Christoph Englert

Future directions on the Higgs sector

HiggsDiscovery@10

01/07/22

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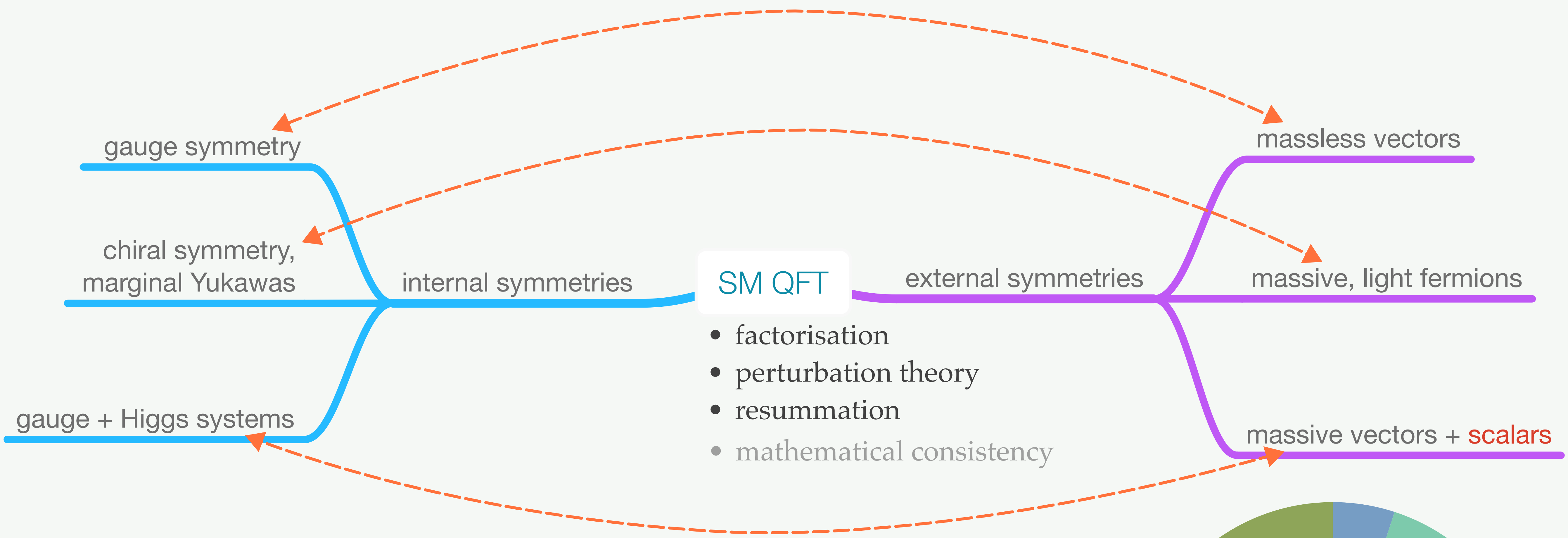
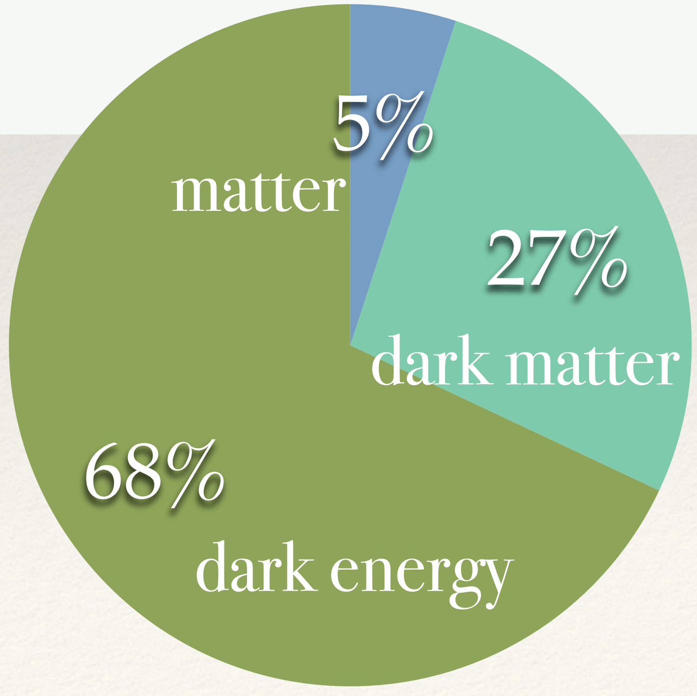
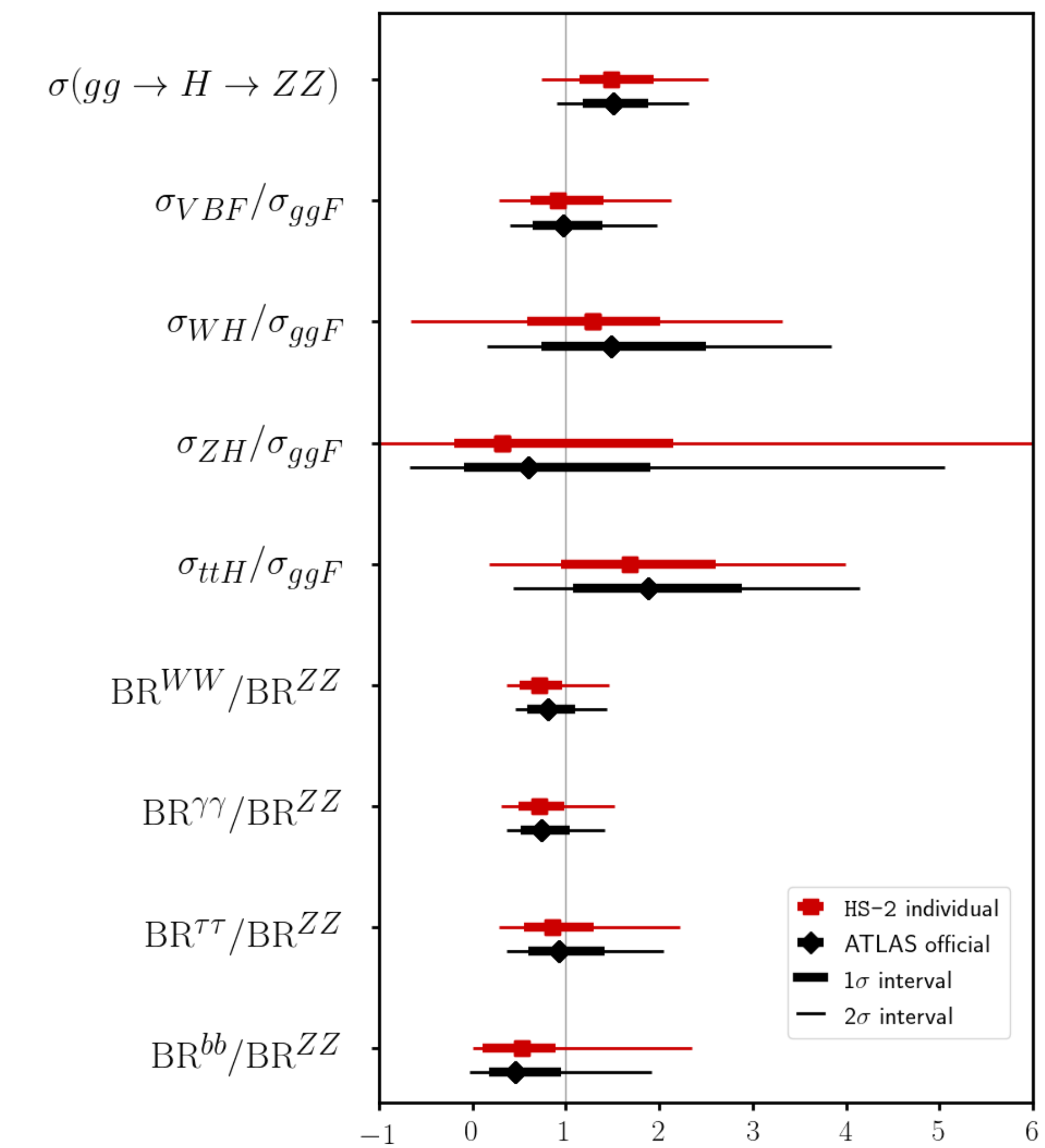
Ingredients of the SM



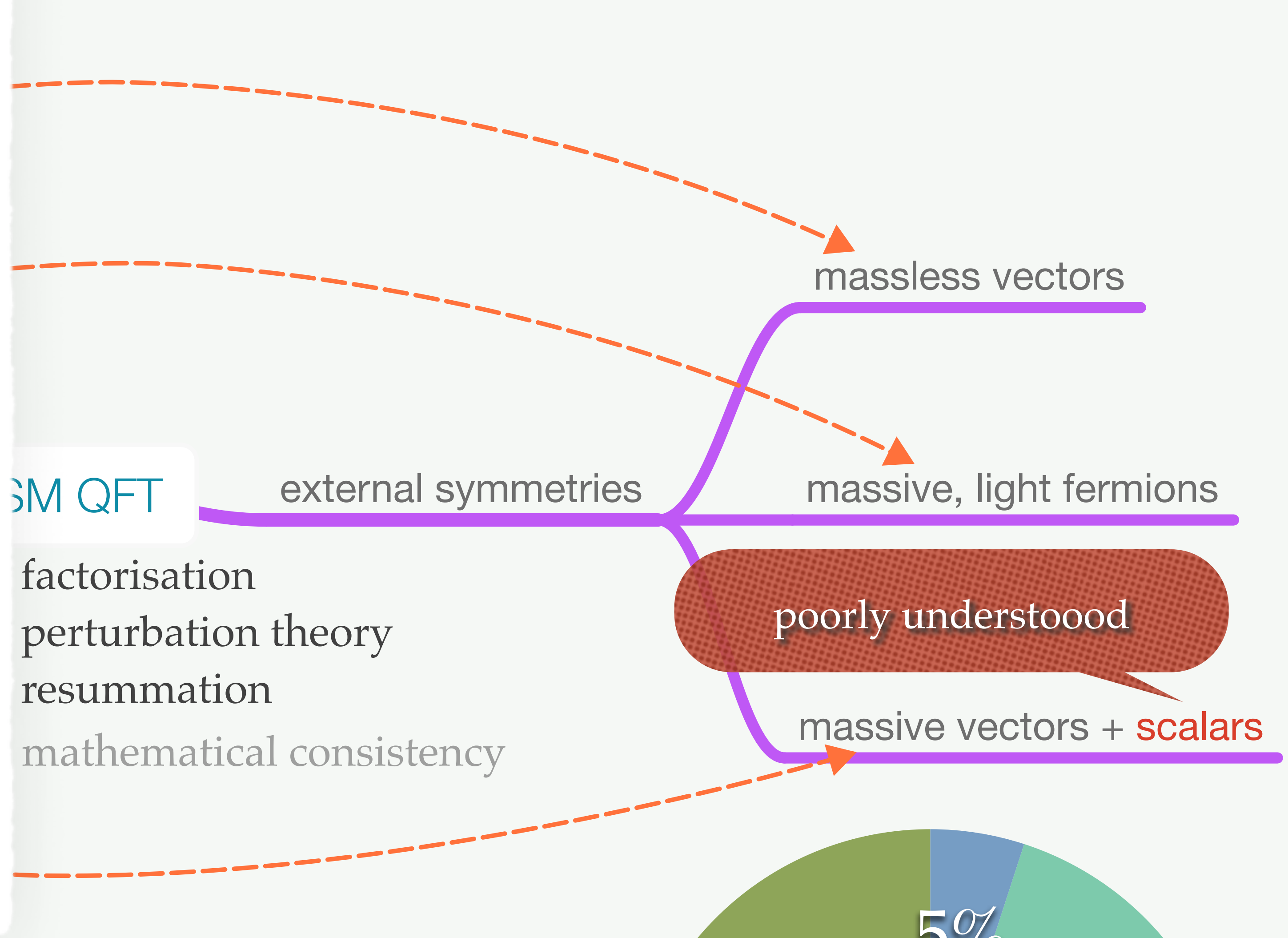
- factorisation
- perturbation theory
- resummation
- mathematical consistency

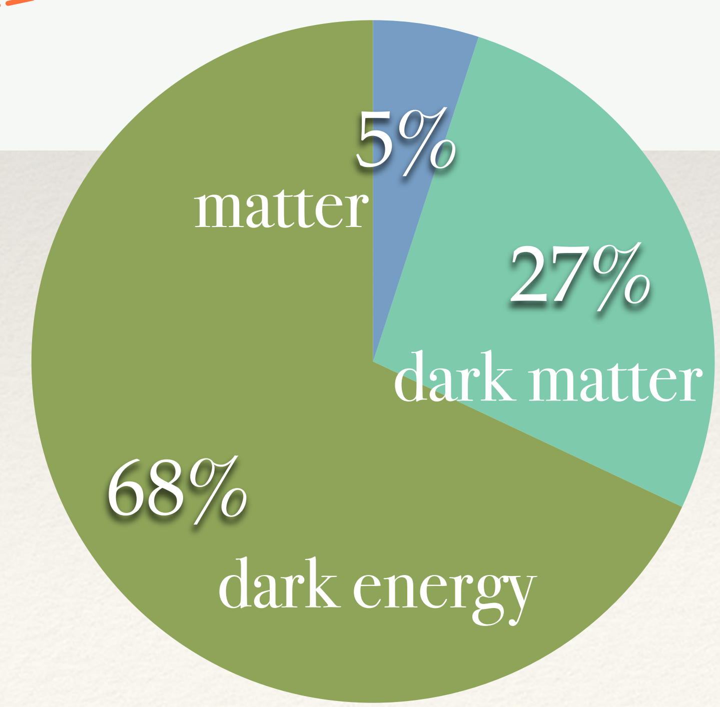


Ingredients of the SM



[Bechtle et al. `20]





"What's the next chapter of this story ?"

...we don't know (yet).

…we don't know (yet). No theoretical consistency argument: spotlight on experiments!

cure theoretical problems
~m_H , m_t

facilitate consistent measurements

- *Large stats context?*
- *Need for BSM - phenomenological implications?*
- *Relevance of current anomalies for the TeV scale?*

…we don't know (yet). No theoretical consistency argument: spotlight on experiments!

cure theoretical problems
~m_H, m_t

facilitate consistent measurements

- *Large stats context?*

enhanced sensitivity to (rare) processes?

- *Need for BSM - phenomenological implications?*

CP violation?
SFOEWPT?

- *Relevance of current anomalies?*

g-2 @ TeV scale?

theory

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

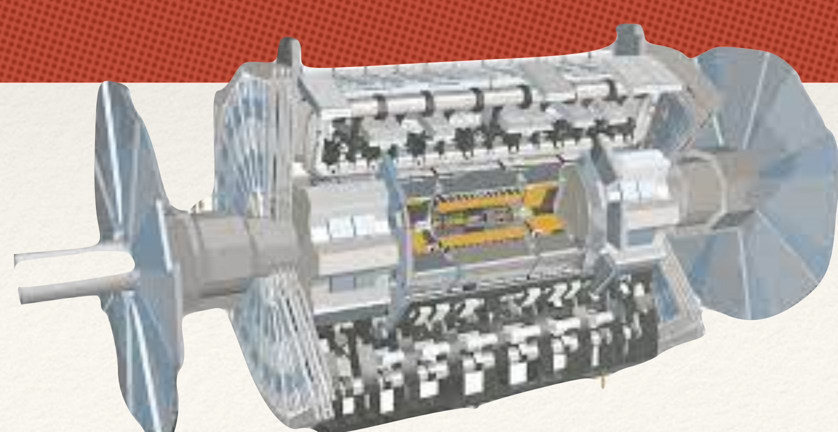
kinematic correlations

helicity correlations

colour correlations

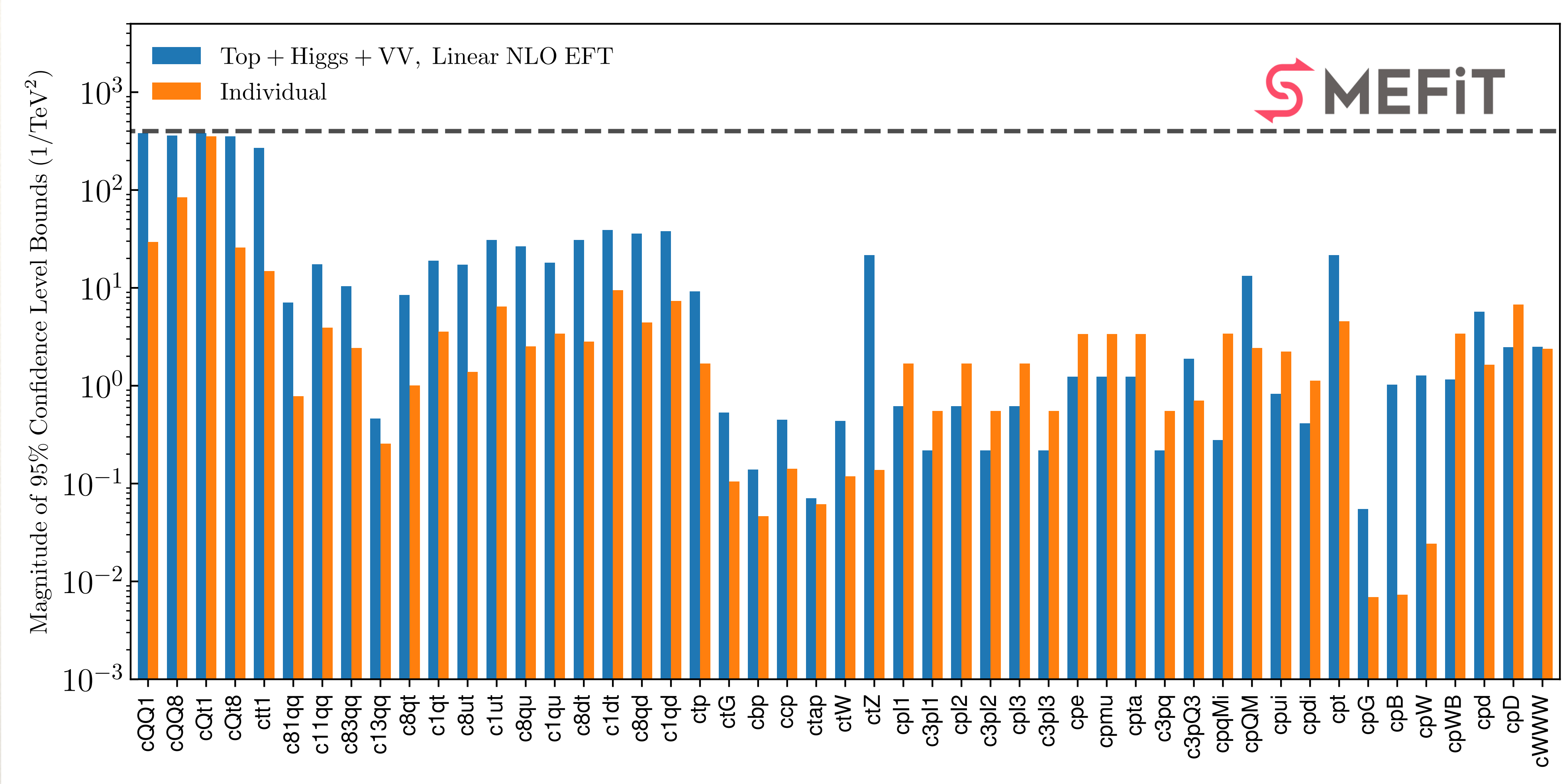
....

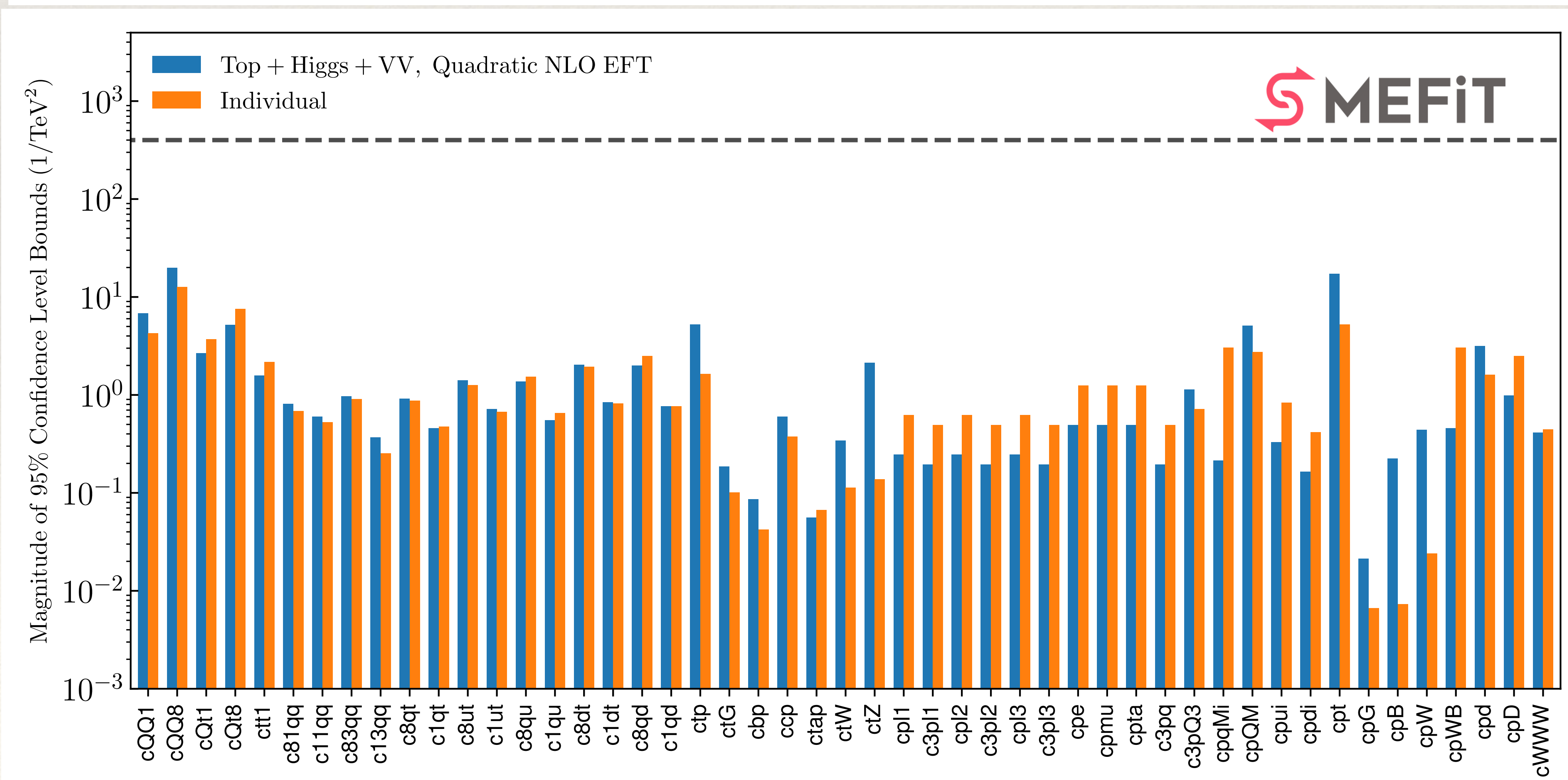
reverse-engineer in terms of collider observables for SM validation or exclusion



experiment

EFT!?





EFT: add anything that is consistent with the SM

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

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

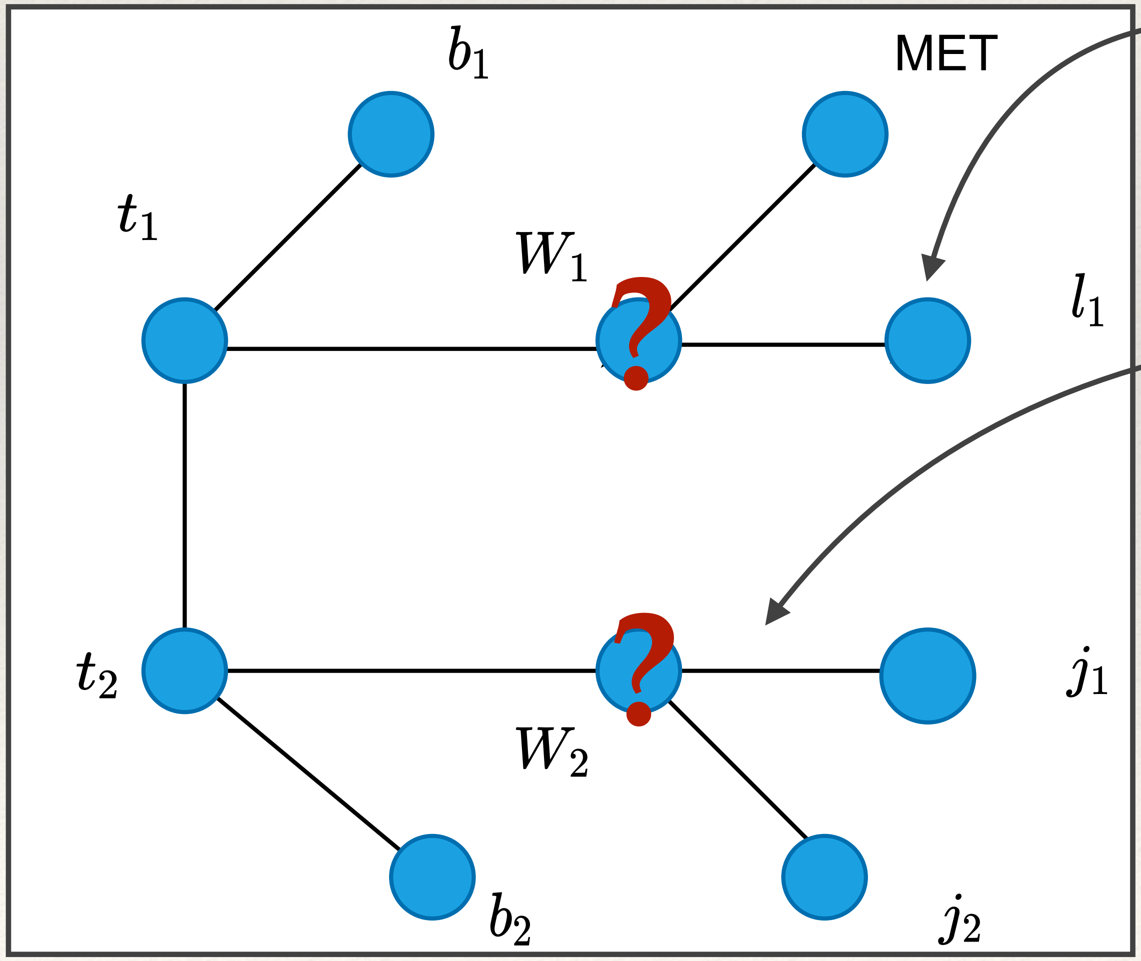
experimental ownership @ R3 ?

- 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]
...

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

ML for EFT (e.g. top pairs)

supervised training over graph structures to enhance BSM sensitivity

traditional approach

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

Distribution	Observable
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_t^h\rvert}$	$\lvert y_t^h\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_t^l\rvert}$	$\lvert y_t^l\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_{t\bar{t}}\rvert}$	$\lvert y_{t\bar{t}}\rvert$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,h}}$	$p_\perp^{t,h}$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,l}}$	$p_\perp^{t,l}$
$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	$m_{t\bar{t}}$
$\frac{1}{\sigma}\frac{d\sigma}{d\lvert y_{t\bar{t}}\rvert d\lvert m_{t\bar{t}}\rvert}$	$\lvert y_{t\bar{t}}\rvert$
	$m_{t\bar{t}}$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,h} d\lvert y_t^h\rvert}$	$p_\perp^{t,h}$
	$\lvert y_t^h\rvert$

[Atkinson et al. `21]

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$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,h}}$	$p_\perp^{t,h}$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,l}}$	$p_\perp^{t,l}$
$\frac{1}{\sigma}\frac{d\sigma}{dm_{t\bar{t}}}$	$m_{t\bar{t}}$
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	$m_{t\bar{t}}$
$\frac{1}{\sigma}\frac{d\sigma}{dp_\perp^{t,h}d\lvert y_t^h\rvert}$	$p_\perp^{t,h}$
	$\lvert y_t^h\rvert$

GNN-improved approach

(i) GNN discrimination of multi-class problem

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

scalability controlled by operator multiplicity

🙂

(iii) traditional fit

[Atkinson et al. `21]

ML for EFT (e.g. top pairs)

supervised training over graph structures to enhance BSM sensitivity

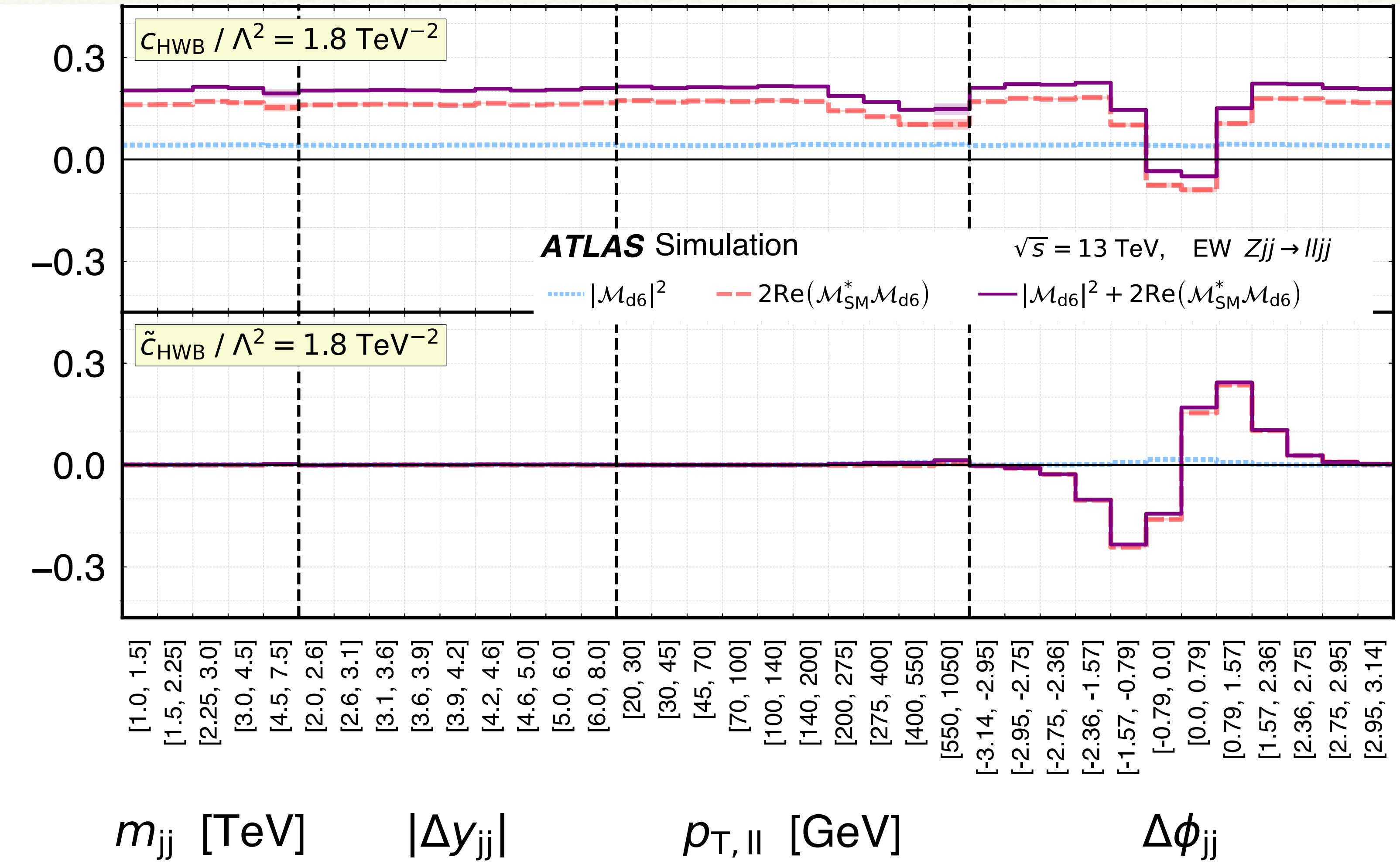
- large improvement attainable when BSM correlations affect exclusive phasespace correlations
- no improvement when inclusive selections determine sensitivity

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%	14.53%	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%

ML for Higgs physics: CP violation

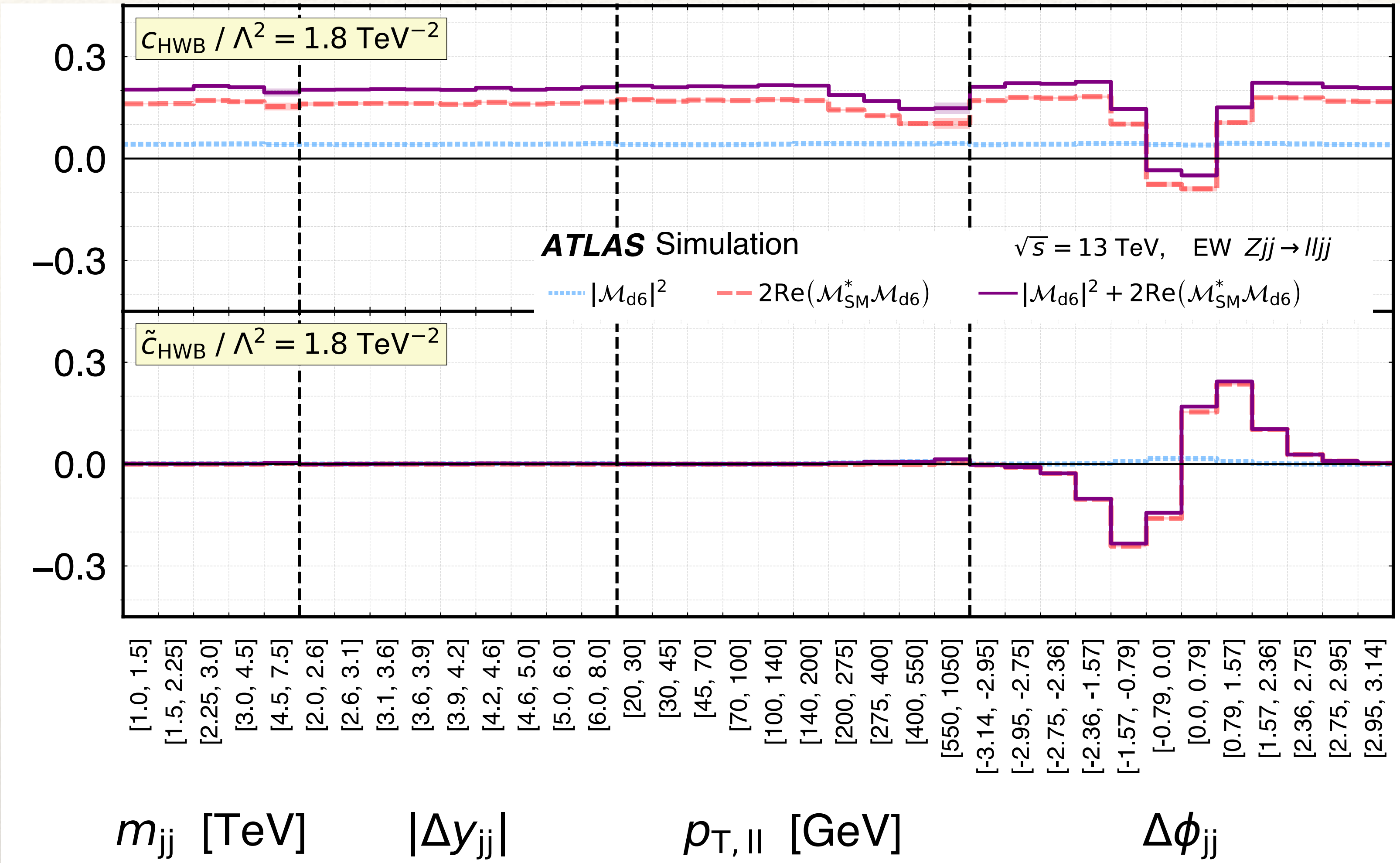


- asymmetry-based measurement in elw. Z+2jet production
- symmetric CP even effects cancel
- challenging to combat fluctuations

- evidence for BSM physics ?

Wilson coefficient	Includes $|\mathcal{M}_{d6}|^2$	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%

Higgs CP violation

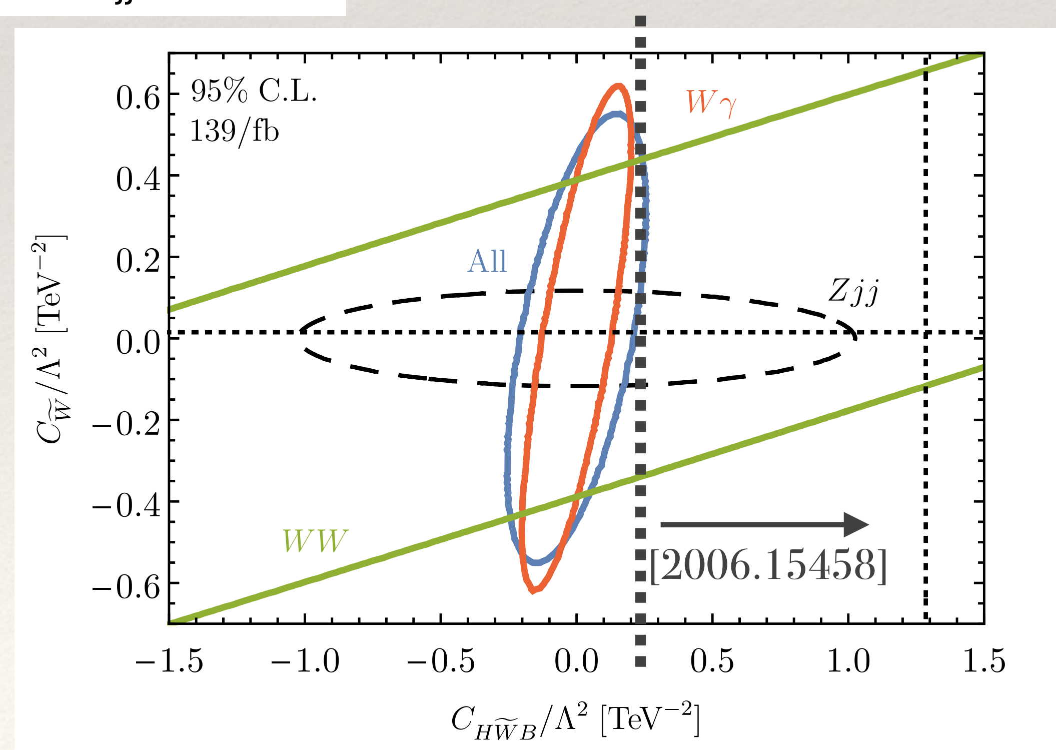


- asymmetry-based measurement in elw. Z+2jet production
- symmetric CP even effects cancel
- challenging to combat fluctuations

- evidence for BSM physics ?

very unlikely but testable

[Das Bakshi et al. `20]
[Biekötter, Gregg, Krauss, Schönherr `21]



- CP-interference net zero results from cancelling event weights

…
[Gritsan et al. `20]

can create (near)
optimal observable
from *binary* ± *weight*
distinction?

[Bhardwaj et al. `21]

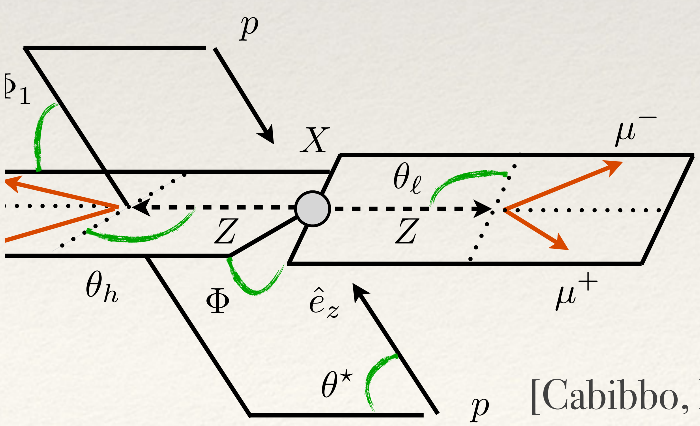
- CP-interference net zero results from cancelling event weights

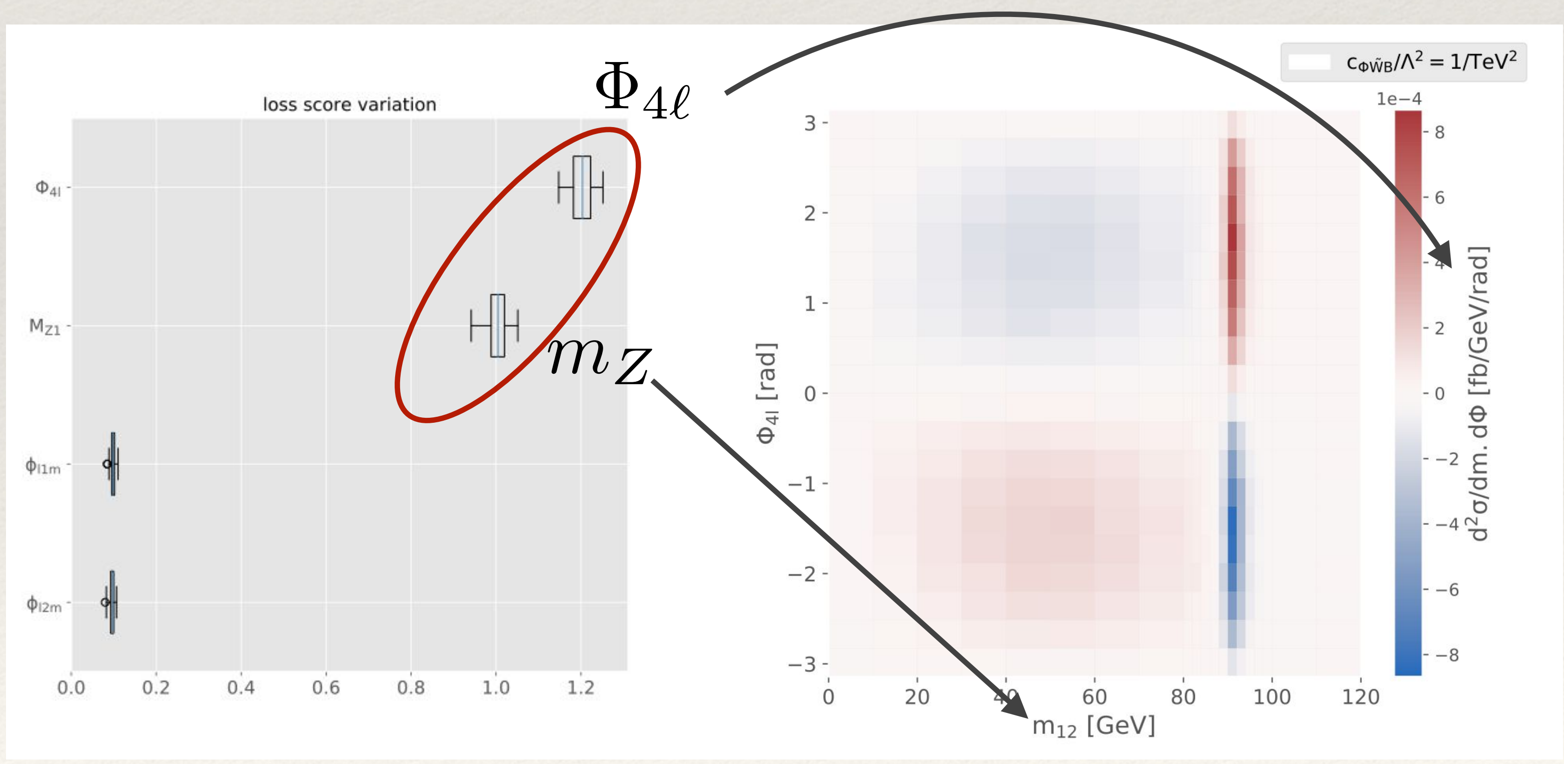
can create (near) optimal observable from *binary* ± *weight* distinction? [Bhardwaj et al. `21]

- test cases $h \to ZZ^*$ (single scale) [works also for and weak boson fusion]

$$\mathcal{O}_{\Phi\widetilde{B}} = \Phi^\dagger \Phi B^{\mu\nu} \widetilde{B}_{\mu\nu}\,,$$
$$\mathcal{O}_{\Phi\widetilde{W}} = \Phi^\dagger \Phi W^{i\,\mu\nu} \widetilde{W}^i_{\mu\nu}$$
$$\mathcal{O}_{\Phi\widetilde{W}B} = \Phi^\dagger \sigma^i \widetilde{W}^{i\,\mu\nu} B_{\mu\nu}$$

$\Longrightarrow$





[Cabibbo, Maksymowicz `68]
[Truman `78]
[Dell`Aquila, Nelson `86]...

Going beyond

- CP-interference net zero results from cancelling event weights

can create (near) optimal observable from *binary* ± *weight* distinction? [Bhardwaj et al. `21]

- test cases $\underline{h \to ZZ^*}$ (single scale) [works also for and weak boson fusion]

$$\mathcal{O}_{\Phi\widetilde{B}} = \Phi^\dagger \Phi B^{\mu\nu} \widetilde{B}_{\mu\nu}\,,$$
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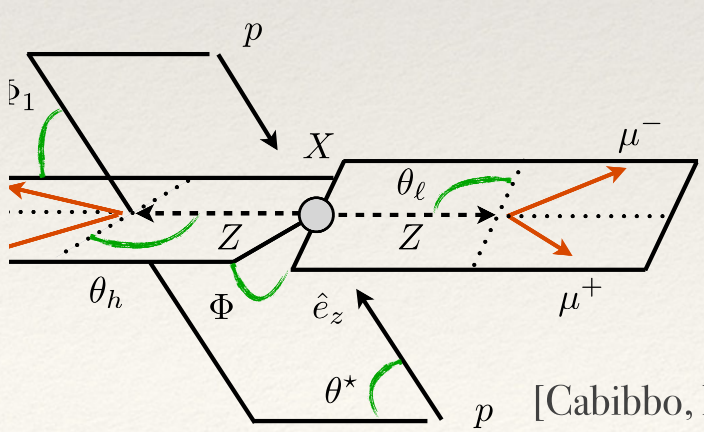
$$\mathcal{O}_{\Phi\widetilde{W}B} = \Phi^\dagger \sigma^i \widetilde{W}^{i\,\mu\nu} B_{\mu\nu} \quad \Longrightarrow$$



[Cabibbo, Maksymowicz `68]
[Truman `78]
[Dell`Aquila, Nelson `86]…

baseline is ATLAS 4l `21 (139/fb) [CERN-EP-2021-019]

CP-odd observable	$c_{\Phi\widetilde{W}B}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{B}}/\Lambda^2$ [TeV^{-2}]	$c_{\Phi\widetilde{W}}/\Lambda^2$ [TeV^{-2}]
$\Phi_{4\ell}$	[-6.2,6.2]	[-1.4,1.4]	[-30,30]
$\Phi_{4\ell}$, m_{12}	[-1.9,1.9]	[-0.85,0.85]	[-3.7,3.7]
O_{NN} (binary)	[-1.5,1.5]	[-0.75,0.75]	[-3.0,3.0]
O_{NN} (multi-class)	[-1.4,1.4]	[-0.71,0.71]	[-2.7,2.7]

improvements beyond multi-dim "traditional" fits

...we don't know (yet). No theoretical consistency argument: spotlight on experiments!

cure theoretical problems

facilitate consistent measurements

enhanced sensitivity to (rare) processes?

- *Large stats context?*

matter / anti matter asymmetry?

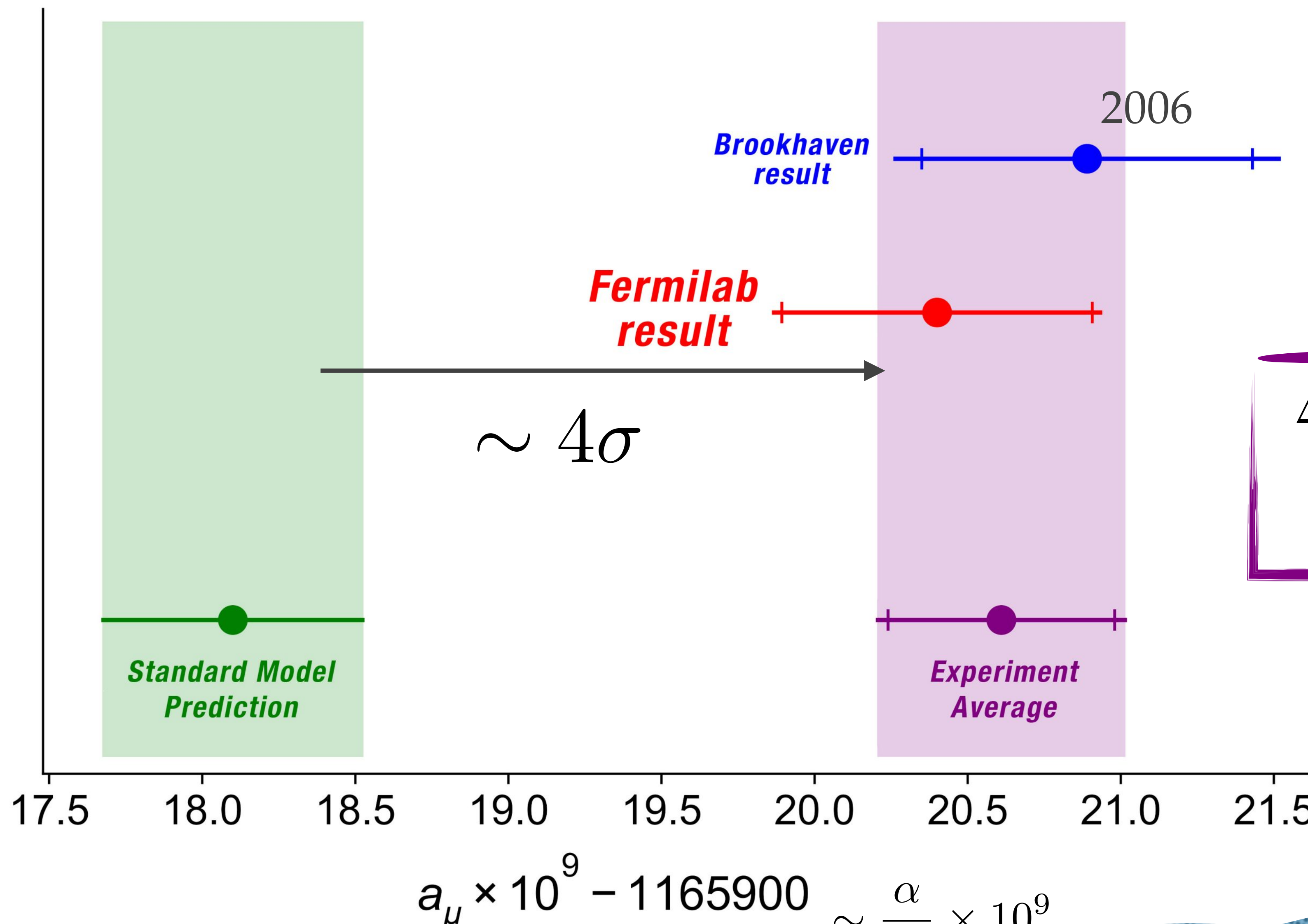
- *Need for BSM - phenomenological implications?*
- *Relevance of current anomalies?*

g-2 @ TeV scale?

- combined experimental and theoretical effort

Theory White Paper
[Aoyama et al. 2006.04822]

[Abi et al. (Muon g-2 collaboration) `21]



$\sim \frac{\alpha}{2\pi} \times 10^9$

$$\Delta a_\mu = a_\mu(\mathrm{exp}) - a_\mu(\mathrm{SM})$$
$$= (25.1 \pm 5.9) \times 10^{-10}$$

- BMW/Mainz results?
  [Borsanyi et al. `21]
  [Cè et al. `22]
- R ratio issue?

MUonE

19

e.g. [Athron et al.`21]

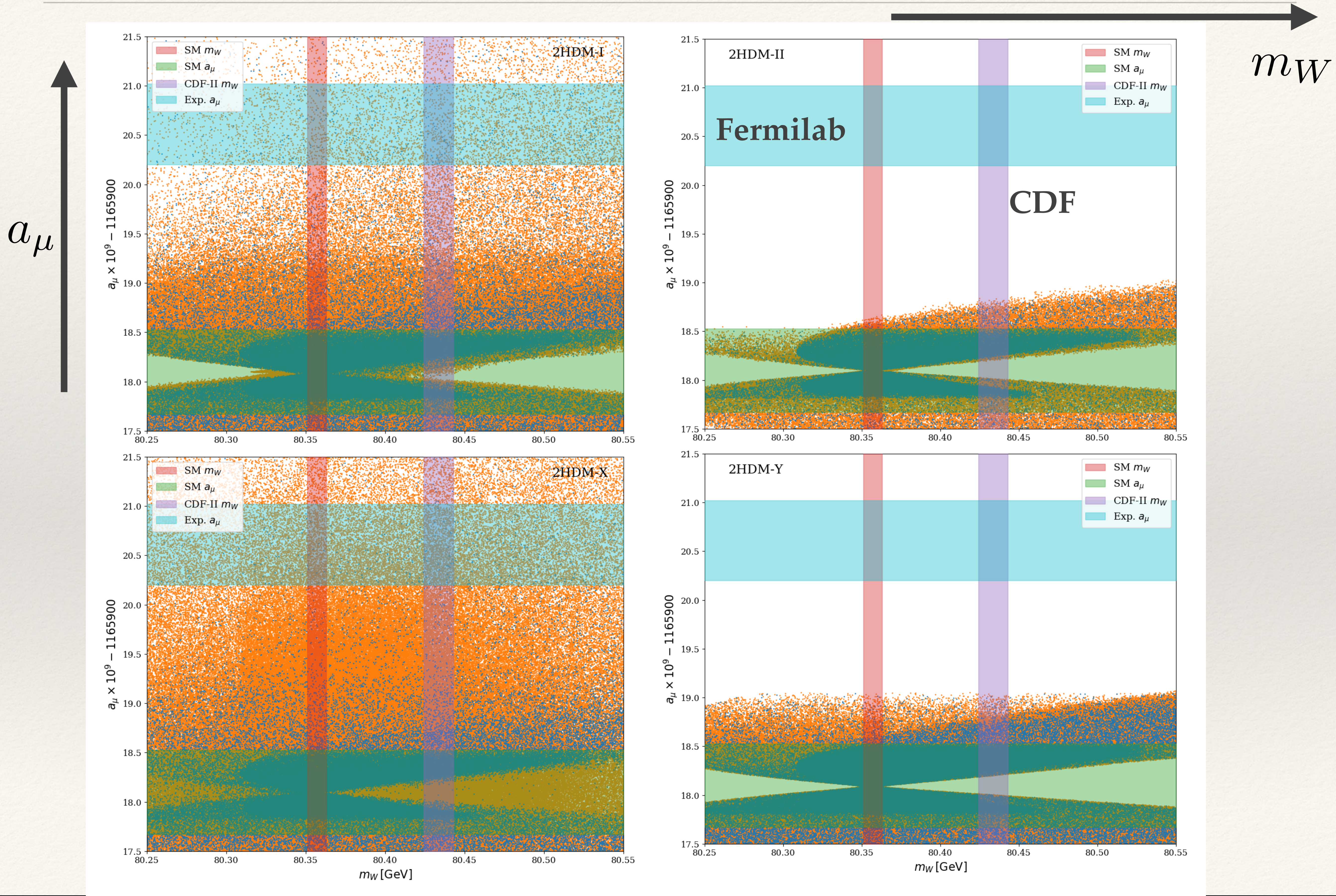
comprehensive analysis of new physics potential

Single field SM extensions

Model	Spin	$SU(3)_C \times SU(2)_L \times U(1)_Y$	Result for $\Delta a_\mu^{\mathrm{BNL}}$, Δa_μ^{2021}
1	0	$(\mathbf{1}, \mathbf{1}, 1)$	Excluded: $\Delta a_\mu < 0$
2	0	$(\mathbf{1}, \mathbf{1}, 2)$	Excluded: $\Delta a_\mu < 0$
3	0	$(\mathbf{1}, \mathbf{2}, -1/2)$	Updated in Sec. 3.2
4	0	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
5	0	$(\overline{\mathbf{3}}, \mathbf{1}, 1/3)$	Updated Sec. 3.3.
6	0	$(\overline{\mathbf{3}}, \mathbf{1}, 4/3)$	Excluded: LHC searches
7	0	$(\overline{\mathbf{3}}, \mathbf{3}, 1/3)$	Excluded: LHC searches
8	0	$(\mathbf{3}, \mathbf{2}, 7/6)$	Updated Sec. 3.3.
9	0	$(\mathbf{3}, \mathbf{2}, 1/6)$	Excluded: LHC searches
10	1/2	$(\mathbf{1}, \mathbf{1}, 0)$	Excluded: $\Delta a_\mu < 0$
11	1/2	$(\mathbf{1}, \mathbf{1}, -1)$	Excluded: Δa_μ too small
12	1/2	$(\mathbf{1}, \mathbf{2}, -1/2)$	Excluded: LEP lepton mixing
13	1/2	$(\mathbf{1}, \mathbf{2}, -3/2)$	Excluded: $\Delta a_\mu < 0$
14	1/2	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: $\Delta a_\mu < 0$
15	1/2	$(\mathbf{1}, \mathbf{3}, -1)$	Excluded: $\Delta a_\mu < 0$
16	1	$(\mathbf{1}, \mathbf{1}, 0)$	Special cases viable
17	1	$(\mathbf{1}, \mathbf{2}, -3/2)$	UV completion problems
18	1	$(\mathbf{1}, \mathbf{3}, 0)$	Excluded: LHC searches
19	1	$(\overline{\mathbf{3}}, \mathbf{1}, -2/3)$	UV completion problems
20	1	$(\overline{\mathbf{3}}, \mathbf{1}, -5/3)$	Excluded: LHC searches
21	1	$(\overline{\mathbf{3}}, \mathbf{2}, -5/6)$	UV completion problems
22	1	$(\overline{\mathbf{3}}, \mathbf{2}, 1/6)$	Excluded: $\Delta a_\mu < 0$
23	1	$(\overline{\mathbf{3}}, \mathbf{3}, -2/3)$	Excluded: proton decay

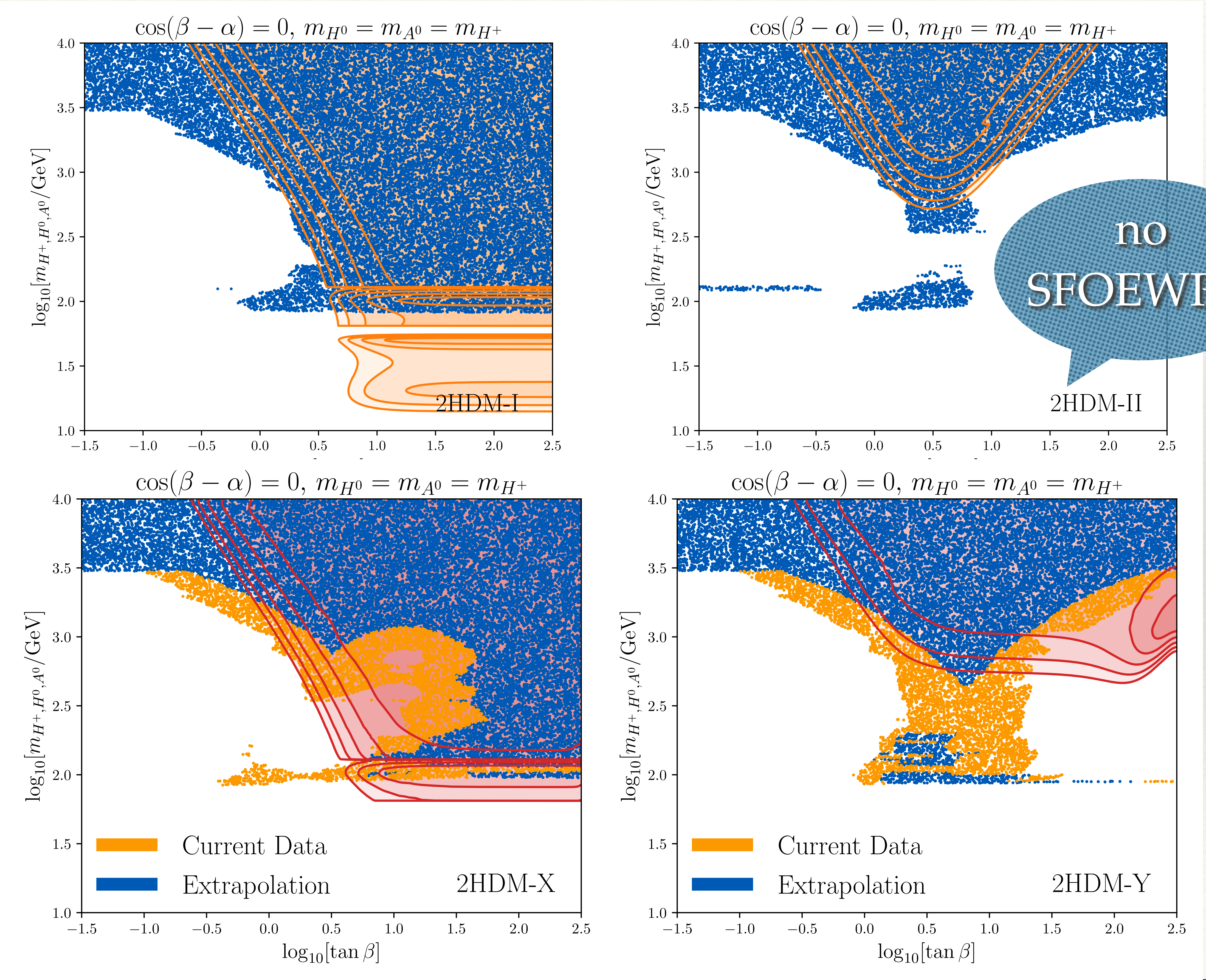
[Atkinson et al. `21, `22]

2HDMs: flavour & colliders



[Atkinson et al. `21, `22]

2HDMs: flavour & colliders



[Anisha et al. `22]

modified ELW baryogenesis: 2HDM

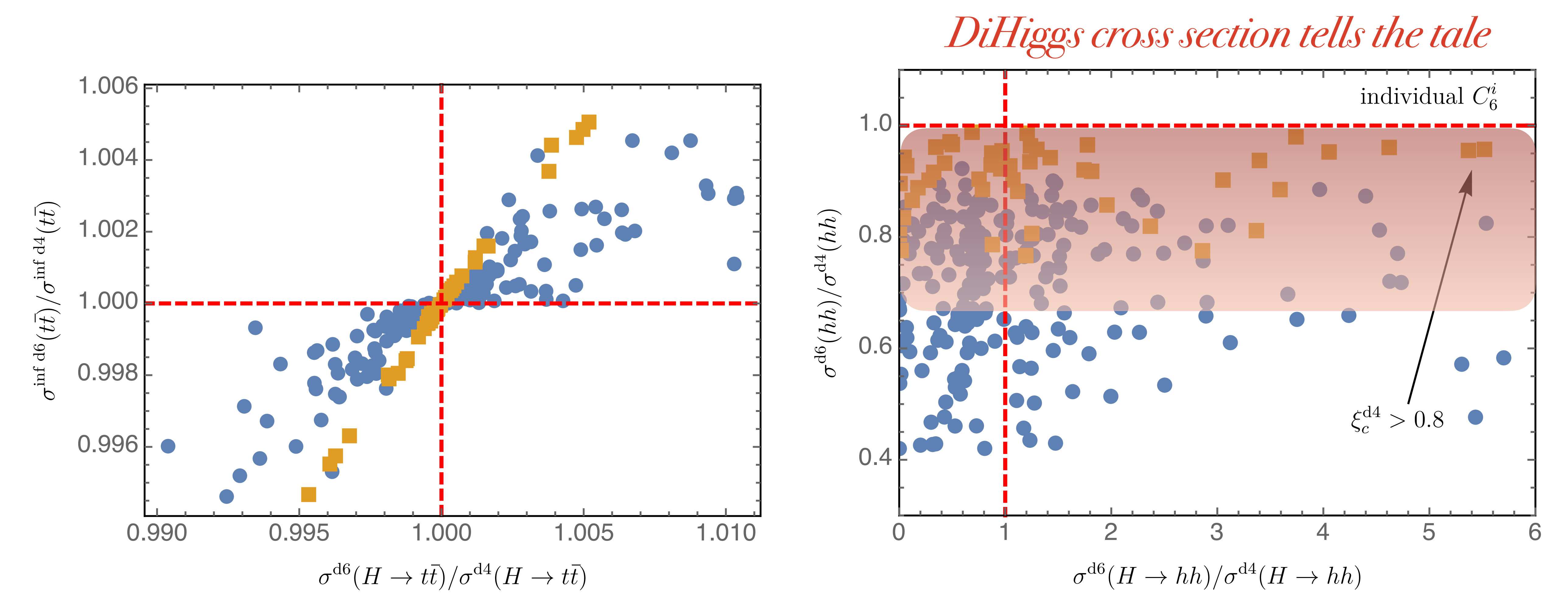
- ELW baryogenesis increasingly disfavoured in 2HDM II [Atkinson et al.` 21]

new EFT-parametrised dynamics

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

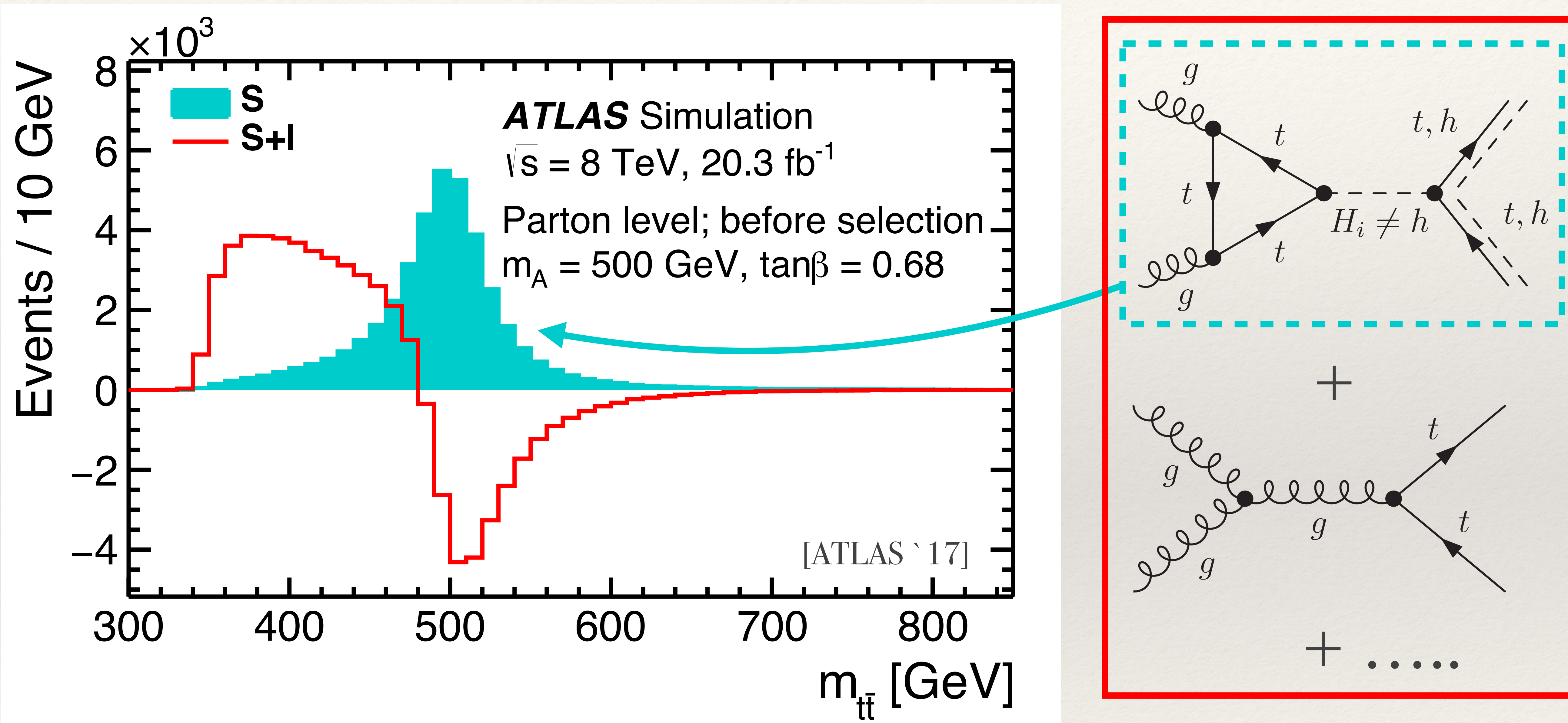
O_6^{111111}	$(\Phi_1^\dagger \Phi_1)^3$	O_6^{222222}	$(\Phi_2^\dagger \Phi_2)^3$
O_6^{111122}	$(\Phi_1^\dagger \Phi_1)^2(\Phi_2^\dagger \Phi_2)$	O_6^{112222}	$(\Phi_1^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)^2$
O_6^{122111}	$(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_1^\dagger \Phi_1)$	O_6^{122122}	$(\Phi_1^\dagger \Phi_2)(\Phi_2^\dagger \Phi_1)(\Phi_2^\dagger \Phi_2)$
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.

DiHiggs cross section tells the tale



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

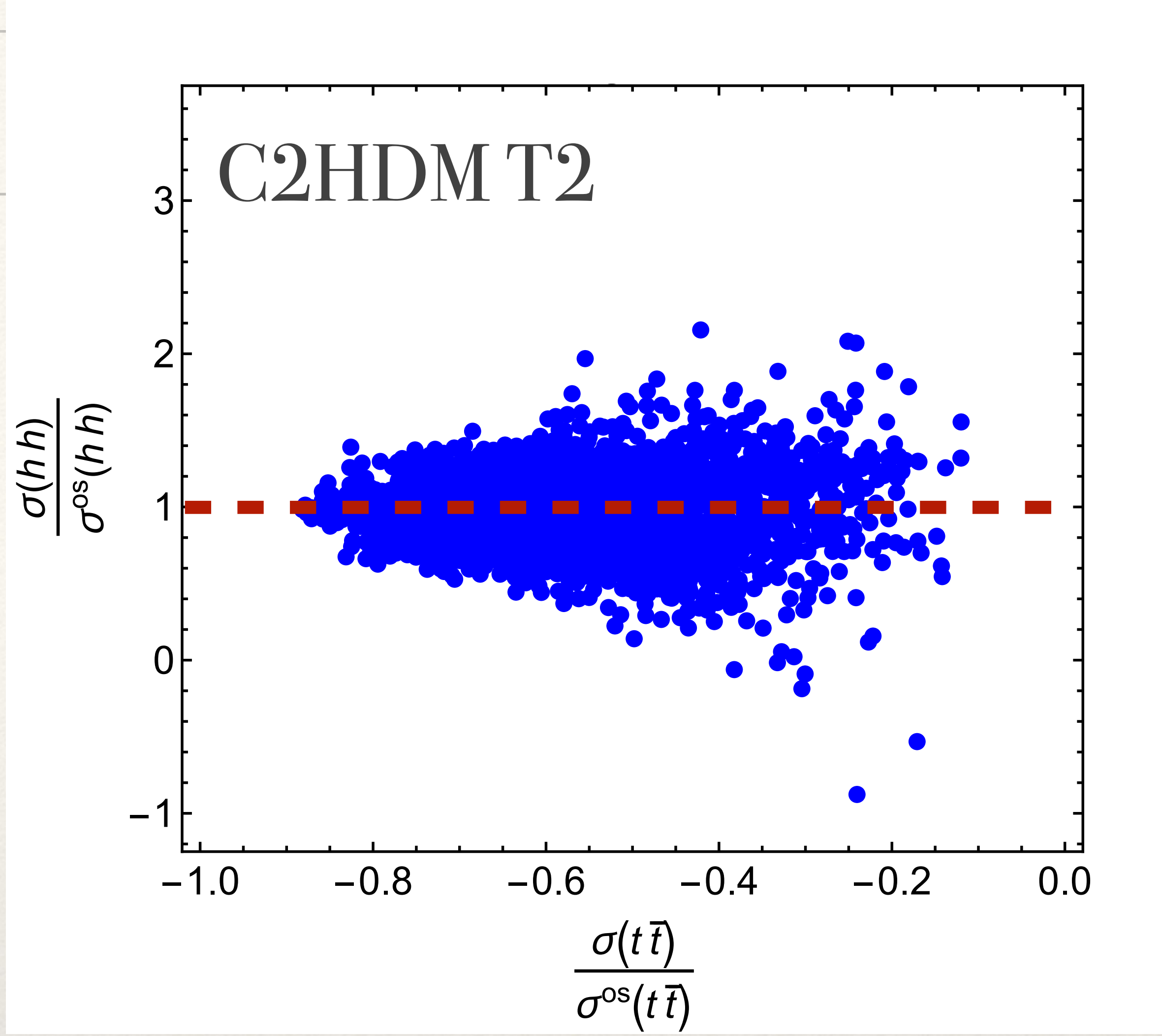
[Gaemers, Hoogeveen `84] [Dicus et al. `94]....



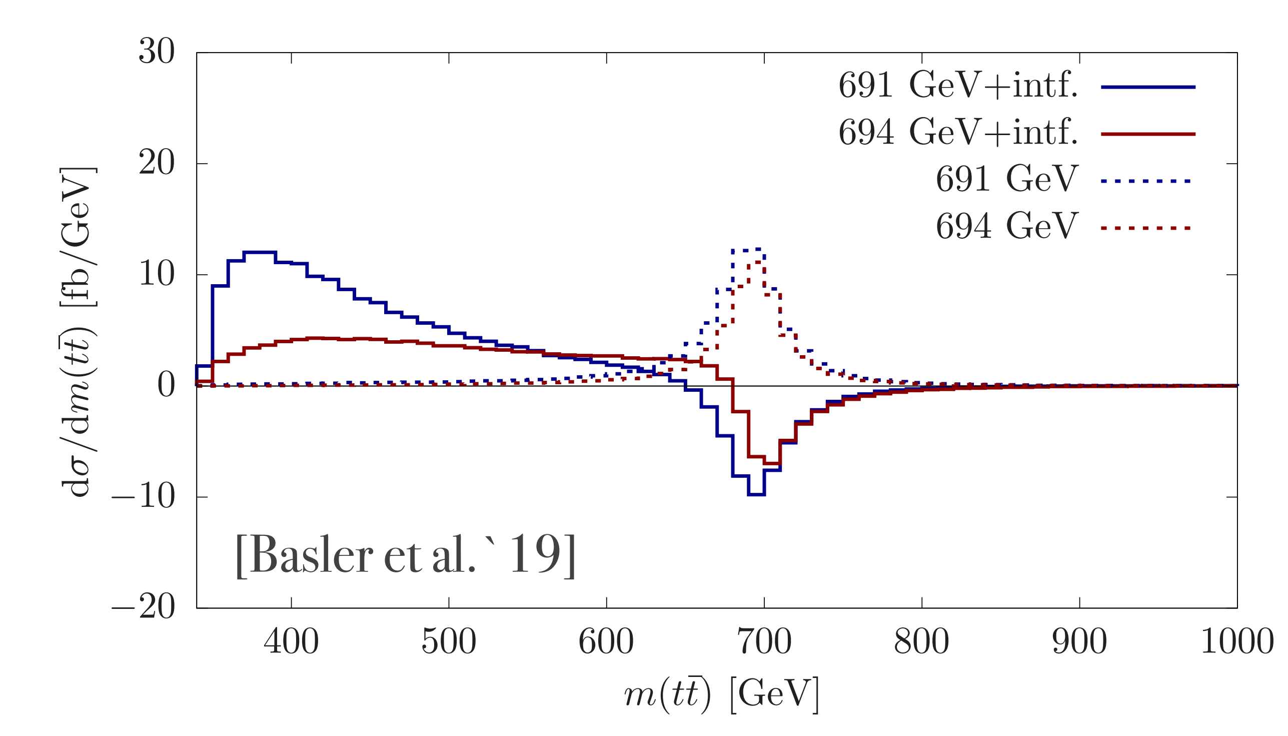
- top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!

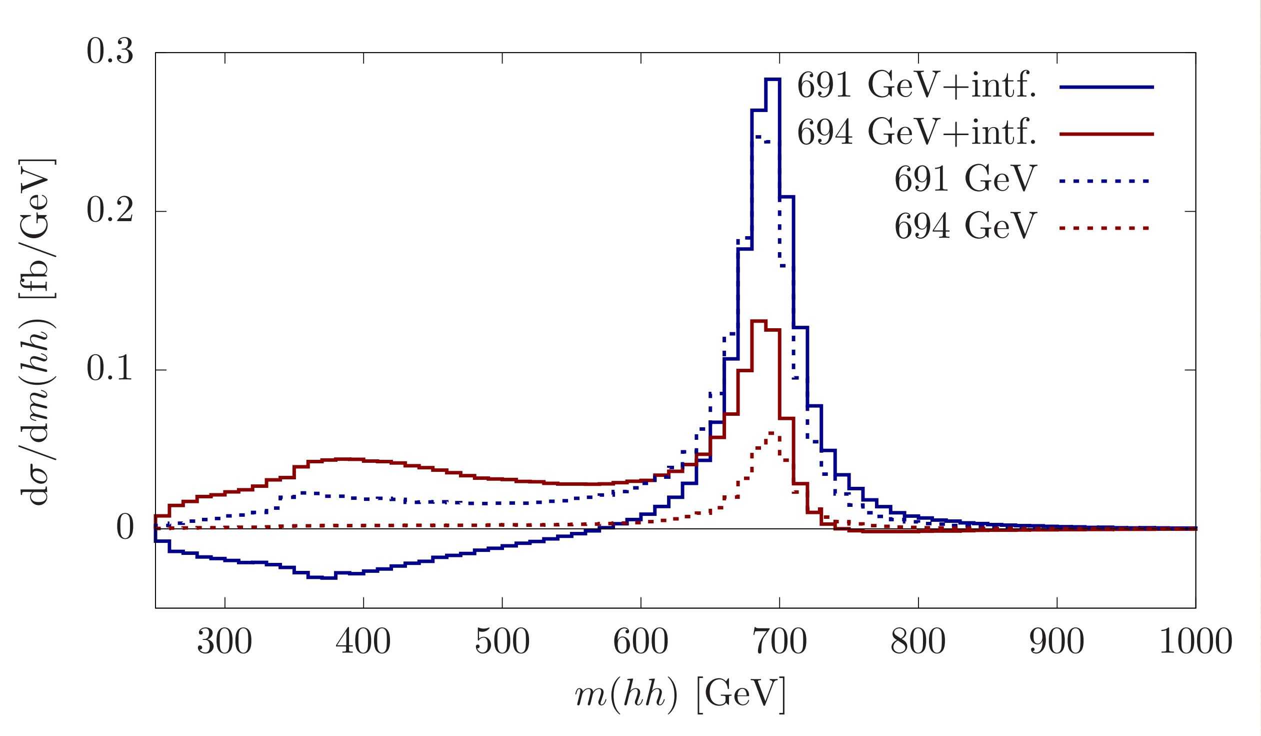
special role of tops

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



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





- *Post-Higgs discovery the goal post has shifted*
  - SM is renormalisable: blessings of the past hold us prisoner today

Summary

- *Post-Higgs discovery the goal post has shifted*
    - SM is renormalisable: blessings of the past hold us prisoner today

- *Post-Higgs discovery the goal post has shifted*
  - SM is renormalisable: blessings of the past hold us prisoner today
  - "Work under the lamppost" – untenable (in my opinion)

[Frank's pep talk]

new ideas:
relaxion, criticality,
cosmology…

new tools:
less traditional
approaches

new territory:
high intensity, …

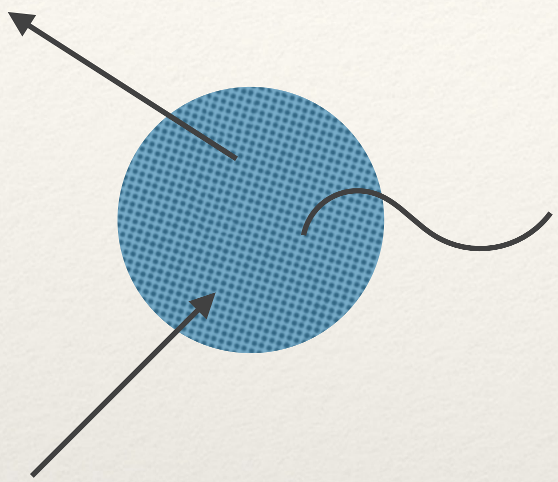
….

- *We know there's BSM physics. Where is it hiding?*
  - scalar sector of the SM still very much unexplored
    - experimental programme is well-developed
    - multi-Higgs production is crucial to understand our vacuum and its potential importance for the early Universe
    - margin for CP violation in Higgs interactions
    - the curious case of $(g-2)_\mu$: looks increasingly unlikely that this is BSM, little motivated phenomenological scope
  - technical advances at the HL frontier will help to get a more fine grained picture of the electroweak scale: huge discovery potential

Sakharov

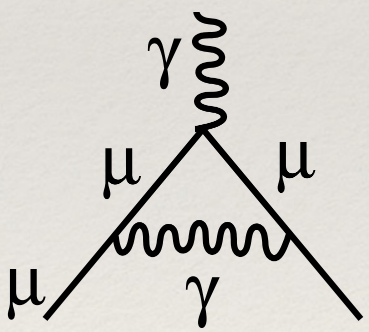
anomalous muon magnetic moment

- general decomposition of three-point QED vertex



$$= -ie\bar{u}(p') \left[\gamma^\mu F_1(k^2) + \frac{i}{2M_\mu} \sigma^{\mu\nu} k_\nu F_2(k^2) + \ldots \right] u(p)$$

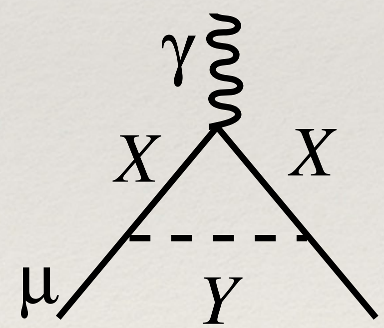
- magnetic moment $\vec{\mu} = \frac{e}{2m}[2\overset{=1}{F_1(0)} + 2\overset{=a_\mu}{F_2(0)}]\vec{S}$ gives $g = 2 + 2F_2(0)$



$$\delta a_\mu^{\mathrm{QED}} = \frac{\alpha}{2\pi}$$

[Schwinger `48]

... [Ayoma et al. `15, `17]



$$\delta a_\mu \sim g_{\mu XY}^2 \frac{m_\mu^2}{m_X^2}$$

new physics predominantly in muons, but large modification means either strong coupling or light states