A global analysis of the minimal MFV SMEFT

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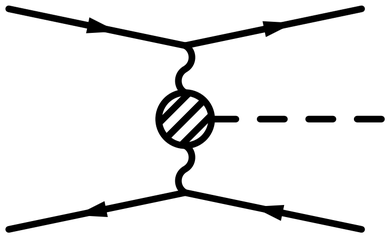
JG|U

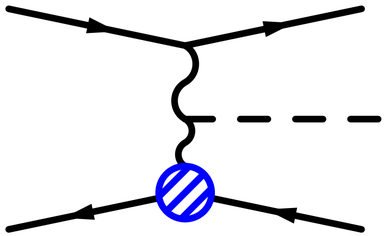
Based on 2311.04963 with
Riccardo Bartocci and Tobias Hurth

LCHP Boston - June 7, 2024

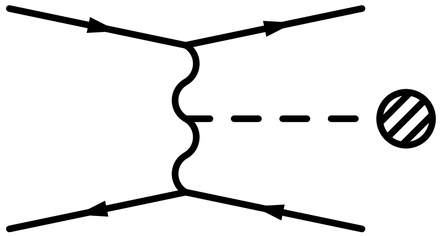
Why global fits?

One observable can be influenced by many operators





Higgs decay



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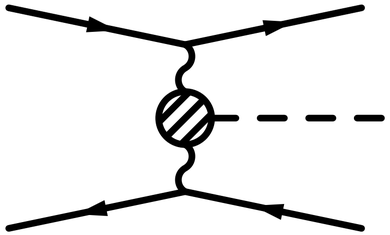

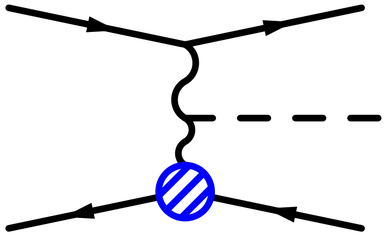

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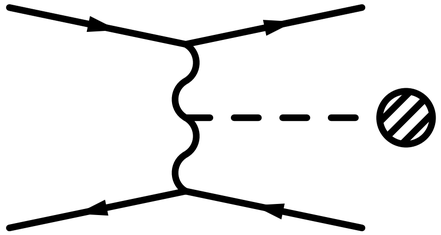
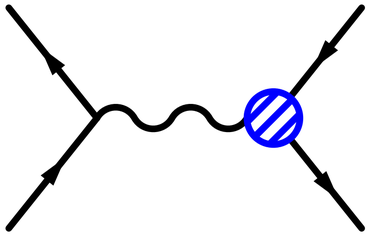
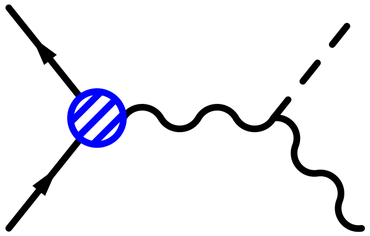


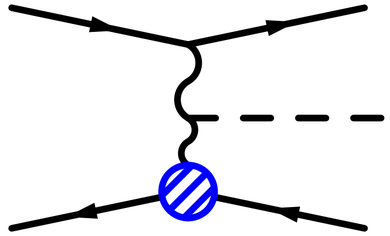
One operator can contribute to many different observables



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



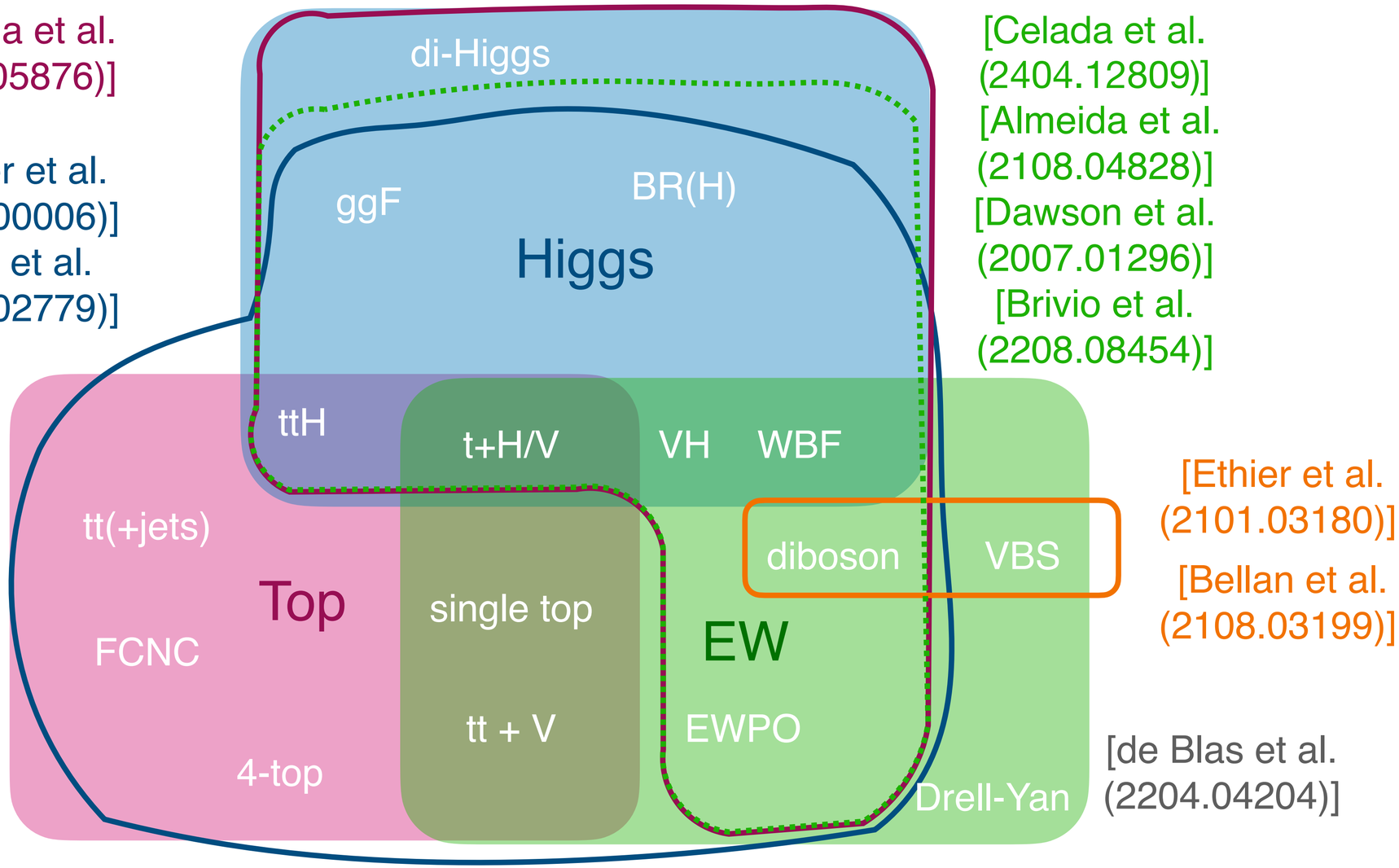
Zh production



Weak boson fusion
Higgs production

Need a global fit to take into account the possible crosstalk of observables and operators

Confronting the SMEFT with data



[Anisha et al. (2111.05876)]

[Ethier et al. (2105.00006)]
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[Celada et al. (2404.12809)]
[Almeida et al. (2108.04828)]
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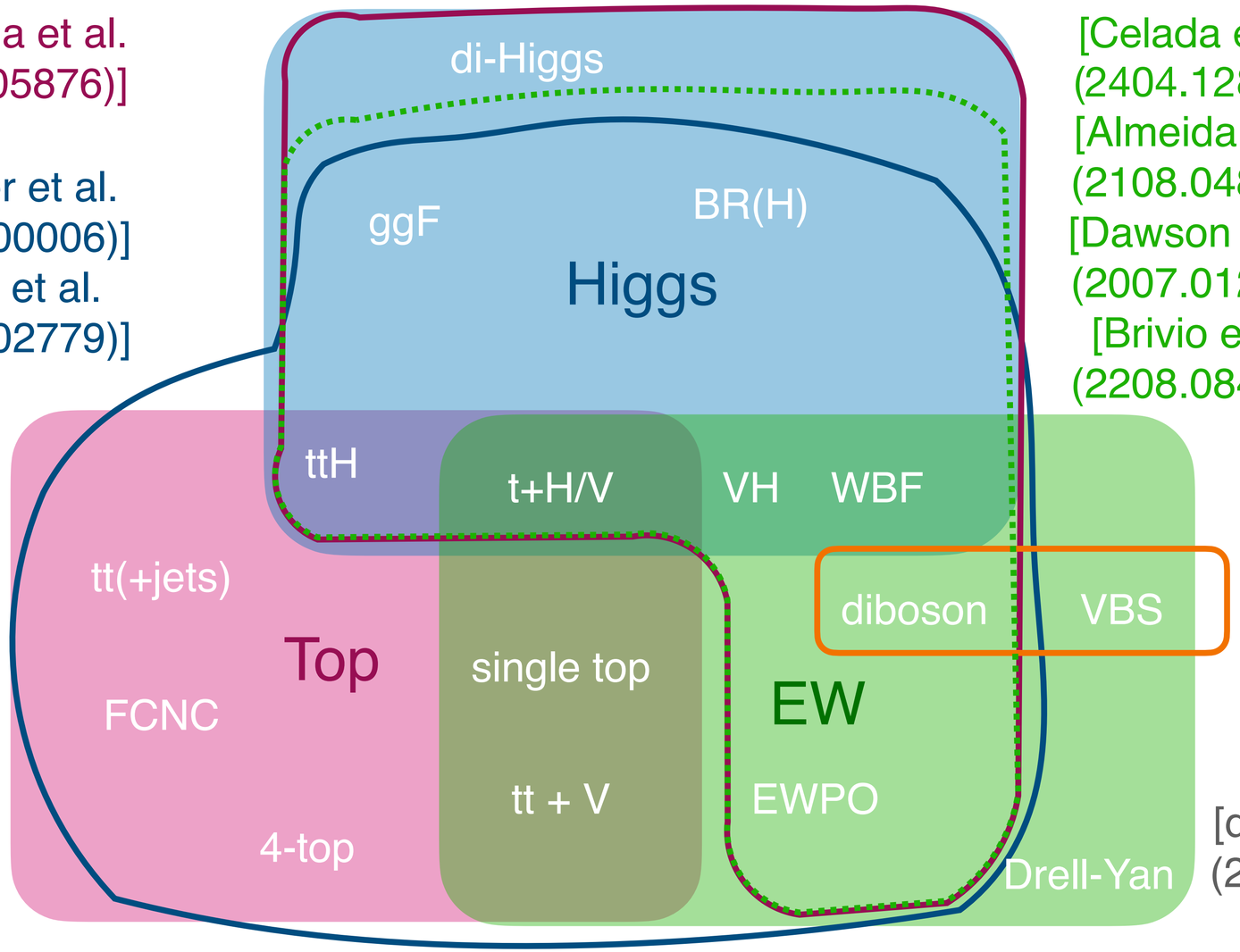

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Operator sets defined by the data

Which datasets do we need to constrain a theory motivated set of operators?

Outline

Are we ready for a global fit starting from theory assumptions?

SMEFT@NLO: Curse or blessing?

Based on 2311.04963 with
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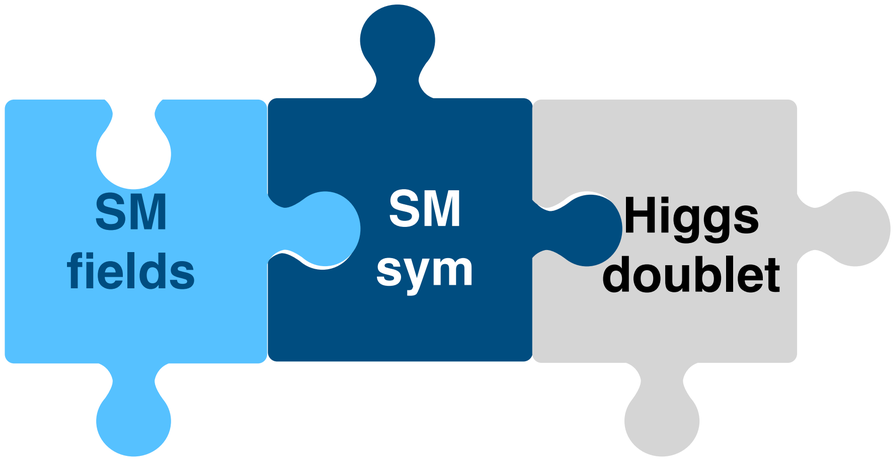
Standard Model Effective Field Theory (SMEFT)

[review: Brivio, Trott (1706.08945)]



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

Odd dimensions violate lepton or baryon number

2499 operators at D6

Many of these are different flavor combinations of the same structure

Reduce number of dof with flavor assumptions

$$\mathcal{O}_{\substack{dH\\ij}} = (H^\dagger H)(\bar{q}_i H d_j)$$

$3 \times 3 + \text{h.c.} \;\; = 18$ Flav. combinations

SMEFT flavor assumptions

More flavor symmetries:

[Faroughy, Isidori, Wilsch, Yamamoto (2005.05366)]

[Greljo, Palavric, Thomsen (2203.09561)]

Assume an exact $U(3)^5$ symmetry

$U(3)^5 = U(3)_\ell \times U(3)_q \times U(3)_e \times U(3)_u \times U(3)_d$ + no CP odd interactions

Same couplings for top, charm, up quark.

$\mathcal{O}_{\substack{dH \\ ij}} = (H^\dagger H)(\bar{q}_i H d_j)$ Operator is forbidden under $U(3)^5$ symmetry

Left with 41 operators

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Minimal flavor violation (MFV)

In the SM, the Yukawas Y_e, Y_u, Y_d are the only sources of the breaking of this symmetry

[Gerard (1983)]
[Chivukula, Georgi (1987)]
[D'Ambrosio, Giudice, Isidori, Strumia (hep-ph/0207036)]

$$\mathcal{O}_{\substack{dH \\ ij}} = (H^\dagger H)(\bar{q}_i H \, Y_d \, d_j)$$

$$\to (H^\dagger H)((\bar{q}\Omega_q^\dagger)_i H \, (\Omega_d Y_q \Omega_d^\dagger) \, (\Omega_d d)_j)$$

Warsaw basis

[Grzadkowski et al. (1008.4884)]

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

$2 : H^6$	
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}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
$Q_{H\widetilde{G}}$	$H^\dagger H\, \widetilde{G}^A_{\mu\nu} G^{A\mu\nu}$
Q_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
$Q_{H\widetilde{W}}$	$H^\dagger H\, \widetilde{W}^I_{\mu\nu} W^{I\mu\nu}$
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}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$Q_{H\widetilde{W}B}$	$H^\dagger \tau^I H\, \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$

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

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

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

Plus more four-fermion operators

Warsaw basis under U(3)^5

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δ_{pr}

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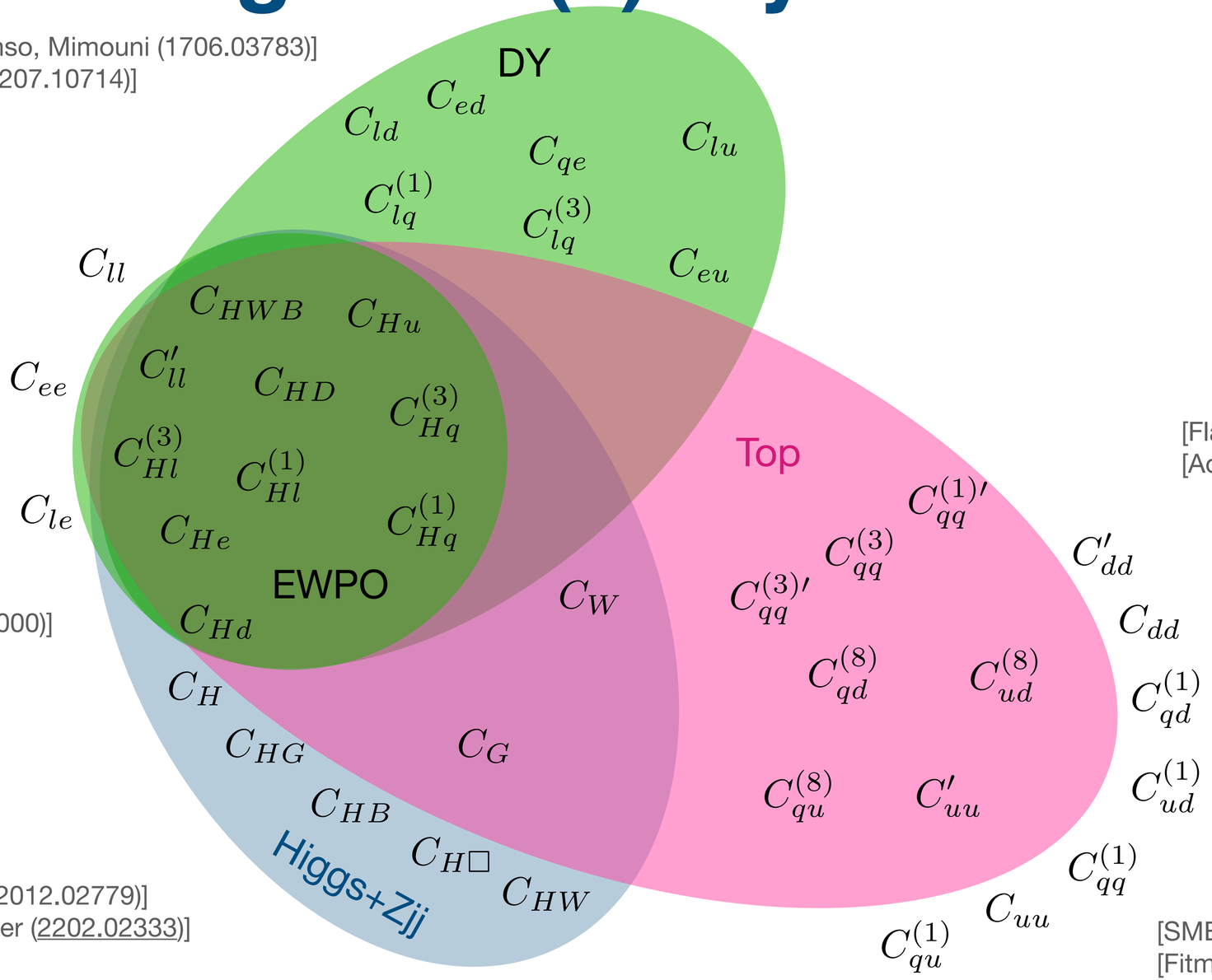
Plus more four-fermion operators

41 parameters in total

Constraining the U(3)^5 symmetric SMEFT

[Falkowski, Gonzalez-Alonso, Mimouni (1706.03783)]
[HighPT: Allwicher et al. (2207.10714)]



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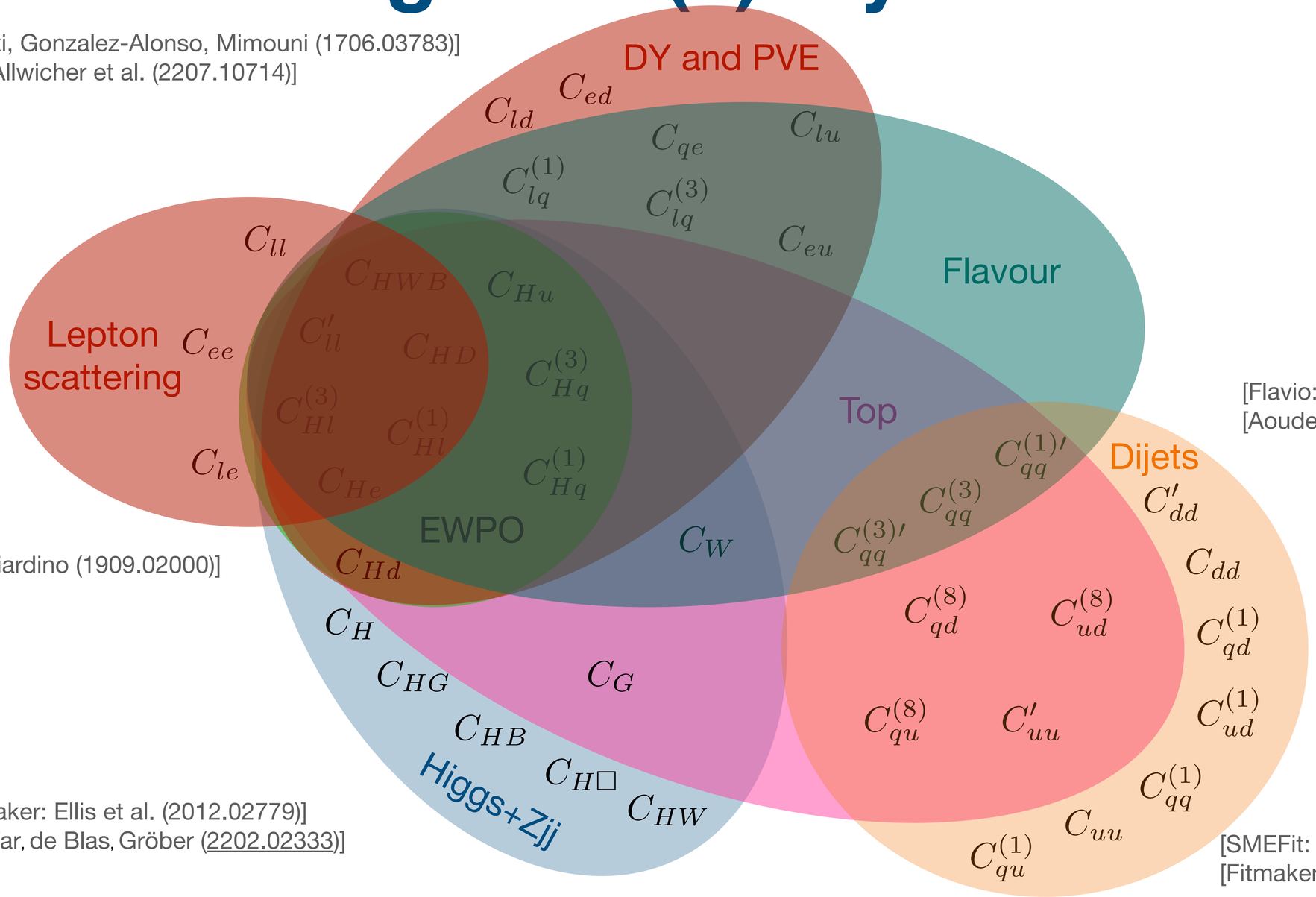

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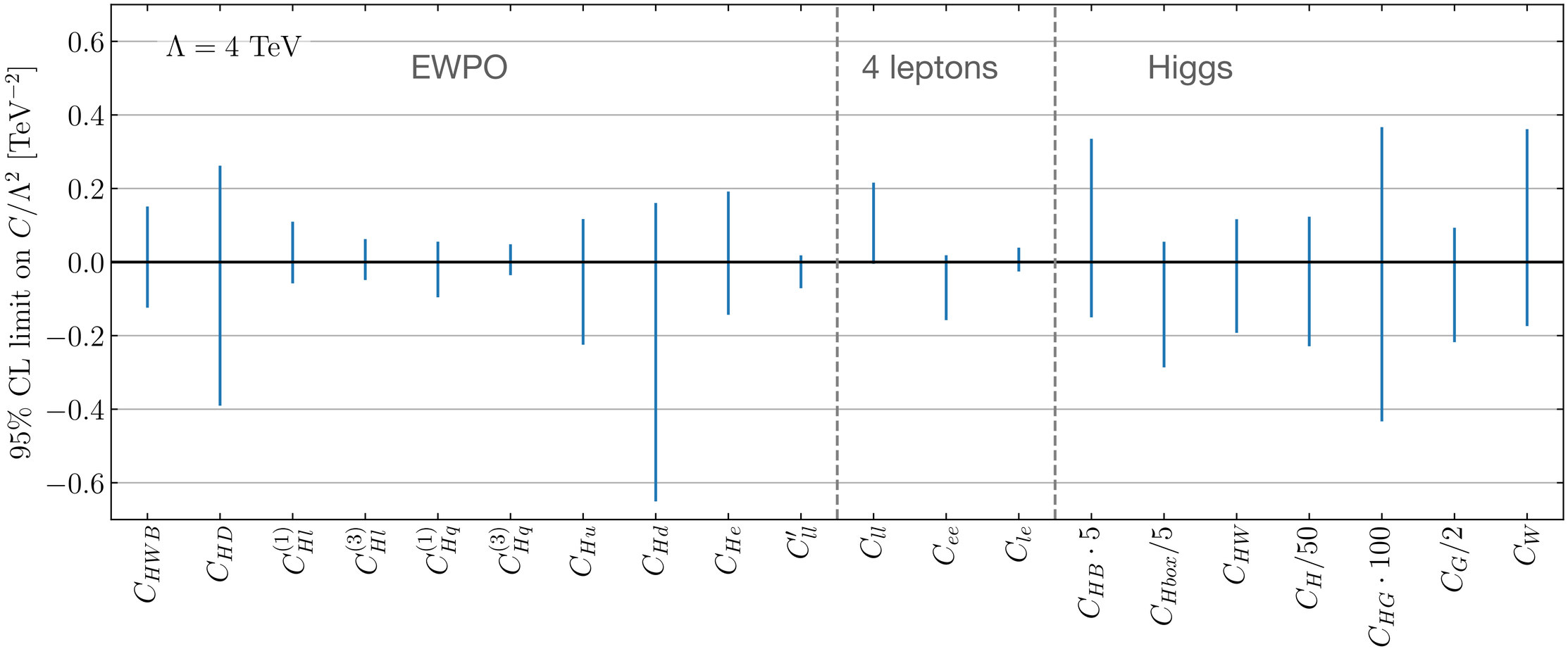
LO fit - Higgs/gauge interactions



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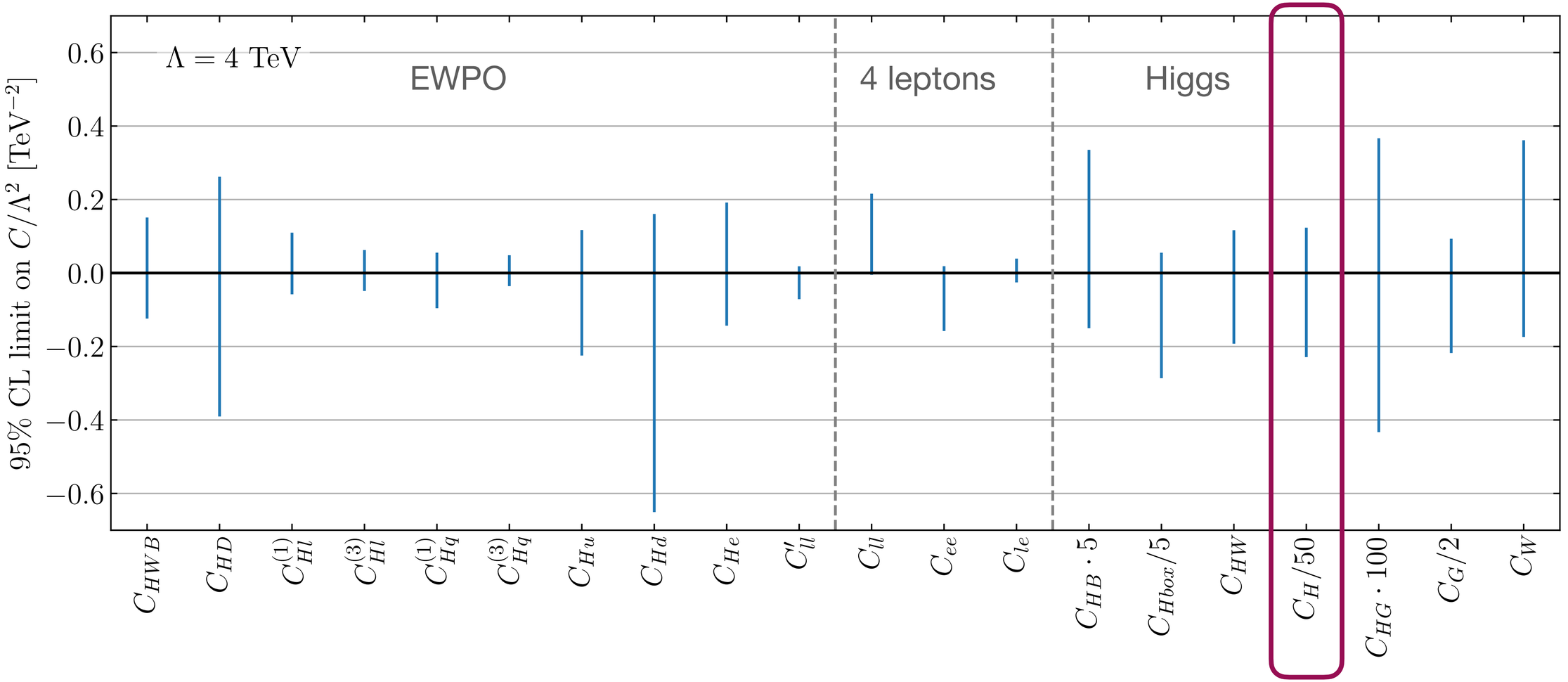
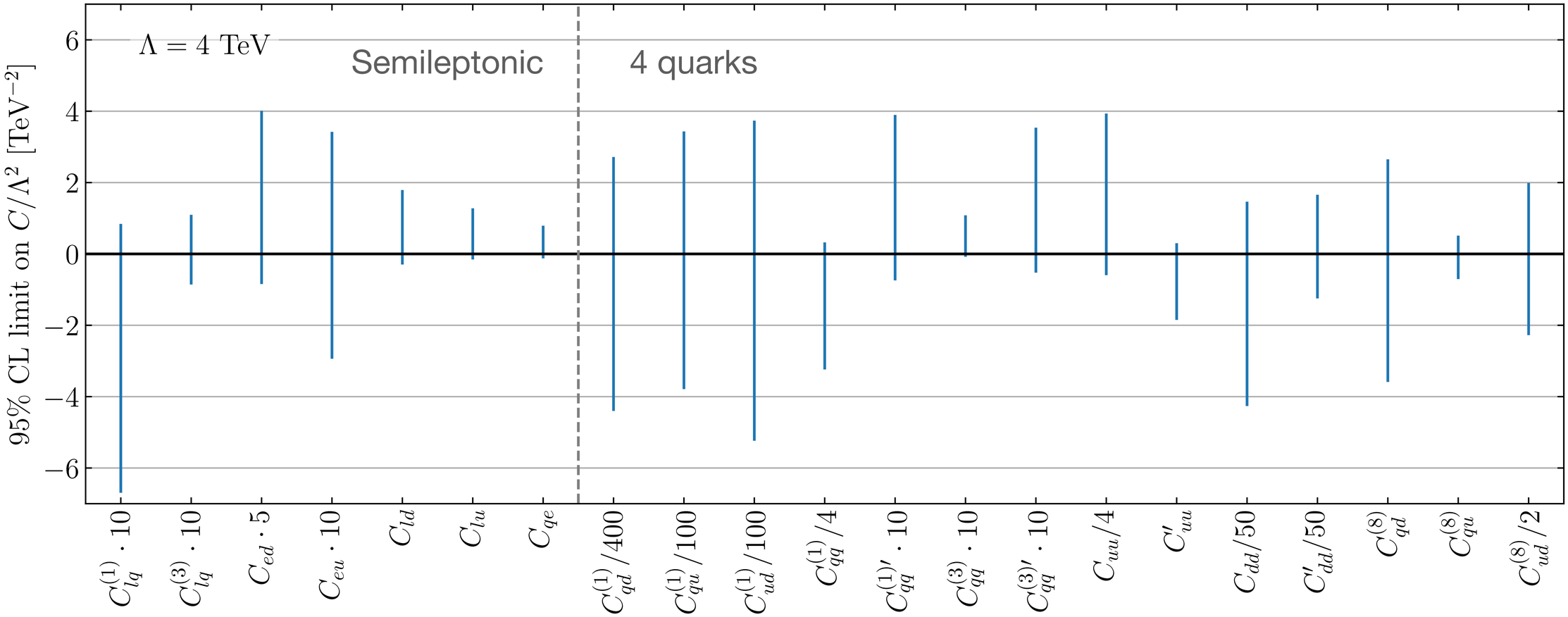
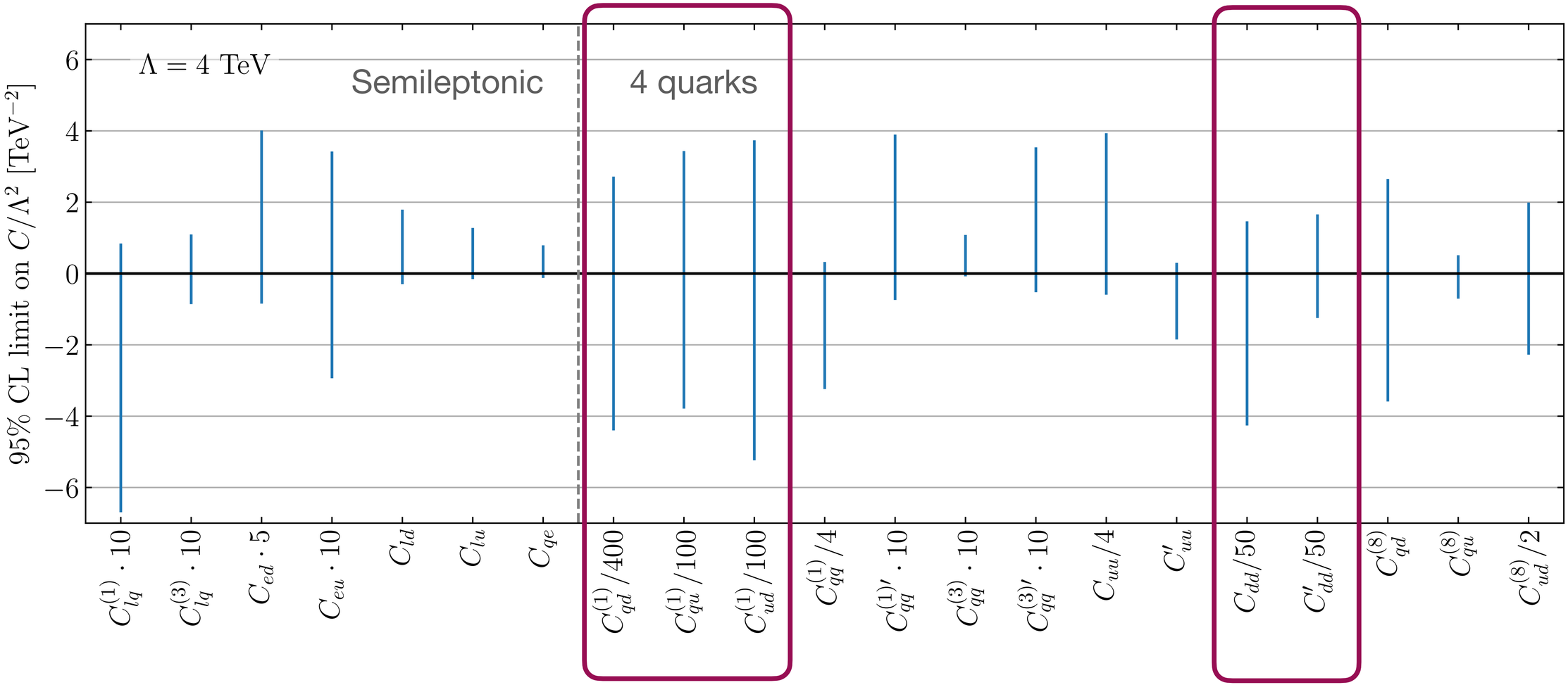


LO fit - 2


$\Lambda = 4$ TeV
Semileptonic
4 quarks
95% CL limit on C/Λ^2 [TeV^{-2}]
6
4
2
0
−2
−4
−6
$C_{lq}^{(1)} \cdot 10$
$C_{lq}^{(3)} \cdot 10$
$C_{ed} \cdot 5$
$C_{eu} \cdot 10$
C_{ld}
C_{lu}
C_{qe}
$C_{qd}^{(1)}/400$
$C_{qu}^{(1)}/100$
$C_{ud}^{(1)}/100$
$C_{qq}^{(1)}/4$
$C_{qq}^{(1)\prime} \cdot 10$
$C_{qq}^{(3)} \cdot 10$
$C_{qq}^{(3)\prime} \cdot 10$
$C_{uu}/4$
C'_{uu}
$C_{dd}/50$
$C'_{dd}/50$
$C_{qd}^{(8)}$
$C_{qu}^{(8)}$
$C_{ud}^{(8)}/2$

LO fit - 2

Do not interfere with dominant SM diagram in dijet(+photon) production

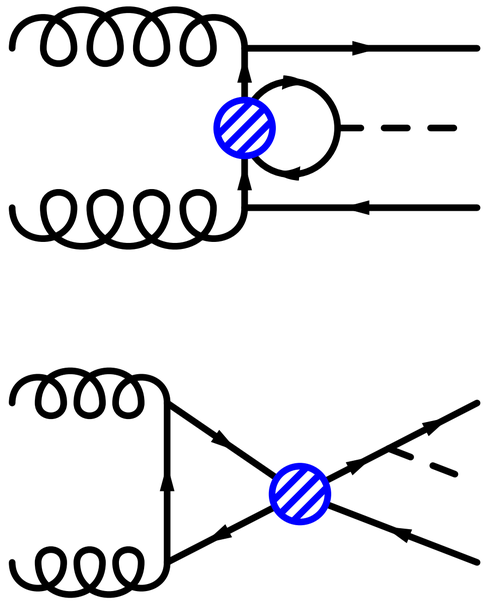


NLO to the rescue?

Additional sensitivity from next-to-leading-order (NLO) SMEFT effects

Higgs: $C_{qu}^{(1)}$ $\bar{t}th$

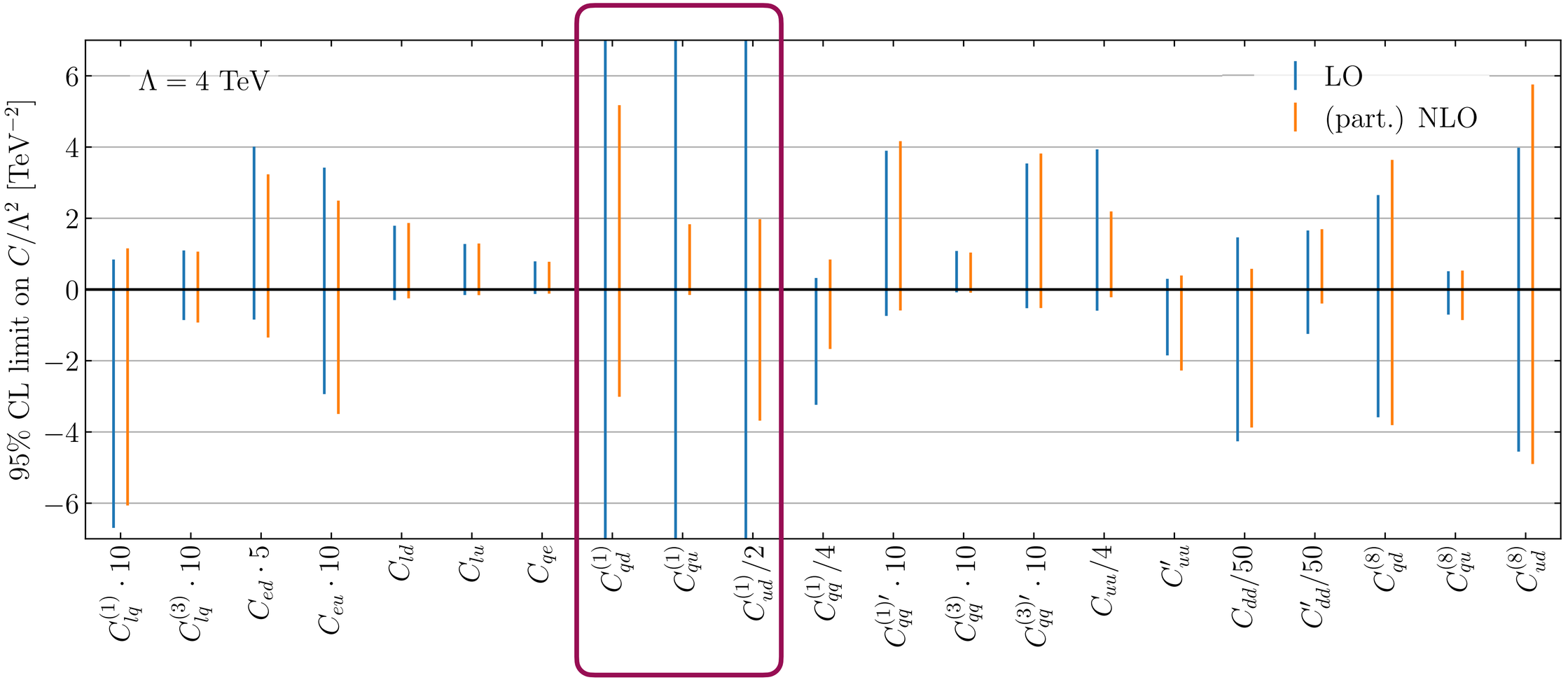
Top: $C_{qd}^{(1)}, C_{ud}^{(1)}$ $\bar{t}t$



[Alasfar, de Blas, Gröber (2202.02333)]
[SMEFit: Kassabov et al. (2303.06159)]

(Partial) NLO fit

Partial: Not all observables are available at NLO



SMEFT@NLO: Blessing & curse

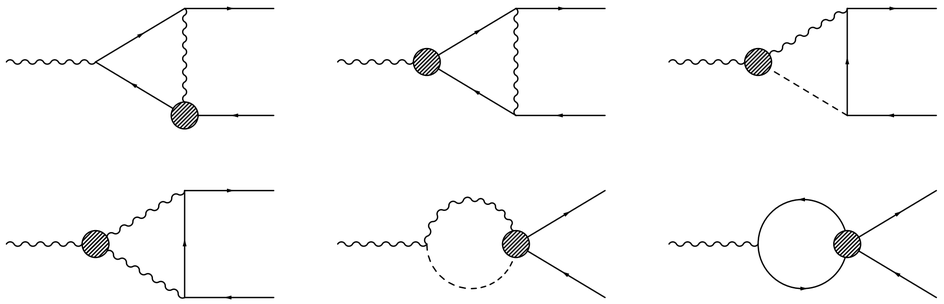
EWPO: 10 ops @LO, 32 ops @NLO ($U(3)^5$ sym)

[Dawson, Giardino (1909.02000)], [AB, Pecjak, Scott, Smith (2305.03763)]

$$\delta\Gamma(Z\to l^+l^-)^{LO} = \frac{v^2}{\Lambda^2}\Big\{-0.1408\mathcal{C}_{\phi e}+0.191\mathcal{C}_{\phi l}^{(1)}-0.037\mathcal{C}_{\phi l}^{(3)}+0.114\mathcal{C}_{ll}-0.057\mathcal{C}_{\phi D} -0.0713\mathcal{C}_{\phi WB}\Big\}\,\text{GeV}$$

$$\begin{aligned}\delta\Gamma(Z\to l^+l^-)^{NLO} = \frac{v^2}{\Lambda^2}\Big\{&-0.1596\mathcal{C}_{\phi e}+0.1834\mathcal{C}_{\phi l}^{(1)}-0.0221\mathcal{C}_{\phi l}^{(3)}+0.0985\mathcal{C}_{ll}-0.0508\mathcal{C}_{\phi D}\\ &-0.0349\mathcal{C}_{\phi WB}-0.0001\mathcal{C}_{\phi W}-0.0002\mathcal{C}_{ed}-0.0005\mathcal{C}_{ee}+0.0035\mathcal{C}_{eu}\\ &-0.0002\mathcal{C}_{\phi d}-0.0042\mathcal{C}_{\phi q}^{(1)}+0.0032\mathcal{C}_{\phi q}^{(3)}+0.0049\mathcal{C}_{\phi u}+0.0002\mathcal{C}_{ld}\\ &+0.0001\mathcal{C}_{le}+0.0034\mathcal{C}_{lq}^{(1)}-0.0031\mathcal{C}_{lq}^{(3)}-0.0045\mathcal{C}_{lu}-0.0001\mathcal{C}_{\phi\Box}\\ &-0.0027\mathcal{C}_{qe}-0.0007\mathcal{C}_{uB}-0.0007\mathcal{C}_{uW}-0.0001\mathcal{C}_{W}\Big\}\,\text{GeV}\end{aligned}$$

More degrees of freedom contribute to each observable at NLO

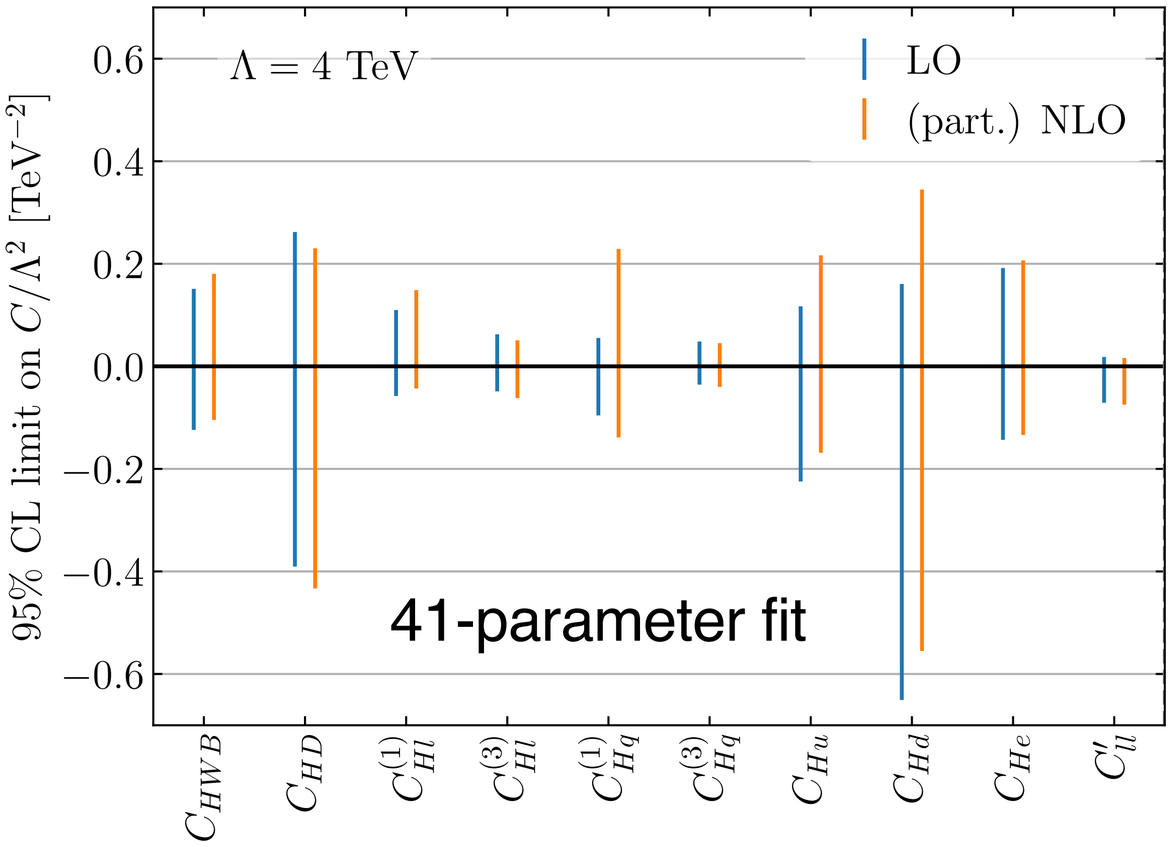


precision & degeneracies

NLO degeneracies

Higgs self coupling [Alasfar, de Blas, Gröber (2202.02333)]

[Bartocci, AB, Hurth (2311.04963)]



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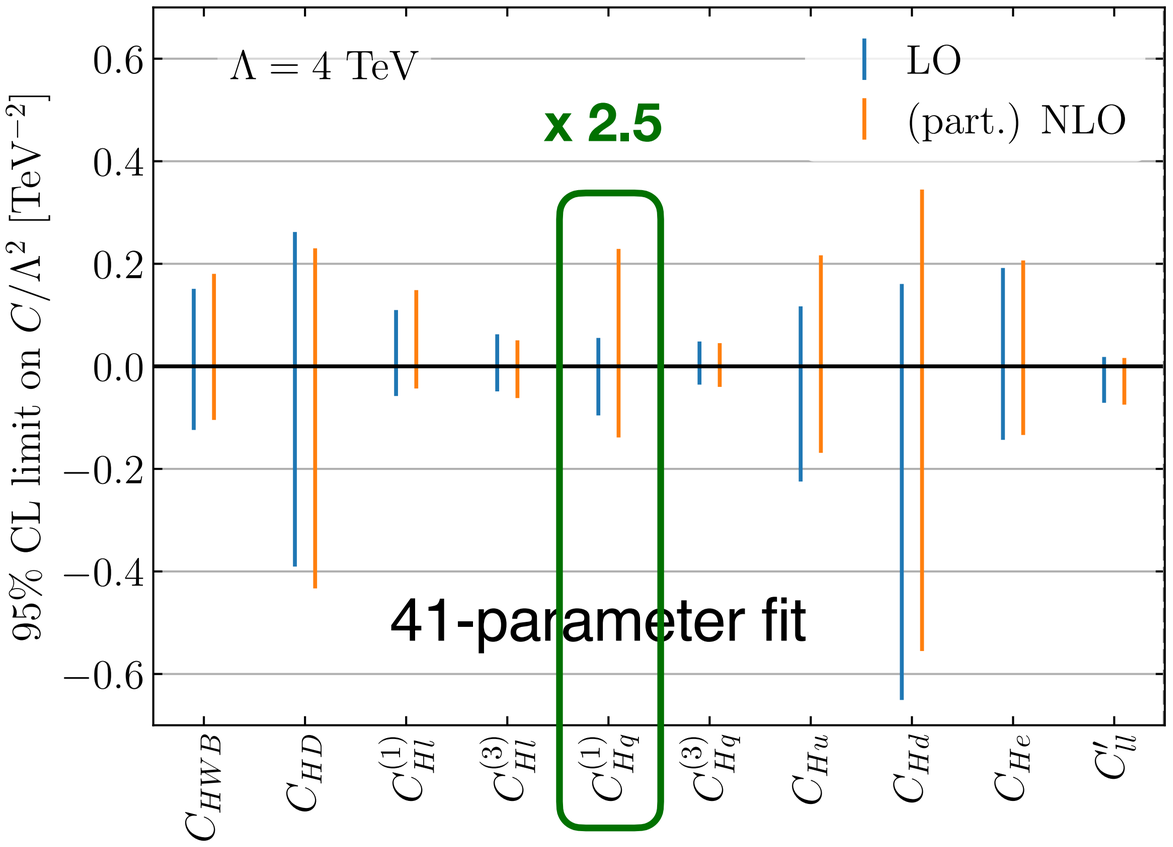

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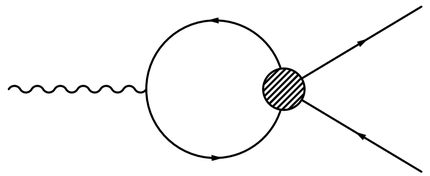

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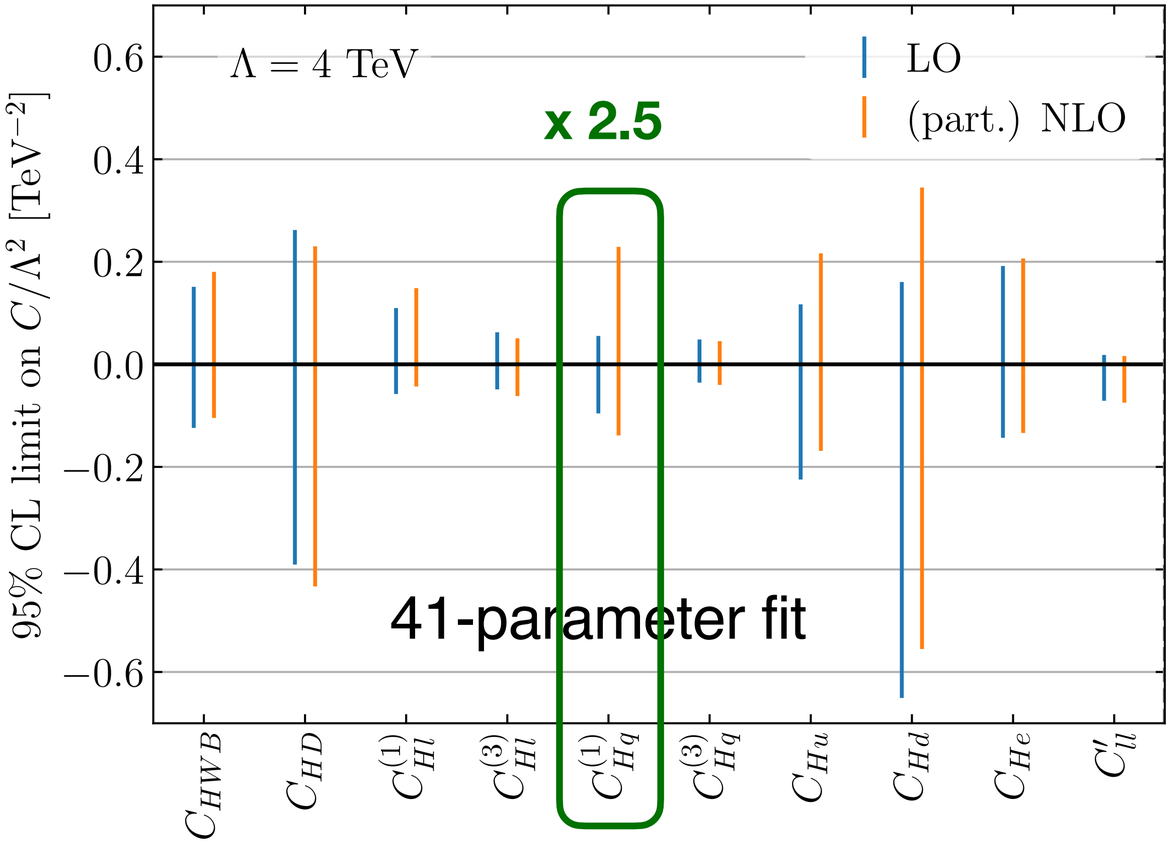

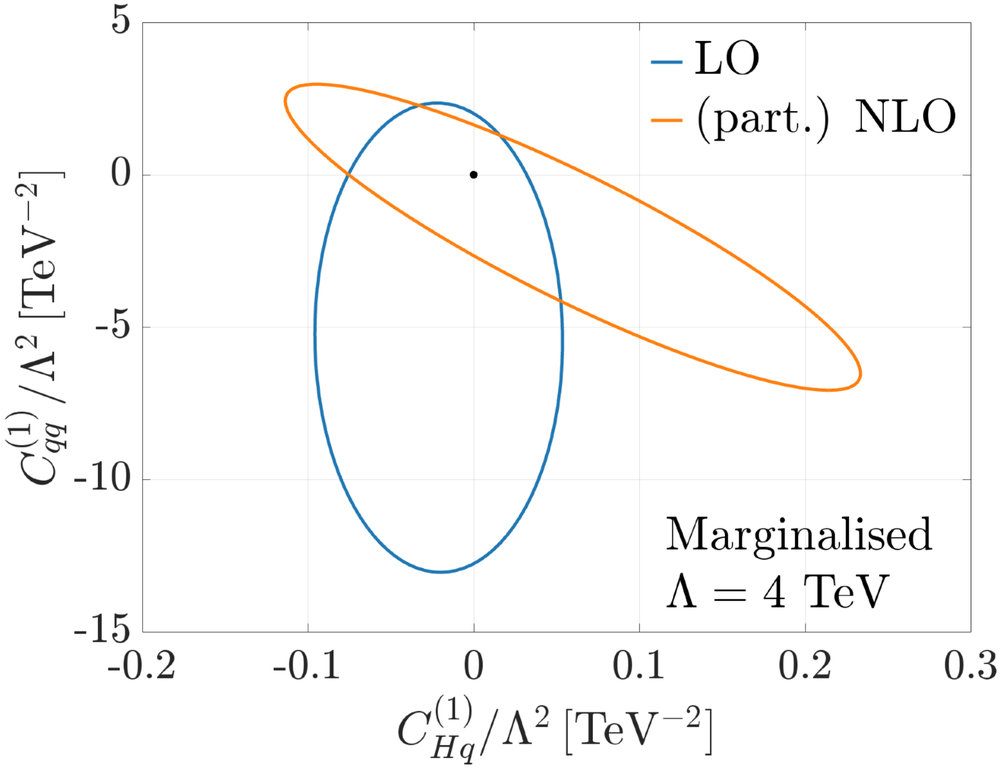

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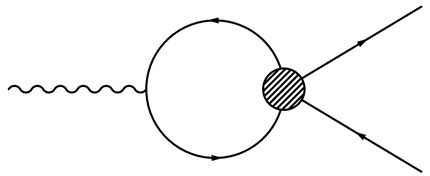

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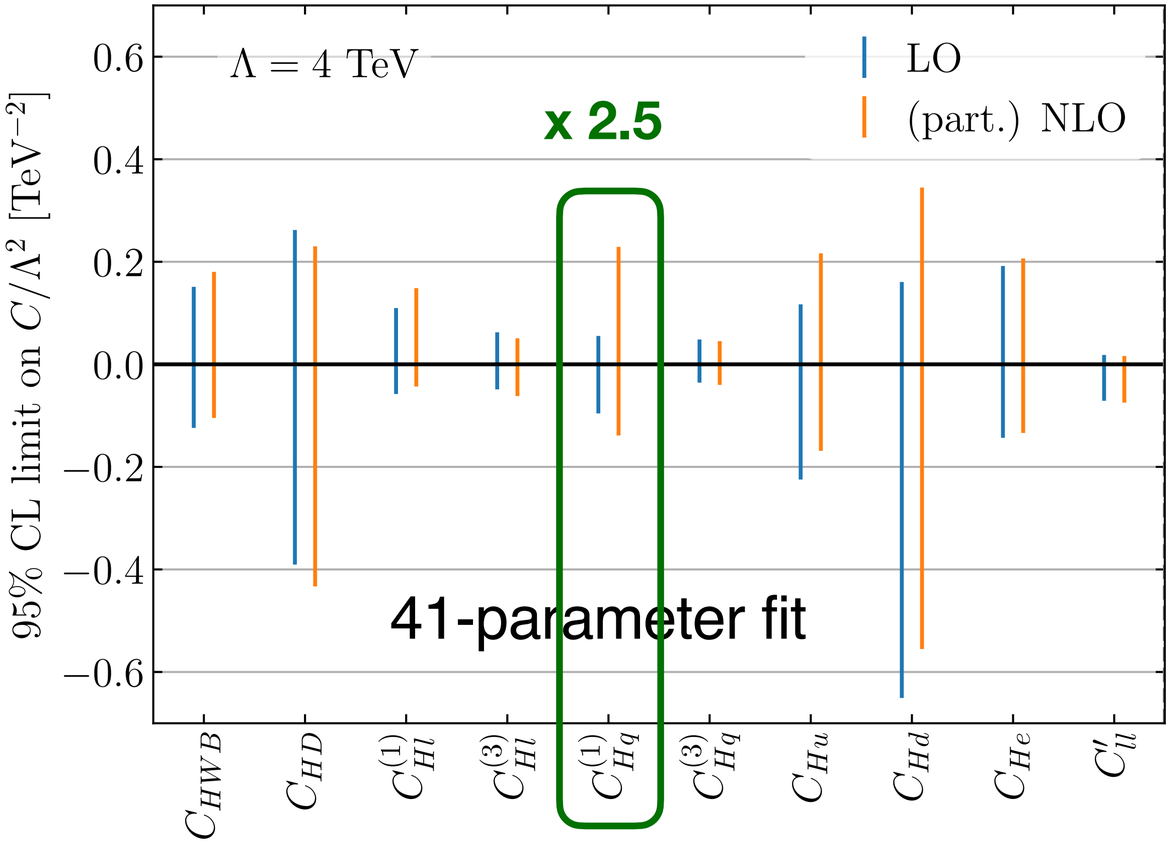

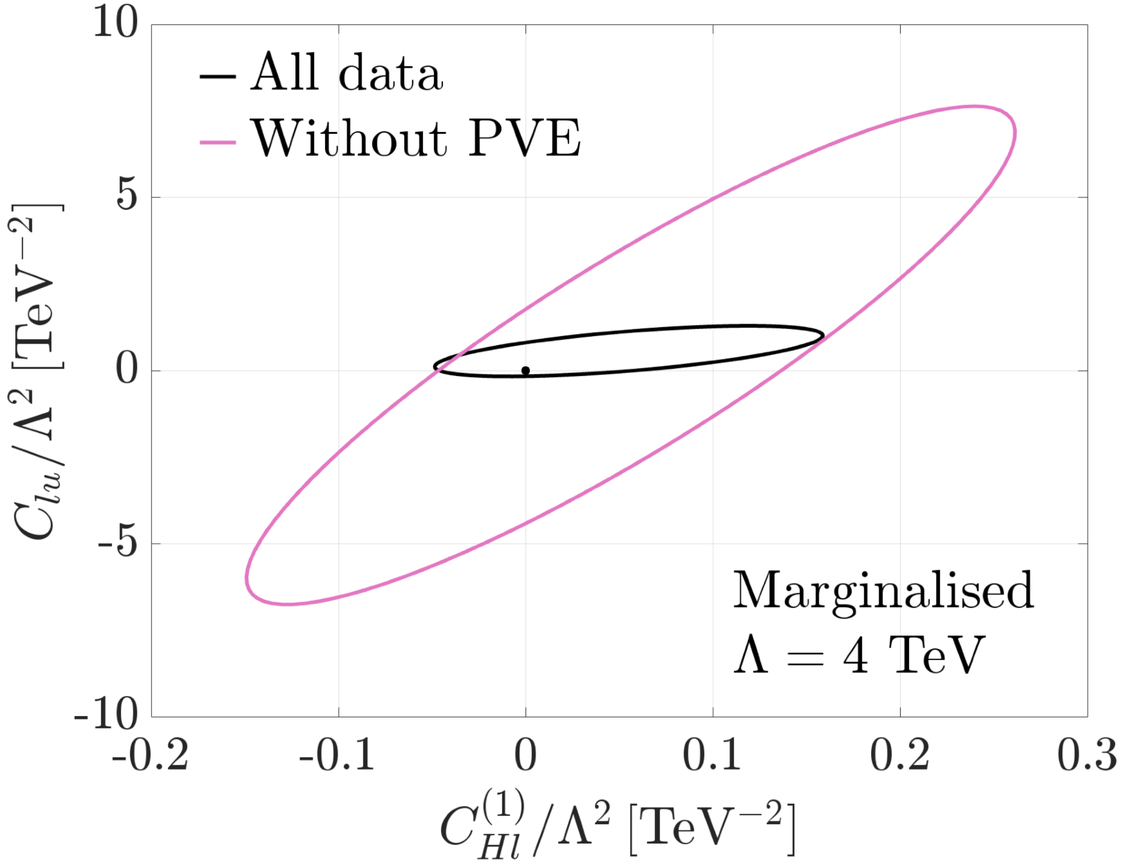

Conclusions

- Fitting theory-motivated operator sets is becoming a reality
- Degeneracies in NLO SMEFT predictions are manageable with current data
- Combination of many observables needed (different scales)

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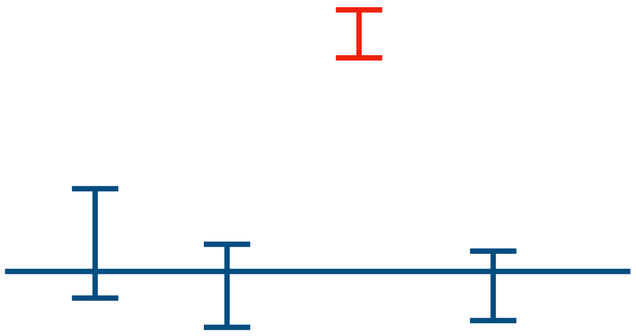
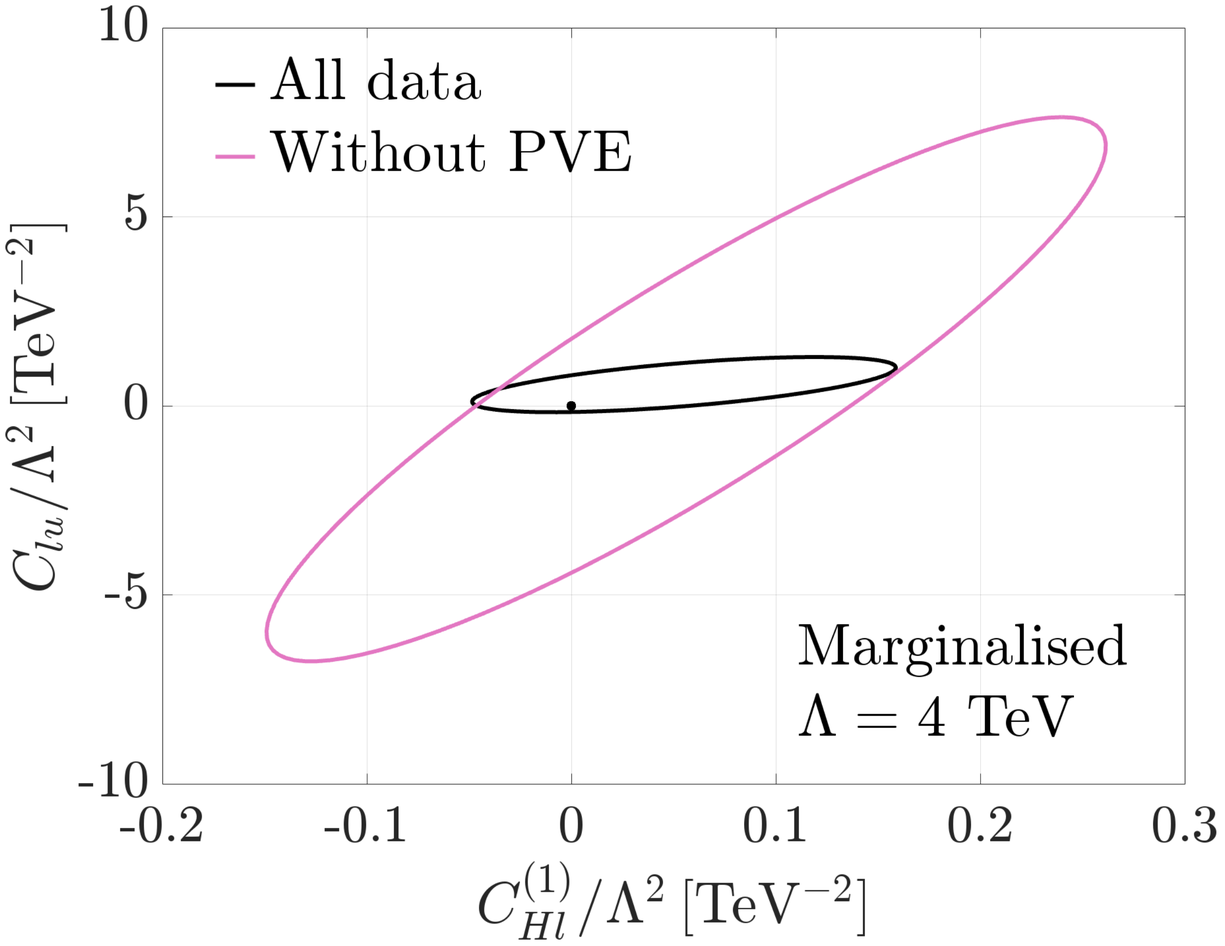
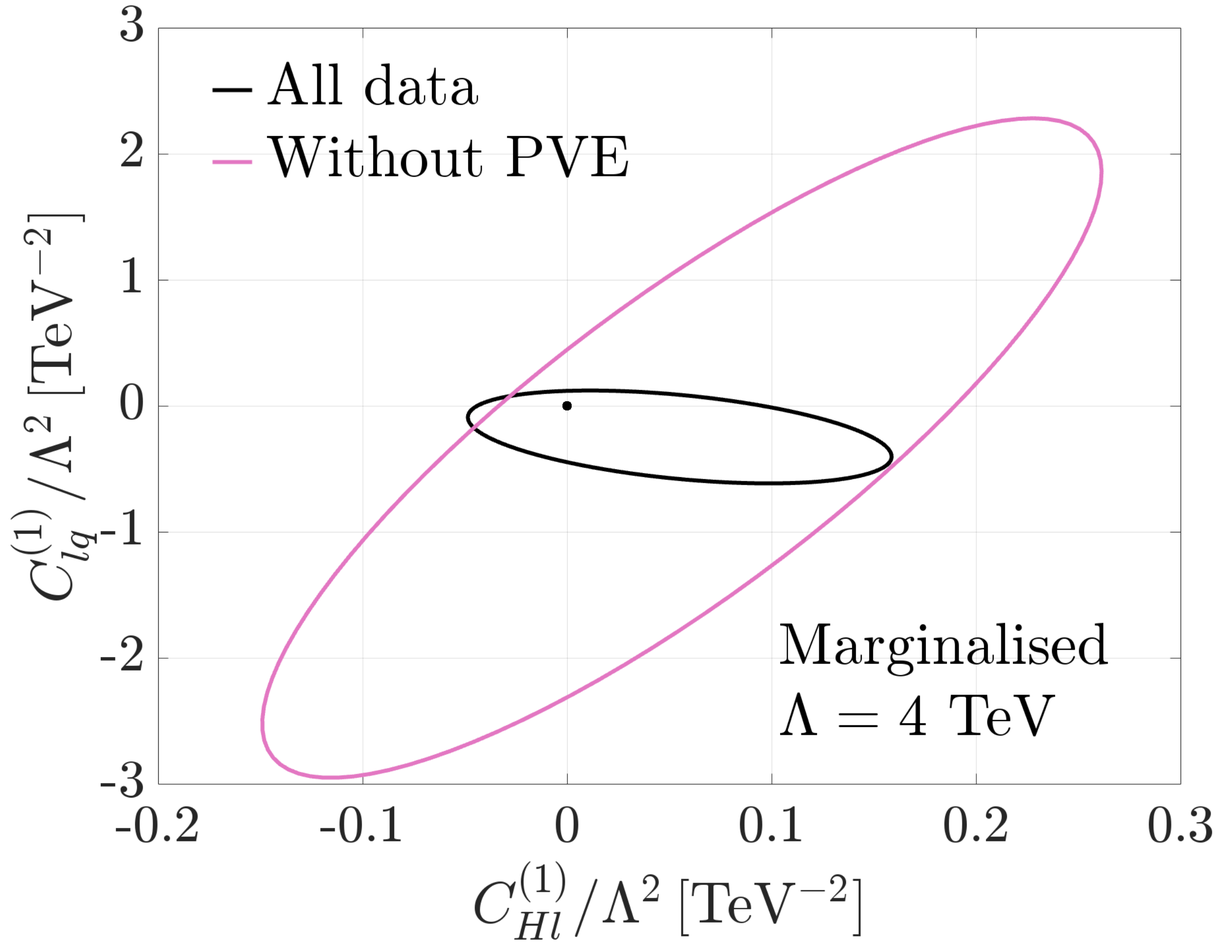


Thank you for your attention!

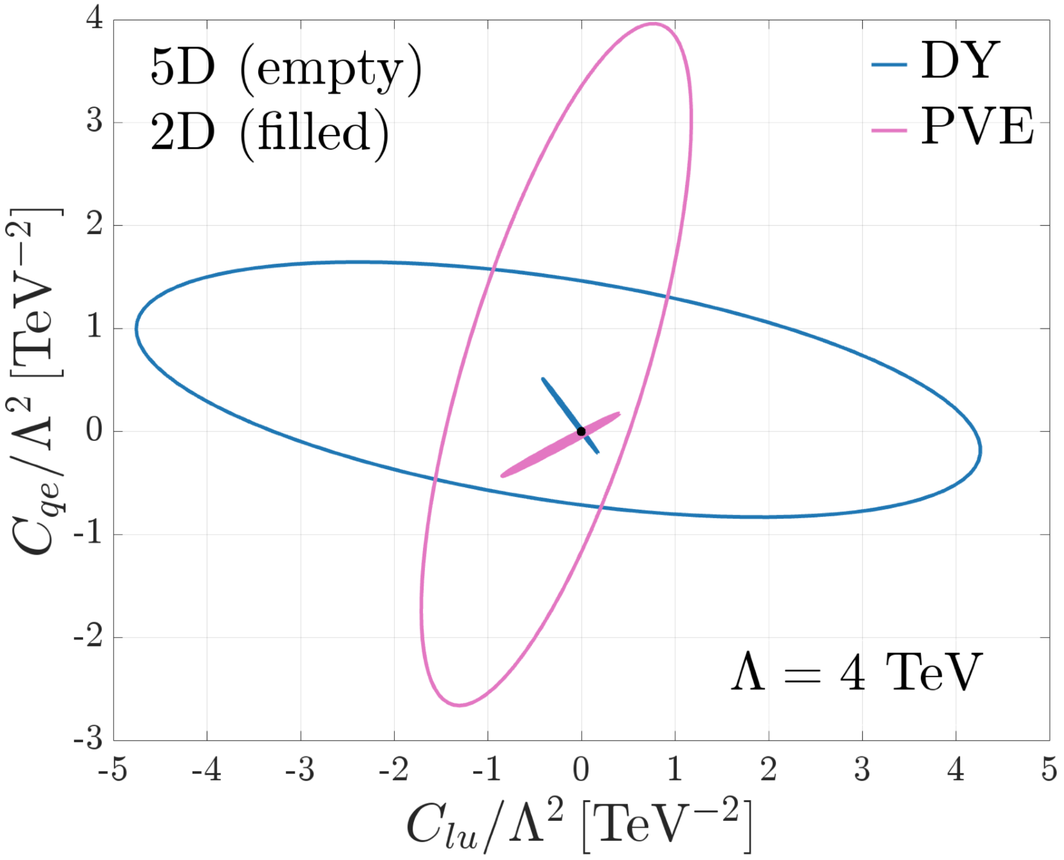
Backup

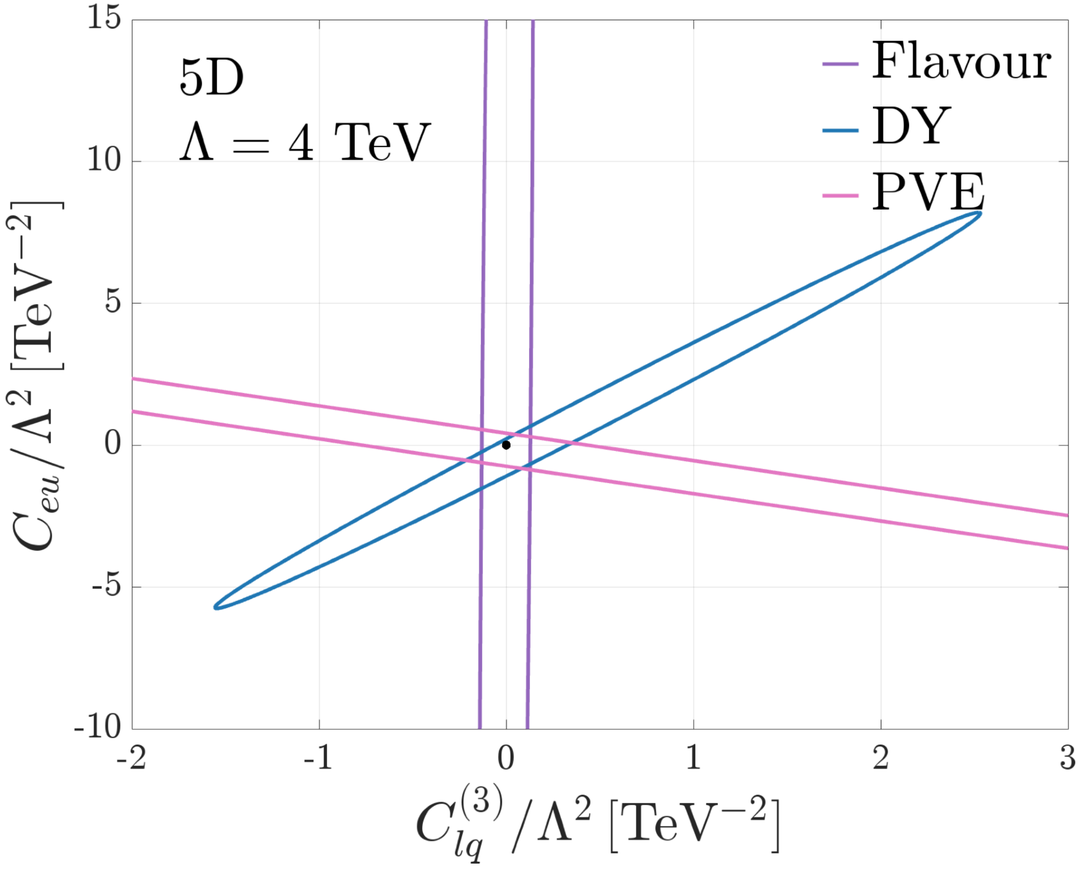
Correlations - PVE and EWPO



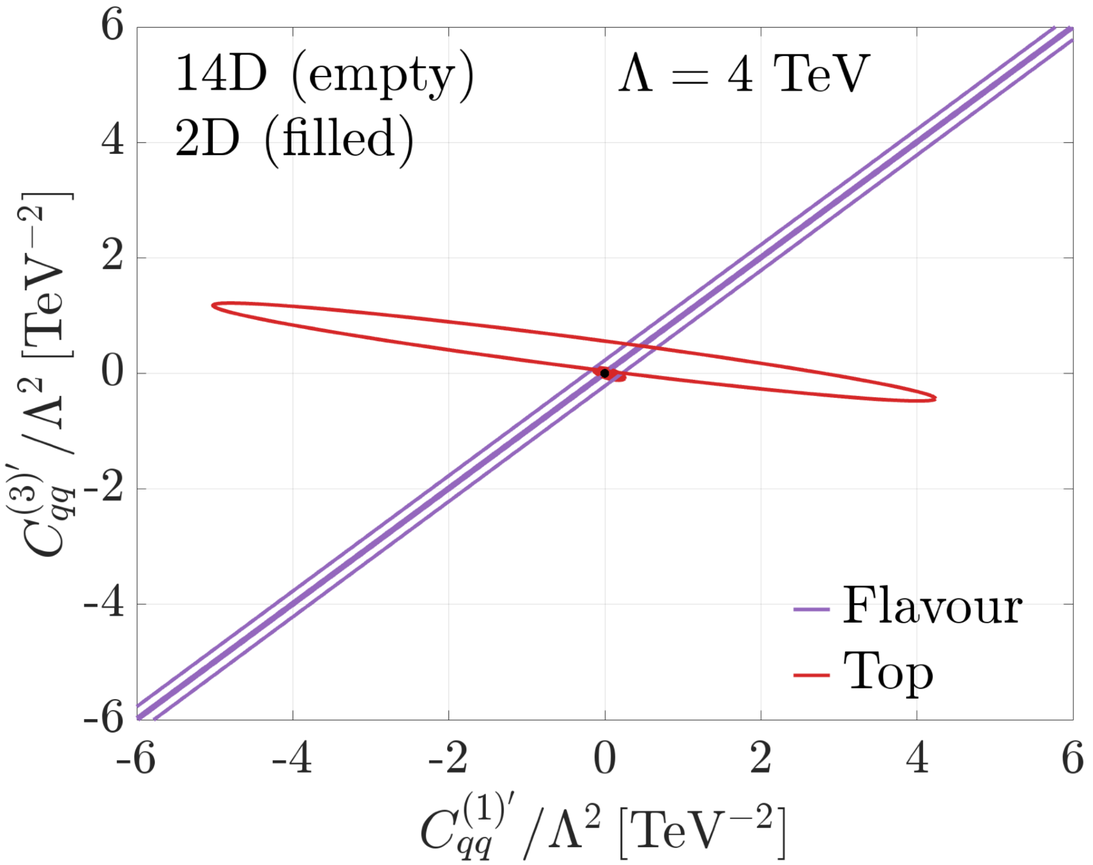


Correlations - PVE and DY

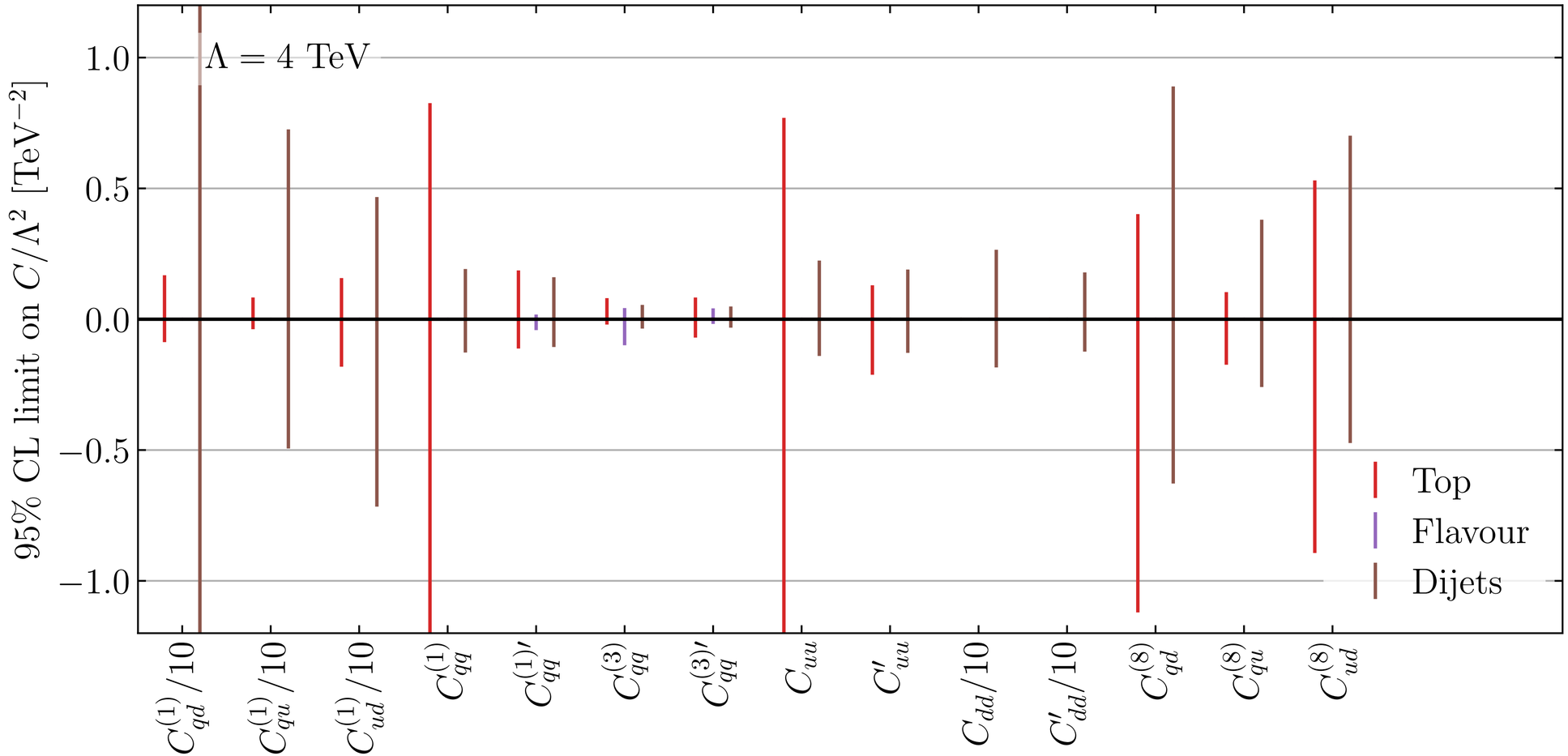




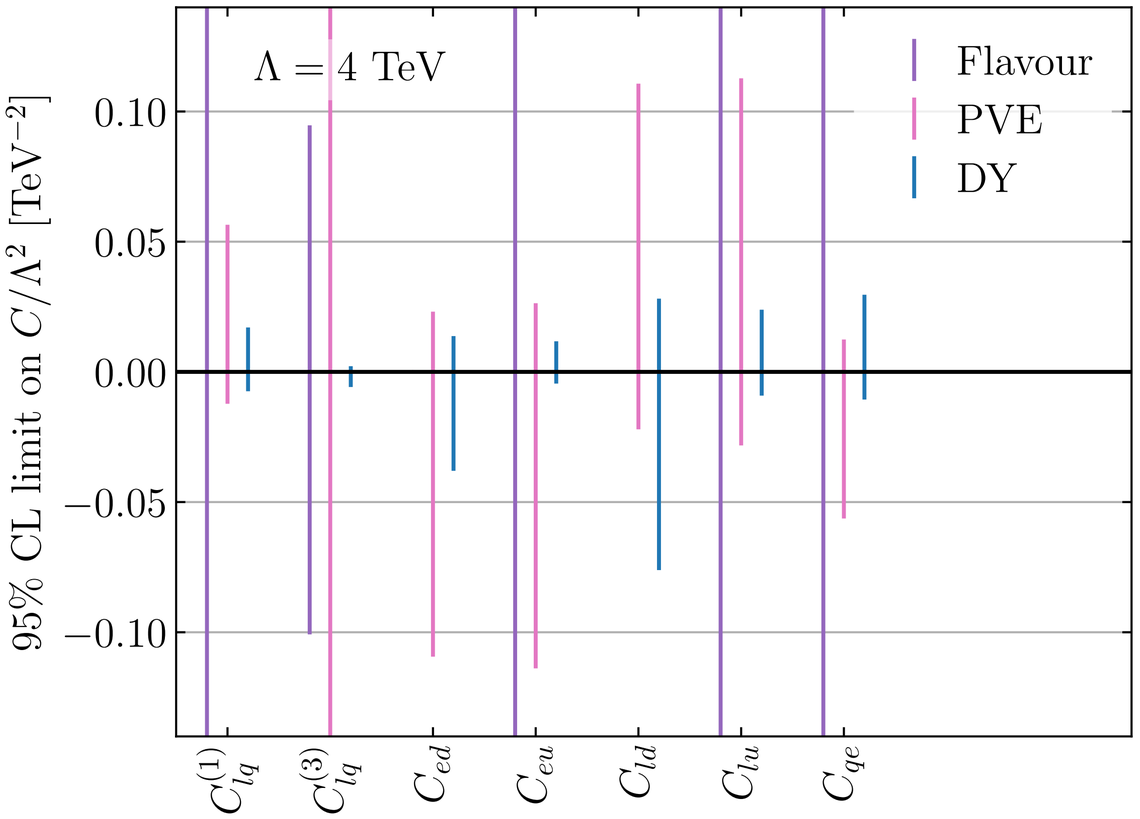
Correlations - top and flavor



1D fits - four-quark operators



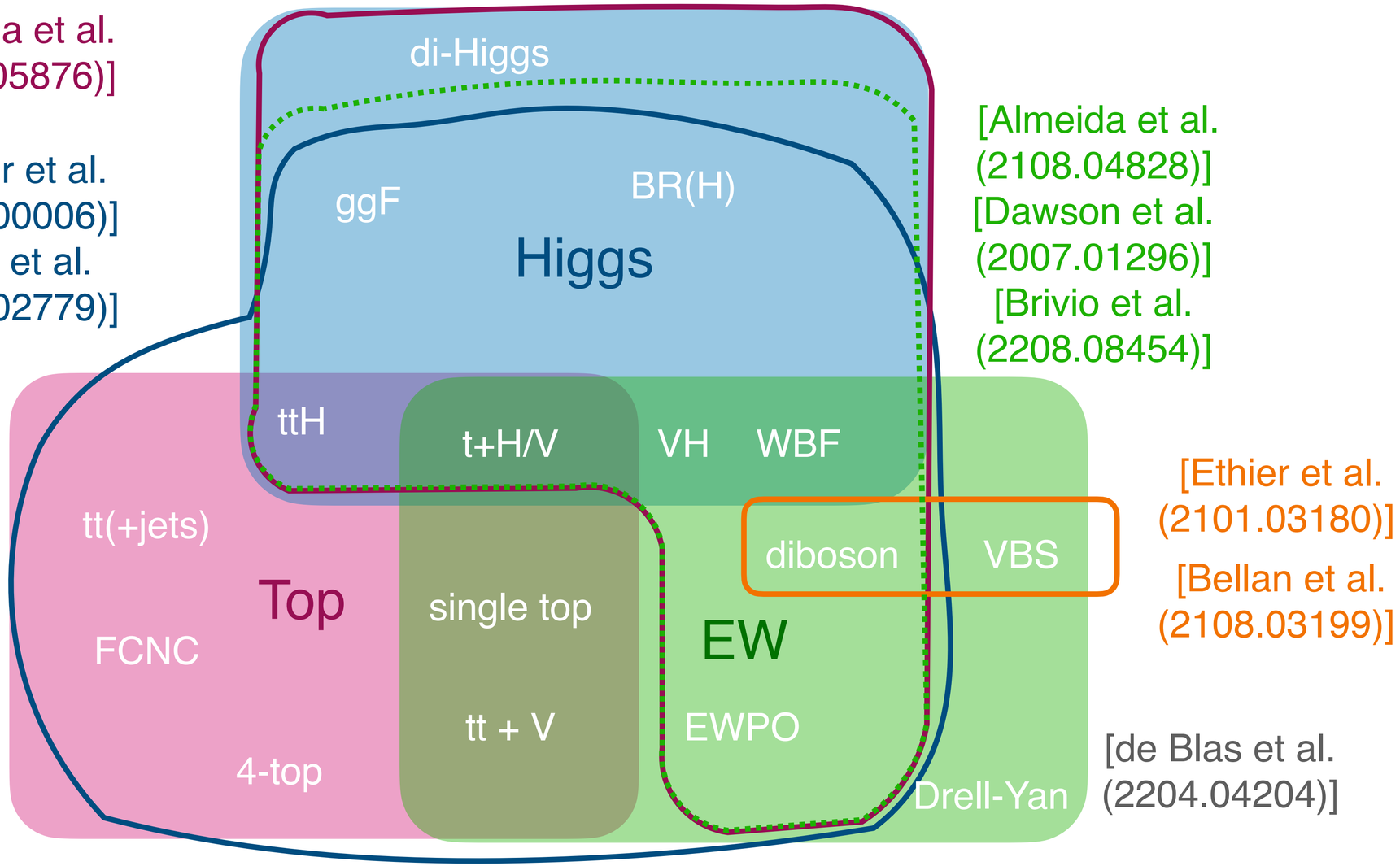
1D fits - semileptonic operators



Confronting the SMEFT with data

[Anisha et al. (2111.05876)]

[Ethier et al. (2105.00006)]
[Ellis et al. (2012.02779)]



[Almeida et al. (2108.04828)]
[Dawson et al. (2007.01296)]
[Brivio et al. (2208.08454)]

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[de Blas et al. (2204.04204)]

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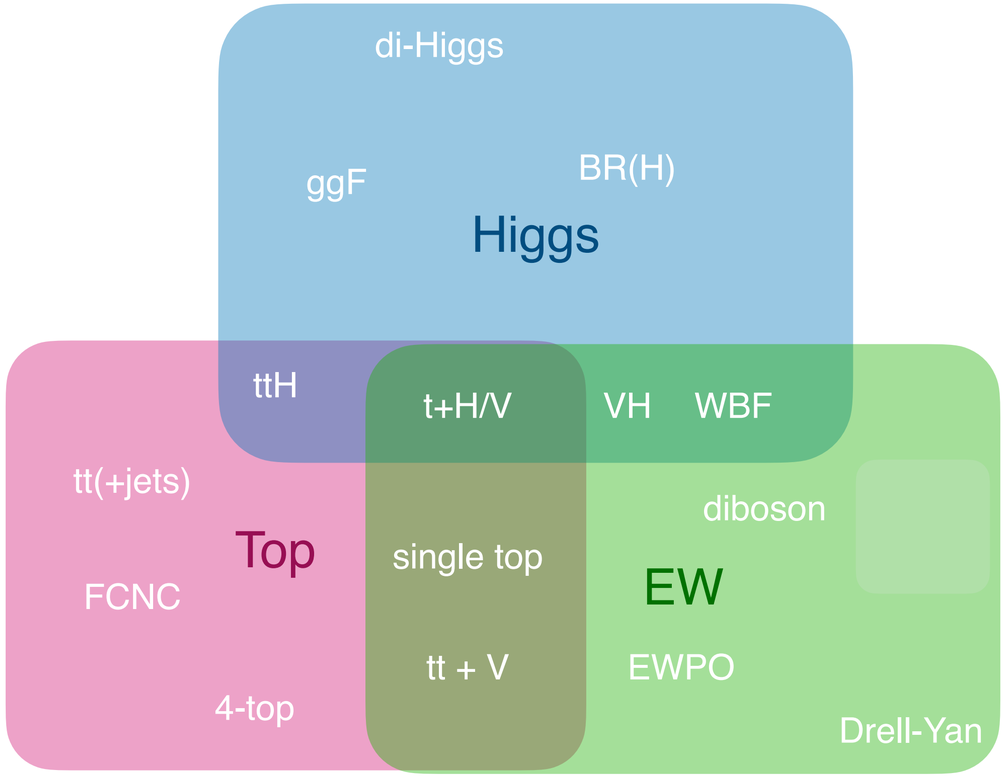

Adapted from Ken Mimasu

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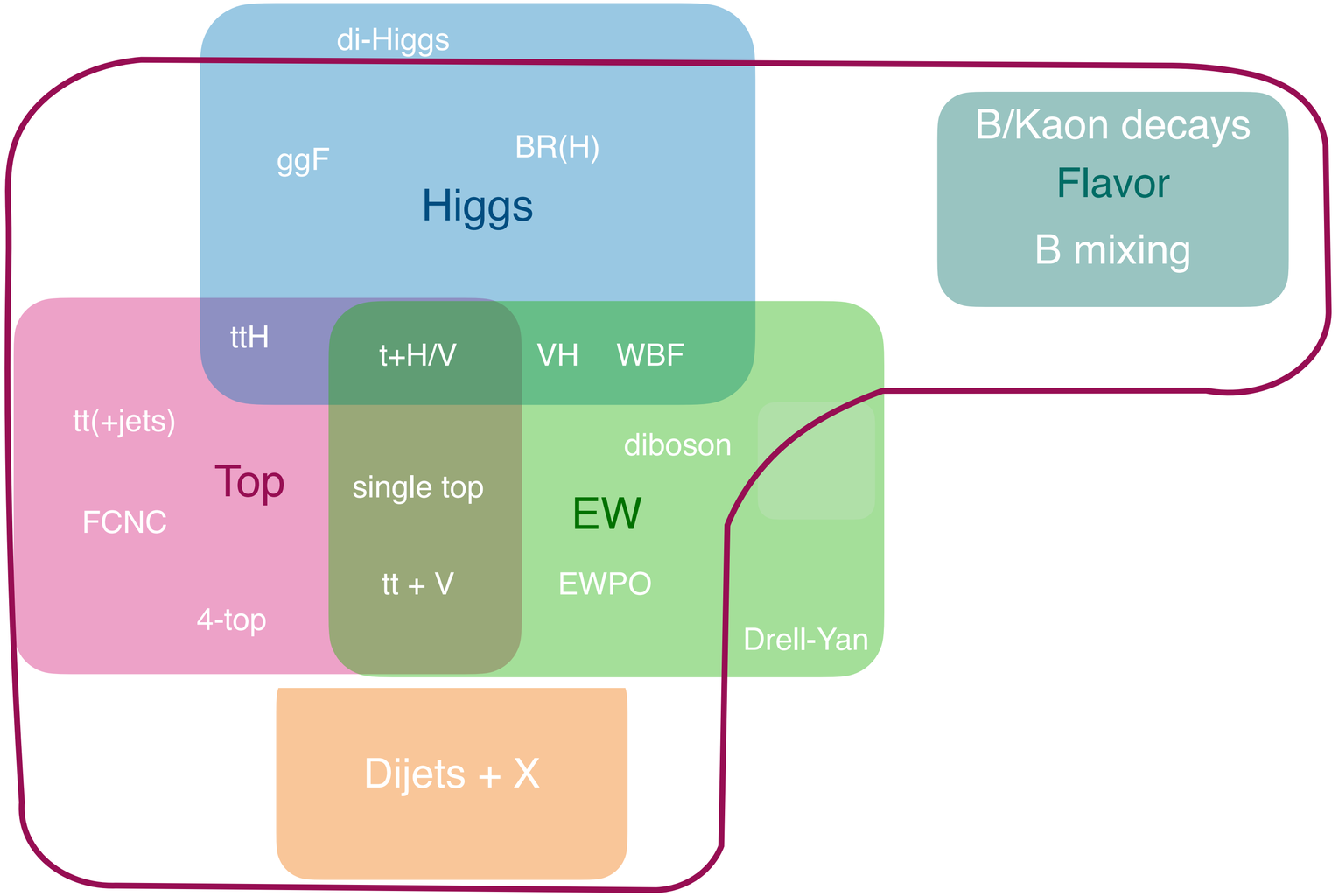

[Bruggisser et al. (2212.02532), (2101.07273)]

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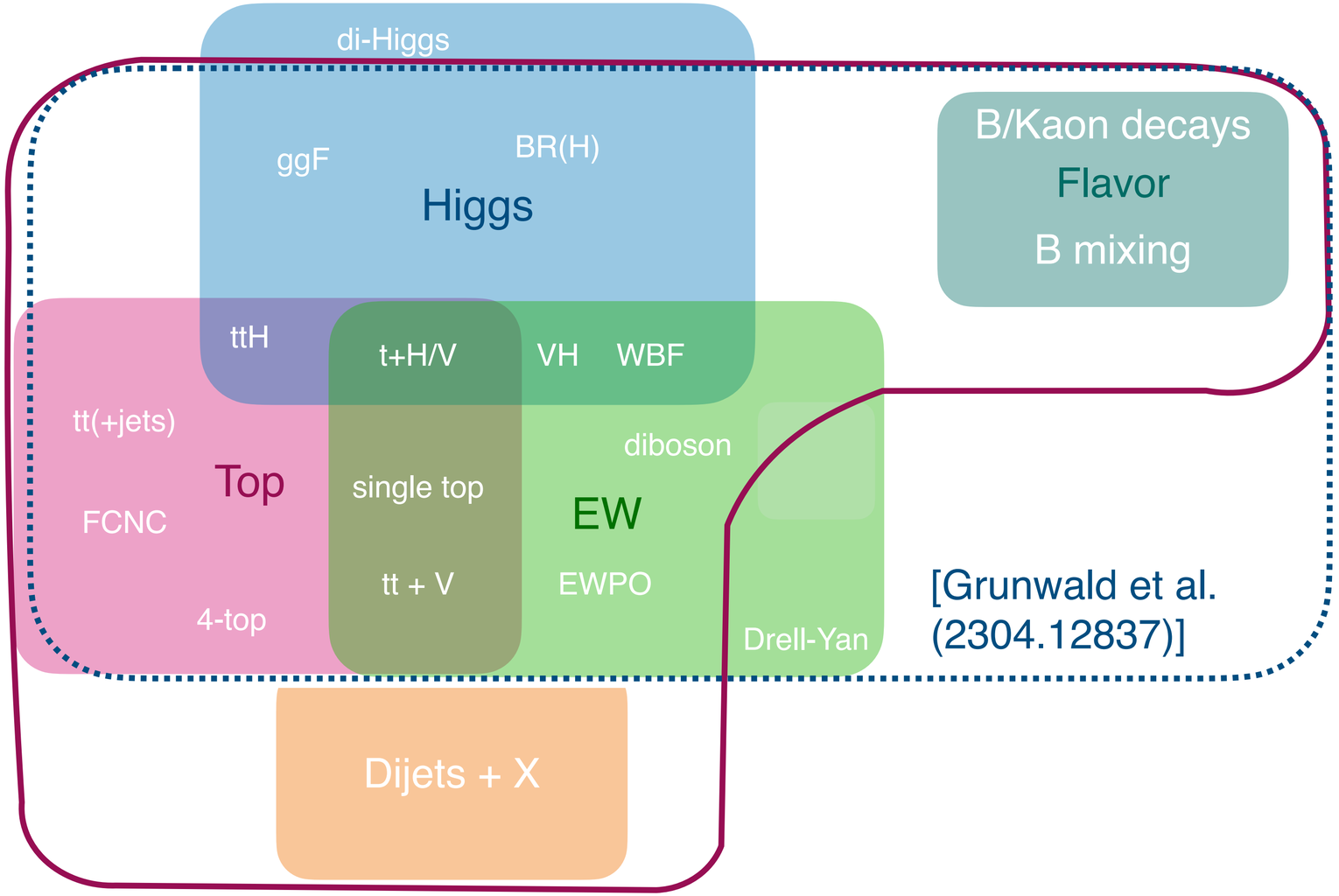

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[Grunwald et al. (2304.12837)]

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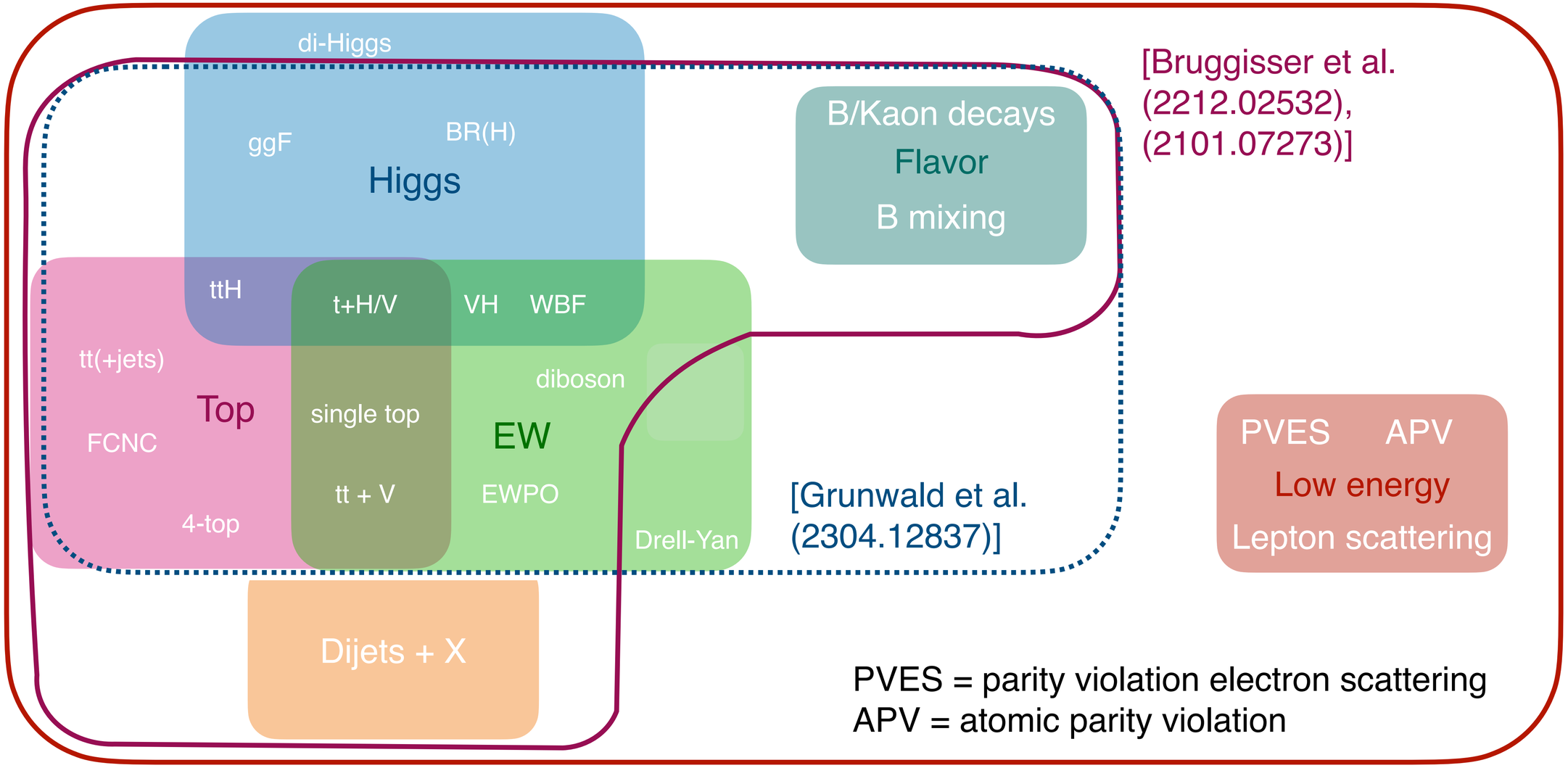
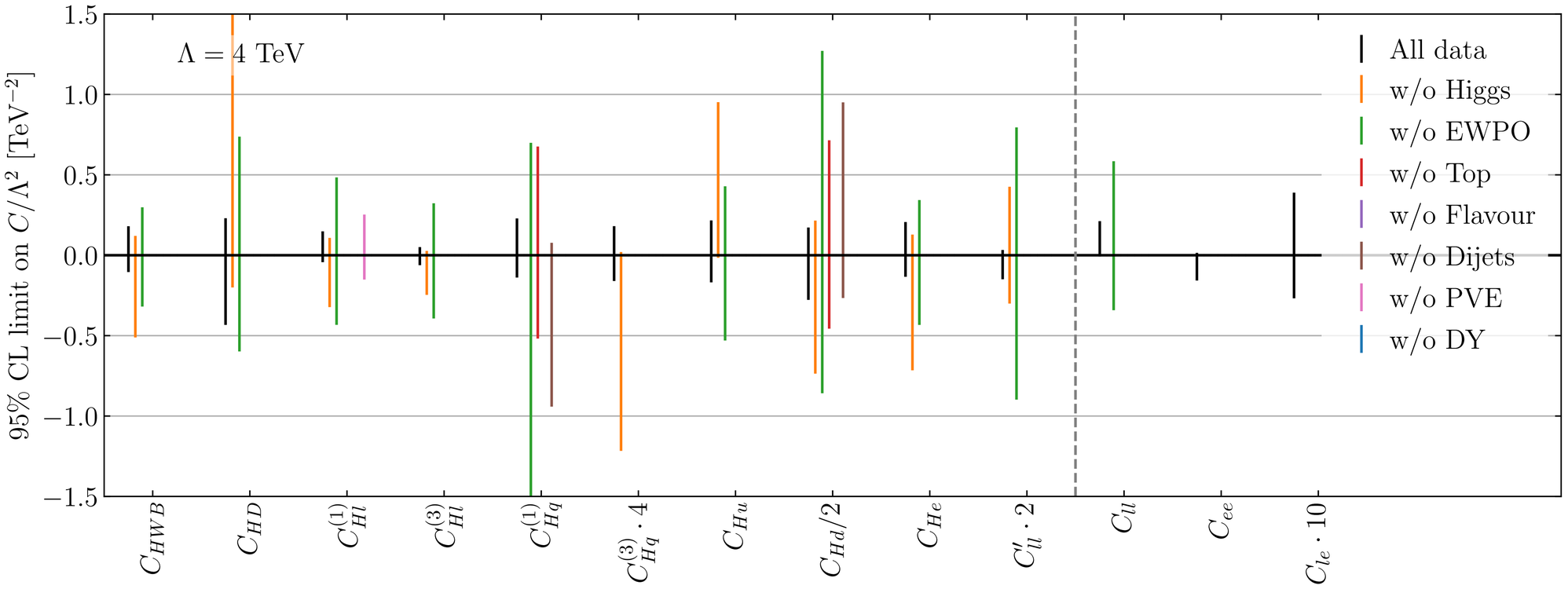
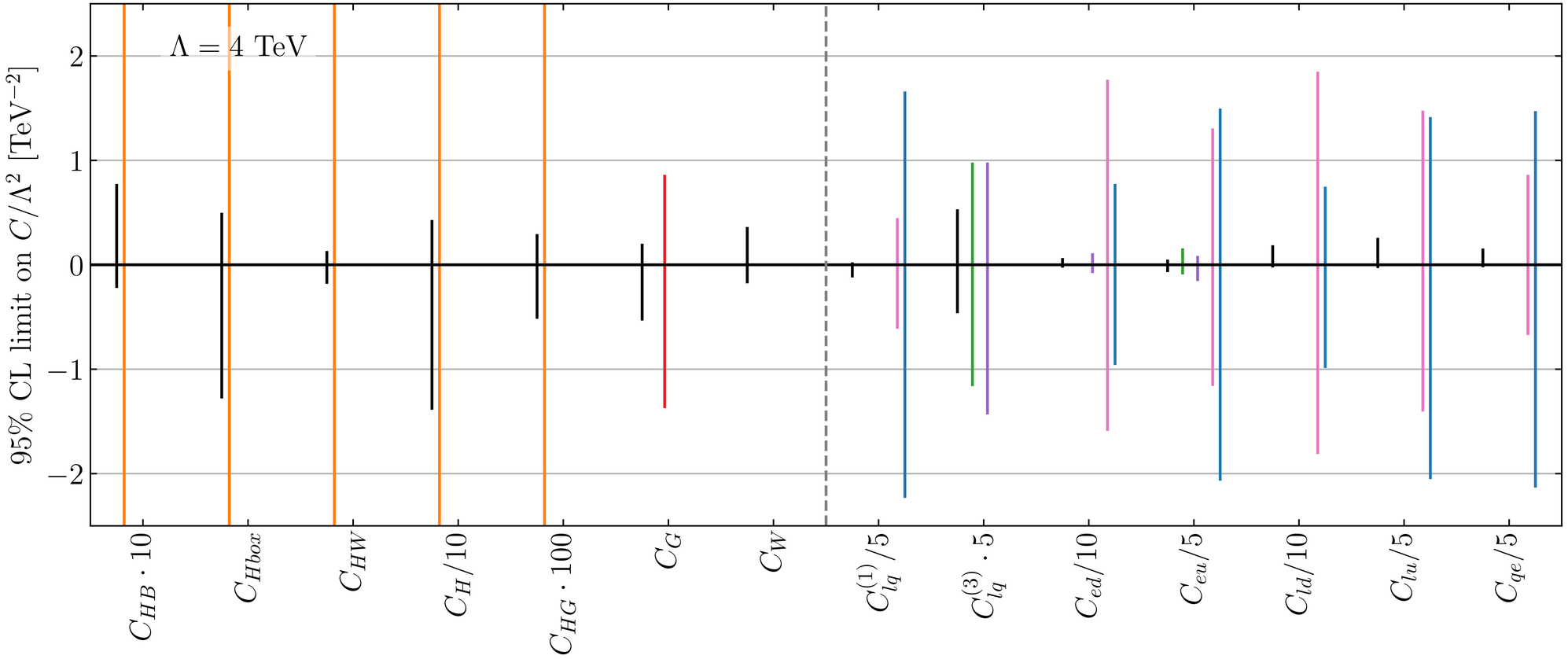


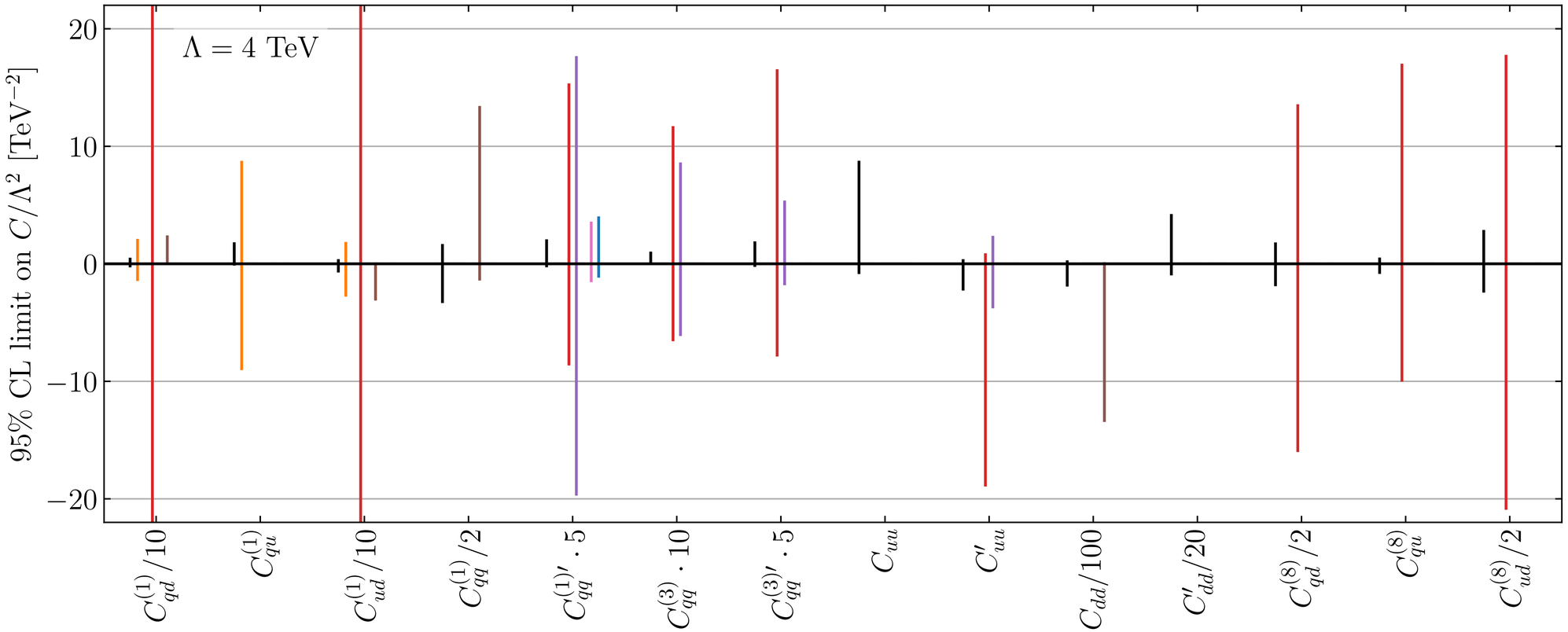
Removing operator sets



Removing operator sets - 2



Removing operator sets - 3



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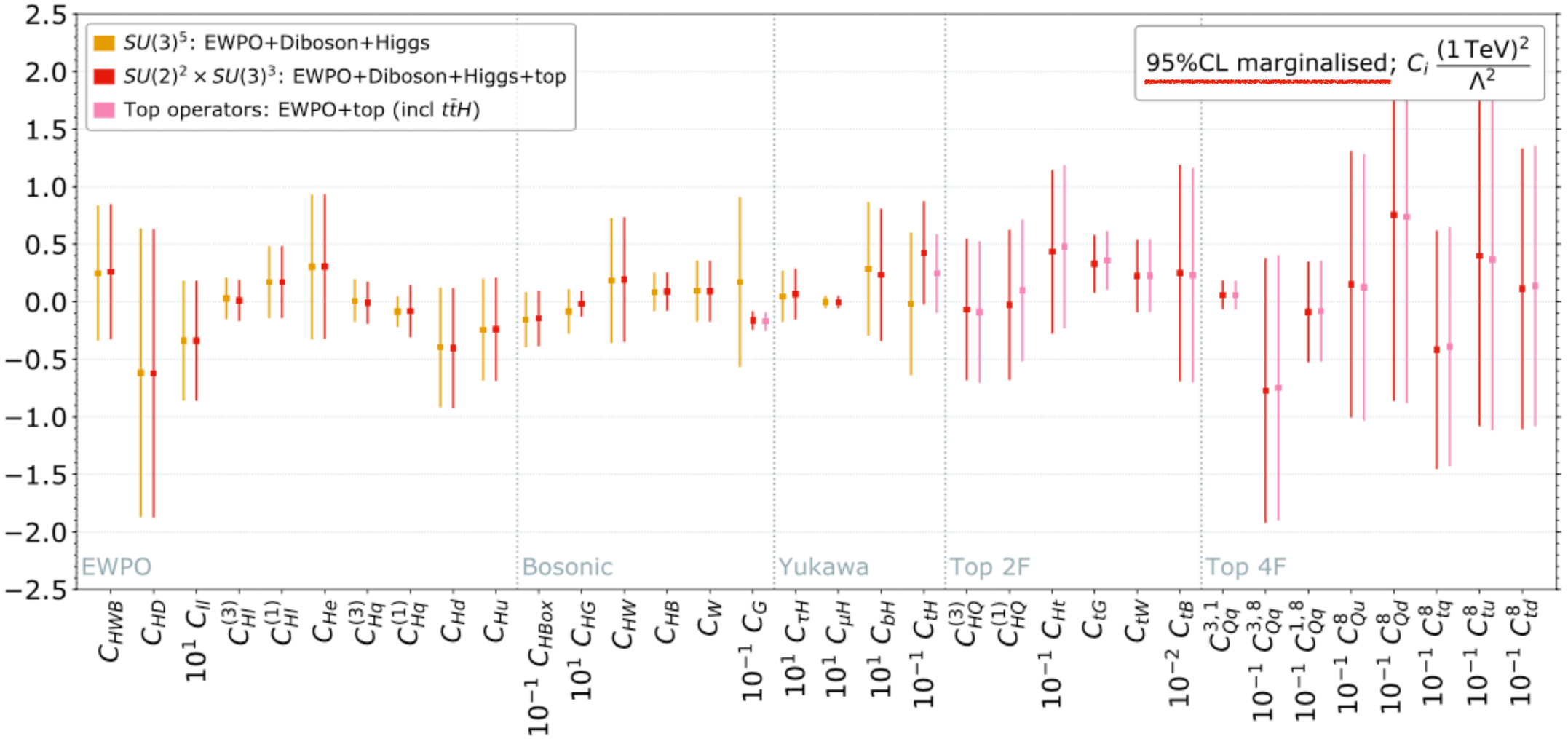
Many groups contribute to the field.
Each of them has their own strength.

Making the top quark stand out

Combining different sectors, e.g. top + Higgs

[Ellis, Madigan, Mimasu, Sanz, You (2012.02779)]

[Ethier et al. (2105.00006)]



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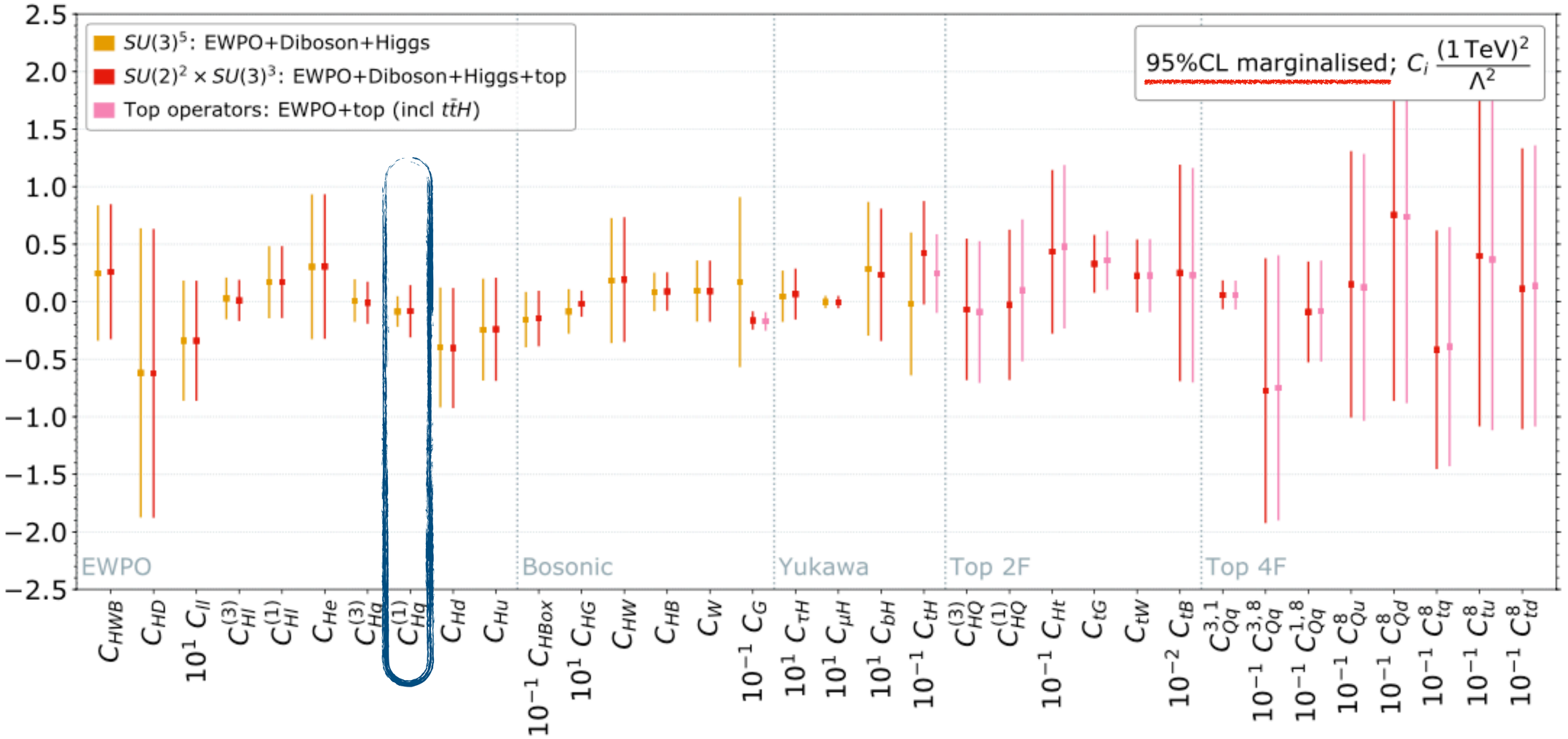

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- Generate a random "toy"-measurement according to the uncertainties
- Construct the Likelihood (or χ^2 equivalently)
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- Report result in Histogram

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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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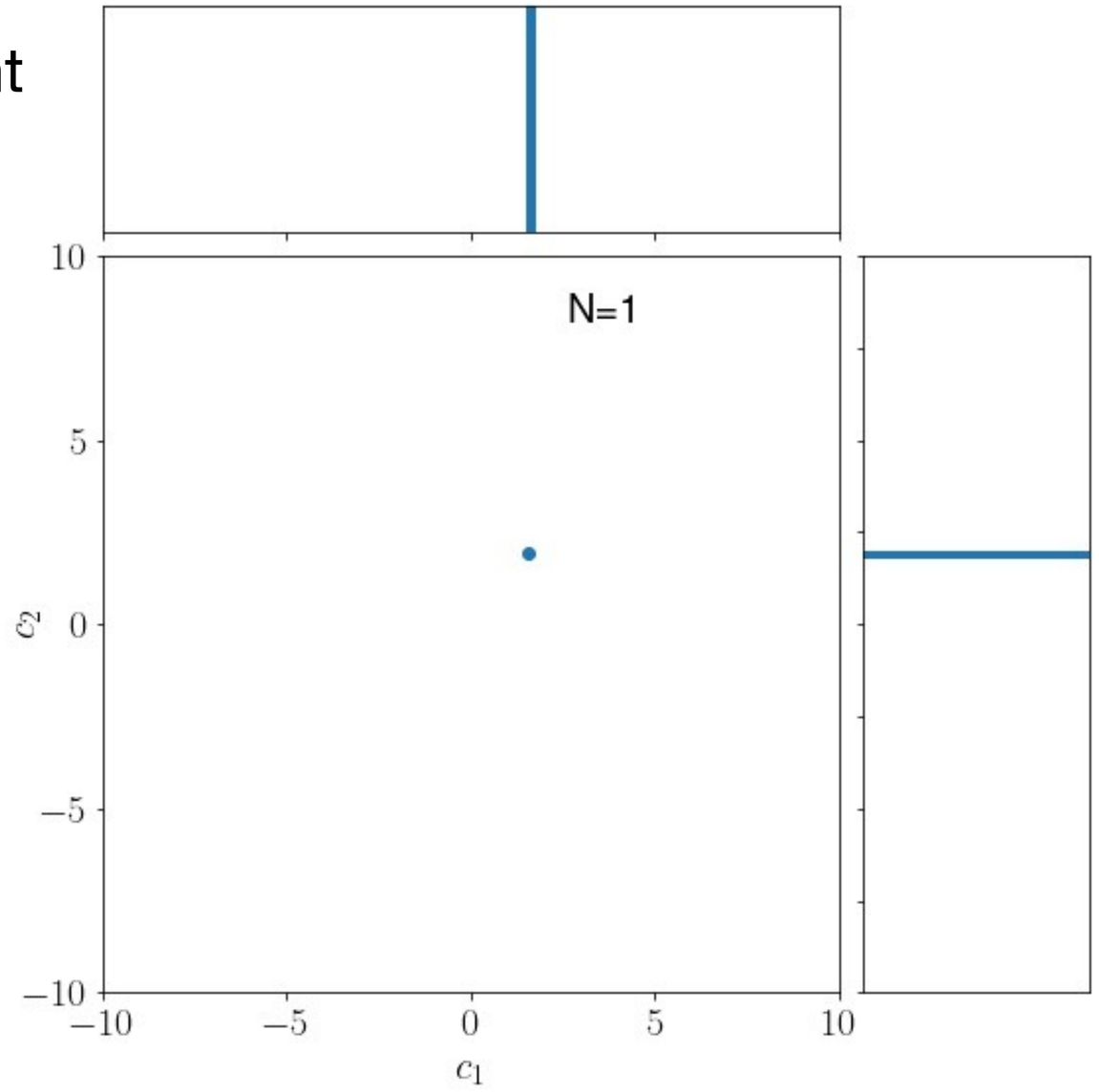

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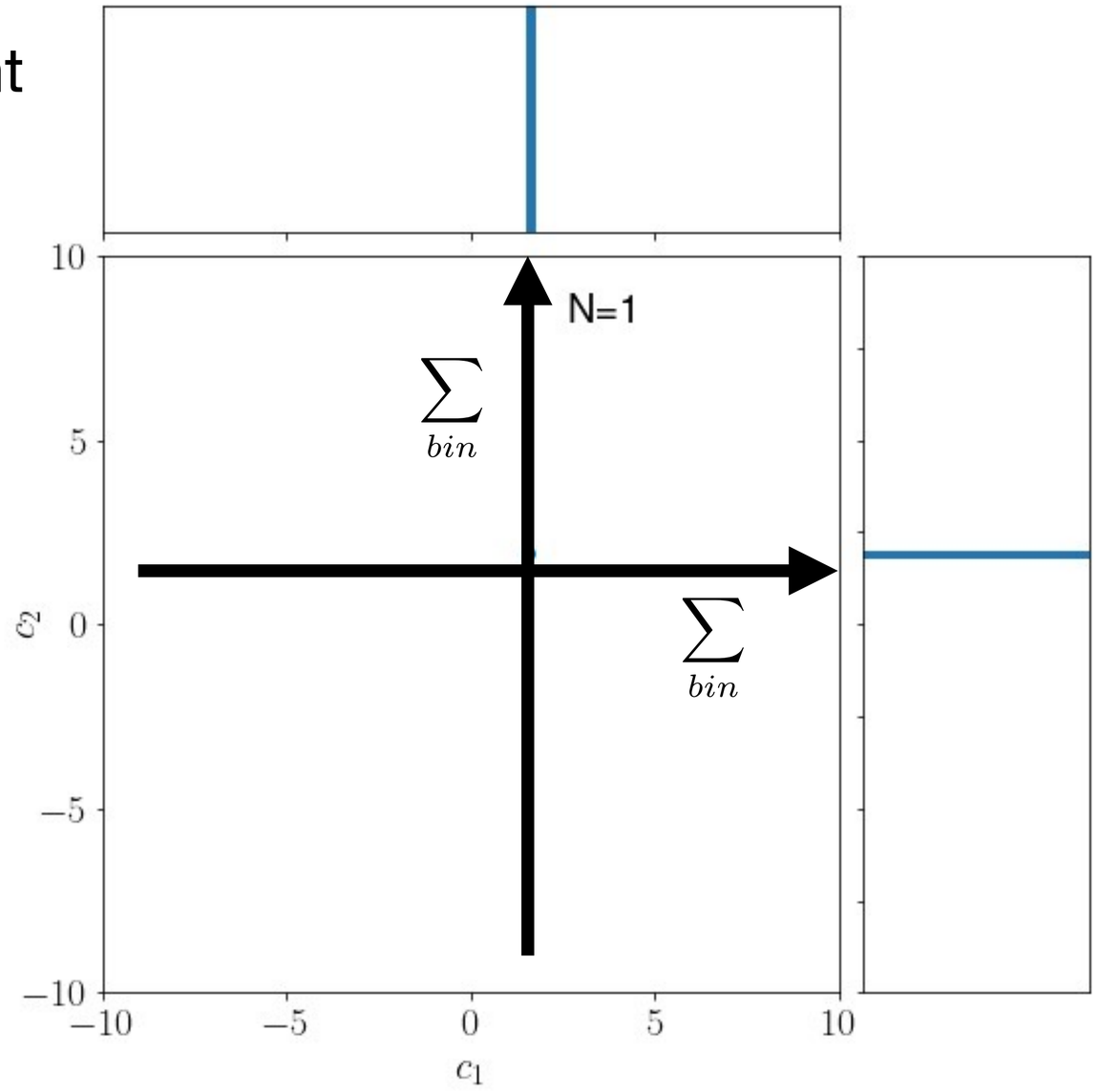

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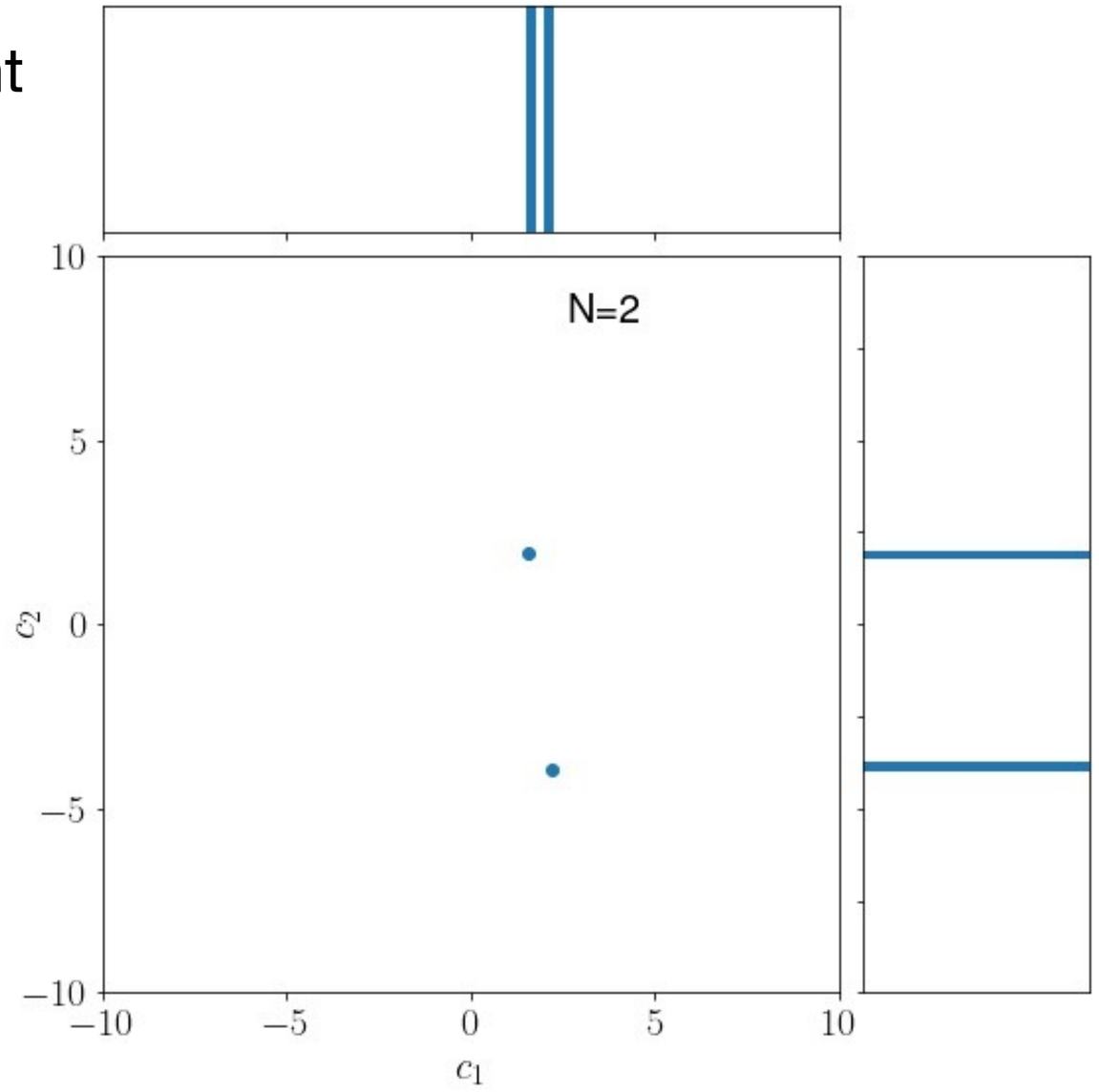

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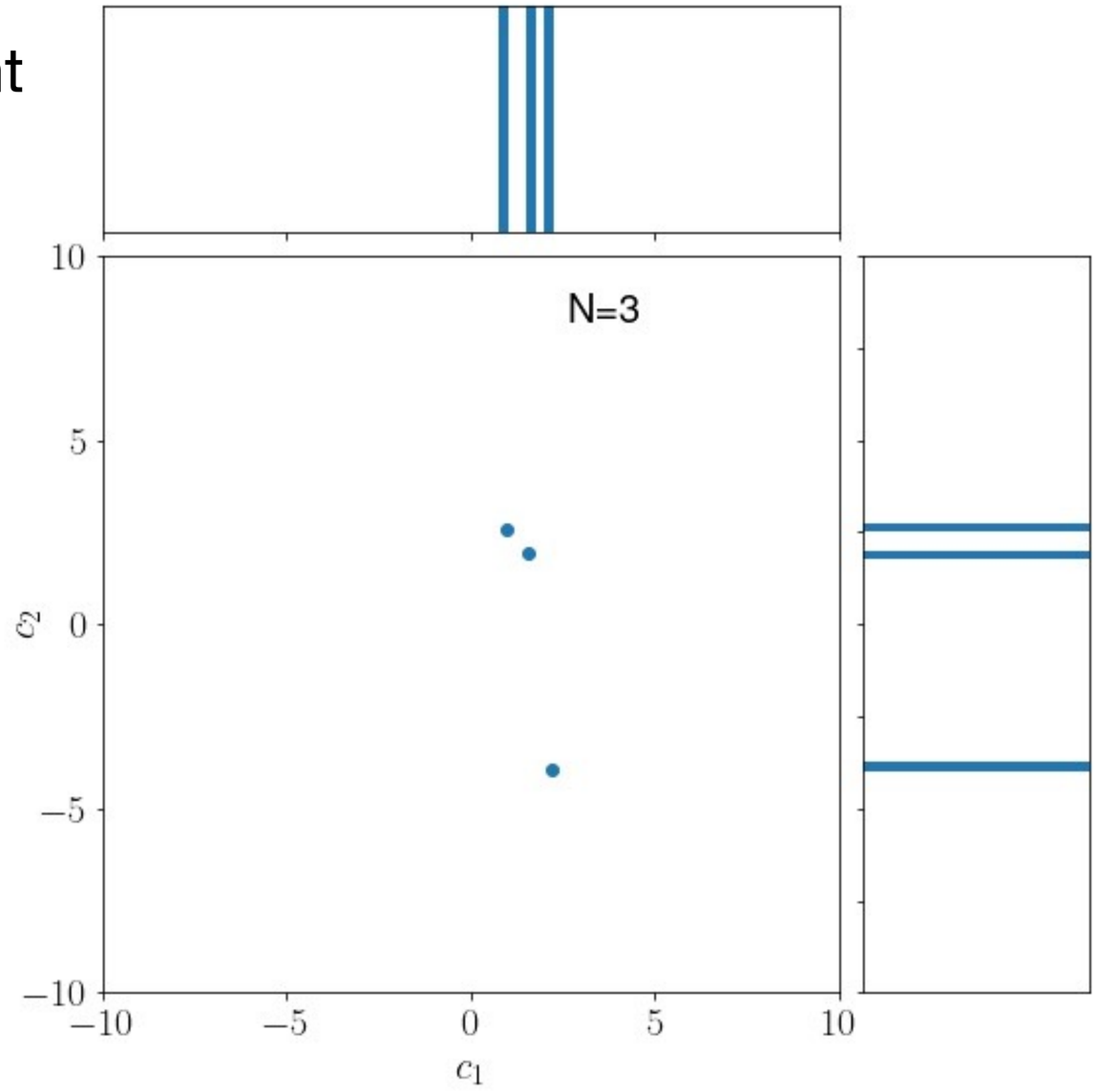

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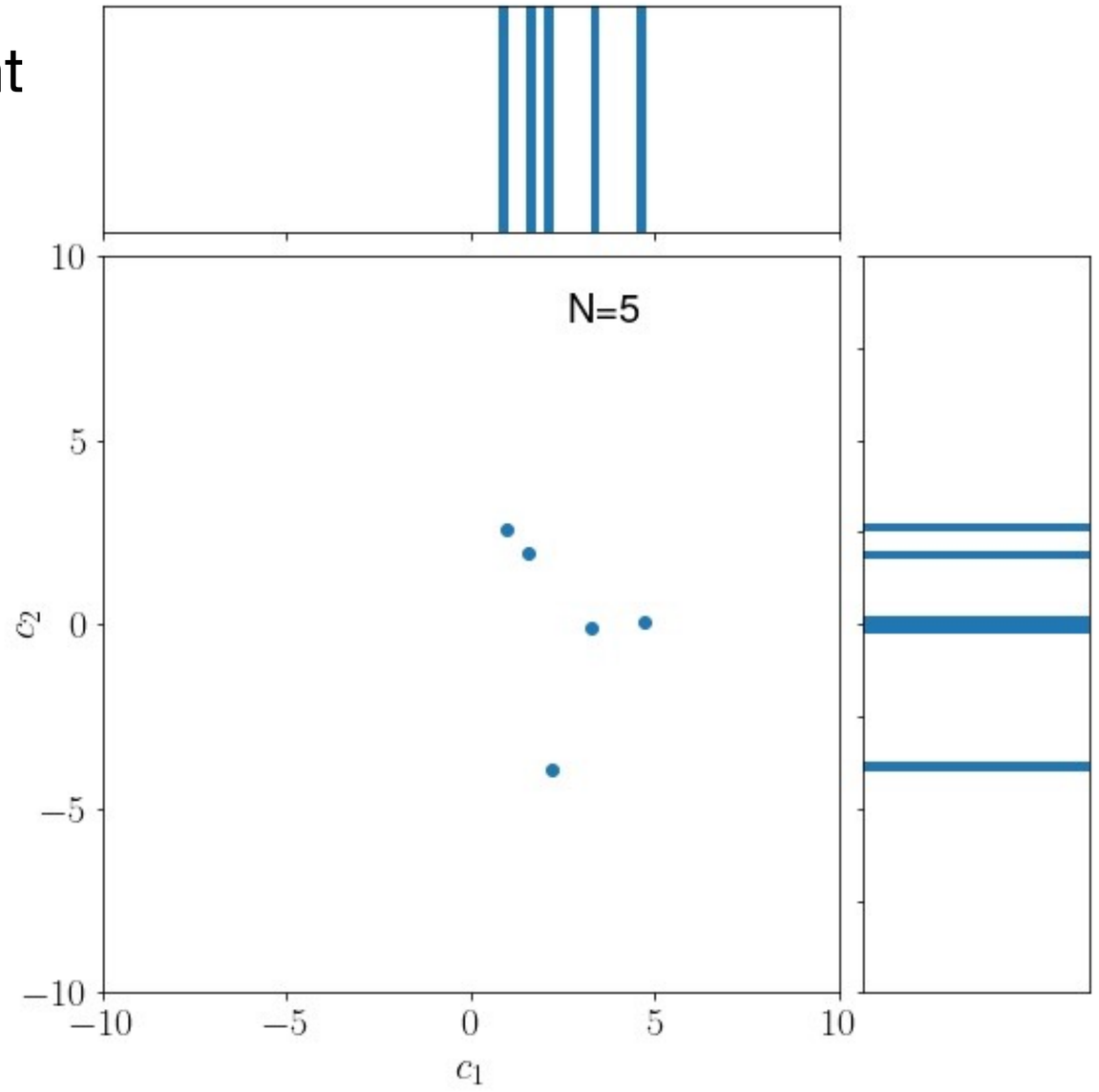

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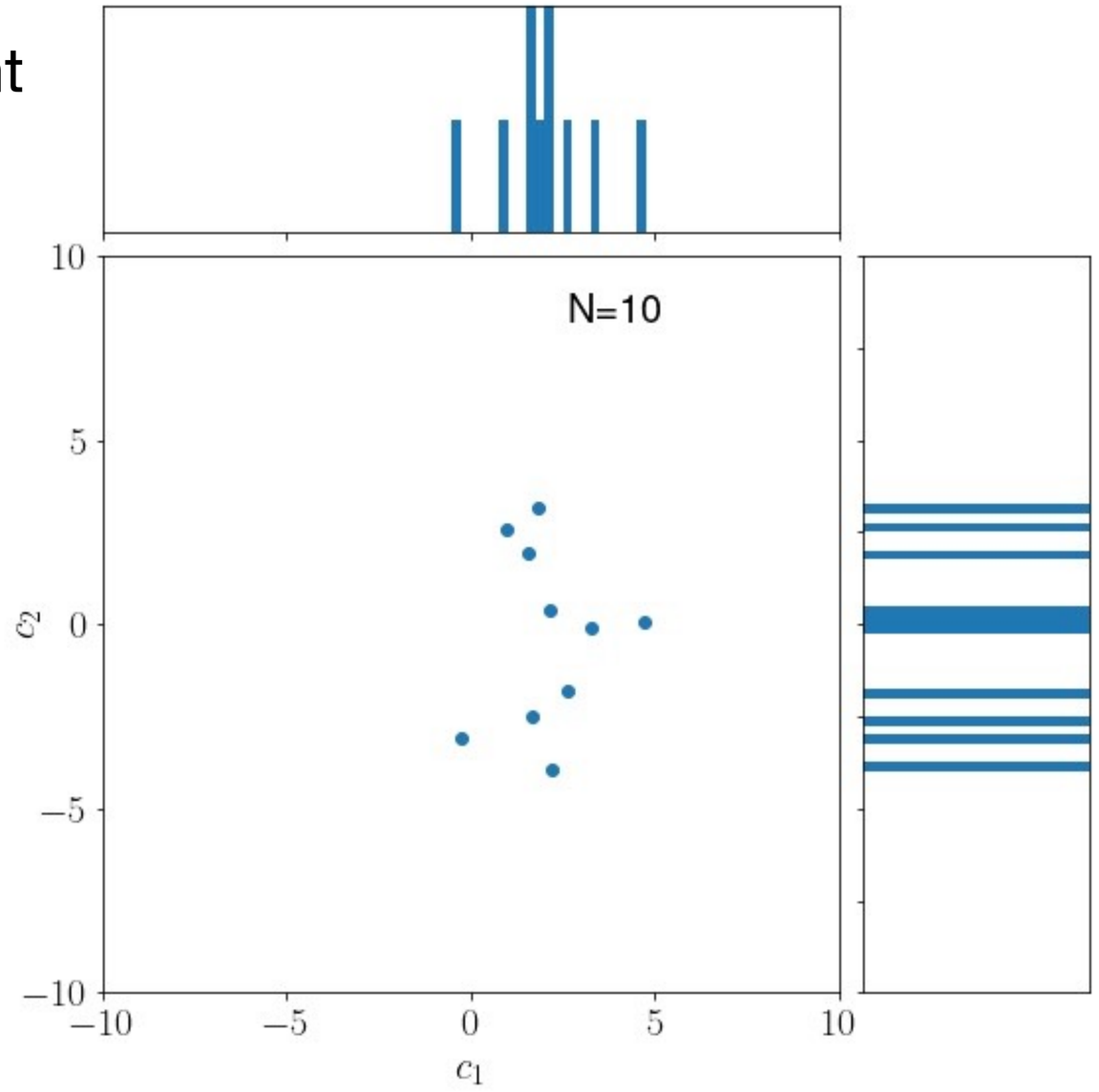

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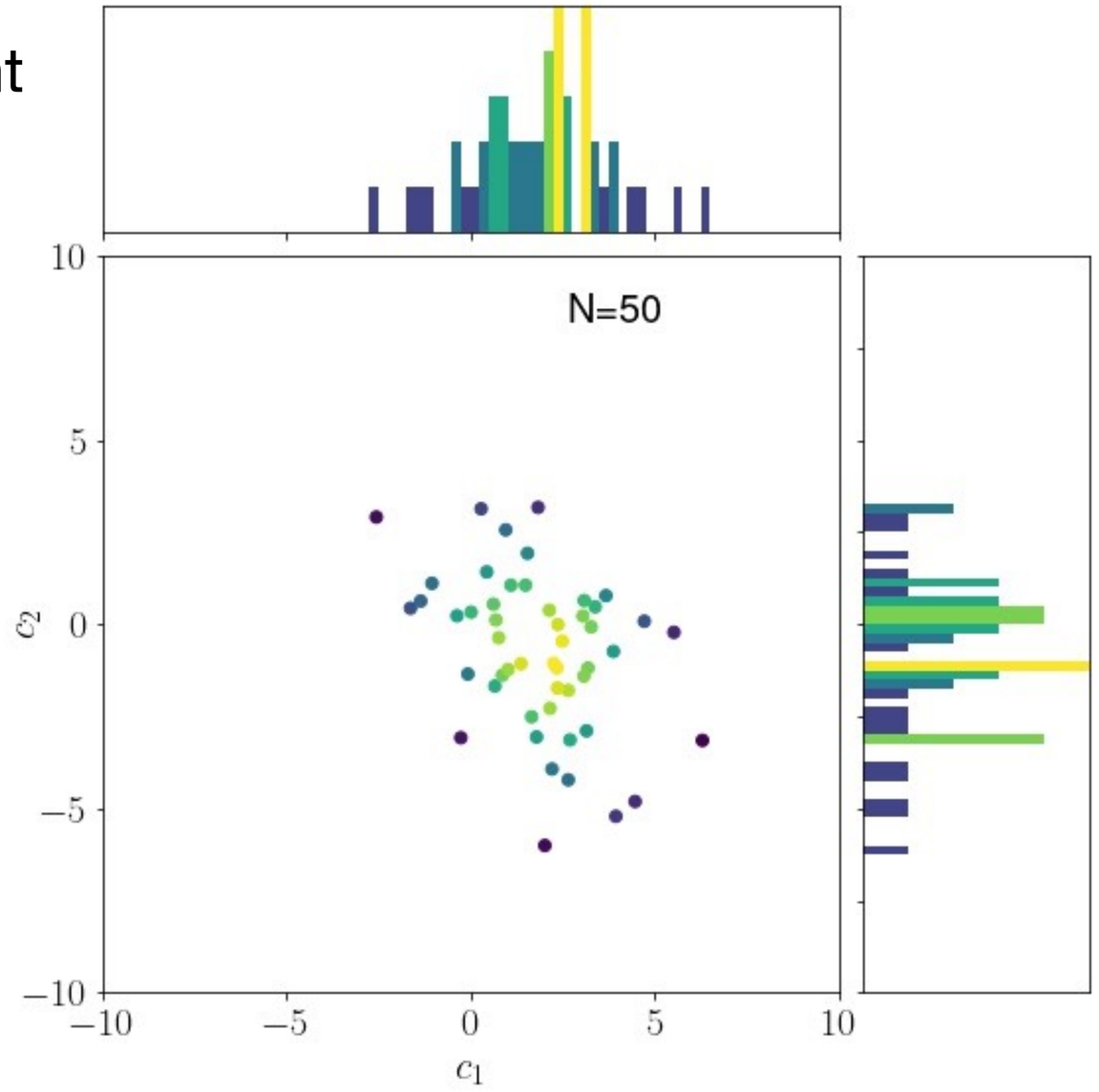

Toy MC

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

$$\mu_1 = 105 - 5(c_1 + c_2)$$

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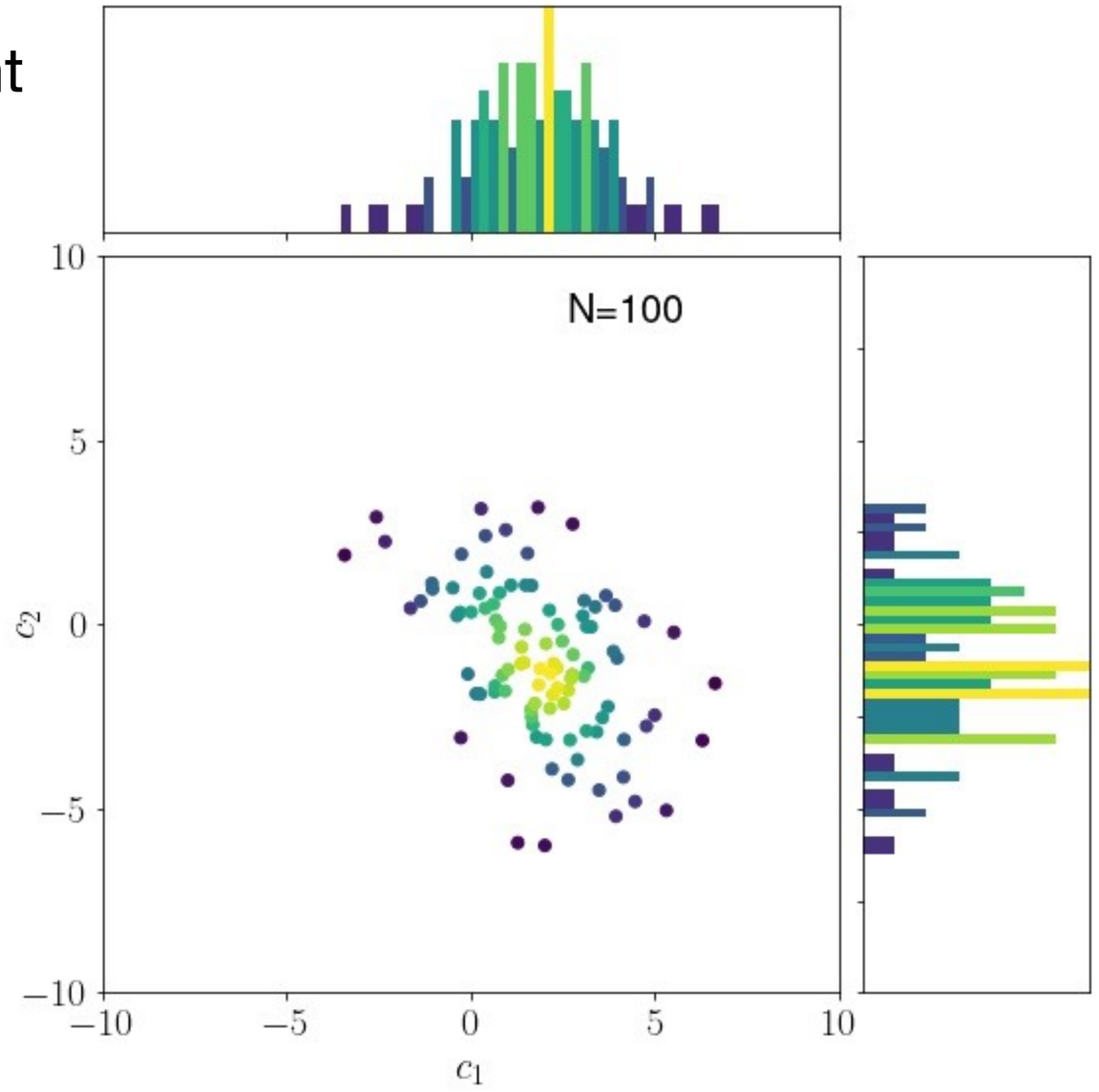

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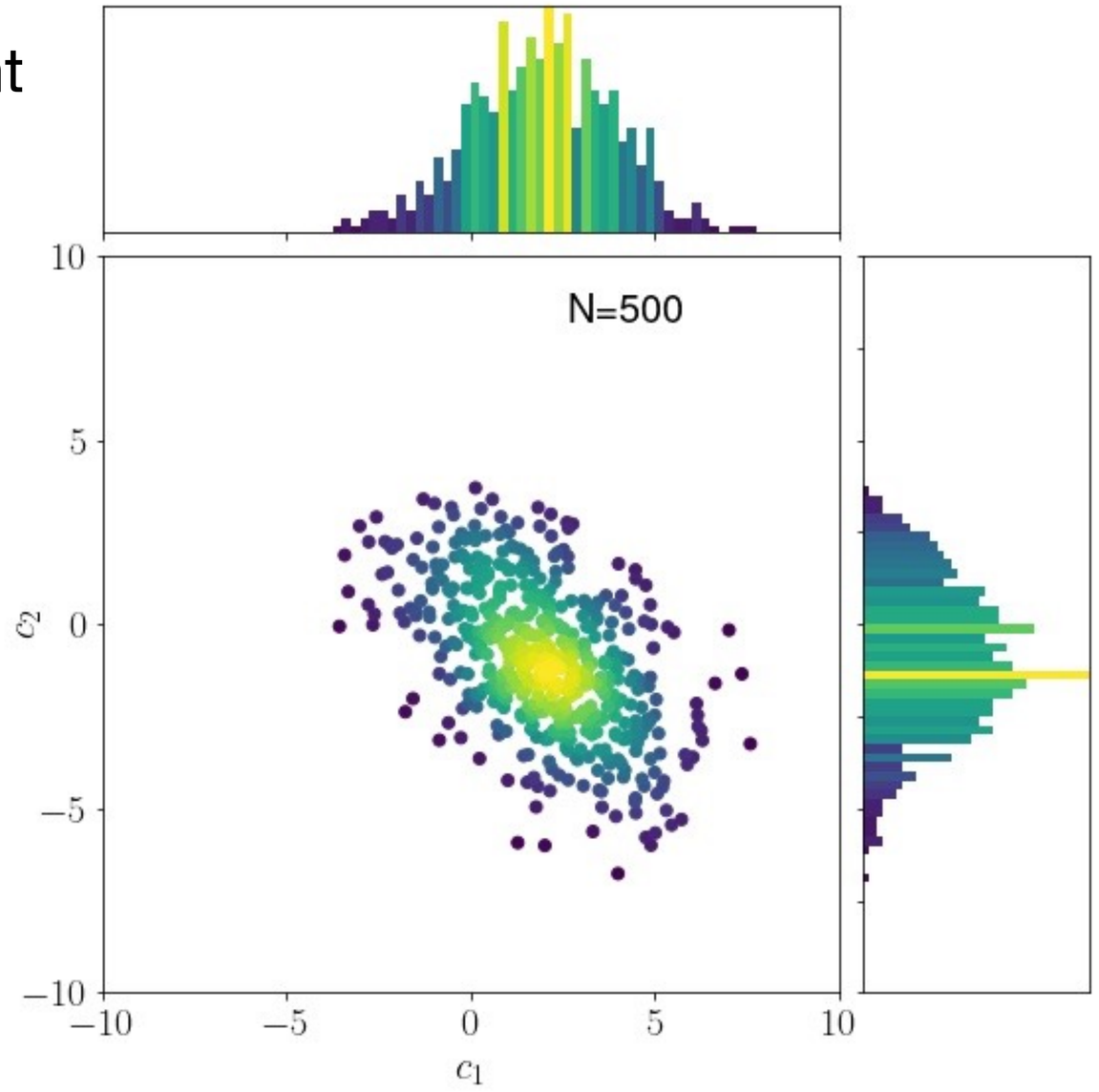

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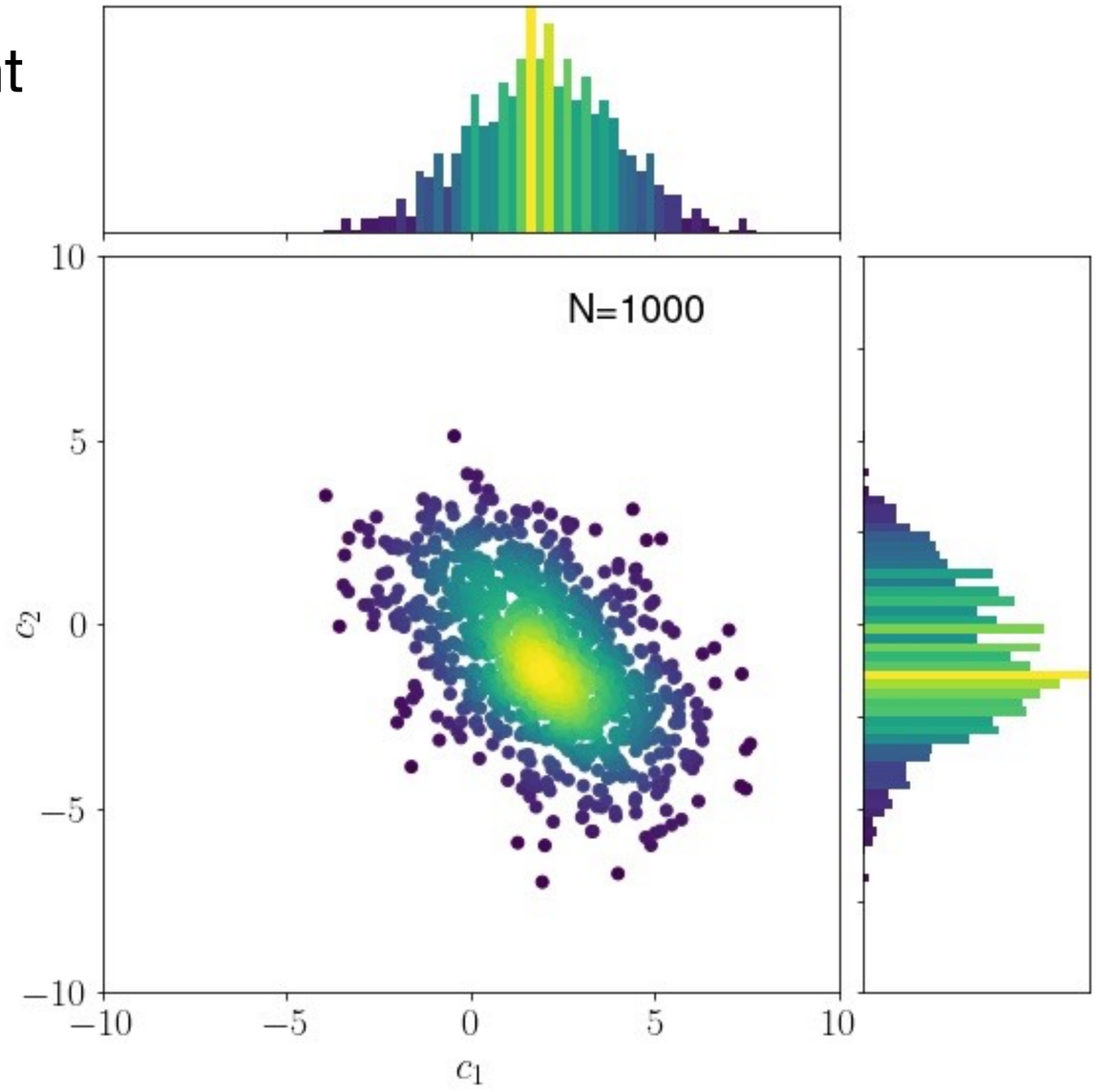

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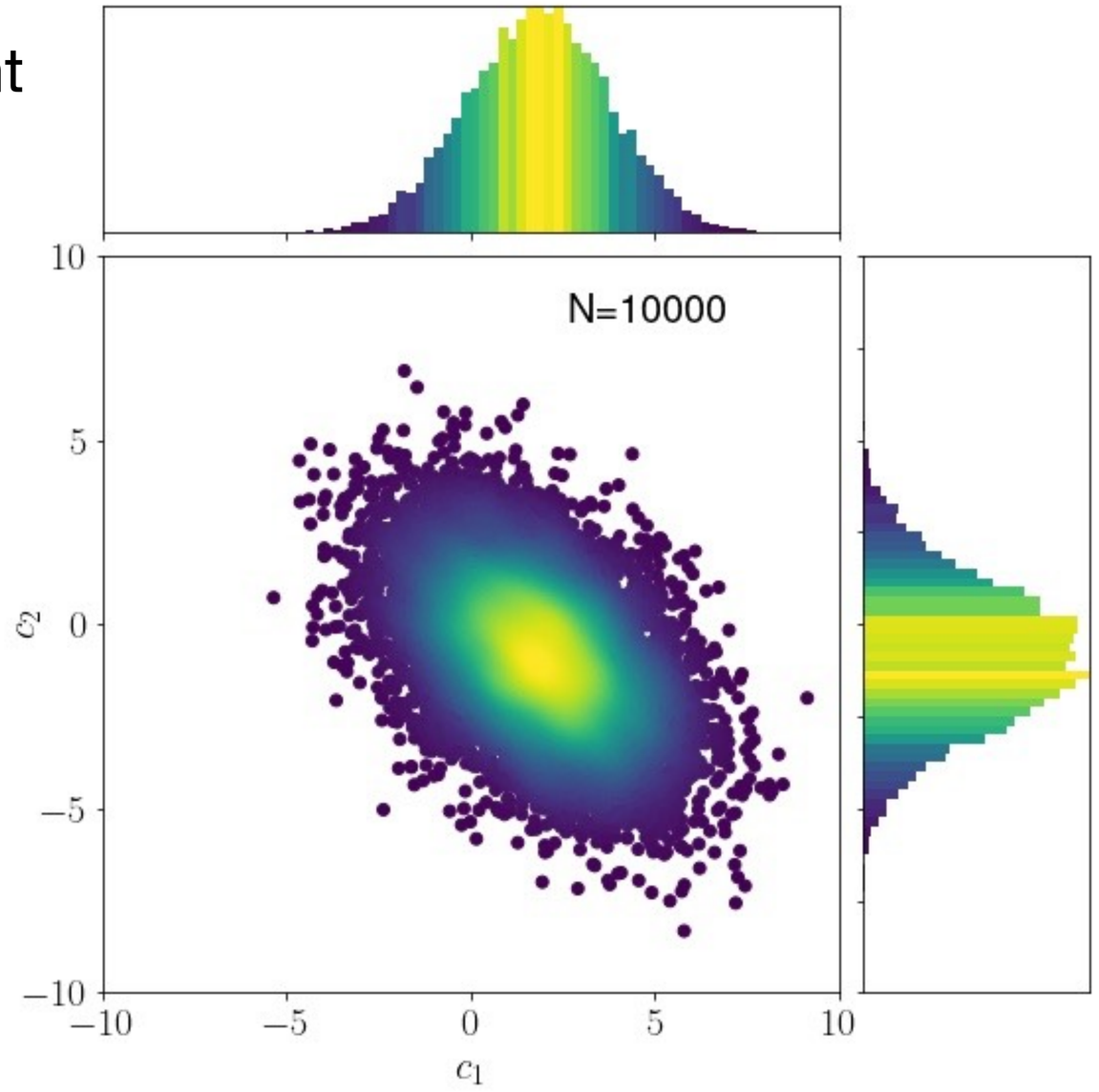

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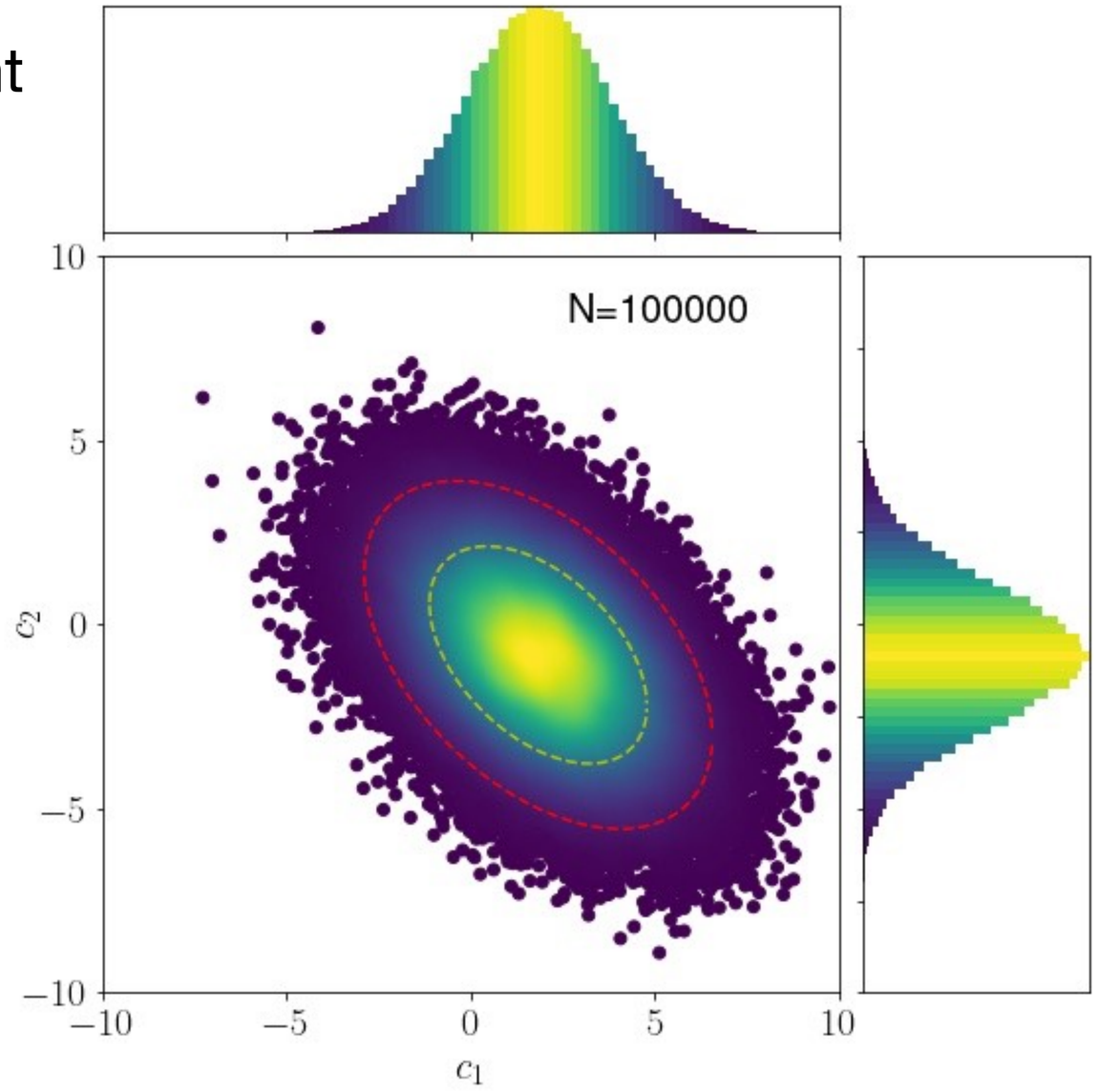

Markov Chains

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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[Sebastian Bruggisser]

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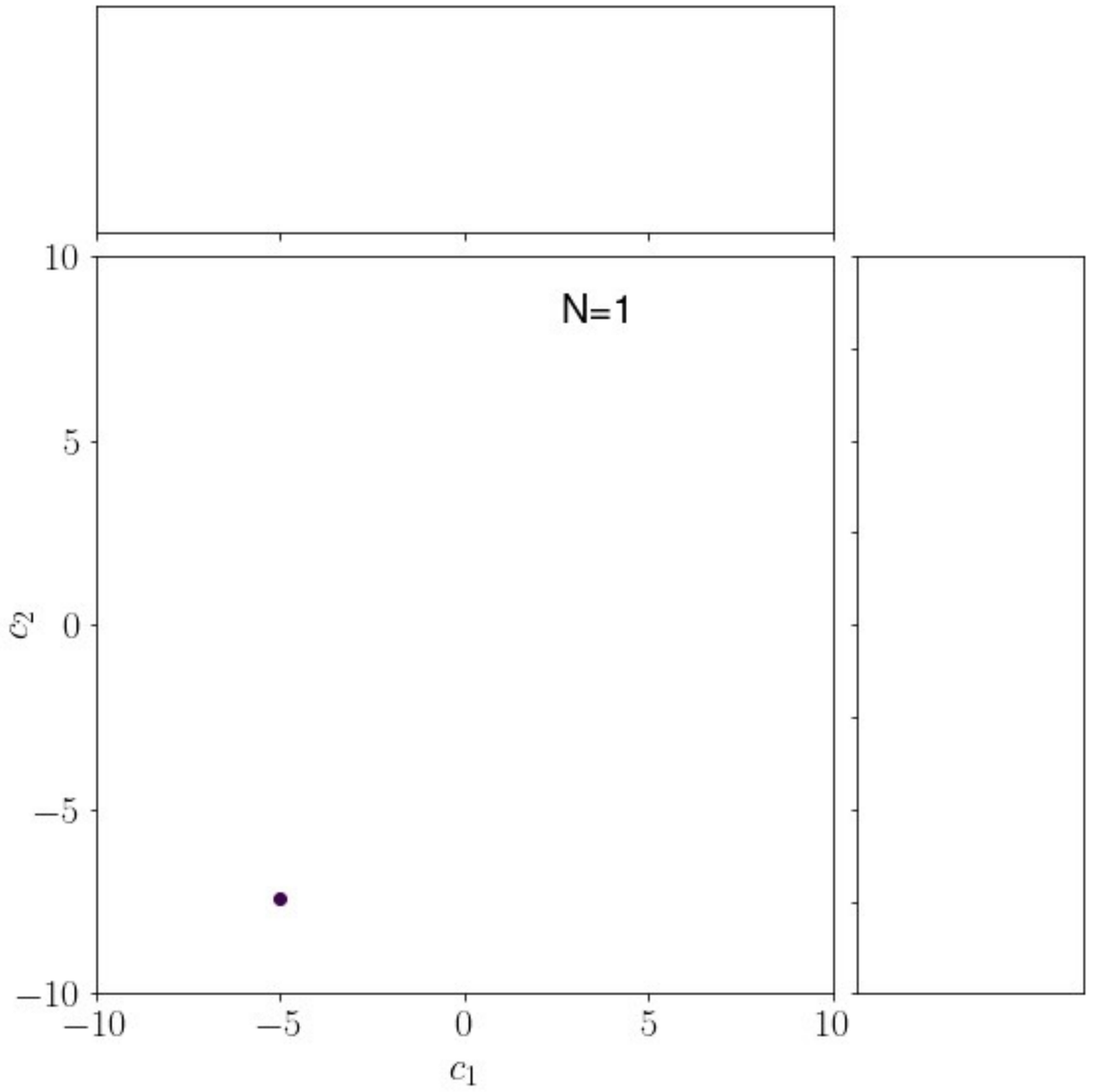

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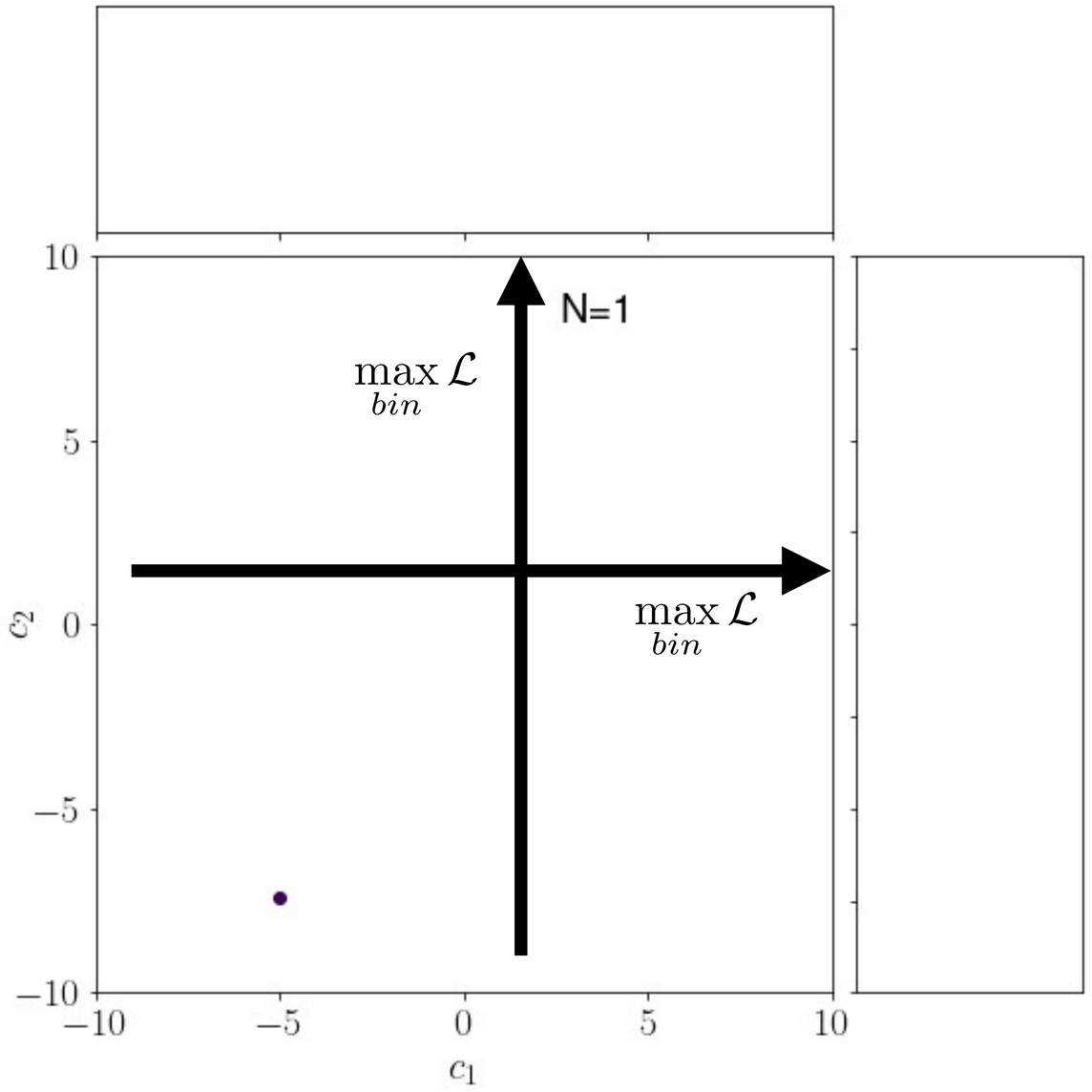

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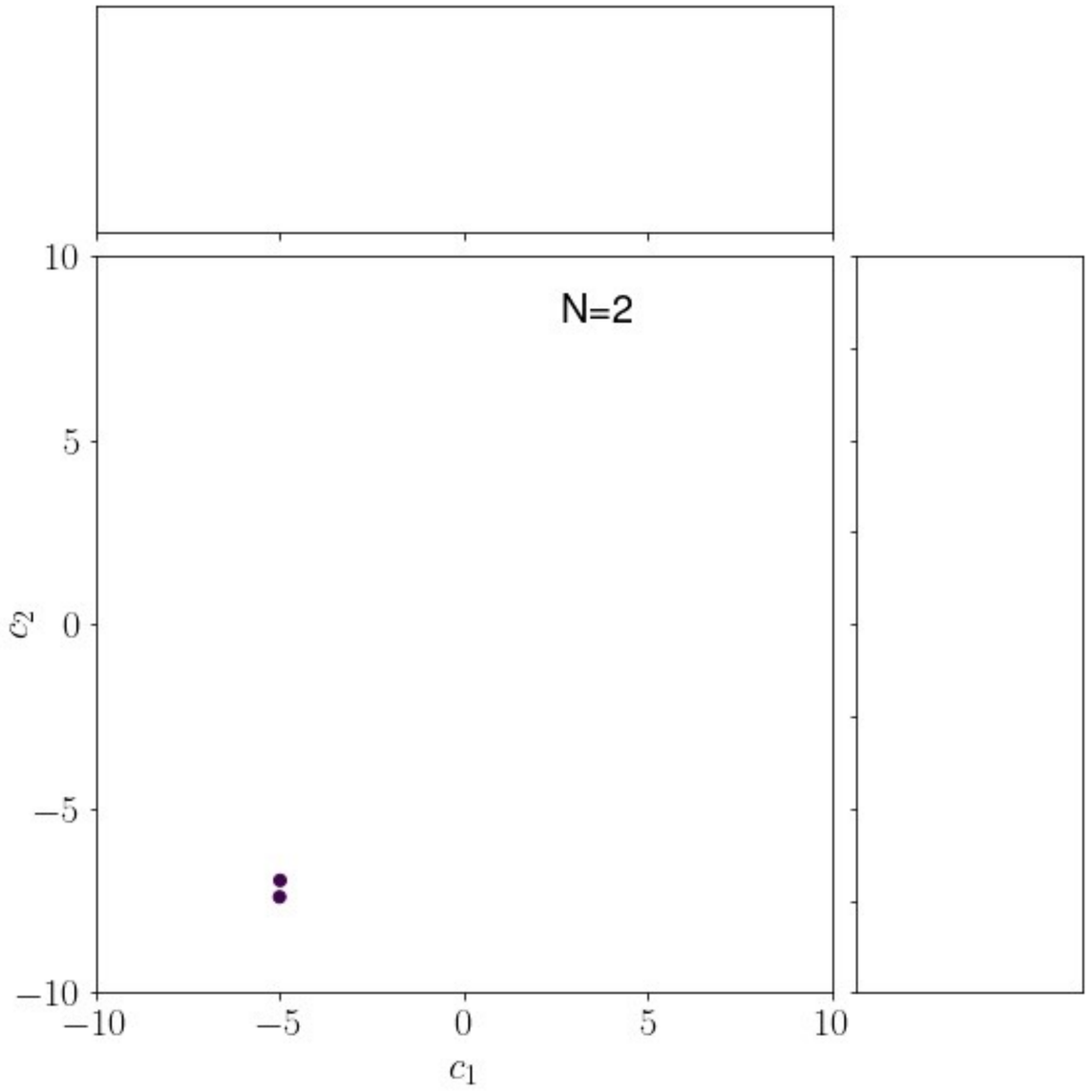

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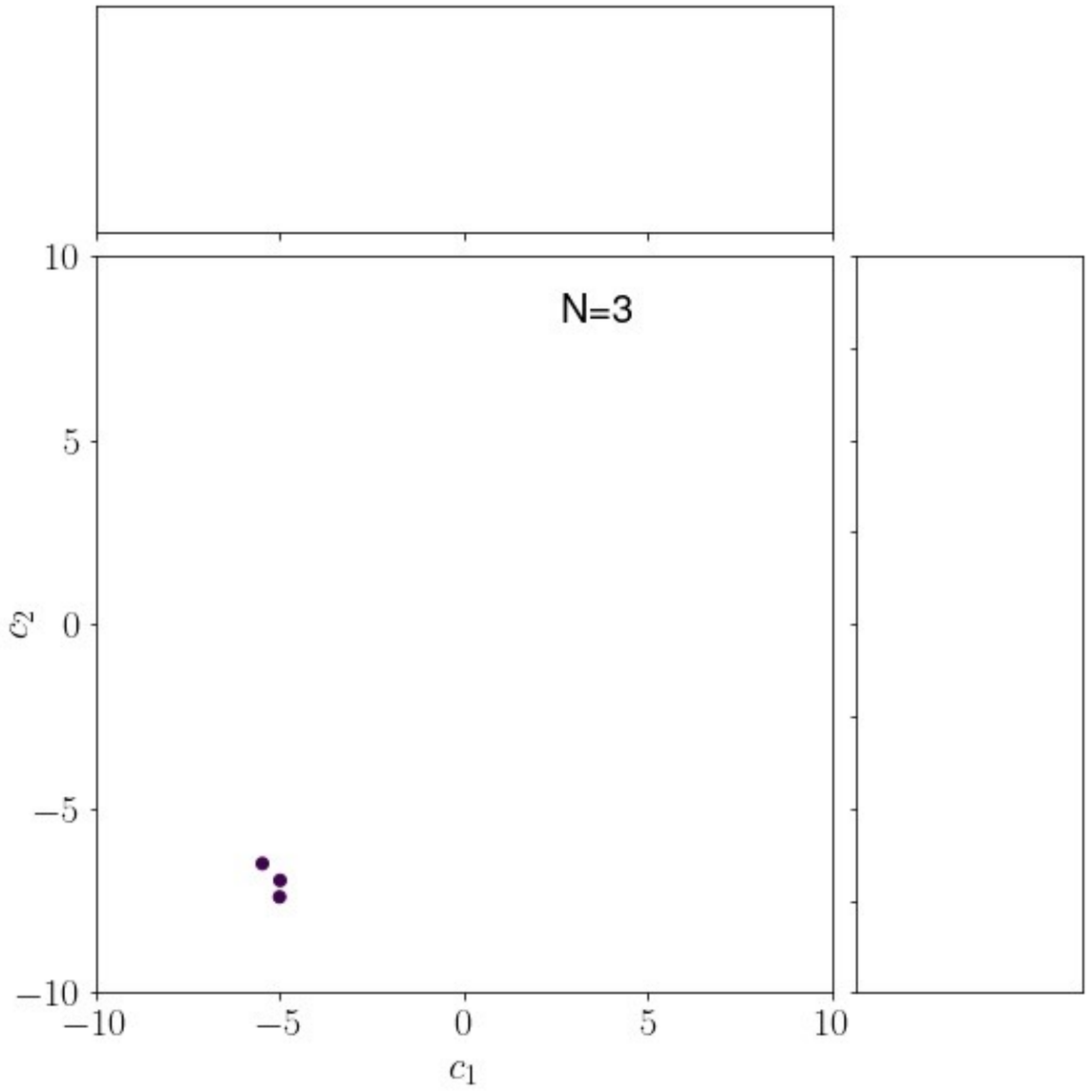

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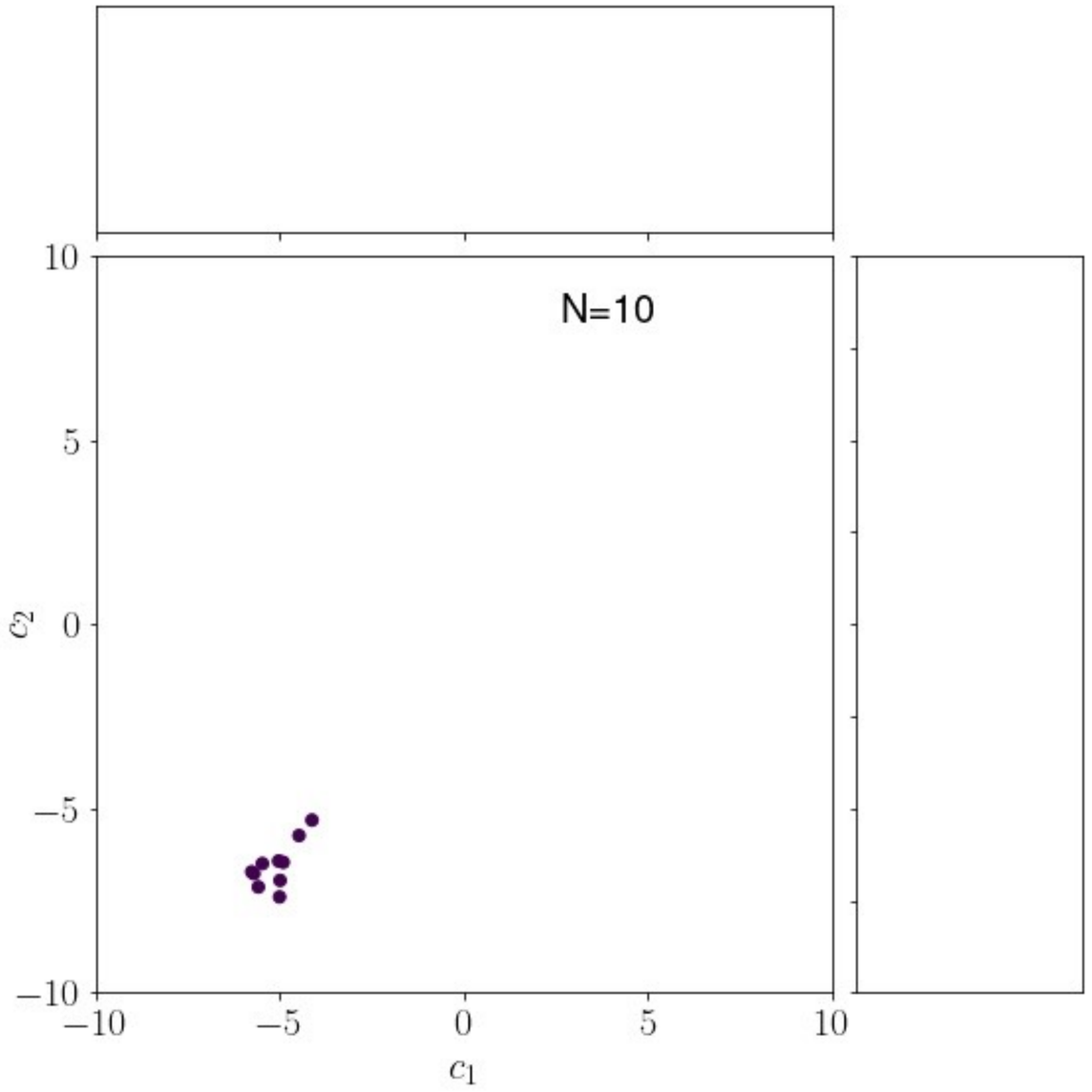

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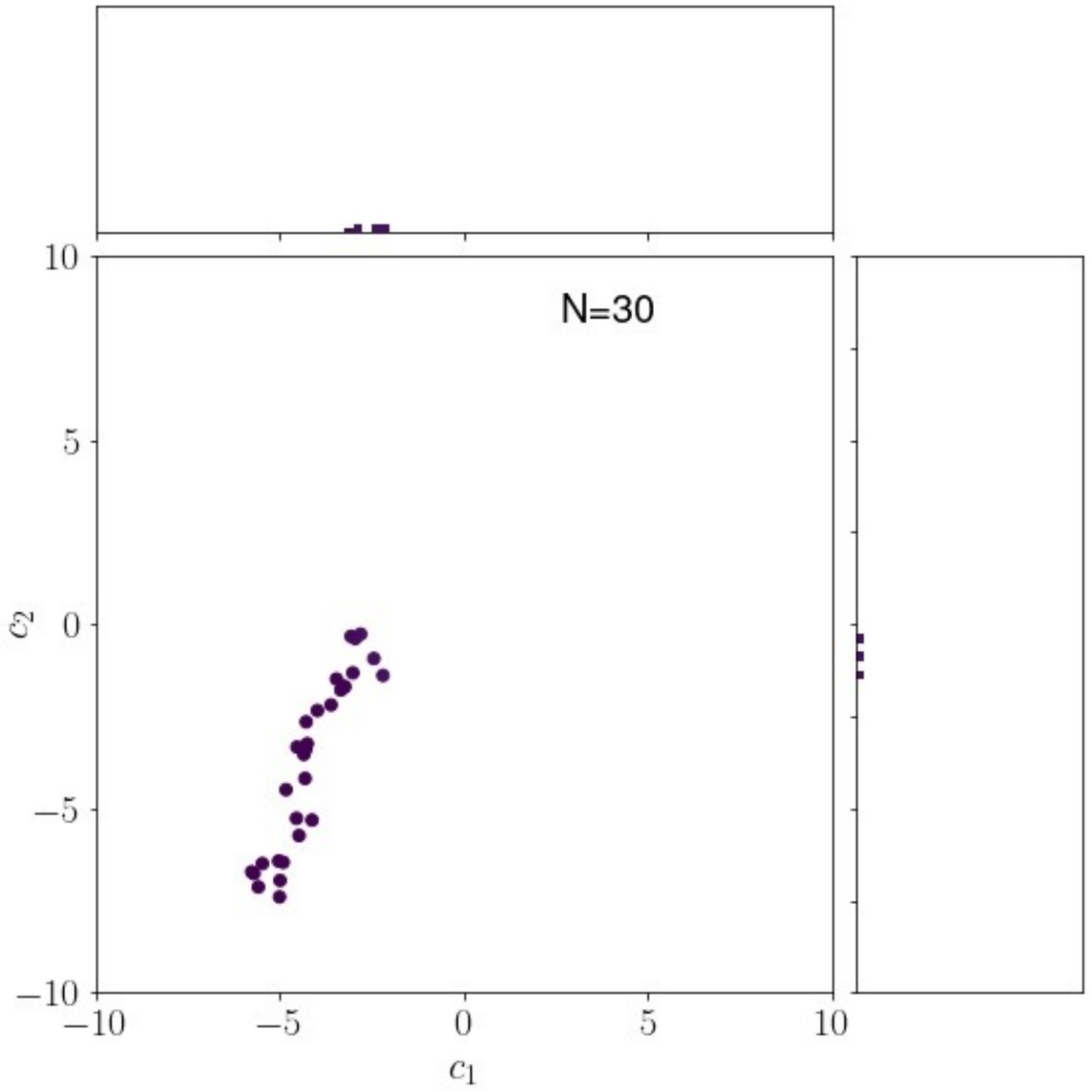

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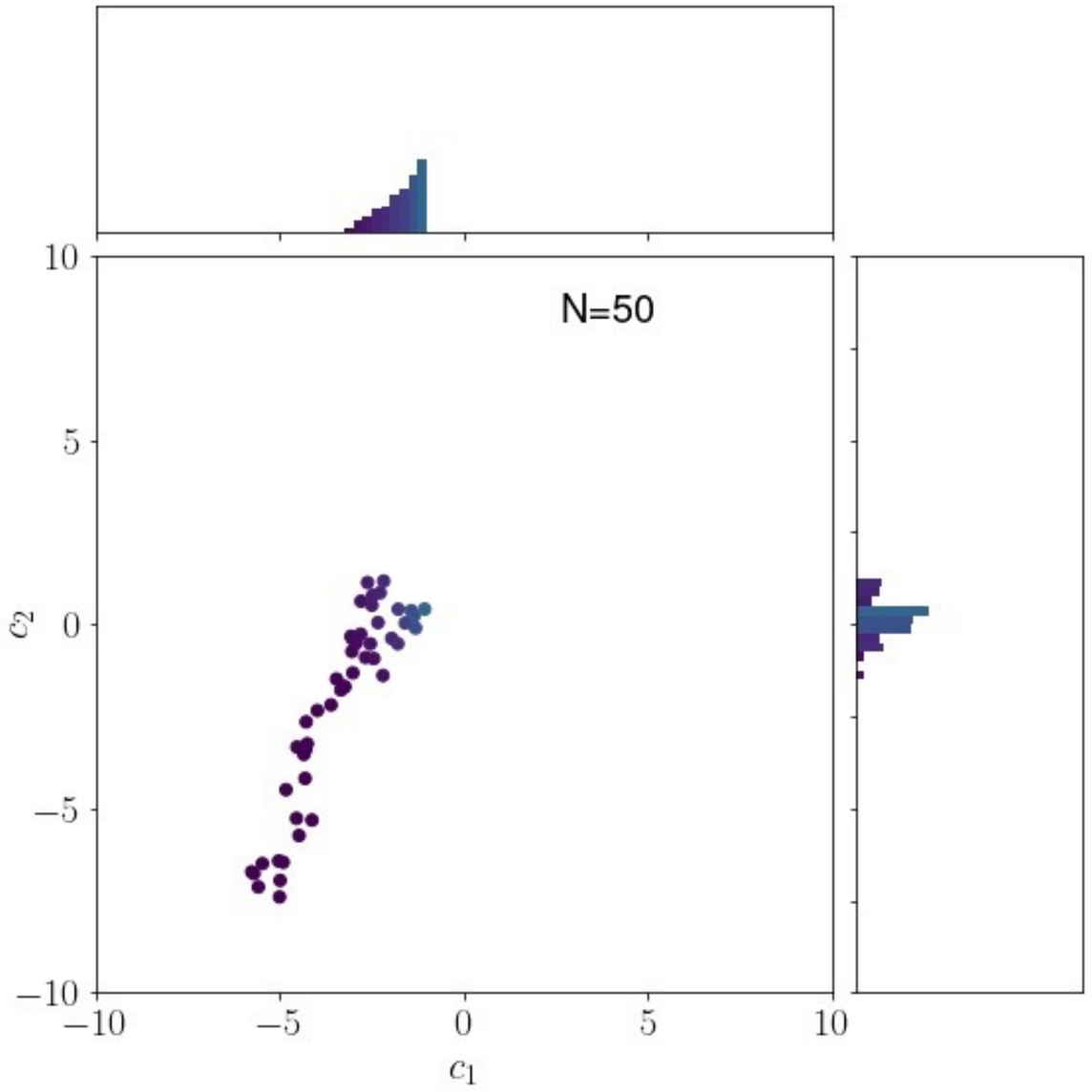

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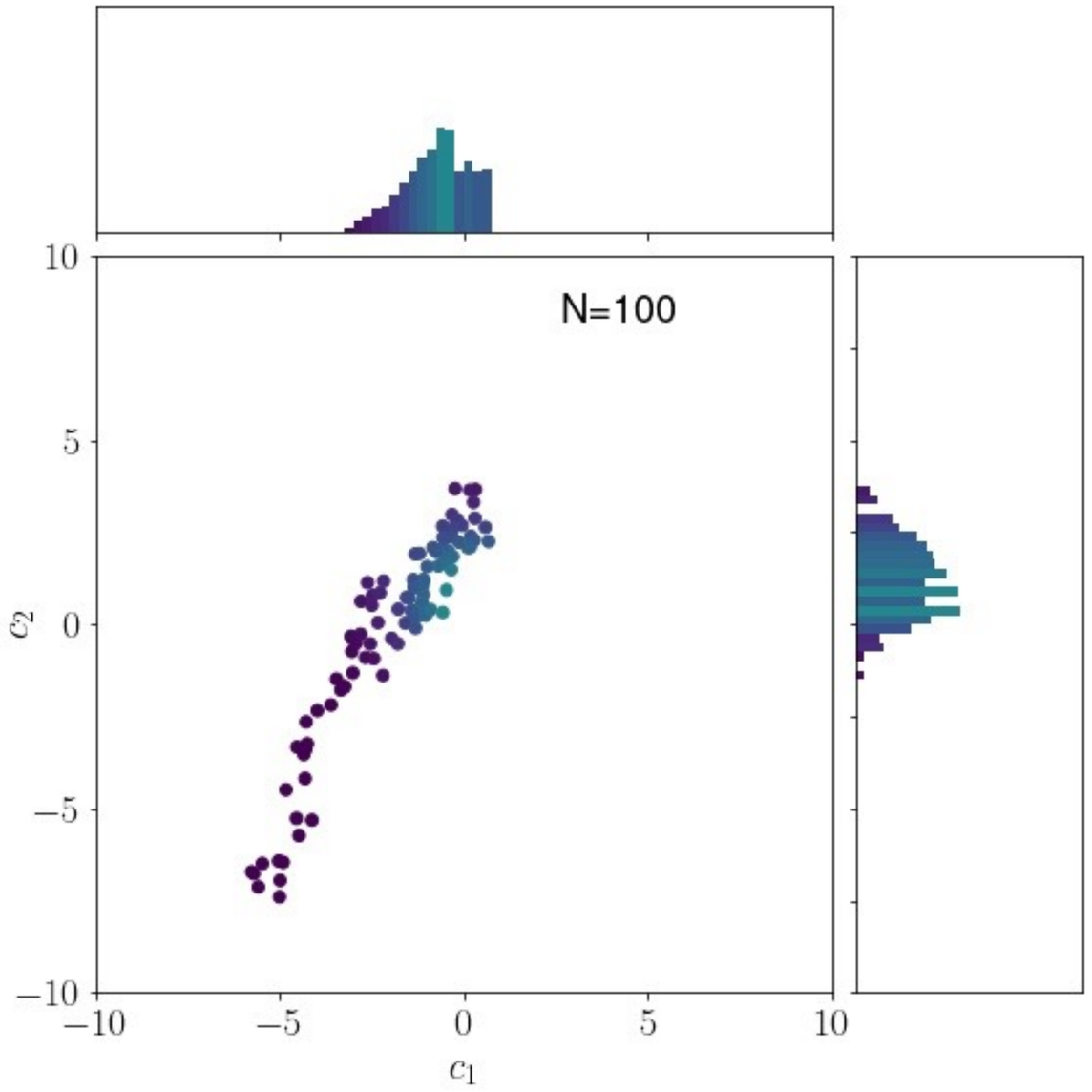

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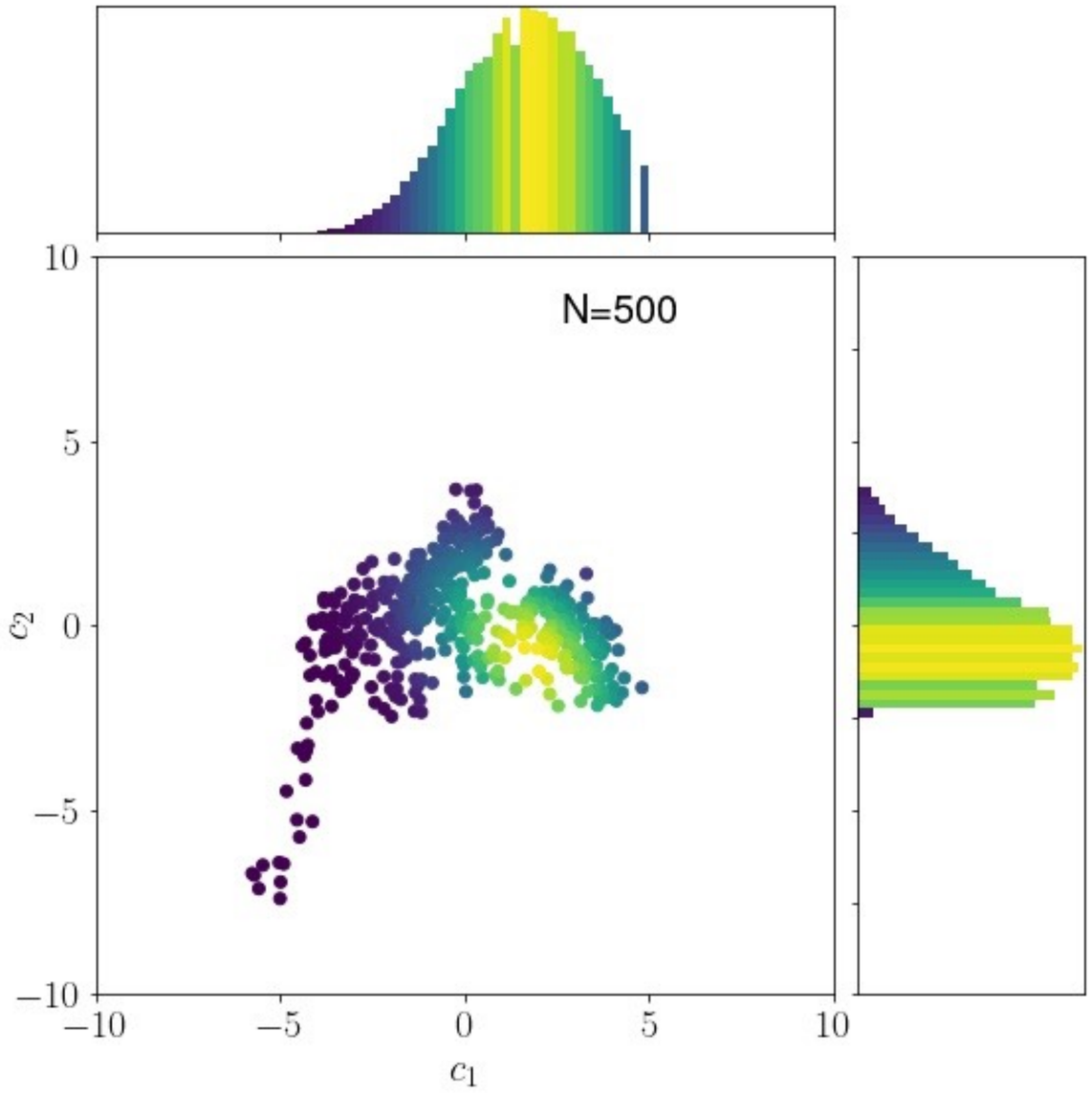

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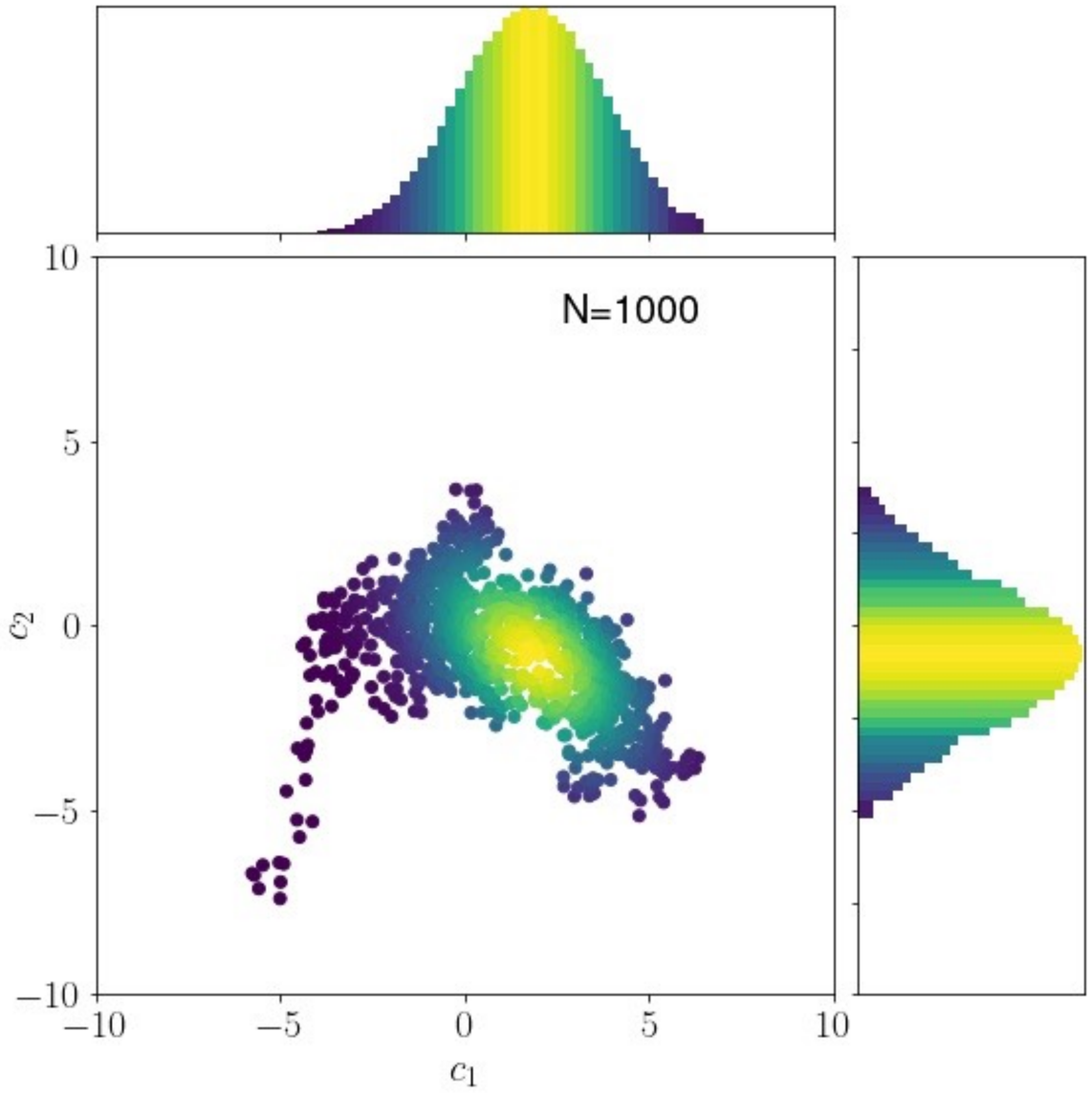

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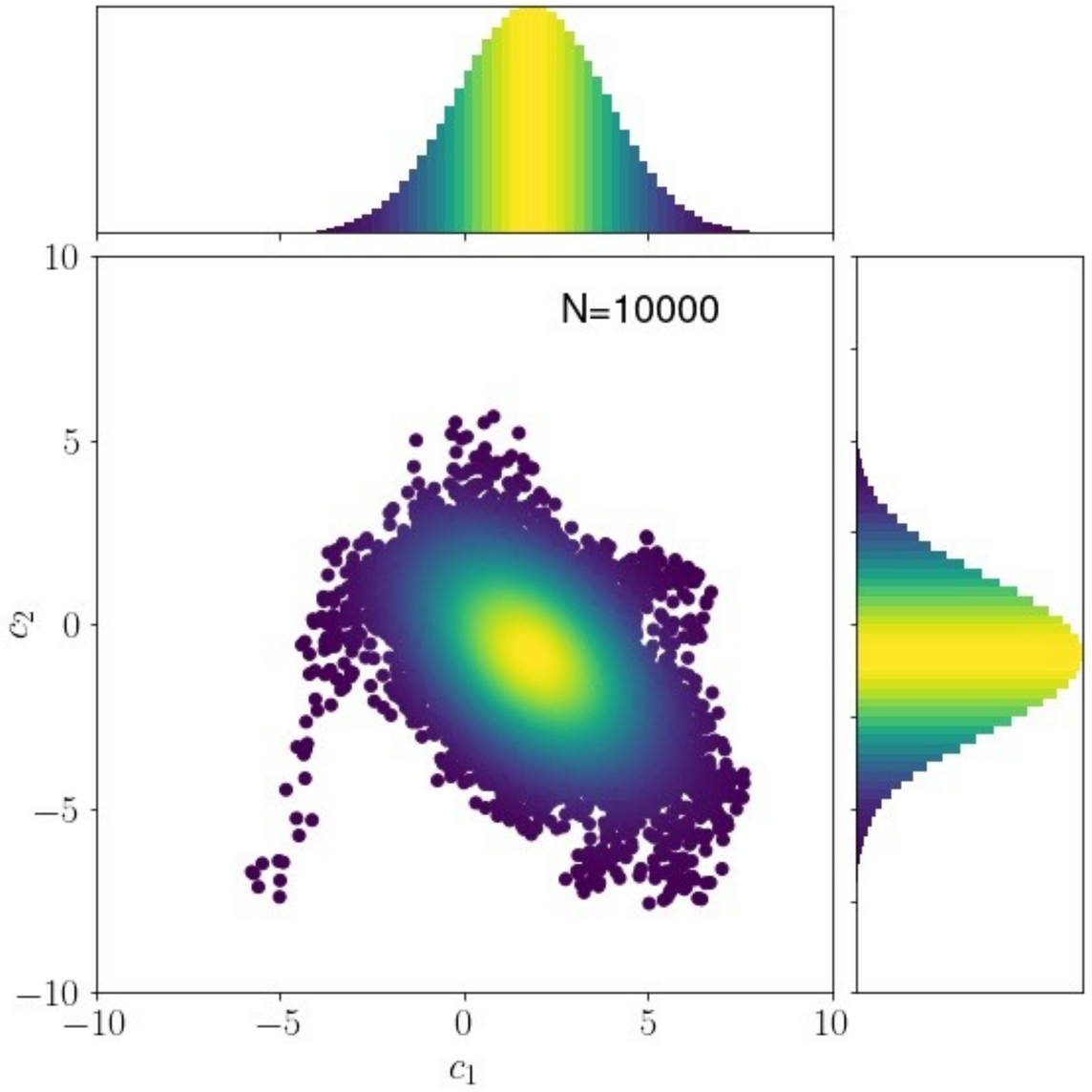

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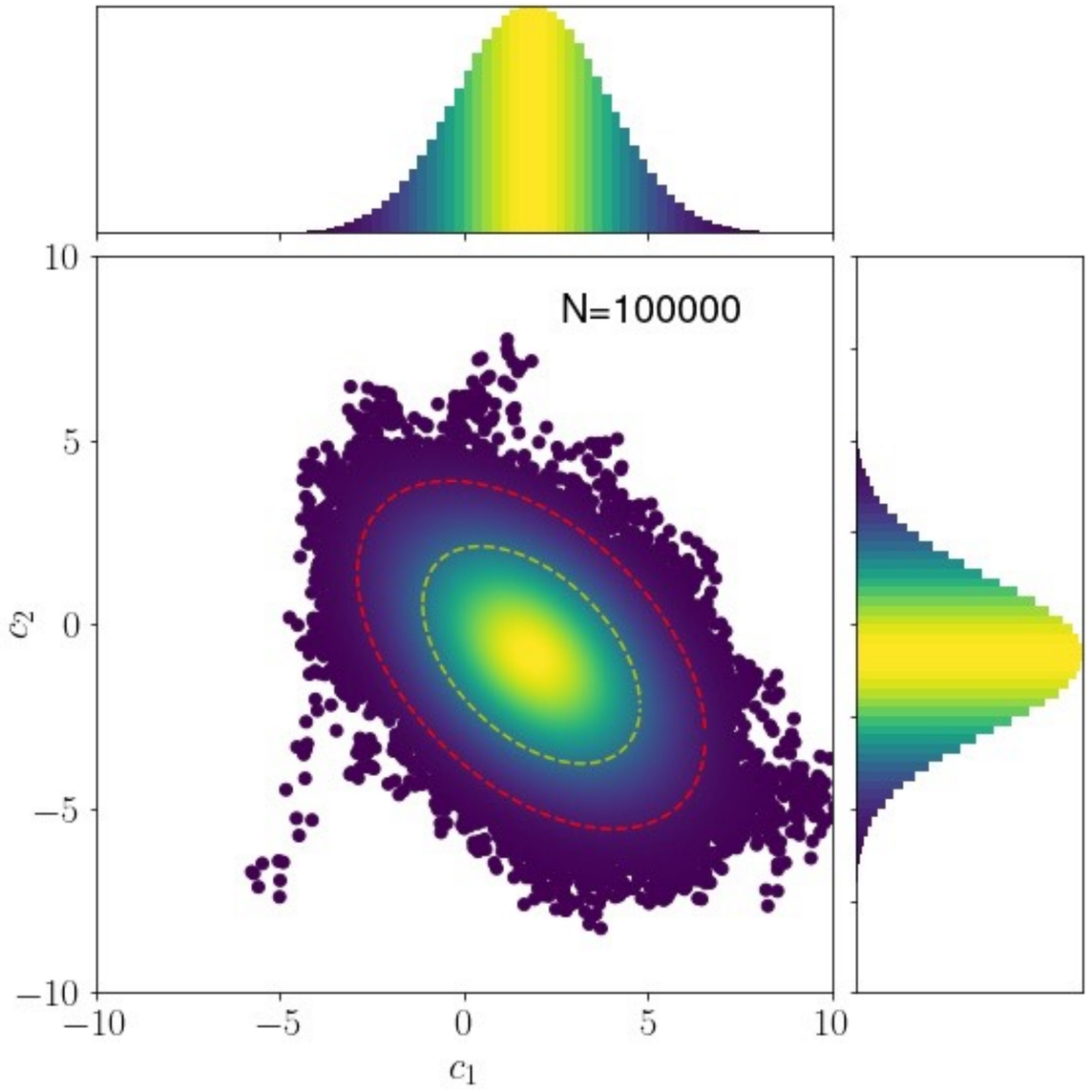

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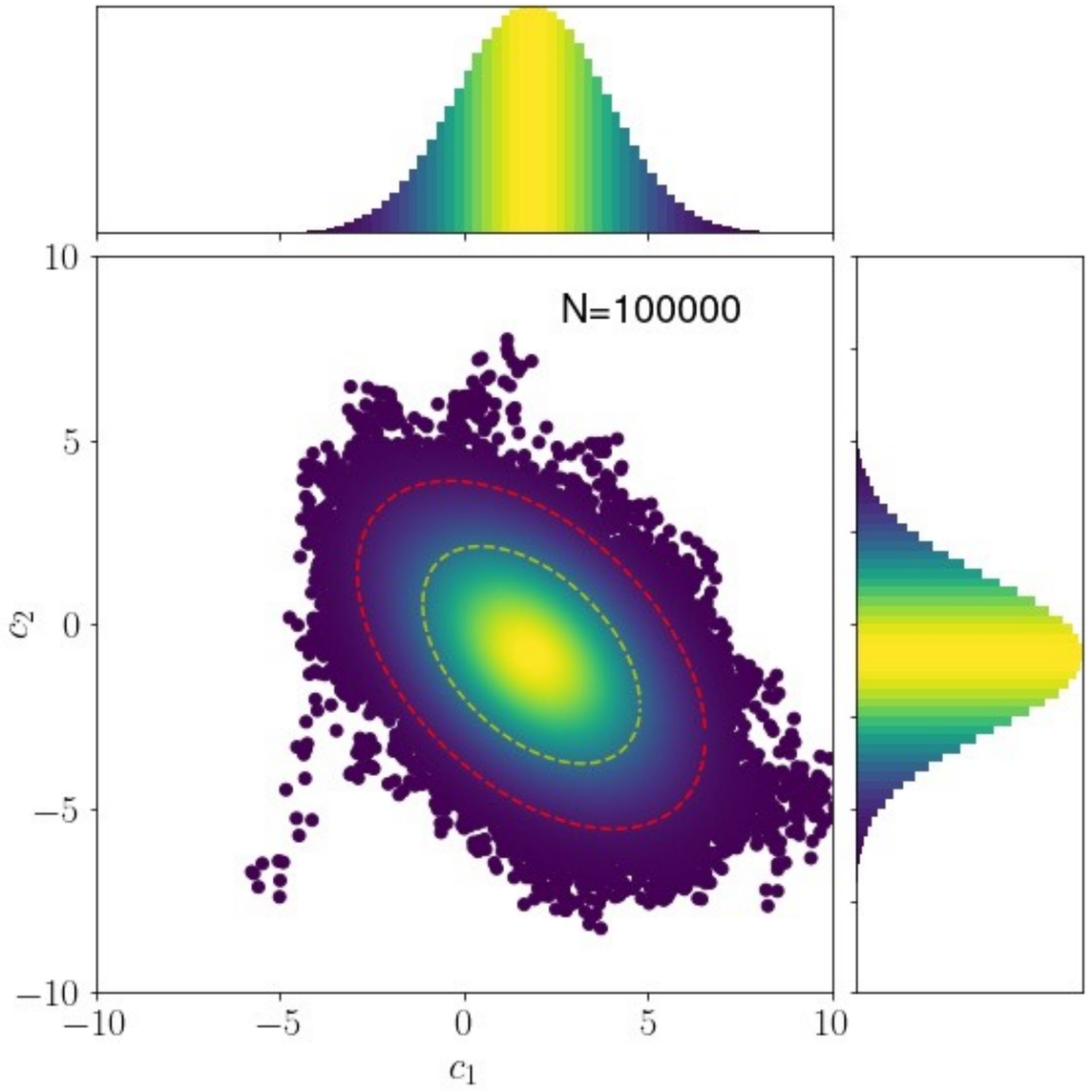
MC vs. Toys

Markov Chain

Toy Monte Carlo



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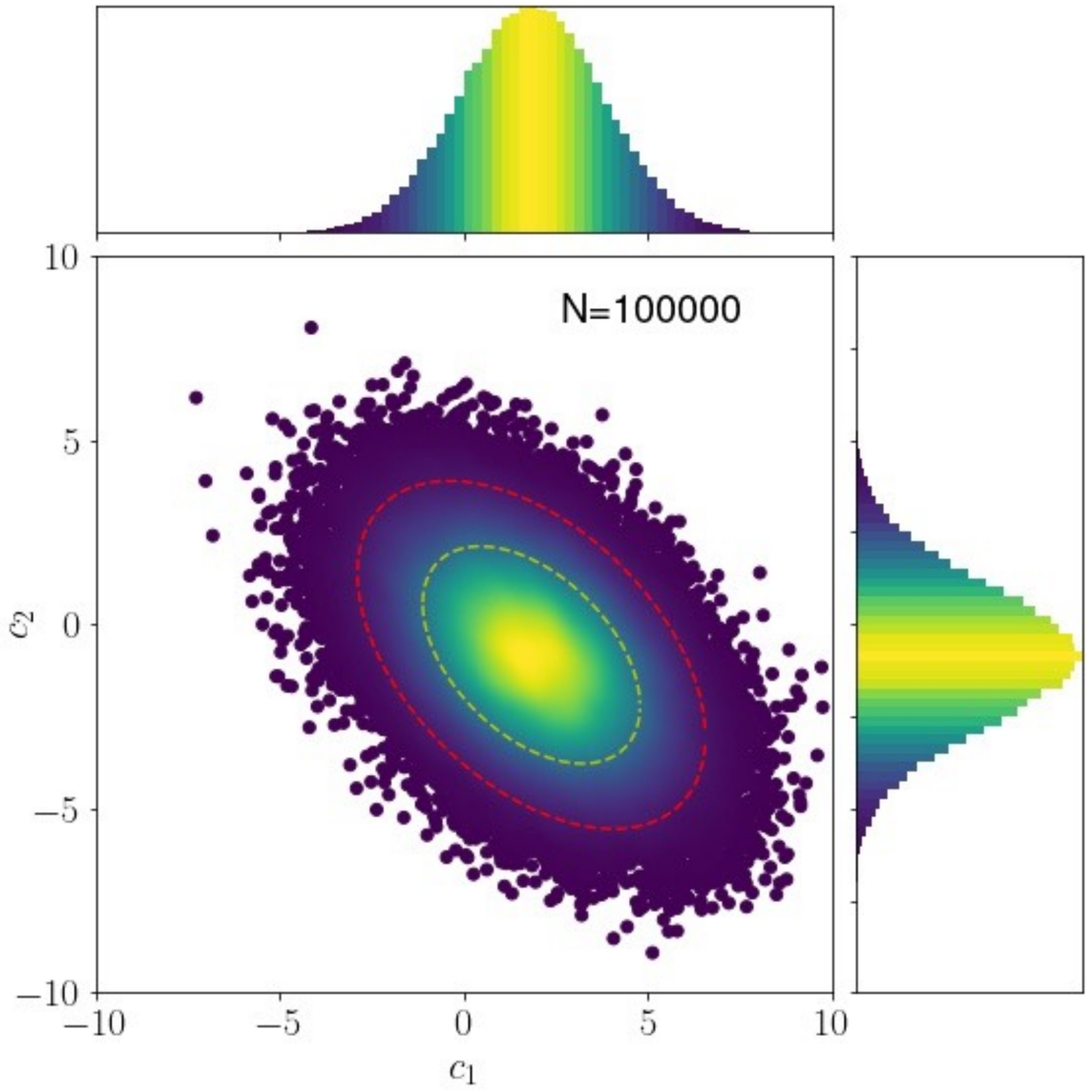
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