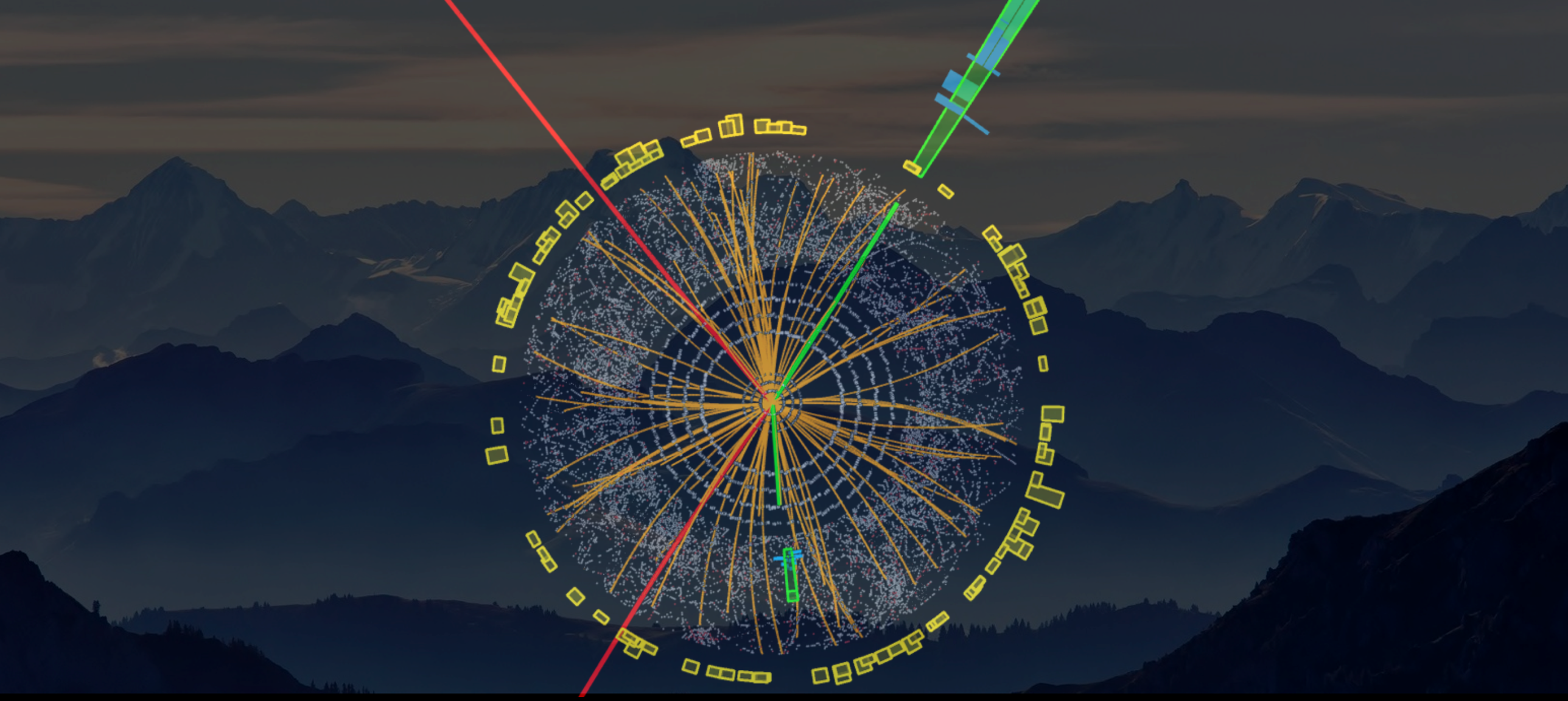


On the SMEFT Basis for aQGCs

[2411.02483 w/ Durieux, Remmen, Éboli, Gonzalez-Garcia, Kondo, Murayama, Okabe]

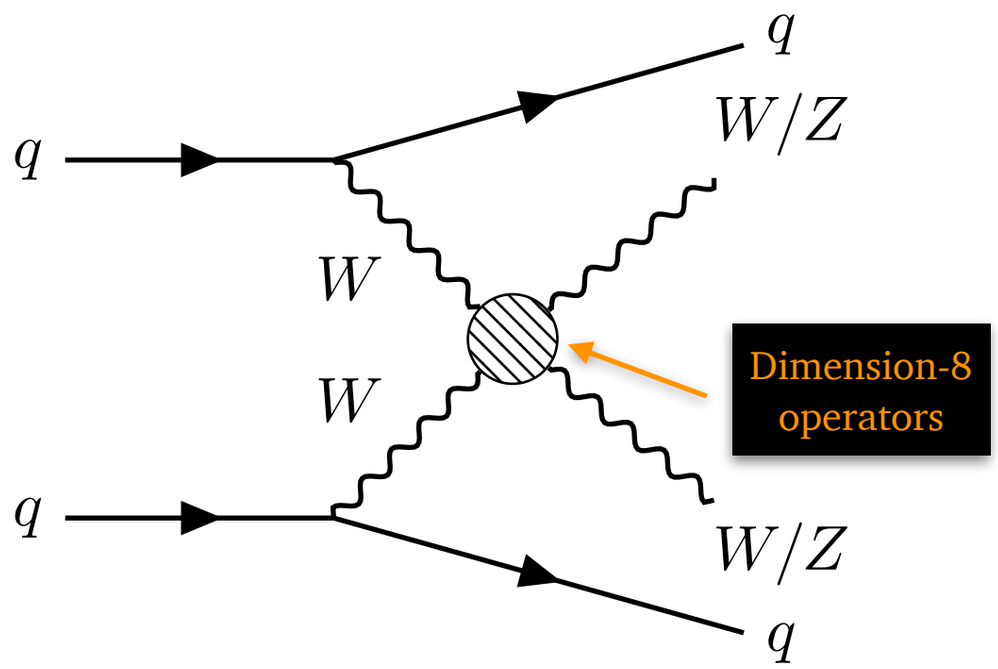
BERKELEY LAB

NICK RODD | LHC EFT Working Group | 2 December 2024

Motivation

Dim-8 SMEFT allows anomalous quartic gauge couplings*

[Eboli, Gonzalez-Garcia, Mizukoshi 2006]



aQGCs modify SM couplings (e.g. W^4) and induce new ones (e.g. Z^4)

*Dim-6 contributions strongly constrained by triple gauge couplings, e.g. [Butter+ 2006]

Motivation

Improvements are a clear target for HL LHC

Evidence for Electroweak Production of $W^{\pm}W^{\pm}jj$ in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector

[ATLAS 2014] - sensitive to $WWWW$

Evidence for electroweak production of two jets in association with a $Z\gamma$ pair in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

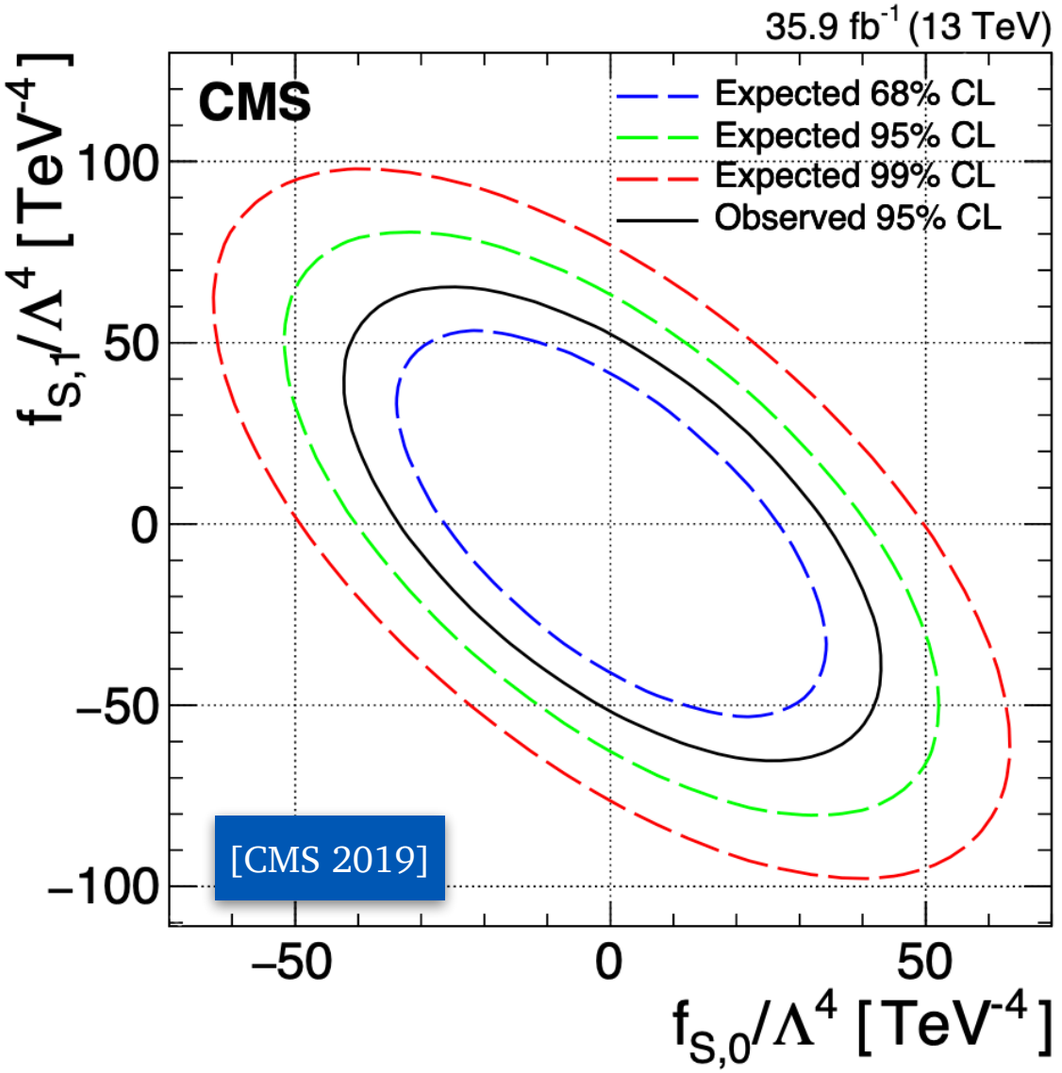
[ATLAS 2020] - sensitive to $WWZ\gamma$

Observation of electroweak production of two jets and a Z-boson pair with the ATLAS detector at the LHC

[ATLAS 2020] - sensitive to $WWZZ$

Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector

[ATLAS 2021] - sensitive to $WW\gamma\gamma$

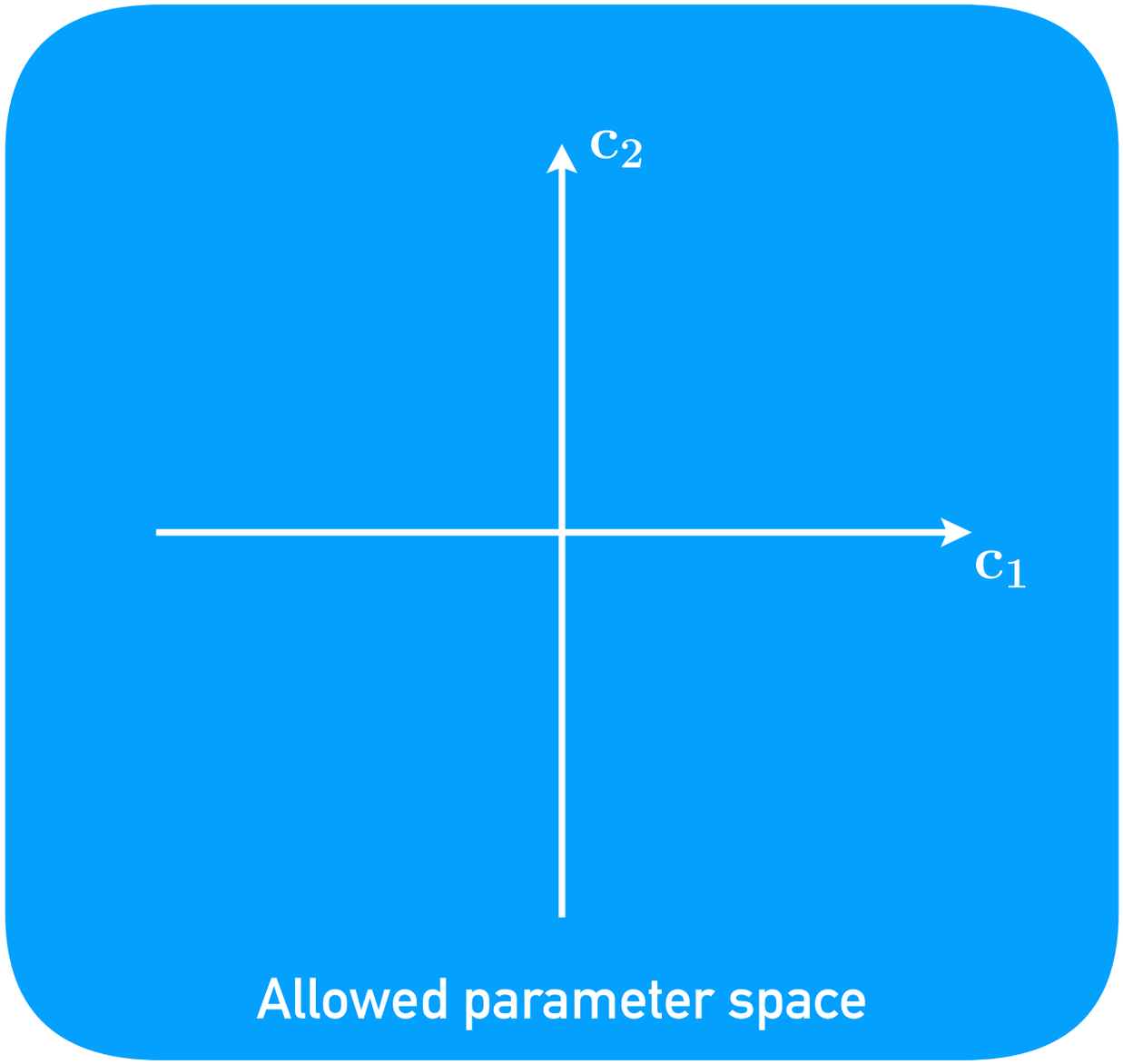


Very incomplete list!

Motivation

Theoretically very interesting due to positivity bounds

Application to the SMEFT, e.g. [Remmen, NLR 2019], [Zhang, Zhou 2020]



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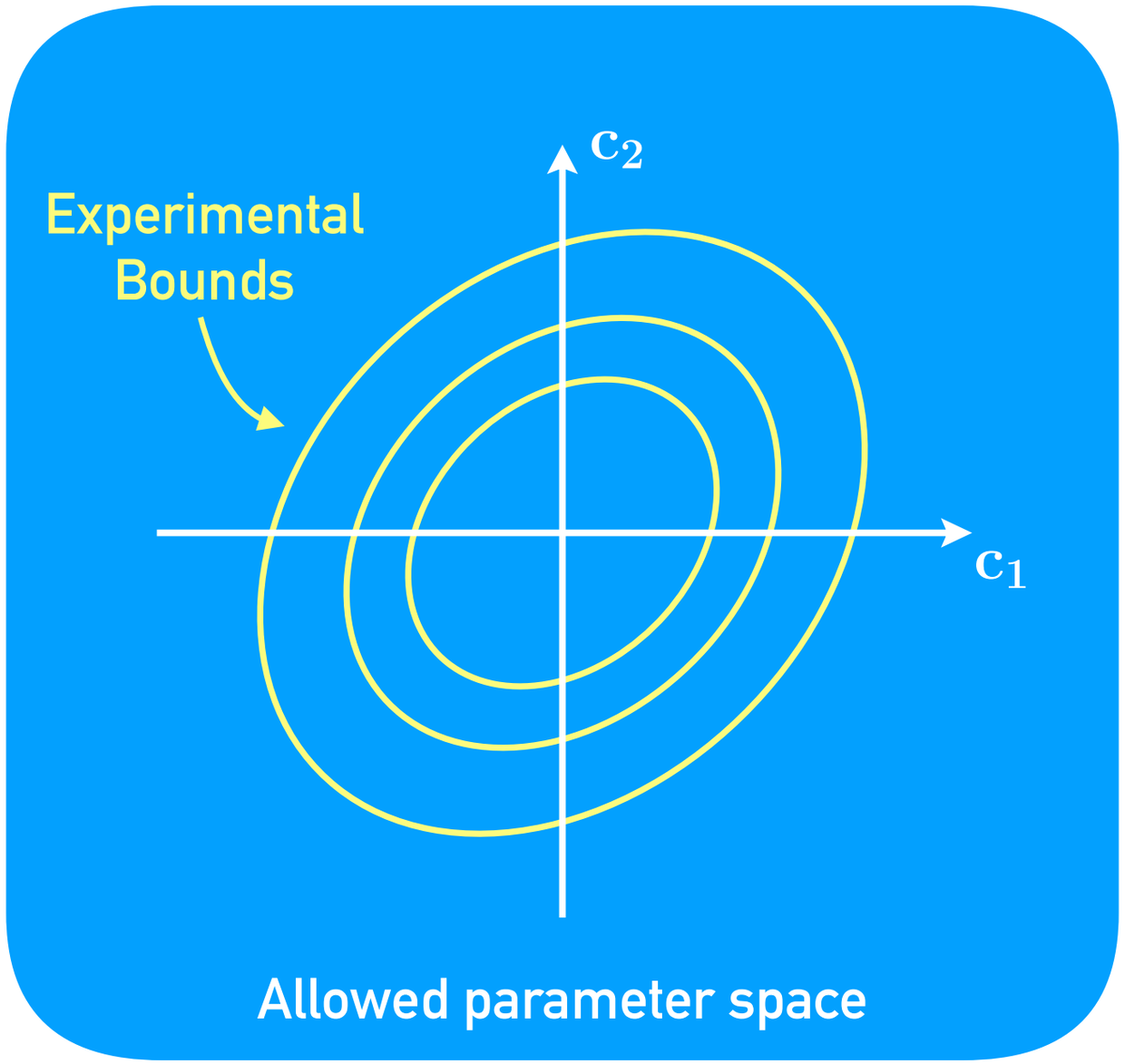

Motivation

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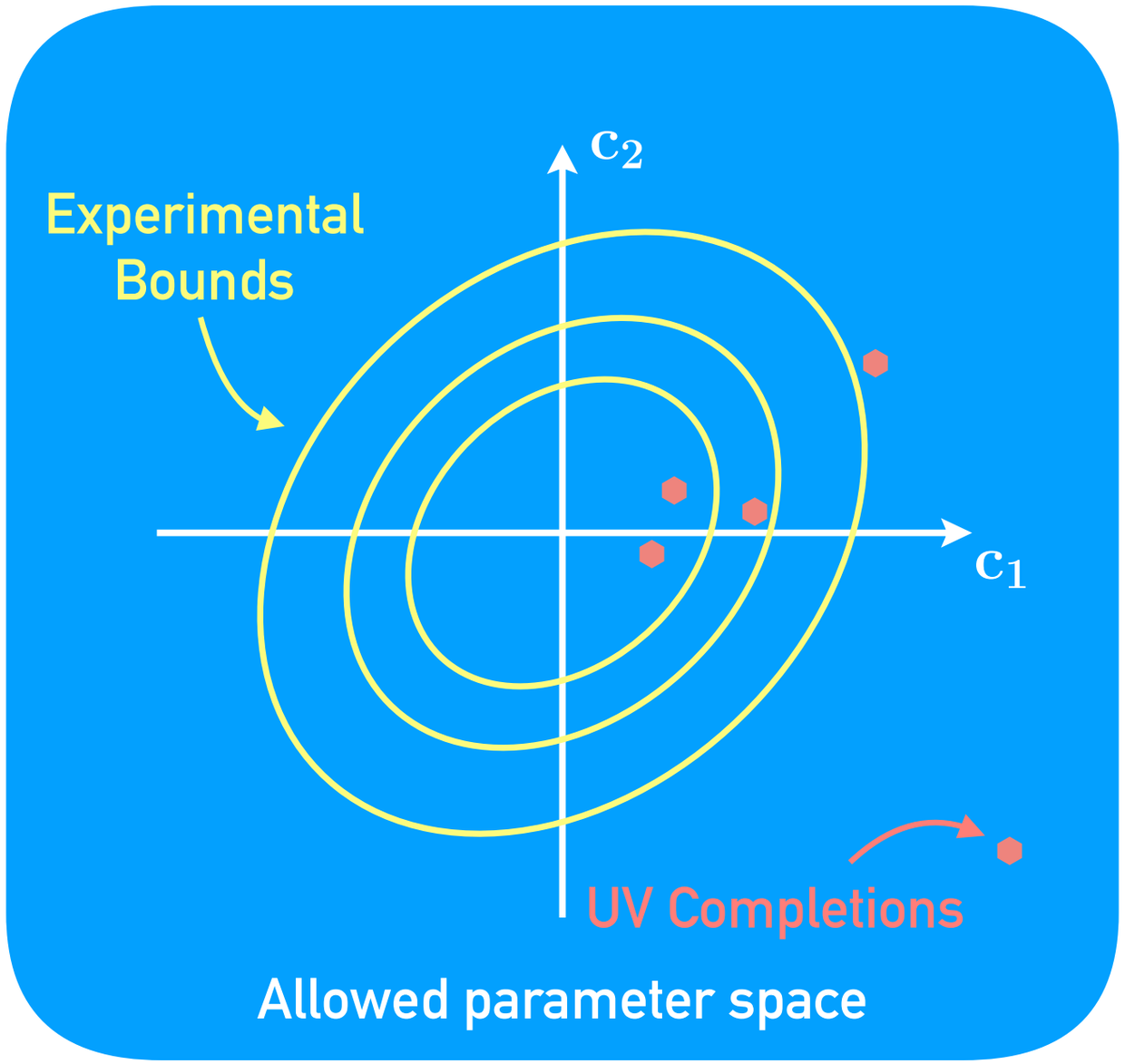

Motivation

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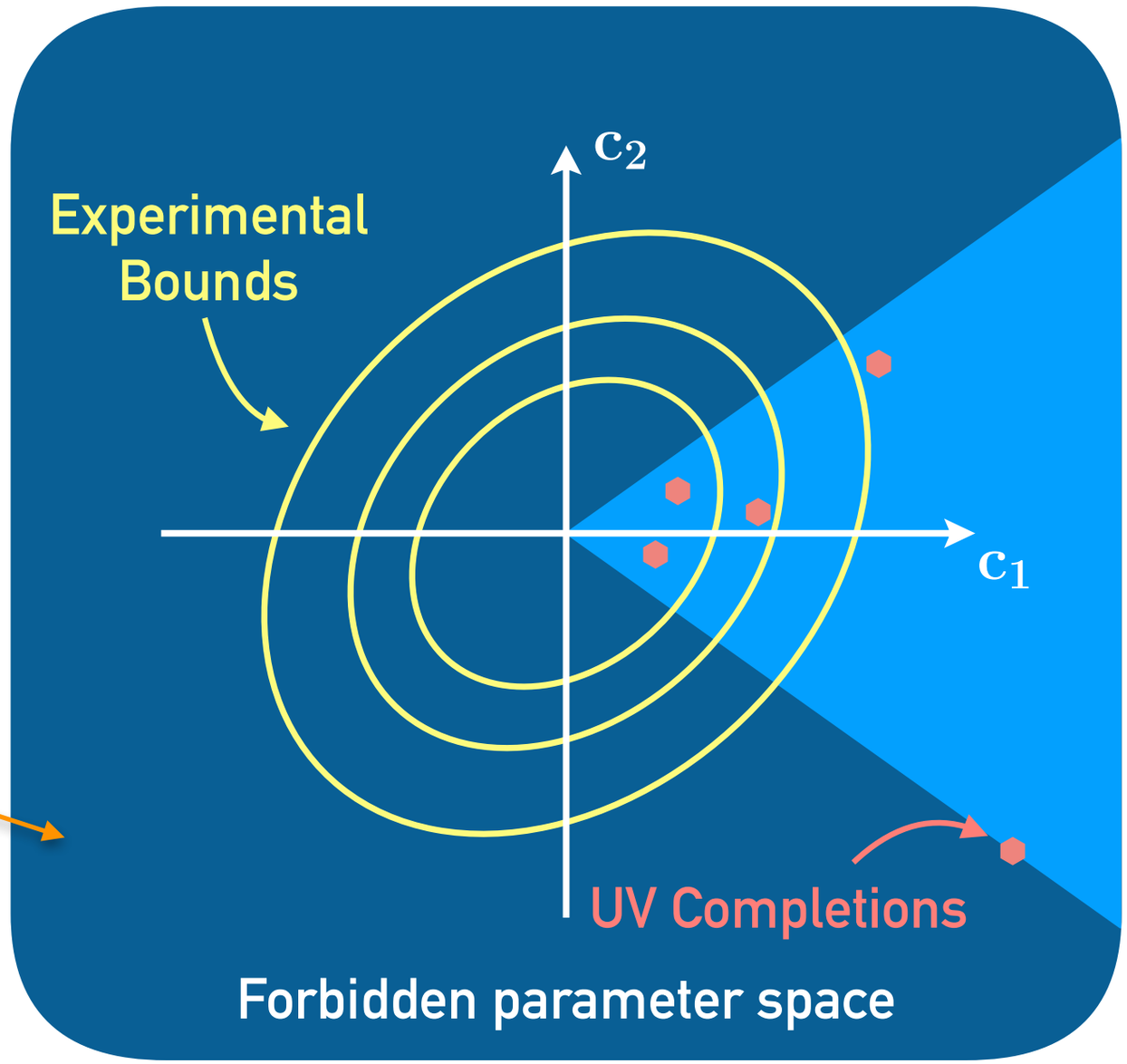
Application to the SMEFT, e.g. [Remmen, NLR 2019], [Zhang, Zhou 2020]

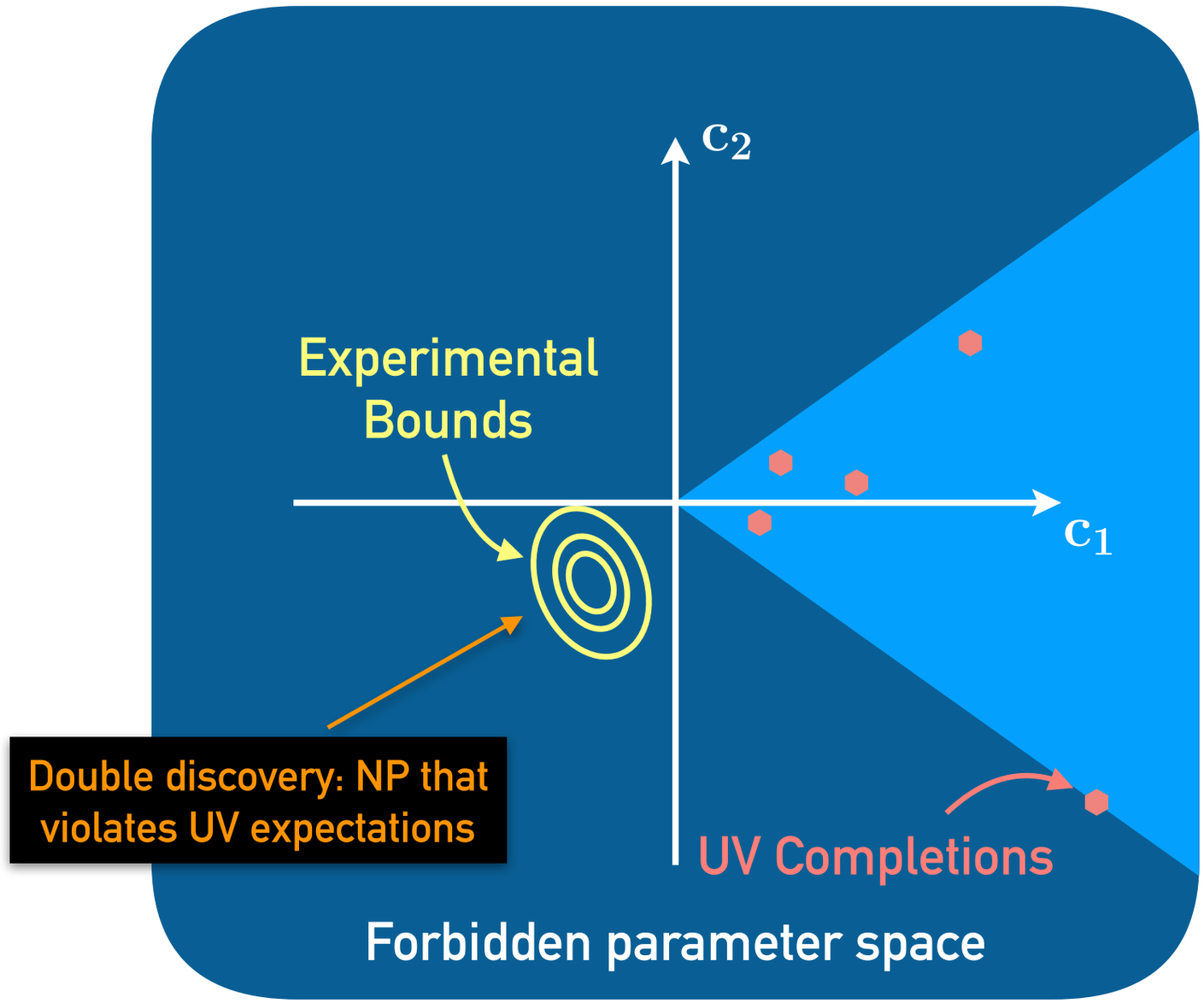


Forbidden if assume UV obeys unitarity, locality, and causality

Motivation

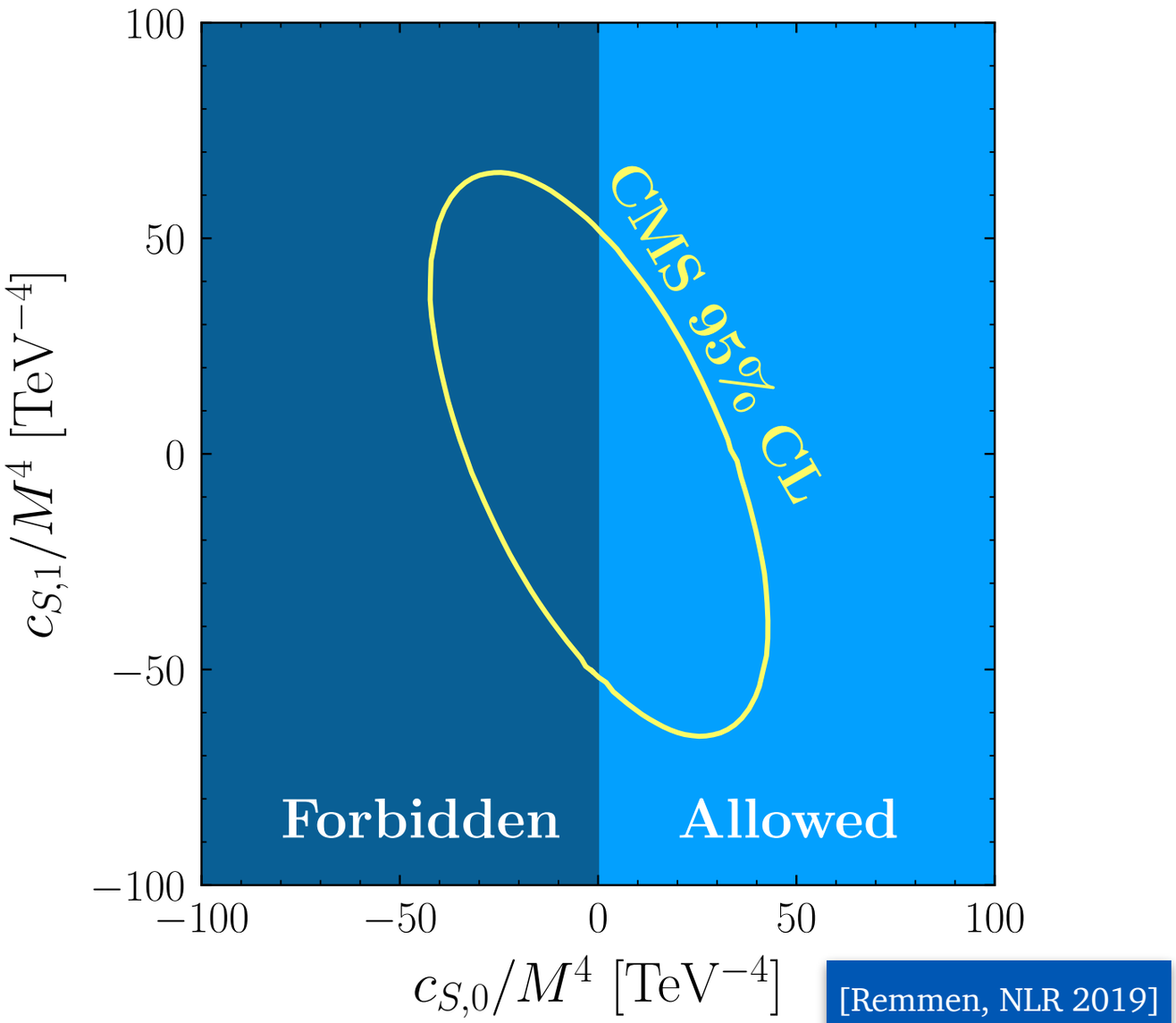
Theoretically very interesting due to positivity bounds

Application to the SMEFT, e.g. [Remmen, NLR 2019], [Zhang, Zhou 2020]



Motivation

aQGCs ideal target for positivity



[Remmen, NLR 2019]

Motivation

Step 0 in accessing all of this physics:

complete EFT basis for aQGCs

The Basis

Three types of operators:

Scalar (S-type): $(\partial H)^4$

Mixed (M-type): $(\partial H)^2 F^2$

Tensor (T-type): F^4

But how many of each?

Notation from [Eboli+ 2006]

The Basis

There has been several attempts

- Almeida, Éboli, Gonzalez-Garcia, Mizukoshi 06, 16, 20
  - Redundancies and omissions corrected in 16 and 20
  - Focused on C-even and P-even operators
  - *Two C-odd & P-odd operators missing*
- Remmen, NLR 19
  - CP-even and -odd all listed and distinguished
  - *CP properties misidentified on 3 operators*
- Murphy 20 (see also Li, Ren, Shu, Xiao, Yu, Zheng 20)
  - same operators as RR, but different naming
  - *CP-even and -odd operators not distinguished*
- Kondo, Murayama, Okabe 22
  - CP-even & odd operators counted using Hilbert series
  - *Misidentified two explicit CP-even vs. odd operators*

Challenge primarily in identifying the properties of operators under C

The Basis

Situation had become murky: many papers with wrong basis

Solution: bring all relevant authors together, resolve the issue and publicize that resolution to the community

The Basis

LHC EFT WG Note:
Basis for Anomalous Quartic Gauge Couplings

Gauthier Durieux,[1,*] *Grant N. Remmen,*[2,*] *Nicholas L. Rodd,*[3,*] *O. J. P. Éboli,*[4]
M. C. Gonzalez-Garcia,[5,6] *Dan Kondo,*[7] *Hitoshi Murayama,*[3,7] *Risshin Okabe*[7]

[*]Editors

- Minimal basis containing all operators, both CP-even and CP-odd, with all CP properties identified and explained
- Approved by the LHC WG - *thanks for feedback, especially the conveners I. Brivio, K. Potamianos, M. Presilla, D. Sutherland*
- UFO implementation made publicly available here:
  - https://github.com/gdurieux/aqgc

The Basis

aQGC Operator Basis		C	P	Almeida, Éboli, Gonzalez-Garcia [3]	Remmen & Rodd [4]	Murphy [6]
$\mathcal{O}_0^S$	$[D_\mu H^\dagger D_\nu H][D^\mu H^\dagger D^\nu H]$	+	+	$\mathcal{O}_{S,0}$	$\mathcal{O}_2^{H^4}$	$Q^{(2)}_{H^4}$
$\mathcal{O}_1^S$	$[D^\mu H^\dagger D_\mu H][D^\nu H^\dagger D_\nu H]$	+	+	$\mathcal{O}_{S,1}$	$\mathcal{O}_3^{H^4}$	$Q^{(3)}_{H^4}$
$\mathcal{O}_2^S$	$[D_\mu H^\dagger D_\nu H][D^\nu H^\dagger D^\mu H]$	+	+	$\mathcal{O}_{S,2}$	$\mathcal{O}_1^{H^4}$	$Q^{(1)}_{H^4}$
$\mathcal{O}_0^M$	$\frac{1}{2}[D^\mu H^\dagger D_\mu H]W^I_{\nu\rho}W^{I\,\nu\rho}$	+	+	$\mathcal{O}_{M,0}$	$\frac{1}{2}\mathcal{O}_2^{H^2W^2}$	$\frac{1}{2}Q^{(2)}_{W^2H^2D^2}$
$\mathcal{O}_1^M$	$-\frac{1}{2}[D^\mu H^\dagger D^\nu H]W^I_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,1}$	$-\frac{1}{2}\mathcal{O}_1^{H^2W^2}$	$-\frac{1}{2}Q^{(1)}_{W^2H^2D^2}$
$\mathcal{O}_2^M$	$[D^\mu H^\dagger D_\mu H]B_{\nu\rho}B^{\nu\rho}$	+	+	$\mathcal{O}_{M,2}$	$\mathcal{O}_2^{H^2B^2}$	$Q^{(2)}_{B^2H^2D^2}$
$\mathcal{O}_3^M$	$-[D^\mu H^\dagger D^\nu H]B_{\mu\rho}B_{\nu}{}^{\rho}$	+	+	$\mathcal{O}_{M,3}$	$-\mathcal{O}_1^{H^2B^2}$	$-Q^{(1)}_{B^2H^2D^2}$
$\mathcal{O}_4^M$	$[D^\mu H^\dagger \tau^I D_\mu H]B^{\nu\rho}W^I_{\nu\rho}$	+	+	$\mathcal{O}_{M,4}$	$\mathcal{O}_1^{H^2BW}$	$Q^{(1)}_{WBH^2D^2}$
$\mathcal{O}_5^M$	$[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho W^I_{\nu\rho} + B_\nu{}^\rho W^I_{\mu\rho})$	+	+	$\mathcal{O}_{M,5}$	$\mathcal{O}_3^{H^2BW}$	$Q^{(4)}_{WBH^2D^2}$
$\mathcal{O}_7^M$	$[D^\mu H^\dagger \tau^I \tau^J D^\nu H]W^J_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,7}$	$\frac{1}{4}\mathcal{O}_1^{H^2W^2} - \frac{1}{2}\mathcal{O}_3^{H^2W^2}$	$\frac{1}{4}Q^{(1)}_{W^2H^2D^2} - \frac{1}{2}Q^{(4)}_{W^2H^2D^2}$
$\mathcal{O}_8^M$	$i[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho \widetilde{W}^I_{\nu\rho} - B_\nu{}^\rho \widetilde{W}^I_{\mu\rho})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2BW}$	$Q^{(5)}_{WBH^2D^2}$
$\mathcal{O}_9^M$	$\epsilon^{IJK}[D^\mu H^\dagger \tau^I D^\nu H](W^J_{\mu\rho}\widetilde{W}^{K\,\rho}_{\nu} - \widetilde{W}^J_{\mu\rho}W^{K\,\rho}_{\nu})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2W^2}$	$Q^{(5)}_{W^2H^2D^2}$
$\mathcal{O}_0^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\,\mu\nu}W^J_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,0}$	$\frac{1}{4}\mathcal{O}_1^{W^4}$	$\frac{1}{4}Q^{(1)}_{W^4}$
$\mathcal{O}_1^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\,\mu\nu}W^I_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,1}$	$\frac{1}{4}\mathcal{O}_3^{W^4}$	$\frac{1}{4}Q^{(3)}_{W^4}$
$\mathcal{O}_2^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\nu\alpha}W^J_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,2}$	$\frac{1}{16}\mathcal{O}_1^{W^4} + \frac{1}{16}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_4^{W^4}$	$\frac{1}{16}Q^{(1)}_{W^4} + \frac{1}{16}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(4)}_{W^4}$
$\mathcal{O}_3^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\nu\alpha}W^I_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,3}$	$\frac{1}{8}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_2^{W^4}$	$\frac{1}{8}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(2)}_{W^4}$
$\mathcal{O}_4^T$	$\frac{1}{2}W^I_{\mu\nu}B^{\nu\alpha}W^I_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,4}$	$\frac{1}{8}\mathcal{O}_2^{B^2W^2} + \frac{1}{4}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{8}Q^{(2)}_{W^2B^2} + \frac{1}{4}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_5^T$	$\frac{1}{2}B_{\mu\nu}B^{\mu\nu}W^I_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,5}$	$\frac{1}{2}\mathcal{O}_1^{B^2W^2}$	$\frac{1}{2}Q^{(1)}_{W^2B^2}$
$\mathcal{O}_6^T$	$\frac{1}{2}B_{\mu\nu}W^{I\,\mu\nu}B_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,6}$	$\frac{1}{2}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{2}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_7^T$	$\frac{1}{2}W^I_{\mu\nu}W^{I\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,7}$	$\frac{1}{8}\mathcal{O}_1^{B^2W^2} + \frac{1}{8}\mathcal{O}_3^{B^2W^2} + \frac{1}{8}\mathcal{O}_4^{B^2W^2}$	$\frac{1}{8}Q^{(1)}_{W^2B^2} + \frac{1}{8}Q^{(3)}_{W^2B^2} + \frac{1}{8}Q^{(4)}_{W^2B^2}$
$\mathcal{O}_8^T$	$B_{\mu\nu}B^{\mu\nu}B_{\rho\sigma}B^{\rho\sigma}$	+	+	$\mathcal{O}_{T,8}$	$\mathcal{O}_1^{B^4}$	$Q^{(1)}_{B^4}$
$\mathcal{O}_9^T$	$B_{\mu\nu}B^{\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,9}$	$\frac{1}{2}\mathcal{O}_1^{B^4} + \frac{1}{4}\mathcal{O}_2^{B^4}$	$\frac{1}{2}Q^{(1)}_{B^4} + \frac{1}{4}Q^{(2)}_{B^4}$

Complete list of CP even operators
CP odd also provided (see backup)

The Basis

Follow AEG as already widely used - mapping to other bases provided

	aQGC Operator Basis	C	P	Almeida, Éboli, Gonzalez-Garcia [3]	Remmen & Rodd [4]	Murphy [6]
$\mathcal{O}_0^S$	$[D_\mu H^\dagger D_\nu H][D^\mu H^\dagger D^\nu H]$	+	+	$\mathcal{O}_{S,0}$	$\mathcal{O}_2^{H^4}$	$Q^{(2)}_{H^4}$
$\mathcal{O}_1^S$	$[D^\mu H^\dagger D_\mu H][D^\nu H^\dagger D_\nu H]$	+	+	$\mathcal{O}_{S,1}$	$\mathcal{O}_3^{H^4}$	$Q^{(3)}_{H^4}$
$\mathcal{O}_2^S$	$[D_\mu H^\dagger D_\nu H][D^\nu H^\dagger D^\mu H]$	+	+	$\mathcal{O}_{S,2}$	$\mathcal{O}_1^{H^4}$	$Q^{(1)}_{H^4}$
$\mathcal{O}_0^M$	$\frac{1}{2}[D^\mu H^\dagger D_\mu H]W^I_{\nu\rho}W^{I\,\nu\rho}$	+	+	$\mathcal{O}_{M,0}$	$\frac{1}{2}\mathcal{O}_2^{H^2W^2}$	$\frac{1}{2}Q^{(2)}_{W^2H^2D^2}$
$\mathcal{O}_1^M$	$-\frac{1}{2}[D^\mu H^\dagger D^\nu H]W^I_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,1}$	$-\frac{1}{2}\mathcal{O}_1^{H^2W^2}$	$-\frac{1}{2}Q^{(1)}_{W^2H^2D^2}$
$\mathcal{O}_2^M$	$[D^\mu H^\dagger D_\mu H]B_{\nu\rho}B^{\nu\rho}$	+	+	$\mathcal{O}_{M,2}$	$\mathcal{O}_2^{H^2B^2}$	$Q^{(2)}_{B^2H^2D^2}$
$\mathcal{O}_3^M$	$-[D^\mu H^\dagger D^\nu H]B_{\mu\rho}B_{\nu}{}^{\rho}$	+	+	$\mathcal{O}_{M,3}$	$-\mathcal{O}_1^{H^2B^2}$	$-Q^{(1)}_{B^2H^2D^2}$
$\mathcal{O}_4^M$	$[D^\mu H^\dagger \tau^I D_\mu H]B^{\nu\rho}W^I_{\nu\rho}$	+	+	$\mathcal{O}_{M,4}$	$\mathcal{O}_1^{H^2BW}$	$Q^{(1)}_{WBH^2D^2}$
$\mathcal{O}_5^M$	$[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho W^I_{\nu\rho} + B_\nu{}^\rho W^I_{\mu\rho})$	+	+	$\mathcal{O}_{M,5}$	$\mathcal{O}_3^{H^2BW}$	$Q^{(4)}_{WBH^2D^2}$
$\mathcal{O}_7^M$	$[D^\mu H^\dagger \tau^I \tau^J D^\nu H]W^J_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,7}$	$\frac{1}{4}\mathcal{O}_1^{H^2W^2} - \frac{1}{2}\mathcal{O}_3^{H^2W^2}$	$\frac{1}{4}Q^{(1)}_{W^2H^2D^2} - \frac{1}{2}Q^{(4)}_{W^2H^2D^2}$
$\mathcal{O}_8^M$	$i[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho \widetilde{W}^I_{\nu\rho} - B_\nu{}^\rho \widetilde{W}^I_{\mu\rho})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2BW}$	$Q^{(5)}_{WBH^2D^2}$
$\mathcal{O}_9^M$	$\epsilon^{IJK}[D^\mu H^\dagger \tau^I D^\nu H](W^J_{\mu\rho}\widetilde{W}^{K\,\rho}_{\nu} - \widetilde{W}^J_{\mu\rho}W^{K\,\rho}_{\nu})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2W^2}$	$Q^{(5)}_{W^2H^2D^2}$
$\mathcal{O}_0^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\,\mu\nu}W^J_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,0}$	$\frac{1}{4}\mathcal{O}_1^{W^4}$	$\frac{1}{4}Q^{(1)}_{W^4}$
$\mathcal{O}_1^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\,\mu\nu}W^I_{\rho\sigma}W^{J\,\rho\sigma}$	+	+	$\mathcal{O}_{T,1}$	$\frac{1}{4}\mathcal{O}_3^{W^4}$	$\frac{1}{4}Q^{(3)}_{W^4}$
$\mathcal{O}_2^T$	$\frac{1}{4}W^I_{\mu\nu}W^{I\nu\alpha}W^J_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,2}$	$\frac{1}{16}\mathcal{O}_1^{W^4} + \frac{1}{16}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_4^{W^4}$	$\frac{1}{16}Q^{(1)}_{W^4} + \frac{1}{16}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(4)}_{W^4}$
$\mathcal{O}_3^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\nu\alpha}W^I_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,3}$	$\frac{1}{8}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_2^{W^4}$	$\frac{1}{8}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(2)}_{W^4}$
$\mathcal{O}_4^T$	$\frac{1}{2}W^I_{\mu\nu}B^{\nu\alpha}W^I_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,4}$	$\frac{1}{8}\mathcal{O}_2^{B^2W^2} + \frac{1}{4}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{8}Q^{(2)}_{W^2B^2} + \frac{1}{4}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_5^T$	$\frac{1}{2}B_{\mu\nu}B^{\mu\nu}W^I_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,5}$	$\frac{1}{2}\mathcal{O}_1^{B^2W^2}$	$\frac{1}{2}Q^{(1)}_{W^2B^2}$
$\mathcal{O}_6^T$	$\frac{1}{2}B_{\mu\nu}W^{I\,\mu\nu}B_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,6}$	$\frac{1}{2}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{2}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_7^T$	$\frac{1}{2}W^I_{\mu\nu}W^{I\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,7}$	$\frac{1}{8}\mathcal{O}_1^{B^2W^2} + \frac{1}{8}\mathcal{O}_3^{B^2W^2} + \frac{1}{8}\mathcal{O}_4^{B^2W^2}$	$\frac{1}{8}Q^{(1)}_{W^2B^2} + \frac{1}{8}Q^{(3)}_{W^2B^2} + \frac{1}{8}Q^{(4)}_{W^2B^2}$
$\mathcal{O}_8^T$	$B_{\mu\nu}B^{\mu\nu}B_{\rho\sigma}B^{\rho\sigma}$	+	+	$\mathcal{O}_{T,8}$	$\mathcal{O}_1^{B^4}$	$Q^{(1)}_{B^4}$
$\mathcal{O}_9^T$	$B_{\mu\nu}B^{\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,9}$	$\frac{1}{2}\mathcal{O}_1^{B^4} + \frac{1}{4}\mathcal{O}_2^{B^4}$	$\frac{1}{2}Q^{(1)}_{B^4} + \frac{1}{4}Q^{(2)}_{B^4}$

Complete list of CP even operators
CP odd also provided (see backup)

The Basis

Follow AEG as already widely used - mapping to other bases provided

	aQGC Operator Basis	C	P	Almeida, Éboli, Gonzalez-Garcia [3]	Remmen & Rodd [4]	Murphy [6]
$\mathcal{O}_0^S$	$[D_\mu H^\dagger D_\nu H][D^\mu H^\dagger D^\nu H]$	+	+	$\mathcal{O}_{S,0}$	$\mathcal{O}_2^{H^4}$	$Q^{(2)}_{H^4}$
$\mathcal{O}_1^S$	$[D^\mu H^\dagger D_\mu H][D^\nu H^\dagger D_\nu H]$	+	+	$\mathcal{O}_{S,1}$	$\mathcal{O}_3^{H^4}$	$Q^{(3)}_{H^4}$
$\mathcal{O}_2^S$	$[D_\mu H^\dagger D_\nu H][D^\nu H^\dagger D^\mu H]$	+	+	$\mathcal{O}_{S,2}$	$\mathcal{O}_1^{H^4}$	$Q^{(1)}_{H^4}$
$\mathcal{O}_0^M$	$\frac{1}{2}[D^\mu H^\dagger D_\mu H]W^I_{\nu\rho}W^{I\,\nu\rho}$	+	+	$\mathcal{O}_{M,0}$	$\frac{1}{2}\mathcal{O}_2^{H^2W^2}$	$\frac{1}{2}Q^{(2)}_{W^2H^2D^2}$
$\mathcal{O}_1^M$	$-\frac{1}{2}[D^\mu H^\dagger D^\nu H]W^I_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,1}$	$-\frac{1}{2}\mathcal{O}_1^{H^2W^2}$	$-\frac{1}{2}Q^{(1)}_{W^2H^2D^2}$
$\mathcal{O}_2^M$	$[D^\mu H^\dagger D_\mu H]B_{\nu\rho}B^{\nu\rho}$	+	+	$\mathcal{O}_{M,2}$	$\mathcal{O}_2^{H^2B^2}$	$Q^{(2)}_{B^2H^2D^2}$
$\mathcal{O}_3^M$	$-[D^\mu H^\dagger D^\nu H]B_{\mu\rho}B_{\nu}{}^{\rho}$	+	+	$\mathcal{O}_{M,3}$	$-\mathcal{O}_1^{H^2B^2}$	$-Q^{(1)}_{B^2H^2D^2}$
$\mathcal{O}_4^M$	$[D^\mu H^\dagger \tau^I D_\mu H]B^{\nu\rho}W^I_{\nu\rho}$	+	+	$\mathcal{O}_{M,4}$	$\mathcal{O}_1^{H^2BW}$	$Q^{(1)}_{WBH^2D^2}$
$\mathcal{O}_5^M$	$[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho W^I_{\nu\rho} + B_\nu{}^\rho W^I_{\mu\rho})$	+	+	$\mathcal{O}_{M,5}$	$\mathcal{O}_3^{H^2BW}$	$Q^{(4)}_{WBH^2D^2}$
$\mathcal{O}_7^M$	$[D^\mu H^\dagger \tau^I \tau^J D^\nu H]W^J_{\mu\rho}W^{I\,\rho}_{\nu}$	+	+	$\mathcal{O}_{M,7}$	$\frac{1}{4}\mathcal{O}_1^{H^2W^2} - \frac{1}{2}\mathcal{O}_3^{H^2W^2}$	$\frac{1}{4}Q^{(1)}_{W^2H^2D^2} - \frac{1}{2}Q^{(4)}_{W^2H^2D^2}$
$\mathcal{O}_8^M$	$i[D^\mu H^\dagger \tau^I D^\nu H](B_\mu{}^\rho \widetilde{W}^I_{\nu\rho} - B_\nu{}^\rho \widetilde{W}^I_{\mu\rho})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2BW}$	$Q^{(5)}_{WBH^2D^2}$
$\mathcal{O}_9^M$	$\epsilon^{IJK}[D^\mu H^\dagger \tau^I D^\nu H](W^J_{\mu\rho}\widetilde{W}^{K\,\rho}_{\nu} - \widetilde{W}^J_{\mu\rho}W^{K\,\rho}_{\nu})$	−	−	———	$\widetilde{\mathcal{O}}_2^{H^2W^2}$	$Q^{(5)}_{W^2H^2D^2}$
				$\mathcal{O}_{T,0}$	$\frac{1}{4}\mathcal{O}_1^{W^4}$	$\frac{1}{4}Q^{(1)}_{W^4}$
				$\mathcal{O}_{T,1}$	$\frac{1}{4}\mathcal{O}_3^{W^4}$	$\frac{1}{4}Q^{(3)}_{W^4}$
				$\mathcal{O}_{T,2}$	$\frac{1}{16}\mathcal{O}_1^{W^4} + \frac{1}{16}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_4^{W^4}$	$\frac{1}{16}Q^{(1)}_{W^4} + \frac{1}{16}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(4)}_{W^4}$
$\mathcal{O}_3^T$	$\frac{1}{4}W^I_{\mu\nu}W^{J\nu\alpha}W^I_{\alpha\beta}W^{J\beta\mu}$	+	+	$\mathcal{O}_{T,3}$	$\frac{1}{8}\mathcal{O}_3^{W^4} + \frac{1}{16}\mathcal{O}_2^{W^4}$	$\frac{1}{8}Q^{(3)}_{W^4} + \frac{1}{16}Q^{(2)}_{W^4}$
$\mathcal{O}_4^T$	$\frac{1}{2}W^I_{\mu\nu}B^{\nu\alpha}W^I_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,4}$	$\frac{1}{8}\mathcal{O}_2^{B^2W^2} + \frac{1}{4}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{8}Q^{(2)}_{W^2B^2} + \frac{1}{4}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_5^T$	$\frac{1}{2}B_{\mu\nu}B^{\mu\nu}W^I_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,5}$	$\frac{1}{2}\mathcal{O}_1^{B^2W^2}$	$\frac{1}{2}Q^{(1)}_{W^2B^2}$
$\mathcal{O}_6^T$	$\frac{1}{2}B_{\mu\nu}W^{I\,\mu\nu}B_{\rho\sigma}W^{I\,\rho\sigma}$	+	+	$\mathcal{O}_{T,6}$	$\frac{1}{2}\mathcal{O}_3^{B^2W^2}$	$\frac{1}{2}Q^{(3)}_{W^2B^2}$
$\mathcal{O}_7^T$	$\frac{1}{2}W^I_{\mu\nu}W^{I\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,7}$	$\frac{1}{8}\mathcal{O}_1^{B^2W^2} + \frac{1}{8}\mathcal{O}_3^{B^2W^2} + \frac{1}{8}\mathcal{O}_4^{B^2W^2}$	$\frac{1}{8}Q^{(1)}_{W^2B^2} + \frac{1}{8}Q^{(3)}_{W^2B^2} + \frac{1}{8}Q^{(4)}_{W^2B^2}$
$\mathcal{O}_8^T$	$B_{\mu\nu}B^{\mu\nu}B_{\rho\sigma}B^{\rho\sigma}$	+	+	$\mathcal{O}_{T,8}$	$\mathcal{O}_1^{B^4}$	$Q^{(1)}_{B^4}$
$\mathcal{O}_9^T$	$B_{\mu\nu}B^{\nu\alpha}B_{\alpha\beta}B^{\beta\mu}$	+	+	$\mathcal{O}_{T,9}$	$\frac{1}{2}\mathcal{O}_1^{B^4} + \frac{1}{4}\mathcal{O}_2^{B^4}$	$\frac{1}{2}Q^{(1)}_{B^4} + \frac{1}{4}Q^{(2)}_{B^4}$

$\mathcal{O}_6^M$ in original AEG basis, but redundant
$\mathcal{O}_{8,9}^M$ are new, C&P odd

Complete list of CP even operators
CP odd also provided (see backup)

Next Steps

With the basis resolved, we can get back to physics

Minimal example: custodially symmetric Higgs sector

Rewrite three Higgs aQGCs as follows

$$\mathcal{O}_+ = \frac{1}{2}(\mathcal{O}_0^S + \mathcal{O}_2^S)$$
$$\mathcal{O}_- = \frac{1}{2}(\mathcal{O}_0^S - \mathcal{O}_2^S)$$
$$\mathcal{O}_\times = \mathcal{O}_1^S$$

Based on ongoing work with Grant Remmen

Next Steps

With the basis resolved, we can get back to physics

Minimal example: custodially symmetric Higgs sector

Rewrite three Higgs aQGCs as follows

$$\mathcal{O}_+ = \frac{1}{2}(\mathcal{O}_0^S + \mathcal{O}_2^S)$$

$$\mathcal{O}_- = \frac{1}{2}(\mathcal{O}_0^S - \mathcal{O}_2^S)$$

Violates custodial symmetry

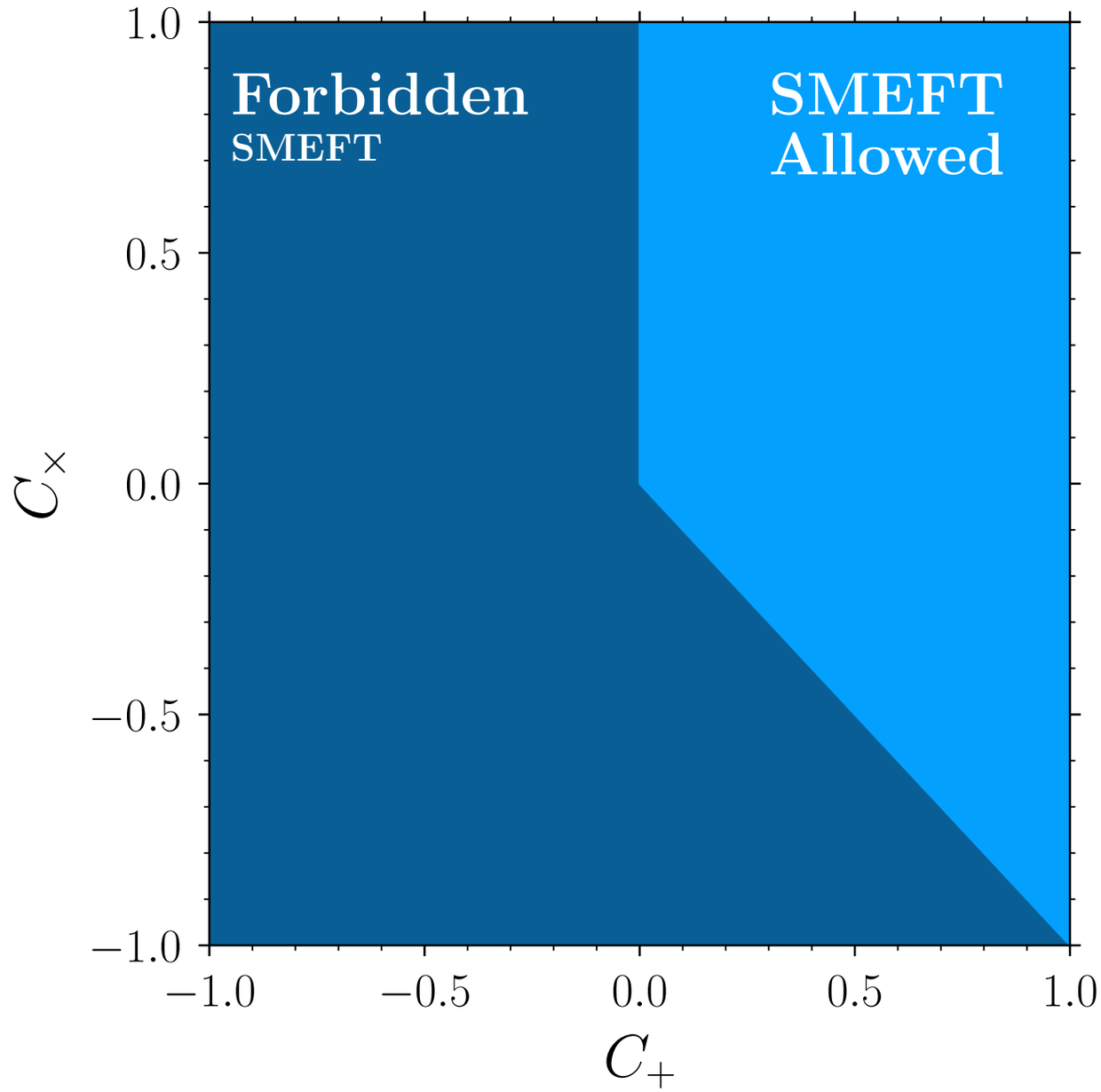
$$\mathcal{O}_\times = \mathcal{O}_1^S$$

Minimal basis for studying positivity

Based on ongoing work with Grant Remmen

Next Steps

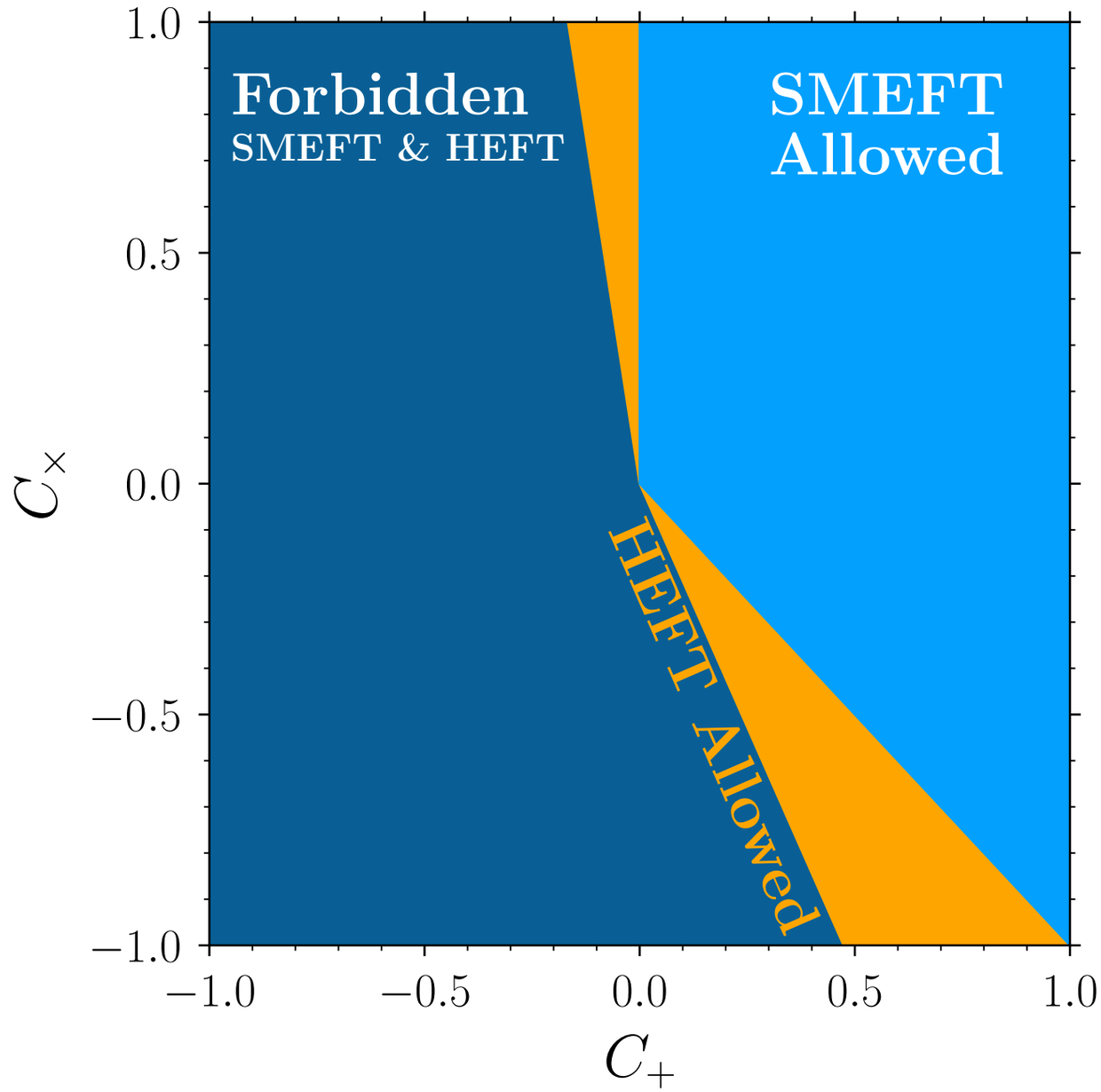
Discovery in the forbidden region: perverse UV or wrong EFT?



Based on ongoing work with Grant Remmen

Next Steps

Discovery in the forbidden region: perverse UV or wrong EFT?



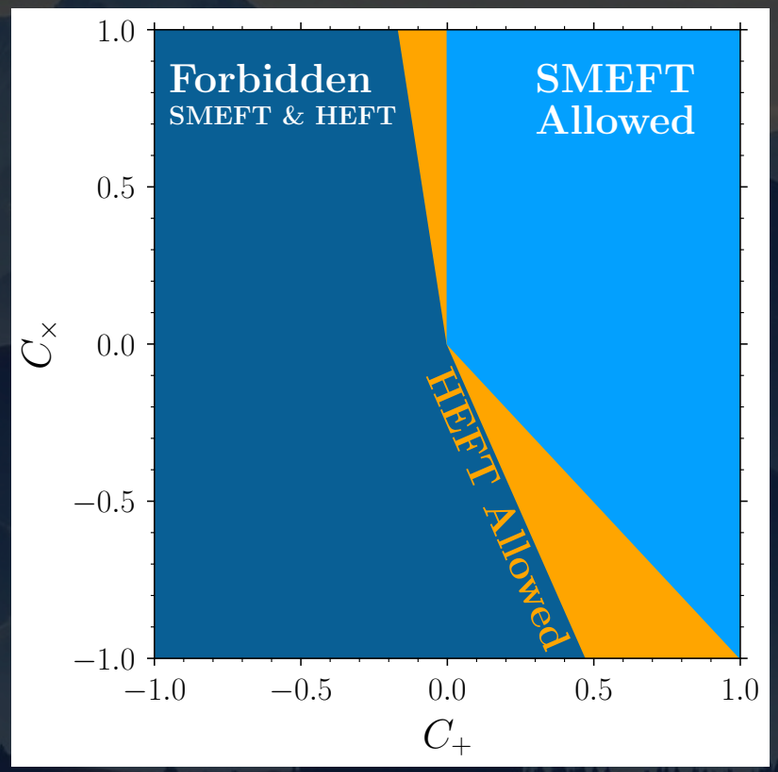
Based on ongoing work with Grant Remmen

Next Steps

More broadly, ultimate goal is to incorporate positivity bounds into future aQGC searches at the LHC

Conclusion

With the aQGC basis resolved,
time to get back to physics!



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Backup Slides

CP Odd Operators

	aQGC Operator Basis	C	P	AEG [3]	RR [4]	M [6]
$\not{\mathcal{O}}_1^M$	$[D^\mu H^\dagger D_\mu H] B_{\nu\rho} \widetilde{B}^{\nu\rho}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{H^2B^2}$	$Q^{(3)}_{B^2H^2D^2}$
$\not{\mathcal{O}}_2^M$	$[D^\mu H^\dagger \tau^I D_\mu H] B_{\nu\rho} \widetilde{W}^{I\,\nu\rho}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{H^2BW}$	$Q^{(2)}_{WBH^2D^2}$
$\not{\mathcal{O}}_3^M$	$i[D^\mu H^\dagger \tau^I D^\nu H](B_{\mu\rho} W_\nu^{I\,\rho} - B_{\nu\rho} W_\mu^{I\,\rho})$	$-$	$+$	N/A	$\mathcal{O}_2^{H^2BW}$	$Q^{(3)}_{WBH^2D^2}$
$\not{\mathcal{O}}_4^M$	$[D^\mu H^\dagger \tau^I D^\nu H](B_{\mu\rho} \widetilde{W}_\nu^{I\,\rho} + B_{\nu\rho} \widetilde{W}_\mu^{I\,\rho})$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_3^{H^2BW}$	$Q^{(6)}_{WBH^2D^2}$
$\not{\mathcal{O}}_5^M$	$[D^\mu H^\dagger D_\mu H] W^I_{\nu\rho} \widetilde{W}^{I\,\nu\rho}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{H^2W^2}$	$Q^{(3)}_{W^2H^2D^2}$
$\not{\mathcal{O}}_6^M$	$i\,\epsilon^{IJK}[D^\mu H^\dagger \tau^I D^\nu H](W^J_{\mu\rho} \widetilde{W}_\nu^{K\,\rho} + \widetilde{W}^J_{\mu\rho} W_\nu^{K\,\rho})$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_3^{H^2W^2}$	$Q^{(6)}_{W^2H^2D^2}$
$\not{\mathcal{O}}_1^T$	$B_{\mu\nu} B^{\mu\nu} B_{\rho\sigma} \widetilde{B}^{\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{B^4}$	$Q^{(3)}_{B^4}$
$\not{\mathcal{O}}_2^T$	$B_{\mu\nu} \widetilde{B}^{\mu\nu} W^I_{\rho\sigma} W^{I\,\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{B^2W^2}$	$Q^{(5)}_{W^2B^2}$
$\not{\mathcal{O}}_3^T$	$B_{\mu\nu} B^{\mu\nu} W^I_{\rho\sigma} \widetilde{W}^{I\,\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_2^{B^2W^2}$	$Q^{(6)}_{W^2B^2}$
$\not{\mathcal{O}}_4^T$	$B_{\mu\nu} W^{I\,\mu\nu} B_{\rho\sigma} \widetilde{W}^{I\,\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_3^{B^2W^2}$	$Q^{(7)}_{W^2B^2}$
$\not{\mathcal{O}}_5^T$	$W^I_{\mu\nu} W^{I\,\mu\nu} W^J_{\rho\sigma} \widetilde{W}^{J\,\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_1^{W^4}$	$Q^{(5)}_{W^4}$
$\not{\mathcal{O}}_6^T$	$W^I_{\mu\nu} W^{J\,\mu\nu} W^I_{\rho\sigma} \widetilde{W}^{J\,\rho\sigma}$	$+$	$-$	N/A	$\widetilde{\mathcal{O}}_2^{W^4}$	$Q^{(6)}_{W^4}$