SMEFT: The High, the Low and the Flat

A story of chasing the ambulance-chasers

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directed by

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SMEFT: a model-independent study

- Step 1: Use the Standard Model EFT

$$\mathcal{L}^{\text{dim-6}}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{i}^{2499} C_i \mathcal{O}_i^{\text{dim-6}}$$

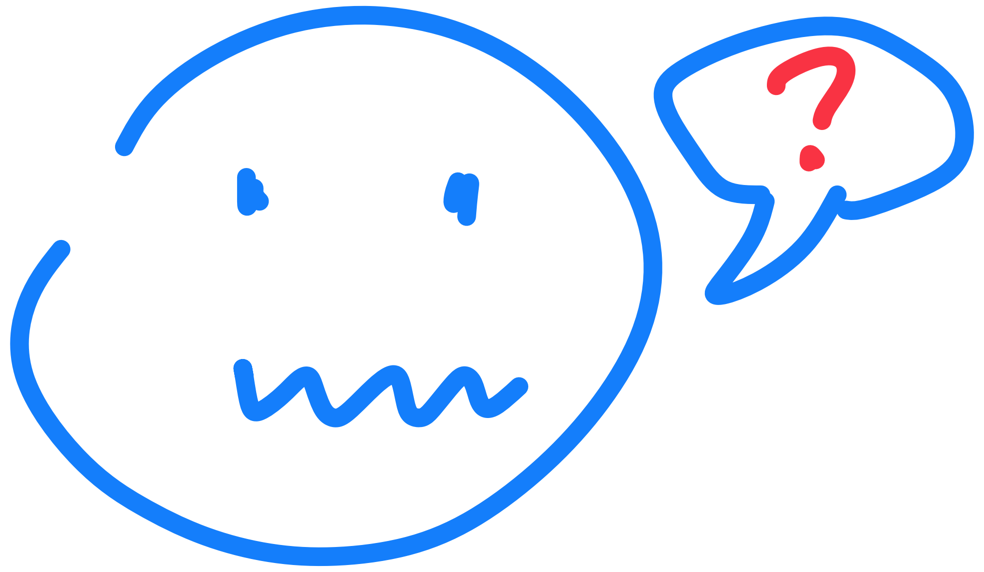
- ~~Step 2: Constrain all the Wilson coefficients with all the observables~~

- Step 2: Make some assumptions to simplify the SMEFT, say oblique, flavor universal, MFV, flavor diagonal, etc.

- Step 3: Choose ***relevant*** Wilson coefficients and ***relevant*** observables

- Step 4: Global fit (within assumptions) !

- But wait... ***relevant*** to what?



Relevant to the W mass, of course!

$\mathcal{O}_{HWB}$	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
$\mathcal{O}_{HD}$	$\left\lvert H^\dagger D_\mu H \right\rvert^2$
$\mathcal{O}^{(3)}_{Hl}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)\,(\bar{l}_p \tau^I \gamma^\mu l_r)$
[redacted]	
$\mathcal{O}_{ll}$	$(\bar{l}_p \gamma_\mu l_r)\,(\bar{l}_s \gamma^\mu l_t)$
[redacted]	

- W mass is one of the EWPO

	Measurement
M_W [GeV]	80.413 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
$\sin^2\theta^{\rm lept}_{\rm eff}(Q^{\rm had}_{\rm FB})$	0.2324 ± 0.0012
$P^{\rm pol}_\tau = \mathcal{A}_\ell$	0.1465 ± 0.0033
Γ_Z [GeV]	2.4955 ± 0.0023
σ^0_h [nb]	41.480 ± 0.033
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
R^0_b	0.21629 ± 0.00066
R^0_c	0.1721 ± 0.0030
$A^{0,b}_{\rm FB}$	0.0996 ± 0.0016
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$\mathcal{A}_b$	0.923 ± 0.020
$\mathcal{A}_c$	0.670 ± 0.027
$\mathcal{A}_s$	0.895 ± 0.091
${\rm BR}_{W\to\ell\bar{\nu}_\ell}$	0.10860 ± 0.00090
$\sin^2\theta^{\rm lept}_{\rm eff}$ (HC)	0.23143 ± 0.00025
R_{uc}	0.1660 ± 0.0090

- In SMEFT @ dim-6, W mass is corrected by

$$\frac{\delta m_W^2}{m_W^2} = v^2\,\frac{s_w c_w}{s_w^2 - c_w^2}\left[\underset{\substack{\downarrow\\ S}}{2\,C_{HWB}} + \frac{c_w}{2 s_w}\,\underset{\substack{\downarrow\\ T}}{C_{HD}} + \frac{s_w}{c_w}\underbrace{\left(2\,C^{(3)}_{Hl} - C_{ll}\right)}_{G_F}\right]$$

SMEFT analysis of EWPO

Impact of the recent measurements of the top-quark and W-boson masses on electroweak precision fits #1

J. de Blas (CAFPE, Granada and Granada U.), M. Pierini (CERN), L. Reina (Florida State U.), L. Silvestrini (INFN, Rome) (Apr 8, 2022)

e-Print: 2204.04204 [hep-ph]

pdf cite 71 citations

- There are 10 SMEFT operators relevant to the EWPO

- Only 8 linear combinations can be constrained

- 2 flat directions remain

$$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_e$$

$$\begin{aligned} \hat{C}^{(1)}_{\varphi f} &= C^{(1)}_{\varphi f} - \frac{Y_f}{2} C_{\varphi D}, \quad f = l, q, e, u, d, \\ \hat{C}^{(3)}_{\varphi f} &= C^{(3)}_{\varphi f} + \frac{c_w^2}{4 s_w^2} C_{\varphi D} + \frac{c_w}{s_w} C_{\varphi WB}, \quad f = l, q, \end{aligned}$$

SMEFT analysis of EWPO

	Result	Correlation Matrix							
	$(\mathrm{IC}_{\mathrm{SMEFT}}/\mathrm{IC}_{\mathrm{SM}} = 31.8/80.2)$								
$\hat{C}^{(1)}_{\varphi l}$	-0.007 ± 0.011	1.00							
$\hat{C}^{(3)}_{\varphi l}$	-0.042 ± 0.015	-0.68	1.00						
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	0.48	0.04	1.00					
$\hat{C}^{(1)}_{\varphi q}$	-0.018 ± 0.044	-0.02	-0.06	-0.13	1.00				
$\hat{C}^{(3)}_{\varphi q}$	-0.113 ± 0.043	-0.03	0.04	-0.16	-0.37	1.00			
$\hat{C}_{\varphi u}$	0.090 ± 0.150	0.06	-0.04	0.04	0.61	-0.77	1.00		
$\hat{C}_{\varphi d}$	-0.630 ± 0.250	-0.13	-0.05	-0.30	0.40	0.58	-0.04	1.00	
$\hat{C}_{ll}$	-0.022 ± 0.028	-0.80	0.95	-0.10	-0.06	-0.01	-0.04	-0.05	1.00

- This would be the ***guide for model building***: try to build models consistent with these values

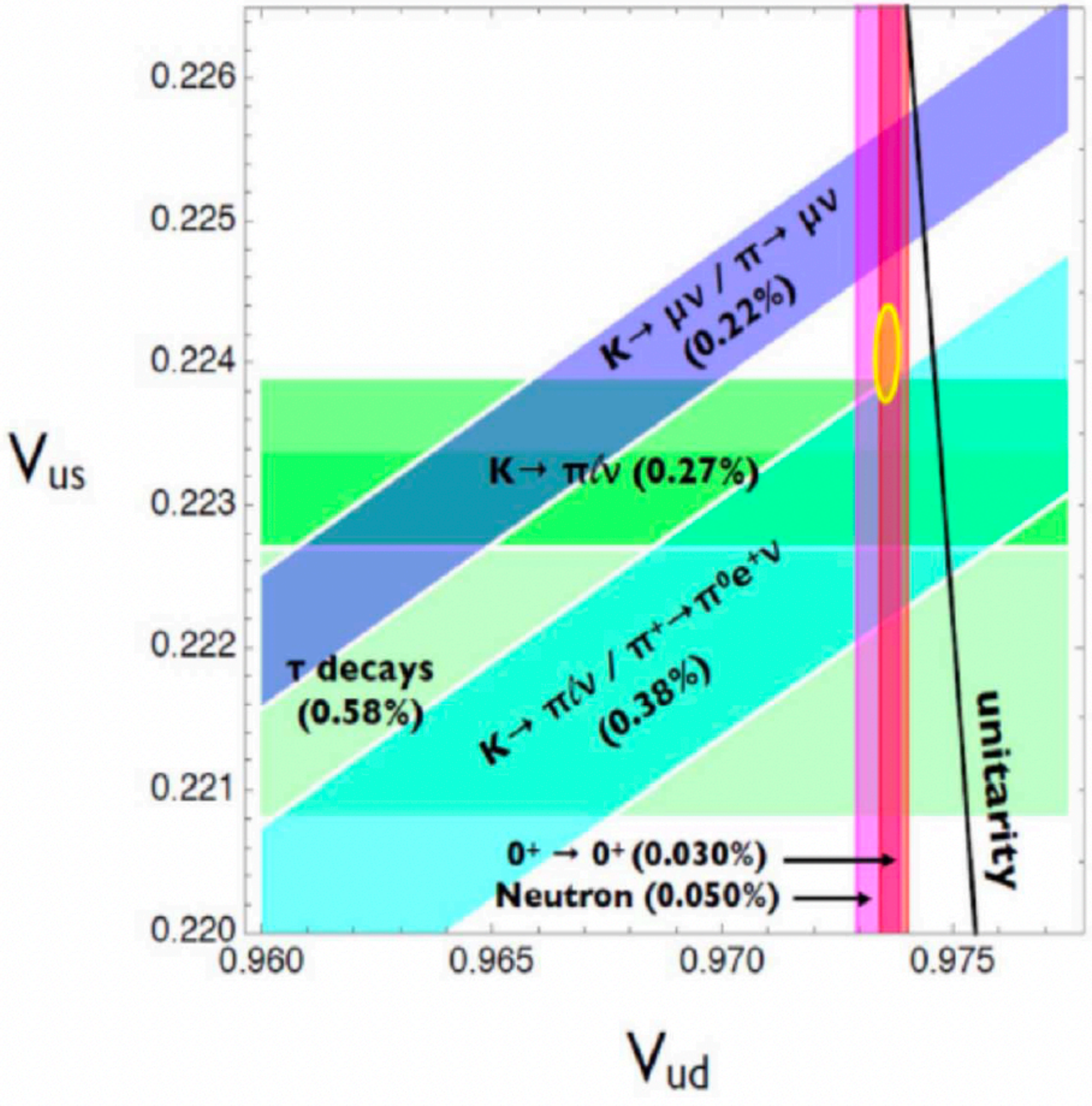
- But treating the EWPO in isolation is problematic

First-row CKM unitarity

$$\Delta_{\text{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$$

- V_{ud} and V_{us} are obtained from nuclear beta decay and Kaon decays
- Requires detailed understanding of radiative corrections
- Very precise determinations are in tension with CKM unitarity

$$\Delta_{CKM}^{PDG} \approx -(0.15 \pm 0.06)\,\%$$



First-row CKM in SMEFT (with MFV)

Beta-decay implications for the W-boson mass anomaly

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2204.08440

$$\Delta_{\rm CKM} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$$

$$= 2\frac{v^2}{\Lambda^2}\left[\underbrace{C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell}}_{C_\Delta} - C_{\ell q}^{(3)}\right]$$

where $C_{lq}^{(3)}$ is irrelevant to the EWPO and does not play a role in the fit

- We combine the relevant Wilson coefficients into C_Δ
- Replace C_{ll} with C_Δ and re-do the fit

Oops!

- From the re-fit, we obtain a large, %-level, deviation from the first-row CKM unitarity

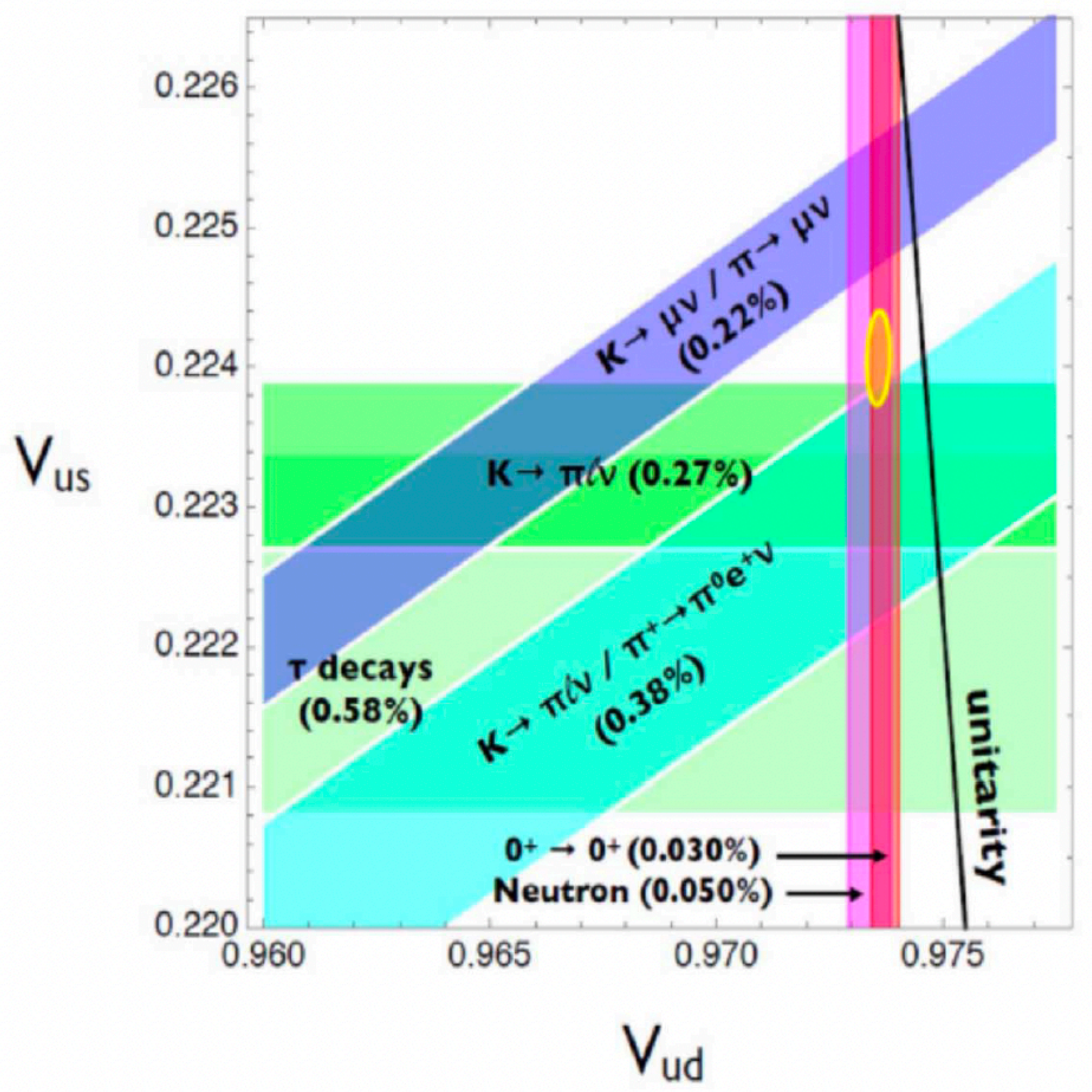
$$\Delta_{CKM}^{fit} \approx -(1 \pm 0.5)\,\%$$

- Based on up-to-date predictions of $0^+ \to 0^+$ nuclear beta-decays and Kaon decays, the PDG average indicates that

$$\Delta_{CKM}^{PDG} \approx -(0.15 \pm 0.07)\,\%$$

- A 2-sigma deviation per se, but much smaller than indicated by the fit
- Refitting with CKM included shifts the values
- **Would point to other models!**

	Result	Result with CKM
$\hat{C}_{\varphi l}^{(1)}$	-0.007 ± 0.011	-0.013 ± 0.009
$\hat{C}_{\varphi l}^{(3)}$	-0.042 ± 0.015	-0.034 ± 0.014
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	-0.021 ± 0.009
$\hat{C}_{\varphi q}^{(1)}$	-0.0181 ± 0.044	-0.048 ± 0.04
$\hat{C}_{\varphi q}^{(3)}$	-0.114 ± 0.043	-0.041 ± 0.015
$\hat{C}_{\varphi u}$	0.086 ± 0.154	-0.12 ± 0.11
$\hat{C}_{\varphi d}$	-0.626 ± 0.248	-0.38 ± 0.22
C_{Δ}	-0.19 ± 0.09	-0.027 ± 0.011



Let's include more high energy data

SMEFT Analysis of m_W

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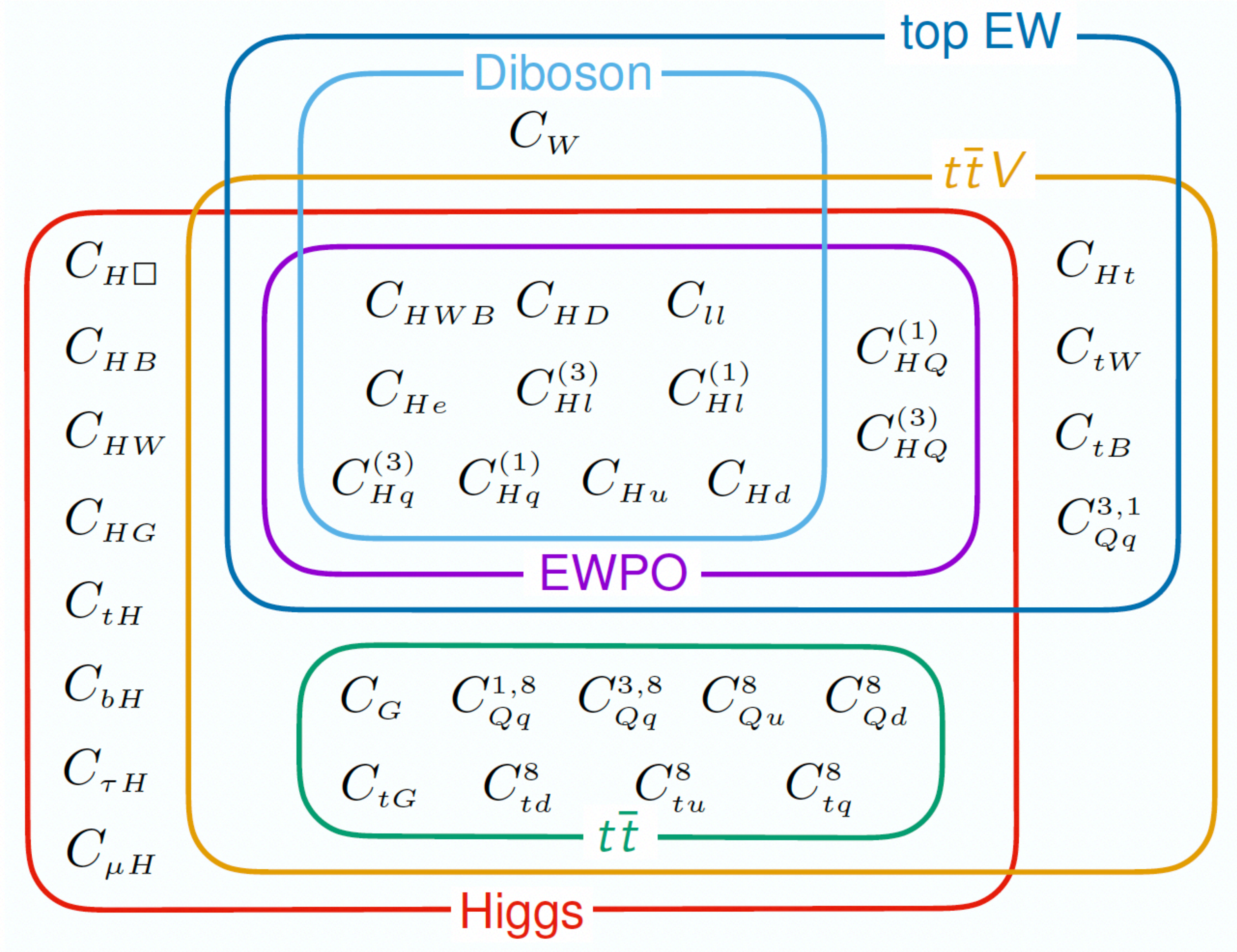
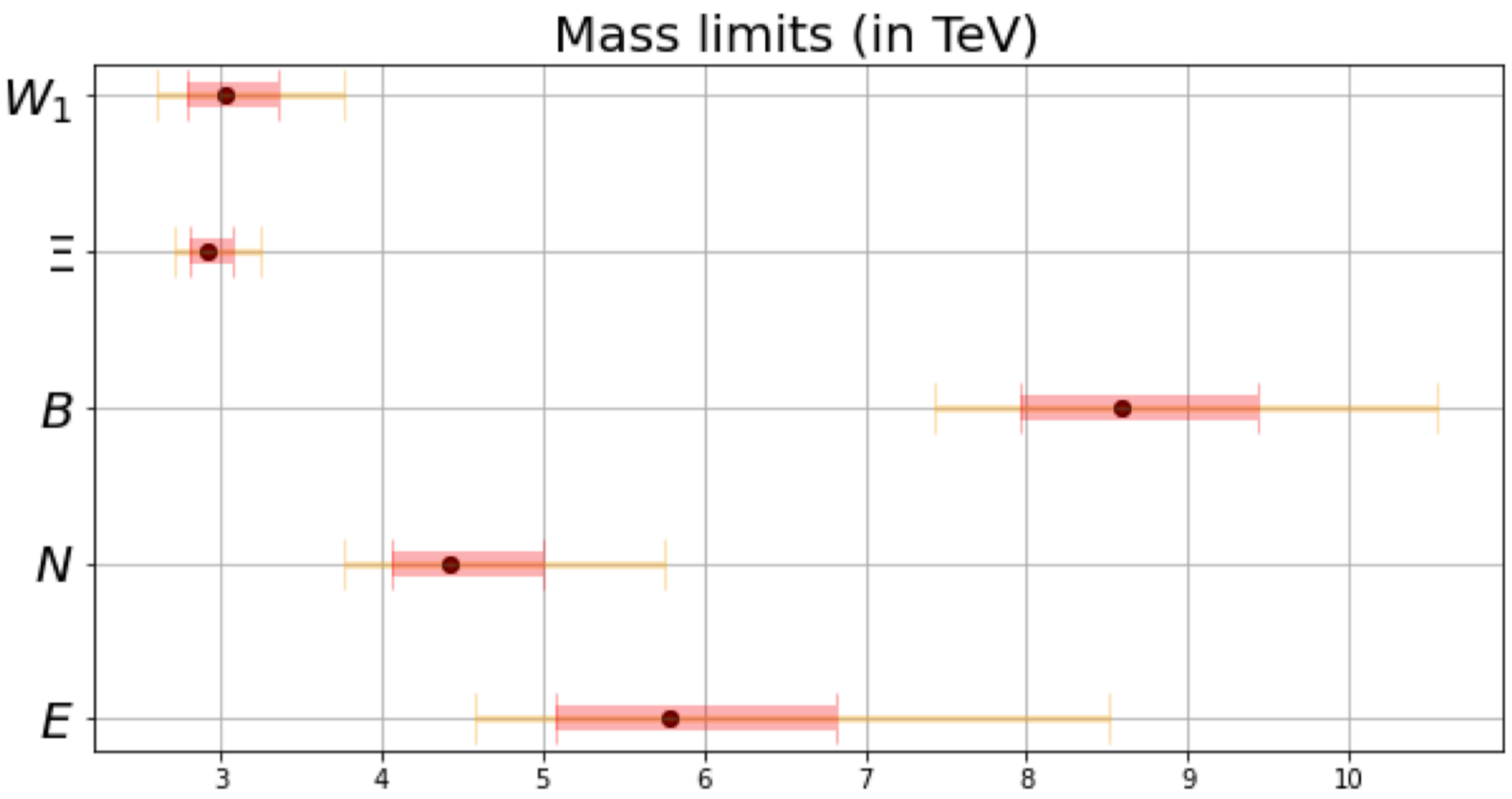


- EWPO + Diboson + Top + Higgs
- More observables, more relevant operators
- Global-fit with 20 operators (flavor universal)
- Well, the same. Percent-level CKM unitarity violation
- Adding more high energy data *does not help!*
- The same if one uses flavor diagonal assumptions (2204.05992, Zupan *et al*)

Model	Spin	SU(3)	SU(2)	U(1)	Parameters
S_1	0	1	1	1	$(M_S,\, \kappa_S)$
Σ	$\frac{1}{2}$	1	3	0	$(M_\Sigma, \lambda_\Sigma)$
Σ_1	$\frac{1}{2}$	1	3	-1	$(M_{\Sigma_1}, \lambda_{\Sigma_1})$
N	$\frac{1}{2}$	1	1	0	(M_N, λ_N)
E	$\frac{1}{2}$	1	1	-1	(M_E, λ_E)
B	1	1	1	0	$(M_B, \hat{g}_H^B)$
B_1	1	1	1	1	(M_{B_1}, λ_{B_1})
Ξ	0	1	3	0	(M_Ξ, κ_Ξ)
W_1	1	1	3	1	$(M_{W_1}, \hat{g}_{W_1}^{\varphi})$
W	1	1	3	0	$(M_W, \hat{g}_W^H)$

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		-1							
Σ			$\frac{1}{16}$	$\frac{3}{16}$			$\frac{y_\tau}{4}$		
Σ_1			$\frac{1}{16}$	$-\frac{3}{16}$			$\frac{y_\tau}{8}$		
N			$-\frac{1}{4}$	$\frac{1}{4}$					
E			$-\frac{1}{4}$	$-\frac{1}{4}$			$\frac{y_\tau}{2}$		
B_1	1					$-\frac{1}{2}$	$-\frac{y_\tau}{2}$	$-\frac{y_t}{2}$	$-\frac{y_b}{2}$
B	-2						$-y_\tau$	$-y_t$	$-y_b$
Ξ	$-2\left(\frac{1}{M_\Xi}\right)^2$					$\frac{1}{2}\left(\frac{1}{M_\Xi}\right)^2$	$y_\tau\left(\frac{1}{M_\Xi}\right)^2$	$y_t\left(\frac{1}{M_\Xi}\right)^2$	$y_b\left(\frac{1}{M_\Xi}\right)^2$
W_1	$-\frac{1}{4}$					$-\frac{1}{8}$	$-\frac{y_\tau}{8}$	$-\frac{y_t}{8}$	$-\frac{y_b}{8}$
W	$\frac{1}{2}$					$-\frac{1}{2}$	$-y_\tau$	$-y_t$	$-y_b$



Model	Pull	Best-fit mass (TeV)	1-σ mass range (TeV)	2-σ mass range (TeV)	1-σ coupling^2 range
W_1	6.4	3.0	[2.8, 3.6]	[2.6, 3.8]	[0.09, 0.13]
B	6.4	8.6	[8.0, 9.4]	[7.4, 10.6]	[0.011, 0.016]
Ξ	6.4	2.9	[2.8, 3.1]	[2.7, 3.2]	[0.011, 0.016]
N	5.1	4.4	[4.1, 5.0]	[3.8, 5.8]	[0.040, 0.060]
E	3.5	5.8	[5.1, 6.8]	[4.6, 8.5]	[0.022, 0.039]

- These two models induce too large CKM unitarity violation

Is it really W mass the perpetrator?

- If not, then the global-fit should be in bad tension with CKM even before the new CDF results

- So, what was Δ_{CKM} before 2022?

- We re-did the old EWPO fits

- It was only $-(0.4 \pm 0.4)\,\%$ in 0908.1754

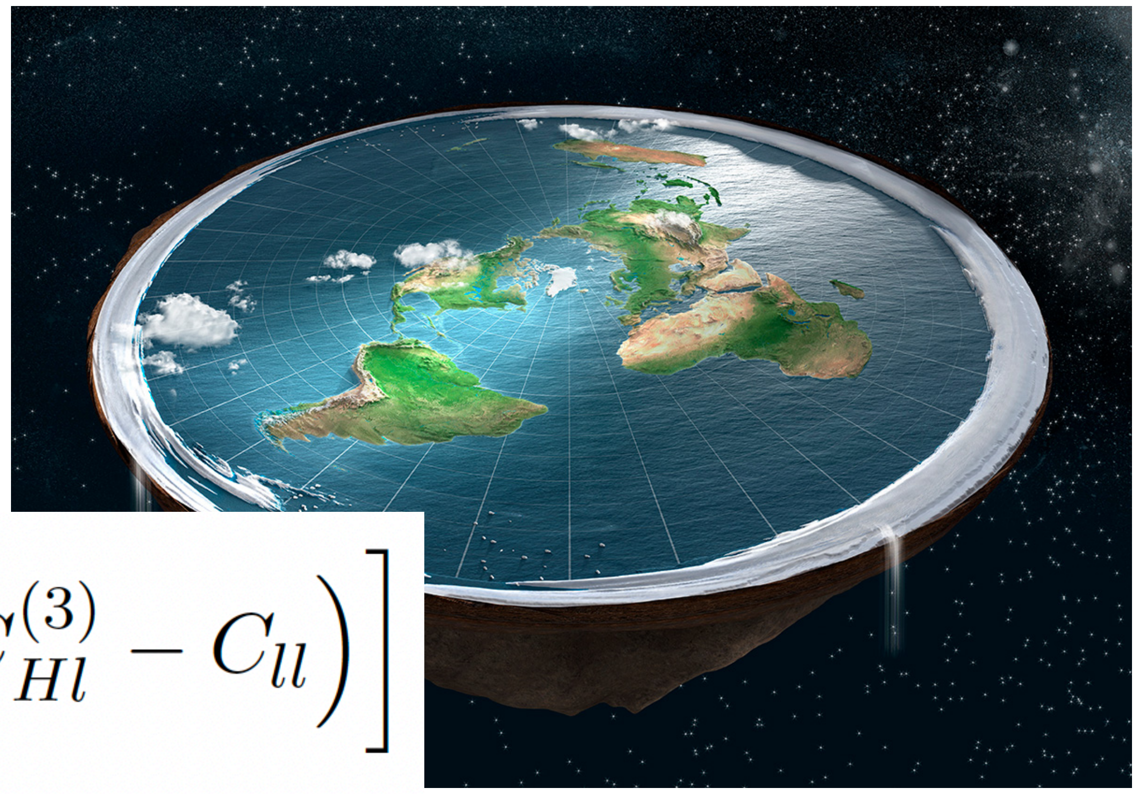
- And a similar value indicated by 2012.02779,

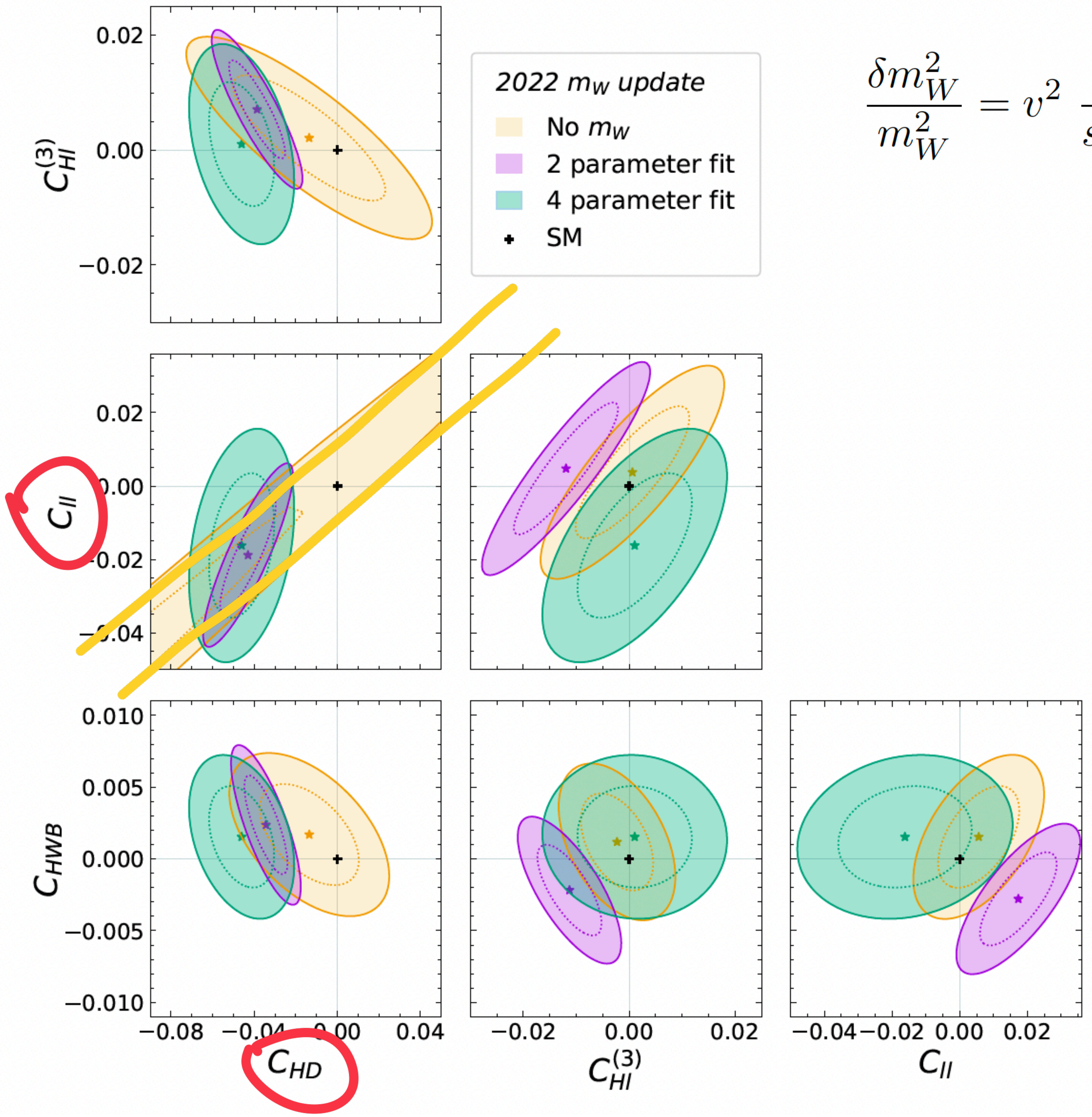
  which is the old version of the 20-parameter fit

- It seems that roughly about half of the deviation was already there, and the CDF W mass has doubled that.

$$\Delta_{CKM}^{fit} \approx -(1 \pm 0.5)\,\%$$

What happened? The Flat

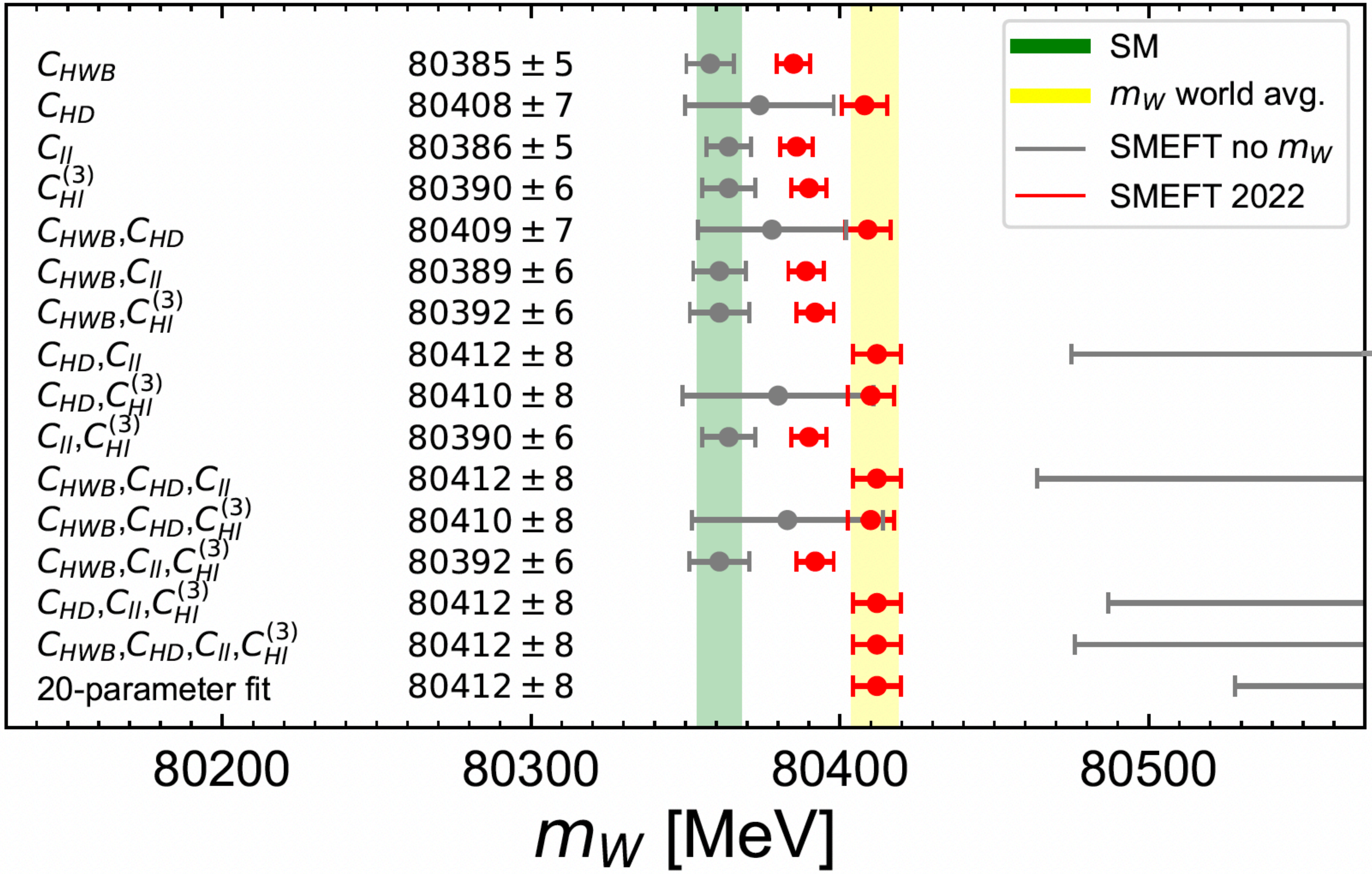




$$\frac{\delta m_W^2}{m_W^2} = v^2 \frac{s_w c_w}{s_w^2 - c_w^2}\left[2\,C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \frac{s_w}{c_w}\left(2\,C_{Hl}^{(3)} - C_{ll}\right)\right]$$

- Fitting to the high energy data, there exists an almost flat direction involving C_{HD} and C_{ll}
- It can only be lifted by the W mass
- The value of W mass largely dominates the constraints on C_{HD} and C_{ll} along this flat direction

The Flat is the Ugly



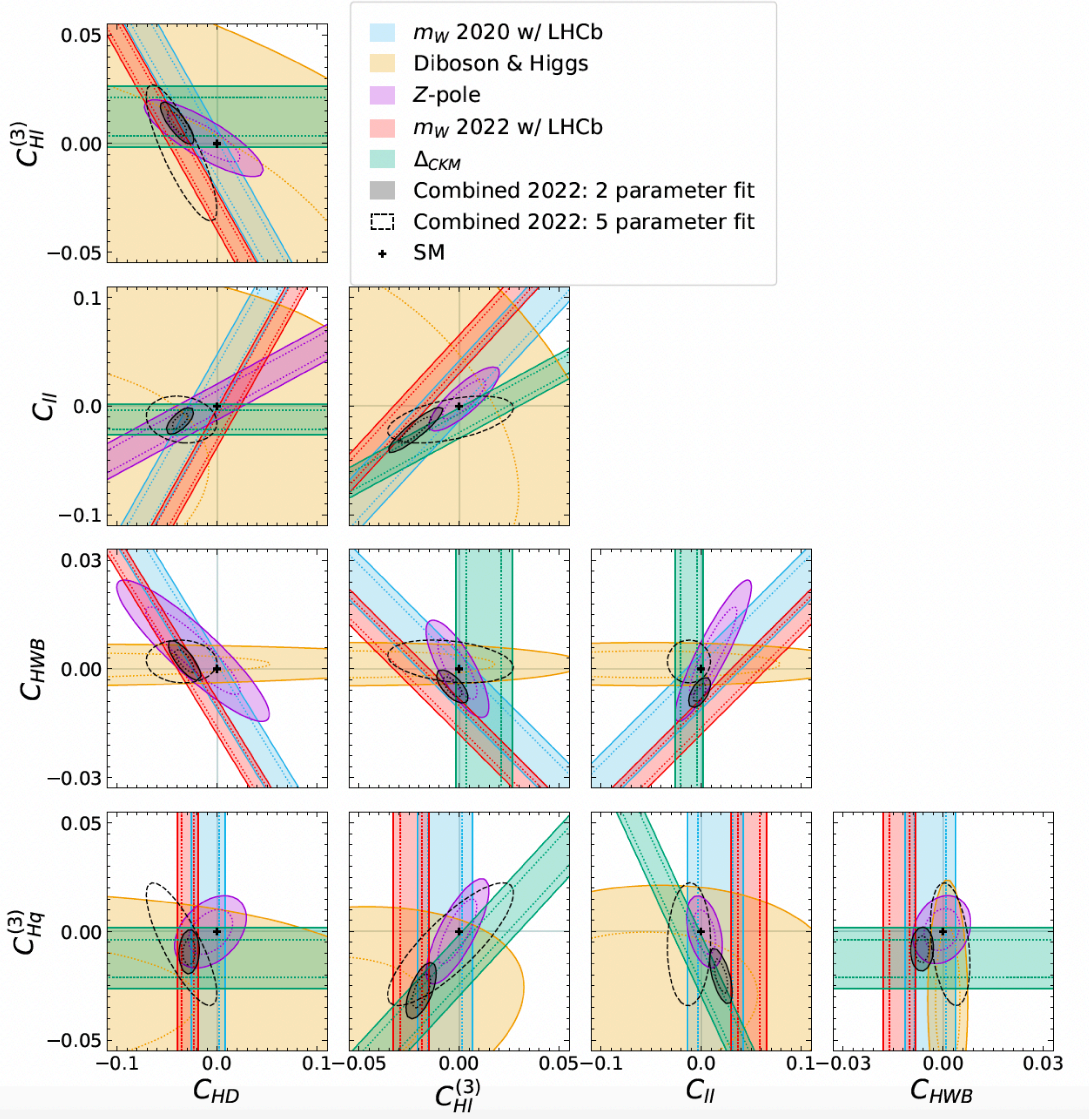
- Grey bars: Fitting results to the high energy data but *without* W mass

- Not even compatible with the real W mass at all, if both C_{HD} and C_{ll} are present

Finally, CKM comes to the rescue

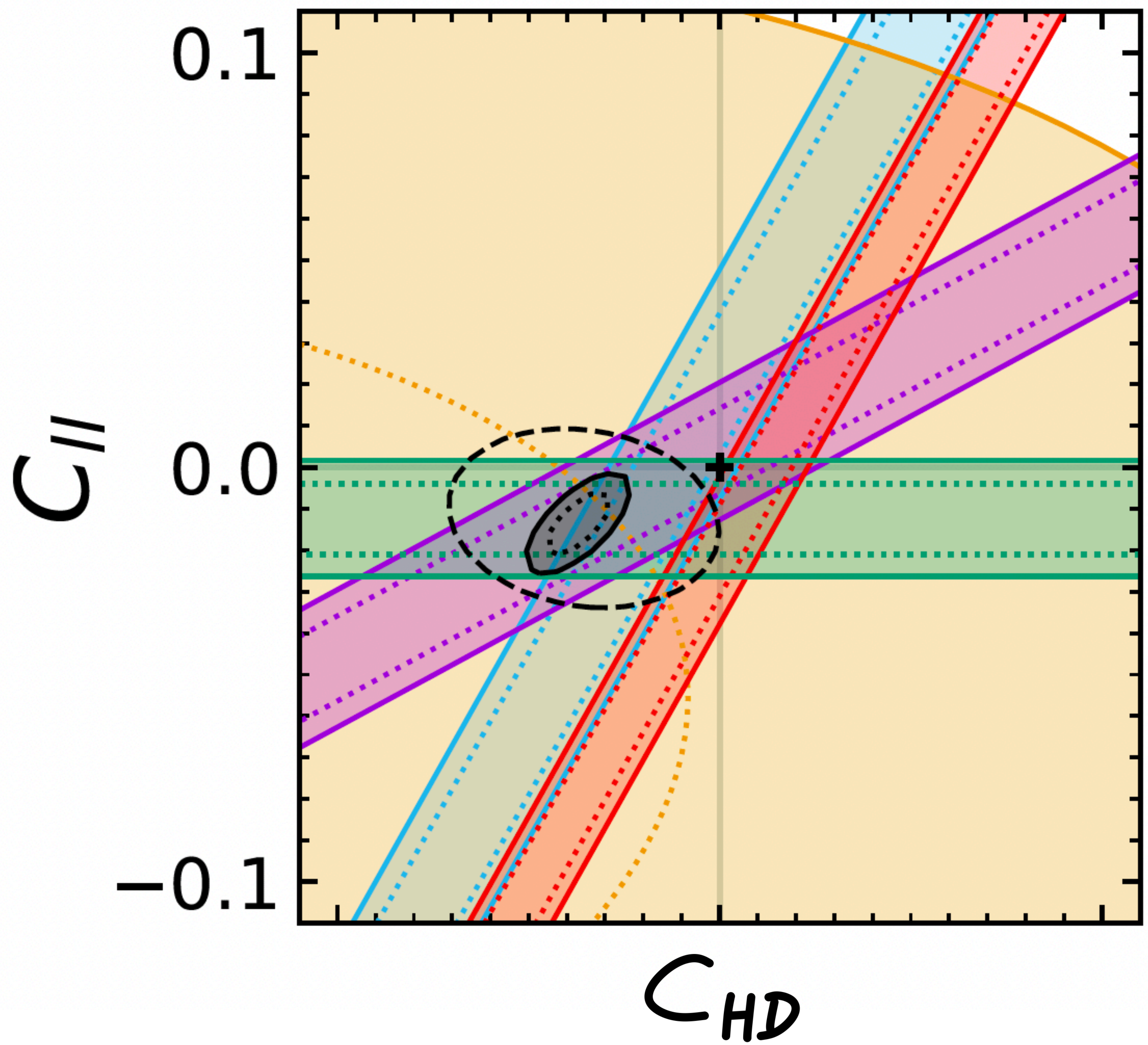
- Δ_{CKM} is sensitive to C_{ll}
- It can help lift the flat direction
- **They've heard us!**
- And 2204.05260 is now ***v2***

Hooray!

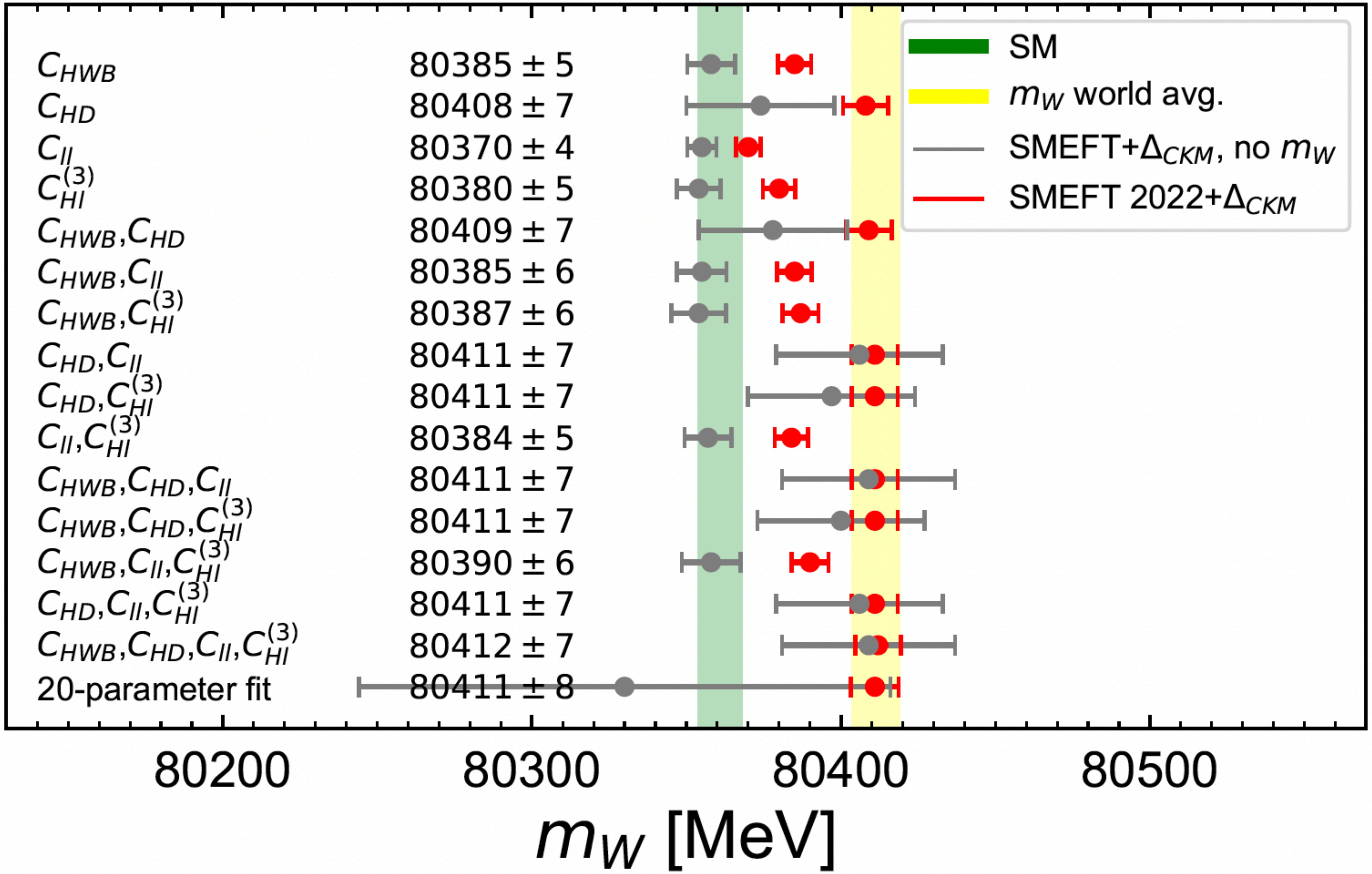


Take a closer look

- The old W mass has already deviated from the CKM and the Z-pole
- Corresponding to the 0.5% tension before CDF
- The new W mass drifted further away
- Worsening the tension into 1%



All good?



- So it seems. The Flat has been resolved

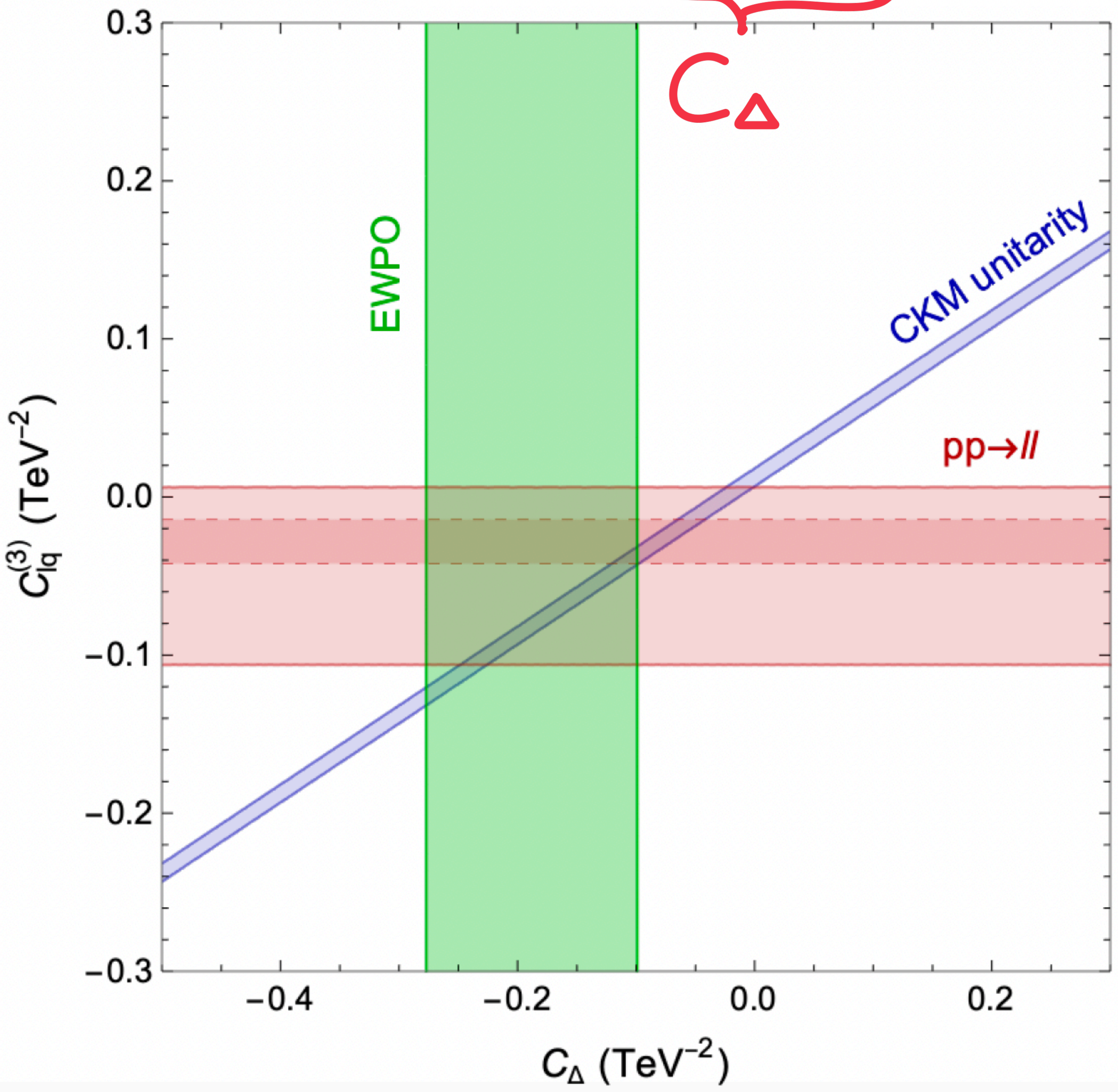
- Although some strong tension still remains between the High and the Low

$C_{lq}^{(3)}$:

“  ”

$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$$
$$= 2\frac{v^2}{\Lambda^2}\left[\underbrace{C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell}}_{C_\Delta} - C_{\ell q}^{(3)}\right]$$

- We may effectively decouple the CKM from EWPO by a non-zero $C_{lq}^{(3)}$
- $C_{lq}^{(3)}$ is constrained by 8 TeV $pp \to ll$ data at the LHC
- Could be tested by 13 TeV data
- And also at the HL-LHC



Summary

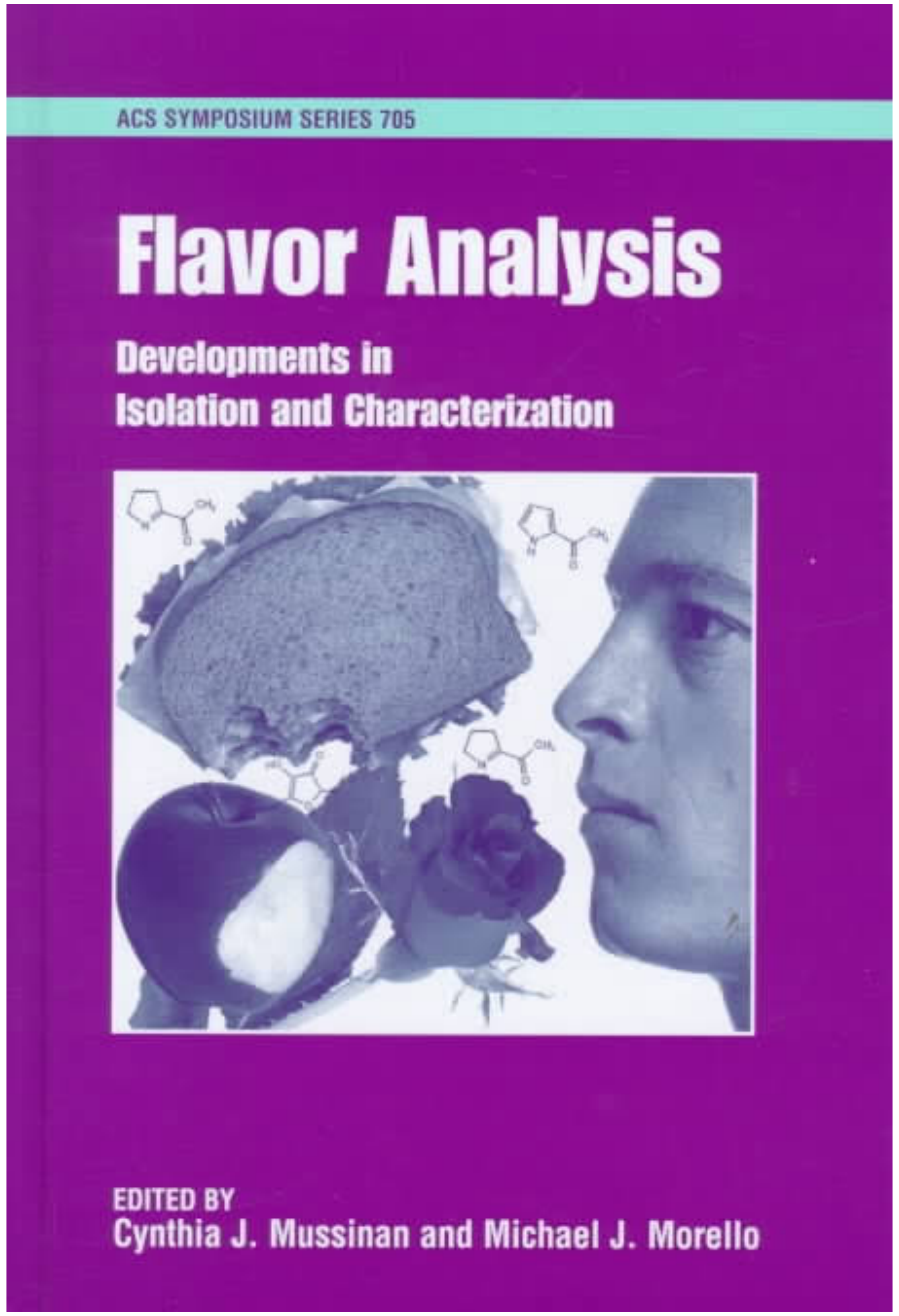
- SMEFT global-fits including only high energy data will damage the CKM unitarity

- Low energy data is important because they can help lift some of the flat directions

- Model-independent global analyses can sometimes be tricky and even deceptive

- The operators are *intertwined* with the observables in a highly non-trivial way

Question



- Choosing the "*relevant*" operators and observables is some kind of art

- In principle, one would like to include as many observables as possible (and hence many more operators), and still be able to make useful statements about new physics

- For example, what about the muon $g-2$, and all those flavor anomalies?

- Question: In the next few years, can the community find patterns in the global data, which may lead to concrete predictions for the experiments to explore?

Thanks for watching!