SMEFT: The High, the Low and the Flat

A story of chasing the ambulance-chasers

UNIVERSITÄT SIEGEN

directed by
Tom Tong

Naturwissenschaftlich Technische Fakultät

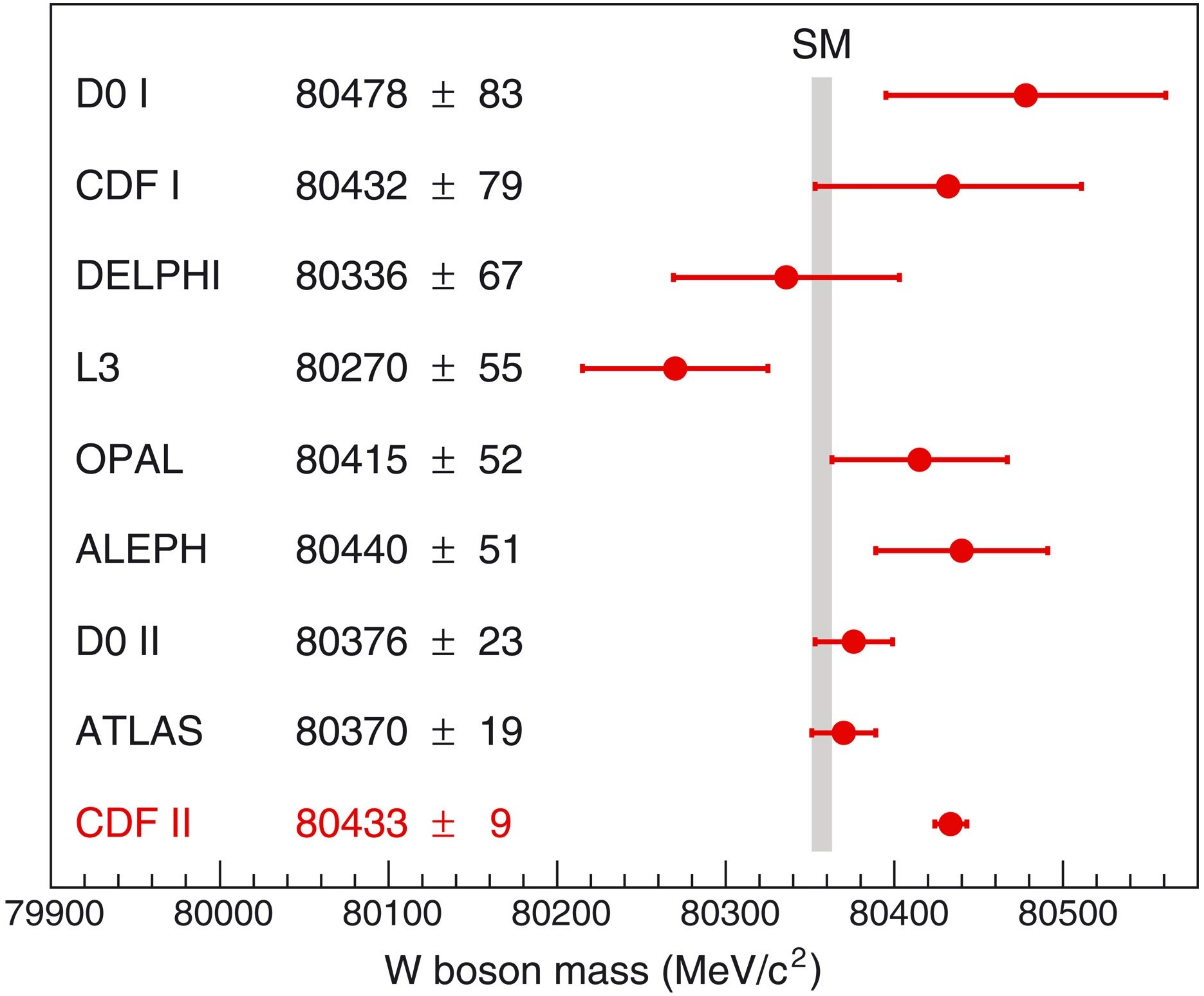
Abstract for the impatient

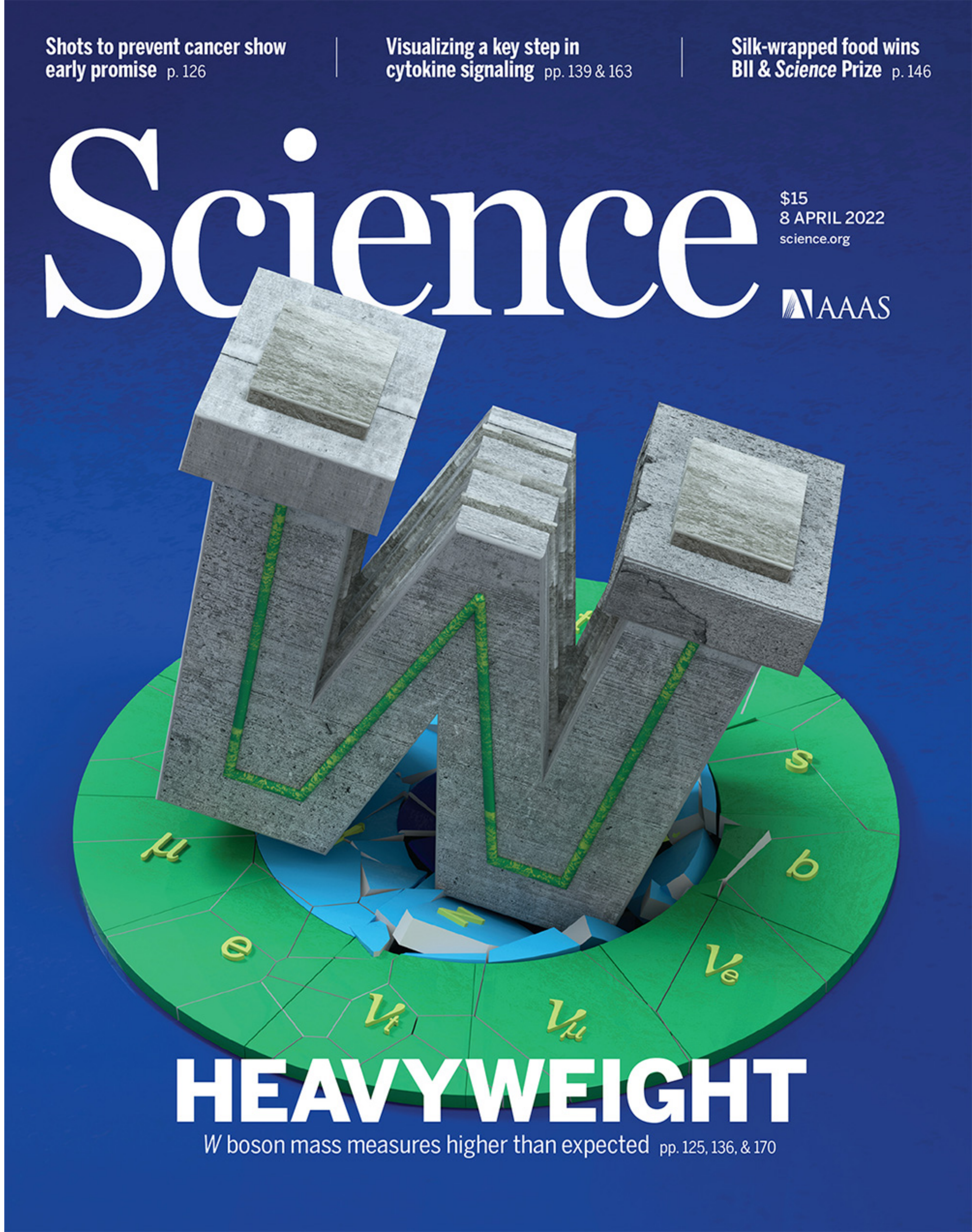
"THAT'S THE END OF MY PRESENTATION. ANY QUESTIONS?"

- SMEFT global-fits including only high energy data will cause %-level damage to the first-row CKM unitarity. Low energy data can help by lifting some of the flat directions. It is important to include them in the global analyses.

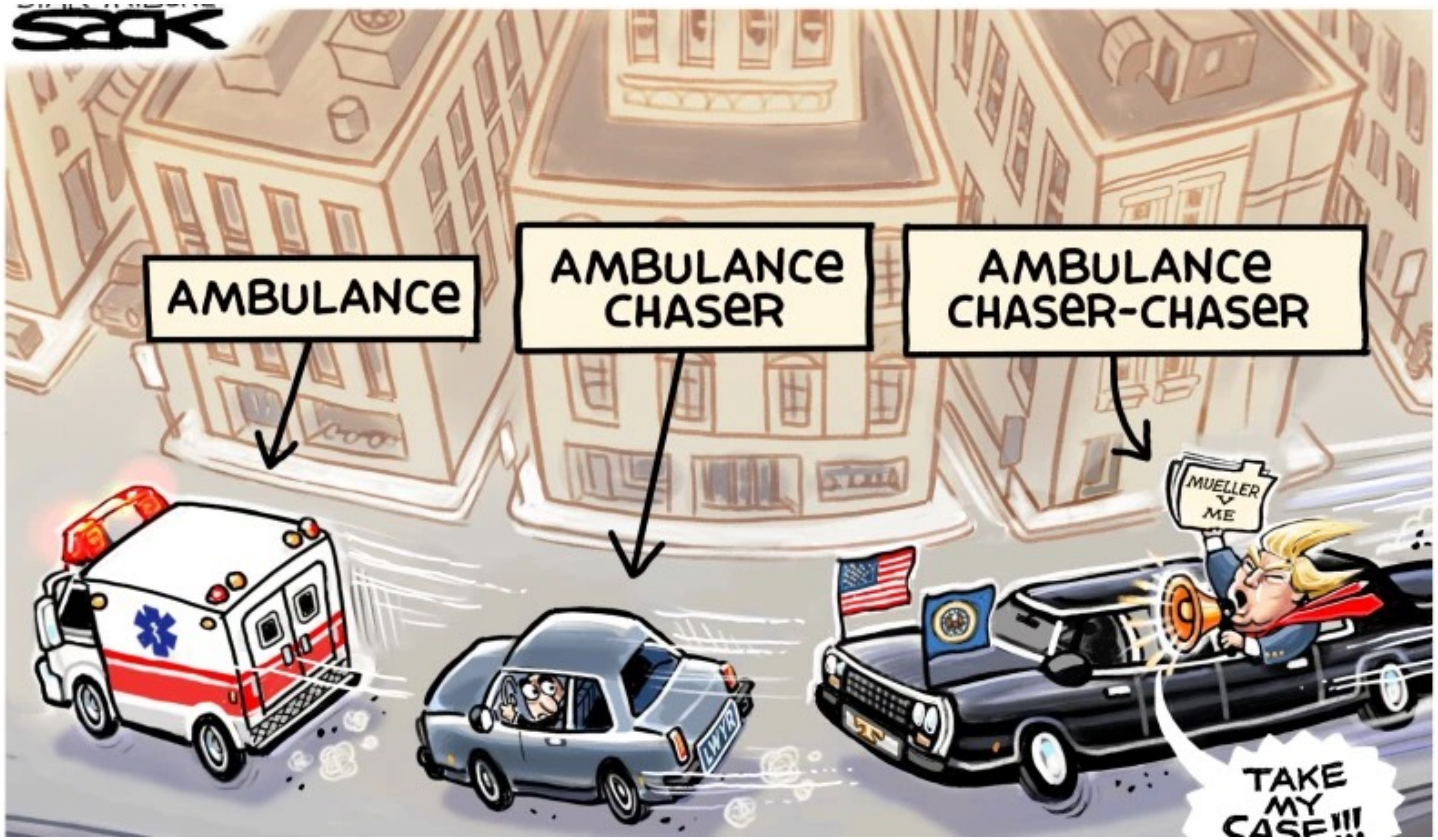
Thanks for watching!

The CDF W mass measurement





Wow! A new ambulance in town



[A story of chasing the ambulance-chasers]

- 135 citations as of this morning
- Although with some controversy, e.g. ResBos1 vs 2
- It's somebody's job (kind of...) to chase it
- What do people usually do?
- Basically in two ways

The good old way to explain an anomaly

- Step 1: Pick up a model you like, e.g. scalar triplet, 2HDM, yada yada
- Step 2: Calculate relevant observables it predicts (the tedious part...)
- Step 3: Compare them with the experiments including the new W mass
- Step 4: If it works, then add it to your paper, else discard it
- Step 5: Go to Step 1

LEGO Master Model Builder

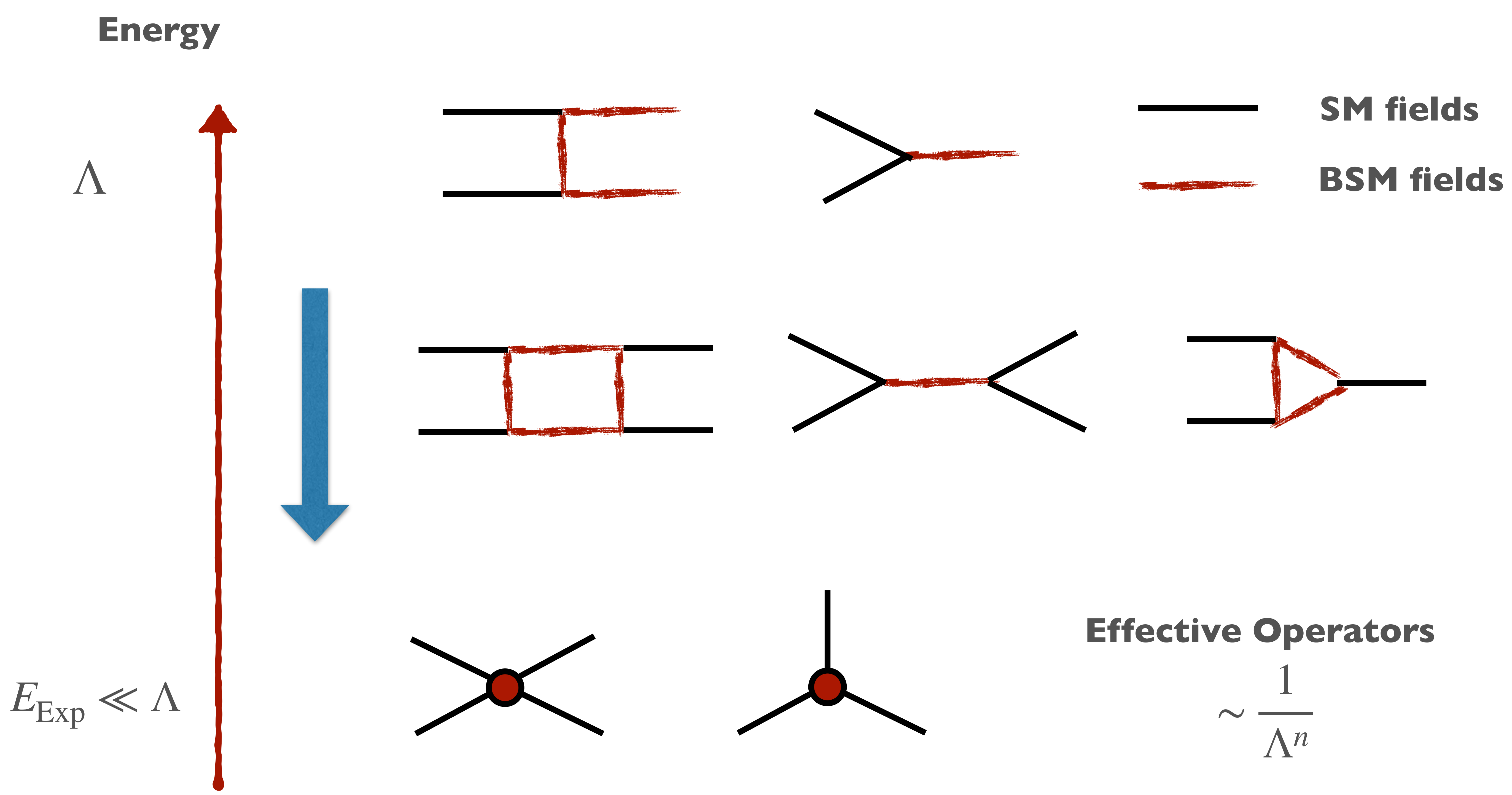
The 'model-independent' way

- Step 1: Use the Standard Model EFT

2499

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

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



The model-independent, and a little bit tricky way

- Step 1: Use the Standard Model EFT

2499

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

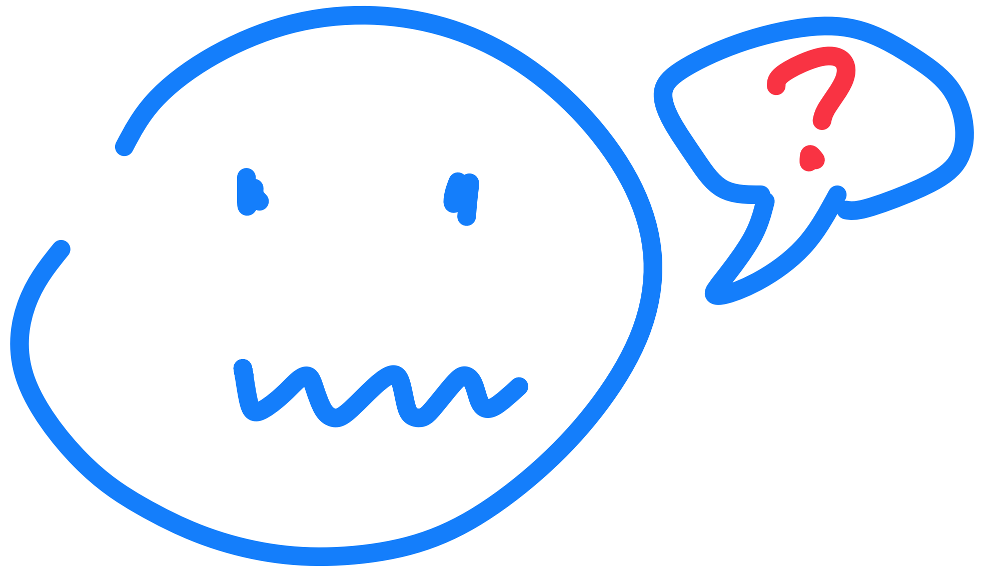
- ~~Step 2: Constrain all the Wilson coefficients with all the observables~~

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

- W mass is one of the EWPO

	Measurement
M_W [GeV]	80.413 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033
Γ_Z [GeV]	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033
R_ℓ^0	20.767 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
R_b^0	0.21629 ± 0.00066
R_c^0	0.1721 ± 0.0030
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016
$A_{\rm FB}^{0,c}$	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
$\mathrm{BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025
R_{uc}	0.1660 ± 0.0090

Relevant to the W mass, of course!

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

- W mass is one of the EWPO

	Measurement
M_W [GeV]	80.413 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033
Γ_Z [GeV]	2.4955 ± 0.0023
σ_h^0 [nb]	41.480 ± 0.033
R_ℓ^0	20.767 ± 0.025
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021
R_b^0	0.21629 ± 0.00066
R_c^0	0.1721 ± 0.0030
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016
$A_{\rm FB}^{0,c}$	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
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025
R_{uc}	0.1660 ± 0.0090

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

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

S T G_F

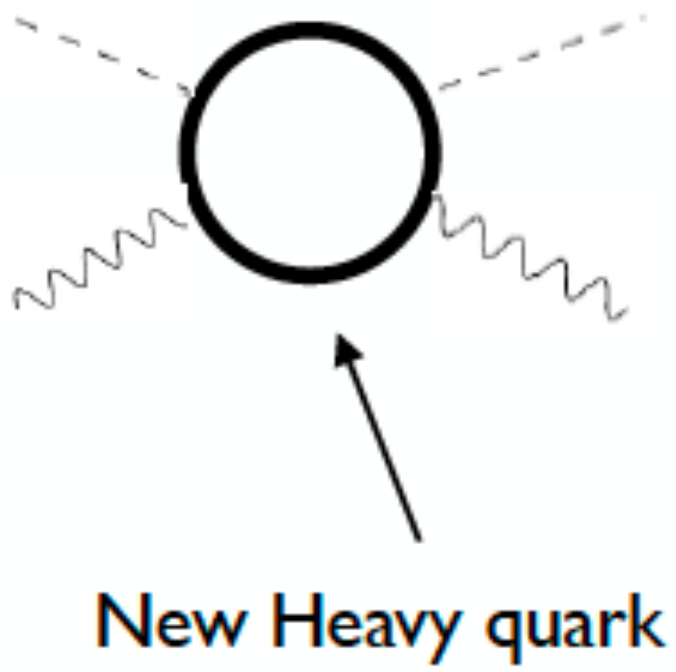
Universal/Oblique corrections

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462

- Universal new physics

$$\frac{\delta m_W^2}{m_W^2} = v^2 \frac{s_w c_w}{s_w^2 - c_w^2}\left[2\,C_{HWB} + \frac{c_w}{2 s_w} C_{HD} + \right.$$

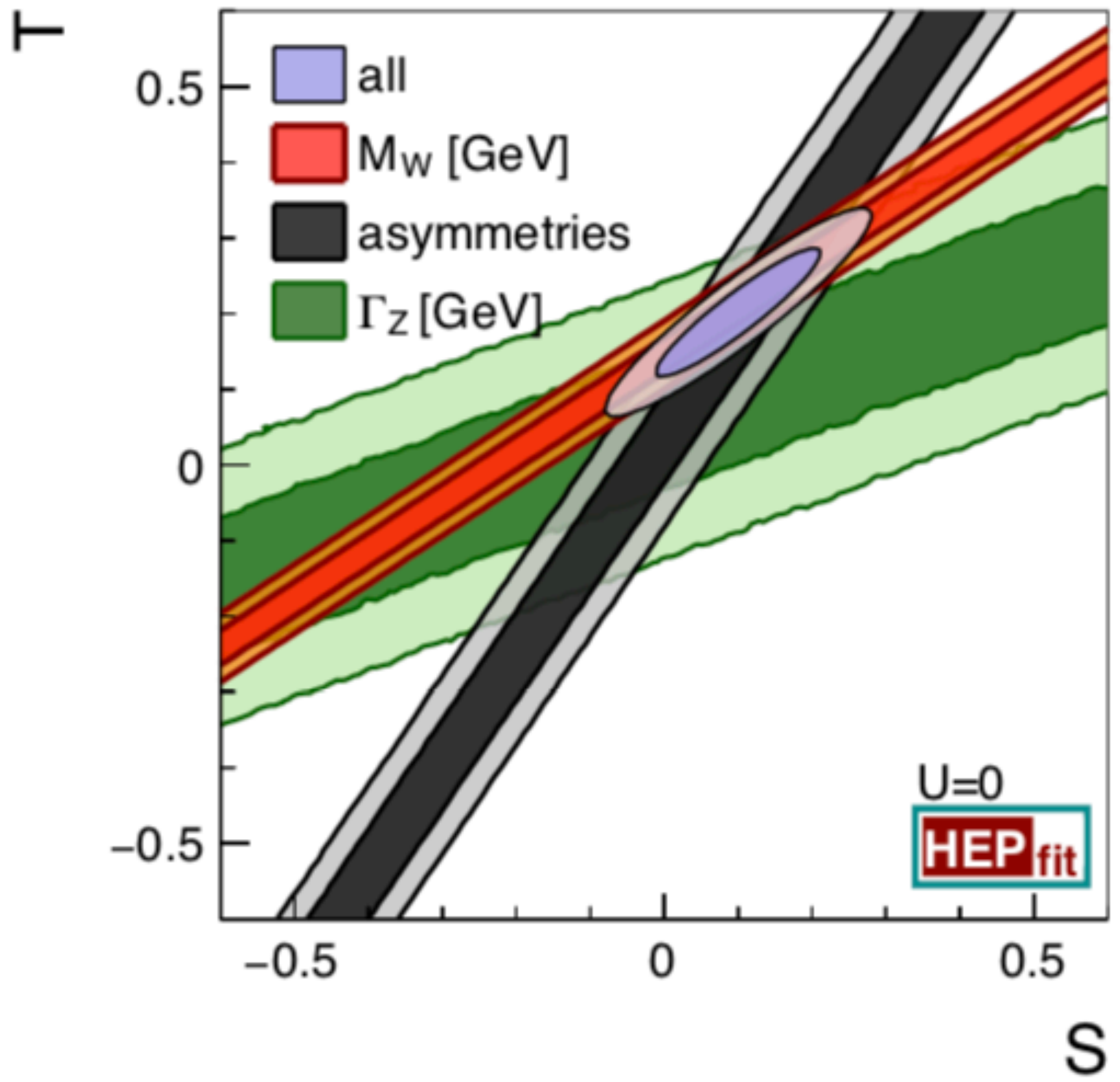
$C_{HWB} \downarrow S$ $C_{HD} \downarrow T$

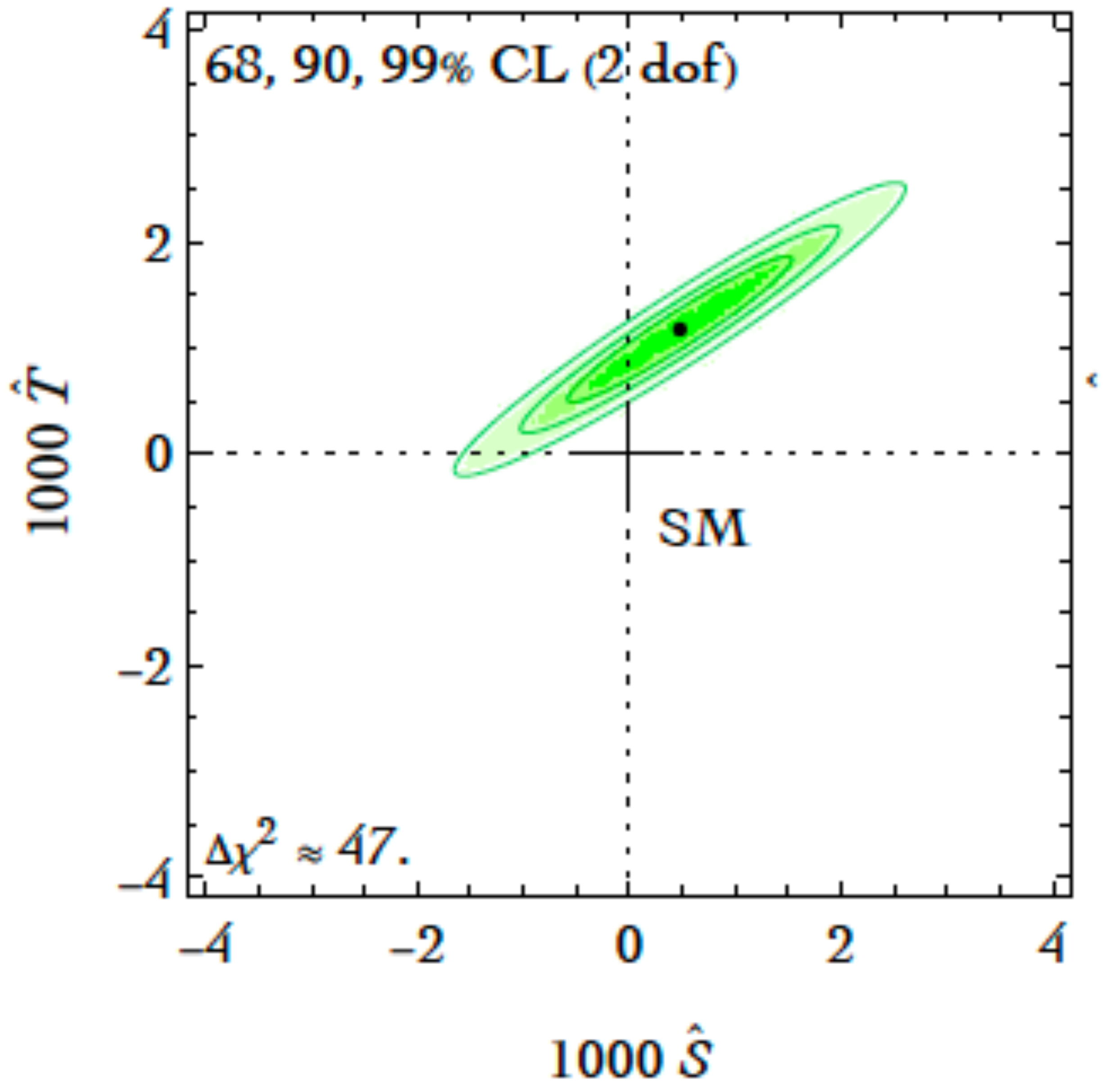


"Universal theories"

- New physics couples to SM bosons, and / or to SM fermions through SM currents
- Consistent framework to analyze EW precision tests (oblique corrections, etc)
- Evade flavor constraints (Minimal Flavor Violation is automatic), scale can be low

Model	Pred. M_W [GeV] *standard average*	Pull
SM	80.3499 ± 0.0056	$6.5\,\sigma$
ST	80.366 ± 0.029	$1.6\,\sigma$



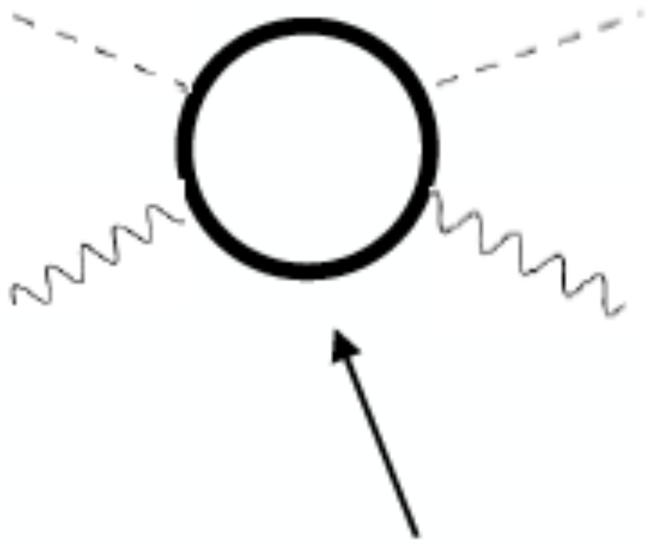


- Quite a few papers do this (results from de Blas et al, etc.)

Universal/Oblique corrections

Peskin-Takeuchi, PRL 65, 964 (1990)
Barbieri-Pomarol-Rattazzi-Strumia hep-ph/0405040
Wells-Zhang, 1510.08462

- Universal new physics



"Universal theories"

- New physics couples to SM bosons, and / or to SM fermions through SM currents
- Consistent framework to analyze EW precision tests (oblique corrections, etc)
- Evade flavor constraints (Minimal Flavor Violation is automatic), scale can be low

- Does not fully explain the discrepancy (still ~2 sigma left)

- The scale of new physics is at the level of a 5-7 TeV
- It is most likely to be **tree-level new physics** (many models on arxiv e.g. Z', little Higgs, etc.) $$C_i \sim \frac{1}{\Lambda^2}$$
- Otherwise the new physics would be O(300 GeV) and thus should have been seen at the LHC (your mileage may vary in 'tuned' models) $$C_i' \sim \frac{1}{\Lambda^2}\frac{\alpha_w}{4\pi}$$

Beyond Oblique: 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]

- There are 10 SMEFT operators relevant to the EWPO
- Only 8 linear combinations can be constrained
- 2 flat directions remain

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

$$\hat{C}^{(1)}_{\varphi f} = C^{(1)}_{\varphi f} - \frac{Y_f}{2} C_{\varphi D}, \quad f = l, q, e, u, d,$$

$$\hat{C}^{(3)}_{\varphi f} = C^{(3)}_{\varphi f} + \frac{c_w^2}{4 s_w^2} C_{\varphi D} + \frac{c_w}{s_w} C_{\varphi WB}, \quad f = l, q,$$

Beyond Oblique: SMEFT analysis of EWPO

	Result	Correlation Matrix							
	$(\mathrm{IC}_{\mathrm{SMEFT}}/\mathrm{IC}_{\mathrm{SM}} = 31.8/80.2)$								
$\hat{C}_{\varphi l}^{(1)}$	-0.007 ± 0.011	1.00							
$\hat{C}_{\varphi l}^{(3)}$	-0.042 ± 0.015	-0.68	1.00						
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	0.48	0.04	1.00					
$\hat{C}_{\varphi q}^{(1)}$	-0.018 ± 0.044	-0.02	-0.06	-0.13	1.00				
$\hat{C}_{\varphi q}^{(3)}$	-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

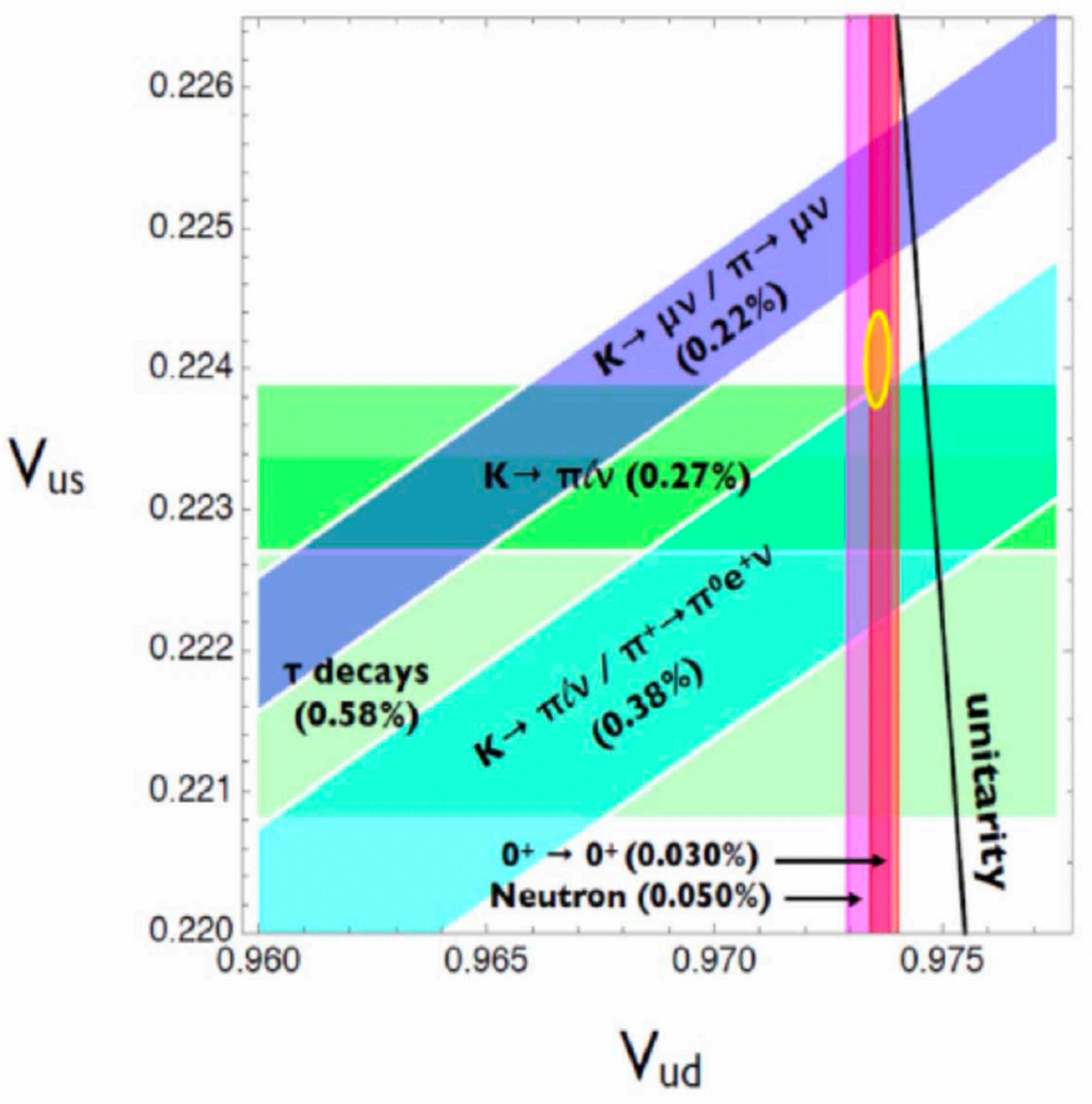
- The preferred ‘solution’ is rather different than just *S* and *T*
- This would be the ***guide for model building***: try to build models consistent with these values
- But can one treat the EWPO in isolation?

First-row CKM unitarity

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

- 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

Vincenzo Cirigliano,[a] Wouter Dekens,[a] Jordy de Vries,[b,c] Emanuele Mereghetti,[d] Tom Tong[e]

[a] Institute for Nuclear Theory, University of Washington, Seattle WA 91195-1550, USA
[b] Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands
[c] Nikhef, Theory Group, Science Park 105, 1098 XG, Amsterdam, The Netherlands
[d] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[e] Center for Particle Physics Siegen, University of Siegen, 57068 Siegen, Germany

2204.08440

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

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

C_Δ

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

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

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

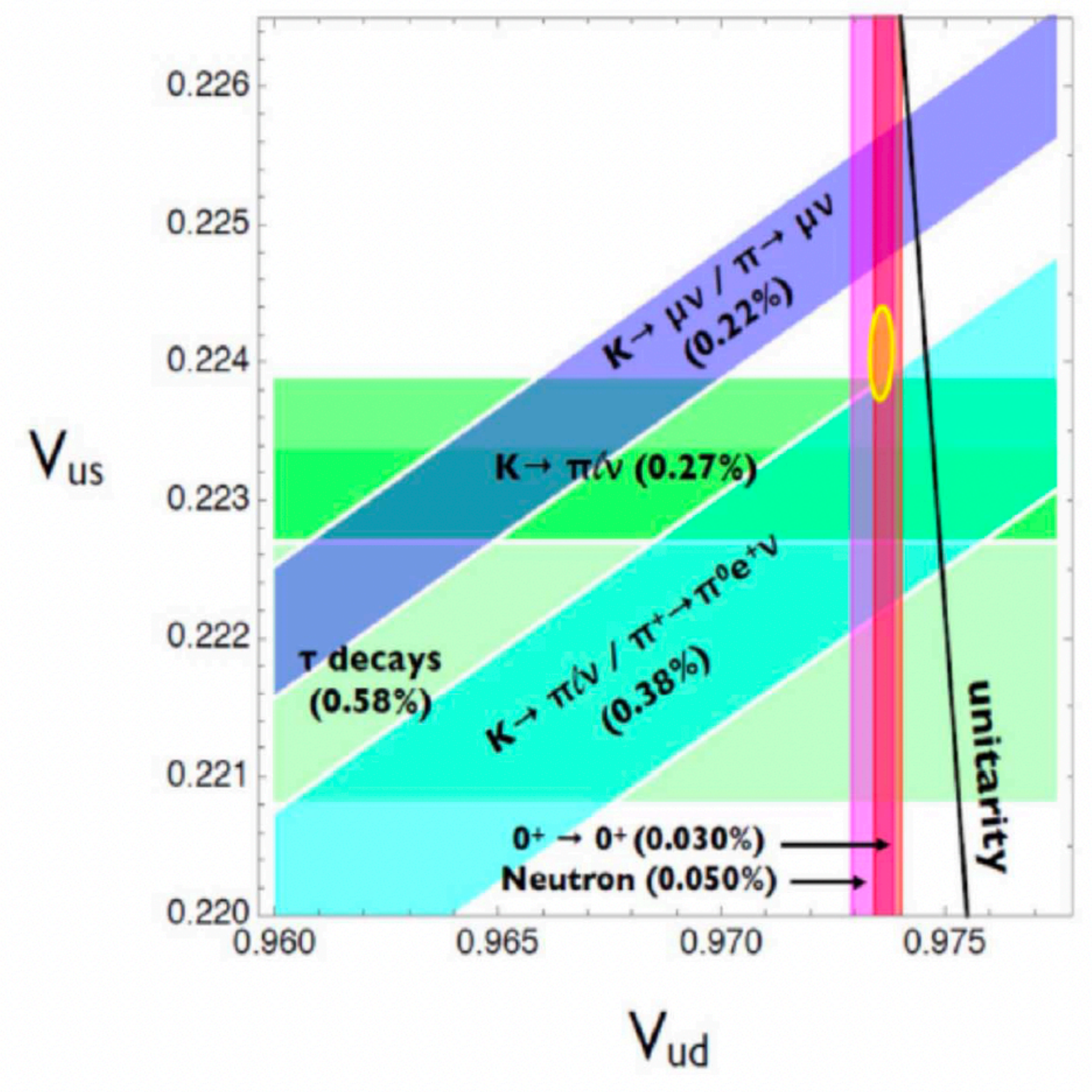
$$\Delta^{PDG}_{CKM} \approx -(0.15 \pm 0.07)\,\%$$

- A 2-sigma deviation per se, but much smaller than indicated by the fit!

- Refitting while including CKM shifts the values

- Would point to other models!

	Result	Result with CKM
$\hat{C}^{(1)}_{\varphi l}$	-0.007 ± 0.011	-0.013 ± 0.009
$\hat{C}^{(3)}_{\varphi l}$	-0.042 ± 0.015	-0.034 ± 0.014
$\hat{C}_{\varphi e}$	-0.017 ± 0.009	-0.021 ± 0.009
$\hat{C}^{(1)}_{\varphi q}$	-0.0181 ± 0.044	-0.048 ± 0.04
$\hat{C}^{(3)}_{\varphi q}$	-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

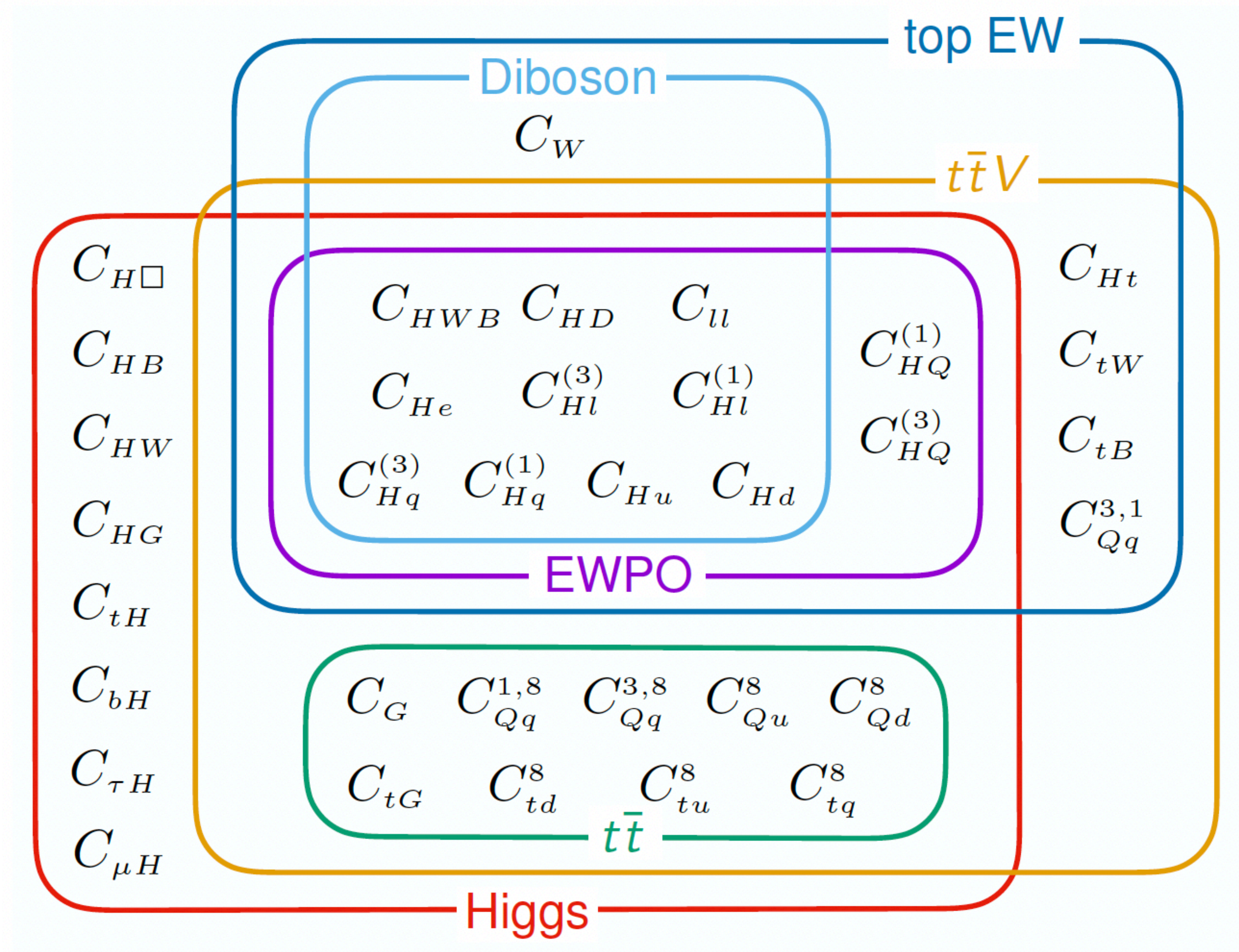


Let's include more high energy data

SMEFT Analysis of m_W

Emanuele Bagnaschi,[a] John Ellis,[b,a,c] Maeve Madigan,[d] Ken Mimasu,[b]
Veronica Sanz[e,f] and Tevong You[b,d,g]

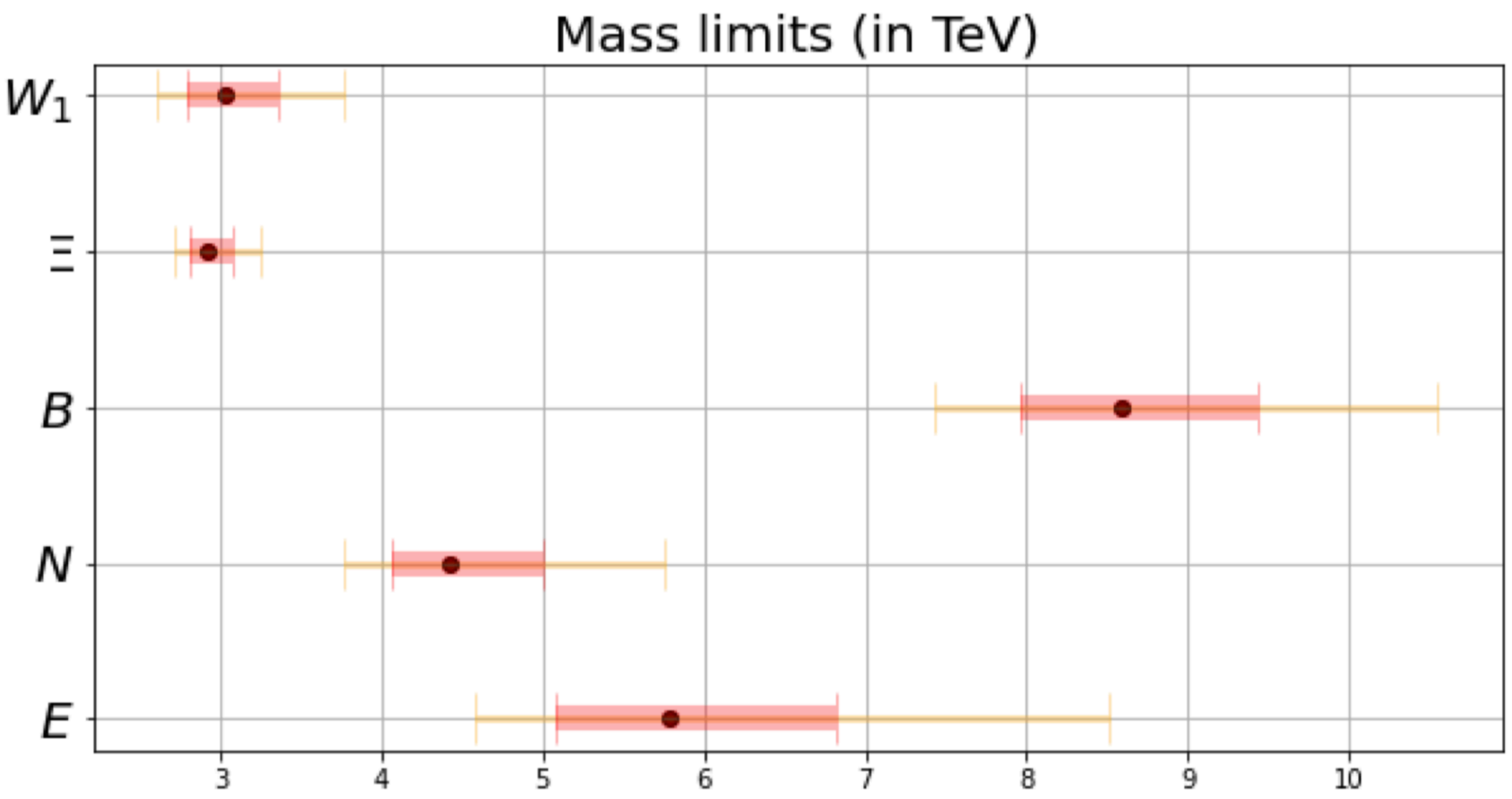
[a] *Theoretical Physics Department, CERN, CH-1211 Geneva 23, Switzerland*
[b] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK*
[c] *National Institute of Chemical Physics & Biophysics, Rävala 10, 10143 Tallinn, Estonia*
[d] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*
[e] *Instituto de Física Corpuscular (IFIC), Universidad de Valencia-CSIC, E-46980 Valencia, Spain*
[f] *Department of Physics and Astronomy, University of Sussex, Brighton BN1 9QH, UK*
[g] *Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, Cambridge CB3 0HE, UK*



- 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!*
- Also if one uses more general flavor assumptions (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

Conclusion (not really...)

- A SMEFT global-fit including only the high energy data will cause %-level damage to the first-row CKM unitarity. Low energy data such as the beta-decay is very important to the global analyses.

Unitarity Damaged!

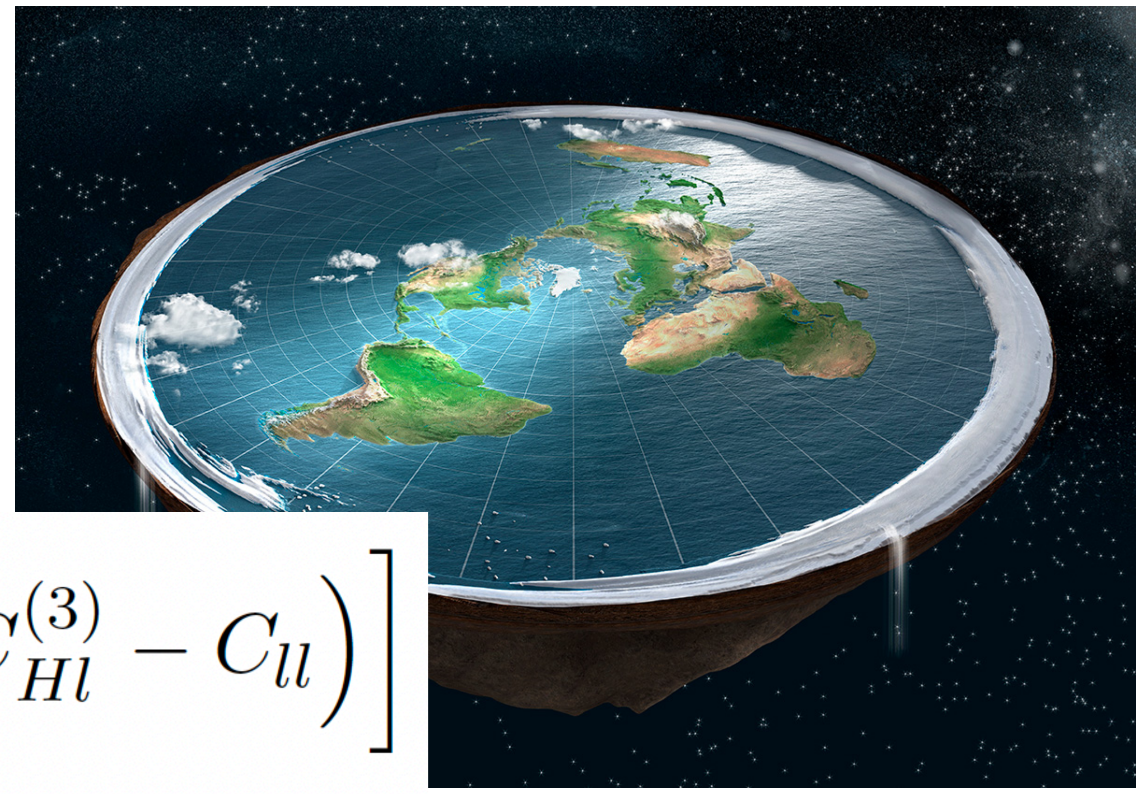
Is it really W mass the perpetrator?

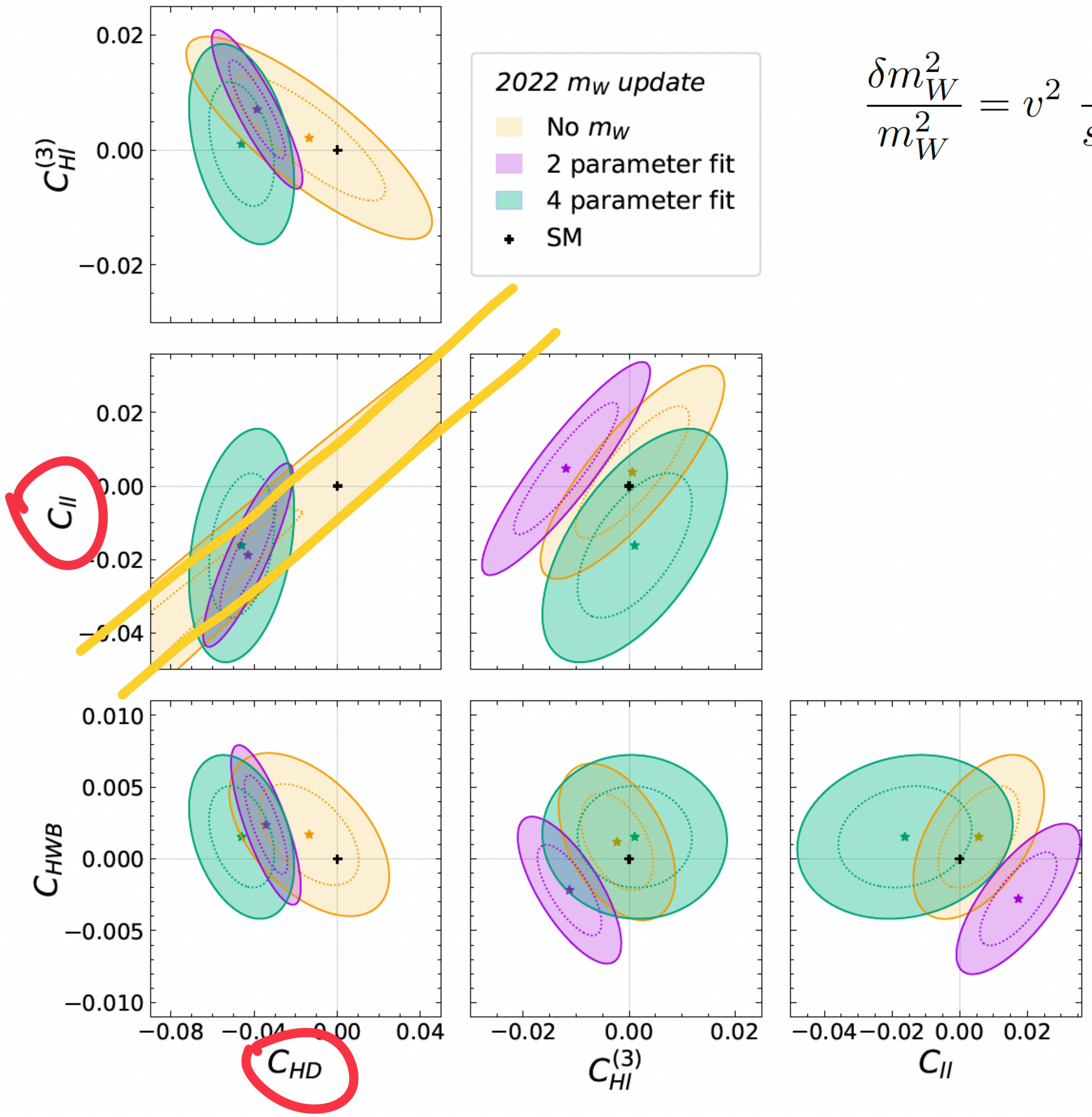
- If not, then the global-fit should be in bad tension with CKM even before the new CDF results
- So, what was Δ_{CKM} before 2022?
- We re-did the old EWPO fits
- It was only $-(0.4 \pm 0.4)\,\%$ in 0908.1754
- And a similar value indicated by 2012.02779,

  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

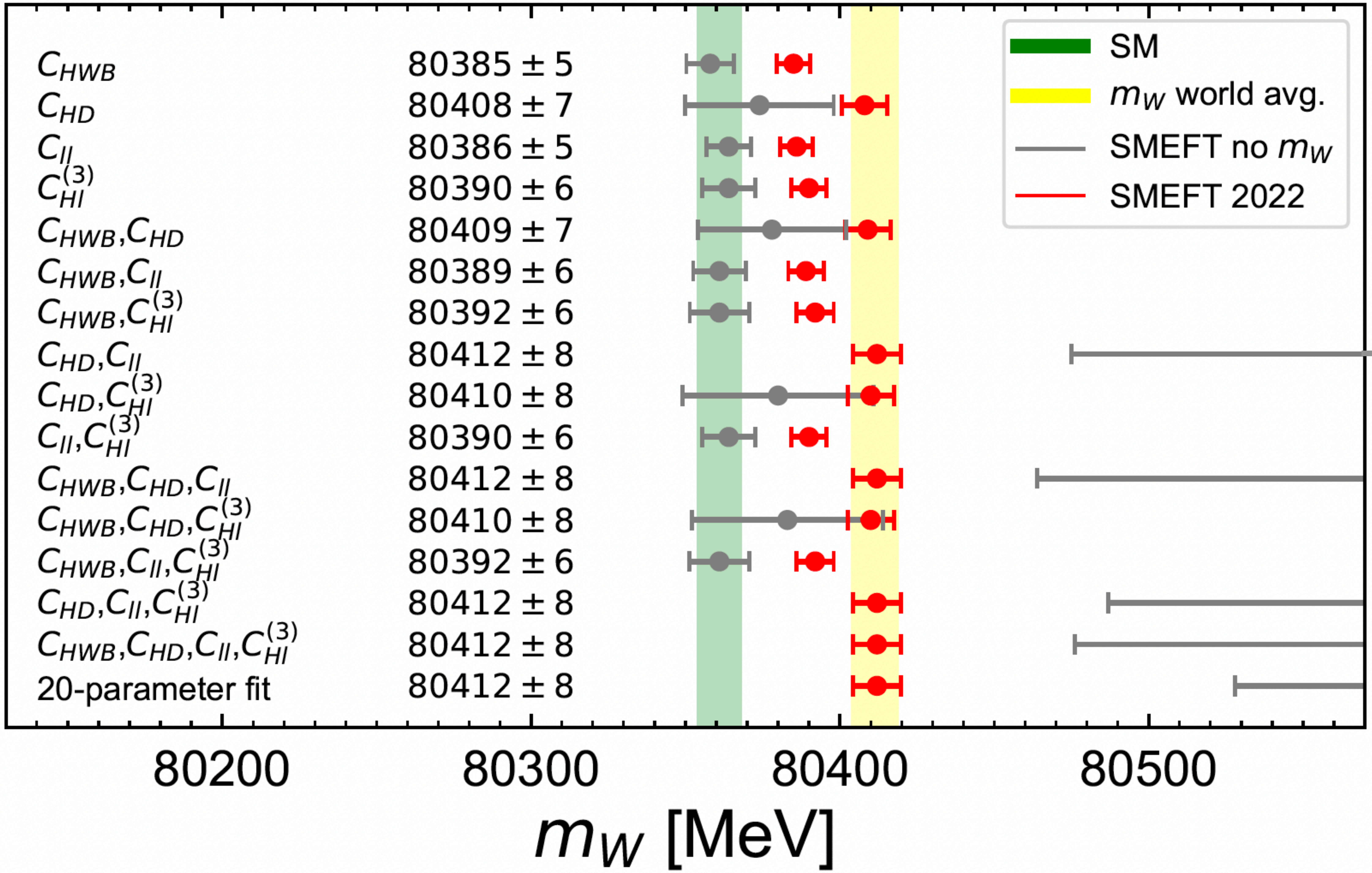




$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[2\, C_{HWB} + \frac{c_w}{2 s_w} \, C_{HD} + \frac{s_w}{c_w} \left(2\, C_{Hl}^{(3)} - C_{ll} \right) \right]$$

- 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***

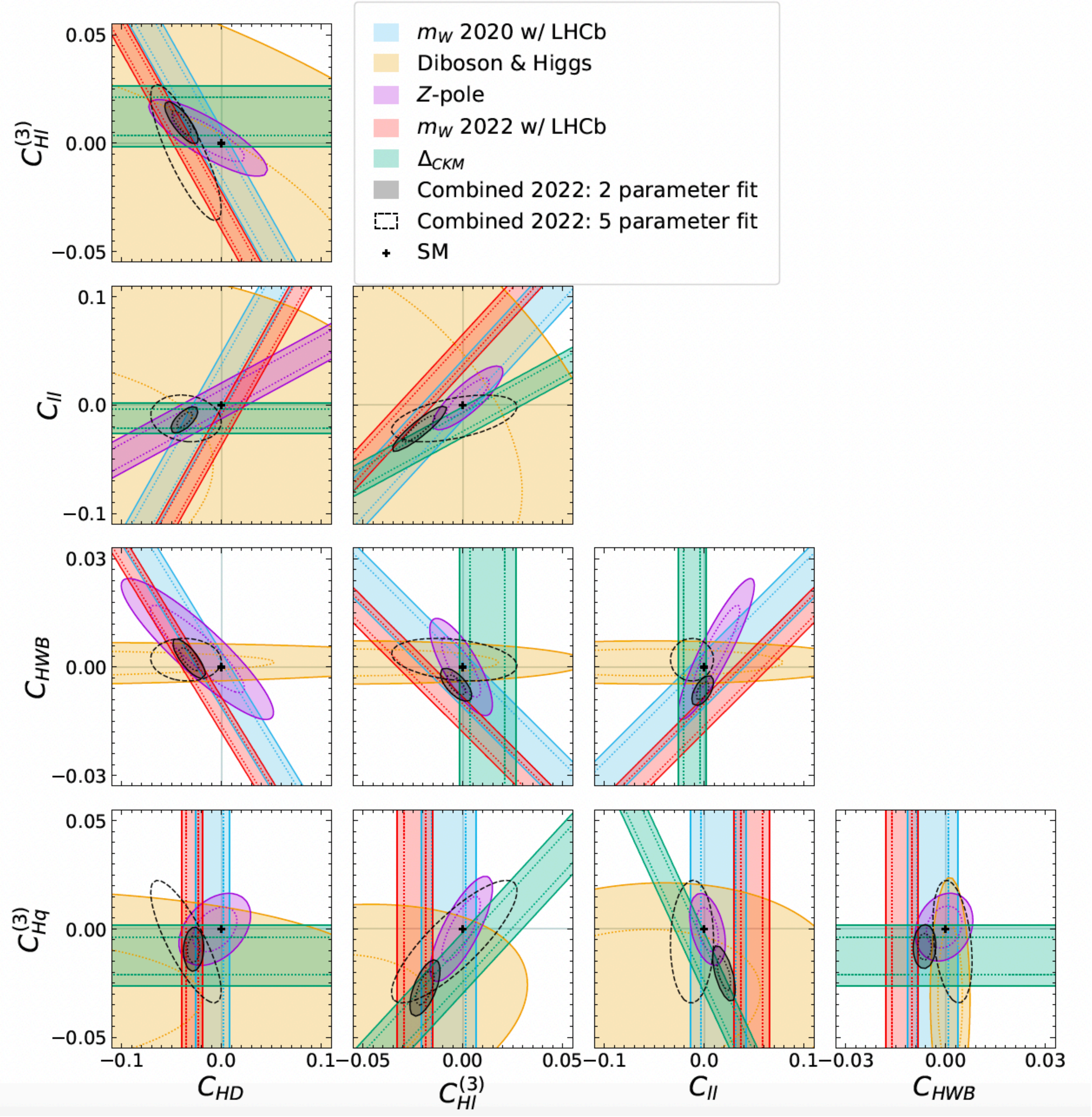
$$\Delta_{\mathrm{CKM}} \equiv |V_{ud}|^2 + |V_{us}|^2 - 1$$
$$= 2\frac{v^2}{\Lambda^2}\left[C_{Hq}^{(3)} - C_{H\ell}^{(3)} + C_{\ell\ell} - C_{\ell q}^{(3)}\right]$$

C_Δ

Finally, CKM comes to the rescue

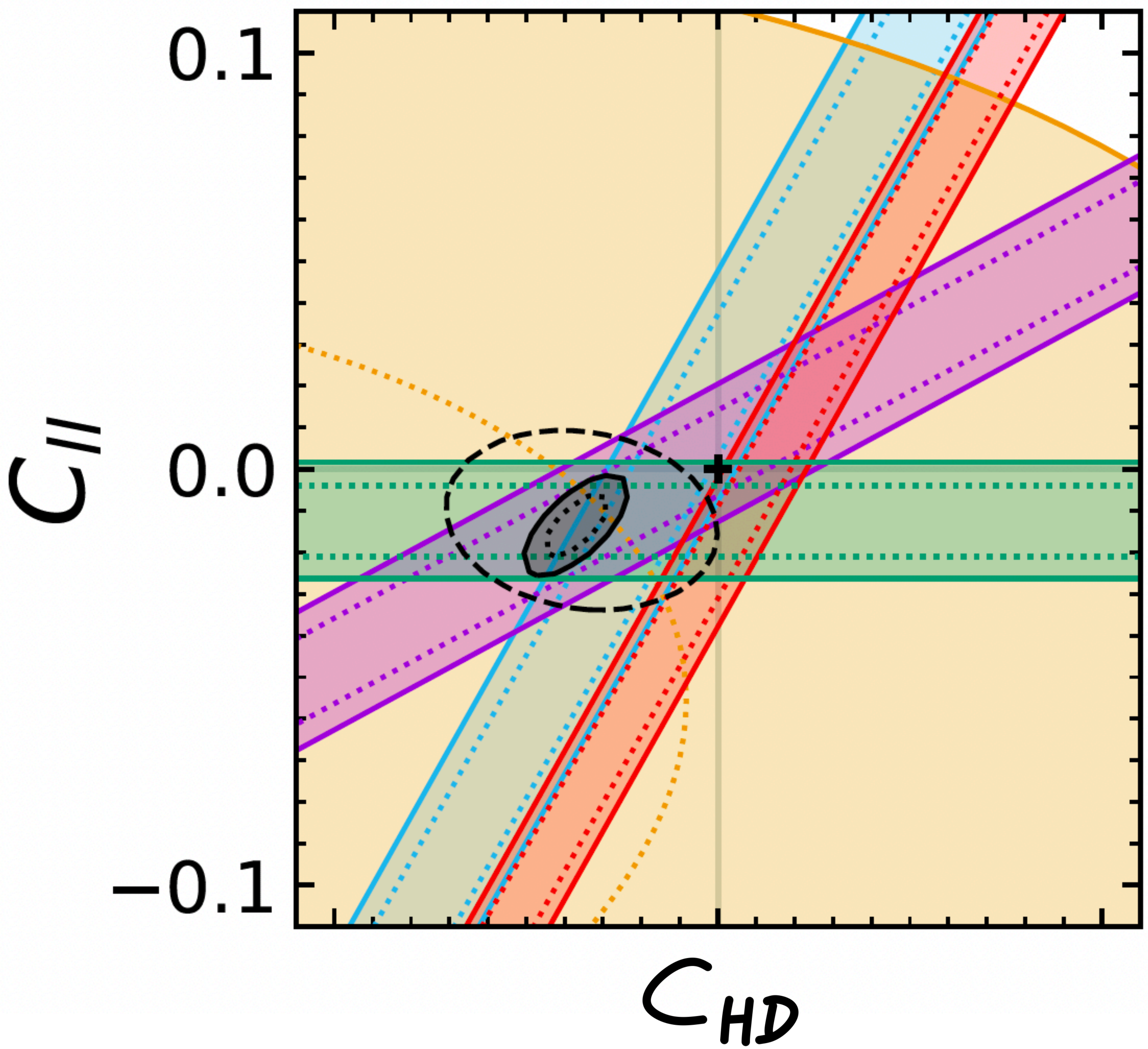
- Δ_{CKM} is sensitive to C_{ll}
- It can help lift the flat direction
- **They've heard us!**
- And 2204.05260 is now ***v2***

Hooray!

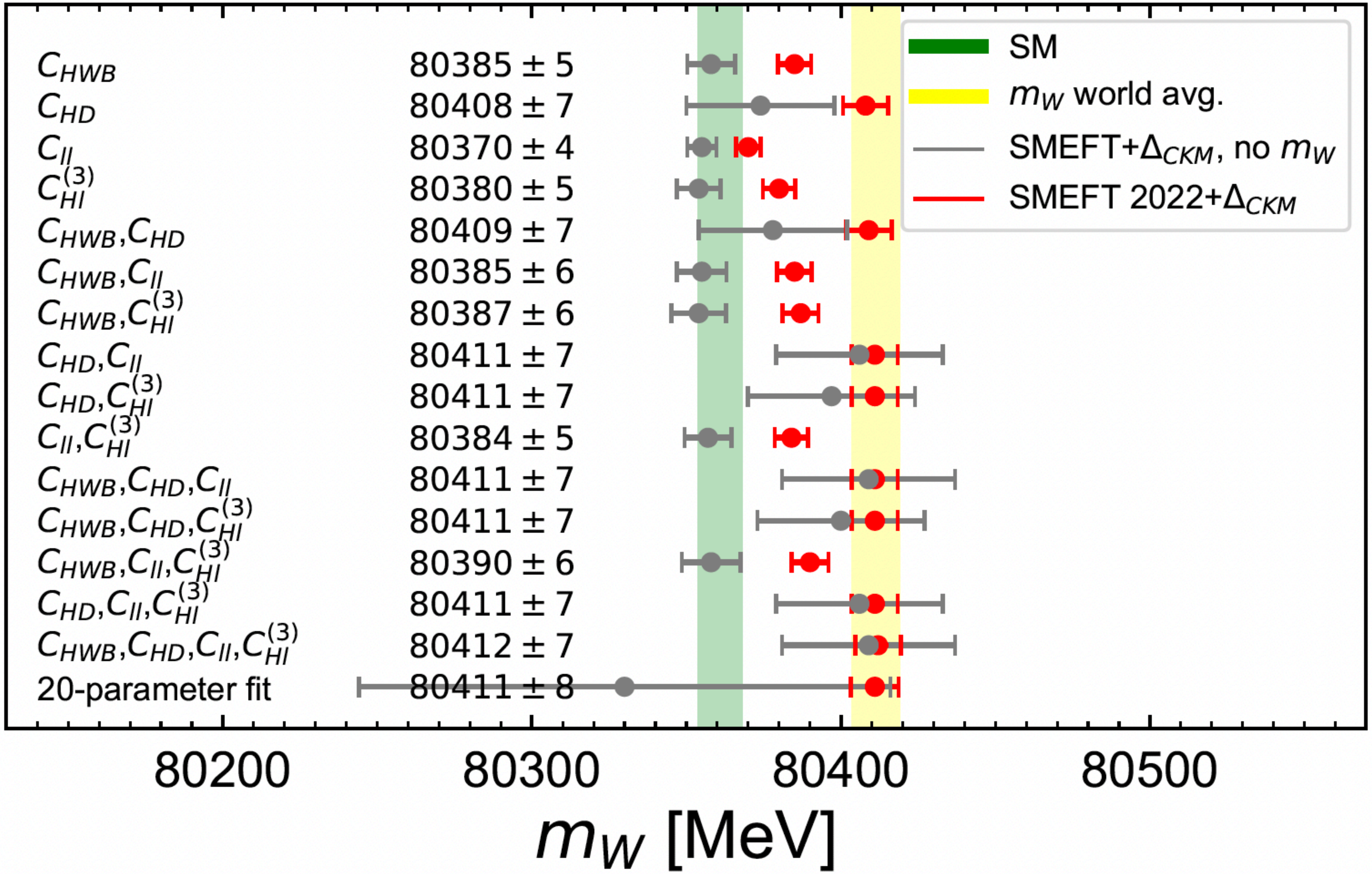


Take a closer look

- 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%



Alles gut?



- So it seems. The Flat has been resolved

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

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

“ 

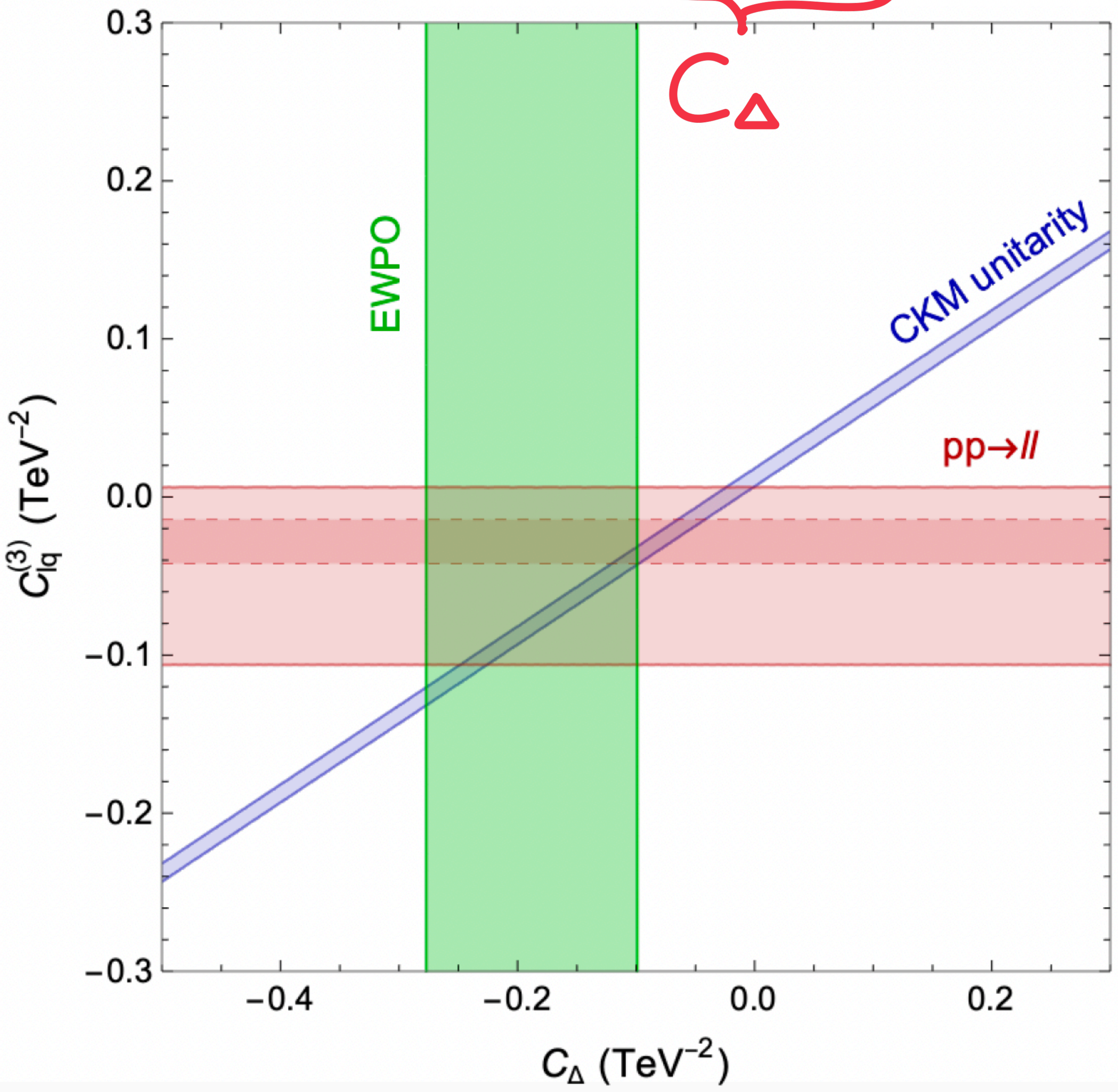
”

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

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

C_Δ

- 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



Conclusion (for real)

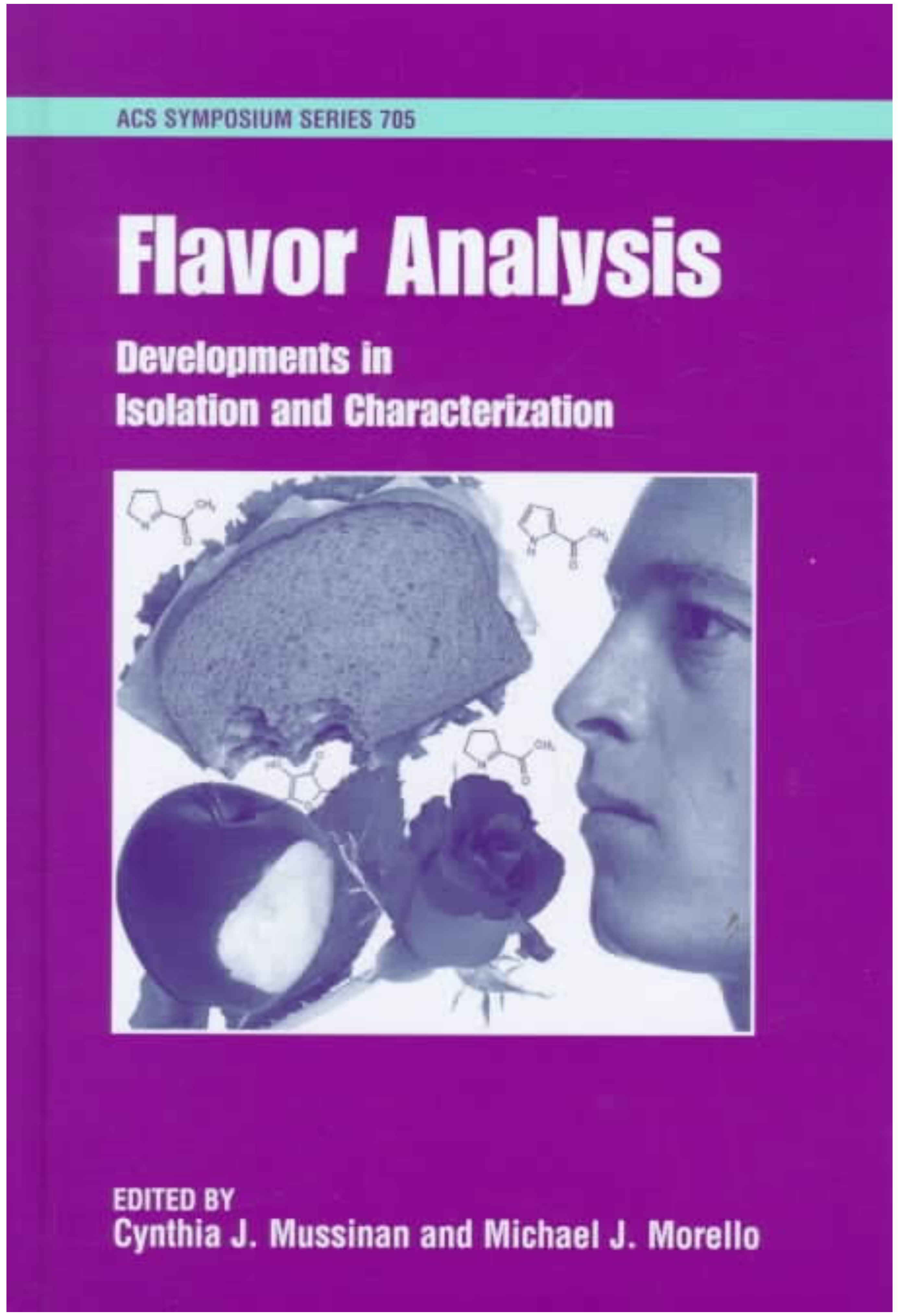
- SMEFT global-fits including only high energy data will damage the CKM unitarity

- 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

Outlook



- 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 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?

- Would like to make a flavorful global analysis (working in progress...)

Thanks for watching!