Christoph Englert

Higgs and CP violation

Discrete 2024

02/12/24

2024
DISCRETE

LEVERHULME TRUST

UKRI

Science and Technology Facilities Council

University of Glasgow

What is the nature of the TeV scale?

...and what are its implications ?

- plethora of *serious* theoretical/observational problems
- somehow SM correlations are unexpectedly accurate

monetise electroweak data correlations towards BSM discovery ?

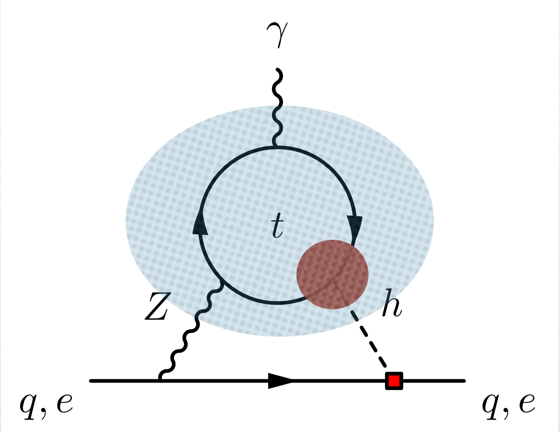
- *New avenues for collider CP sensitivity ?*
- *BSM sensitivity from rare multi-Higgs processes ?*
- *What can the LHC do for us ?*

"Low energy physics highly rules the Higgs CP game."

e.g. [Pospelov, Ritz `05] [Engel, Ramsay-Musolf, van Kolck `13]

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$

[Grzadkowski et al. `17]



vs.

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

+...

$B \to X_s\gamma, \ldots$

e.g. [Cirigliano, Crivellin, Dekens et al. `19]

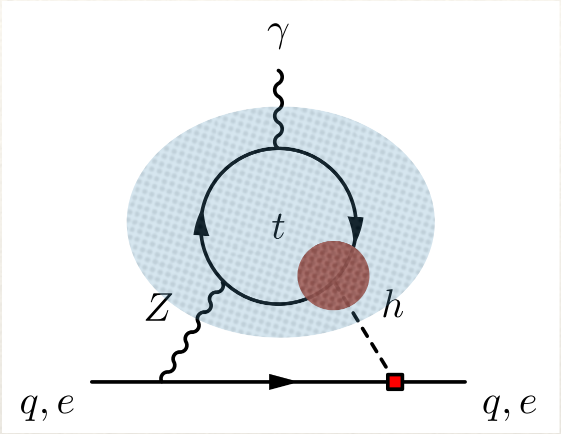
high energies?

"Low energy physics highly rules the Higgs CP game."

e.g. [Pospelov, Ritz `05] [Engel, Ramsay-Musolf, van Kolck `13]

$X^2\varphi^2$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi\widetilde{G}}$	$\varphi^\dagger\varphi\, \widetilde{G}^A_{\mu\nu}G^{A\mu\nu}$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi\widetilde{W}}$	$\varphi^\dagger\varphi\, \widetilde{W}^I_{\mu\nu}W^{I\mu\nu}$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{B}}$	$\varphi^\dagger\varphi\, \widetilde{B}_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu}B^{\mu\nu}$
$Q_{\varphi\widetilde{W}B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde{W}^I_{\mu\nu}B^{\mu\nu}$

[Grzadkowski et al. `17]



vs.

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

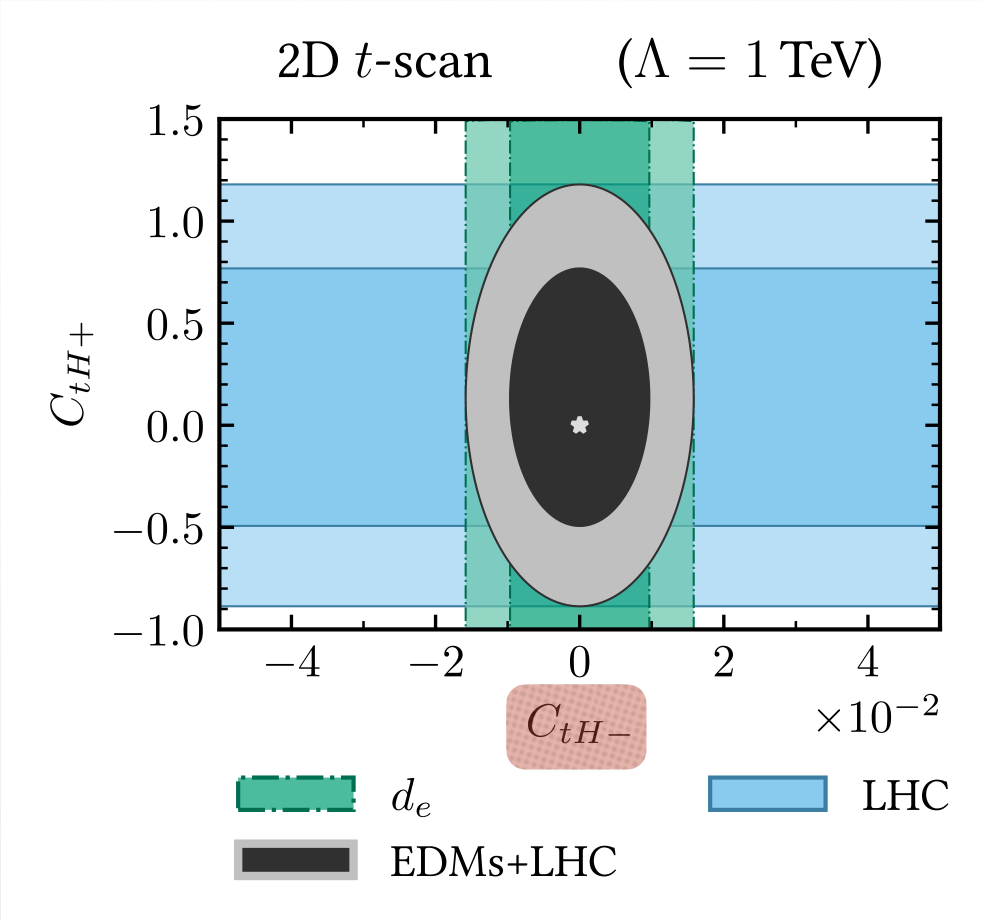
+...

underlying UV dynamics can often imply delicate cancellations

→ comp. Higgs ...

high energies?

...[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24] ...

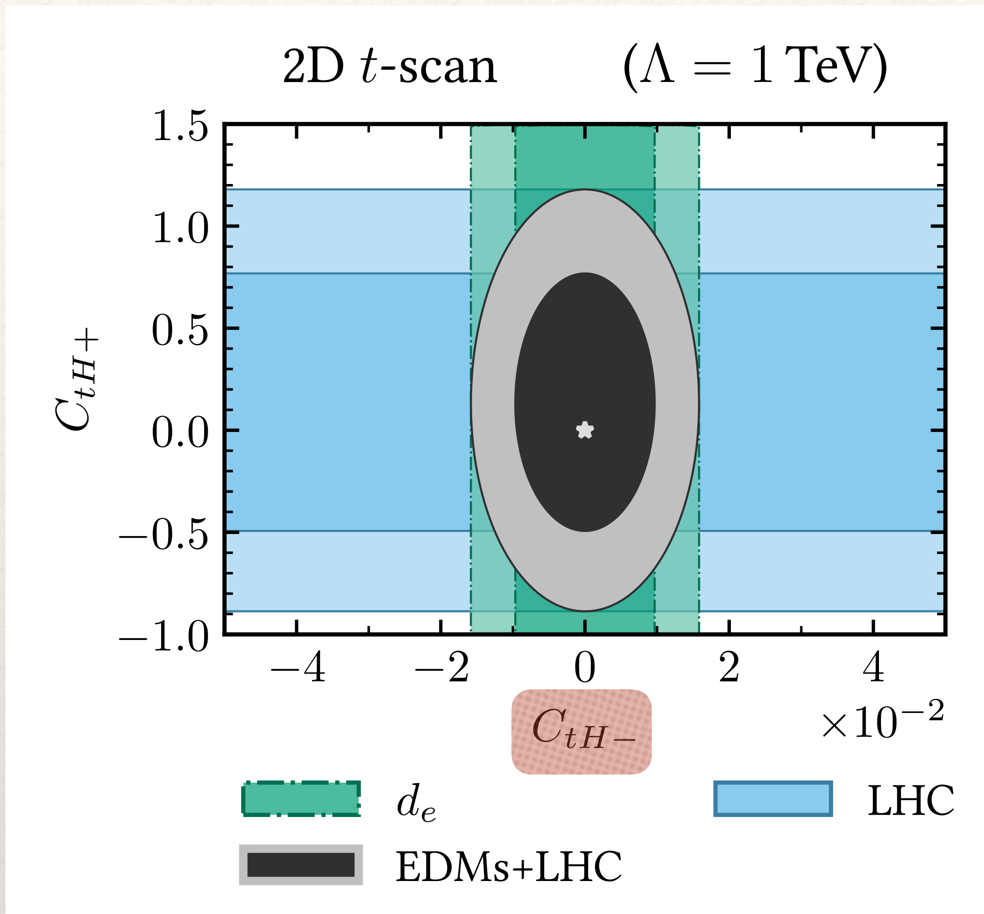


[Brod, Cornell, Skodras, Stamou `22]

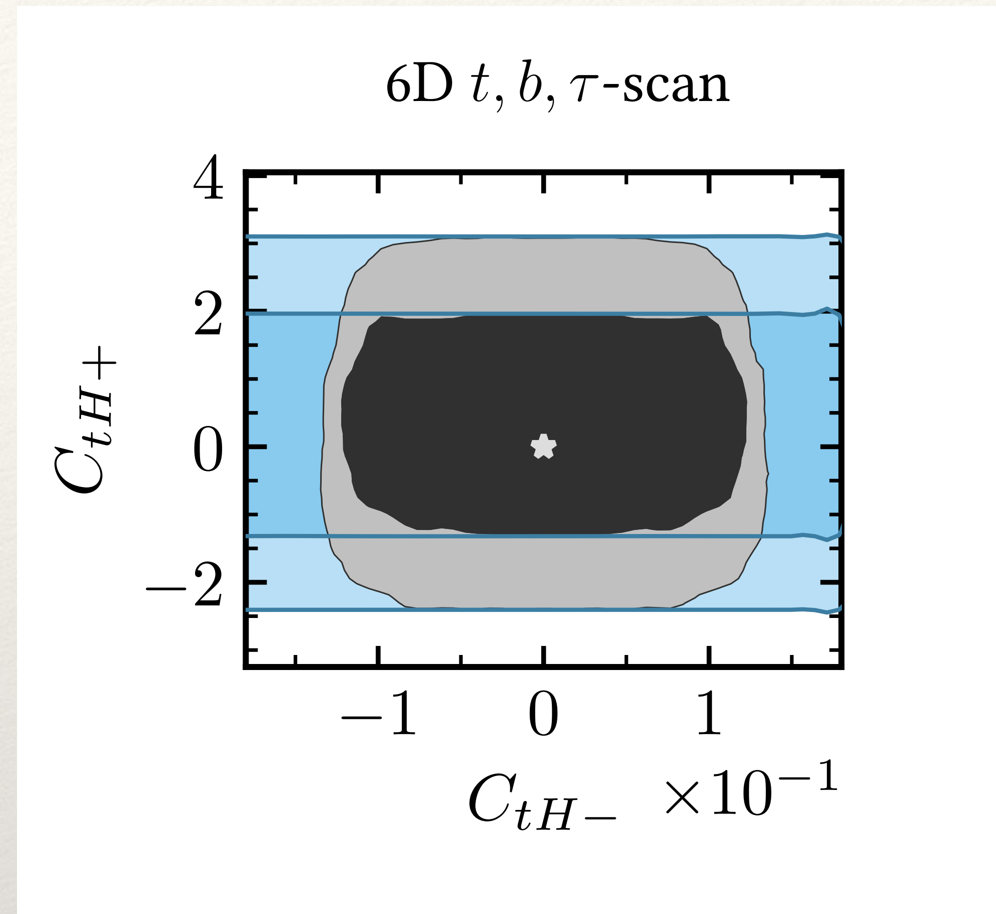
high energies?

…[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24]

…

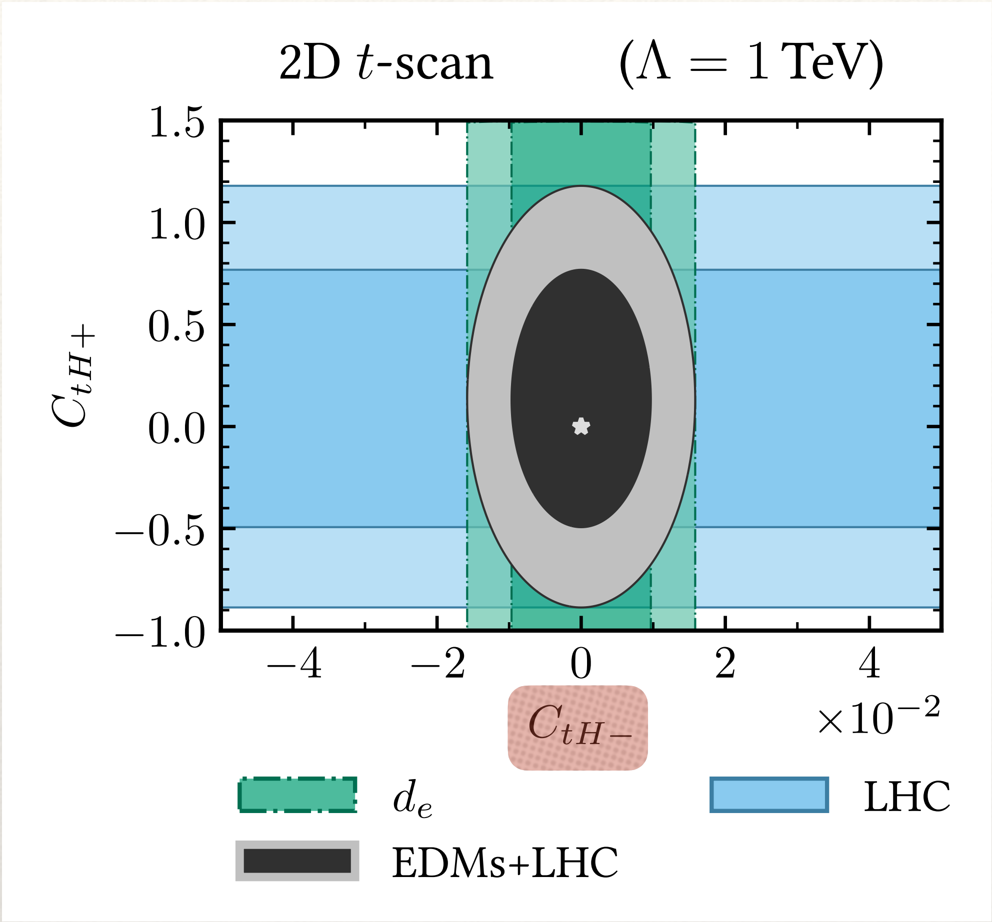


[Brod, Cornell, Skodras, Stamou `22]

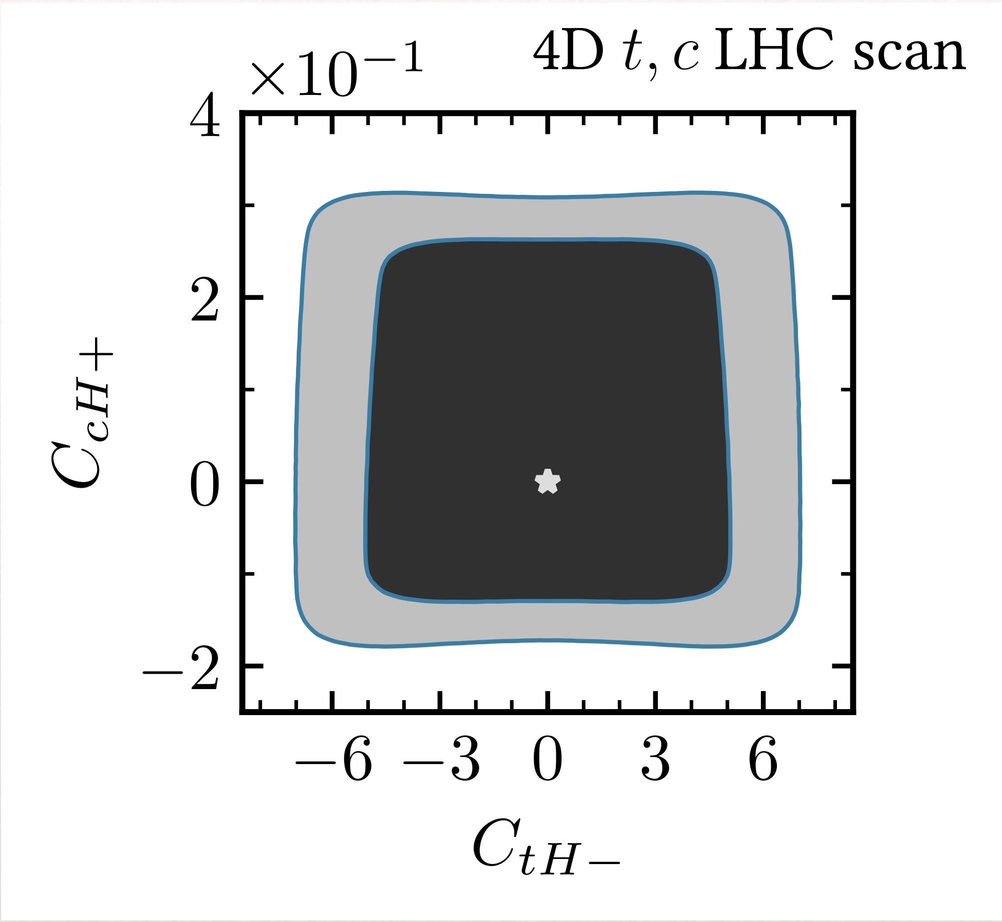


...[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24]

...

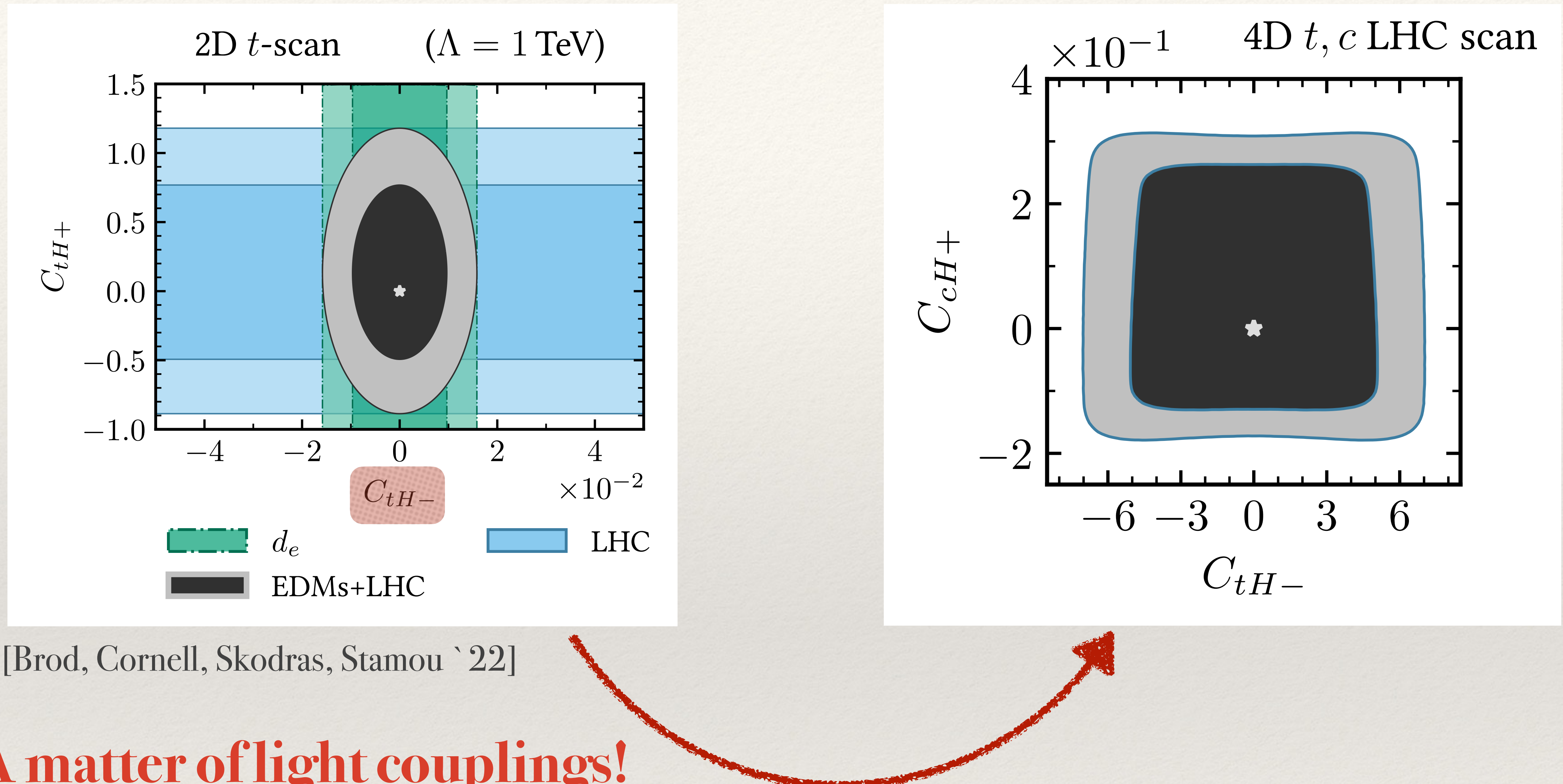


[Brod, Cornell, Skodras, Stamou `22]



...[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24]

...

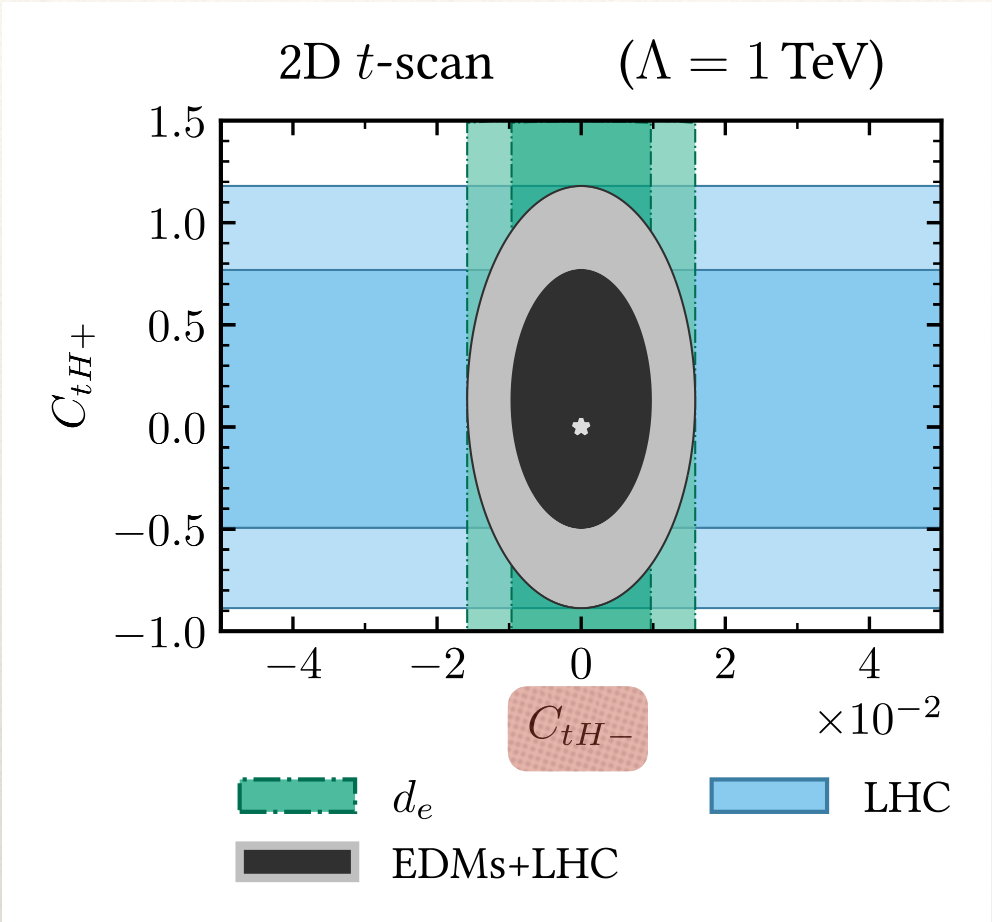


[Brod, Cornell, Skodras, Stamou `22]

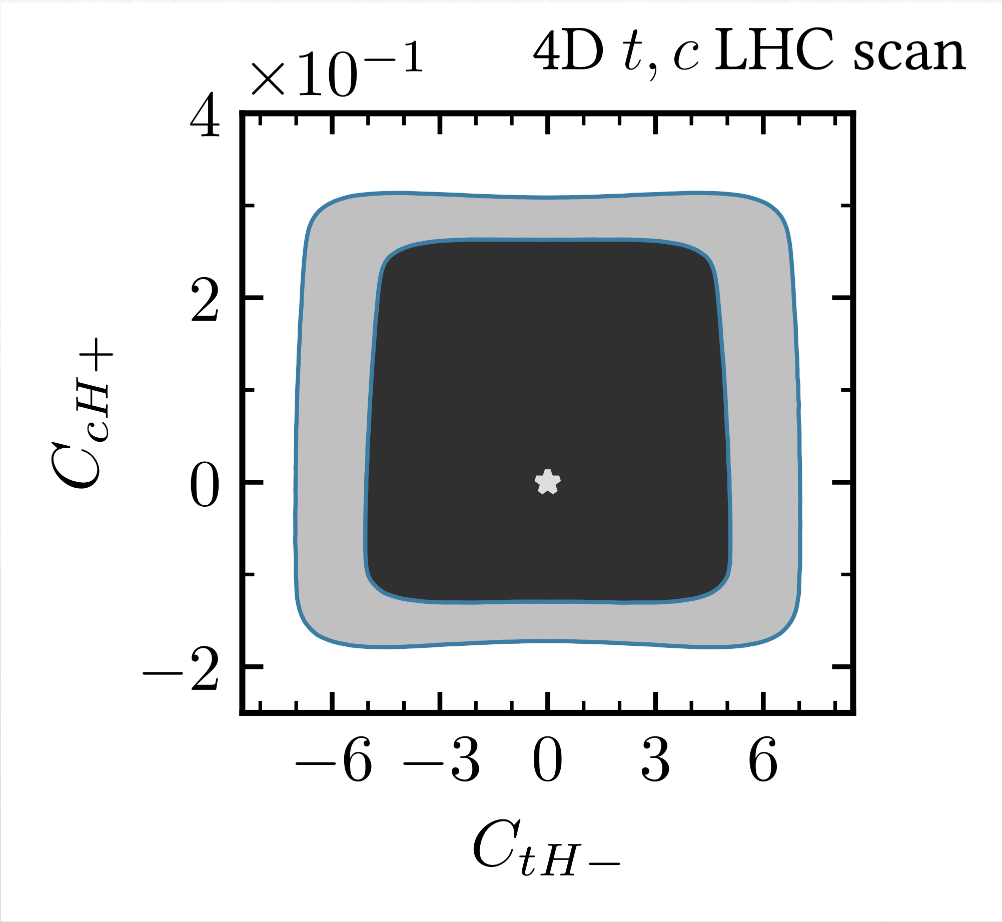
A matter of light couplings!

...[Brod, Cornell, Skodras, Stamou `22], [Brod, Polonsky, Stamou `23], [Degenkolb, Elmer, Modak, Muhlleitner, Plehn `24]

...



[Brod, Cornell, Skodras, Stamou `22]



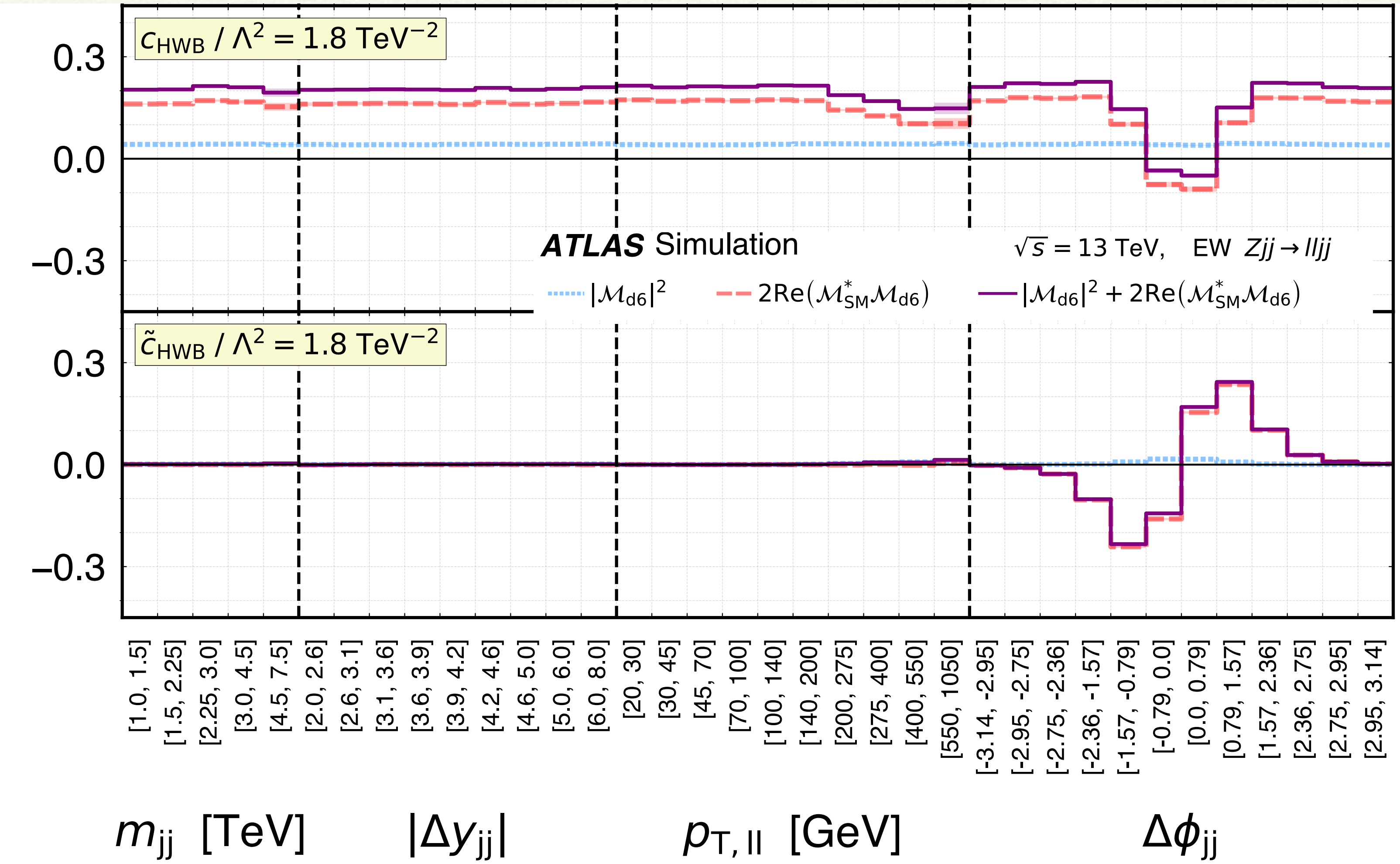
A matter of light couplings!

Current exclusion makes LHC improvements a high priority target

→ top-Higgs, gauge-Higgs sectors

[ATLAS, 2006.15458]

…and we are already in the deep end



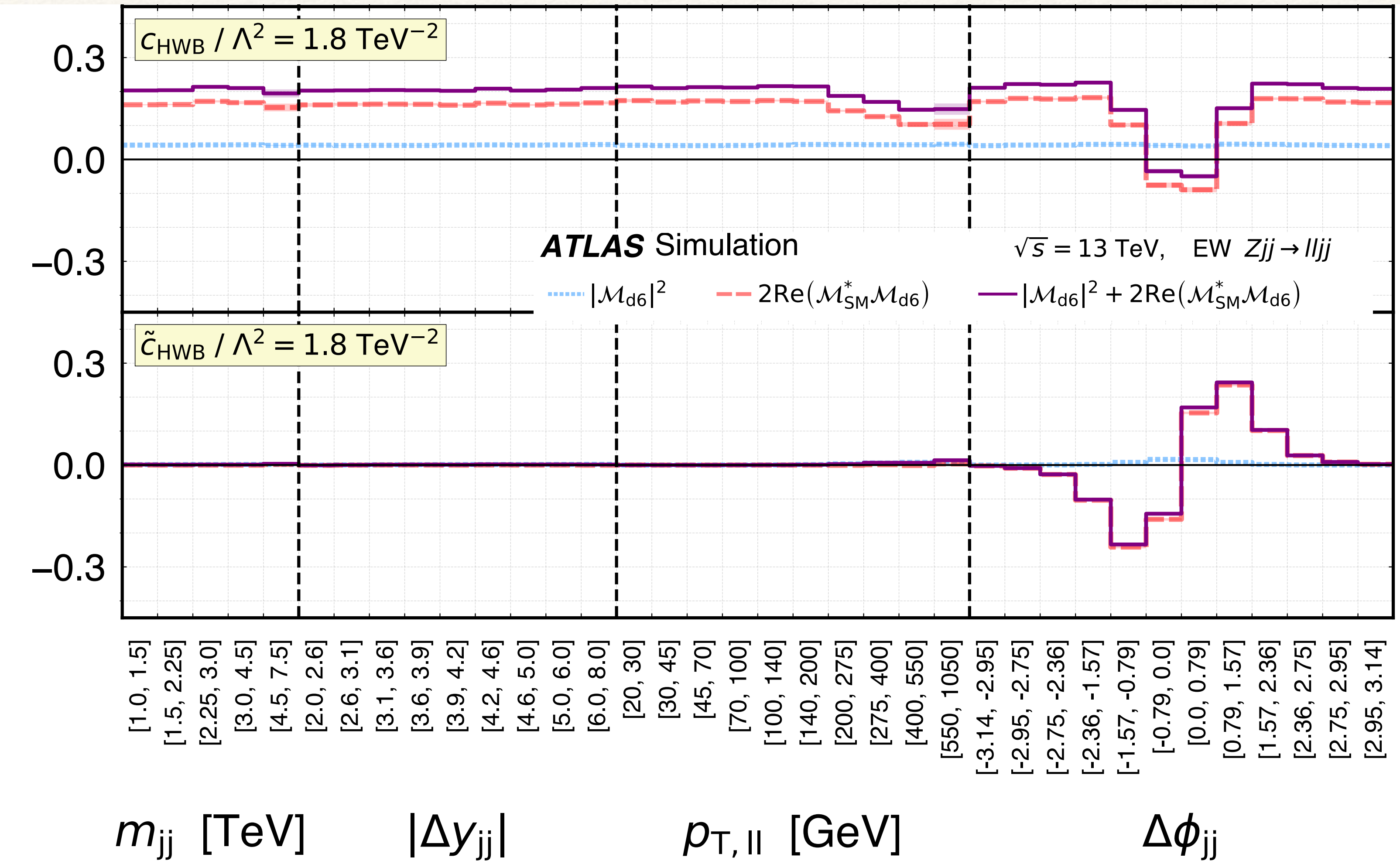
- asymmetry-based measurement in elw. Z+2jet production
- symmetric CP even effects cancel
- challenging to combat fluctuations

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%

- evidence for BSM physics ?

[ATLAS, 2006.15458]

Higgs CP violation ?



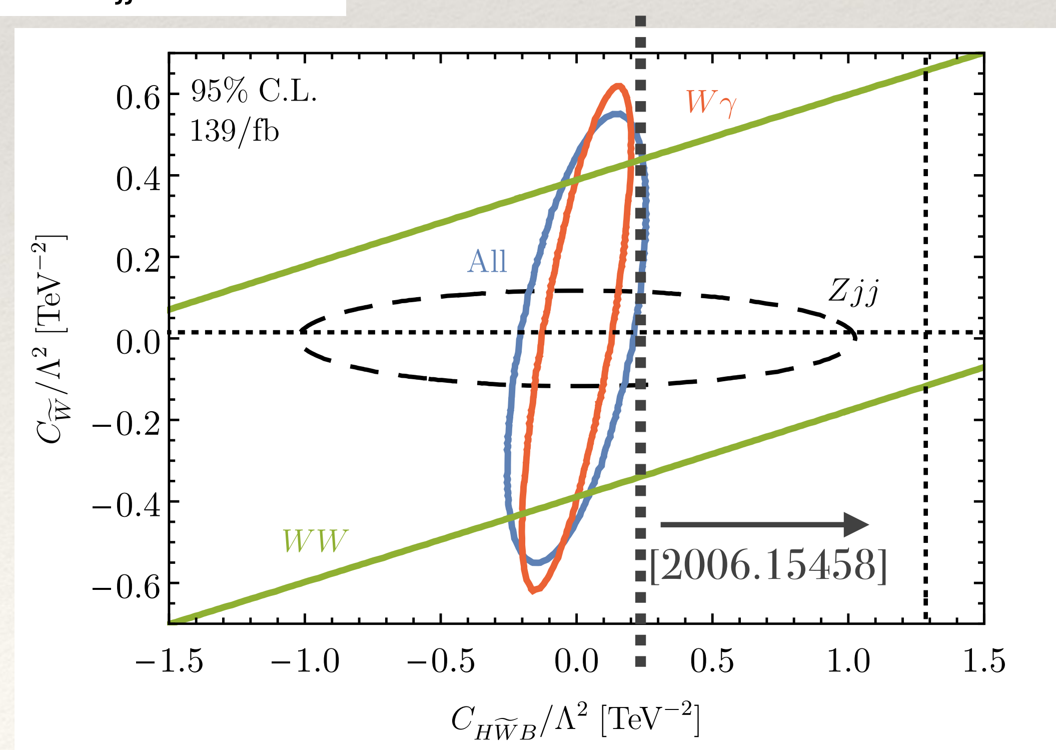
- asymmetry-based measurement in elw. Z+2jet production
- symmetric CP even effects cancel
- challenging to combat fluctuations

- evidence for BSM physics ?

unlikely but directly testable

[Das Bakshi et al. `20]

[Bieкötter, Gregg, Krauss, Schönherr `21]



- CP-interference net zero results from cancelling event weights

e.g. [Gritsan et al. `20]

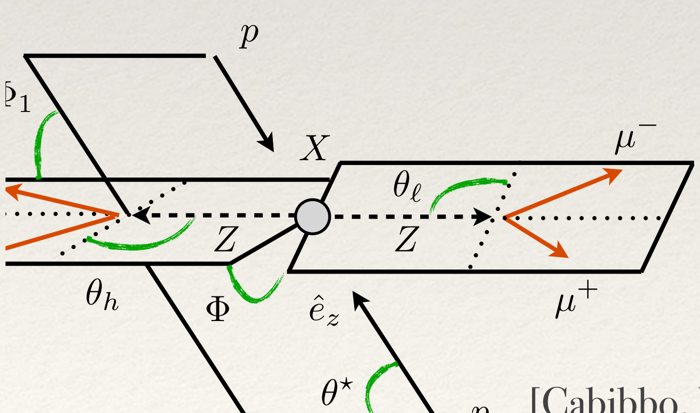
can create (near) optimal observable from
binary ± *weight* distinction?

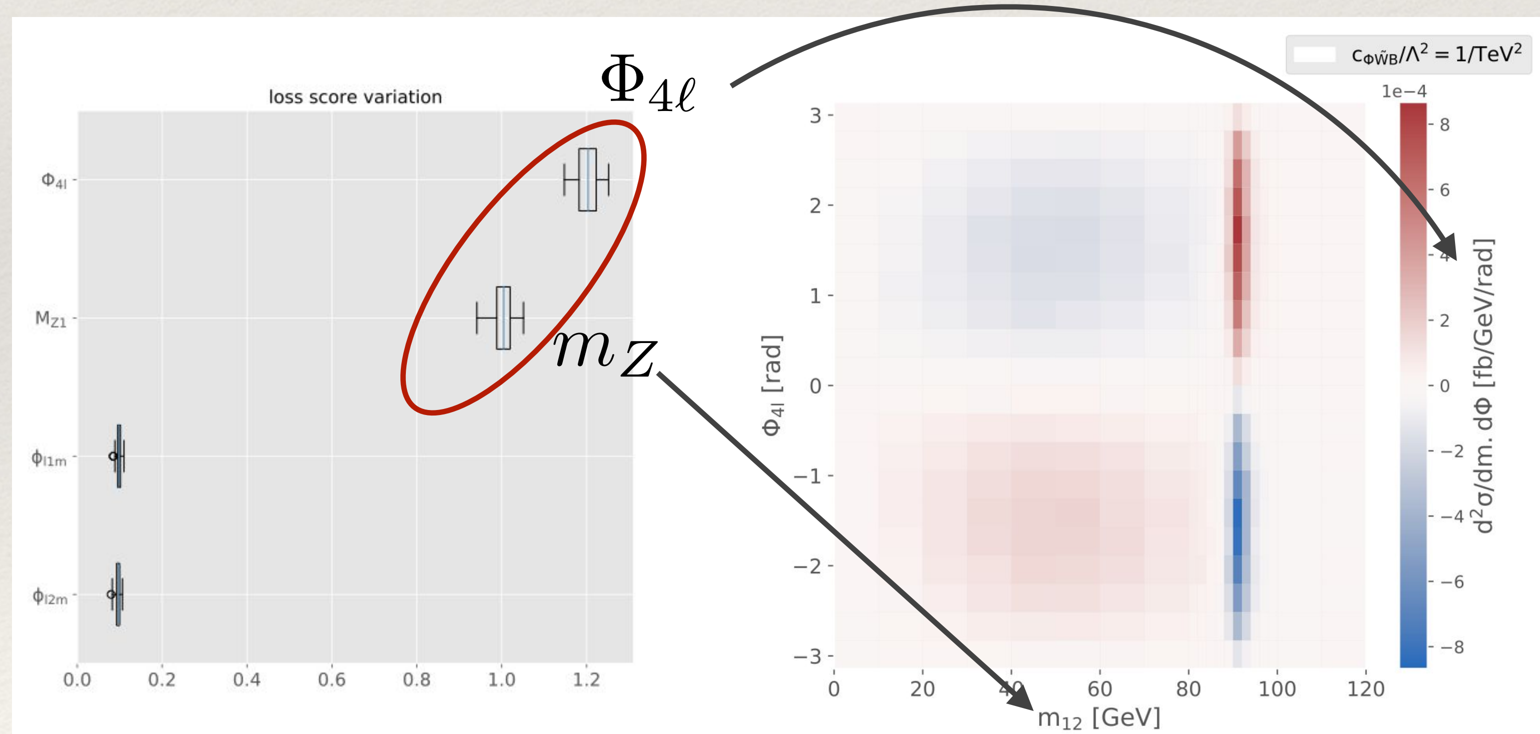
[Bhardwaj et al. `21]

- test cases $h \rightarrow ZZ^*$ (single scale) and weak boson fusion (*h+2jets*)

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

$$\Longrightarrow$$





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

going beyond

- CP-interference net zero results from cancelling event weights

e.g. [Gritsan et al. `20]

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

[Bhardwaj et al. `21]

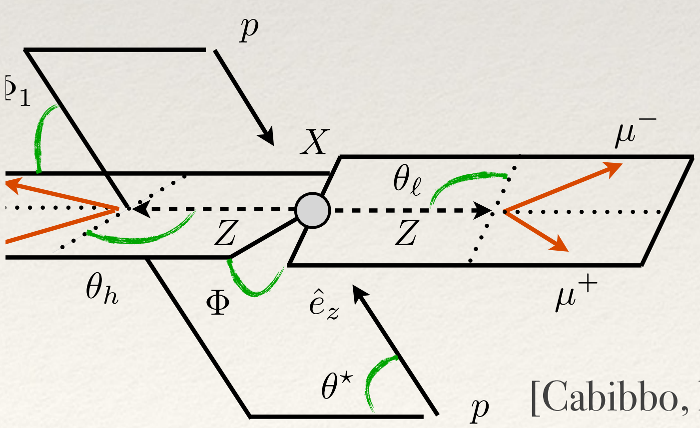
- test cases $h \to ZZ^*$ (single scale) and weak boson fusion (h+2$jets$)

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

$\Longrightarrow$

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]



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

improvements beyond multi-dim fits

- CP-interference net zero results from cancelling event weights

e.g. [Gritsan et al. `20]

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

[Bhardwaj et al. `21]

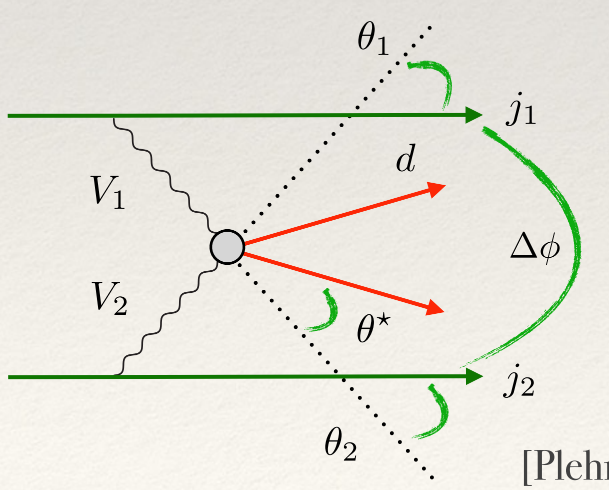
- test cases $h \to ZZ^*$ (single scale) and weak boson fusion (h+2$jets$)

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

$\Longrightarrow$

baseline is ATLAS $\tau\tau$ VBF_1 (**139/fb**) [ATLAS-CONF-2021-044]

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}]
$\Delta\phi_{jj}$	[-21,+21]	[-149,+149]	[-0.60,+0.60]
O_{NN} (binary)	[-11,+11]	[-43,+43]	[-0.66,+0.66]
O_{NN} (multi-class)	[-10,+10]	[-36,+36]	[-0.42,+0.42]

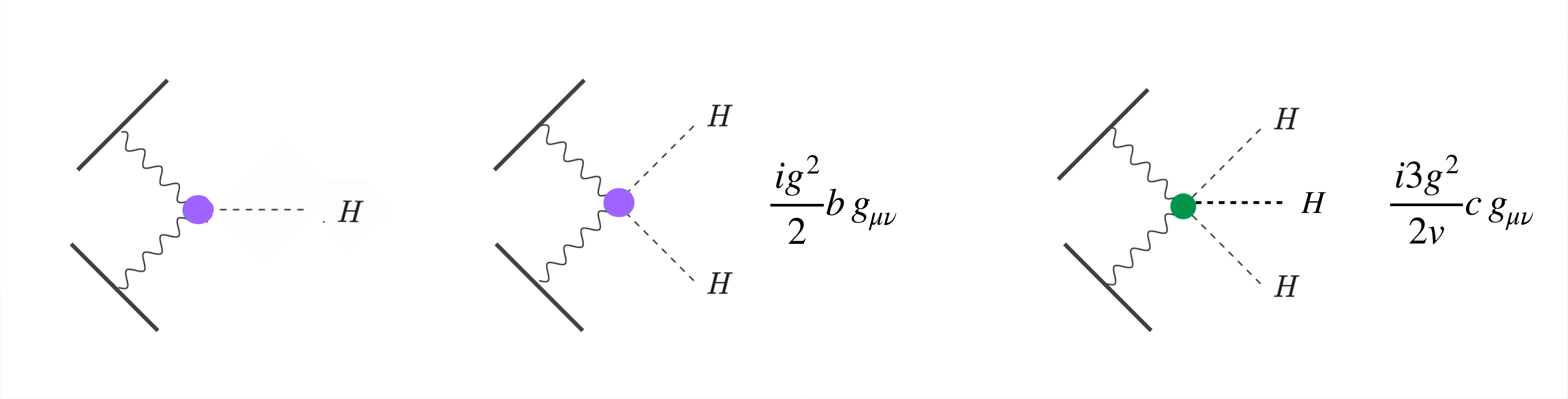


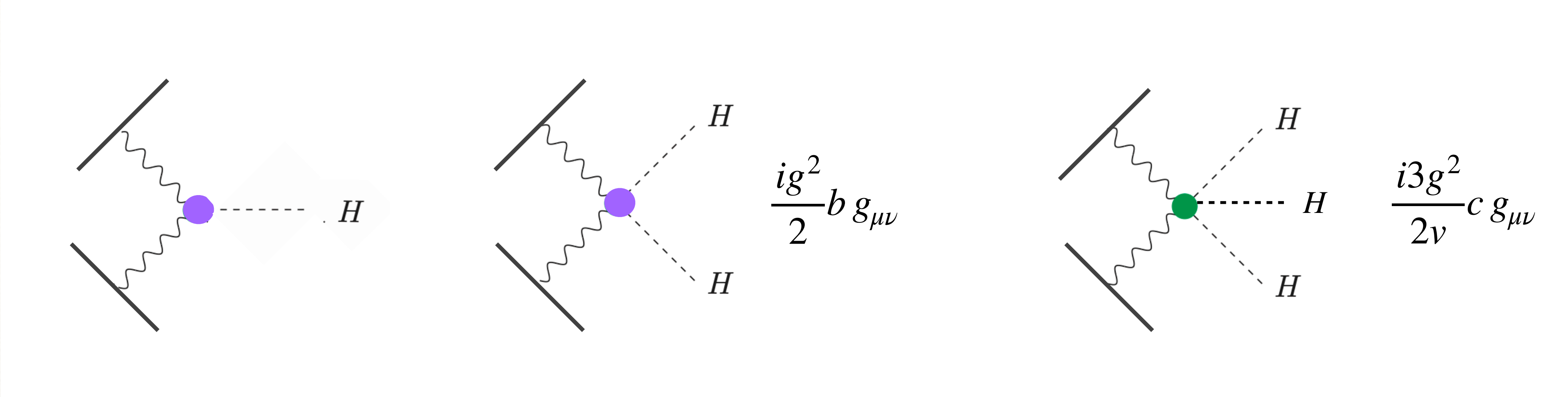
[Plehn, Rainwater `01]

...

improvements beyond multi-dim fits possible but reference to SM necessary to gain kinematic reference point

Going beyond linearity?

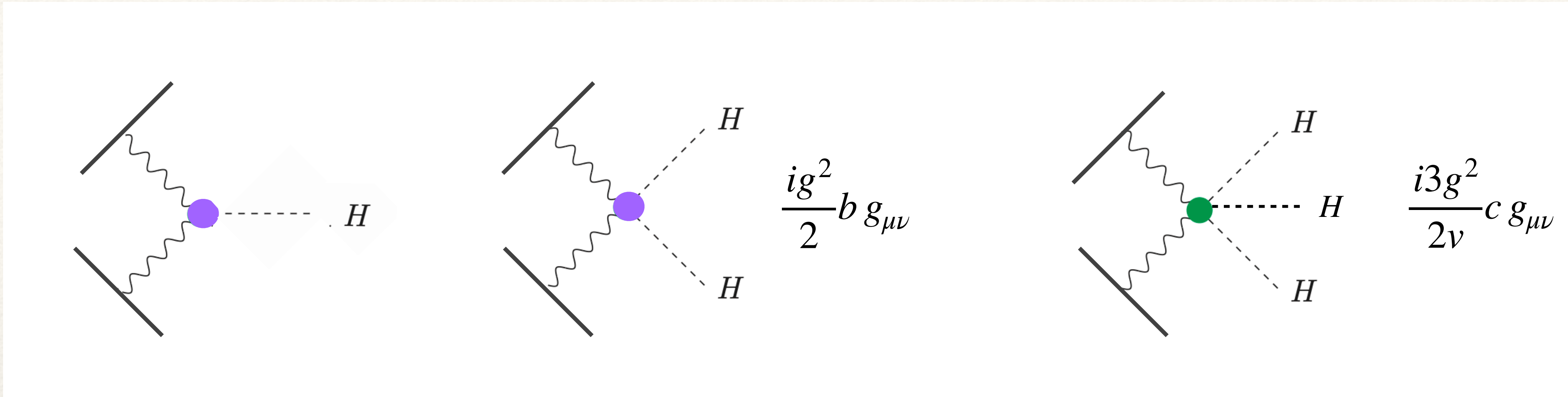




- How does the mechanism providing masses to the W/Z bosons look like?

[Alonso et al., `16, `16, and `21]

Going beyond linearity?

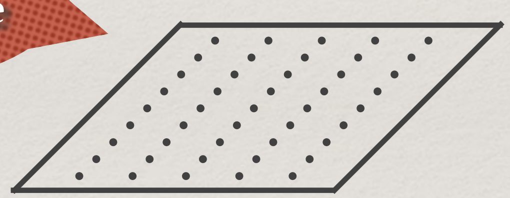


- How does the mechanism providing masses to the *W/Z* bosons look like?

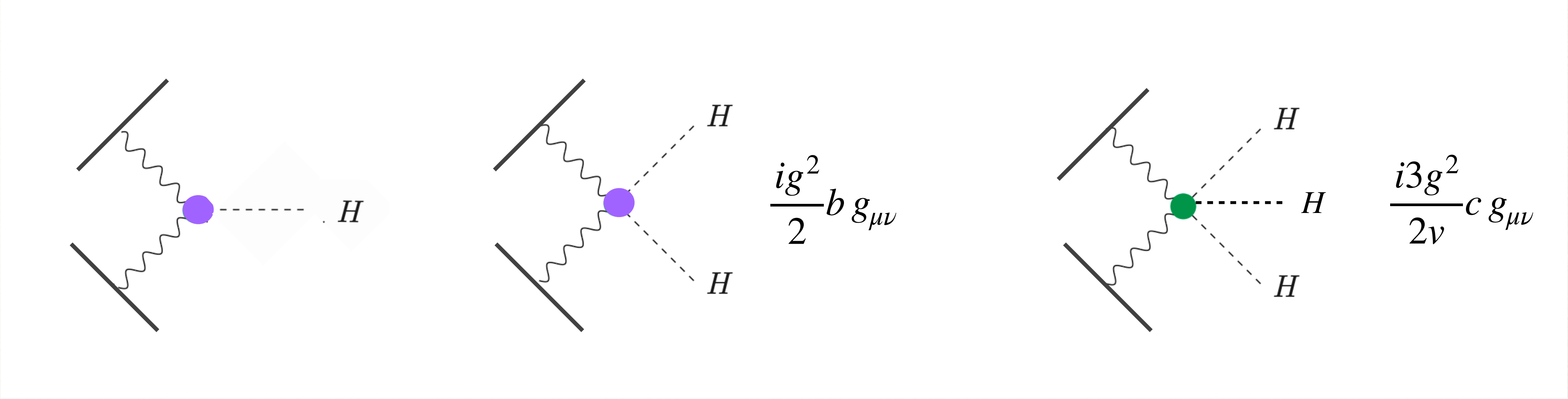
[Alonso et al., `16, `16, and `21]

clear CP landscape

SM (…2HDMs…)

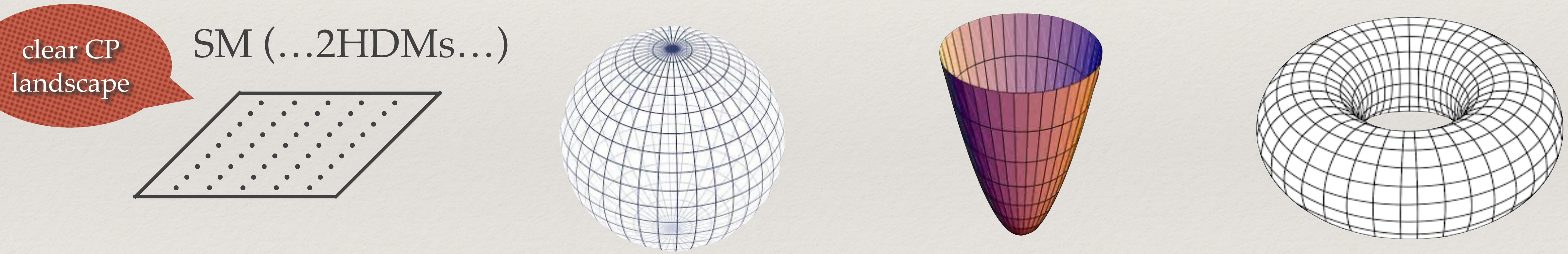


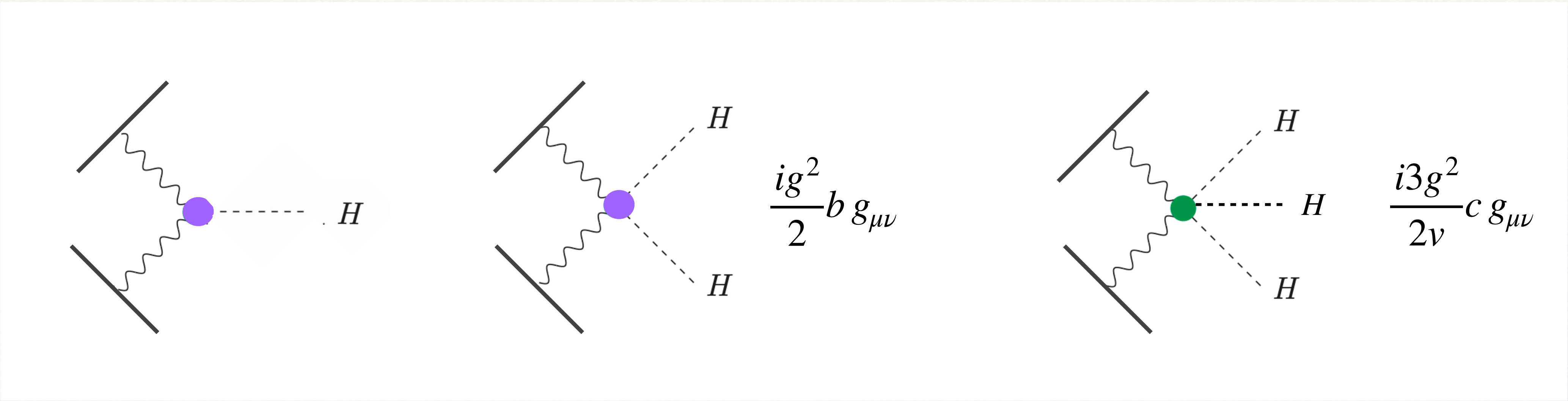
Going beyond linearity?



- How does the mechanism providing masses to the *W/Z* bosons look like?

[Alonso et al., `16, `16, and `21]

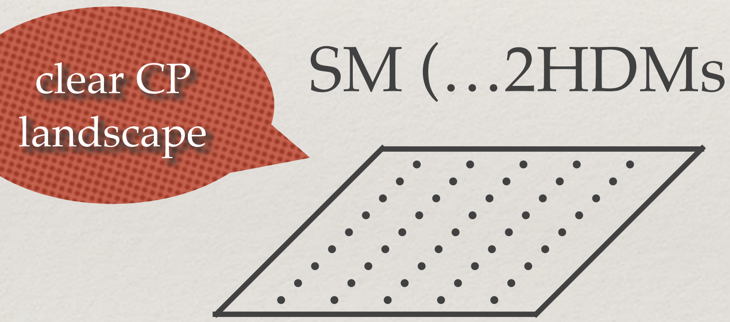


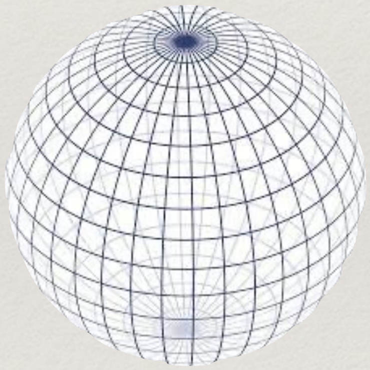


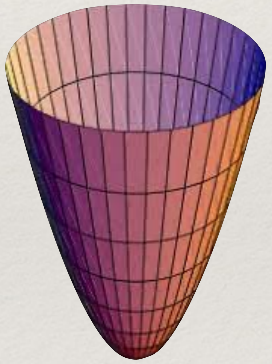
- How does the mechanism providing masses to the *W/Z* bosons look like?

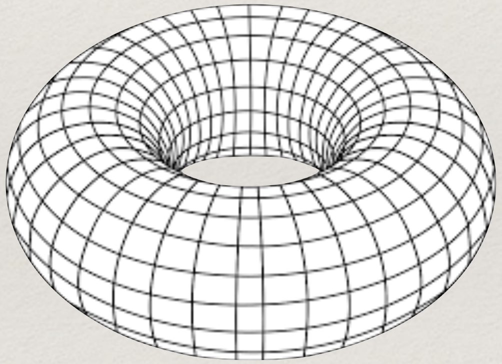
[Alonso et al., `16, `16, and `21]

SM (…2HDMs…)



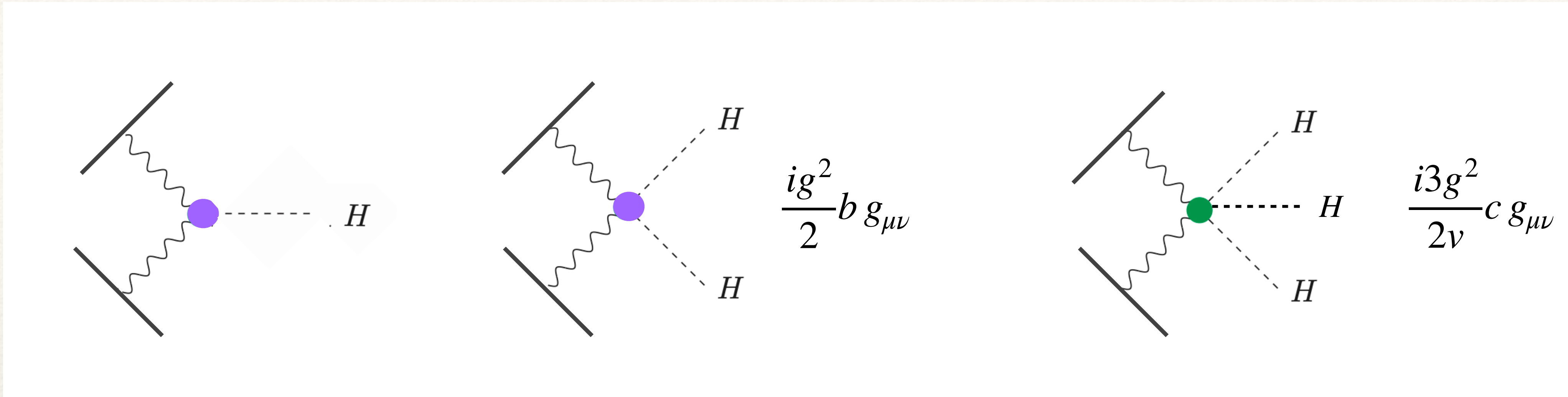






$a_{\rm SM}, b_{\rm SM} = 1, c_{\rm SM} = 0$ | $a, b \lesssim 1, c_{\rm SM} = 0$ | $a, b \gtrsim 1, c_{\rm SM} = 0$ | $a, b \simeq 1, c_{\rm SM} \lesssim 1$

Going beyond linearity?

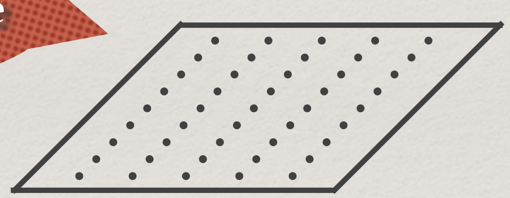


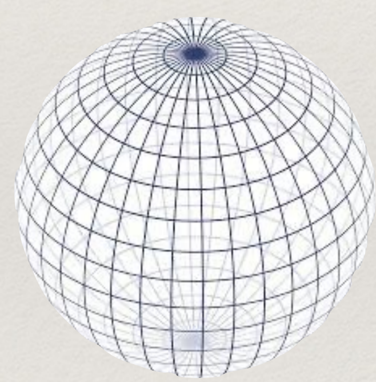
- How does the mechanism providing masses to the *W/Z* bosons look like?

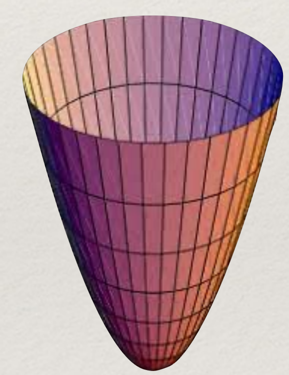
[Alonso et al., `16, `16, and `21]

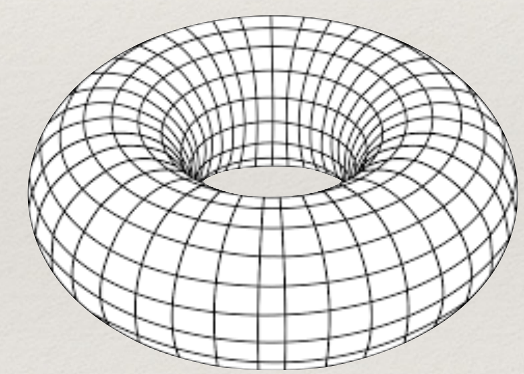
clear CP landscape

SM (…2HDMs…)









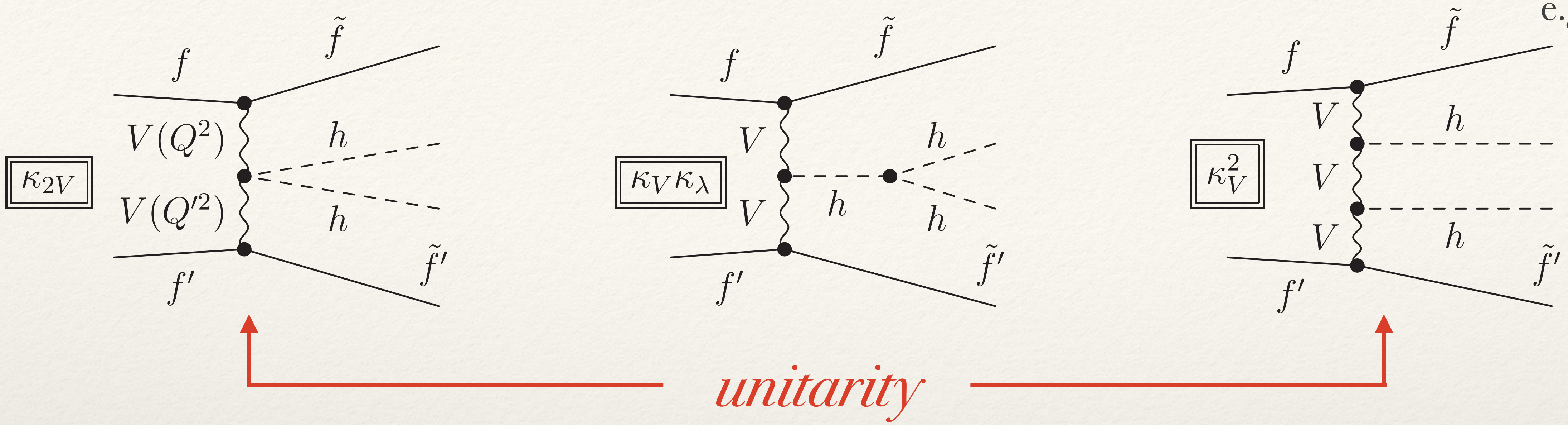
$a_{\rm SM}, b_{\rm SM} = 1, c_{\rm SM} = 0$ $\quad$ $a, b \lesssim 1, c_{\rm SM} = 0$ $\quad$ $a, b \gtrsim 1, c_{\rm SM} = 0$ $\quad$ $a, b \simeq 1, c_{\rm SM} \lesssim 1$

perturbative BSM

composite Higgs

SM as a BSM mirage

e.g. [ATLAS `23]



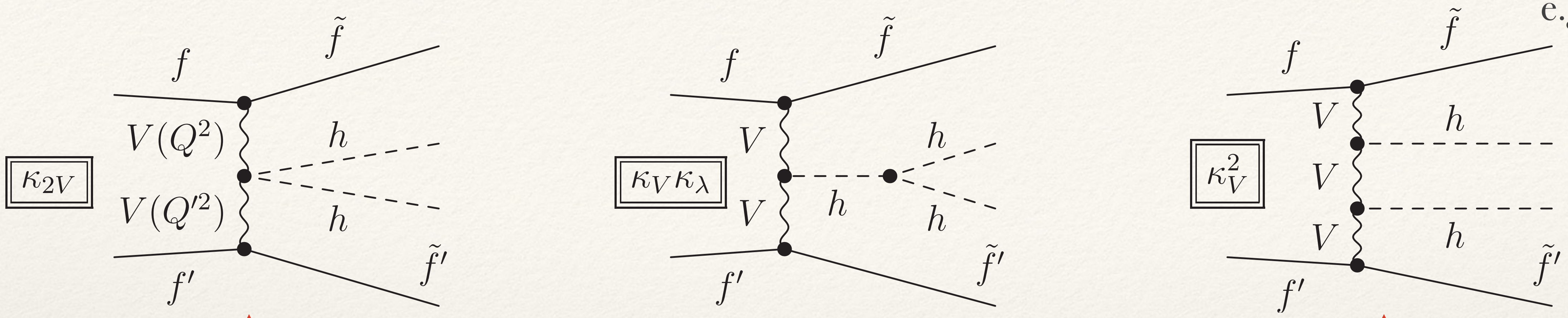
~1 fb

SMEFT SU(2)xU(1)/U(1)

HEFT SU(2)xSU(2)/SU(2)

(non-linear) gauge-Higgs interactions

e.g. [ATLAS `23]



~1 fb

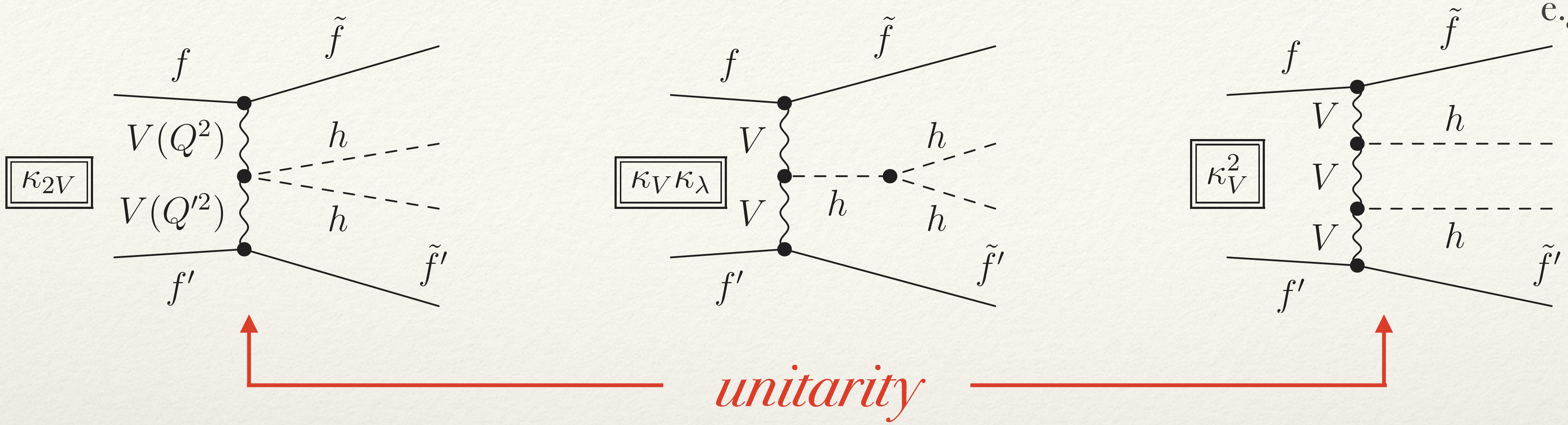
unitarity

SMEFT SU(2)xU(1)/U(1)

$$\mathcal{O}_{\Phi\widetilde{B}} = \frac{c_{\Phi\widetilde{B}}}{\Lambda^2}\Phi^\dagger\Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

HEFT SU(2)xSU(2)/SU(2)

e.g. [ATLAS `23]



~1 fb

SMEFT SU(2)xU(1)/U(1)

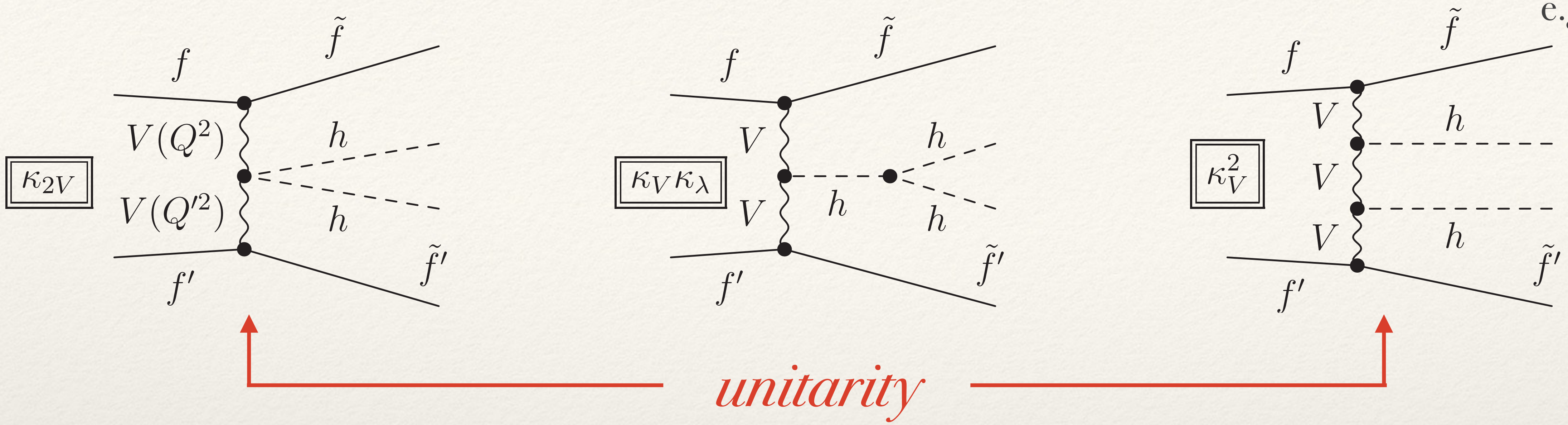
$$\mathcal{O}_{\Phi\widetilde{B}} = \frac{c_{\Phi\widetilde{B}}}{\Lambda^2}\Phi^\dagger\Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

HEFT SU(2)xSU(2)/SU(2)

$$\mathcal{F}_{h,B}\mathrm{Tr}\left[B_{\mu\nu}\sigma^3\widetilde{B}^{\mu\nu}\sigma^3\right]$$
$$= \left(c_{hB}\frac{h}{v} + c_{hhB}\frac{h^2}{2v^2} + \ldots\right)B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

(non-linear) gauge-Higgs interactions

e.g. [ATLAS `23]



~1 fb

SMEFT SU(2)xU(1)/U(1)

$$\mathcal{O}_{\Phi\widetilde{B}} = \frac{c_{\Phi\widetilde{B}}}{\Lambda^2}\Phi^\dagger \Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

correlation across multiplicities

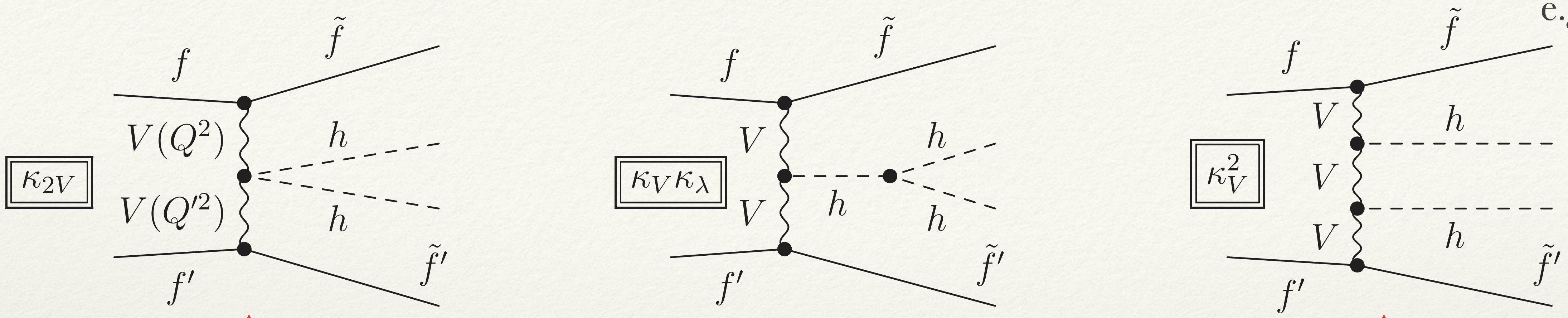
$$\frac{c_{h\widetilde{B}}}{v} = c_{\Phi\widetilde{B}}\frac{v}{\Lambda^2}\,,\; c_{hh\widetilde{B}} = c_{\Phi\widetilde{B}}\frac{v^2}{\Lambda^2}\,,\ldots$$

HEFT SU(2)xSU(2)/SU(2)

$$\mathcal{F}_{h,B}\mathrm{Tr}\left[B_{\mu\nu}\sigma^3\widetilde{B}^{\mu\nu}\sigma^3\right] = \left(c_{hB}\frac{h}{v} + c_{hhB}\frac{h^2}{2v^2} + \ldots\right)B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

(non-linear) gauge-Higgs interactions

e.g. [ATLAS `23]



~1 fb

unitarity

SMEFT SU(2)xU(1)/U(1)

$$\mathcal{O}_{\Phi\widetilde{B}} = \frac{c_{\Phi\widetilde{B}}}{\Lambda^2}\Phi^\dagger \Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

correlation across multiplicities

$$\frac{c_{h\widetilde{B}}}{v} = c_{\Phi\widetilde{B}}\frac{v}{\Lambda^2}\,,\; c_{hh\widetilde{B}} = c_{\Phi\widetilde{B}}\frac{v^2}{\Lambda^2}\,,\ldots$$

HEFT SU(2)xSU(2)/SU(2)

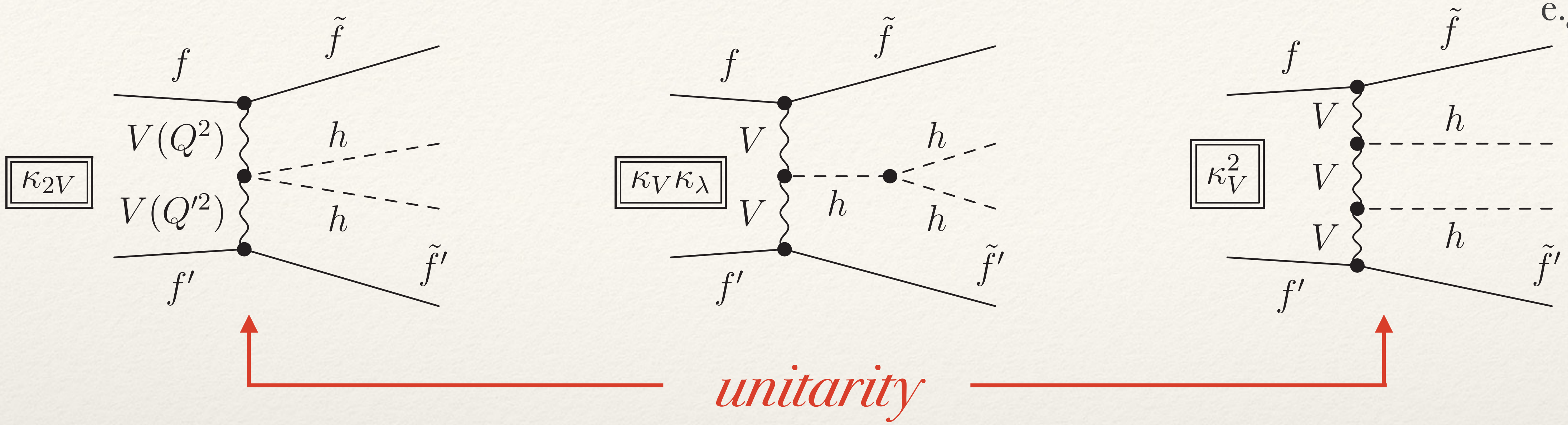
$$\mathcal{F}_{h,B}\mathrm{Tr}\left[B_{\mu\nu}\sigma^3\widetilde{B}^{\mu\nu}\sigma^3\right] = \left(c_{hB}\frac{h}{v} + c_{hhB}\frac{h^2}{2v^2} + \ldots\right)B^{\mu\nu}\widetilde{B}_{\mu\nu}$$

free parameters

$$c_{h\widetilde{B}}, c_{hh\widetilde{B}}, \ldots$$

(non-linear) gauge-Higgs interactions

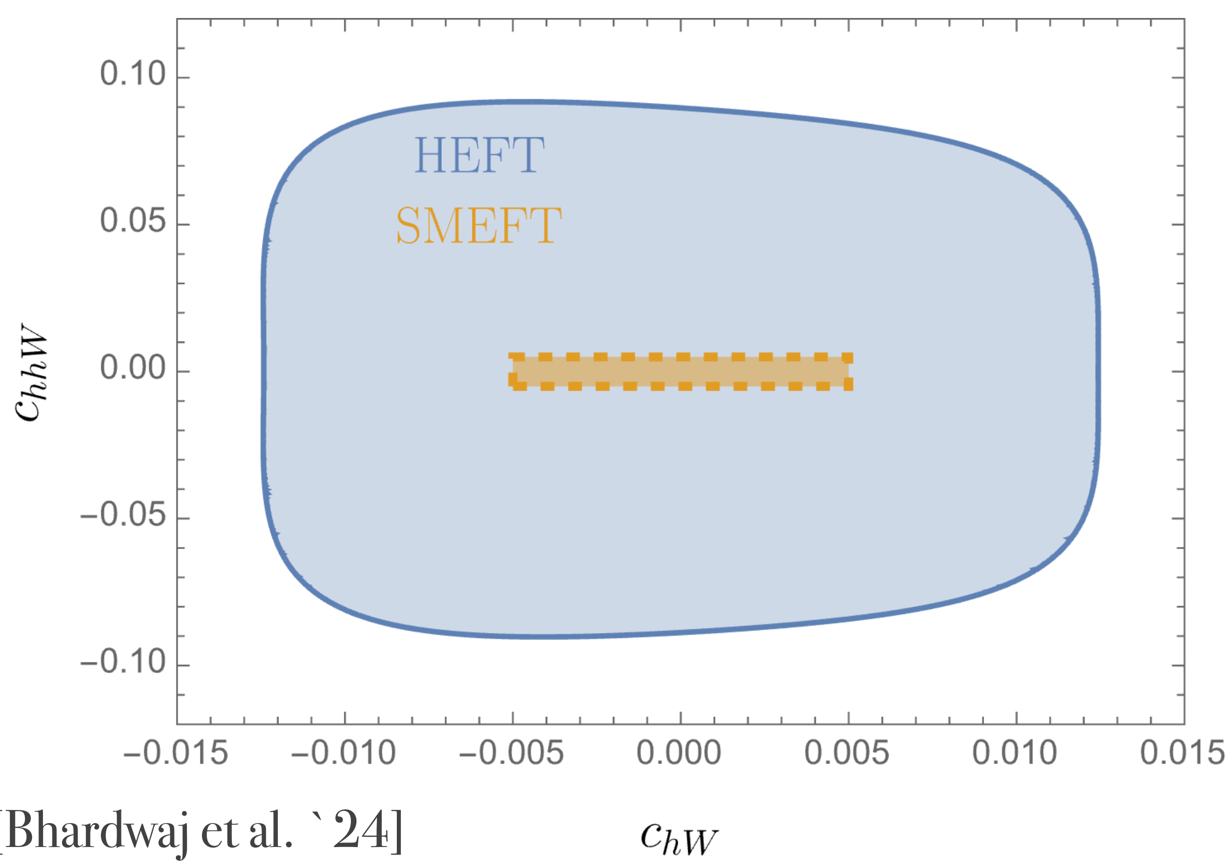
e.g. [ATLAS `23]



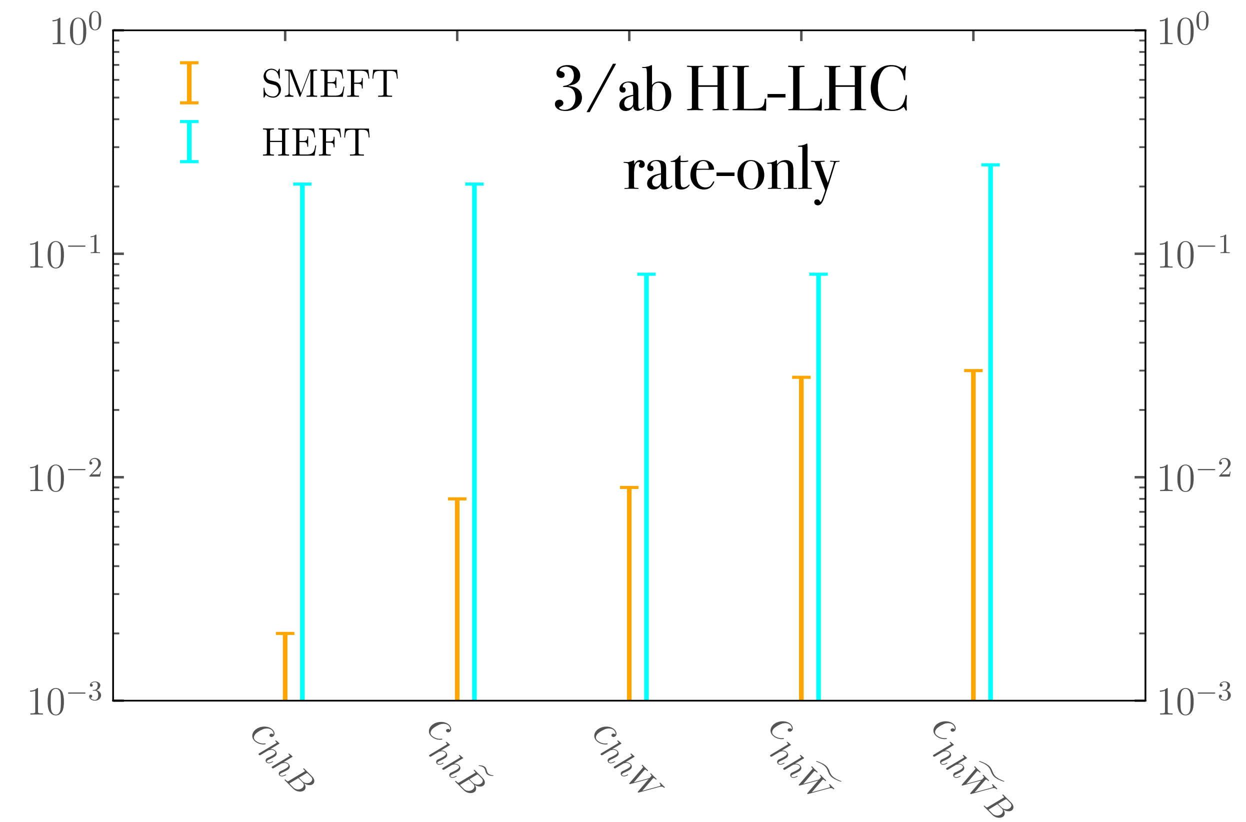
~1 fb

SMEFT SU(2)xU(1)/U(1)

HEFT SU(2)xSU(2)/SU(2)



[Bhardwaj et al. `24]



(non-linear) fermion-Higgs interactions

SMEFT SU(2)xU(1)/U(1)

$$\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$$

HEFT SU(2)xSU(2)/SU(2)

$$\mathcal{O}_{\bar{t}t} = -m_t\, \bar{Q}_L U t_R\, Y(h)$$

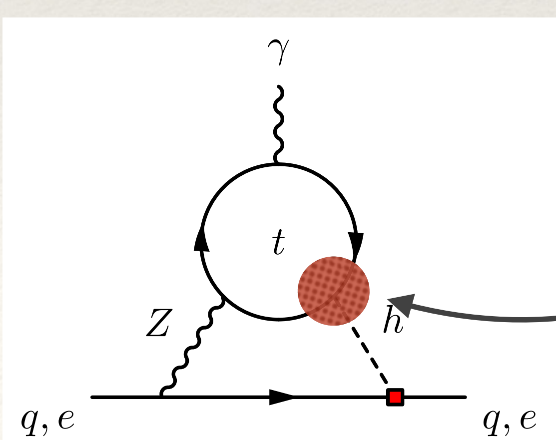
$$Y_t(h) = 1 + c^{(1)}\frac{h}{v} + c^{(2)}\frac{h^2}{2v^2} + \ldots$$

$$\mathcal{L}_{\rm eff} \supset -\frac{m_t}{v}\,\kappa_t\,\bar{t}(\cos\alpha + i\gamma^5\sin\alpha)\,t\,h$$
$$-\frac{m_t}{2v^2}\,\kappa_{tt}\,\bar{t}(\cos\beta + i\gamma^5\sin\beta)\,t\,h^2\,.$$

correlation across multiplicities

$$\kappa_{tt}^2 = 9(1 - 2\kappa_t\cos\alpha + \kappa_t^2)\,,$$

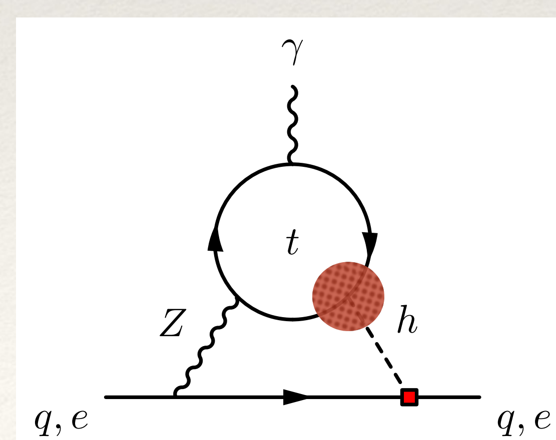
$$\tan\beta = \frac{\kappa_t\sin\alpha}{\kappa_t\cos\alpha - 1}\,.$$

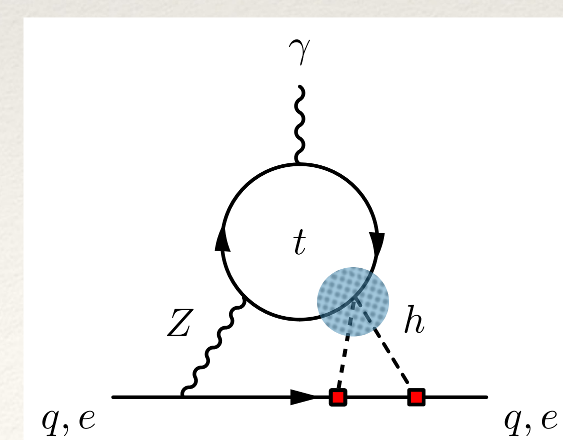


free parameters

$\kappa_t, \alpha, \kappa_{tt}, \beta$

non-linear EDM contributions suppressed





(non-linear) fermion-Higgs interactions

SMEFT SU(2)xU(1)/U(1)

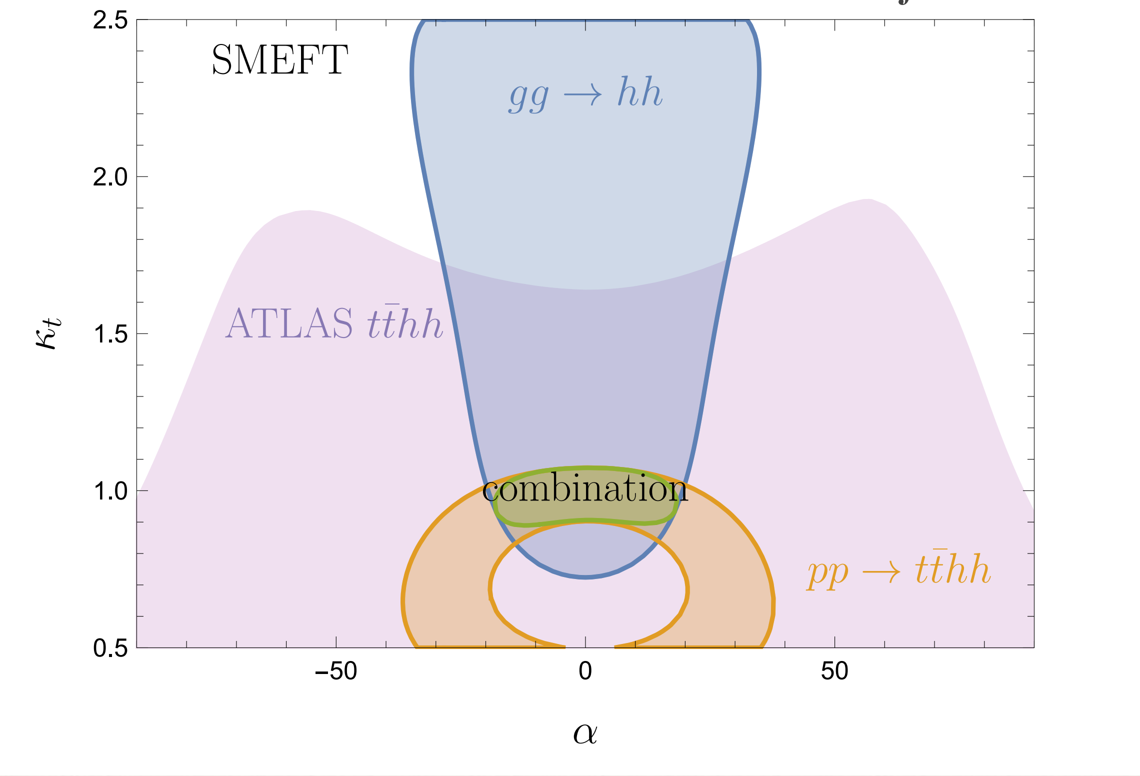
$$\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$$

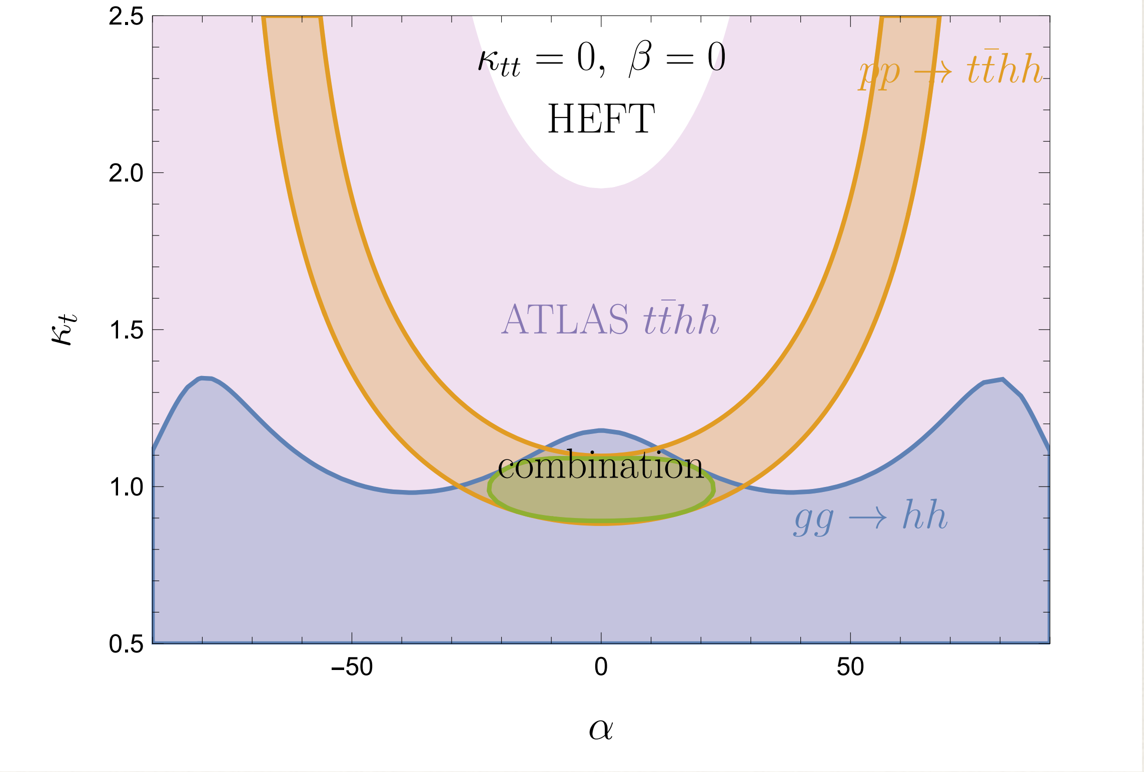
HEFT SU(2)xSU(2)/SU(2)

$$\mathcal{O}_{\bar{t}t} = -m_t \, \bar{Q}_L U t_R Y(h)$$

$$Y_t(h) = 1 + c^{(1)} \frac{h}{v} + c^{(2)} \frac{h^2}{2v^2} + \ldots$$

[Bhardwaj et al. `23]





- quartic top-Higgs contact interaction drive phenomenology

[Grober et al. `10]
[Banerjee et al. `22]

(non-linear) fermion-Higgs interactions

SMEFT SU(2)xU(1)/U(1)

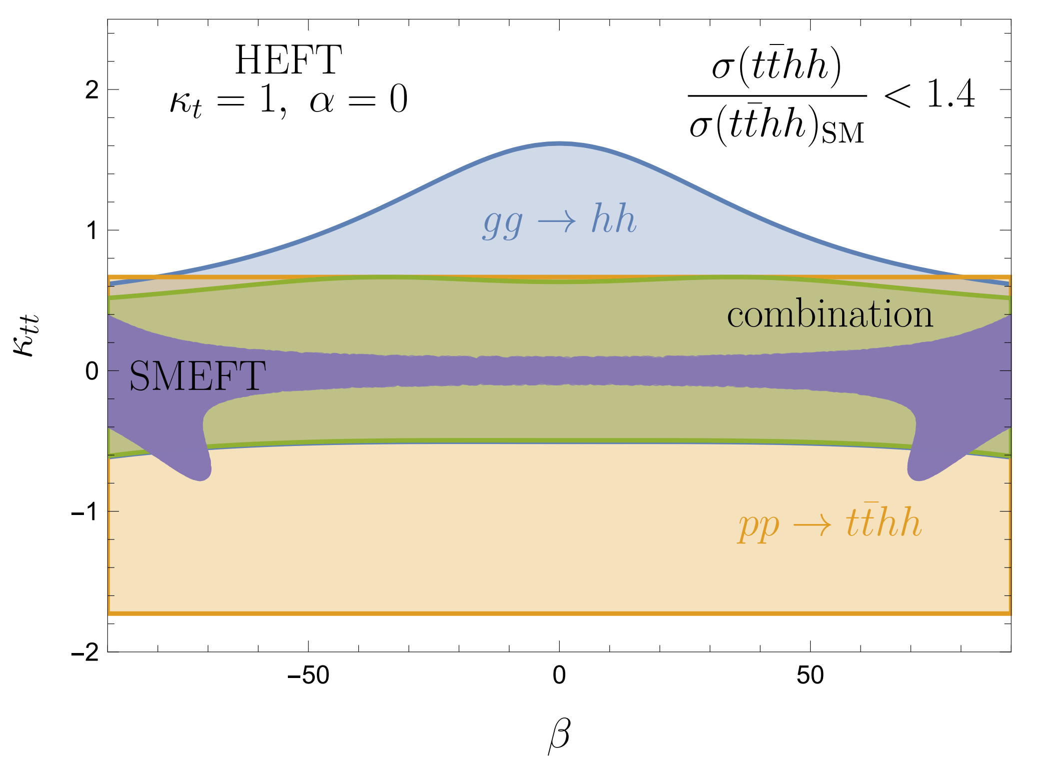
$$\mathcal{O}_{t\Phi} = |\Phi|^2 \bar{Q}_L \Phi^c t_R$$

HEFT SU(2)xSU(2)/SU(2)

$$\mathcal{O}_{\bar{t}t} = -m_t\, \bar{Q}_L U t_R\, Y(h)$$

$$Y_t(h) = 1 + c^{(1)}\frac{h}{v} + c^{(2)}\frac{h^2}{2v^2} + \dots$$

[Bhardwaj et al. `23]



- additional *tthh* sensitivity mitigates limitations (more work to be done for the LHC)

[CE, Krauss, Spannowsky, Thompson `14]
[ATLAS `16]

Summary

- sad but true: jury is still out on what's at play at the electroweak scale

Summary

- sad but true: jury is still out on what's at play at the electroweak scale
- crucially need a more fine-grained picture of Higgs boson interactions
    - CP-sensitivity of Higgs interactions within reach of the LHC, optimisation can gain up to factors of 2-10
    - geometric view on the symmetry-breaking sector
        - entirely new (effective) perspective on the nature of the TeV scale
        - relevance for Higgs boson CP

Summary

- sad but true: jury is still out on what’s at play at the electroweak scale
- crucially need a more fine-grained picture of Higgs boson interactions
    - CP-sensitivity of Higgs interactions within reach of the LHC, optimisation can gain up to factors of 2-10
    - geometric view on the symmetry-breaking sector
        - entirely new (effective) perspective on the nature of the TeV scale
        - relevance for Higgs boson CP
        - testable at the LHC!