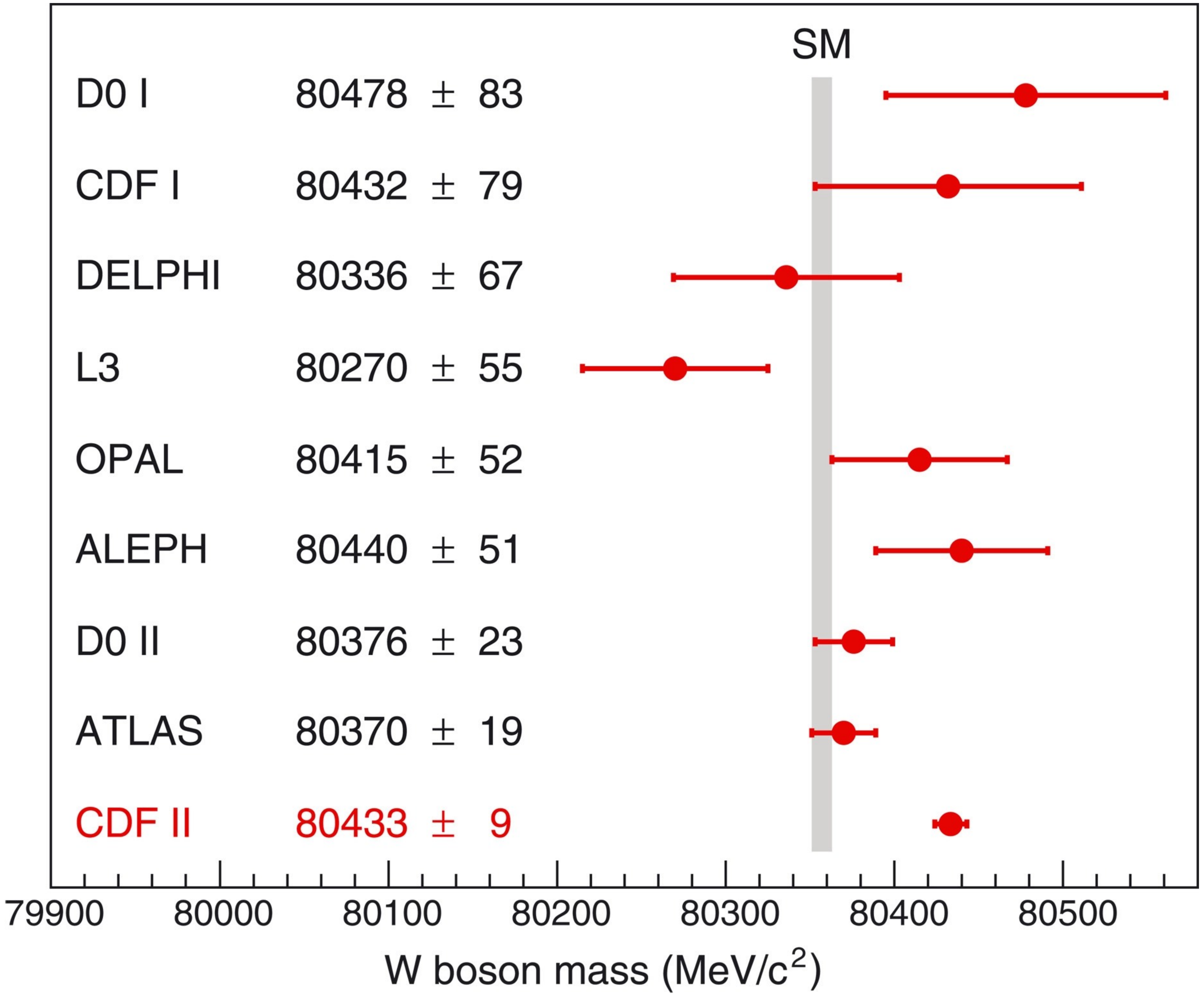
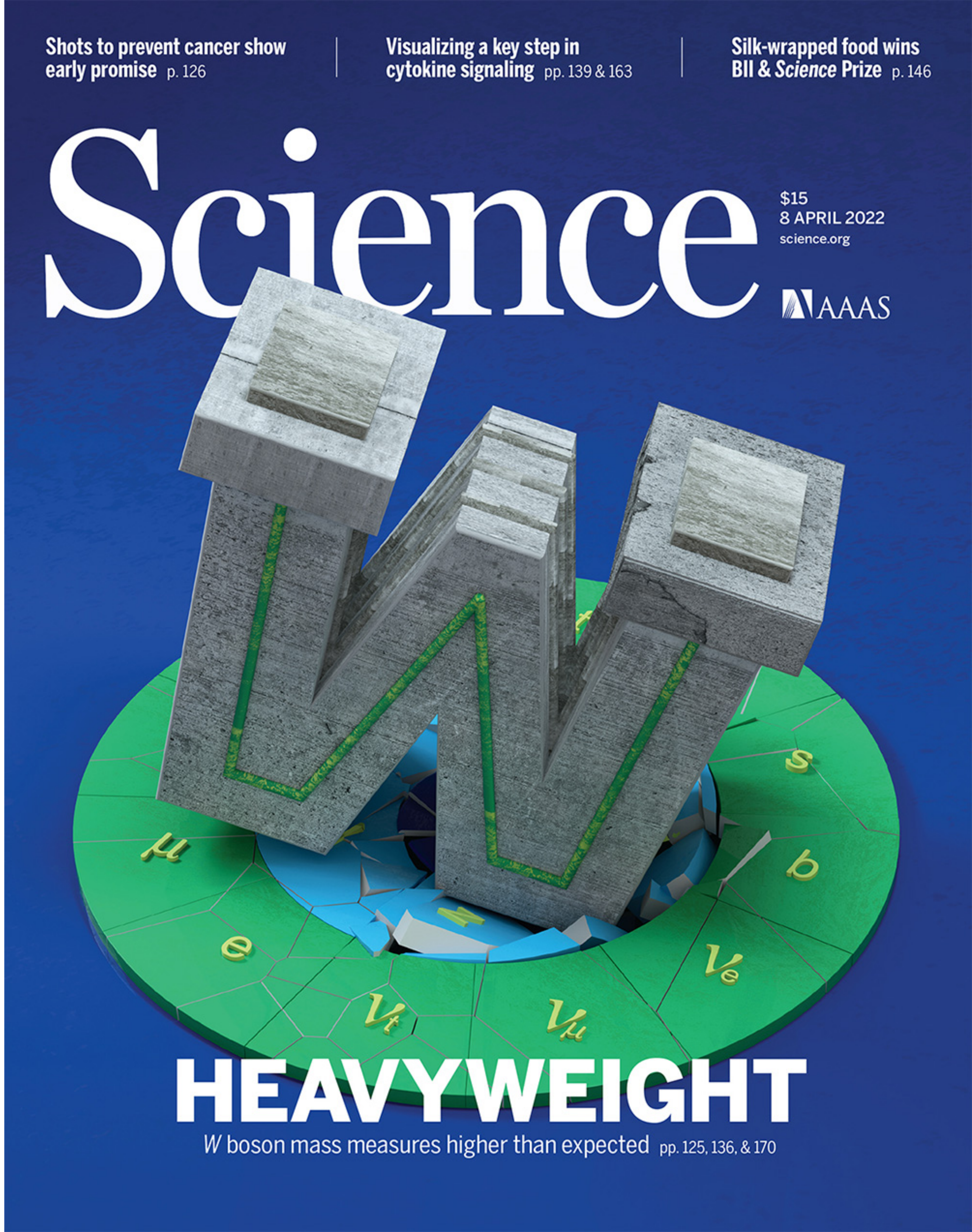
# W-mass and the Standard Model EFT

I adapted (**read: stole**) most of these slides from **Tom Tong**
(postdoc in my group in U-Mass, now in Siegen)

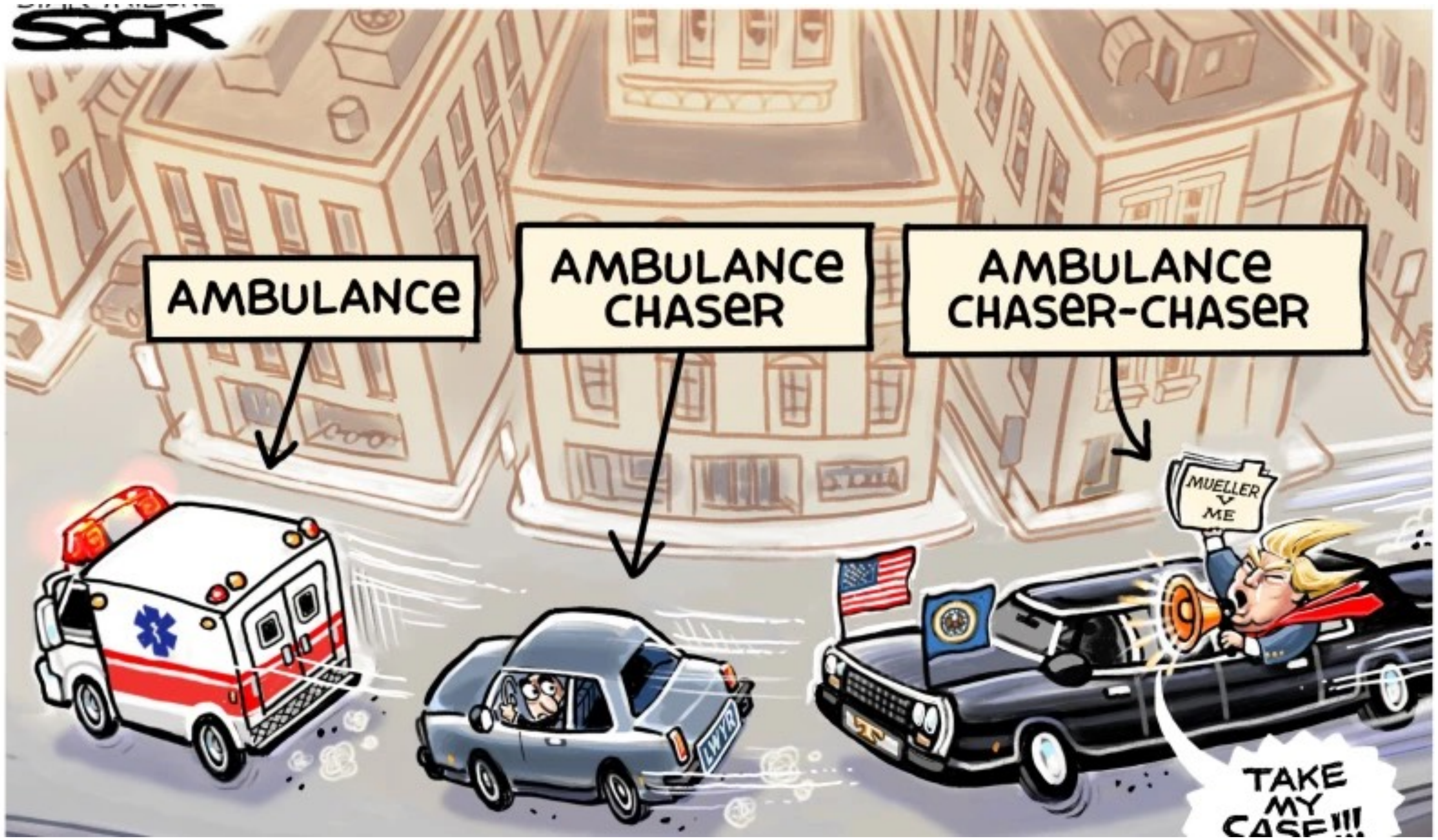
*Jordy de Vries*
*Theory Meets Experiment, June 3*

# The CDF W mass measurement



# Wow! A new ambulance in town




[A story of chasing the ambulance-chasers]

- 131 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

# Explaining an anomaly

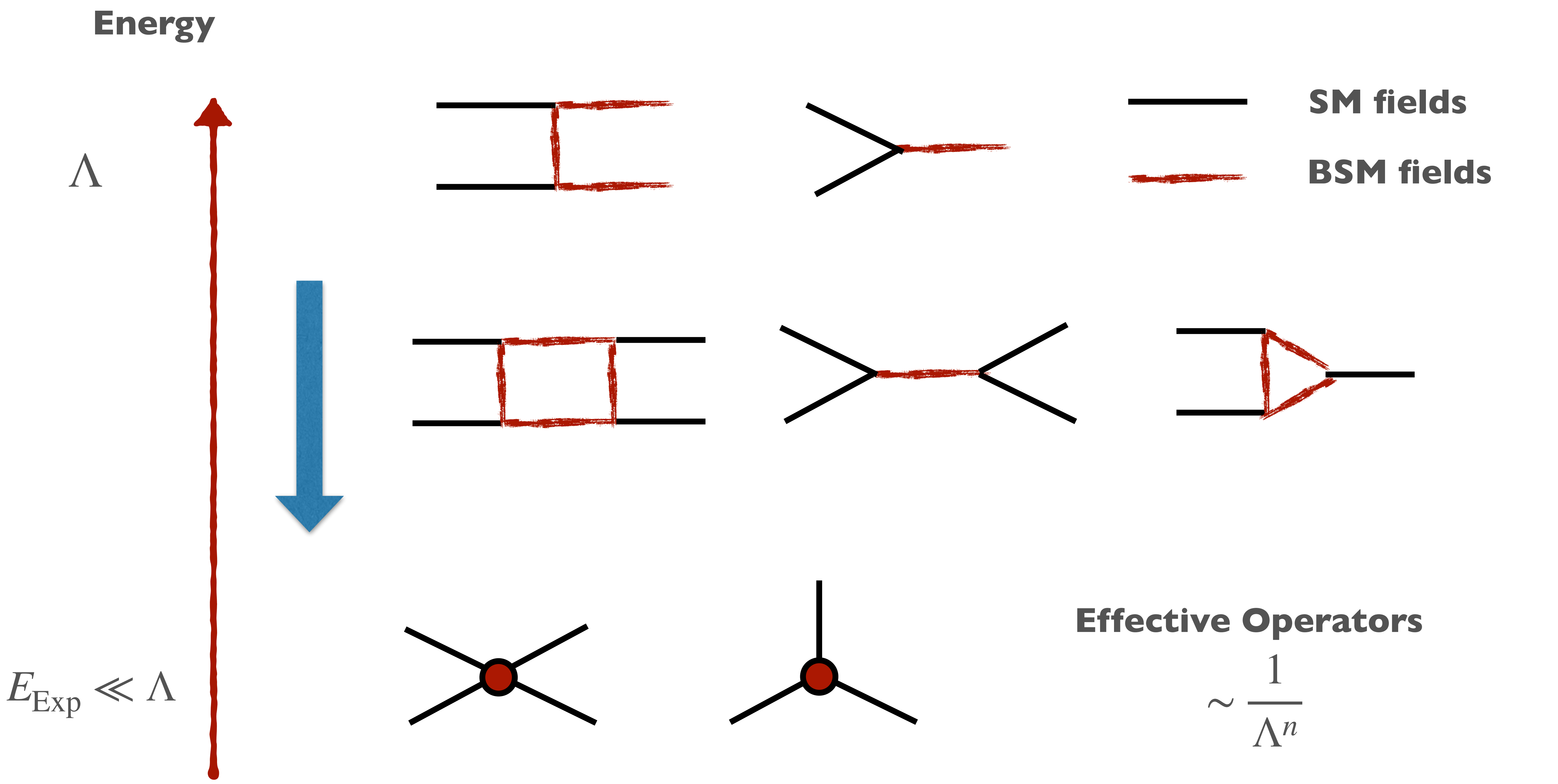
- Step 1: Pick up a model you like, e.g. scalar triplet, 2HDM, yada yada
- Step 2: Calculate relevant observables (the tedious part although a lot is automized nowadays)
- Step 3: Compare them with the experiments including the new W mass
- Step 4: Fit parameters and write paper
- Step 5: Collect citations and go to step 1

**LEGO Master Model Builder**

# The ‘model-independent’ way

- Step 1: Use the Standard Model EFT

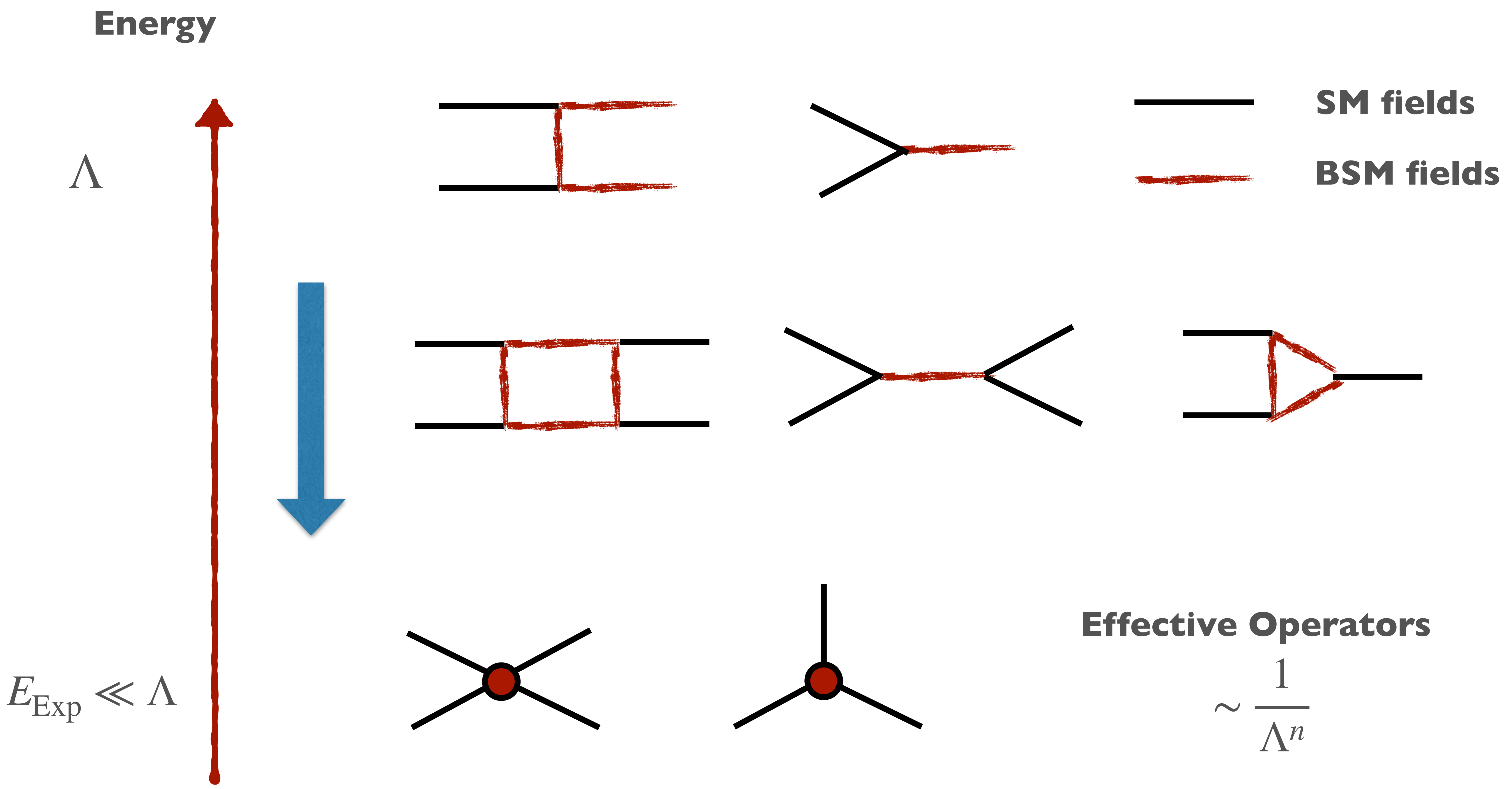
$$\mathcal{L}_{\text{SMEFT}}^{\text{dim-6}} = \mathcal{L}_{\text{SM}} + \sum_i C_i \mathcal{O}_i^{\text{dim-6}}$$



# The ‘model-independent’ way

- Step 1: Use the Standard Model EFT

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



# The ‘model-independent’ way

- Step 1: use the Standard Model Effective Field Theory

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

- ~~*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*** operators and relevant observables

- Step 4: Global fit (well global within assumptions)!

- But what are ***relevant*** operators and observables?

# 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] | |

$$C_i \sim \frac{1}{\Lambda^2}$$

- W mass is one of the EWPO

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

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

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

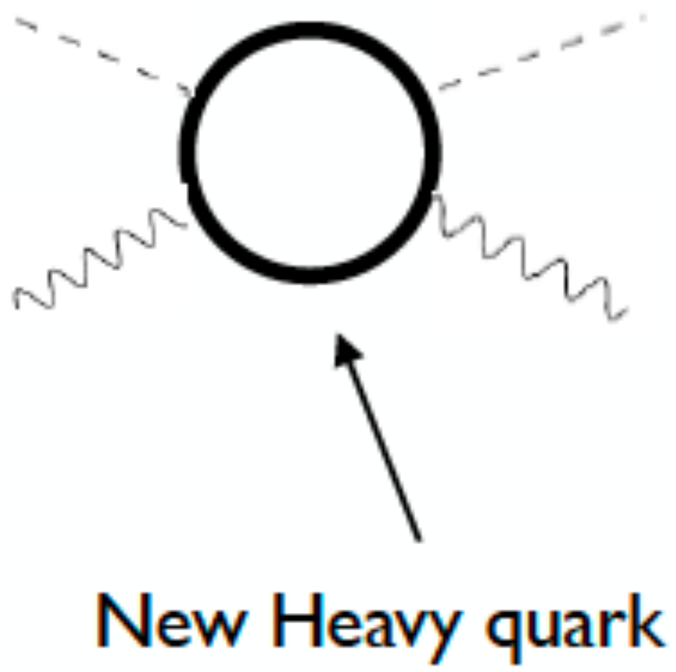
*Trott et al '15 '16*

# Universal/Oblique corrections

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

- Universal new physics

$$\frac{\delta m_W^2}{m_W^2} = v^2 \frac{s_w c_w}{s_w^2 - c_w^2}\Big[\underbrace{2\,C_{HWB}}_{S} + \frac{c_w}{2 s_w}\underbrace{C_{HD}}_{T} + $$




"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

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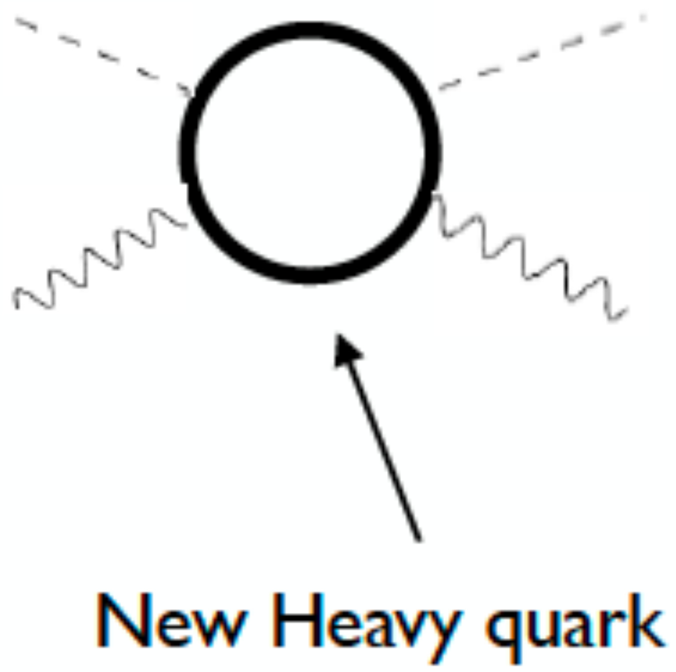


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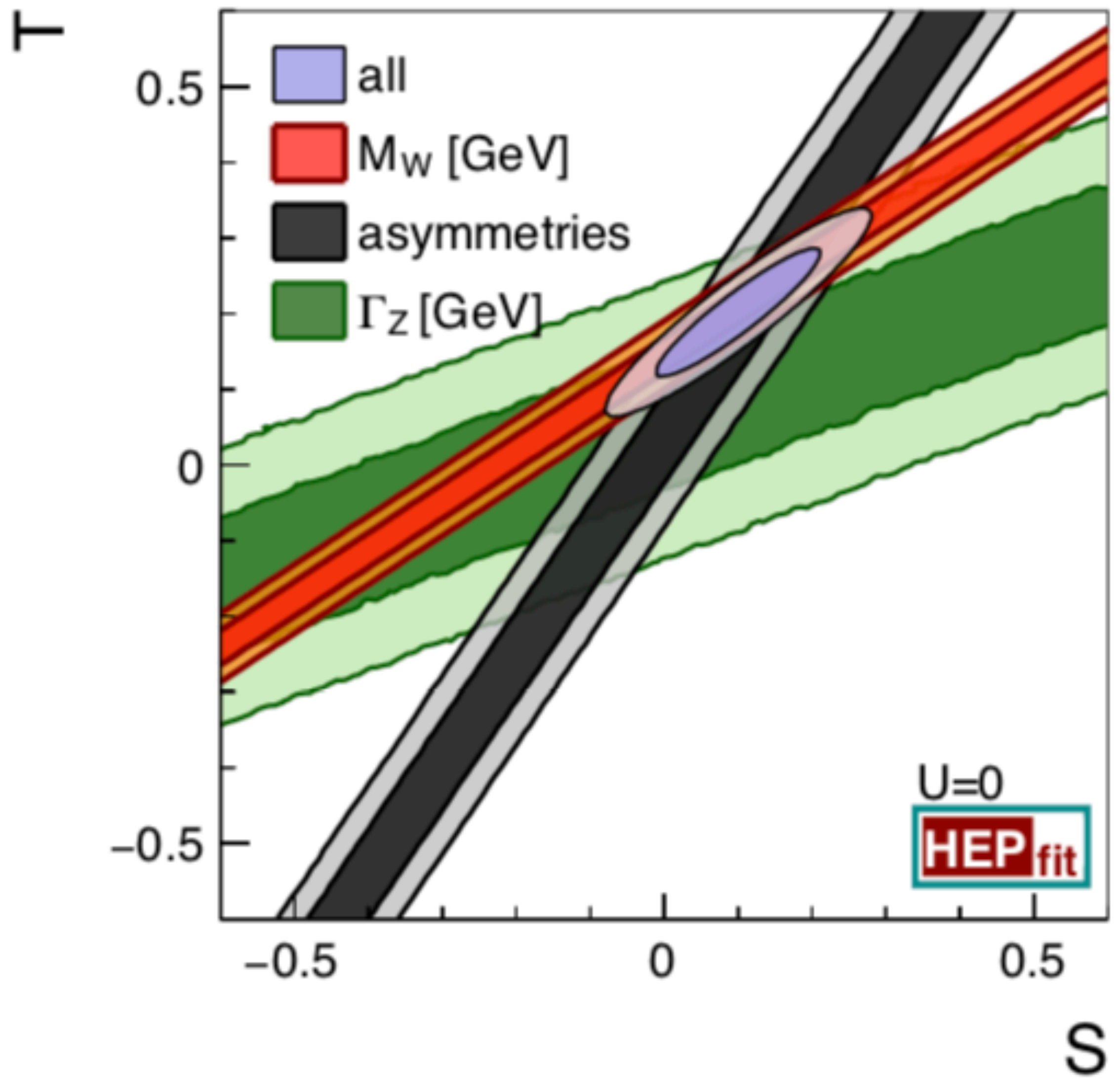
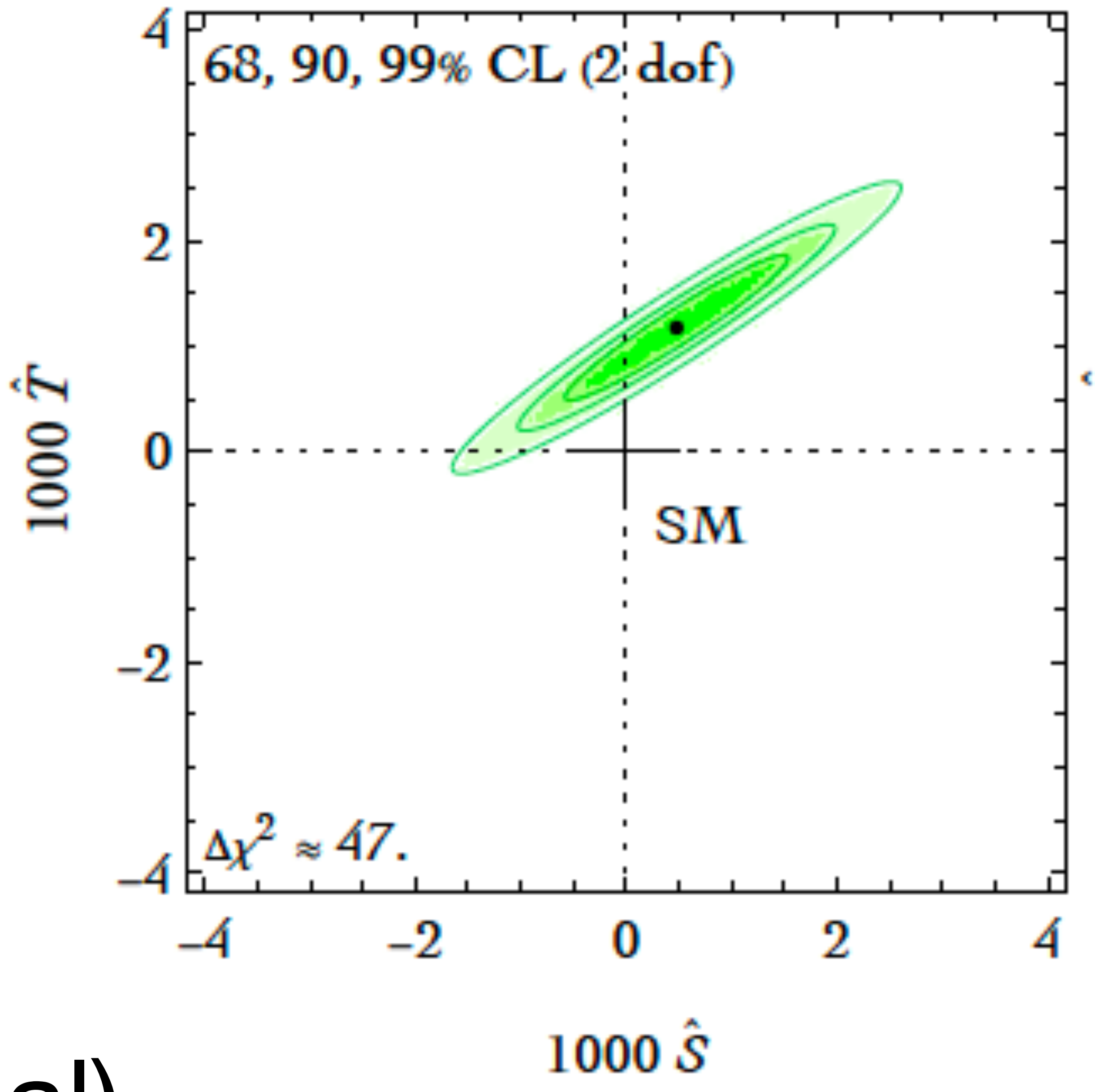
| Model | Pred. $M_W$ [GeV] *standard average* | Pull |
|---|---|---|
| SM | $80.3499 \pm 0.0056$ | $6.5\,\sigma$ |
| ST | $80.366 \pm 0.029$ | $1.6\,\sigma$ |




- Quite a few papers do this (results from Strumia and de Blas et al)

# Universal/Oblique corrections

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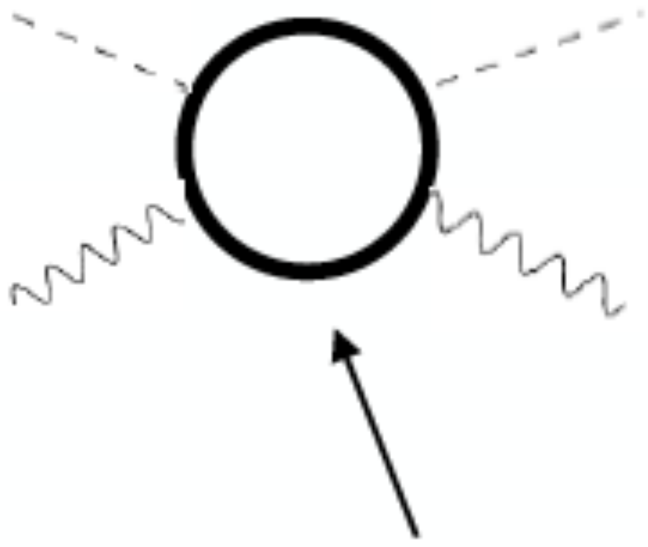
- Universal new physics




"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 $$C_i \sim \frac{1}{\Lambda^2}$$

  - Strumia: this means it must be **tree-level new physics (many models on arxiv e.g. Z', little Higgs, etc)**

  - Otherwise the new particles would be O(300 GeV) and thus should have been seen at the LHC (your mileage may vary in 'tuned' models) $$C_i' \sim \frac{1}{\Lambda^2}\frac{\alpha_w}{4\pi}$$

# Flavor universal assumption

- Under Flavor ‘universality’ or MFV

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

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 8 combinations of SMEFT operators relevant to the EWPO

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

- This includes the ’S’ and ’T’ operators and operators that couple to fermions

# Flavor universal assumption

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

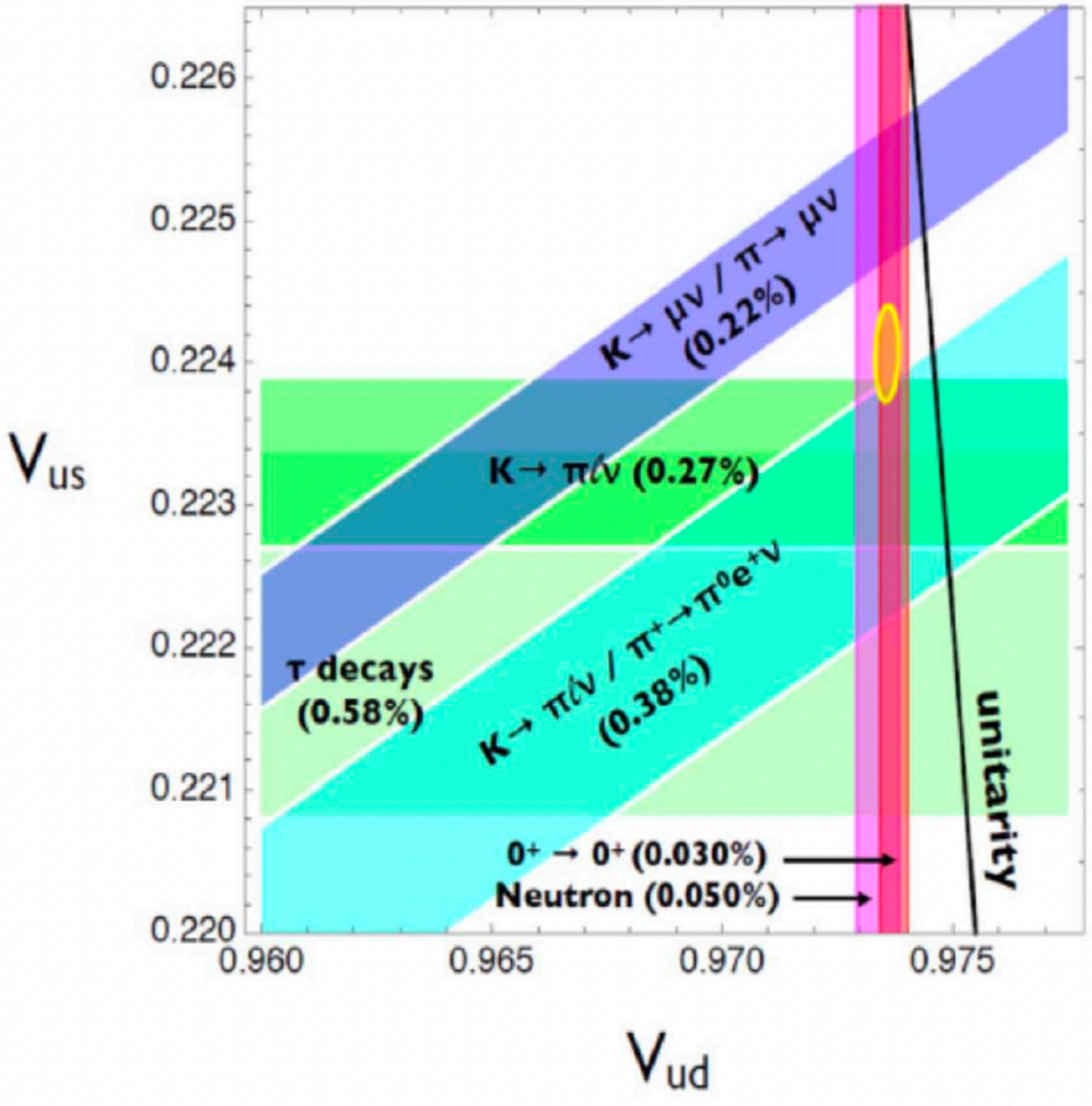
- The preferred ‘solution’ is rather different than just S and T
- This would be the guide for model building: try to build models consistent with these values (beyond `universal models’ link to other anomalies?)
- **But can one treat the EWPO in isolation ?**

# 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 interesting, you should really read my papers, but not for today)
- 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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[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

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

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

- We combine the relevant Wilson coefficients into $C_\Delta$
- Same couplings enter CKM and W-mass !

# Oops!

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

$$\Delta_{CKM}^{fit} \approx -(1 \pm 0.4)\,\%$$

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

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

- Refitting while including CKM shifts the values of the LECs —> Would point to other models !

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

# Let's include more high energy data: 2204.05260

SMEFT Analysis of $m_W$

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Veronica Sanz[e,f] and Tevong You[b,d,g]

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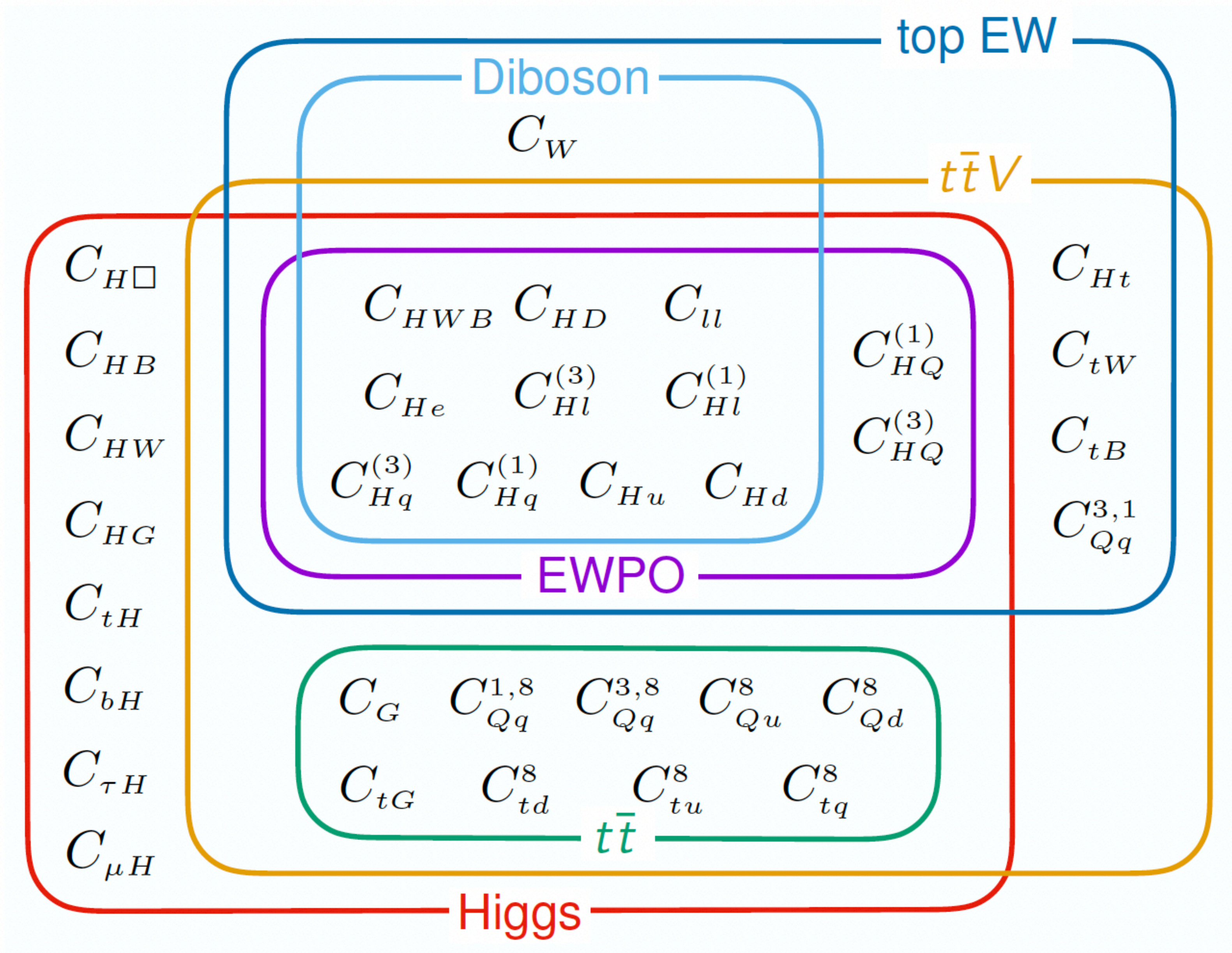
[b] *Theoretical Particle Physics and Cosmology Group, Department of Physics, King's College London, London WC2R 2LS, UK*
[c] *National Institute of Chemical Physics & Biophysics, Rävala 10, 10143 Tallinn, Estonia*
[d] *DAMTP, University of Cambridge, Wilberforce Road, Cambridge CB3 0WA, UK*
[e] *Instituto 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
- Also if one includes other flavor assumptions (Zupan et al)

# Conclusion (not really...)

- A SMEFT global-fit including only the high energy data will cause %-level damage to the first-row CKM unitarity.

- One has to include low-energy beta decay data into the fits .

Unitarity

Damaged !

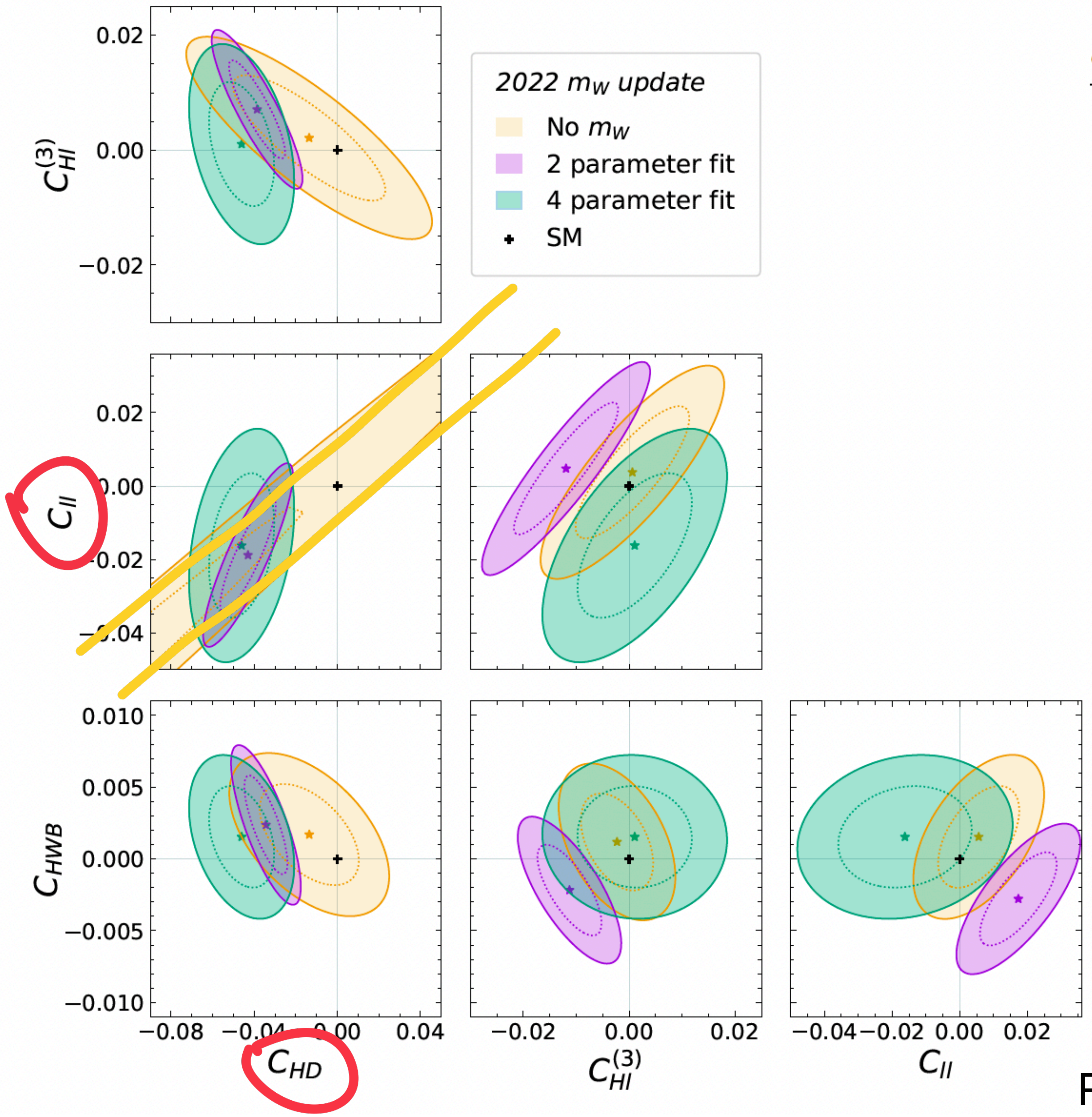
# Is it really W mass the perpetrator?

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


$$\Delta^{fit}_{CKM} \approx -(1 \pm 0.4)\,\%$$

# Flat directions

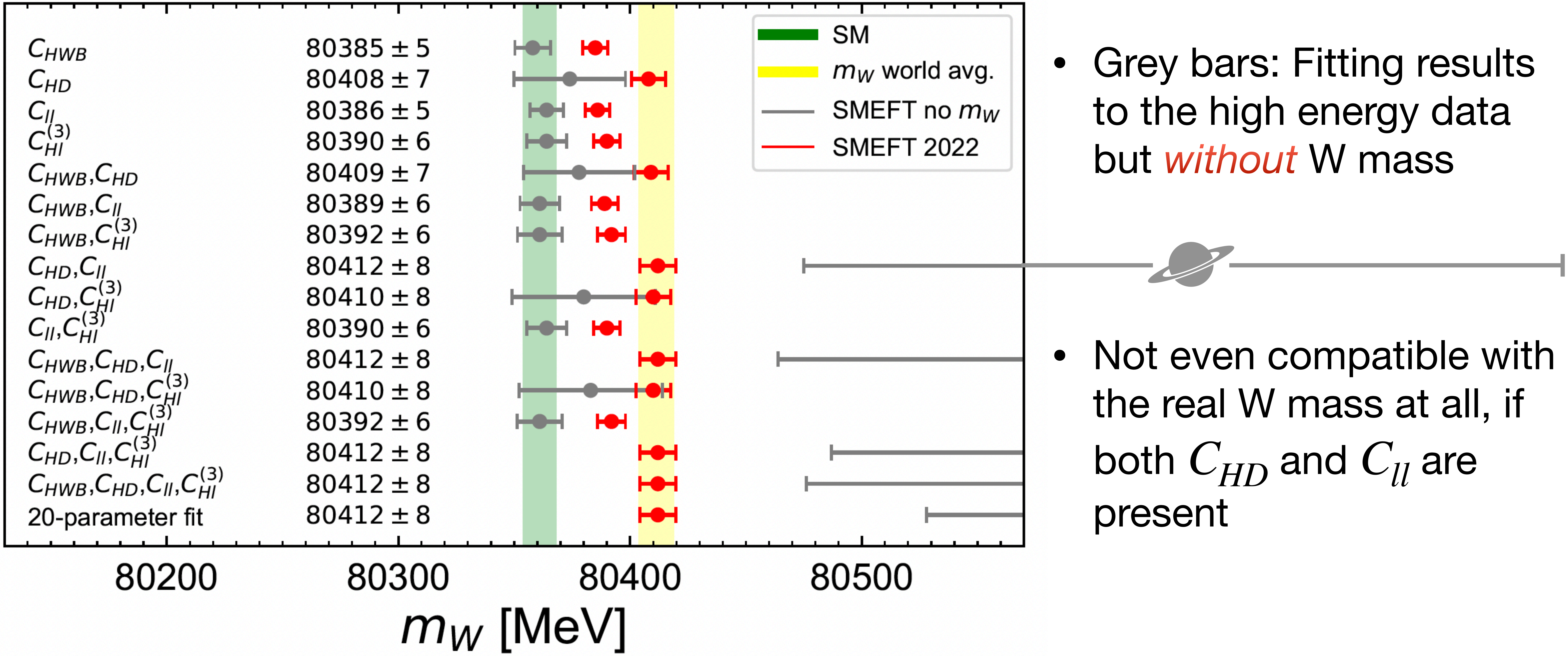



$$\frac{\delta m_W^2}{m_W^2} = v^2 \, \frac{s_w c_w}{s_w^2 - c_w^2} \left[ 2\, C_{HWB} + \frac{c_w}{2 s_w} \, C_{HD} + \frac{s_w}{c_w} \left( 2\, C_{Hl}^{(3)} - C_{ll} \right) \right]$$

- Fitting to the all EWPO but the W-mass, 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

Plots from 2204.05260

# Flat directions 2

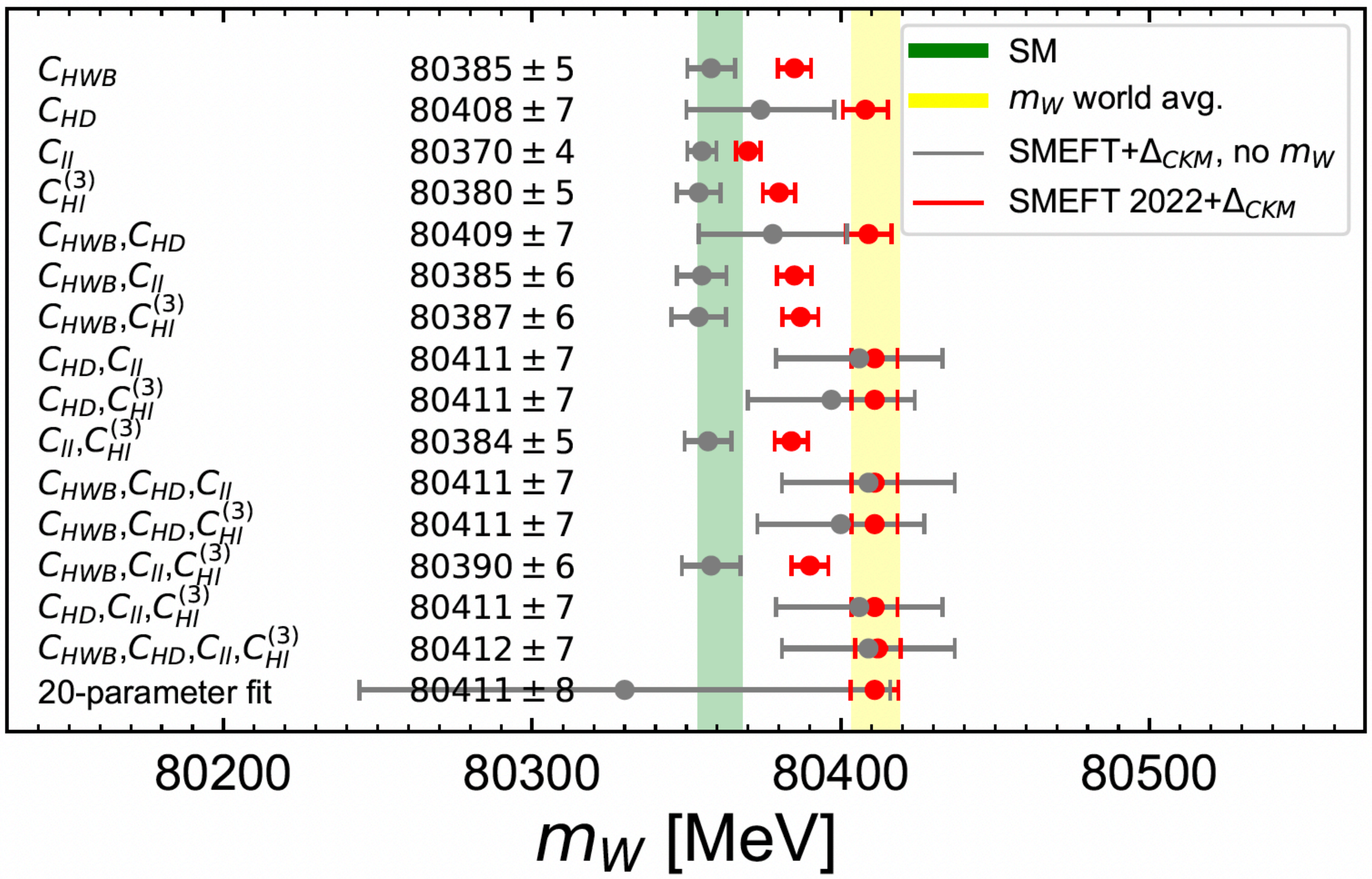



- Grey bars: Fitting results to the high energy data but *without* W mass

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

# Flat directions III

- The fits are now updated in v2 of 2204.05260

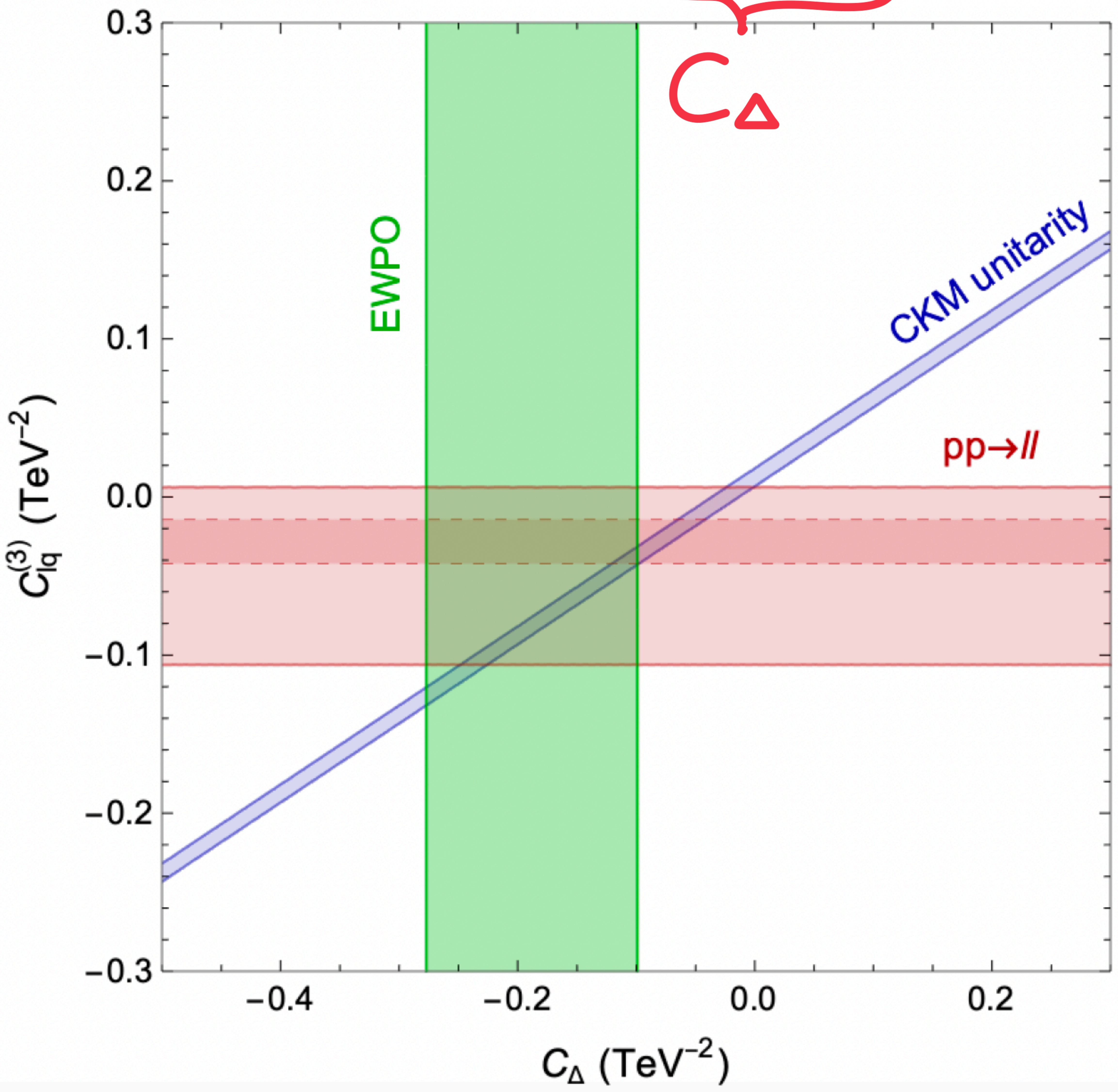


$C_{lq}^{(3)}$ :

“


”

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



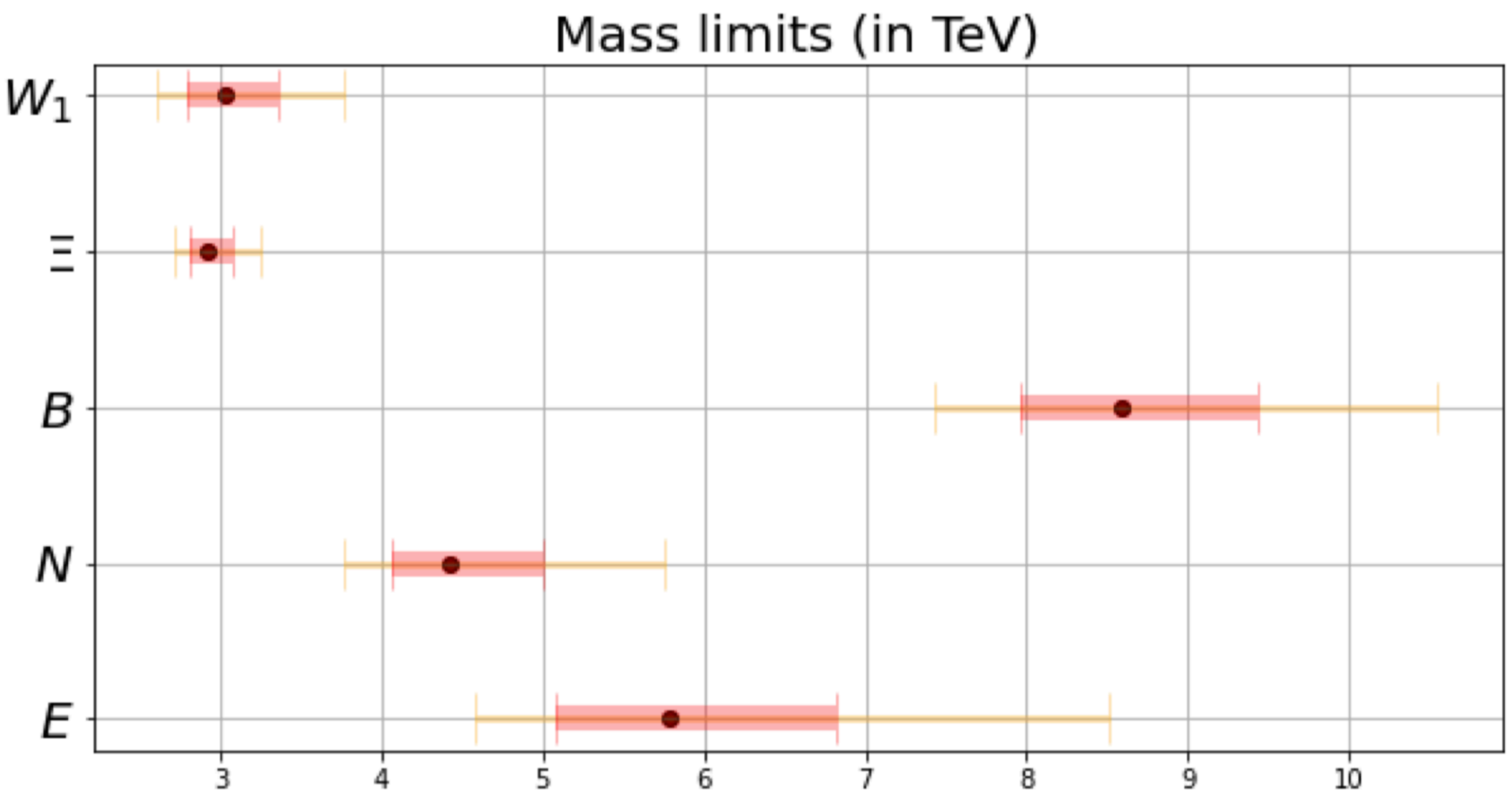

- We may effectively decouple the CKM from EWPO by a non-zero $C_{lq}^{(3)}$
- $C_{lq}^{(3)}$ is constrained by 8 TeV $pp \rightarrow ll$ data at the LHC
- Could be tested by 13 TeV data
- And also at the HL-LHC

# Conclusion (for real)

- SMEFT global-fits including only high energy data seems to damage CKM unitarity
- Low energy data is important because they can help lift some of the flat directions
- But adding more observables requires more SM-EFT operators and thus more observables and thus more SM-EFT operators and thus more…..
- Would like to make a flavorful global analysis (working in progress…) Also including g-2, flavor anomalies, etc.

| Model | Spin | SU(3) | SU(2) | U(1) | Parameters |
|---|---|---|---|---|---|
| $S_1$ | 0 | 1 | 1 | 1 | $(M_S,\, \kappa_S)$ |
| $\Sigma$ | $\frac{1}{2}$ | 1 | 3 | 0 | $(M_\Sigma, \lambda_\Sigma)$ |
| $\Sigma_1$ | $\frac{1}{2}$ | 1 | 3 | -1 | $(M_{\Sigma_1}, \lambda_{\Sigma_1})$ |
| $N$ | $\frac{1}{2}$ | 1 | 1 | 0 | $(M_N, \lambda_N)$ |
| $E$ | $\frac{1}{2}$ | 1 | 1 | -1 | $(M_E, \lambda_E)$ |
| $B$ | 1 | 1 | 1 | 0 | $(M_B, \hat{g}_H^B)$ |
| $B_1$ | 1 | 1 | 1 | 1 | $(M_{B_1}, \lambda_{B_1})$ |
| $\Xi$ | 0 | 1 | 3 | 0 | $(M_\Xi, \kappa_\Xi)$ |
| $W_1$ | 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 | | | | | | | |
| $\Sigma$ | | | $\frac{1}{16}$ | $\frac{3}{16}$ | | | $\frac{y_\tau}{4}$ | | |
| $\Sigma_1$ | | | $\frac{1}{16}$ | $-\frac{3}{16}$ | | | $\frac{y_\tau}{8}$ | | |
| $N$ | | | $-\frac{1}{4}$ | $\frac{1}{4}$ | | | | | |
| $E$ | | | $-\frac{1}{4}$ | $-\frac{1}{4}$ | | | $\frac{y_\tau}{2}$ | | |
| $B_1$ | 1 | | | | | $-\frac{1}{2}$ | $-\frac{y_\tau}{2}$ | $-\frac{y_t}{2}$ | $-\frac{y_b}{2}$ |
| $B$ | $-2$ | | | | | | $-y_\tau$ | $-y_t$ | $-y_b$ |
| $\Xi$ | $-2\left(\frac{1}{M_\Xi}\right)^2$ | | | | | $\frac{1}{2}\left(\frac{1}{M_\Xi}\right)^2$ | $y_\tau\left(\frac{1}{M_\Xi}\right)^2$ | $y_t\left(\frac{1}{M_\Xi}\right)^2$ | $y_b\left(\frac{1}{M_\Xi}\right)^2$ |
| $W_1$ | $-\frac{1}{4}$ | | | | | $-\frac{1}{8}$ | $-\frac{y_\tau}{8}$ | $-\frac{y_t}{8}$ | $-\frac{y_b}{8}$ |
| $W$ | $\frac{1}{2}$ | | | | | $-\frac{1}{2}$ | $-y_\tau$ | $-y_t$ | $-y_b$ |




| Model | Pull | Best-fit mass (TeV) | 1-$\sigma$ mass range (TeV) | 2-$\sigma$ mass range (TeV) | 1-$\sigma$ 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] |
| $\Xi$ | 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 models induce too large CKM unitarity violation