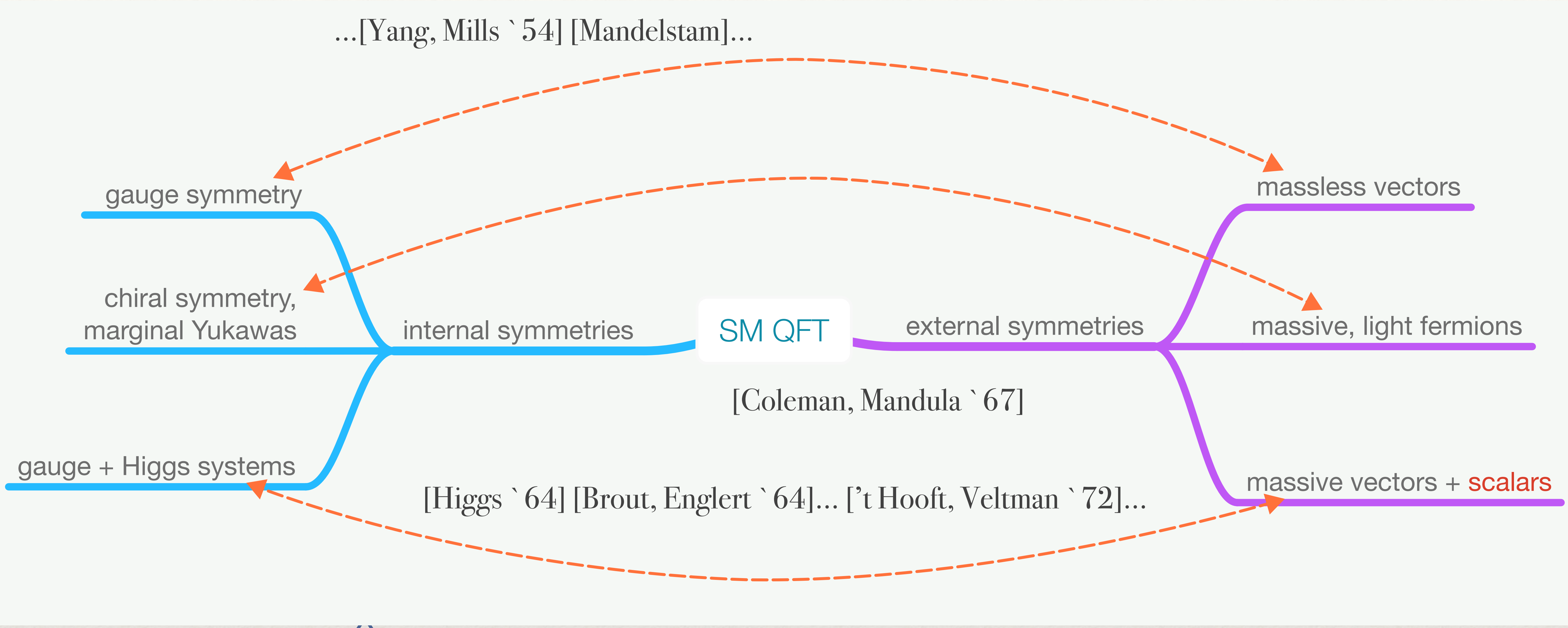
Christoph Englert

Effective Field Theory for Higgs and Top Physics

King's College London

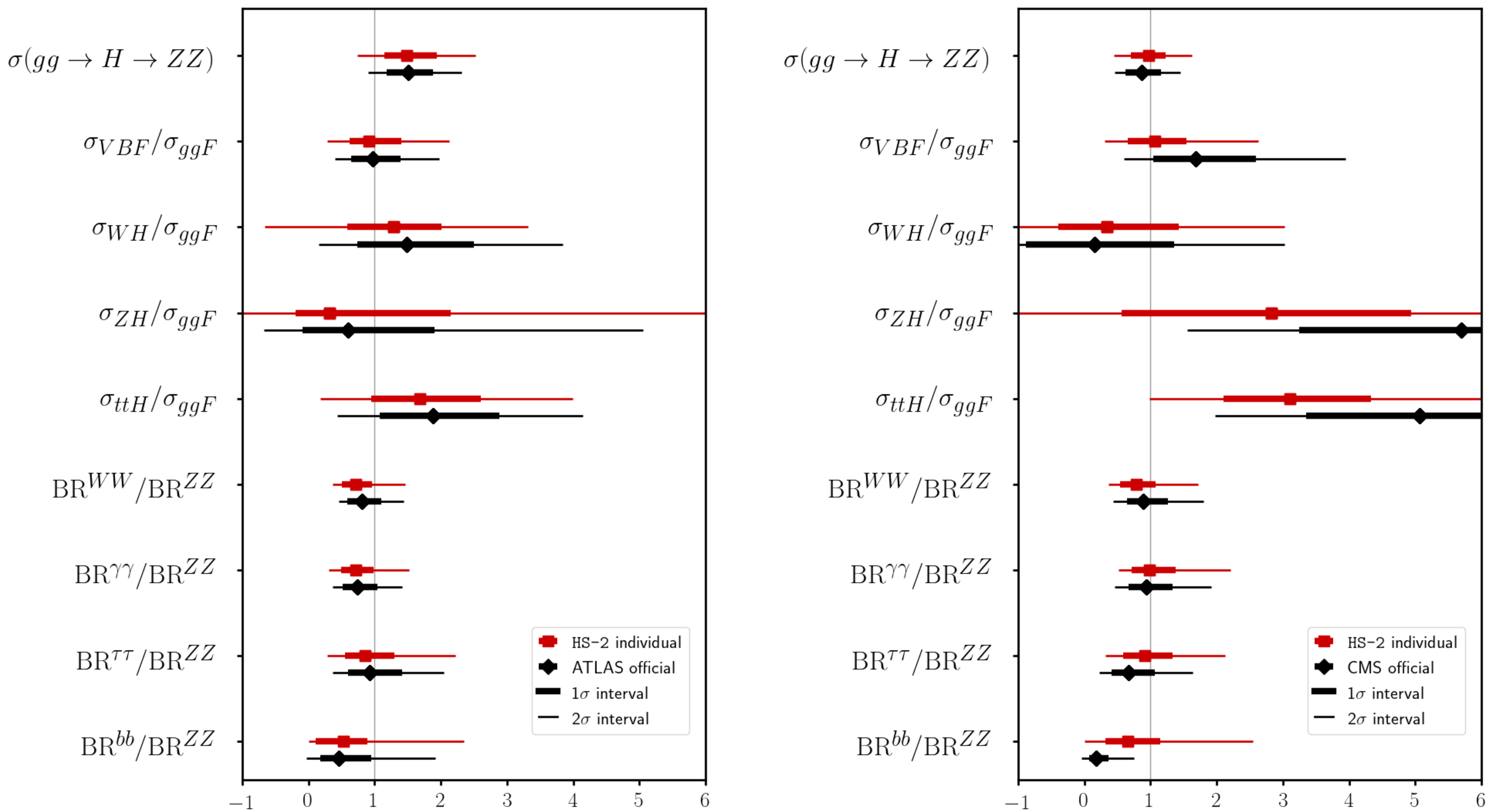
10/02/21

The Standard Model: taking stock



"What's next ?"

Status of LHC measurements



[Bechtle et al. `20]

- everything is consistent with the SM Higgs hypothesis (so far) but what are the implications for new physics?

Fingerprinting the lack of new physics

the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

<u>Effective Field Theory</u>

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \dots$$

[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Giudice, Grojean, Pomarol, Rattazzi `07]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]
[Brivio, Jiang, Trott `17]....

59 B-conserving operators ⊗ flavor ⊗ h.c., d=6
2499 parameters (reduces to 76 with N_f=1)

<u>concrete models</u>

- extended SMEFT
- (ℂ) Higgs portals
- 2HDMs
- simplified models
- compositeness….

Overview

- *Improving the expected: beyond the SM-like Higgs*
  - improving our understanding of Higgs couplings

    [CE, Galler, Harris, Spannowsky ` 18]
  - improving our understanding Higgs propagation

    [CE, Giudice, Greljo, McCullough ` 19]

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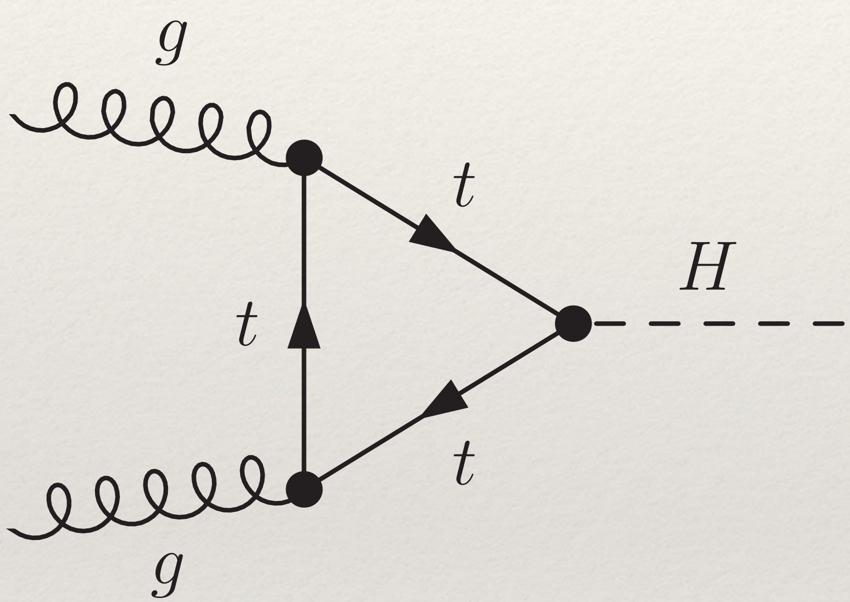
- *Constraining/observing the unexpected*
    - CP violating Higgs interactions CP violation
    - interplay of top/Higgs sectors

      [Bernlochner, CE, Hays, et al, `18]
      [CE, Galler, Pilkington, Spannowsky `19]
      [CE, Galler, White `19]
      [Brown, CE, Galler, Stylianou `20]
      [Bakshi, Chakrabortty, CE, Spannowsky, Stylianou `20]

SM-like couplings

- large number of EFT parameters leads to phenomenological degeneracies = *"blind directions"*
- one of the most prominent an relevant for Higgs physics

[Vainstein et al. `70]
[Ellis et al. `76]
....



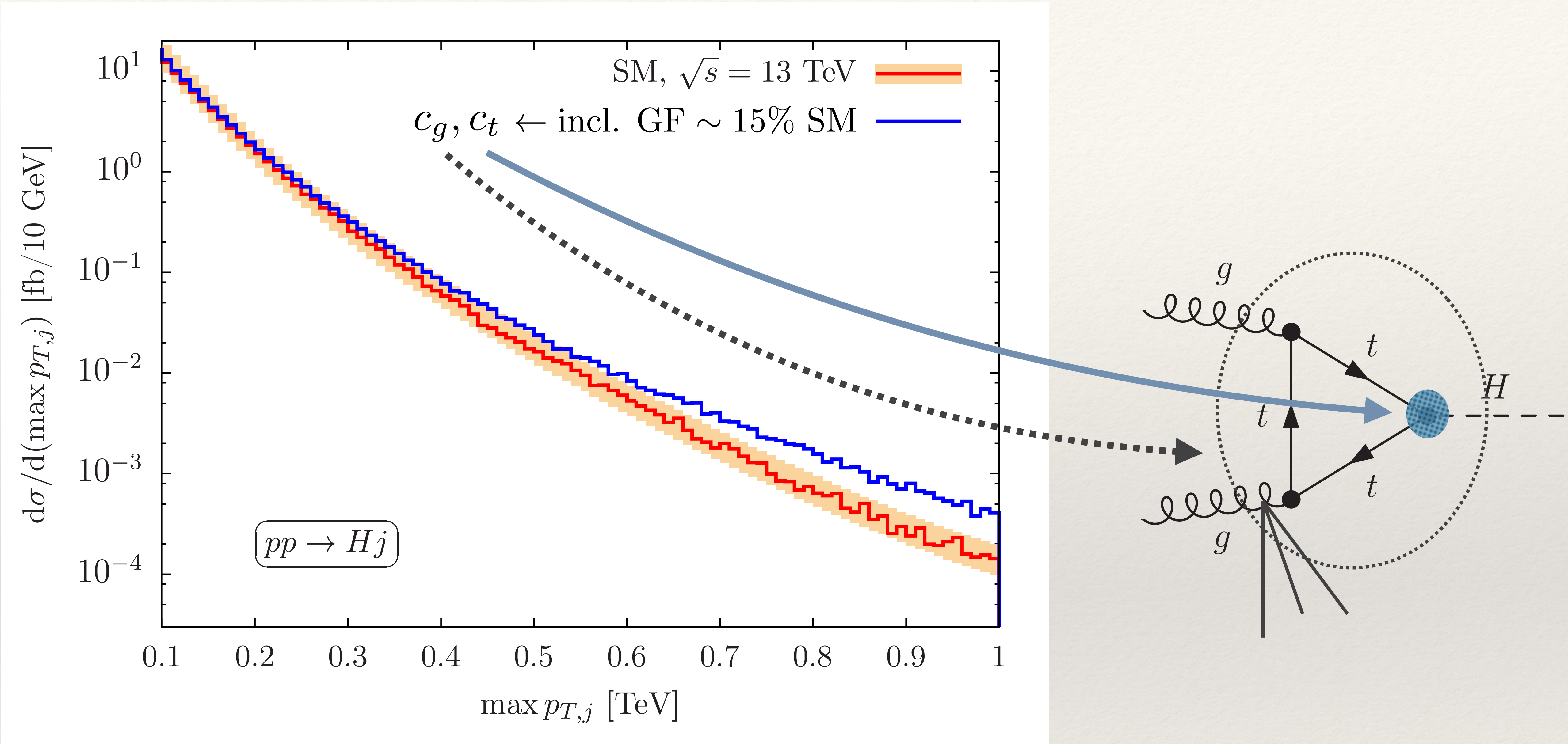
$$\xrightarrow{m_t \to \infty} \quad \supset \frac{\alpha_s}{12\pi} G^{a\mu\nu} G^a_{\mu\nu} \frac{H}{v}$$

contact ggH interactions mask top Yukawa measurements

- way out: resolve loop dynamics for $p_T(H) \gtrsim m_t$ with one or more jets

[Banfi, Martin, Sanz ` 13] [Grojean, Salvioni, Schalffer, Weiler ` 13]
[Schalffer et al` 14] [Buschmann et al. ` 14] [Buschmann et al. ` 14]

SM-like couplings



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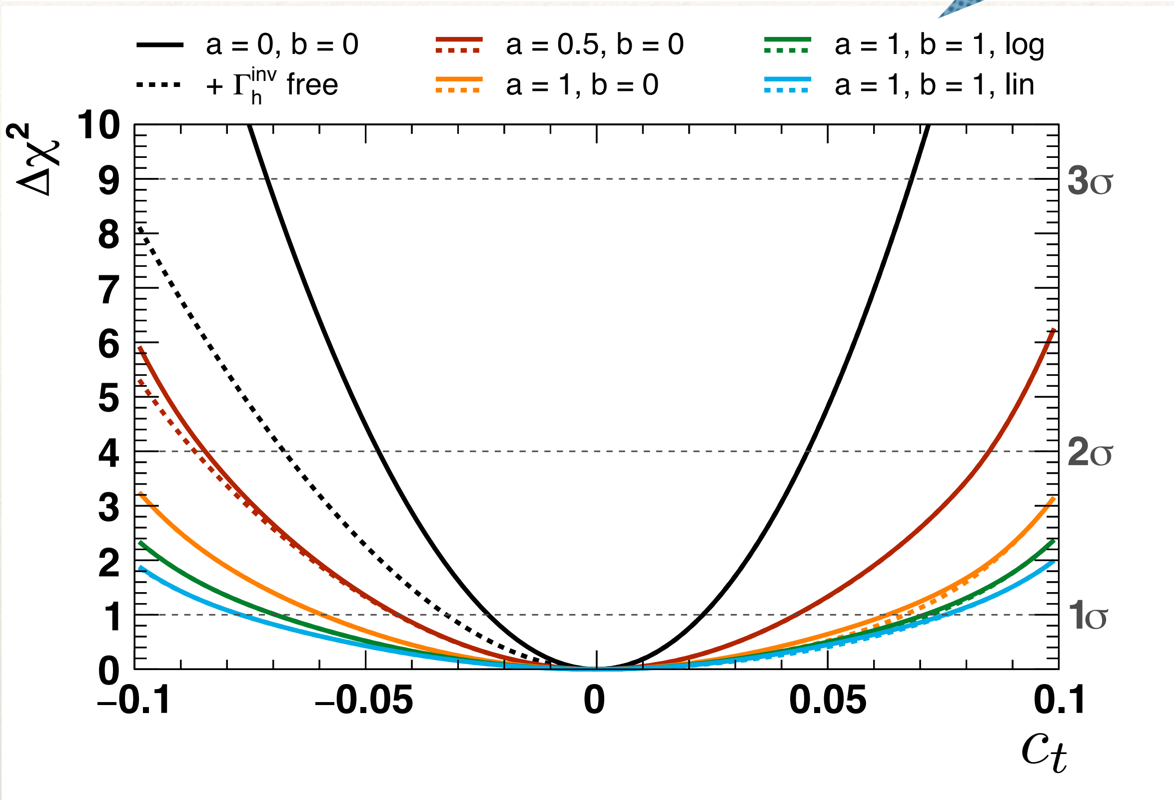
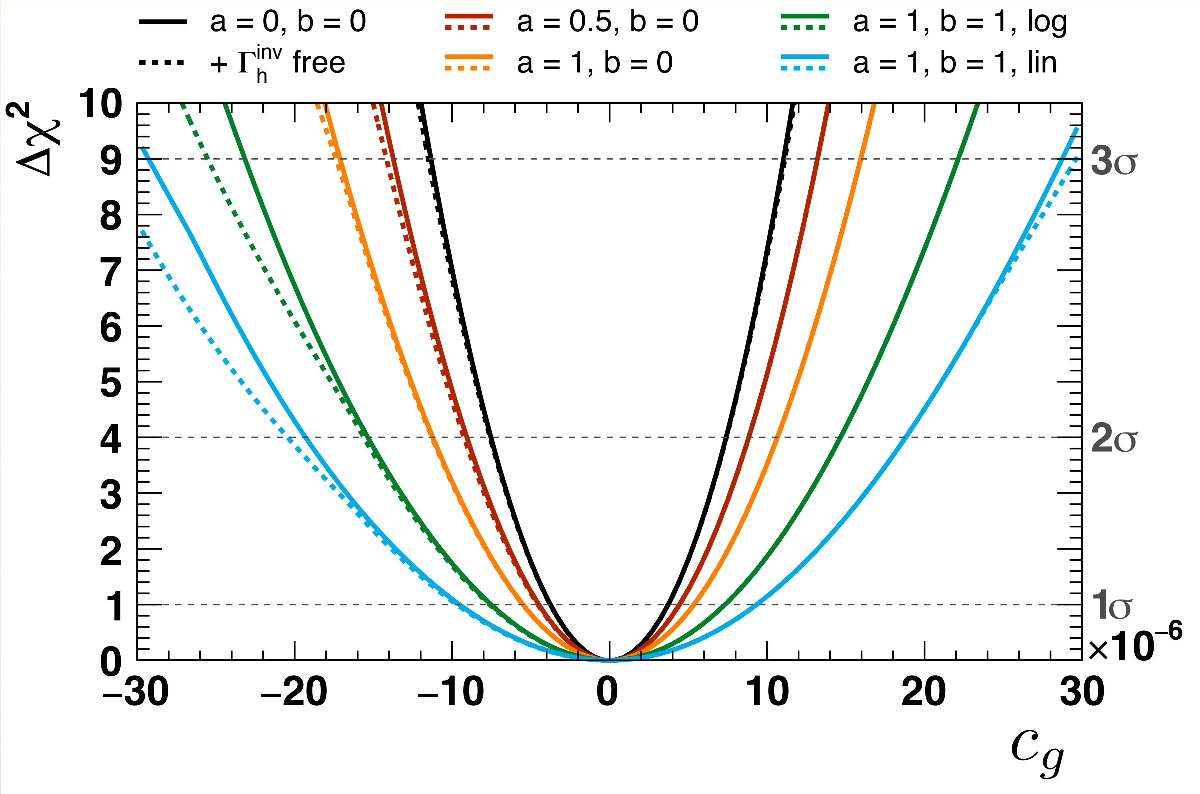
Role of uncertainties

[CE, Kogler, Schulz, Spannowsky ` 17]

[Ellis et al. ` 14, ` 18, ` 20], [Sfitter …]

steer $p_T(H)$ shape uncertainty



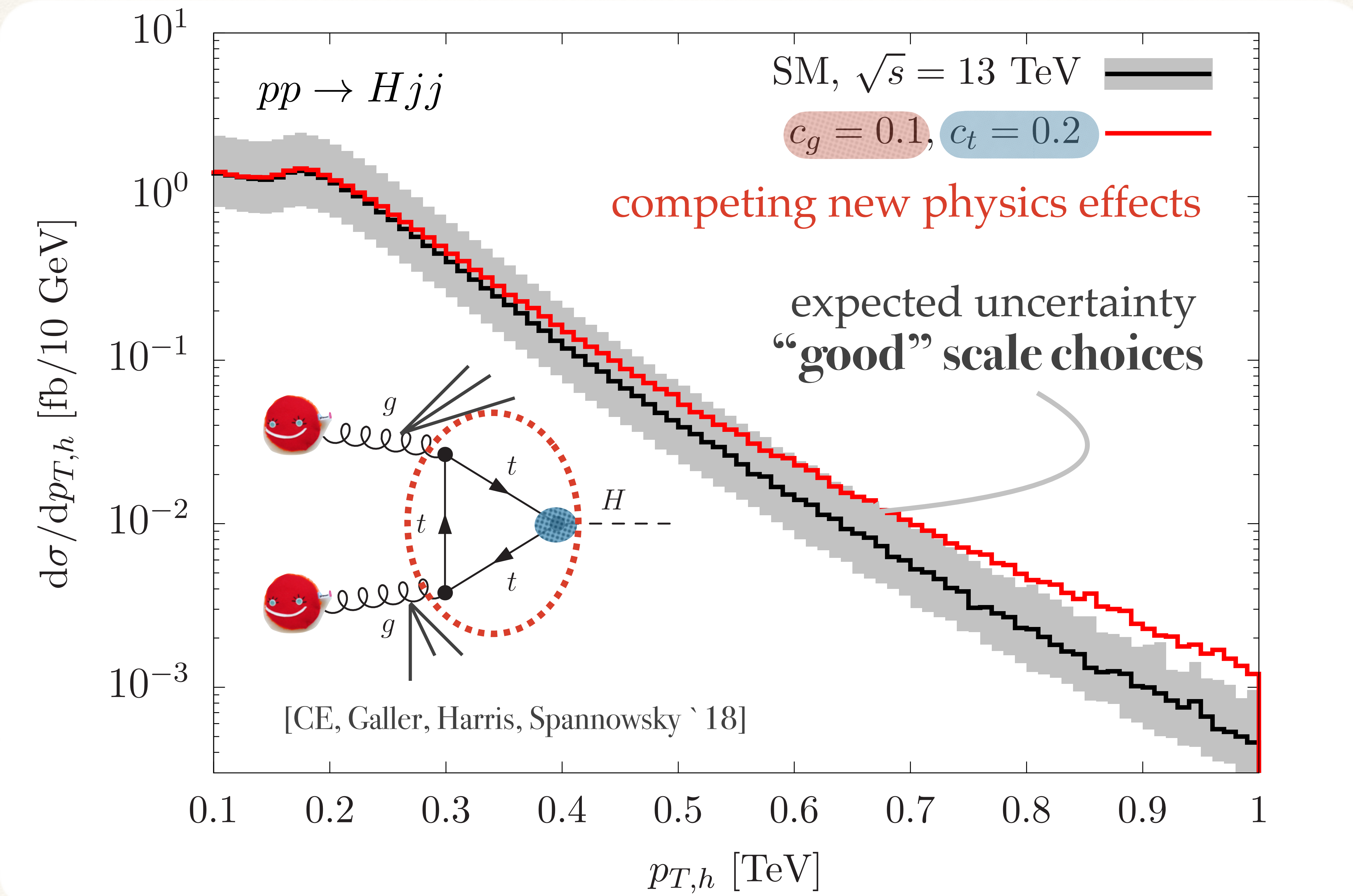


- comparably small impact of tail uncertainties (lin vs log ~ 35% different shape uncertainty at 150 GeV p_T
- decoupled (non-resonant) new physics perturbatively constrained at relatively low transverse momentum
- **turn to multi-scale processes to gain kinematic handles!**

large stats!

SM-like couplings

- more kinematic information for H+2j, which is particularly promising, unfortunately $m_t=\infty$ SM limit accidentally good [Del Duca et al. `03] …



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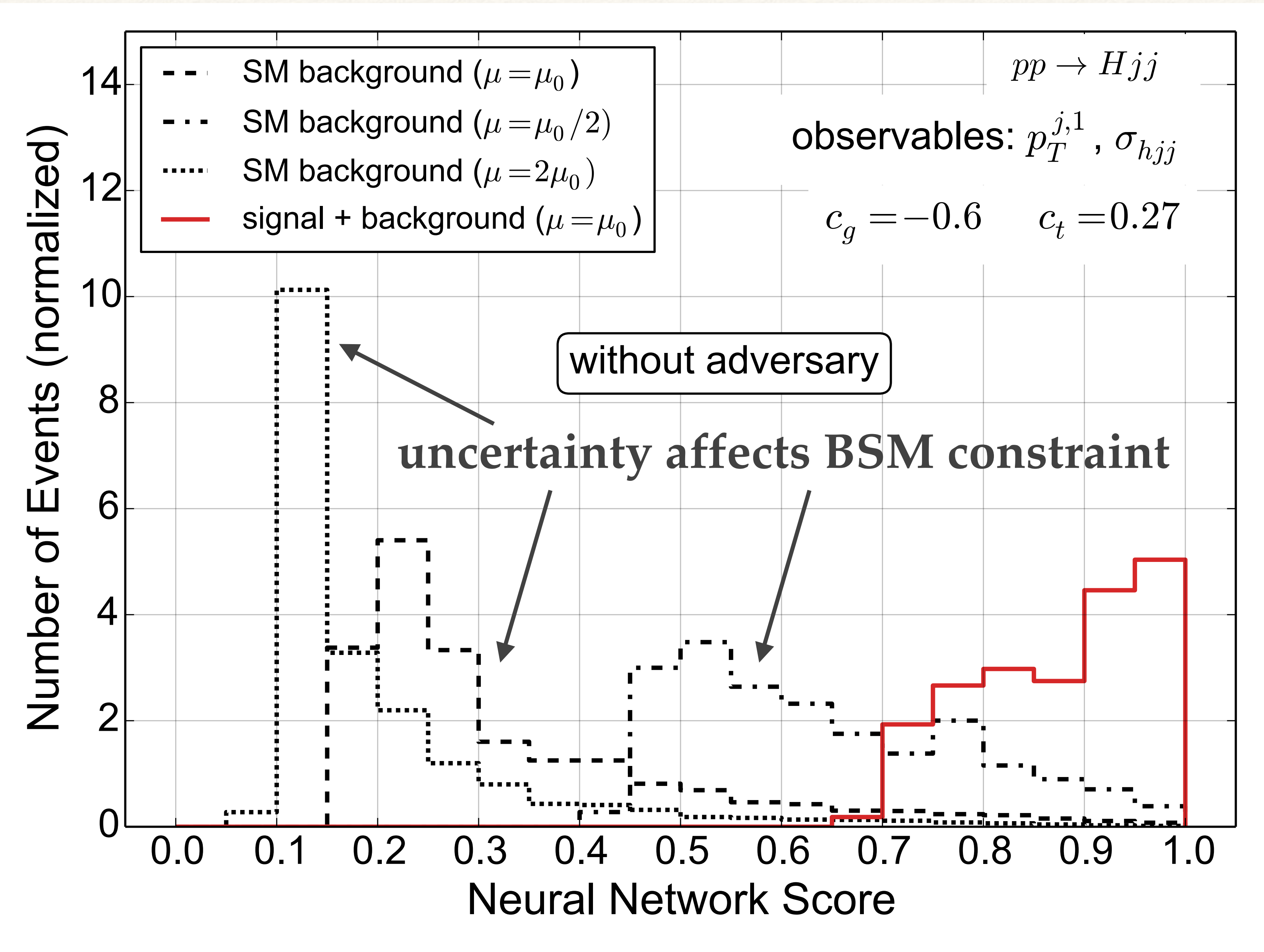

neural net learns regions that are sensitive to uncertainty….

[Goodfellow et al. ` 14] [Louppe, Kagan, Cranmer ` 16] …

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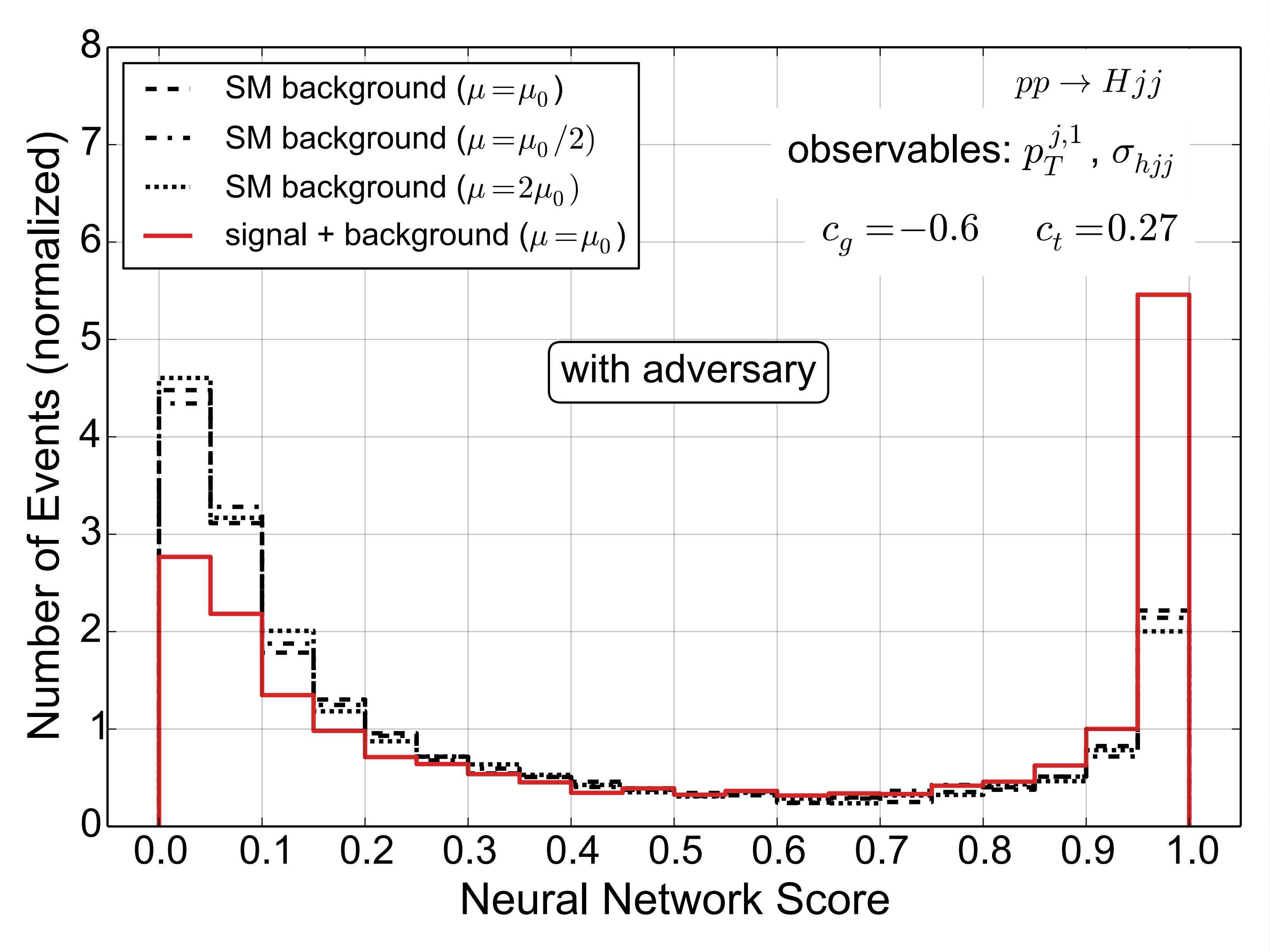

… and can be forced to avoid them → **most robust constraints**

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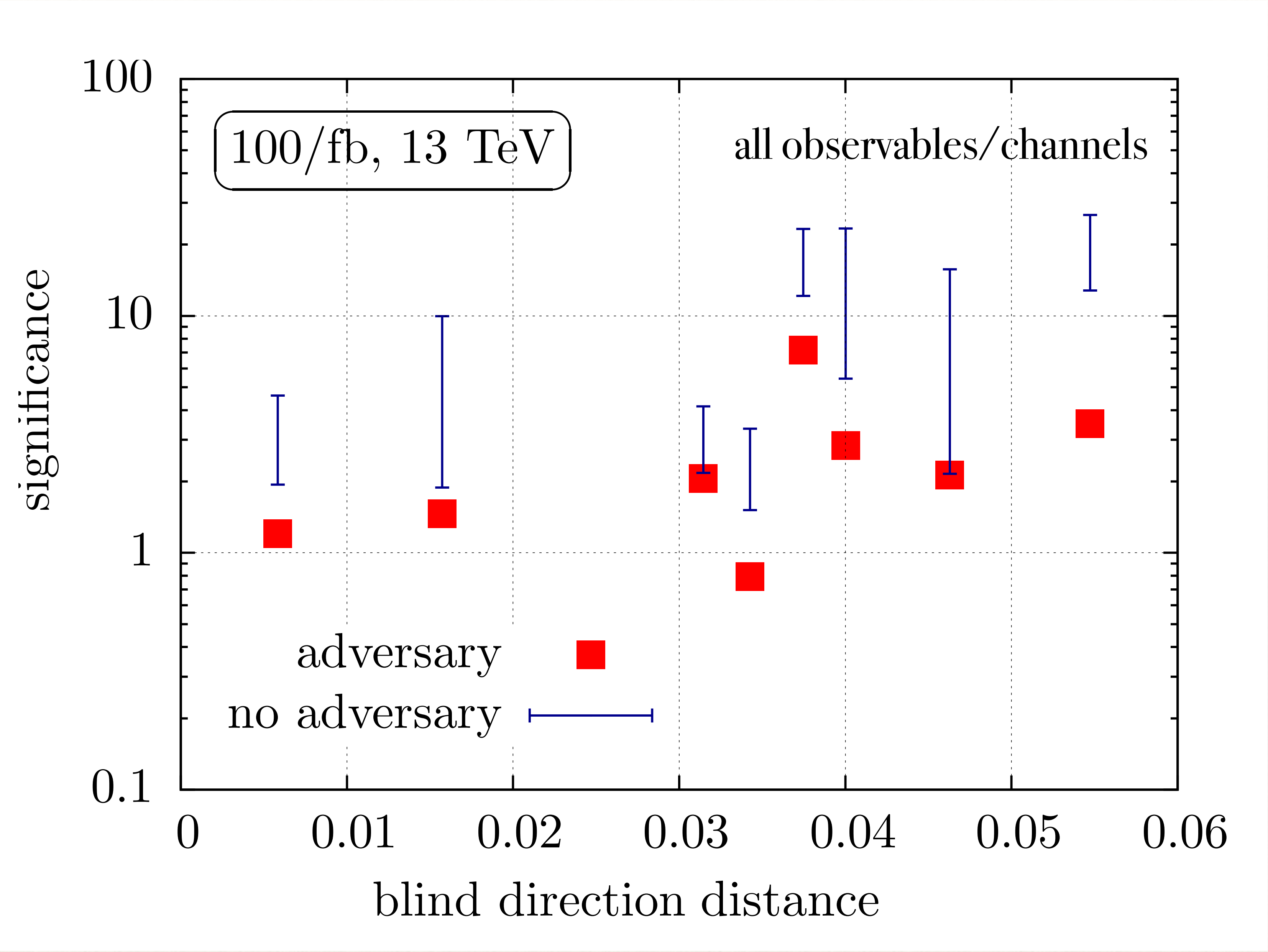

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CP violation

- Higgs sector is a primary candidate for CP violation - how is this captured in a dimension 6 approach?

matching

MC perturbativity

unitarity…

$$\mathrm{d}\sigma \sim |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{d6}}\} + |\mathcal{M}_{\mathrm{d6}}|^2$$

$$\sim \Lambda^0 \qquad\qquad \sim \Lambda^{-2} \qquad\qquad \sim \Lambda^{-4}$$

dim 8

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unitarity…

- in practice this is (often) not a huge problem for large data samples

- **but qualitatively different for CP-violation:**

naive perturbative power counting

$\frac{c_i}{\Lambda^2}$ **~ dim 6**

~ (dim 6)² $\frac{c_i^2}{\Lambda^4}$

- only genuinely CP-sensitive observables carry information

signed $\Delta\phi_{jj}$, asymmetries, ….

…[Plehn et al. `01]… [Figy et al. `06]…

- every CP-even observable carries information

cross sections, widths, p_T spectra…

CP violation

[Bernlochner, CE, Hays, Lohwasser, Mildner, Pilkington, Price, Spannowsky ` 18]

- the linearised upshot

$$O_{H\tilde{G}} = H^\dagger H G^{a\mu\nu}\tilde{G}^a_{\mu\nu}\,,$$
$$O_{H\tilde{W}} = H^\dagger H W^{a\mu\nu}\tilde{W}^a_{\mu\nu}\,,$$
$$O_{H\tilde{B}} = H^\dagger H B^{\mu\nu}\tilde{B}_{\mu\nu}\,,$$
$$O_{H\tilde{W}B} = H^\dagger \tau^a H B_{\mu\nu}\tilde{W}^{a\mu\nu}$$

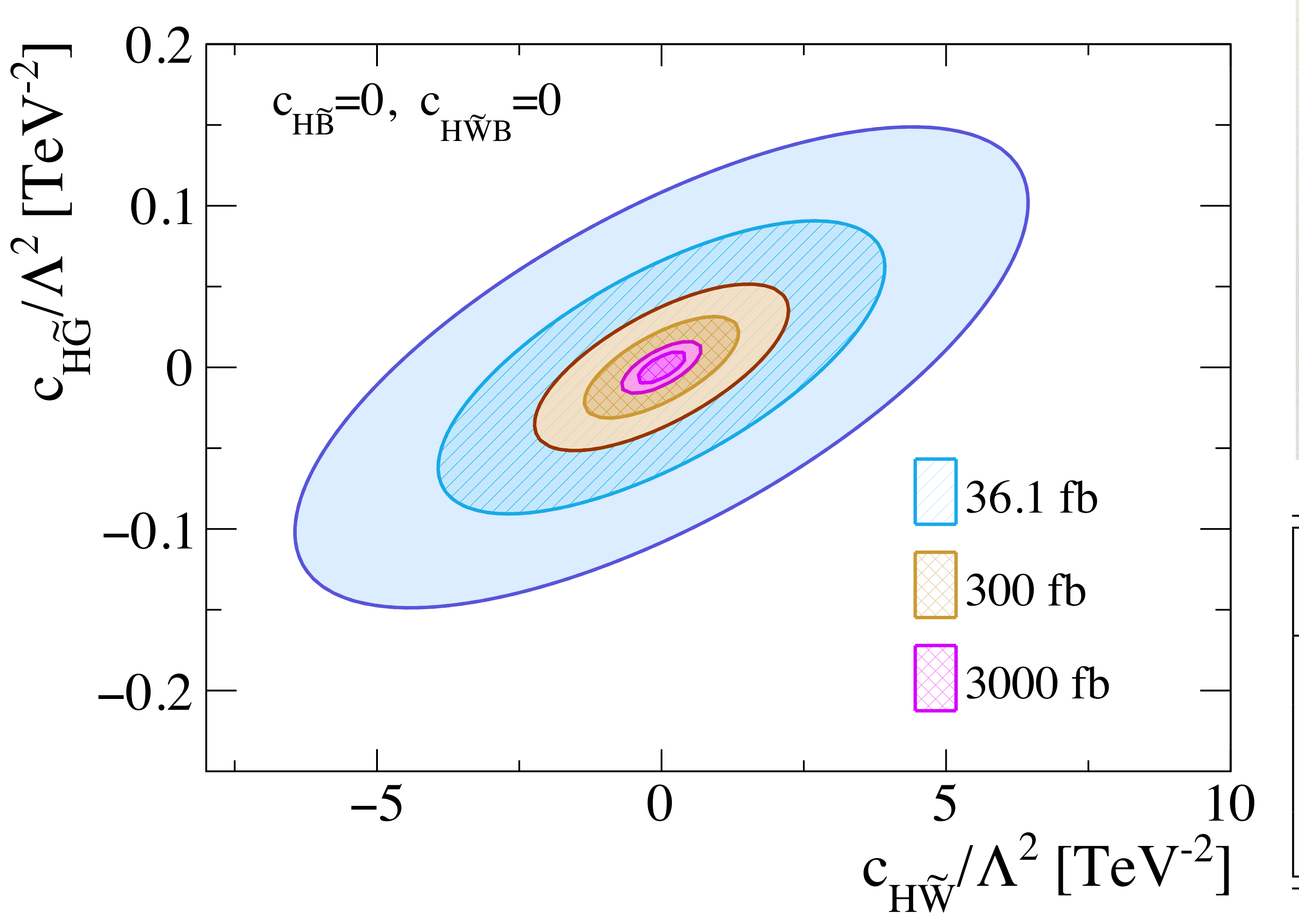
top quark

$$\sim \frac{\alpha_s}{8\pi v} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} h \;= \tilde{O}_G$$

+ Yukawa phases

ignore here: Can be tackled in GF

[CE, Galler, Pilkington, Spannowsky ` 19]



LHC and HL-LHC extrapolations

WBF+GF production and optimised selection, 4l final states

Coefficient [TeV^{-2}]	36.1 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
$c_{H\tilde{G}}/\Lambda^2$	$[-0.19, 0.19]$	$[-0.067, 0.067]$	$[-0.021, 0.021]$
$c_{H\tilde{W}}/\Lambda^2$	$[-11, 11]$	$[-3.8, 3.8]$	$[-1.2, 1.2]$
$c_{H\tilde{B}}/\Lambda^2$	$[-5.9, 5.9]$	$[-2.1, 2.1]$	$[-0.65, 0.65]$
$c_{H\tilde{W}B}/\Lambda^2$	$[-14, 14]$	$[-4.9, 4.9]$	$[-1.5, 1.5]$

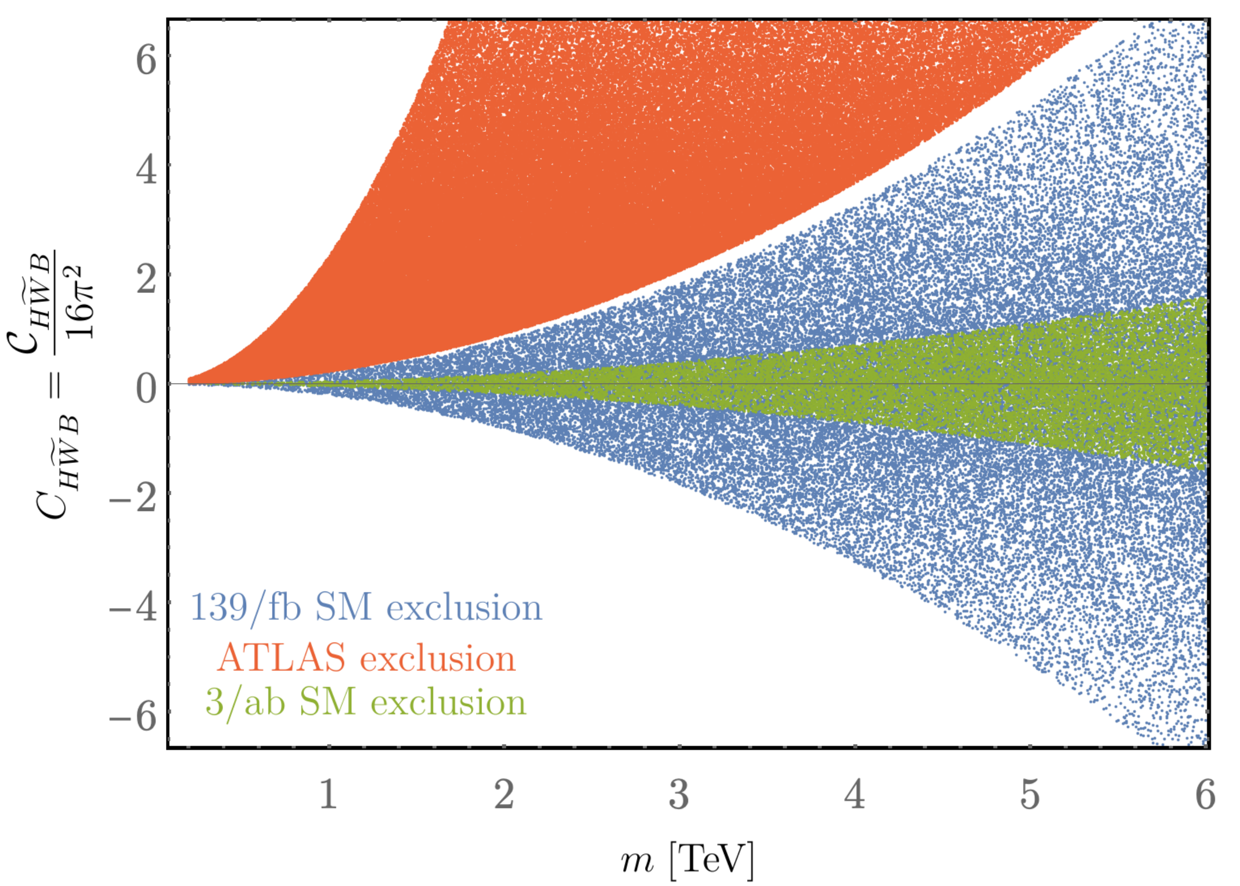
CP violation

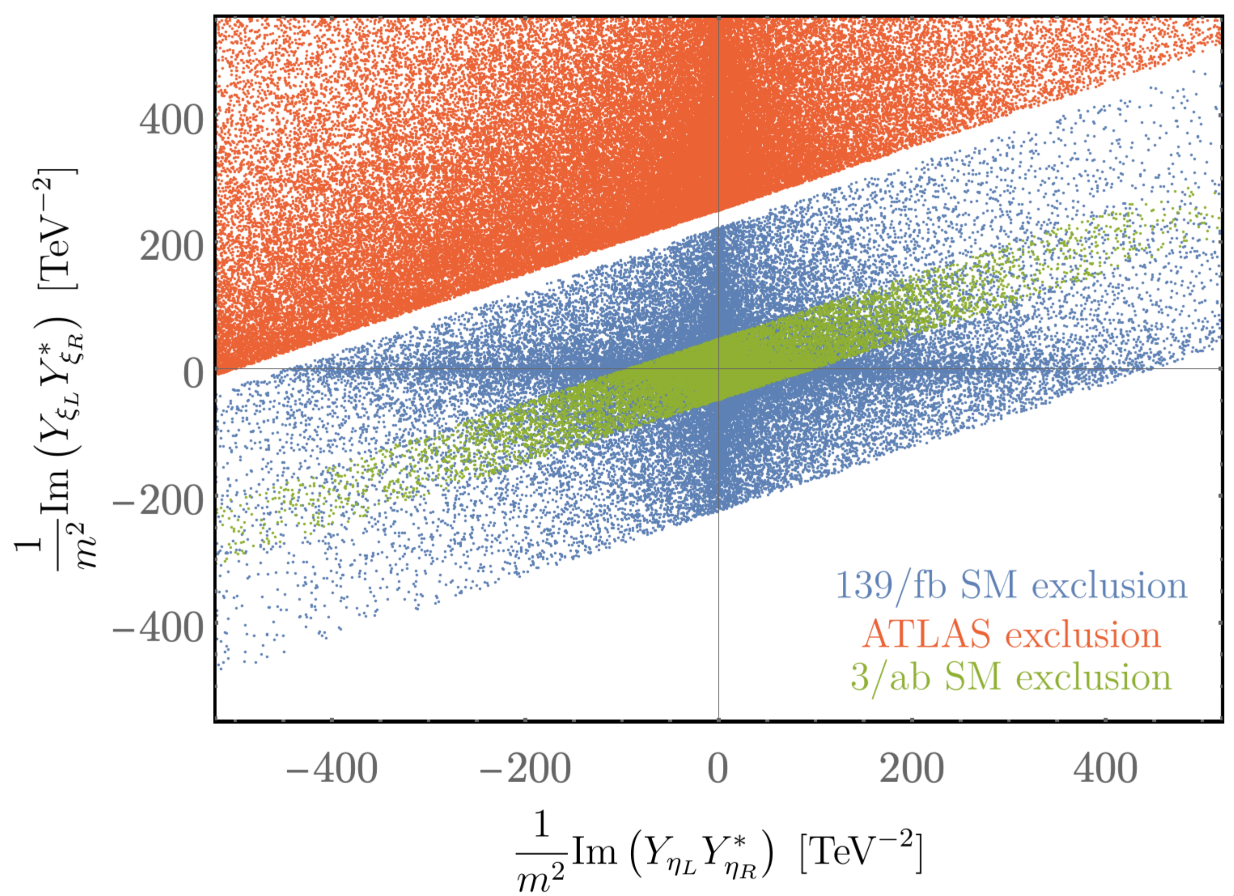
[ATLAS, 2006.15458]

Wilson coefficient	Includes $\lvert\mathcal{M}_{d6}\rvert^2$	95% confidence interval [TeV^{-2}] Expected	Observed	p-value (SM)
c_W/Λ^2	no	[−0.30, 0.30]	[−0.19, 0.41]	45.9%
	yes	[−0.31, 0.29]	[−0.19, 0.41]	43.2%
$\tilde{c}_W/\Lambda^2$	no	[−0.12, 0.12]	[−0.11, 0.14]	82.0%
	yes	[−0.12, 0.12]	[−0.11, 0.14]	81.8%
c_{HWB}/Λ^2	no	[−2.45, 2.45]	[−3.78, 1.13]	29.0%
	yes	[−3.11, 2.10]	[−6.31, 1.01]	25.0%
$\tilde{c}_{HWB}/\Lambda^2$	no	[−1.06, 1.06]	[0.23, 2.34]	1.7%
	yes	[−1.06, 1.06]	[0.23, 2.35]	1.6%

- ATLAS see a tension related to CP violation in WBF Z production
- sign for hierarchical new physics beyond the SM ?

[Das Bakshi, Chakrabortty, CE, Spannowsky, Stylianou `20]





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- what can be learned from this?

[Das Bakshi, Chakrabortty, CE, Spannowsky, Stylianou `20 & in prep]

  - Assumptions of two-parameter CP fits theoretically consistent in a wide class of vector-like leptons
  - Hierarchy $|C_{H\widetilde{W}B}|/\Lambda^2 > |C_{\widetilde{W}}|/\Lambda^2$ predicted in these scenarios
  - broad UV assumptions reduce complexity of fit whilst facilitating matching more straightforwardly

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Higgs propagation

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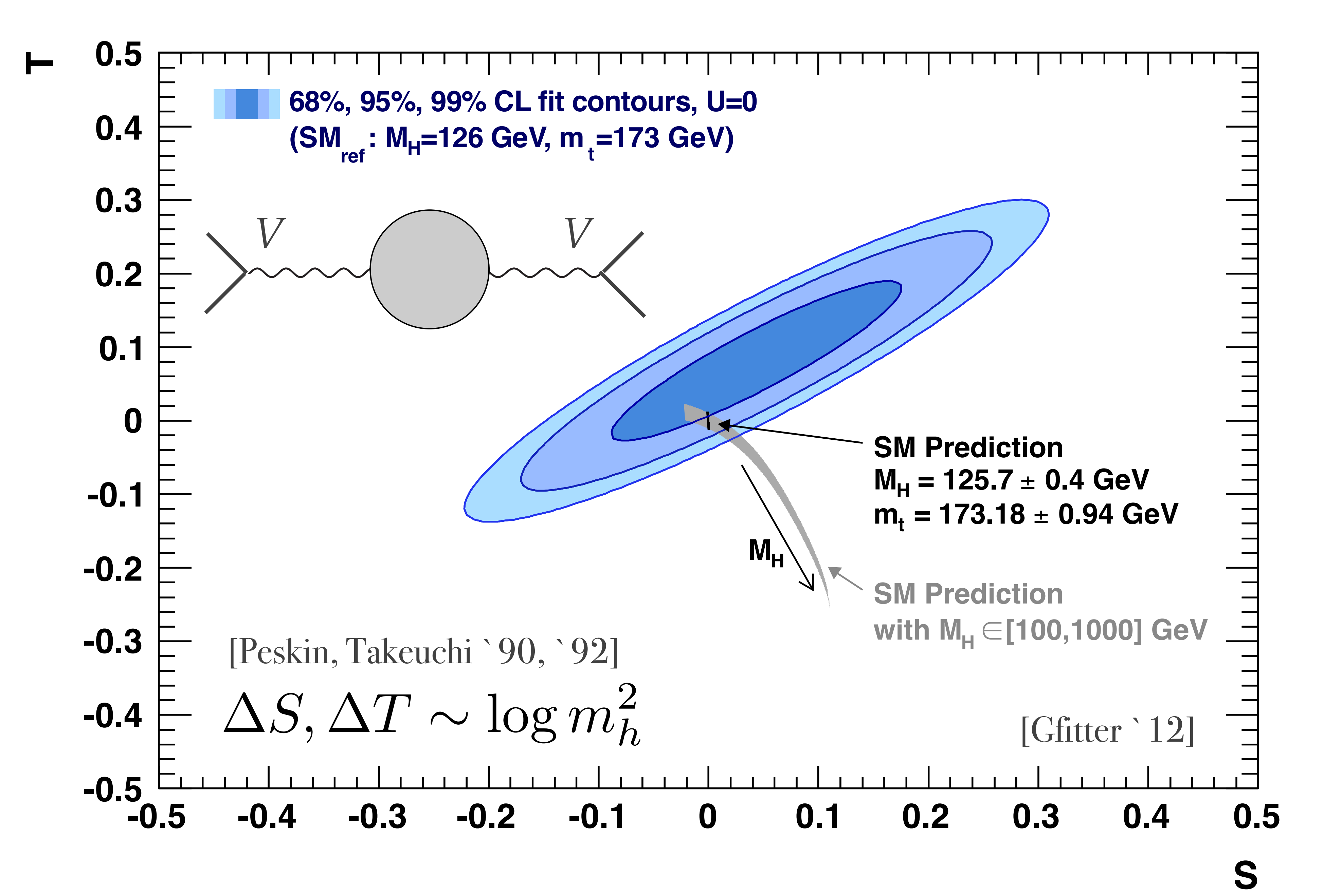


see also [Berthier, Trott `15...]

- specific dim 6 operators much better constraint than naively expected! Can we use similar tricks for the Higgs?

Higgs propagation

[CE, Giudice, Greljo, McCullough ` 19]

- access oblique Higgs propagator corrections

$$\Delta_h(p^2) = \frac{1}{p^2 - m_h^2} - \frac{\hat{H}}{m_h^2} \qquad \hat{H} = -\frac{m_h^2}{2}\Sigma_h''(m_h^2)$$

similar to

$$\ldots.\quad \mathcal{L}_{\hat{W}} = -\frac{\hat{W}}{4m_W^2}(D_\rho W^a_{\mu\nu})^2 \;,\quad \mathcal{L}_{\hat{Y}} = -\frac{\hat{Y}}{4m_W^2}(\partial_\rho B_{\mu\nu})^2 \;,\quad \mathcal{L}_{\hat{H}} = \frac{\hat{H}}{m_h^2}|\Box H|^2$$

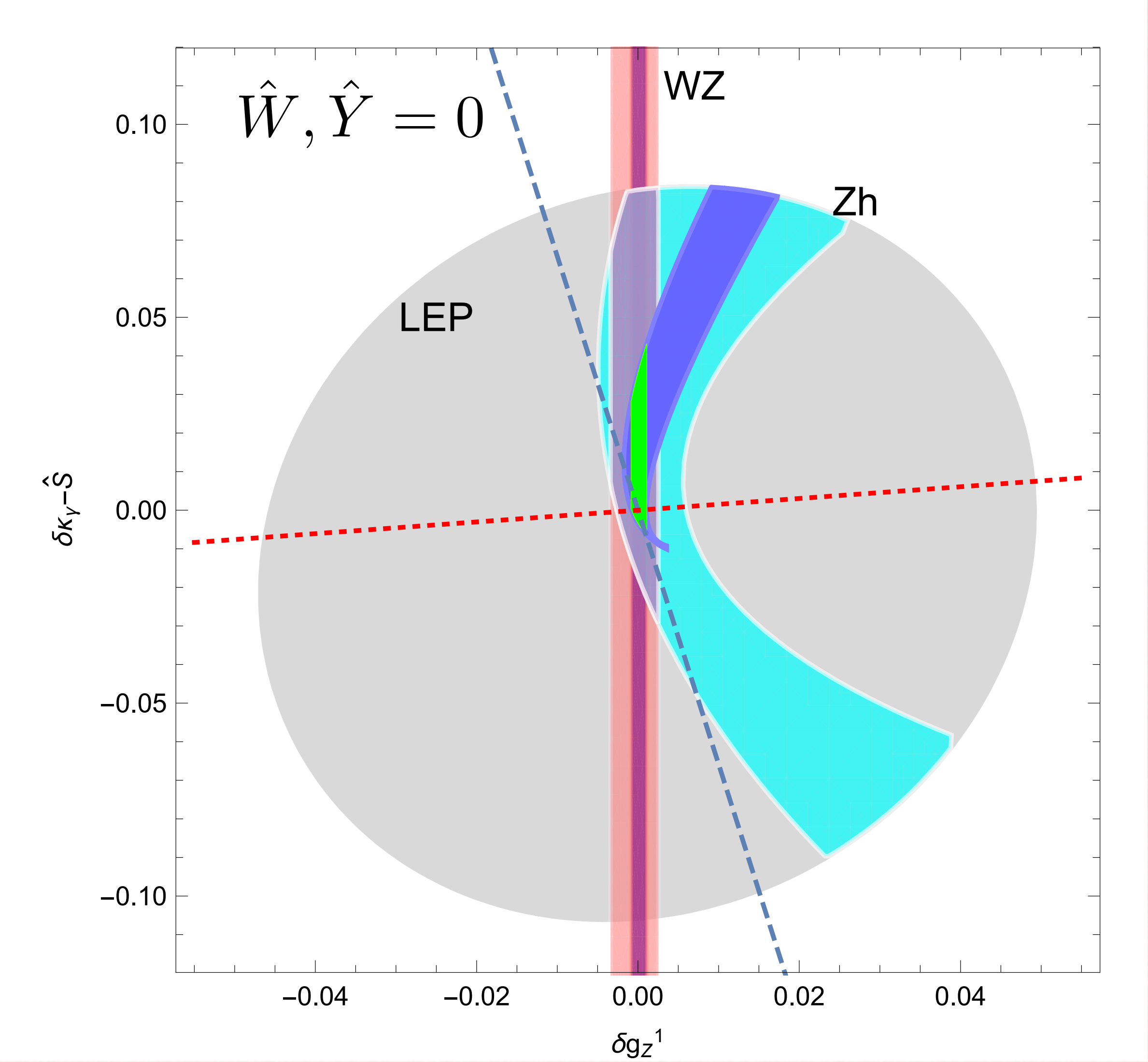
$\Box \equiv D^\mu D_\mu$

[Barbieri et al. ` 04]

- excellent prospects to surpass LEP(2) sensitivity at high energy colliders due to scaling

$$\hat{T} = \mathcal{O}(q^0)$$
$$\hat{S} = \mathcal{O}(q^2)$$
$$\hat{W}, \hat{Y} = \mathcal{O}(q^4)$$

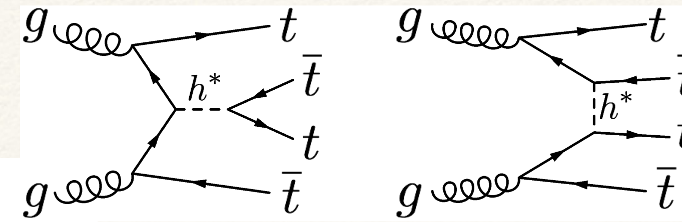
[Farina et al. ` 17]
[Franceschini et al. ` 18]
[Banerjee, Gupta, CE, Spannowsky ` 18]
...

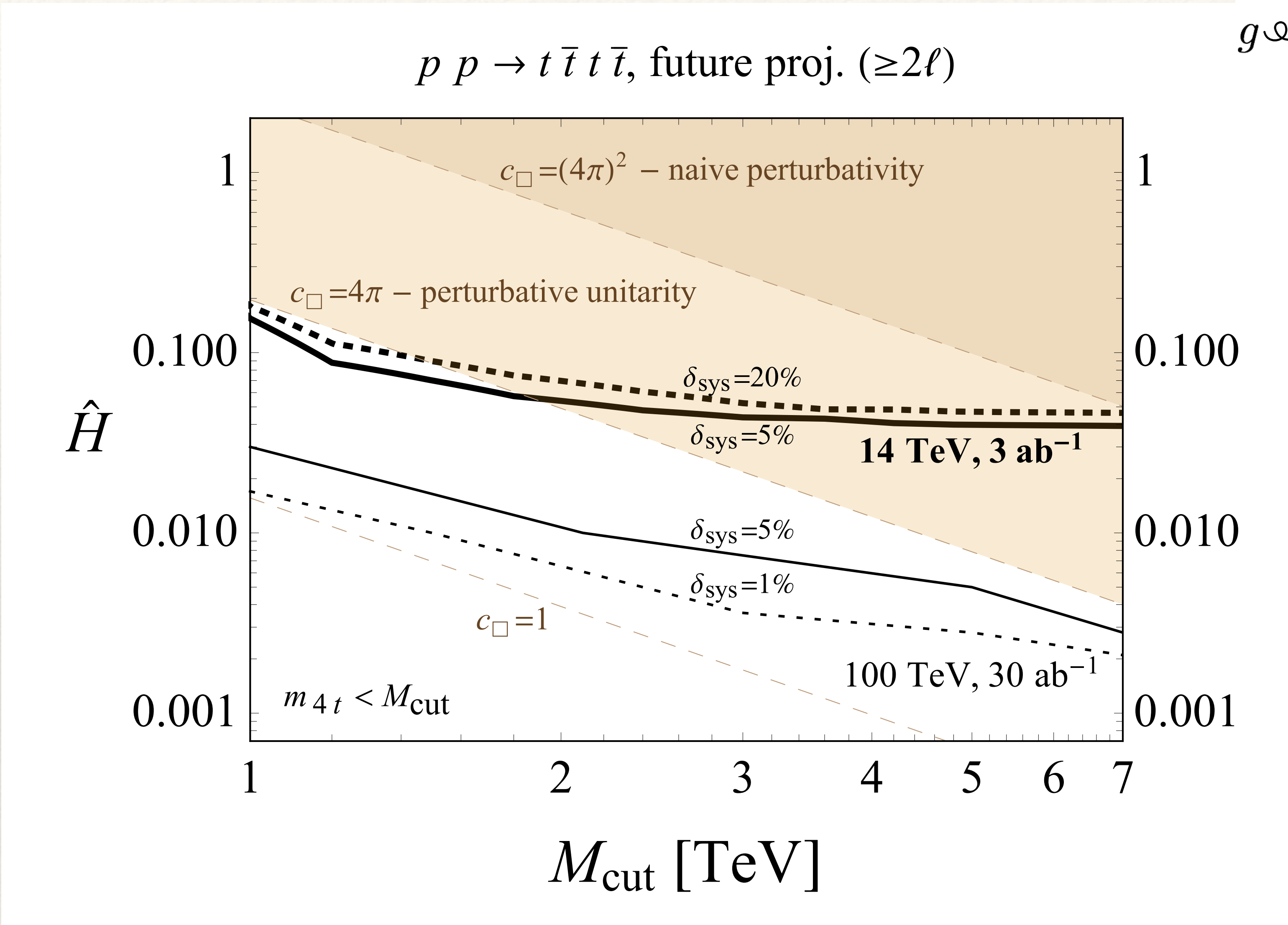


Higgs propagation

[CE, Giudice, Greljo, McCullough ` 19]

- phenomenological details captured via





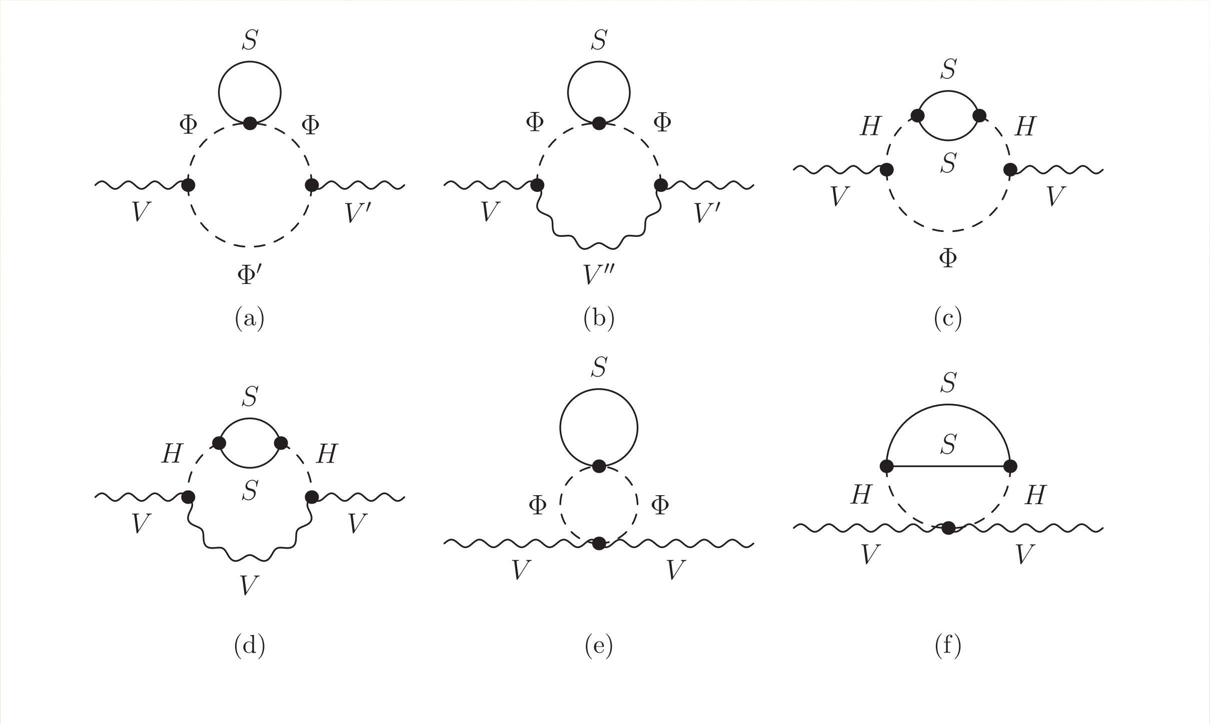
cf. [ATL-PHYS-PUB-2018-047]
[CMS-PAS-FTR-18-031]

- high energy frontier is an efficient probe at large cutoff

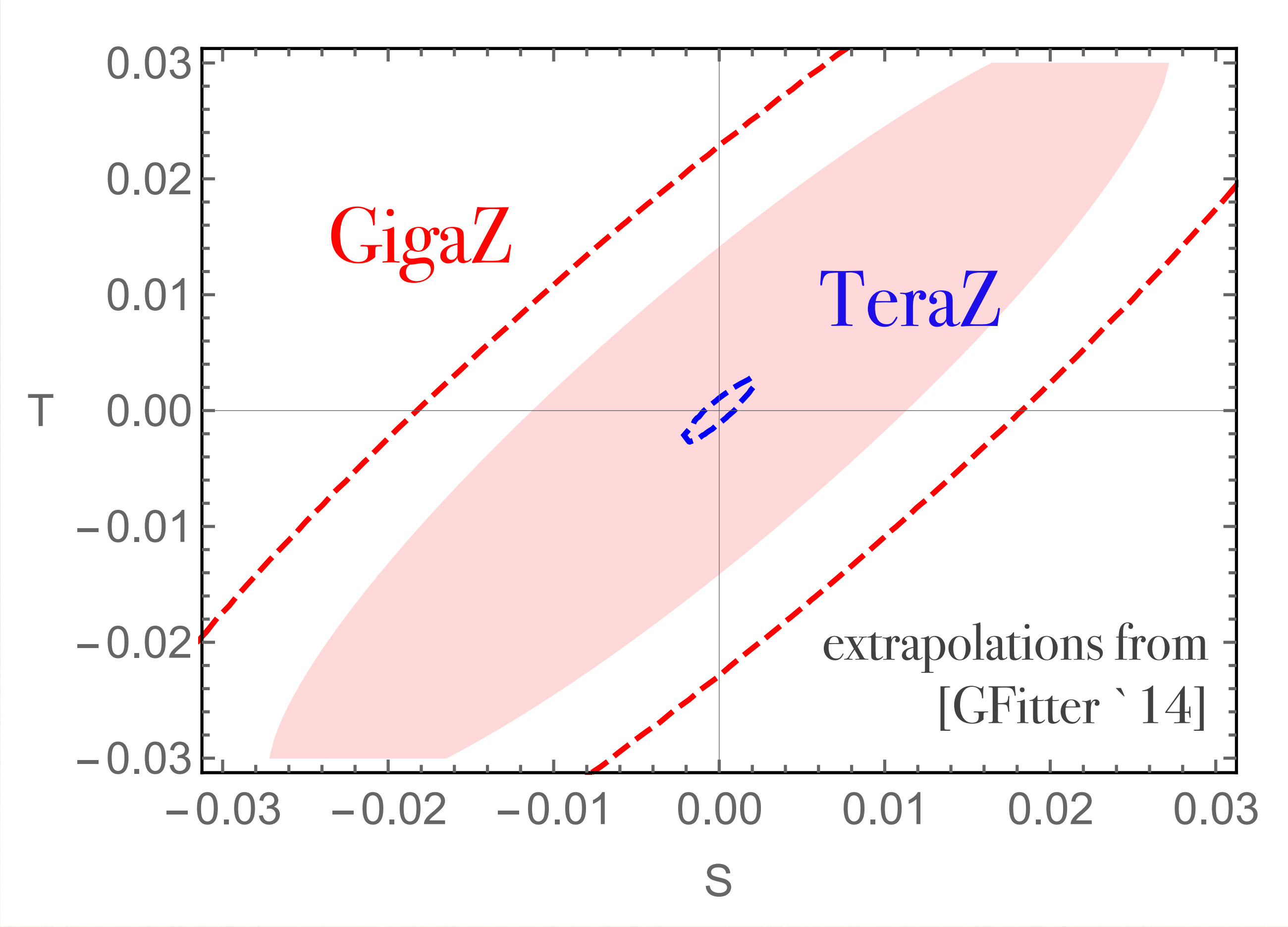
$$\text{FCC-ee} \quad |\hat{H}| \lesssim 0.5\%$$

[FCC Collaboration ` 19]

- precision analysis of Z-pole measurements ($e^+ e^- \to f\bar{f}'$) sensitive to Higgs corrections $\mathcal{L} \supset -\lambda S^2(\Phi^\dagger\Phi - v^2/2)$ [CE, Jaeckel, Spannowsky, Stylianou `20]



- Oblique corrections suppressed, but large statistics and clean measurement at Higgs factories!



GigaZ gives non-trivial constraint

massive improvement for TeraZ (if attainable)

Higgs propagation

relevance...

Oblique corrections

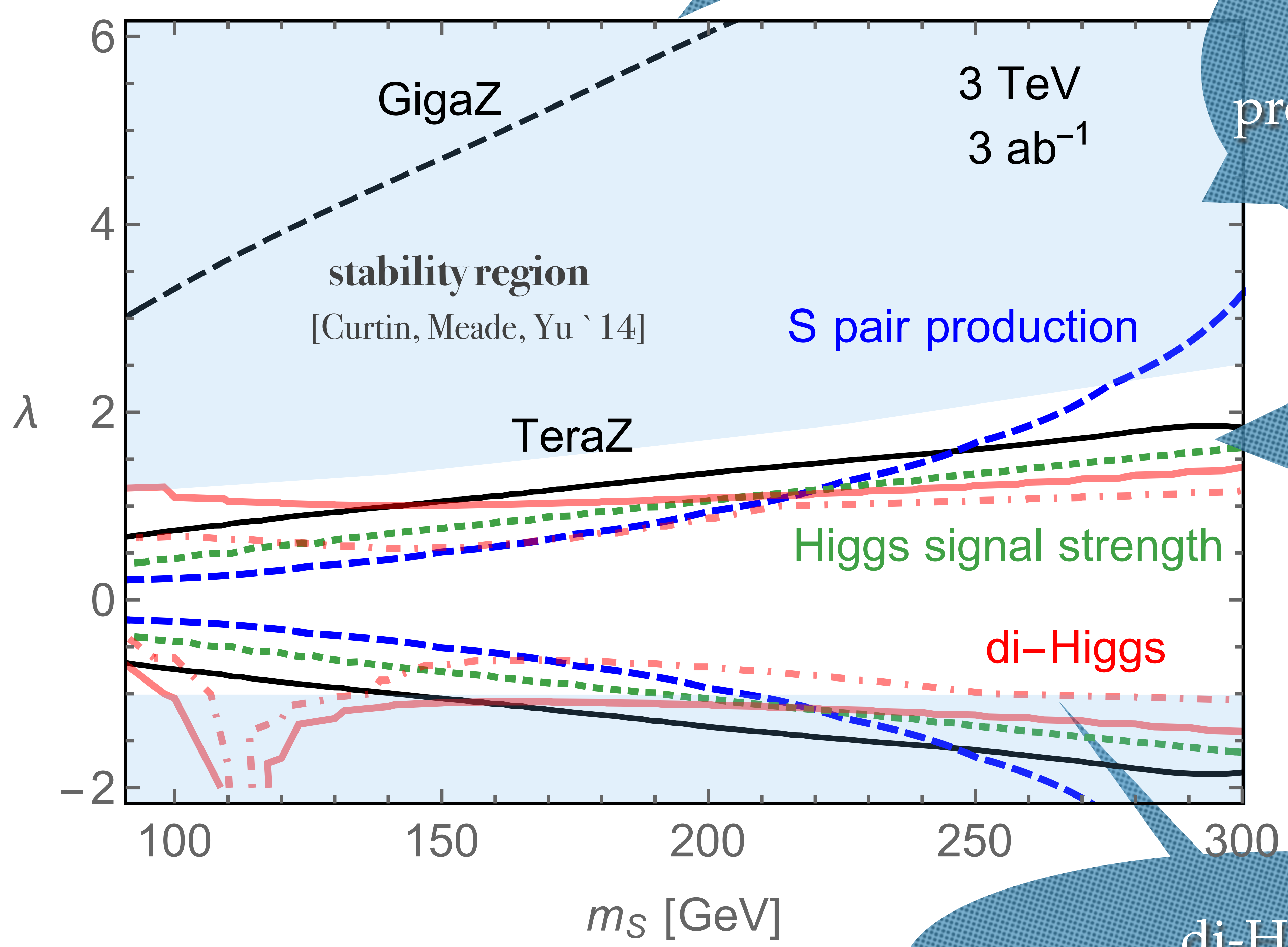
off-shell production: WBF

Higgs couplings @0.4%

[de Blas et al. `19]

di-Higgs physics @ 5-10%

[CE, Jaeckel, Spannowsky, Stylianou `20]



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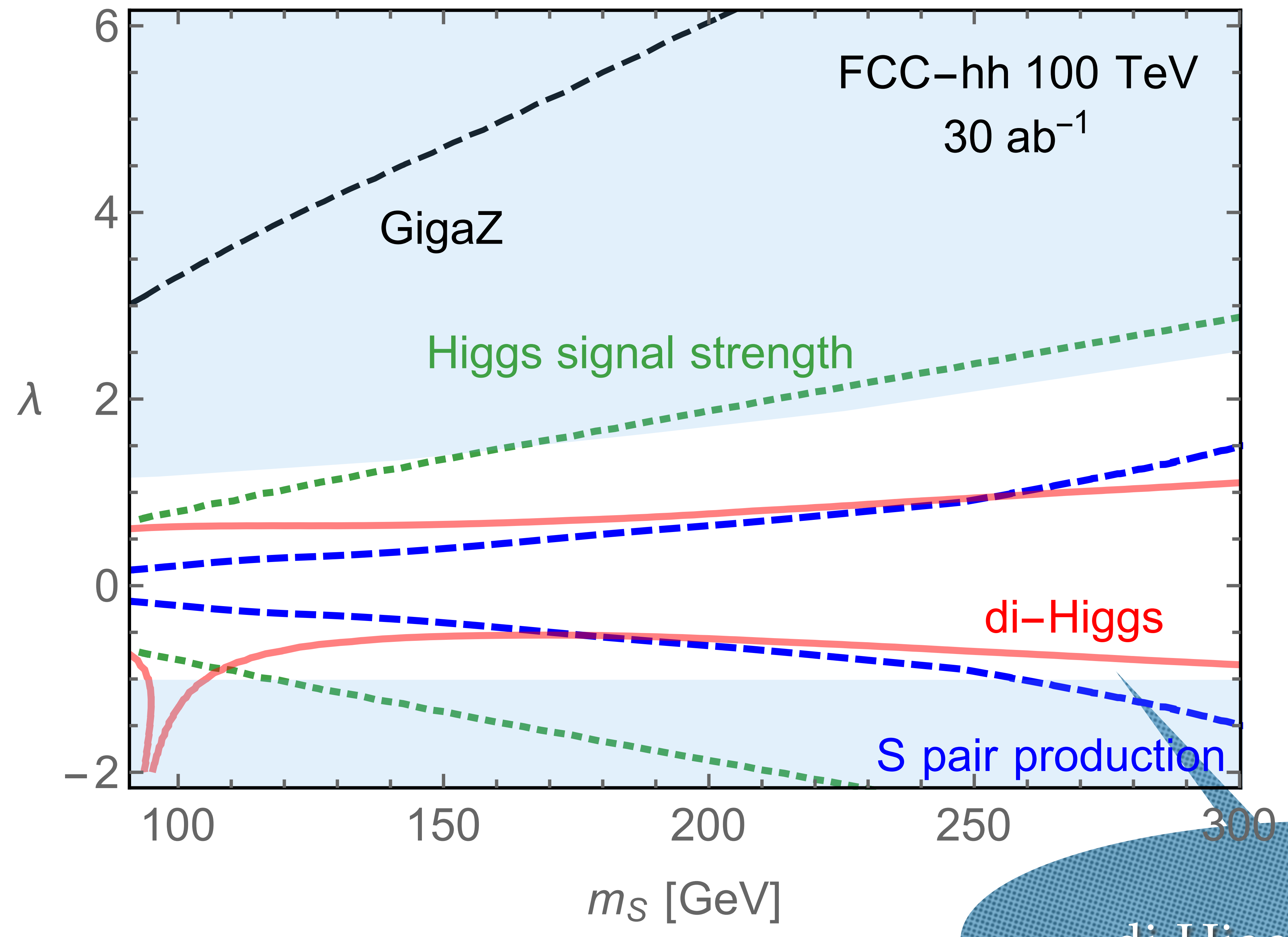

di-Higgs FCC @ 6%

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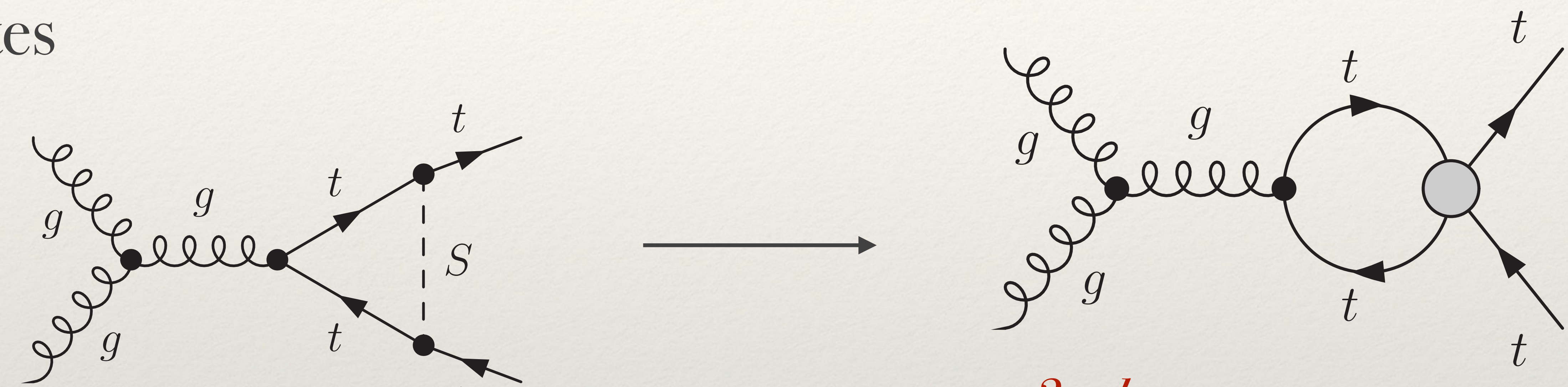
    [Bakshi, Chakrabortty, CE, Spannowsky, Stylianou ` 20]

New physics in tops

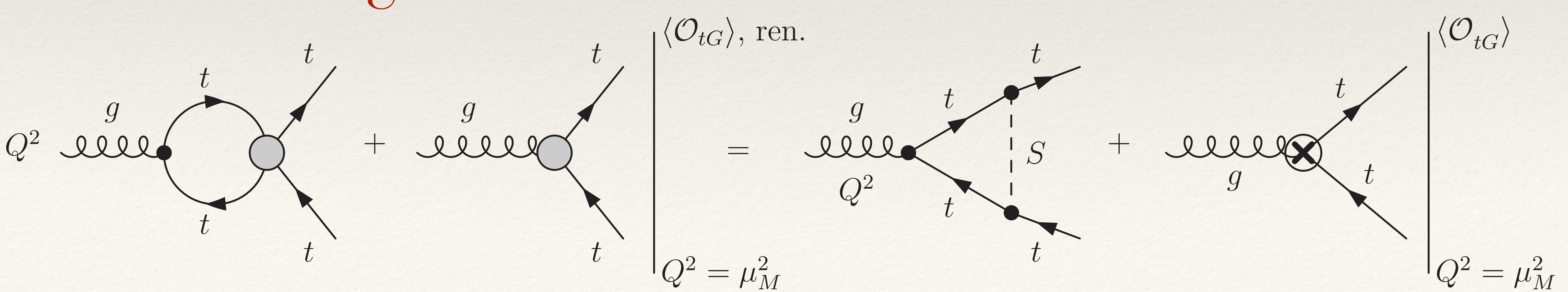
- new top-philic states arise in many BSM theories: $-\left(c_S \bar{t}_L t_R S + \text{h.c.}\right)$
- top pair production with large cross section could fingerprint such states



3 relevant operators

- EFT is suitable tool to constrain such states model-independently, *however matching is crucial!*

[CE, Galler, White ` 19]



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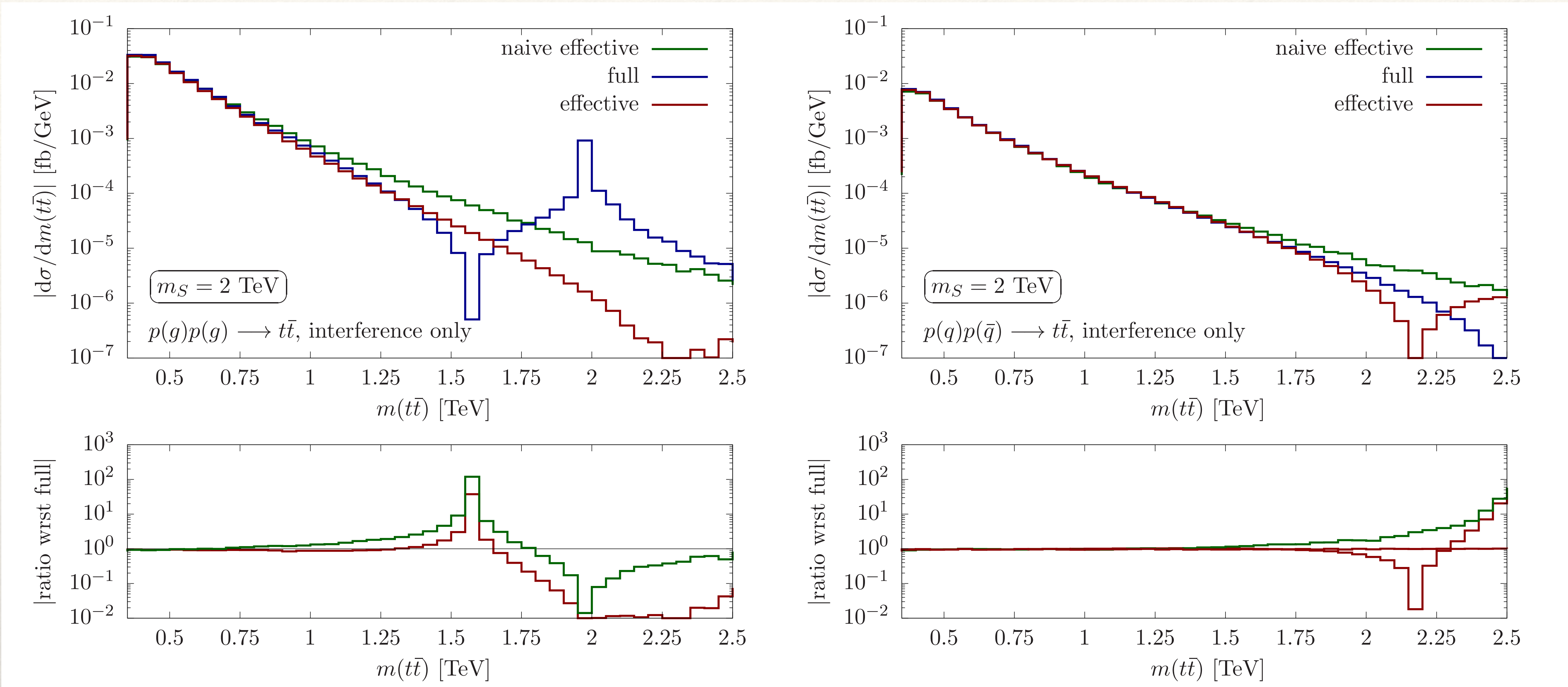

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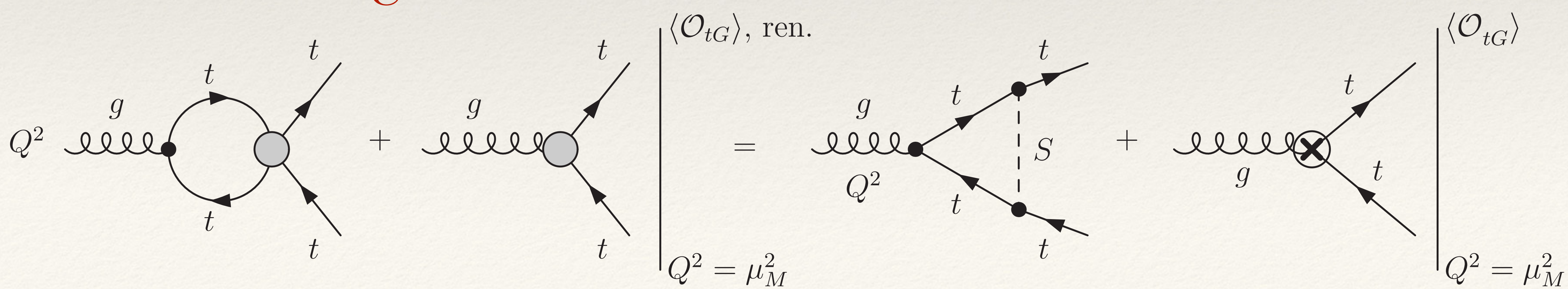
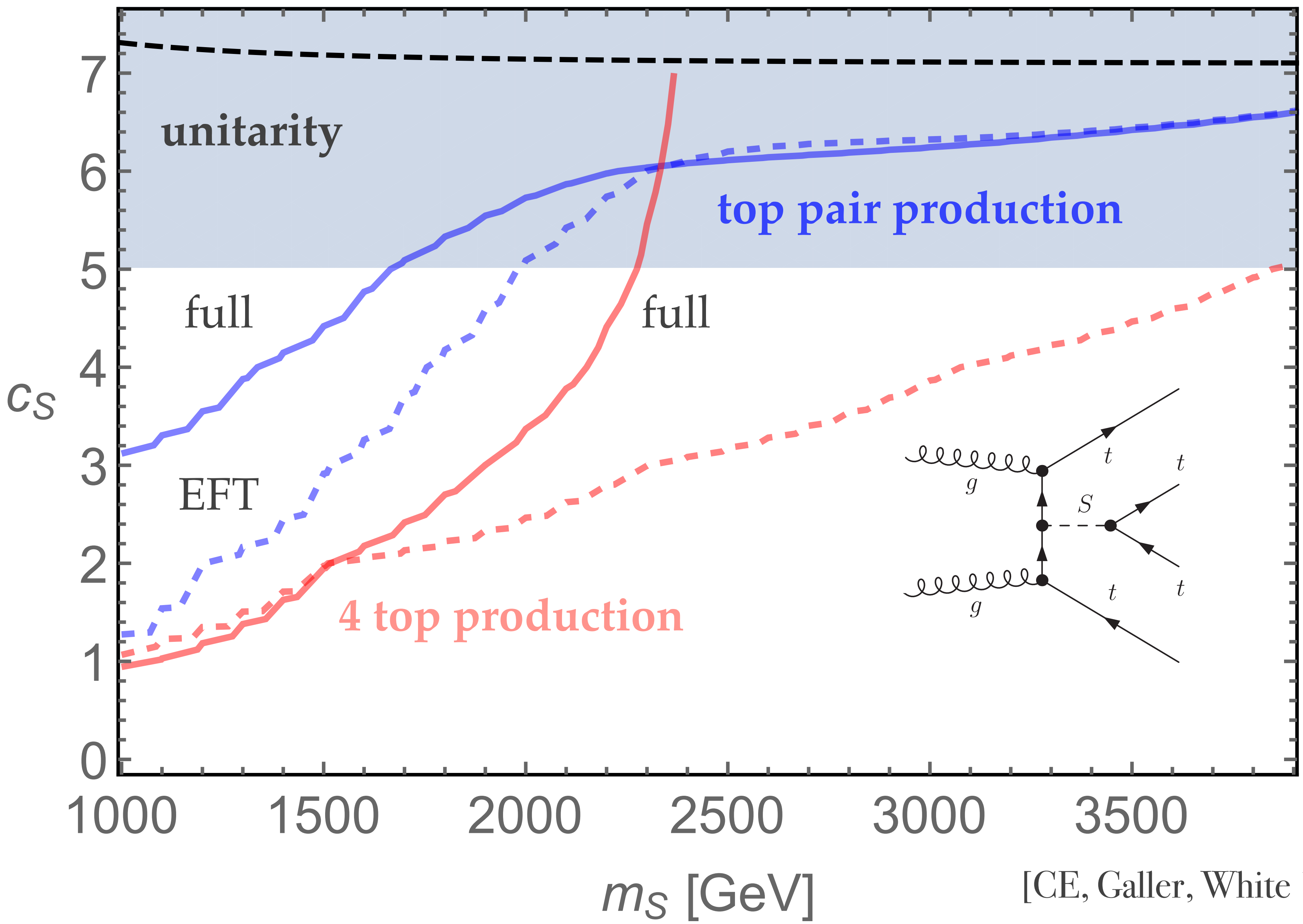


New physics in tops

- EFT is suitable tool to constrain such states model-independently, *however matching is crucial and so are expected uncertainties*



[CE, Galler, White ` 19]

Strong interactions? Compositeness….

- gauge boson masses through symmetry choices e.g. [Contino `10]
- fermion masses through mixing with baryonic matter (part. compositeness)
- minimal pheno model $SO(5) \rightarrow SO(4) \simeq SU(2)_L \times SU(2)_R$
- fermions (and hypercolour baryons) in a 5 of SO(5)

A concrete model of compositeness

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so far no UV completion known for this!

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so far no UV completion known for this!

- but

$$\underbrace{SU(4)}_{G_{\mathrm{HC}}} \times \underbrace{SU(5) \times SU(3) \times SU(3)' \times U(1)_X \times U(1)'}_{G_F}$$

[Ferretti ` 14]

could work with

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3) \times SU(3)'}{SU(3)} \times U(1)'$$

A concrete model of compositeness

- model predicts a number of exotics phenomenological implications

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3)\times SU(3)'}{SU(3)} \times U(1)'$$

[CE, Schichtel, Spannowsky `17]

Exotic Higgs bosons and SM Higgs coupling modifications

$\mathbf{1}_0 + \mathbf{2}_{\pm 1/2} + \mathbf{3}_0 + \mathbf{3}_{\pm 1}$

top partners and top coupling modifications

hyperpions

[Belyaev et al. `17]

[Ferretti `14]
[Matsedonskyi, Panico, Wulzer `15]
[Brown, CE, Galler, Stylianou `20]

$$J^\mu_{W^+}/e = c_{XT}\bar{X}\gamma^\mu T + c_{XY}\bar{X}\gamma^\mu Y + c_{XR}\bar{X}\gamma^\mu R + c_{TB}\bar{T}\gamma^\mu B + c_{YB}\bar{Y}\gamma^\mu B + c_{RB}\bar{R}\gamma^\mu B\,,$$

....

- Higgs coupling constraints
- compatibility with exotics searches
- cosmology
- here: focus on elw top properties

A concrete model of compositeness

- model predicts a number of exotics phenomenological implications

$$G_F/H_F = \frac{SU(5)}{SO(5)} \times \frac{SU(3)\times SU(3)'}{SU(3)} \times U(1)'$$

partial compositeness (MCHM5 “lookalike”) [Agashe, Contino, Pomarol `04] [Contino, da Rold, Pomarol `06]

$$-\mathcal{L} \supset M\bar{\Psi}\Psi + \lambda_q f \bar{\hat{Q}}_L \Sigma \Psi_R + \lambda_t f \bar{\hat{t}}_R \Sigma^* \Psi_L$$

[Ferretti `14]

$$+ \sqrt{2}\mu_b \mathrm{Tr}(\bar{\hat{Q}}_L U \hat{b}_R) + \text{h.c.}$$

gauge interactions

$$\mathcal{L} \supset \bar{\Psi}\gamma^\mu \left(\frac{2}{3} e A_\mu - \frac{2}{3} t_w e Z_\mu + v_\mu + K p_\mu \right) \Psi$$

$$\Psi = \frac{1}{\sqrt{2}} \begin{pmatrix} iB - iX \\ B + X \\ iT + iY \\ -T + Y \\ \sqrt{2} i R \end{pmatrix} \qquad \hat{Q}_L = \begin{pmatrix} i b_L \\ b_L \\ i t_L \\ -t_L \\ 0 \end{pmatrix}, \quad \hat{t}_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ t_R \end{pmatrix}, \quad \hat{b}_R = \begin{pmatrix} 0 \\ 0 \\ 0 \\ 0 \\ b_R \end{pmatrix}$$

top partners and top coupling modifications

$$(T, B) \in (\mathbf{3}, \mathbf{2})_{1/6}, \; R \in (\mathbf{3}, \mathbf{1})_{2/3}, \; (X, Y) \in (\mathbf{3}, \mathbf{2})_{7/6}.$$

[Brown, CE, Galler, Stylianou ` 20]

indirect top sector constraints

- include range of data (for extrapolation)

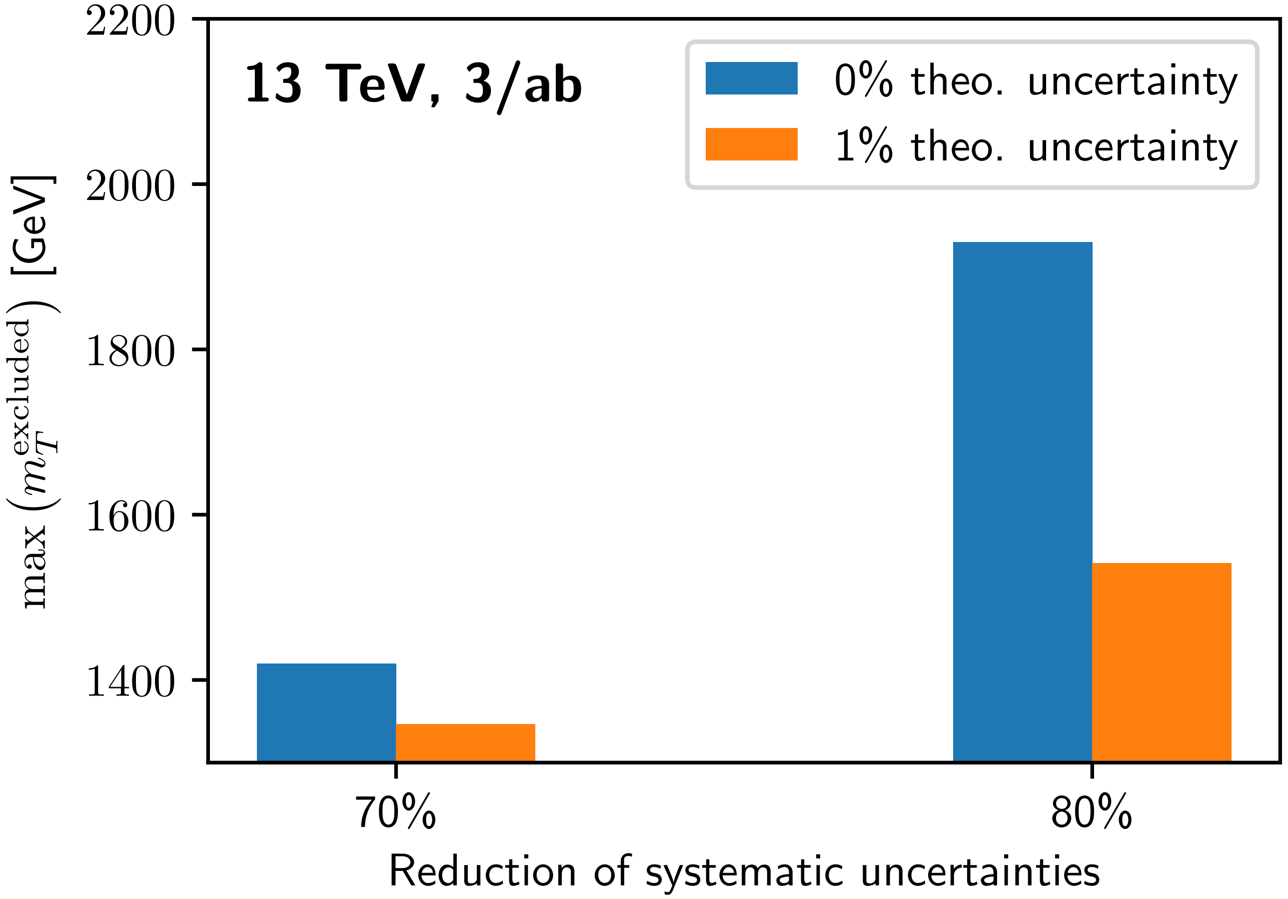
Analysis	Collaboration	$\sqrt{s}$ [TeV]	Observables	dof
single top t-channel				
1503.05027 [45]	CDF, D0	1.96	$\sigma_{\rm tot}$	1
1406.7844 [46]	ATLAS	7	$\frac{\sigma_t}{\sigma_{\bar t}}$, $\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^t}$, $\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{\bar t}}$, $\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_t\rvert}$, $\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_{\bar t}\rvert}$	1 8 6
1902.07158 [47]	ATLAS,CMS	7,8	$\sigma_{\rm tot}$	2
1609.03920 [48]	ATLAS	13	σ_t, $\frac{\sigma_t}{\sigma_{\bar t}}$	2
1812.10514 [49]	CMS	13	$\frac{\sigma_t}{\sigma_{\bar t}}$, σ_t	2
single top s-channel				
1402.5126 [50]	CDF, D0	1.96	$\sigma_{\rm tot}$	1
1902.07158 [47]	ATLAS, CMS	7, 8	$\sigma_{\rm tot}$	2
tW				
1902.07158 [47]	ATLAS, CMS	7, 8	$\sigma_{\rm tot}$	2
1612.07231 [51]	ATLAS	13	$\sigma_{\rm tot}$	1
1805.07399 [52]	CMS	13	$\sigma_{\rm tot}$	1
tjZ				
1710.03659 [53]	ATLAS	13	$\sigma_{\rm tot}$	1
1812.05900 [54]	CMS	13	$\sigma_{\rm tot}$	1

Analysis	Collaboration	$\sqrt{s}$ [TeV]	Observables	dof
$t\bar tZ$				
1509.05276 [55]	ATLAS	8	$\sigma_{\rm tot}$	1
1510.01131 [56]	CMS	8	$\sigma_{\rm tot}$	1
1901.03584 [57]	ATLAS	13	$\sigma_{\rm tot}$	1
1907.11270 [58]	CMS	13	$\sigma_{\rm tot}$, $\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^Z}$, $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_Z^*}$	4 3
W boson helicity fractions				
1211.4523 [59]	CDF	1.96	F_0, F_R	2
1205.2484 [60]	ATLAS	7	F_0, F_L, F_R	3
1308.3879 [61]	CMS	7	F_0, F_L, F_R	3
1612.02577 [62]	ATLAS	8	F_0, F_L	2
top quark decay width				
1201.4156 [63]	D0	1.96	Γ_t	1
1308.4050 [64]	CDF	1.96	Γ_t	1
1709.04207 [65]	ATLAS	8	Γ_t	1

see also
[TopFitter ` 15 ` 16]
[SMEFiT` 19]
[SFitter ` 19]
[Durieux et al. ` 19]

+ checks that resonance contributions are negligible away from resonance

indirect top sector constraints



$$\begin{aligned}\mathcal{L} \supset\ & \bar{t}\gamma^\mu \left[g_L^t P_L + g_R^t P_R\right] t Z_\mu \\ &+ \bar{b}\gamma^\mu \left[g_L^b P_L + g_R^b P_R\right] b Z_\mu \\ &+ \left(\bar{b}\gamma^\mu \left[V_L P_L + V_R P_R\right] t W_\mu^+ + \text{h.c.}\right)\end{aligned}$$

$$V_L = -\frac{g}{\sqrt{2}}\left[1+\delta_{W,L}\right] \quad \text{etc.}$$

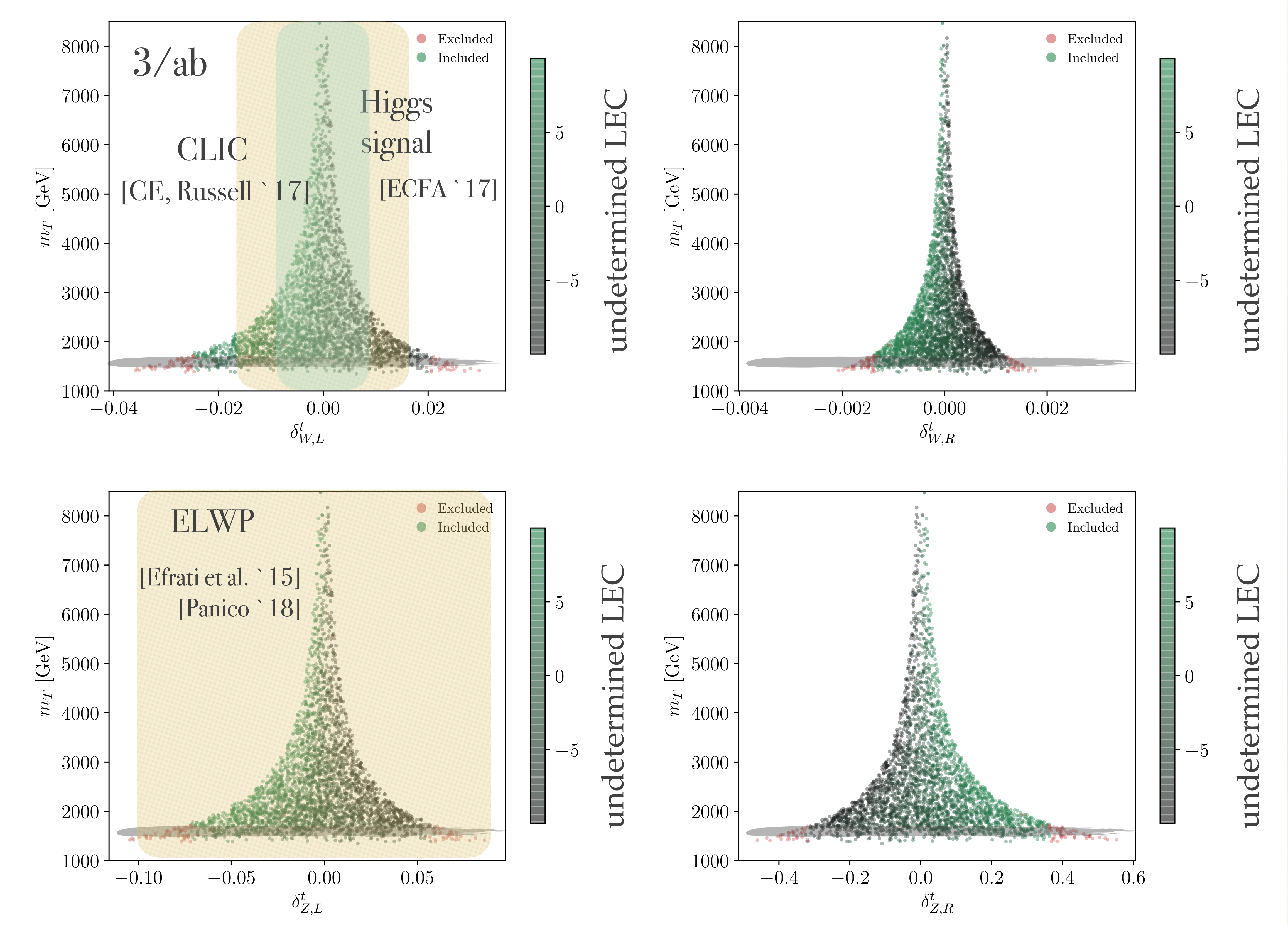
$$\delta_{W,L} \in [-0.029, 0.019]\,, \qquad \delta_{W,R} \in [-0.009, 0.009]\,,$$
$$\delta^t_{Z,L} \in [-0.639, 0.277]\,, \qquad \delta^t_{Z,R} \in [-1.566, 1.350]\,.$$

↓ model correlations

$$\delta_{W,L} \in [-0.025, 0.02]\,, \qquad \delta_{W,R} \in [-0.0014, 0.0013]\,,$$
$$\delta^t_{Z,L} \in [-0.073, 0.06]\,, \qquad \delta^t_{Z,R} \in [-0.33, 0.37]$$

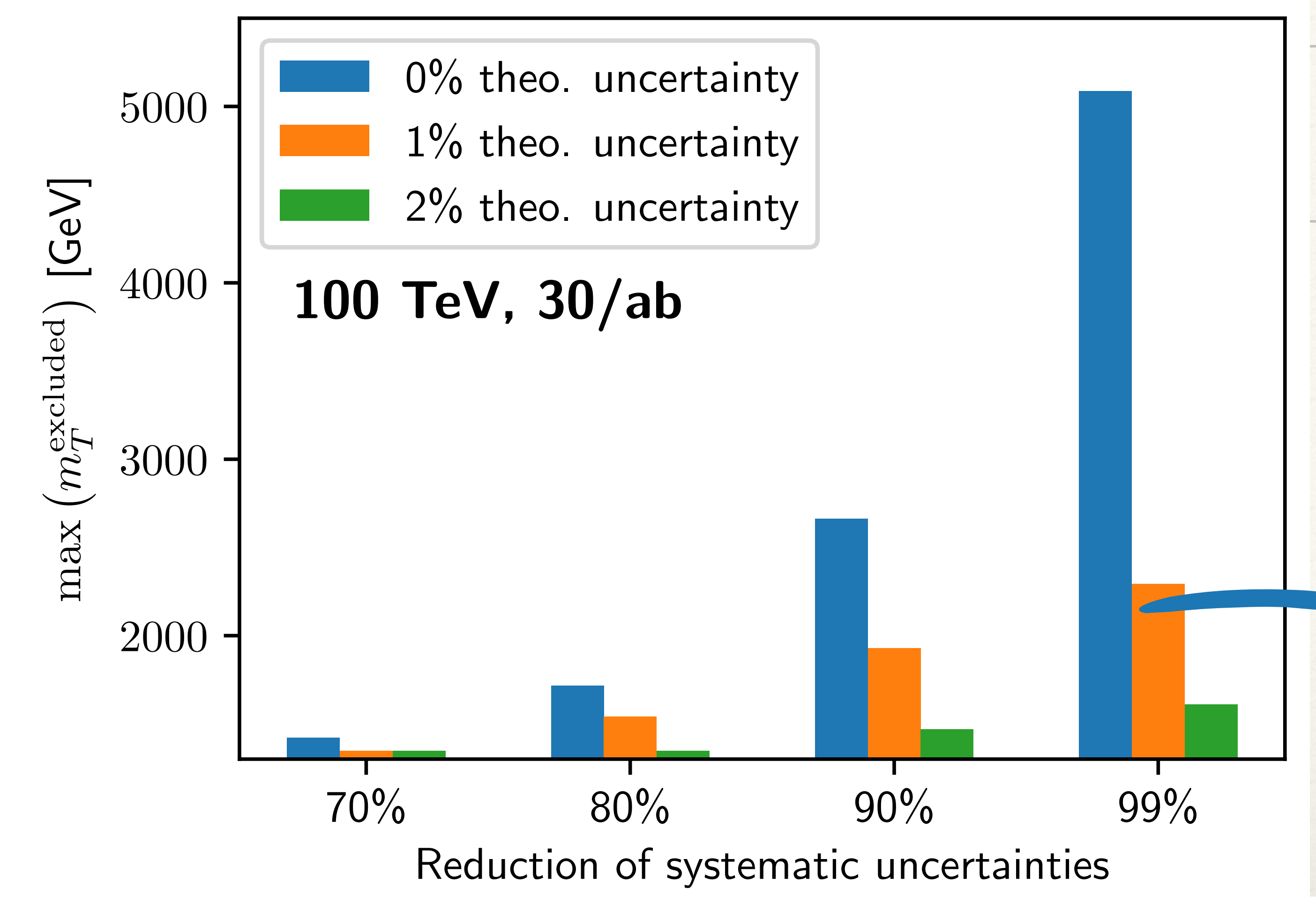
- existing direct top partner constraints in the range of $\gtrsim 1.5$ TeV compatible [Matsedonskyi, Panico, Wulzer ` 15]
- theoretical uncertainties is main sensitivity limitation, adding additional channels does not change this picture dramatically

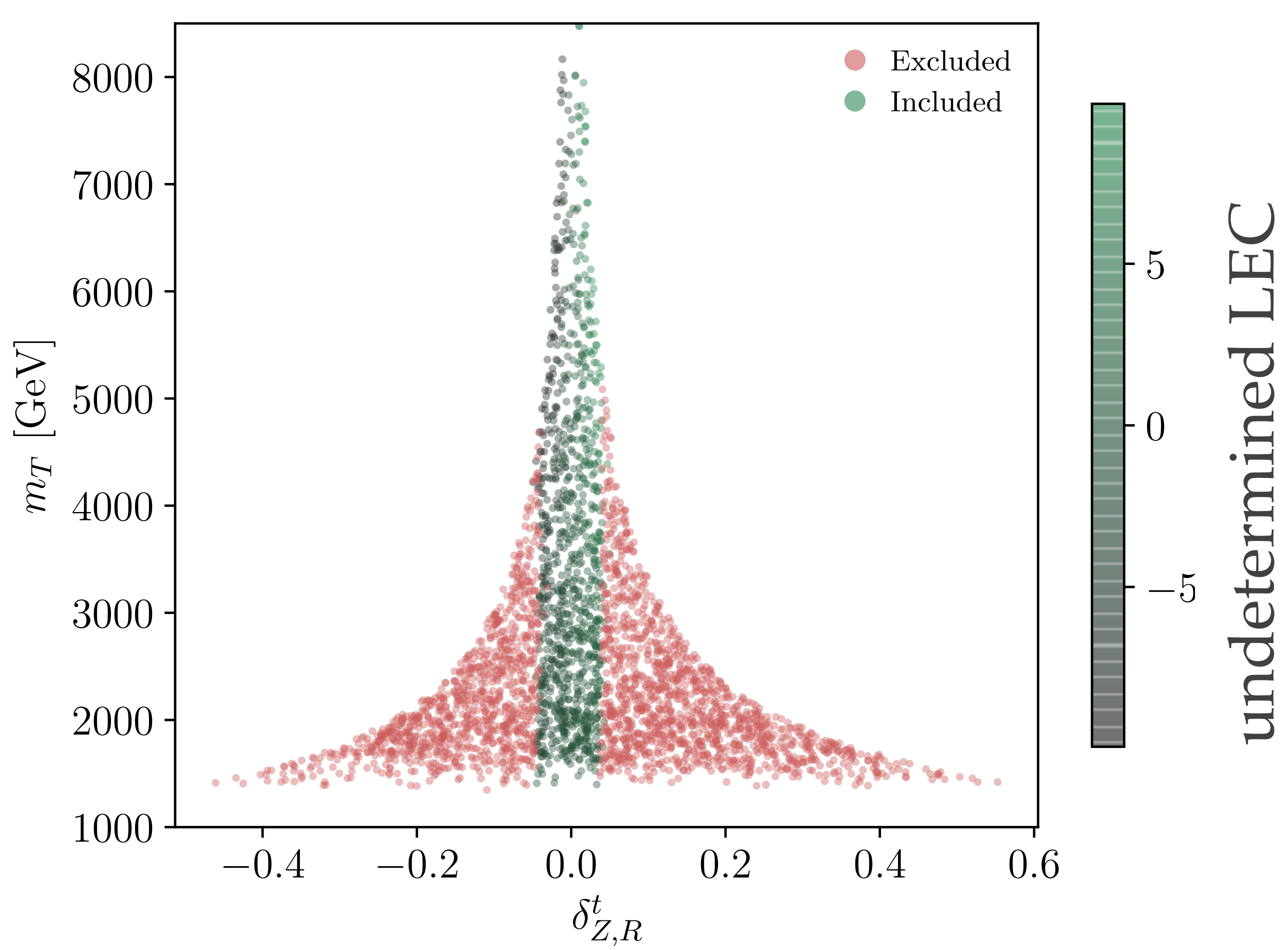
indirect top sector constraints

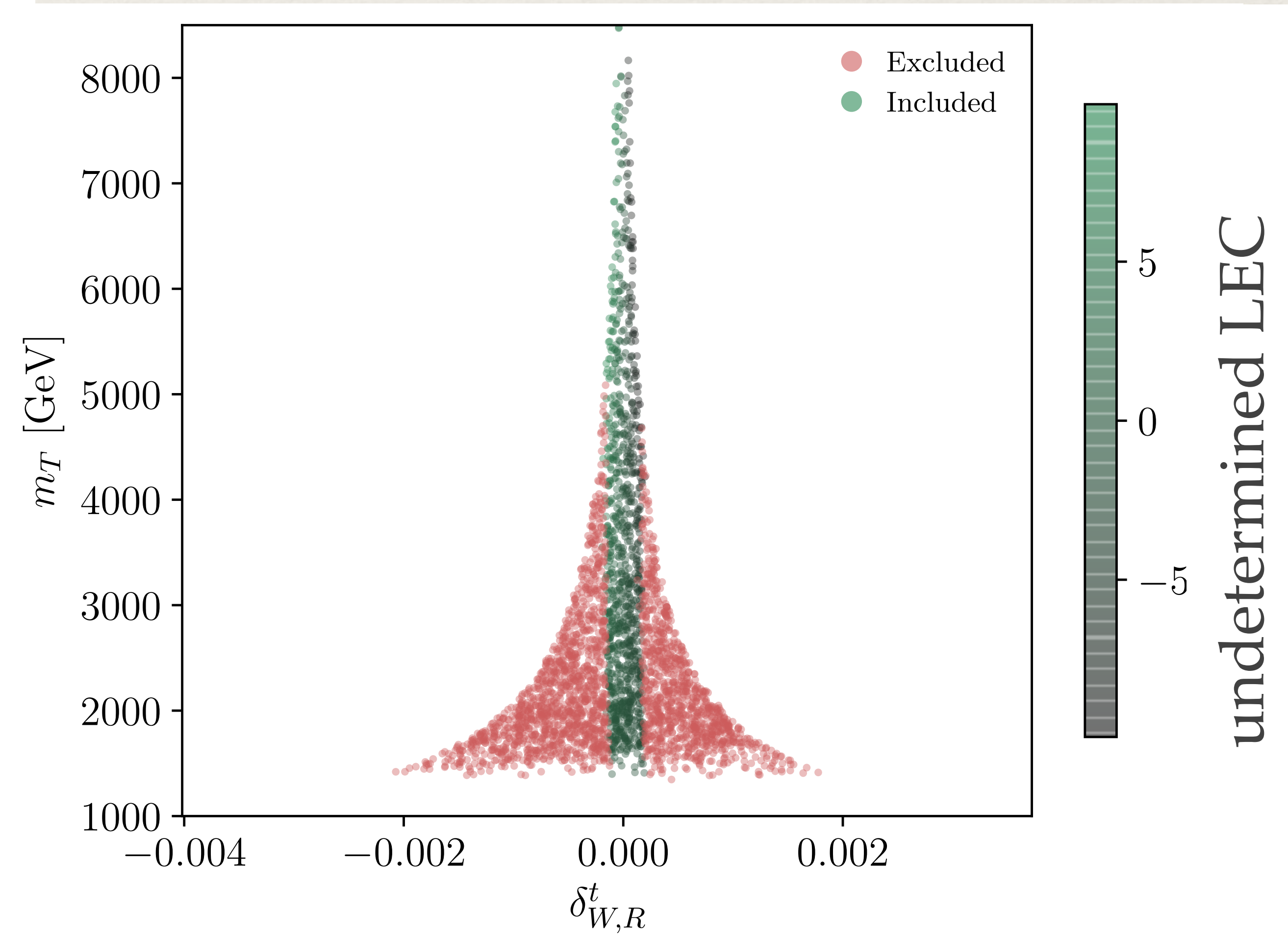


indirect top sector constraints

- optimistic extrapolations provide indirect sensitivity up to about 5 TeV

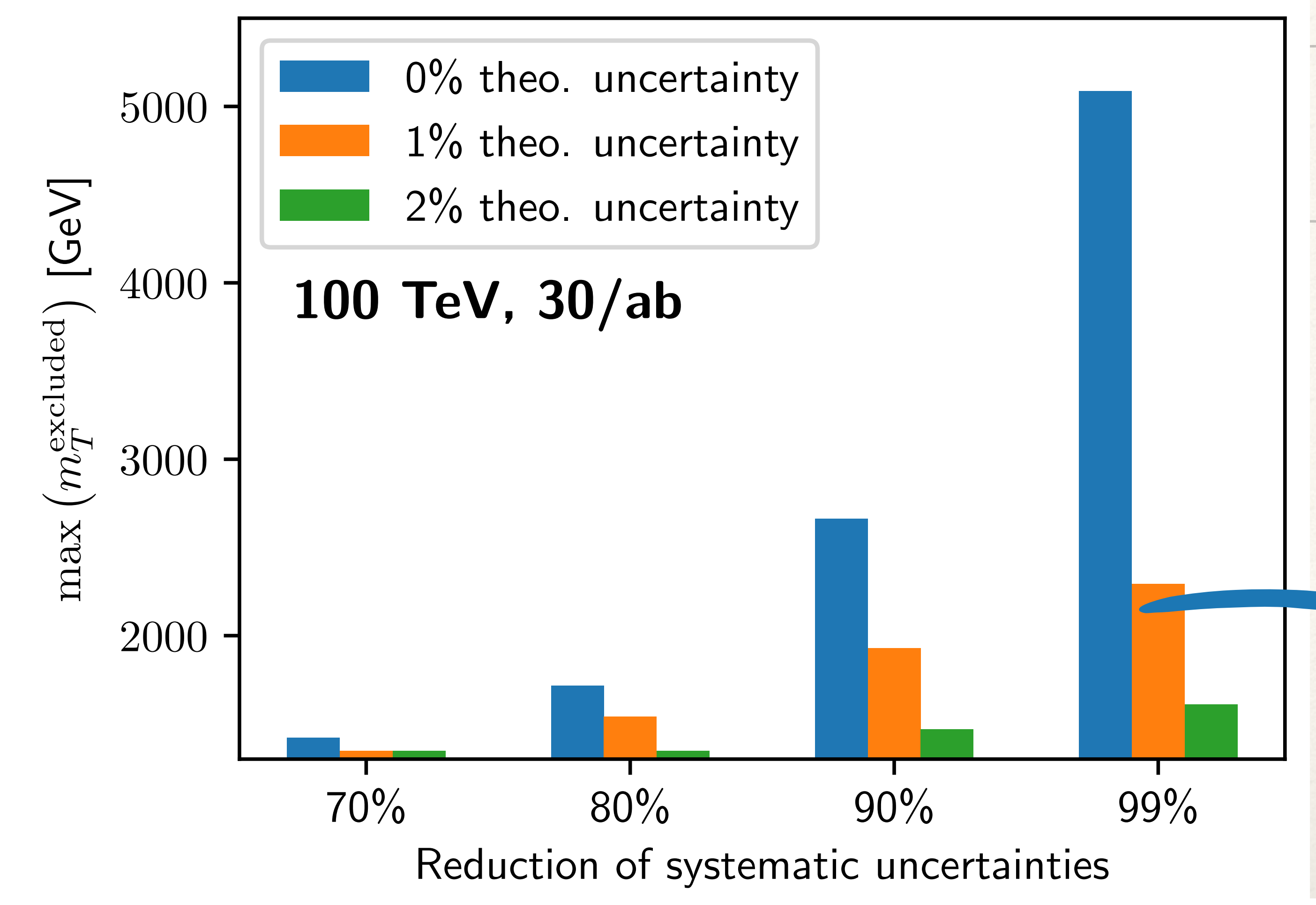


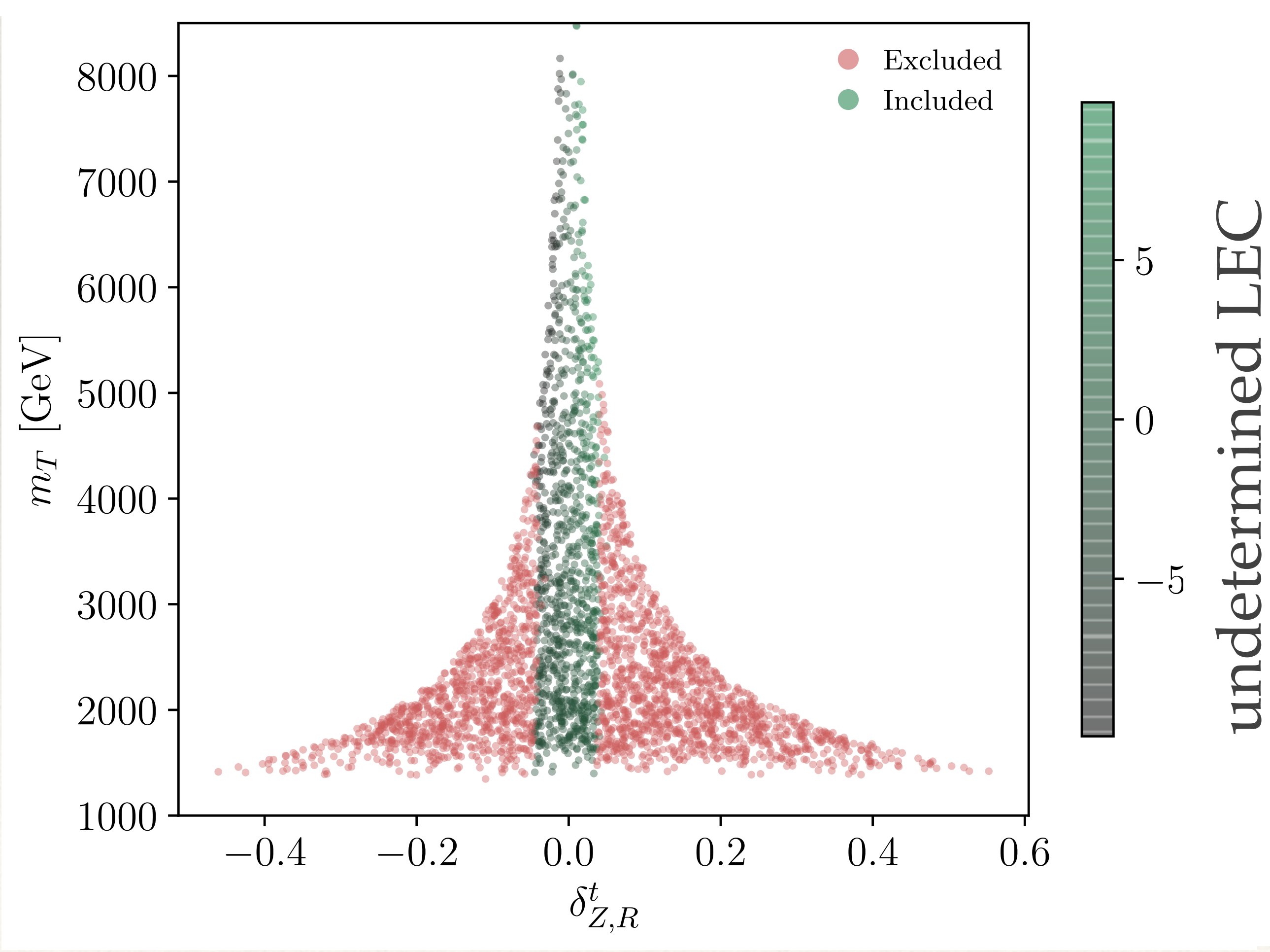


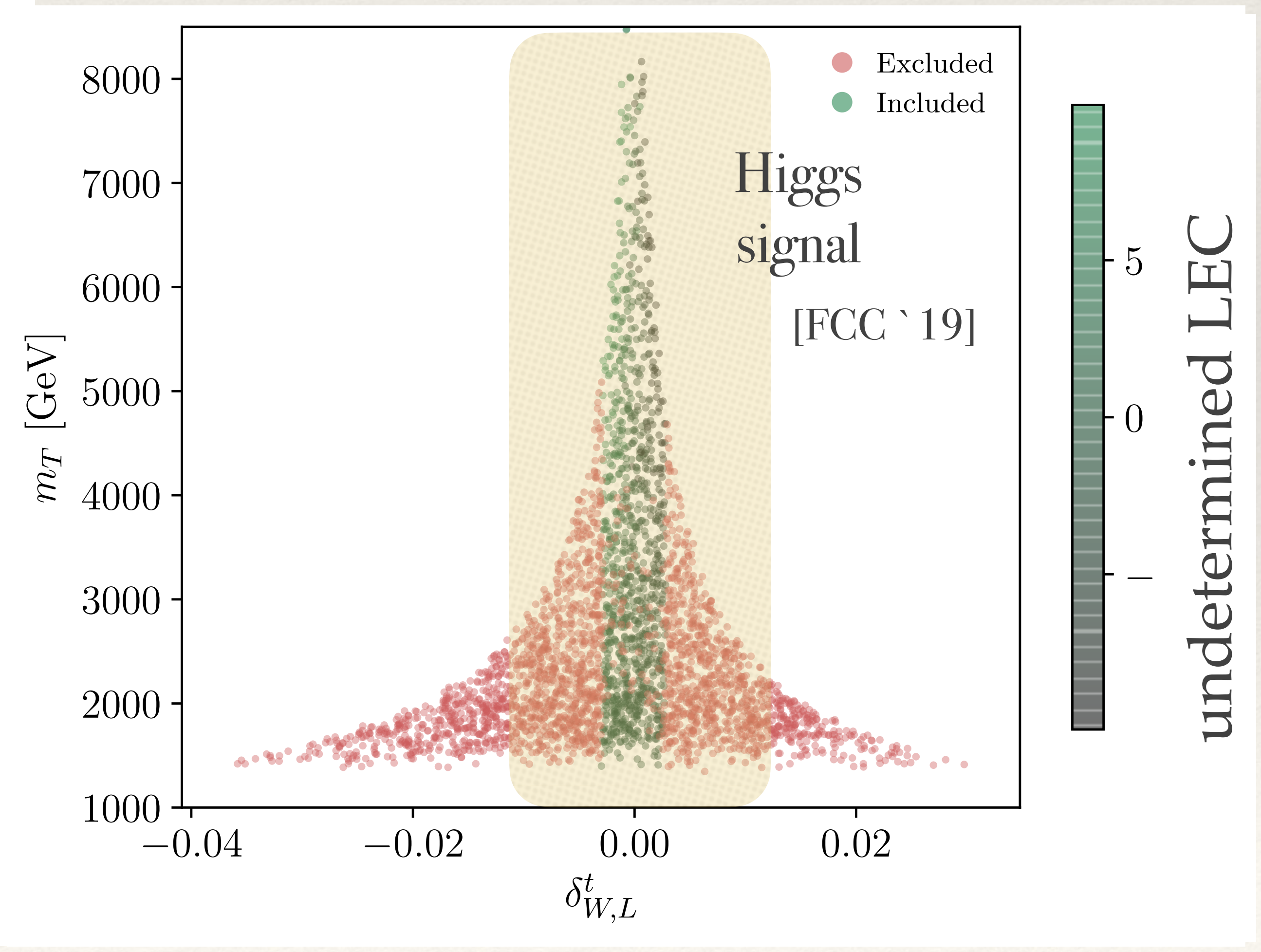


indirect top sector constraints

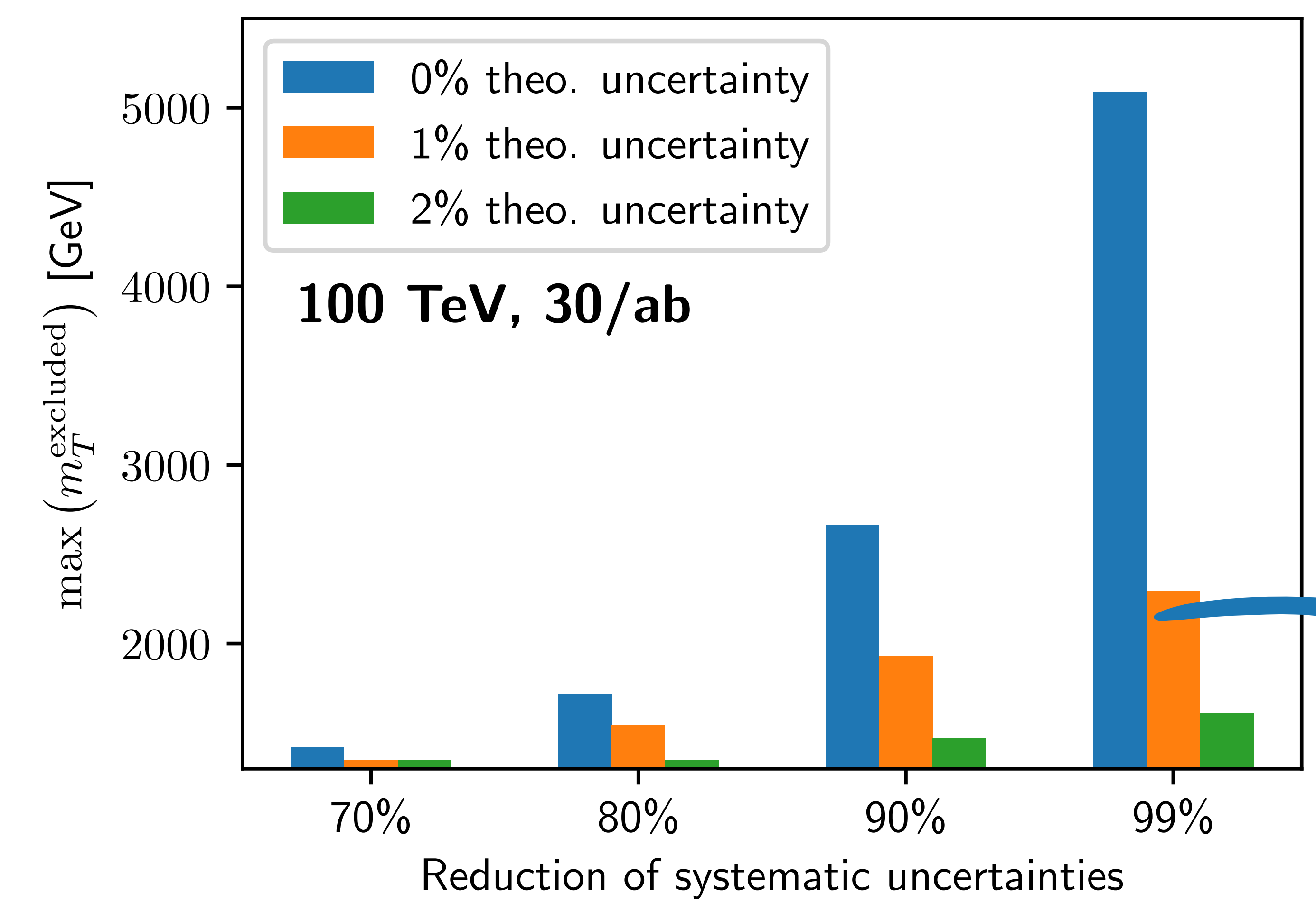
- optimistic extrapolations provide <u>indirect</u> sensitivity up to about 5 TeV



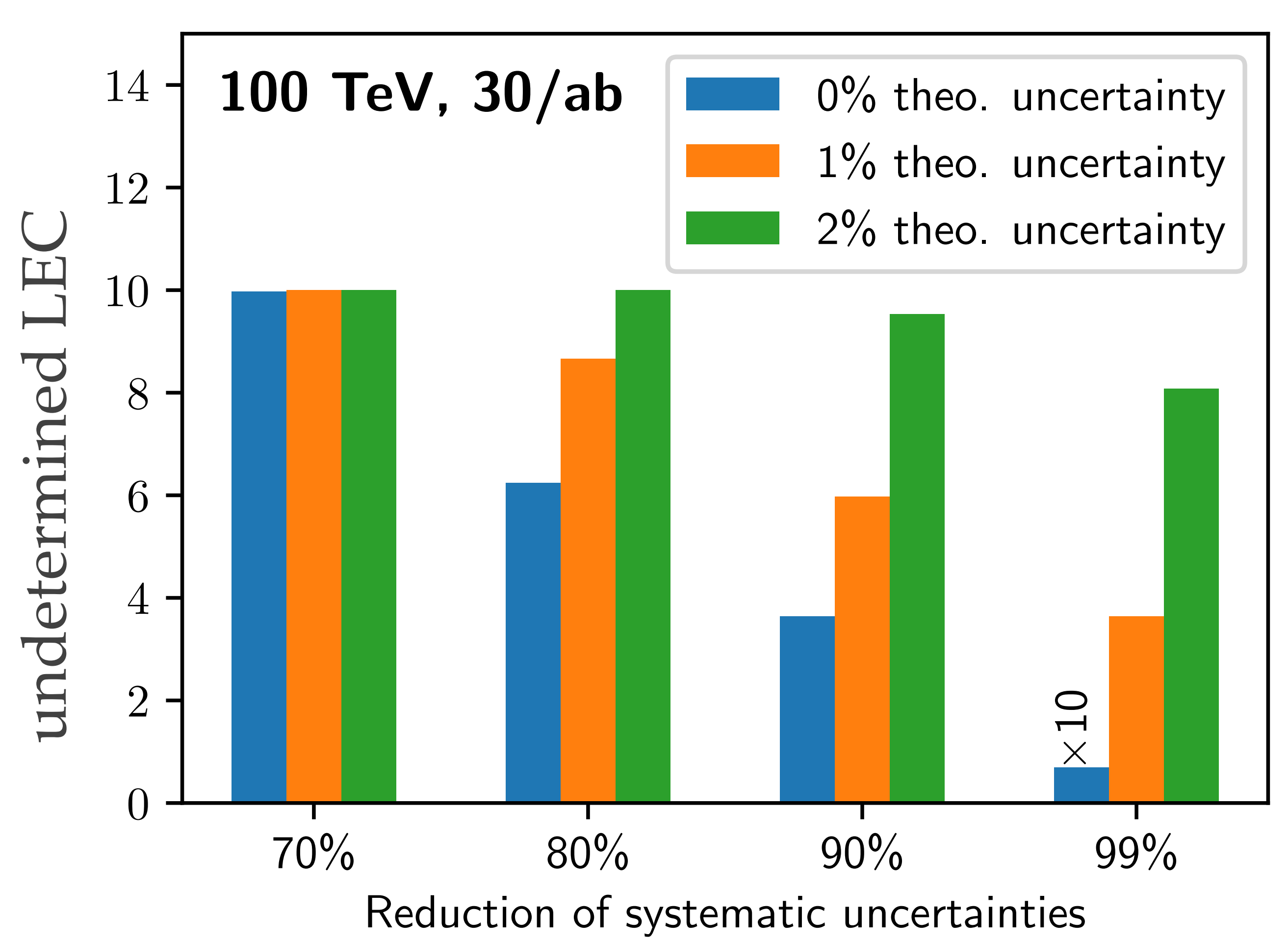




indirect top sector constraints

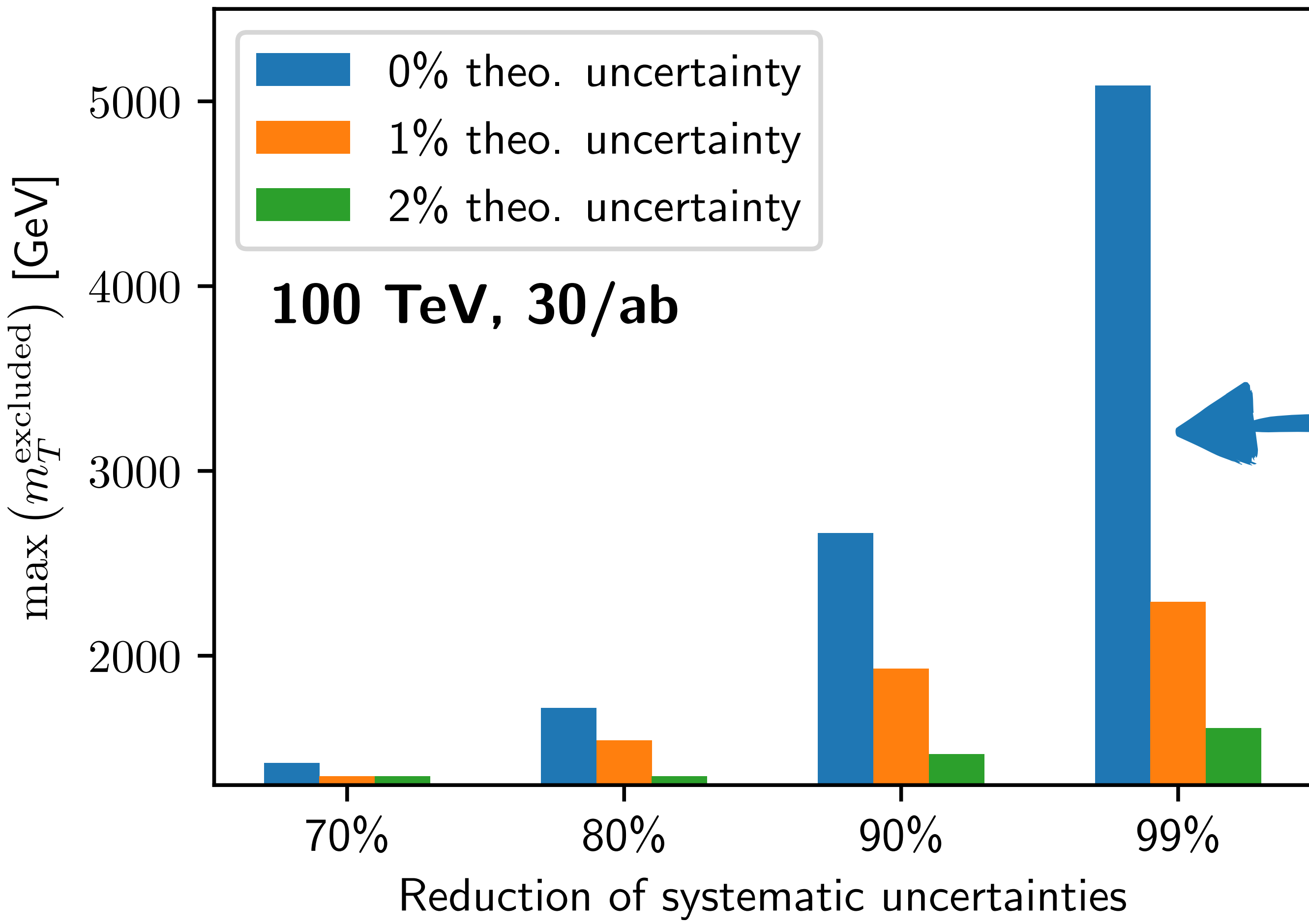


- optimistic extrapolations provide indirect sensitivity up to about 5 TeV



- can understand constraint as LEC-related constraint
  - complementarity to derivatively-coupled PNGBs
  - LEC ~ 1 attainable, motivates T+Z searches

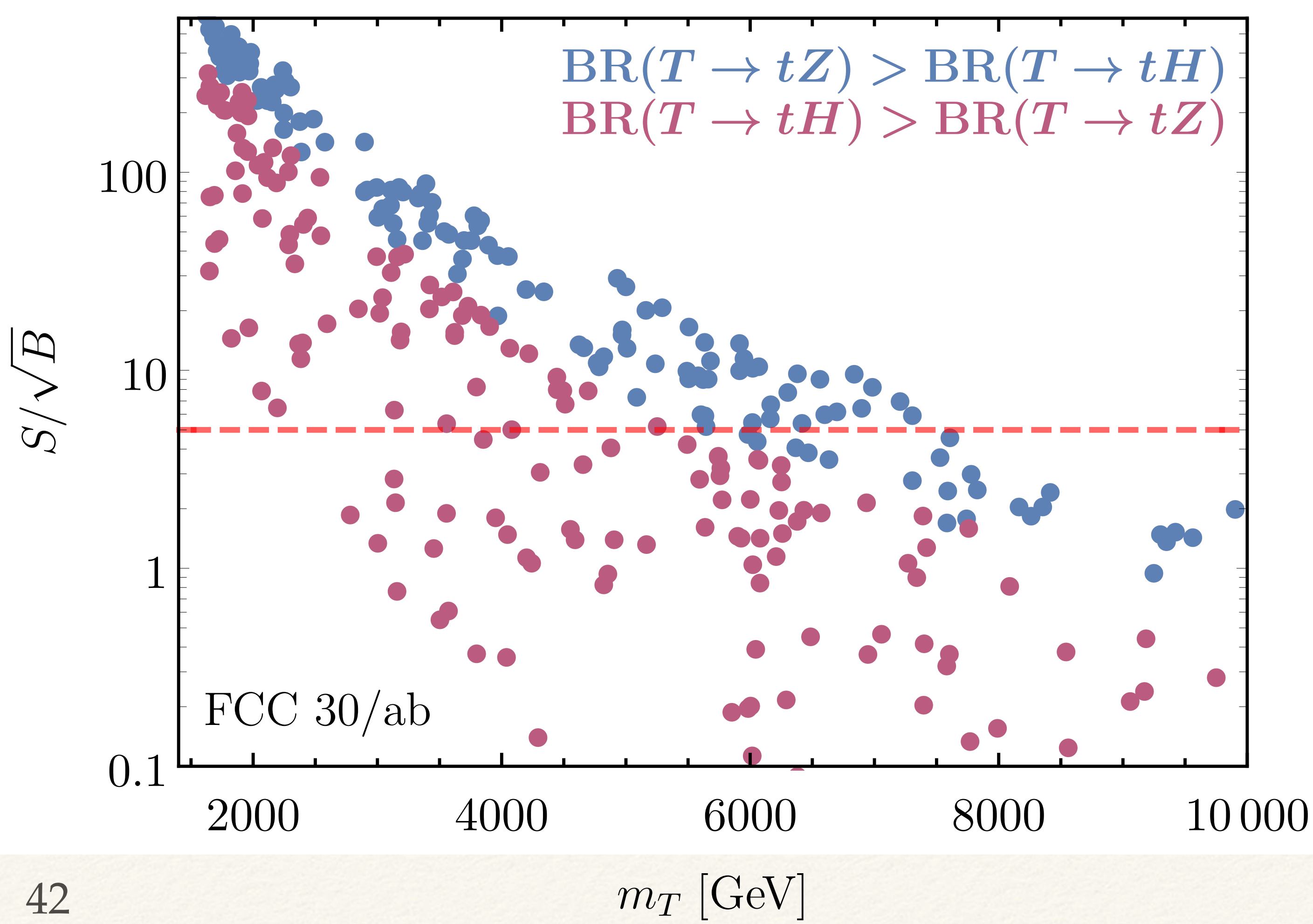
indirect top sector constraints



- optimistic extrapolations provide indirect sensitivity up to about 5 TeV

- direct top partner searches in electroweak channels providing direct sensitivity up to 8 TeV

[de Simone et al. `14]
[Azatov et al. `14]
[Matsedonskyi et al. `14]
[Golling et al. `16]
[Barducci et al. `17]
[Li et al. 19]



- *EFT @ colliders progress has been rapid*
  - matching, validity re:momentum coverage at hadron machines
  - simulation in realistic setups
  - ...but still ways to improve: limit setting - machine learning
  - uncertainties/deviations crucial for continued EFT efforts to be fruitful; adopt UV inspired-restrictions as way out?
- *Opportunity to link the Higgs/top sector to new physics*
  - cure SM shortcomings (CP violation, hierarchy, DM, ...)
  - (multi-)Higgs/(multi-)top production as an avenue for BSM
  - LHC not enough to achieve this in full glory