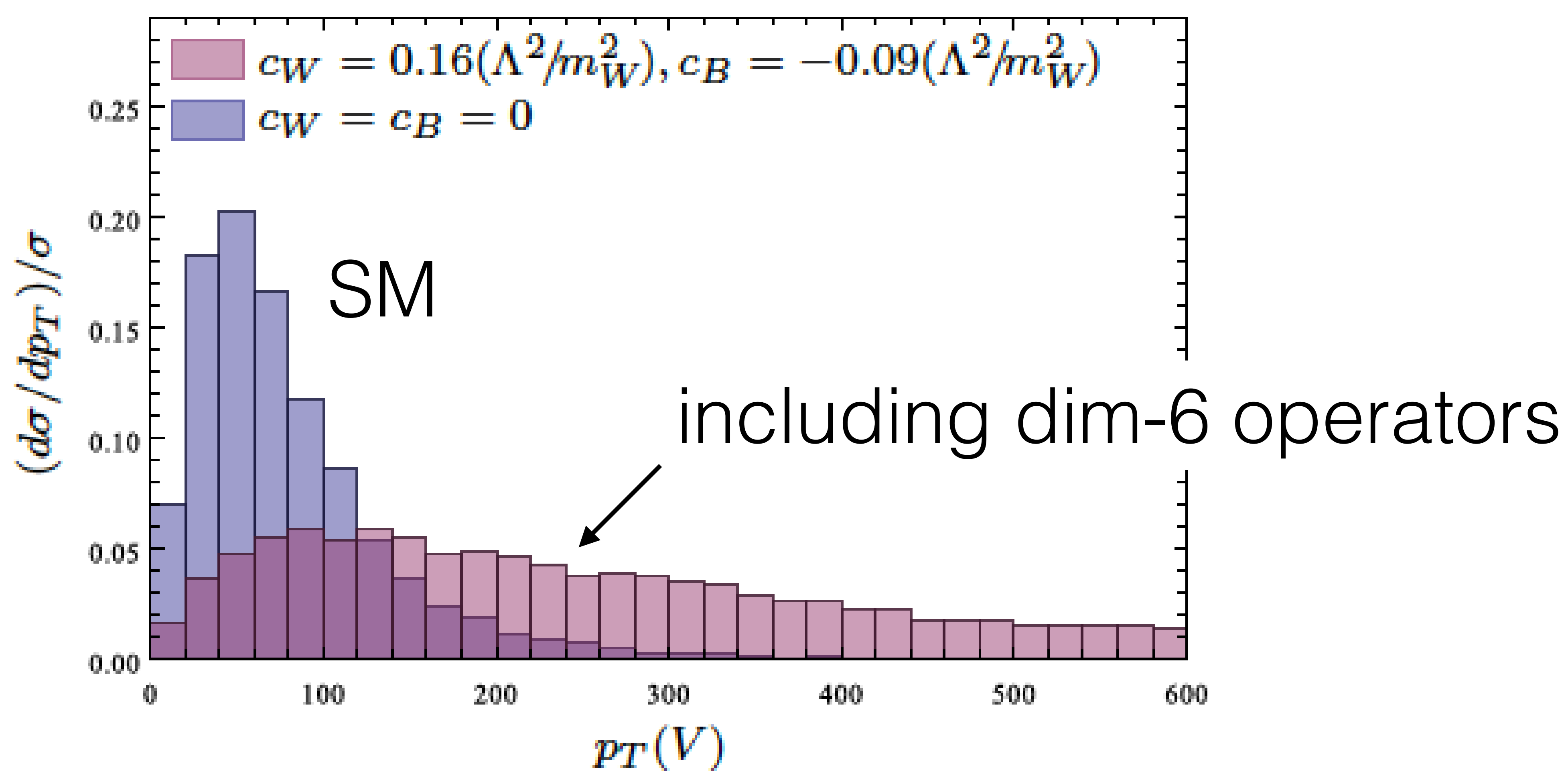
simplified models



Virtues and vices of Higgs EFTs

Biekötter, Knochel, MK, Liu, Riva (Phys.Rev. D91 (2015) 055029

Higher-dimensional operators may change the energy dependence of cross sections and thus kinematic distributions, e.g. in pp → ZH:



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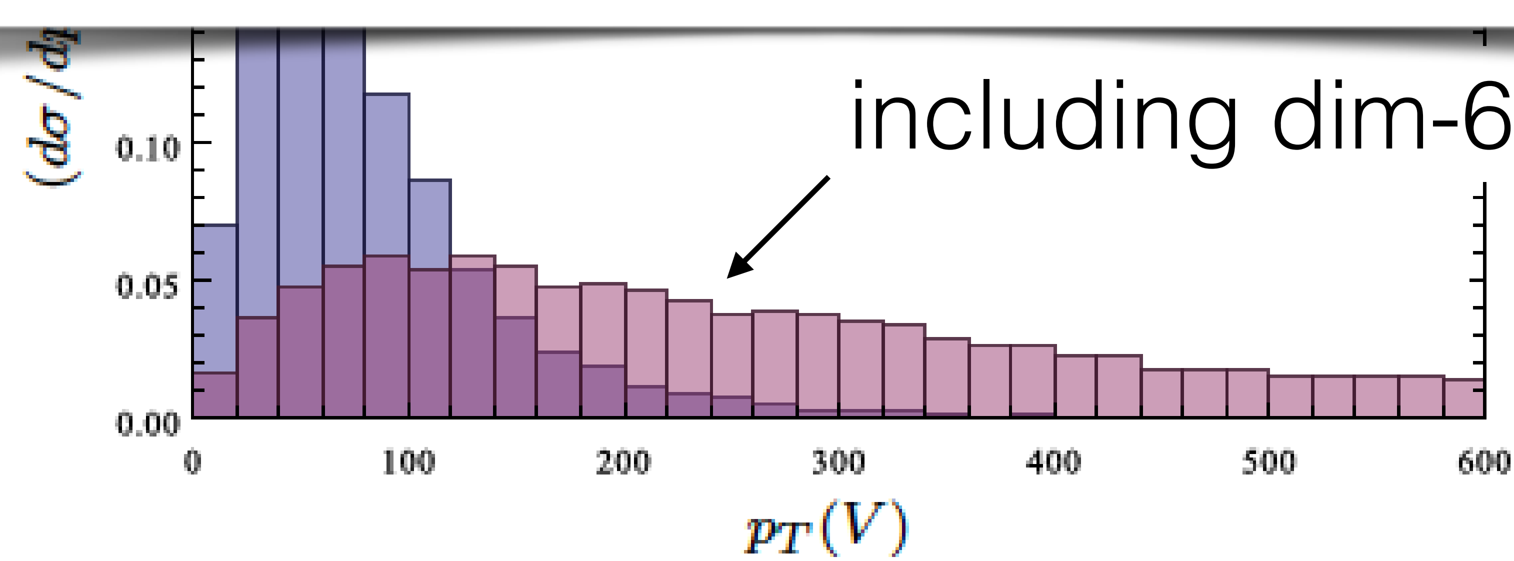
allows to measure dim-6 operators through distributions



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- However, EFTs are only reliable if $\Lambda \gg E_{LHC}$
- If the effect of dim-6 operators is large, the EFT expansion is doubtful; expect to find new particles with $M \lesssim \mathcal{O}(\text{TeV})$

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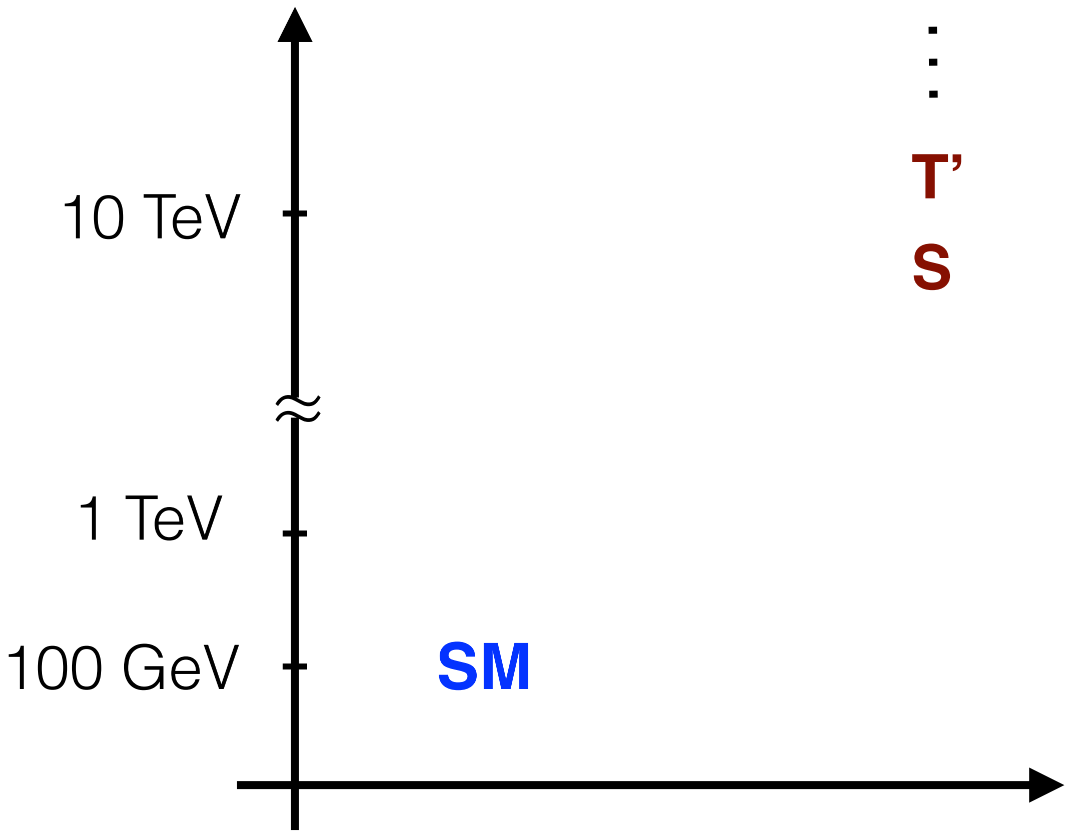
cf. Contino, Falkowski, Goertz, Grojean, Riva (JHEP 1607 (2016) 144); Brehmer, Freitas, Lopez-Val, Plehn (Phys. Rev. D 93, 075014 (2016)); Biekötter, Brehmer, Plehn (arXiv:1602.05202 [hep-ph])

BSM models for Higgs physics: bottom-up

effective field theories



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

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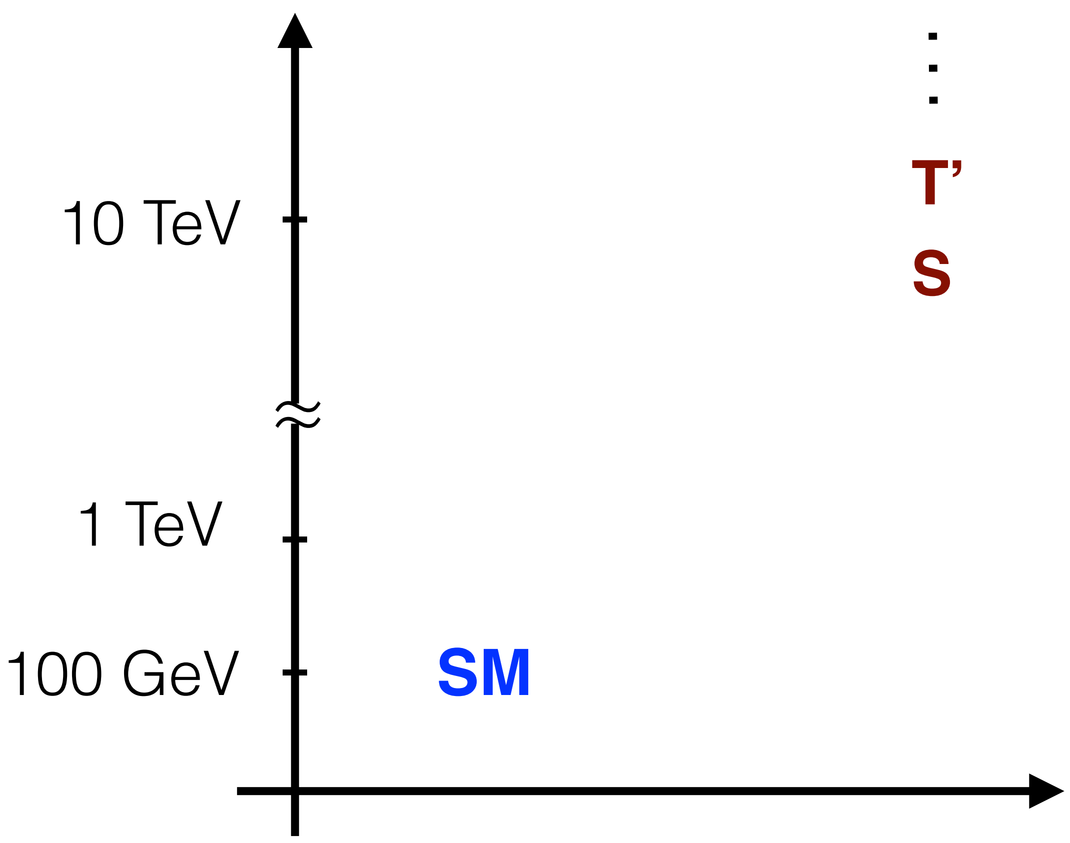

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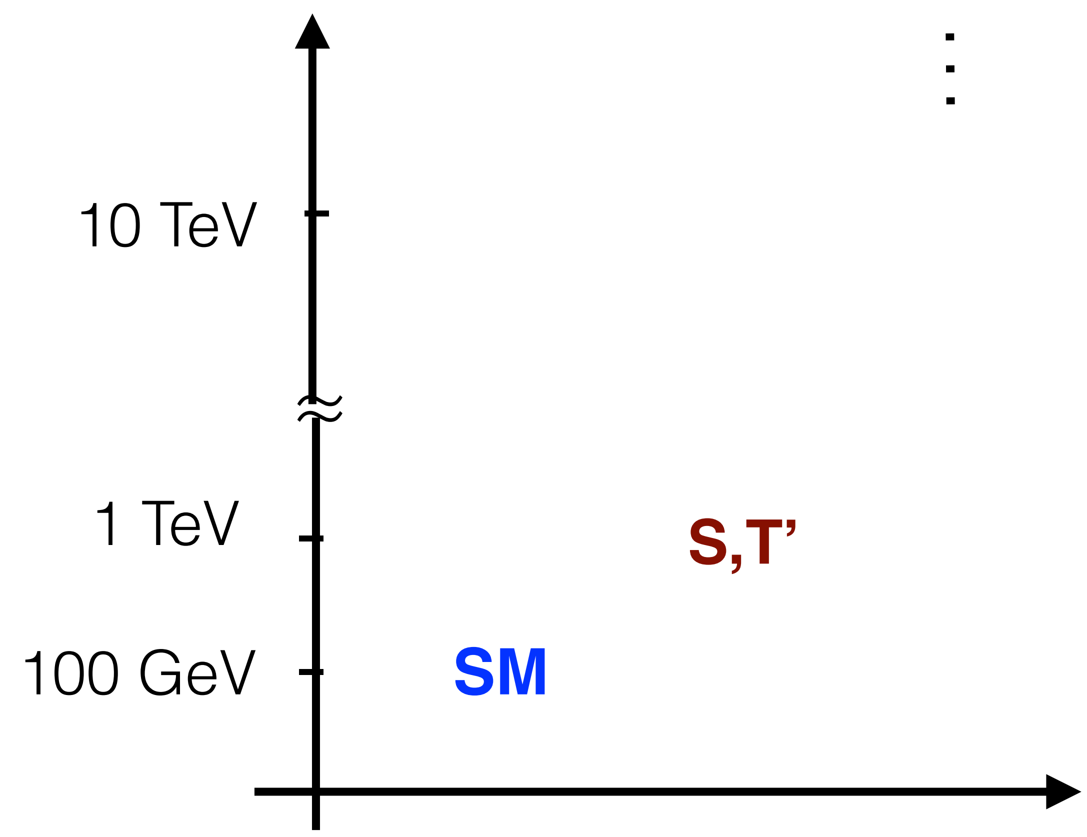

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \mathcal{L}_{S,T'} + \mathcal{L}_6 + \ldots$$

Simplified models

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

cf. **Models as Mediators**: Perspectives on Natural and Social Science - M. S. Morgan and M. Morrison (Eds.)

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Simplified models have become standard for SUSY and dark matter searches at the LHC. We wanted 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

Dolan, Hewett, MK, Rizzo (JHEP 1607 (2016) 039)

We take the SM and add

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

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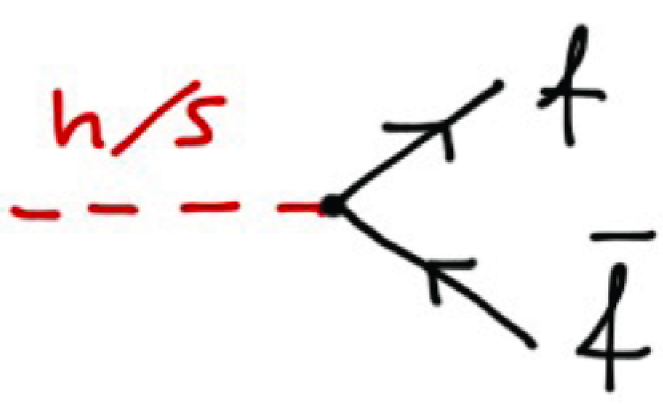
We take the SM and add

- 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.

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

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

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

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

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

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

The simplest simplified model with F = T 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.

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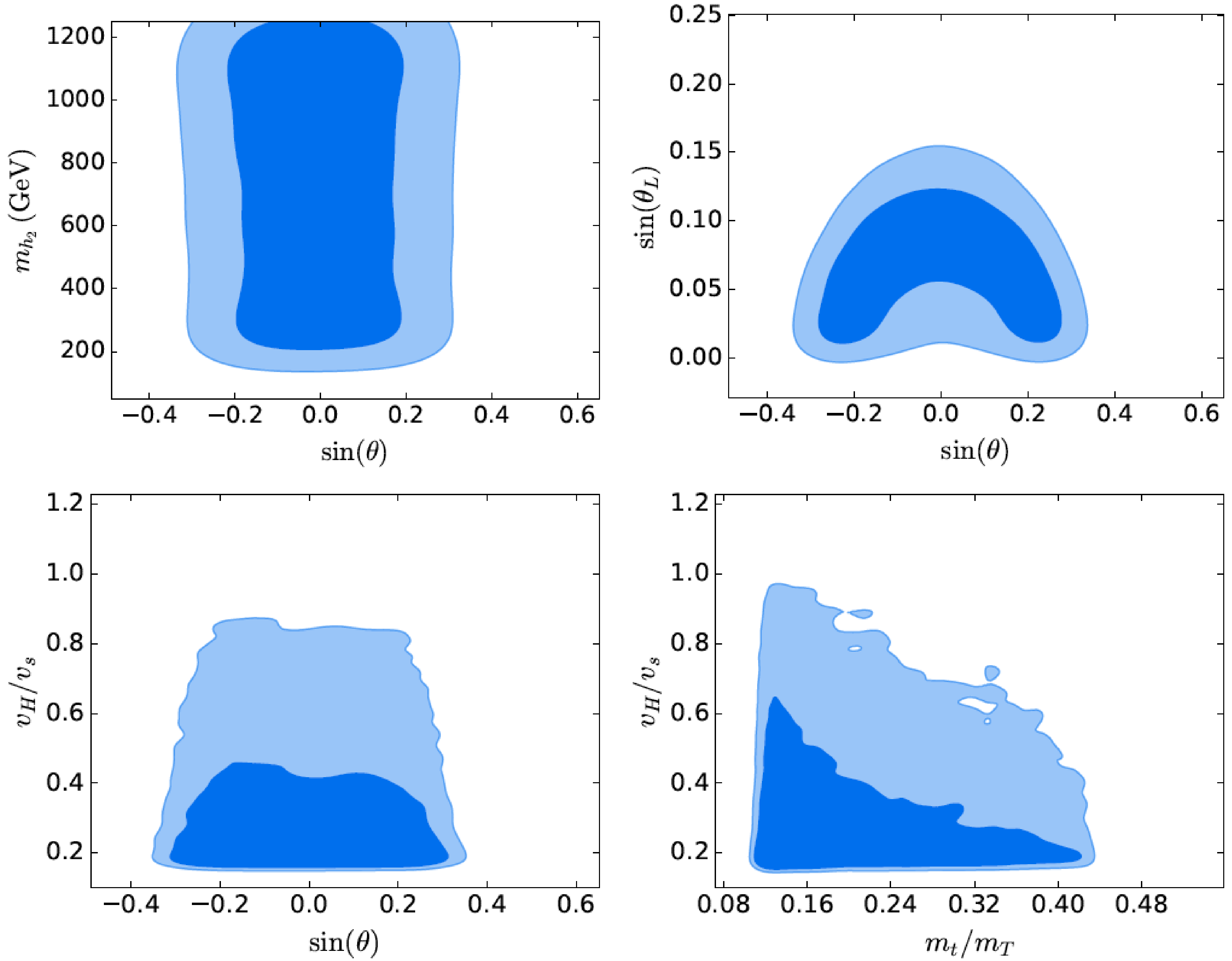
The parameters are constrained by

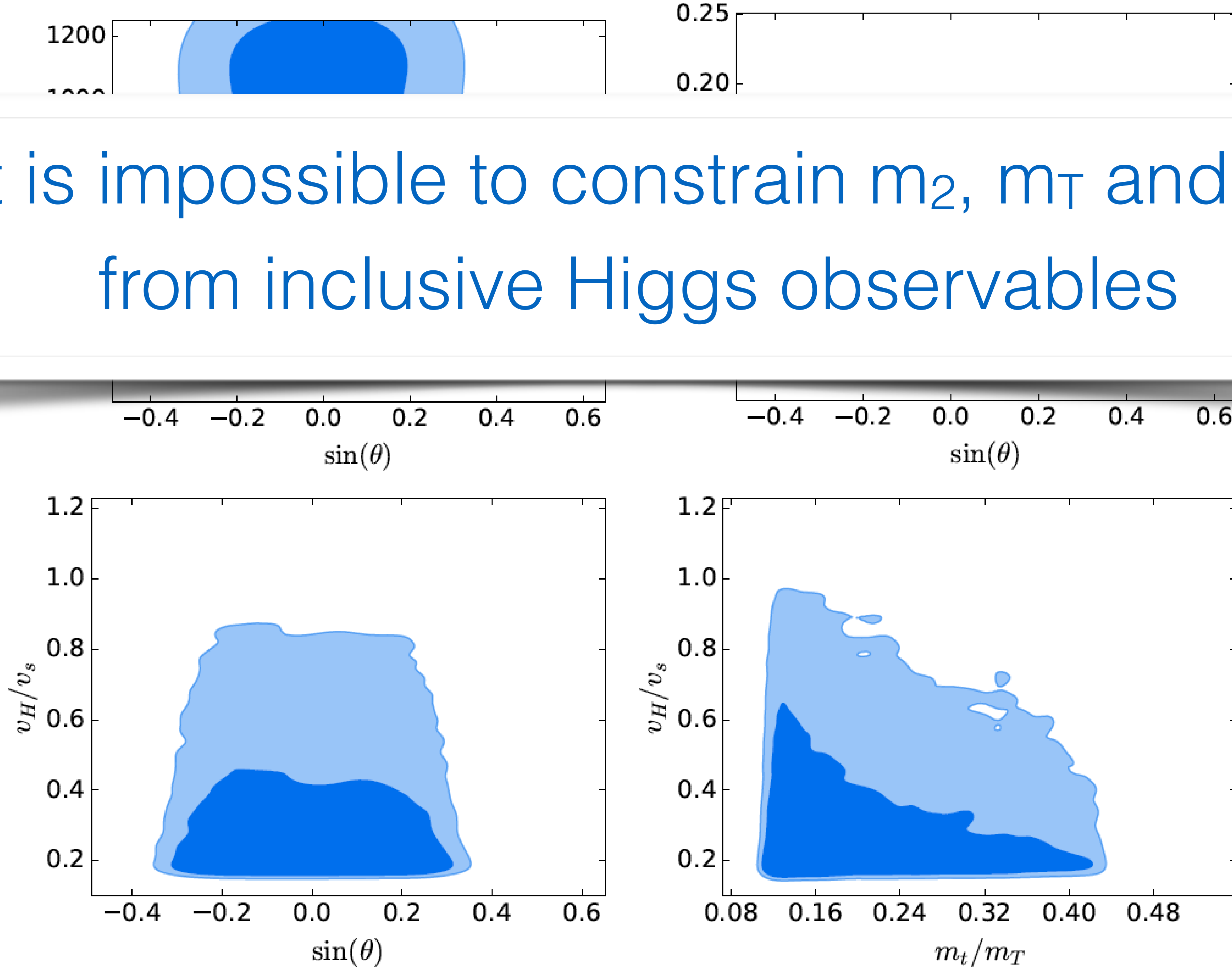
- perturbative unitary
- precision EW data: S, T and U
- Higgs cross sections and branching ratios

A fit to the Higgs cross sections and BRs



HiggsSignals/HiggsBounds

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

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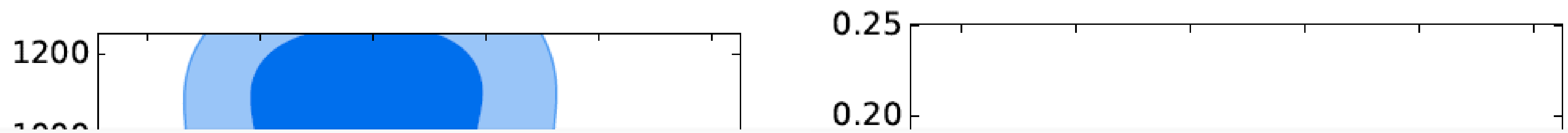

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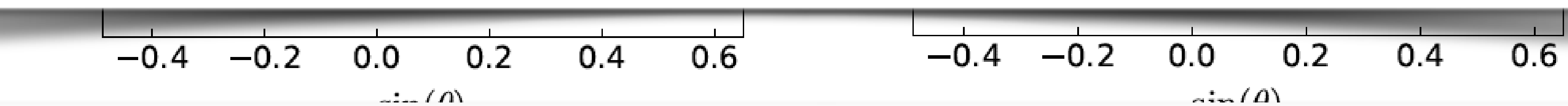
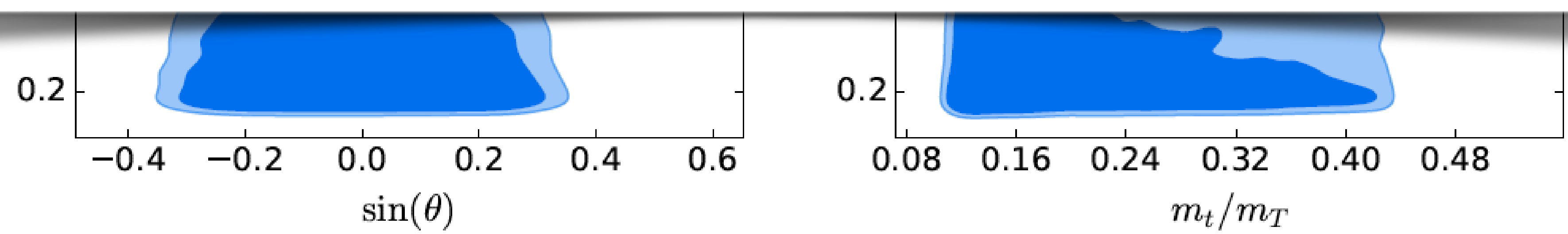


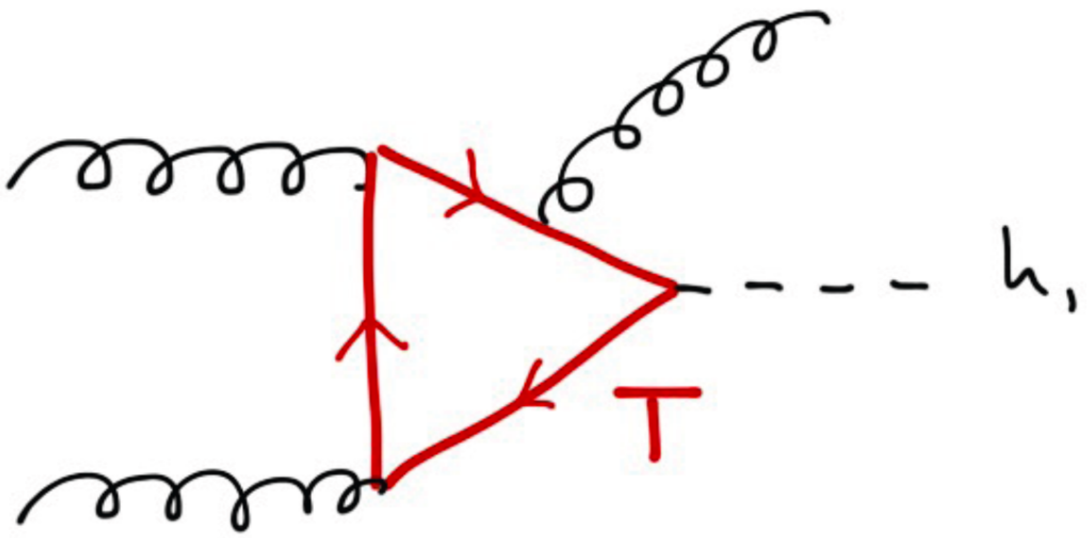
Need to consider more exclusive Higgs observables and direct searches for h_2 and T.



HiggsSignals/HiggsBounds

The Higgs P_T distribution

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



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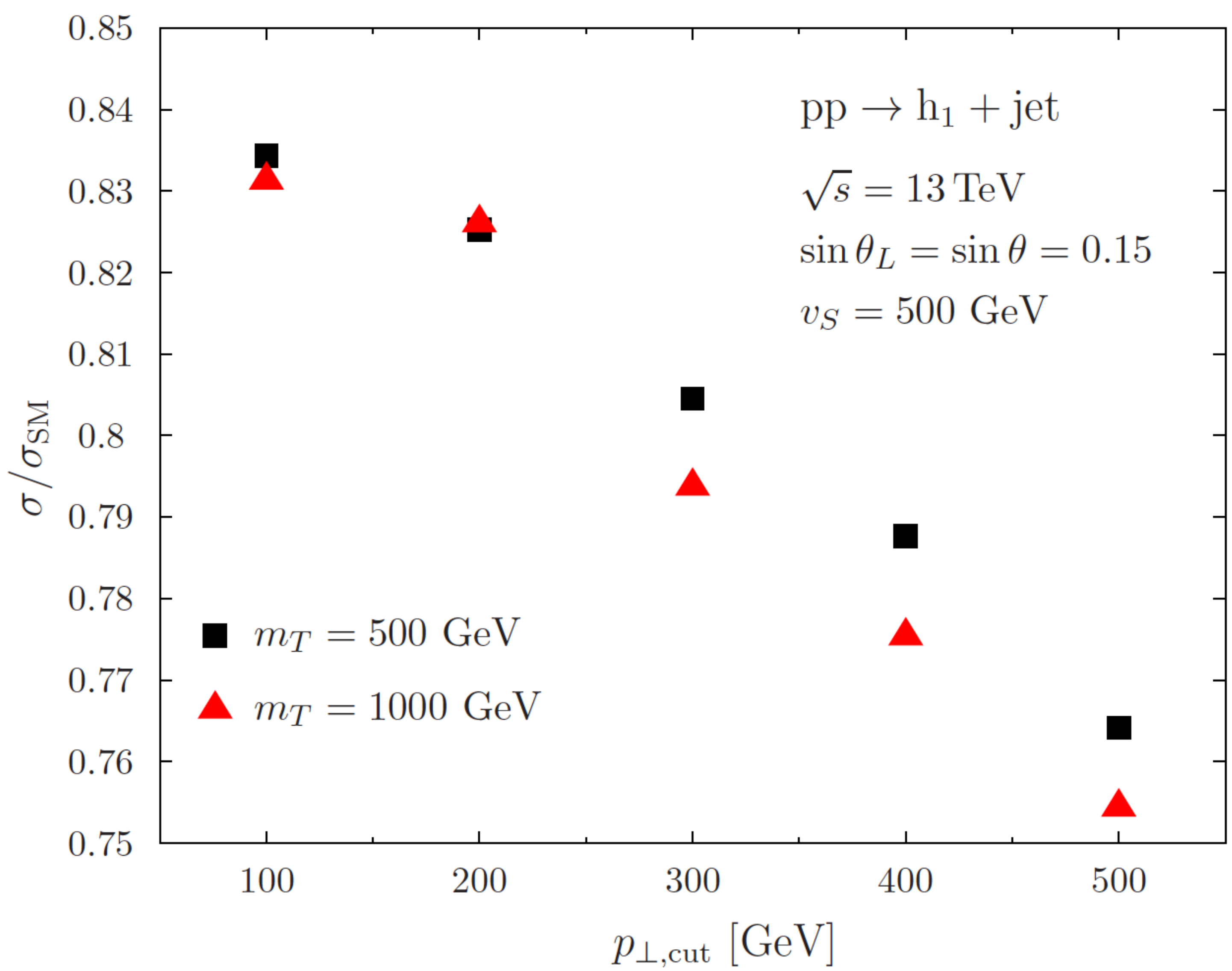
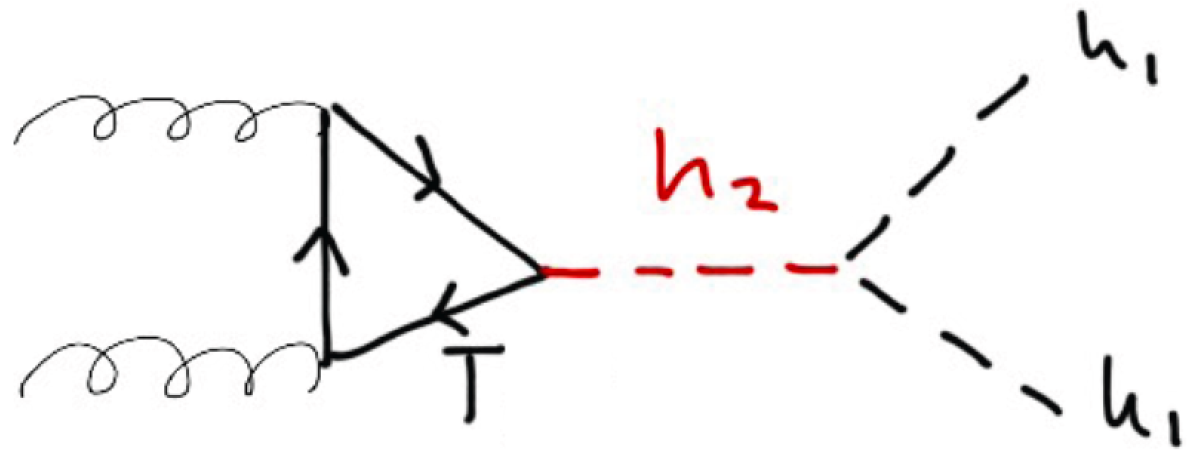


Madgraph5@NLO

Higgs pair production

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



$$\mathcal{L} \supset g_{tty}^{\rm SM}\left(\bar{t}th_1 + \frac{m_T}{m_t}\frac{v_H}{v_S}\bar{T}Th_2\right)$$

for $\sin\theta = \sin\theta_L = 0$

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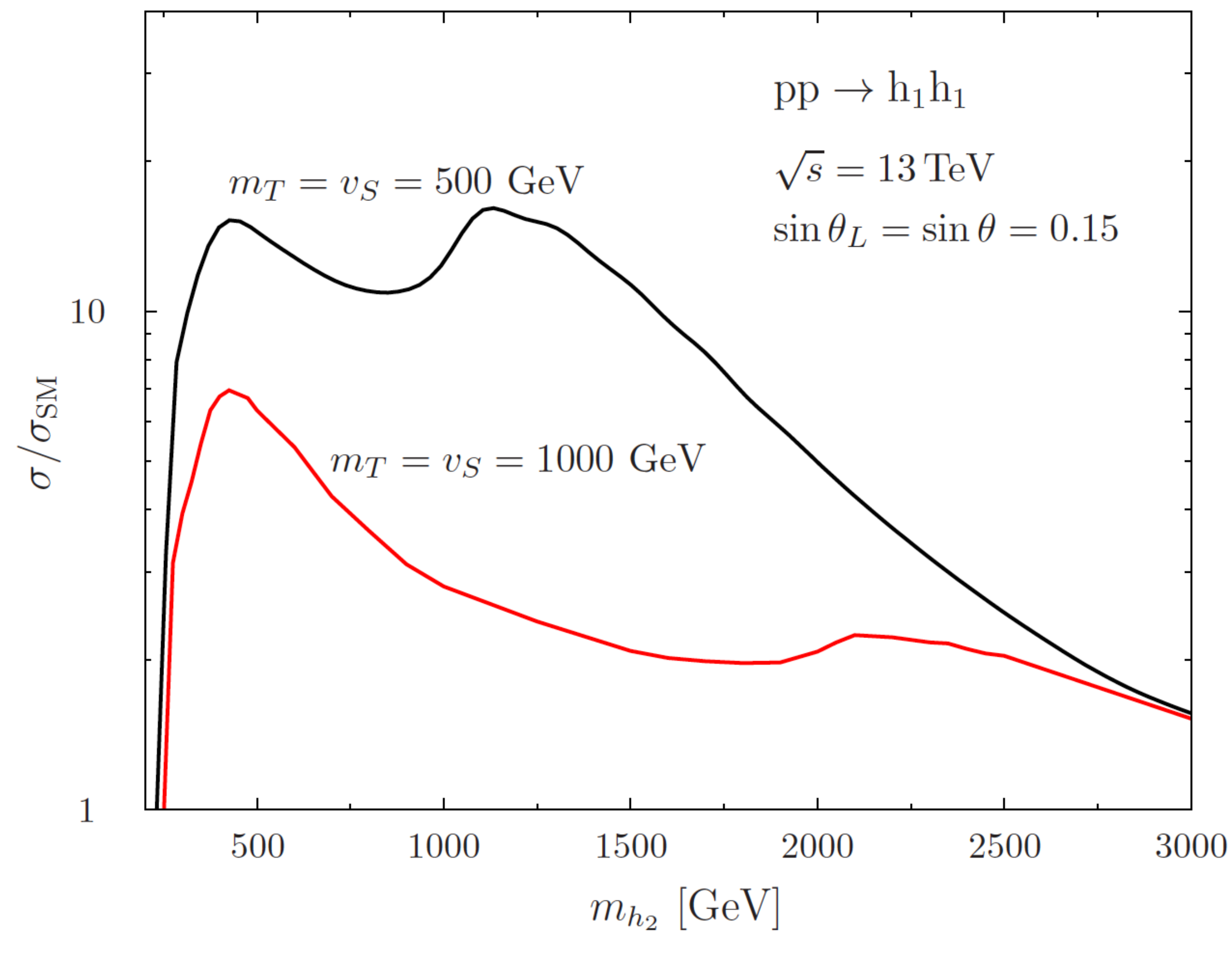

$\sin\theta = \sin\theta_L = 0.15$

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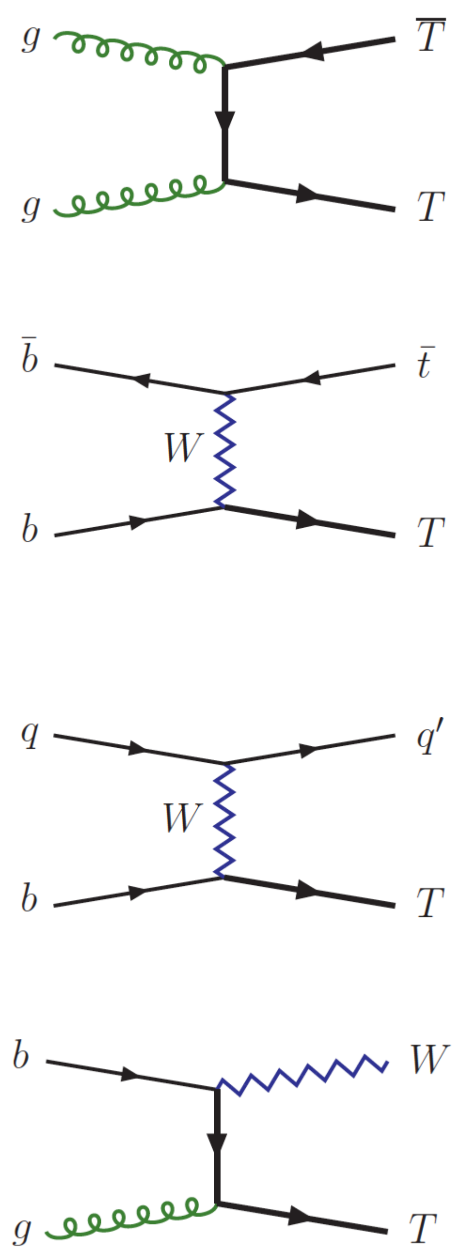
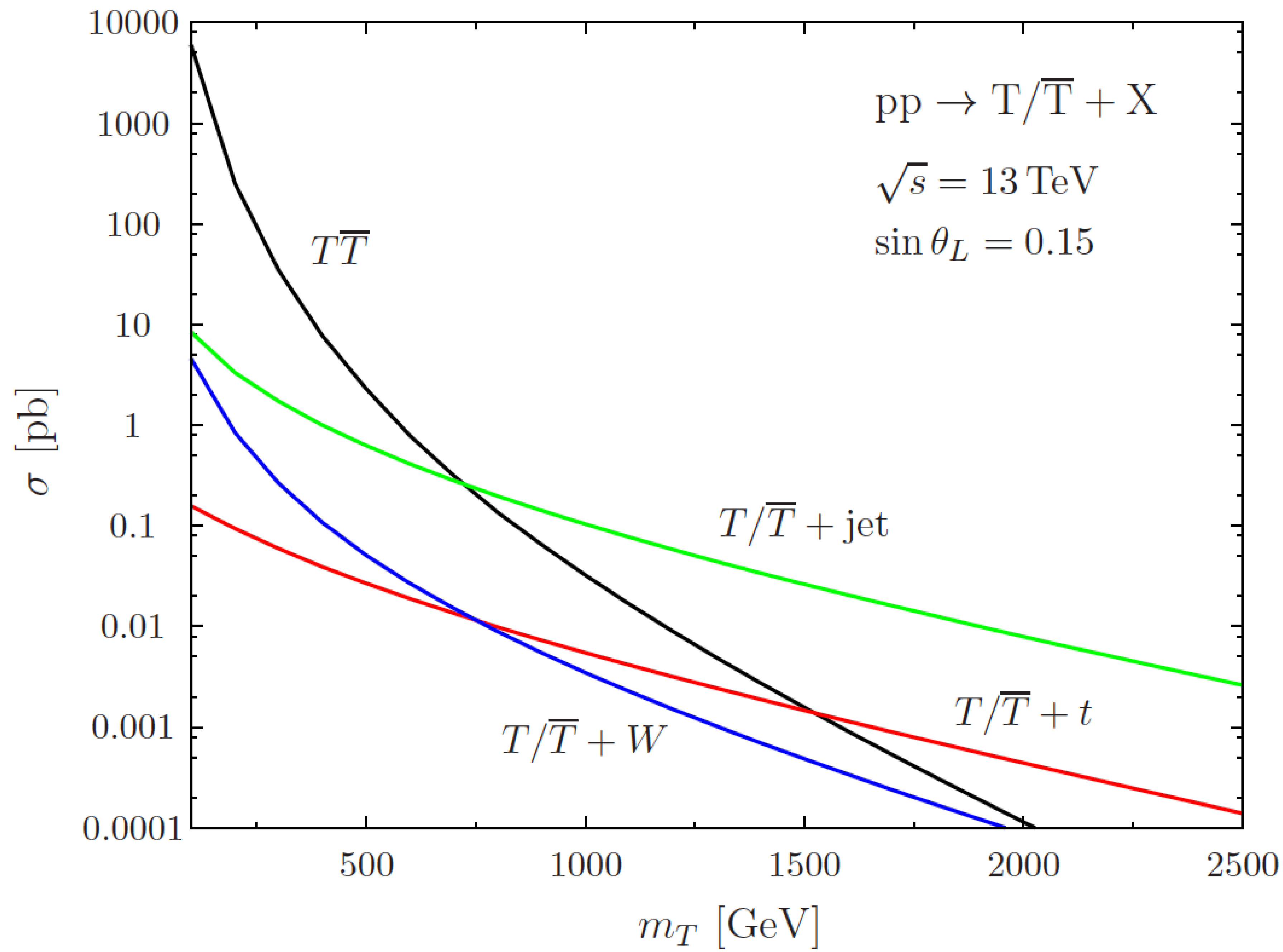
Direct searches for S and T





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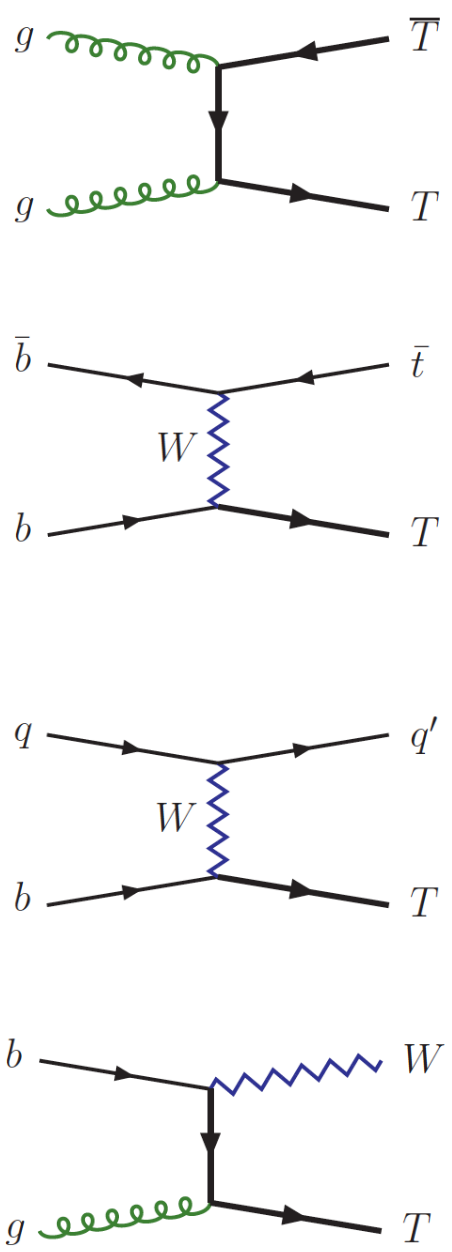

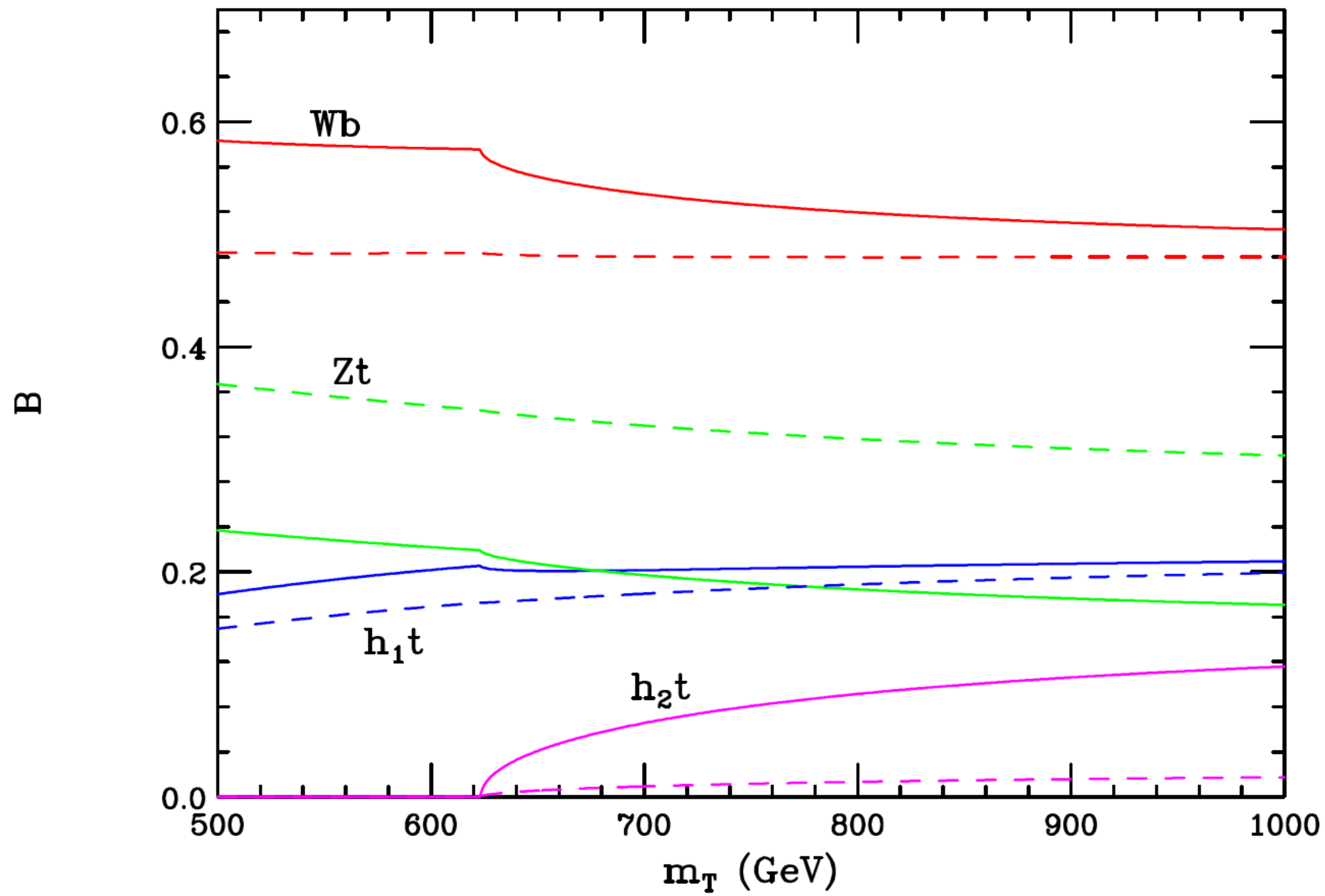

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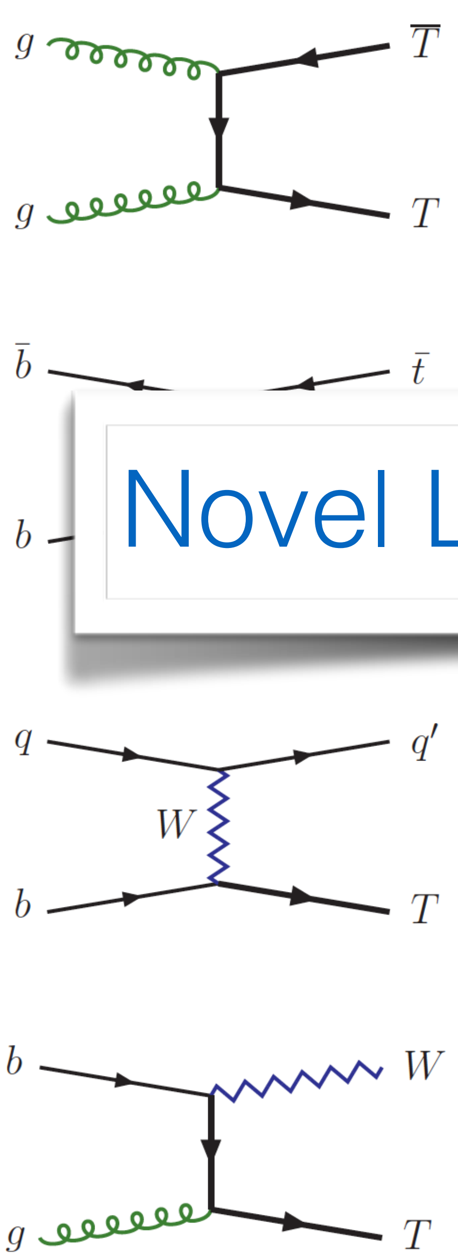

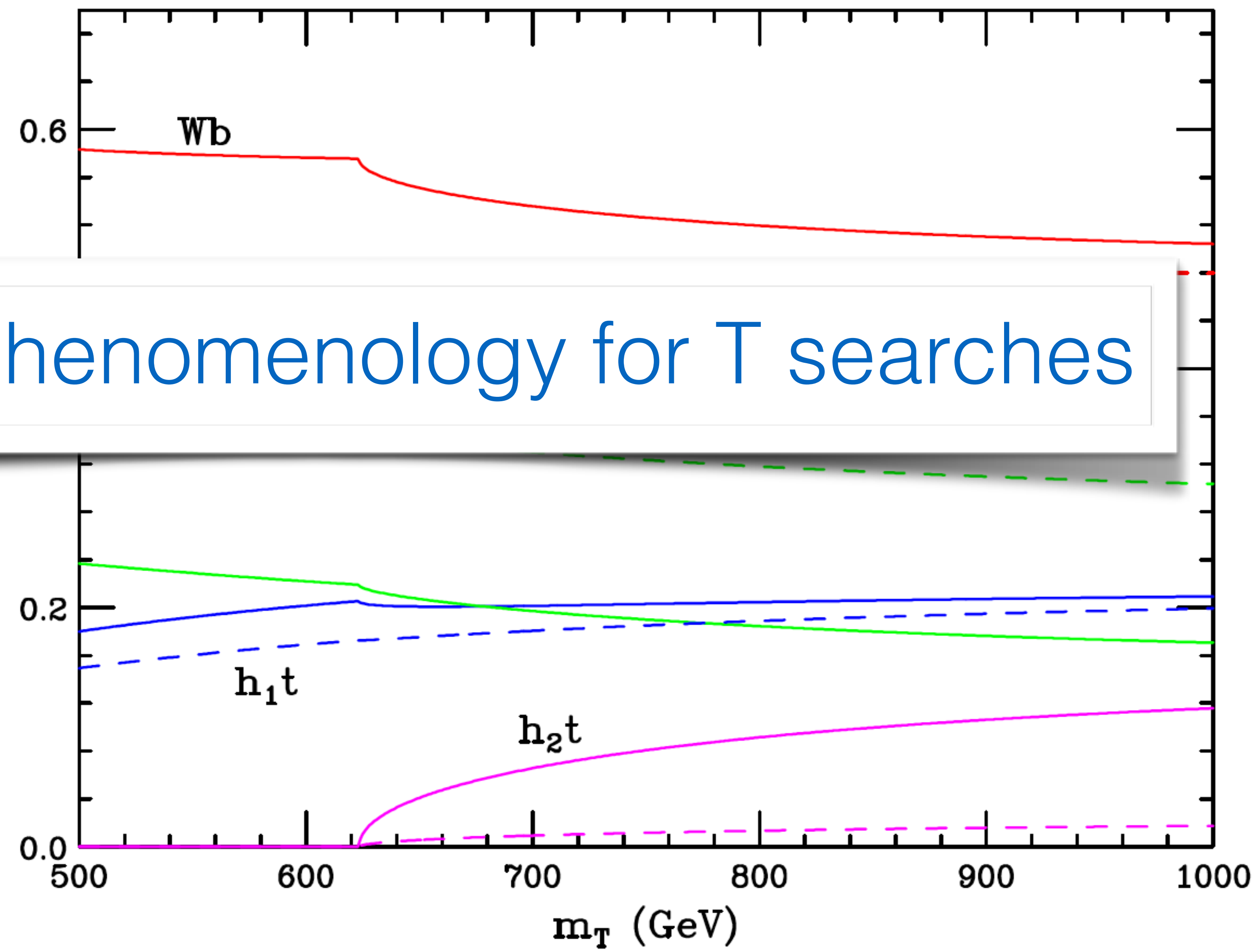

Novel LHC phenomenology for T searches

Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches

Biekötter et al. (arXiv:1608.01312 [hep-ph])

Imagine that a new scalar resonance has been discovered, with a mass of ≃ 750 GeV, and decaying into $\gamma\gamma$

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- Choose a VLQ representation and try to fit the signal

  → (X,T) with quantum numbers (3,2,7/6) and charge $Q_X=5/3$, $Q_T=2/3$

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- Work out the signatures in the scalar sector:

VLQ model	Representation	$\gamma Z/\gamma\gamma$	$ZZ/\gamma\gamma$	$WW/\gamma\gamma$	$gg/\gamma\gamma$	$\Gamma_{s\to\gamma\gamma}$ [MeV]	Γ_{Tot} [MeV]	$R_{\gamma\gamma}$ [fb]
(X,T)	$(3, 2, \frac{7}{6})$	0.07	0.59	0.90	17.0	1.03	20.0	6.2

Complementarity of Resonant Scalar, Vector-Like Quark and Superpartner Searches

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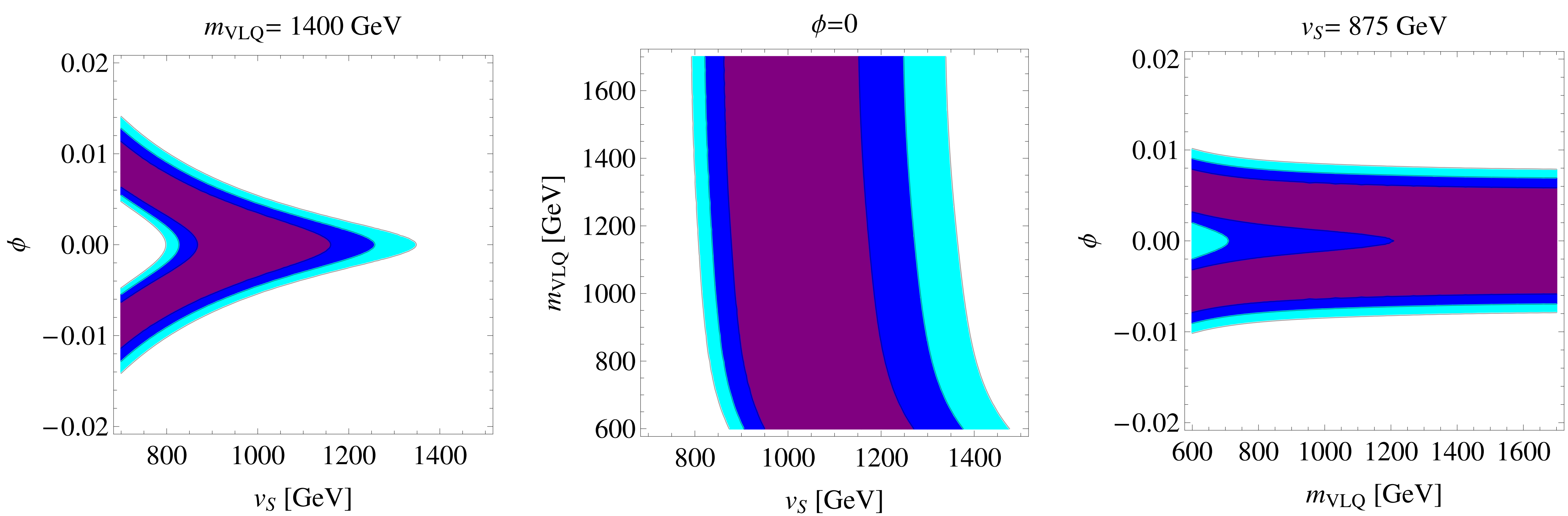
- Consider searches for the VLQ:

Di-photon rate only:



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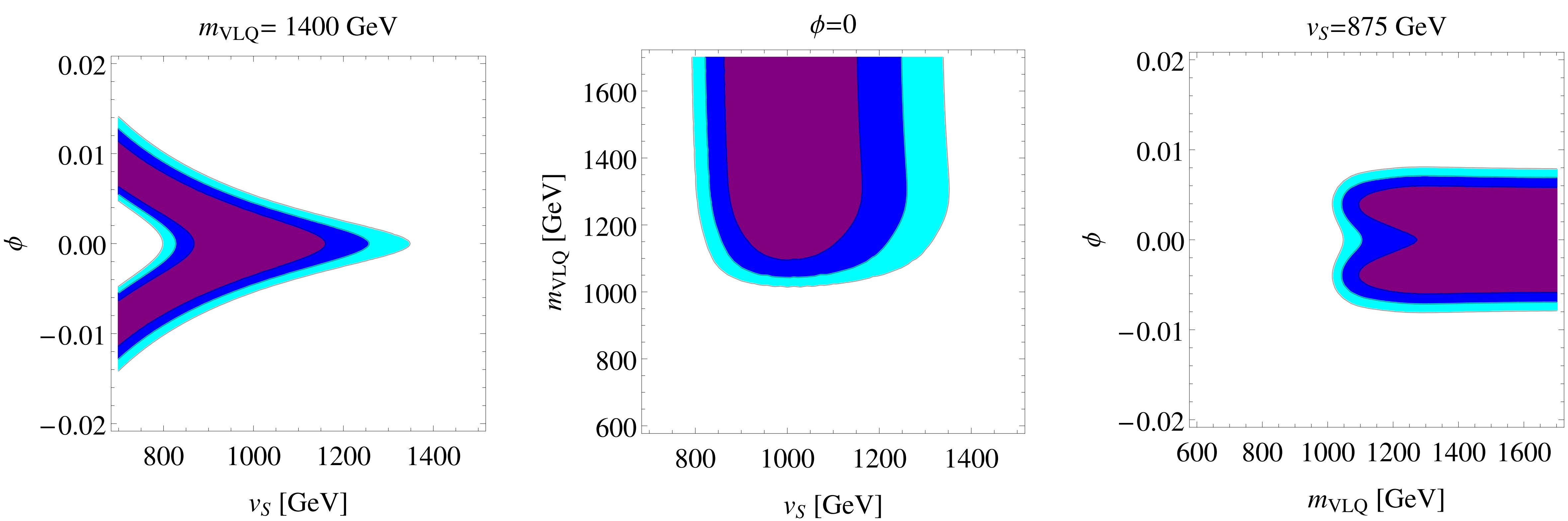
Adding a large suite of searches (using CheckMate):



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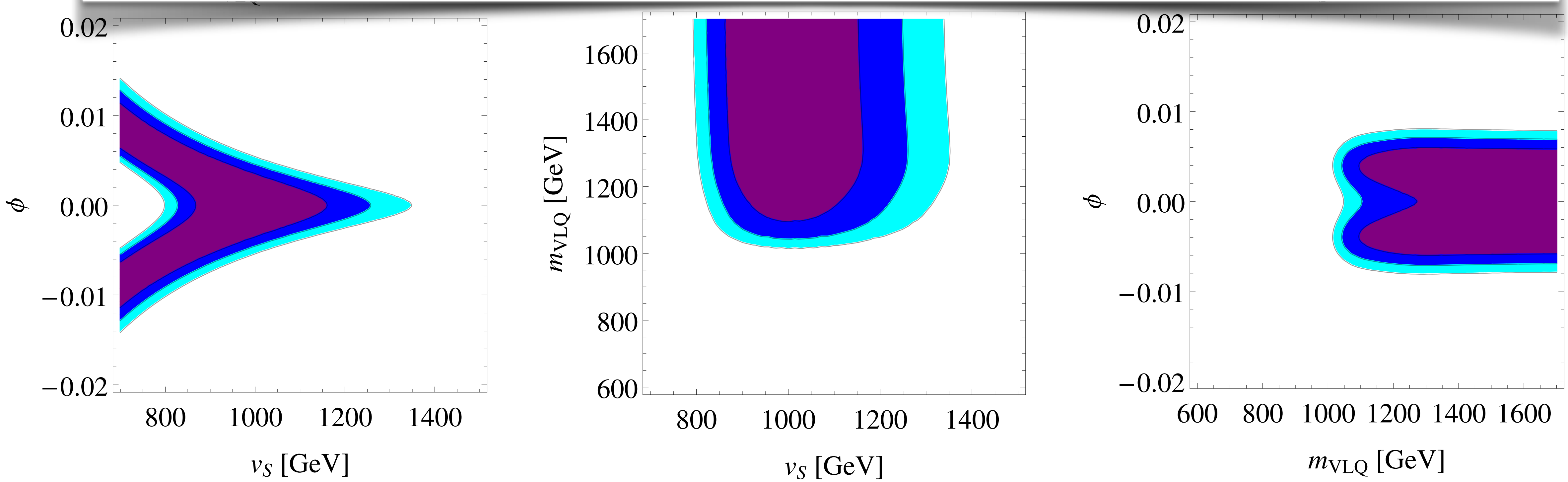
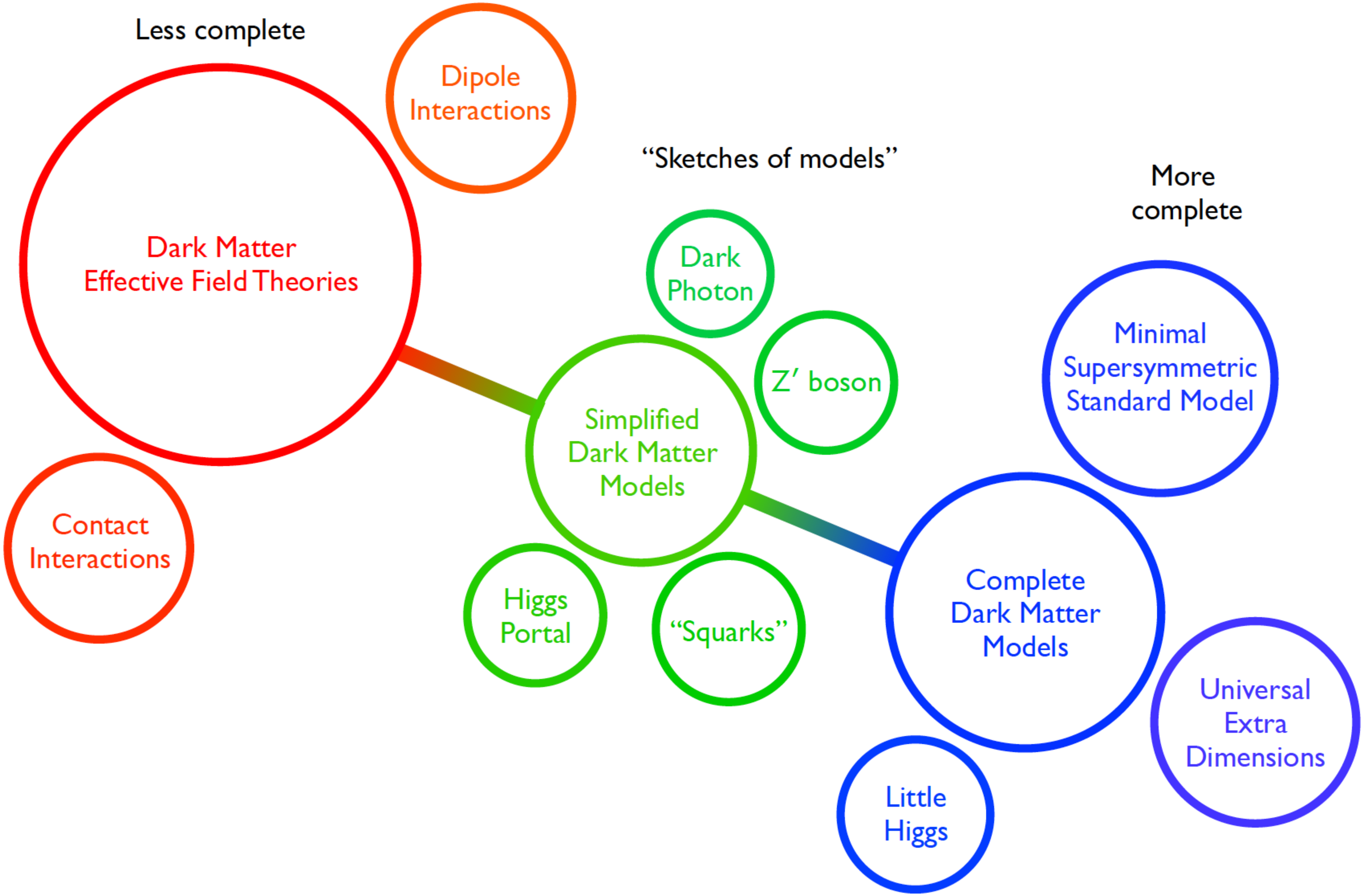
- Consider searches for the VLQ:

Tightest bound on VLQ from SUSY search!



BSM physics: from SUSY to simplified models (and back…)



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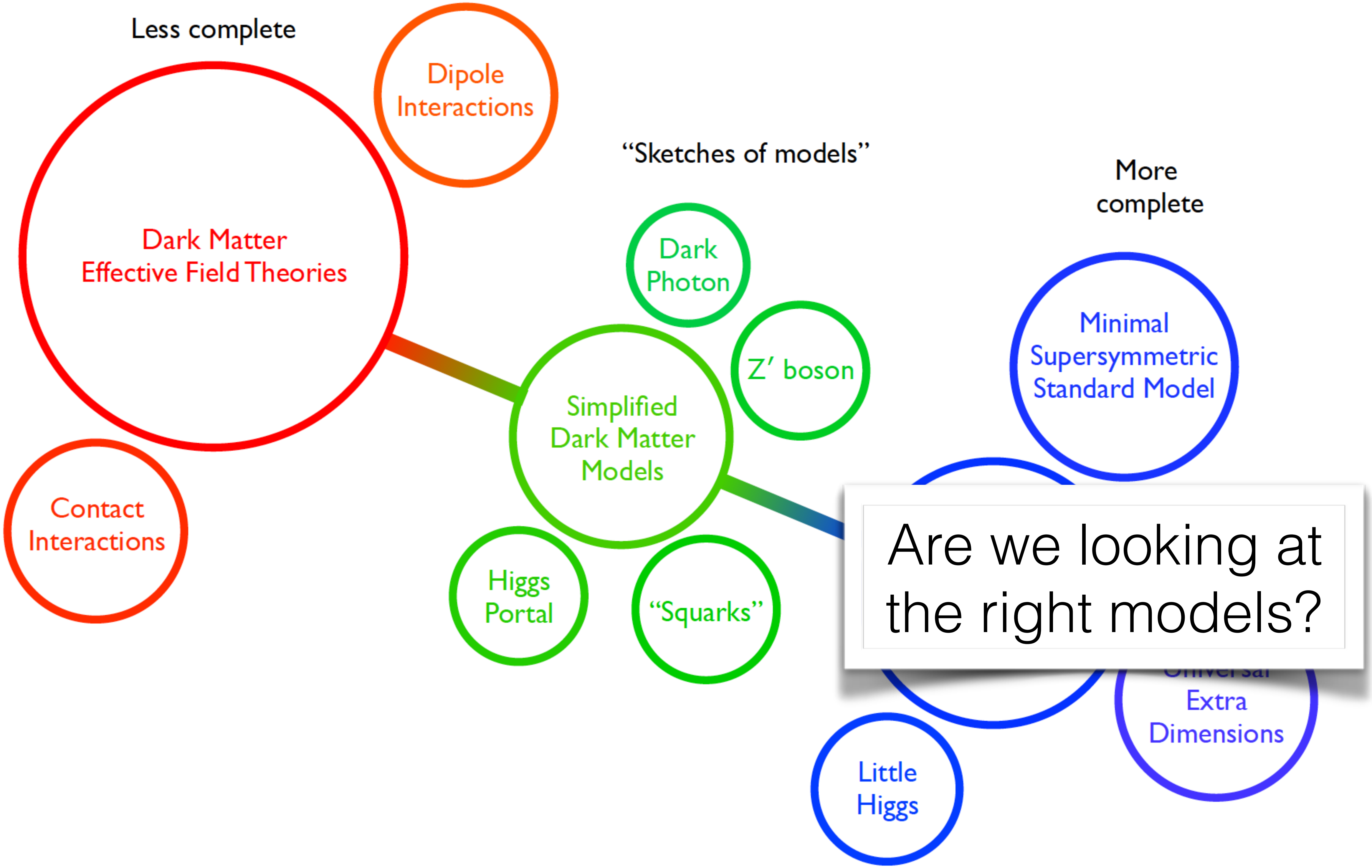
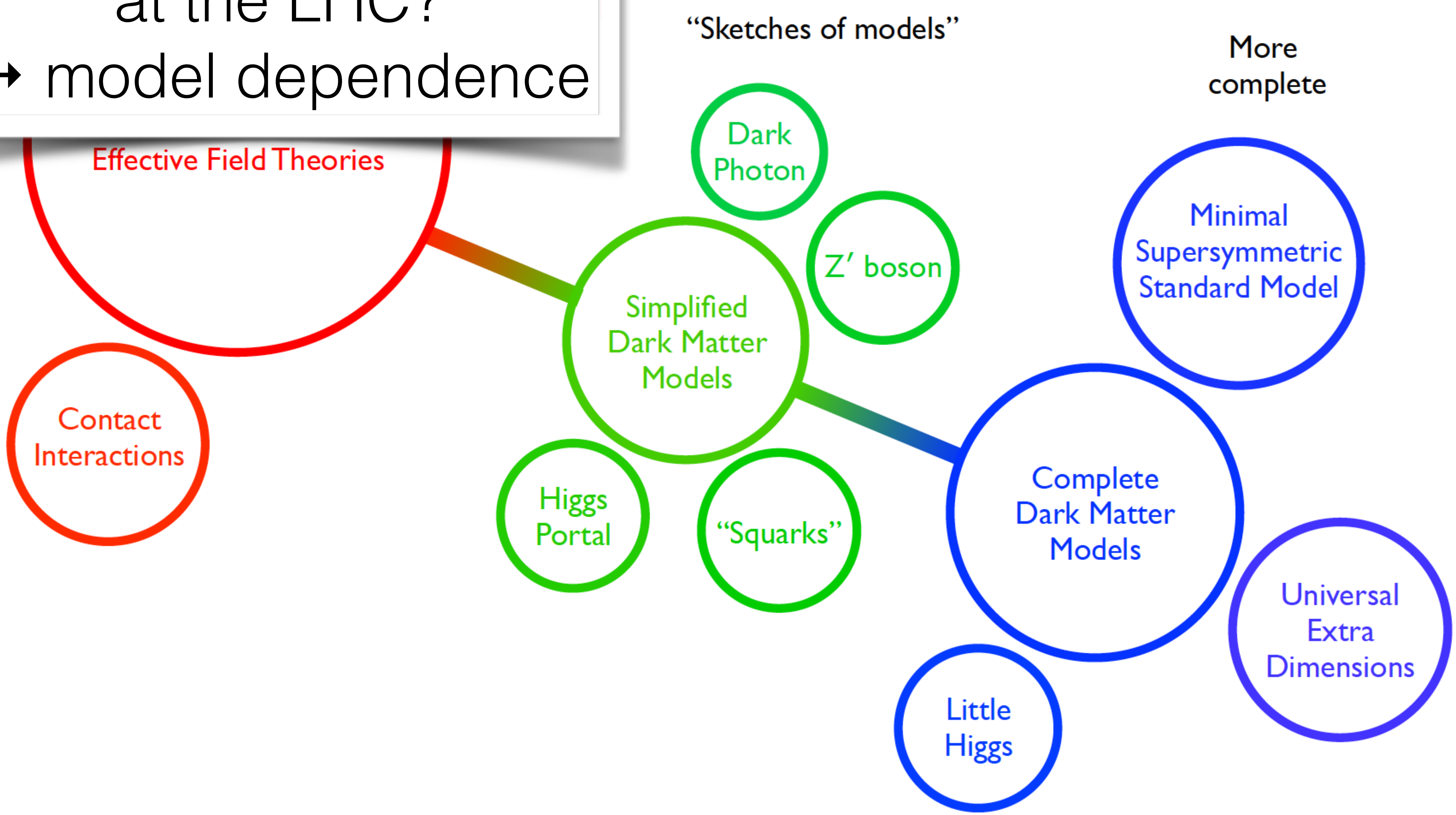


BSM physics: from SUSY to simplified models (and back…)

Are EFTs reliable at the LHC?
→ model dependence



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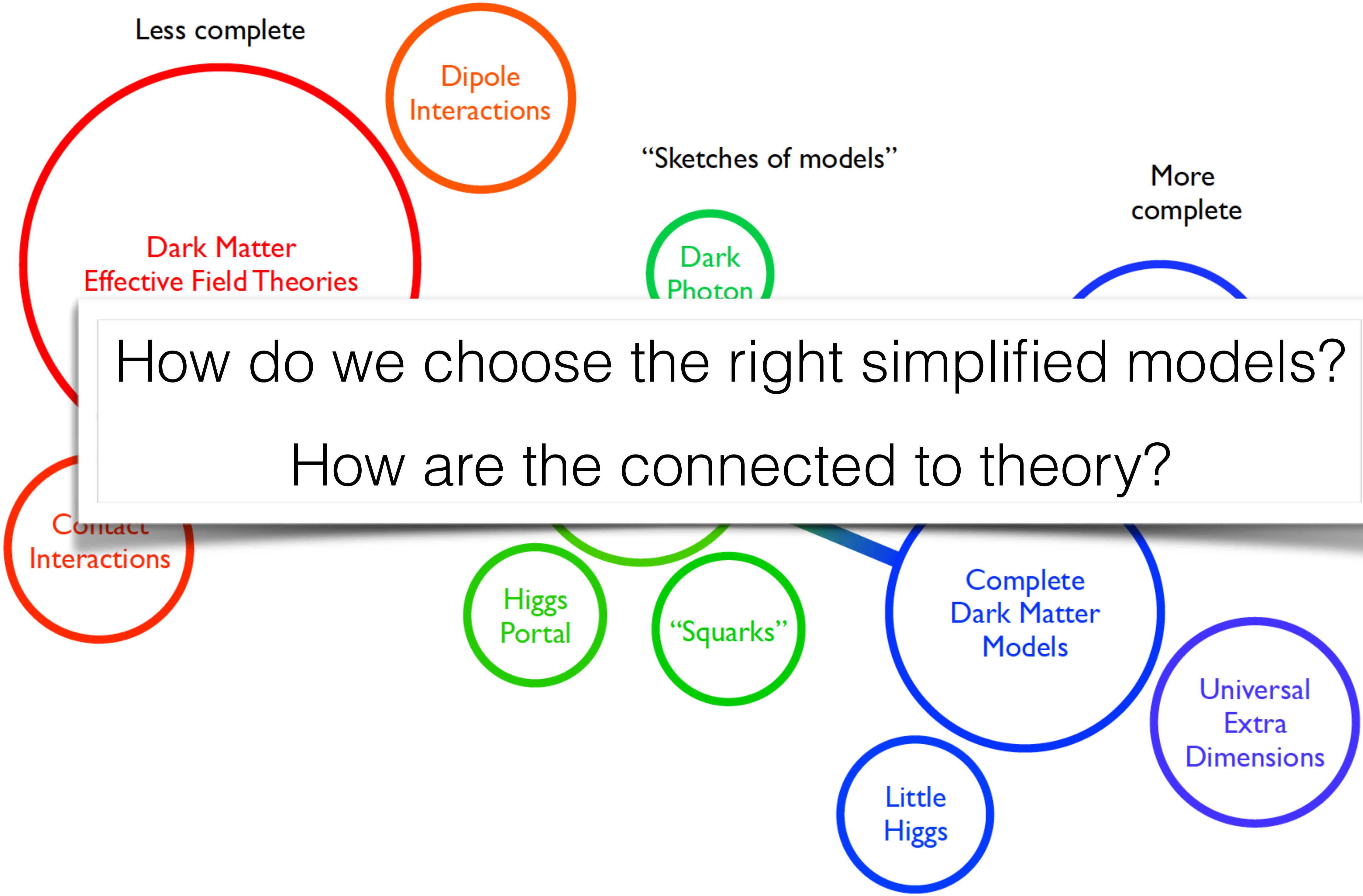
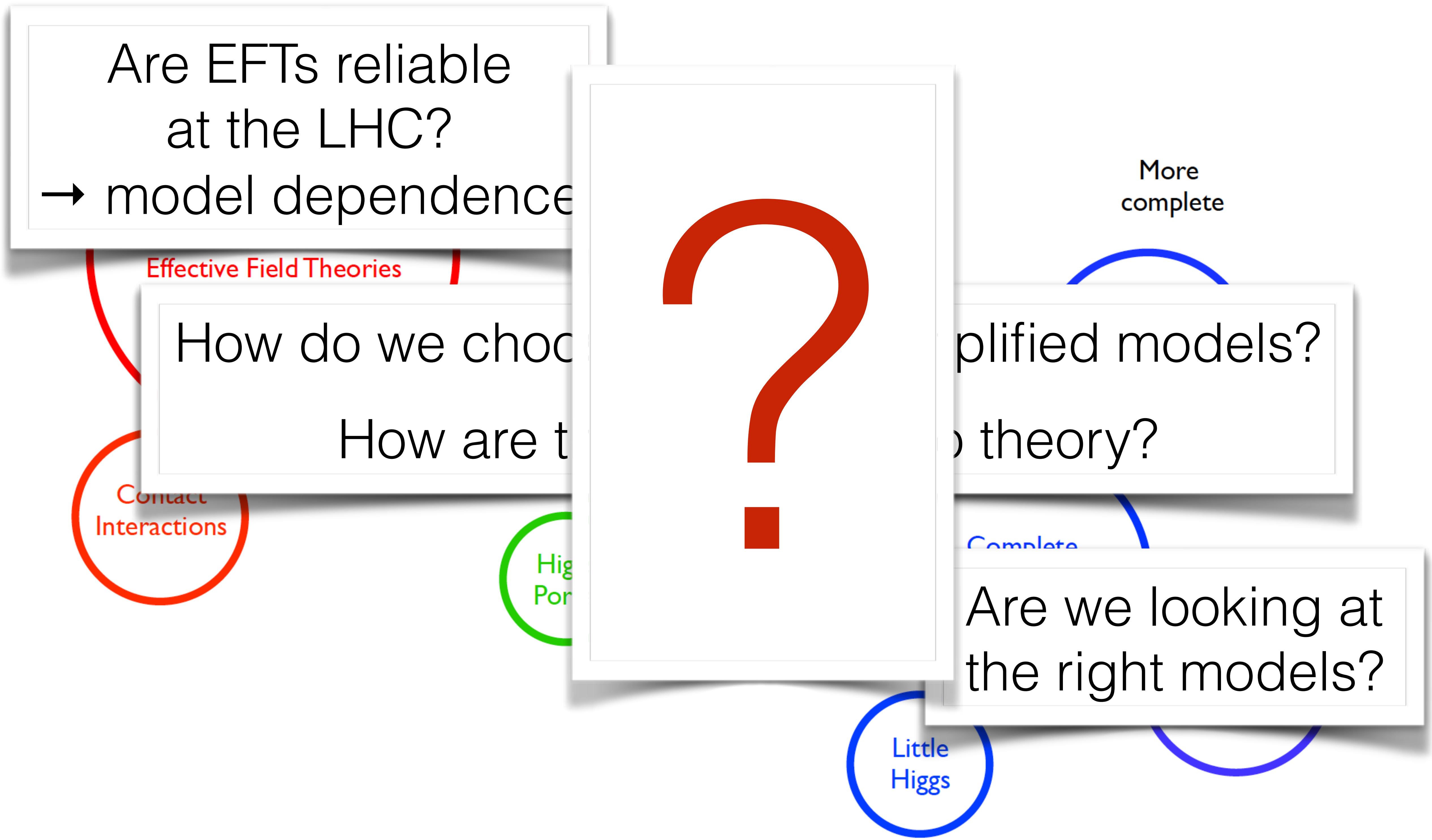


How do we choose the right simplified models?

How are the connected to theory?

BSM physics: from SUSY to simplified models (and back…)



Thank you!

Backup

A simplified model for Higgs physics

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

A simplified model for Higgs physics

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

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

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

A simplified model for Higgs physics

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

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

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

A simplified model for Higgs physics

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

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 $a_1 = b_1 = b_3 = 0$.

A simplified model for Higgs physics

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

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

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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 **h_1** and **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

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

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

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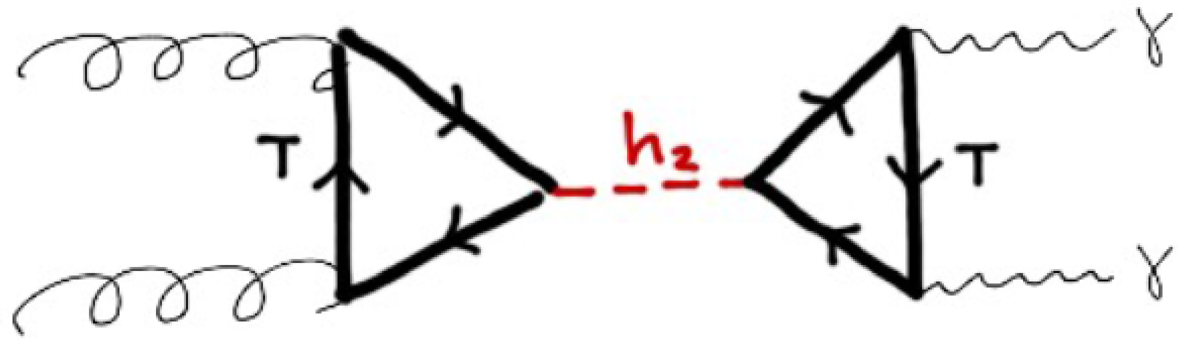
For the loop-induced couplings one has

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

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

Is the new the scalar h_2 the 750 GeV resonance?



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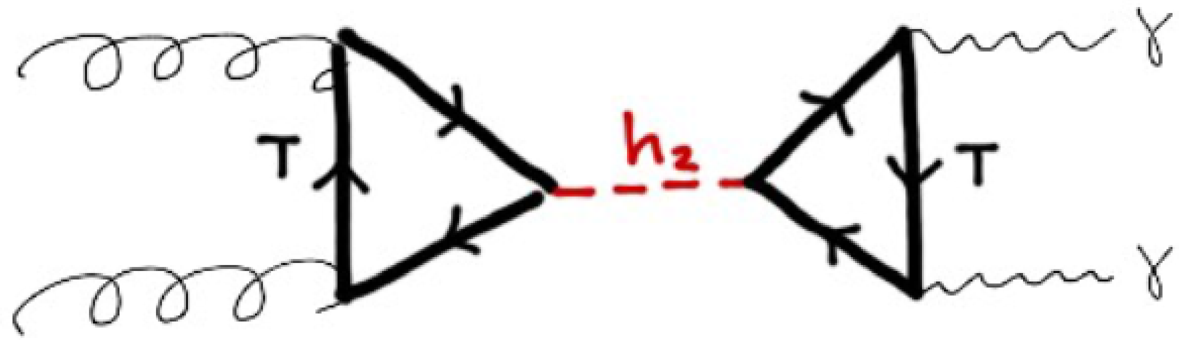

Need $\sigma(pp \to h_2) \times \mathrm{BR}(h_2 \to \gamma\gamma) \sim \mathcal{O}(\mathrm{few\,fb})$

With $\mathrm{BR}(h_2 \to \gamma\gamma) \approx \dfrac{\Gamma(h_2 \to \gamma\gamma)}{\Gamma(h_2 \to gg)} = \dfrac{8}{9}\left(\dfrac{\alpha}{\alpha_\mathrm{s}}\right)^2 \approx 0.5\%$

this corresponds to $\sigma(pp \to h_2) \approx 1\,\mathrm{pb}$

and thus $y_T = \dfrac{m_T}{v_S} \gg 1$

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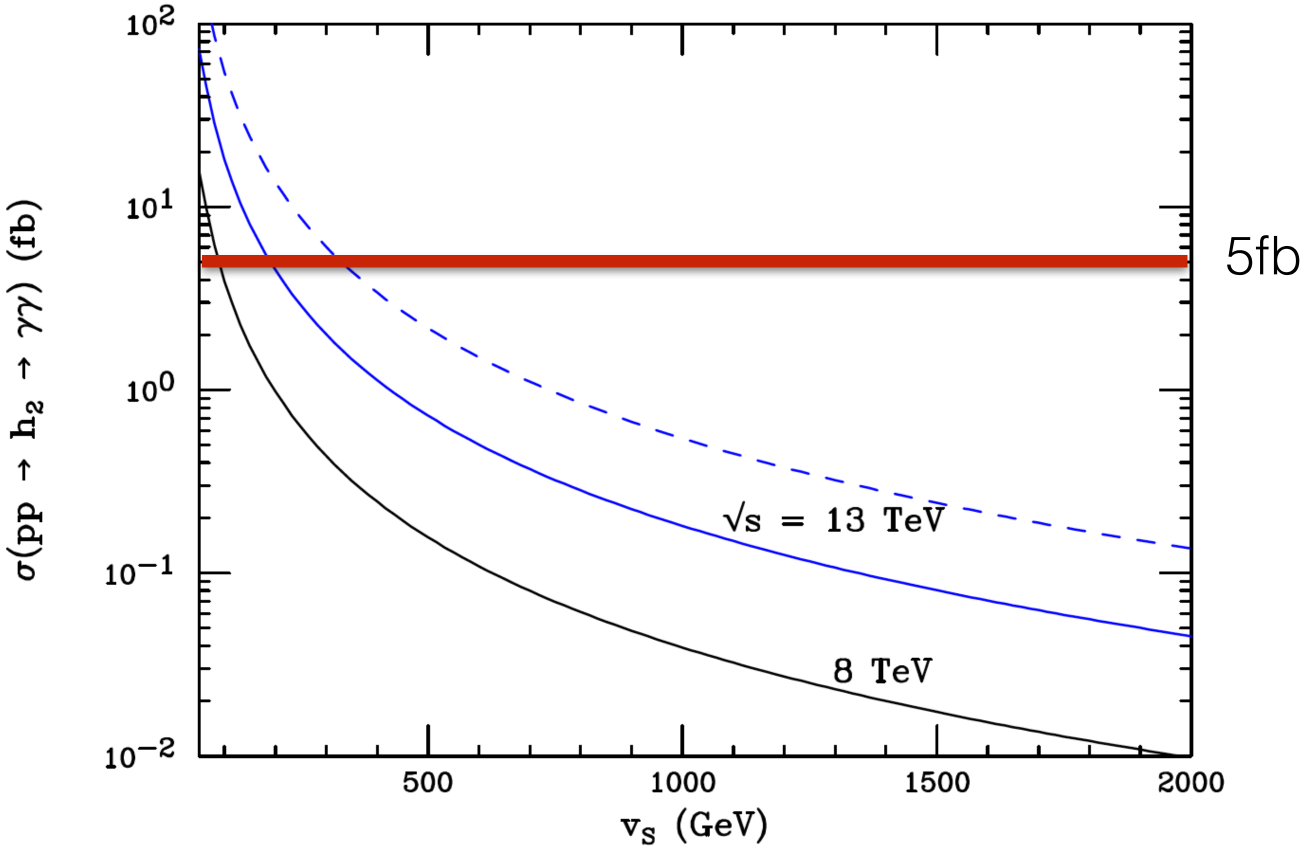

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and a violation of perturbative unitarity.

Can restore perturbativity by adding more generations of new fermions.

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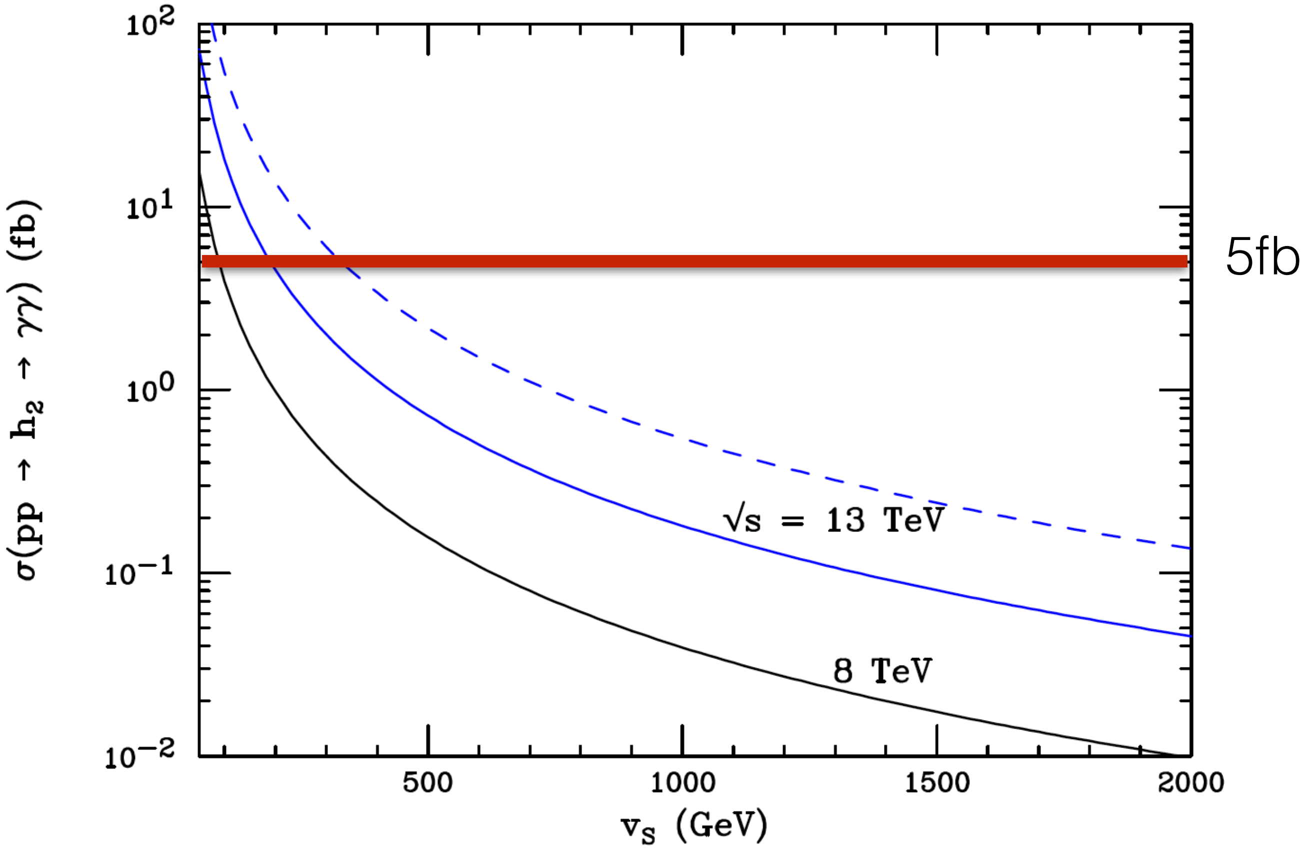

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However, a large width $\Gamma_{h_2} \approx 45\,\mathrm{GeV}$ as favoured by ATLAS,
would most likely imply non-perturbative dynamics. (See e.g. 1512.04933)