Christoph Englert

Top views on BSM interactions

Top2022

Durham

05/09/22

LEVERHULME TRUST

UKRI Science and Technology Facilities Council

University of Glasgow

What's wrong with the top quark?

- top quark heavy $m_t \backsim v$, strongly coupled, decay before hadronisation

$$\Gamma(t \to Wb) \sim (g^2 + y_t^2)^2 (g^2 - 2y_t^2)^2 \, \frac{v}{y_t^3}$$

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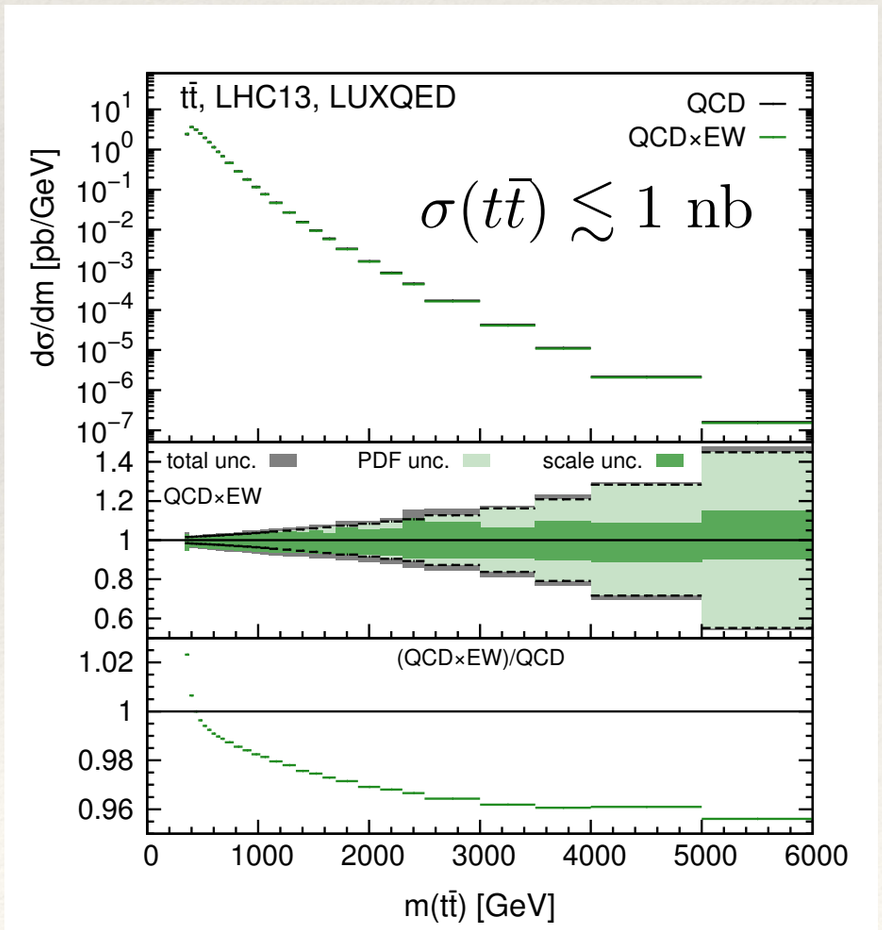
direct handle on properties



[Czakon et al. `17]

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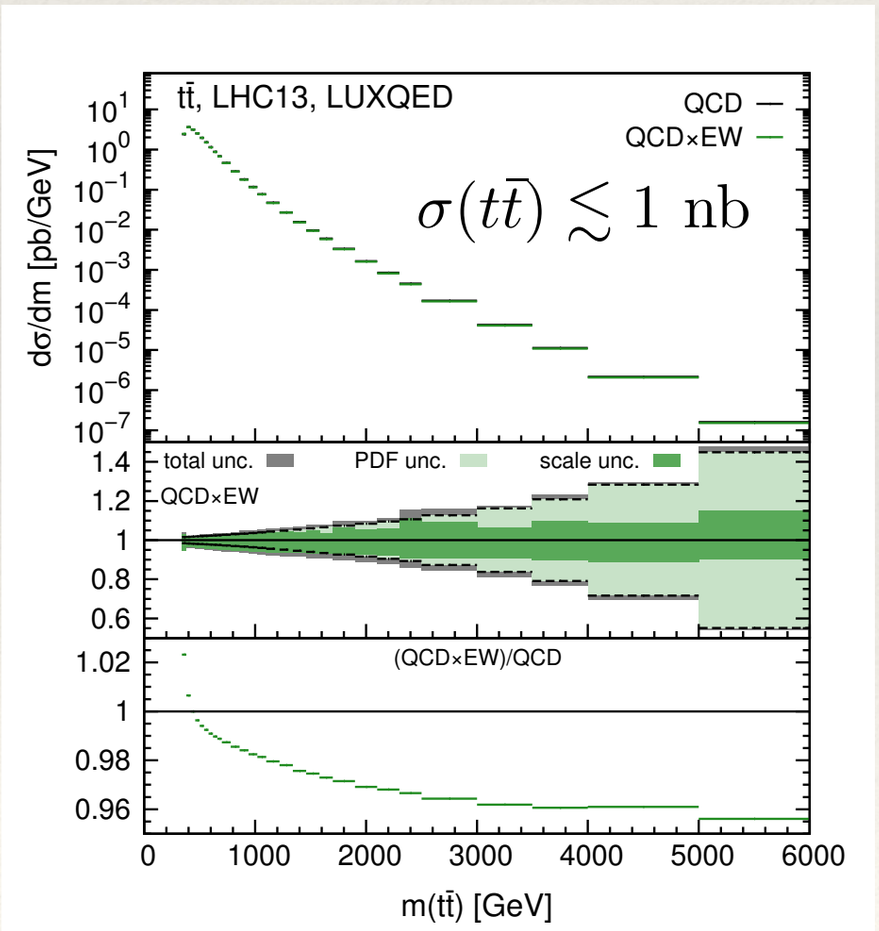

[Czakon et al. `17]

11:00	Top quark cross section measurements
14:00	Associated Production
	Top quark mass
17:00	

09:00	Top spin and polarisation
11:00	Top quark properties other than mass

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large pull @ weak scale

relevant threshold

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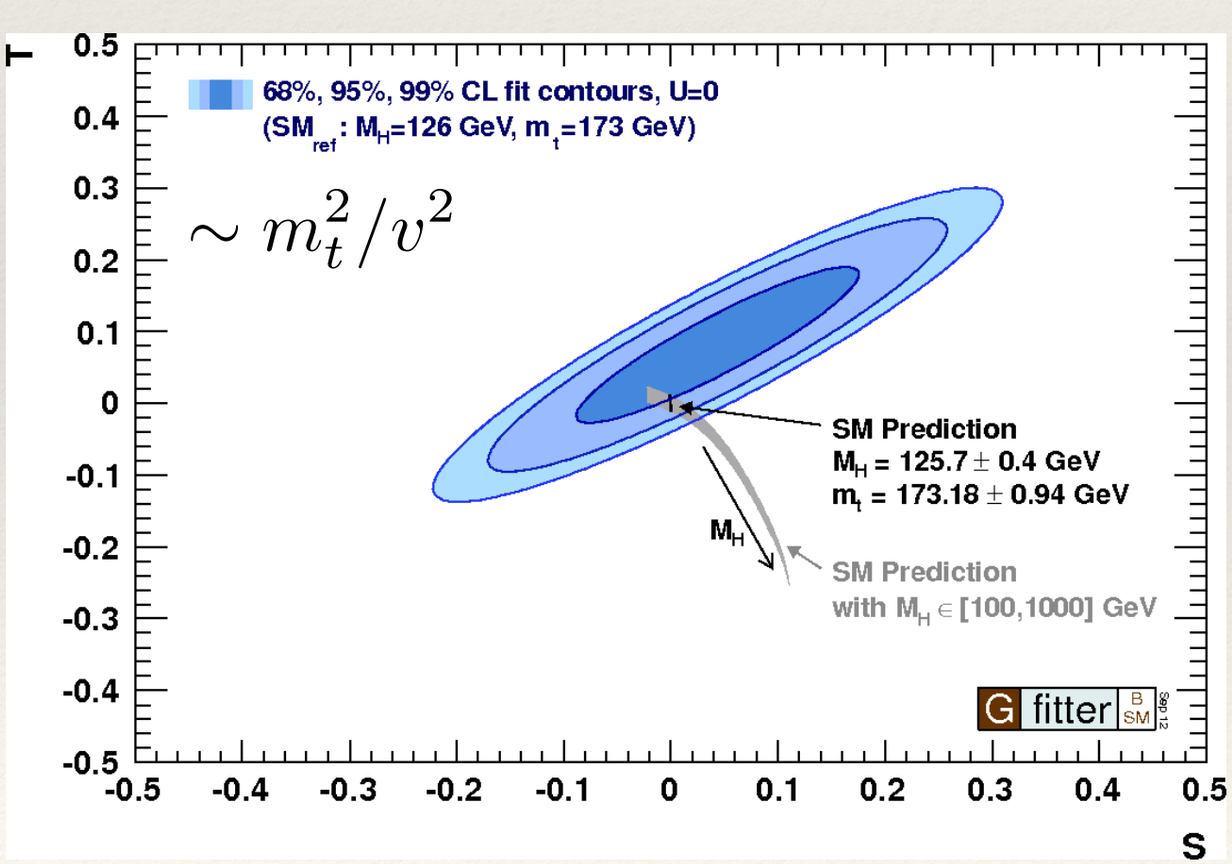

[GFitter `12]

- Higgs mass precisely predicted after determination m_t

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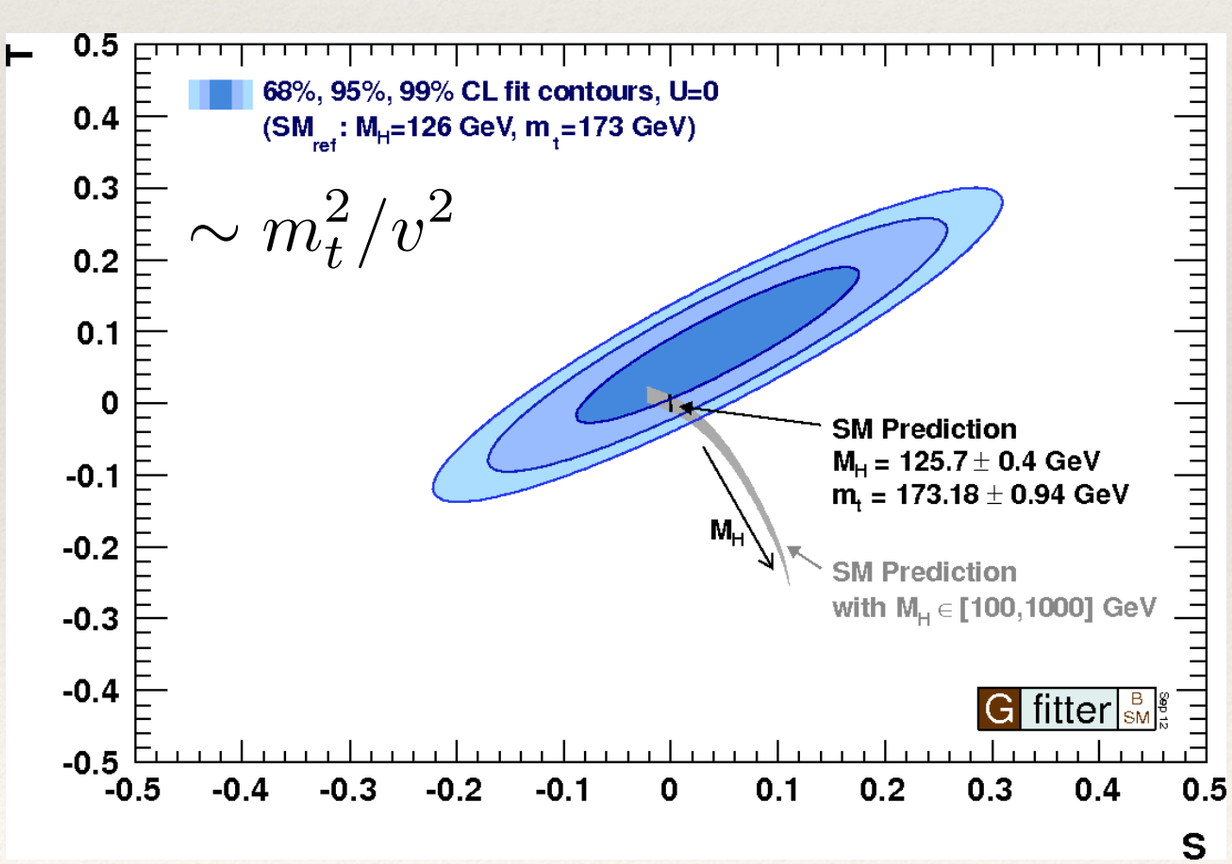

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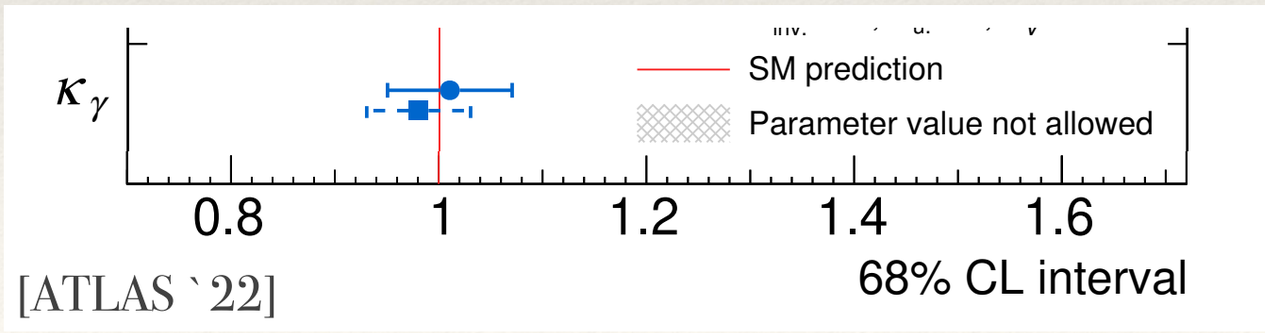
- Higgs mass precisely predicted after determination m_t
- Higgs $\gamma\gamma$ discovery mode is a direct window to fermion mass generation



[ATLAS `22]

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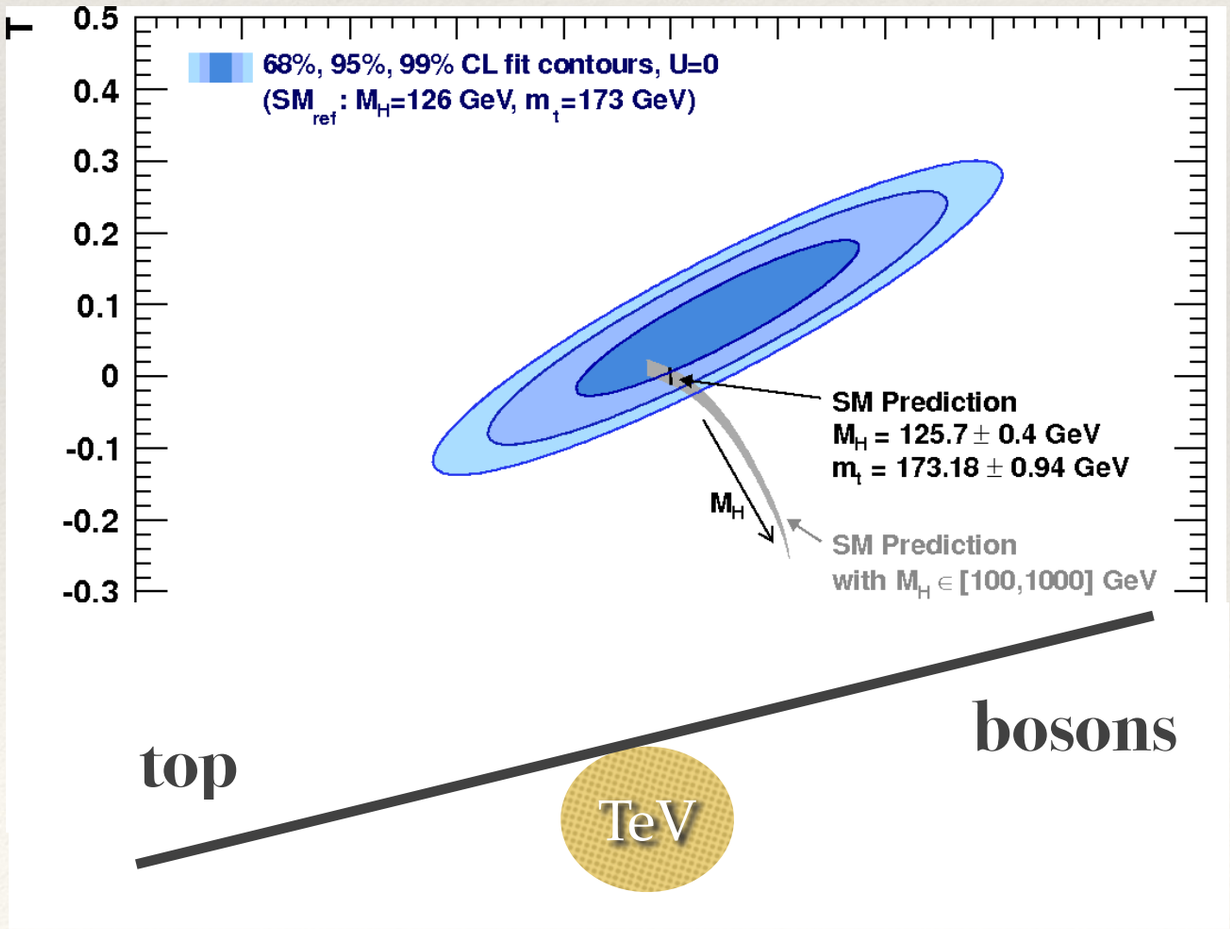

- Higgs mass precisely predicted after determination m_t
- Higgs $\gamma\gamma$ discovery mode is a direct window to fermion mass generation
- Weak scale physics sensitive to the interplay of bosons and split top

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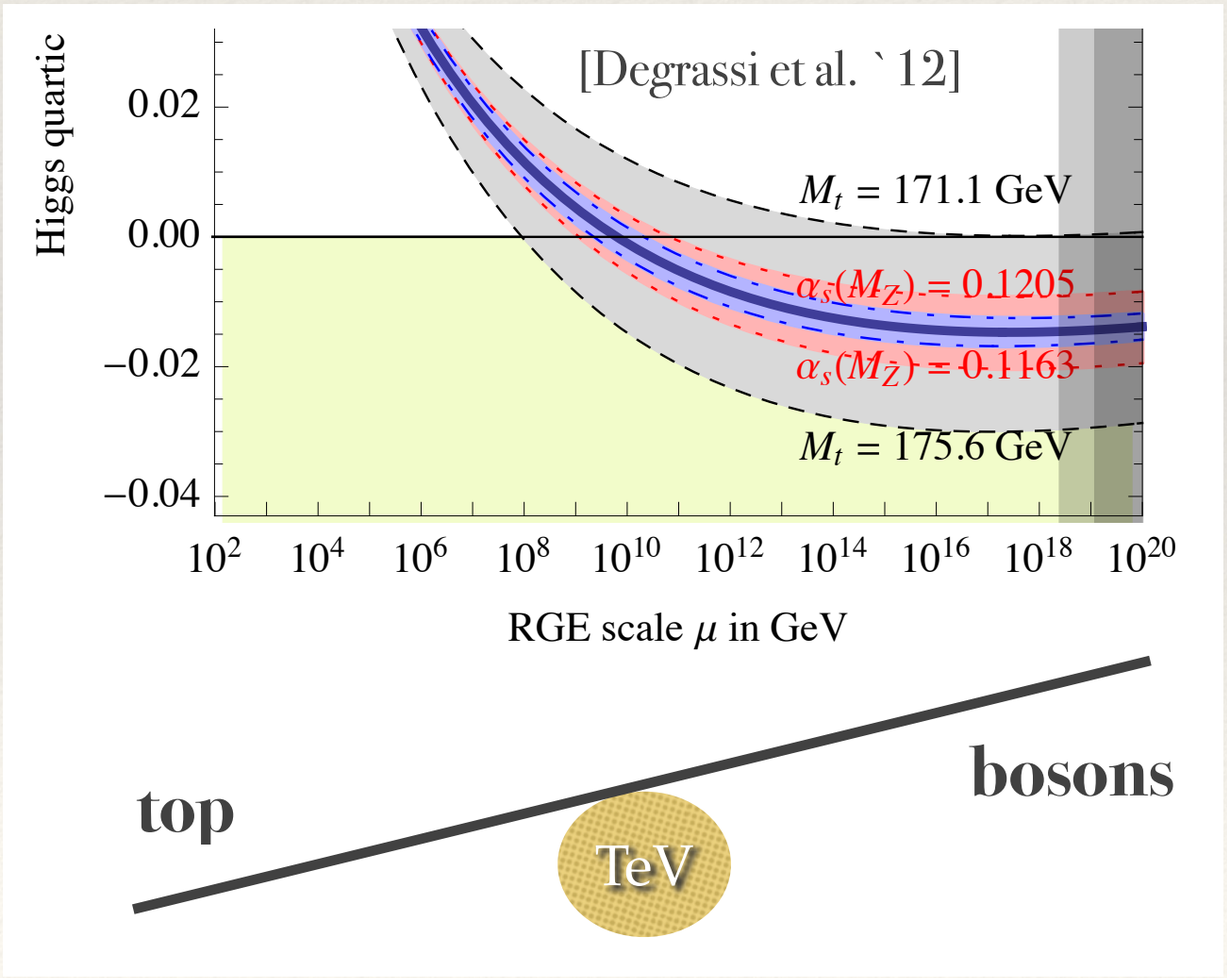

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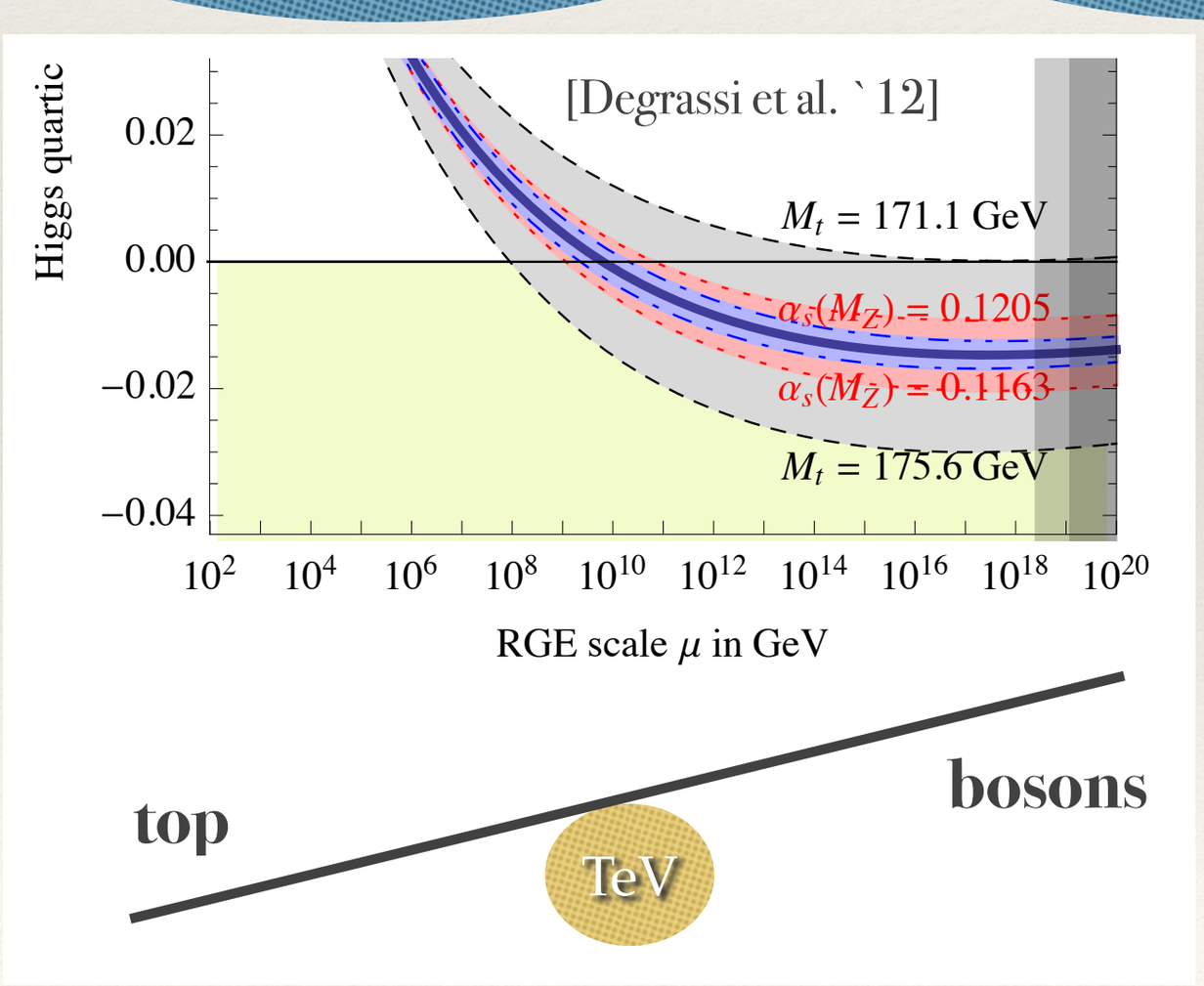

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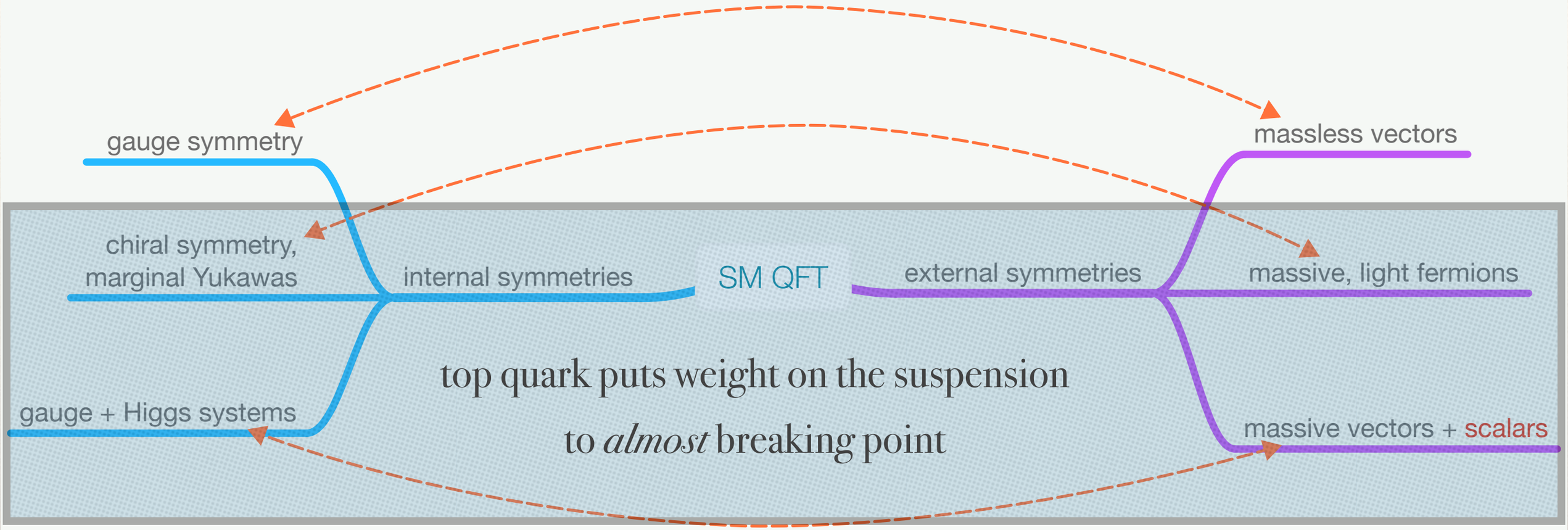
Higgs pairs, associated Higgs production,…

What's next?



Phenomenological appeal

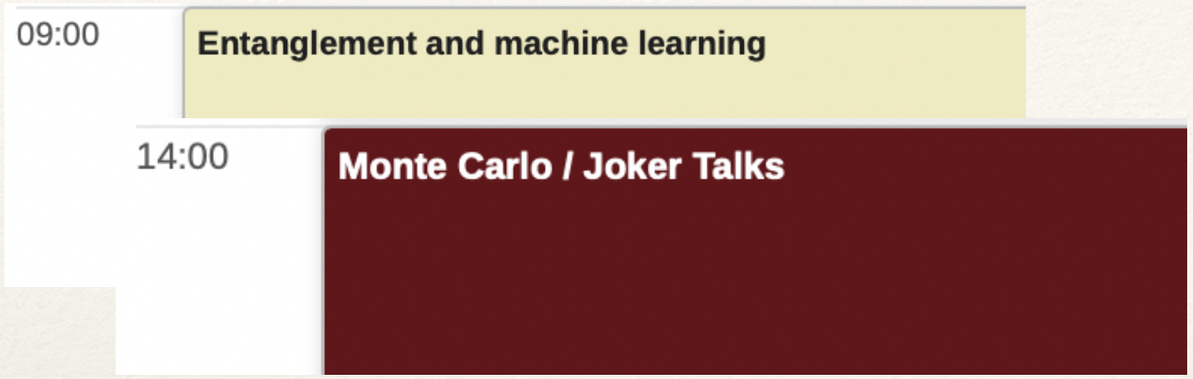
- abundantly produced
- rich final state phenomenology
- testbed for new strategies/tools

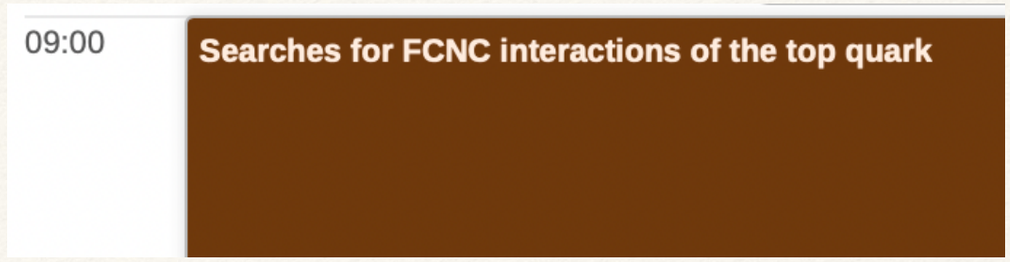
Top quark

Theoretical appeal

- central to weak scale dynamics
- crucial in BSM theories
- window to SM UV completions

What's next? Attempts discussed here!





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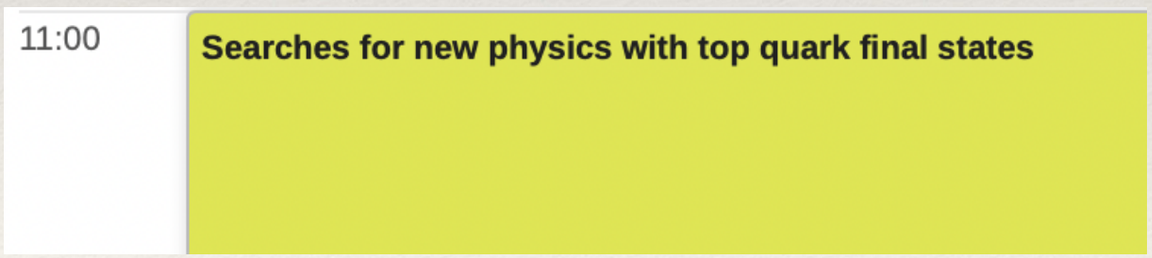
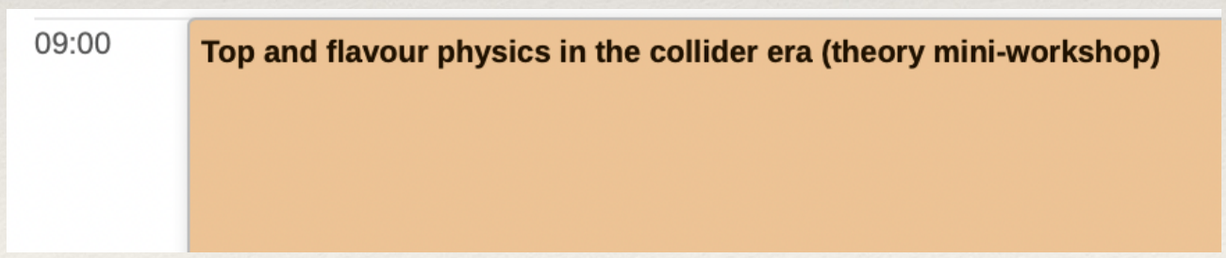




A general route to success?

the SM is flawed

no evidence for exotics

coupling/scale separated BSM physics

Effective Field Theory

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

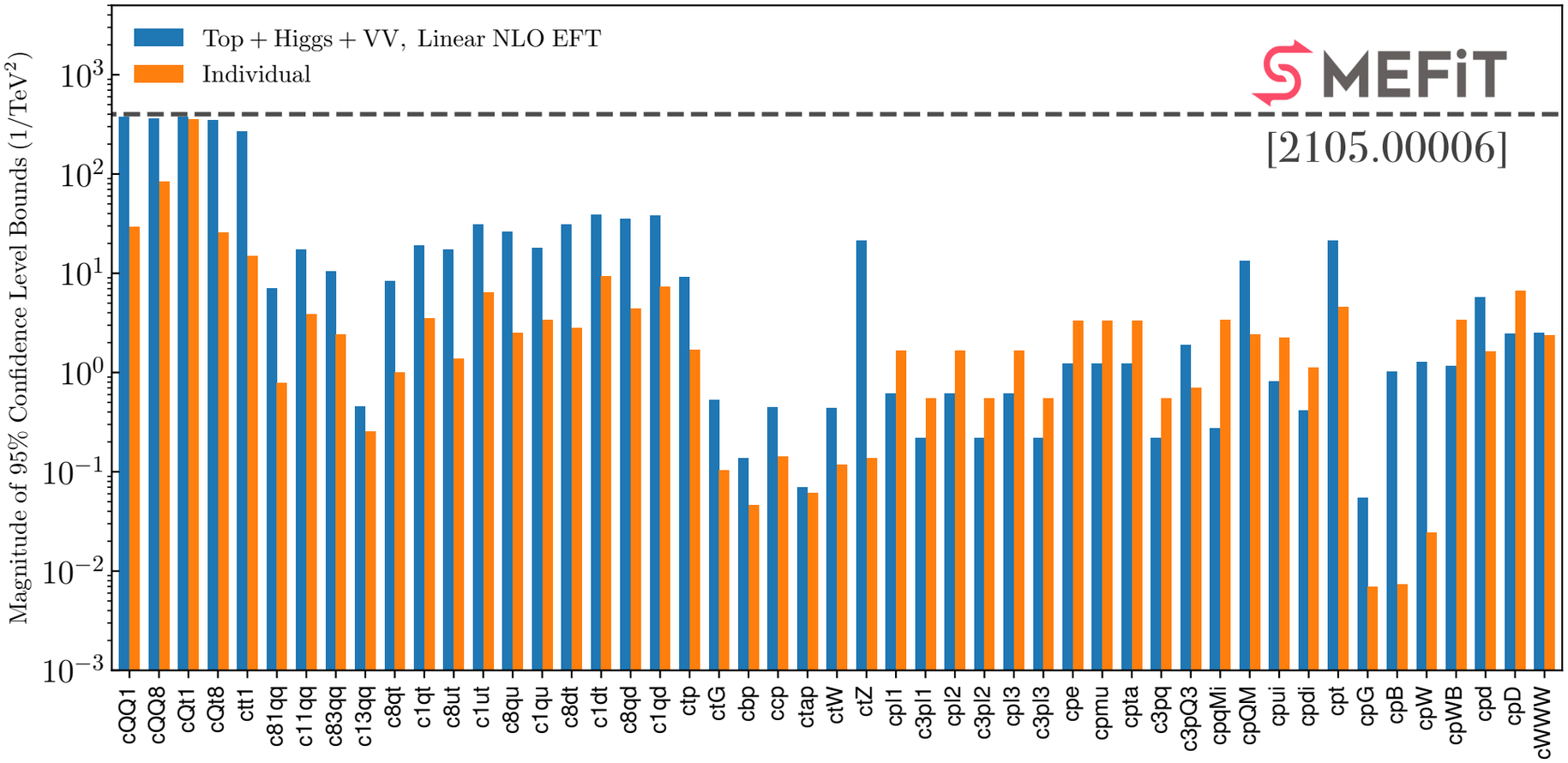
[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

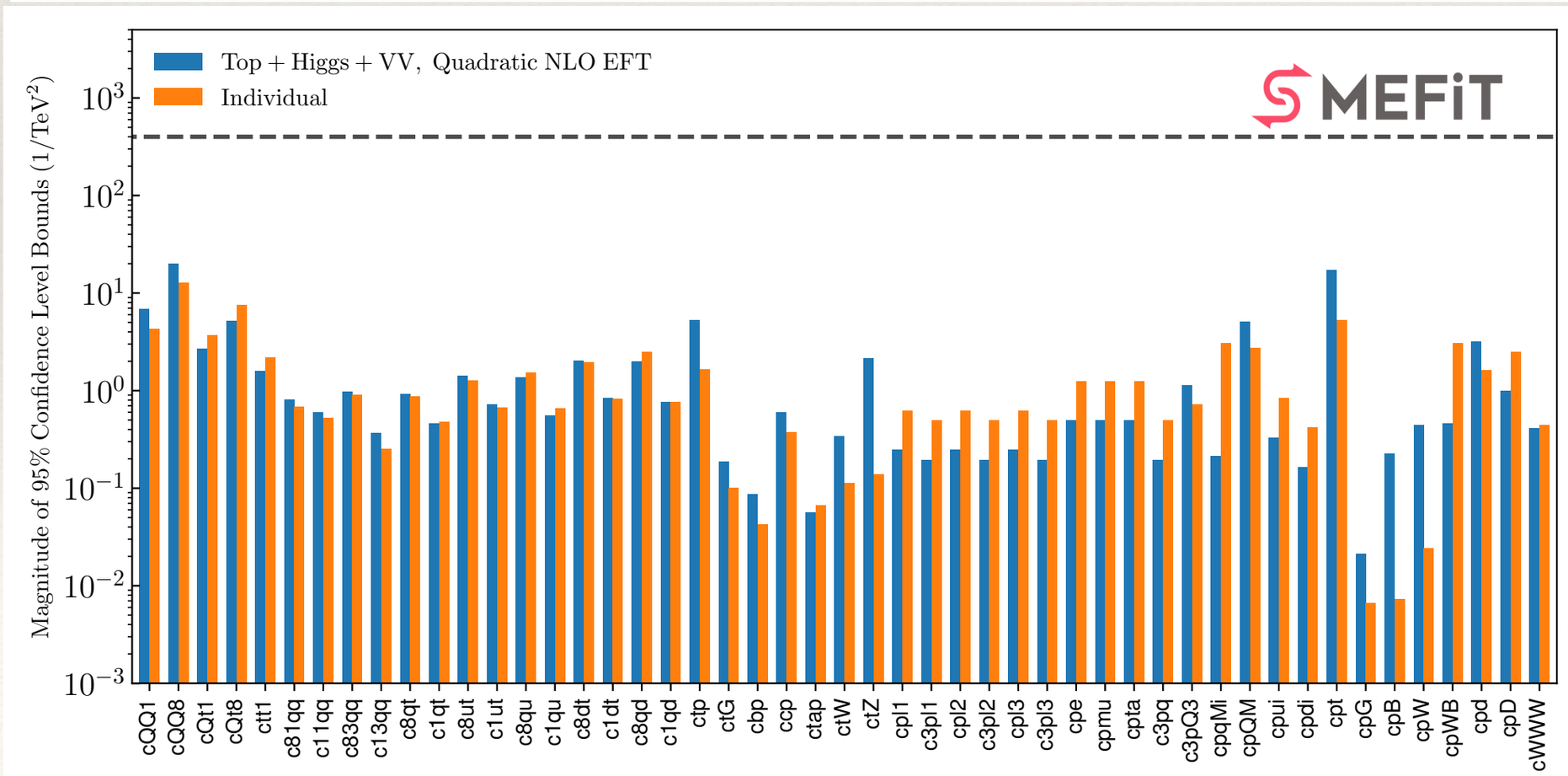
59 B-conserving operators ⊗ flavor ⊗ h.c., d=6
2499 parameters (reduces to 76 with N_f=1)

concrete models

- νSMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- compositeness
- …

To EFT...





EFT: major thrust after Higgs discovery

[Ellis, Sanz, You]
[TopFitter]
[Sfitter]
[GFitter]
[SMEFiT]
...

proof-of-principle case + N×LO tools

experimental ownership @ R3

To EFT...

theory

- correlations in particle physics, when perturbative, are parametrisable by Feynman diagrams

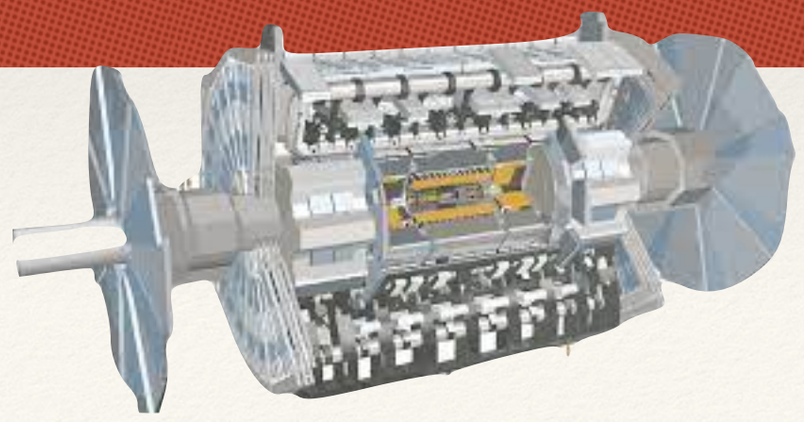
kinematic correlations

helicity correlations

colour correlations

....

reverse-engineer in terms of collider observables for SM validation or exclusion



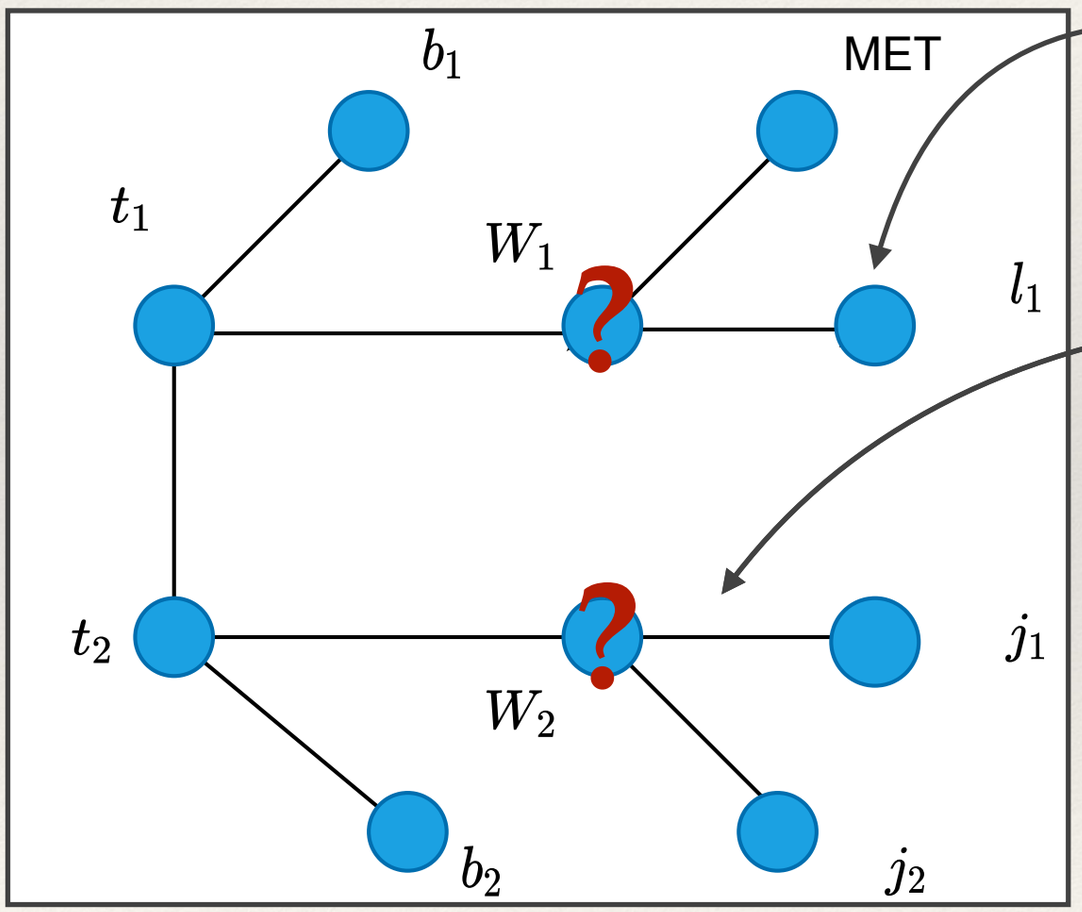
experiment

To (better?) EFT…

- Can we impart Feynman-graph correlations on measurements to enhance BSM sensitivity?

…Graph Neural Networks

jet tagging [Dreyer, Hu `20]
anomaly detection [Atkinson et al. `21]
…



nodes with *features*

$[p_T, \eta, \phi, E, m, \text{PID}]$

edges for *feature correlation*

e.g. W reconstructions vs four fermion discrimination

supervised training over graph structures to enhance BSM sensitivity

[Atkinson et al. `21]

To (better?) EFT...

supervised training over graph structures to enhance BSM sensitivity

- large improvement attainable when BSM correlations affect exclusive phasespace correlations
- no improvement when inclusive selections determine sensitivity

expect additional improvements for UV-matched fits

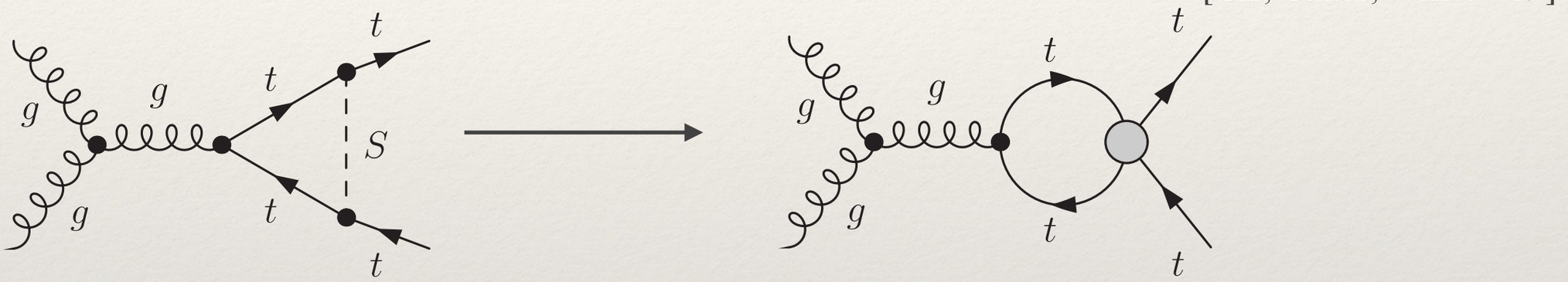
fractional improvement vs CMS-TOP-16-008

	2.3 fb^{-1}		3 ab^{-1}	
	Individual	Profiled	Individual	Profiled
$\bar{C}_G$	0.07%	14.12%	0.07%	11.09%
$\bar{C}_{\varphi q}^{(3)33}$	33.74%	34.19%	33.73%	33.48%
$\bar{C}_{uG}^{33}$	28.29%	32.18%	28.28%	30.74%
$\bar{C}_{uW}^{33}$	34.86%	35.35%	34.85%	35.53%
$\bar{C}_{qd}^{(8)33ii}$	4.71%	4.68%	4.71%	4.76%
$\bar{C}_{qq}^{(1)i33i}$	3.50%	3.45%	3.50%	4.73%
$\bar{C}_{qq}^{(3)i33i}$	4.35%	4.28%	4.35%	5.00%
$\bar{C}_{qq}^{(3)ii33}$	63.83%	–	63.83%	71.91%
$\bar{C}_{qu}^{(8)33ii}$	3.45%	3.51%	3.45%	3.48%
$\bar{C}_{qu}^{(8)ii33}$	3.74%	3.72%	3.74%	3.77%
$\bar{C}_{ud}^{(8)33ii}$	4.62%	4.46%	4.62%	4.79%
$\bar{C}_{uu}^{i33i}$	3.38%	3.35%	3.38%	1.95%
$\bar{C}_{qq}^{(3)ii33}$	–	–	10.57%	35.52%

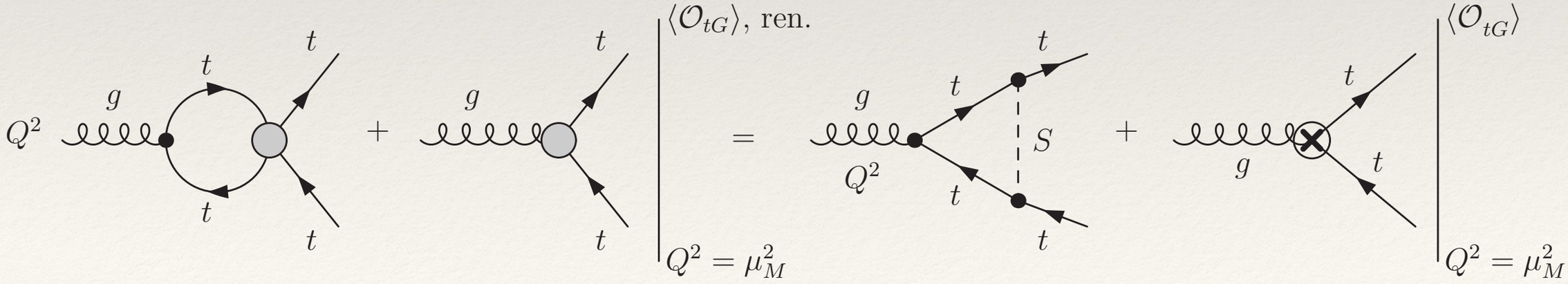
...or not(?) to EFT...

- 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 ...

[Franzosi, Vryonidou, Zhang `17]
[CE, Galler, White `19]



- EFT is suitable tool to constrain such states model-independently, matching is crucial.



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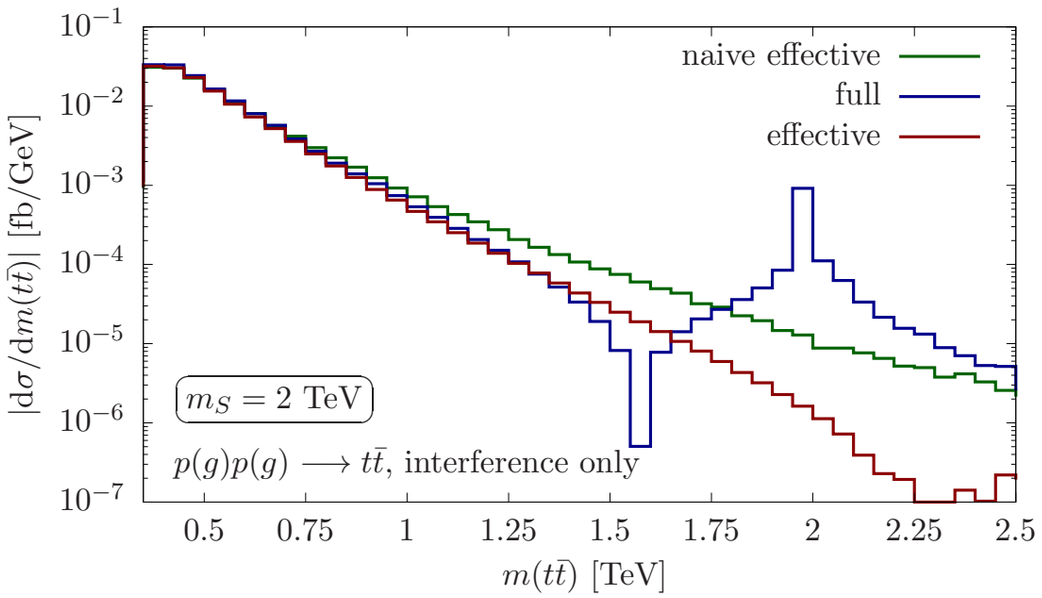

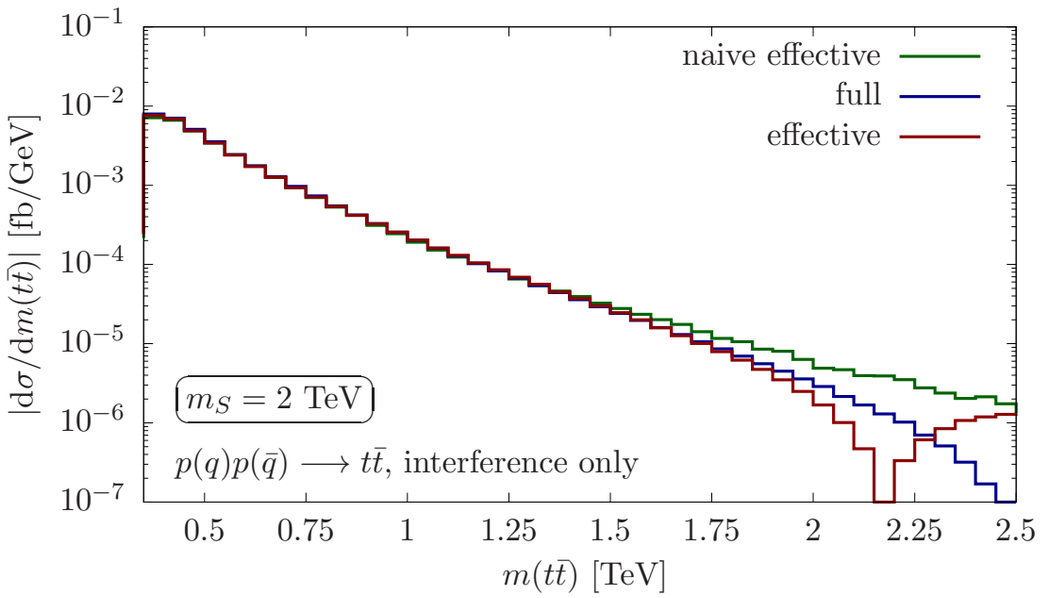

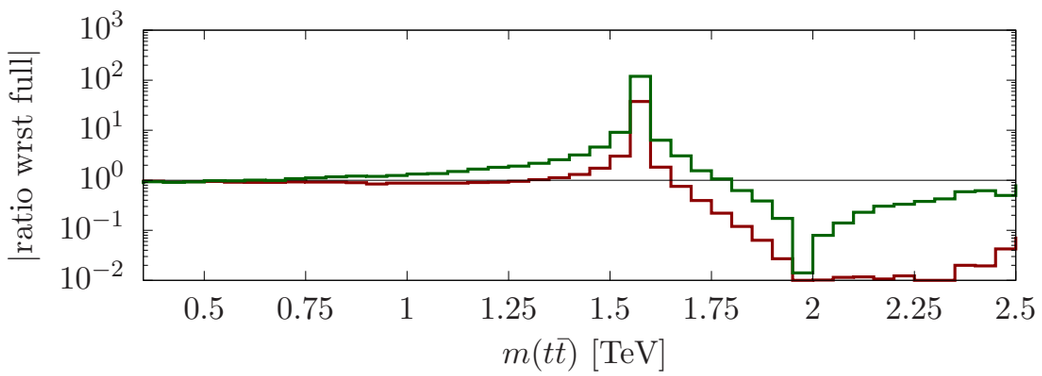

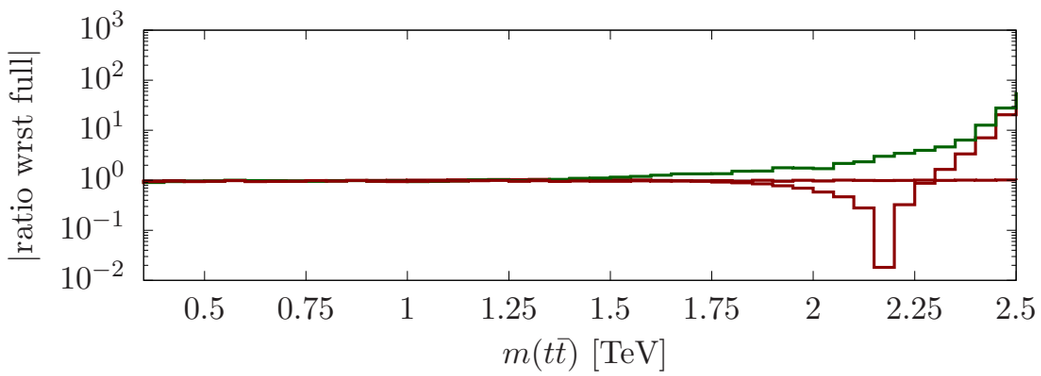

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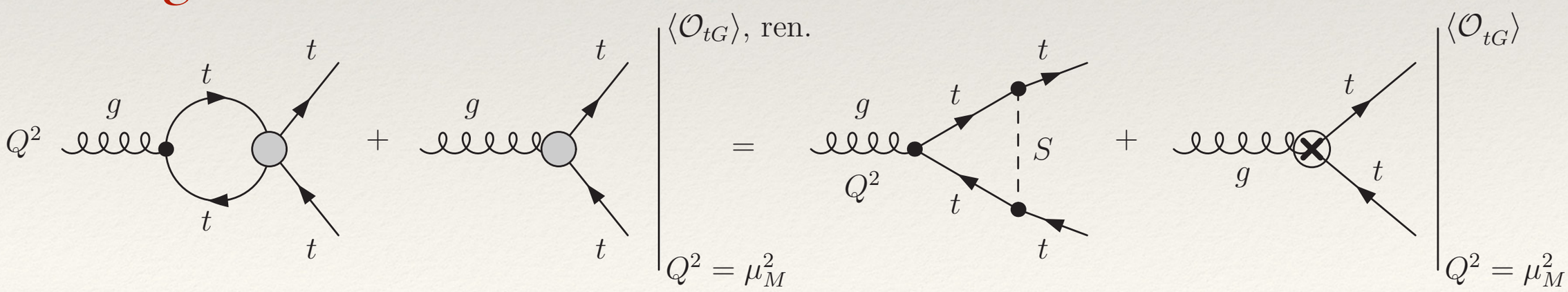

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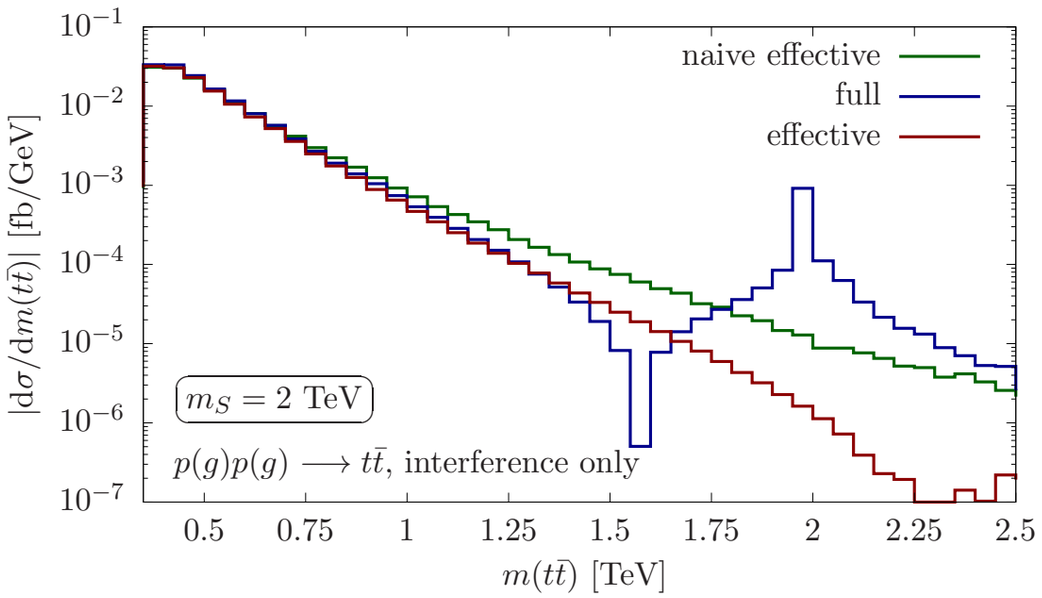
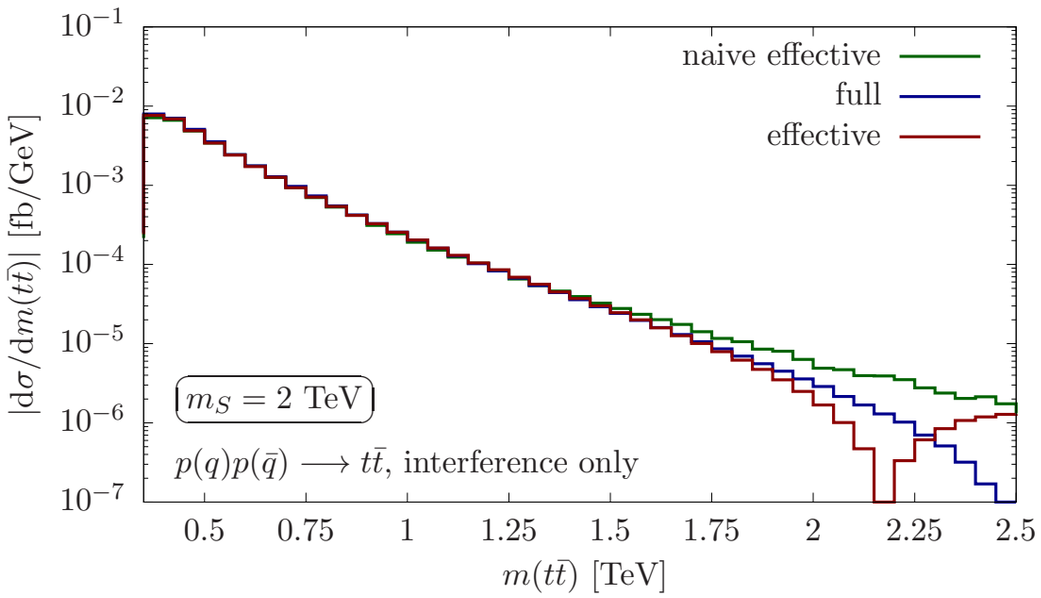
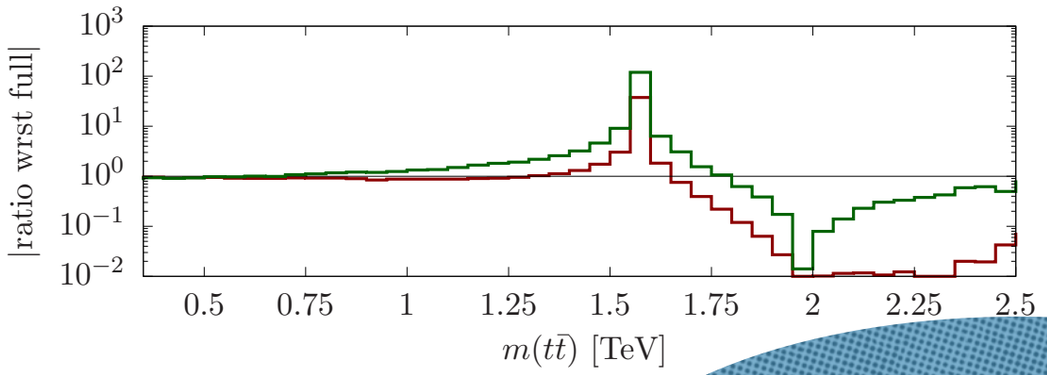
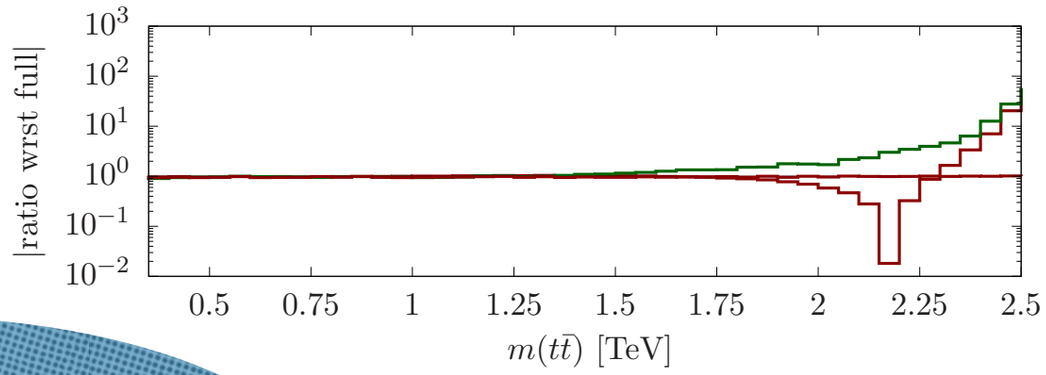


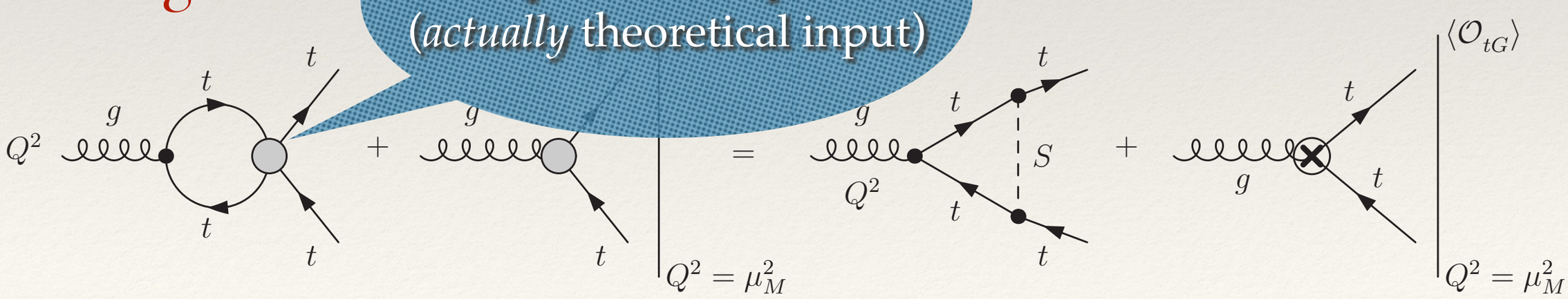






matching is crucial.

probe in 4tops
(*actually* theoretical input)



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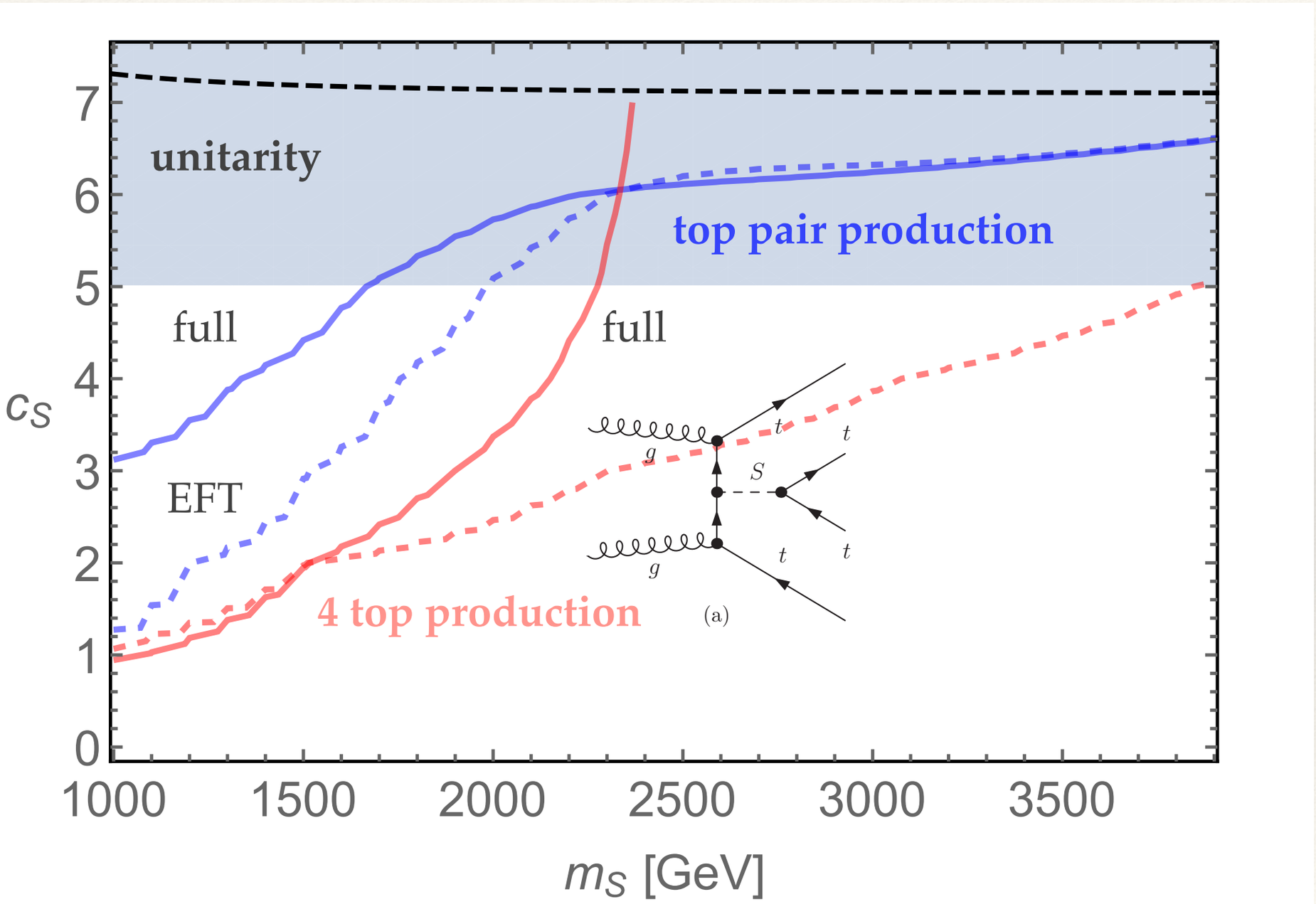

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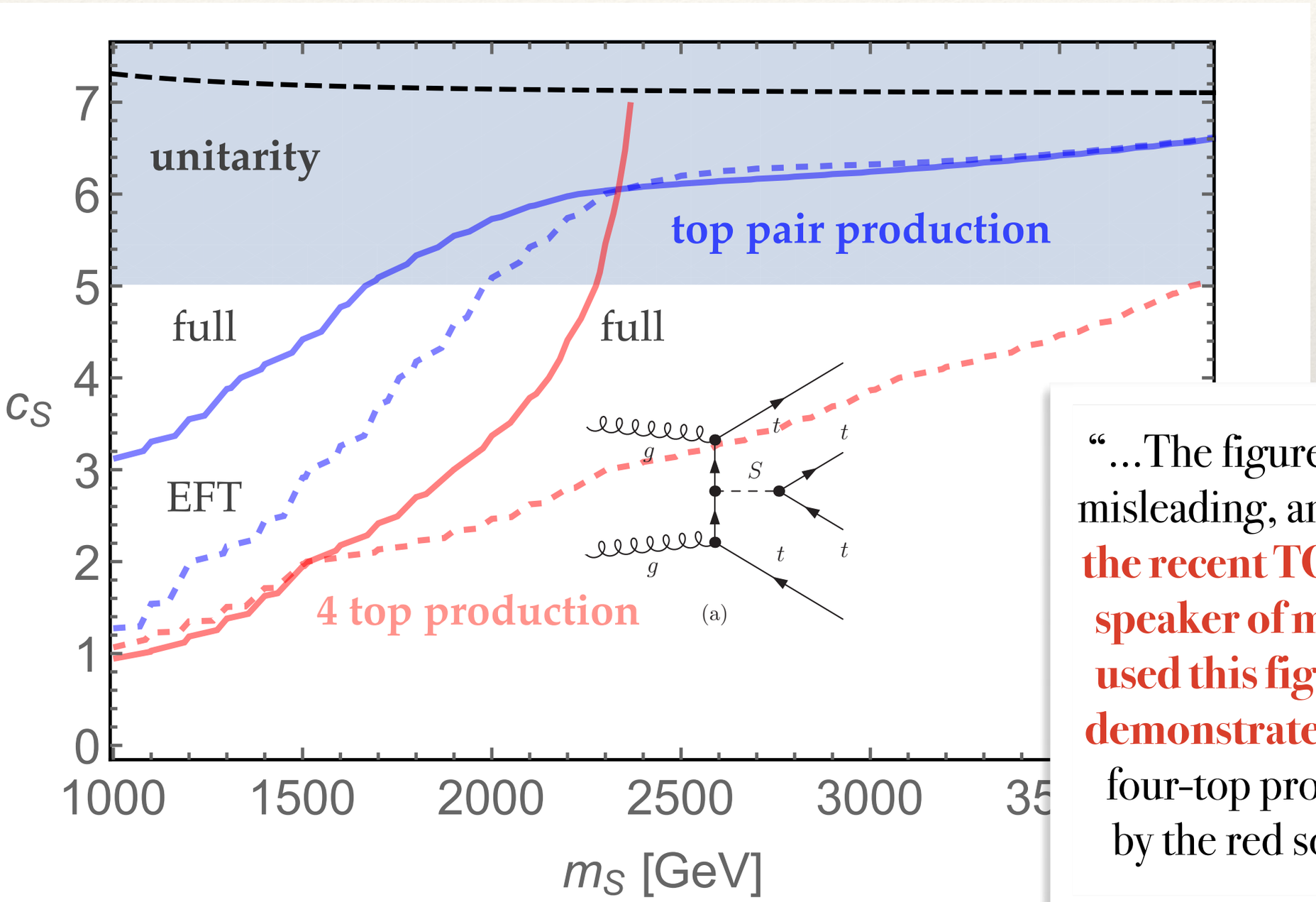
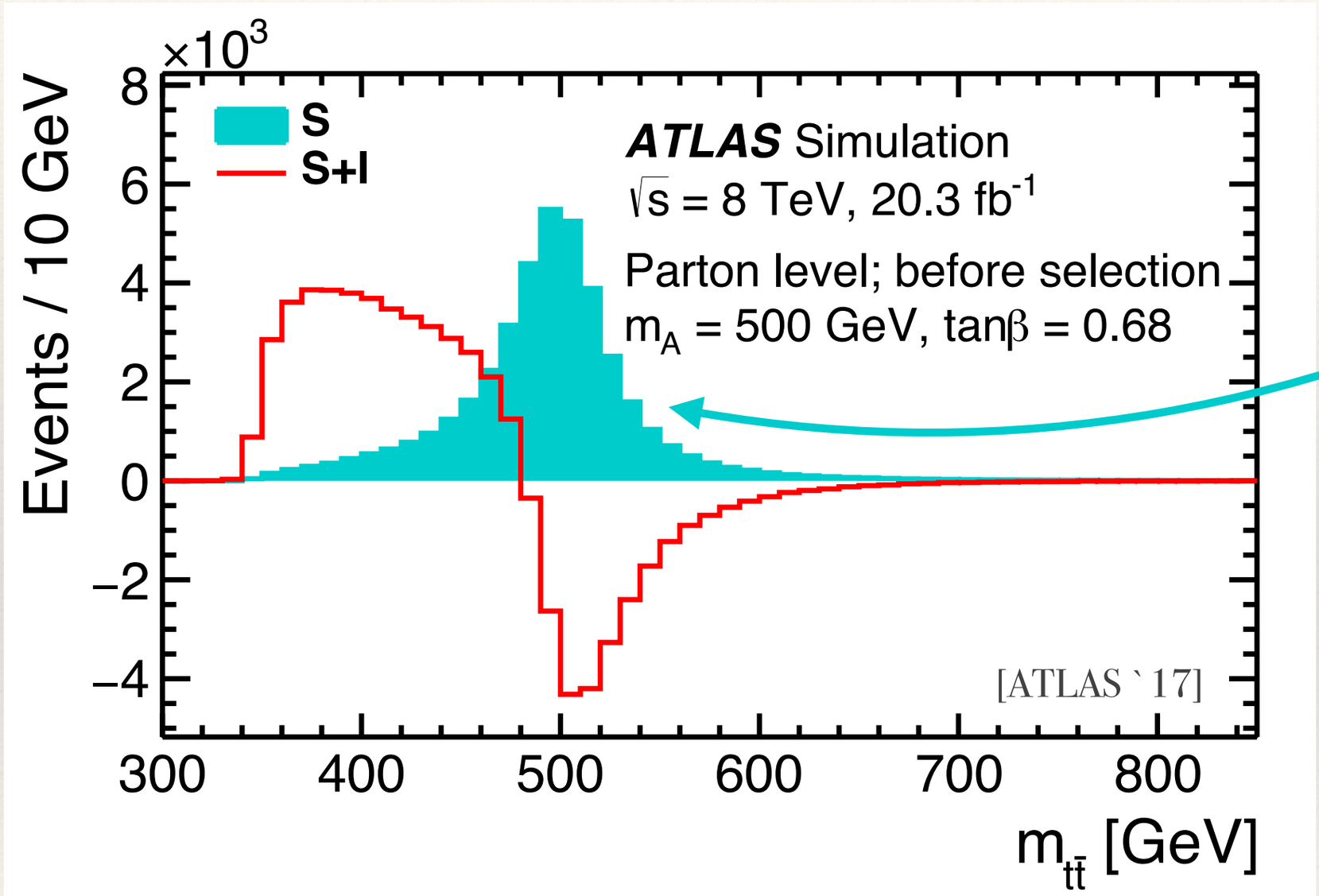


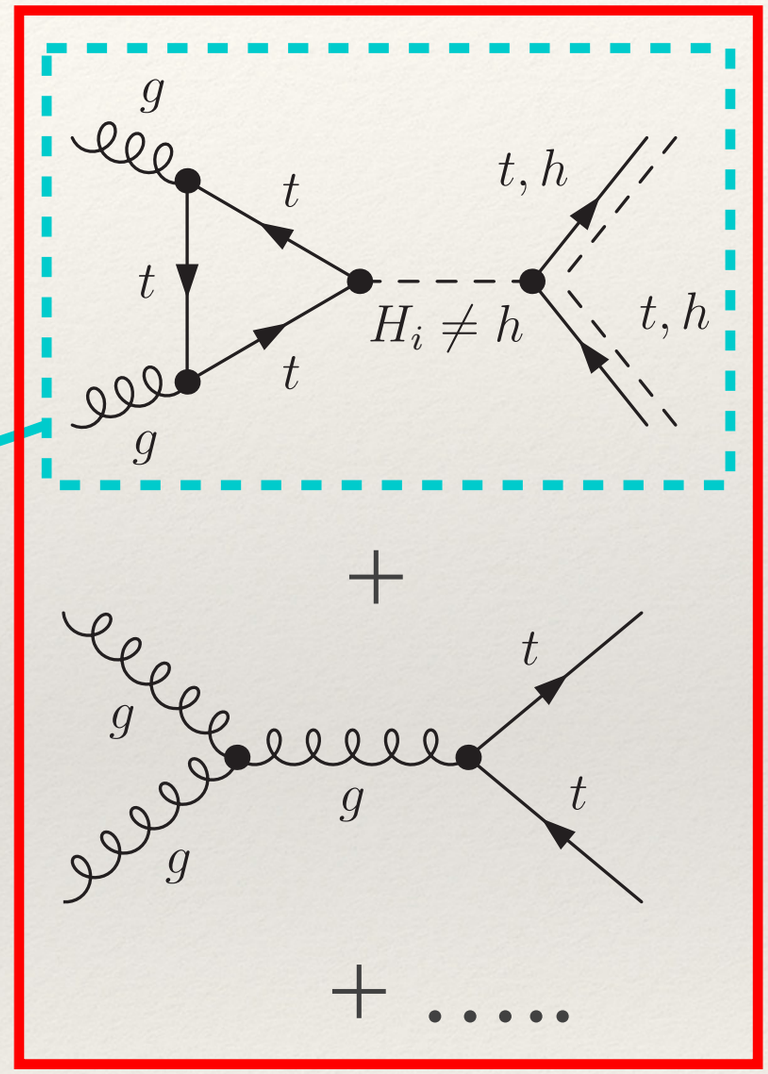
"...The figure is however somewhat misleading, and **I say this because at the recent TOP 2019 workshop, a speaker of multi-top production used this figure as an evidence to demonstrate that the EFT fails** for four-top production, as indicated by the red solid/dashed curves."

Top caveats for light resonances

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84] [Dicus et al. `94]....





- top resonance searches in Higgs sector extensions with narrow width approximation inadequate!

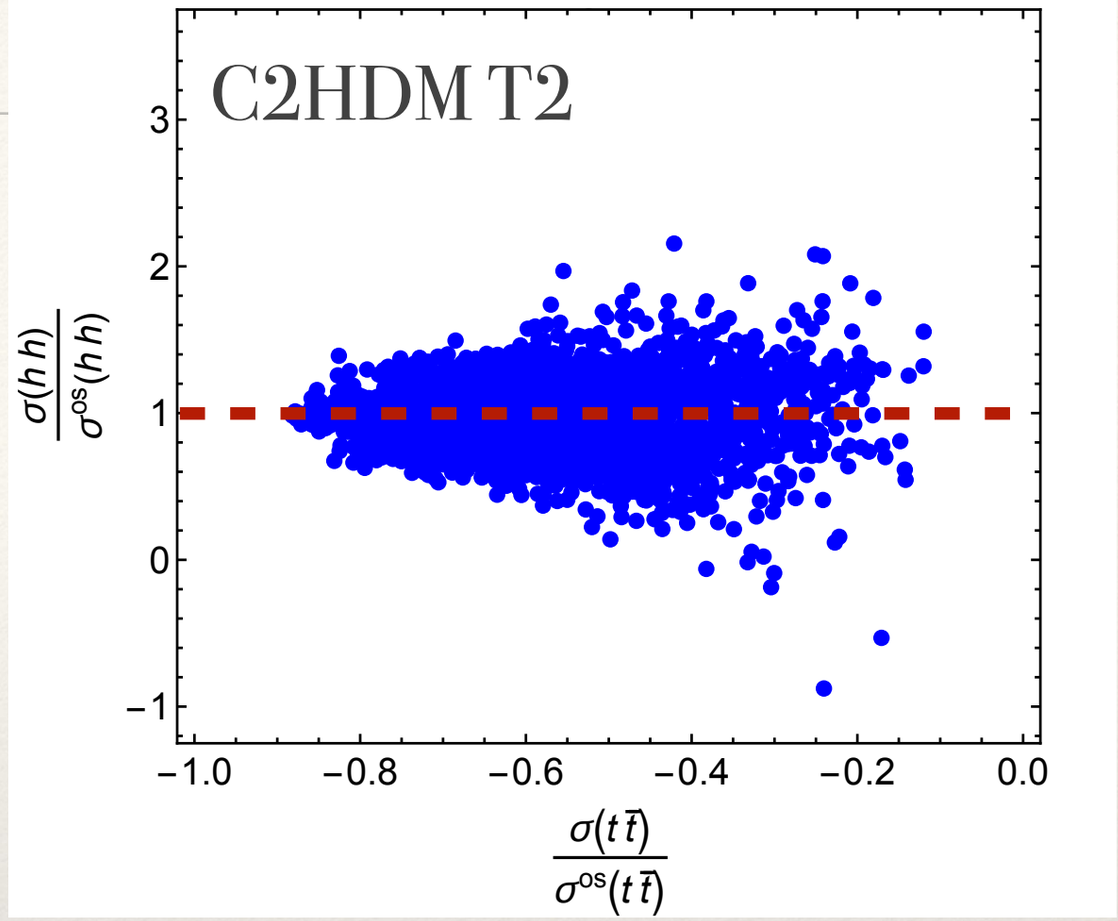
Top caveats for light resonances

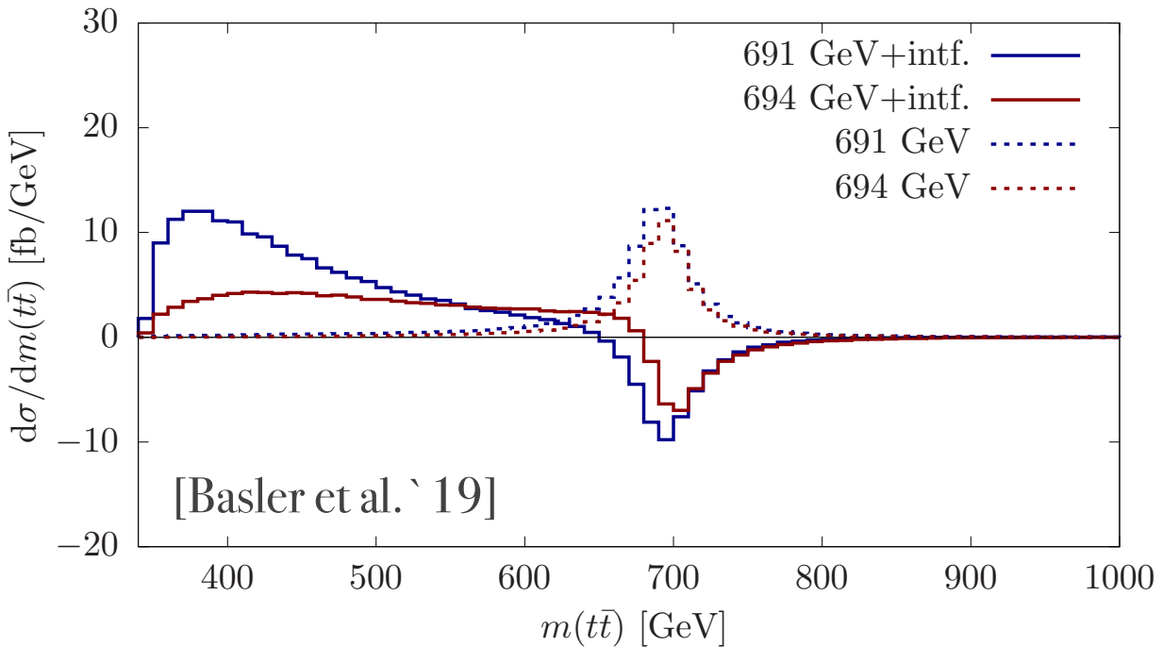
- interference in top final states is a tell-tale story of BSM characteristics

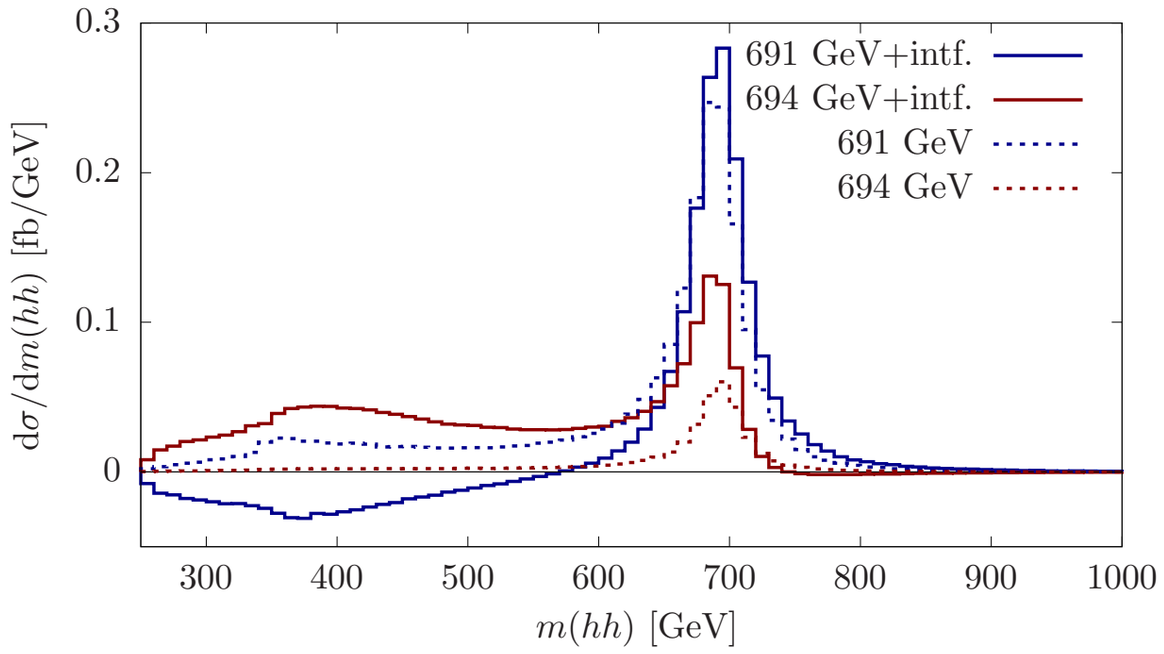
[Carena, Liu` 19]
[Djouadi et al.` 19]
...

- Higgs pairs: top threshold in HH defines discovery potential

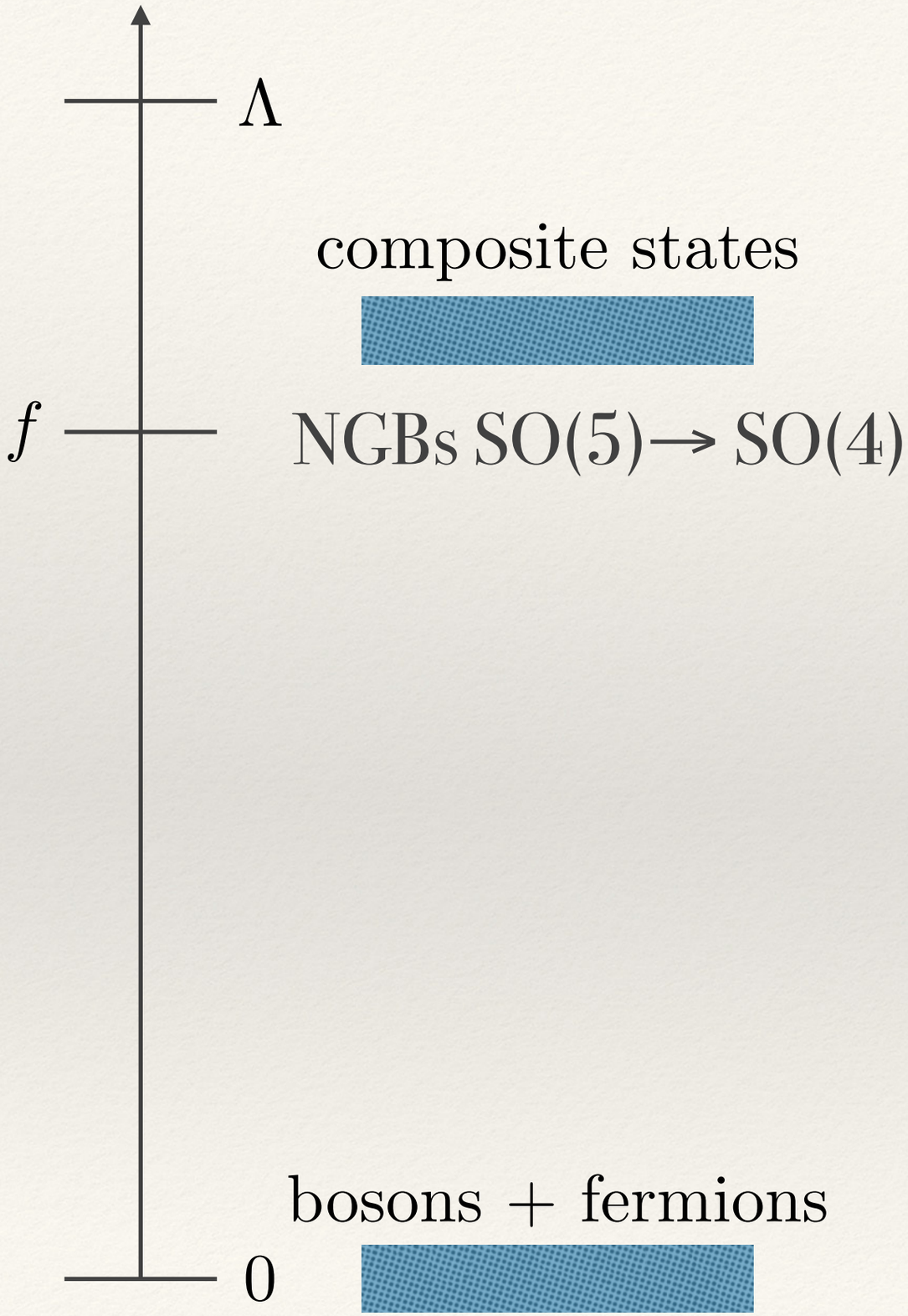
[Baglio et al. ` 19]
[Mühlleitner et al.` 22]







Strong interaction alternatives?



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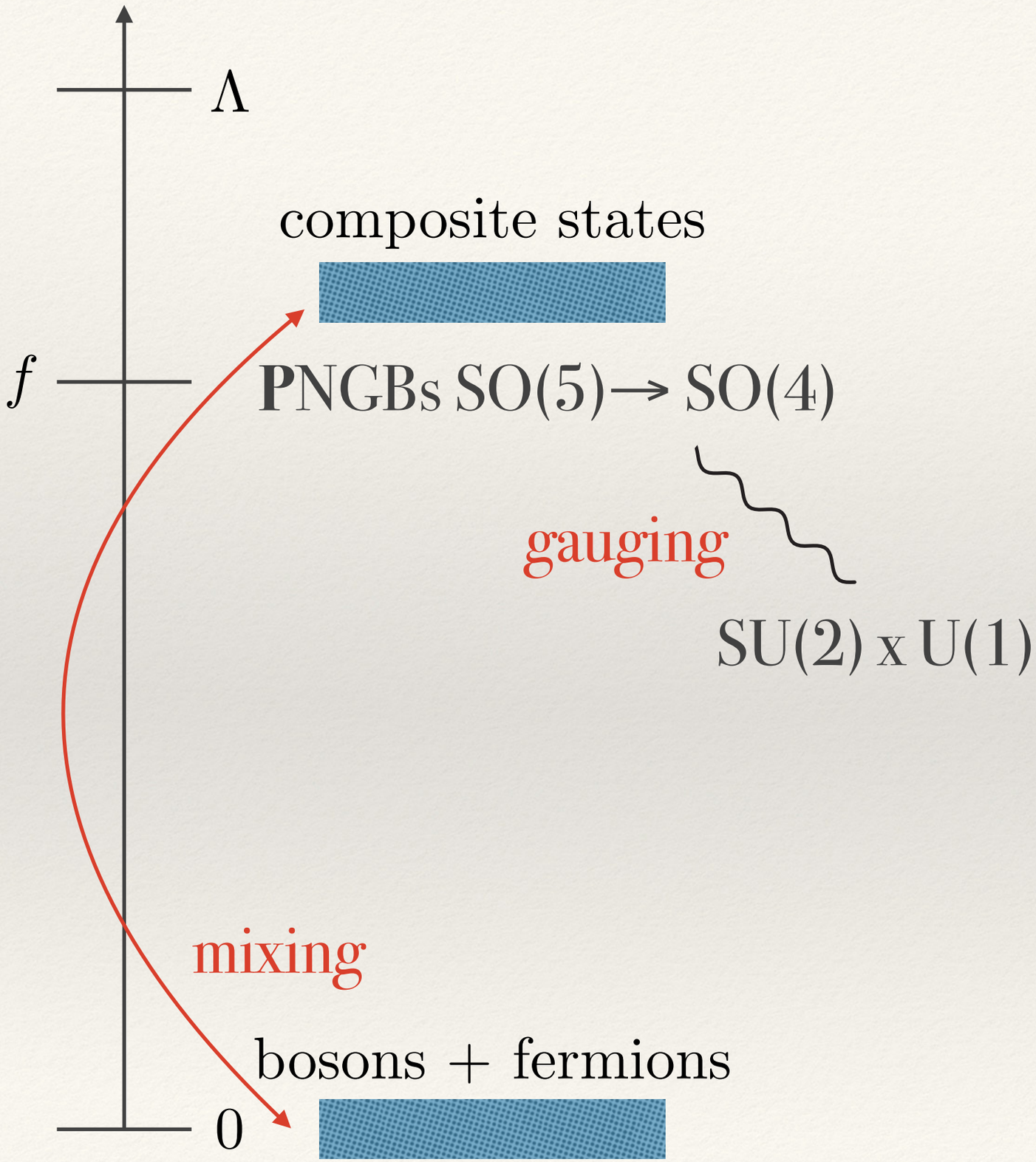

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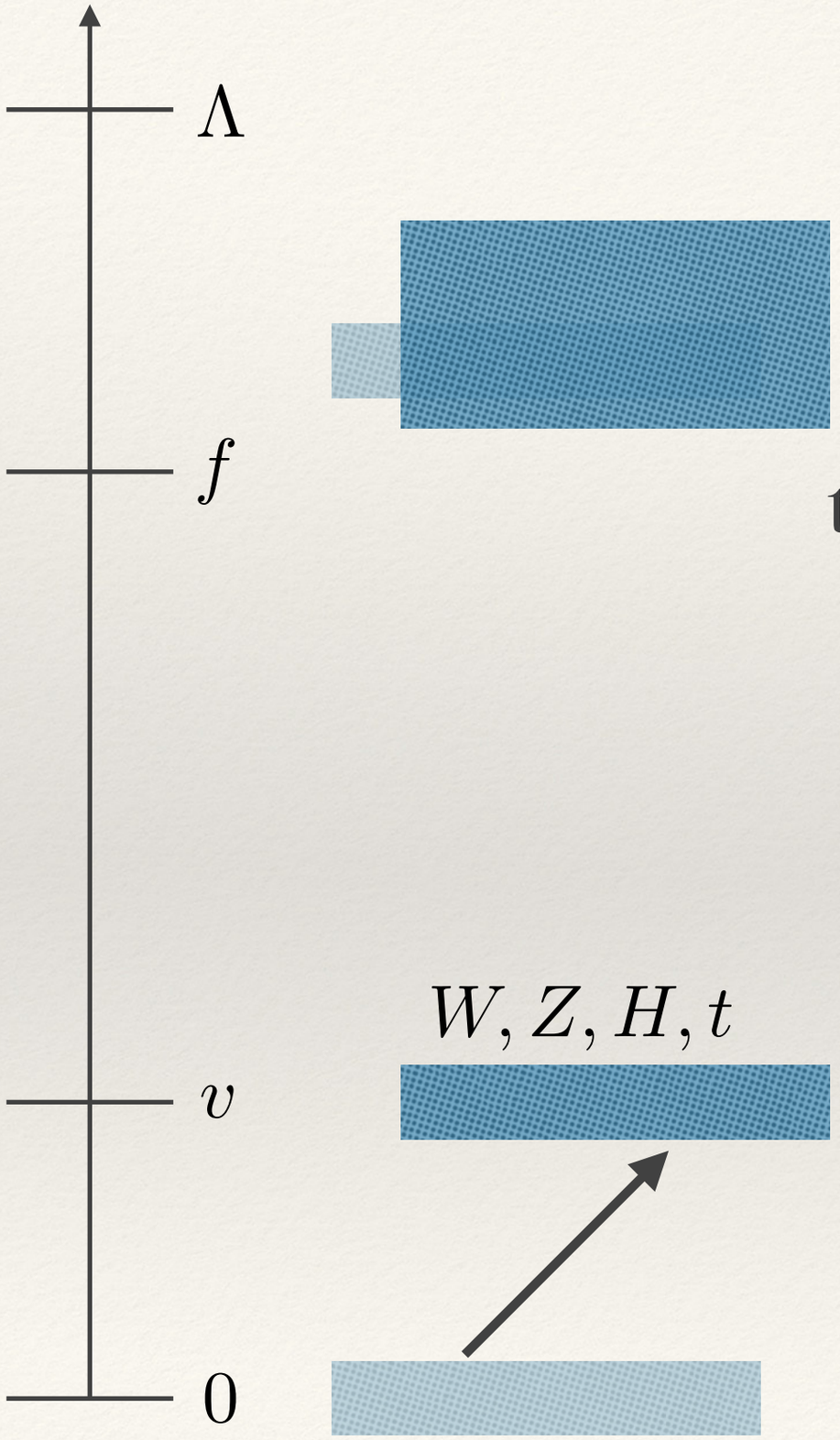
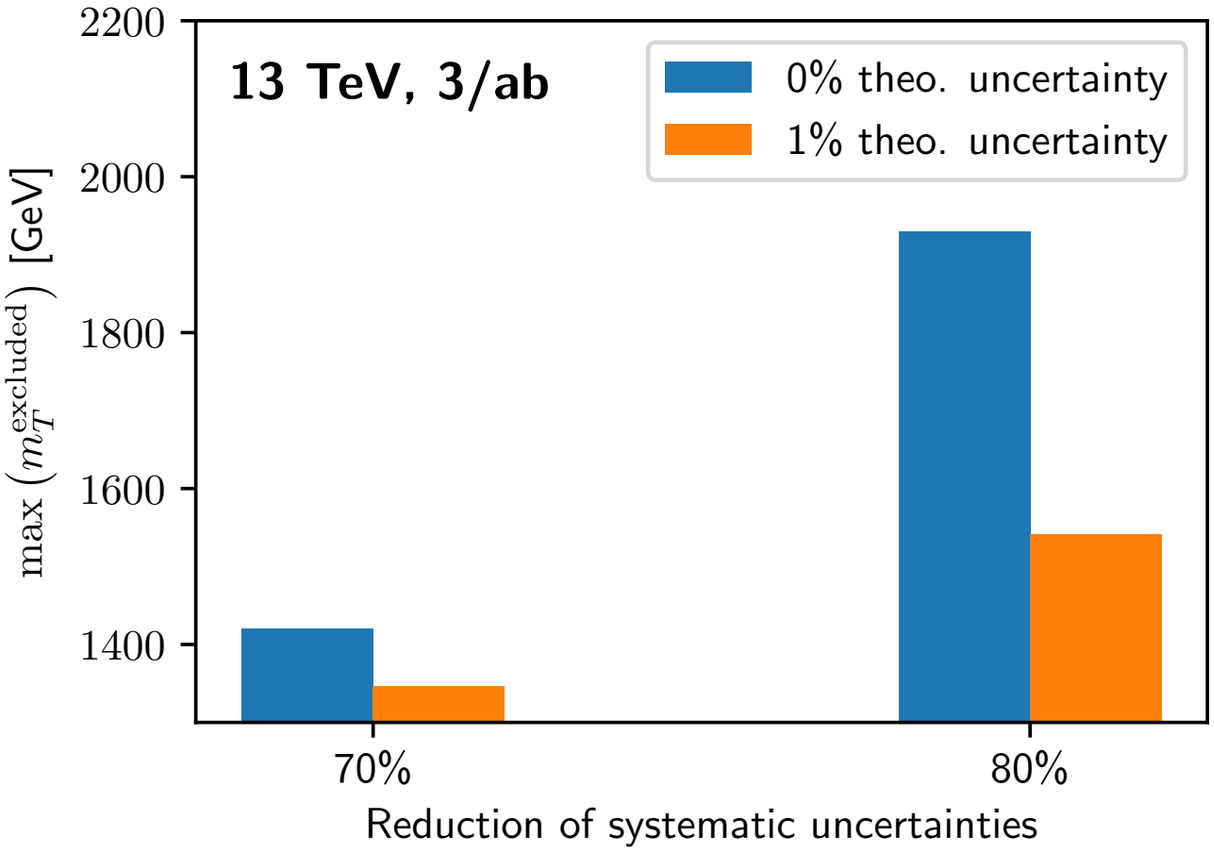


two main model building ingredients

- weak gauging of subgroup
- fermion masses through mixing with baryonic matter [Agashe, Contino, Pomarol `04] [Contino, da Rold, Pomarol `06]
- minimal phenomenological $SO(5) \to SO(4) \simeq SU(2)^2$ e.g. [Contino `10]...
- realistic scenarios more complicated [Ferretti `14]

[Brown et al. `20]

indirect top sector constraints



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

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

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

↓ model correlations

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

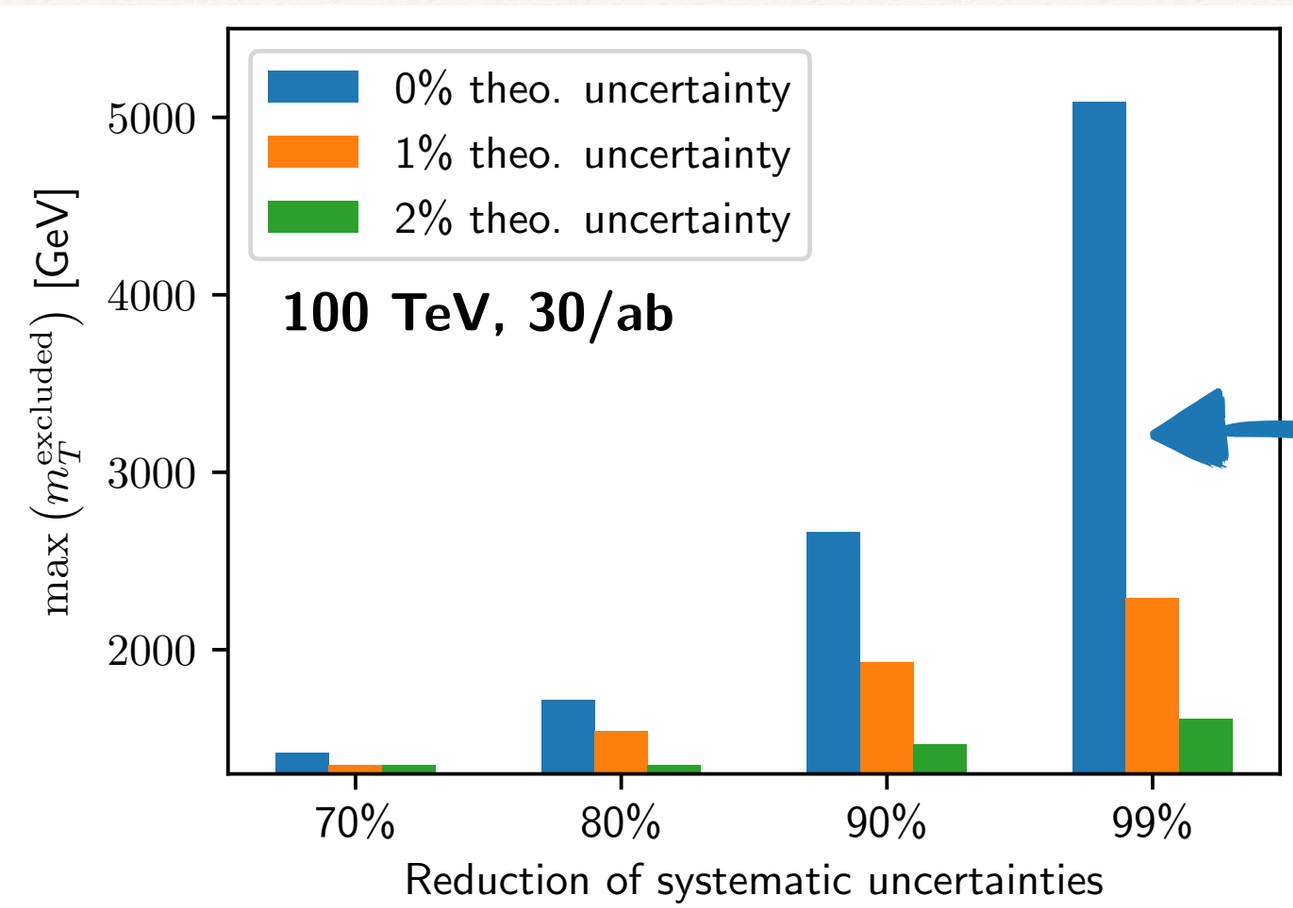
- existing direct top partner constraints in the range of $\gtrsim 1.5$ TeV compatible

  [Matsedonskyi, Panico, Wulzer `15]

  ...

- theoretical uncertainties is main sensitivity limitation, adding additional channels does not change this picture dramatically

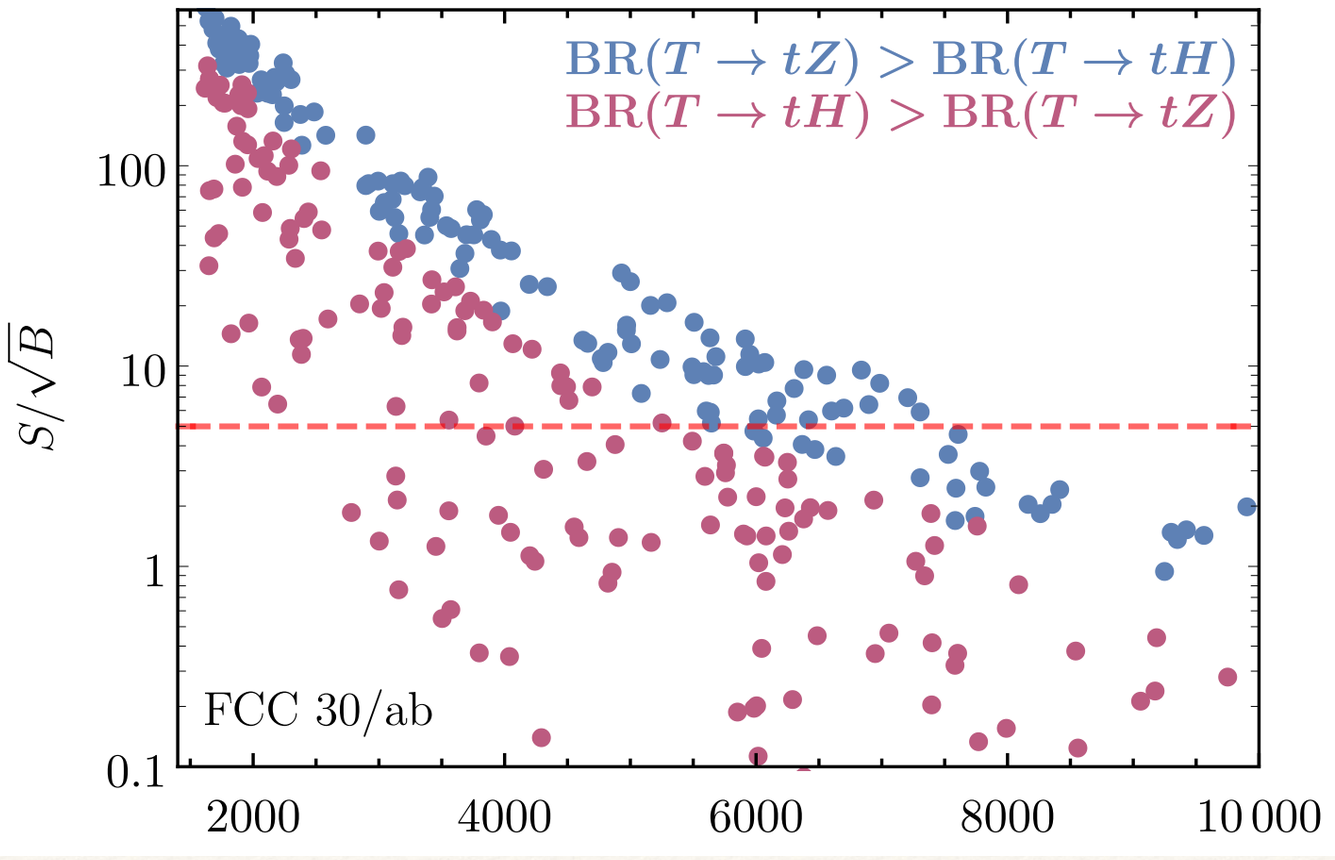
indirect top sector constraints

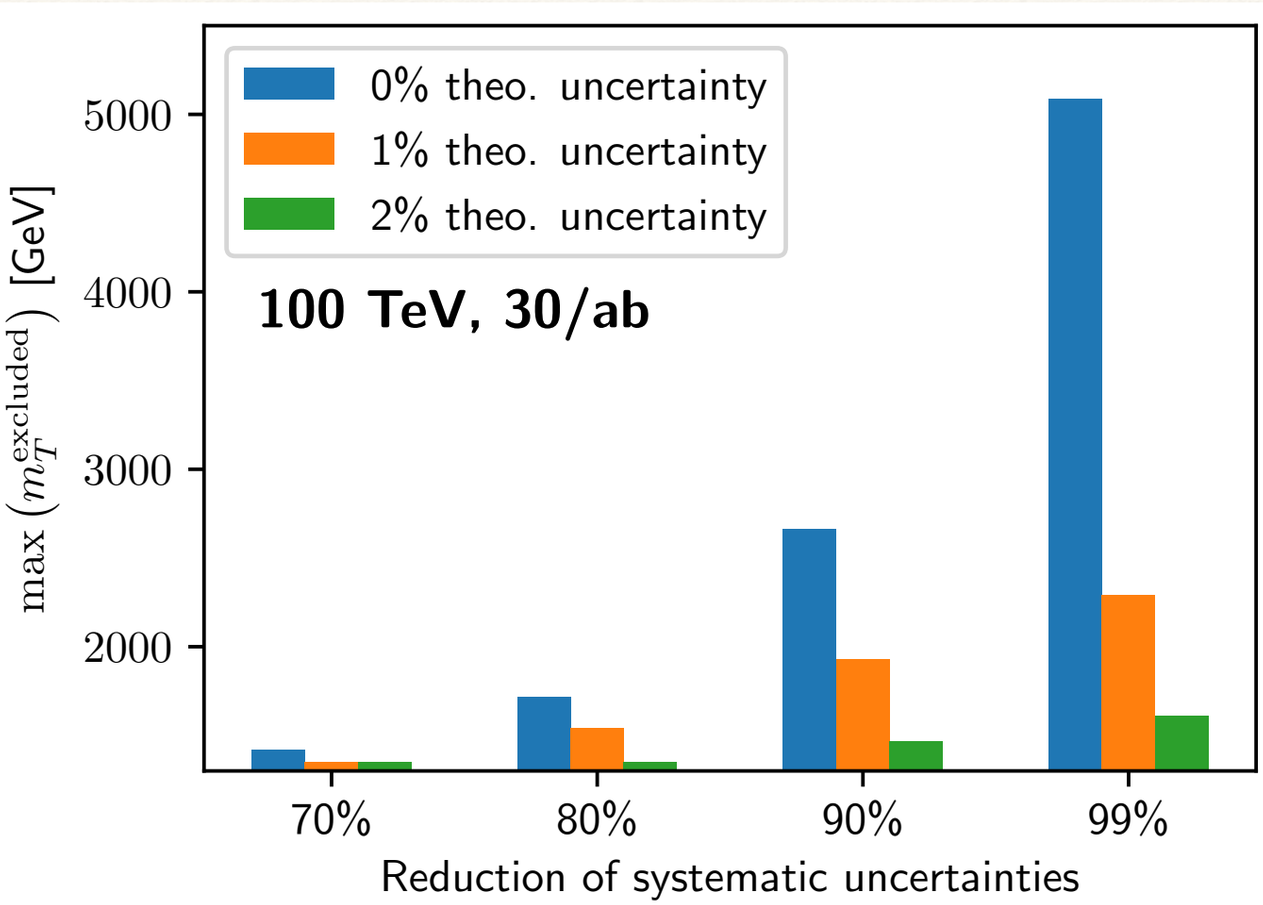


- optimistic extrapolations provide <u>indirect</u> sensitivity up to about 5 TeV

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

[Barducci et al. `17]
[Li et al. `19]
...

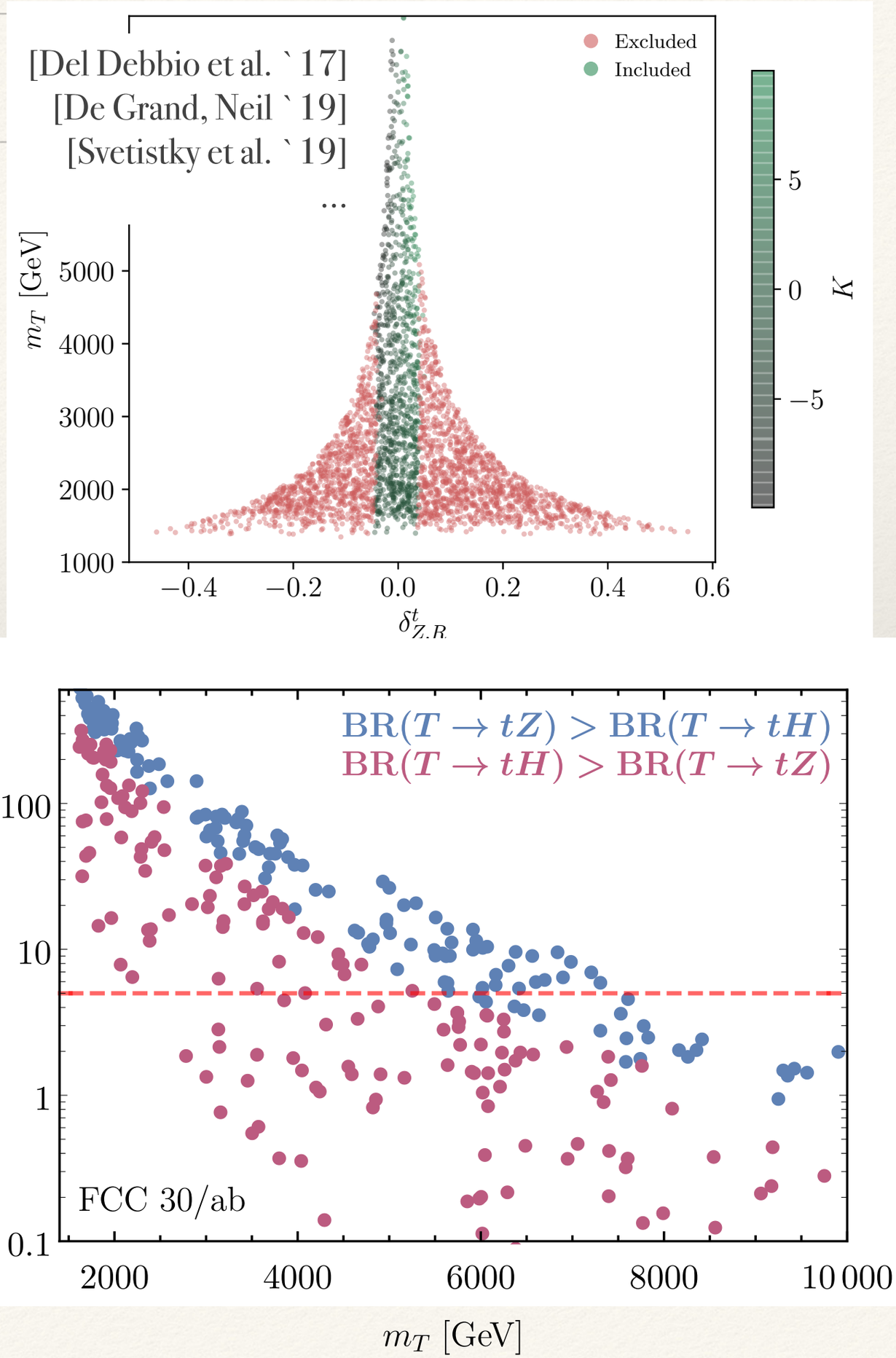




- direct top partner searches in electroweak channels providing direct sensitivity up to 8 TeV

[Barducci et al. `17]
[Li et al. `19]
...

- no necessarily a discovery tool, but important for spectroscopy



- *no new physics yet, but*
  - top physics occupies a major space in the electroweak landscape

resonant extension *elw. baryogenesis* *CP violation* *…*

  - less ad-hoc descriptions of the weak scale crucially centre around extensions/modifications of the top quark sector
- *theoretical and experimental more resilient than ever*
  - EFT vs full models vs uncertainties vs discovery sensitivity
  - new tools increase sensitivity often beyond naive extrapolations

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Where's BSM?

Top Physics in 2022

Summary

- *no new physics yet, but*
  - top physics occupies a major space in the electroweak landscape

resonant extension | *elw. baryogenesis* | *CP violation* | *…*

  - less ad-hoc descriptions of the weak scale crucially centre around extensions/modifications of the top quark sector
- *theoretical and experimental more resilient than ever*
  - EFT vs full models vs uncertainties vs discovery sensitivity
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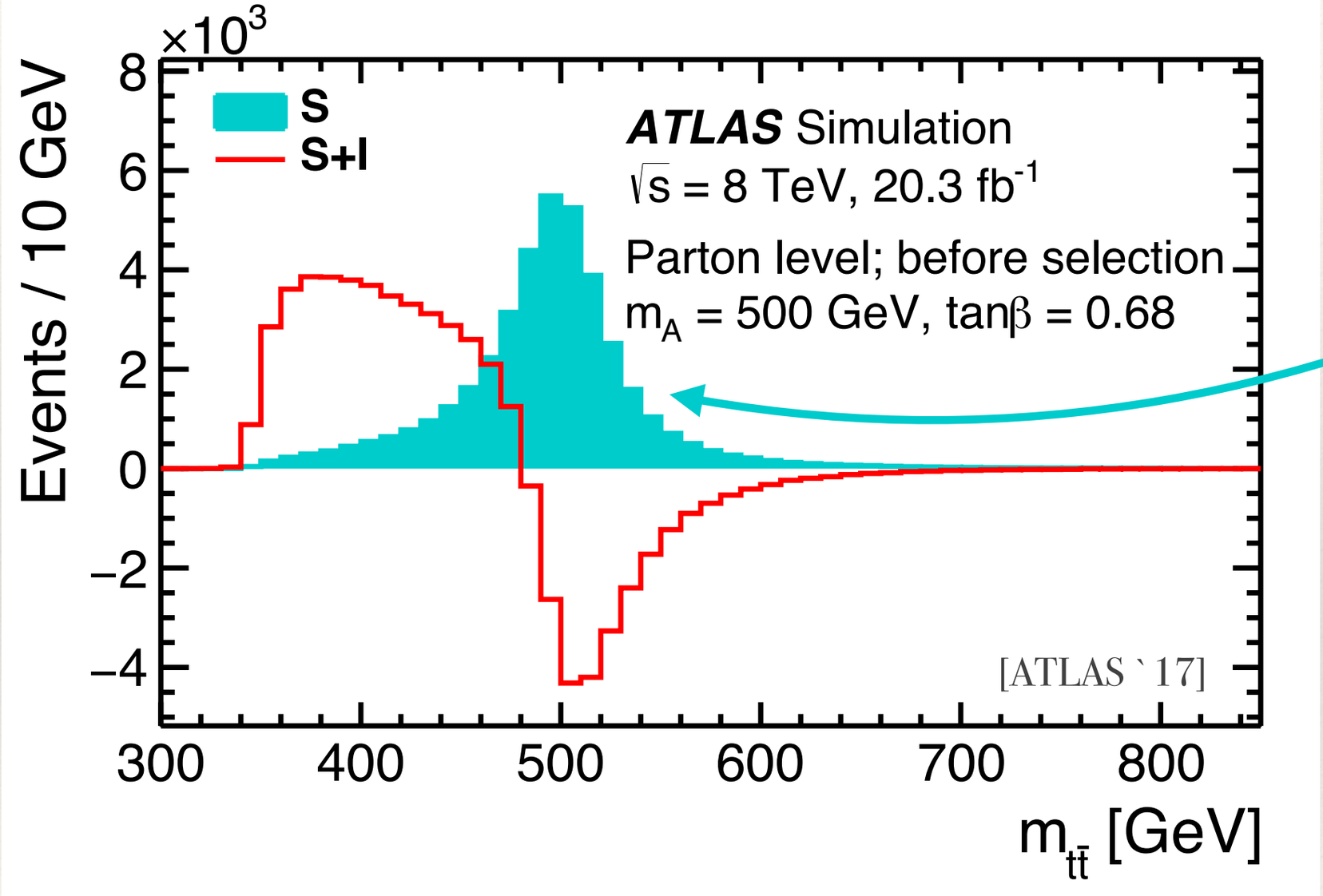
Where's BSM? — Top physics might well hold the answer

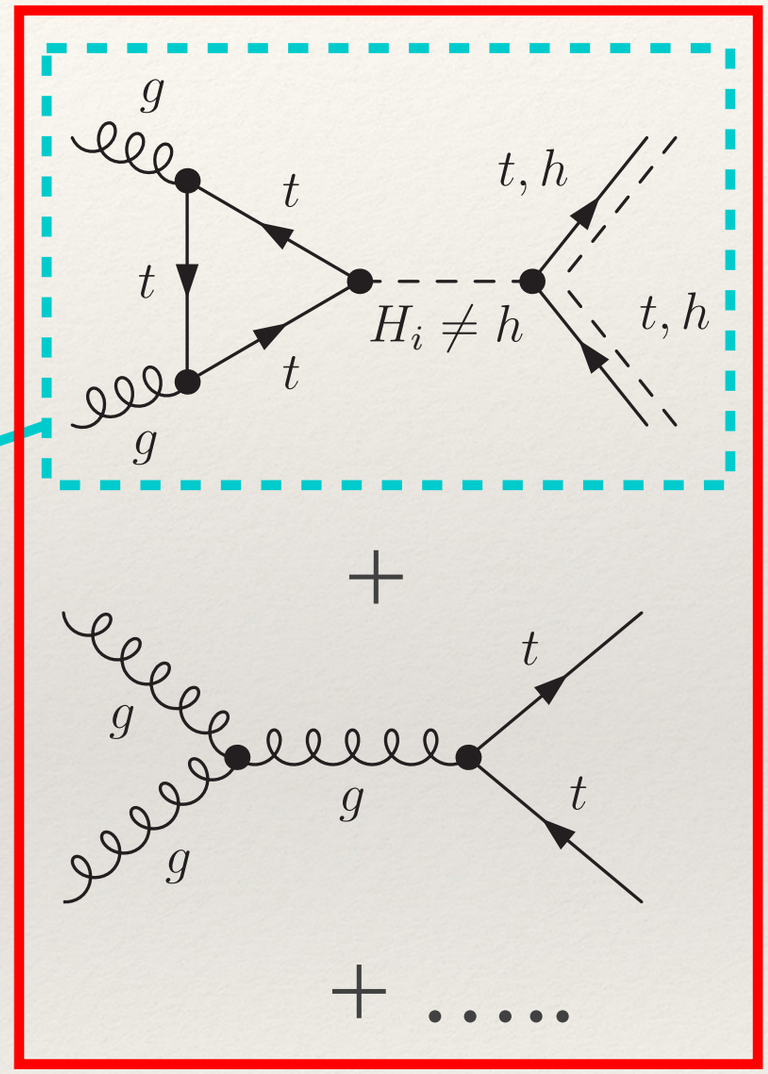
…but there's more work to do.

top caveats

- large interference effects of Higgs "signal" with QCD background

[Gaemers, Hoogeveen `84] [Dicus et al. `94]....





- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

special role of tops

- destructive interference in top final states can be correlated with excess in HH?

- phenomenologically viable regions exhibit compressed spectra: **signal-signal interference**