The effective landscape of new physics

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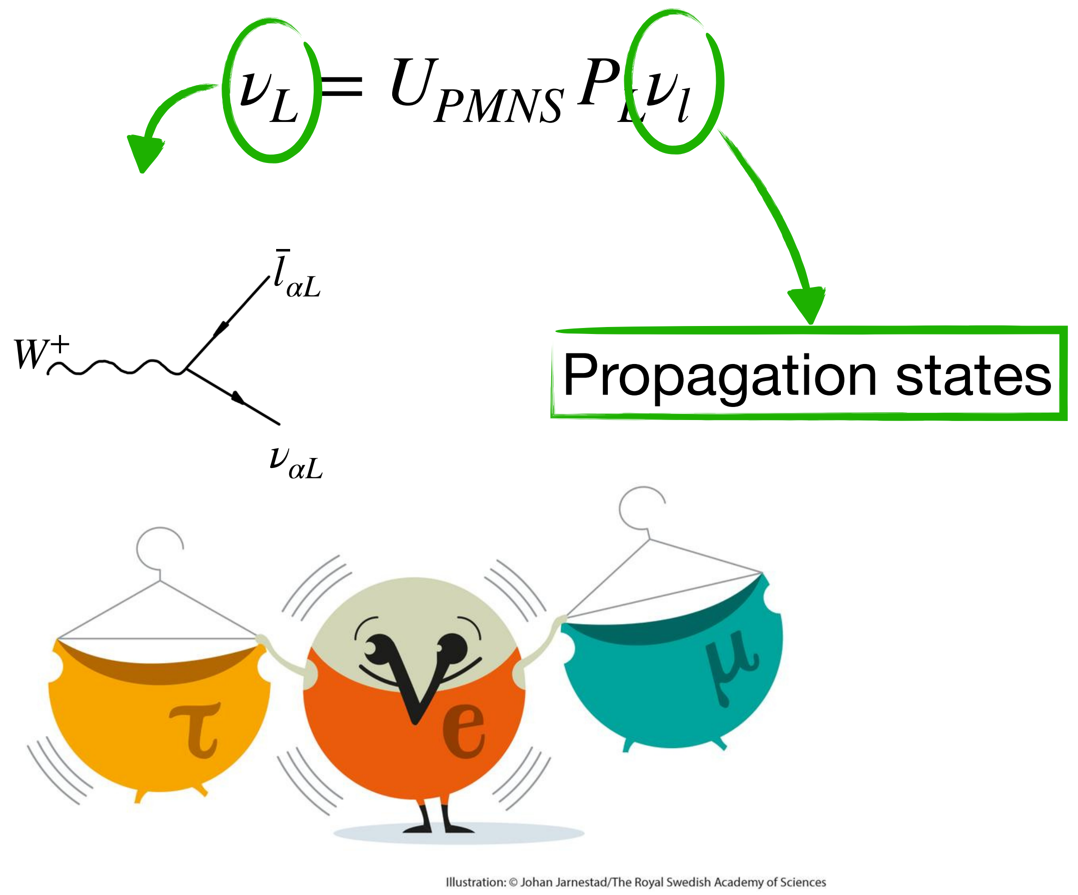
Invisibles'23 Workshop - 30 August 2023

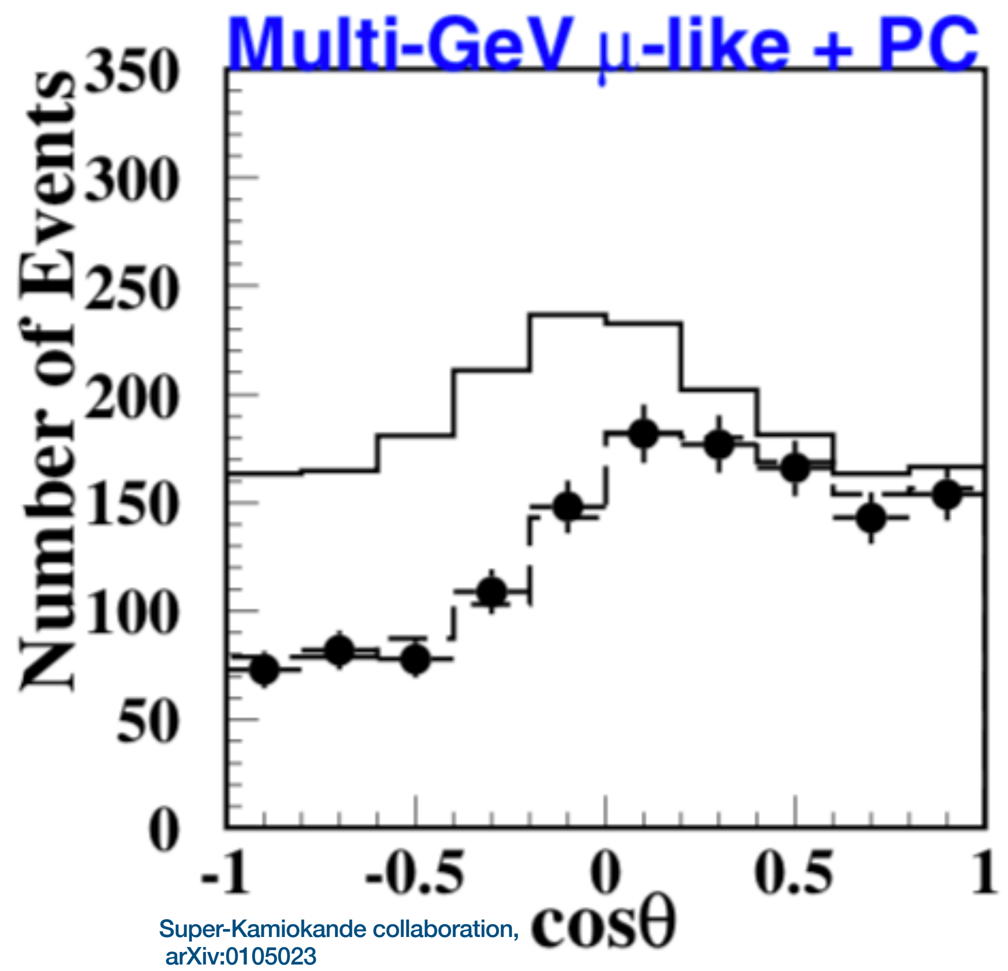
Physics beyond the Standard Model

[Manibrata Sen]

Introduction [Salvador Rosauro-Alcaraz]

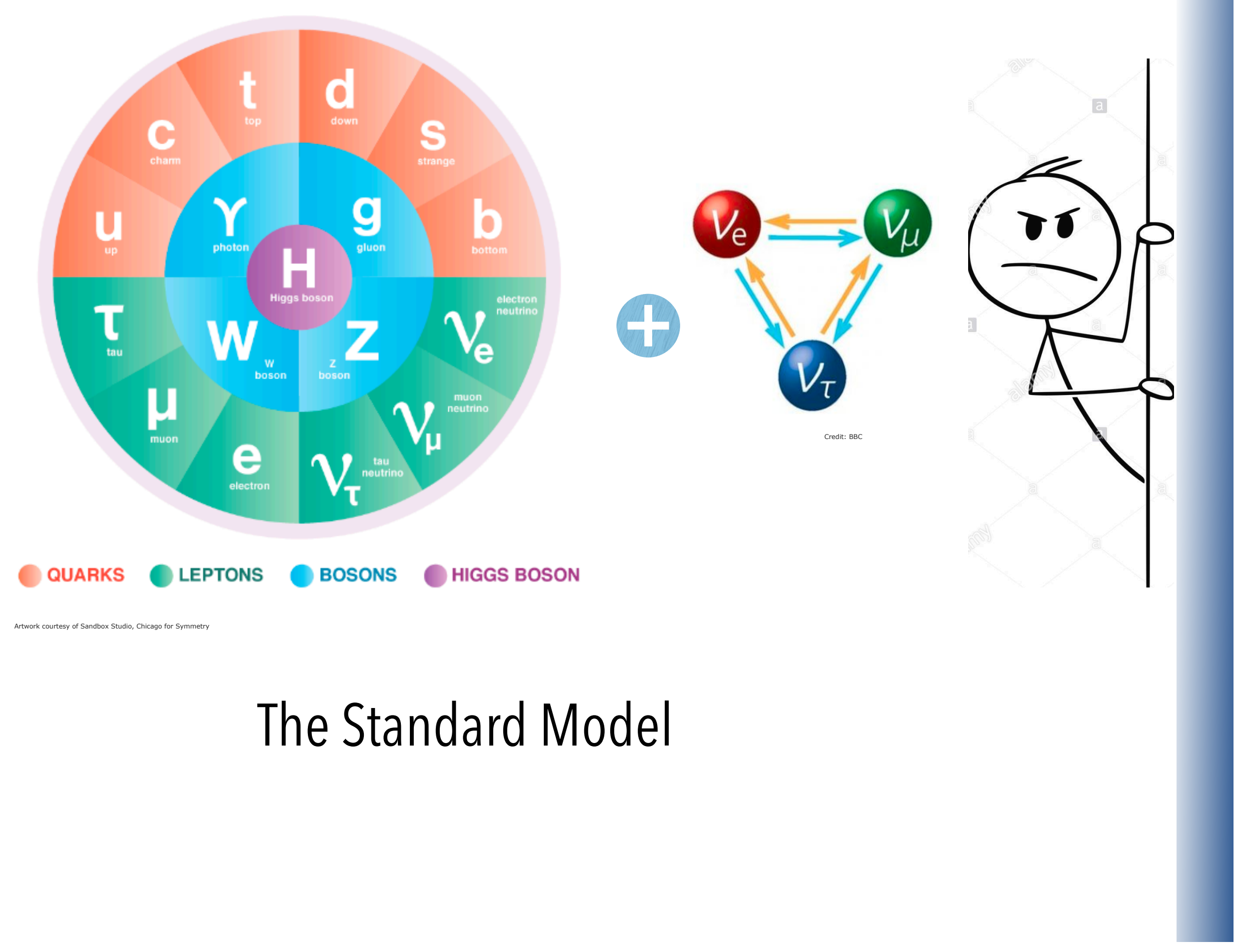
Origin of neutrino masses





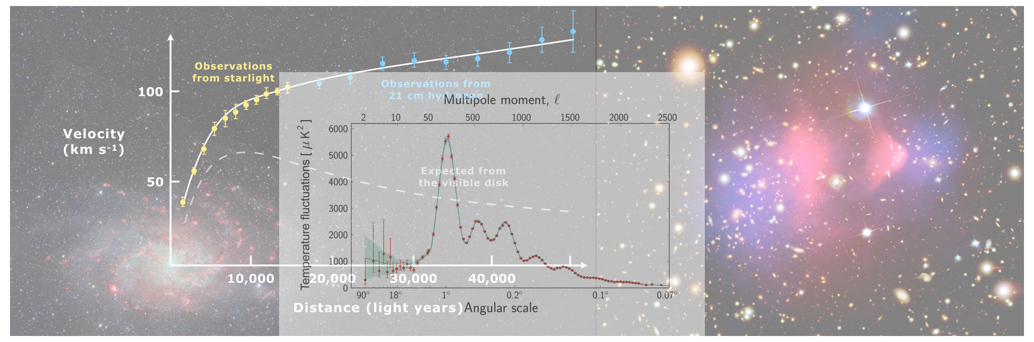
Super-Kamiokande collaboration, arXiv:0105023

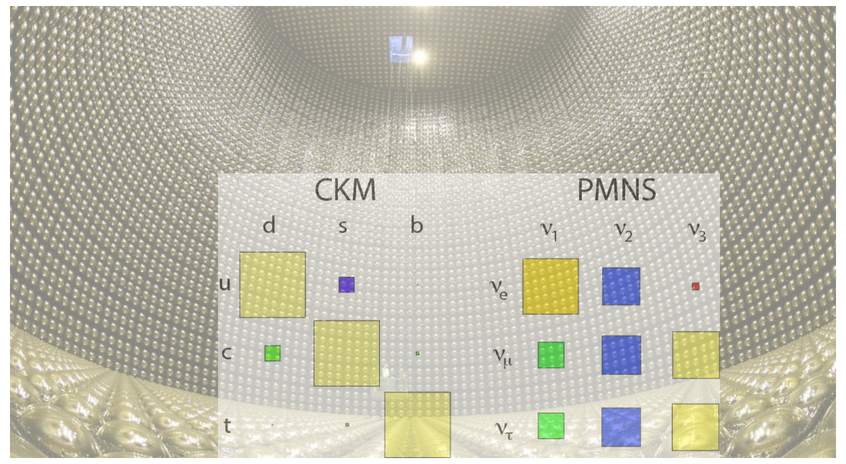
Sensitive to new physics



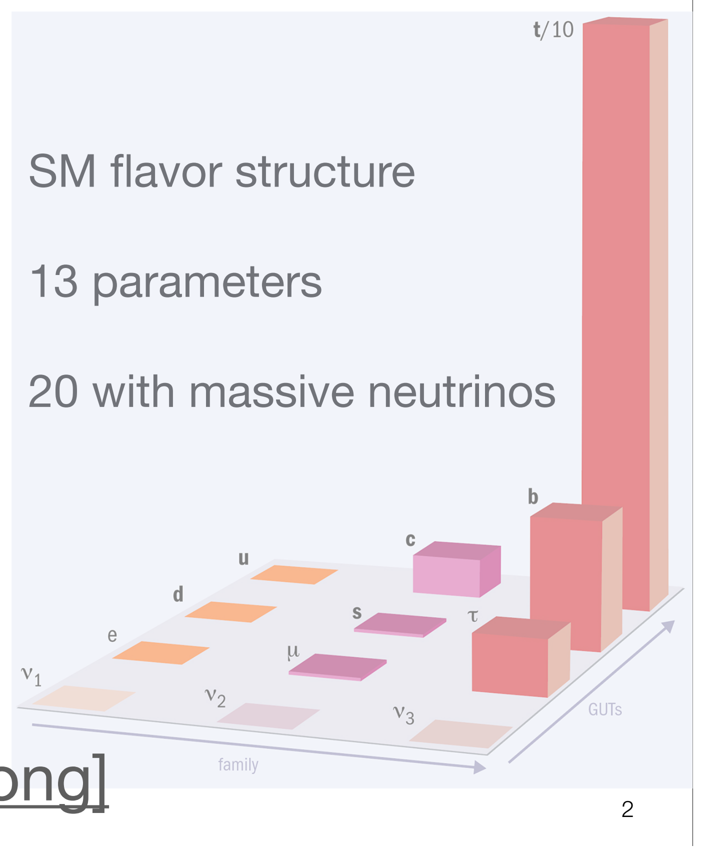
The Standard Model

Evidence of new physics



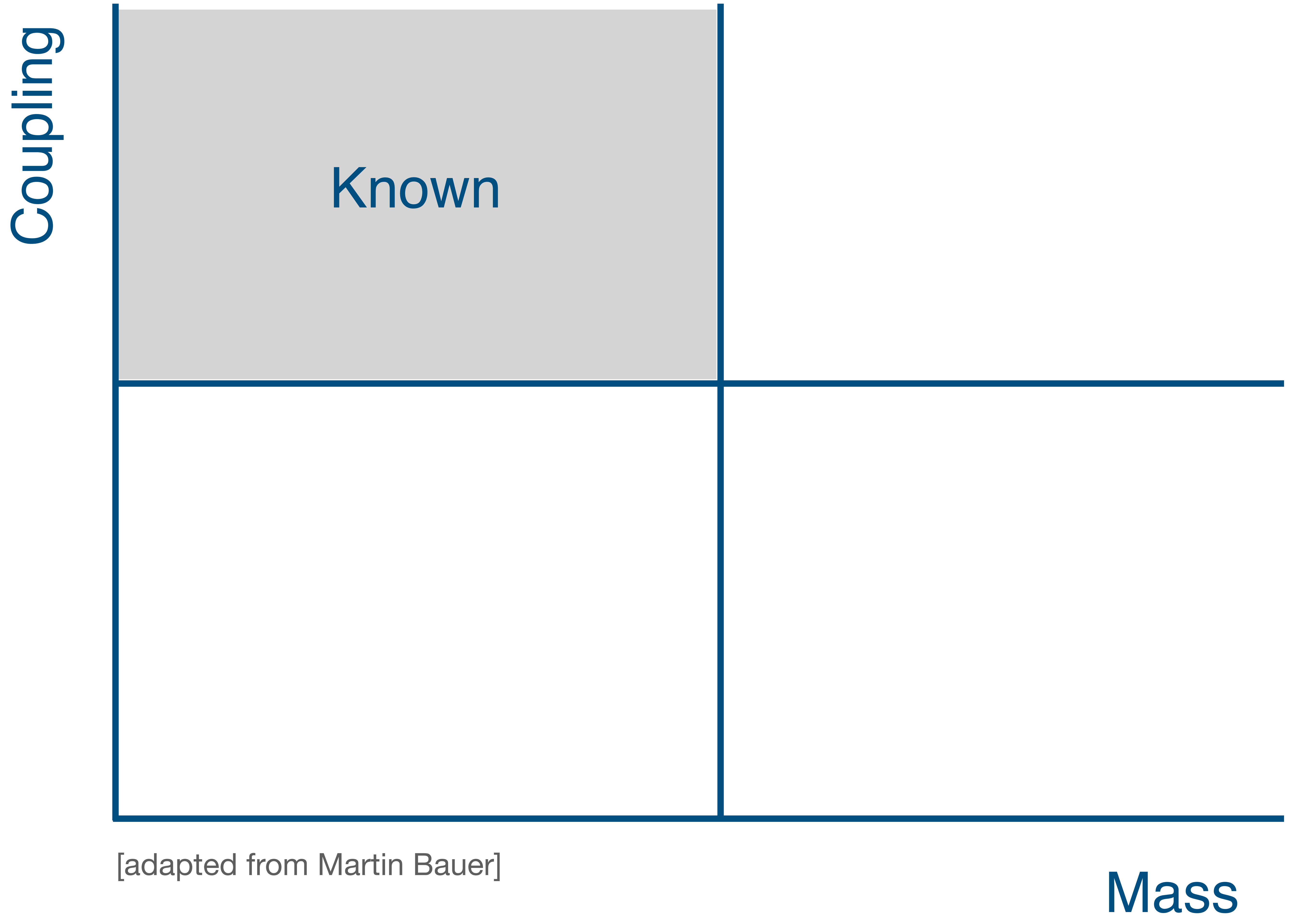


Mystery of flavor



[Tom Tong]

The Landscape of (new) physics



[adapted from Martin Bauer]

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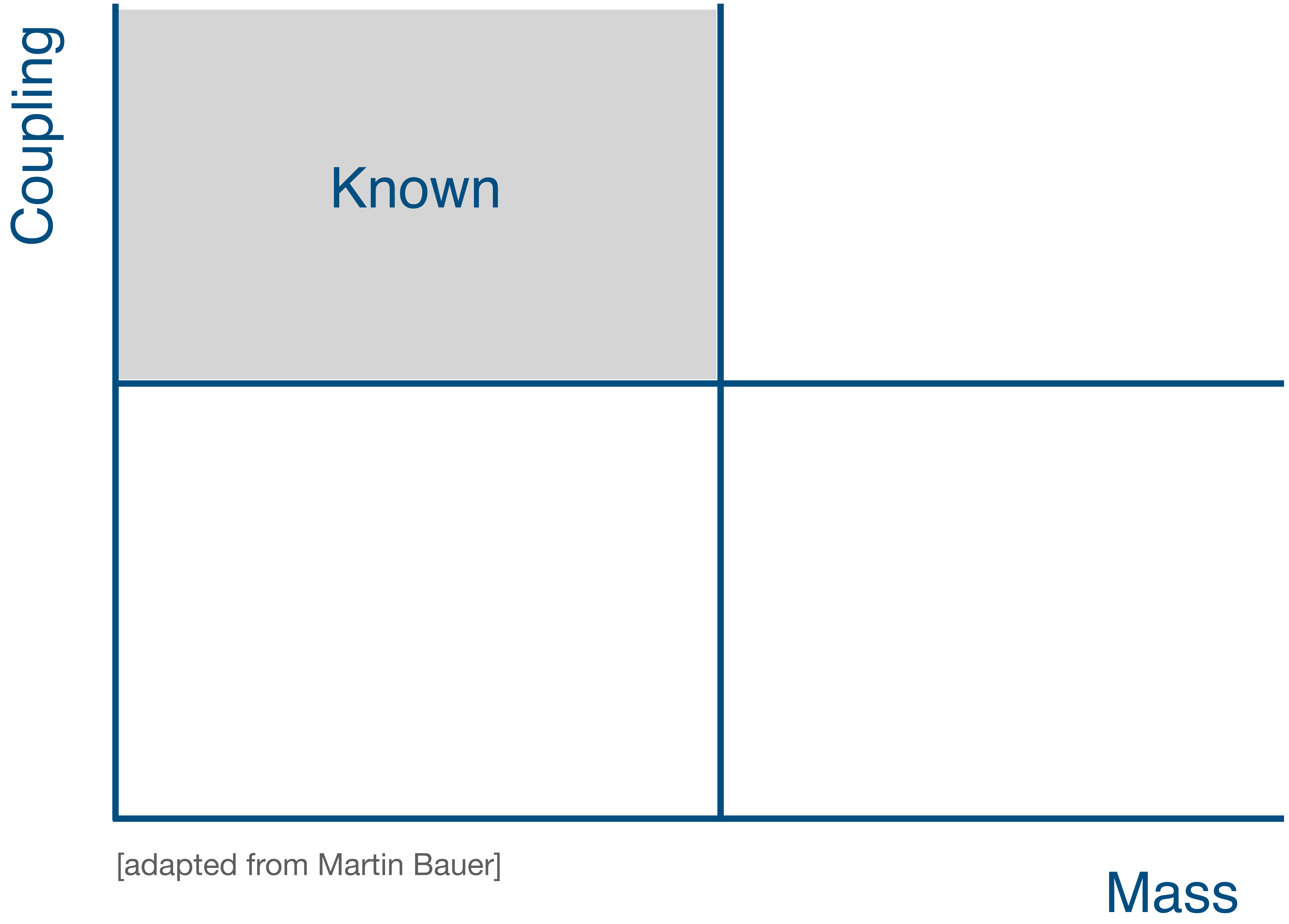

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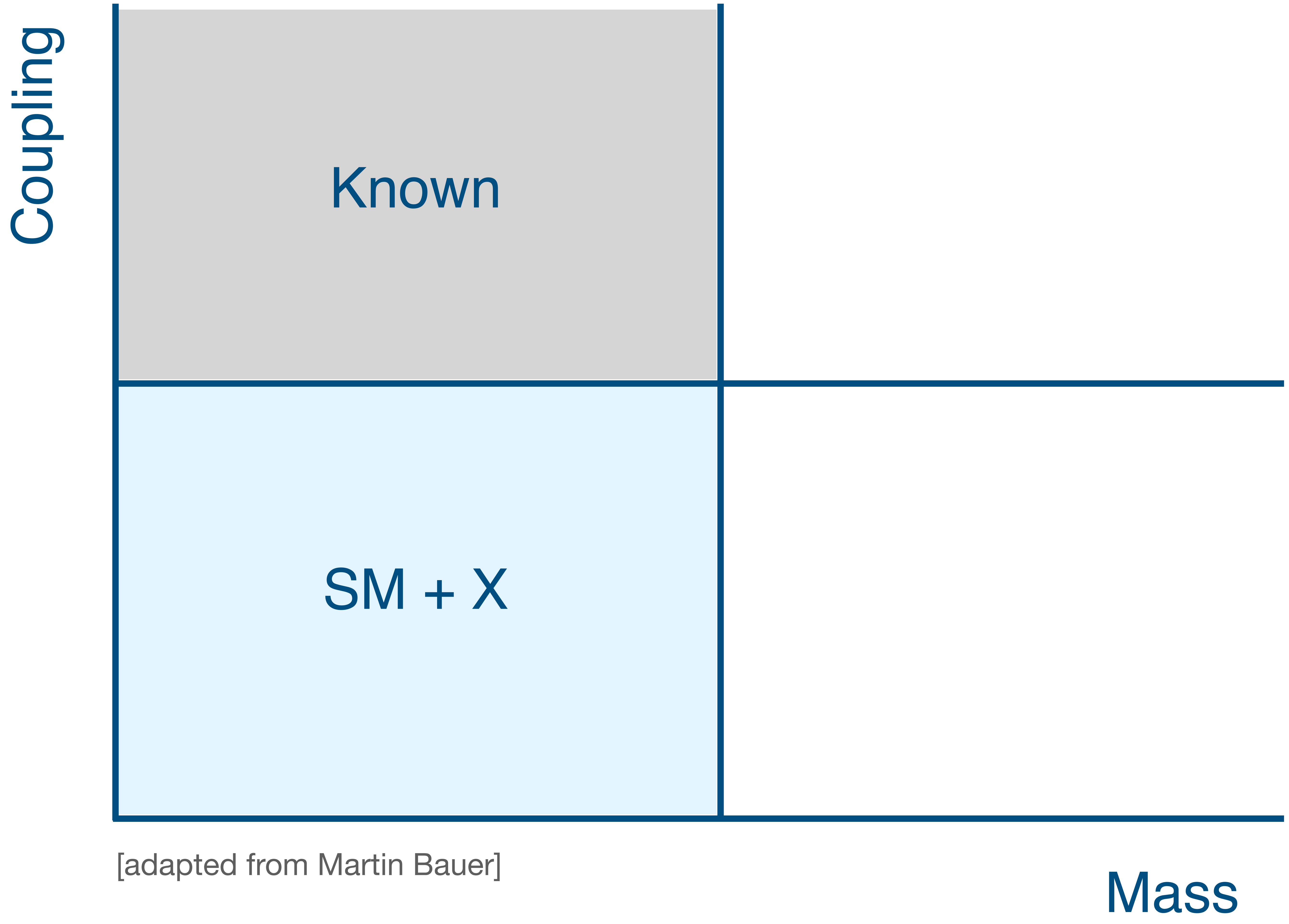
New physics has to be…

The Landscape of (new) physics



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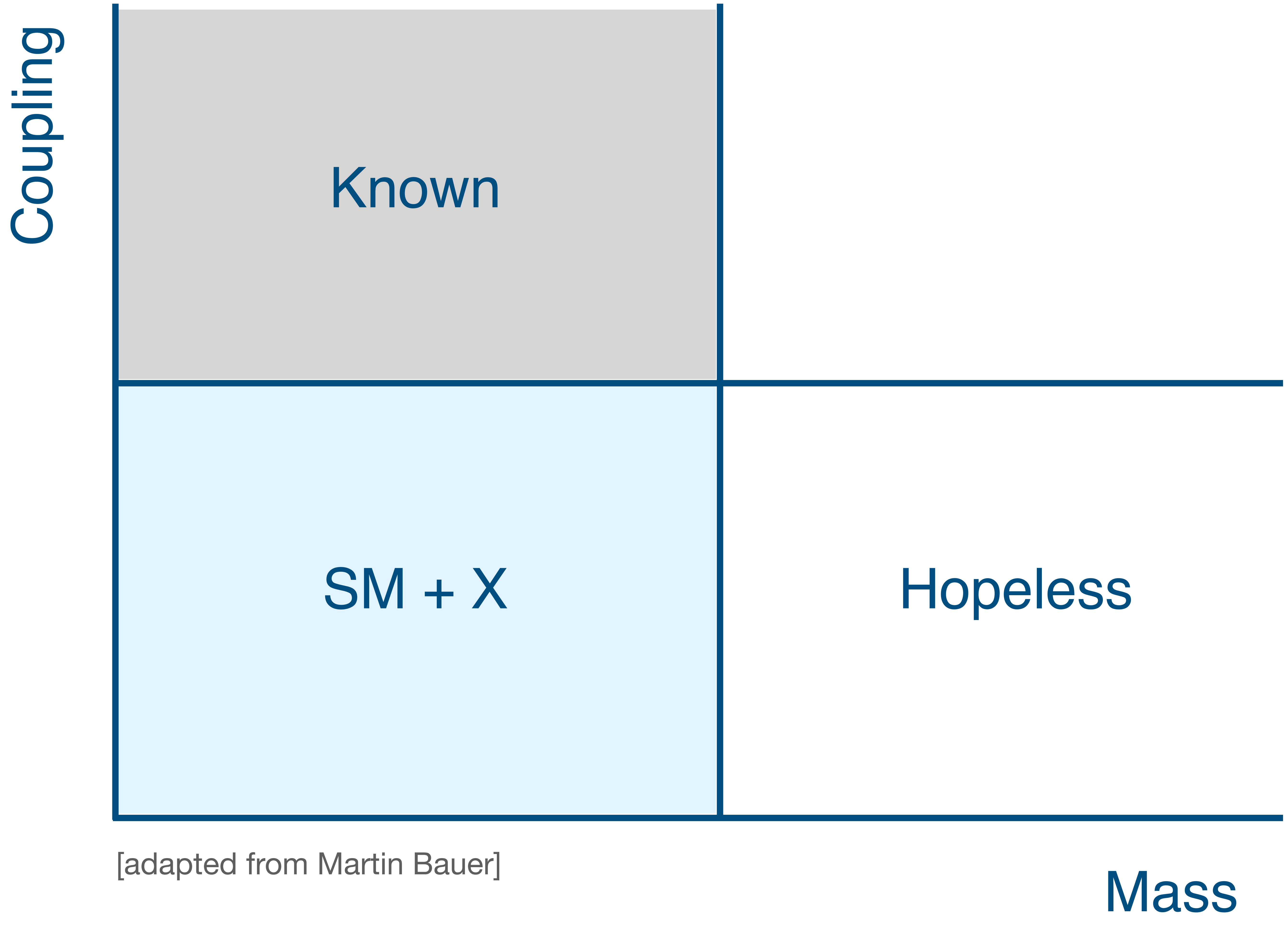
New physics has to be…

… (light and) very weakly interacting with the SM

Axion-like particles

Neutrinos

The Landscape of (new) physics



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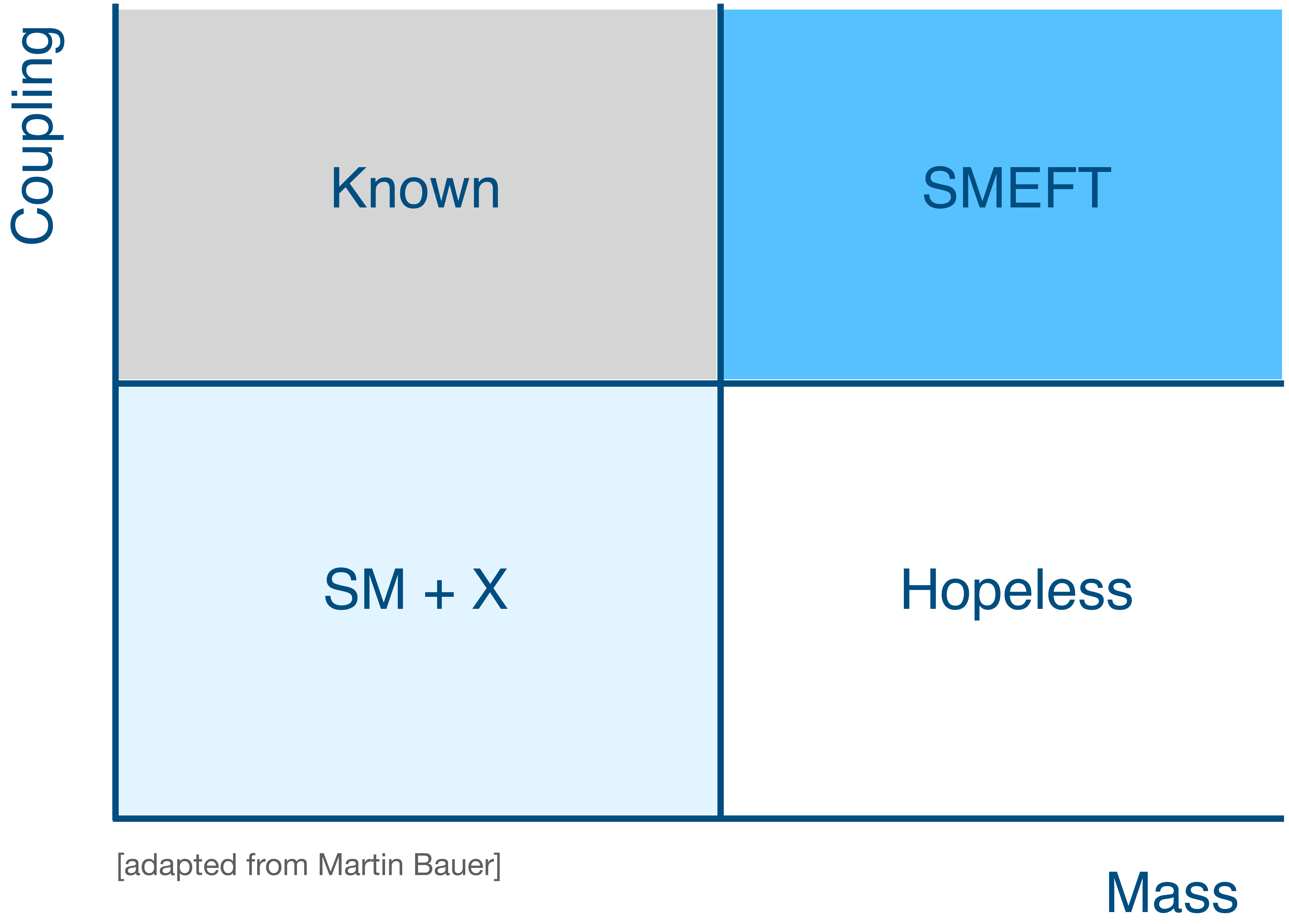

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New physics has to be…

… (light and) very weakly interacting with the SM

Axion-like particles

Neutrinos

… very heavy

SMEFT

Leptoquarks

Z' bosons

Supersymmetry

Outline

- Effective field theory
  - SMEFT

- Global analyses

- Relation to light new physics

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  - SMEFT

SMEFT describes the effects of heavy new physics at lower energy scales

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Global analyses enable us to fully exploit the data and the correlations between different observables

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Global analyses enable us to fully exploit the data and the correlations between different observables

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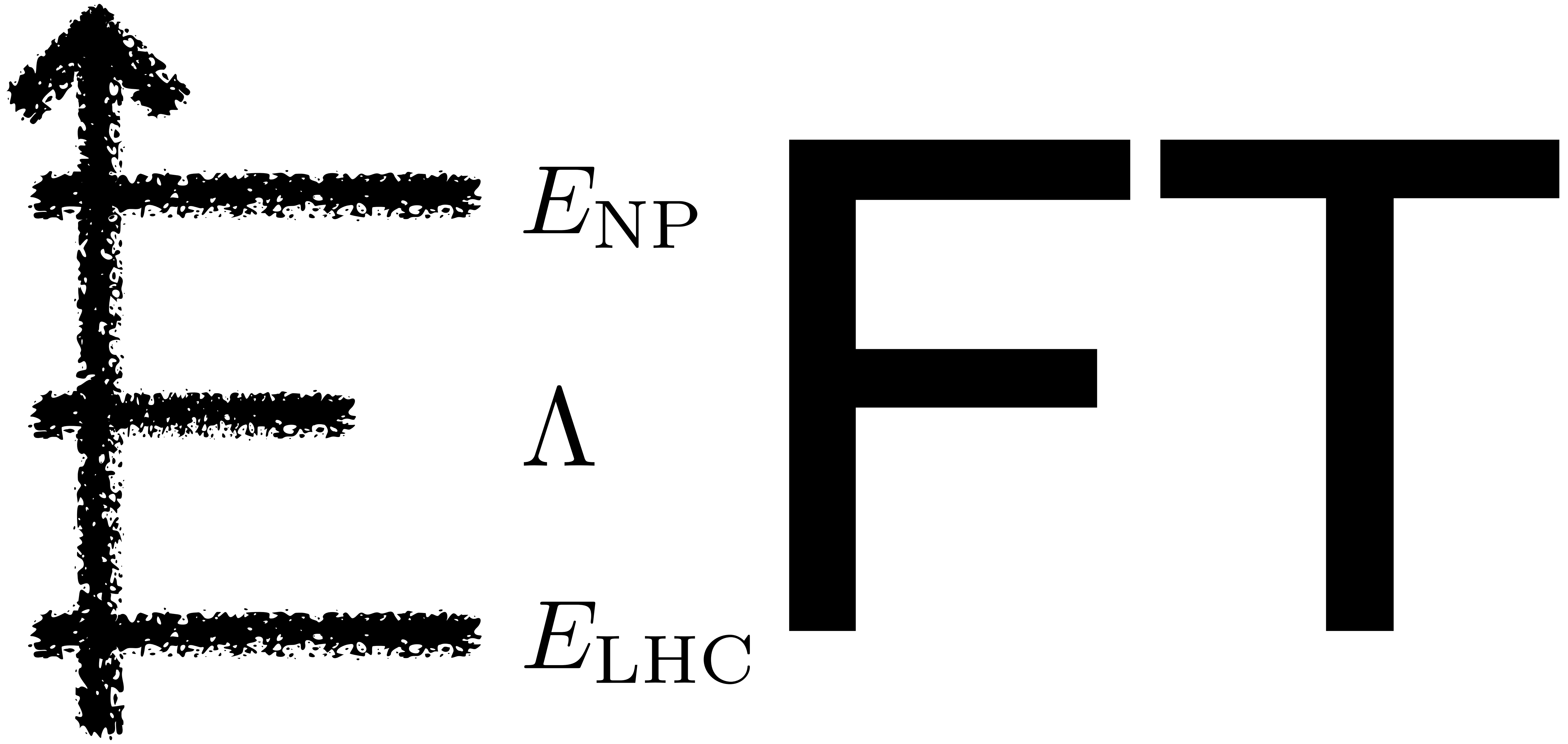
SMEFT analyses can be reused to constrain axion-like particle (ALP) interactions

Effective field theory - EFT

EFT

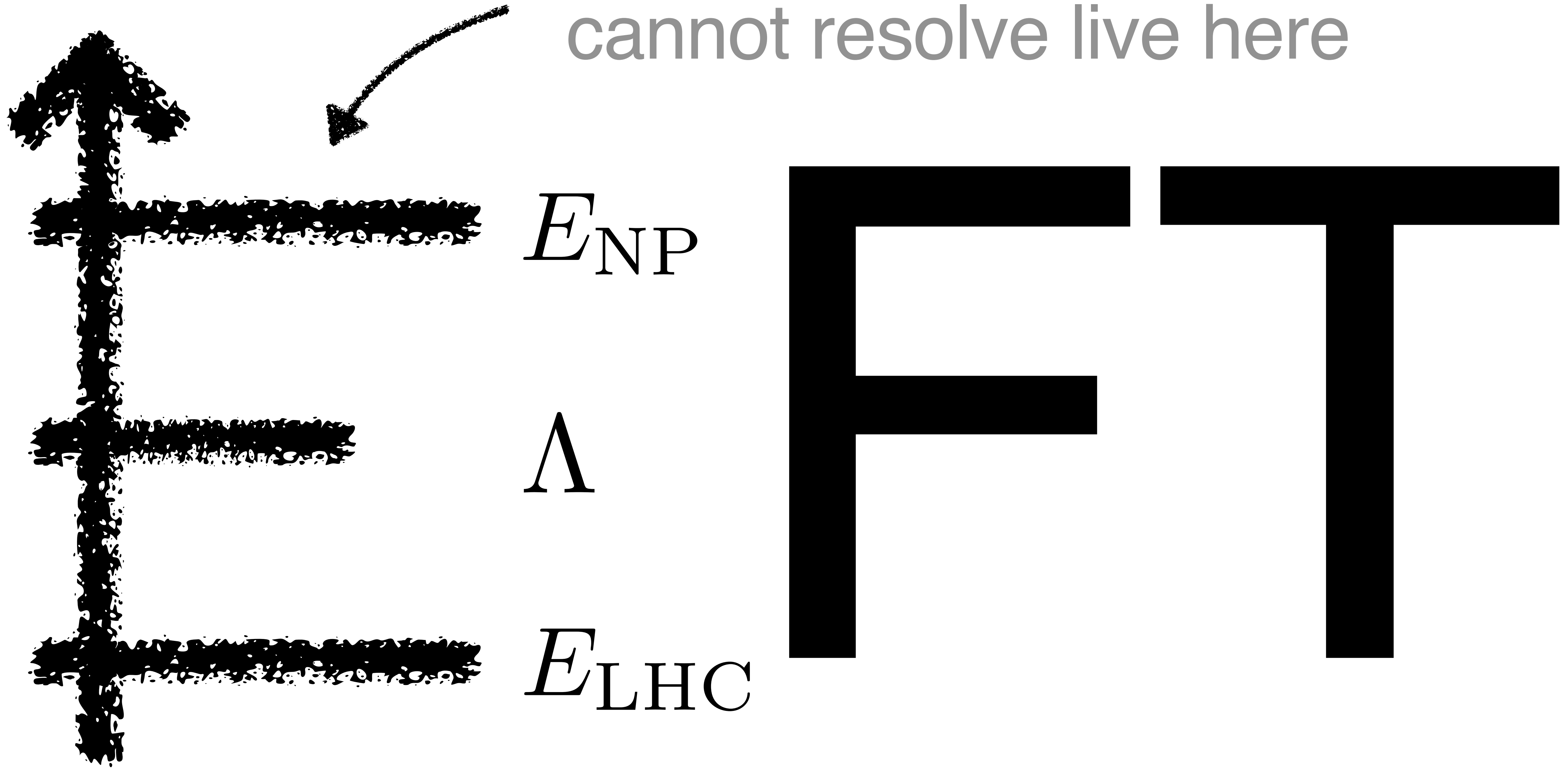
Effective field theory - EFT



Hierarchy of scales

Effective field theory - EFT

Heavy particles that we cannot resolve live here



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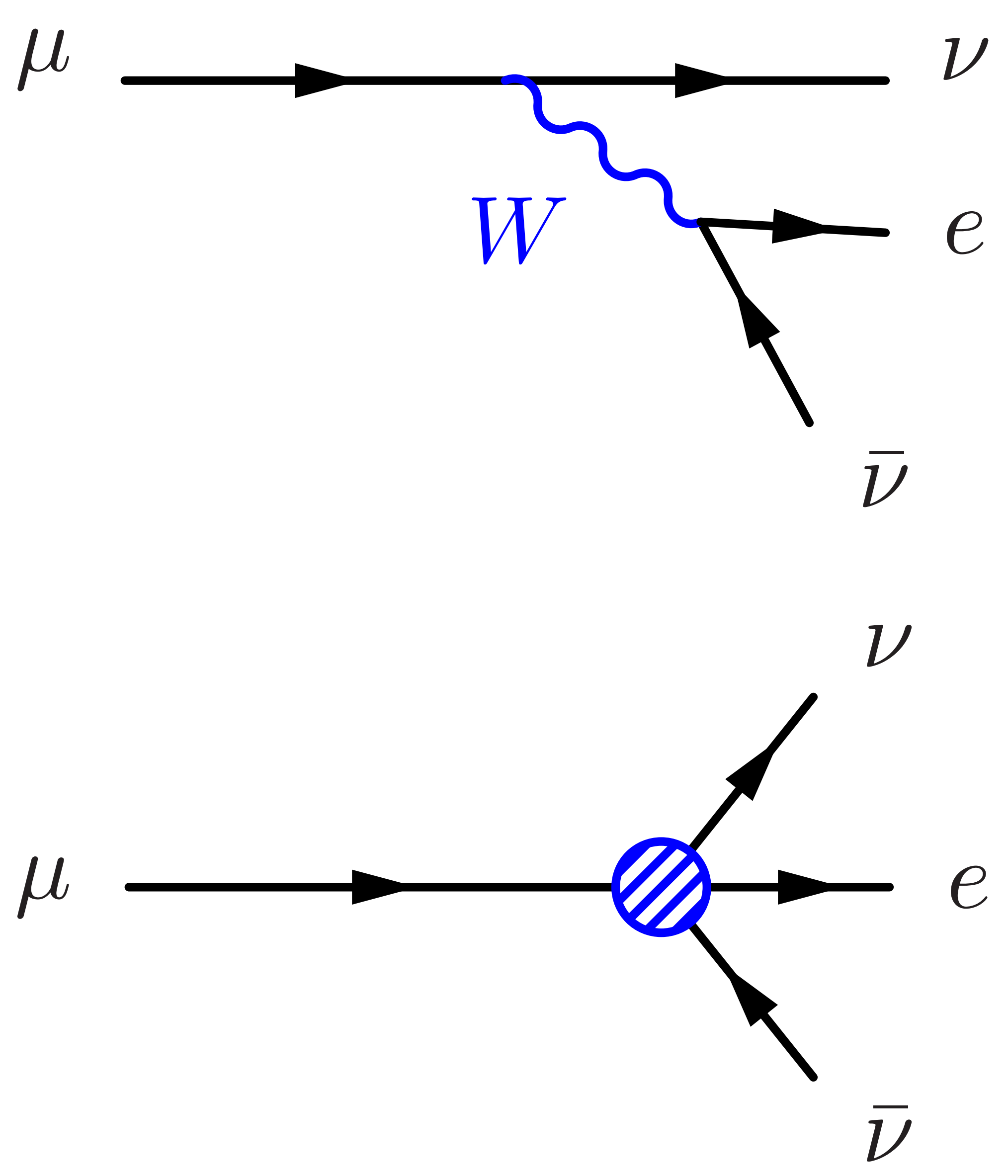
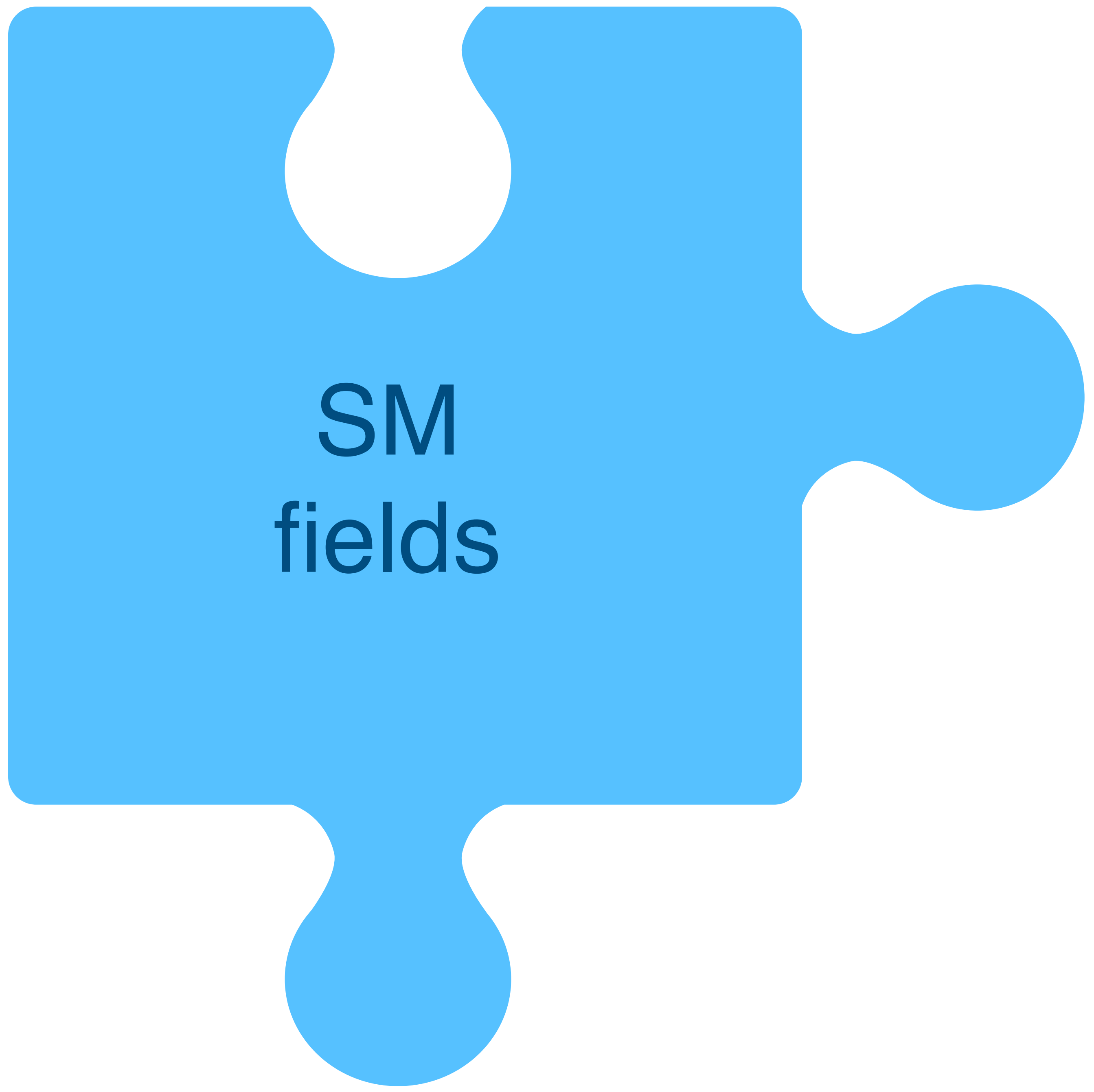


Describe NP by higher-order interactions of SM fields

EFTs from the bottom-up

[review: Brivio, Trott (1706.08945)]

At low energies, the SM does a very good job.



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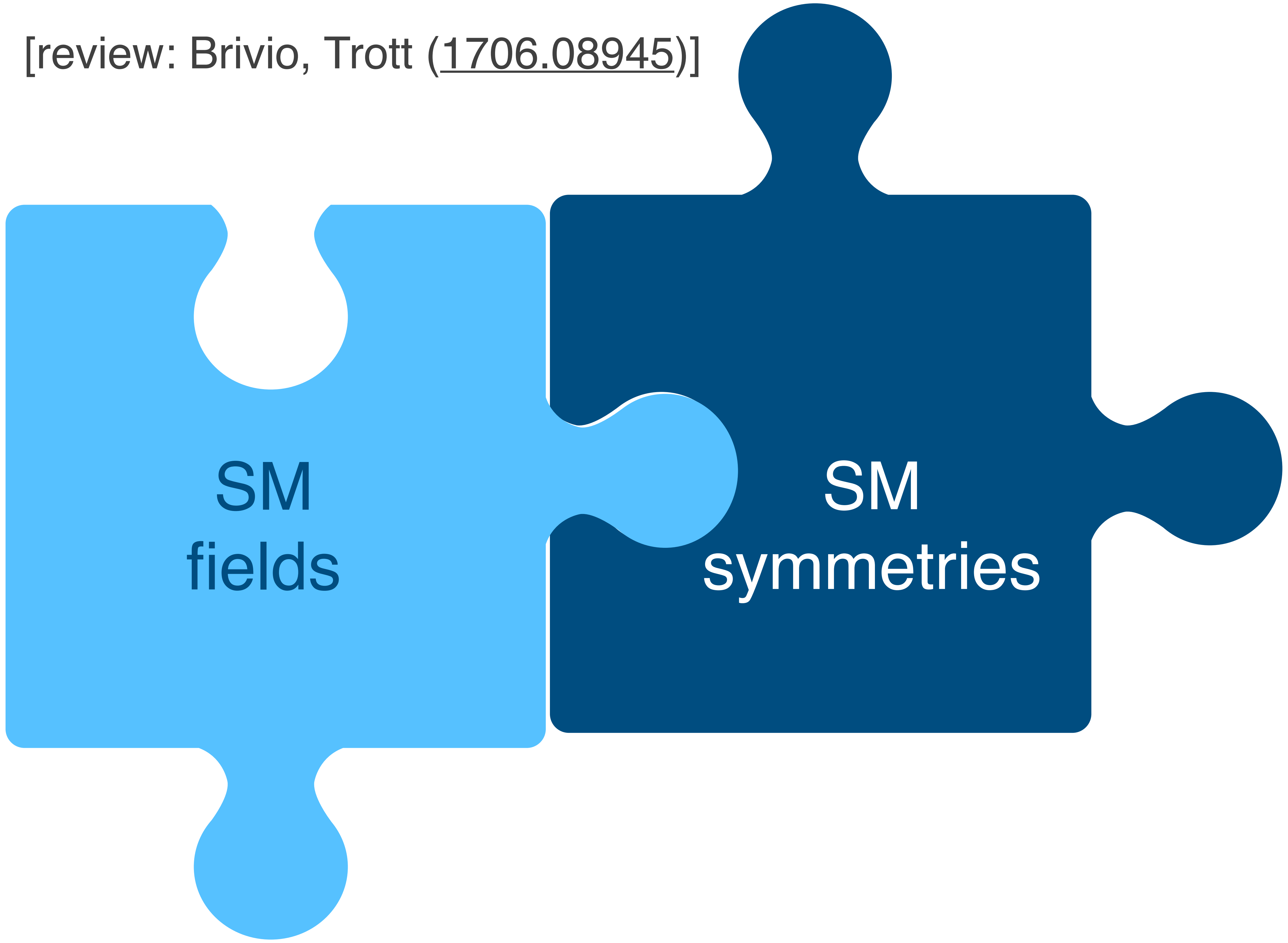

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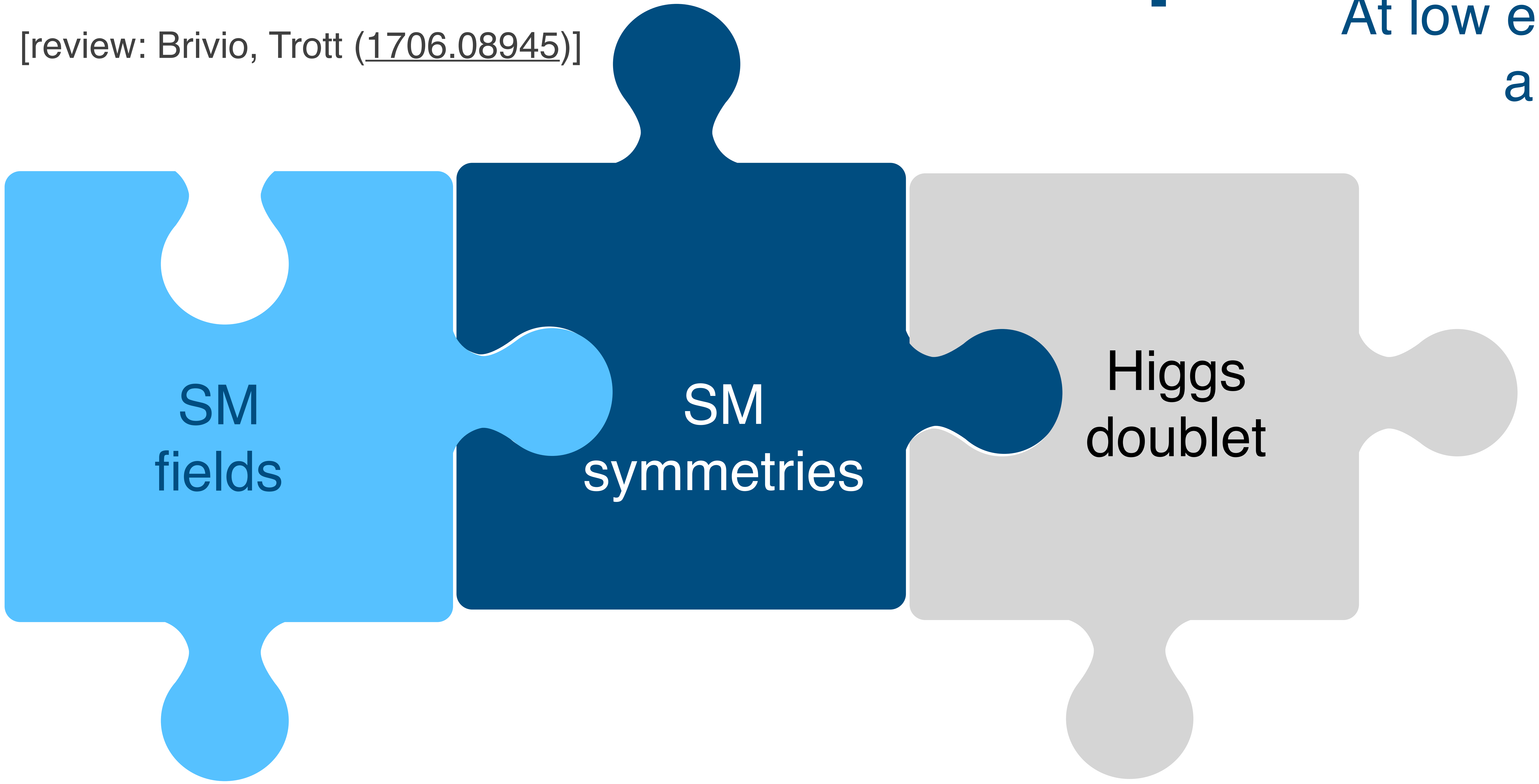

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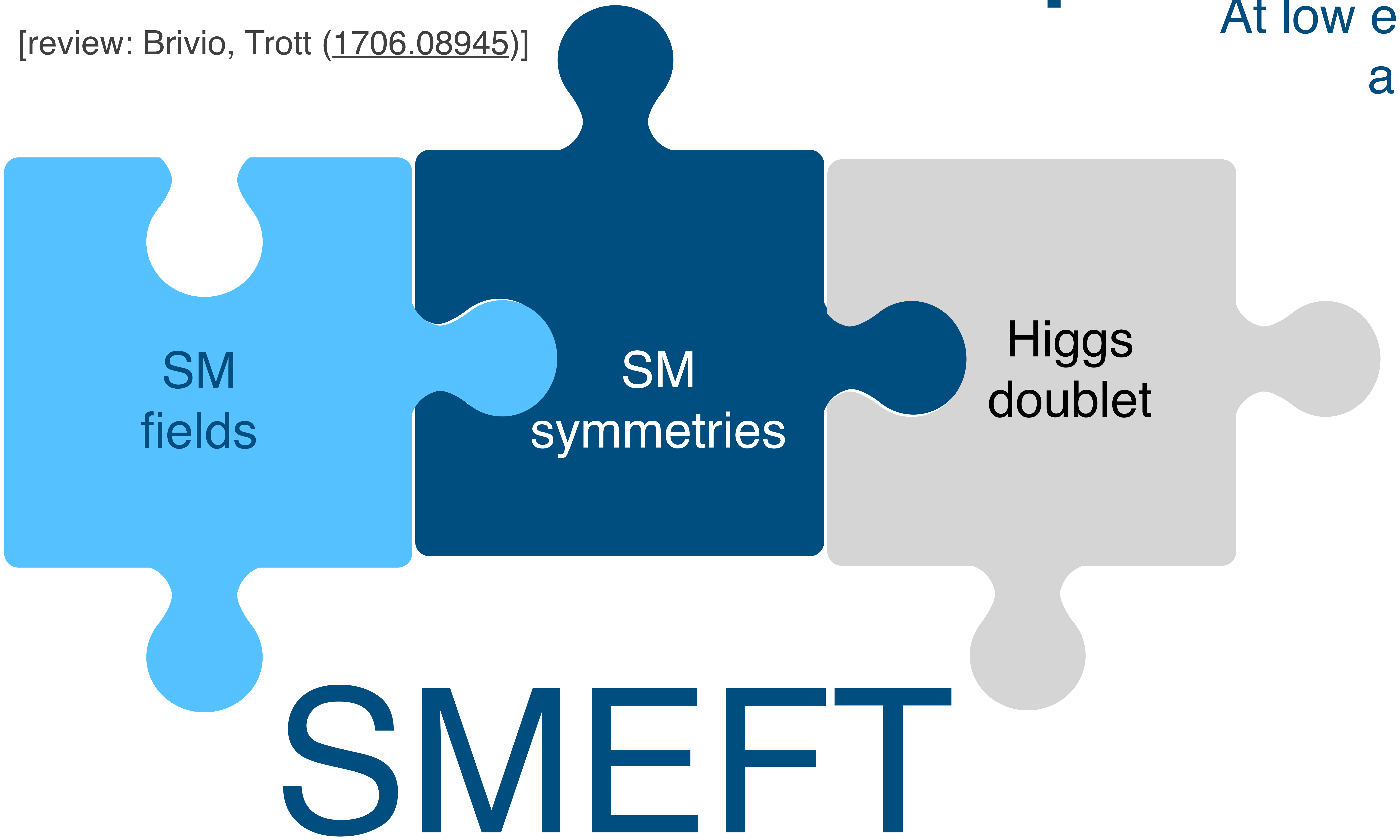

At low energies, the SM does a very good job.

- Proper, renormalisable **quantum field theory**
- **Minimal assumptions** on UV completion
- **Universal language** for data interpretation

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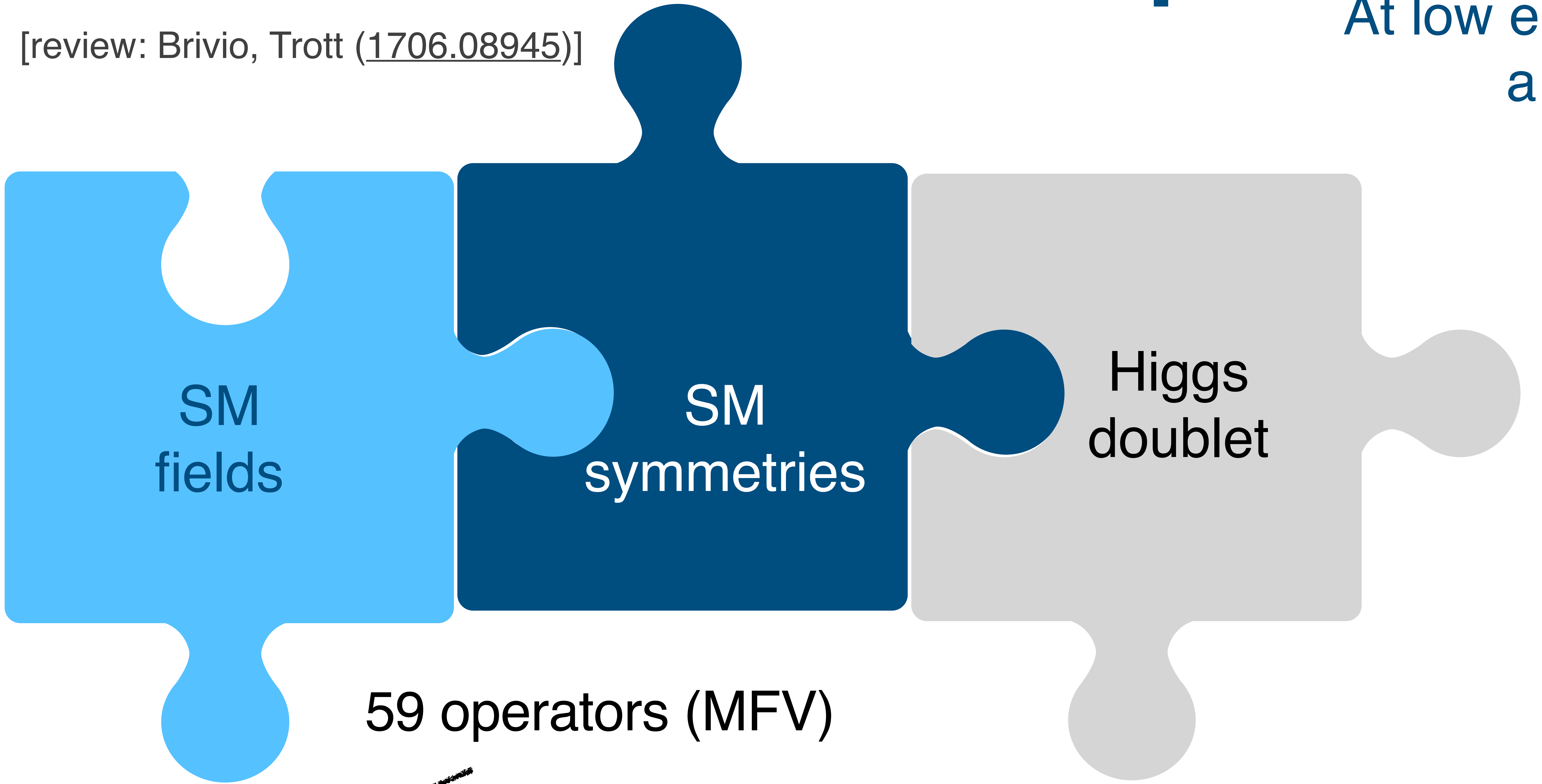

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59 operators (MFV)

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4}\mathcal{O}_j^{(8)} + \cdots$$

Odd dimensions violate lepton or baryon number

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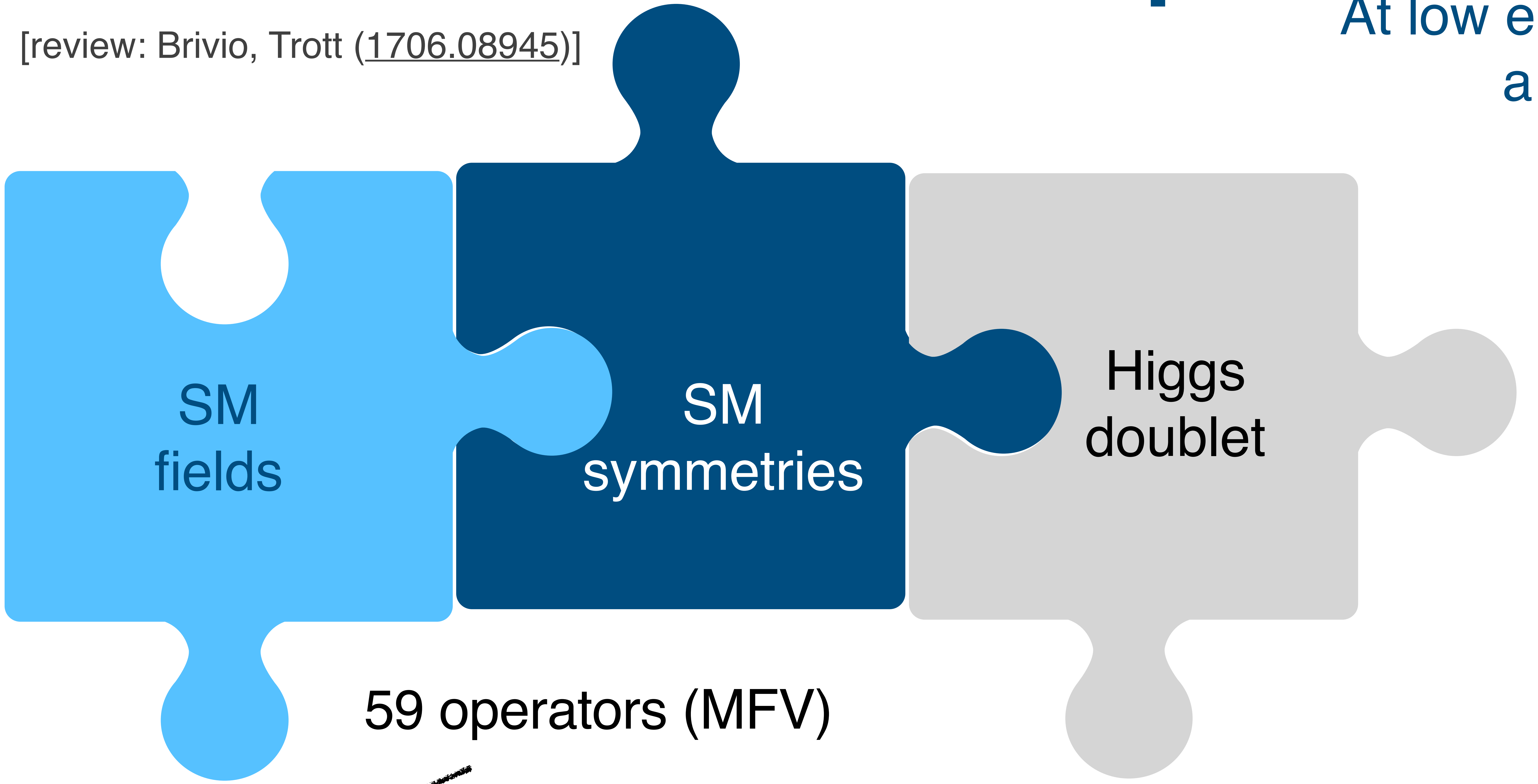

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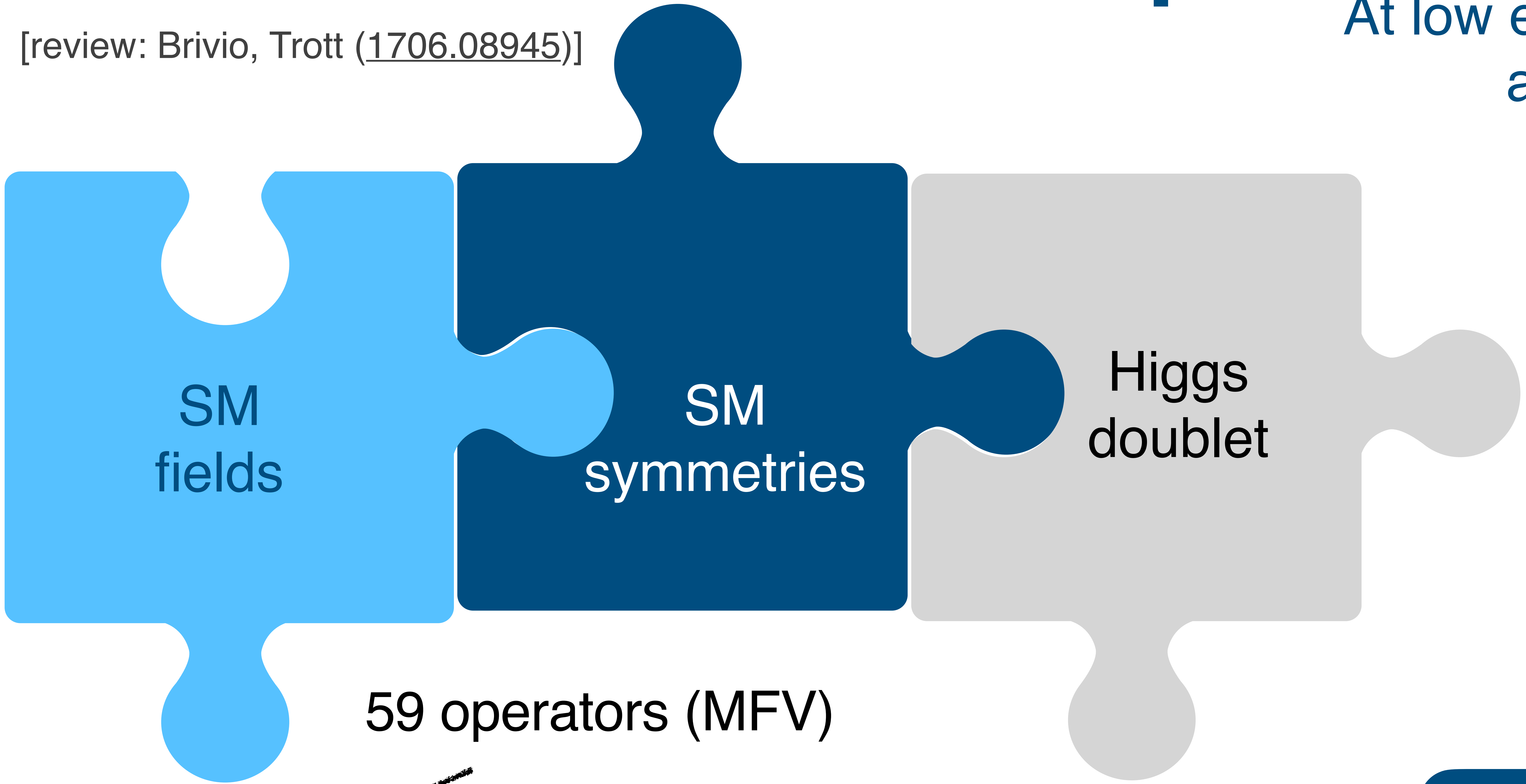

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- **Universal language** for data interpretation

Systematic program for indirect searches!

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Odd dimensions violate lepton or baryon number

Warsaw basis

[Grzadkowski et al. (1008.4884)]

$1: X^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
$Q_{\widetilde{G}}$	$f^{ABC} \widetilde{G}_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$
Q_W	$\epsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$
$Q_{\widetilde{W}}$	$\epsilon^{IJK} \widetilde{W}_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$

$2: H^6$	
Q_H	$(H^\dagger H)^3$

$3: H^4 D^2$	
$Q_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
Q_{HD}	$\left(H^\dagger D_\mu H\right)^* \left(H^\dagger D_\mu H\right)$

$5: \psi^2 H^3 + \text{h.c.}$	
Q_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
Q_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
Q_{dH}	$(H^\dagger H)(\bar{q}_p d_r H)$

$4: X^2 H^2$	
Q_{HG}	$H^\dagger H\, G_{\mu\nu}^A G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}_{\mu\nu}^A G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W_{\mu\nu}^I W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}_{\mu\nu}^I W^{I\mu\nu}$
Q_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{B}}$	$H^\dagger H\, \widetilde{B}_{\mu\nu} B^{\mu\nu}$
Q_{HWB}	$H^\dagger \tau^I H\, W_{\mu\nu}^I B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}_{\mu\nu}^I B^{\mu\nu}$

$6: \psi^2 X H + \text{h.c.}$	
Q_{eW}	$(\bar{l}_p \sigma^{\mu\nu} e_r)\tau^I H W_{\mu\nu}^I$
Q_{eB}	$(\bar{l}_p \sigma^{\mu\nu} e_r) H B_{\mu\nu}$
Q_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G_{\mu\nu}^A$
Q_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W_{\mu\nu}^I$
Q_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
Q_{dG}	$(\bar{q}_p \sigma^{\mu\nu} T^A d_r) H\, G_{\mu\nu}^A$
Q_{dW}	$(\bar{q}_p \sigma^{\mu\nu} d_r)\tau^I H\, W_{\mu\nu}^I$
Q_{dB}	$(\bar{q}_p \sigma^{\mu\nu} d_r) H\, B_{\mu\nu}$

$7: \psi^2 H^2 D$	
$Q_{Hl}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
Q_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$Q_{Hq}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
Q_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
Q_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$
Q_{Hud} + h.c.	$i(\widetilde{H}^\dagger D_\mu H)(\bar{u}_p \gamma^\mu d_r)$

$8: (\bar{L}L)(\bar{L}L)$	
$Q_{\ell\ell}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$

Plus another 24 four-fermion operators

Warsaw basis

[Grzadkowski et al. (1008.4884)]

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$Q_{H\widetilde G}$	$H^\dagger H\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p\sigma^{\mu\nu}e_r)H B_{\mu\nu}$	$Q_{Hl}^{(3)}$	$(H^\dagger i\overleftrightarrow{D}_\mu^I H)(\bar l_p\tau^I\gamma^\mu l_r)$
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$Q_{H\widetilde W}$	$H^\dagger H\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p\sigma^{\mu\nu}u_r)\tau^I\widetilde H\, W_{\mu\nu}^I$	$Q_{Hq}^{(1)}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar q_p\gamma^\mu q_r)$
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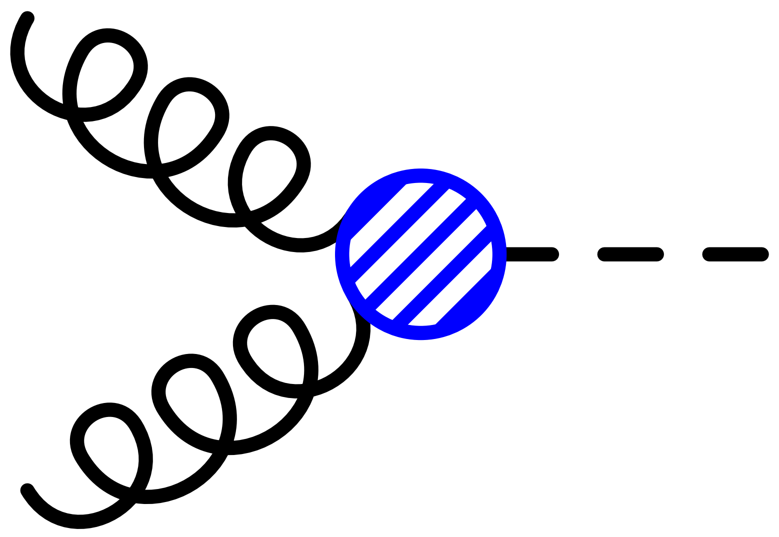
$Q_{\ell\ell}$	$(\bar l_p\gamma_\mu l_r)(\bar l_s\gamma^\mu l_t)$

Plus another 24 four-fermion operators

The operator $\mathcal{O}_{HG}$

$$\mathcal{O}_{HG} = H^\dagger H\, G^A_{\mu\nu} G^{A,\mu\nu} \to vh\, G^A_{\mu\nu} G^{A\mu\nu}$$

Feynman rules



SM: $-i\, G_H\, \delta_{a_1,a_2}\, (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

EFT: $-i\, v\, \delta_{a_1,a_2}\, (p_1^\mu p_2^\nu - \eta^{\mu\nu} p_1 \cdot p_2)$

Structurally the same

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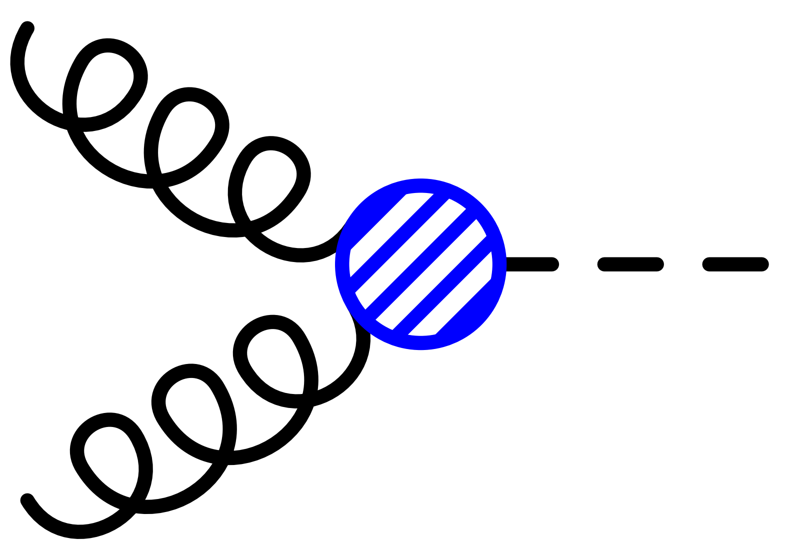

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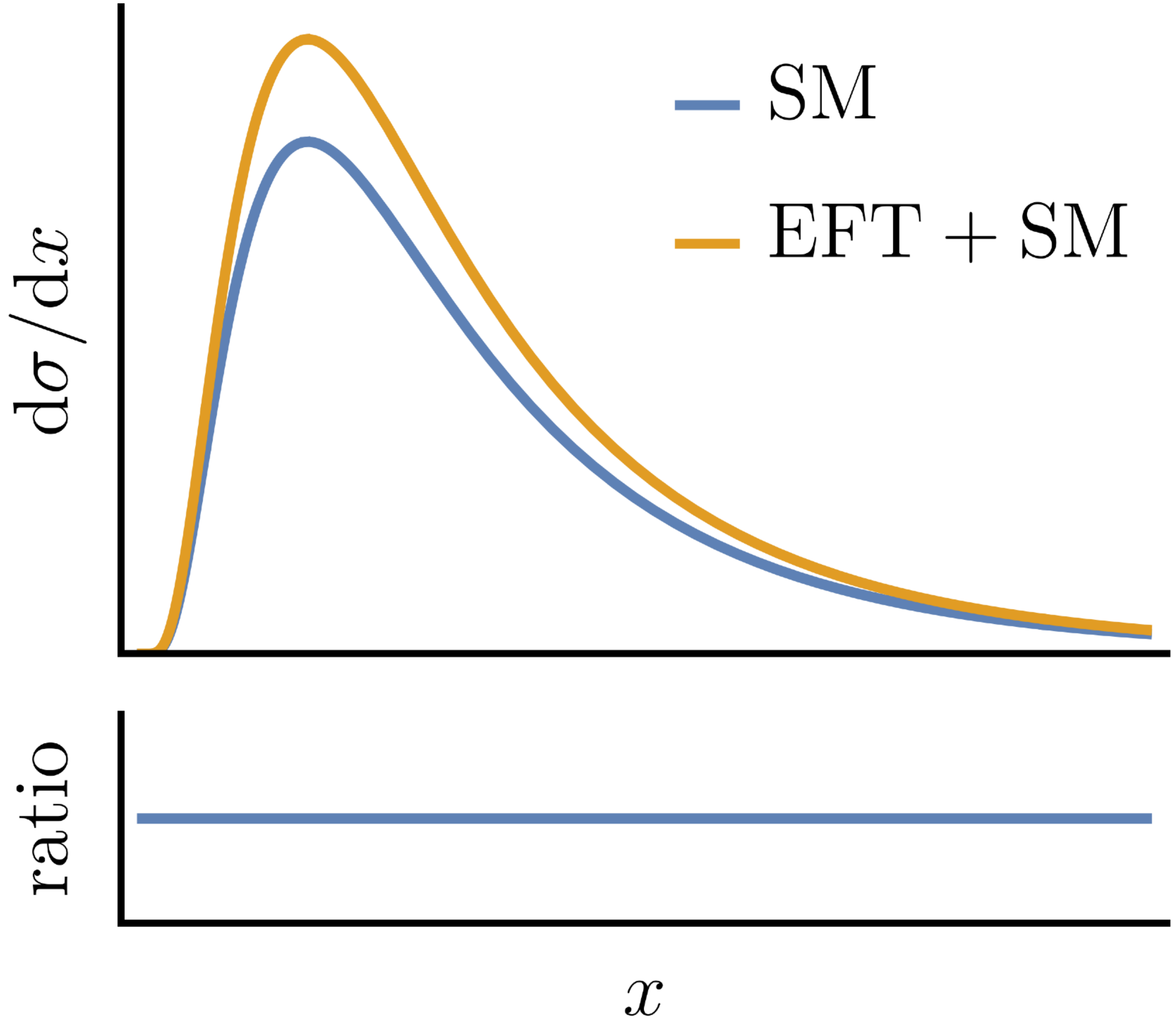
Structurally the same

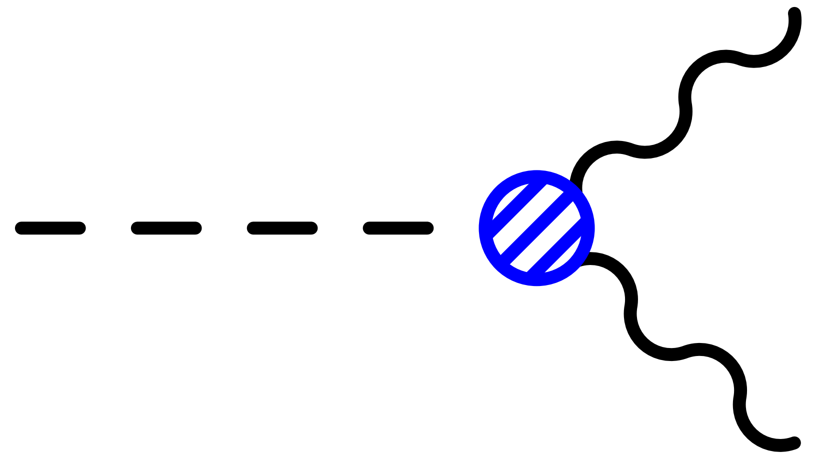
Affects total cross section only



The operator $\mathcal{O}_{HB}$

$$\mathcal{O}_{HB} = H^\dagger H \, B_{\mu\nu} B^{\mu\nu} \to c^{\text{EFT}}_{HZZ} \, h \, Z_{\mu\nu} Z^{\mu\nu}$$

Feynman rules



SM: $g^{\text{SM}}_{ZZh} \, \eta^{\mu\nu}$

EFT: $g^{\text{EFT}}_{hZZ} \left[p^\mu_{Z_1} p^\nu_{Z_2} - \eta^{\mu\nu} \, p_{Z_1} \cdot p_{Z_2} \right]$

EFT contribution has additional momentum dependence

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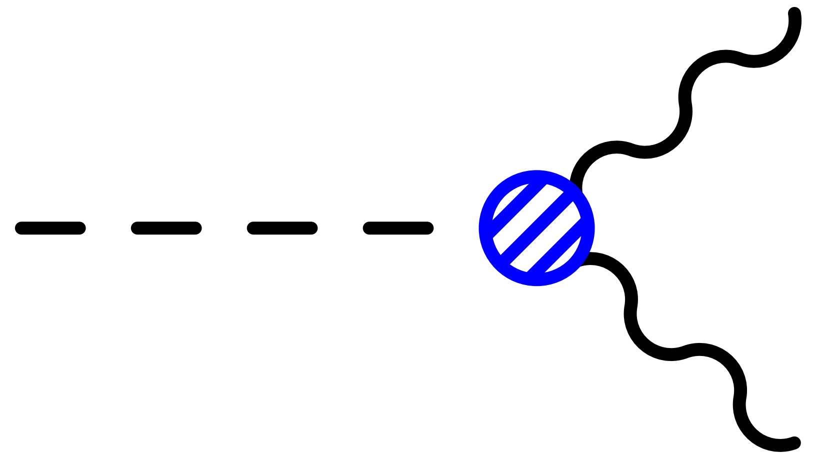

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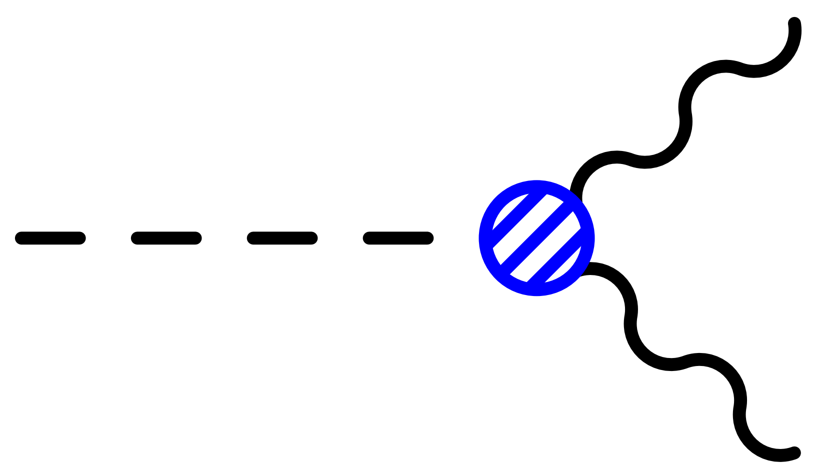

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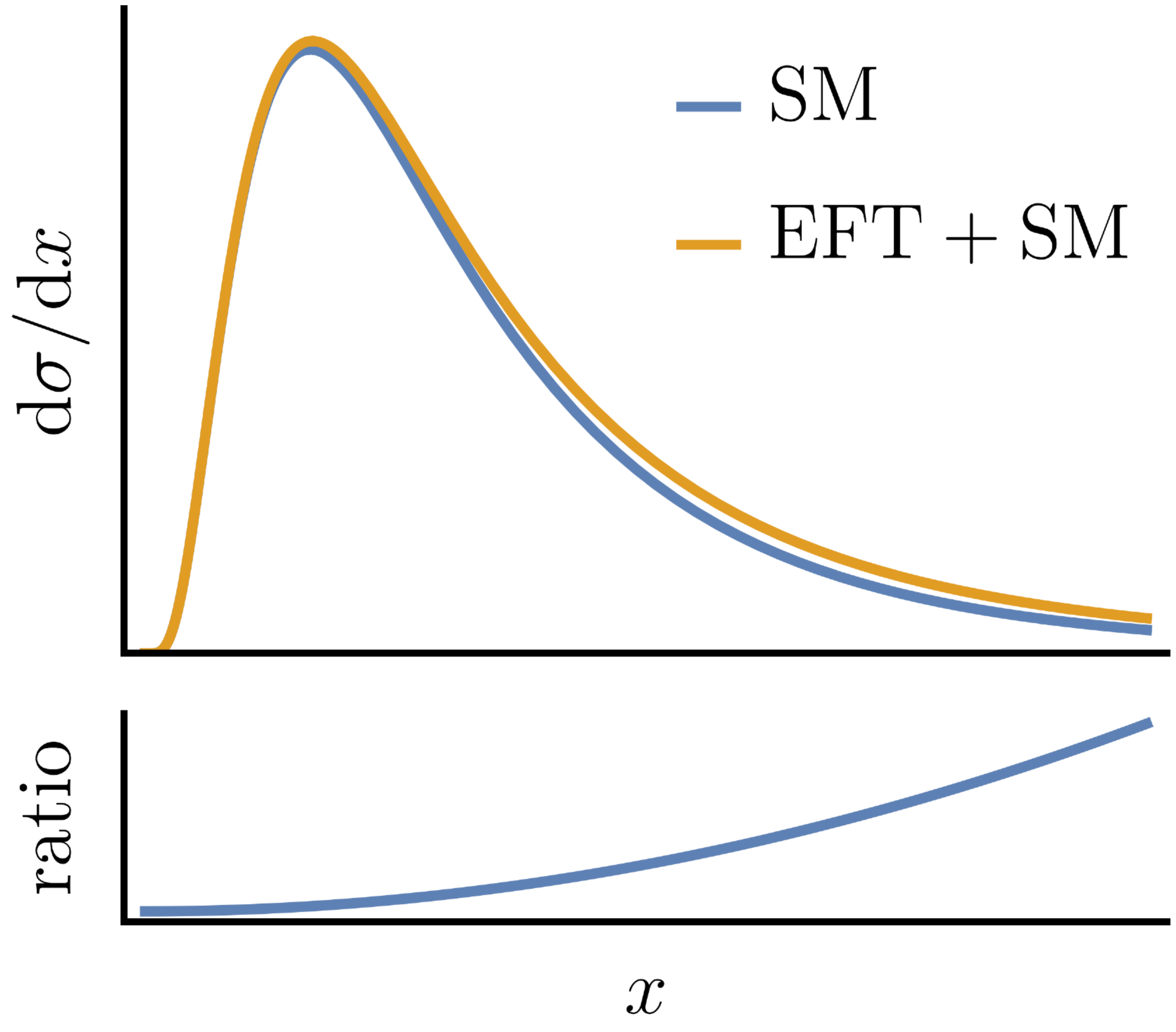
EFT contribution has additional momentum dependence

Affects distributions



e.g. m_{Zh} in HZ production

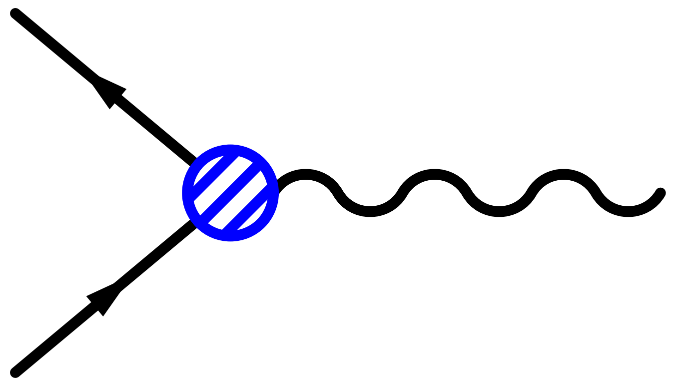
The operator $\mathcal{O}_{Hu}$

$$\mathcal{O}_{Hu} = (H^\dagger i\overleftrightarrow{D}_\mu H)\,(\bar{u}_R\gamma^\mu u_R) \to (h+v)\,Z_\mu(\bar{u}_R\gamma^\mu u_R)$$

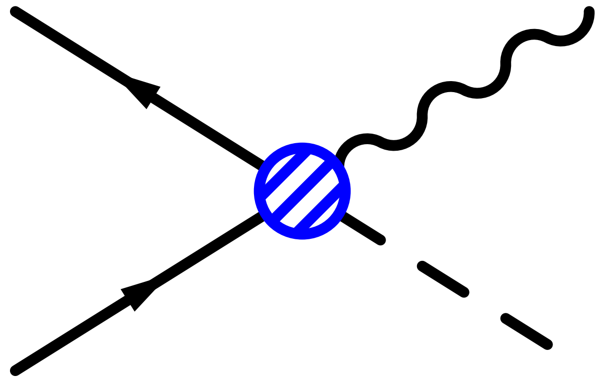
Feynman rules

SM Zuu : $g^{\text{SM}}_{Zuu}\,\gamma^\mu\,P_R$

EFT Zuu: $g^{\text{EFT}}_{Zuu}\,\gamma^\mu\,P_R$



EFT Zhuu: $g^{\text{EFT}}_{Zuu}/v\,\gamma^\mu\,P_R$



New contact interaction

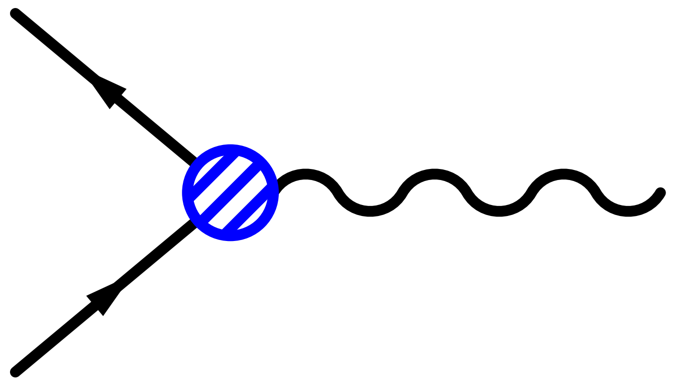
The operator $\mathcal{O}_{Hu}$

$$\mathcal{O}_{Hu} = (H^\dagger i \overleftrightarrow{D}_\mu H)\,(\bar{u}_R \gamma^\mu u_R) \to (h+v)\, Z_\mu (\bar{u}_R \gamma^\mu u_R)$$

Feynman rules

SM Zuu : $g^{\mathrm{SM}}_{Zuu}\, \gamma^\mu\, P_R$

EFT Zuu: $g^{\mathrm{EFT}}_{Zuu}\, \gamma^\mu\, P_R$



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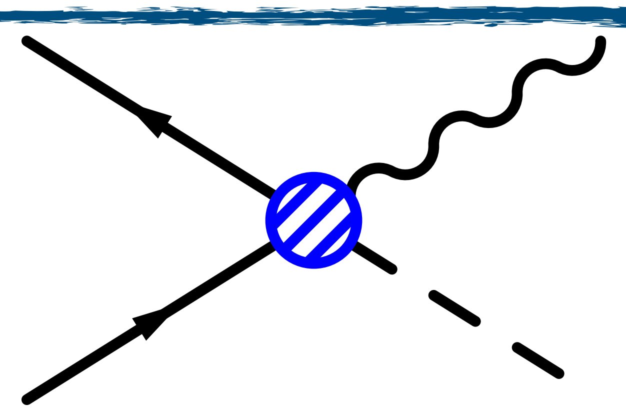
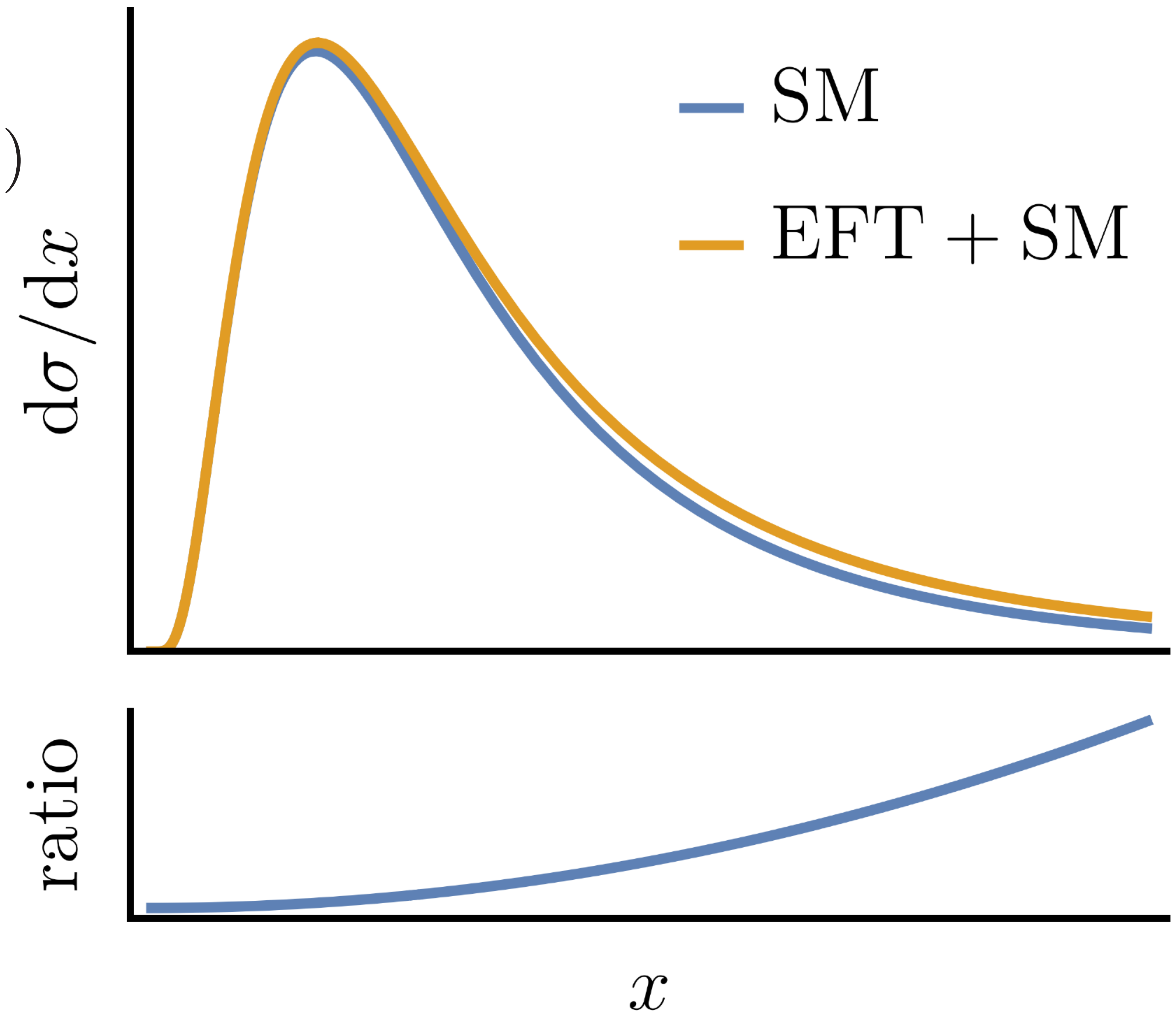
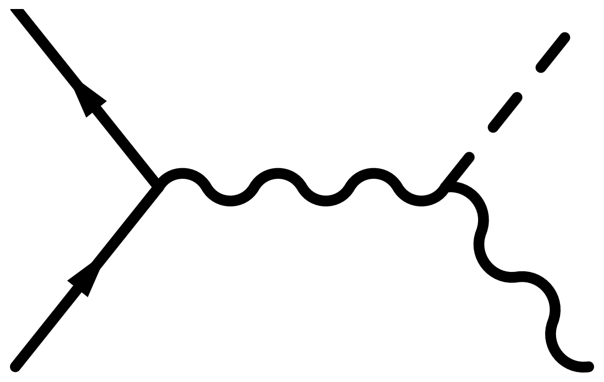


New contact interaction

Affects distributions



SM: propagator suppression



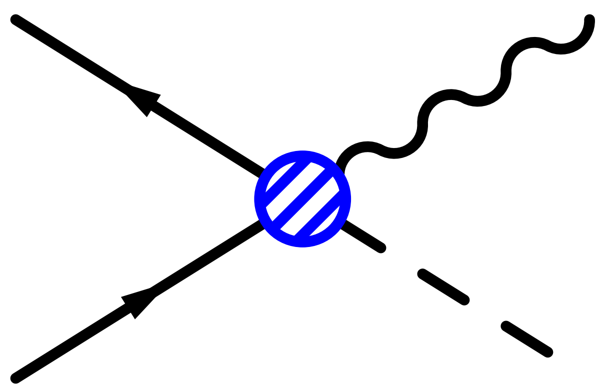
SMEFT effects

SMEFT universally describes the low-energy effects of new physics

- Modifications of SM-like structures
  (same Lorentz structure as in SM)

Changes of total cross sections

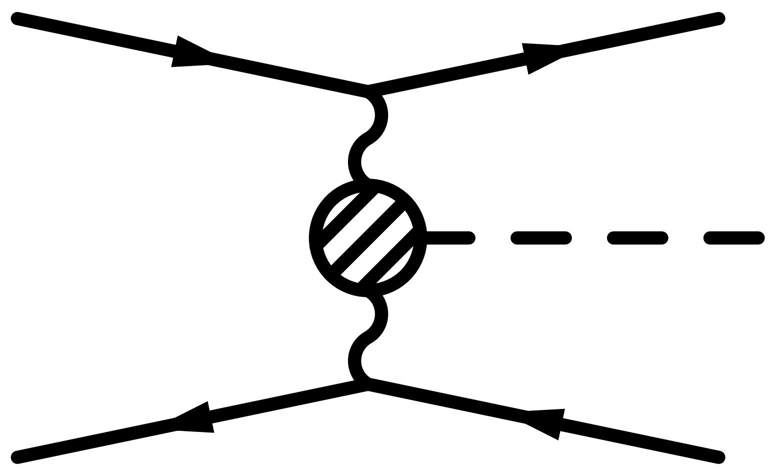
- New Lorentz structures in known interactions
- New contact interactions
  (not present in the SM)

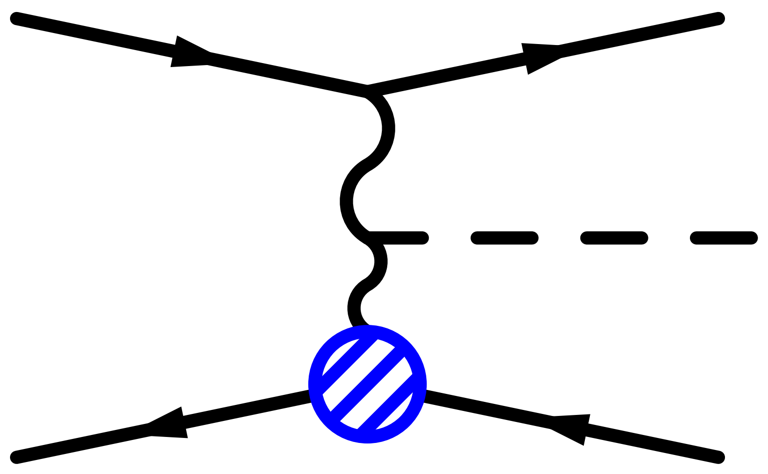


Changes of distributions

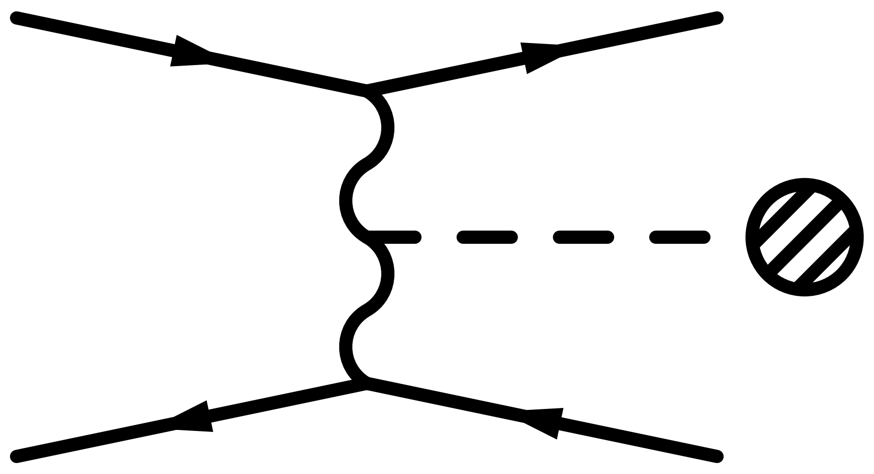
Why global fits?

One observable can be influenced by many operators





Higgs decay



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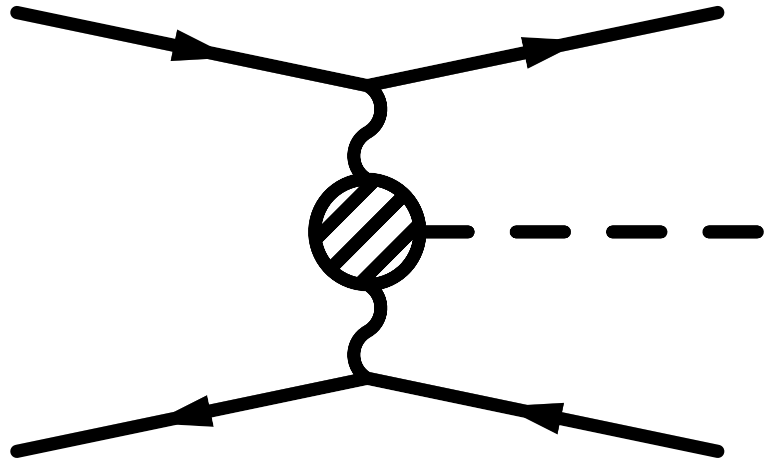
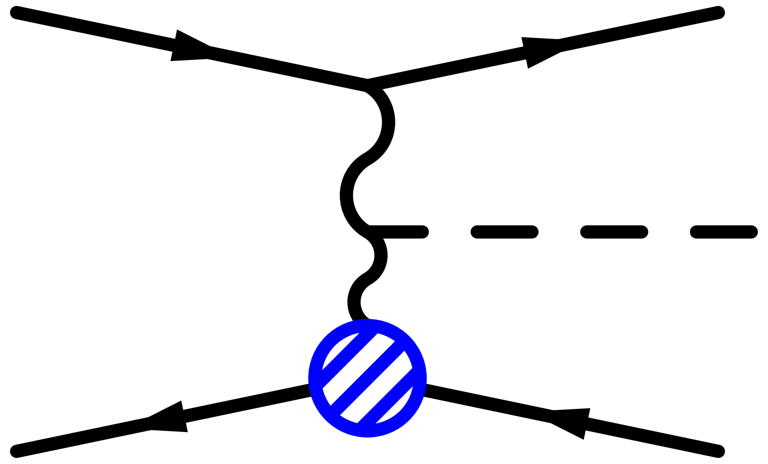
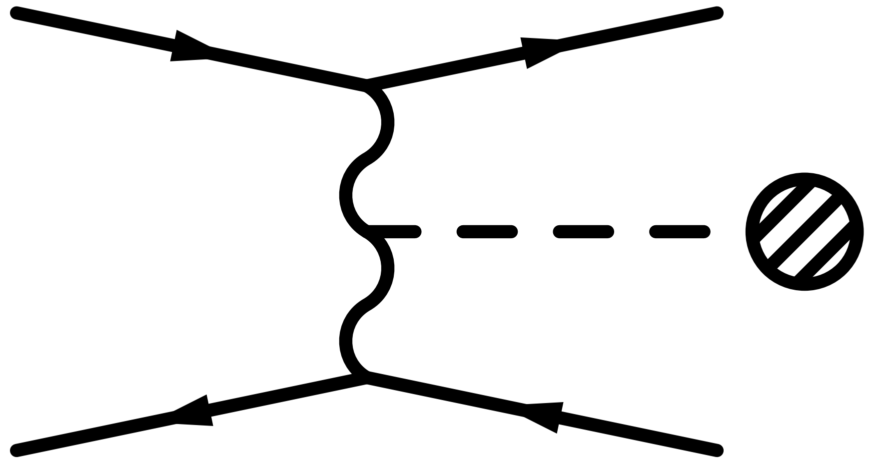
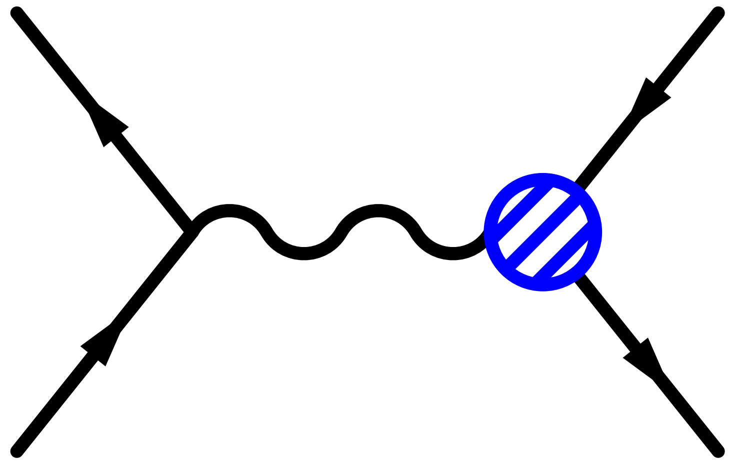




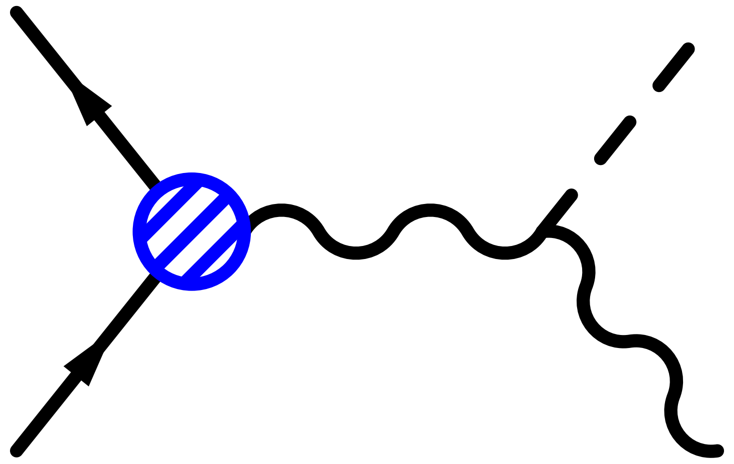
Higgs decay



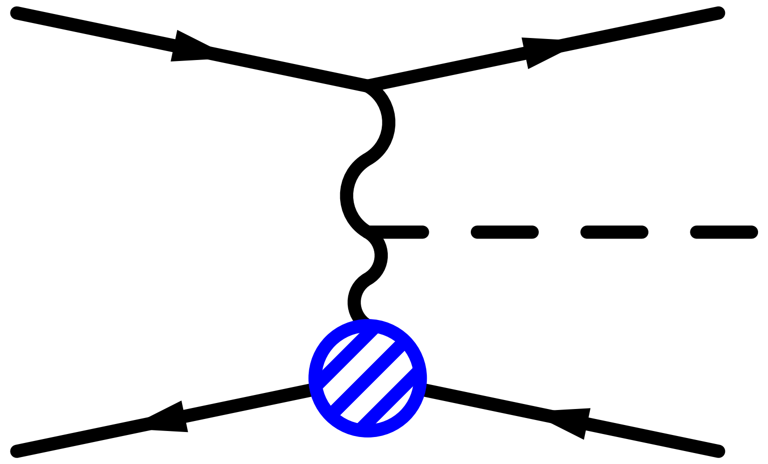
One operator can contribute to many different observables



$e^+e^- \to f\bar{f}$



Zh production

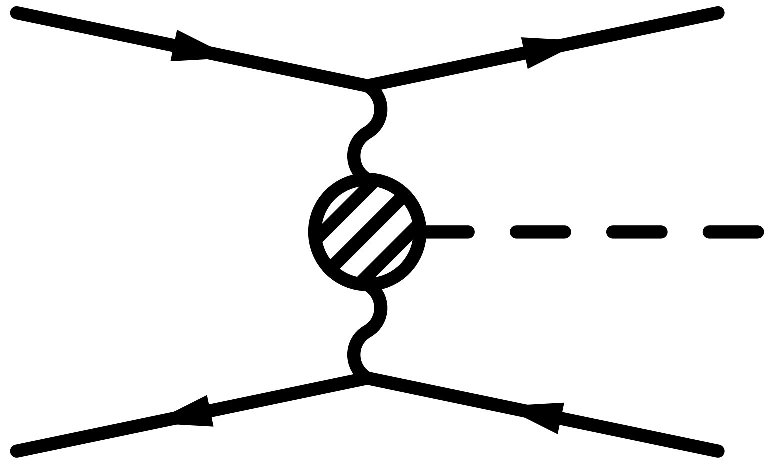


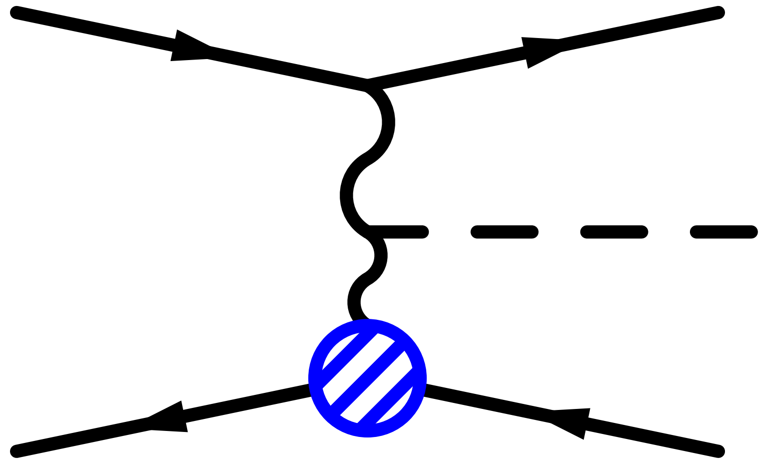
Weak boson fusion
Higgs production

Why global fits?

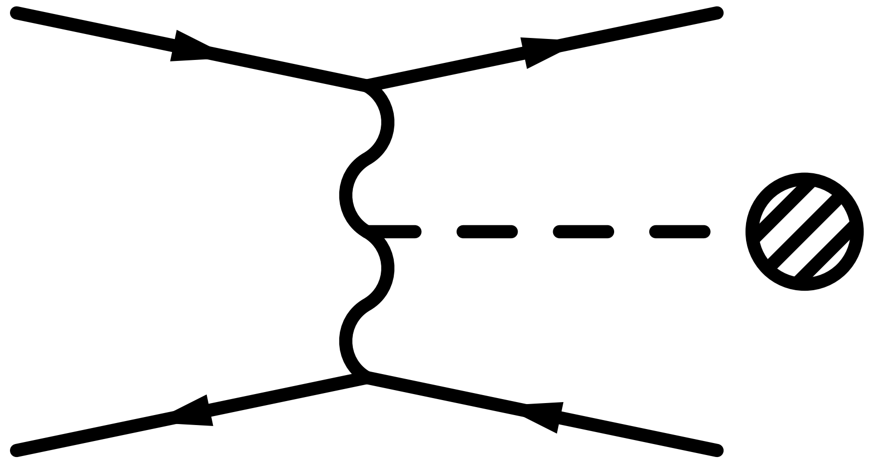
Need a global analysis of all EFT coefficients to map all direction of new fundamental physics

One observable can be influenced by many operators

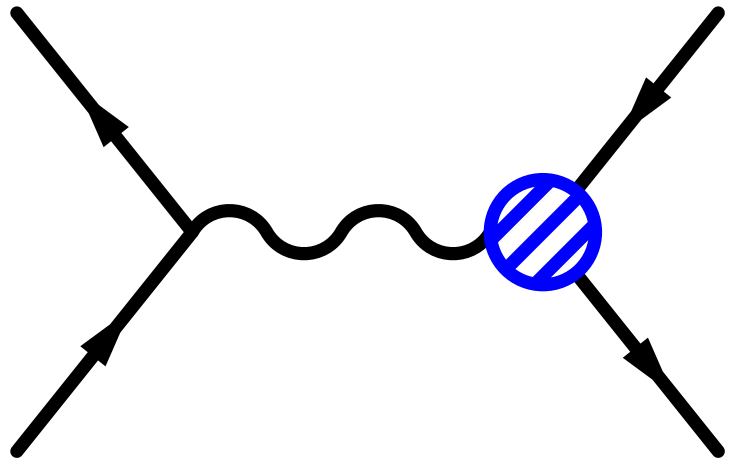




Higgs decay



One operator can contribute to many different observables



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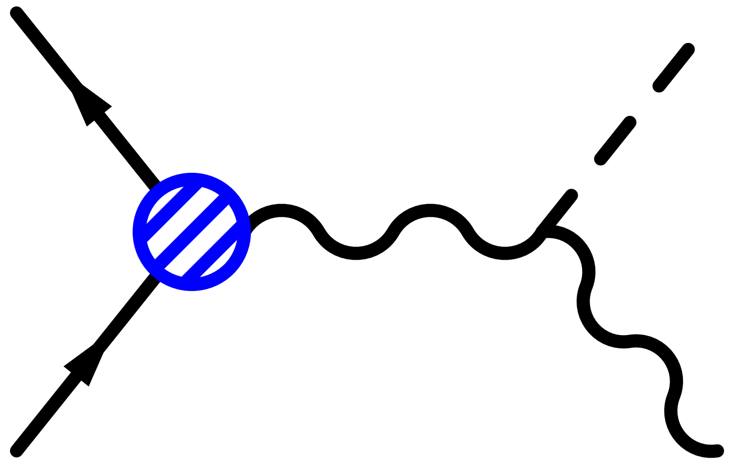
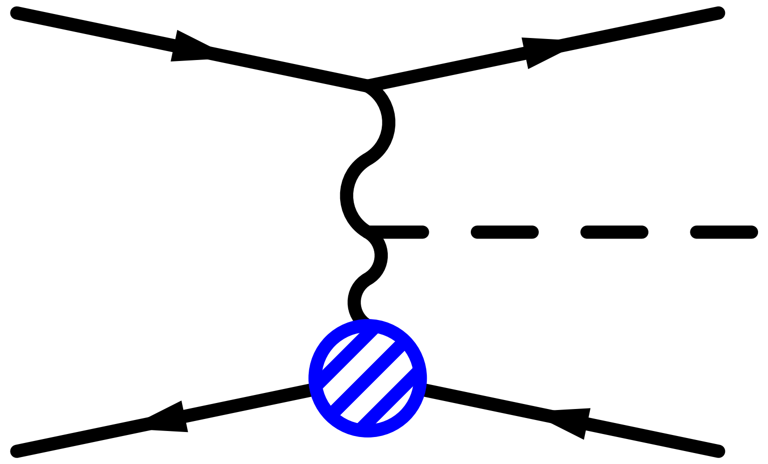
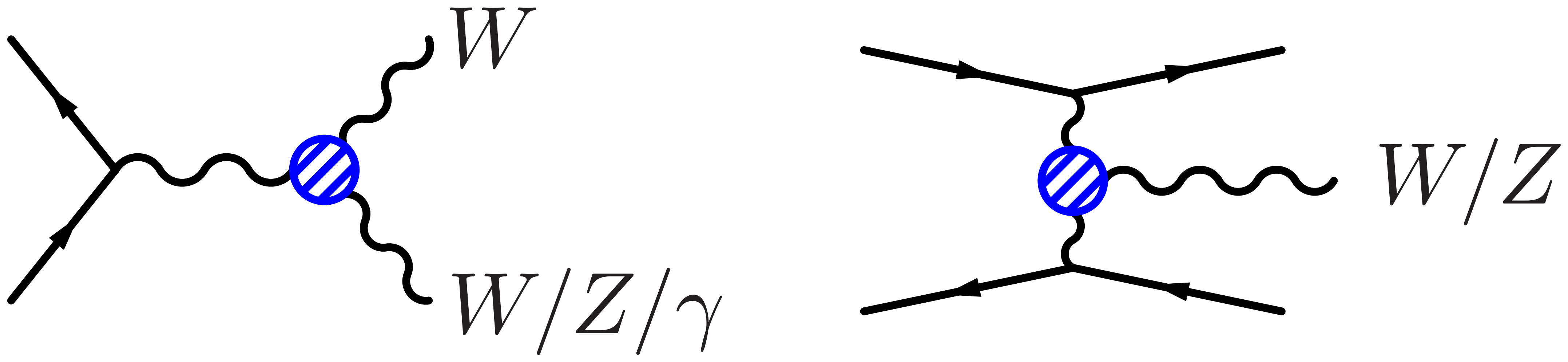


Zh production



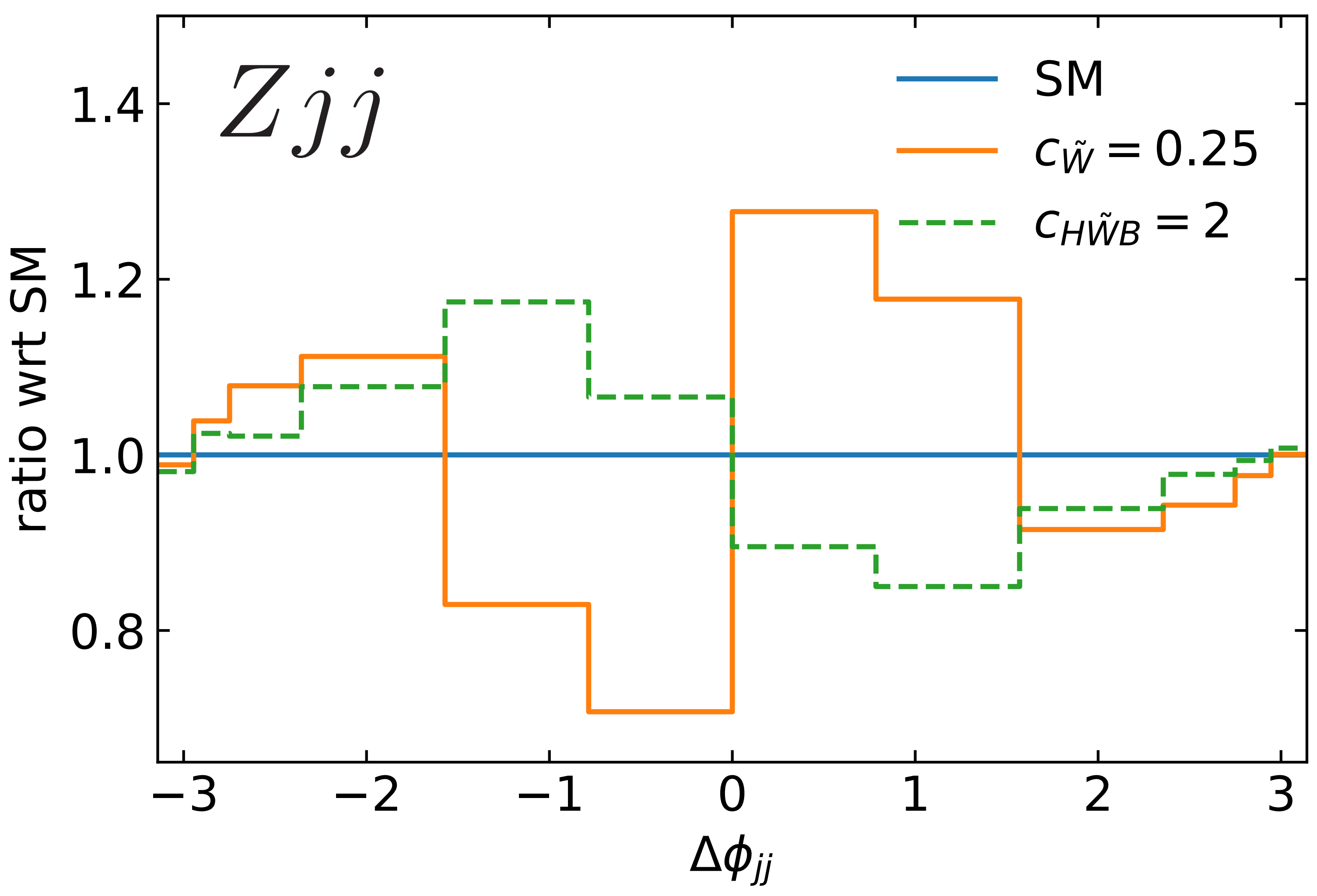
Weak boson fusion
Higgs production

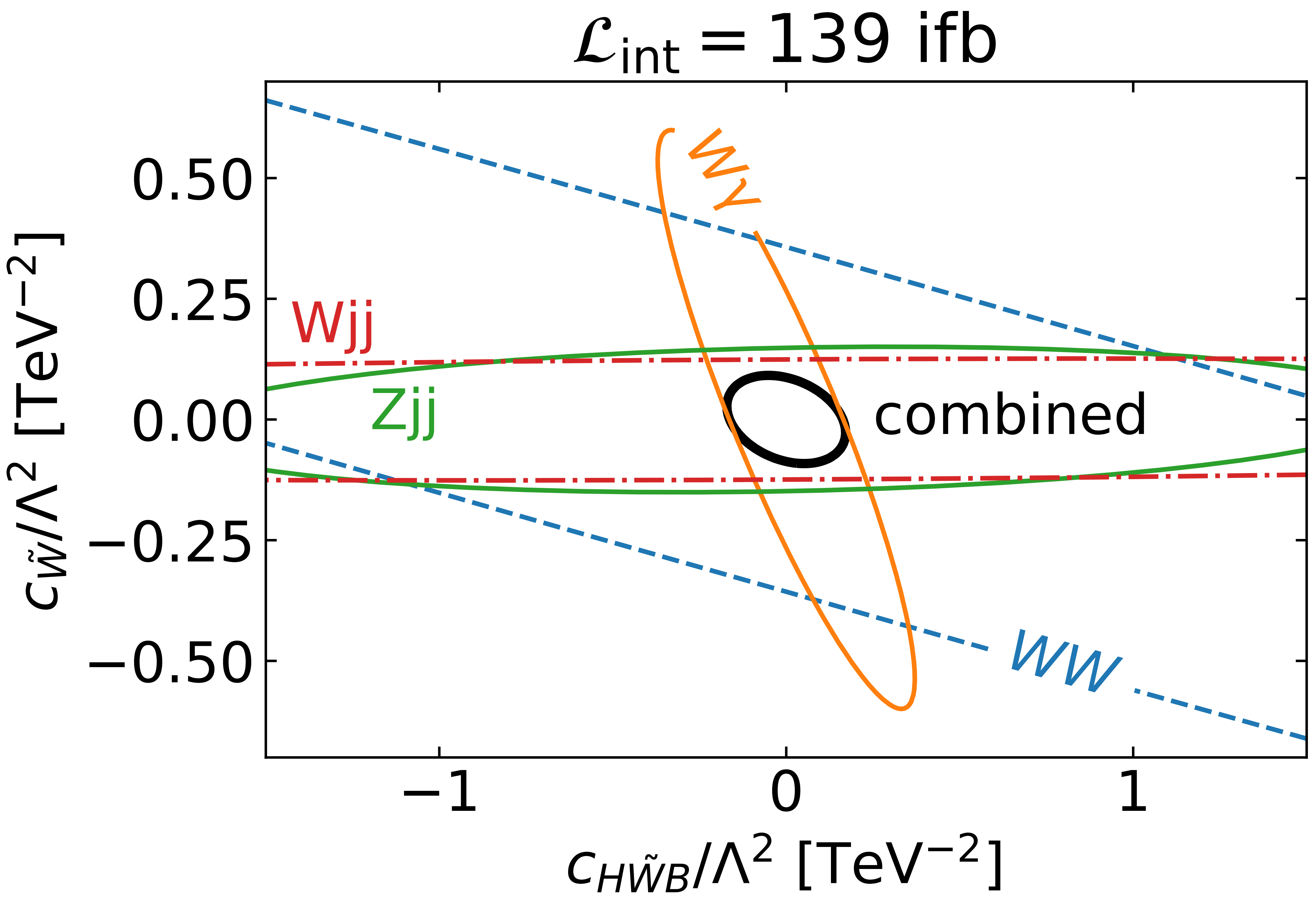
CP-odd Triple gauge couplings - the role of the data



$$\mathcal{O}_{\tilde{W}} = \epsilon^{IJK}\, \tilde{W}_{\mu}^{I\nu}\, W_{\nu}^{J\rho}\, W_{\rho}^{K\mu}$$

$$\mathcal{O}_{H\tilde{W}B} = H^{\dagger}\tau^{I} H\, \tilde{W}_{\mu\nu}^{I}\, B^{\mu\nu}$$





[AB, Gregg, Krauss, Schönherr (2102.01115)]

The role of the operator set

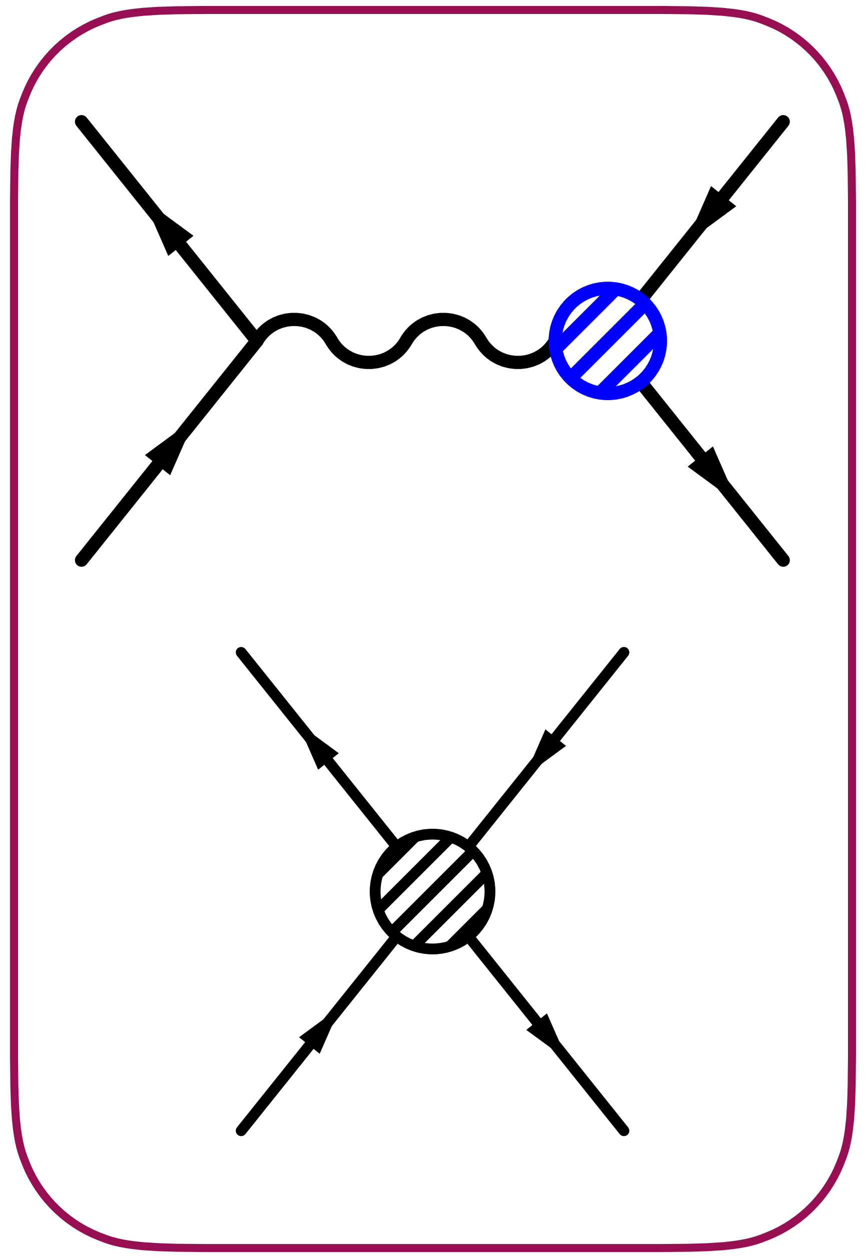
EWPO: Electroweak precision observables (LEP)

EWPO

$\mathcal{C}_{HWB}$ $\mathcal{C}_{HD}$ $\mathcal{C}_{ll}$

$\mathcal{C}_{He}$ $\mathcal{C}_{Hl}^{(1)}$ $\mathcal{C}_{Hl}^{(3)}$

$\mathcal{C}_{Hq}^{(1)}$ $\mathcal{C}_{Hq}^{(3)}$ $\mathcal{C}_{Hu}$ $\mathcal{C}_{Hd}$



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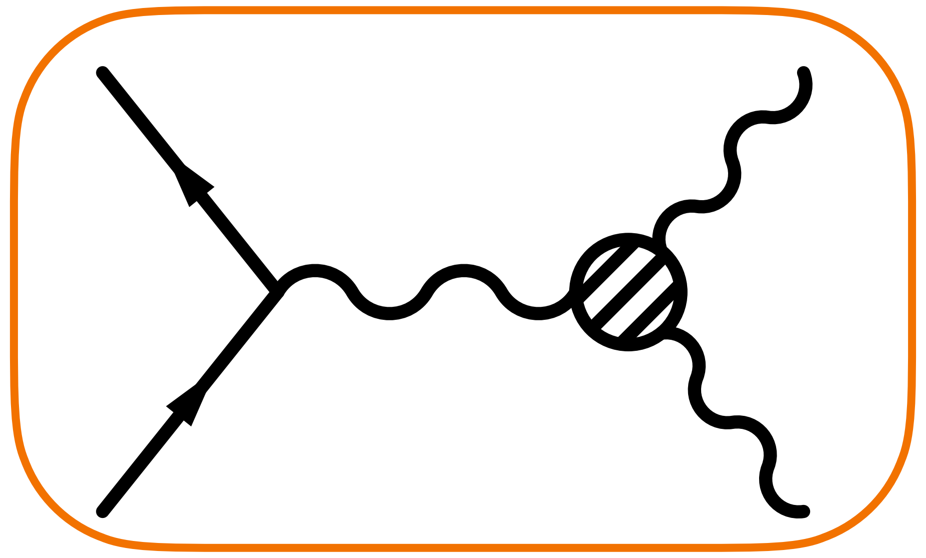

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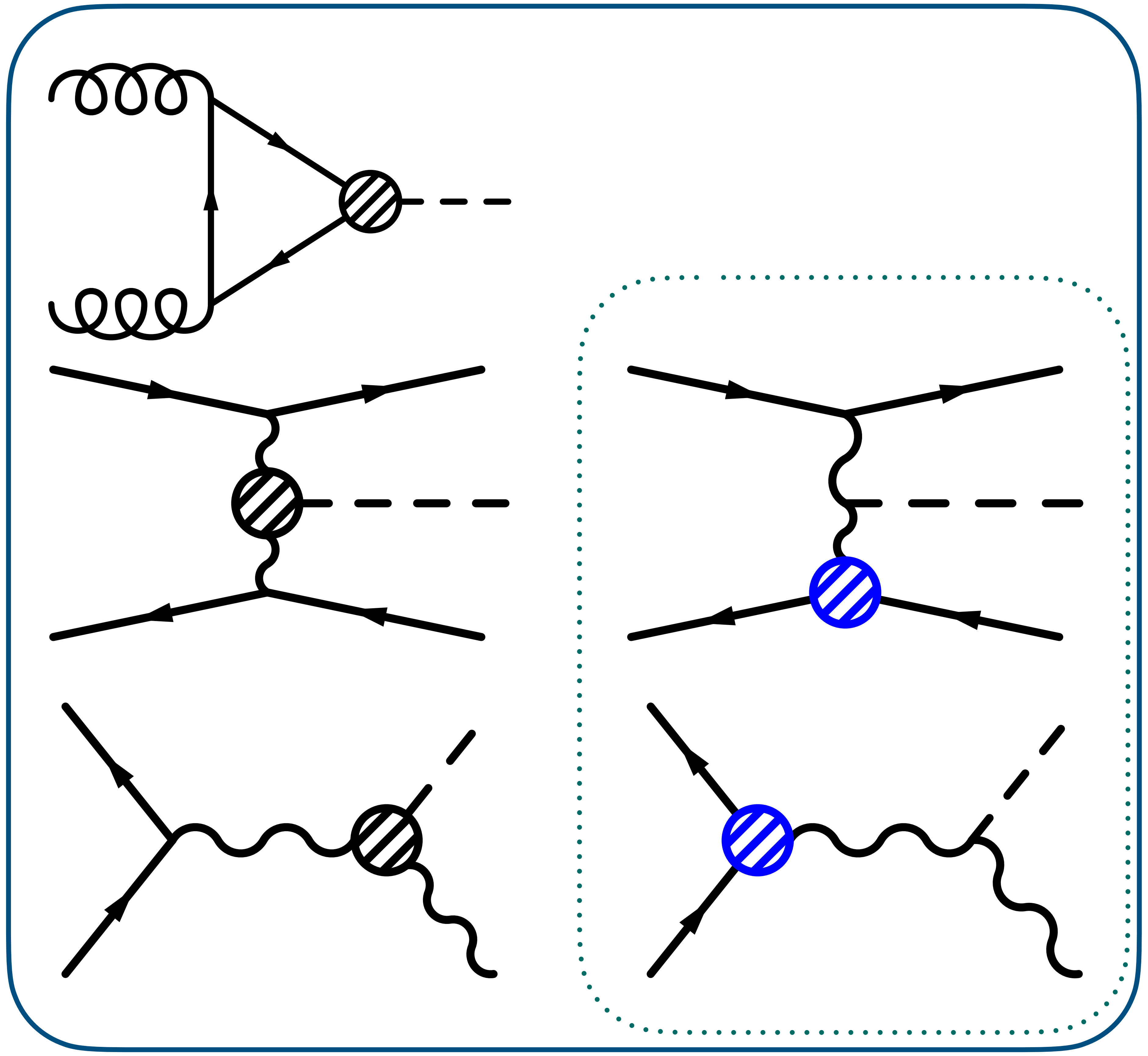

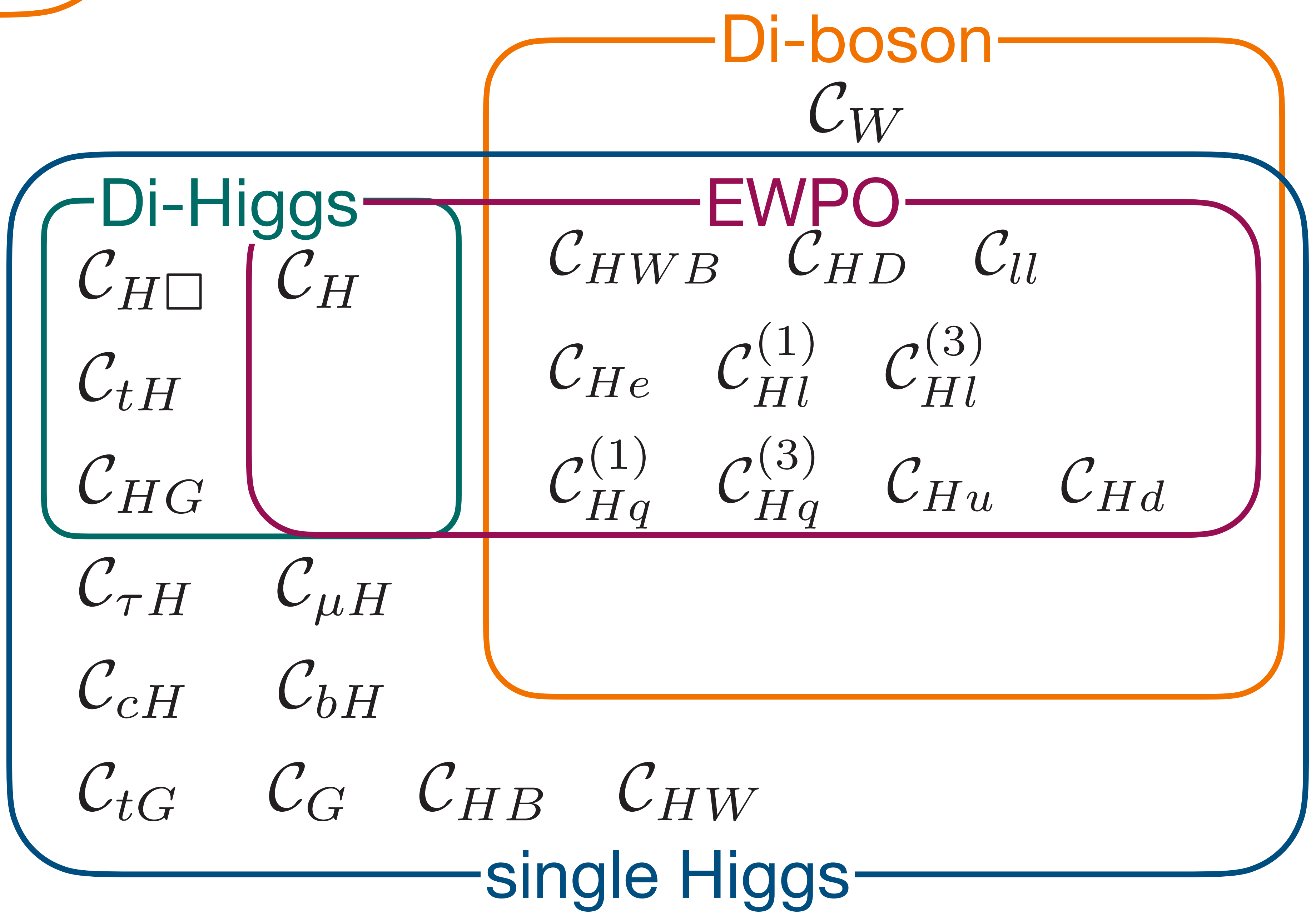

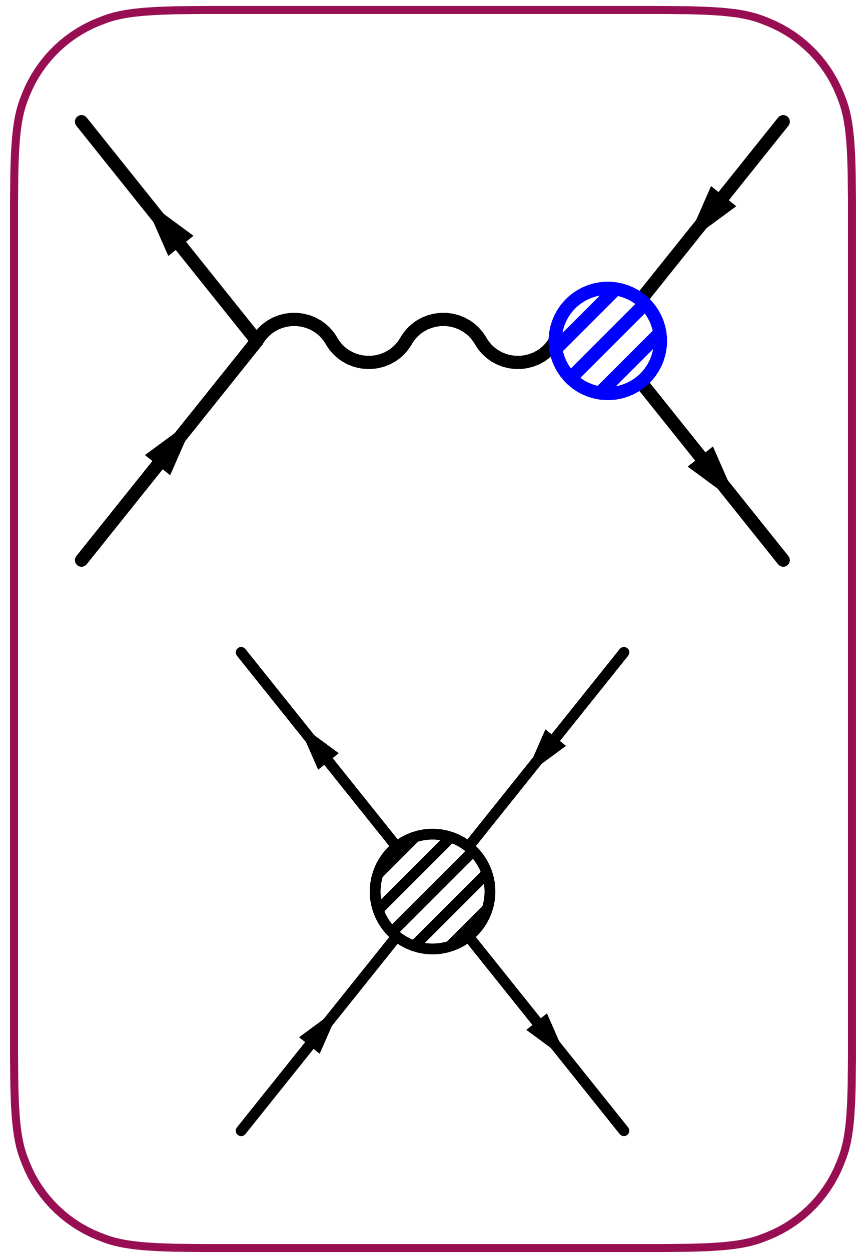

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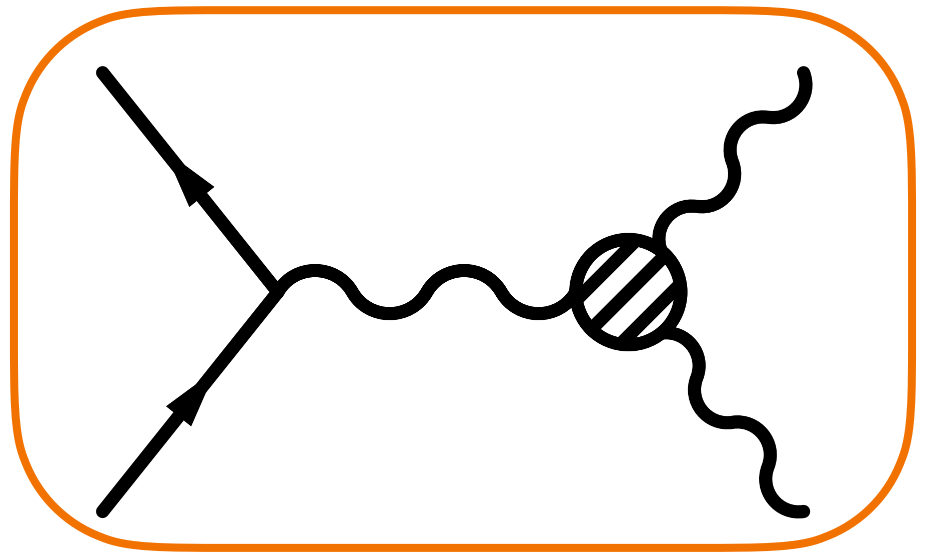

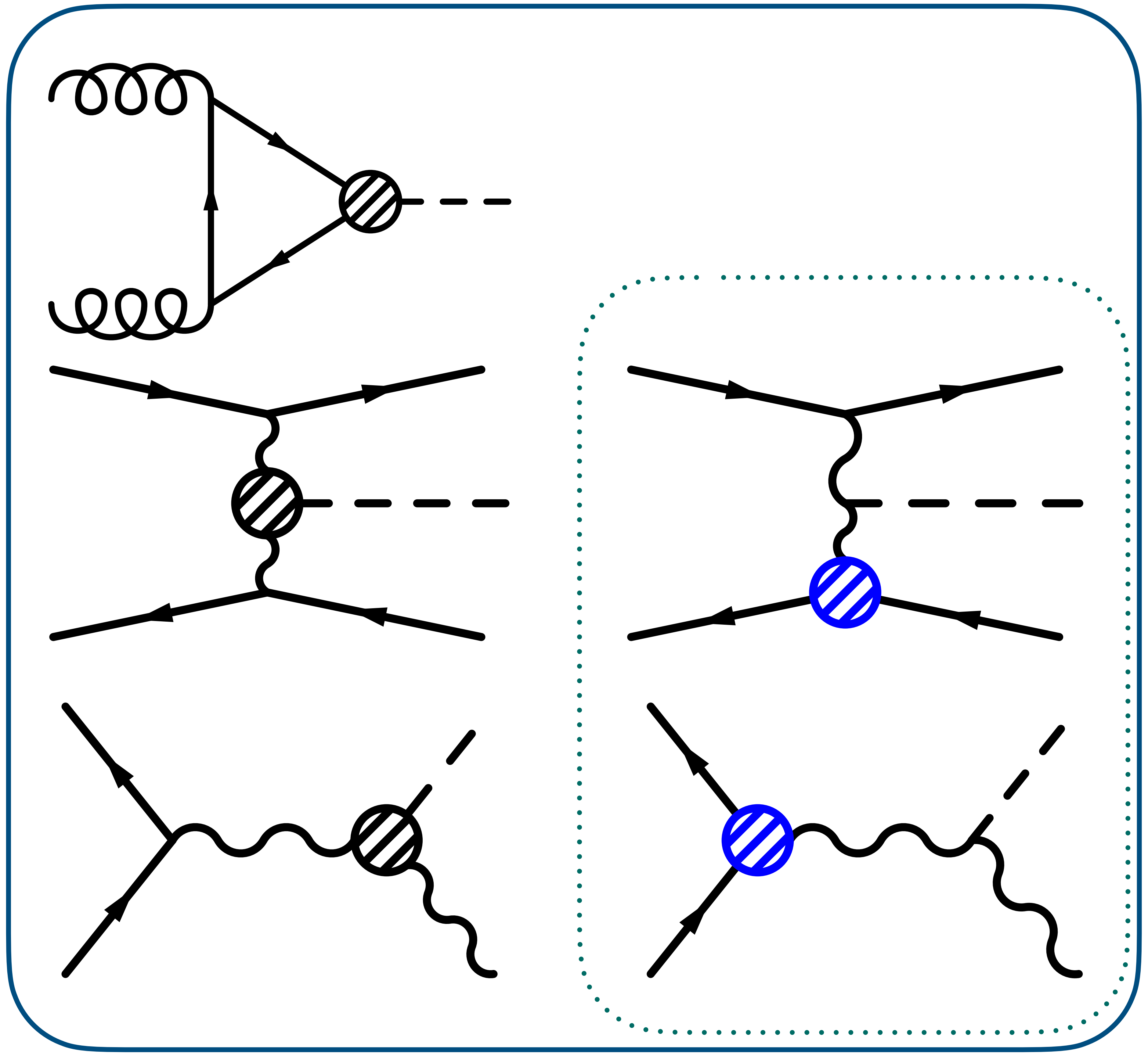

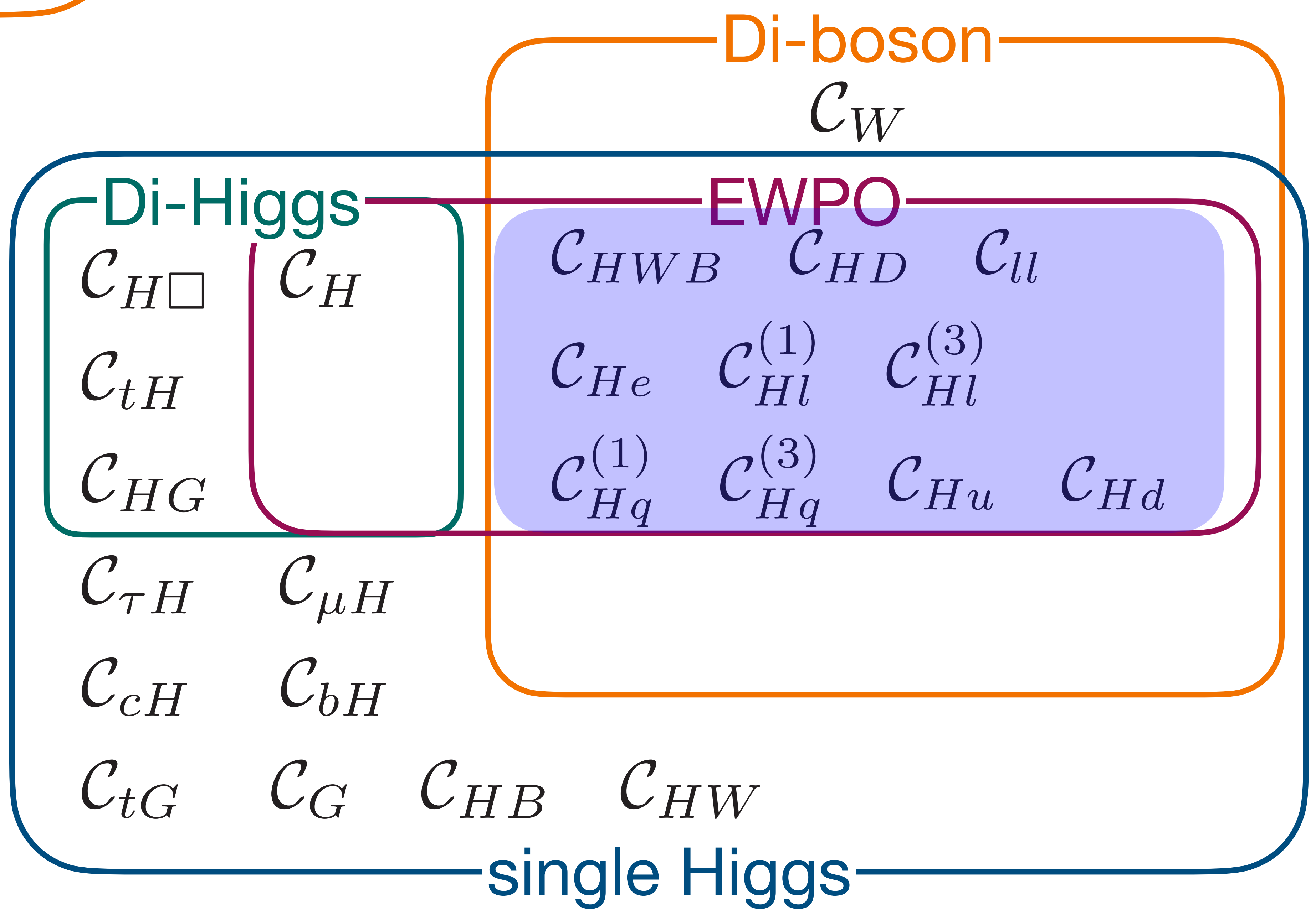

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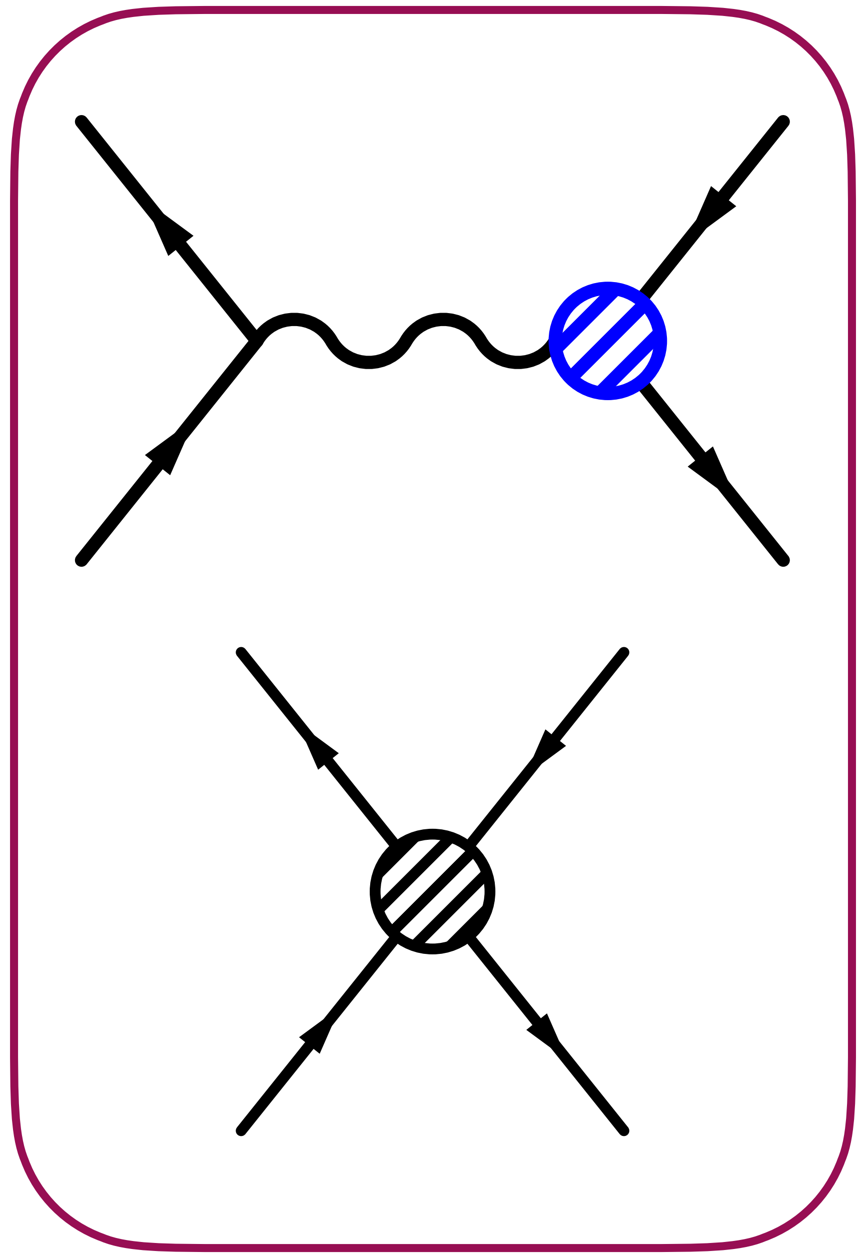


How much do fermion-gauge couplings influence a Higgs fit?

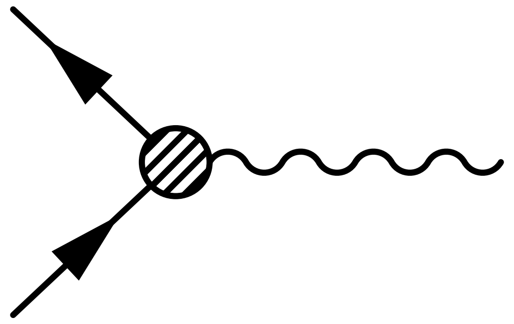
LHC 2018 fit - increasing the operator set

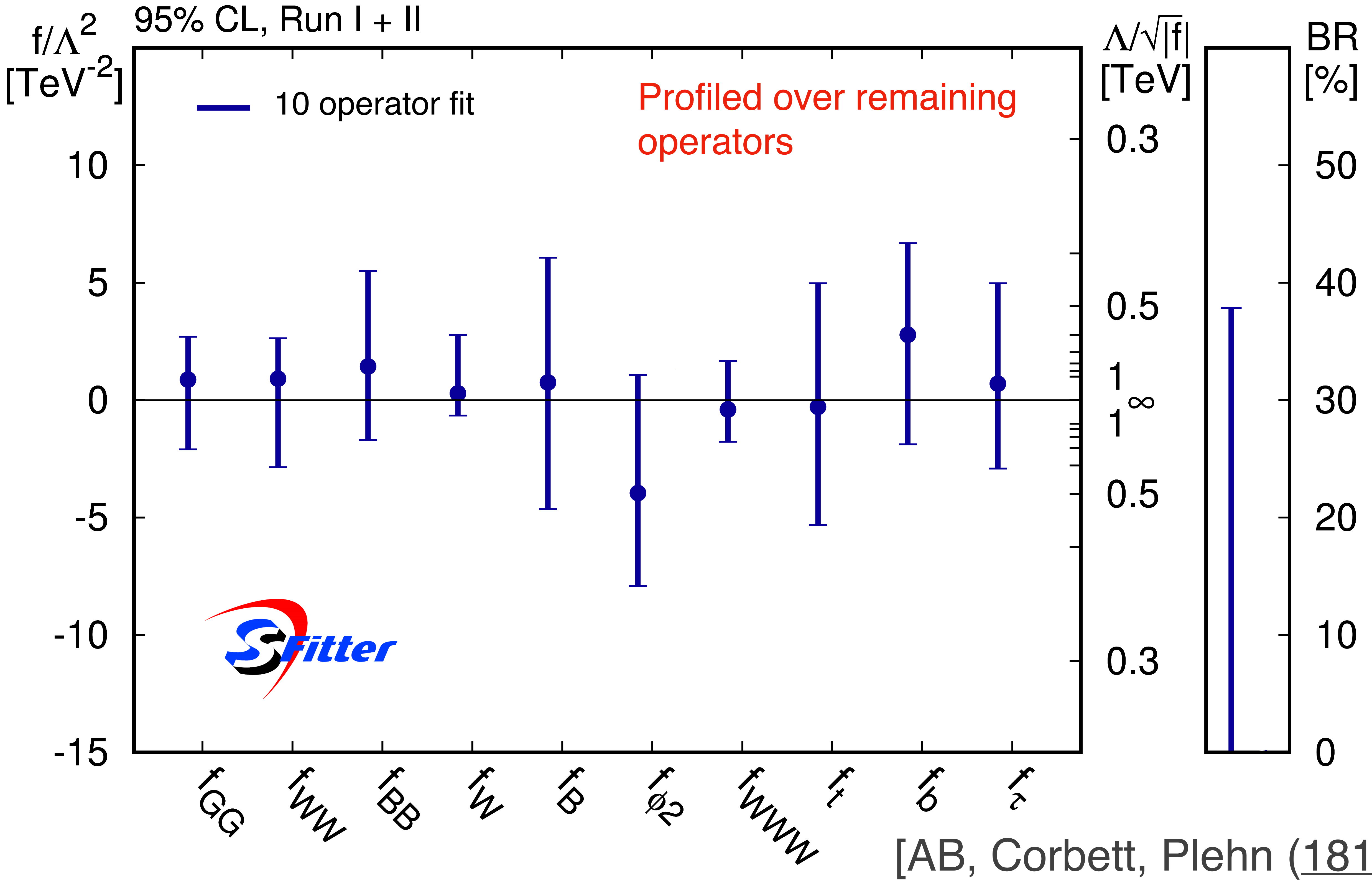
[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis] (operator definitions in backup)

10 operators (solid): Higgs only

18 operators (dashed): Higgs + EWPO operator set

Fermion-gauge couplings





[AB, Corbett, Plehn (1812.07587)]

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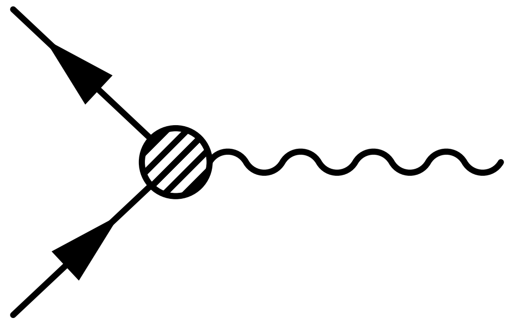
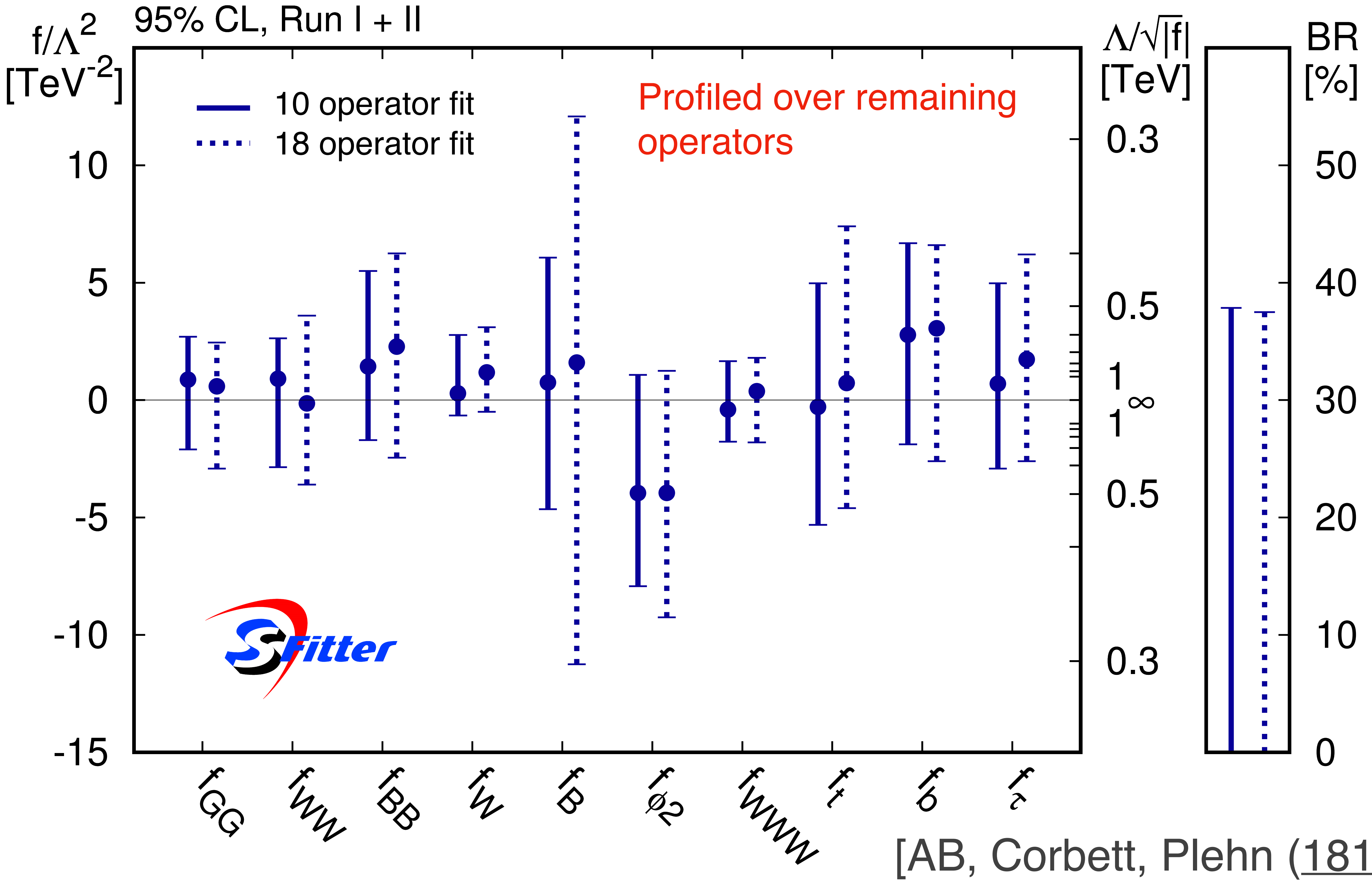




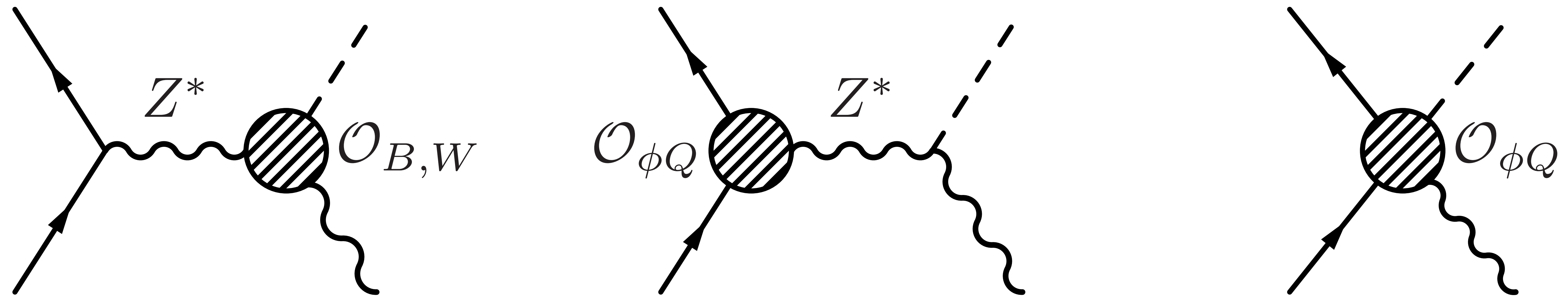
[AB, Corbett, Plehn (1812.07587)]

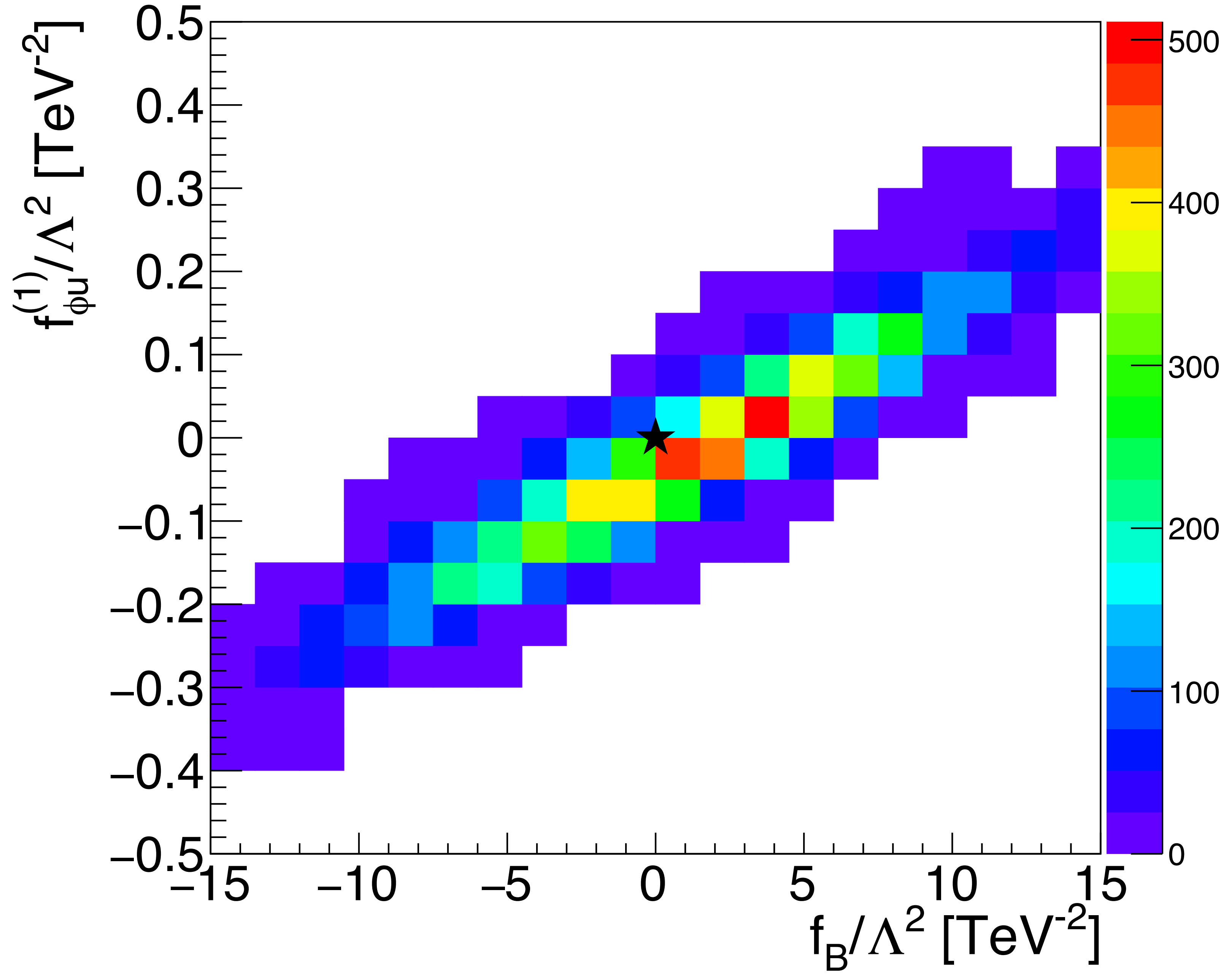
LHC 2018 fit - correlations

[Banerjee et al (1807.01796)]

[AB, Corbett, Plehn (1812.07587)]

Contributions to Zh production





$$\mathcal{O}_B = (D_\mu\phi)^\dagger \hat{B}^{\mu\nu}(D_\nu\phi)$$

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$$\mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger(i\overleftrightarrow{D}_\mu\phi)(\bar{Q}\gamma^\mu Q)$$

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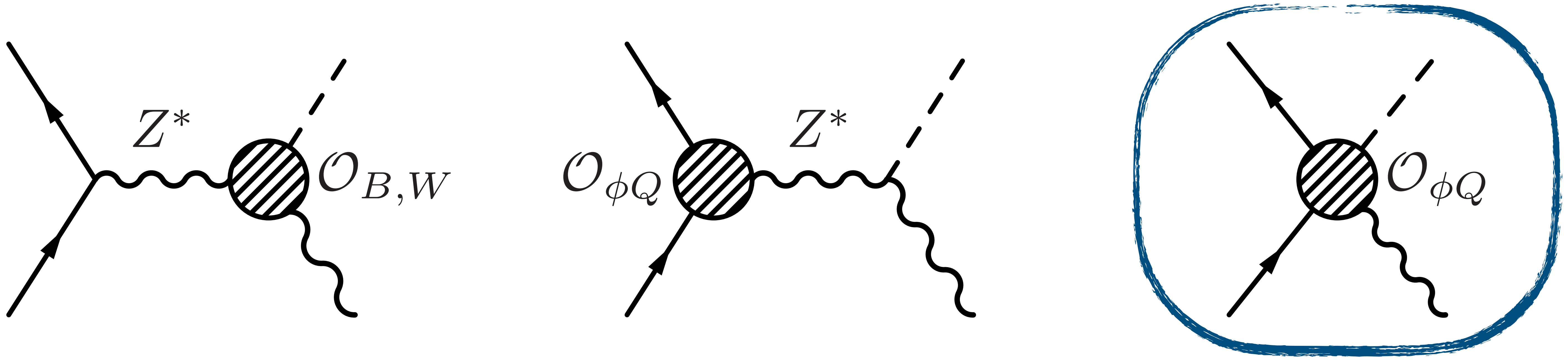
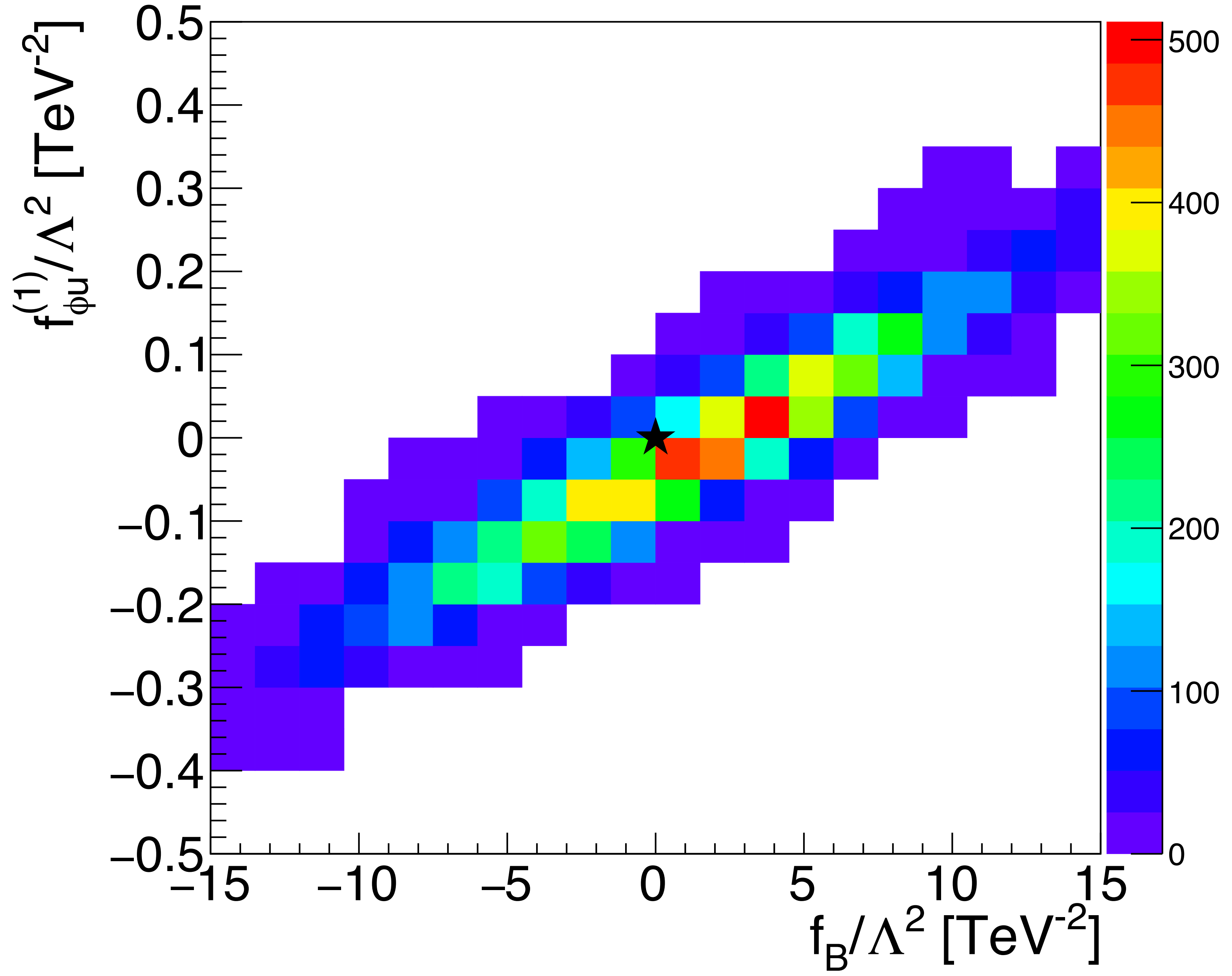


No propagator suppression



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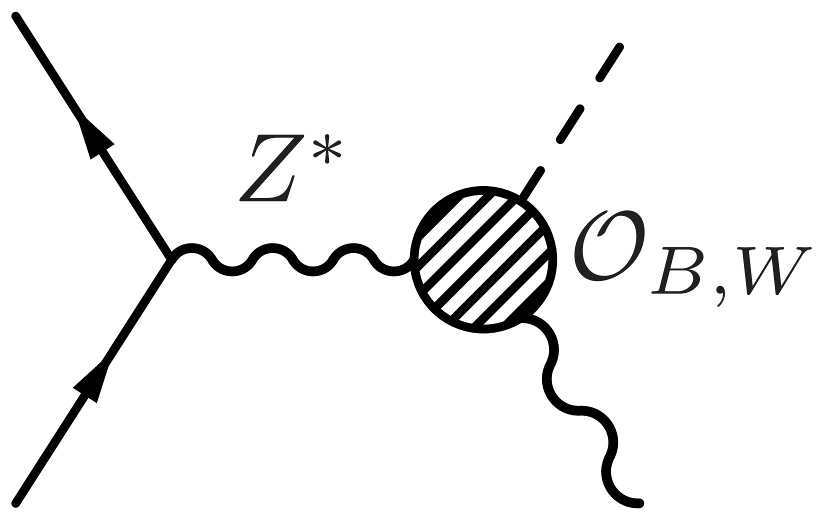

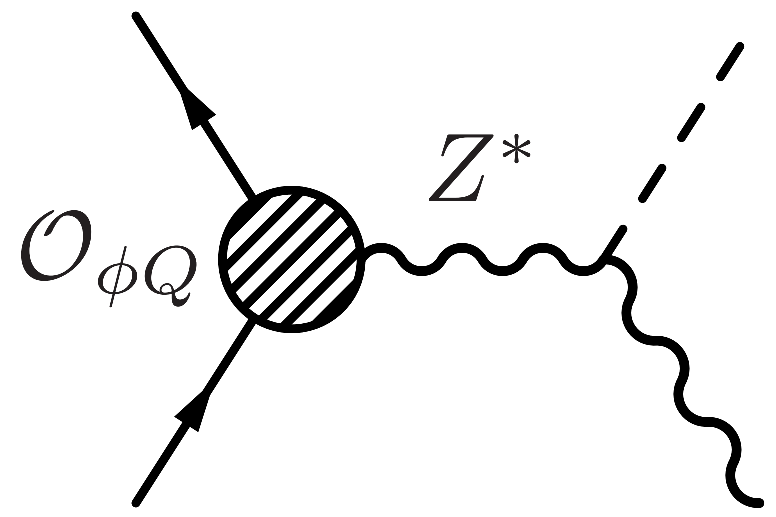

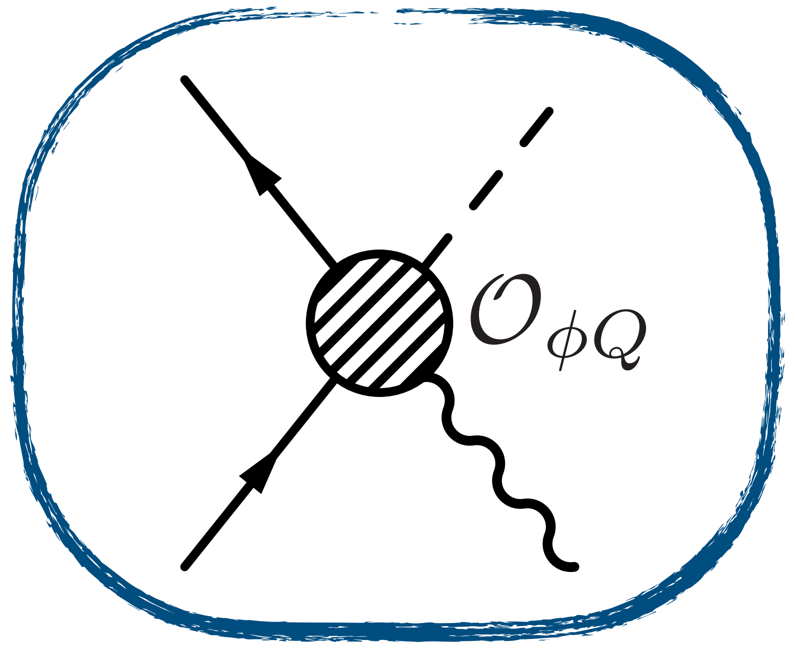

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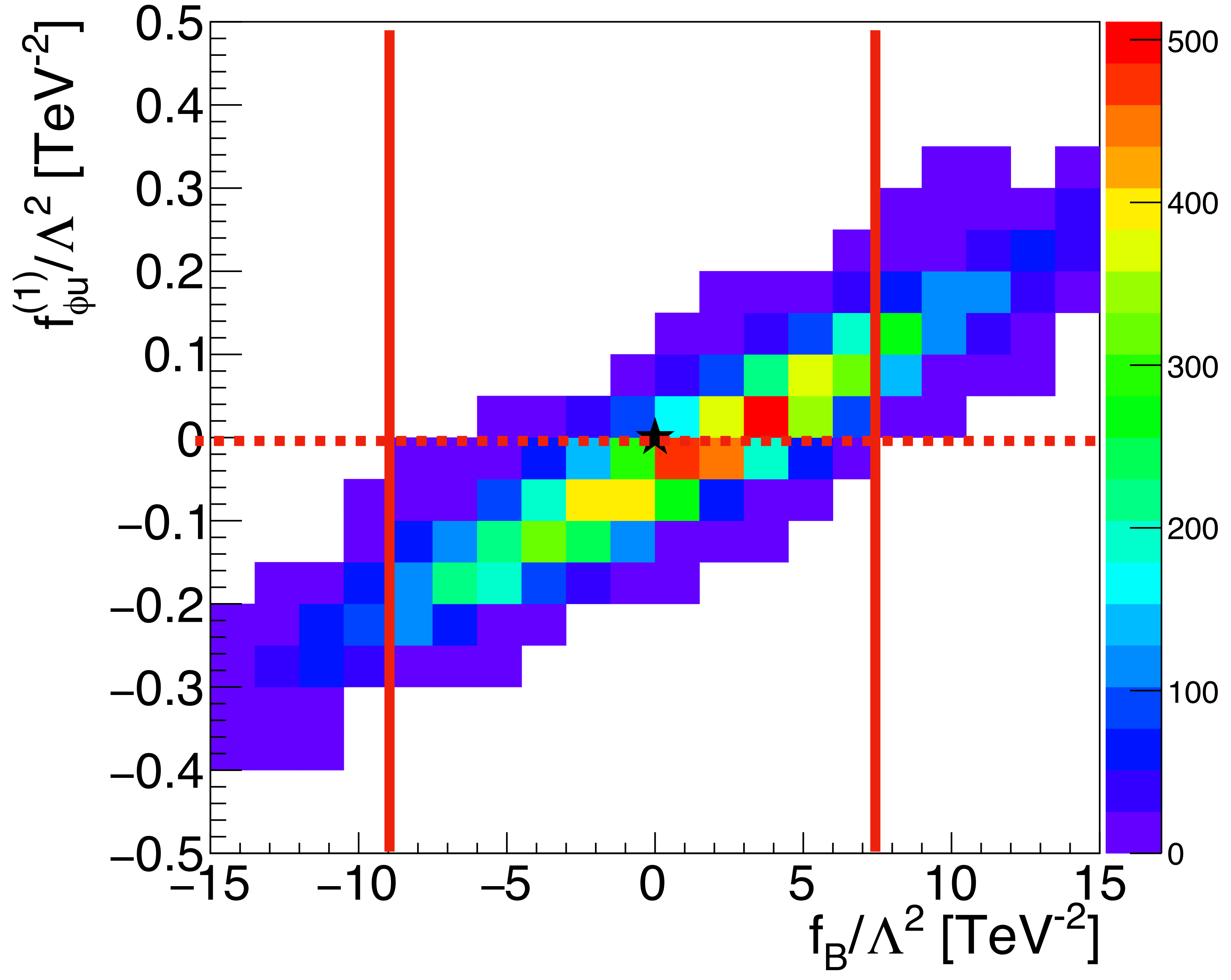

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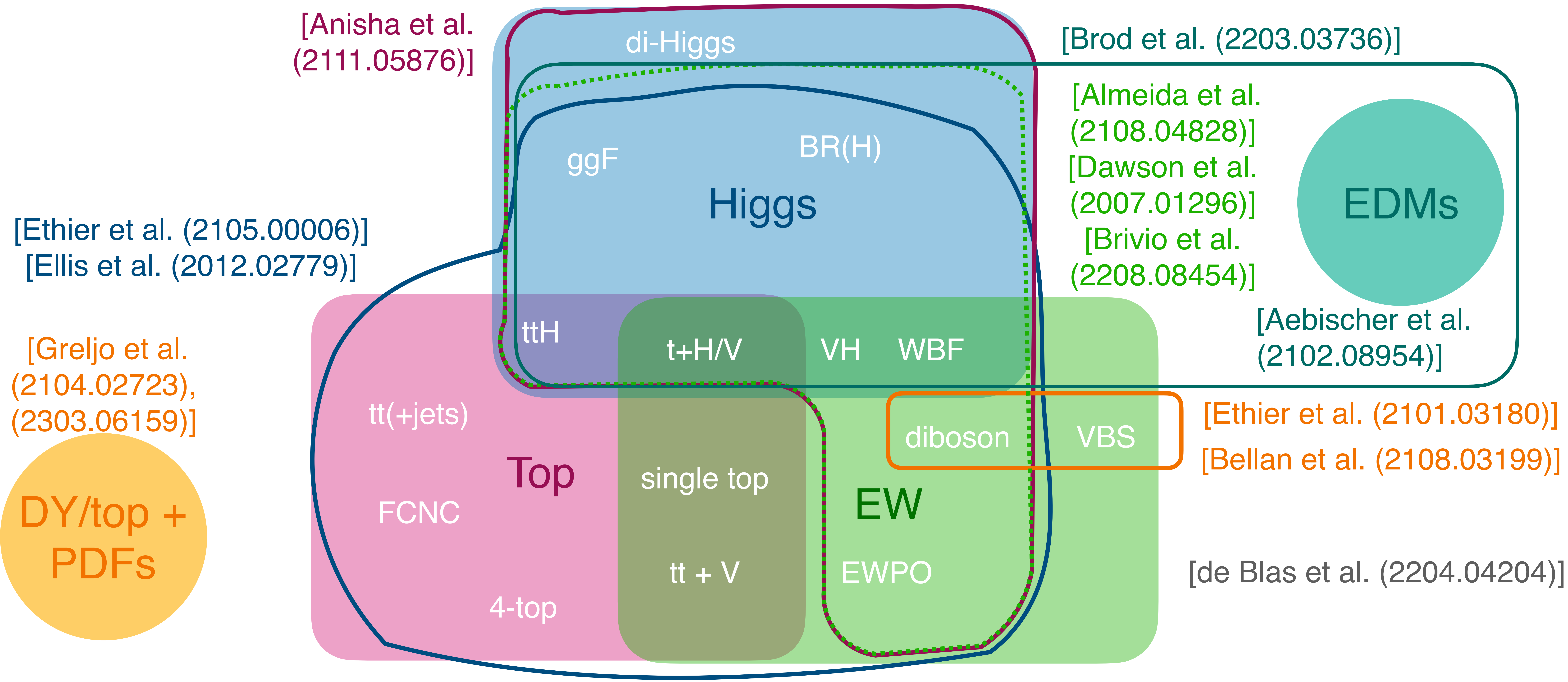
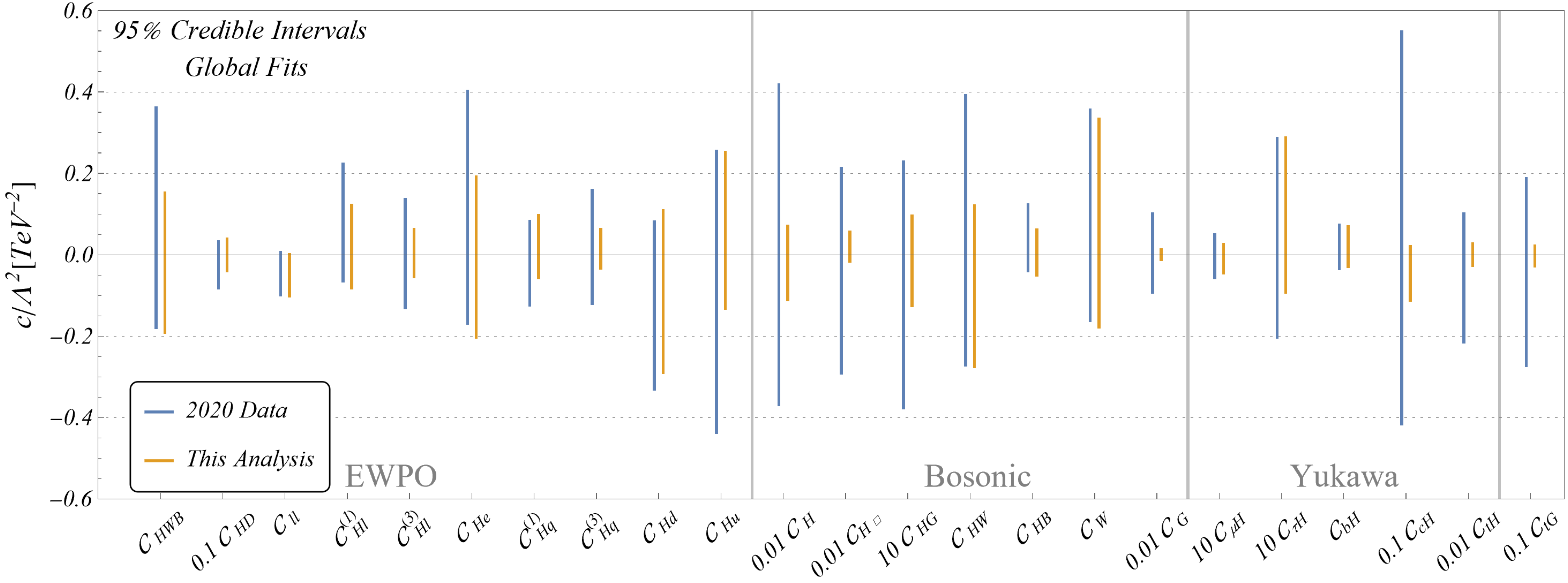
Confronting the SMEFT with data



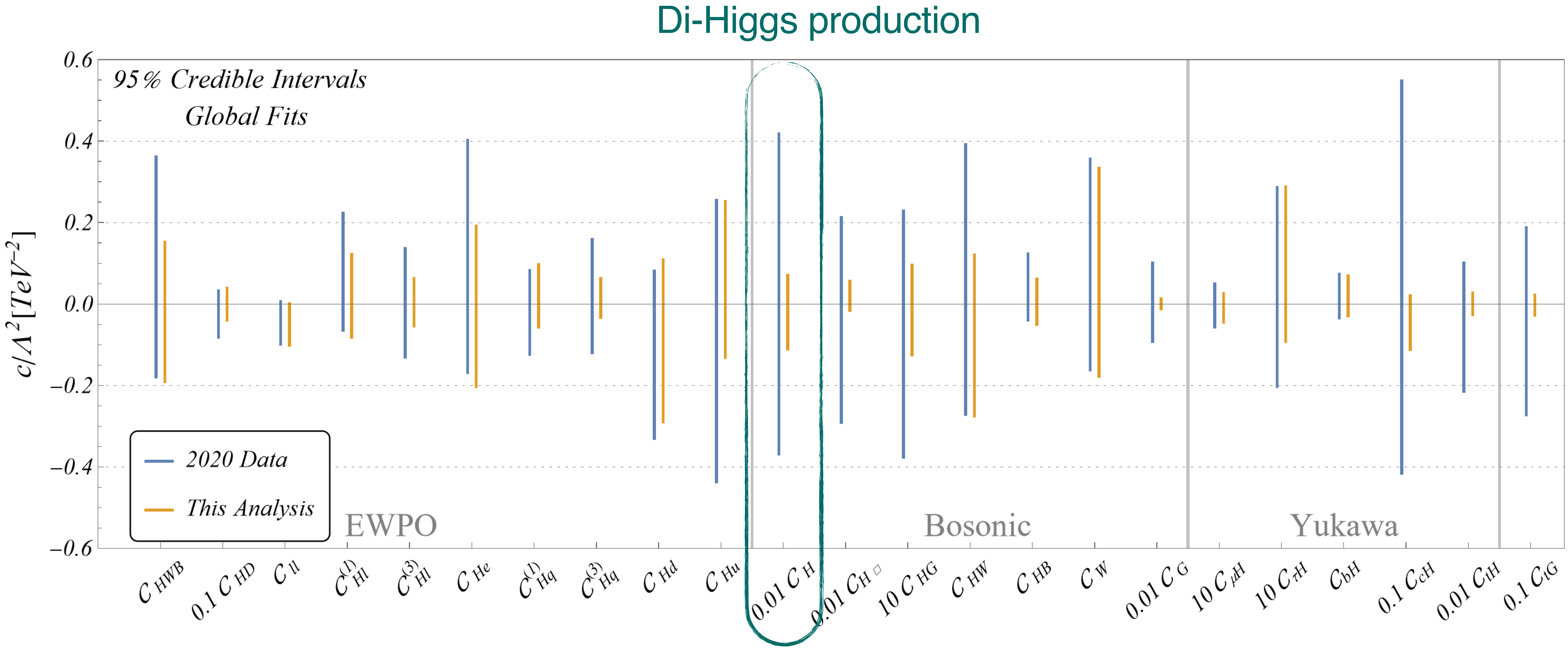
Adapted from Ken Mimasu

LHC 2021 fit



[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

LHC 2021 fit



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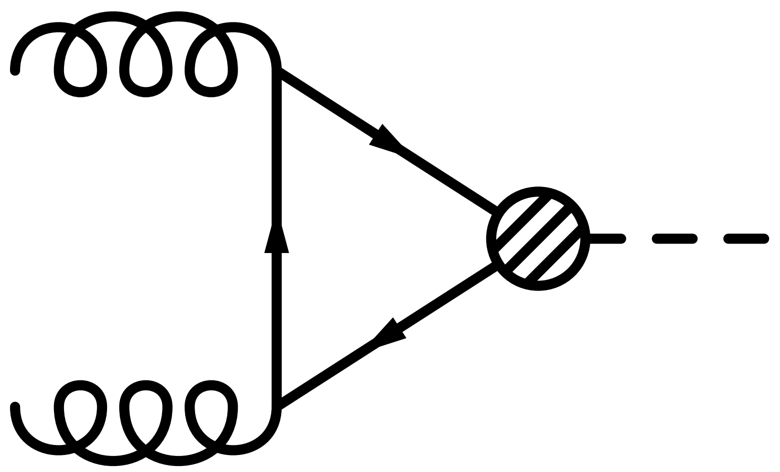
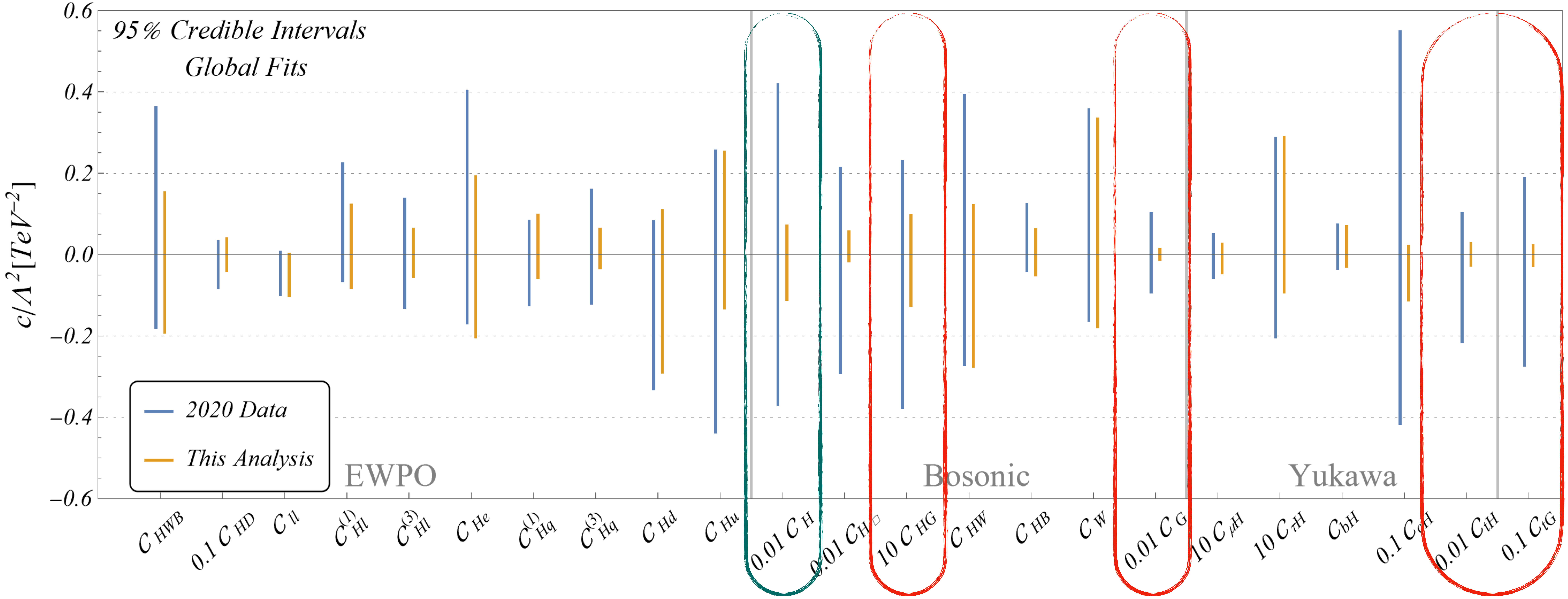
LHC 2021 fit

Distributions allow to disentangle correlated operators



Di-Higgs production



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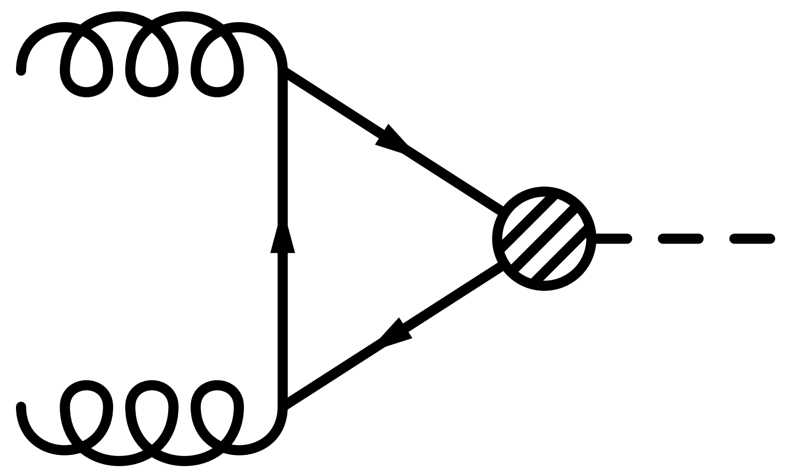

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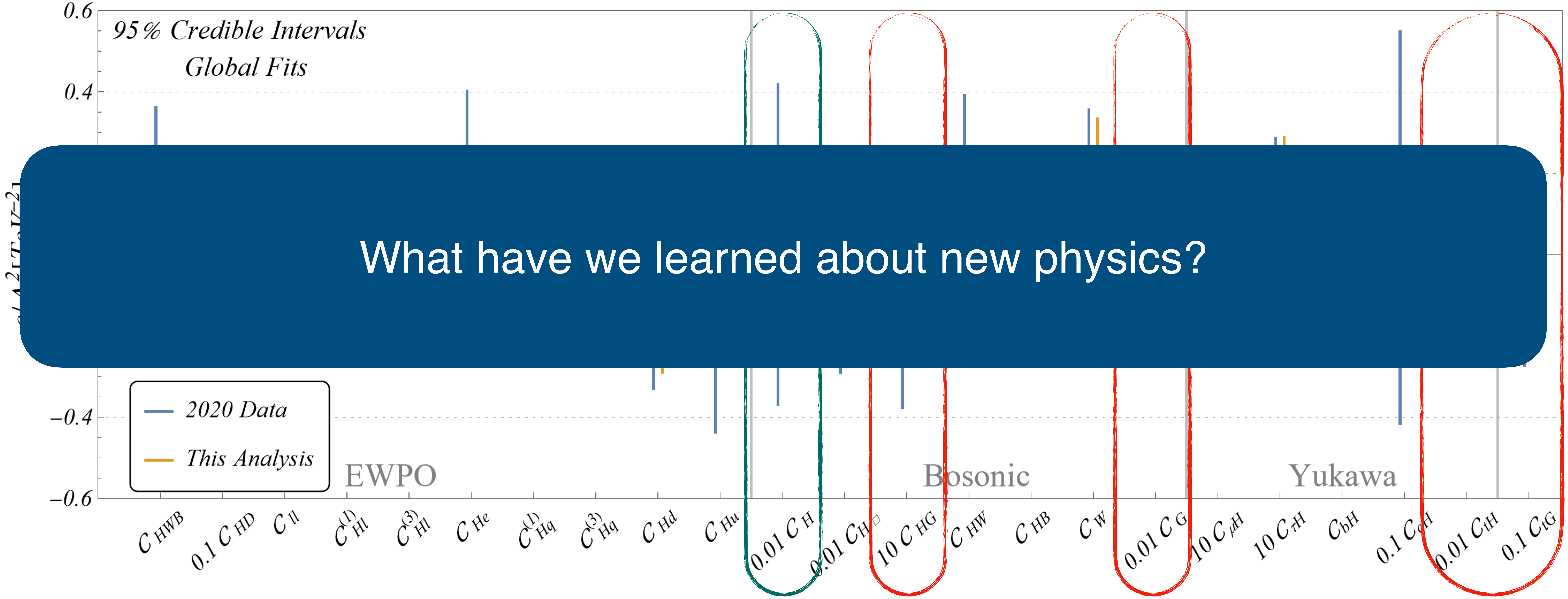

What have we learned about new physics?

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

UV complete model fits

- MatchmakerEFT [Carmona et al. (2112.10787)]
- CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]
- Matchete [Fuentes-Martín et al. (2212.04510)]

UV model

↓

SMEFT

UV complete model fits

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[Anisha, Bakshi, Chakrabortty, Kumar Patra (2010.04088)]
[Gorbahn, No, Sanz (1502.07352)]
[Drozd, Ellis, Quevillon, You (1504.02409)]
[Ellis, (Madigan, Mimasu, Murphy), Sanz, You (1803.03252), (2012.02779)]
[Dawson, Homiller, Lane (2007.01296), (2102.02823)]
[Bakshi, Chakrabortty, (Englert), Spannowsky, (Stylianou) (2009.13394), (2012.03839)]
[Krämer, Summ, Voigt (1908.04798)]
[Brivio, Brugisser, Geoffray, Kilian, Krämer (2108.01094)]
[…]

UV model

↓

SMEFT

Subset of operators induced

Correlations

Model	C_{HD}	C_{ll}	C_{Hl}^3	C_{Hl}^1	C_{He}	$C_{H\Box}$	$C_{\tau H}$	C_{tH}	C_{bH}
S						-1			
S_1		1							
Σ			$\frac{5}{8}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$-\frac{5}{8}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
Δ_1					$\frac{1}{2}$		$\frac{y_\tau}{2}$		
Δ_3					$-\frac{1}{2}$		$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
Ξ	-2					$\frac{1}{2}$	y_τ	y_t	y_b
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
φ							$-y_\tau$	$-y_t$	$-y_b$
$\{B, B_1\}$						1	y_τ	y_t	y_b
$\{Q_1, Q_7\}$								y_t	

[Ellis et al. (2012.02779)]

Two Higgs doublet model

$$\mathcal{L}_{\mathcal{H}_2} \supset -\lambda_{\mathcal{H}_2,1}|\tilde{H}|^2|\mathcal{H}_2|^2 - \lambda_{\mathcal{H}_2,2}|\tilde{H}^\dagger\mathcal{H}_2|^2$$

↓ CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]

$$C_{HB} = \frac{g_Y^2}{384\pi^2 m_{\mathcal{H}_2}^2}\left(\lambda_{\mathcal{H}_2,1} + \frac{1}{2}\lambda_{\mathcal{H}_2,2}\right)$$

$$C_{HW} = \frac{g_W^2}{384\pi^2 m_{\mathcal{H}_2}^2}\left(\lambda_{\mathcal{H}_2,1} + \frac{1}{2}\lambda_{\mathcal{H}_2,2}\right)$$

$$C_{HWB} = \frac{g_W g_Y}{384\pi^2 m_{\mathcal{H}_2}^2}\lambda_{\mathcal{H}_2,2}$$

$$\dots$$

EWPO: Electroweak precision observables (mostly LEP data)

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

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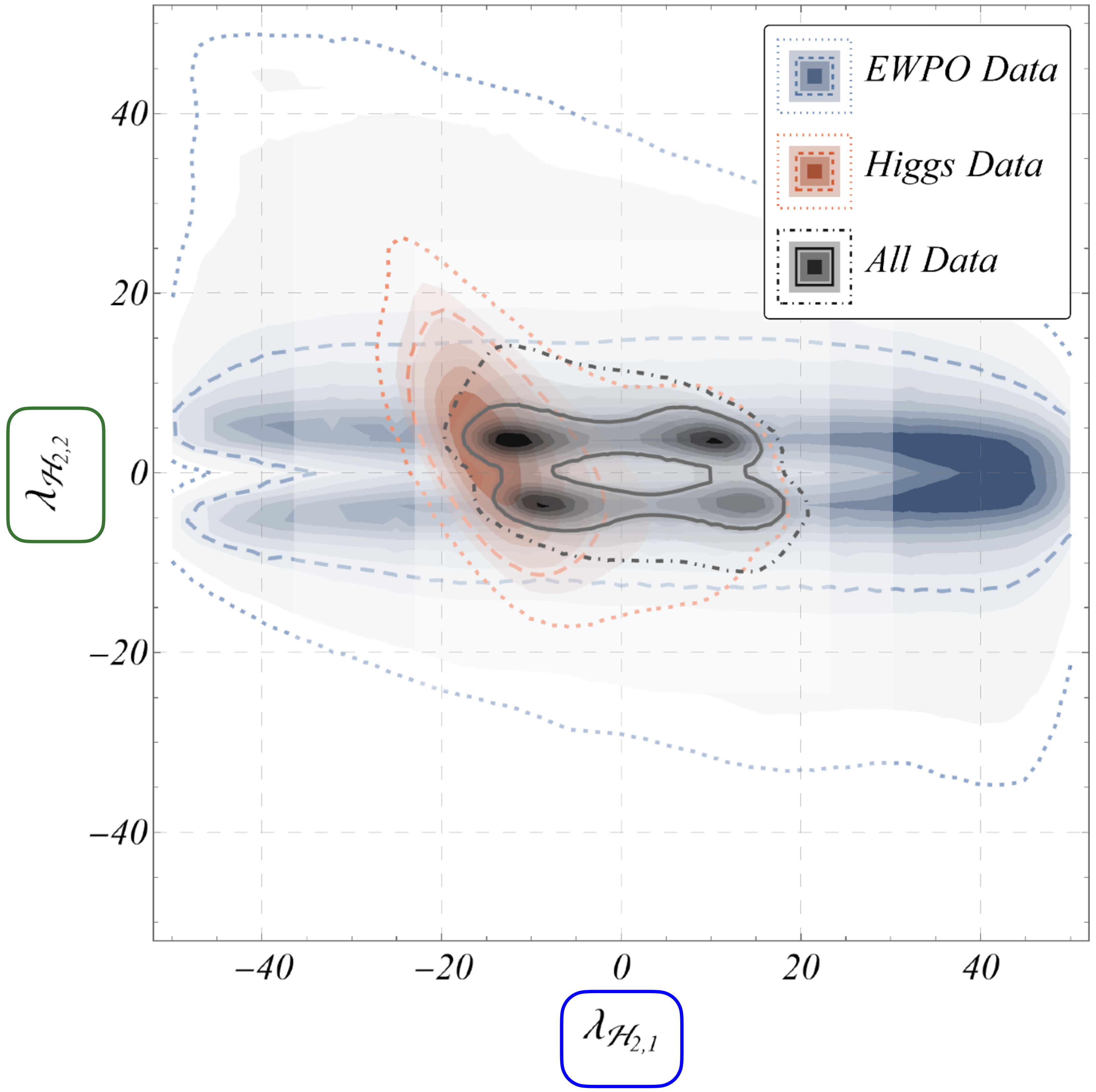

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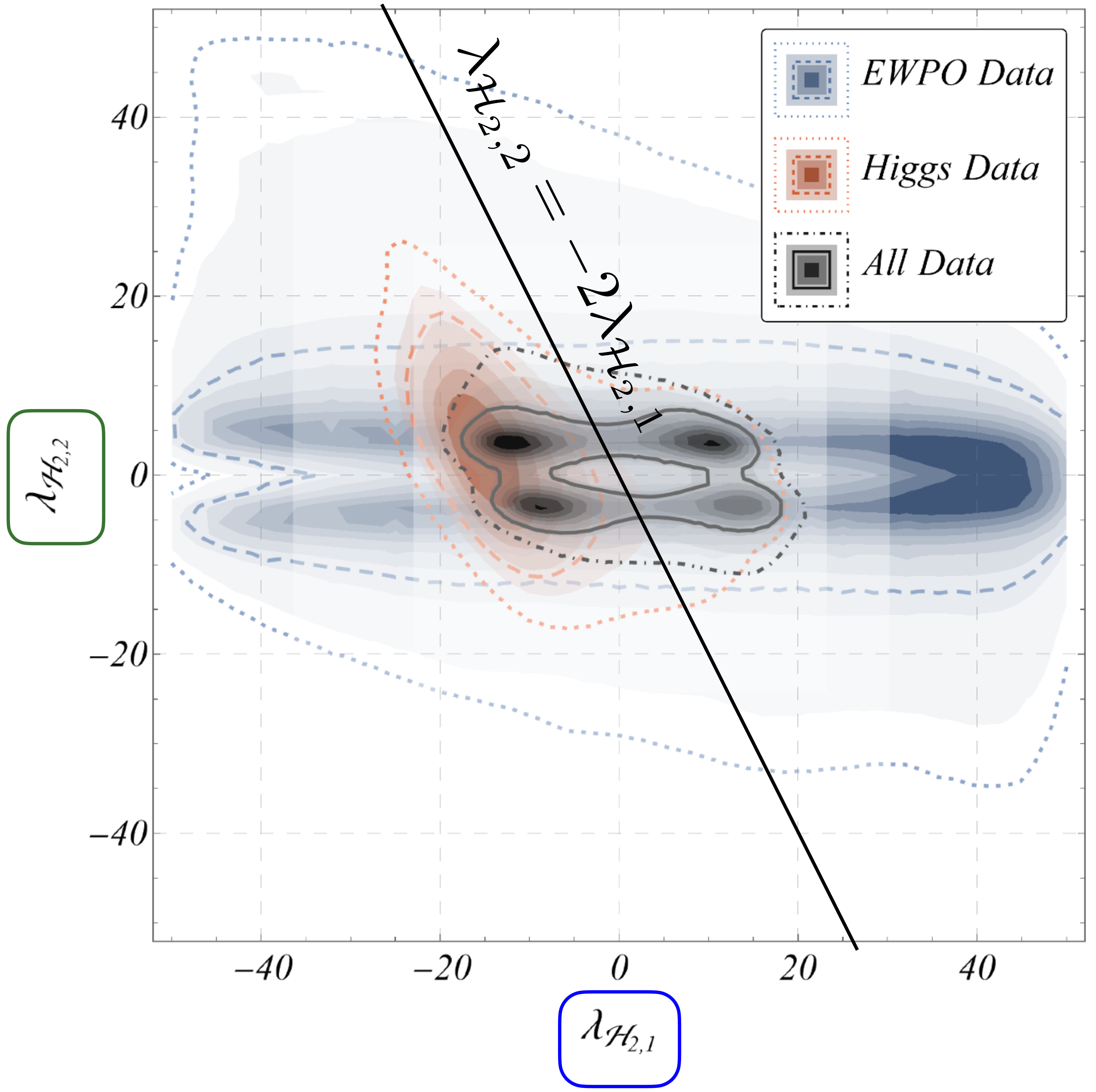
...



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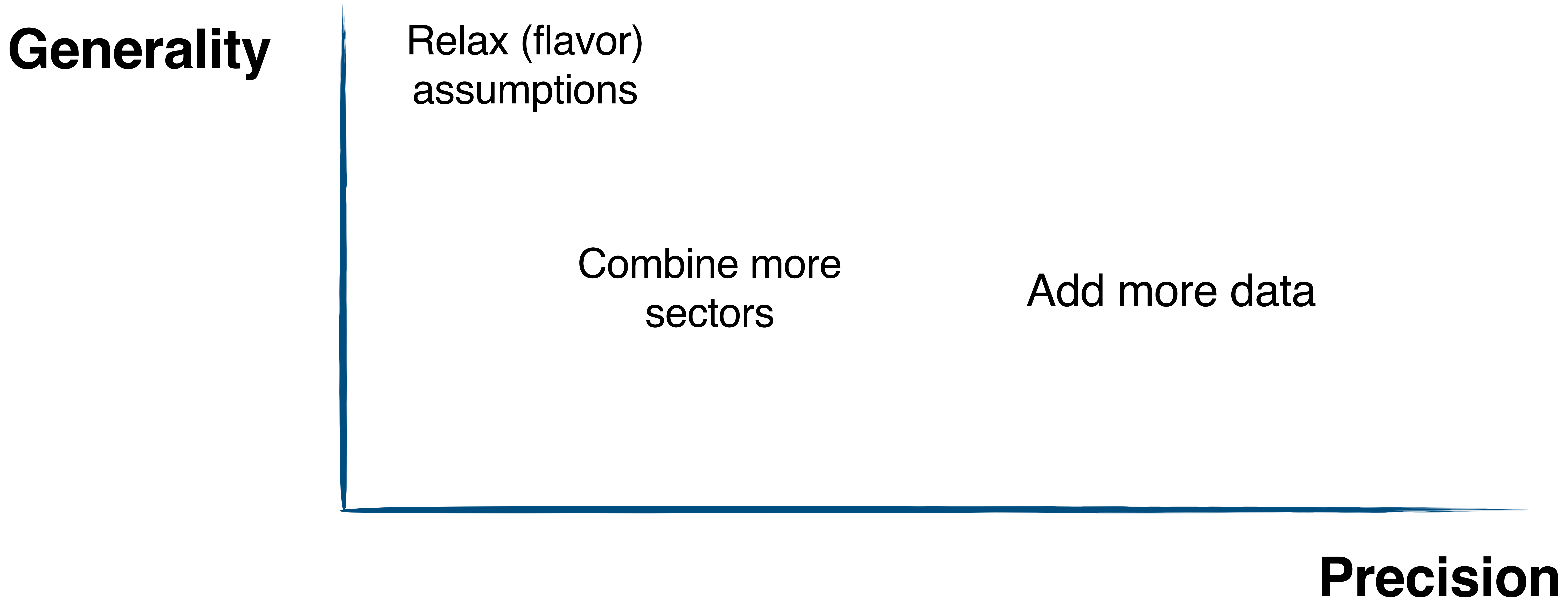
Future directions in SMEFT (fits)



Future directions in SMEFT (fits)

$$\mathcal{A} = \mathcal{A}_{\mathrm{SM}} + a_i \frac{C_i^{(6)}}{\Lambda^2} + b_{jk} \frac{C_j^{(6)} C_k^{(6)}}{\Lambda^4} + c_l \frac{C_l^{(8)}}{\Lambda^4} + \frac{1}{16\pi^2}\left[d_m \frac{C_m^{(6)}}{\Lambda^2} + e_n \frac{C_n^{(6)}}{\Lambda^2} \log\left(\frac{\mu^2}{\Lambda^2}\right)\right] + \cdots$$

Generality

Relax (flavor) assumptions

Dim6^2 effects

Dim8 effects

Combine more sectors

Add more data

SMEFT@NLO

Precision

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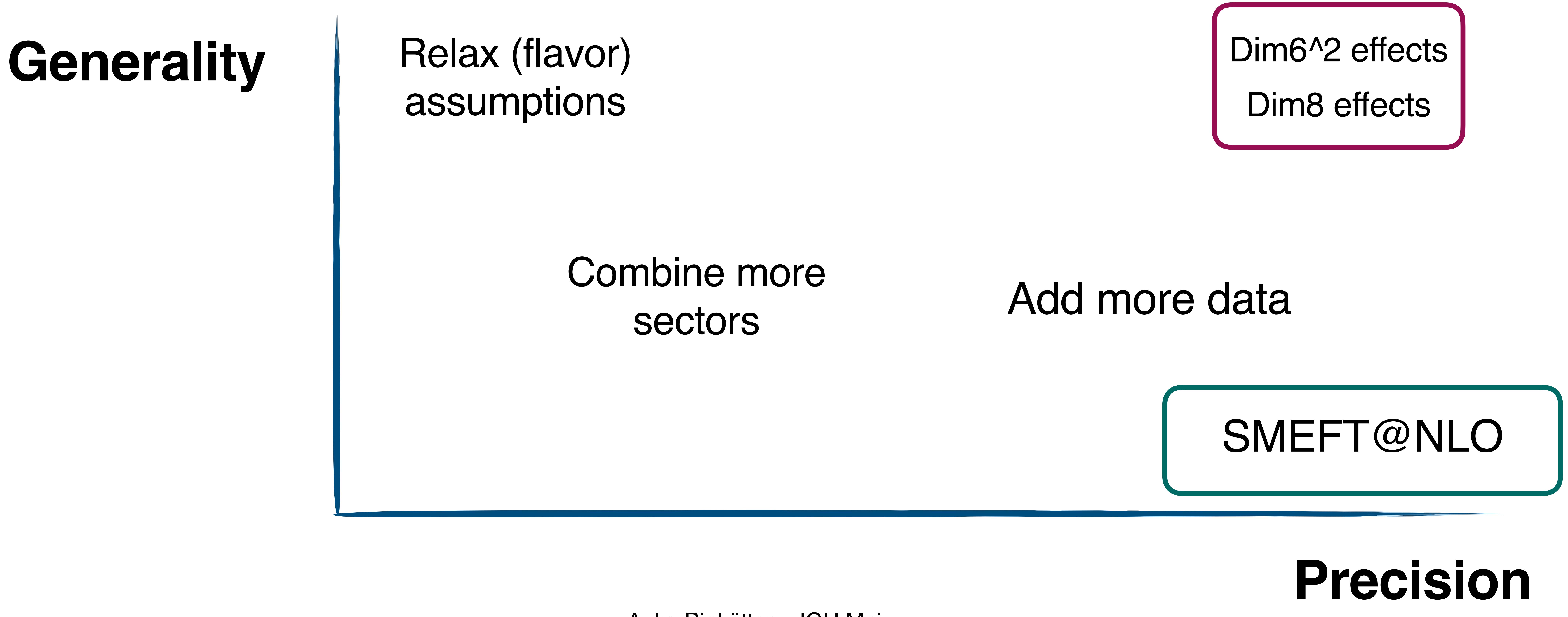


Future directions in SMEFT (fits)

$$\mathcal{A} = \mathcal{A}_{\rm SM} + a_i \frac{C_i^{(6)}}{\Lambda^2} + \boxed{b_{jk}\frac{C_j^{(6)}C_k^{(6)}}{\Lambda^4} + c_l \frac{C_l^{(8)}}{\Lambda^4}} + \frac{1}{16\pi^2}\left[\boxed{d_m \frac{C_m^{(6)}}{\Lambda^2} + e_n \frac{C_n^{(6)}}{\Lambda^2}\log\left(\frac{\mu^2}{\Lambda^2}\right)}\right] + \cdots$$

[Corbett et al. (2102.02819)]
[Dawson et al. (2205.01561)]
[Ellis et al. (2304.06663)]

Generality

Relax (flavor) assumptions

[Bruggisser et al. (2212.02532)]
[Grunwald et al. (2304.12837)]
[Greljo et al. (2203.09561)]

Dim6^2 effects

Dim8 effects

Combine more sectors

Add more data

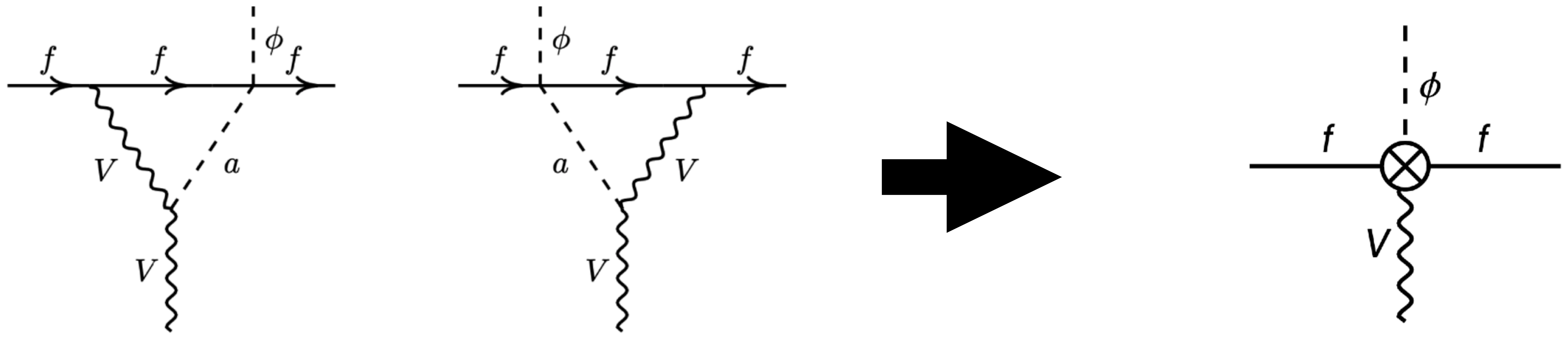
[Degrande et al. (2008.11743)]

SMEFT@NLO

Precision

[Galda, Neubert, Renner (2105.01078)]
[AB, Fuentes, Galda, Neubert (2307.10372)]

The ALP-SMEFT interference

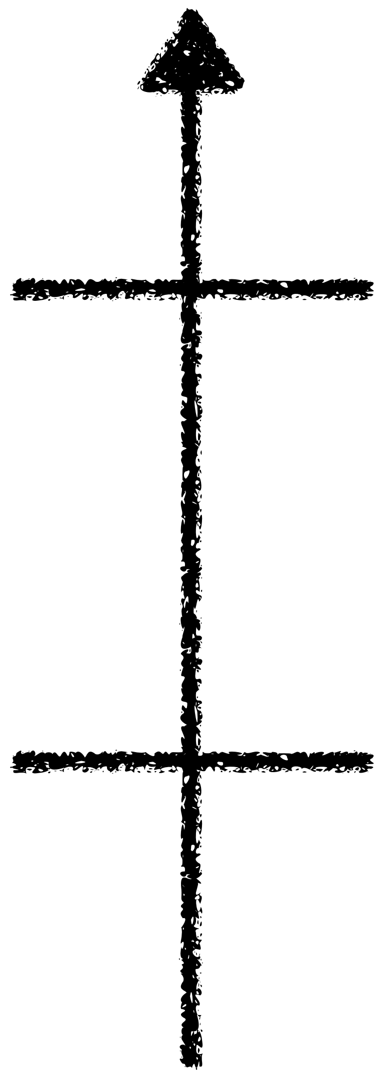


Renormalisation group evolution

$$\frac{\mathrm{d}}{\mathrm{d}\log\mu} C_i^{\mathrm{SMEFT}} - \gamma_{ji}^{\mathrm{SMEFT}} C_j^{\mathrm{SMEFT}} = \frac{S_i}{(4\pi f)^2}$$

$$\begin{aligned} S_{HG} &= 0\,, & S_{H\widetilde{G}} &= 0\,,\\ S_{HW} &= -2g_2^2\, C_{WW}^2\,, & S_{H\widetilde{W}} &= 0\,,\\ S_{HB} &= -2g_1^2\, C_{BB}^2\,, & S_{H\widetilde{B}} &= 0\,,\\ S_{HWB} &= -4g_1 g_2\, C_{WW} C_{BB}\,, & S_{H\widetilde{W}B} &= 0\,. \end{aligned}$$

C_{WW}, C_{BB} : ALP couplings



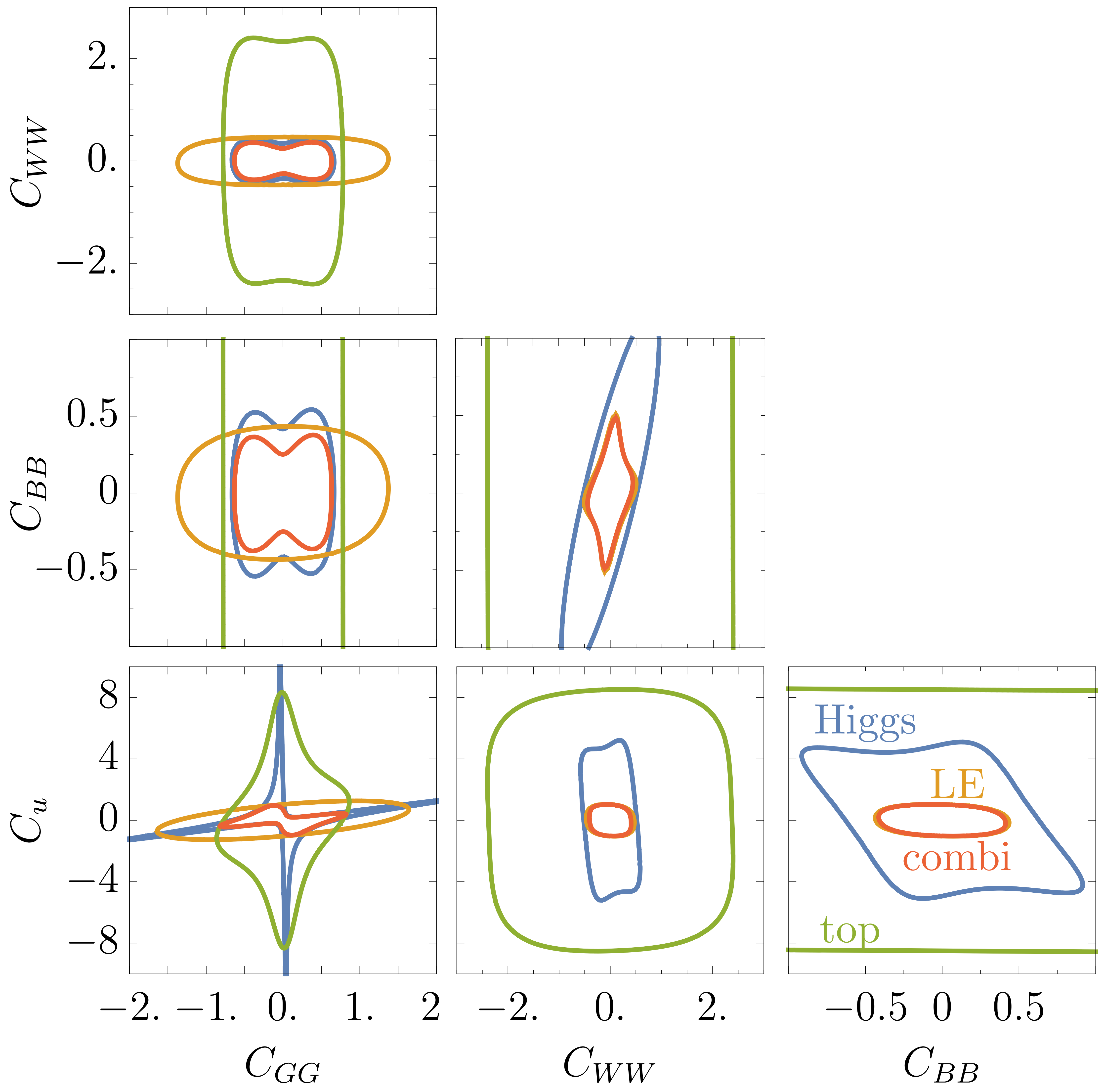
$C^{\mathrm{ALP}}(\Lambda) \neq 0,$
$C^{\mathrm{SMEFT}}(\Lambda) = 0$

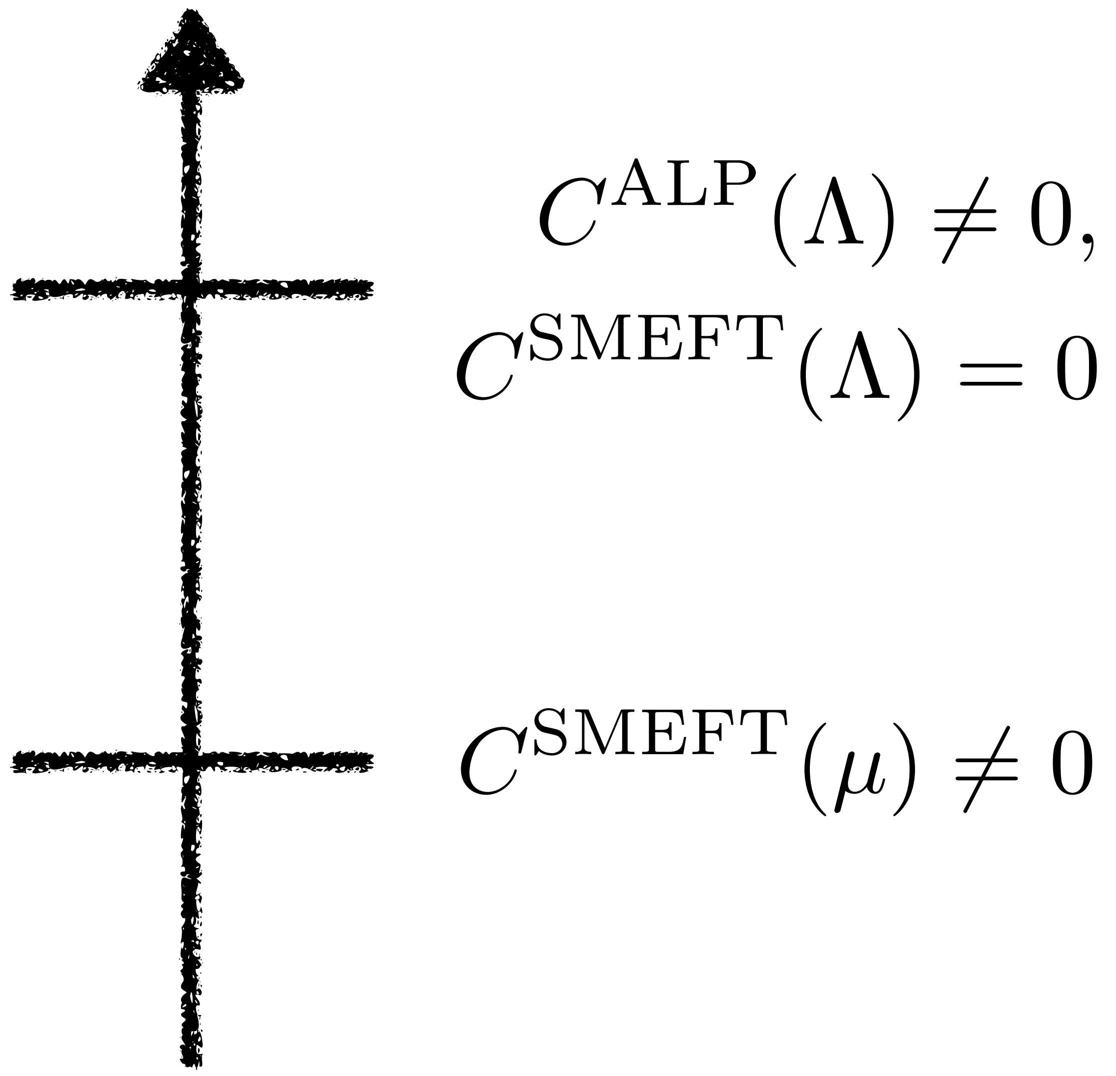
$C^{\mathrm{SMEFT}}(\mu) \neq 0$

[Anne Galda's talk/poster]

[Galda, Neubert, Renner (2105.01078)]
[AB, Fuentes, Galda, Neubert (2307.10372)]

The ALP-SMEFT interference





[Anne Galda's talk/poster]

Summary

SMEFT

- Universal description of the effects of heavy new physics
- Global analyses enable us to fully exploit the data
- Results can be reused to constrain light new physics

Outlook

- Combining more sectors
- Precision
  - SMEFT@NLO
  - Dimension-8
- Ongoing efforts by experimentalists and theorists

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Thank you for your attention!

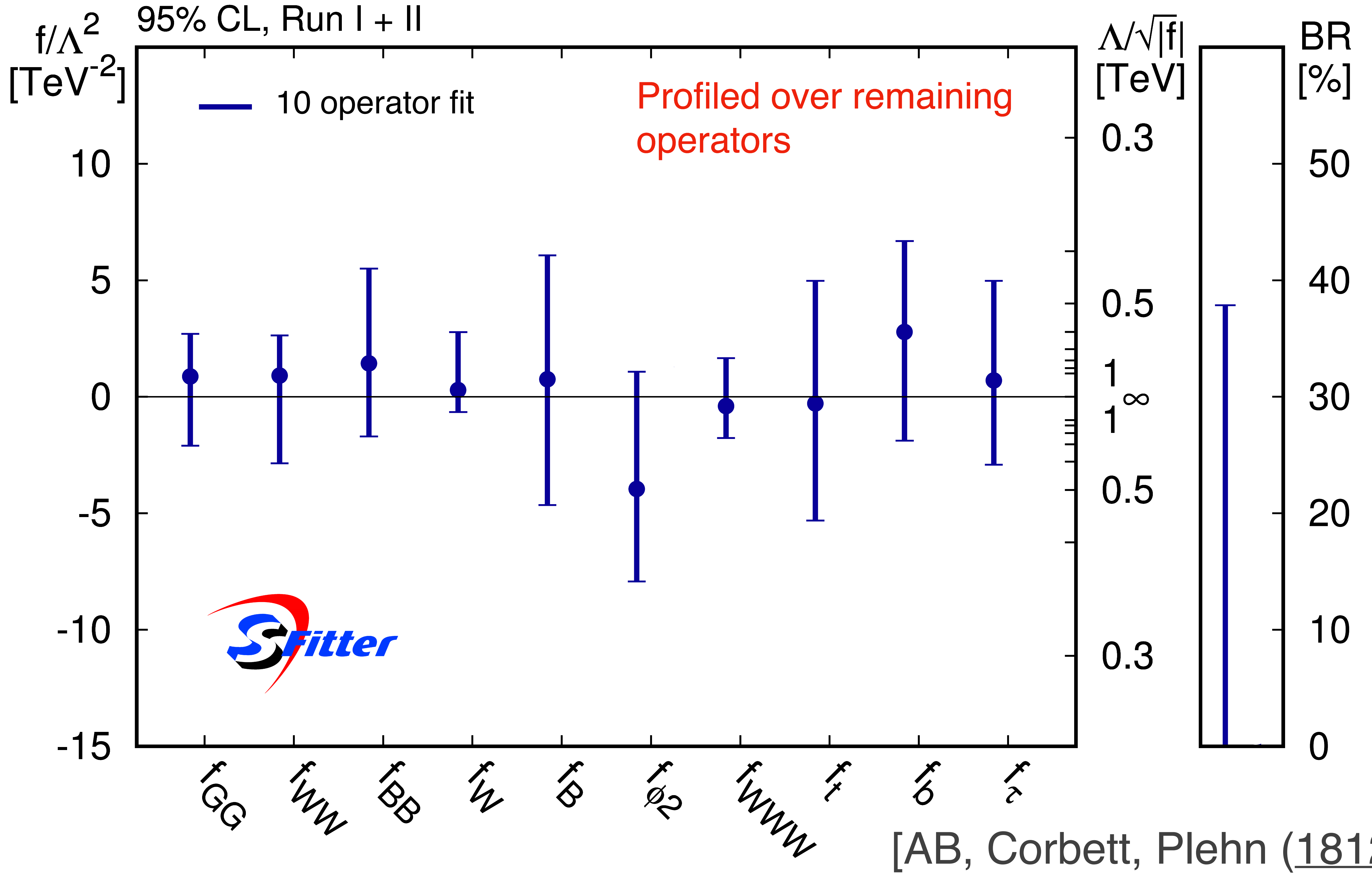
Backup

LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

Higgs only

$$\mathcal{O}_{GG} = \phi^\dagger\phi\, G^a_{\mu\nu}G^{a\mu\nu}$$
$$\mathcal{O}_{WW} = \phi^\dagger\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}\phi$$
$$\mathcal{O}_{BB} = \phi^\dagger\hat{B}_{\mu\nu}\hat{B}^{\mu\nu}\phi$$
$$\mathcal{O}_{W} = (D_\mu\phi)^\dagger\hat{W}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_{B} = (D_\mu\phi)^\dagger\hat{B}^{\mu\nu}(D_\nu\phi)$$
$$\mathcal{O}_{\phi 2} = \frac{1}{2}\partial^\mu(\phi^\dagger\phi)\partial_\mu(\phi^\dagger\phi)$$
$$\mathcal{O}_{WWW} = \mathrm{Tr}\left(\hat{W}_{\mu\nu}\hat{W}^{\nu\rho}\hat{W}^{\mu}_{\rho}\right)$$
$$\mathcal{O}_{\tau} = \phi^\dagger\phi\, \bar{L}_3\phi e_{R,3}$$
$$\mathcal{O}_{t} = \phi^\dagger\phi\, \bar{Q}_3\tilde{\phi}u_{R,3}$$
$$\mathcal{O}_{b} = \phi^\dagger\phi\, \bar{Q}_3\phi d_{R,3}$$



[AB, Corbett, Plehn (1812.07587)]

LHC 2018 fit - fermion-gauge operators

[Hagiwara-Ishihara-Szalapski-Zeppenfeld basis]

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$$\mathcal{O}_{GG} = \phi^\dagger\phi \; G^a_{\mu\nu} G^{a\mu\nu}$$
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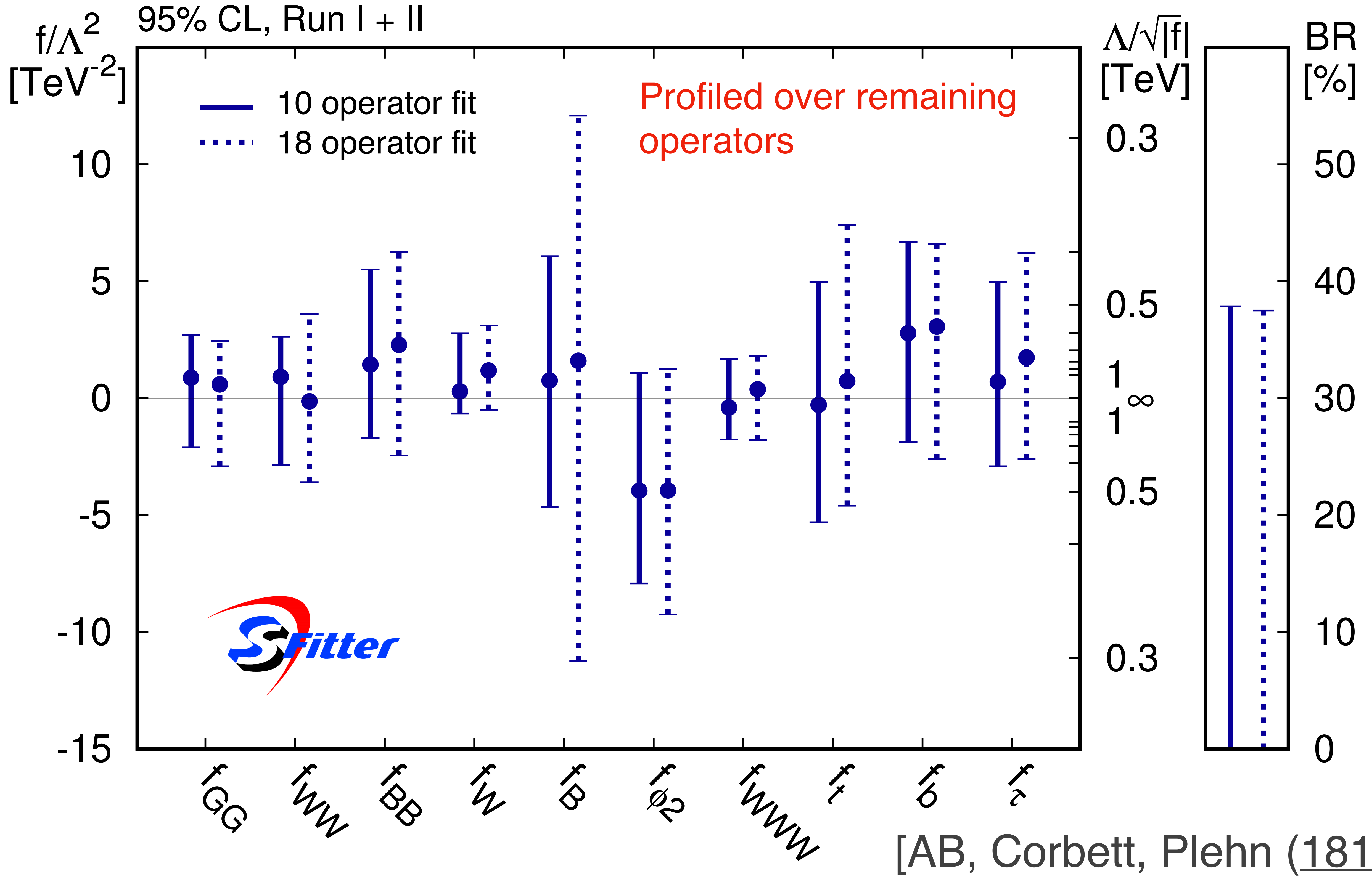
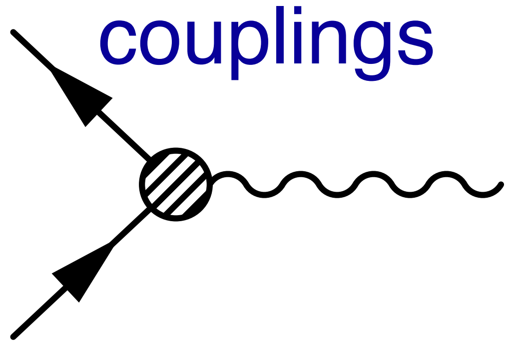


[AB, Corbett, Plehn (1812.07587)]

Fermion-gauge couplings



$$\mathcal{O}_{\phi 1} = (D_\mu \phi)^\dagger \; \phi \phi^\dagger \; (D^\mu \phi) \qquad \mathcal{O}_{BW} = \phi^\dagger \hat{B}_{\mu\nu} \hat{W}^{\mu\nu} \phi$$
$$\mathcal{O}^{(1)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{Q}\gamma^\mu Q) \qquad \mathcal{O}^{(3)}_{\phi Q} = \phi^\dagger (i \overleftrightarrow{D}^a{}_\mu \phi)(\bar{Q}\gamma^\mu \sigma^a Q) \qquad \mathcal{O}^{(1)}_{\phi u} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{u}_R \gamma^\mu u_R)$$
$$\mathcal{O}^{(1)}_{\phi d} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{d}_R \gamma^\mu d_R) \qquad \mathcal{O}^{(1)}_{\phi e} = \phi^\dagger (i \overleftrightarrow{D}_\mu \phi)(\bar{e}_R \gamma^\mu e_R) \qquad \mathcal{O}_{LLLL} = (\bar{L}\gamma_\mu L)(\bar{L}\gamma^\mu L)$$

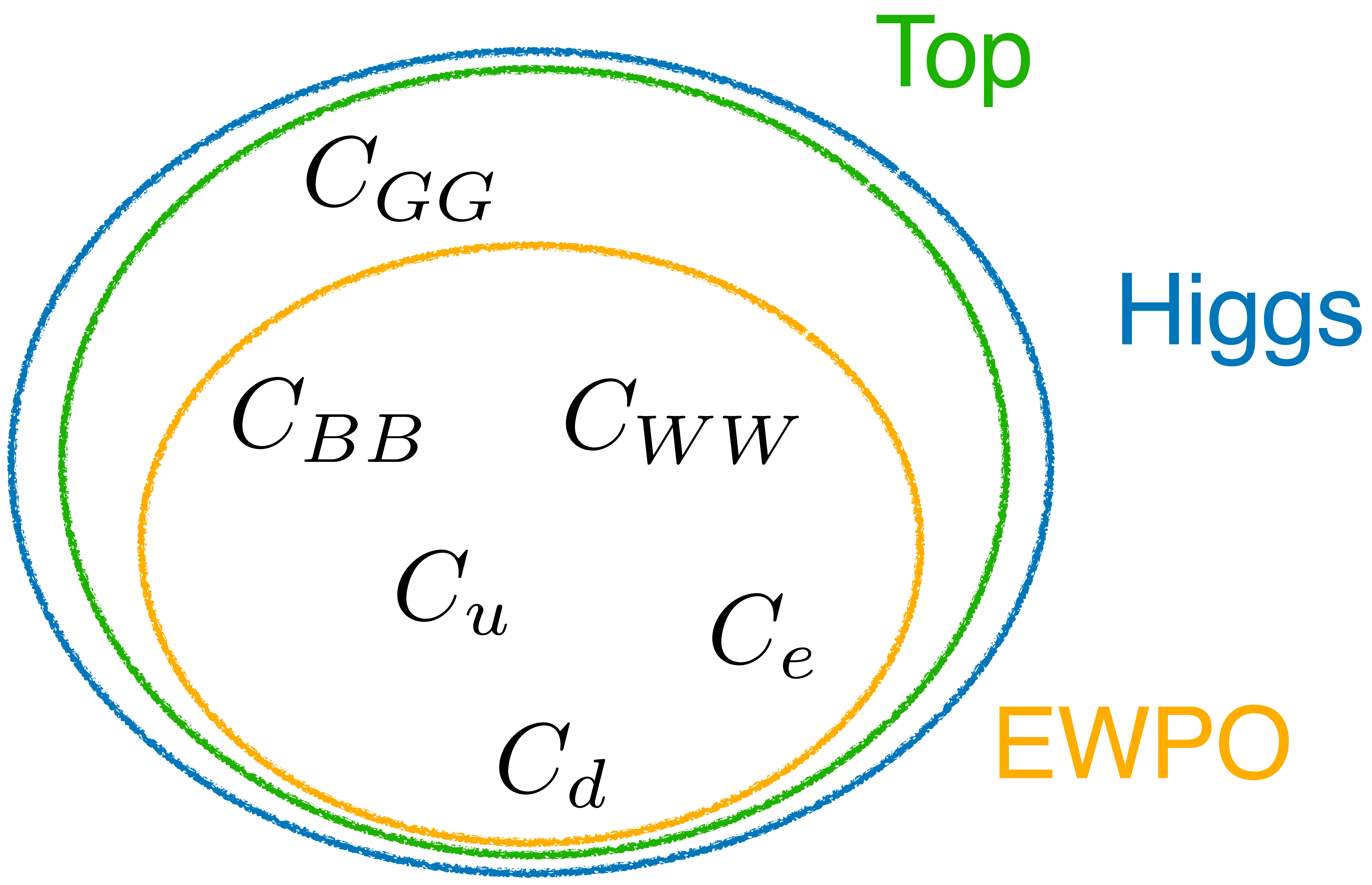
Exploiting the ALP-SMEFT interference

Observables used

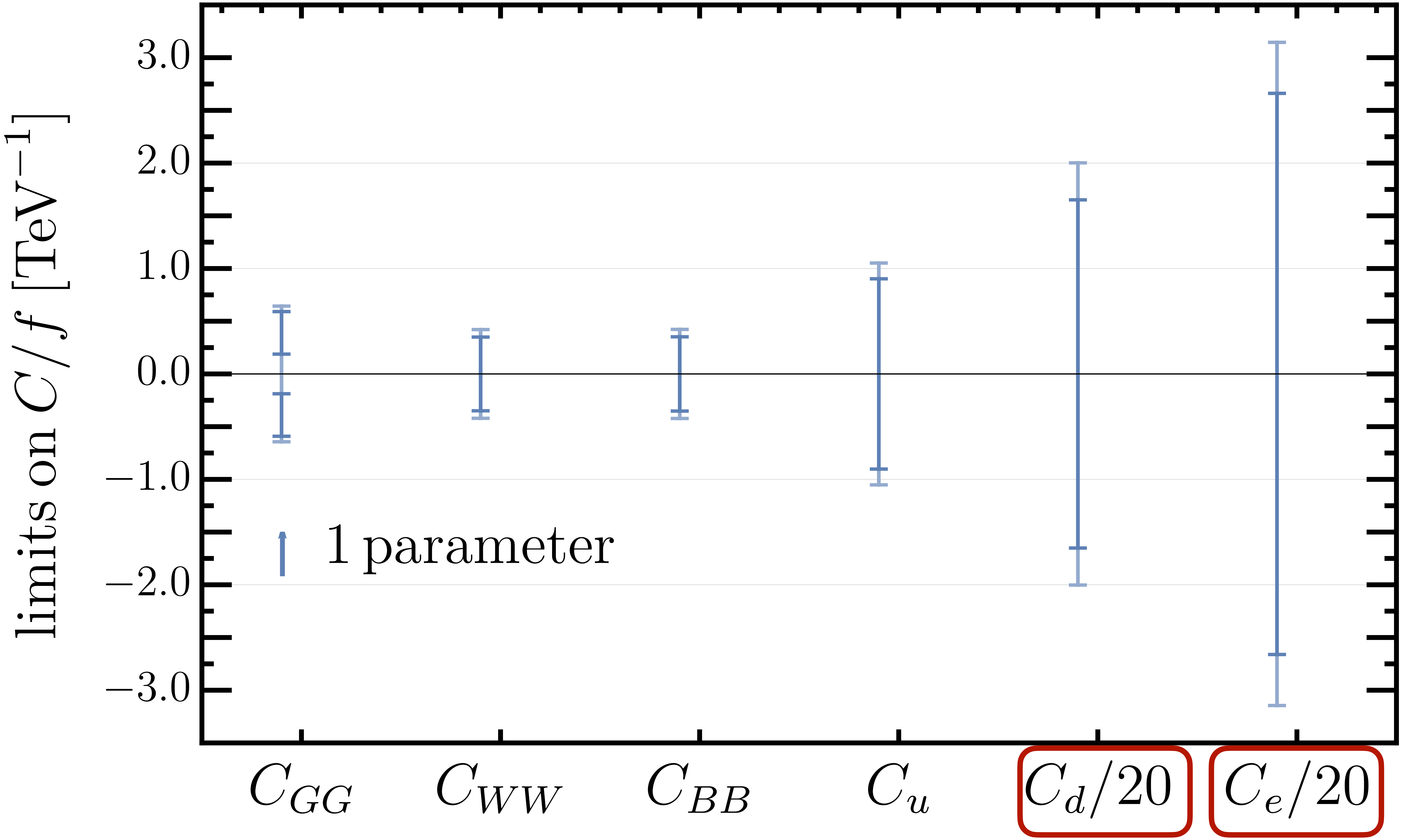
- Electroweak precision observables (EWPO)
- Higgs
- Top [Ellis et al. (2012.02779)]

Six free parameters

$$C_{GG}, C_{WW}, C_{BB}, C_u, C_d, C_e$$



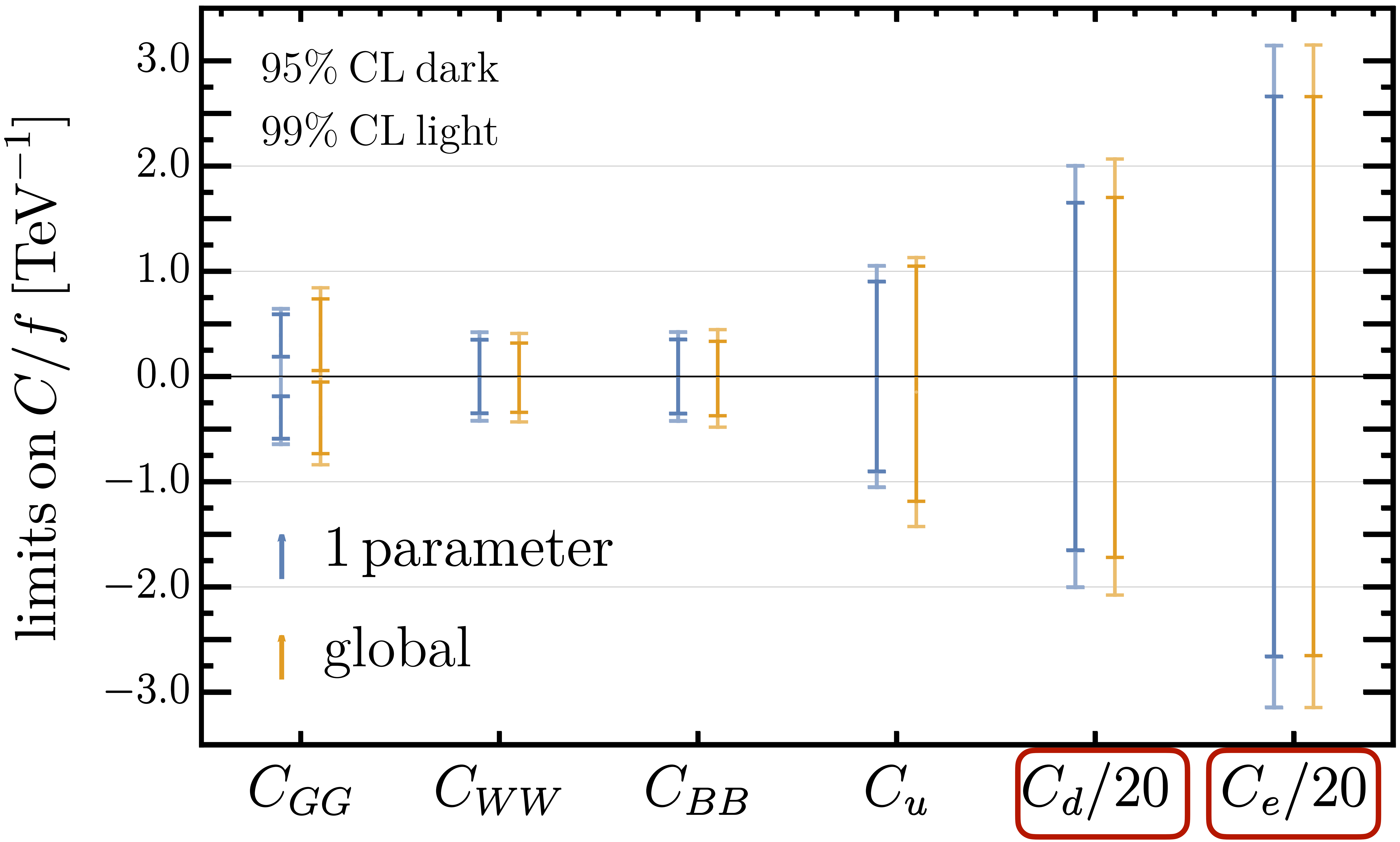
Exploiting the ALP-SMEFT interference



$\Lambda = 4\pi f$

$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

Exploiting the ALP-SMEFT interference



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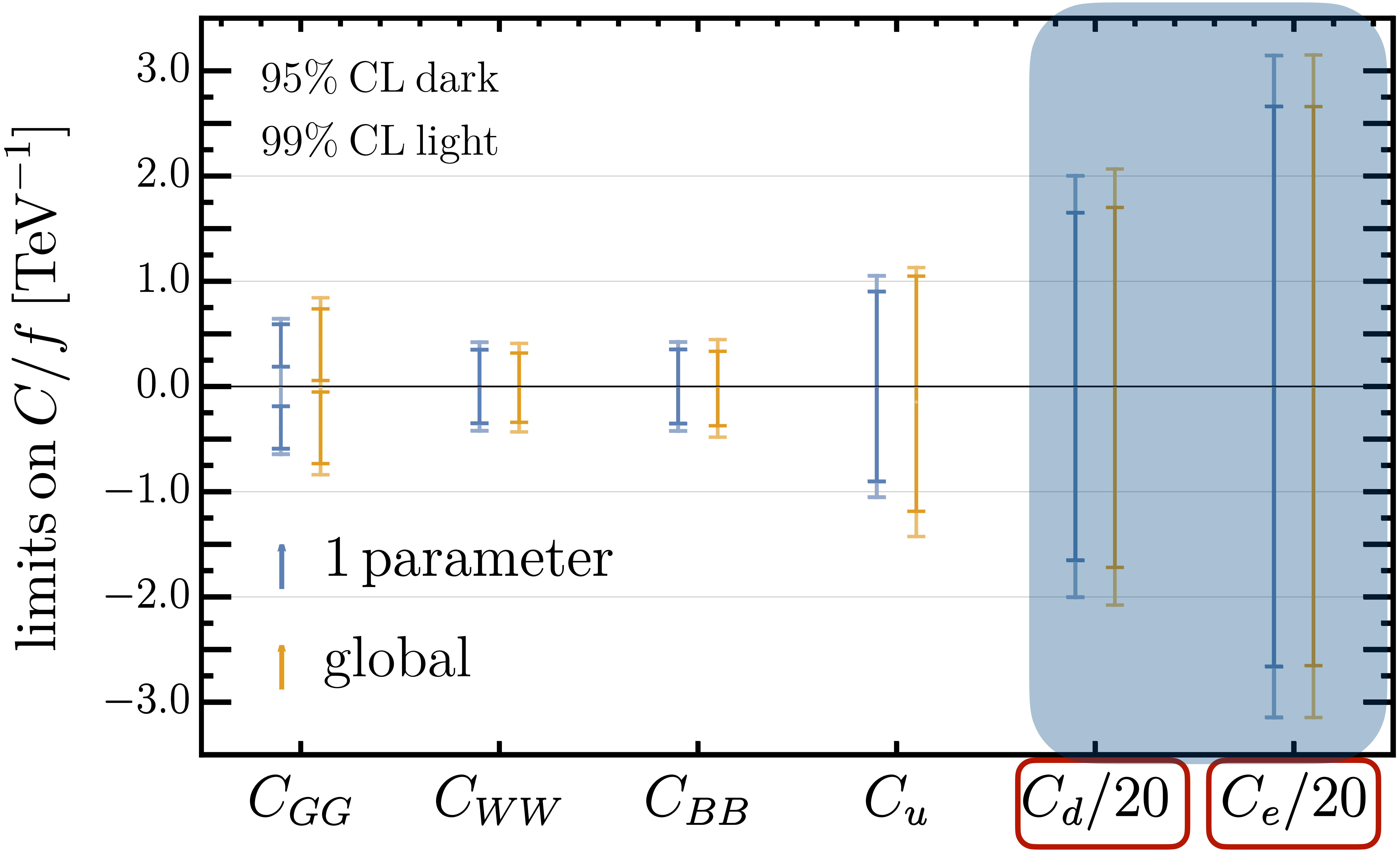


$\Lambda = 4\pi f$

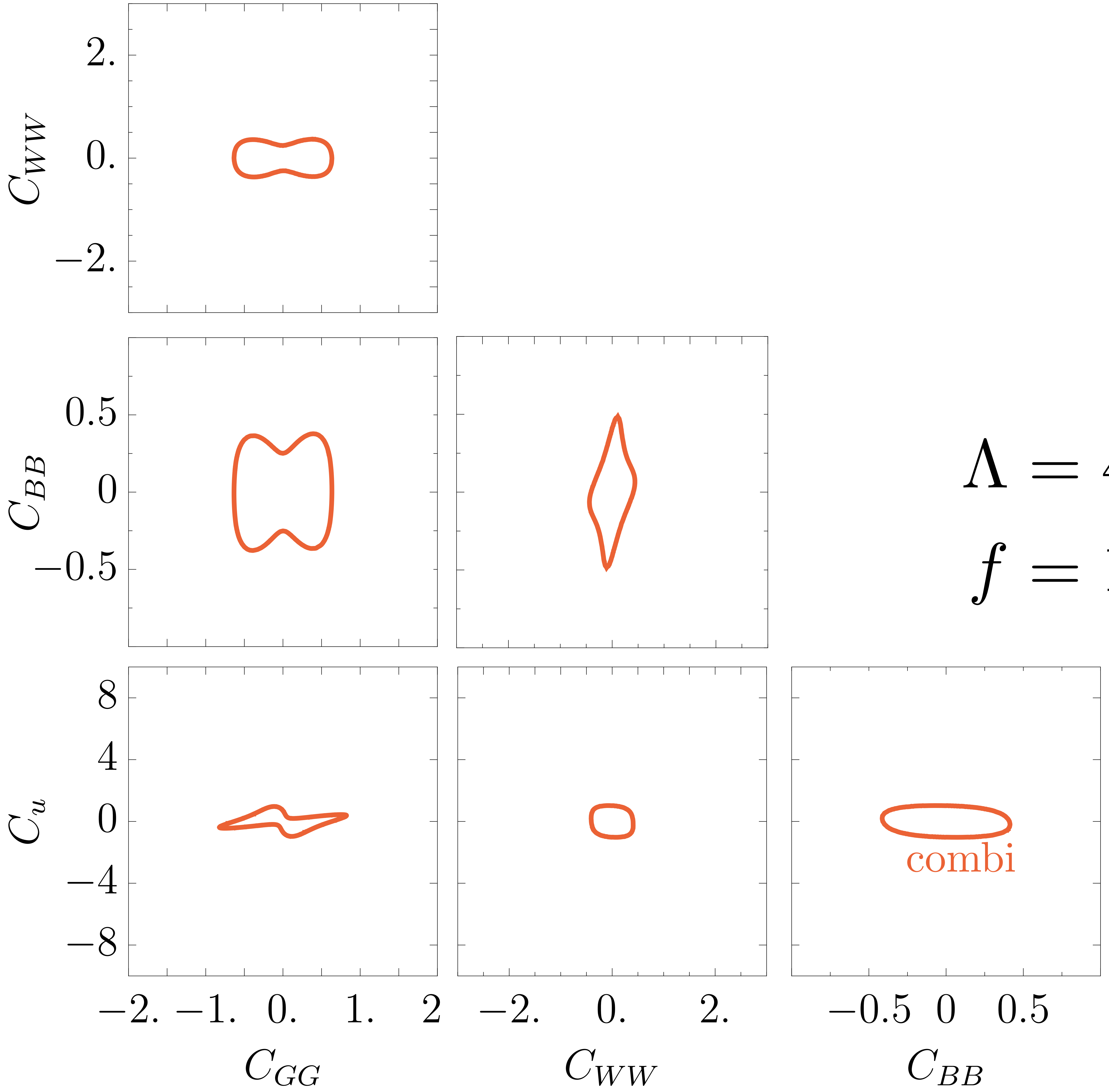
$\mathcal{O}(1)$ limits on ALP couplings for $f = 1$ TeV

Correlations

Dominant constraints

- C_{GG} : Higgs + Top
- C_{WW} : LE + Higgs
- C_{BB} : low energy
- C_u : low energy

- C_d : low energy
- C_e : low energy



$$\Lambda = 4\pi f$$

$$f = 1\ \text{TeV}$$

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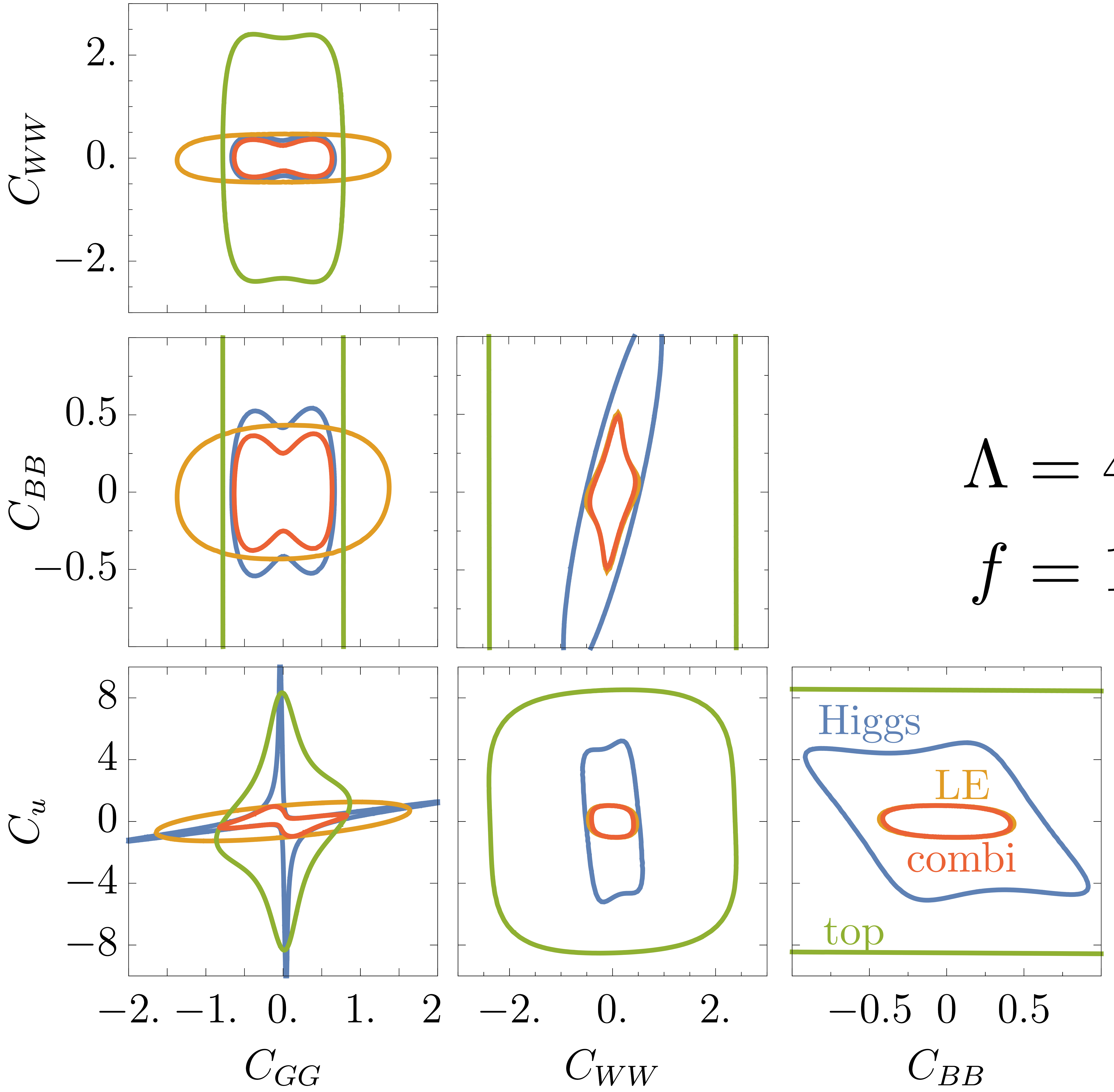
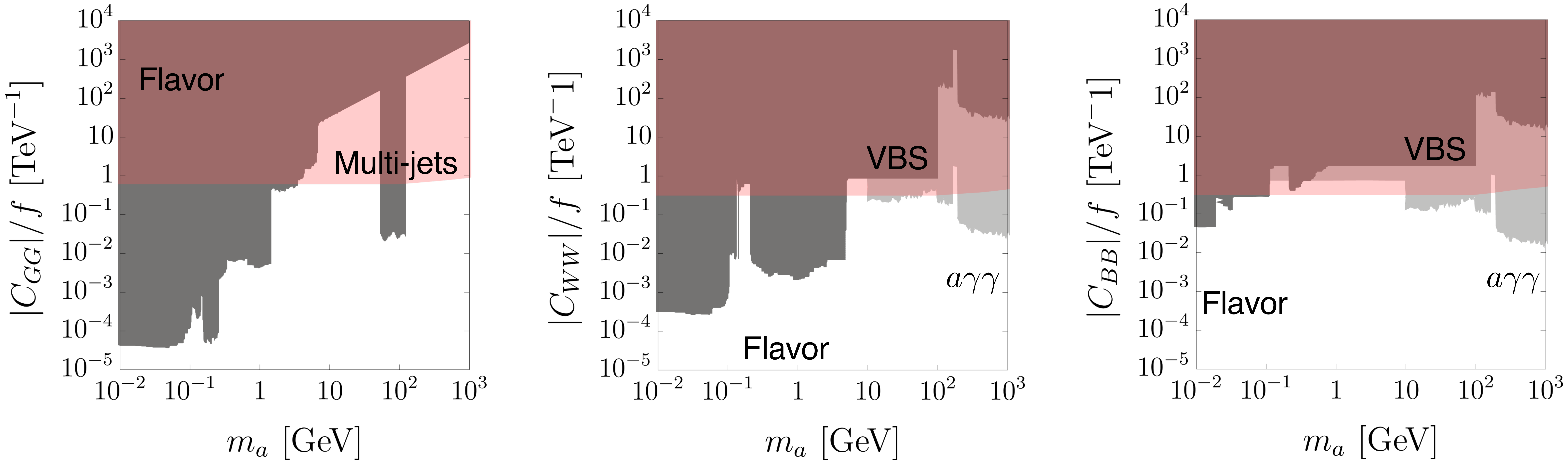


$$\Lambda = 4\pi f$$

$$f = 1 \text{ TeV}$$

Comparison with direct bounds

Light gray bounds with additional assumptions



[Mariotti, Redigolo, Sala, Tobiok (1710.01743)]

[Bonilla, Brivio, Machado-Rodríguez, de Trocóniz (2202.03450)]

[Bauer, Neubert, Thamm (1708.00443)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

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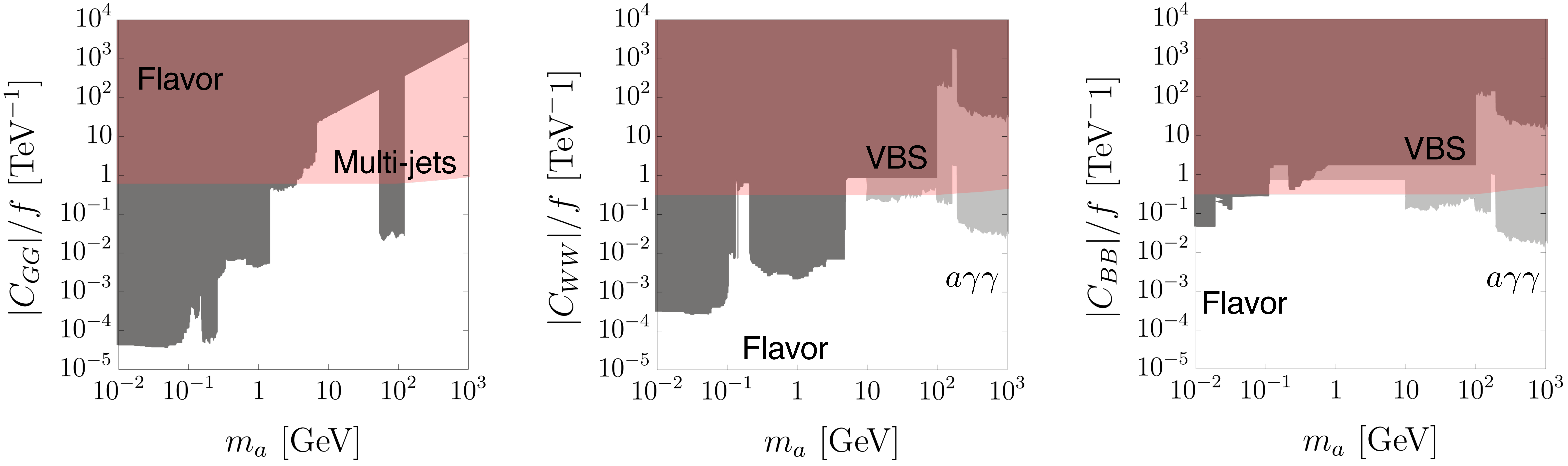

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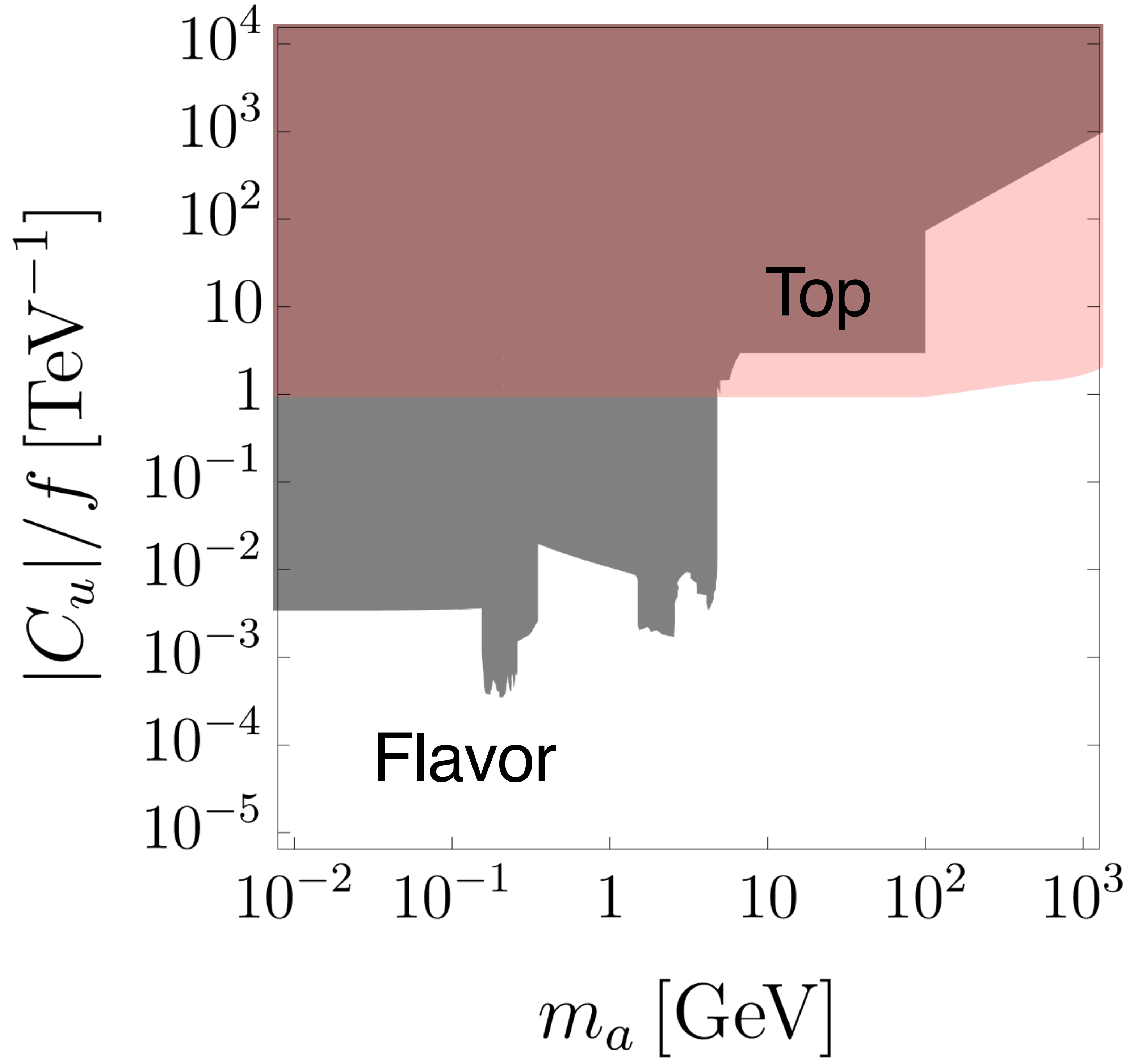
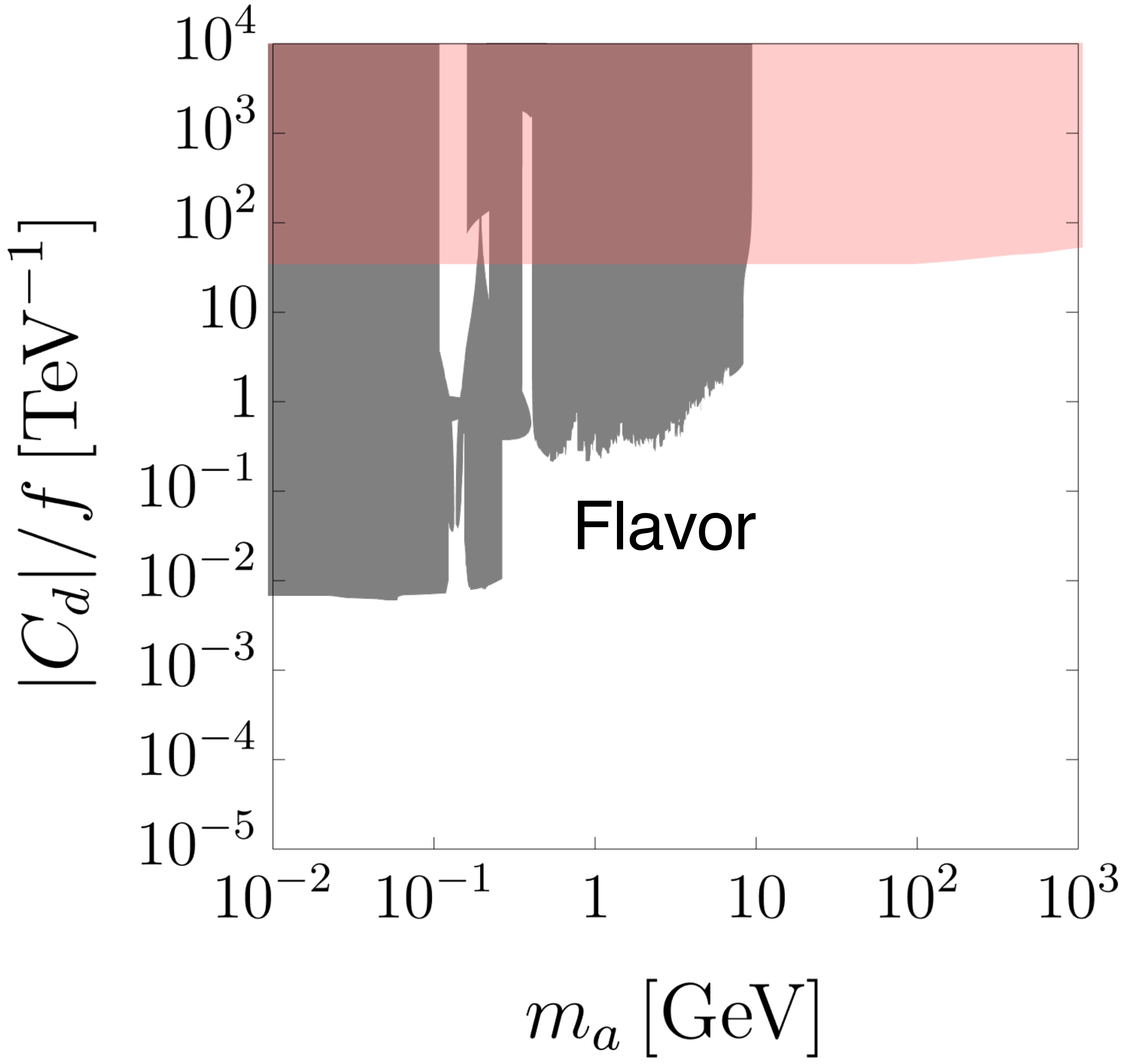
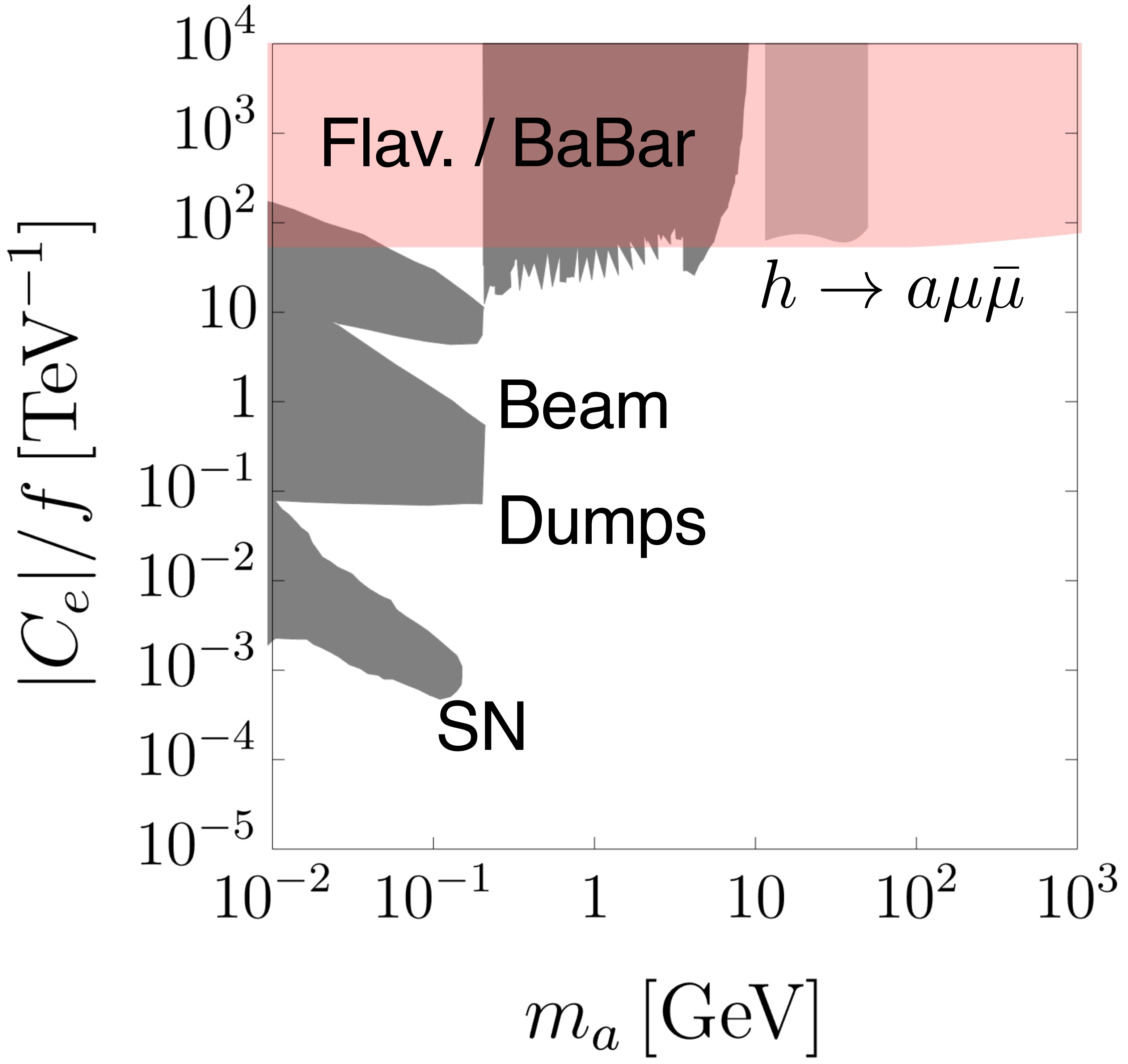
ALP-SMEFT interference tests unconstrained parameter space

Comparison with direct bounds







[BaBar (1406.2980)]

[Esser, Madigan, Sanz, Ubiali (2303.17634)]

[AB, Chala, Spannowski (2203.14984)]

[Lucente, Carenza (2107.12393)]

[Bauer, Neubert, Renner, Schnubel, Thamm (2110.10698)]

[Essig, Harnik, Kaplan, Toro (1008.0636)]

$1/\Lambda^4$ effects

- Large number of dim8 operators

  (Wh production: 66 dim8 operators)

- Focus on dim8 operators induced in matching of specific UV-complete models in a specific process

  (few parameters, relation between WCs)

- Or: all dim8 operators have the same magnitude

  Wh: O(10%) effect

  [Hays, Martin, Sanz, Setford (1808.00442)]

SMEFT fits - a global effort!

Filled to my best knowledge

	Eboli, Gonzalez-Garcia et al	Fitmaker	SFitter	TopFitter	HEPfit	SMEFit	Dawson et al.	Chakrabortty et al.
Input	EWPD+Higgs+VV, DY +VV	EWPD+Higgs+VV + top	EWPD+Higgs+VV, top	top	EWPD+Higgs+VV Flavor	EWPD+Higgs+VV, VBS + diboson, top	EWPD+Higgs+VV	EWPD + Higgs
Linear/ quadratic	Both	Linear	Both	Linear	Linear	Both	Linear	Linear
Basis	HISZ	Warsaw	HISZ (Higgs) Warsaw (top)	Warsaw	Warsaw	Warsaw	Warsaw	Warsaw
EW scheme	Alpha	Alpha	Alpha	-	Alpha	mW	mW	Alpha
Flavor assumptions	$SU(3)^5$	$SU(3)^5$ $SU(2)^2 \times SU(3)^3$	$SU(3)^5$ $SU(2)^2 \times SU(3)^3$	$SU(3)^5$	$SU(3)^5$ general	$SU(2)^2 \times SU(3)^3$	$SU(2)^2 \times SU(3)^3$	$SU(3)^5$
NLO QCD included	LO	Top only	Top only	LO	LO	Top only	Vh, diboson, EWPO	EWPO only
Fitting procedure	Chi2	Bayesian	Toy MC, Chi2, Bayesian	Chi2	Bayesian	Toy MC	Chi2	Bayesian
Uncertainties	Gaussian, theory correlated	Gauss	Gauss, Poisson, flat	Gauss	(Asymmetric) Gauss, flat	Gauss	Gauss, uncorrelated	Gauss
UV complete model fits	✗	✓	✓	✓	✓	✗	✓	✓
Specialties	VV + DY	Higgs + EWPO + top + diboson	Correlation of uncertainty classes	Top	Projections	CP odd operators VBS	NLO for VV and Vh	UV complete models
References	1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828	1404.3667, 1803.03252, 2012.02779	1308.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606	1506.08845, 1512.03360, 1901.03164	1710.0540, 1905.03764, 1907.04311, 1910.14012	1901.05965, 1906.05296, 2101.03180	2007.01296	2009.13394, 2010.04088, 2012.03839, 2111.05876

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Linear/ quadratic	Both	Linear	Both	Linear	Linear	Both	Linear	Linear
Basis	HISZ	Warsaw	HISZ (Higgs) Warsaw (top)	Warsaw	Warsaw	Warsaw	Warsaw	Warsaw
EW scheme	Alpha	Alpha	Alpha		Alpha	mW	mW	Alpha
Uncertainties	correlated	Gauss	flat	Gauss	Gauss, flat	Gauss	uncorrelated	Gauss
UV complete model fits	✗	✓	✓	✓	✓	✗	✓	✓
Specialties	VV + DY	Higgs + EWPO + top + diboson	Correlation of uncertainty classes	Top	Projections	CP odd operators VBS	NLO for VV and Vh	UV complete models
References	1211.4580, 1509.01585, 1805.11108, 1812.01009, 2108.04828	1404.3667, 1803.03252, 2012.02779	1308.1979, 1505.05516, 1604.03105, 1812.07587, 1910.03606	1506.08845, 1512.03360, 1901.03164	1710.0540, 1905.03764, 1907.04311, 1910.14012	1901.05965, 1906.05296, 2101.03180	2007.01296	2009.13394, 2010.04088, 2012.03839, 2111.05876

Many groups contribute to the field.
Each of them has their own strength.

Dim-8 effects in specific UV models

- Heavy U(1) boson mixing with B, vector-triplet model contributions to EWPD

  [Corbett, Helset, Martin, Trott (2102.02819)]

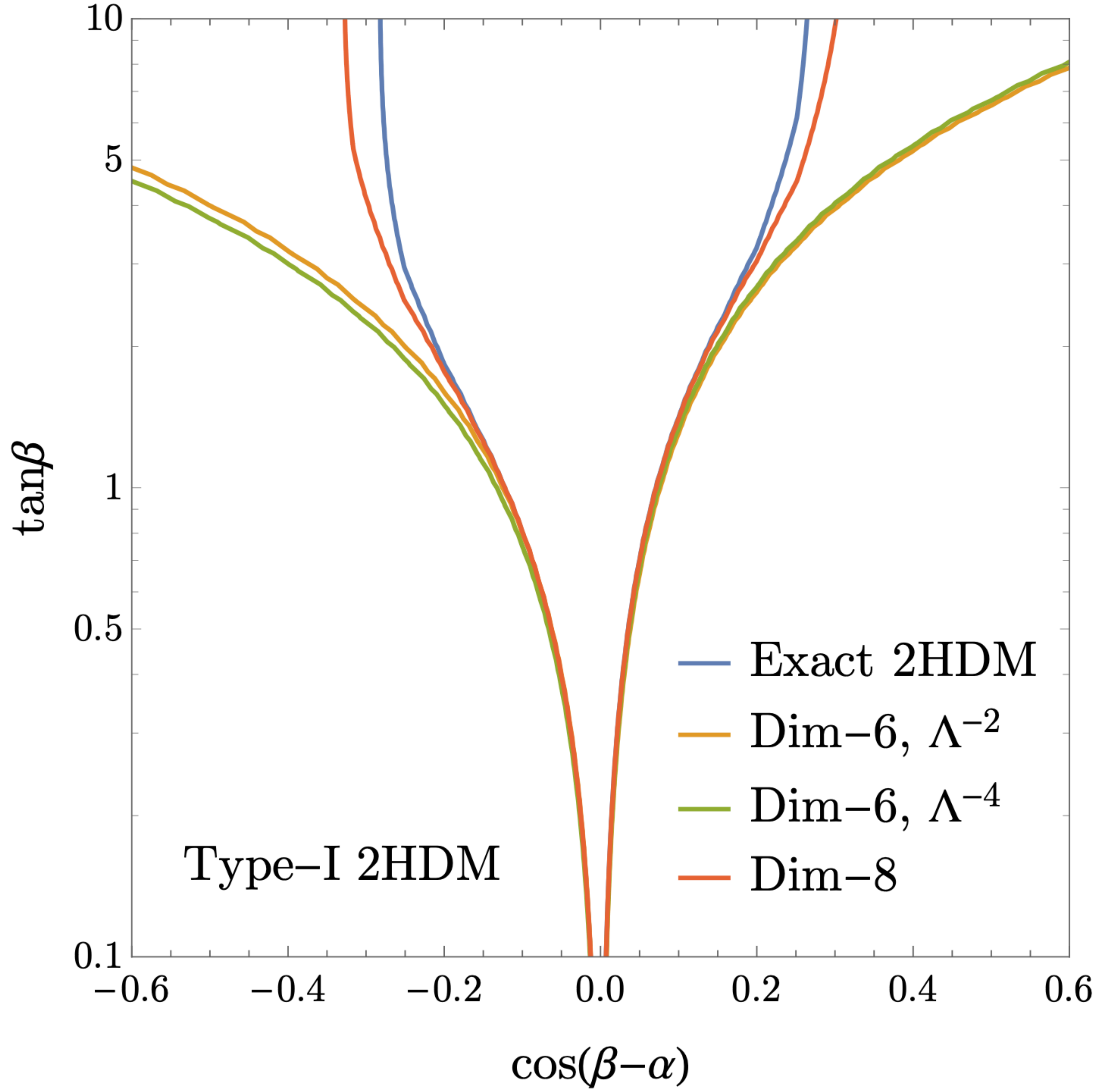
- vector-like top partner contribution to tth: O(1%)

  [Dawson, Homiller, Sullivan (2110.06929)]

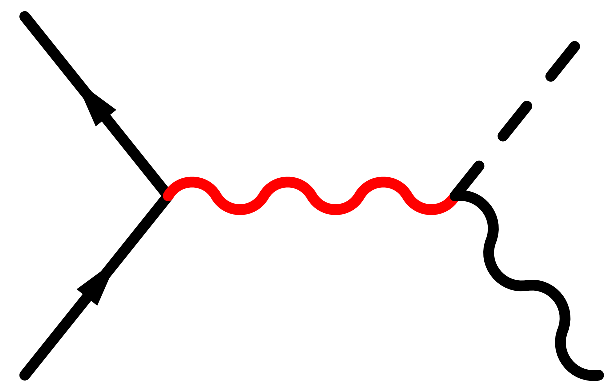
- Size of effects depends on input parameter shifts
- 2HDM: improved description of UV limits when including dim8

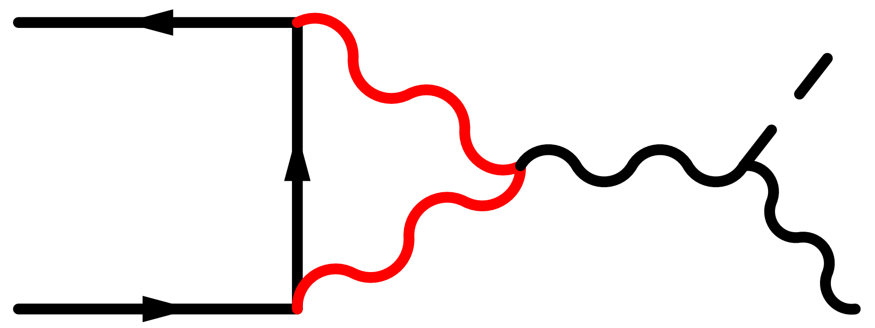
  [Dawson, Fontes, Homiller, Sullivan (2205.01561)]

[Dawson et al. (2205.01561)] 95% CL



Top down - matching of a new model



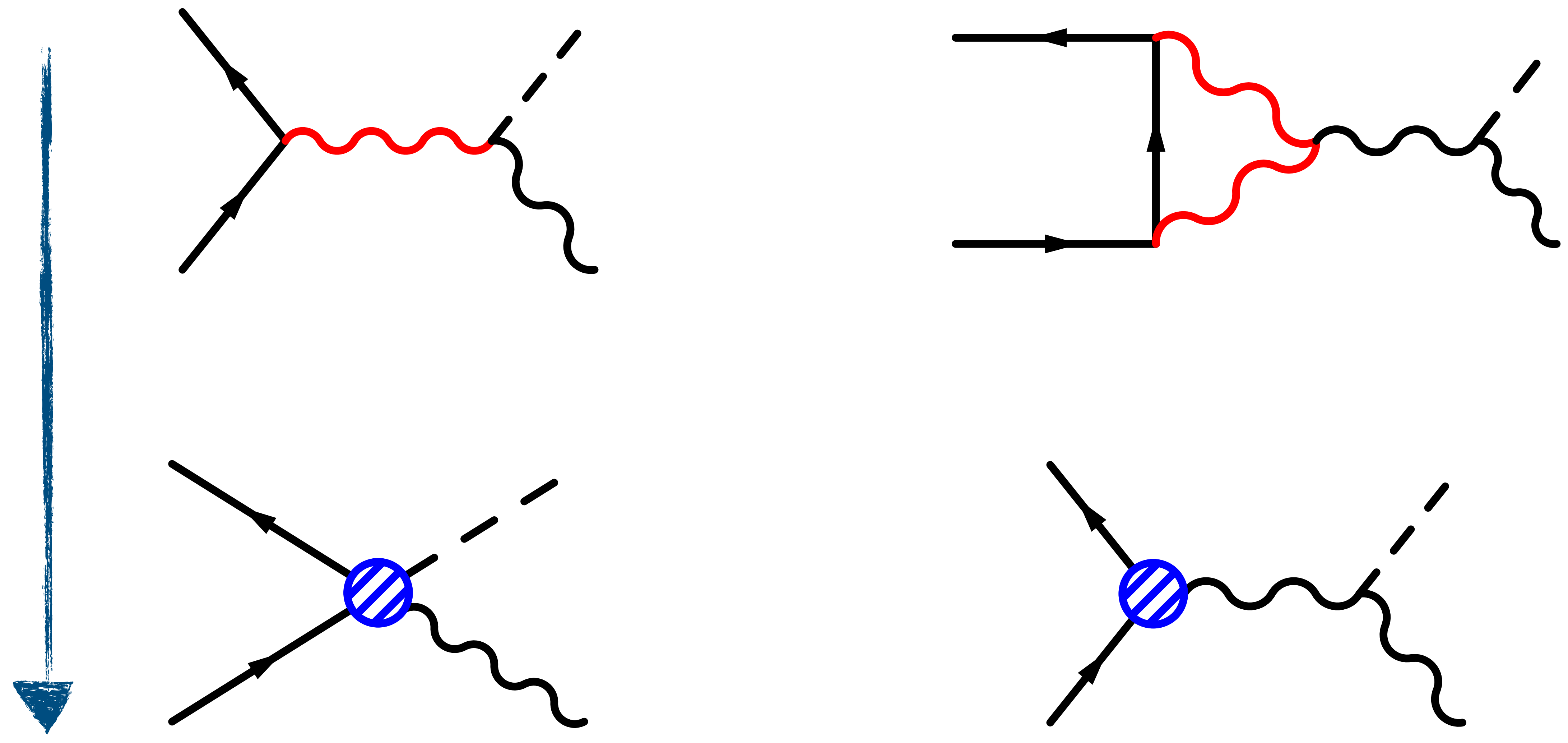


Tree level | One loop

Model with new heavy vector boson

Start from full UV-complete model and match onto EFT

Top down - matching of a new model



Tree level   One loop

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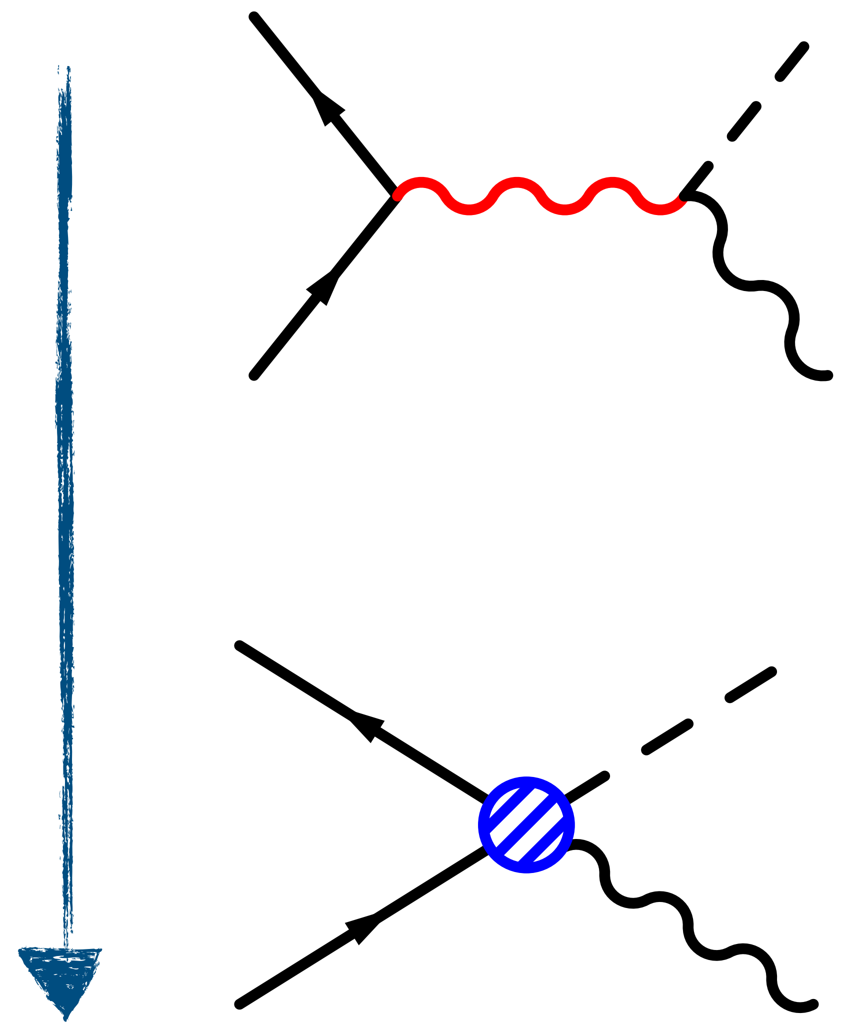
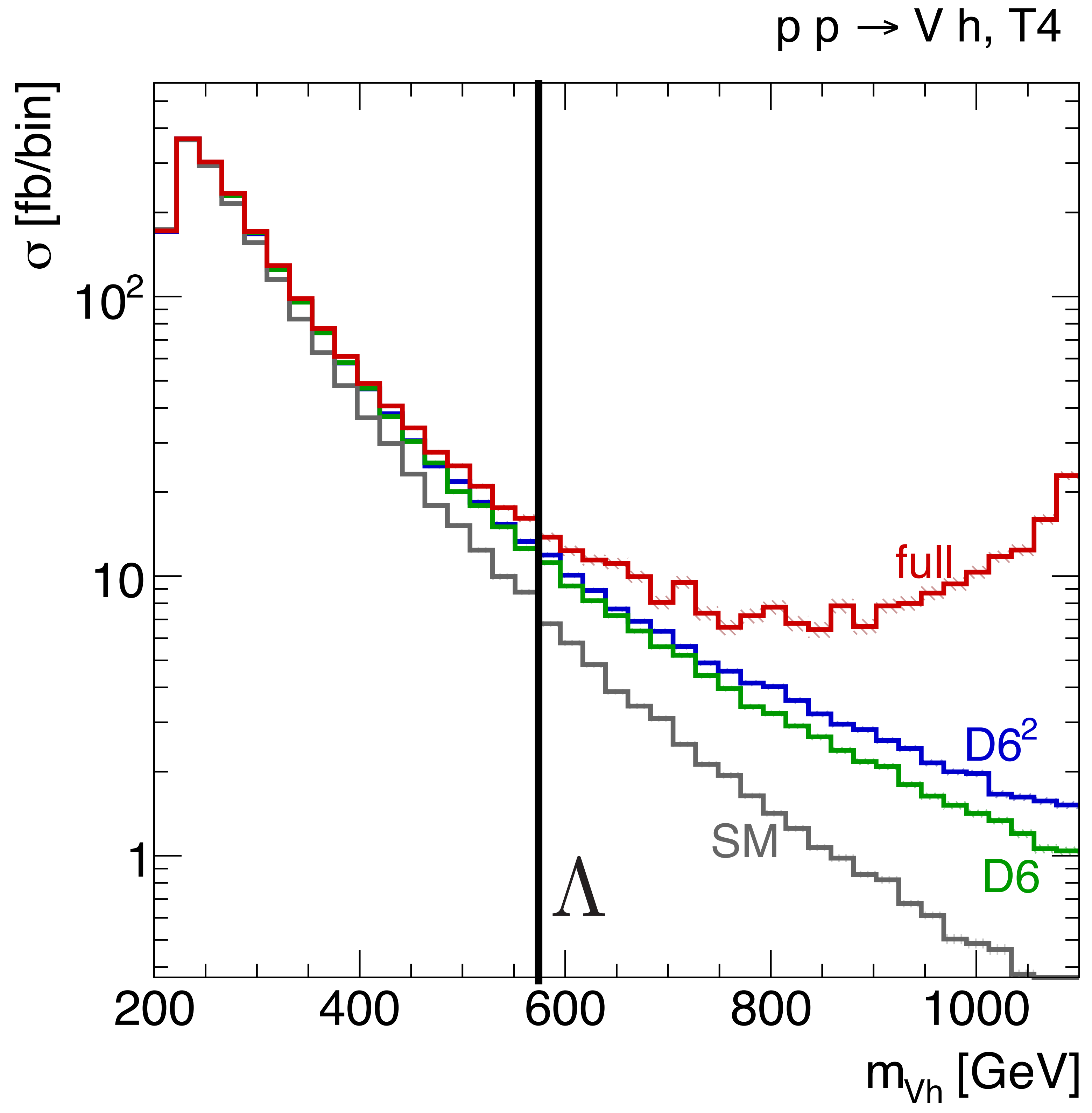


Tree level



Model with new heavy vector boson

Start from full UV-complete model and match onto EFT

Two Higgs doublet model

$$\mathcal{L}_{\mathcal{H}_2} = \mathcal{L}_{\text{SM}}^{d\leq 4} + |\mathcal{D}_\mu \mathcal{H}_2|^2 - m_{\mathcal{H}_2}^2 |\mathcal{H}_2|^2 - \frac{\lambda_{\mathcal{H}_2}}{4}|\mathcal{H}_2|^4$$
$$- (\eta_H |\widetilde{H}|^2 + \eta_{\mathcal{H}_2}|\mathcal{H}_2|^2)(\widetilde{H}^\dagger \mathcal{H}_2 + \mathcal{H}_2^\dagger \widetilde{H})$$
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$$- \left\{ Y_{\mathcal{H}_2}^{(e)} \bar{l}_L \widetilde{\mathcal{H}}_2 e_R + Y_{\mathcal{H}_2}^{(u)} \bar{q}_L \mathcal{H}_2 u_R + Y_{\mathcal{H}_2}^{(d)} \bar{q}_L \widetilde{\mathcal{H}}_2 d_R + \text{h.c.} \right\}.$$

CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]

Higgs

$$C_{HB} = \frac{g_Y^2}{384\pi^2 m_{\mathcal{H}_2}^2}\left(\lambda_{\mathcal{H}_2,1} + \frac{1}{2}\lambda_{\mathcal{H}_2,2}\right)$$

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EWPO

$$C_{HWB} = \frac{g_W g_Y}{384\pi^2 m_{\mathcal{H}_2}^2}\lambda_{\mathcal{H}_2,2}$$

...

EWPO: Electroweak precision observables (mostly LEP data)

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

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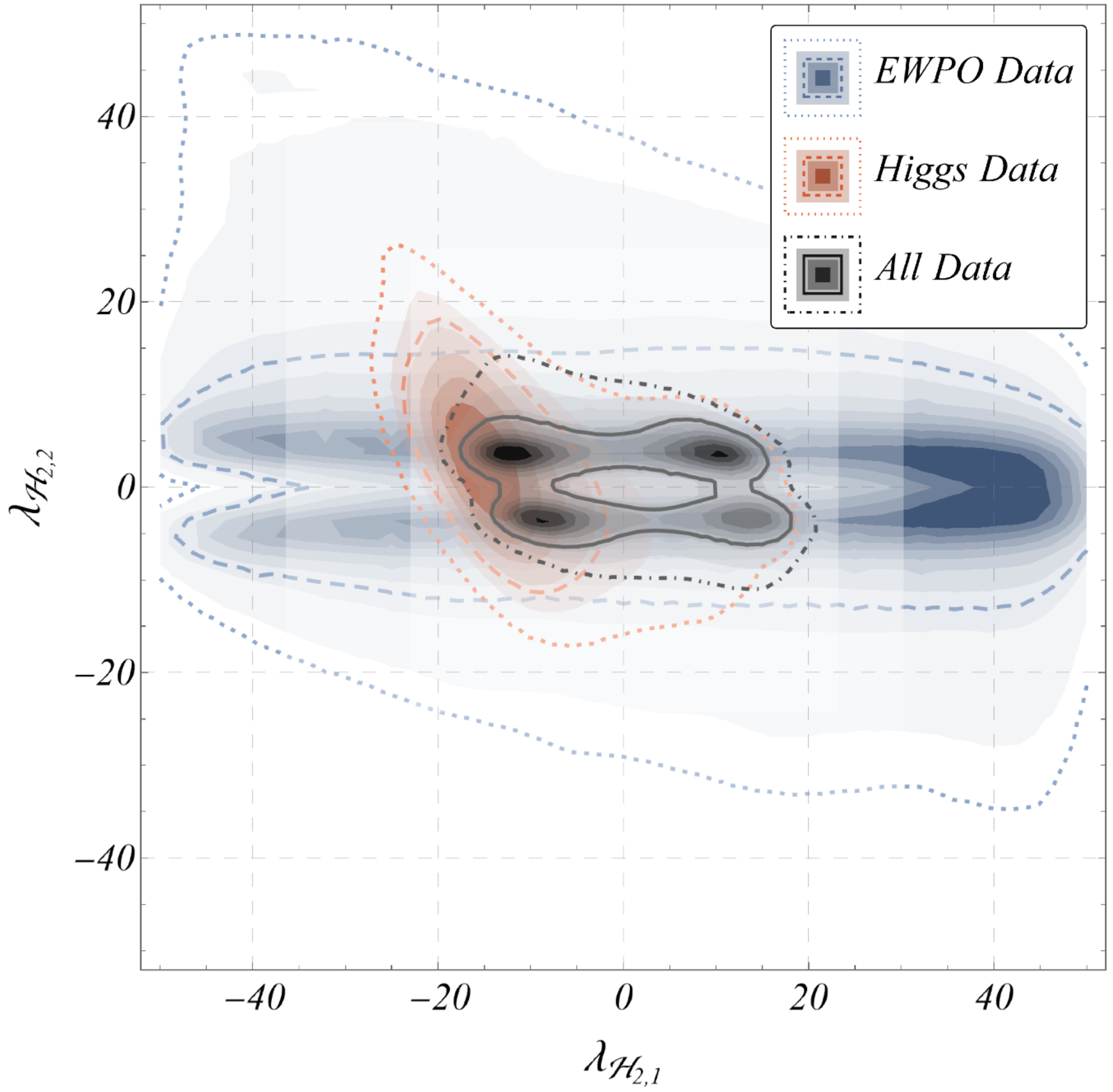
$\ldots$



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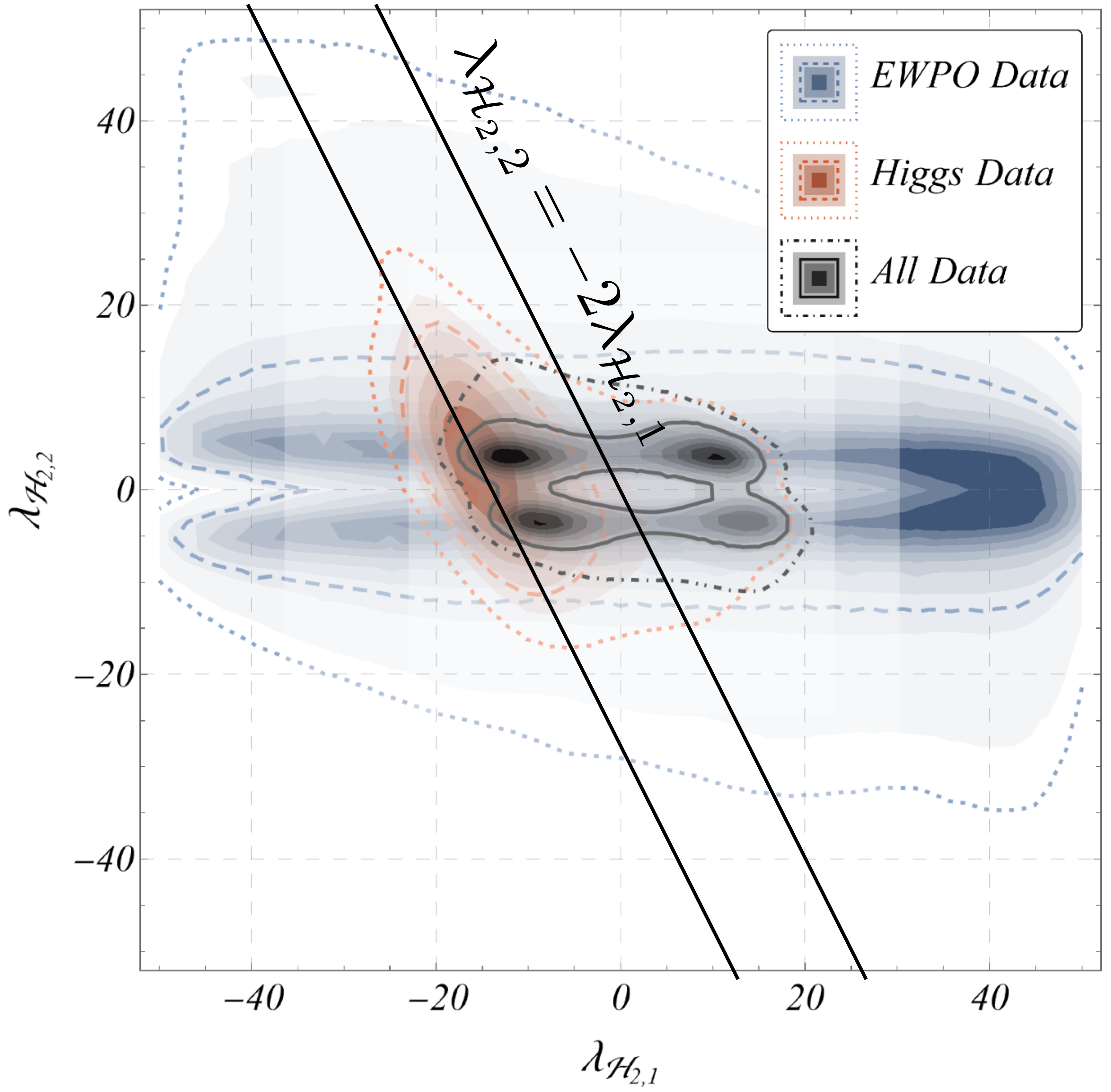

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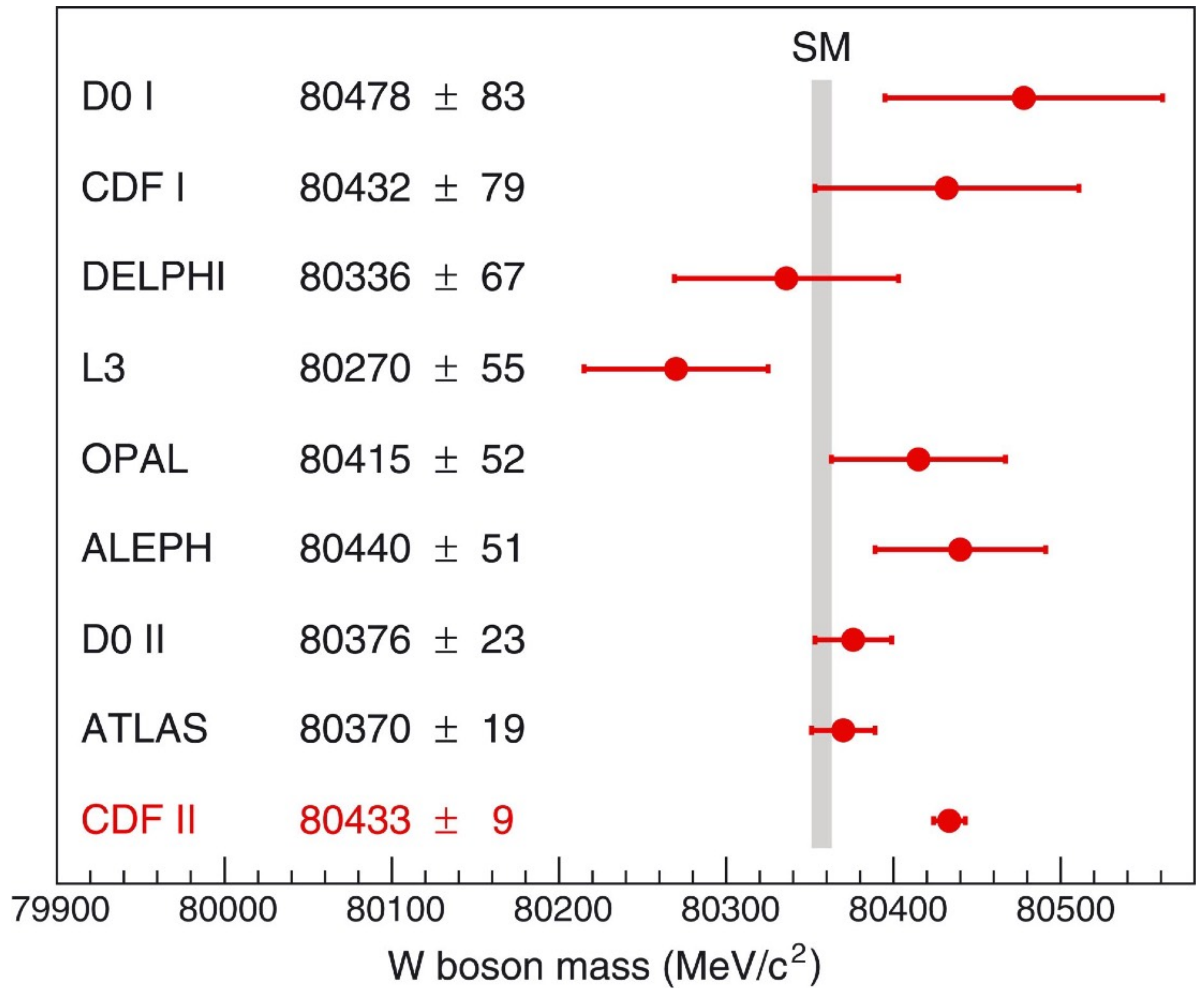
W boson mass - SMEFT interpretations

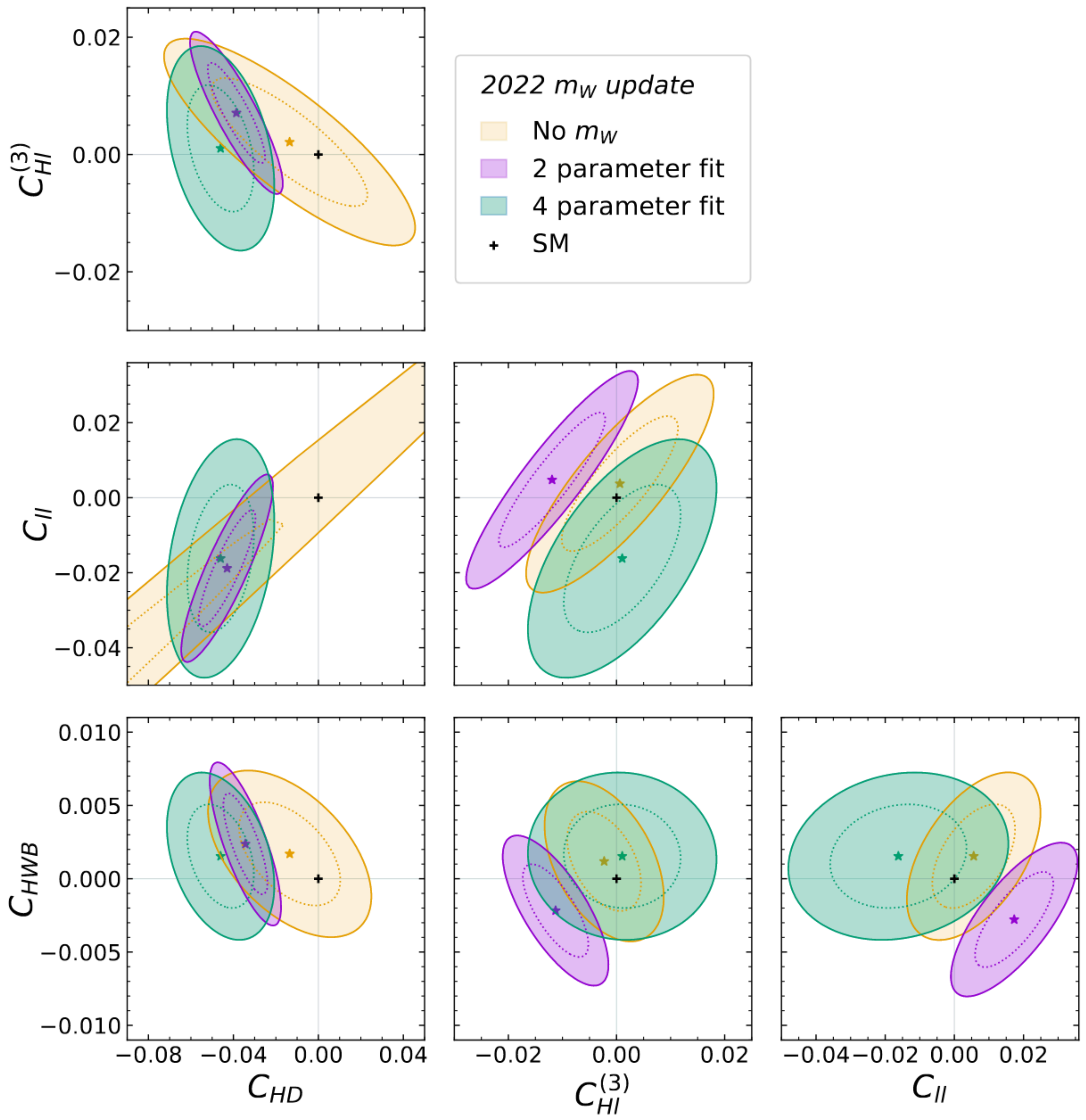
[CDF II (Science)]



global fits and SMEFT studies

[de Blas et al. (2204.04204)]
[Bagnaschi et al. (2204.05260)]
[Balkin, Madge et al. (2204.05992)]
[Almeida et al. (2204.10130)]
[many more (…)]

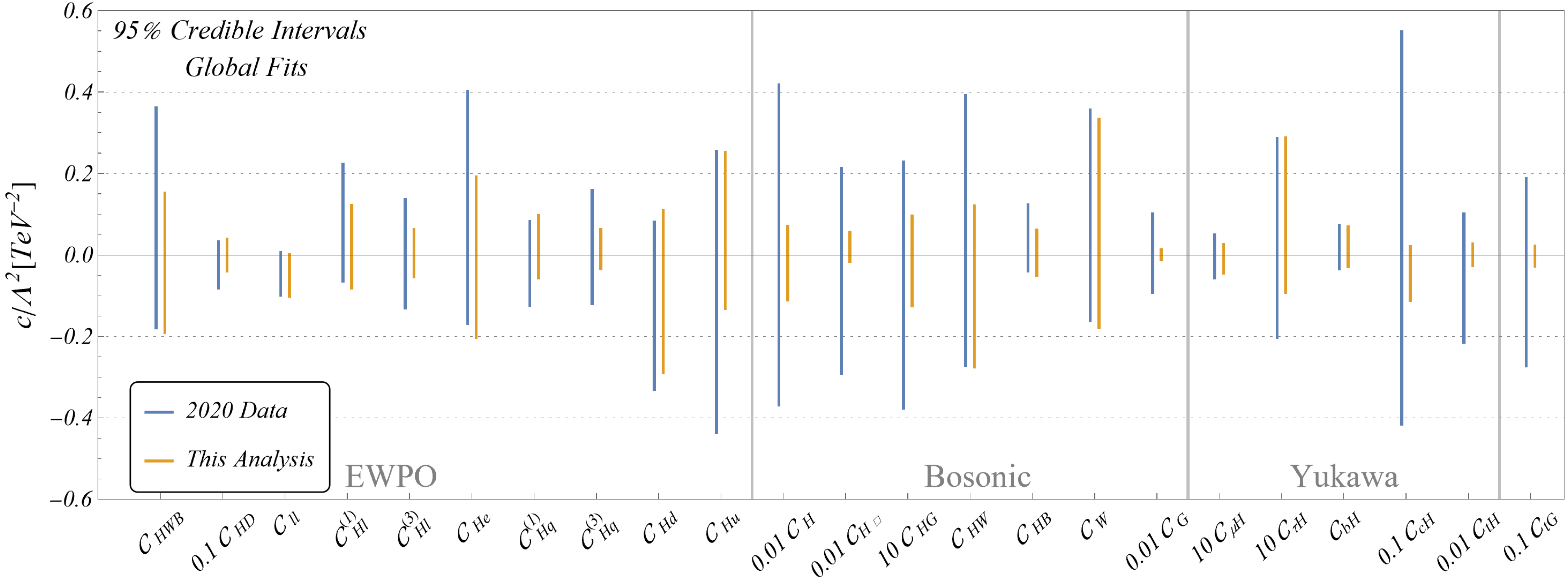
[Bagnaschi et al. (2204.05260)]



$\{\alpha_{EW}, G_F, M_Z\}$ scheme

$$\frac{\delta m_W^2}{m_W^2} = -\frac{s_{2W}}{4c_{2W}}\frac{v^2}{\Lambda^2}\left(\frac{c_W}{s_W}C_{HD} + \frac{s_W}{c_W}\left(4C_{Hl}^{(3)} - 2C_{ll}\right) + 4C_{HWB}\right)$$

LHC 2021 fit



Limits keep improving with more data - especially with more differential measurements

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

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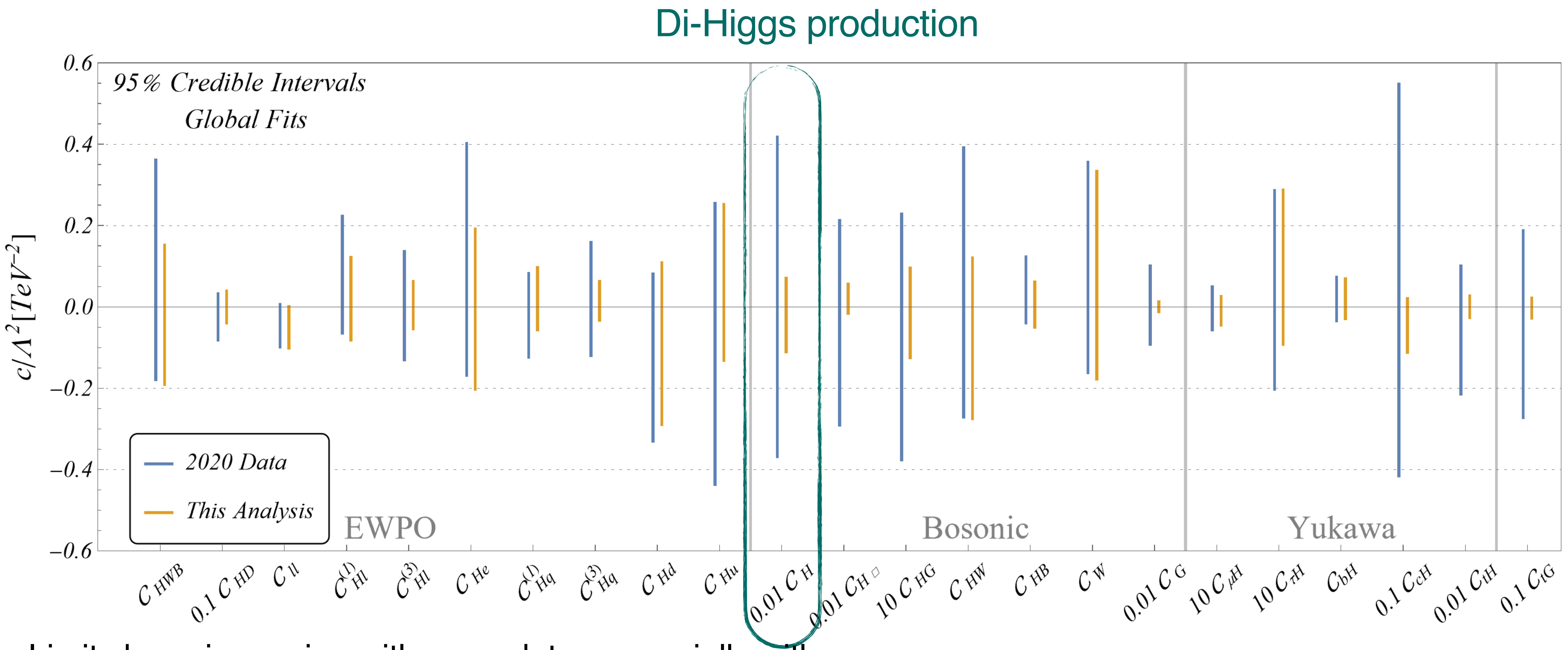

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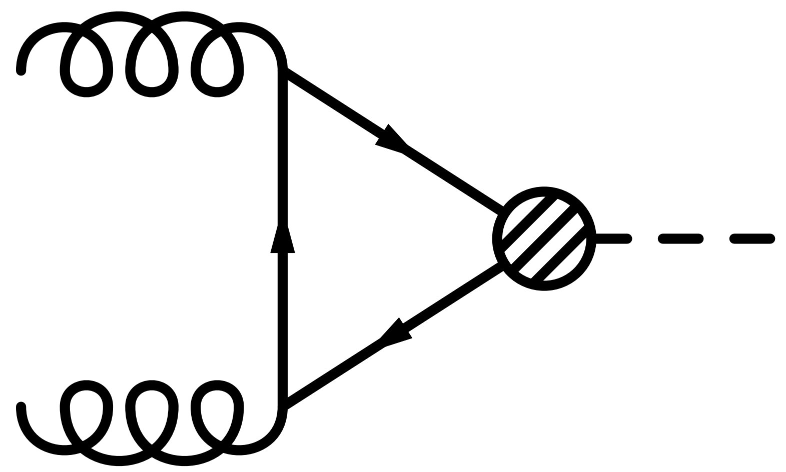
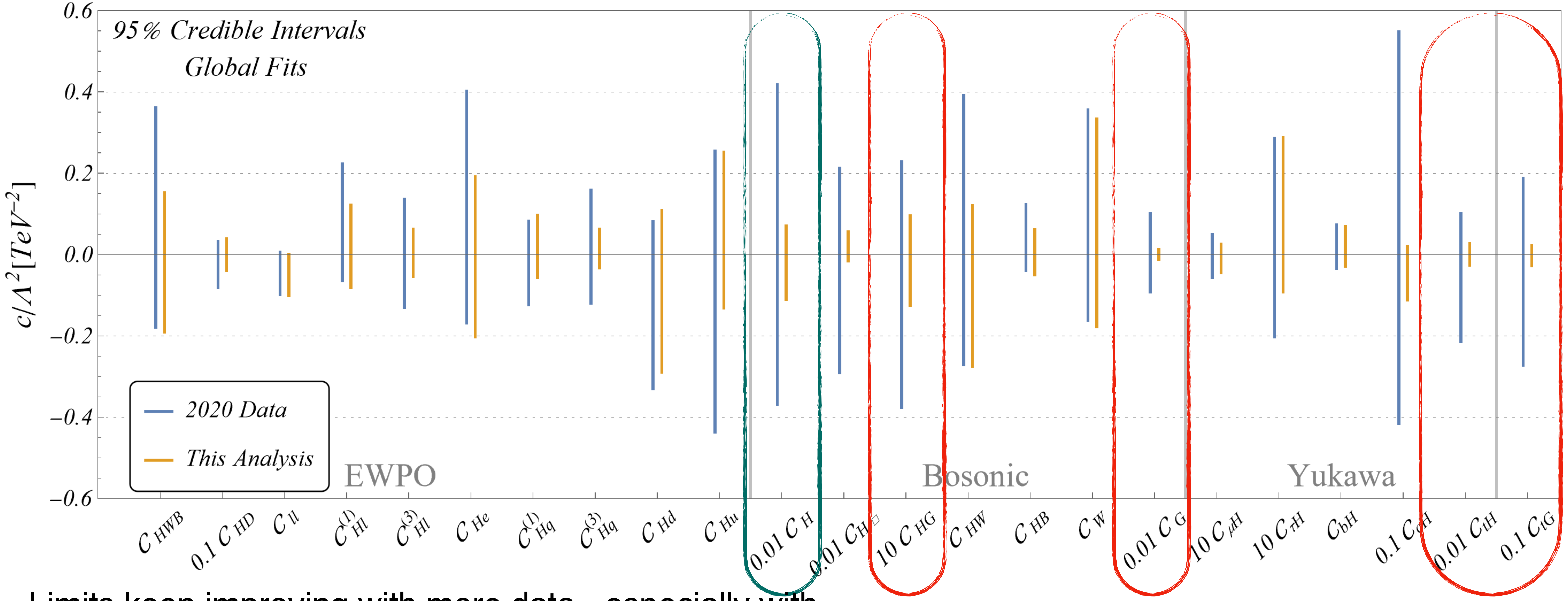


Di-Higgs production



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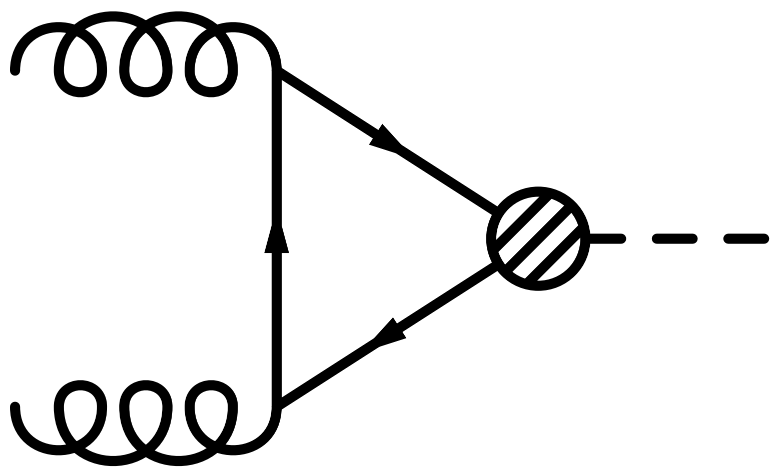

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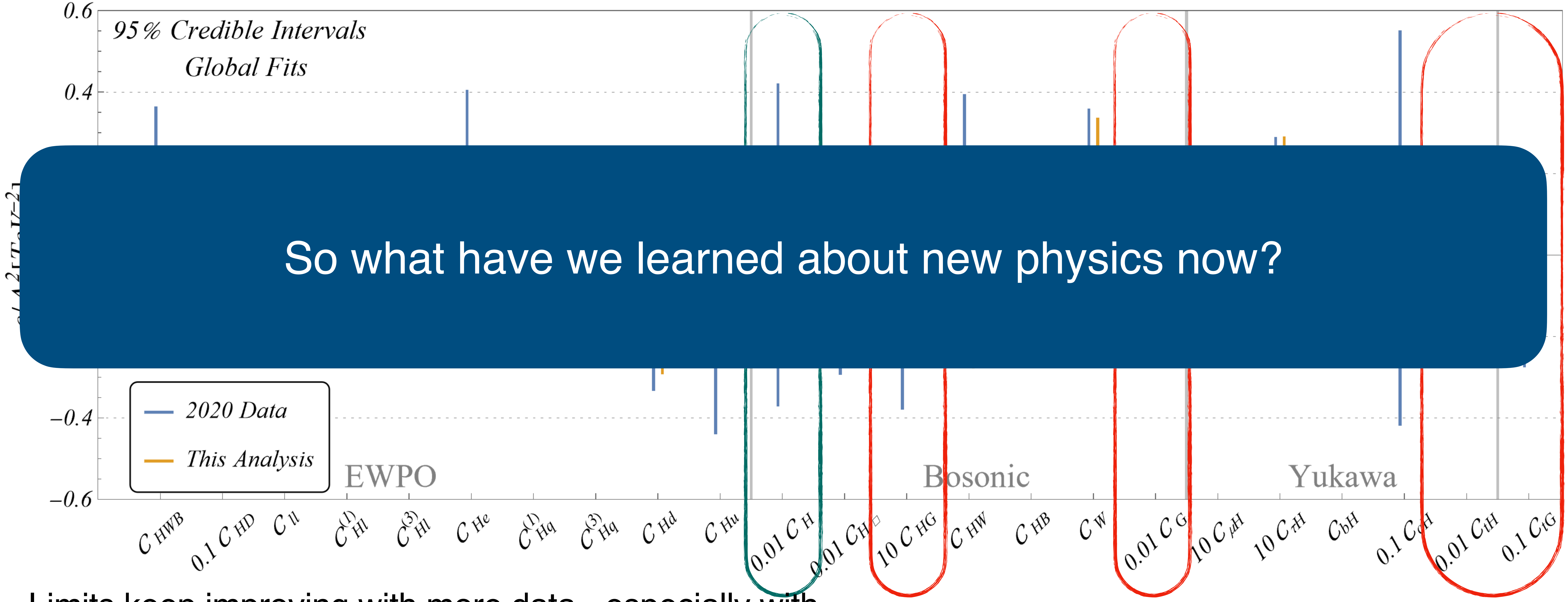

So what have we learned about new physics now?

Limits keep improving with more data - especially with more differential measurements

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

Two Higgs doublet model

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CoDEx [Bakshi, Chakrabortty, Patra (1808.04403)]

$$Q_{\rm HB} \to \frac{g_Y^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_Y^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$$
$$Q_{\rm HW} \to \frac{g_W^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_W^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$$
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Table 3: Warsaw basis effective operators and the associated WCs that emerge after integrating-out the heavy field $\mathcal{H}_2 : (1, 2, -\frac{1}{2})$. Operators highlighted in red do not affect our current set of observables and are thus absent from our analysis. Operators highlighted in blue are functions of SM parameters only, while the red coloured ones do not contribute to our observables.

Dim-6 Ops.	Wilson coefficients
$Q_{\rm dH}$	$\frac{\eta_H^2 Y_d^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_d^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{\eta_H Y_{\mathcal{H}_2}^{(d)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(d)}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(d)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_d^{\rm SM}}{192\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_{\mathcal{H}_2}^{(d)}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2 Y_d^{\rm SM}}{48\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm eH}$	$\frac{\eta_H^2 Y_e^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_e^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{\eta_H Y_{\mathcal{H}_2}^{(e)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(e)}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(e)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_e^{\rm SM}}{192\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_{\mathcal{H}_2}^{(e)}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2 Y_e^{\rm SM}}{48\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm uH}$	$\frac{\eta_H^2 Y_u^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(u)}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H Y_{\mathcal{H}_2}^{(u)}}{m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} Y_u^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(u)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1} Y_{\mathcal{H}_2}^{(u)}}{16\pi^2 m_{\mathcal{H}_2}^2}$ $- \frac{\eta_H \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(u)}}{4\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2} Y_{\mathcal{H}_2}^{(u)}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2 Y_u^{\rm SM}}{192\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{\lambda_{\mathcal{H}_2,3}^2 Y_u^{\rm SM}}{48\pi^2 m_{\mathcal{H}_2}^2} - \frac{5\eta_H \lambda_{\mathcal{H}_2,3} Y_{\mathcal{H}_2}^{(u)}}{8\pi^2 m_{\mathcal{H}_2}^2}$
Q_H	$\frac{3\eta_H^2 \lambda_{\mathcal{H}_2}}{32\pi^2 m_{\mathcal{H}_2}^2} + \frac{17\eta_H^2 \lambda_H^{\rm SM}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{\eta_H^2}{m_{\mathcal{H}_2}^2}$ $- \frac{3\eta_H^2 \lambda_{\mathcal{H}_2,1}}{4\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_H^{\rm SM}}{8\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,1}}{8\pi^2 m_{\mathcal{H}_2}^2}$ $- \frac{13\eta_H^2 \lambda_{\mathcal{H}_2,2}}{16\pi^2 m_{\mathcal{H}_2}^2} + \frac{3\eta_H \eta_{\mathcal{H}_2} \lambda_{\mathcal{H}_2,2}}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^3}{48\pi^2 m_{\mathcal{H}_2}^2}$ $\frac{\lambda_H^{\rm SM} \lambda_{\mathcal{H}_2,2}^2}{96\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^2 \lambda_{\mathcal{H}_2,2}}{32\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,2}^2}{32\pi^2 m_{\mathcal{H}_2}^2}$ $- \frac{7\eta_H^2 \lambda_{\mathcal{H}_2,3}}{4\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_H^{\rm SM} \lambda_{\mathcal{H}_2,3}^2}{24\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2}^3}{96\pi^2 m_{\mathcal{H}_2}^2}$ $- \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,3}^2}{8\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2} \lambda_{\mathcal{H}_2,3}^2}{8\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{H\Box}$	$- \frac{g_W^4}{7680\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\eta_H^2}{32\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,1}^2}{96\pi^2 m_{\mathcal{H}_2}^2}$ $- \frac{\lambda_{\mathcal{H}_2,1} \lambda_{\mathcal{H}_2,2}}{96\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,2}^2}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2}{96\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm HD}$	$- \frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2} - \frac{\lambda_{\mathcal{H}_2,2}^2}{96\pi^2 m_{\mathcal{H}_2}^2} + \frac{\lambda_{\mathcal{H}_2,3}^2}{24\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm HB}$	$\frac{g_Y^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_Y^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm HW}$	$\frac{g_W^2 \lambda_{\mathcal{H}_2,1}}{384\pi^2 m_{\mathcal{H}_2}^2} + \frac{g_W^2 \lambda_{\mathcal{H}_2,2}}{768\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm HWB}$	$\frac{g_W g_Y \lambda_{\mathcal{H}_2,2}}{384\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm Hl}}^{(1)}$	$\frac{g_Y^4}{3840\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm Hq}}^{(1)}$	$- \frac{g_Y^4}{11520\pi^2 m_{\mathcal{H}_2}^2}$

Dim-6 Ops.	Wilson coefficients
$Q_{\rm Hd}$	$\frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm He}$	$\frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm Hu}$	$- \frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm Hl}}^{(3)}$	$- \frac{g_W^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm Hq}}^{(3)}$	$- \frac{g_W^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
Q_W	$\frac{g_W^3}{5760\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm ll}$	$- \frac{g_W^4}{7680\pi^2 m_{\mathcal{H}_2}^2} - \frac{g_Y^4}{7680\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm ud}}^{(1)}$	$\frac{g_Y^4}{4320\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm lq}}^{(3)}$	$- \frac{g_W^4}{3840\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm qq}}^{(3)}$	$- \frac{g_W^4}{7680\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm dd}$	$- \frac{g_Y^4}{17280\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm ed}$	$- \frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm ee}$	$- \frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm eu}$	$\frac{g_Y^4}{1440\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm uu}$	$- \frac{g_Y^4}{4320\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm lu}$	$\frac{g_Y^4}{2880\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm qe}$	$\frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm ld}$	$- \frac{g_Y^4}{5760\pi^2 m_{\mathcal{H}_2}^2}$
${Q_{\rm qq}}^{(1)}$	$- \frac{g_Y^4}{69120\pi^2 m_{\mathcal{H}_2}^2}$
$Q_{\rm le}$	$- \frac{g_Y^4}{1920\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(e)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(e)2}}{4m_{\mathcal{H}_2}^2}$
${Q_{\rm qd}}^{(1)}$	$\frac{g_Y^4}{17280\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(d)2}}{4m_{\mathcal{H}_2}^2}$
${Q_{\rm qu}}^{(1)}$	$- \frac{g_Y^4}{8640\pi^2 m_{\mathcal{H}_2}^2} - \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(u)2}}{128\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(u)2}}{4m_{\mathcal{H}_2}^2}$
${Q_{\rm quqd}}^{(1)}$	$- \frac{3\lambda_{\mathcal{H}_2} Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(u)}}{64\pi^2 m_{\mathcal{H}_2}^2} - \frac{Y_{\mathcal{H}_2}^{(d)} Y_{\mathcal{H}_2}^{(u)}}{2m_{\mathcal{H}_2}^2}$
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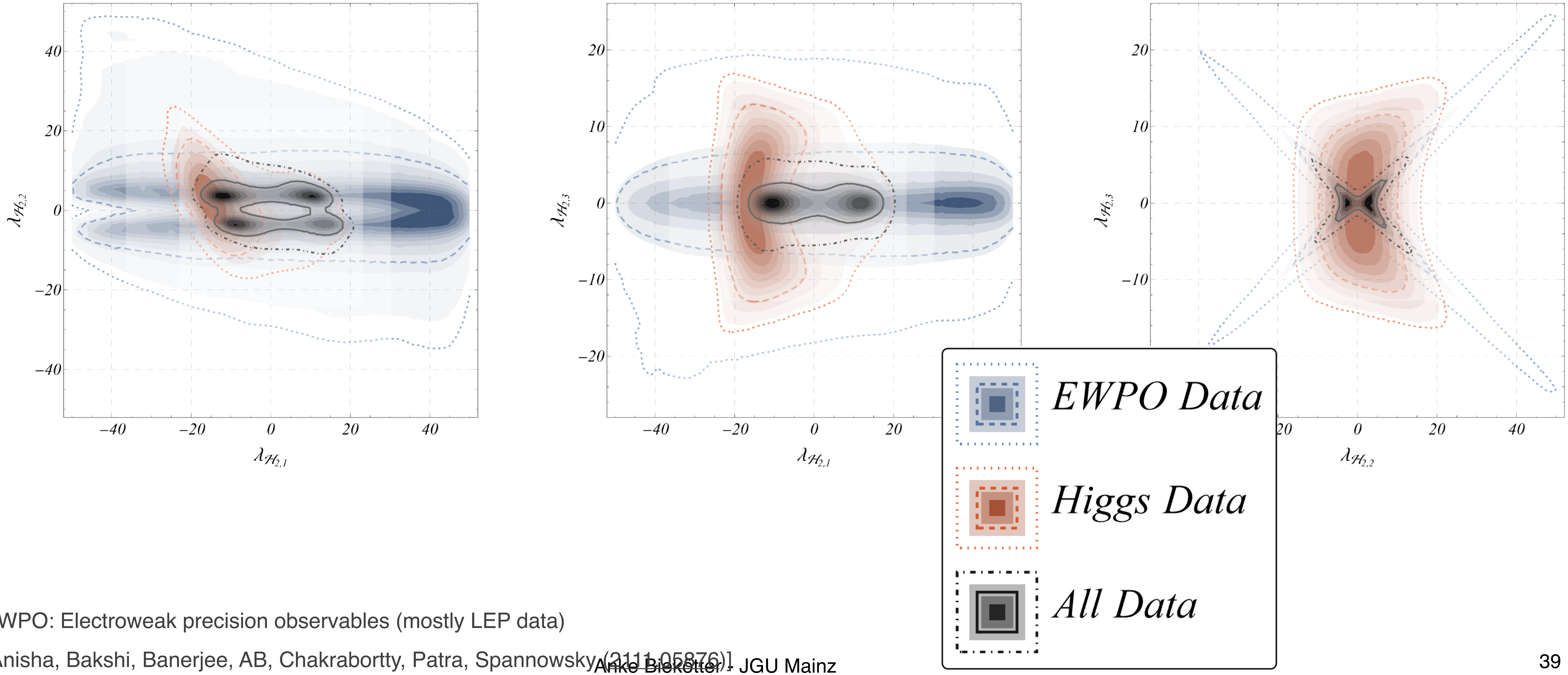
[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

Constraints on two Higgs doublet model



EWPO: Electroweak precision observables (mostly LEP data)

[Anisha, Bakshi, Banerjee, AB, Chakrabortty, Patra, Spannowsky (2111.05876)]

$1/\Lambda^4$ effects

- Large number of dim8 operators

  (Wh production: 66 dim8 operators)
- Focus on dim8 operators induced in matching of specific UV-complete models in a specific process

  (few parameters, relation between WCs)
- Or: all dim8 operators have the same magnitude

  Wh: O(10%) effect

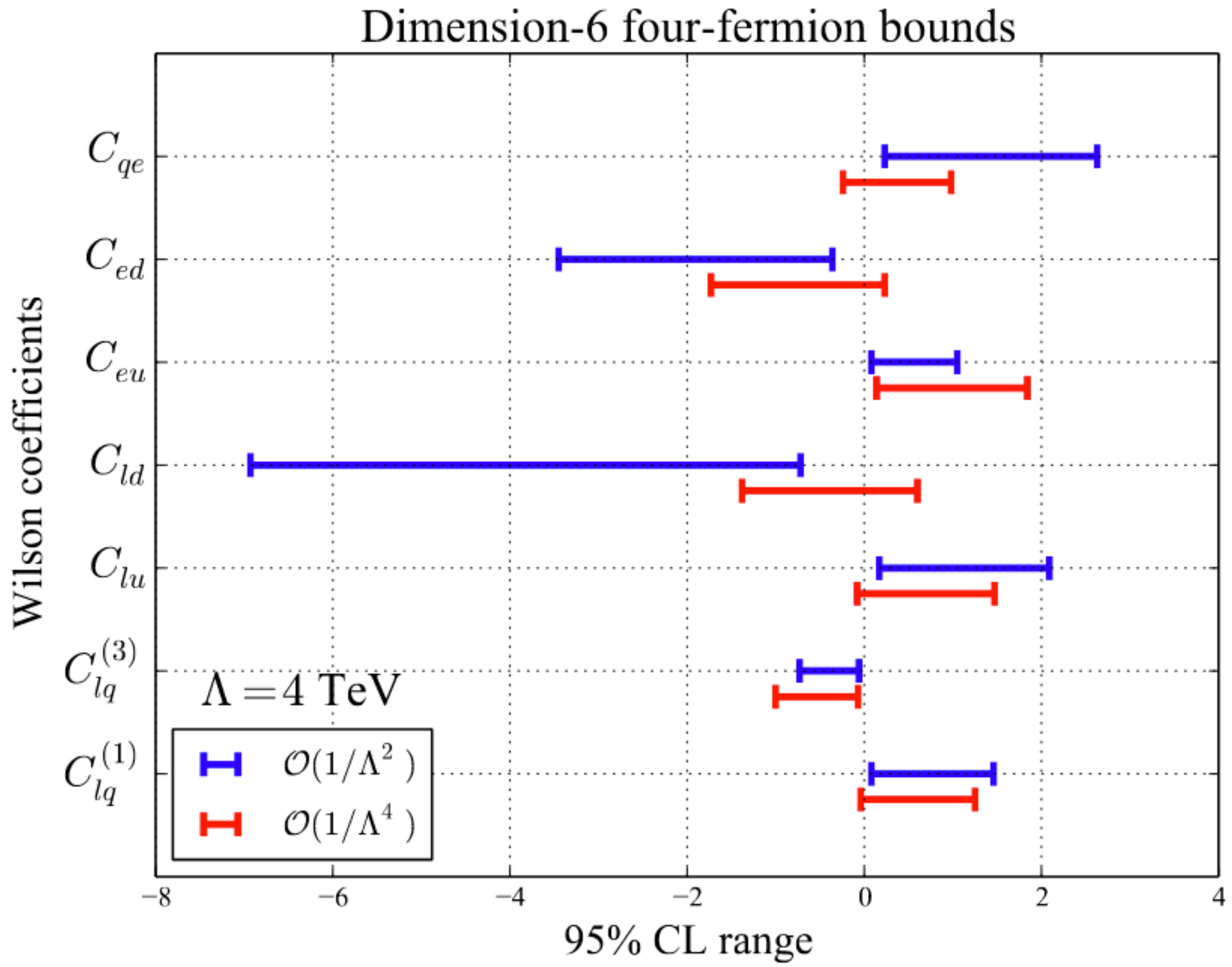
  [Hays, Martin, Sanz, Setford (1808.00442)]

[Bougheza, Mereghetti, Petriello (2106.05337)]

Dilepton production,

single operator fits,

inclusion of dim6 squared terms



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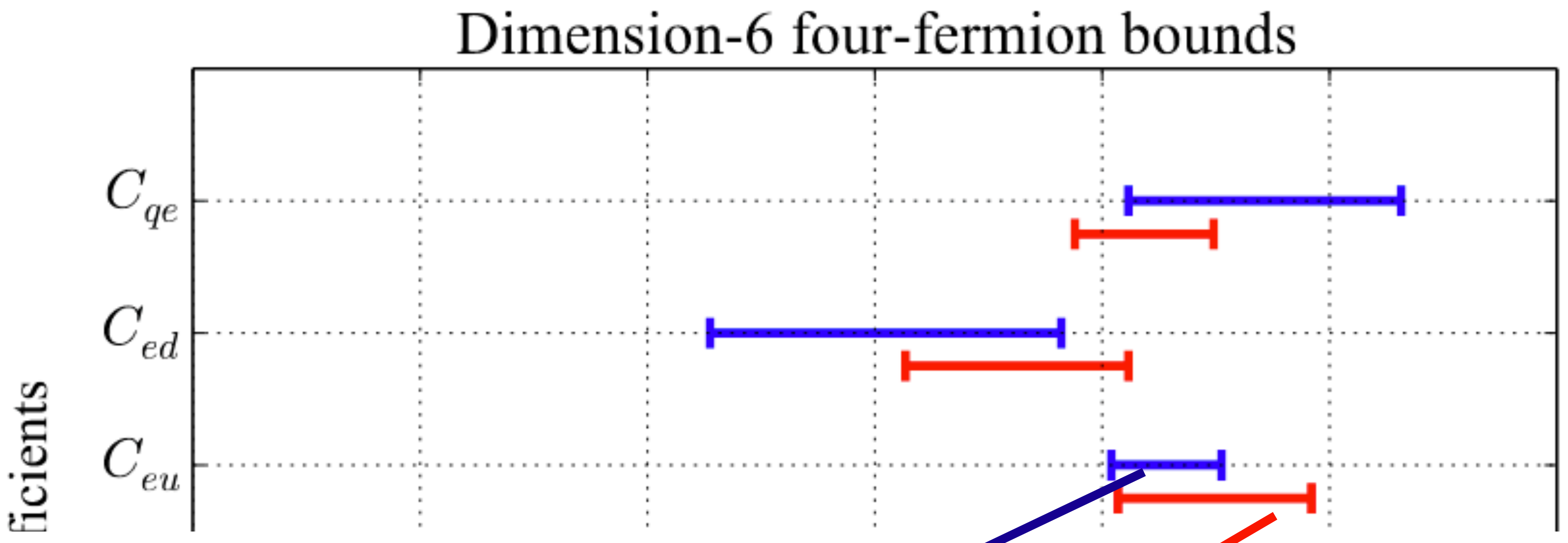

	dim-6	single coupling	marginalized	marginalized*
C_{eu}	$[0.08, 1.0]$	$[0.1, 1.8]$	$[-39, 39]$	$[-0.6, 2.4]$
$C_{e^2u^2D^2}$	–	$[-1.5, 13]$	$[-17, 9.2 \cdot 10^3]$	$[-14, 18]$
$C_{e^2u^2H^2}$	–	$[45, 555]$	$[-1.9, 1.2] \cdot 10^4$	$[-256, 256]$
$C^{(1)-(2)}_{u^2H^2D^3}$	–	$[-24, -1.8] \cdot 10^3$	$[-1.2, 1.8] \cdot 10^5$	$[-256, 256]$

Global fit

with 4 operators

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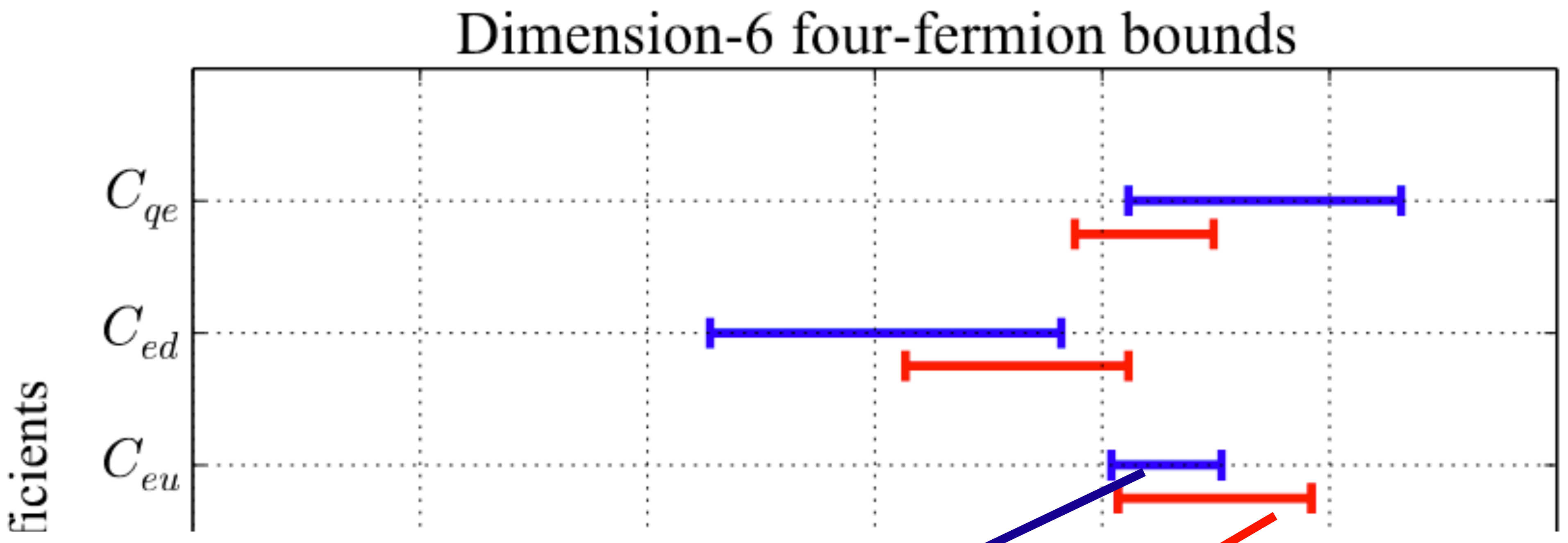

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Including NLO QCD corrections

[MG: Degrande et al. (2008.11743)]
Top sector fits including NLO QCD:
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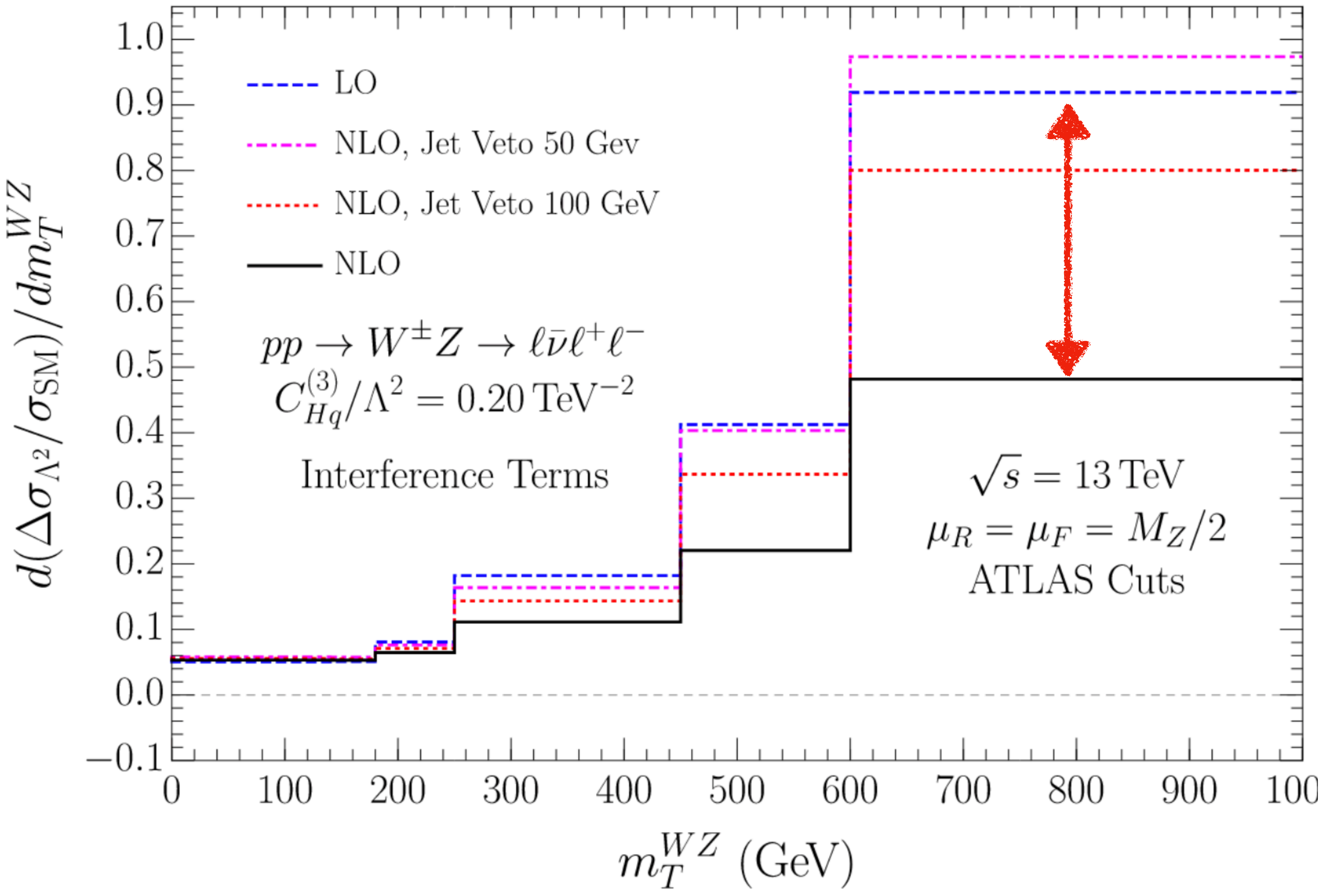
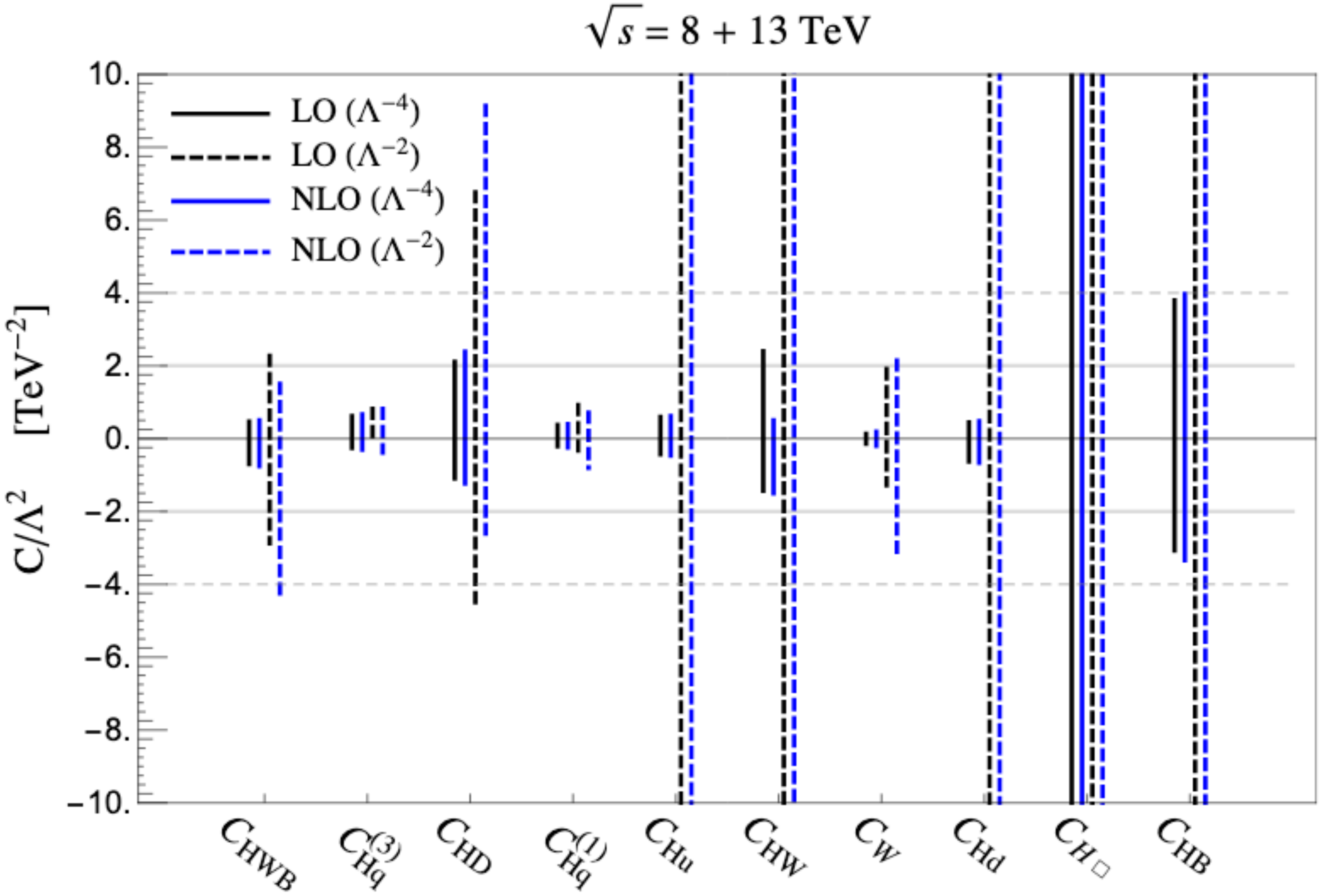
SMEFT @ NLO, e.g. NLO QCD for diboson + Vh





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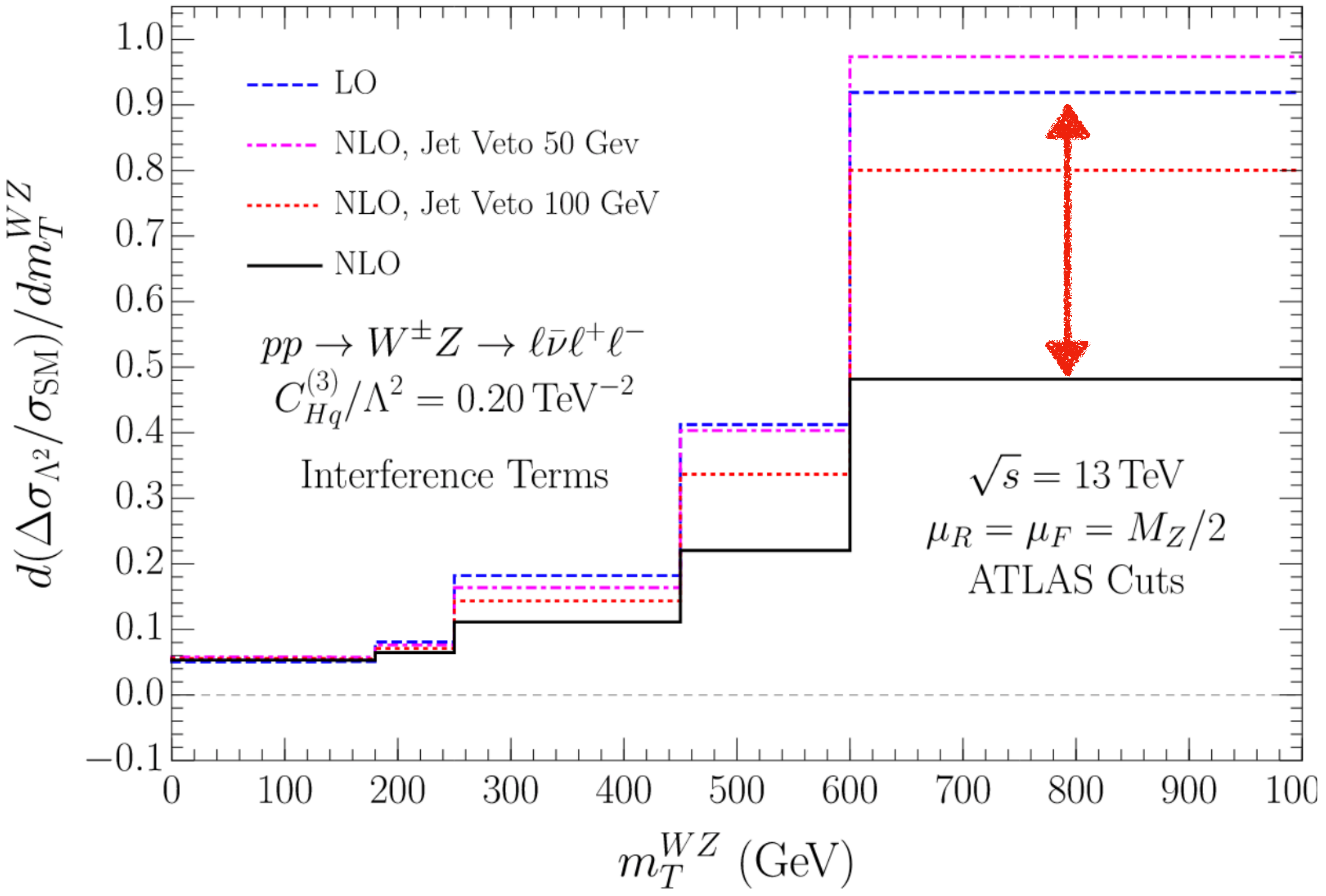

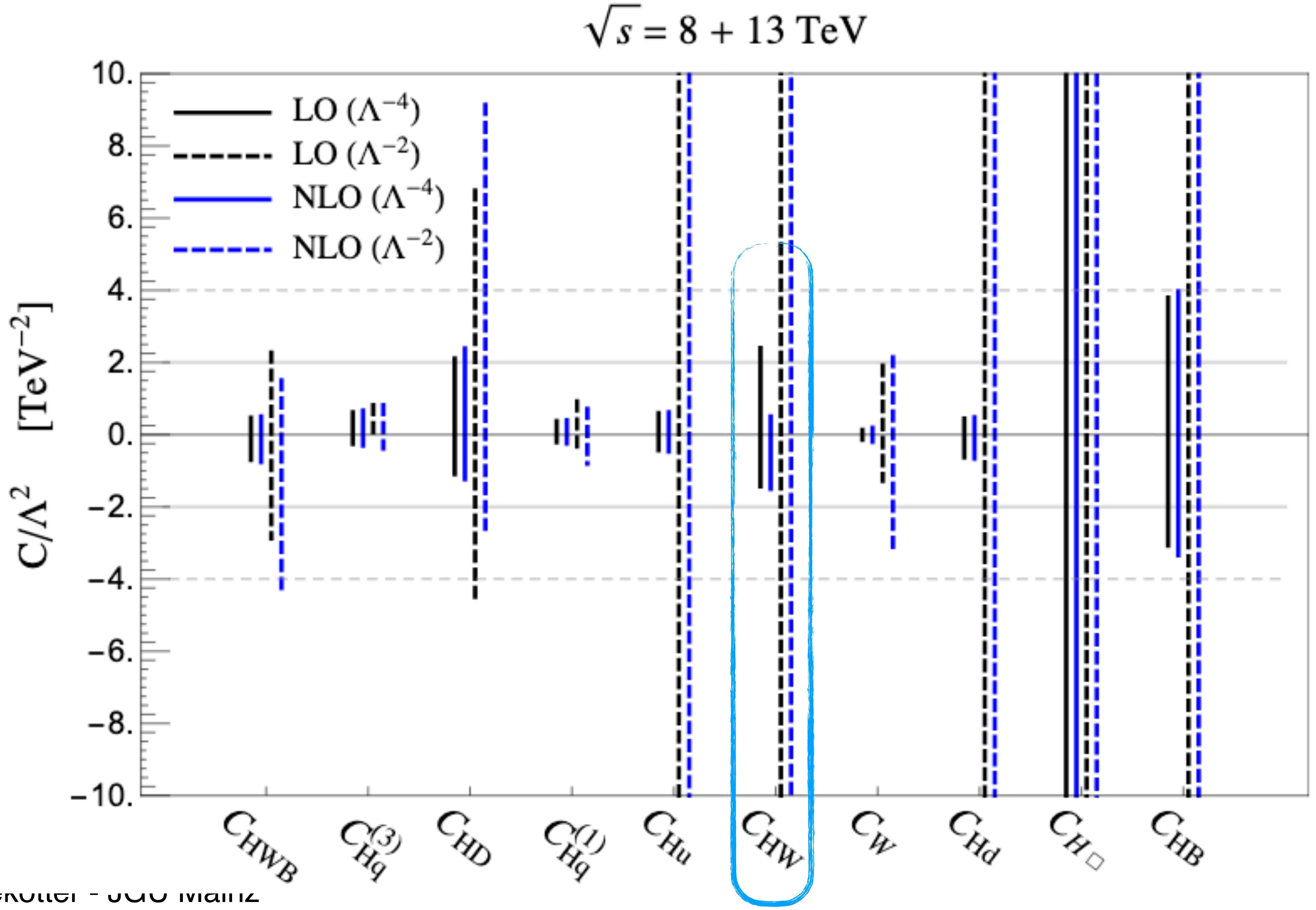

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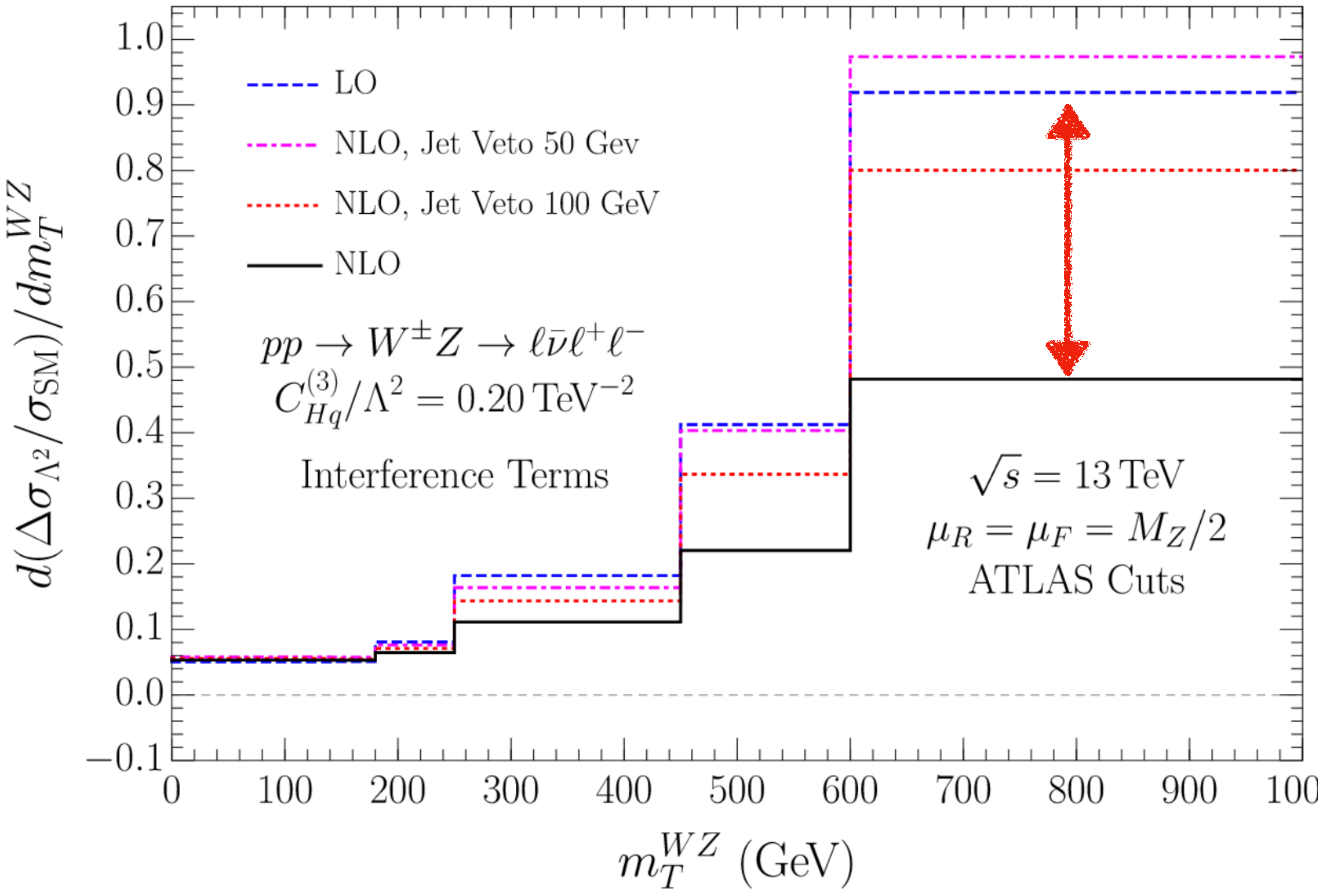

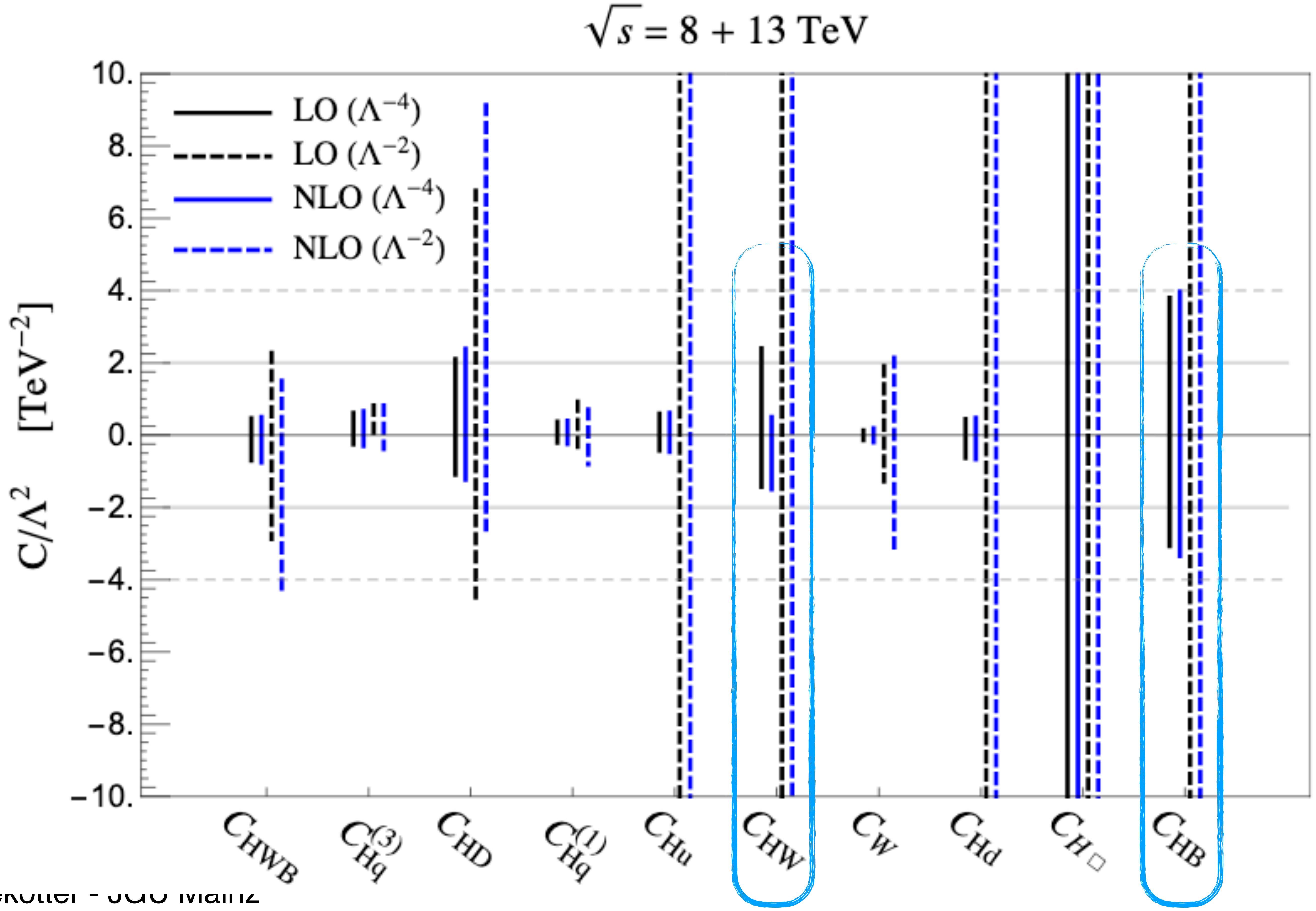

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Combining more sectors

Combining different sectors, e.g. top + Higgs

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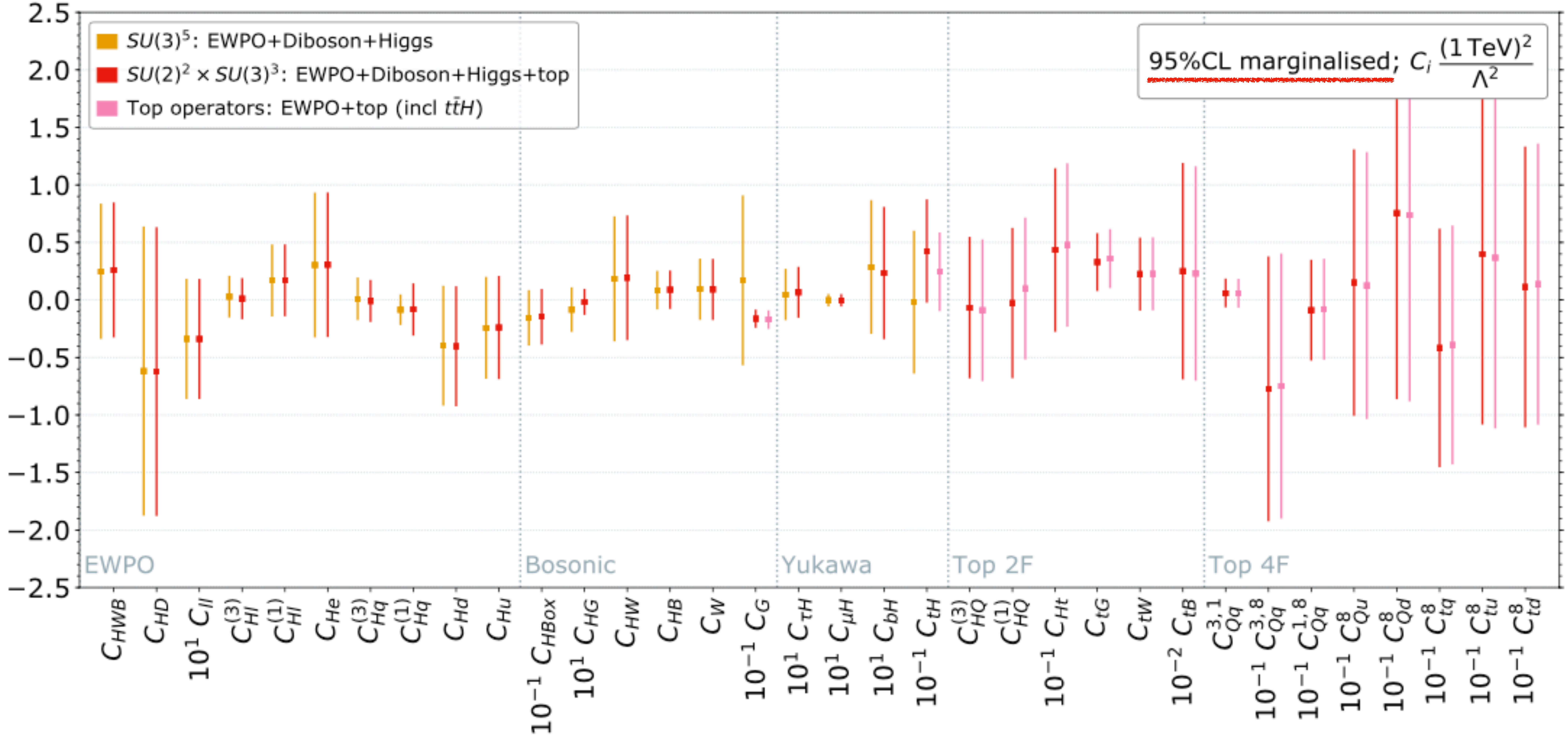

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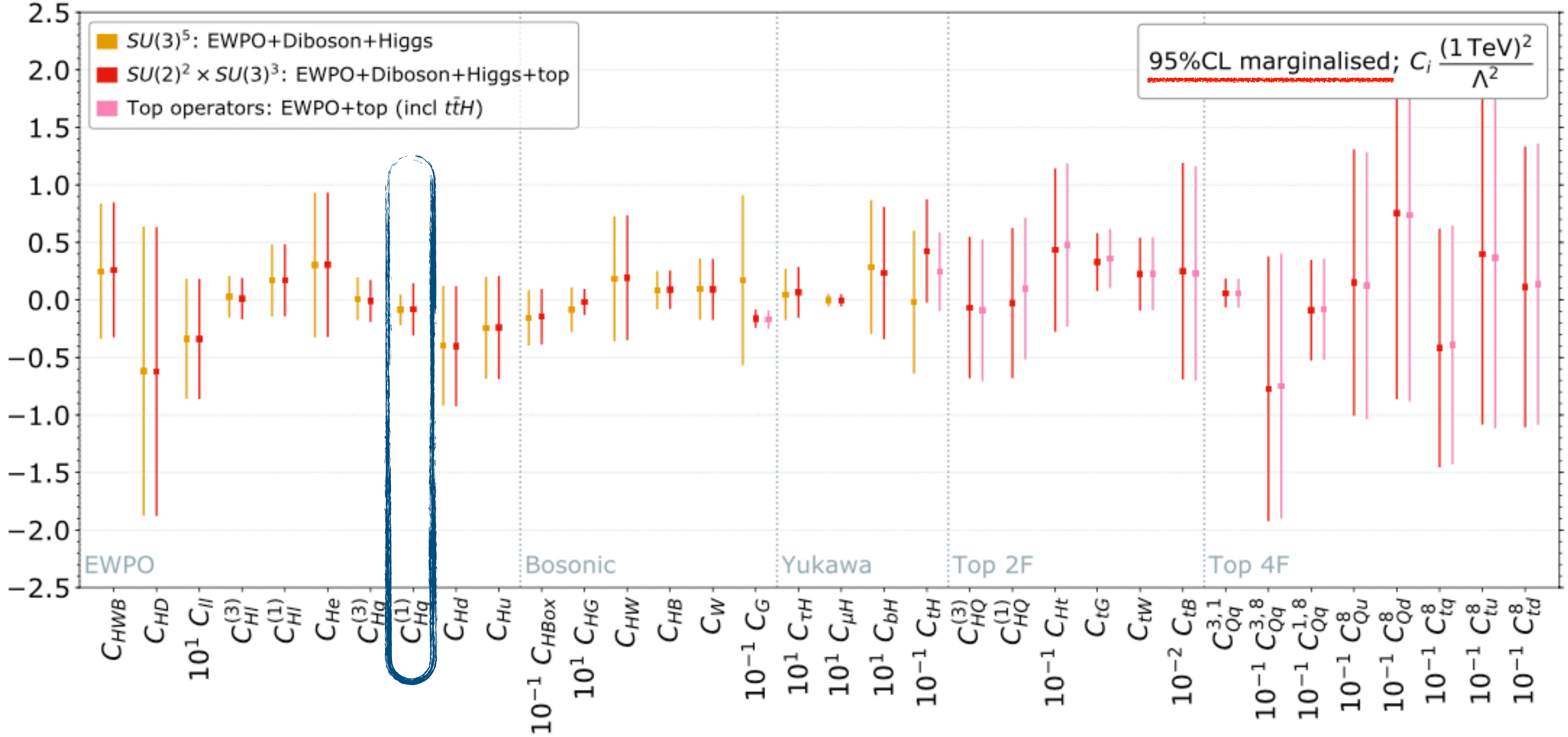

Toy MC

- Generate a random "toy"-measurement according to the uncertainties
- Construct the Likelihood (or χ^2 equivalently)
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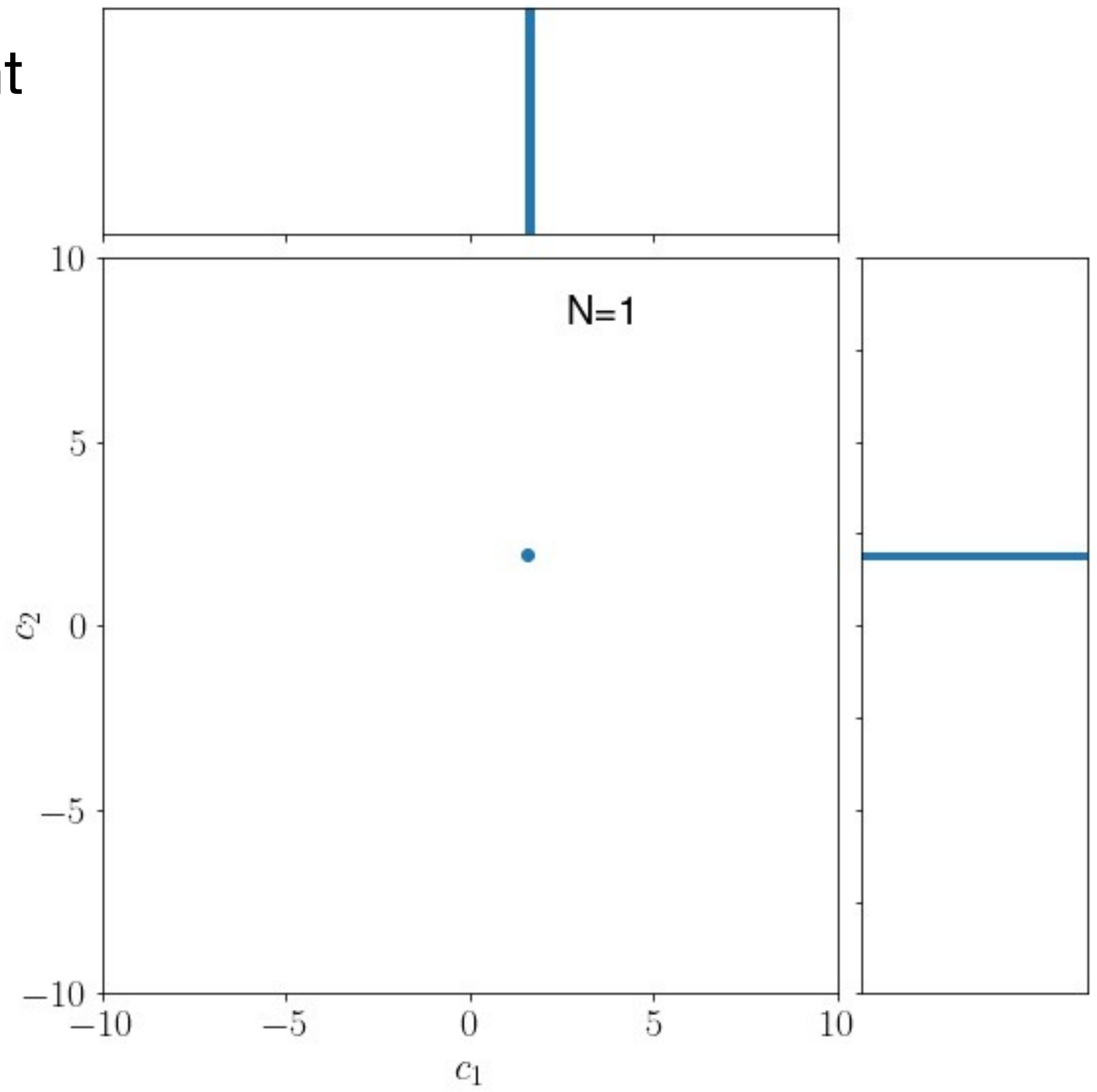

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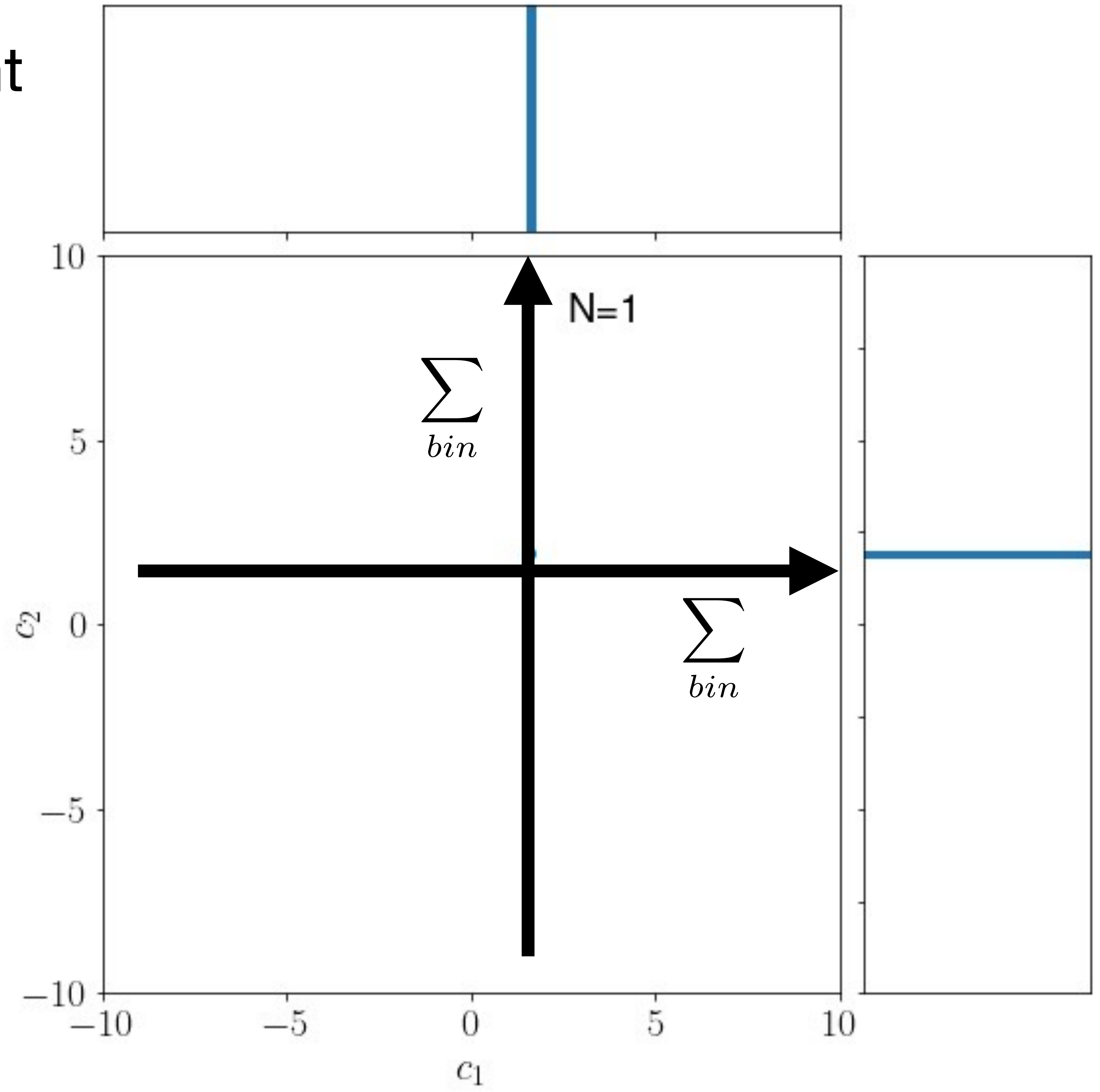

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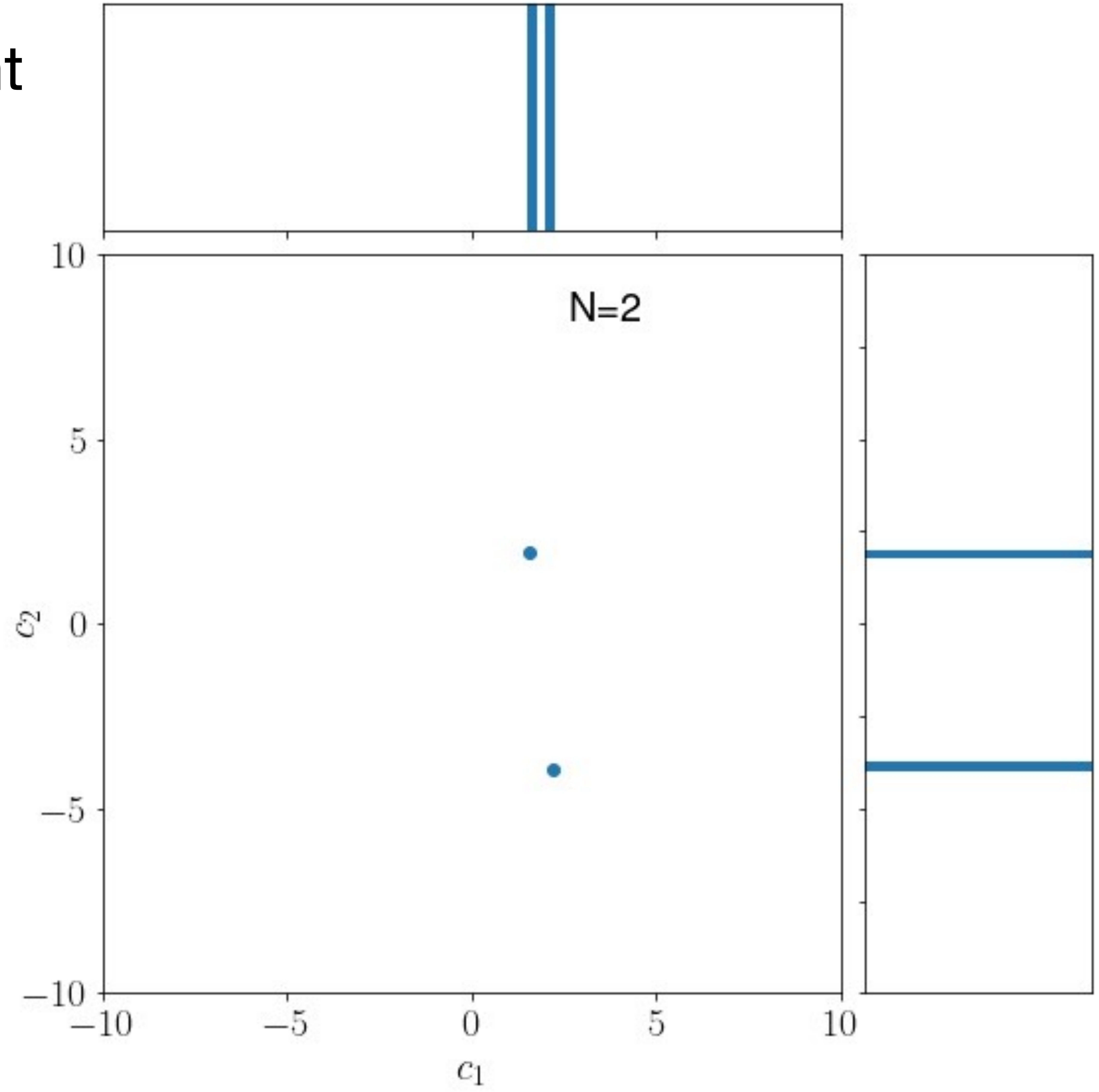

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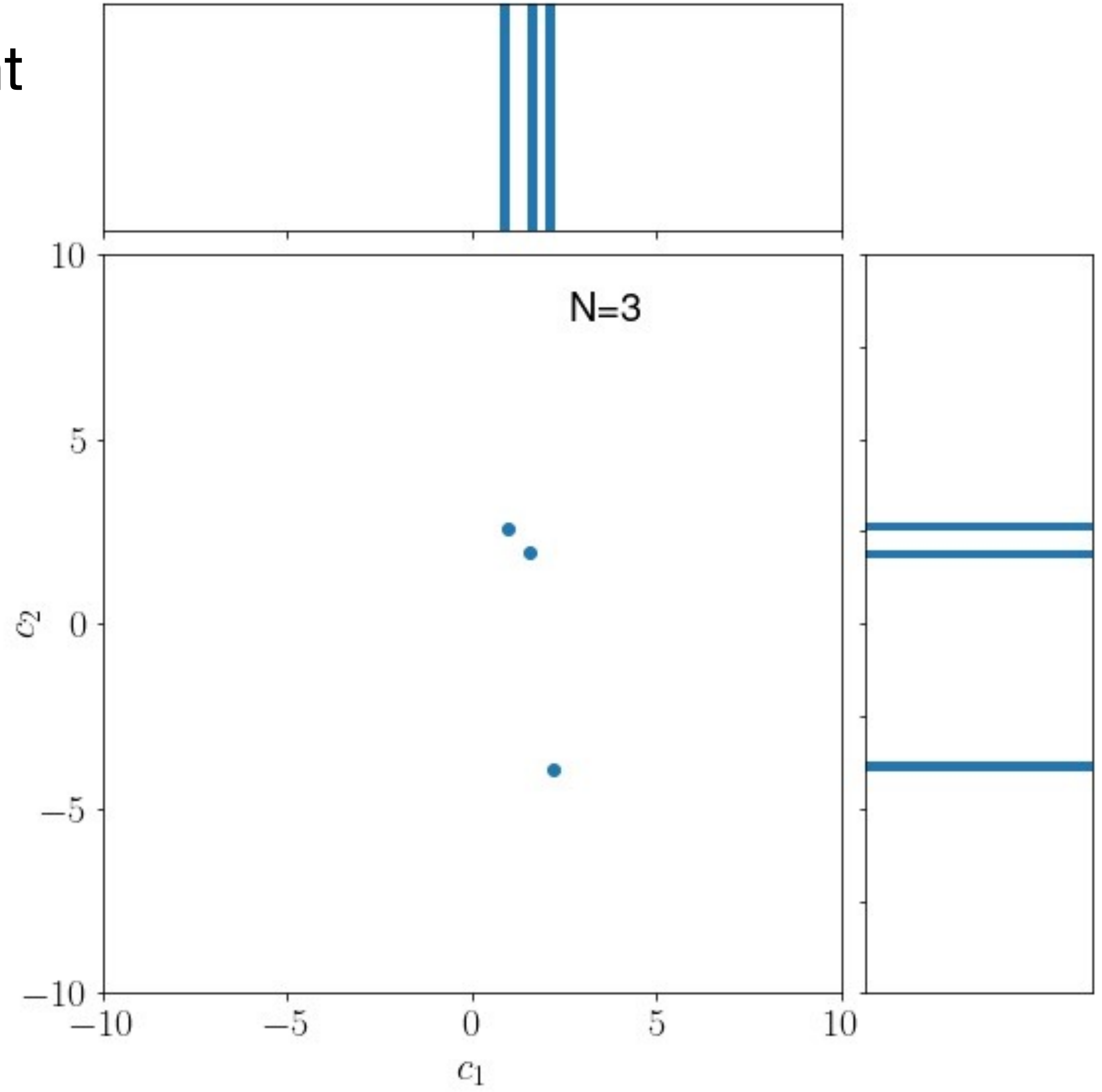

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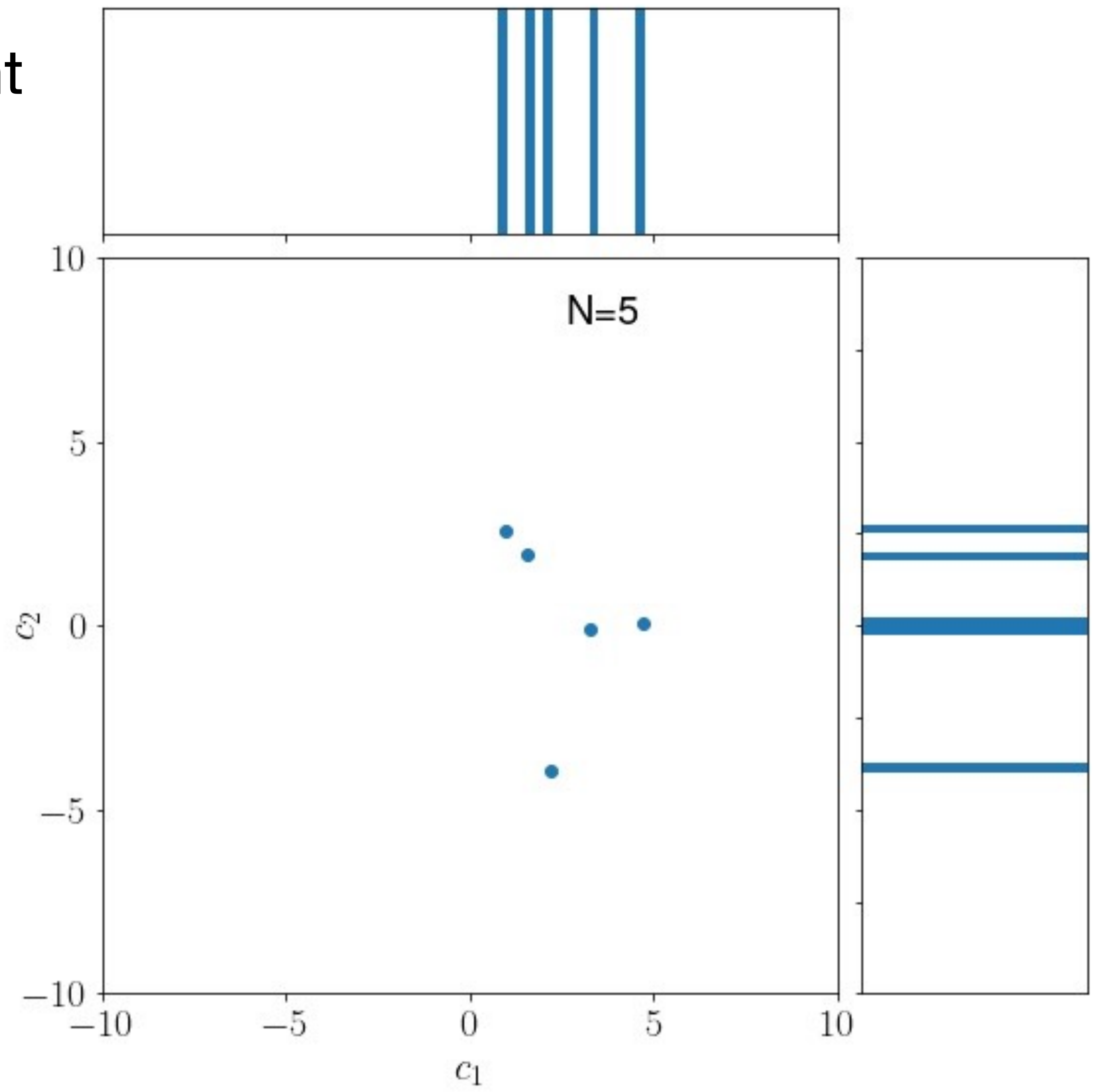

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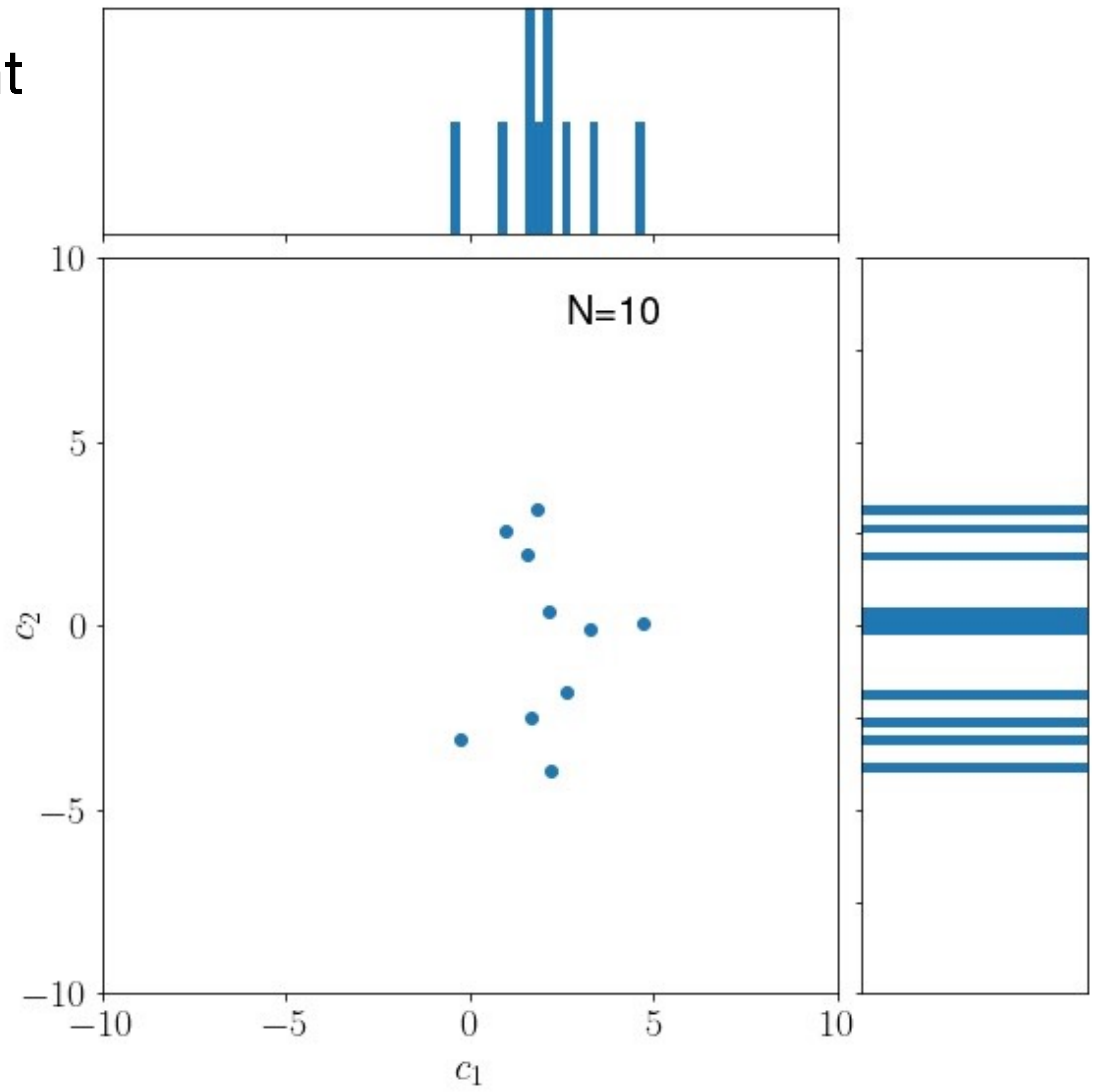

[Sebastian Bruggisser]

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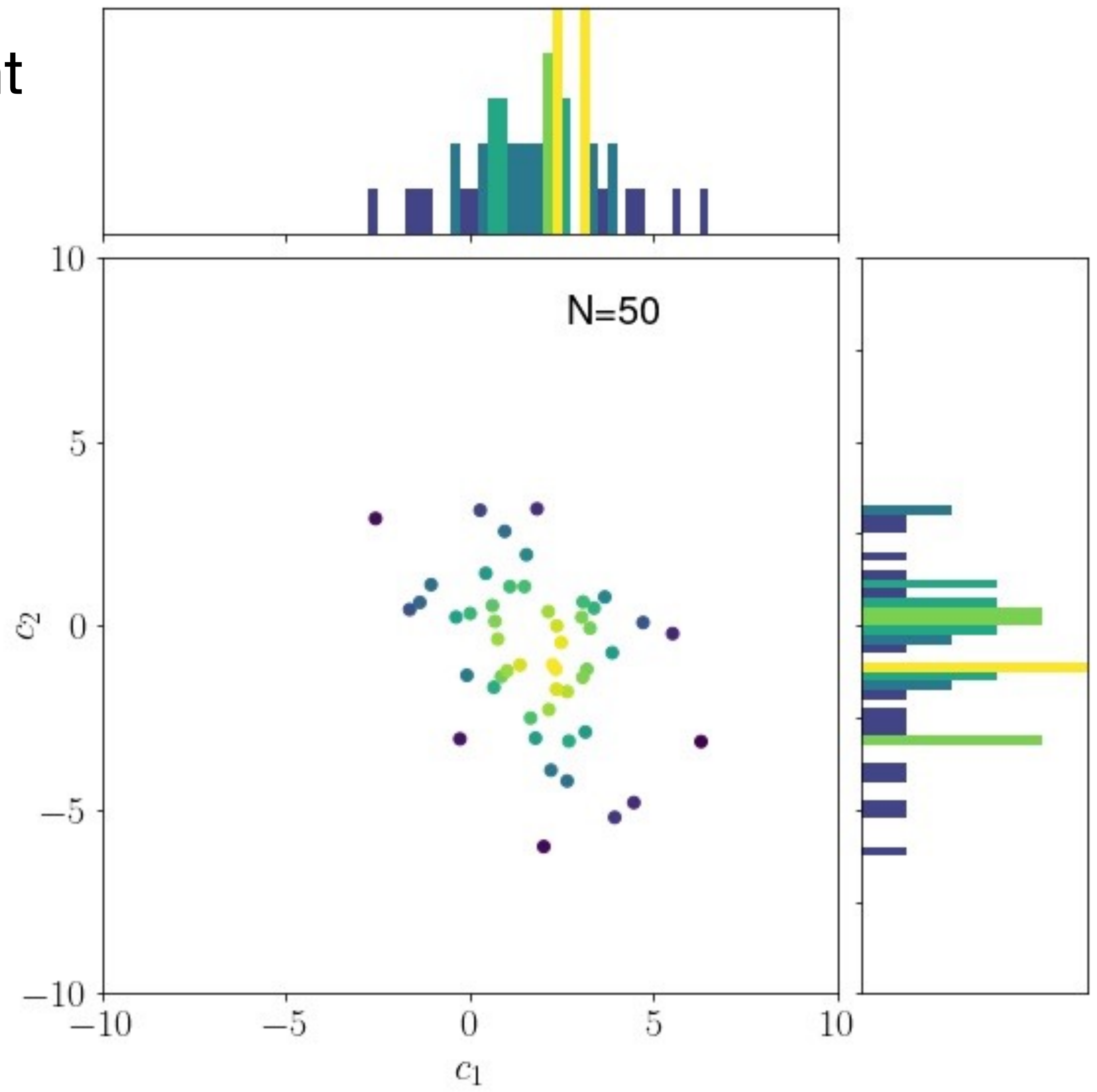
$$\mu_2 = 93 + 3(c_1 - c_2)$$

Predictions

$$\mu_{1/2}^{exp} = 100 \pm 10$$

Measurements



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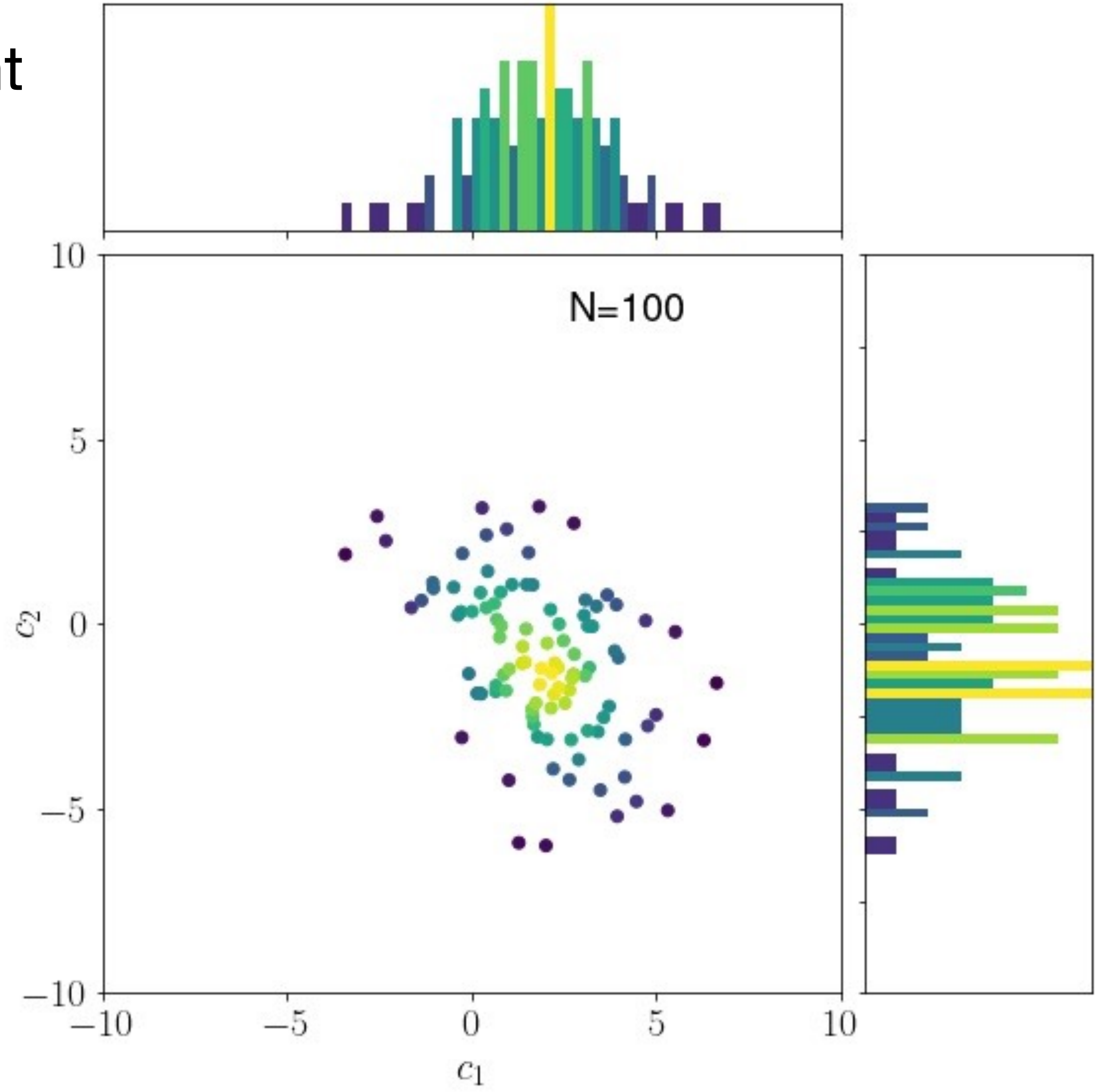

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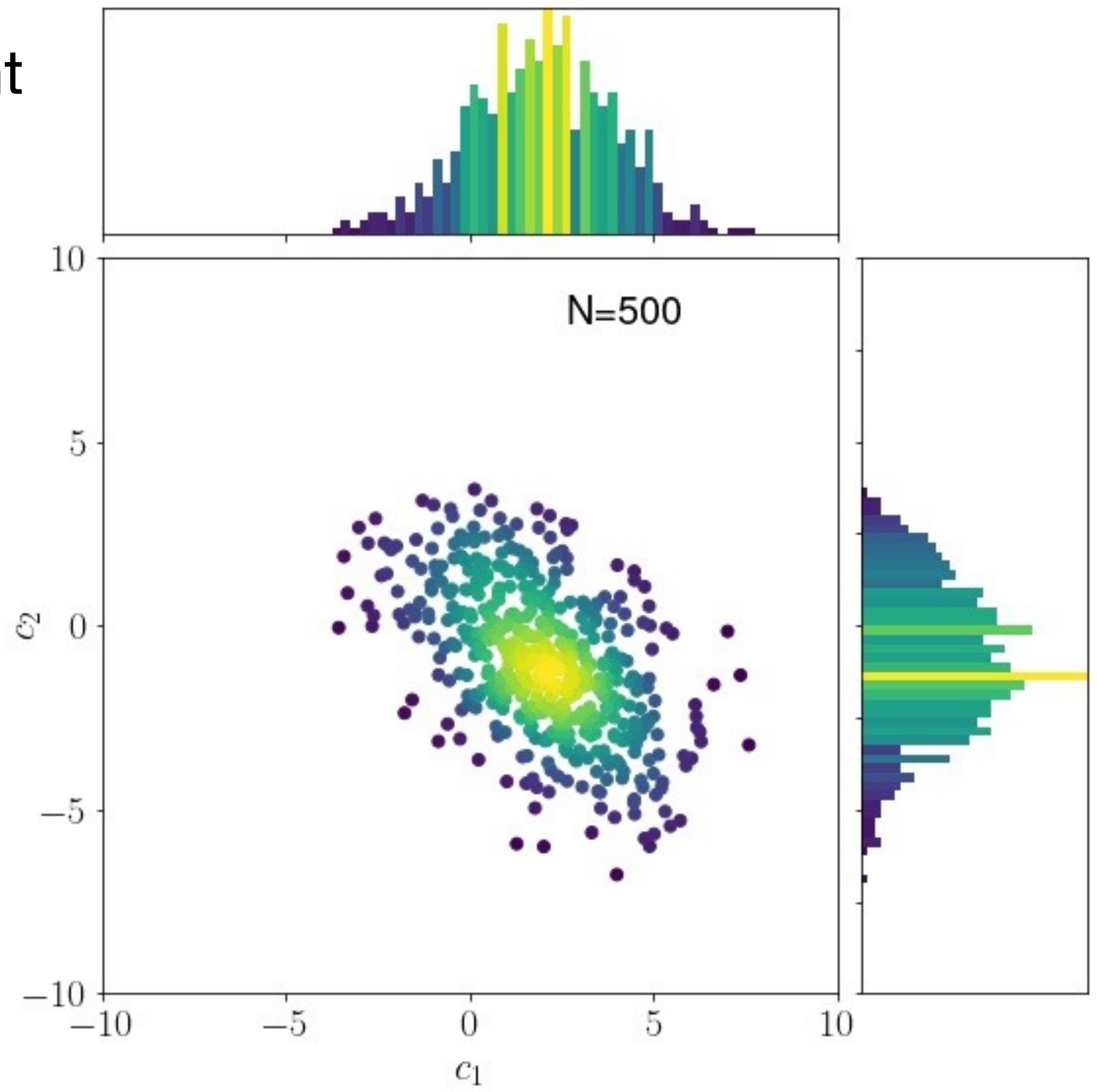

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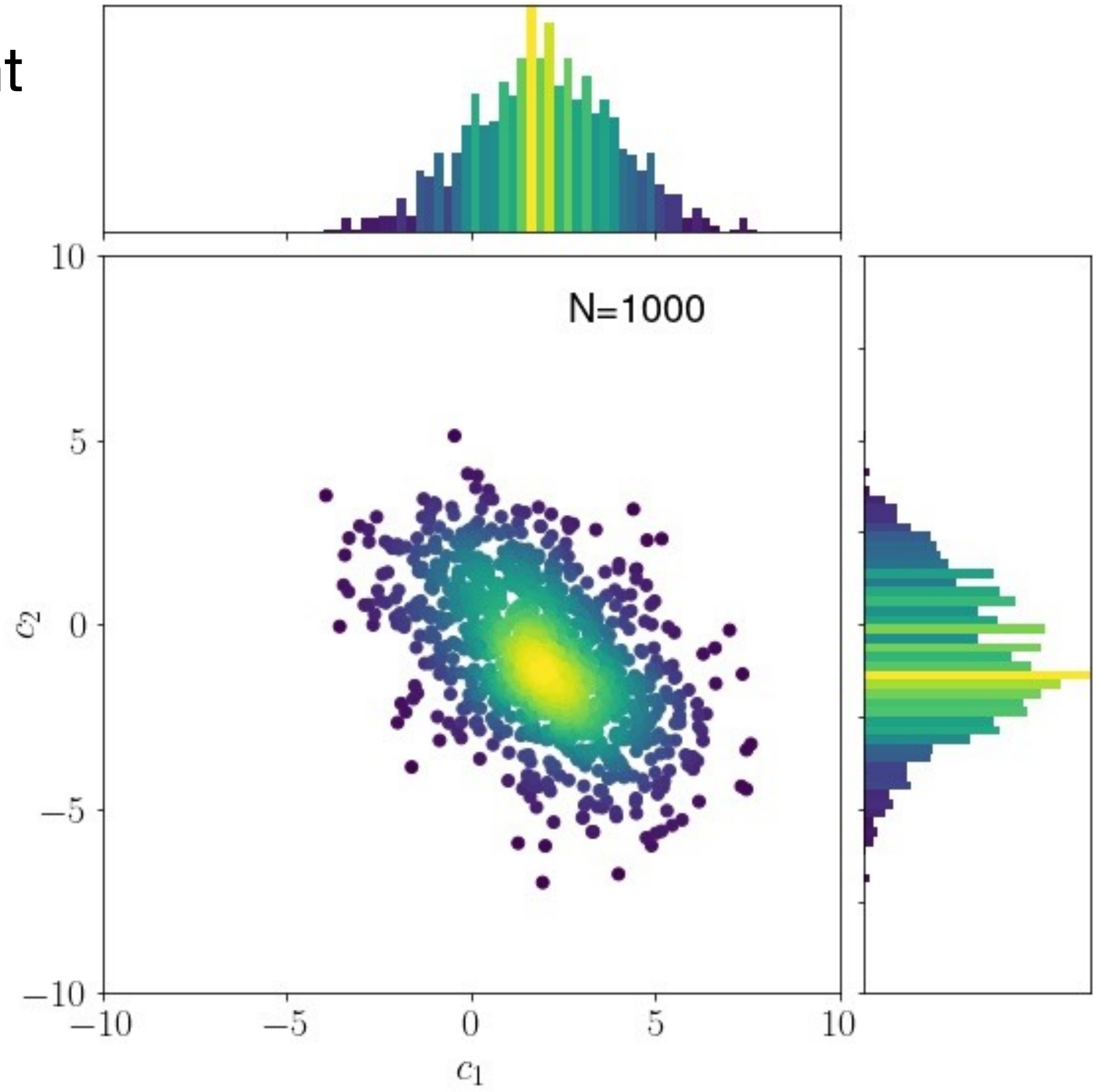

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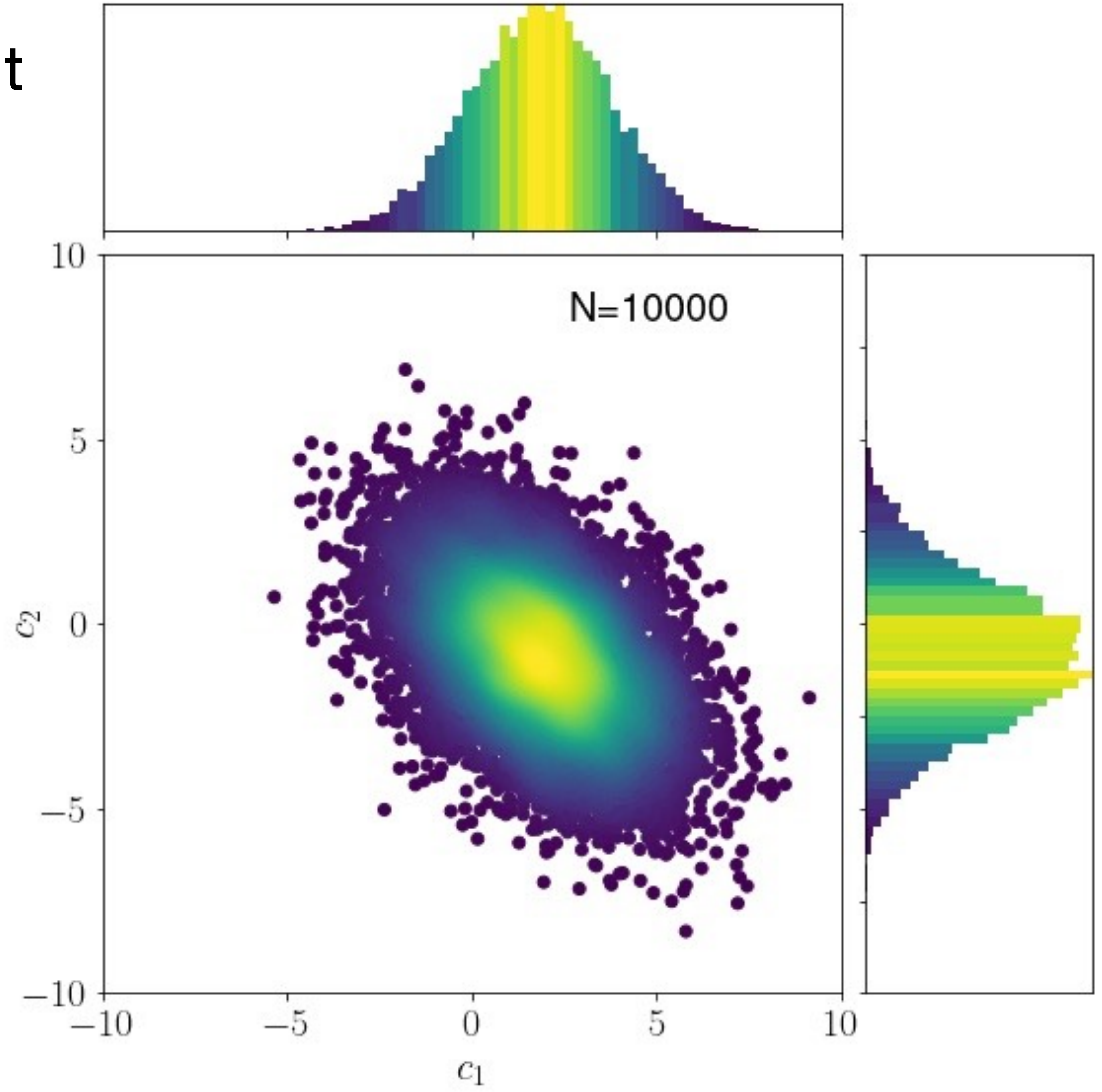

[Sebastian Bruggisser]

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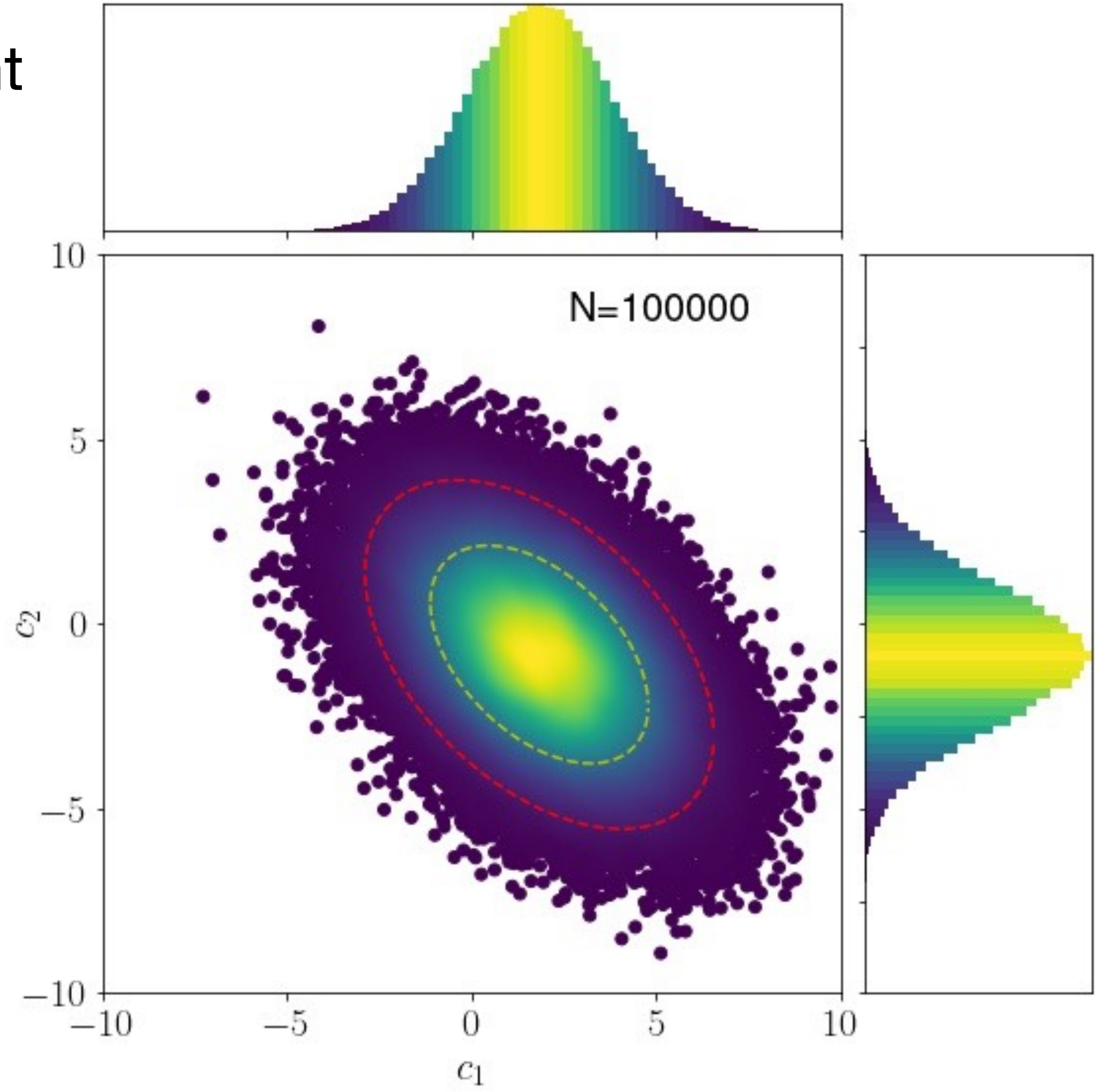

Markov Chains

Metropolis-Hastings

- Start at random point x_i
- Make one random step to x_{i+1}
- Generate random number u in (0,1)
- if $L(x_{i+1})/L(x_i) > u$ keep x_{i+1} and repeat
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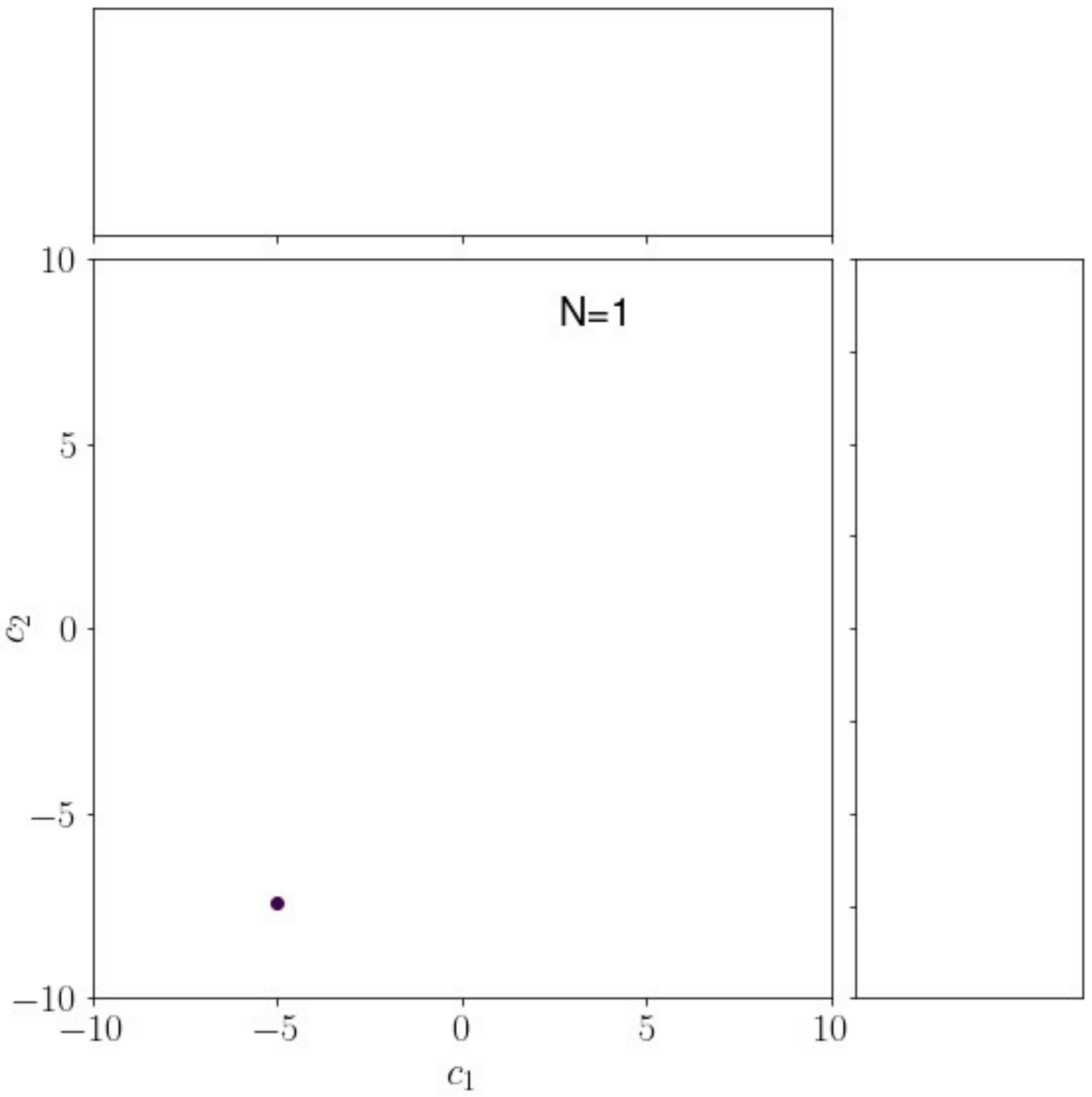

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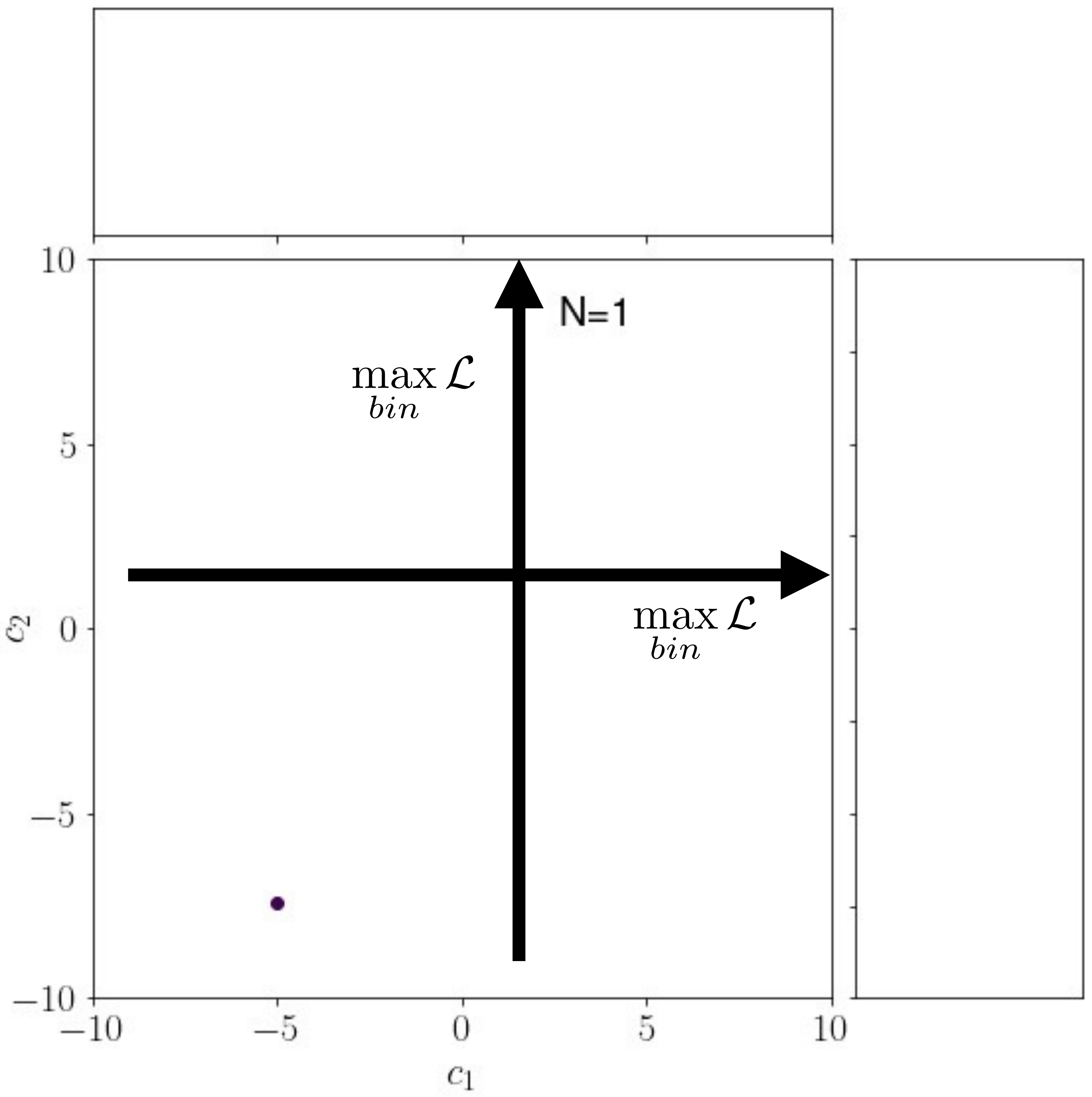

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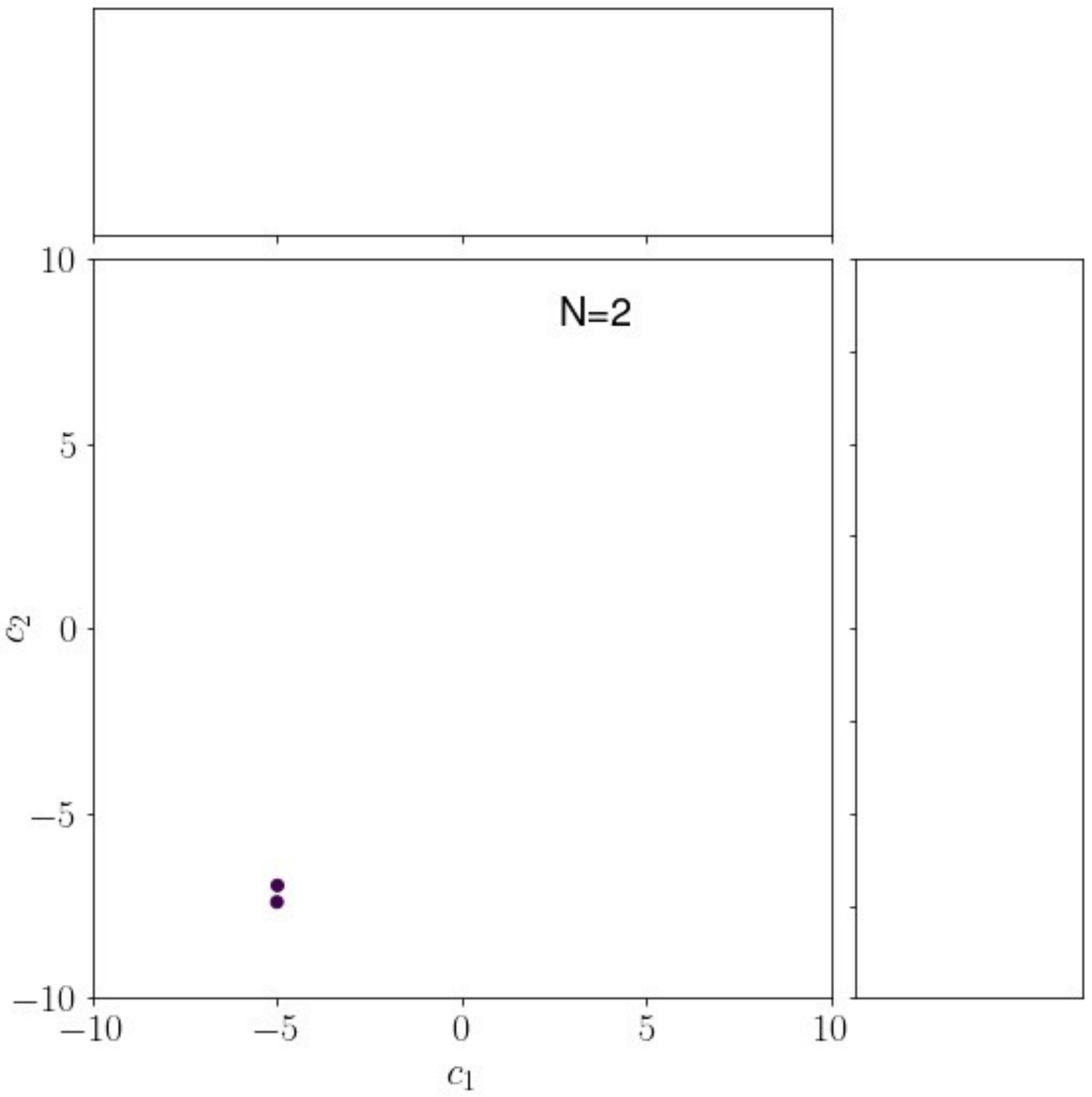

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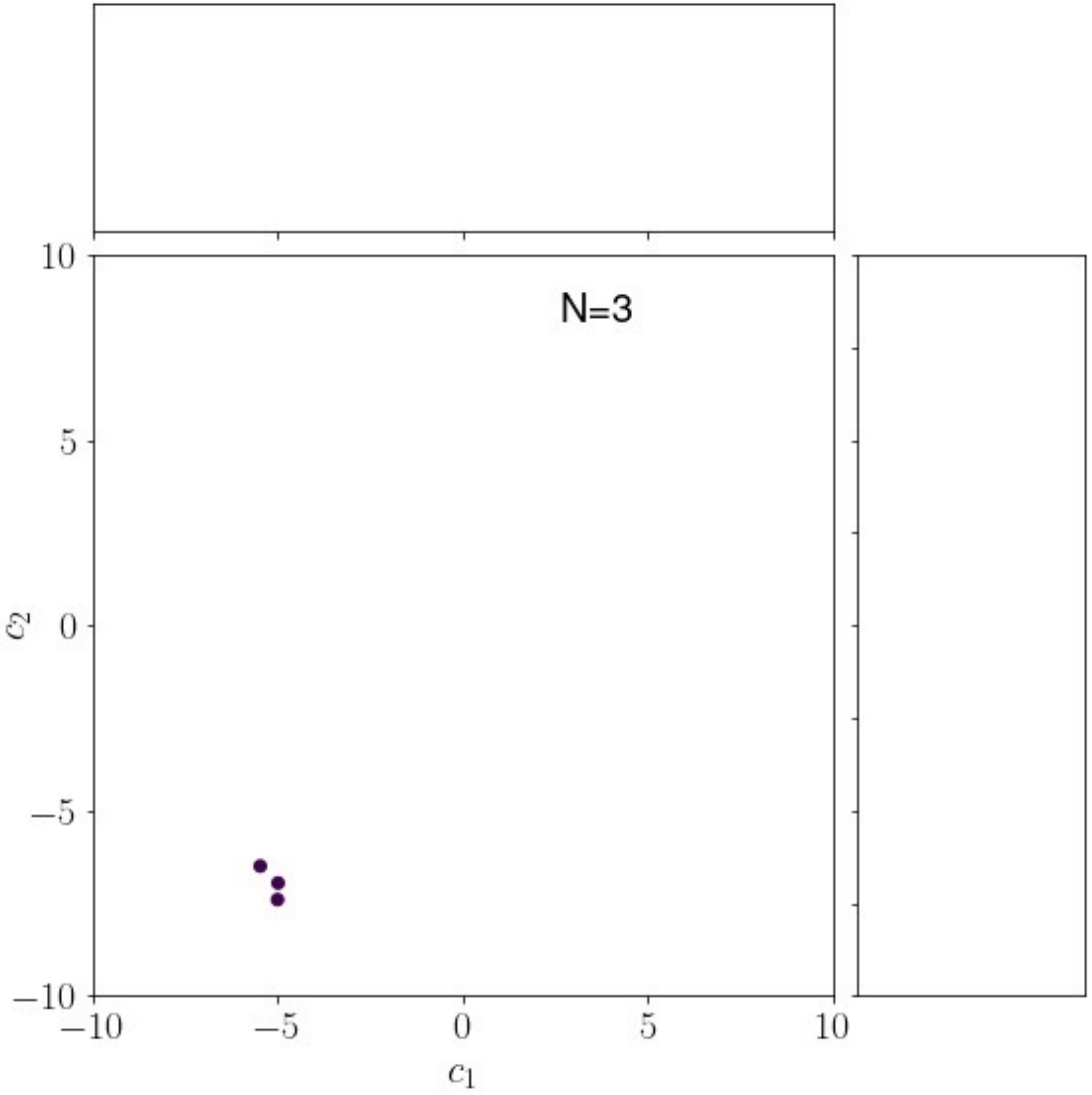

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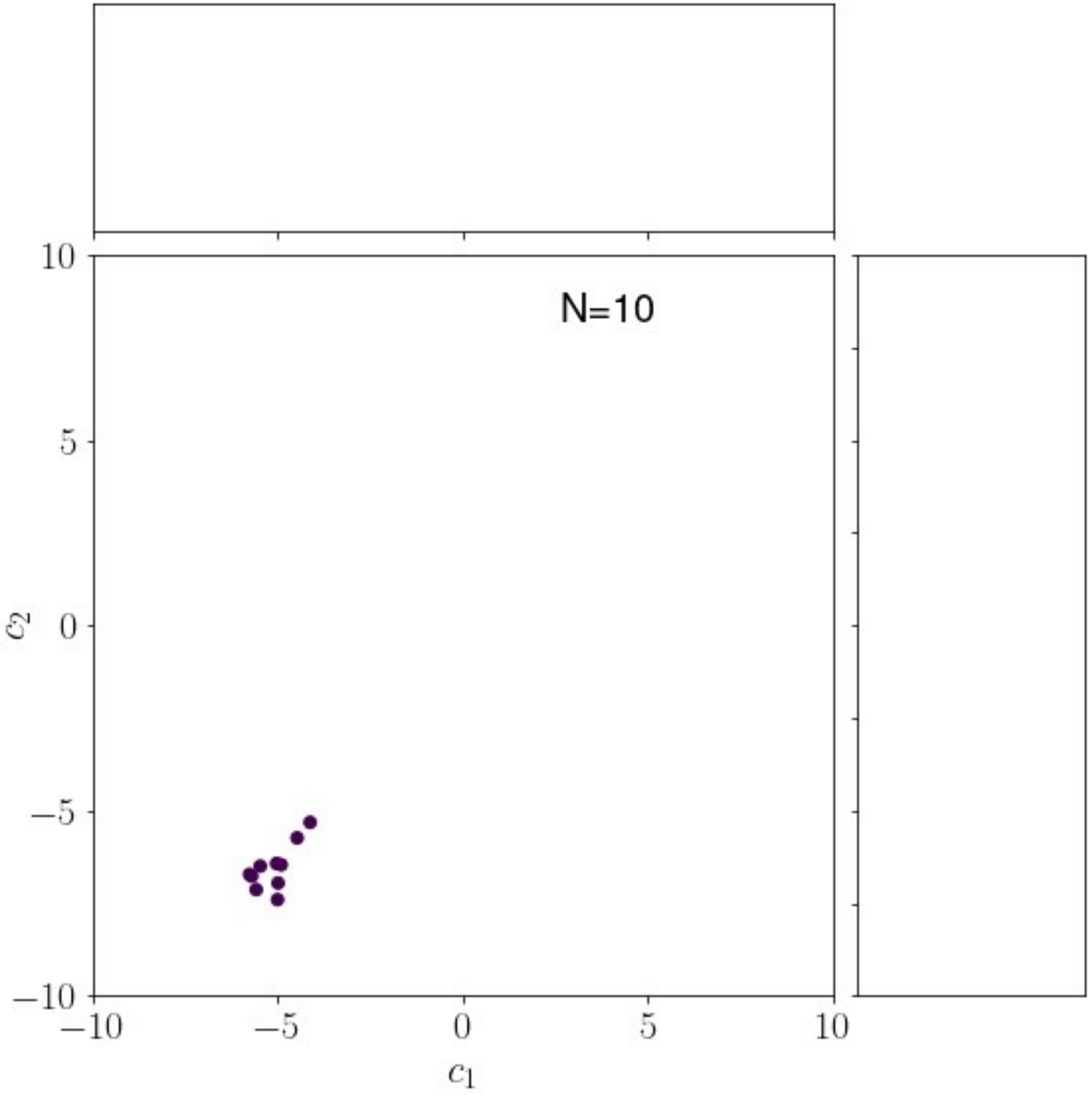

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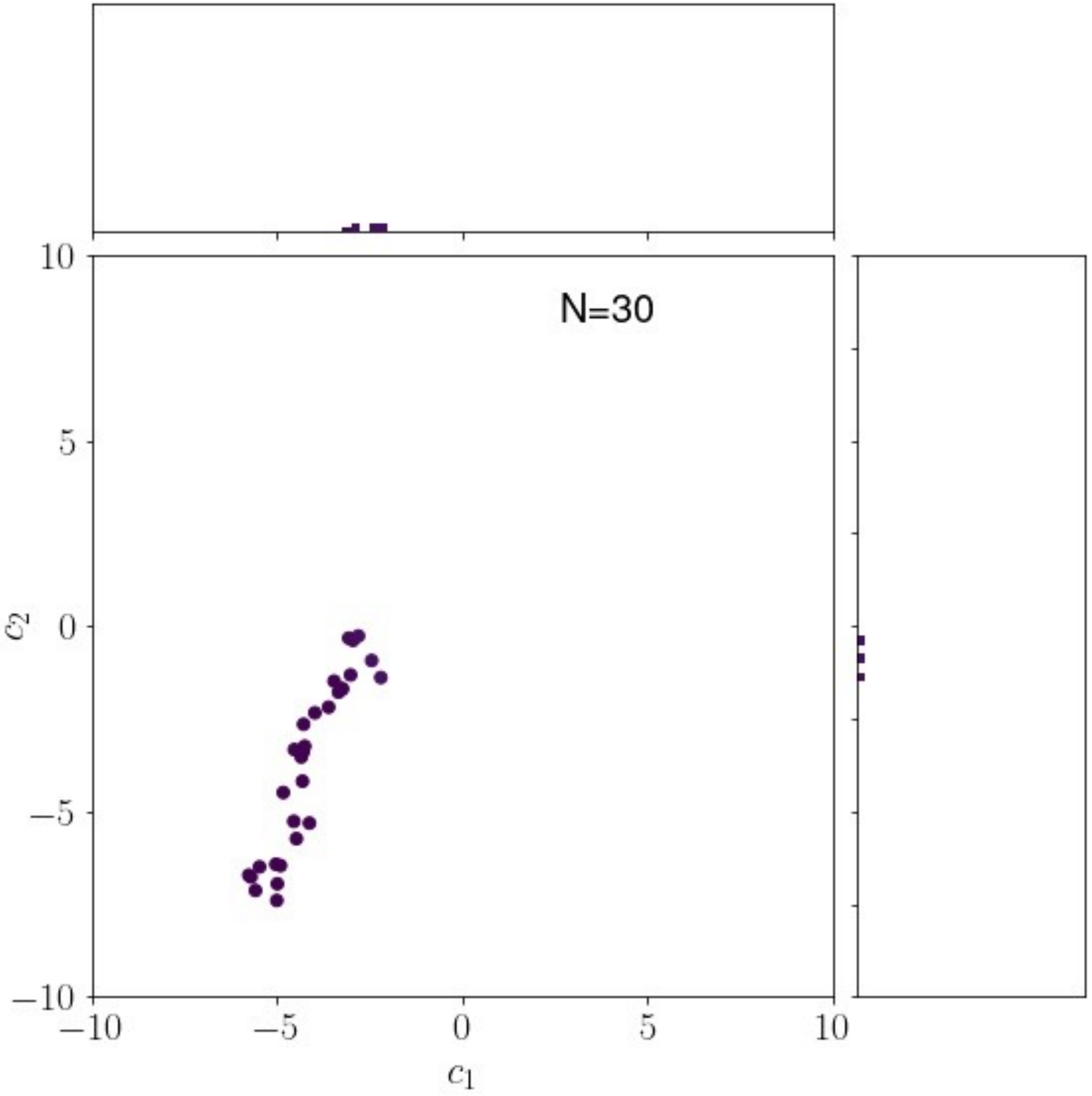

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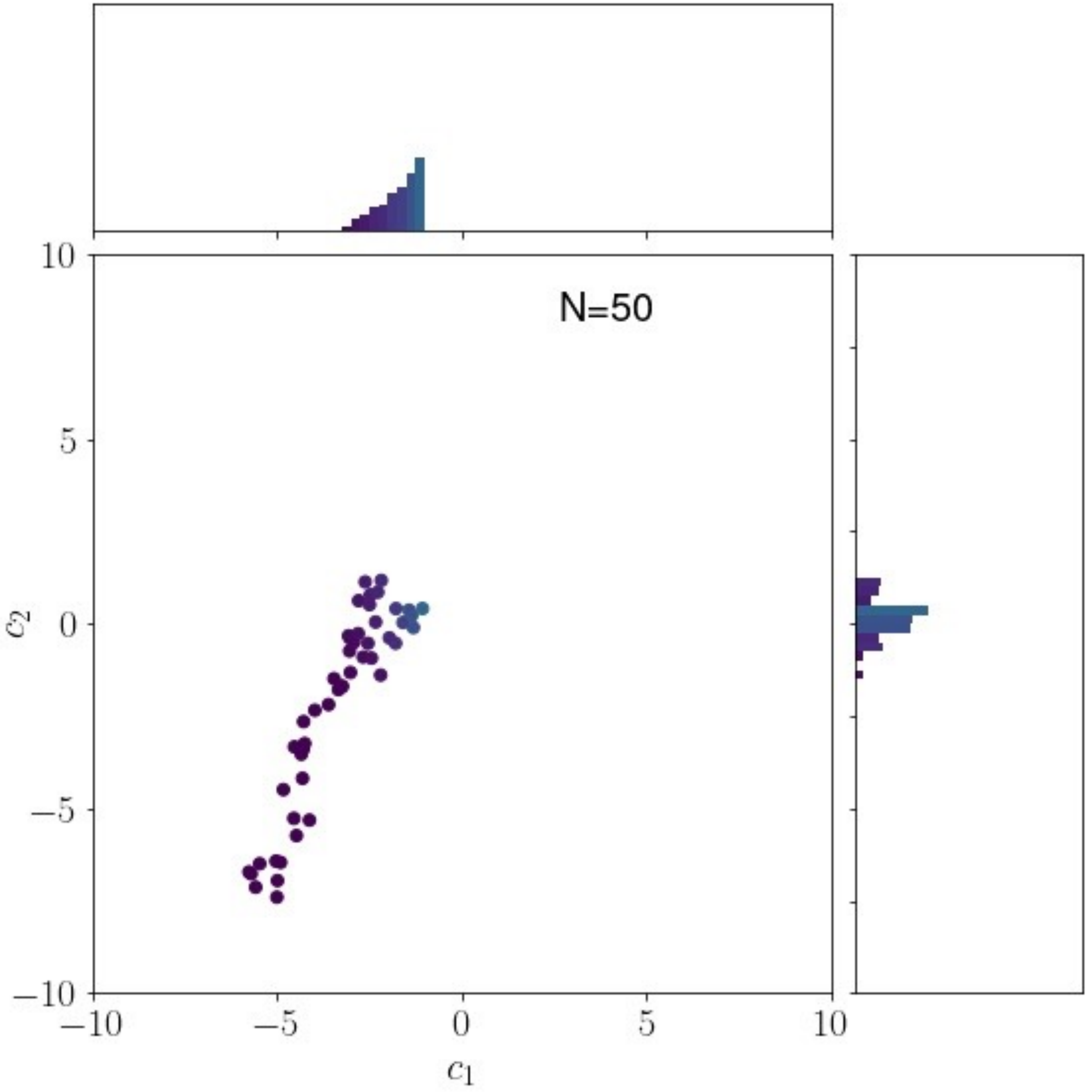

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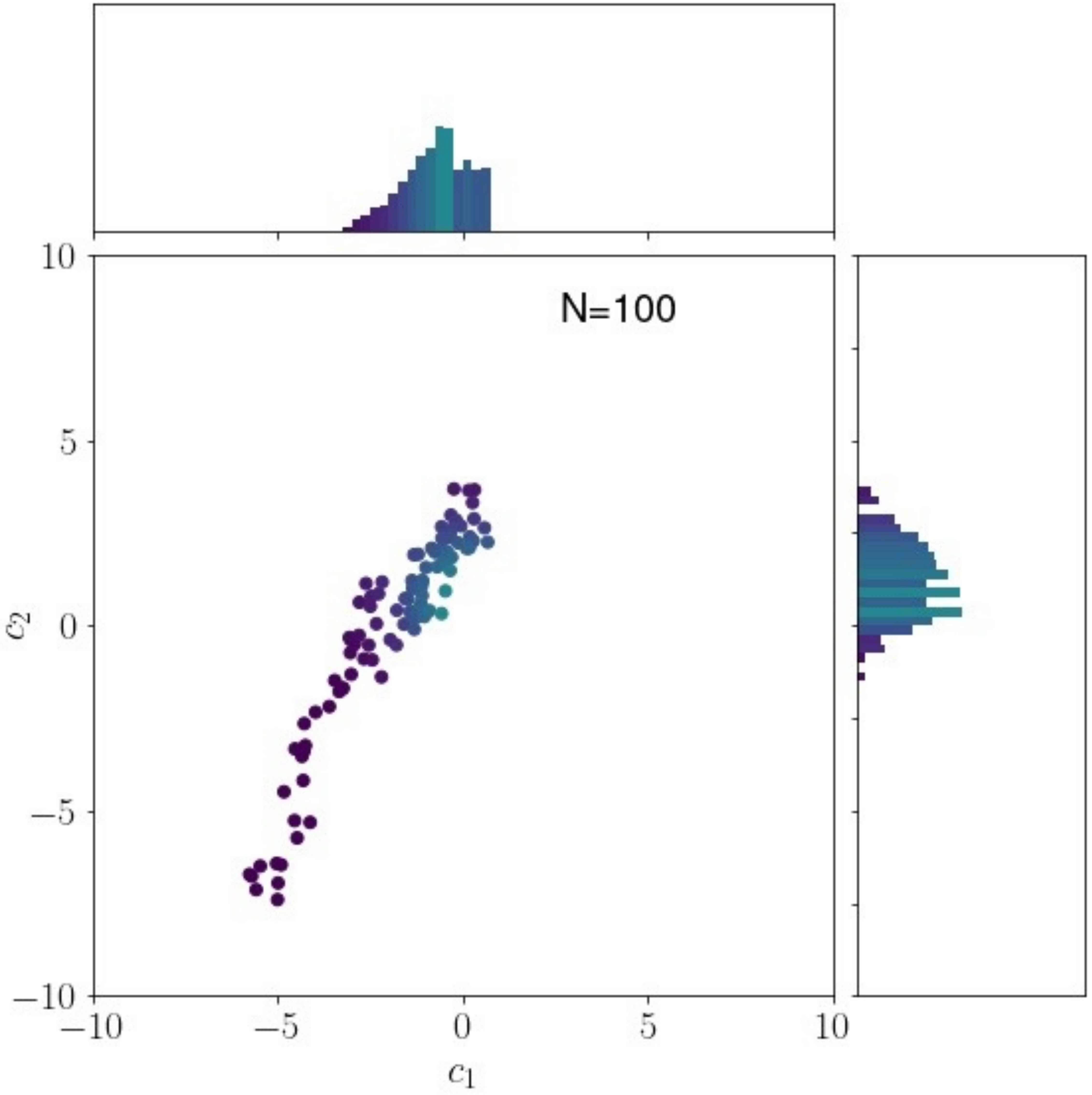

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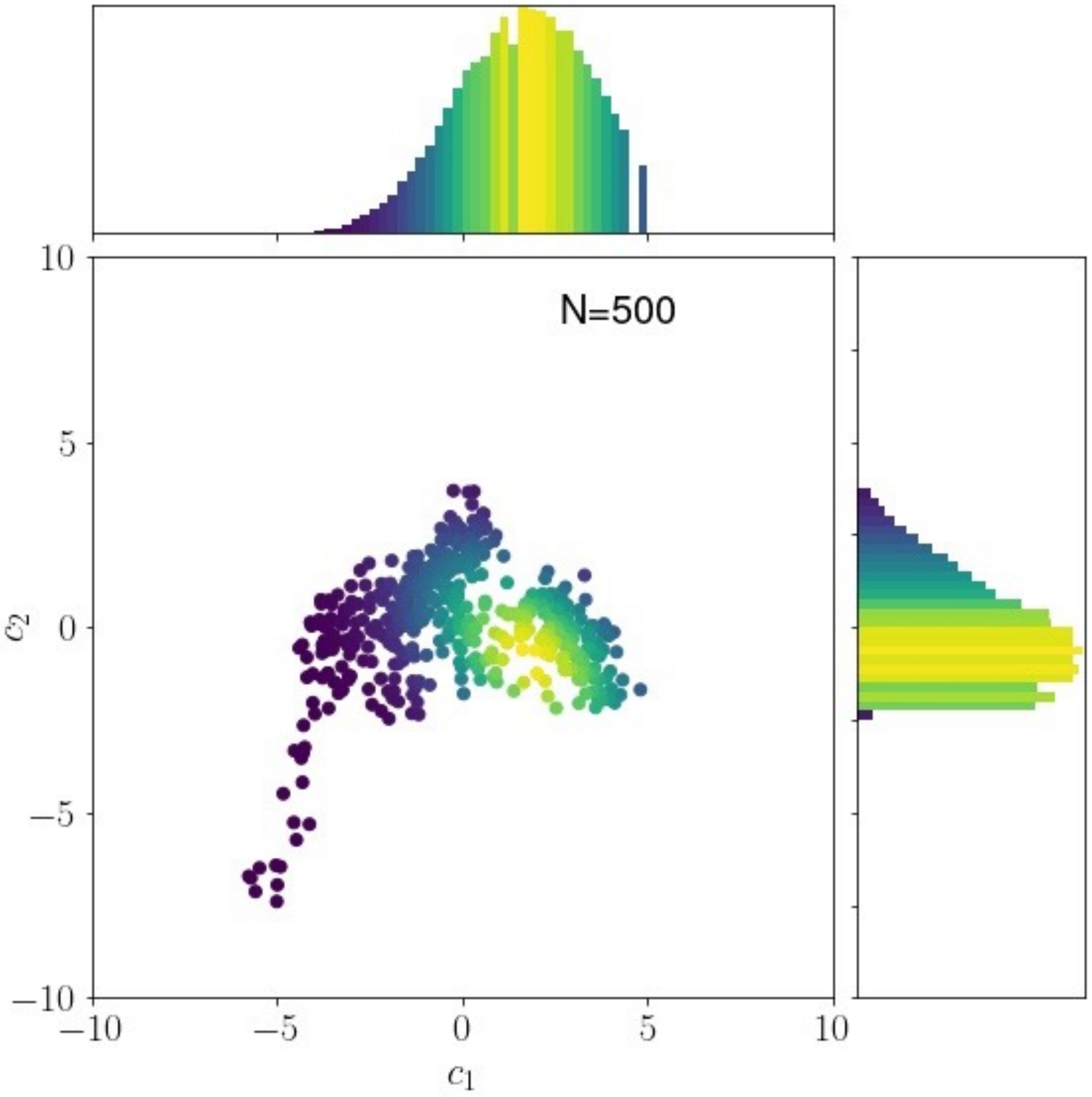

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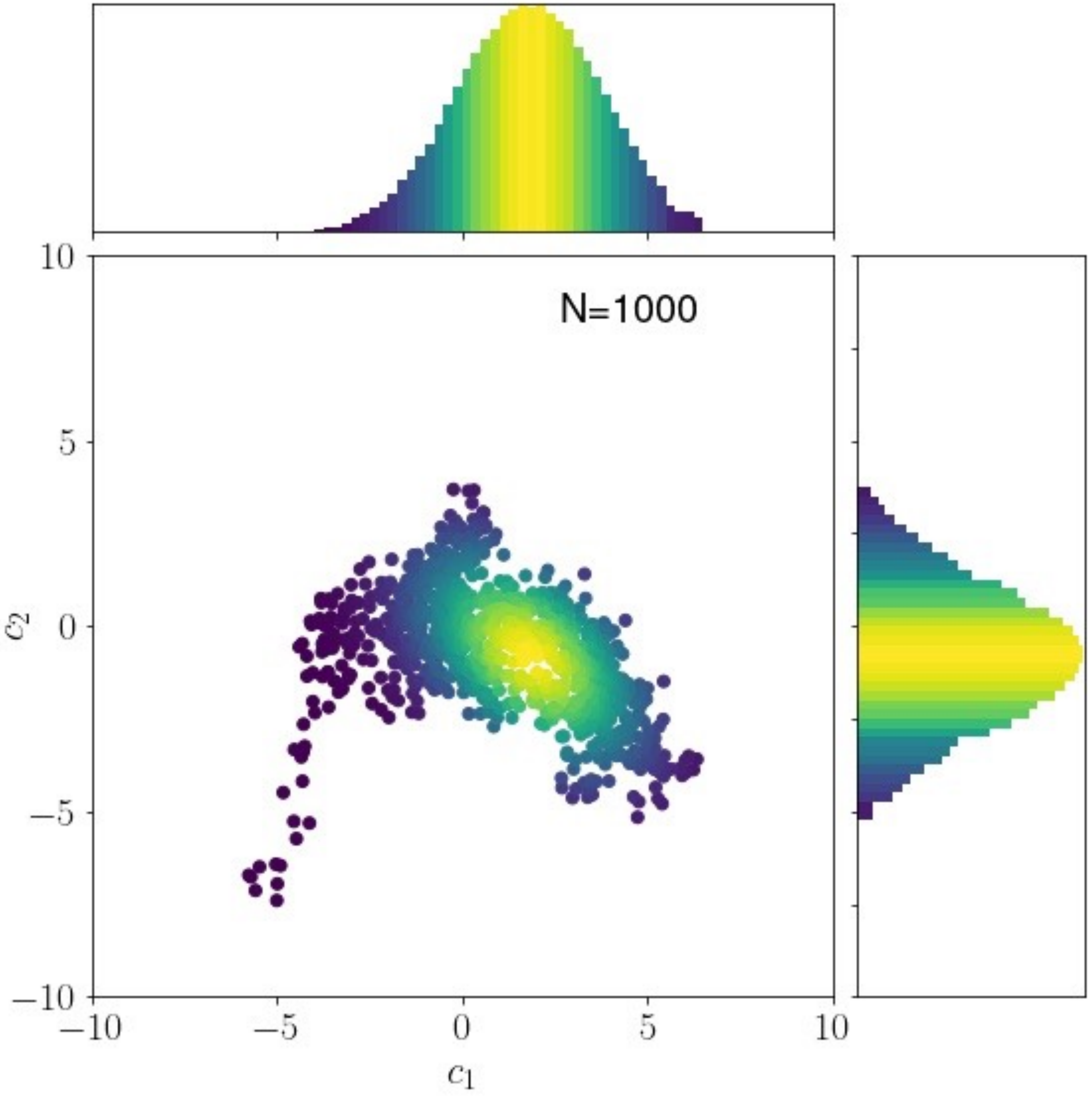

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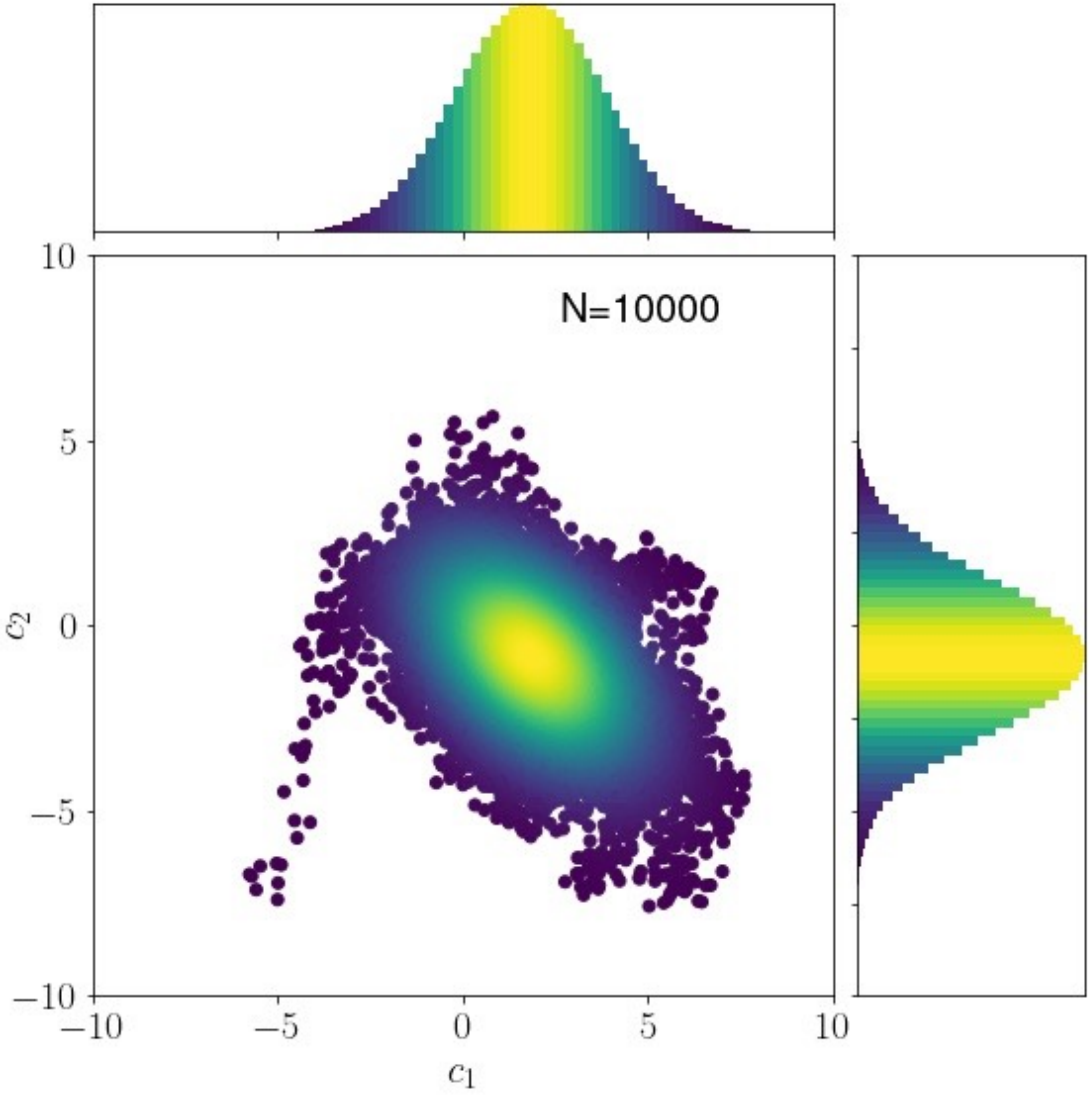

[Sebastian Bruggisser]

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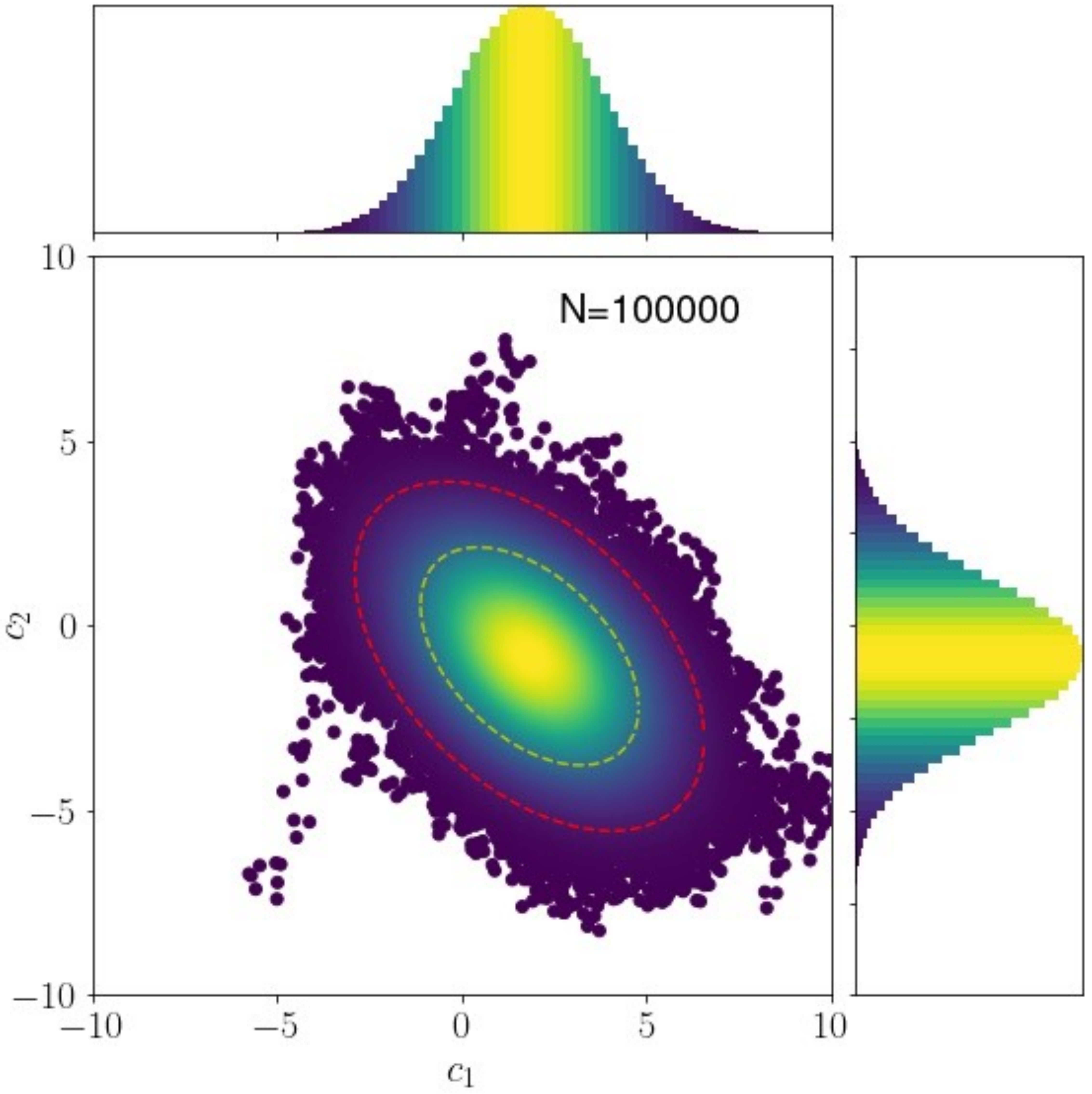
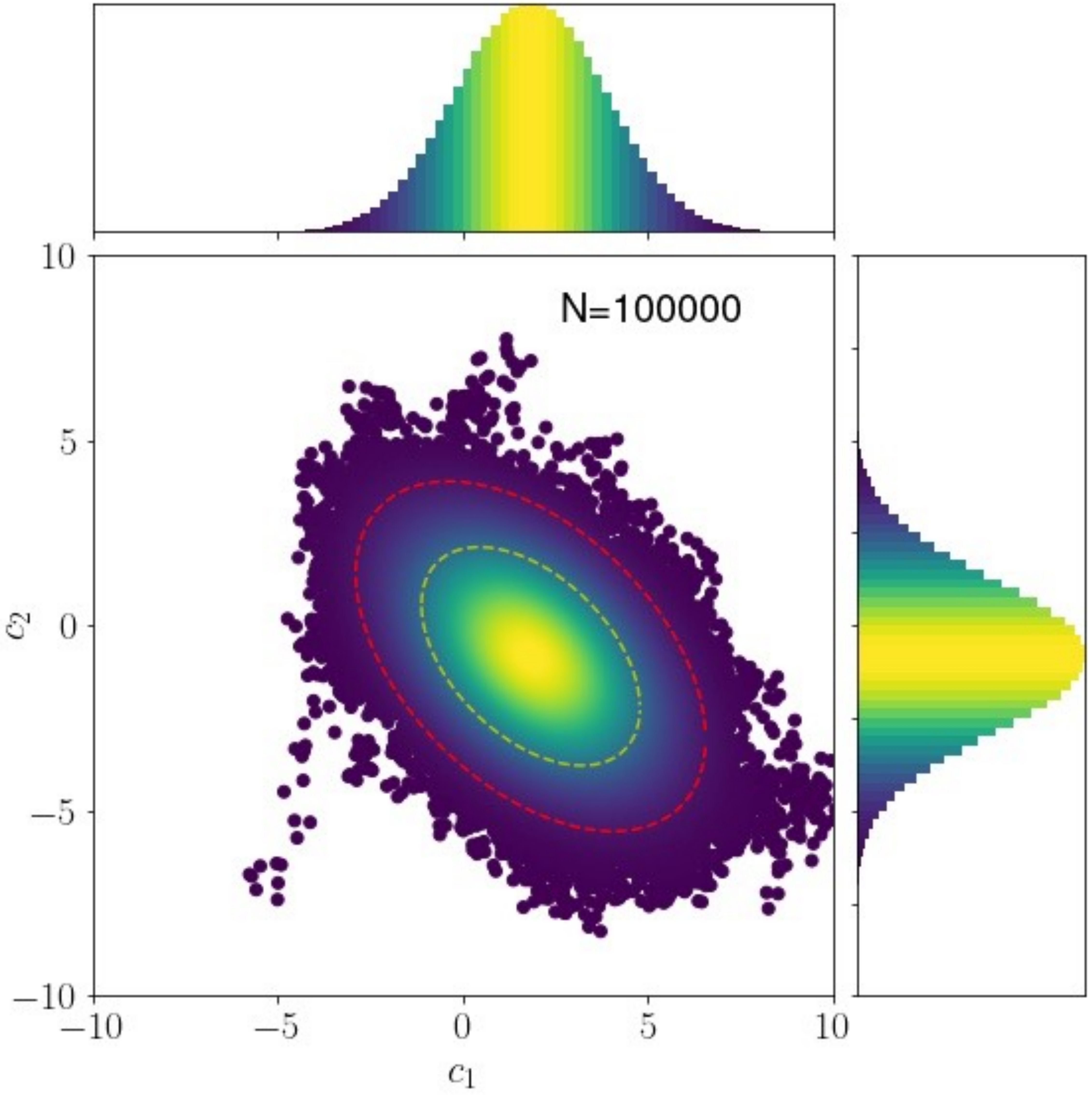


[Sebastian Bruggisser]

MC vs. Toys

Markov Chain

Toy Monte Carlo



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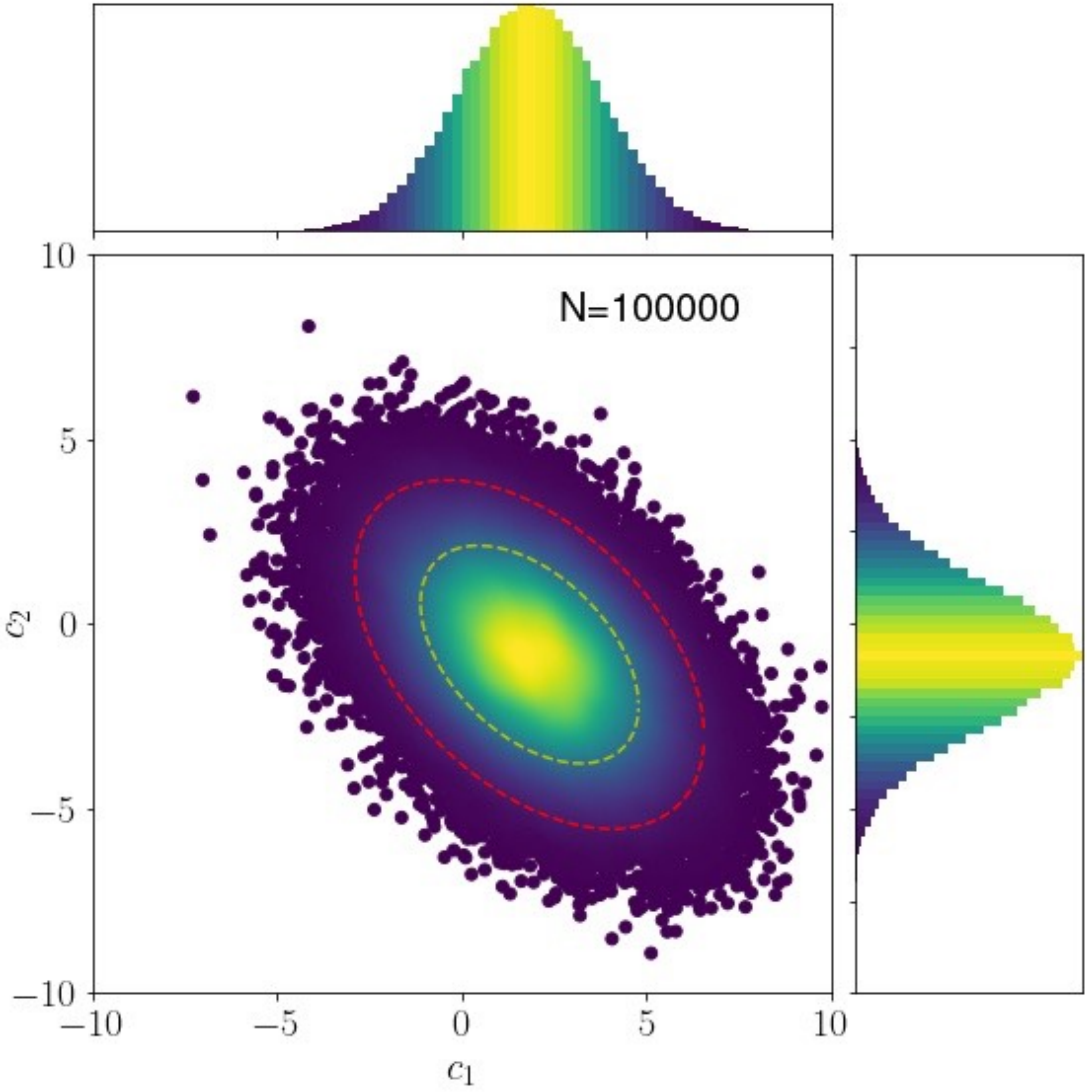


A 2D example:

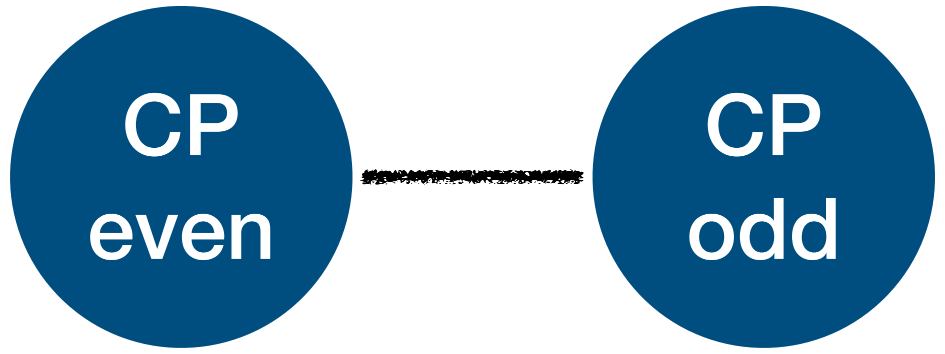
CP-odd triple gauge couplings

CP-odd dimension-6 operators

- Linear effect of CP-odd operators on the total cross section is very small

(zero before kinematic cuts)

- Influence of CP-odd operators on CP-even+CP-odd fit often negligible [Ethier et al (2101.03180)]



- Need dedicated observables

- Only few fits of CP-odd SMEFT operators
- Higgs production and decay

  [Brehmer et al (1712.02350)]

  [Bernlochner et al (1808.06577)]

  [Englert et al (1901.05982)]

  [Bhardwaj et al. (2112.05052)]

- Low-energy experiments (EDMs + LEP+ $B \to X_s \gamma$)

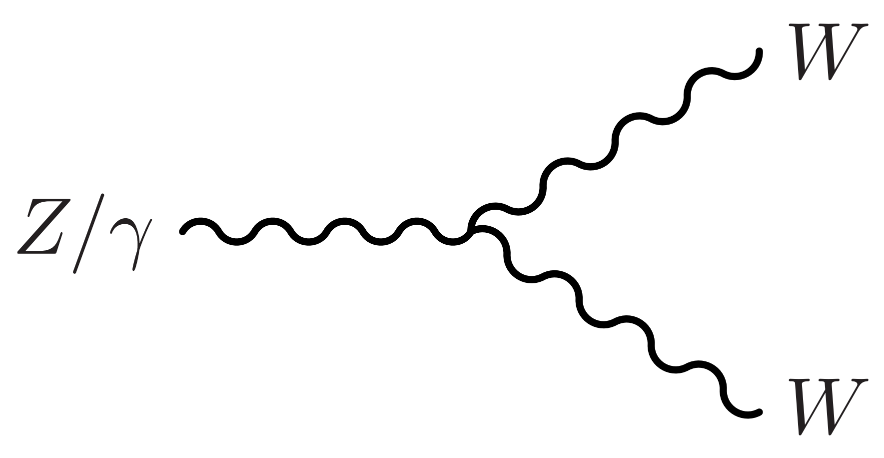
  [Cirigliano et al (1903.03625)]

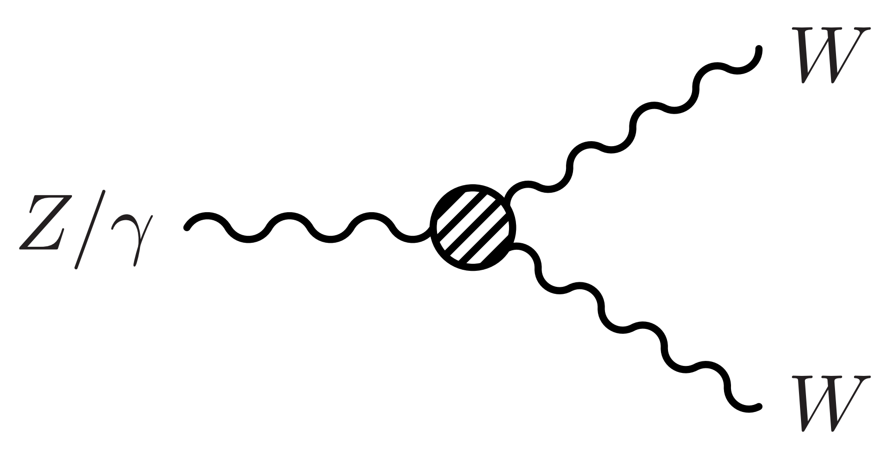
- Diboson production

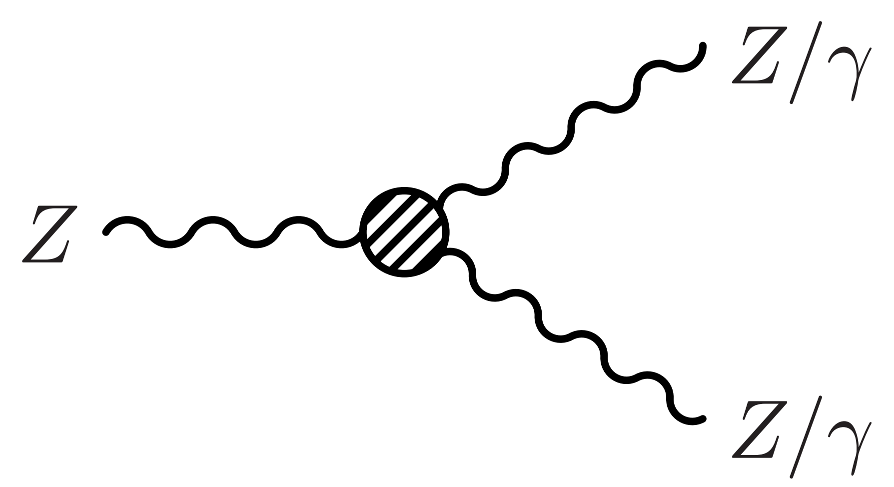
  [Bakshi et al (2009.13394)]

  [Ethier et al (2101.03180)] (distributions)

CP-odd triple gauge couplings

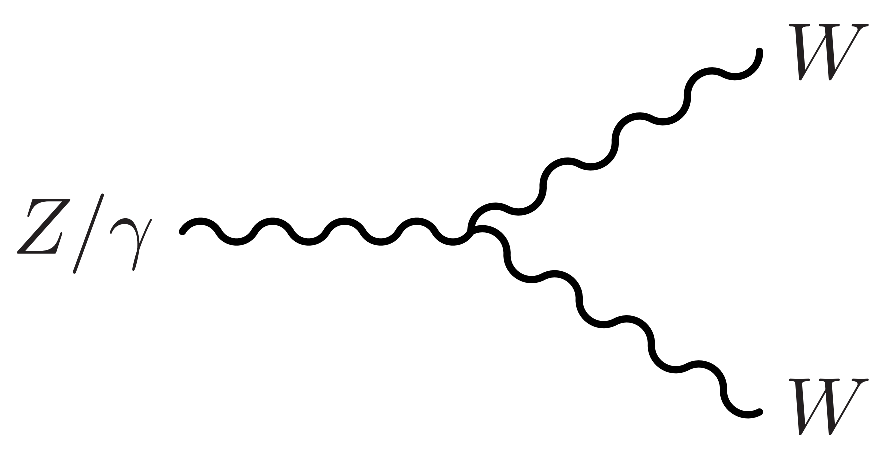


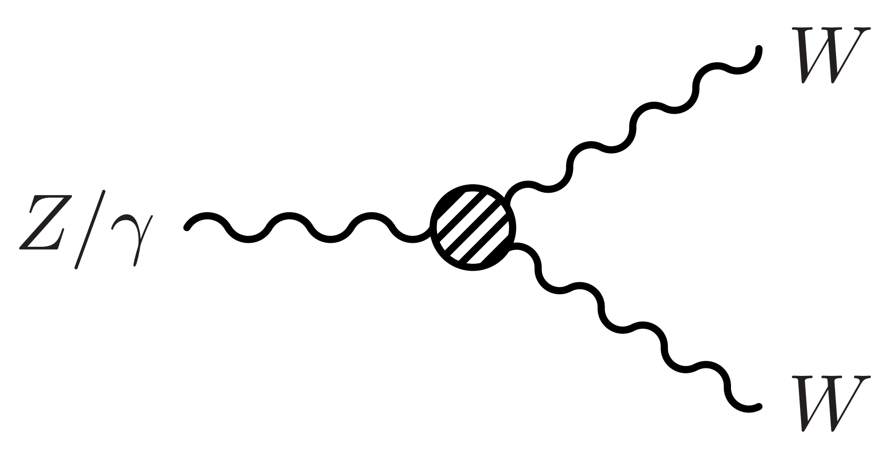


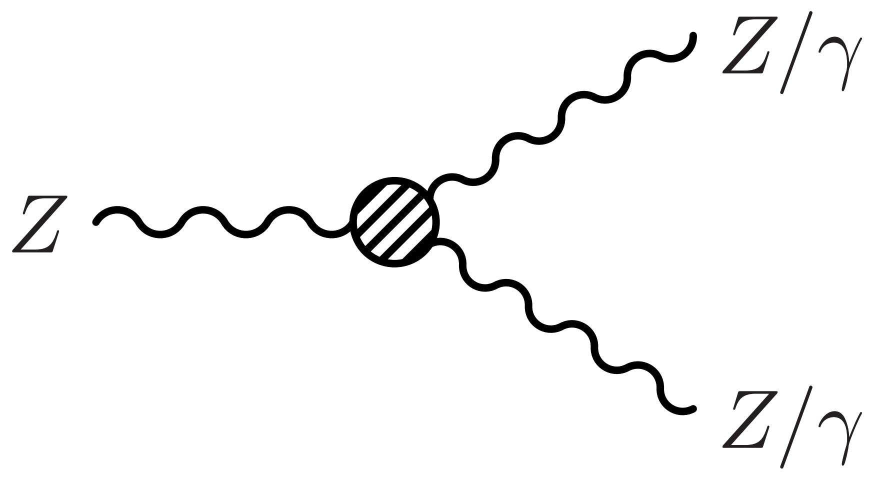


$$\mathcal{L}_{\mathrm{SM}} = -i g_{WWV} \Big[\big(W^{+}_{\mu\nu} W^{-\mu} V^{\nu} - W^{-}_{\mu\nu} W^{+\mu} V^{\nu} \big) + W^{+}_{\mu} W^{-}_{\nu} V^{\mu\nu} \Big]$$

CP-odd triple gauge couplings







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Luckily only two dim-6 operators contribute

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{c_{\tilde{W}}}{\Lambda^2} \mathcal{O}_{\tilde{W}} + \frac{c_{H\tilde{W}B}}{\Lambda^2} \mathcal{O}_{H\tilde{W}B}$$

$$\mathcal{O}_{\tilde{W}} = \epsilon^{IJK} \, \tilde{W}^{I\nu}_{\mu} \, W^{J\rho}_{\nu} \, W^{K\mu}_{\rho}$$

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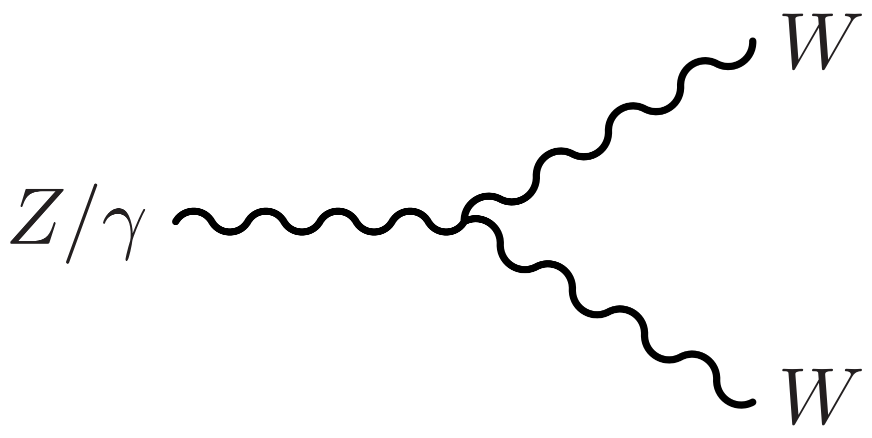
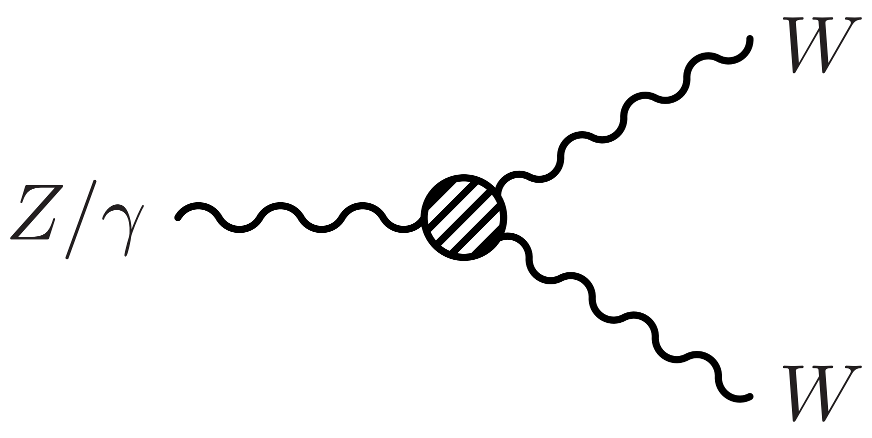
CP-odd triple gauge couplings





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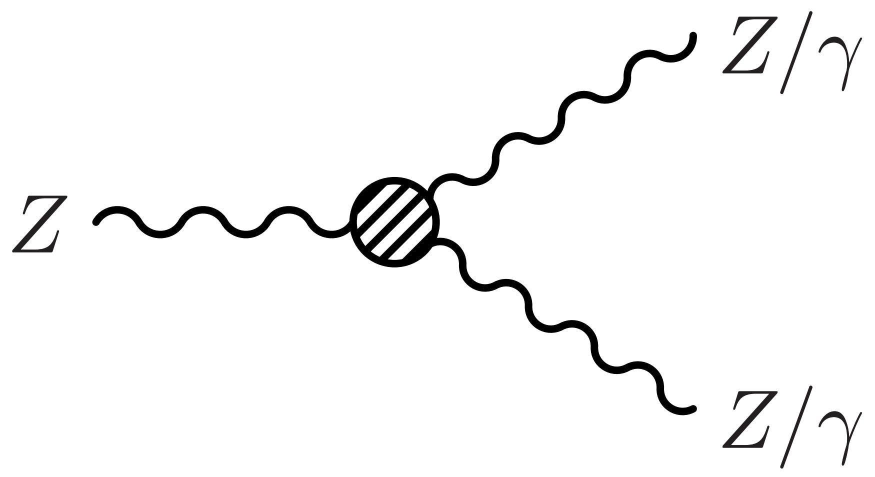

Does not exist in the SM

First contribution appears at dim-8

Luckily only two dim-6 operators contribute

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