Christoph Englert

Top quarks as a window to new physics

effective improvements and quantum loopholes

2nd Asian-European Institute

Workshop, Jeju Island

16/11/22

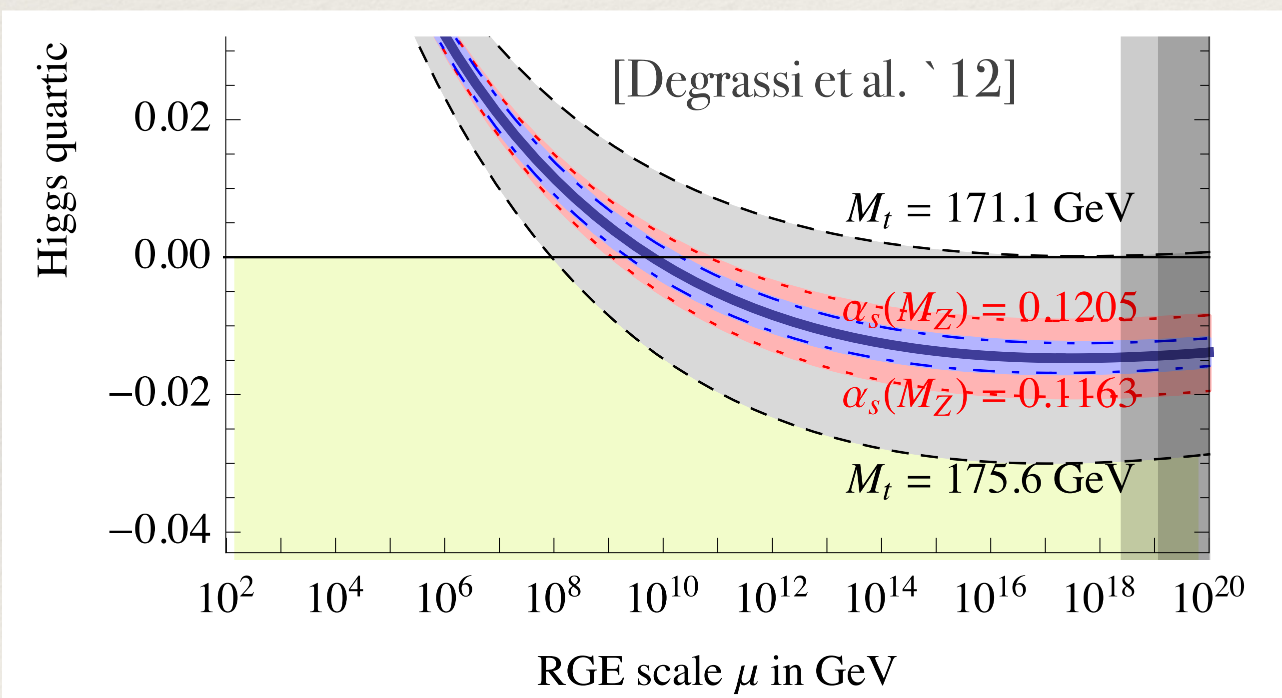
Why the top quark?

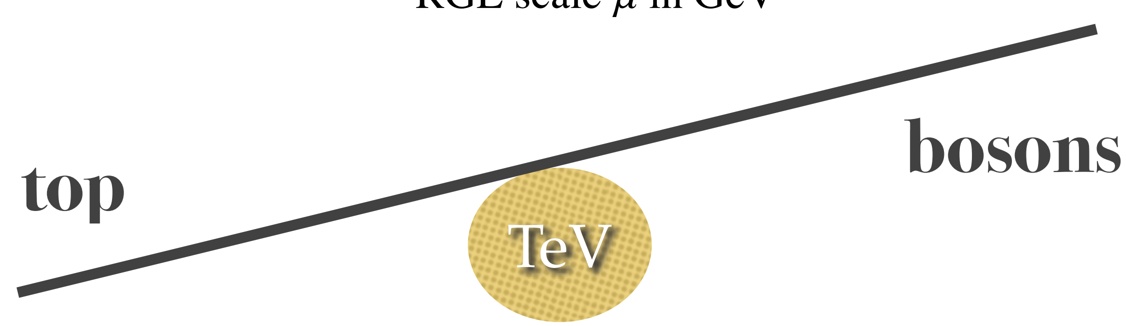
- top quark heavy $m_t \sim v$, strongly coupled, decay before hadronisation

direct handle on properties

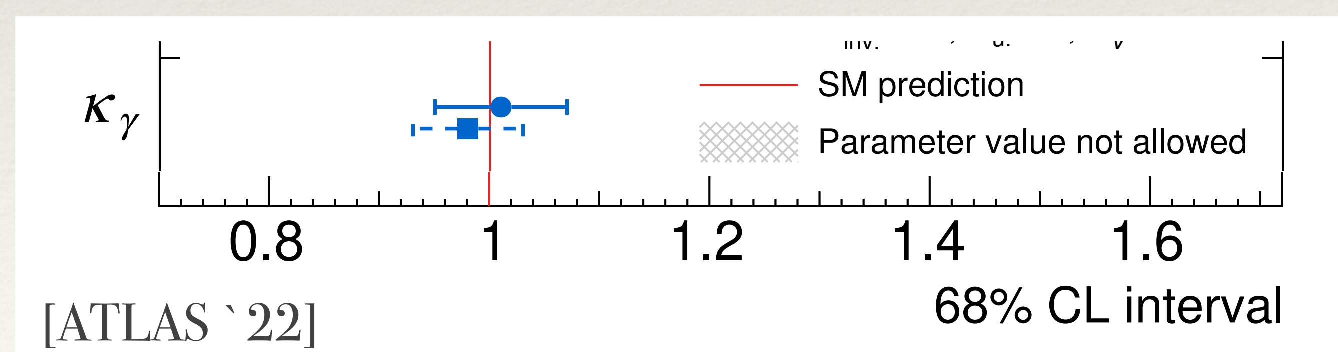
large pull @ weak scale

relevant threshold





- top determines electroweak fit and Higgs precision data
- Stability of weak scale crucially related to top quark properties



…we don't know (yet).

cure theoretical problems
exploit BSM facts (Sakharov…)

understand experimental
correlations as guidance

this talk: Top Quark as MVP

What completes the SM towards the UV?

…we don't know (yet).

cure theoretical problems
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understand experimental
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this talk: Top Quark as MVP

- *Agnostic high scale BSM: ways to improve in the future*
- *Model-specific low scale new physics: top loopholes*

coupling/scale separated BSM physics

Effective Field Theory

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

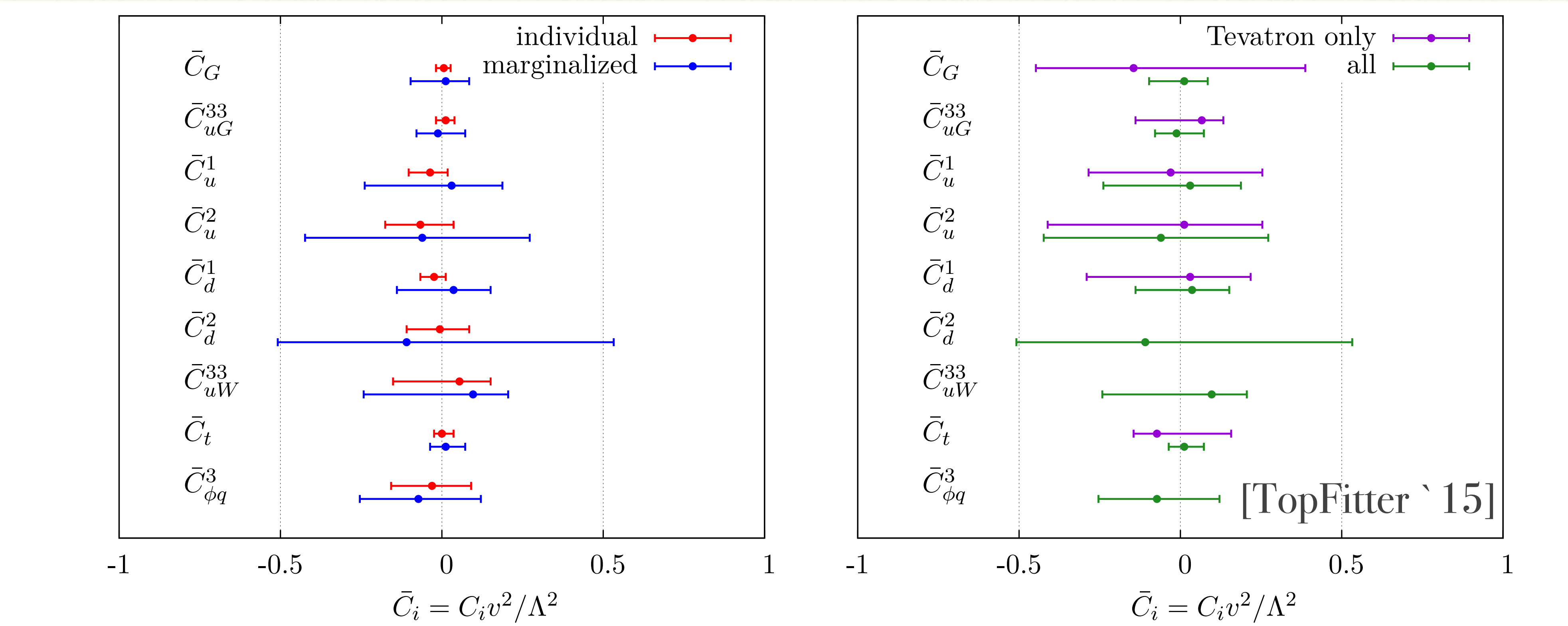
[Buchmüller, Wyler `87]
[Hagiwara, Peccei, Zeppenfeld, Hikasa `87]
[Grzadkowski, Iskrzynski, Misiak, Rosiek `10]

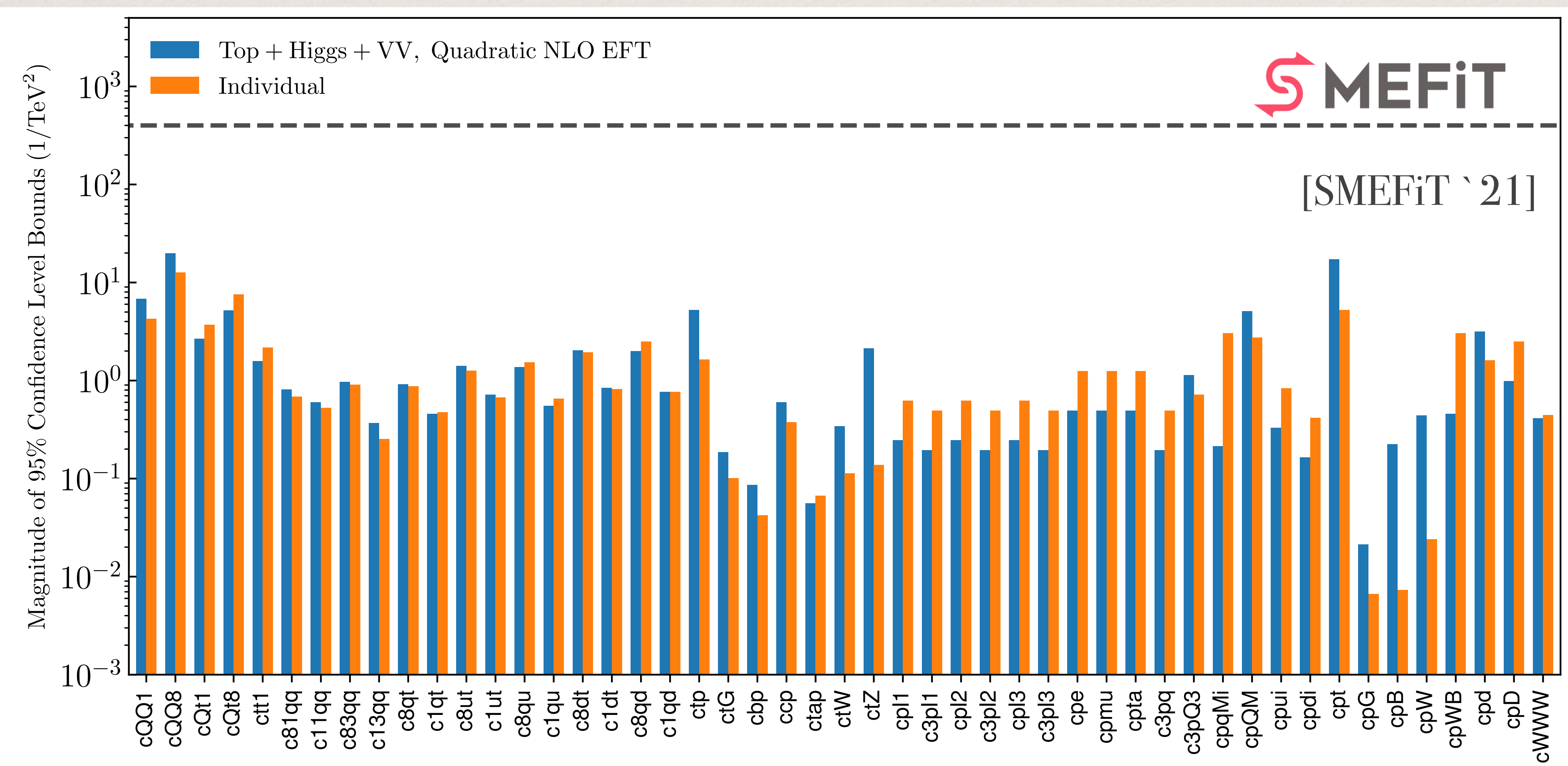
see also Minho's talk

concrete models

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

EFT@LHC





EFT: major thrust after Higgs discovery

proof-of-principle case + N^{x}LO tools

experimental ownership @ R3

Towards high statistics/energy

precision

see also Frank's talk

- *loops/legs/resummation*
- tops @N^{2}LO [Czakon, Mitov `13]...
- Higgs @ N^{3}LO [Anastasiou et al. `15]...
- Higgs pairs @NLO ... [Borowka et al. `16]...

- *robust BSM classification*
- data driven techniques
- machine learning
- anomaly detection

(HL-)LHC/ FCC sensitivity

coupling/scale separated BSM physics

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rich particle-level event structure

concrete models

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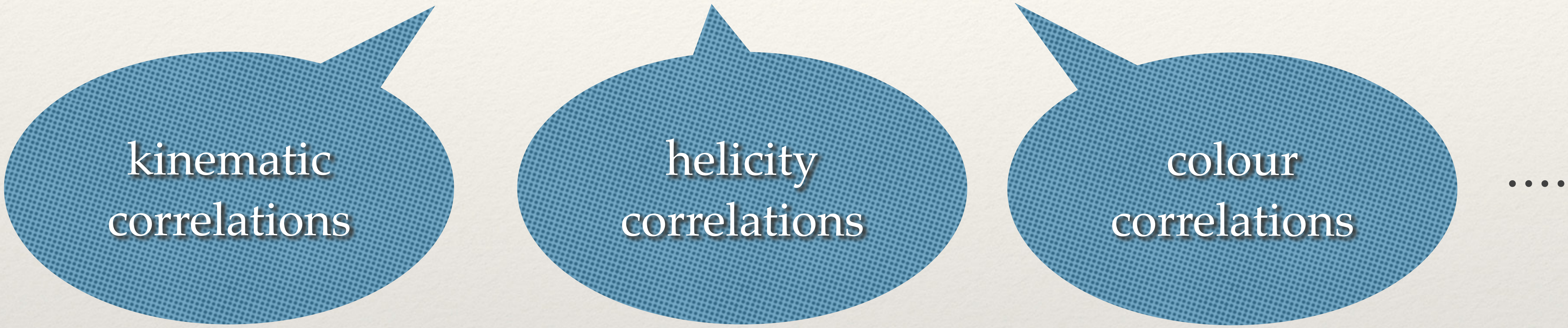
theory

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



monetarising correlations

theory

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

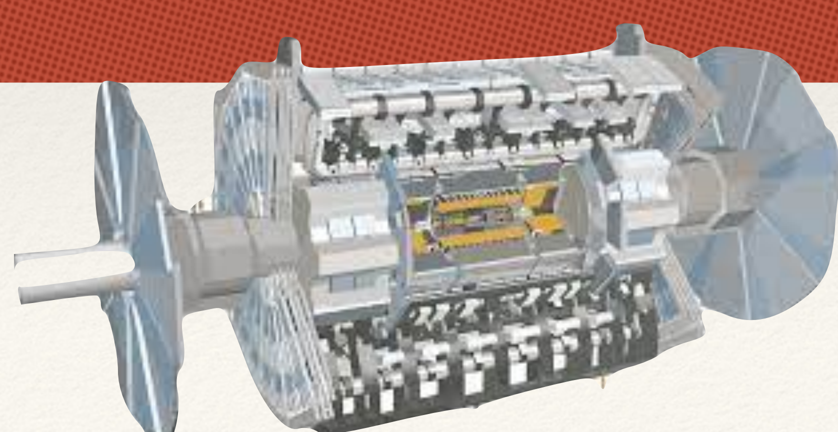
kinematic correlations

helicity correlations

colour correlations

....

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



experiment

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

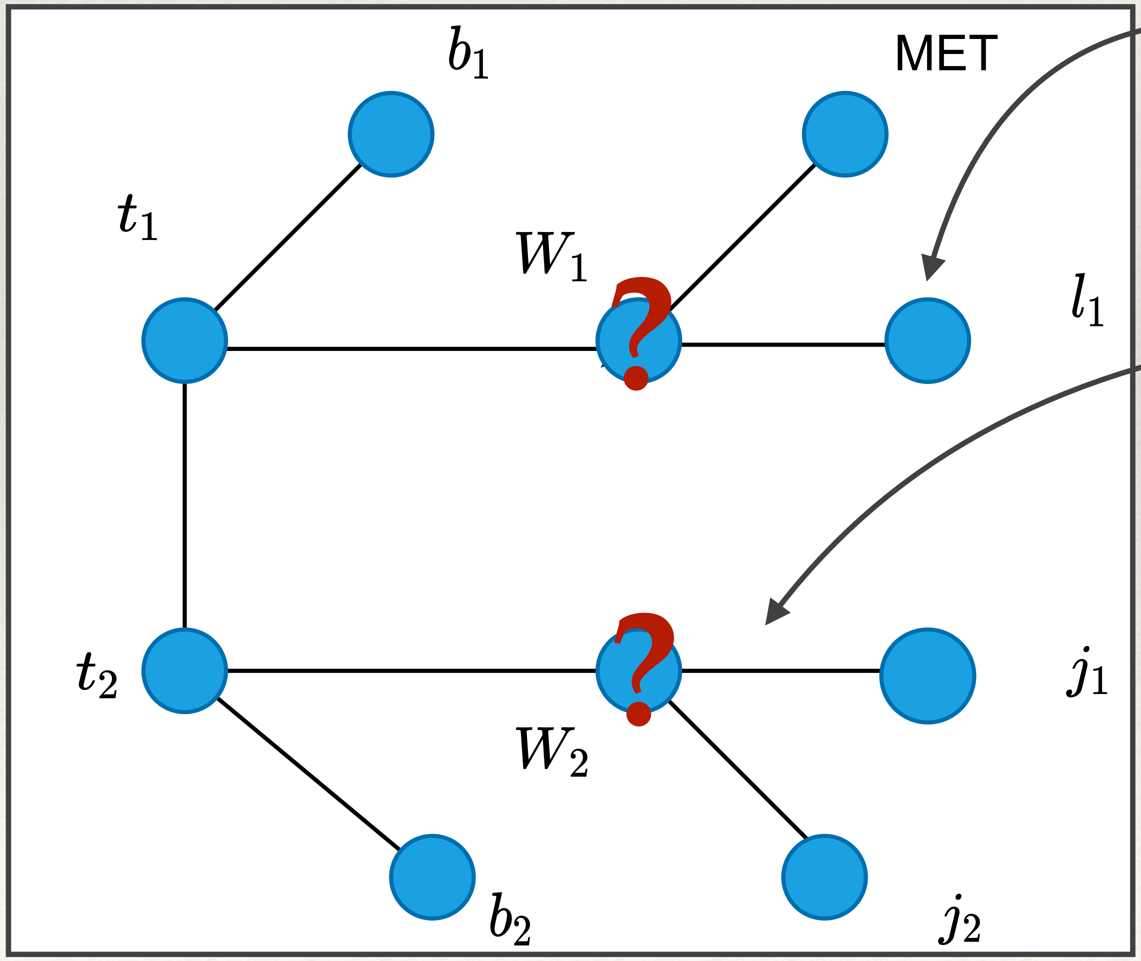
- Can we impart Feynman-graph correlations on measurements to enhance BSM sensitivity? *Graph Neural Networks*

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

see also Mihoko's talk

GNN EFT analysis of semi-leptonic top pair production

[Atkinson et al. `21]



nodes with *features*

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

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]

GNN EFT analysis of semi-leptonic top pairs

supervised training over graph structures to enhance BSM sensitivity

13 relevant operator contributions @ interference-level $\sim \frac{2c_i}{\Lambda^2}\,\mathrm{Re}(\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{d6})$

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traditional approach

identify fiducial region + multi-dimensional fit to differential distributions e.g. [CMS-TOP-16-008]

Distribution	Observable
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_t^h\rvert}$	$\lvert y_t^h\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_t^l\rvert}$	$\lvert y_t^l\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_{t\bar{t}}\rvert}$	$\lvert y_{t\bar{t}}\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,h}}$	$p_\perp^{t,h}$
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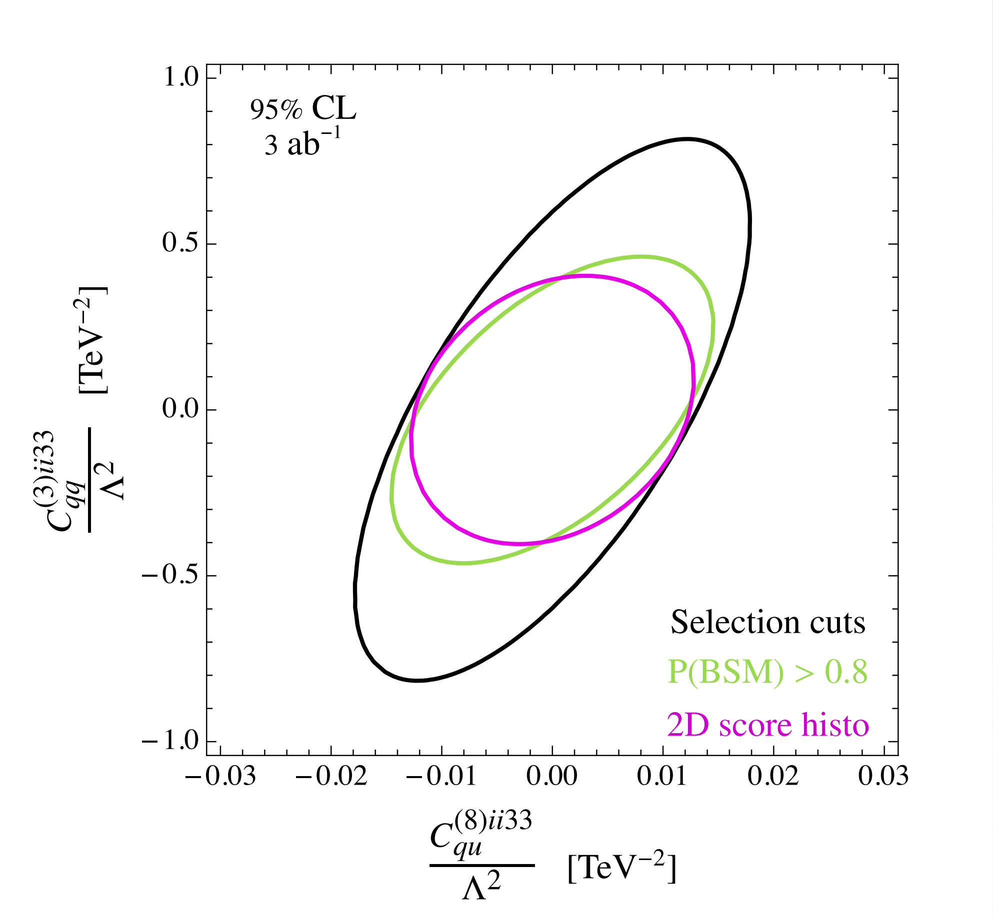
GNN-improved approach

(i) GNN discrimination of multi-class problem

(ii) fit based on NN score



scalability ☹

[Atkinson et al. `21]

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GNN-improved approach

(i) GNN discrimination of multi-class problem

(ii) luminosity-optimised NN output event selection, minimising SM probability

scalability reduced to operator multiplicity

🙂

(iii) traditional fit

[Atkinson et al. `21]

GNN EFT analysis of semi-leptonic top pairs

supervised training over graph structures to enhance BSM sensitivity

13 relevant operator contributions @ interference-level $\sim \frac{2c_i}{\Lambda^2}\,\mathrm{Re}(\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{d6})$

- large improvement attainable
  exclusive phase space correlations
- no improvement when inclusive selections determine sensitivity
- expect further improvement when including model correlations
- pivot uncertainties through GANs

[Louppe, Kagan, Cranmer ` 16]
[CE, Galler, Harris, Spannowsky ` 18]

fractional improvement vs CMS-TOP-16-008

	$2.3\ \mathrm{fb}^{-1}$		$3\ \mathrm{ab}^{-1}$	
	Individual	Profiled	Individual	Profiled
$\bar{C}_G$	0.07%	14.53%	0.07%	11.72%
$\bar{C}_{\varphi q}^{(3)33}$	33.74%	34.16%	33.73%	33.82%
$\bar{C}_{uG}^{33}$	28.29%	32.12%	28.28%	30.76%
$\bar{C}_{uW}^{33}$	34.86%	35.36%	34.85%	35.57%
$\bar{C}_{qq}^{(1)i33i}$	3.50%	3.52%	3.50%	3.23%
$\bar{C}_{qq}^{(3)i33i}$	4.35%	4.31%	4.35%	5.01%
$\bar{C}_{qq}^{(3)ii33}$	63.83%	–	63.83%	72.06%
$\bar{C}_{qu}^{(8)33ii}$	3.45%	3.45%	3.45%	3.39%
$\bar{C}_{qu}^{(8)ii33}$	3.74%	3.80%	3.74%	3.77%
$\bar{C}_{ud}^{(8)33ii}$	4.62%	4.63%	4.62%	4.64%
$\bar{C}_{uu}^{i33i}$	3.38%	3.41%	3.38%	3.83%
$\bar{C}_{lq}^{(3)ii33}$	–	–	10.57%	40.26%

coupling/scale separated BSM physics

Effective Field Theory

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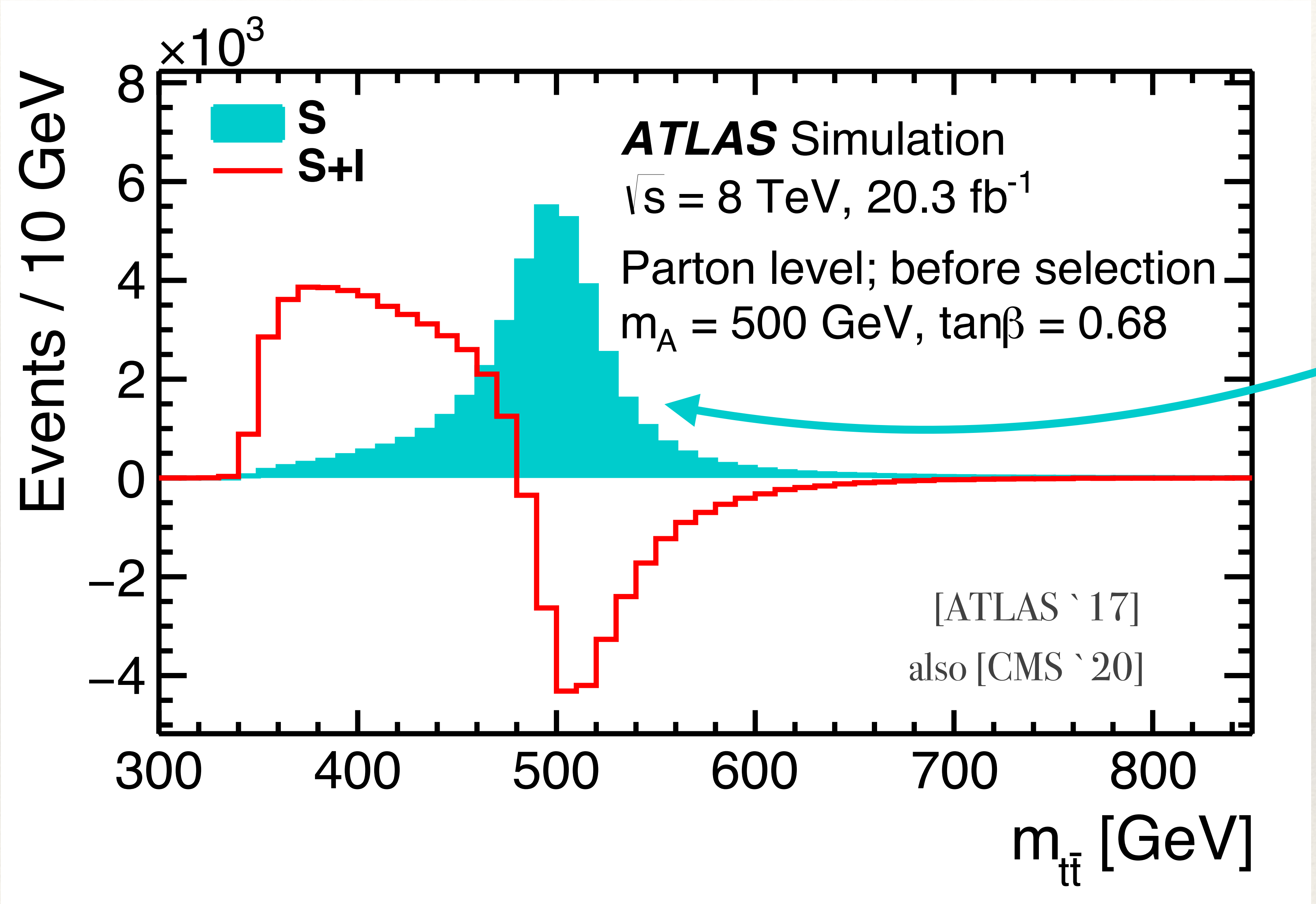
concrete models

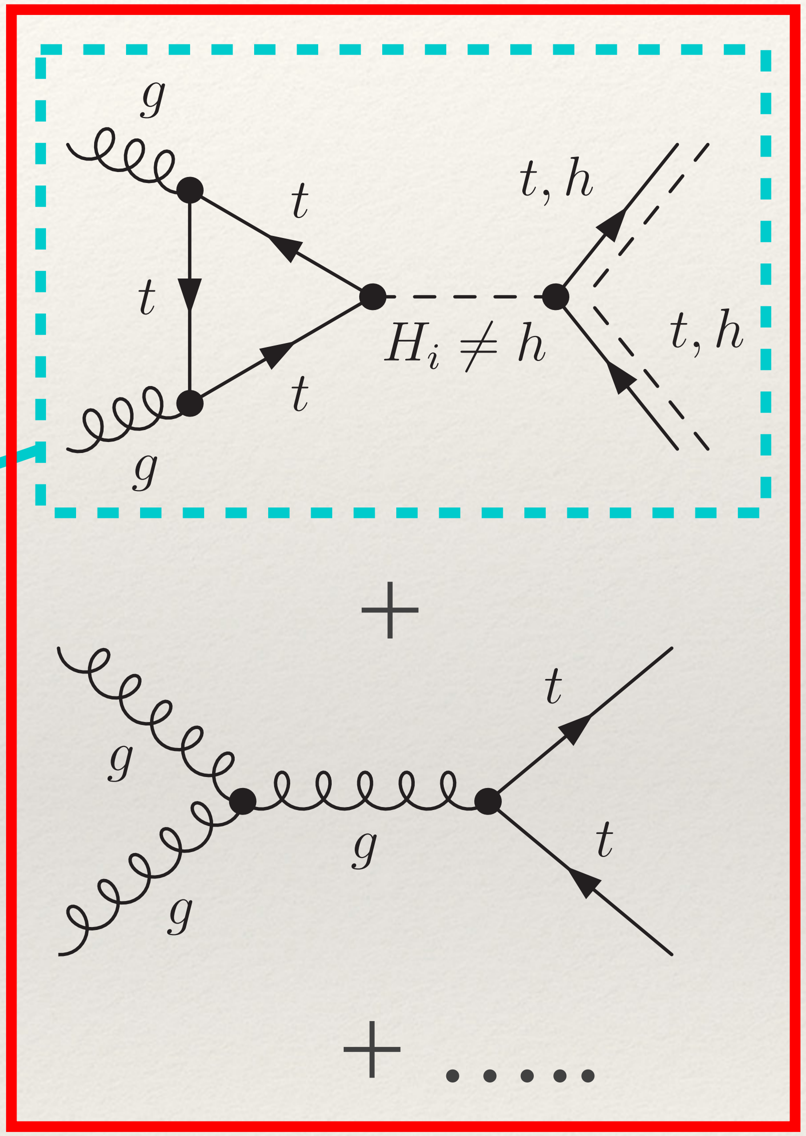
- extended SMEFT
- ($\mathbb{C}$) Higgs portals
- 2HDMs
- simplified models
- compositeness….

top-philic states arise in any low-scale BSM scenario!

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

[Gaemers, Hoogeveen `84] [Dicus et al. `94] [Carena, Liu `16]…





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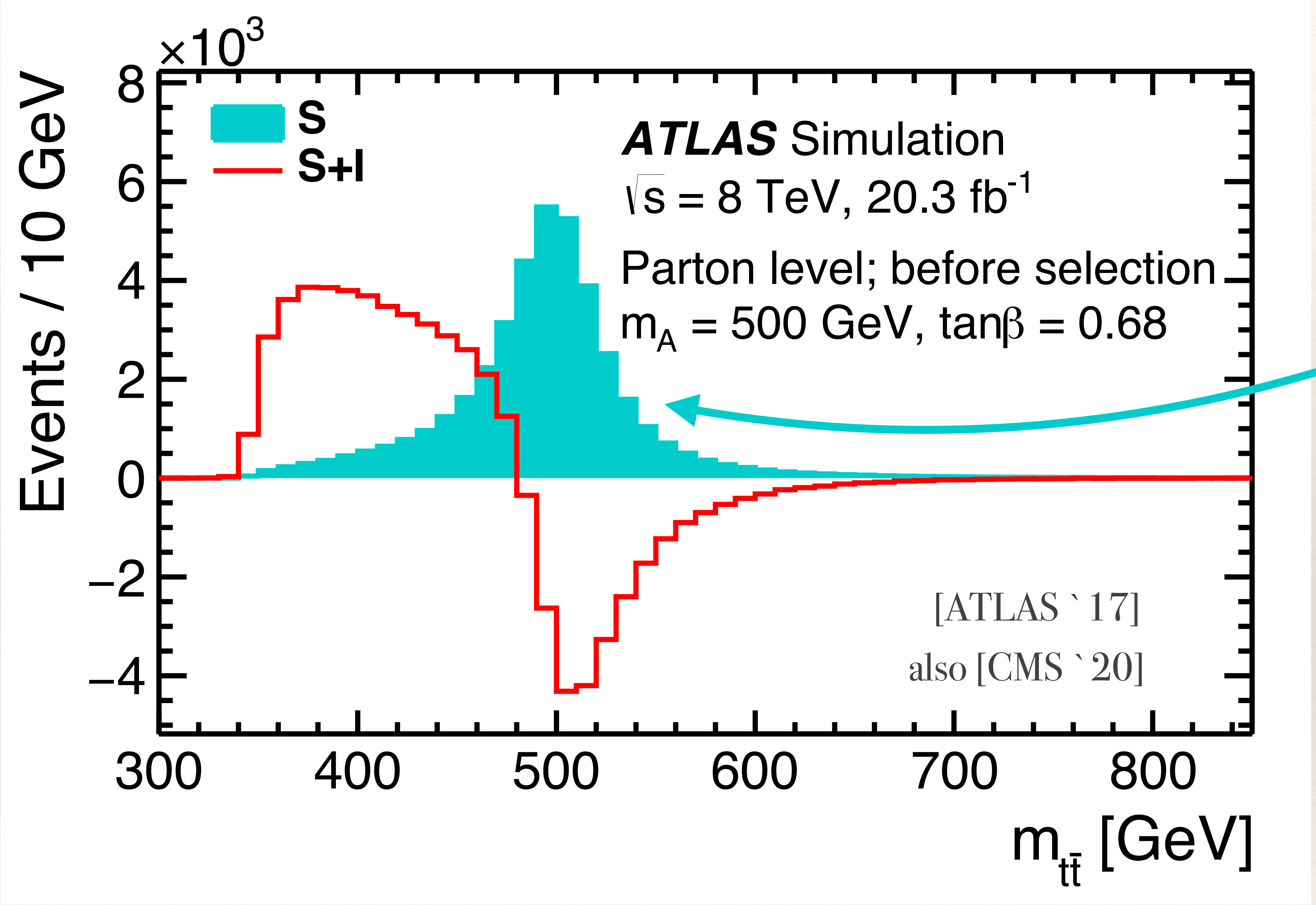
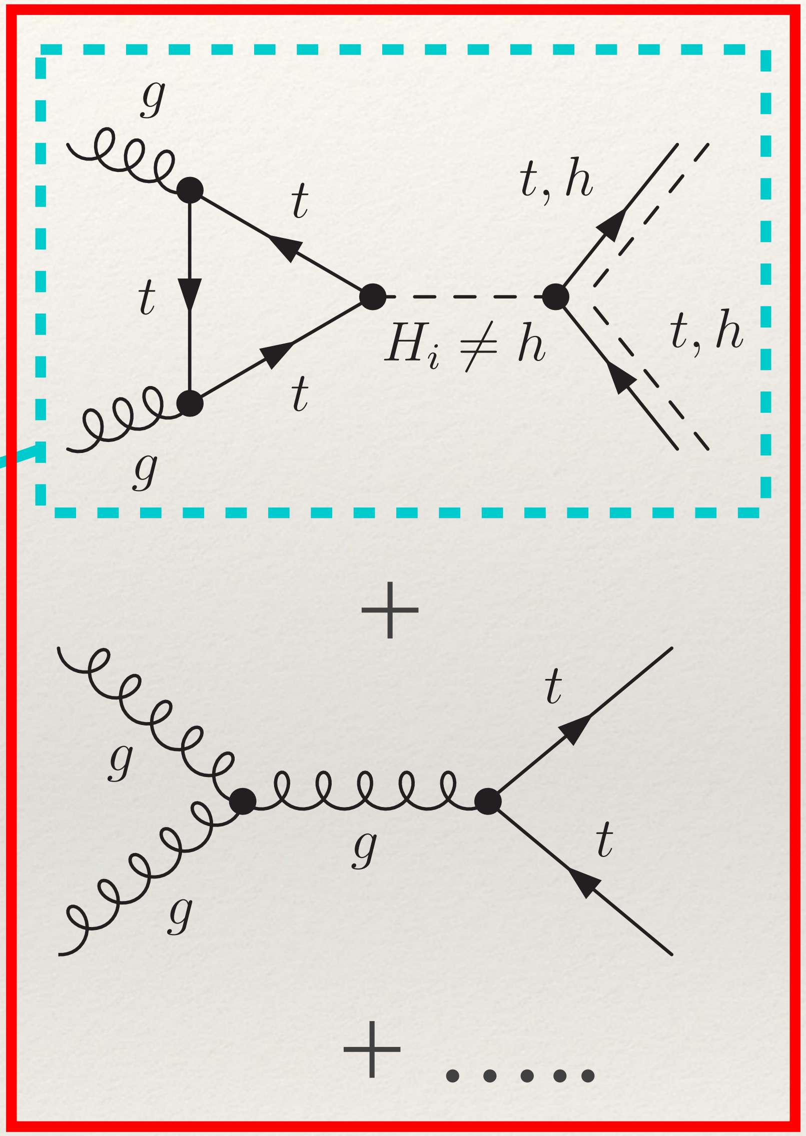
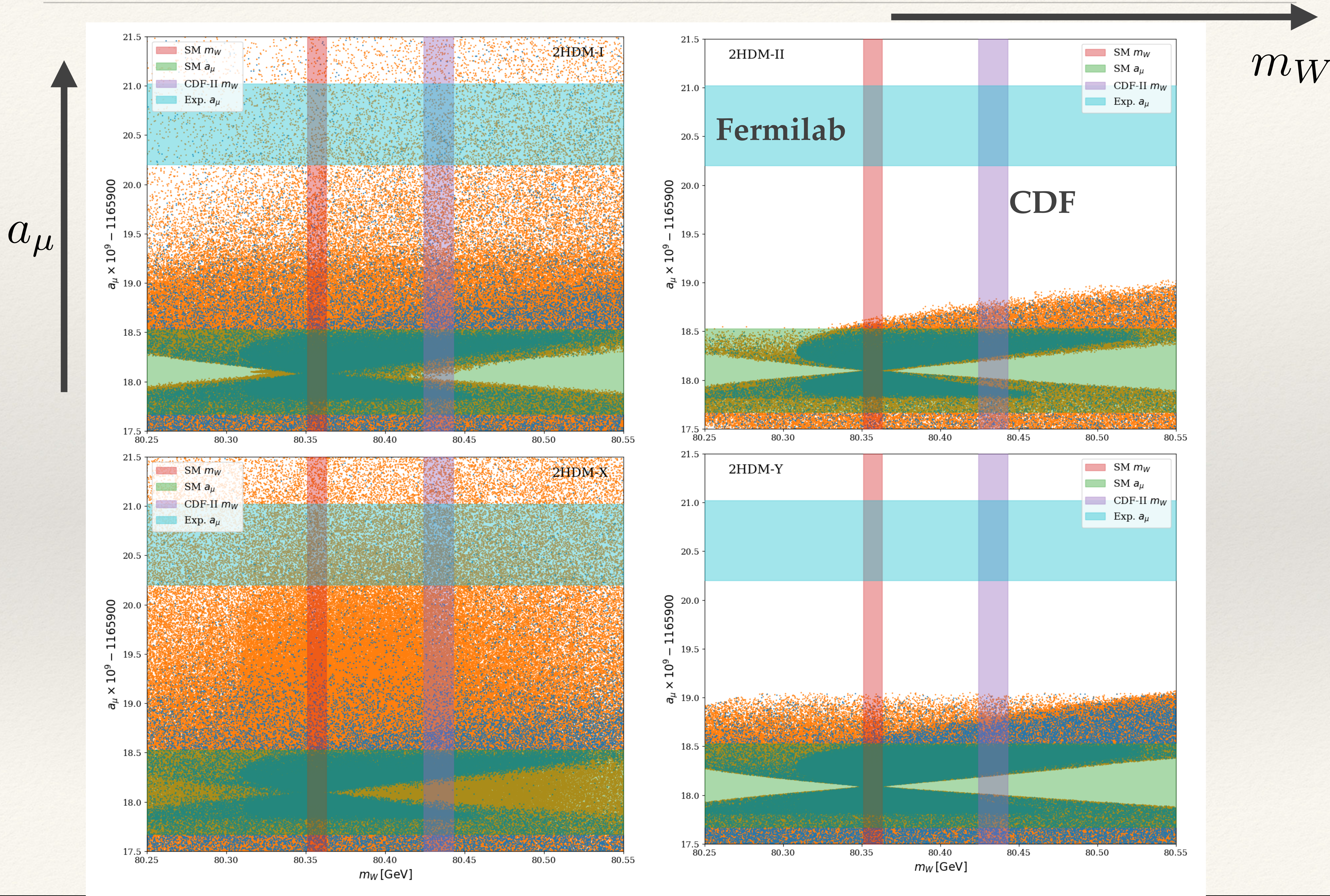




- top resonance searches in Higgs sector extensions with narrow width approximation can be inadequate! **Is this a problem?**

[Atkinson et al. `21, `22]

2HDMs: a_μ & m_W



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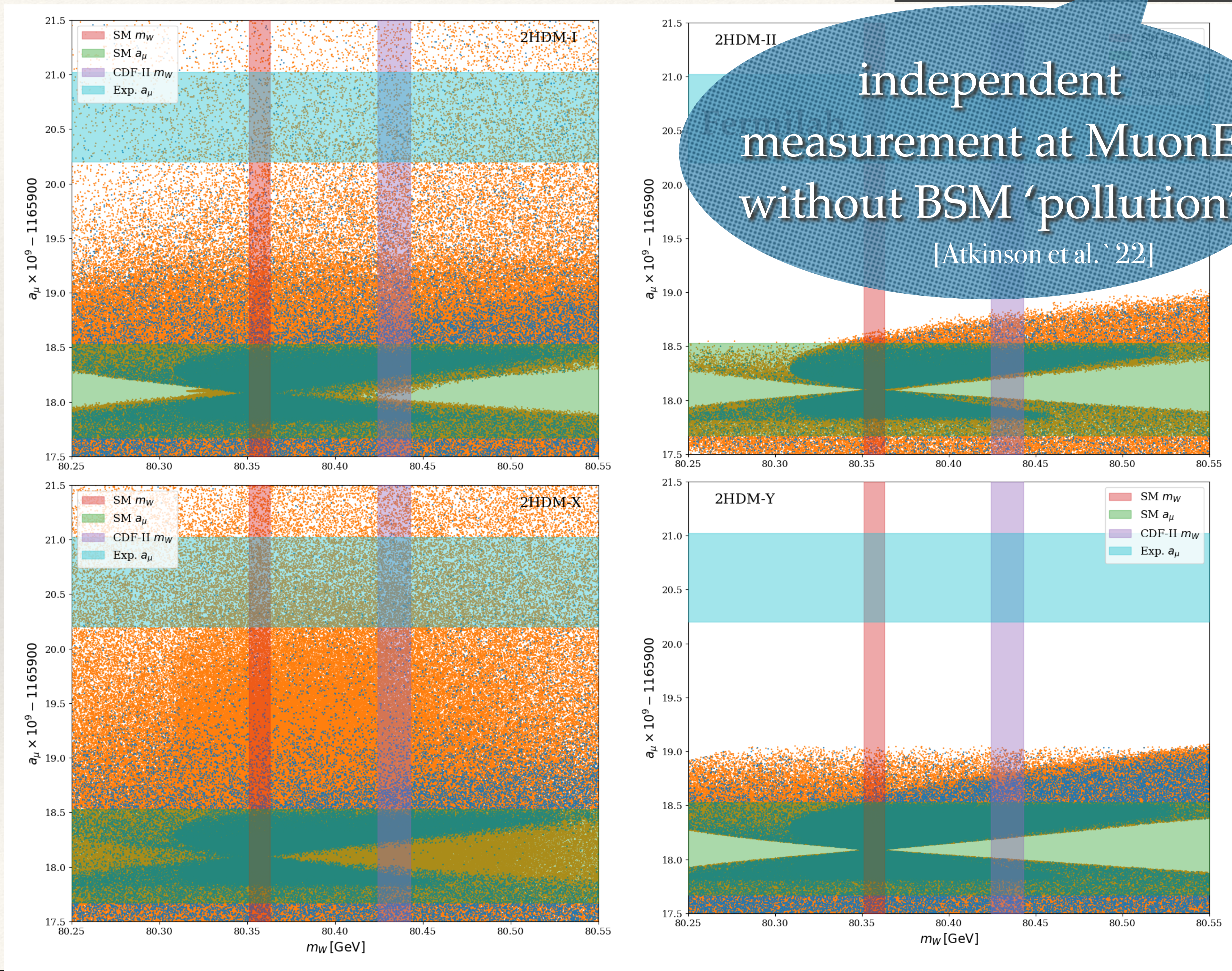
[Atkinson et al. `21, `22]

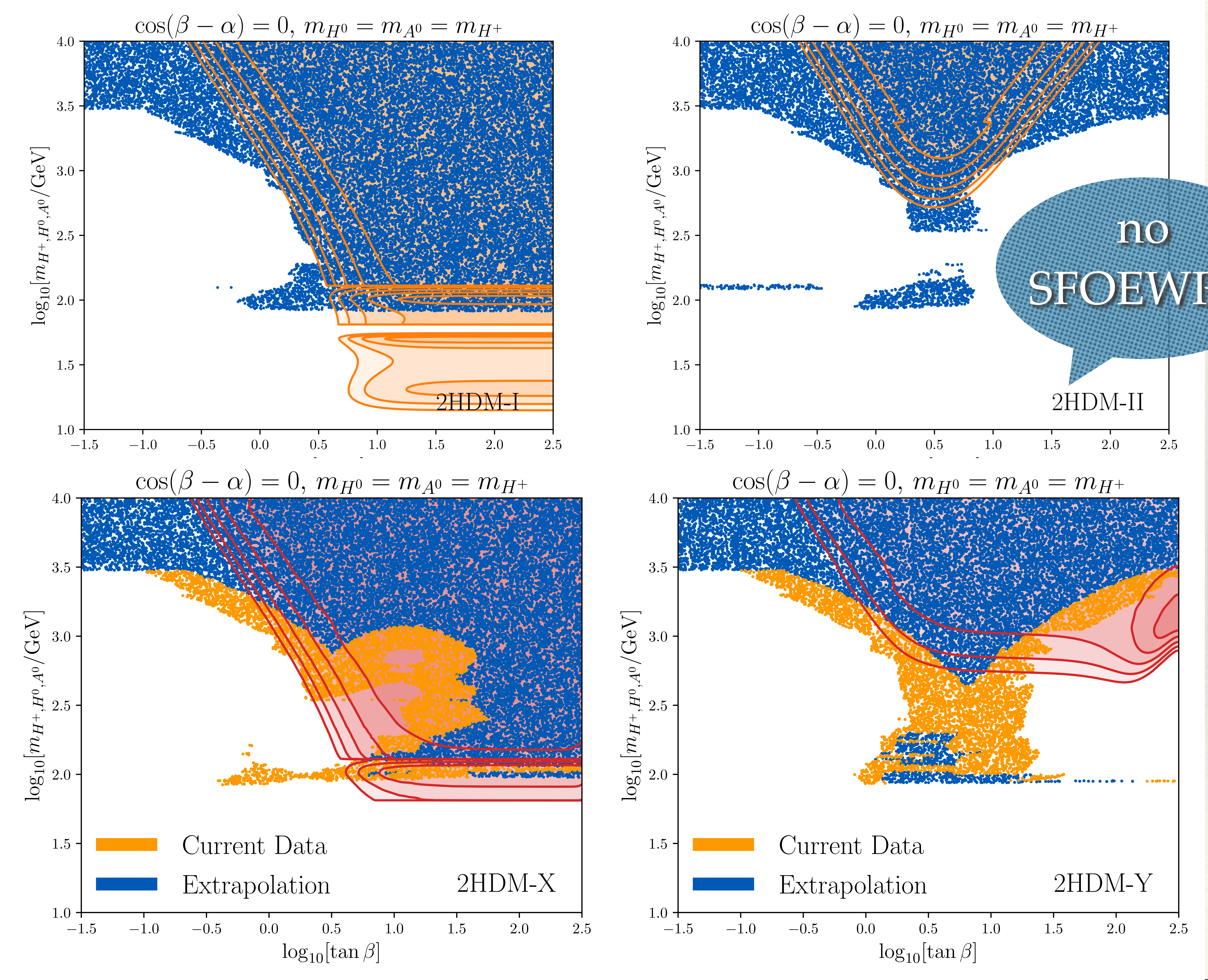
m_W

a_μ



[Atkinson et al. `21, `22]

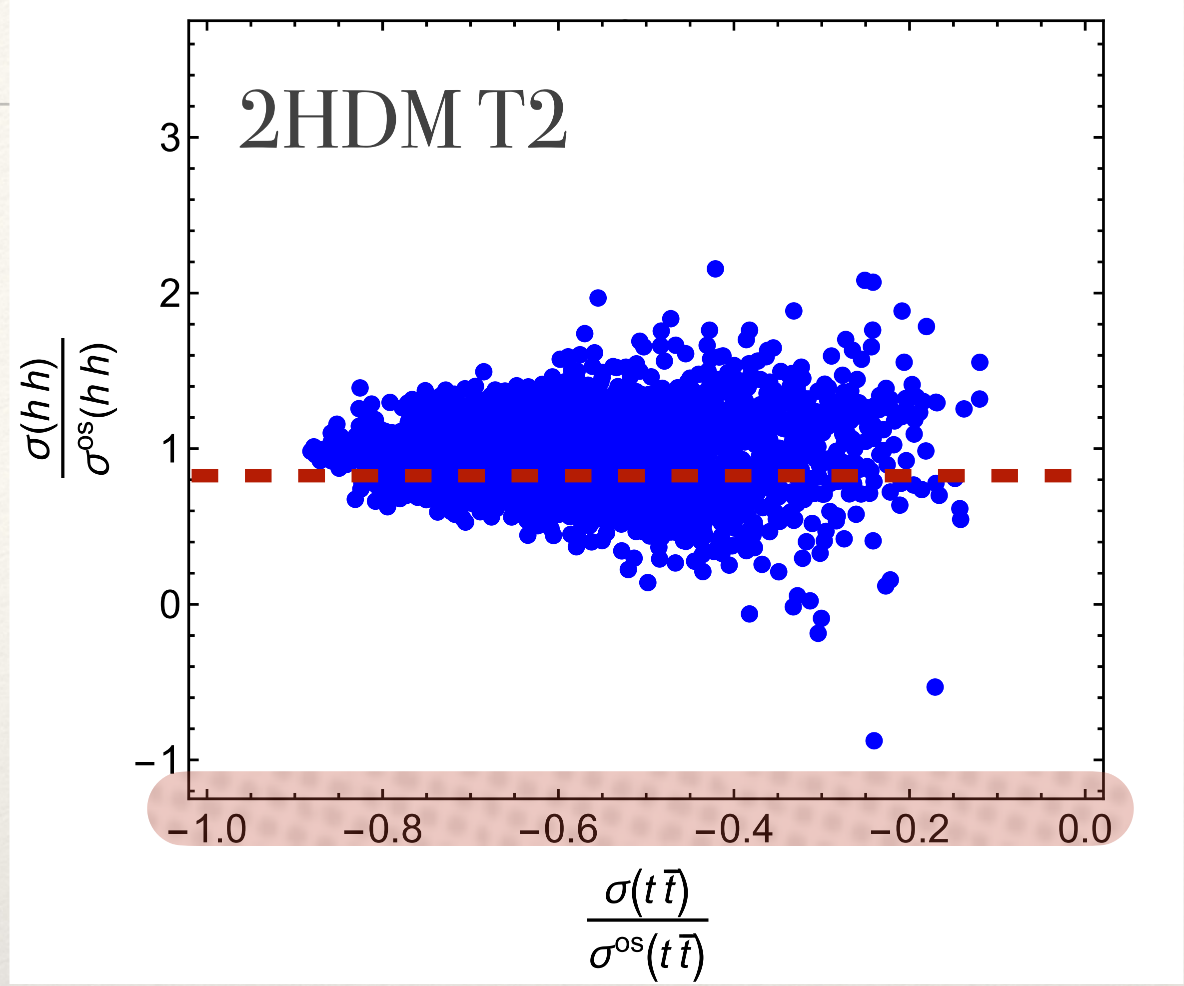
2HDMs: flavour & colliders



special role of top quarks

- destructive interference highlighted when including theoretical, flavour, collider, ELW constraints…

[Basler, Dawson, CE, Mühlleitner `18, `19]



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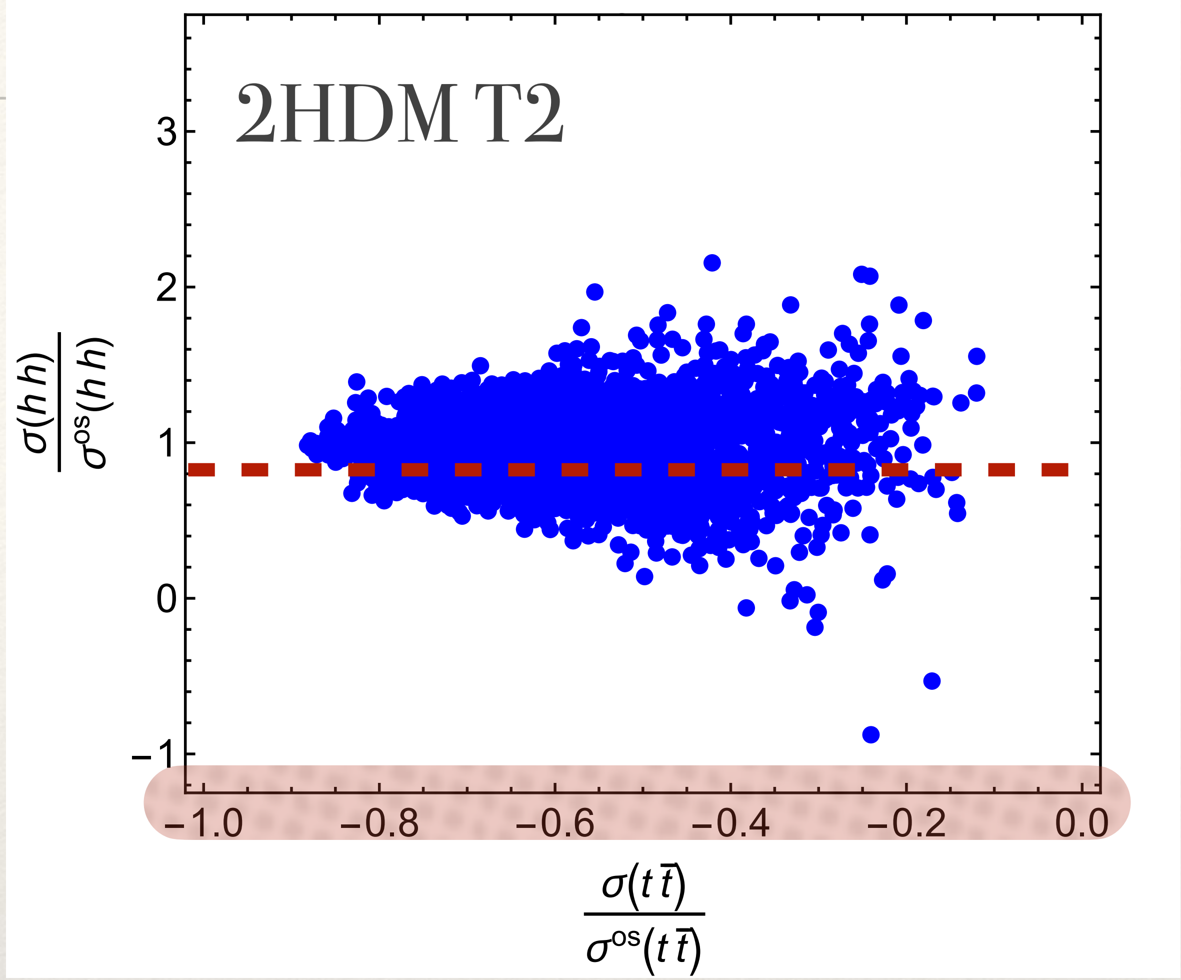
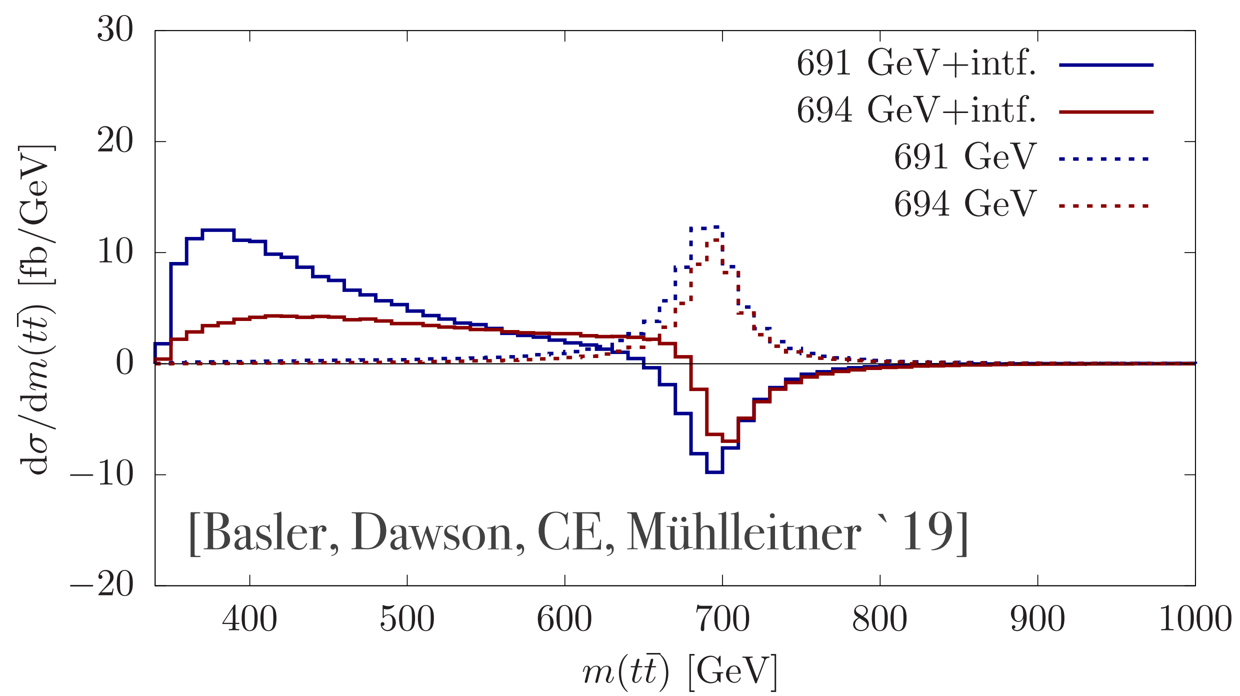
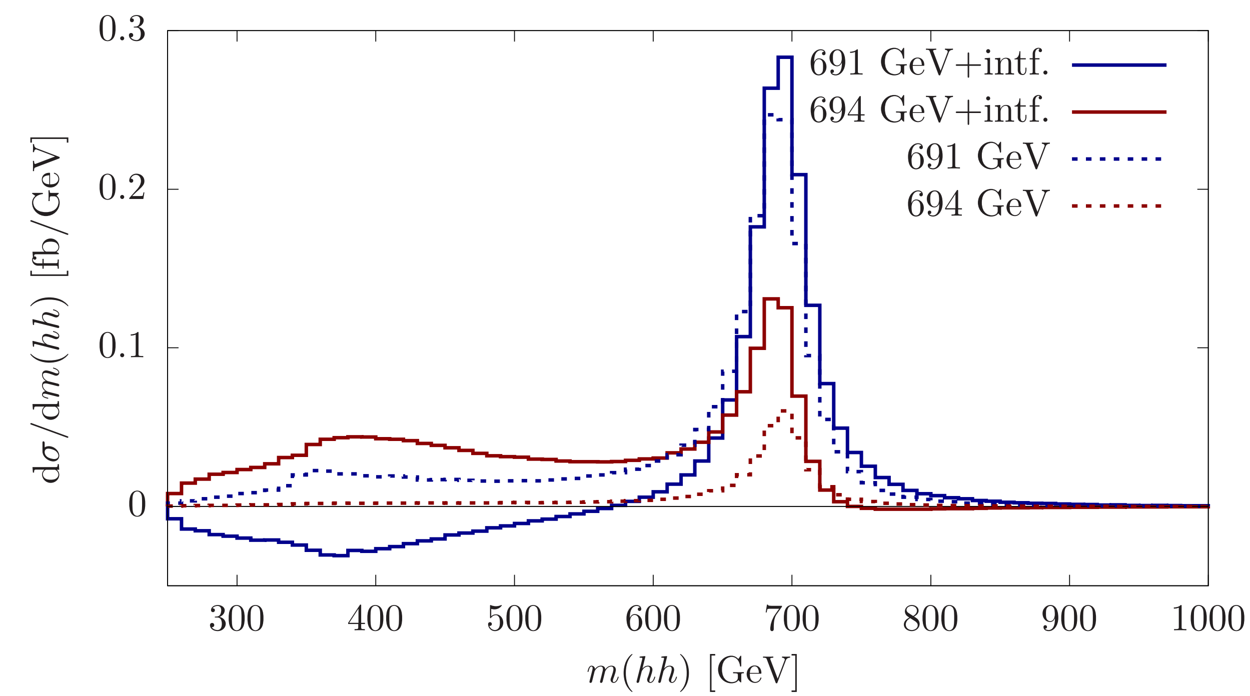
- phenomenologically viable regions with compressed spectra: **signal-signal interference**

[Basler, Dawson, CE, Mühlleitner `18, `19]







modified ELW baryogenesis: 2HDM

[Basler, Dawson, CE, Mühlleitner ` 18, ` 19], [Atkinson et al.`21]

- data ELW baryogenesis increasingly disfavoured in 2HDM II

new EFT-parametrised dynamics

$$\xi_c = \frac{v(T_C)}{T_C} \gtrsim 1$$

O_6^{111111}	$(\Phi_1^\dagger \Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger \Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger \Phi_1)^2(\Phi_2^\dagger \Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)^2$
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O_6^{121211}	$(\Phi_1^\dagger \Phi_2)^2(\Phi_1^\dagger \Phi_1)$ + h.c.	O_6^{121222}	$(\Phi_1^\dagger \Phi_2)^2(\Phi_2^\dagger \Phi_2)$ + h.c.

[Anisha et al. `22]

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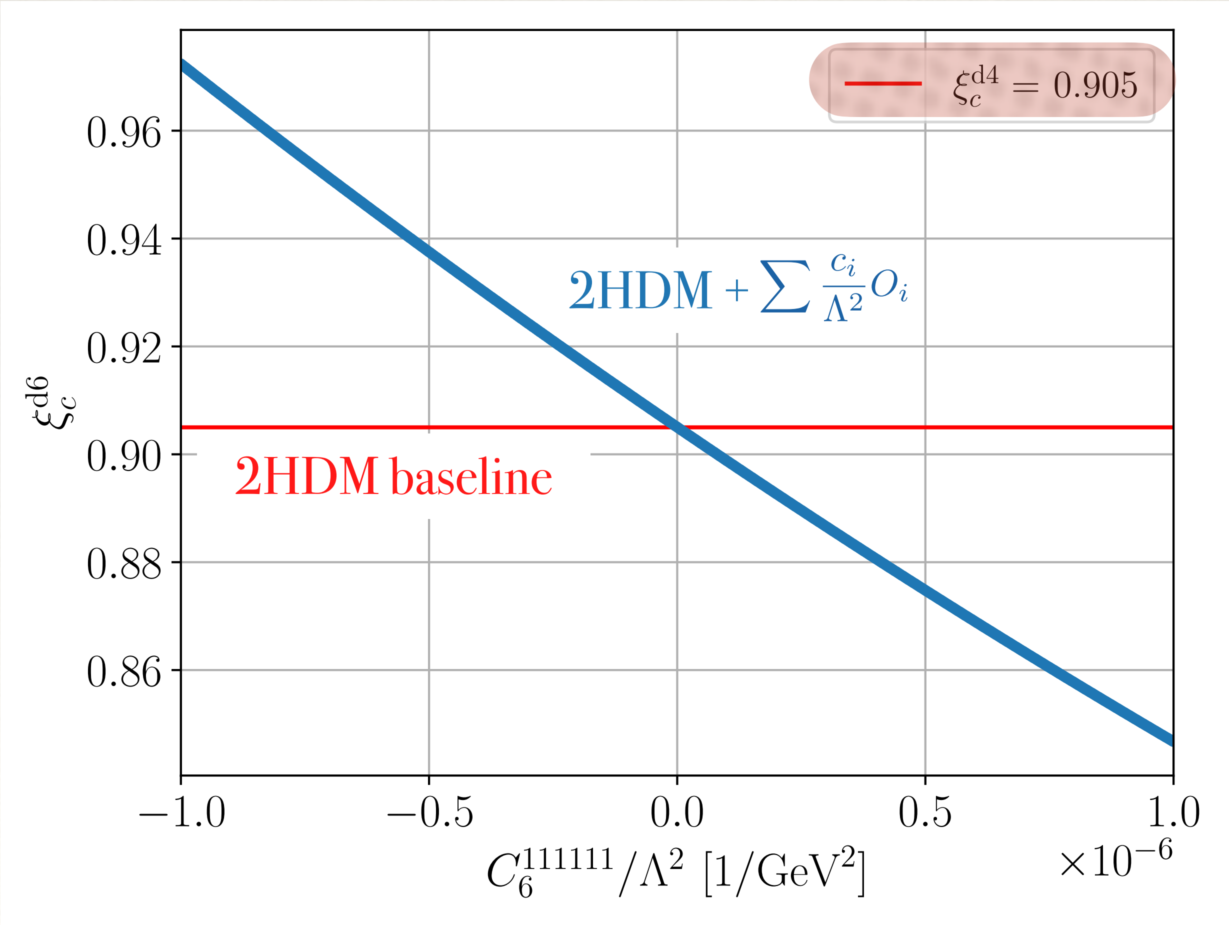

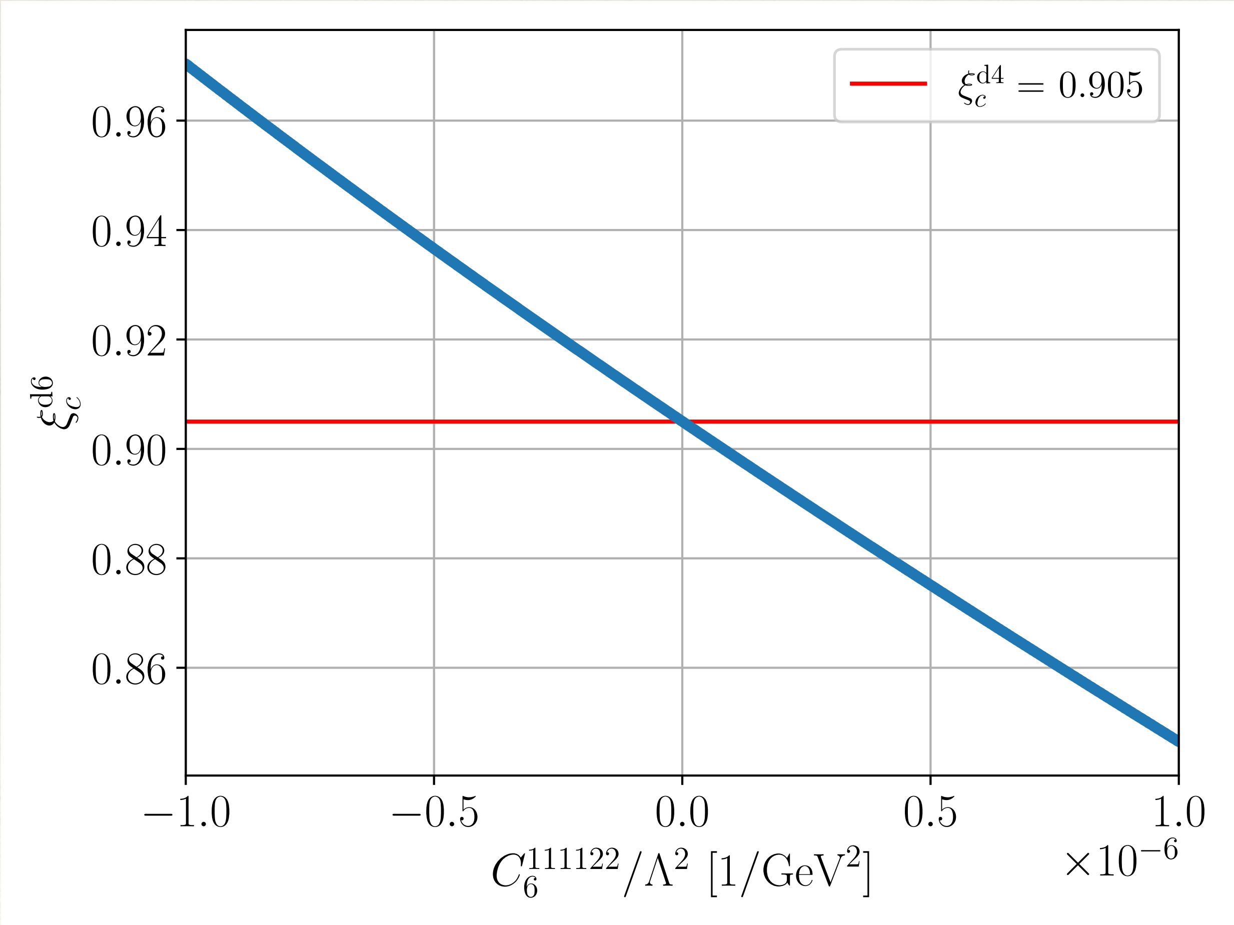

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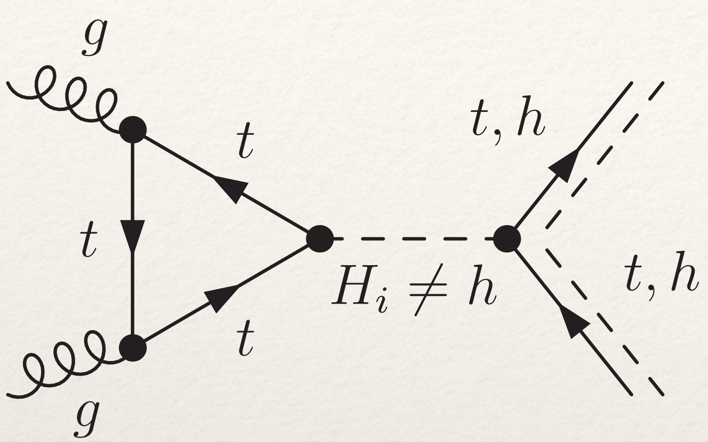

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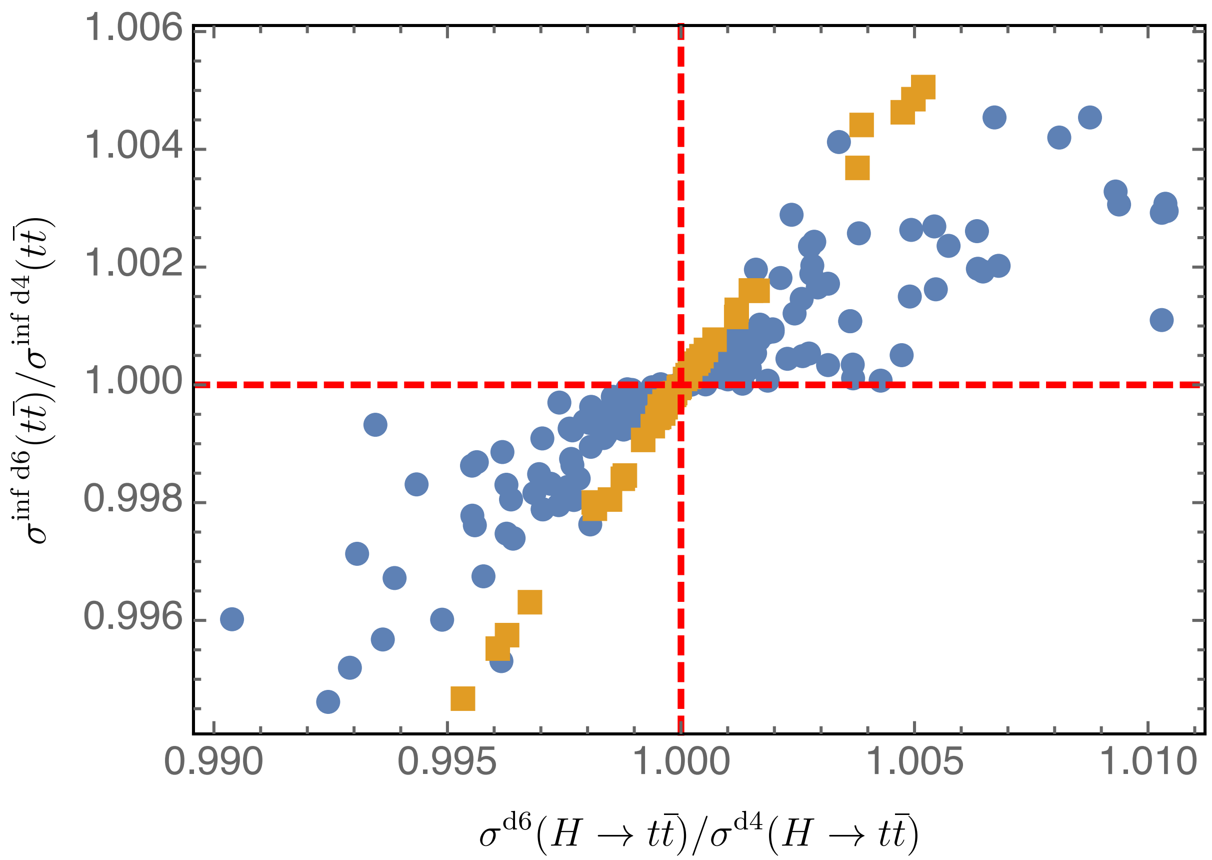
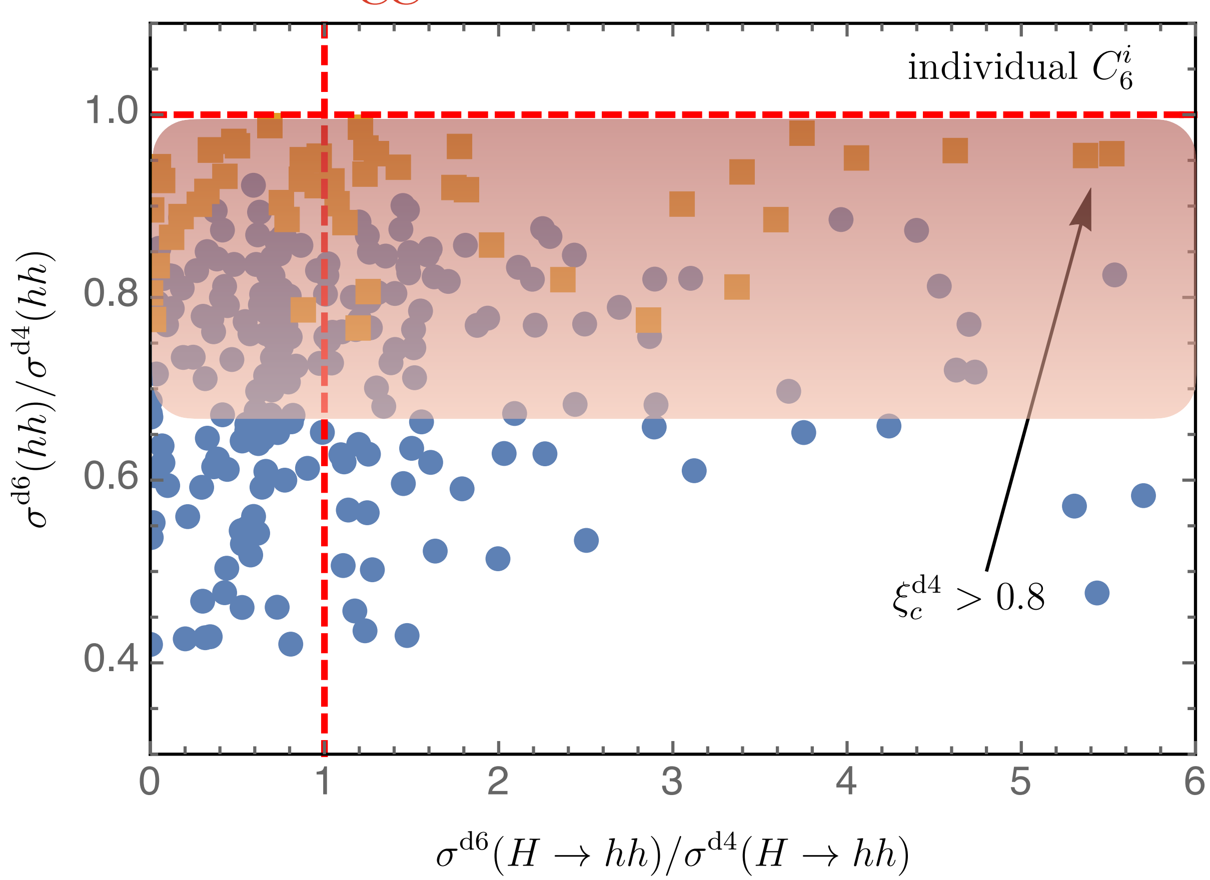
Line-shape not sensitive enough



DiHiggs cross section tells the tale



top physics occupies a major space in the electroweak & BSM 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
- new approaches to data analysis will enhance agnostic BSM potential
- QM interference might hide BSM that's right in front of our eyes and where it's like to be found…

top is relevant threshold:
LHC will provide clarification