University of Glasgow

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Effective Field Theory for Higgs and Top Physics

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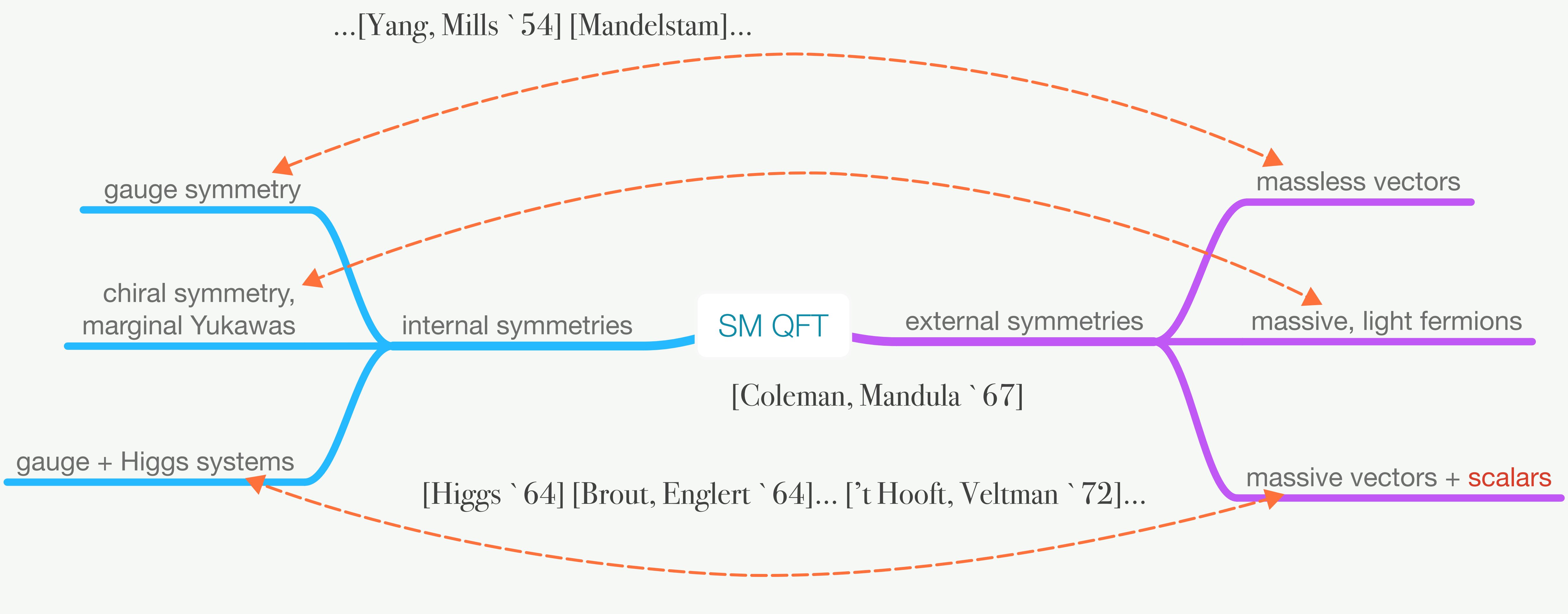
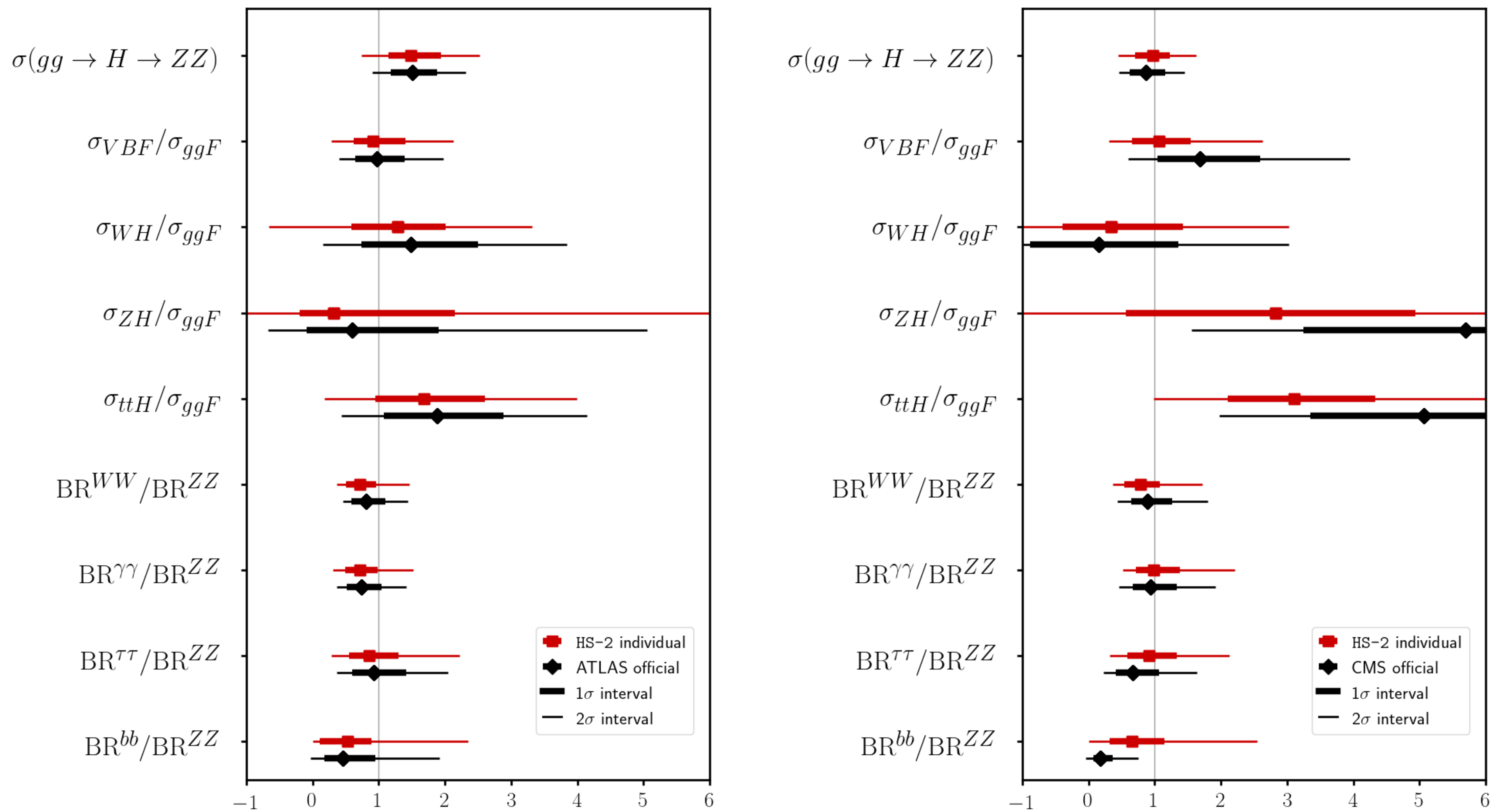
30/09/21

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

Effective Field Theory

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

[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)

concrete models

- extended SMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- simplified models
- compositeness….

Are EFTs collider tools to improve on the expected and perhaps even observe the unexpected?

- *CP violating Higgs interactions ?*
- *improving our understanding Higgs propagation ?*
- *BSM interplay of top/Higgs sectors ?*

CP violation

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

matching

MC perturbativity

unitarity…

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

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

dim 8

CP violation

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

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matching

MC perturbativity

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

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

+

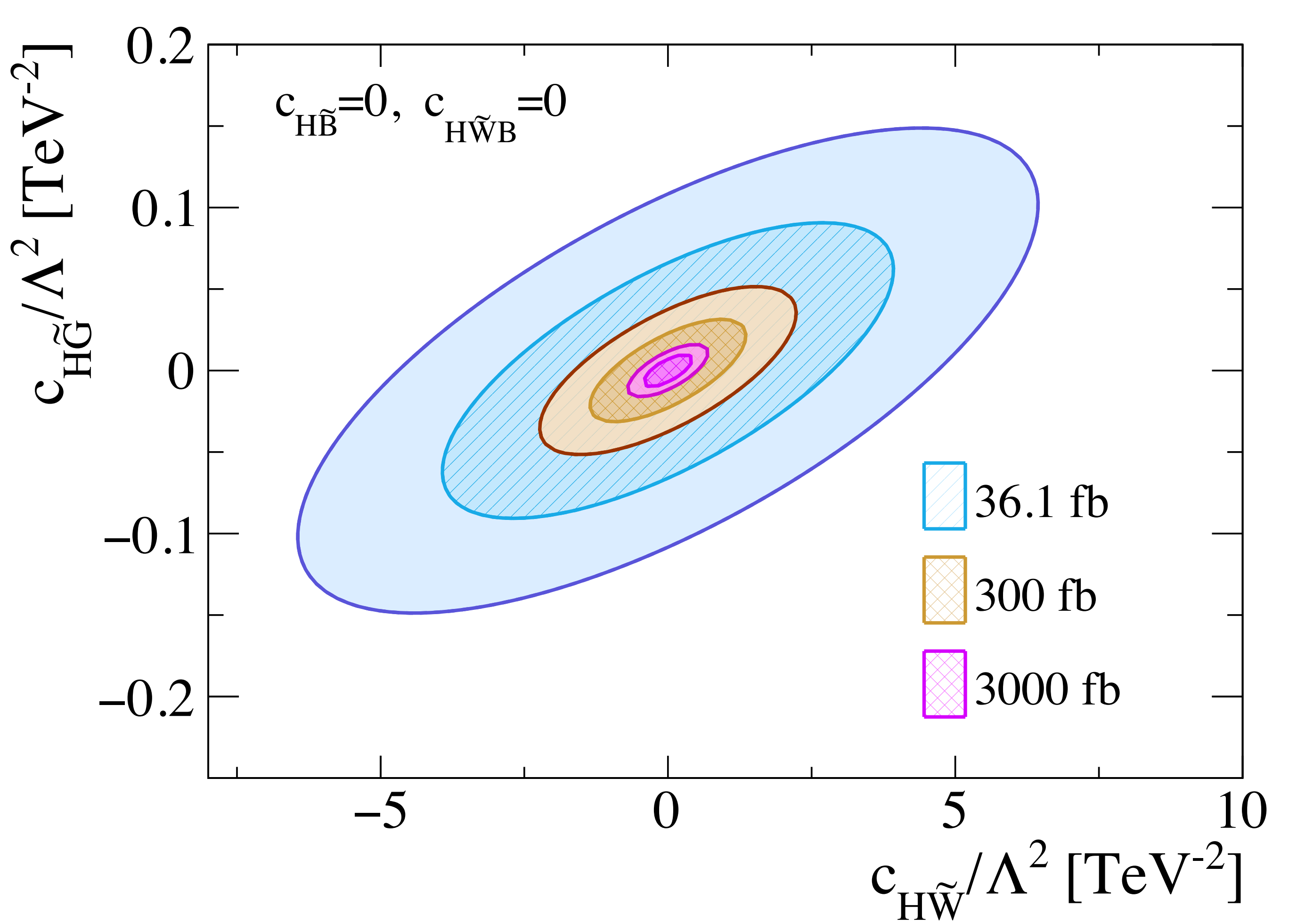
top quark

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

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

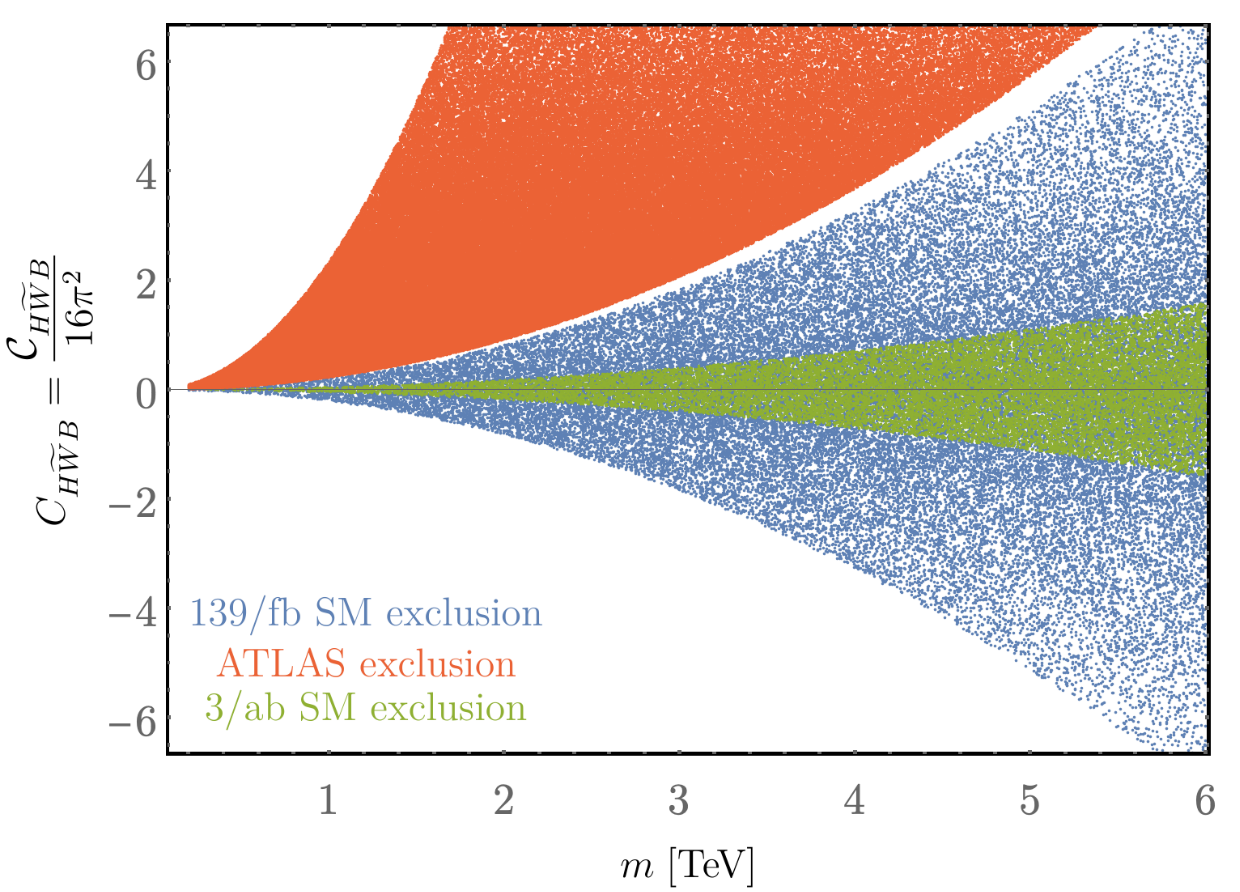
CP violation

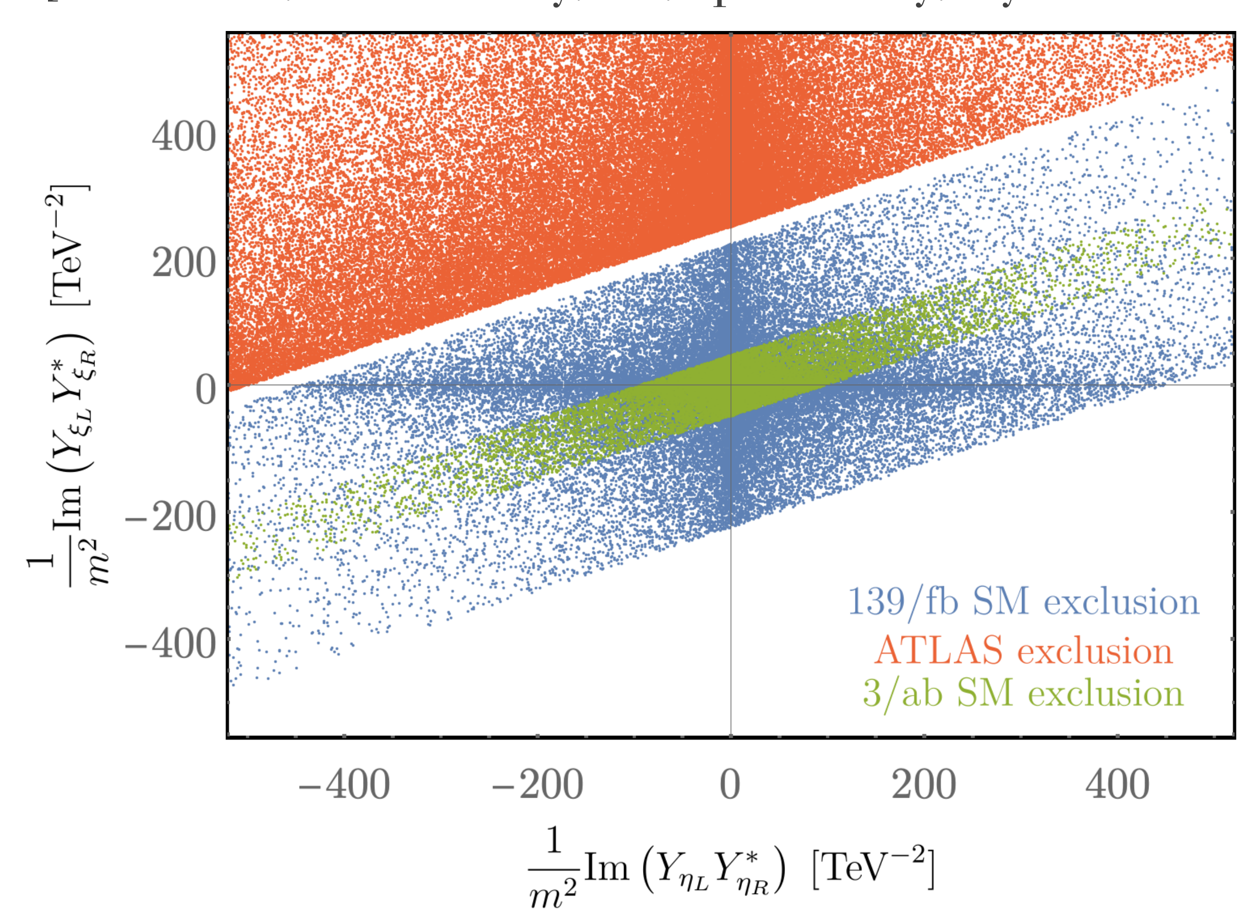
[ATLAS, 2006.15458]

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]
    - 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

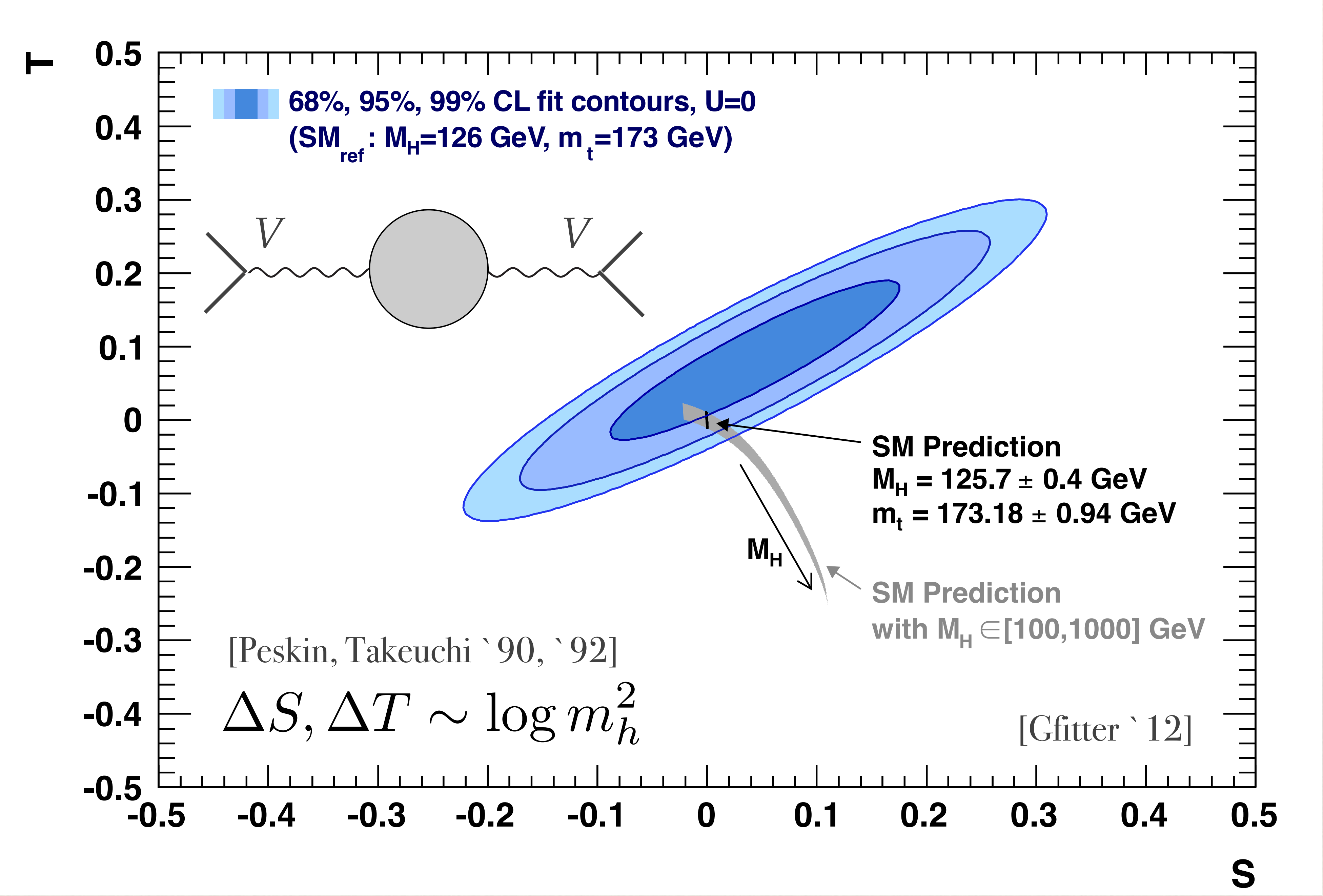
Overview

Are EFTs collider tools to improve on the expected and perhaps even observe the unexpected?

- *CP violating Higgs interactions ?*
- *improving our understanding Higgs propagation ?*
- *BSM interplay of top/Higgs sectors ?*

Higgs propagation

[CE, Giudice, Greljo, McCullough ` 19]



- specific dim 6 operators much better constrained 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

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

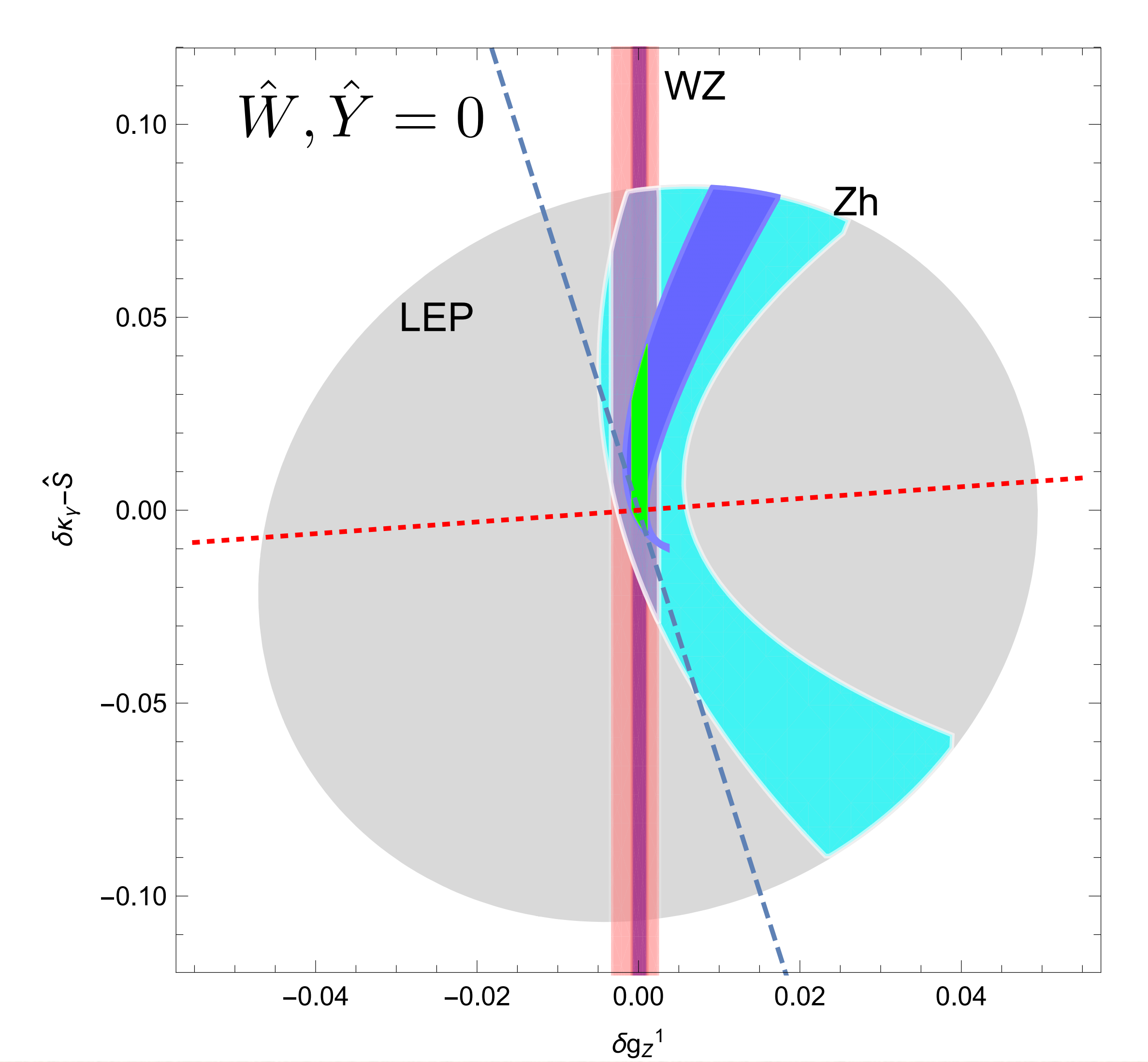
$\Box \equiv D^\mu D_\mu$

[Barbieri et al. ` 04]

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

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

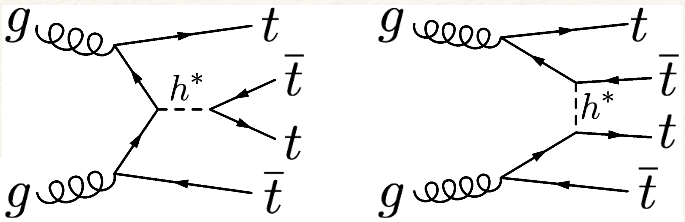
[Farina et al. ` 17]
[Franceschini et al. ` 18]
[Banerjee, Gupta, CE, Spannowsky ` 18]
…

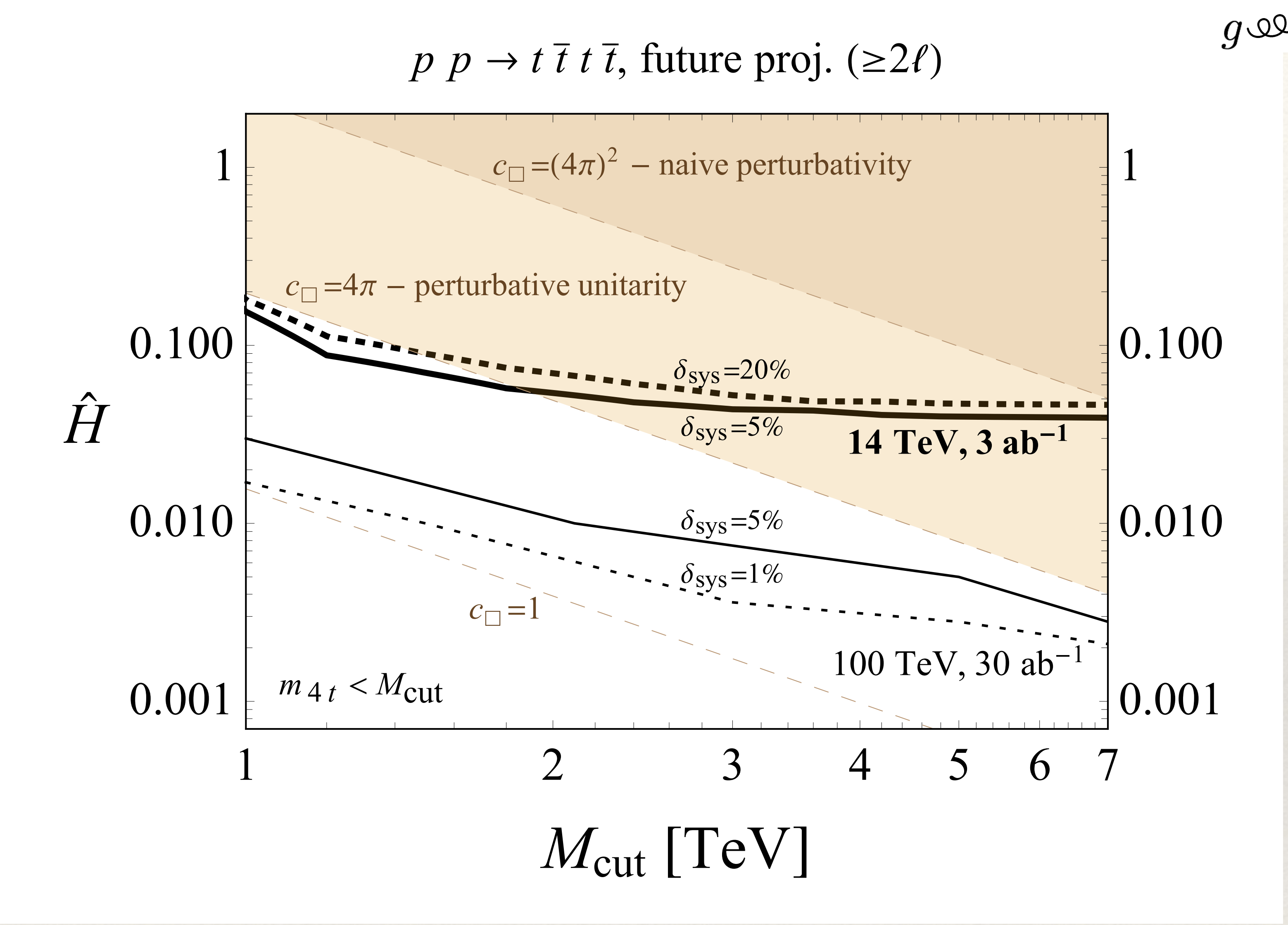


Higgs propagation

[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

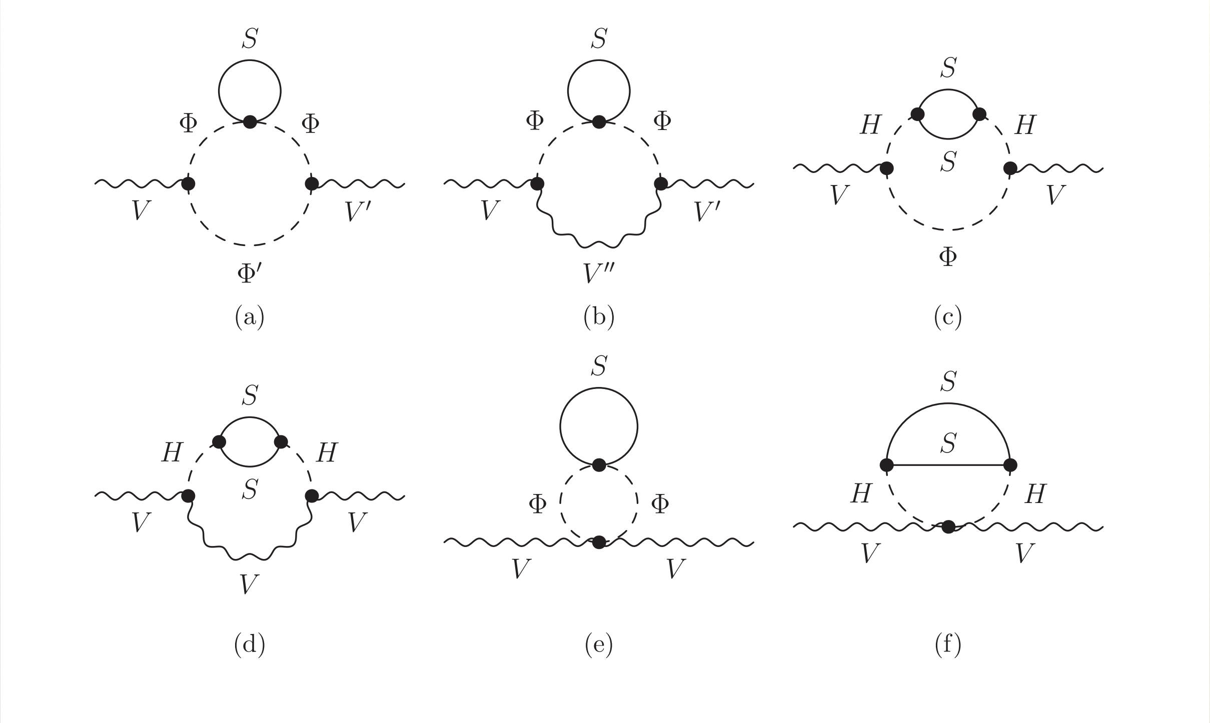
$$\text{FCC-ee} \quad |\hat{H}| \lesssim 0.5\%$$

[FCC Collaboration ` 19]

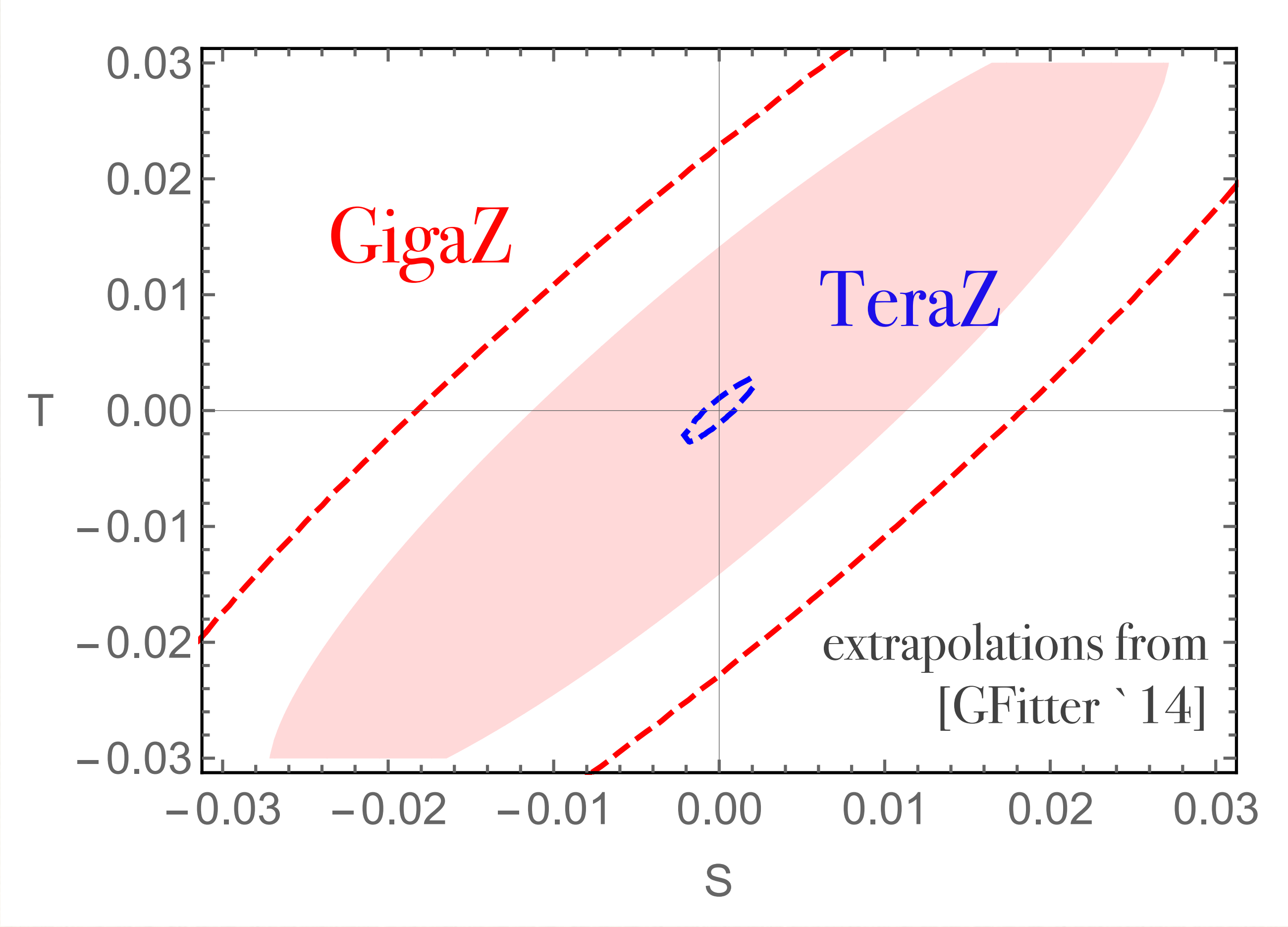
Higgs propagation

...in loops...

- 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

singlets above threshold

- $\mathbb{Z}_2$-symmetric Higgs portal

[Craig , Lou. et al.` 14]
[Curtin, Meade, Yu ` 14]
…

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}(\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 (\Phi^\dagger \Phi - v^2/2)$$

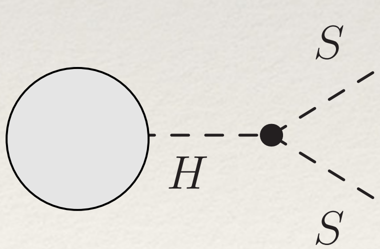
- for $m_S > m_H/2$ no direct SM Higgs decays
- BSM Higgs physics via momentum- or loop-suppressed effects

off-shell production

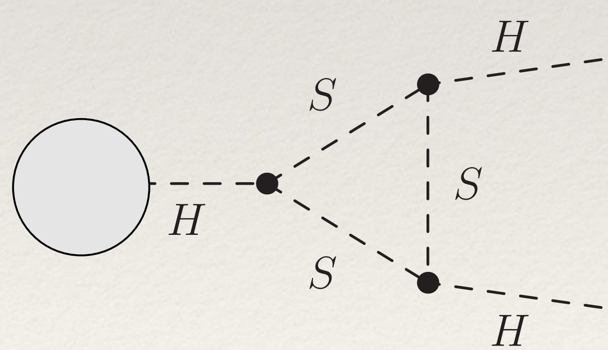
di-Higgs physics

Higgs couplings

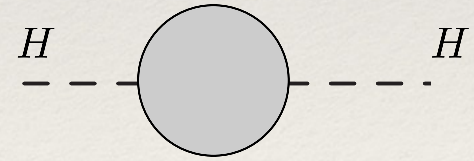
Electroweak precision



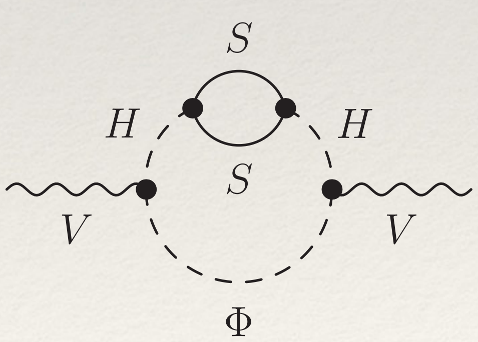
[Craig , Lou. et al.` 14]
[Ruhdorfer, Salvioni, Weiler ` 19]



[Curtin, Meade, Yu ` 14]
[He, Zhu ` 16]
[Voigt, Westhoff ` 17]



[CE, McCullough ` 13]
[Craig, CE, McCullough ` 13]
[Goncalves, Han, Mukhopadhyay ` 18]

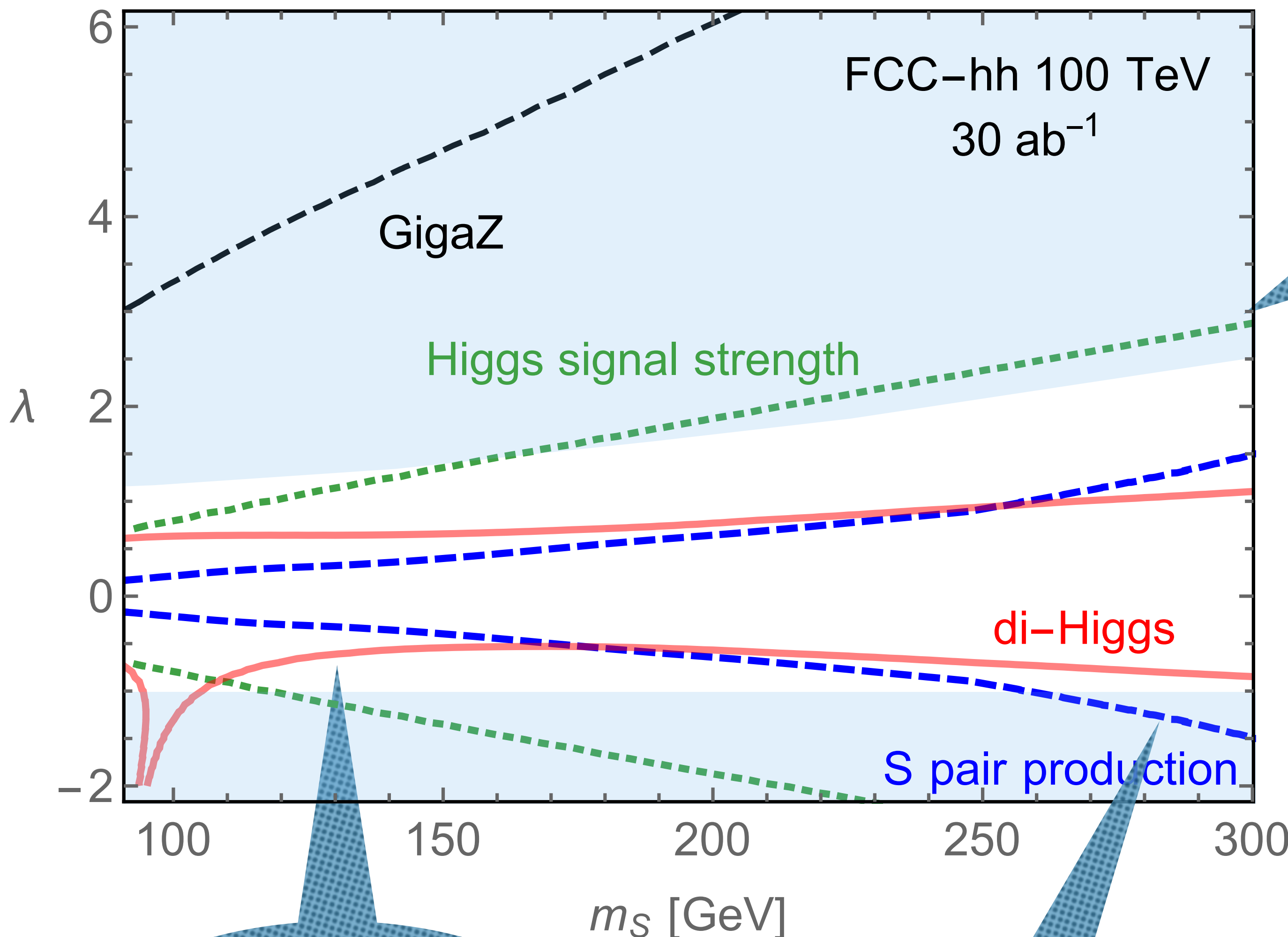


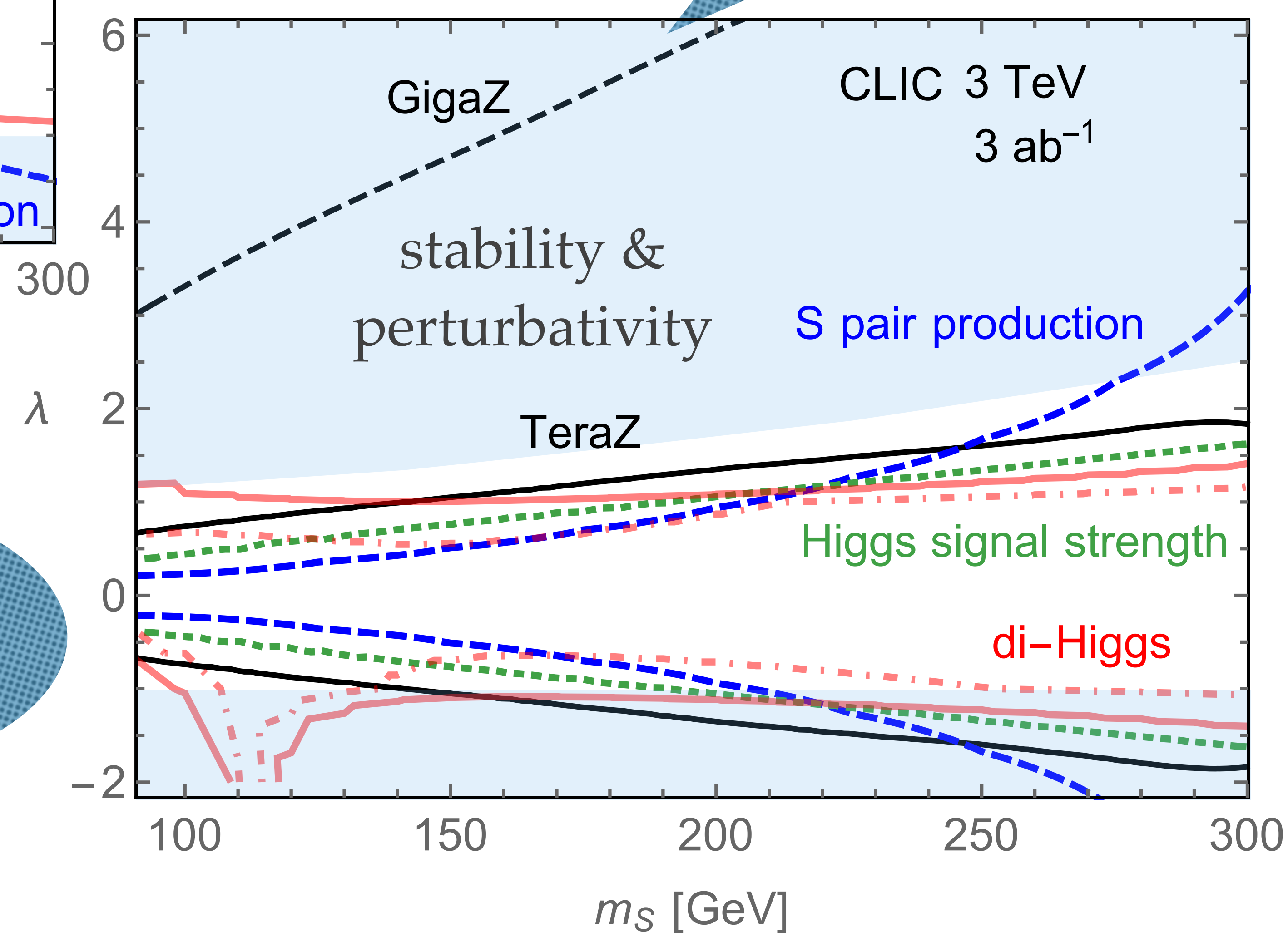
[CE, Jaeckel, Spannowsky, Stylianou `20]

Higgs propagation

singlets above threshold

[CE, Jaeckel, Spannowsky, Stylianou `20]





Higgs couplings

Oblique corrections

di-Higgs physics

off-shell production

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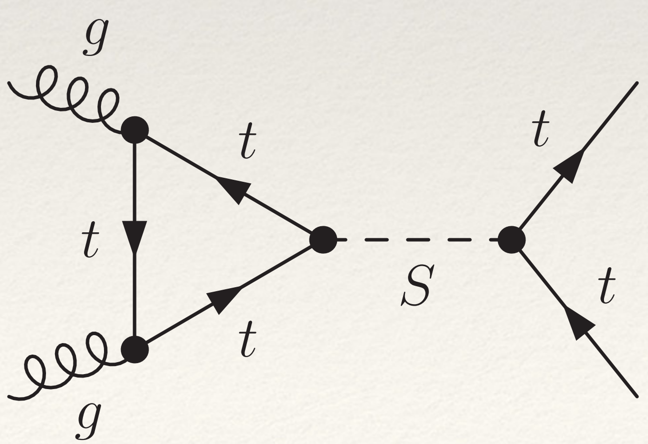
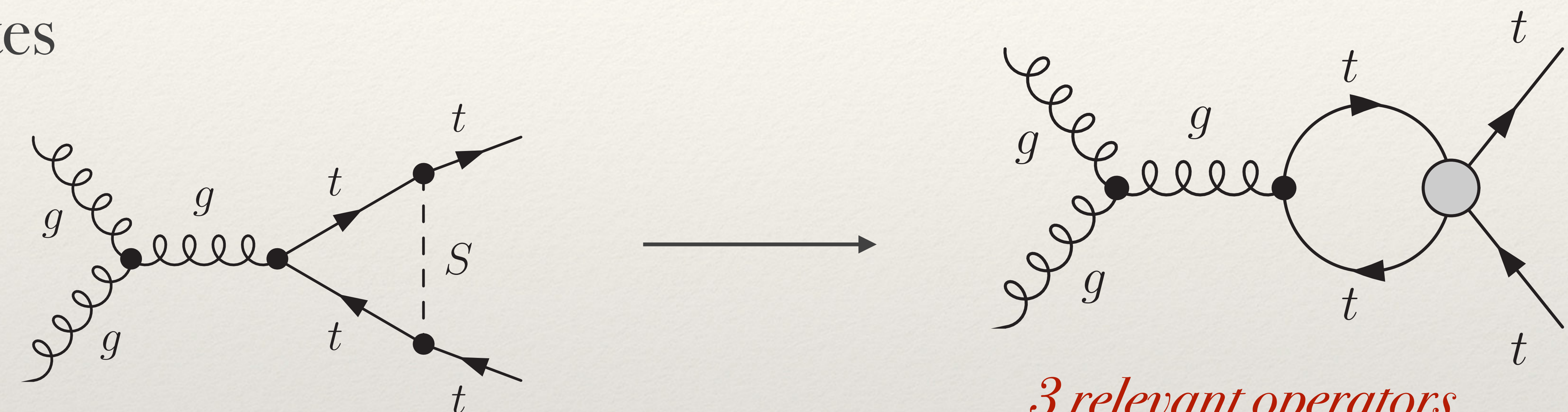


What do tops have to say about the presence of new scalar states?

New physics in tops

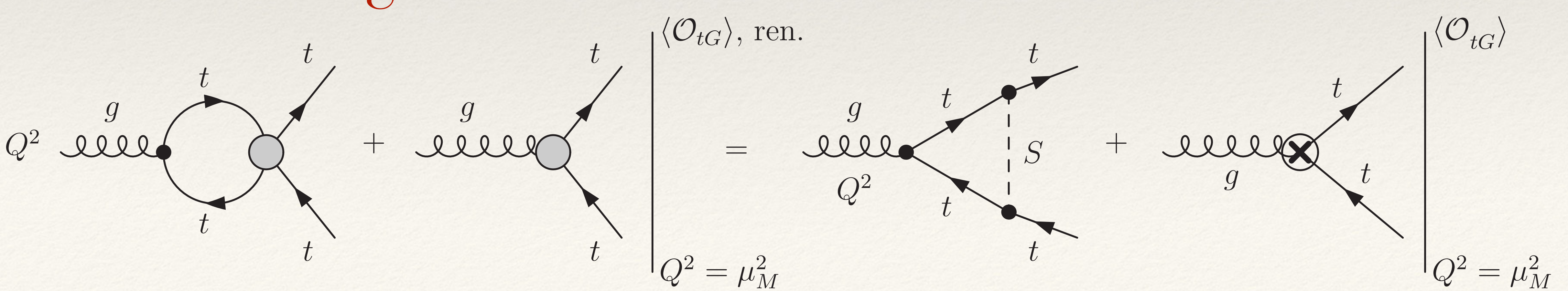
- new top-philic states arise in many BSM theories: $-\left(c_S \bar{t}_L t_R S + \text{h.c.}\right)$
- top pair production with large cross section could fingerprint such states



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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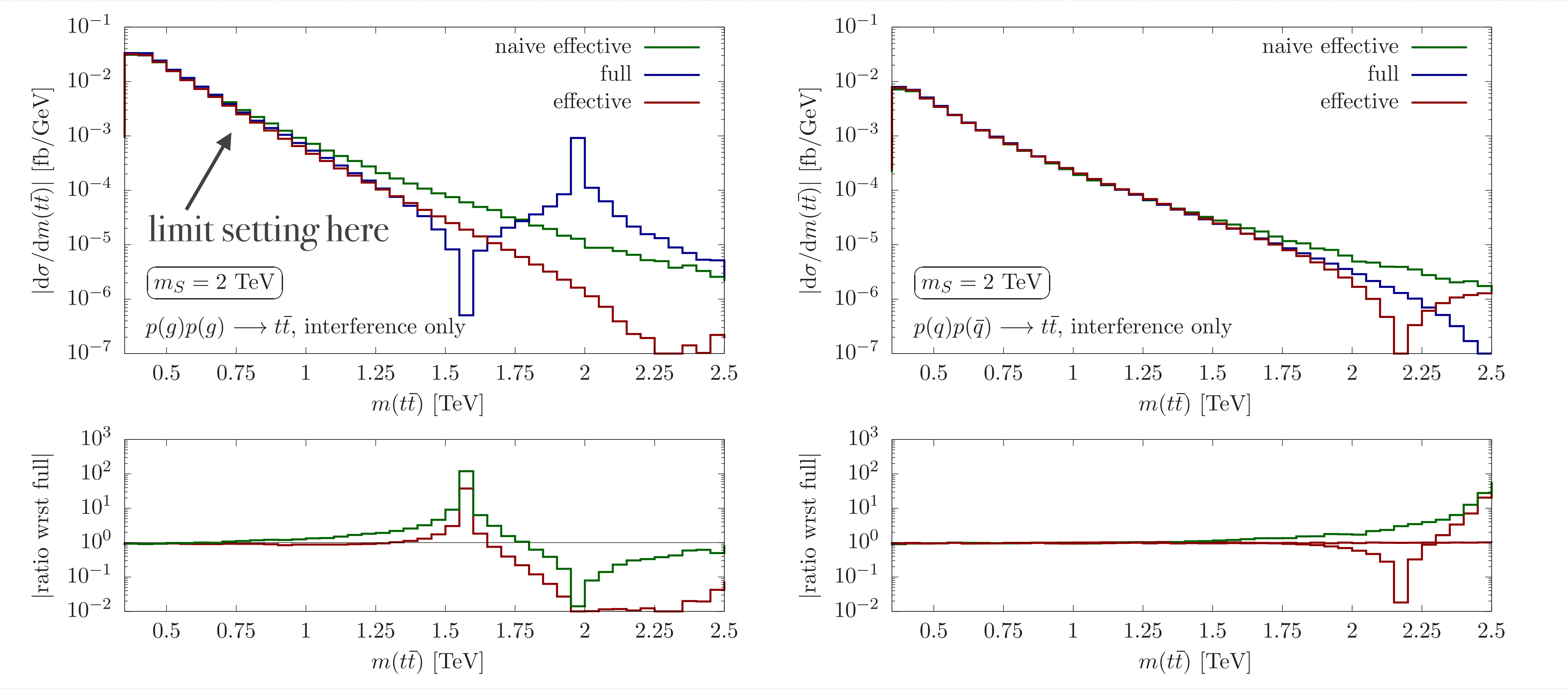

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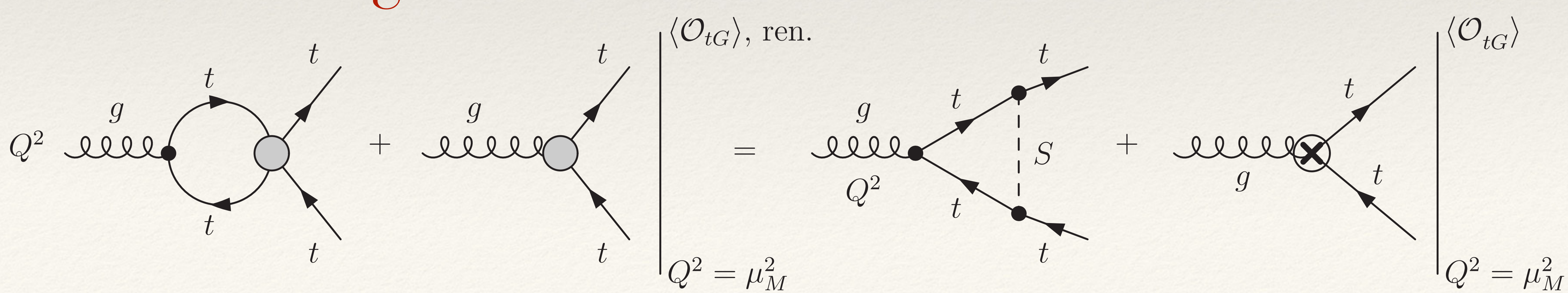
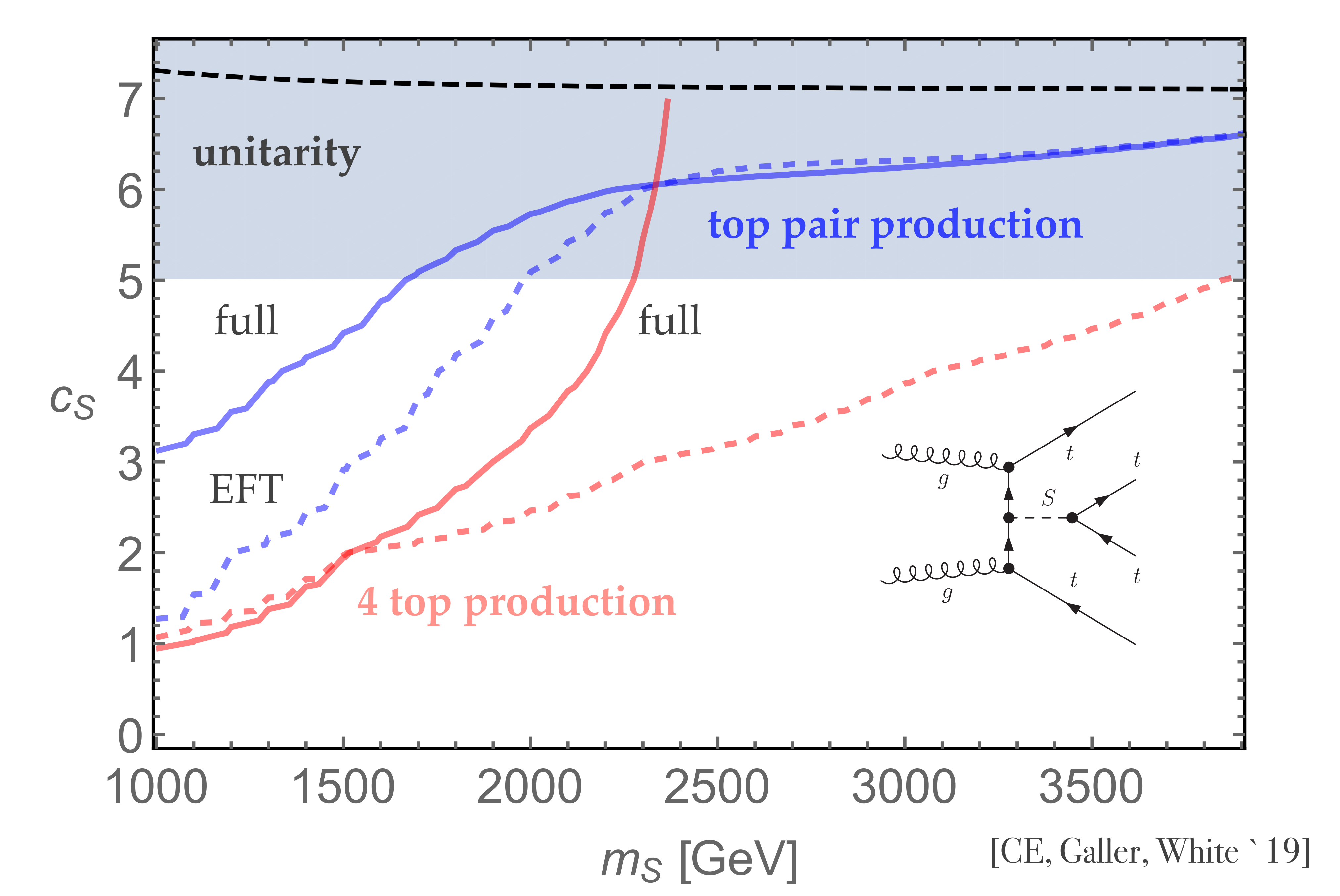


New physics in tops

- 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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- 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

top partners and top coupling modifications

hyperpions

[Belyaev et al. `17]

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

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

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

....

- 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 [Agashe, Contino, Pomarol `04] [Contino, da Rold, Pomarol `06]

(MCHM5 "lookalike")

gauge interactions

$$-\mathcal{L} \supset M\bar{\Psi}\Psi + \lambda_q f \bar{\hat{Q}}_L \Sigma \Psi_R + \lambda_t f \bar{\hat{t}}_R \Sigma^* \Psi_L + \sqrt{2}\mu_b \mathrm{Tr}(\bar{\hat{Q}}_L U \hat{b}_R) + \text{h.c.}$$

[Ferretti `14]

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

top partners and top coupling modifications

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

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

[Brown, CE, Galler, Stylianou `20]

indirect top sector constraints

- include range of data (for extrapolation)

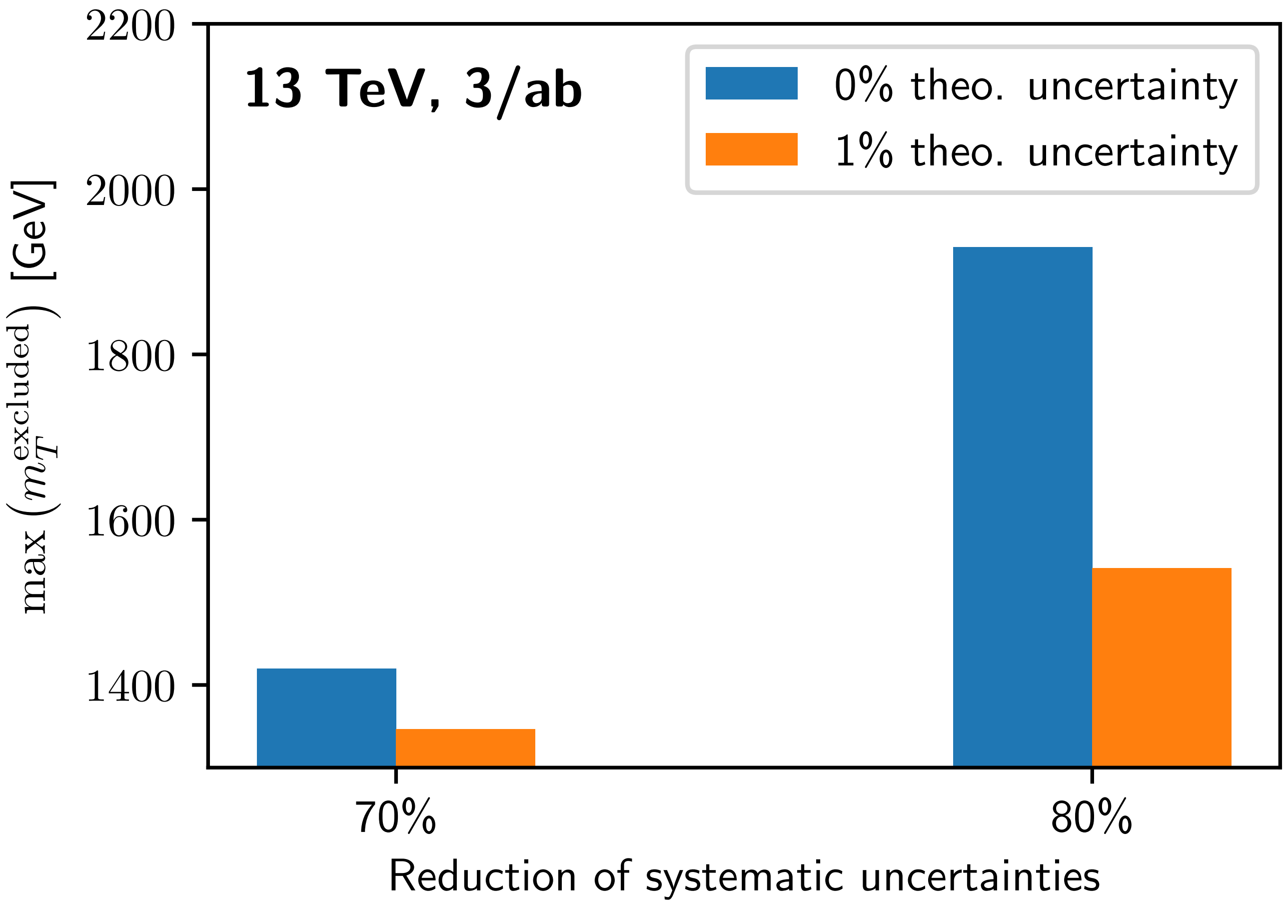
Analysis	Collaboration	$\sqrt{s}$ [TeV]	Observables	dof
single top t-channel				
1503.05027 [45]	CDF, D0	1.96	σ_{tot}	1
1406.7844 [46]	ATLAS	7	$\frac{\sigma_t}{\sigma_{\bar{t}}}$, $\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^t}$, $\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{\bar{t}}}$, $\frac{1}{\sigma}\frac{d\sigma}{d\|y_t\|}$,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

Analysis	Collaboration	$\sqrt{s}$ [TeV]	Observables	dof
$t\bar{t}Z$				
1509.05276 [55]	ATLAS	8	σ_{tot}	1
1510.01131 [56]	CMS	8	σ_{tot}	1
1901.03584 [57]	ATLAS	13	σ_{tot}	1
1907.11270 [58]	CMS	13	σ_{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



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

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

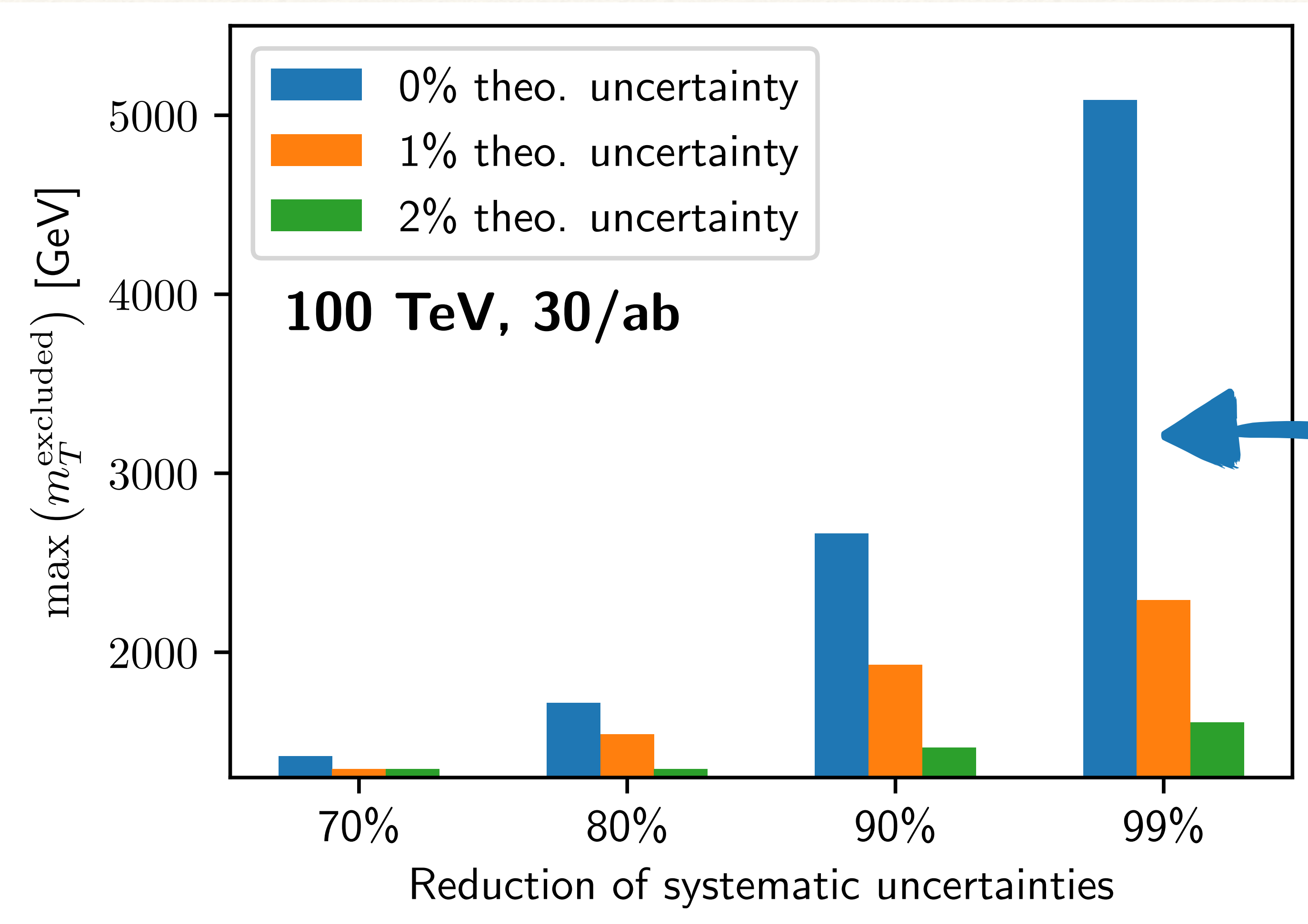
$$\delta_{W,L} \in [-0.029, 0.019]\,, \quad \delta_{W,R} \in [-0.009, 0.009]\,,$$
$$\delta^t_{Z,L} \in [-0.639, 0.277]\,, \quad \delta^t_{Z,R} \in [-1.566, 1.350]\,.$$

model correlations

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

- 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

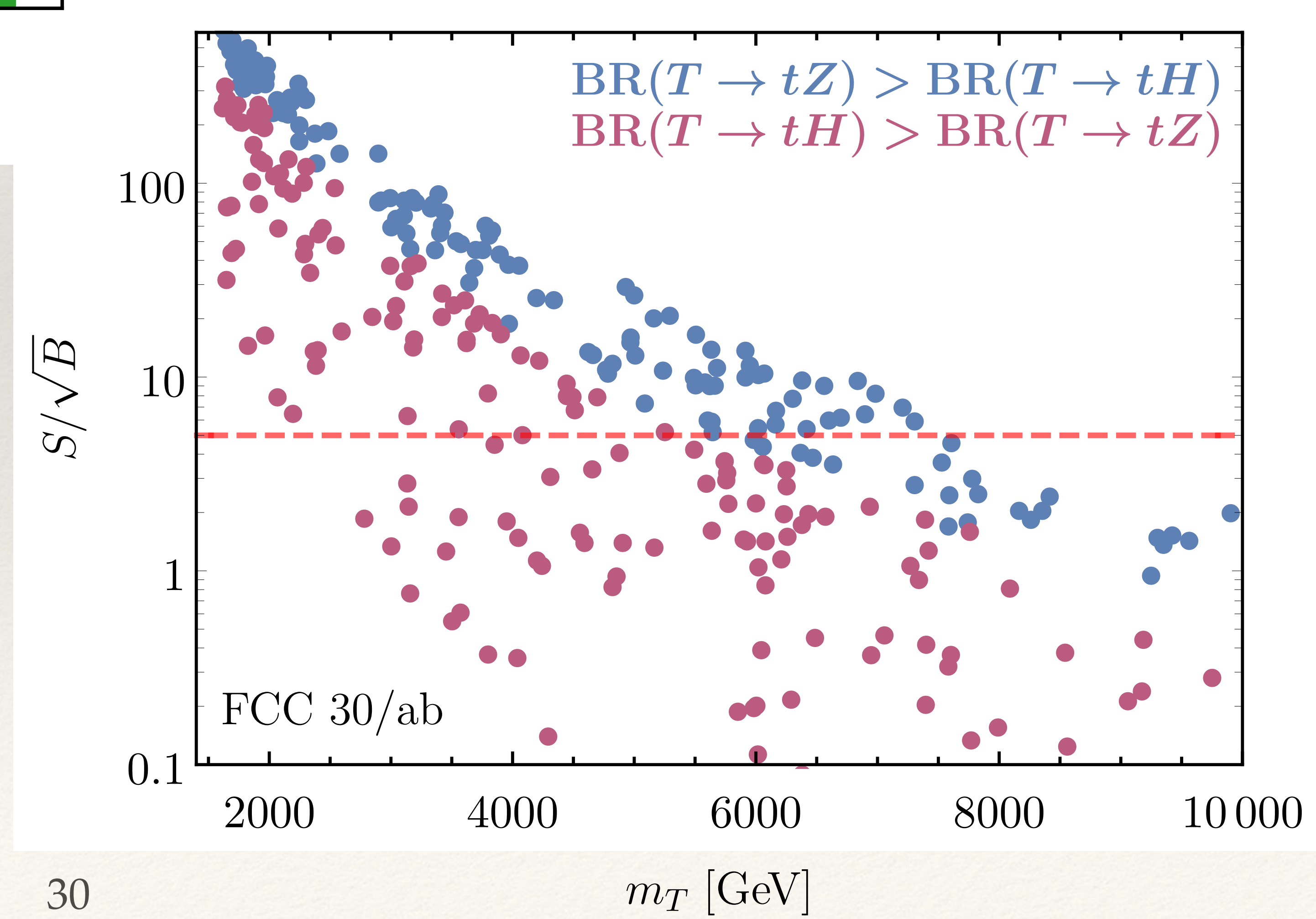
indirect top sector constraints

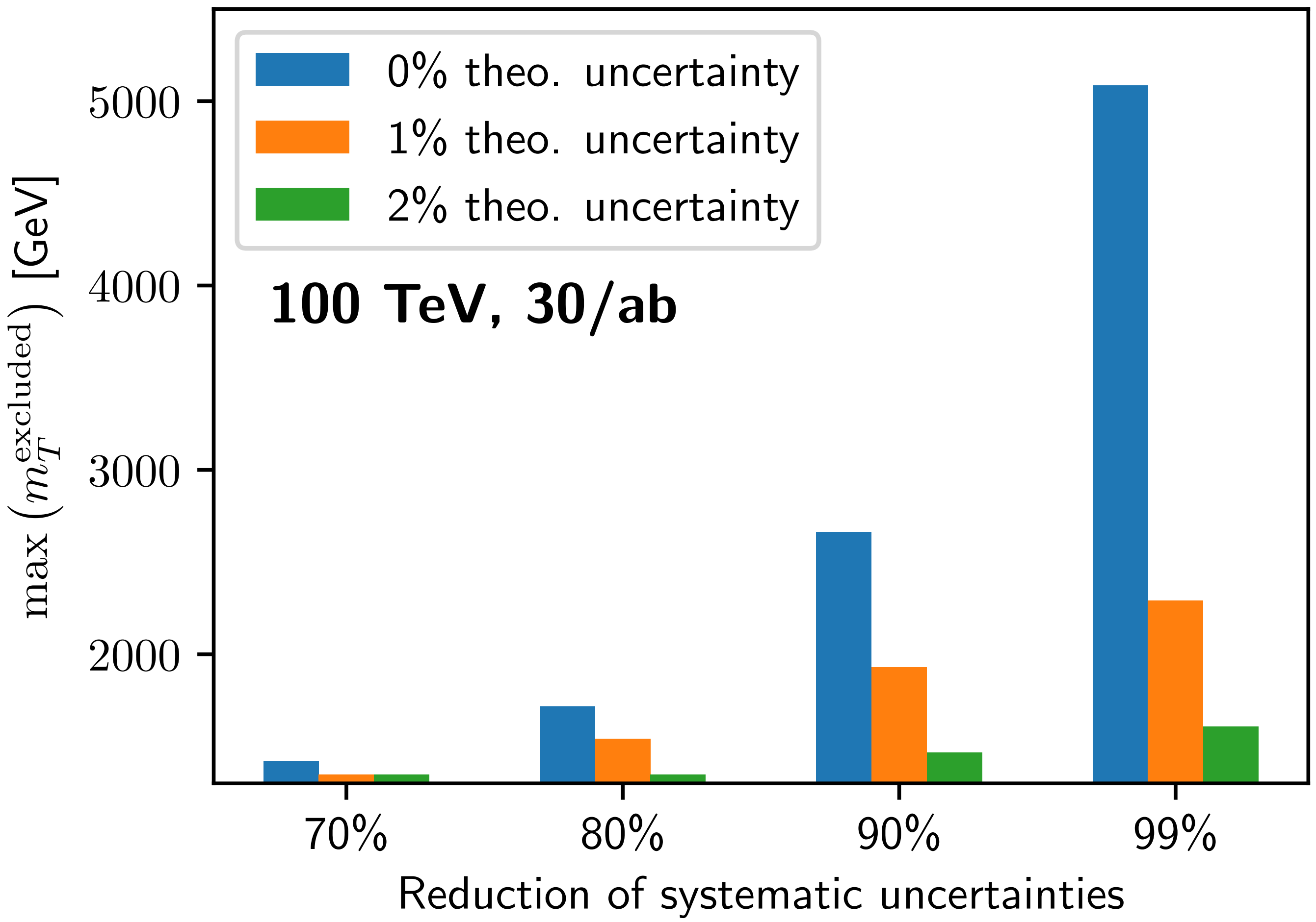


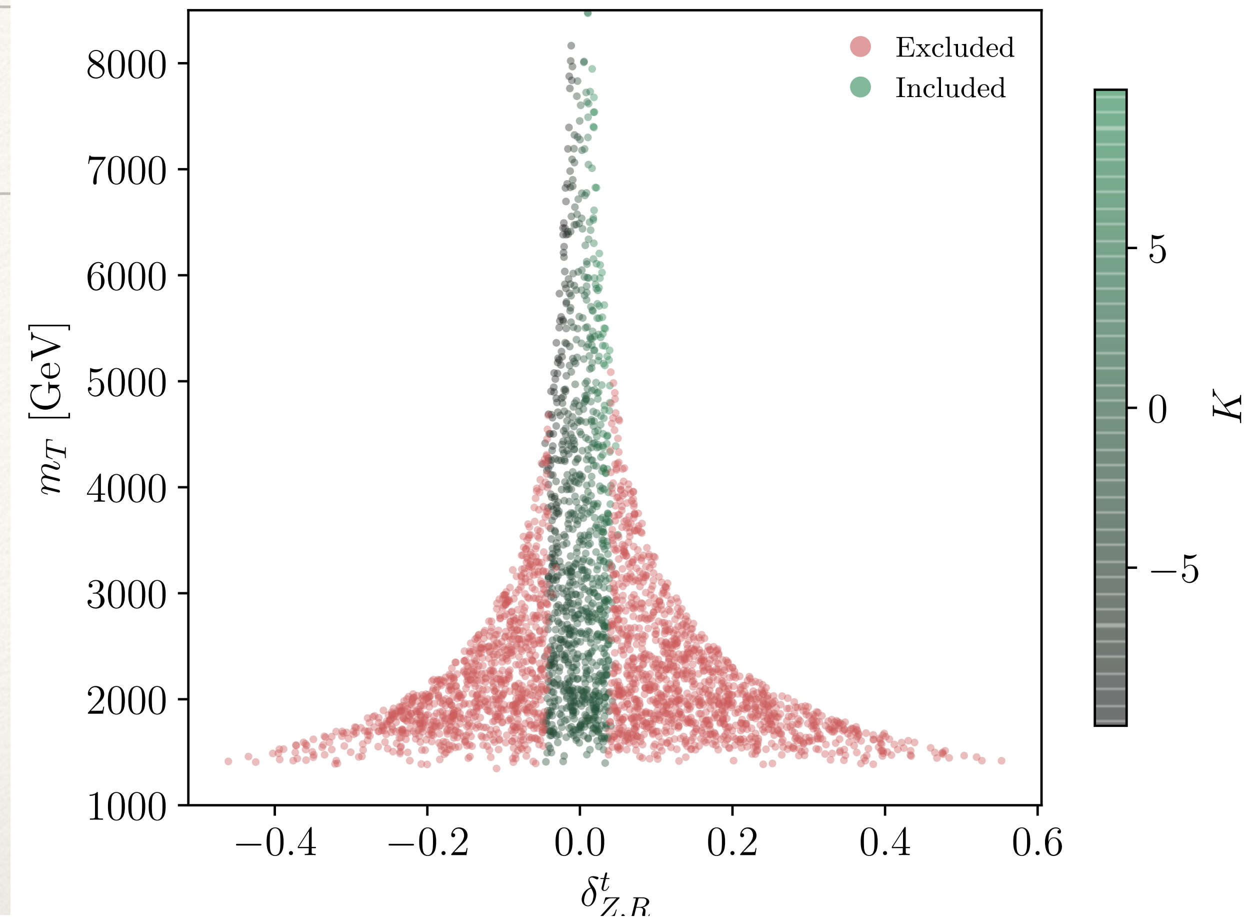
- optimistic extrapolations provide <u>indirect</u> sensitivity up to about 5 TeV

- 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]







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

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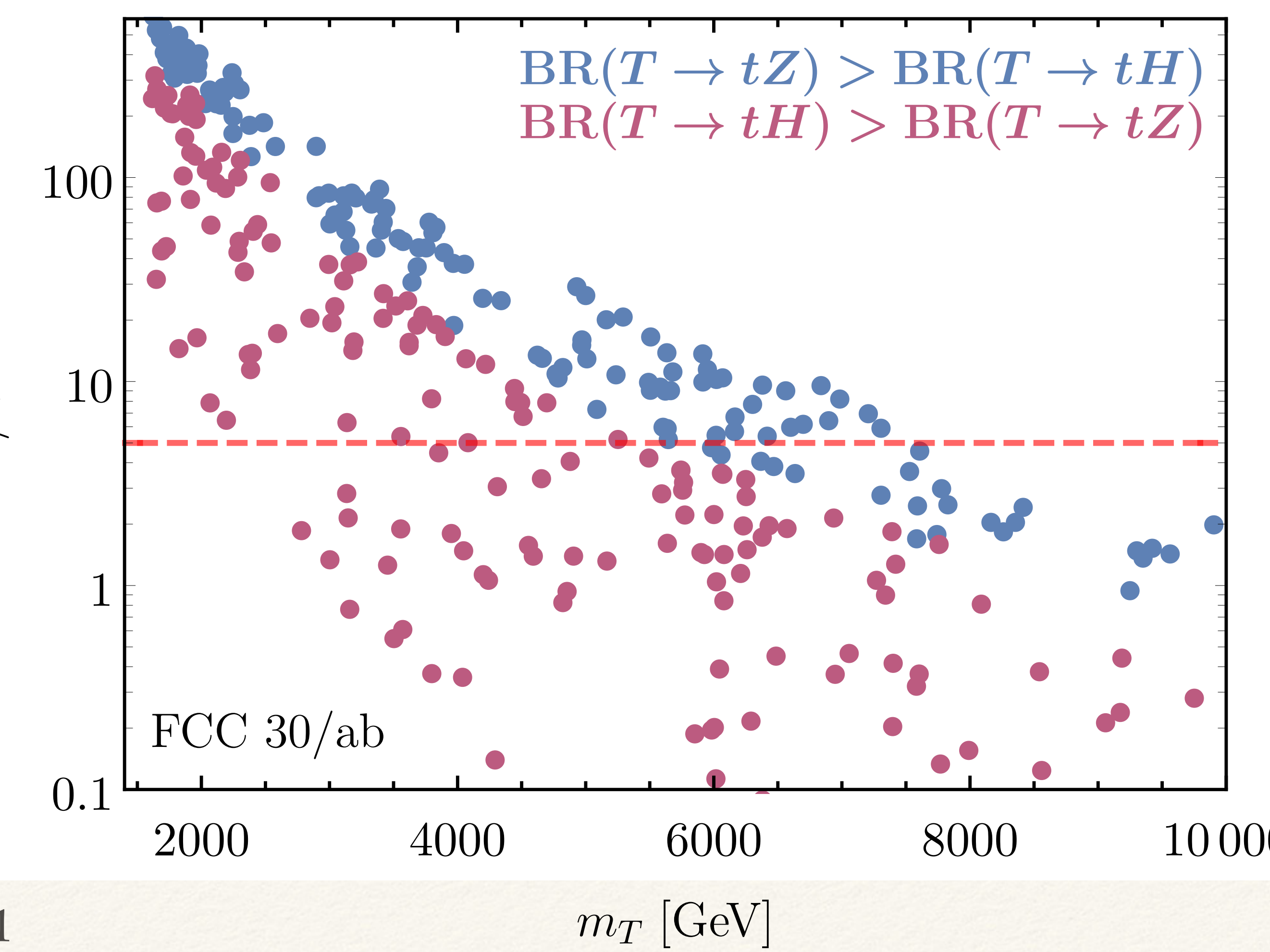

- *EFT @ colliders progress has been rapid*
  - matching, validity re:momentum coverage at hadron machines
  - but no sensitivity when uncertainties are large
  - uncertainties/deviations crucial for continued EFT efforts to be fruitful; adopt UV inspired-restrictions as way out?

- *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