New physics interpretation of W-boson mass anomaly

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E-lab. 1998-2004

M.Endo and SM, arXiv:2204.05965

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Our publications

CDF anomaly

✦ M. Endo, S.M., arXiv:2204.05965

EW precision fit

✦ J. de Blas, M. Ciuchini, E. Franco, A. Goncalves, S.M., M. Pierini, L. Reina, L. Silvestrini, arXiv:2112.07274, accepted in PRD

✦ J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, JHEP 1612 (2016) 135

✦ M. Ciuchini, E. Franco, S.M., L. Silvestrini, JHEP08 (2013) 106

✦ J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, PoS EPS-HEP2017 (2017) 467

✦ J. de Blas, M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, PoS ICHEP2016 (2017) 690

✦ J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, S.M., M. Pierini, L. Reina, L. Silvestrini, PoS LeptonPhoton2015 (2016) 013

✦ J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, S.M., M. Pierini, L. Reina, L. Silvestrini, PoS EPS-HEP2015 (2015) 187

✦ M. Ciuchini, E. Franco, S.M., M. Pierini, L. Reina, L. Silvestrini, Nucl. Part. Phys. Proc. 273-275 (2016) 2219

✦ J. de Blas, M. Ciuchini, E. Franco, D. Ghosh, S.M., M. Pierini, L. Reina, L. Silvestrini, Nucl. Part. Phys. Proc. 273-275 (2016) 834

✦ M. Ciuchini, E. Franco, S.M., L. Silvestrini, EPJ Web Conf. 60 (2013) 08004

New W-mass anomaly

✦ CDF recently announced an updated measurement of M_W.

$$M_W = 80433.5 \pm 6.4_{\mathrm{stat}} \pm 6.9_{\mathrm{syst}}\ \mathrm{MeV}$$

✦ 7σ away from SM value.

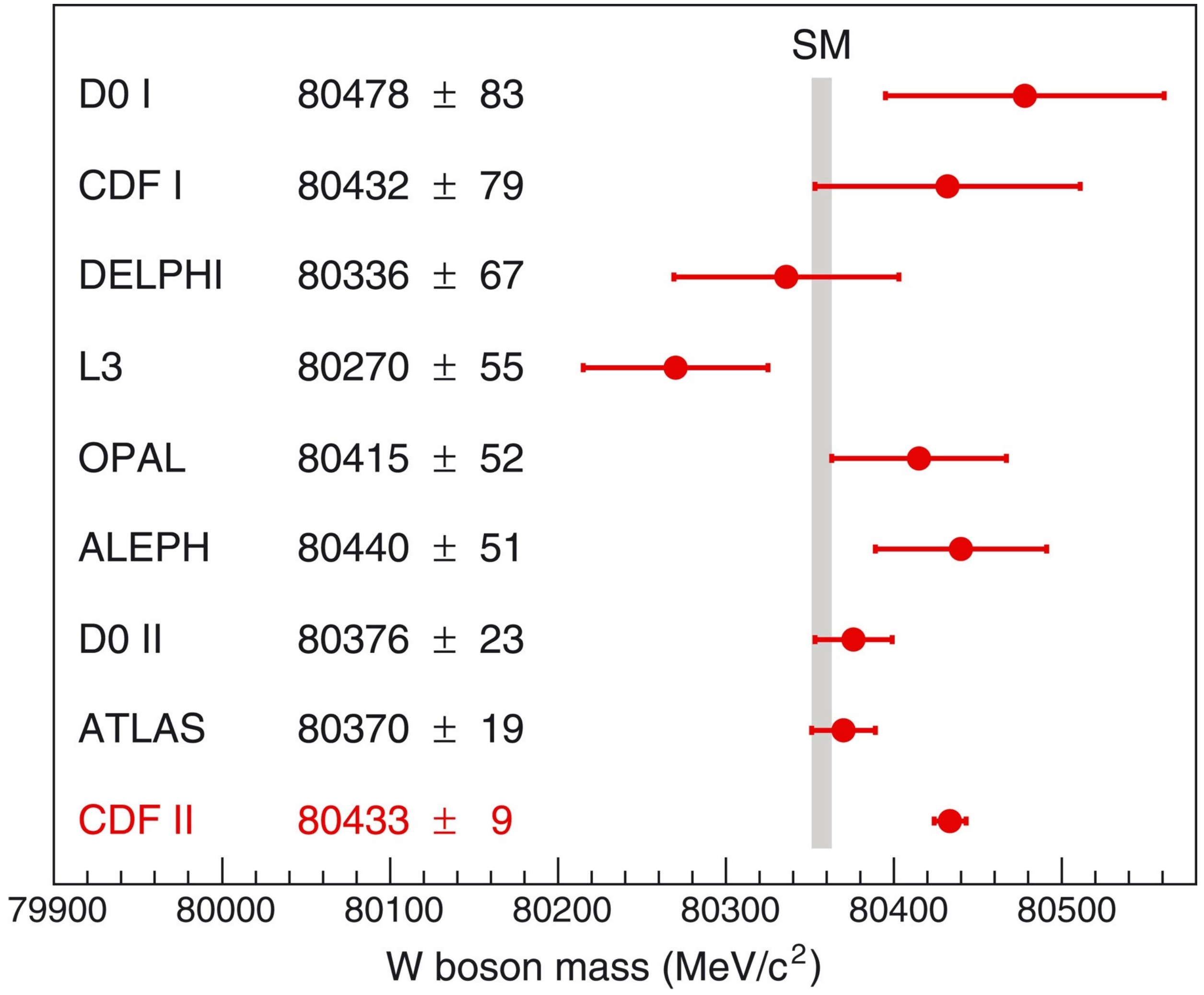
$$M_W^{\mathrm{SM}} = 80357 \pm 4_{\mathrm{inputs}} \pm 4_{\mathrm{theory}}\ \mathrm{MeV}$$

✦ M_W^{SM} is calculated from inputs (M_Z, m_t, G_F, α, $\Delta\alpha_{had}$, m_H) with full 2-loop + leading 3-loop and 4-loop corrections.

Awramik et al., hep-ph/0311148

✦ CDF new result also disagrees with previous measurements by ATLAS and D0.

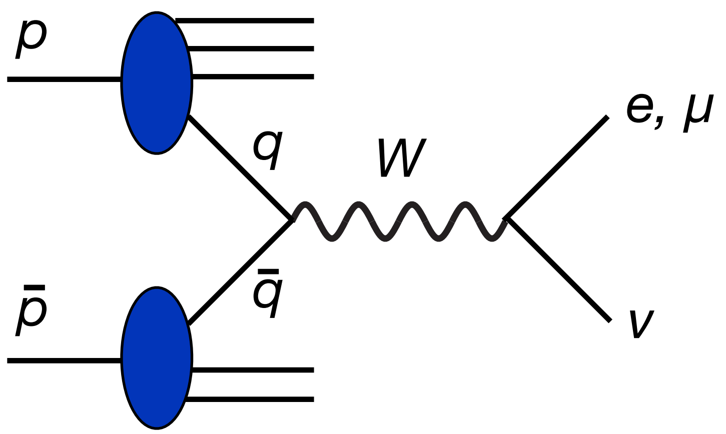
CDF, Science 376, 170 (2022)



ATLAS: 2011 (7 TeV, 4.6 fb^{-1})
D0 II : 2002-2009 (5.3 fb^{-1})
CDF II : 2002-2011 (8.8 fb^{-1}) *full dataset*

LHCb (2021): $80354 \pm 32\ \mathrm{MeV}$

CDF updates



- ✦ More statistics.
- ✦ Up-to-date proton PDFs.
- ✦ A number of improvements in analysis give reduction of systematic uncertainty.

Previous CDF Result (2.2 fb^{-1})
Combined Fit Systematic Uncertainties

Source	Uncertainty (MeV)
Lepton Energy Scale	7
Lepton Energy Resolution	2
Recoil Energy Scale	4
Recoil Energy Resolution	4
$u_{\|\|}$ efficiency	0
Lepton Removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton Distributions	10
QED radiation	4
W boson statistics	12
Total	19

New CDF Result (8.8 fb^{-1})
Combined Fit Systematic Uncertainties

Kotwal, talk@Fermilab

Source	Uncertainty (MeV)
Lepton energy scale	3.0
Lepton energy resolution	1.2
Recoil energy scale	1.2
Recoil energy resolution	1.8
Lepton efficiency	0.4
Lepton removal	1.2
Backgrounds	3.3
p_T^Z model	1.8
p_T^W/p_T^Z model	1.3
Parton distributions	3.9
QED radiation	2.7
W boson statistics	6.4
Total	9.4

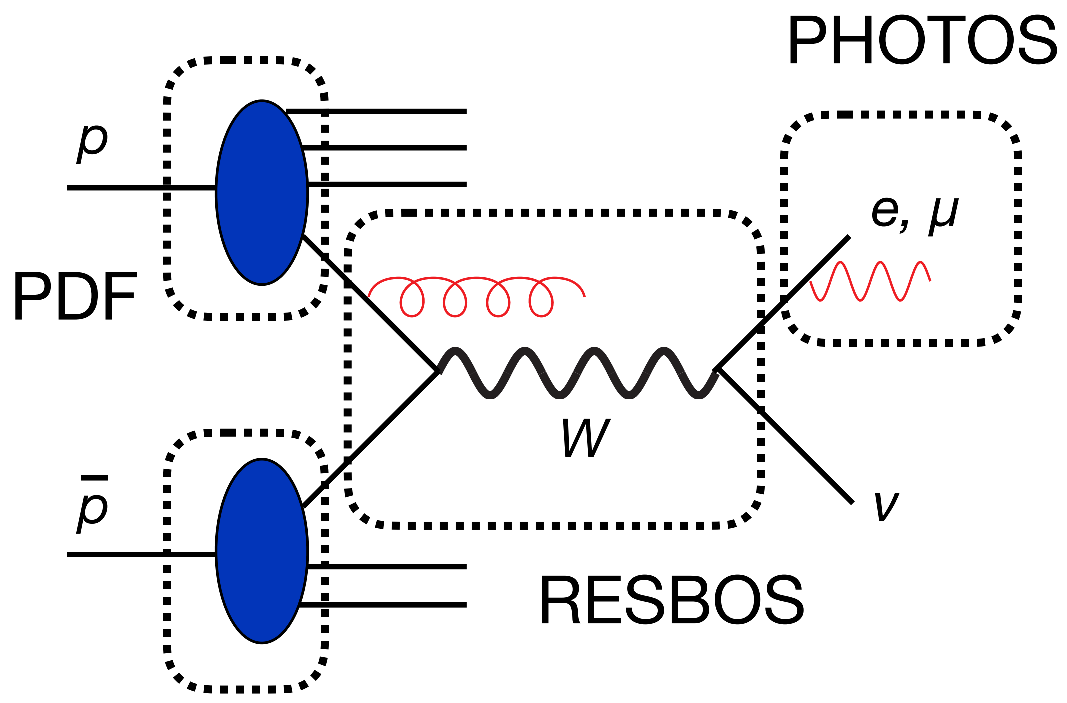
RESBOS uncertainty?

- ✦ RESBOS (RESummation for BOSons) is used to simulate p_T distribution of W boson.

- ✦ CDF used RESBOS v1 (NNLL+NLO), while RESBOS v2 (N^{3}LL+NNLO) is also available.

- ✦ Higher-order corrections would result in a decrease in the value reported by CDF by at most 10 MeV (consistent with 0 MeV), and may reduce the anomaly from 7σ to 6σ.

Isaacson, Fu and Yuan, 2205.02788

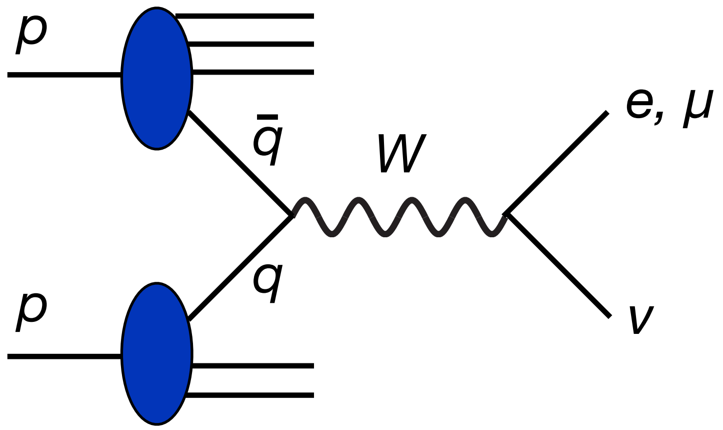


	Mass Shift [MeV]	
Observable	ResBos2	+Detector Effect+FSR
m_T	1.5 ± 0.5	0.2 ± 1.8 ± 1.0
$p_T(\ell)$	3.1 ± 2.1	4.3 ± 2.7 ± 1.3
$p_T(\nu)$	4.5 ± 2.1	3.0 ± 3.4 ± 2.2

TABLE II. Summary of the shift in M_W due to higher order corrections. For reference, the CDF result was 80,433 ± 9 MeV [2] and the SM predicted value is 80,359.1 ± 5.2 MeV [1]. The second column shows the shift in the mass neglecting detector effects and final state radiation (FSR), while the third column includes an estimate for detector effects and FSR in the mass shift. The first uncertainty is the statistical uncertainty induced in the mass extraction due to the number of ResBos events generated for the pseudoexperiments and the mass templates. The second uncertainty is the detector effect uncertainty calculated by using 100 different smearings of the data to extract the W mass. Additional details on the smearing can be found in Appendix C.

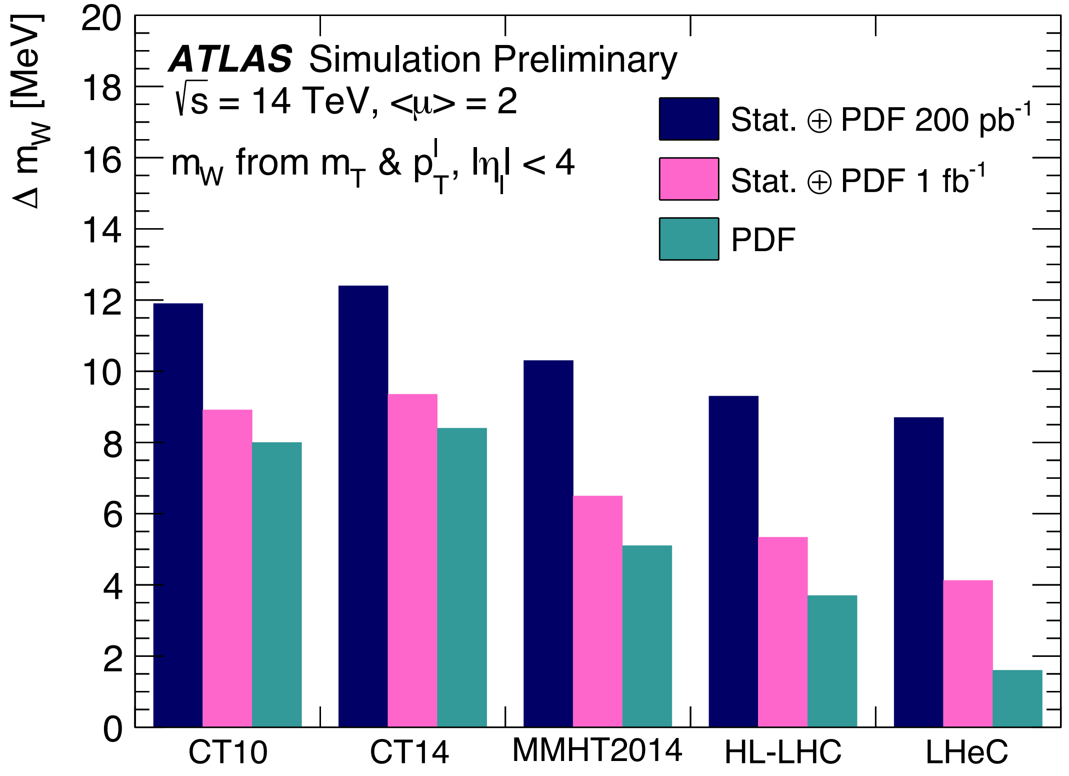
LHC measurements

- ✦ ATLAS result is consistent with SM, and dominated by systematic uncertainty.



- ✦ CMS result is not yet available.
- ✦ In general, M_W measurement at LHC is more challenging compared with Tevatron.
  - LHC measurements require PDFs in smaller x region due to its higher energy.
  - Since LHC is a proton-proton collider, a sea quark participates in Drell-Yan.
  - A large number of pileup events.

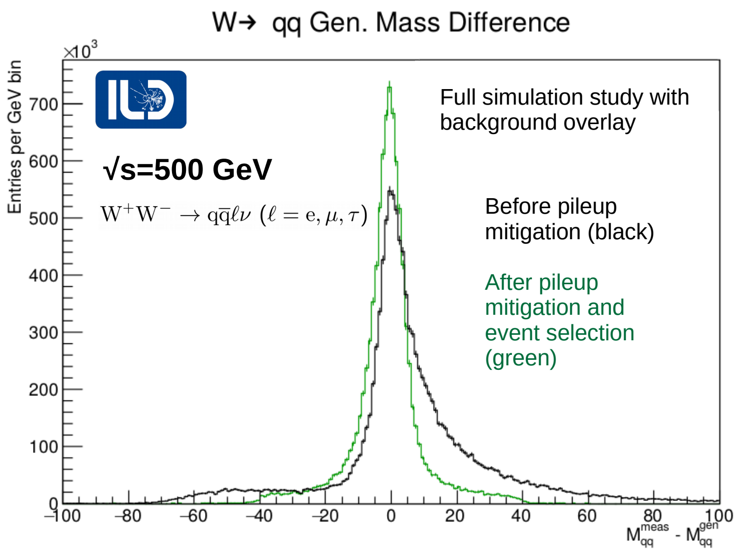
ATL-PHYS-PUB-2018-026

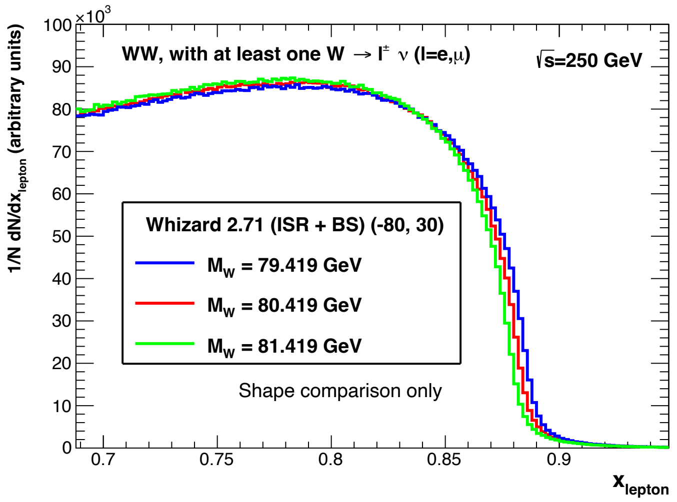


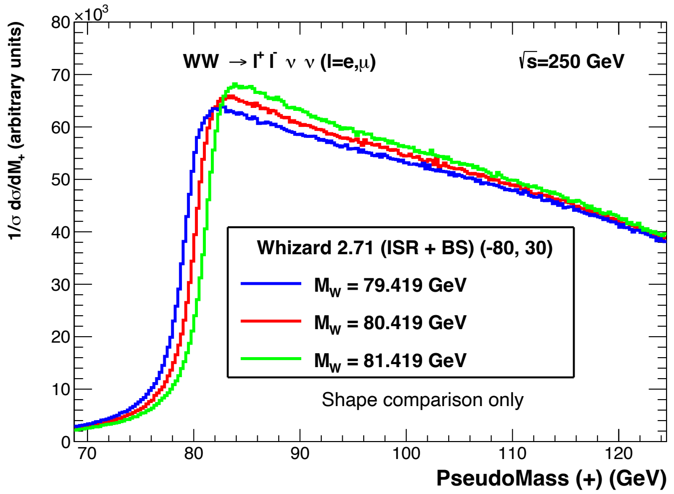
Future lepton colliders

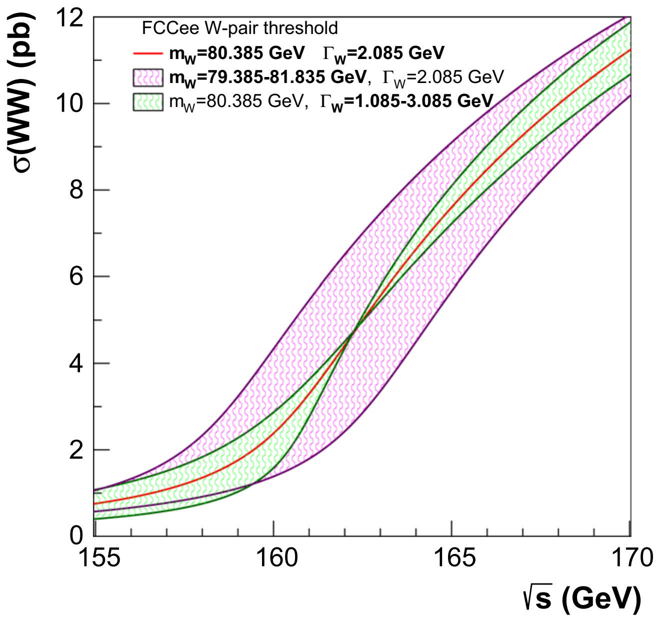
✦ Future e^+e^- colliders would be able to measure Mw very precisely.

- ILC: δM_W~2.5 MeV *2203.07622*
- CEPC: δM_W~1 MeV *1811.10545*
- FCC-ee: $\delta M_W \sim \pm 0.5_{stat} \pm 0.3_{syst}$ MeV *FCC CDR Vol.1 (2019)*









Outline

- ✦ Standard Model prediction of M_W
- ✦ New physics interpretations of CDF anomaly
  - Oblique NP
  - Non-oblique NP *M.Endo and SM, arXiv:2204.05965*

    SMEFT fit

    single-field extensions
- ✦ Summary

W-boson mass in SM

✦ At tree level, W-boson mass is related to three parameters:

$$G_F = \frac{\pi\,\alpha}{\sqrt{2}\,s_W^2\,M_W^2}\,, \qquad s_W^2 = \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- G_μ : Fermi constant extracted from muon lifetime
- α : EM coupling determined very precisely at low energy
- M_Z : Z-boson mass measured at LEP

✦ This relation is corrected by loop contributions, which depend also on

- α_s : strong coupling constant
- $\Delta\alpha_{had}$: hadronic contribution to EM coupling
- m_t : top-quark mass
- m_H : Higgs-boson mass
- m_f : light-fermion masses

quadratic

$$\begin{aligned} G_F &= \frac{\pi\,\alpha}{\sqrt{2}\,s_W^2\,M_W^2}\left(1 + \Delta\alpha_{\mathrm{had}}^{(5)} + \bigcirc \times \alpha\, m_t^2 + \triangle \times \alpha \log\frac{m_H^2}{m_W^2} + \cdots\right) \\ &= \frac{\pi\,\alpha}{\sqrt{2}\,s_W^2\,M_W^2}(1+\Delta r) \end{aligned}$$

Theoretical uncertainty

Awramik et al., hep-ph/0311148

$$G_F = \frac{\pi\,\alpha}{\sqrt{2}\,s_W^2\,M_W^2}\left(1 + \Delta\alpha_{\rm had}^{(5)} + \bigcirc \times \alpha\, m_t^2 + \triangle \times \alpha \log\frac{m_H^2}{m_W^2} + \cdots\right) = \frac{\pi\,\alpha}{\sqrt{2}\,s_W^2\,M_W^2}(1+\Delta r)$$

✦ Δr is calculated with full 2-loop + leading 3- and 4-loop corrections.

$M_{\rm H}/{\rm GeV}$	$\Delta r^{(\alpha)}$	$\Delta r^{(\alpha\alpha_s)}$	$\Delta r^{(\alpha\alpha_s^2)}$	$\Delta r^{(\alpha\alpha_s^3 m_t^2)}$	$\Delta r^{(\alpha^2)}_{\rm ferm}$	$\Delta r^{(\alpha^2)}_{\rm bos}$	$\Delta r^{(G_\mu^2 \alpha_s m_t^4)}$	$\Delta r^{(G_\mu^3 m_t^6)}$
100	283.41	35.89	7.23	1.27	28.56	0.64	−1.27	−0.16
200	307.35	35.89	7.23	1.27	30.02	0.35	−2.11	−0.09
300	323.27	35.89	7.23	1.27	31.10	0.23	−2.77	−0.03
δM_W [MeV]	-450	-50	-10	-2	-40	-1	+2	+0.2

in units of 10^{-4}

✦ The size of missing higher-order corrections is estimated as

$$\boxed{\delta M_W^{\rm theo} \approx 4\ {\rm MeV}}$$

✦ Numerical formula is available:

$$\begin{aligned} M_W = M_W^0 &- c_1\,{\rm dH} - c_2\,{\rm dH}^2 + c_3\,{\rm dH}^4 + c_4\,({\rm dh}-1) \\ &- c_5\,{\rm d}\alpha + c_6\,{\rm dt} - c_7\,{\rm dt}^2 - c_8\,{\rm dH}\,{\rm dt} \\ &+ c_9\,{\rm dh}\,{\rm dt} - c_{10}\,{\rm d}\alpha_s + c_{11}\,{\rm dZ} \end{aligned}$$

$${\rm dH} = \ln\left(\frac{m_h}{100\,{\rm GeV}}\right), \quad {\rm dh} = \left(\frac{m_h}{100\,{\rm GeV}}\right)^2, \quad {\rm dt} = \left(\frac{M_t}{174.3\,{\rm GeV}}\right)^2 - 1,$$

$${\rm dZ} = \frac{M_Z}{91.1875\,{\rm GeV}} - 1, \quad {\rm d}\alpha = \frac{\Delta\alpha^{\ell+5q}(M_Z^2)}{0.05907} - 1, \quad {\rm d}\alpha_s = \frac{\alpha_s(M_Z)}{0.119} - 1,$$

Parametric uncertainty

- There are small tensions in measurements of m_t (and those of m_H).
- Two scenarios are considered to estimate parametric uncertainty.

	standard scenario	conservative scenario
$\alpha_s(M_Z^2)$	0.1177 ± 0.0010	0.1177 ± 0.0010
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02766 ± 0.00010	0.02766 ± 0.00010
M_Z [GeV]	91.1875 ± 0.0021	91.1875 ± 0.0021
m_t [GeV]	172.58 ± 0.45	172.6 ± 1.0
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.21

de Blas, …., SM,…, 2112.07274

- Parametric uncertainty on M_W is dominated by δm_t (and δM_Z), where δm_H is negligibly small.

	Prediction	$\alpha_s(M_Z^2)$	$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	M_Z	*standard* scenario m_t	*standard* scenario Total	*conservative* scenario m_t	*conservative* scenario Total
M_W [GeV]	80.3545	± 0.0006	± 0.0018	± 0.0027	± 0.0027	± 0.0042	± 0.0060	± 0.0069

$$\delta M_W^{\rm inputs} \approx 4 \text{ MeV}$$

SM prediction

de Blas, Pierini, Reina & Silvestrini, 2204.04204

✦ Up-to-date input parameters:

	standard scenario	conservative scenario
$\alpha_s(M_Z^2)$	0.1177 ± 0.0010	0.1177 ± 0.0010
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02766 ± 0.00010	0.02766 ± 0.00010
M_Z [GeV]	91.1875 ± 0.0021	91.1875 ± 0.0021
m_t [GeV]	171.79 ± 0.38	171.8 ± 1.0
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12

✦ "Standard" and "conservative" averages of M_W data, including CDF:

$$M_W^{\rm exp} = \begin{cases} 80.4133 \pm 0.0080 \text{ MeV} & \text{(standard scenario)} \\ 80.413 \pm 0.015 \text{ MeV} & \text{(conservative scenario)} \end{cases}$$

✦ SM predictions with above input parameters:

$$M_W^{\rm theo} = \begin{cases} 80.3496 \pm 0.0057 \text{ MeV} & \text{(standard scenario)} & 6.5\,\sigma \\ 80.3497 \pm 0.0079 \text{ MeV} & \text{(conservative scenario)} & 3.7\,\sigma \end{cases}$$

EW precision fit

- Input parameters can be further constrained by EW precision fit.

$M_Z\,,\ \Gamma_Z\,,\ \sigma_h^0,\ \sin^2\theta_{\rm eff}^{\rm lept}\,,\ \mathcal{A}_f\,,\ A_{\rm FB}^{0,f},\ R_f^0$ Z-pole obs. (LEP/SLD)

$M_W\,,\ \Gamma_W$ W obs. (LEP2, Tevatron, LHC)

- EW precision fit provides indirect determination of M_W, omitting experimental constraint on M_W,

$$M_W^{\rm indirect} = \begin{cases} 80.3499 \pm 0.0056\ \text{MeV} & (\text{standard scenario}) \quad 6.5\ \sigma \\ 80.3505 \pm 0.0077\ \text{MeV} & (\text{conservative scenario}) \quad 3.7\ \sigma \end{cases}$$

Without EW fit: $$M_W^{\rm theo} = \begin{cases} 80.3496 \pm 0.0057\ \text{MeV} & (\text{standard scenario}) \quad 6.5\ \sigma \\ 80.3497 \pm 0.0079\ \text{MeV} & (\text{conservative scenario}) \quad 3.7\ \sigma \end{cases}$$

- Results are very similar to those obtained without EW precision fit, since constraints from Z-pole observables are much weaker than those from input parameters.

EW precision fit

de Blas, Pierini, Reina & Silvestrini, 2204.04204

	Measurement	Posterior	Indirect/Prediction	Pull
$\alpha_s(M_Z)$	0.1177 ± 0.0010	0.11762 ± 0.00095	0.11685 ± 0.00278	0.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z)$	0.02766 ± 0.00010	0.027535 ± 0.000096	0.026174 ± 0.000334	4.3
M_Z [GeV]	91.1875 ± 0.0021	91.1911 ± 0.0020	91.2314 ± 0.0069	-6.1
m_t [GeV]	171.79 ± 0.38	172.36 ± 0.37	181.45 ± 1.49	-6.3
m_H [GeV]	125.21 ± 0.12	125.20 ± 0.12	93.36 ± 4.99	4.3
M_W [GeV]	80.4133 ± 0.0080	80.3706 ± 0.0045	80.3499 ± 0.0056	6.5
Γ_W [GeV]	2.085 ± 0.042	2.08903 ± 0.00053	2.08902 ± 0.00052	-0.1
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231471 ± 0.000055	0.231469 ± 0.000056	0.8
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14742 ± 0.00044	0.14744 ± 0.00044	-0.3
Γ_Z [GeV]	2.4955 ± 0.0023	2.49455 ± 0.00065	2.49437 ± 0.00068	0.5
σ_h^0 [nb]	41.480 ± 0.033	41.4892 ± 0.0077	41.4914 ± 0.0080	-0.3
R_ℓ^0	20.767 ± 0.025	20.7487 ± 0.0080	20.7451 ± 0.0087	0.8
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.016300 ± 0.000095	0.016291 ± 0.000096	0.8
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14742 ± 0.00044	0.14745 ± 0.00045	1.8
R_b^0	0.21629 ± 0.00066	0.215892 ± 0.000100	0.215886 ± 0.000102	0.6
R_c^0	0.1721 ± 0.0030	0.172198 ± 0.000054	0.172197 ± 0.000054	-0.1
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10335 ± 0.00030	0.10337 ± 0.00032	-2.3
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07385 ± 0.00023	0.07387 ± 0.00023	-0.9
$\mathcal{A}_b$	0.923 ± 0.020	0.934770 ± 0.000039	0.934772 ± 0.000040	-0.6
$\mathcal{A}_c$	0.670 ± 0.027	0.66796 ± 0.00021	0.66797 ± 0.00021	0.1
$\mathcal{A}_s$	0.895 ± 0.091	0.935678 ± 0.000039	0.935677 ± 0.000040	-0.4
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108388 ± 0.000022	0.108388 ± 0.000022	0.2
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.231471 ± 0.000055	0.231474 ± 0.000056	-0.2
R_{uc}	0.1660 ± 0.0090	0.172220 ± 0.000031	0.172220 ± 0.000032	-0.7

- Strong constraints from input parameters and M_W.
- Fit prefers heavier m_t and lighter m_H.
- Pull between measurement and indirect determination of M_W is 6.5σ.
- Pull between measurement and posterior of M_W is 4.7σ.

Outline

- ✦ Standard Model prediction of M_W
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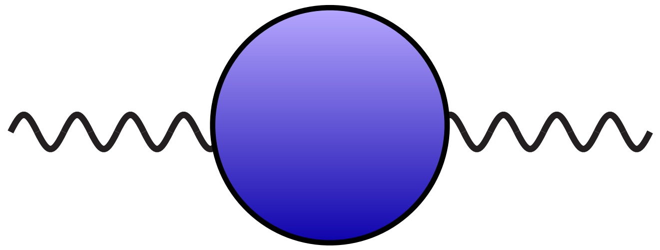
  - Oblique NP
  - Non-oblique NP *M.Endo and SM, arXiv:2204.05965*

    SMEFT fit

    Single-field extensions
- ✦ Summary

Oblique NP

✦ Suppose that dominant NP effects appear in self-energies of gauge bosons:



$$\mathcal{L} = -\frac{1}{2}W^3_\mu \Pi_{W_3W_3}(p^2) W^{3\mu} - \frac{1}{2} B_\mu \Pi_{BB}(p^2) B^\mu - W^3_\mu \Pi_{W_3B}(p^2) B^\mu - W^+_\mu \Pi_{W^+W^-}(p^2) W^\mu_-$$

$$\Pi_i(p^2) = \Pi_i(0) + p^2\, \Pi_i'(0) + \cdots$$

✦ Two of them are zero due to $U(1)_{em}$, and three of them can be fixed by M_Z, G_F & α

Kennedy & Lynn (89); Peskin & Takeuchi (90,92); Barbieri, Pomarol, Rattazzi & Strumia, hep-ph/0405040

✦ The others can be parameterized as

$$S = 16\pi\, \Pi^{\mathrm{NP}\prime}_{W_3B}(0)$$

$$T = \frac{4\pi}{s_W^2 c_W^2 M_Z^2}\left[\Pi^{\mathrm{NP}}_{W_3W_3}(0) - \Pi^{\mathrm{NP}}_{W^+W^-}(0)\right]$$

$$U = 16\pi\left[\Pi^{\mathrm{NP}\prime}_{W_3W_3}(0) - \Pi^{\mathrm{NP}\prime}_{W^+W^-}(0)\right]$$ (*U* is associated with dim. 8 operator.)

Oblique NP

✦ EW precision observables depend on three combinations S and T:

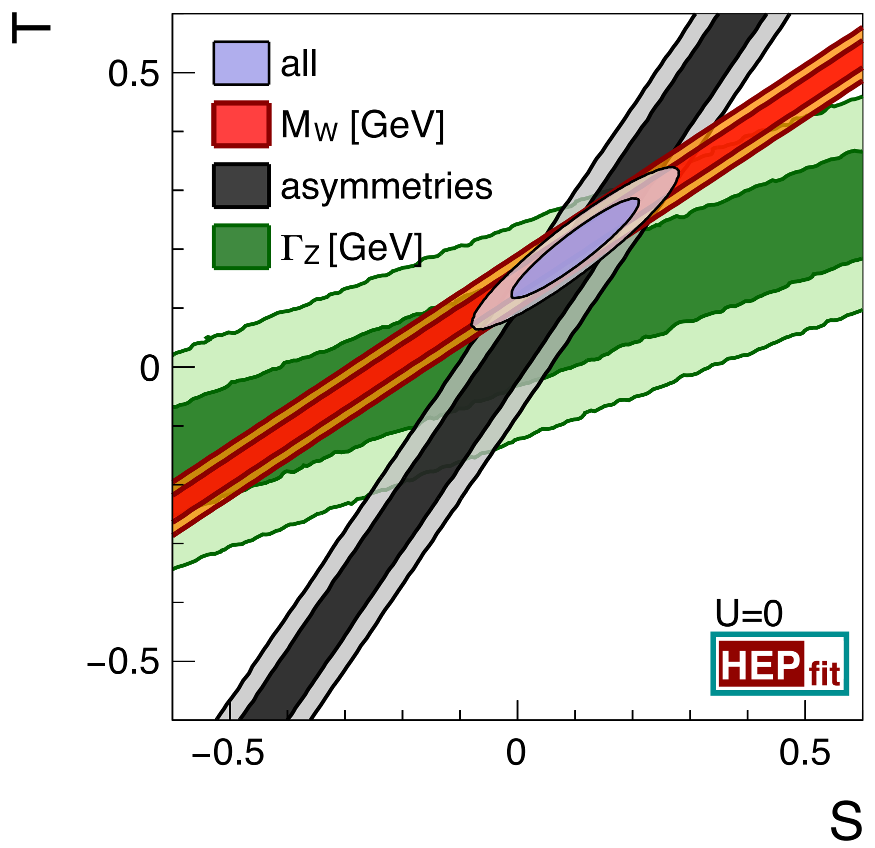
$$\delta M_W,\, \delta\Gamma_W \propto S - 2c_W^2\, T - \frac{(c_W^2 - s_W^2)\, U}{2s_W^2}$$

$$\delta\Gamma_Z \propto -10(3 - 8s_W^2)\, S + (63 - 126 s_W^2 - 40 s_W^4)\, T$$

$$\text{others} \propto S - 4c_W^2 s_W^2\, T$$

✦ CDF M_W can be explained well by introducing non-zero T, which breaks custodial and weak isospin symmetries.

de Blas et al., 2204.04204



✦ In recent papers, various UV models have been considered to explain non-zero T.

(singlet, doublet or triplet scalar, SUSY, vector-like fermions, leptoquarks, etc.)

More general case

- Generic heavy NP can be described by higher-dimensional operators in SMEFT.

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_i C_i \mathcal{O}_i$$

- M_W receives oblique & non-oblique corrections:

$$M_W = (M_W)_{\rm SM}\left[1 - \frac{1}{4(c_W^2 - s_W^2)}\Big(4 s_W c_W v^2 C_{\phi WB} + c_W^2 v^2 C_{\phi D} + 2 s_W^2 \delta_{G_F}\Big)\right]$$

$$G_F = \frac{1}{\sqrt{2}\,v^2}\,(1+\delta_{G_F})\,, \quad \delta_{G_F} = v^2\Big[(C_{\phi\ell}^{(3)})_{11} + (C_{\phi\ell}^{(3)})_{22} - (C_{\ell\ell})_{1221}\Big]$$

$$\left.\begin{aligned} \mathcal{O}_{\phi WB} &= \big(\phi^\dagger \sigma^a \phi\big) W^a_{\mu\nu} B^{\mu\nu} \\ \mathcal{O}_{\phi D} &= \big(\phi^\dagger D^\mu \phi\big)^* \big(\phi^\dagger D_\mu \phi\big) \end{aligned}\right\} \text{ oblique NP:} \quad S = \frac{4 s_W c_W v^2}{\alpha(M_Z^2)} C_{\phi WB}\,, \quad T = -\frac{v^2}{2\alpha(M_Z^2)} C_{\phi D}$$

$$\left.\begin{aligned} (\mathcal{O}_{\ell\ell})_{ijkl} &= \big(\bar\ell_i \gamma_\mu \ell_j\big)\big(\bar\ell_k \gamma^\mu \ell_l\big) \\ (\mathcal{O}_{\phi\ell}^{(3)})_{ij} &= \big(\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi\big)\big(\bar\ell_i \gamma^\mu \sigma^a \ell_j\big) \end{aligned}\right\} \text{ non-oblique NP via Fermi constant } G_F$$

Non-oblique NP

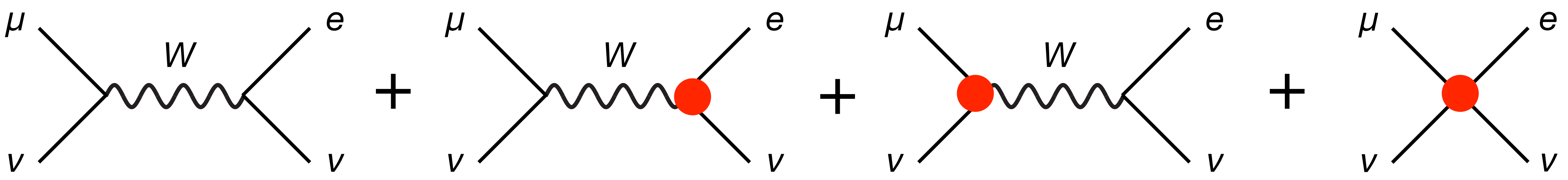
- ✦ $O_{\phi l}^{(3)}$ gives corrections to charged-current and neutral-current interactions after EW symmetry breaking:

$$\phi^\dagger \overleftrightarrow{D}^a_\mu \phi = \phi^\dagger \sigma^a (D_\mu \phi) - (D_\mu \phi)^\dagger \sigma^a \phi$$

$$\begin{aligned}\mathcal{O}^{(3)}_{\phi\ell} &= (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{\ell}\,\gamma^\mu \sigma^a \ell) \\ &= \left[\frac{g v^2}{\sqrt{2}} W^+_\mu \left(1 + \frac{2h}{v} + \frac{h^2}{v^2}\right)(\bar{\nu}_L\,\gamma^\mu e_L) + \text{h.c.}\right] + \frac{g v^2}{2 c_W} Z_\mu \left(1 + \frac{2h}{v} + \frac{h^2}{v^2}\right)\left[(\bar{\nu}_L\,\gamma^\mu \nu_L) - (\bar{e}_L\,\gamma^\mu e_L)\right]\end{aligned}$$

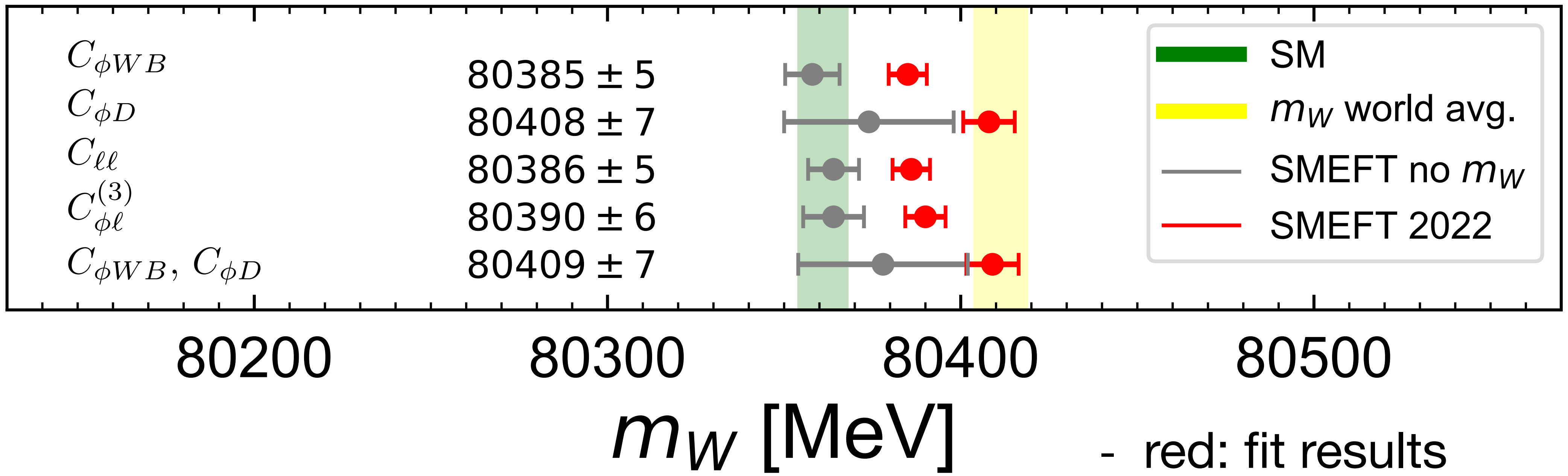
- ✦ Therefore, $O_{\phi l}^{(3)}$ and O_{ll} modify relation between Higgs VEV and G_F, where latter is extracted from muon decay:

$$G_F = \frac{1}{\sqrt{2}\,v^2}\,(1 + \delta_{G_F})\,, \quad \delta_{G_F} = v^2\left[(C^{(3)}_{\phi\ell})_{11} + (C^{(3)}_{\phi\ell})_{22} - (C_{\ell\ell})_{1221}\right]$$



SMEFT fit

Bagnaschi et al., 2204.05260



$$\mathcal{O}_{\phi WB} = (\phi^\dagger \sigma^a \phi) W^a_{\mu\nu} B^{\mu\nu}$$

$$\mathcal{O}_{\phi D} = (\phi^\dagger D^\mu \phi)^* (\phi^\dagger D_\mu \phi)$$

$$(\mathcal{O}_{\ell\ell})_{ijkl} = (\bar{\ell}_i \gamma_\mu \ell_j)(\bar{\ell}_k \gamma^\mu \ell_l)$$

$$(\mathcal{O}^{(3)}_{\phi\ell})_{ij} = (\phi^\dagger i \overleftrightarrow{D}^a_\mu \phi)(\bar{\ell}_i \gamma^\mu \sigma^a \ell_j)$$

- red: fit results
- gray: results omitting direct measurements of Mw

✦ Mw anomaly can be explained by $C_{\phi D}$ (=T).

✦ $C_{\phi WB}$, C_{ll} and $C_{\phi l}^{(3)}$ can relax anomaly, but not as good as $C_{\phi D}$.

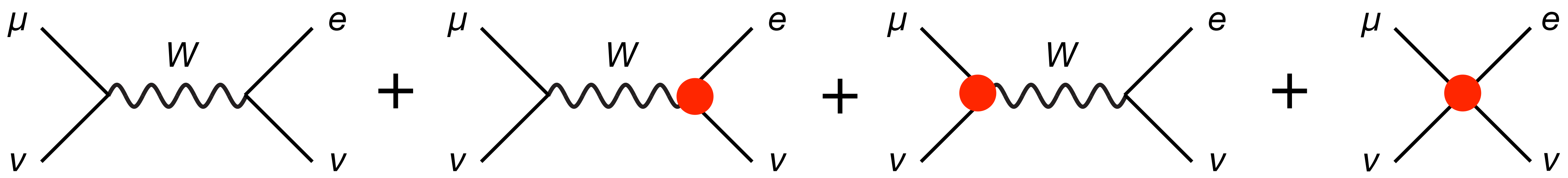
✦ Λ_{NP} ~ 19(ϕWB), 11(ϕD), 10(ll), 14(ϕL$^{(3)}$) TeV for C_i=1.

Our scenarios

✦ We assume that oblique corrections are not significant, e.g., due to custodial symmetry.

✦ We focus on the cases where NP affects G_F through $C_{\phi l}^{(3)}$ & C_{ll}.

$$G_F = \frac{1}{\sqrt{2}\, v^2}\left(1+\delta_{G_F}\right), \quad \delta_{G_F} = v^2\left[(C_{\phi\ell}^{(3)})_{11} + (C_{\phi\ell}^{(3)})_{22} - (C_{\ell\ell})_{1221}\right]$$



✦ CDF M_W anomaly is explained by δG_F.

✦ We perform SMEFT fits to EW precision data, and consider tree-level single-field extensions of SM.

NP contributions via G_F

- M_W receives corrections in G_F:

Fermi constant: $$G_F = \frac{1}{\sqrt{2}\,v^2}\,(1+\delta_{G_F})\,, \quad \delta_{G_F} = v^2\Big[(C^{(3)}_{\phi\ell})_{11} + (C^{(3)}_{\phi\ell})_{22} - (C_{\ell\ell})_{1221}\Big]$$

W mass: $$M_W = (M_W)_{\rm SM}\left[1 - \frac{s_W^2}{2(c_W^2 - s_W^2)}\delta_{G_F}\right]$$

$$(\mathcal{O}_{\ell\ell})_{ijkl} = \big(\bar\ell_i\gamma_\mu\ell_j\big)\big(\bar\ell_k\gamma^\mu\ell_l\big)$$
$$(\mathcal{O}^{(3)}_{\phi\ell})_{ij} = \big(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi\big)\big(\bar\ell_i\gamma^\mu\sigma^a\ell_j\big)$$

- δG_F and $C_{\phi l}^{(3)}$ contributes to W widths:

W widths: $$\Gamma(W^+\to\ell_i^+\nu_{\ell i}) = \Gamma(W^+\to\ell_i^+\nu_{\ell i})_{\rm SM}\left[1 - \frac{(1+c_W^2)}{2(c_W^2-s_W^2)}\,\delta_{G_F} + 2v^2(C^{(3)}_{\phi\ell})_{ii}\right]$$
$$\Gamma(W^+\to\bar q_i q_j) = \Gamma(W^+\to\bar q_i q_j)_{\rm SM}\left[1 - \frac{(1+c_W^2)}{2(c_W^2-s_W^2)}\,\delta_{G_F}\right]$$

- Z couplings are also modified by δG_F and $C_{\phi l}^{(3)}$:

Z couplings: $$\mathcal{L}_Z = \frac{g}{c_W}\,\bar f\gamma^\mu\Big[(T_L'^3 - Qs_W^2 + \delta g_L)P_L + (T_R'^3 - Qs_W^2 + \delta g_R)P_R\Big] f\, Z_\mu$$

$$\delta g_L = \begin{cases} -\frac{1}{2}\left[T_L'^3 + \frac{Qs_W^2}{c_W^2 - s_W^2}\right]\delta_{G_F} + T_L'^3 v^2 (C^{(3)}_{\phi\ell})_{ii} & \text{for} \quad f = \ell_i, \nu_{\ell i} \\ -\frac{1}{2}\left[T_L'^3 + \frac{Qs_W^2}{c_W^2 - s_W^2}\right]\delta_{G_F} & \text{otherwise} \end{cases}$$

$$\delta g_R = -\frac{Qs_W^2}{2(c_W^2 - s_W^2)}\,\delta_{G_F}$$

EW precision fit

✦ We perform a Bayesian fit of SMEFT coefficients to EW precision data.

	Measurement		Measurement
$\alpha_s(M_Z^2)$	0.1177 ± 0.0010	M_Z [GeV]	91.1876 ± 0.0021
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02766 ± 0.00010	Γ_Z [GeV]	2.4955 ± 0.0023
m_t [GeV]	171.79 ± 0.38	σ_h^0 [nb]	41.4807 ± 0.0325
m_h [GeV]	125.21 ± 0.12	R_e^0	20.8038 ± 0.0497
M_W [GeV]	80.4133 ± 0.0080	R_μ^0	20.7842 ± 0.0335
Γ_W [GeV]	2.085 ± 0.042	R_τ^0	20.7644 ± 0.0448
$\mathcal{B}(W \to e\nu)$	0.1071 ± 0.0016	$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025
$\mathcal{B}(W \to \mu\nu)$	0.1063 ± 0.0015	$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013
$\mathcal{B}(W \to \tau\nu)$	0.1138 ± 0.002	$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017
$R(\tau/\mu)$	0.992 ± 0.013	R_b^0	0.21629 ± 0.00066
$\mathcal{A}_e$ (SLD)	0.1516 ± 0.0021	R_c^0	0.1721 ± 0.0030
$\mathcal{A}_\mu$ (SLD)	0.142 ± 0.015	$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016
$\mathcal{A}_\tau$ (SLD)	0.136 ± 0.015	$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035
$\mathcal{A}_e$ (LEP)	0.1498 ± 0.0049	$\mathcal{A}_b$	0.923 ± 0.020
$\mathcal{A}_\tau$ (LEP)	0.1439 ± 0.0043	$\mathcal{A}_c$	0.670 ± 0.027

flavor non-universal NP

ATLAS $R(\tau/\mu) = \dfrac{\mathcal{B}(W \to \tau\nu)}{\mathcal{B}(W \to \mu\nu)}$

ATLAS, 2007.14040

massive O(α_s^2) corrections to $A_{FB}^{0,b}$

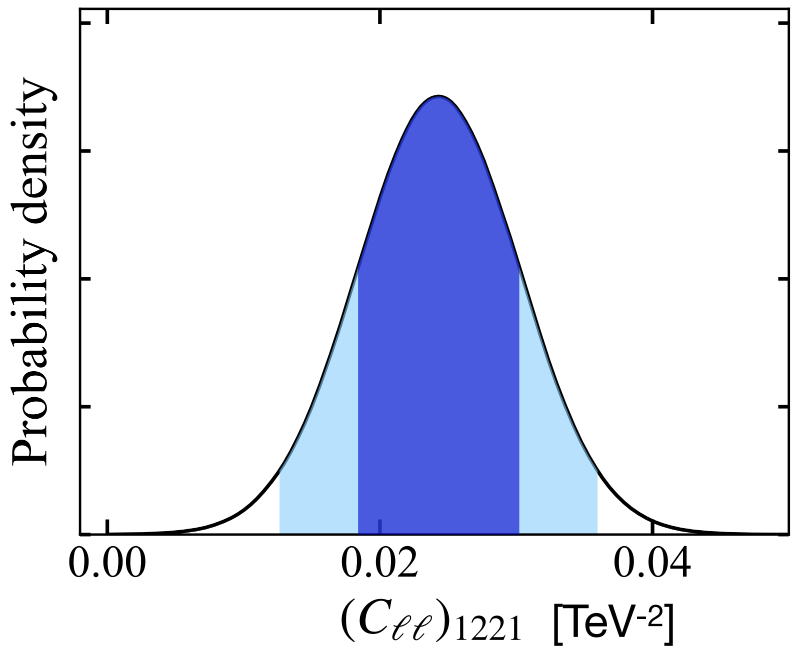
Bernreuther, 1611.07942

Fit results

- Positive shift in M_W leads to positive (negative) shift in C_{ll} ($C_{\phi l}^{(3)}$).

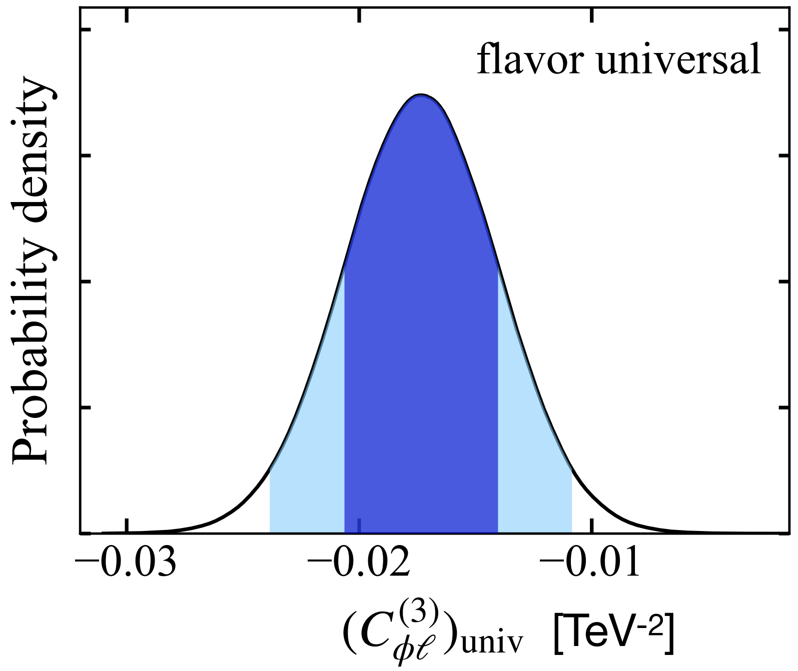
$$M_W = (M_W)_{\rm SM}\left[1 - \frac{s_W^2}{2(c_W^2 - s_W^2)}\left[(C_{\phi\ell}^{(3)})_{11} + (C_{\phi\ell}^{(3)})_{22} - (C_{\ell\ell})_{1221}\right]\right]$$

$$(\mathcal{O}_{\ell\ell})_{ijkl} = \left(\bar{\ell}_i\gamma_\mu\ell_j\right)\left(\bar{\ell}_k\gamma^\mu\ell_l\right)$$



$$\left(C_{\ell\ell}\right)_{1221} > 0$$

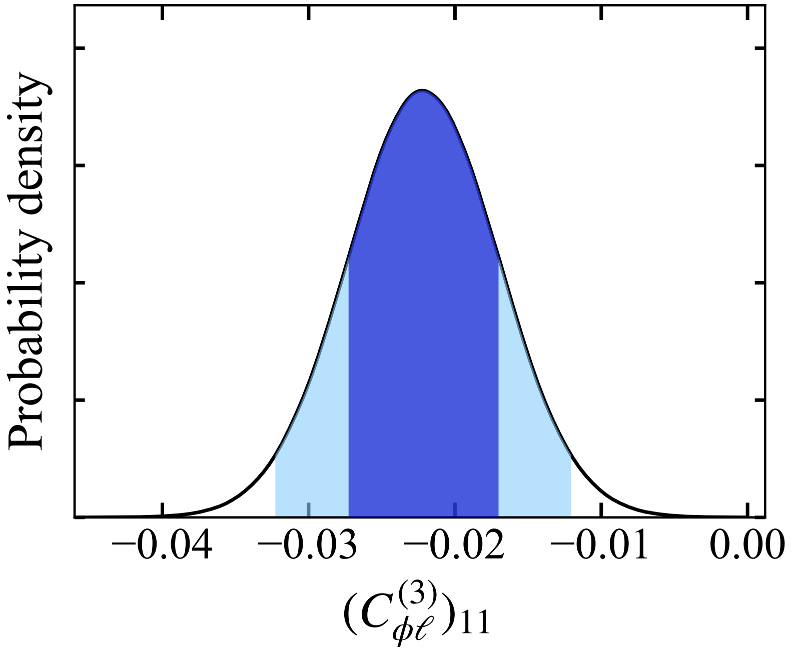
$$(\mathcal{O}_{\phi\ell}^{(3)})_{ij} = \left(\phi^\dagger i\overleftrightarrow{D}_\mu^a\phi\right)\left(\bar{\ell}_i\gamma^\mu\sigma^a\ell_j\right)$$

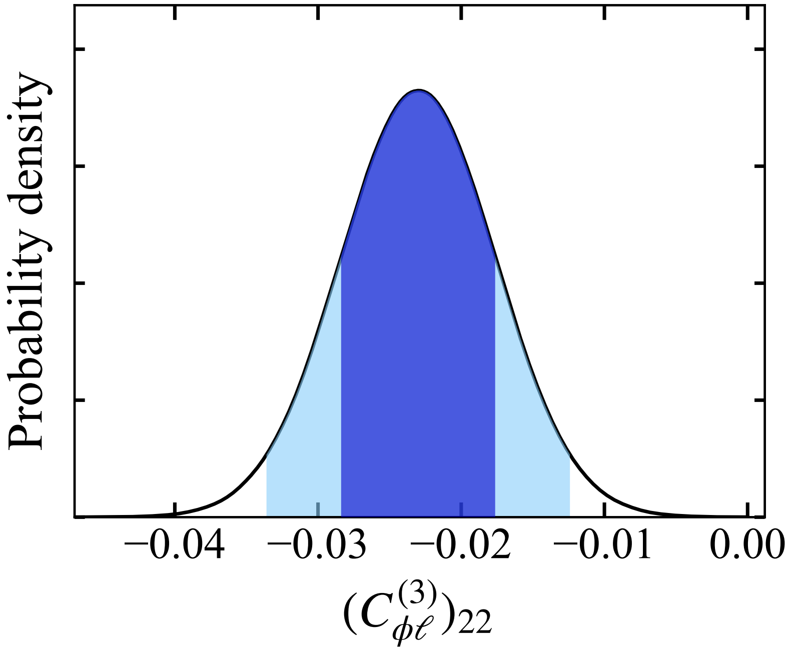


$$\left(C_{\phi\ell}^{(3)}\right)_{\rm univ} \equiv \left(C_{\phi\ell}^{(3)}\right)_{11} = \left(C_{\phi\ell}^{(3)}\right)_{22} < 0$$

Flavor non-universal cases

✦ Either $(C_{\phi l}{}^{(3)})_{11}$ or $(C_{\phi l}{}^{(3)})_{22}$ is switched on:



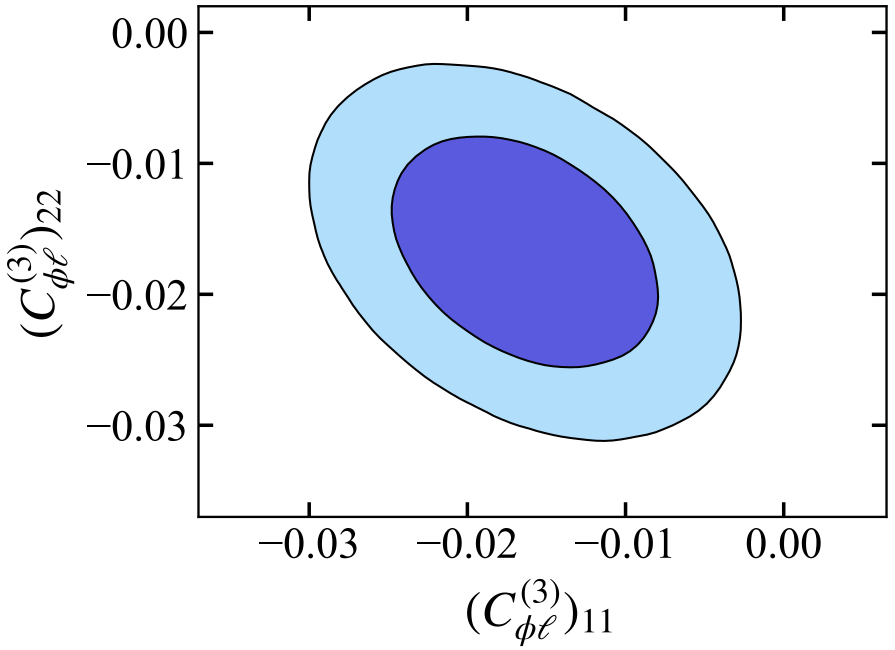


$$\left(C^{(3)}_{\phi\ell}\right)_{11} < 0$$

$$\left(C^{(3)}_{\phi\ell}\right)_{22} < 0$$

✦ Simultaneous fit of $(C_{\phi l}{}^{(3)})_{11}$ and $(C_{\phi l}{}^{(3)})_{22}$:

$$\left(C^{(3)}_{\phi\ell}\right)_{11} < 0 \quad \& \quad \left(C^{(3)}_{\phi\ell}\right)_{22} < 0$$



Pulls

- Pulls for M_W & A_e(SLD) are relaxed, but that for $A_{FB}^{0,b}$ is worsened.
- Overall quality of fit can be evaluated with Information Criterion (IC):

$$IC = -2\,\overline{\ln L} + 4\,\sigma^2_{\ln L}, \quad \overline{\ln L},\ \sigma^2_{\ln L} : \text{mean and variance of the posterior log-likelihood distribution.}$$

$c.f.,$ $IC = 40$ for $C_{\phi D}(= T \text{ param.})$

	SM	$C_{\ell\ell}$ 1221	$C_{\phi\ell}^{(3)}$ 11	$C_{\phi\ell}^{(3)}$ 22	$C_{\phi\ell}^{(3)}$ univ	$C_{\phi\ell}^{(3)}$ 11, 22
IC	86	65	65	64	54	58
$\alpha_s(M_Z^2)$	−0.1	0.1	0.5	0.2	0.5	0.5
$\Delta\alpha^{(5)}_{\text{had}}(M_Z^2)$	0.9	0.2	0.4	0.2	0.0	0.1
m_t	−1.1	−0.5	−0.7	−0.6	−0.4	−0.4
m_h	0.0	0.0	0.0	0.0	0.0	0.0
M_W	4.6	2.9	2.9	3.0	2.1	2.2
$\delta_{\text{th}} M_W$	−2.0	−1.3	−1.3	−1.3	−1.0	−1.0
Γ_W	−0.1	−0.2	−0.2	−0.2	−0.2	−0.2
$\mathcal{B}(W \to e\nu)$	−0.8	−0.8	−0.7	−0.8	−0.7	−0.7
$\mathcal{B}(W \to \mu\nu)$	−1.4	−1.4	−1.4	−1.2	−1.3	−1.3
$\mathcal{B}(W \to \tau\nu)$	2.6	2.6	2.6	2.6	2.6	2.5
$R(\tau/\mu)$	−0.6	−0.6	−0.6	−0.8	−0.6	−0.8
$\mathcal{A}_e$ (SLD)	2.0	0.4	1.7	0.5	0.6	0.7
$\mathcal{A}_\mu$ (SLD)	−0.4	−0.6	−0.6	−0.4	−0.5	−0.5
$\mathcal{A}_\tau$ (SLD)	−0.8	−1.0	−1.0	−1.0	−0.9	−1.1

$\mathcal{A}_e$ (LEP)	0.5	−0.2	0.4	−0.1	−0.1	−0.1
$\mathcal{A}_\tau$ (LEP)	−0.8	−1.5	−1.5	−1.5	−1.5	−1.8
M_Z	−1.2	−0.4	−0.7	−0.5	−0.3	−0.3
Γ_Z	0.4	−1.4	−0.9	−1.0	−1.4	−1.5
σ_h^0	−0.2	−0.3	2.2	−1.0	0.8	1.0
R_e^0	1.4	1.3	0.2	1.3	0.4	0.5
R_μ^0	1.5	1.3	1.4	−0.3	0.0	0.1
R_τ^0	−0.3	−0.5	−0.4	−0.4	−1.4	−0.5
$A_{\text{FB}}^{0,e}$	−0.7	−1.0	−0.8	−1.0	−1.0	−1.0
$A_{\text{FB}}^{0,\mu}$	0.5	−0.1	0.1	0.2	−0.0	0.0
$A_{\text{FB}}^{0,\tau}$	1.5	1.0	1.2	1.1	1.1	1.0
R_b^0	0.6	0.6	0.6	0.6	0.6	0.6
R_c^0	−0.0	−0.0	−0.0	−0.0	−0.0	−0.0
$A_{\text{FB}}^{0,b}$	−2.3	−3.5	−2.6	−3.5	−3.5	−3.4
$A_{\text{FB}}^{0,c}$	−0.9	−1.4	−1.0	−1.4	−1.4	−1.3
$\mathcal{A}_b$	−0.6	−0.6	−0.6	−0.6	−0.6	−0.6
$\mathcal{A}_c$	0.1	0.0	0.0	0.0	−0.0	0.0

New physics interpretation

✦ We consider single-field extensions of SM:

	S_1	Ξ_1	E	Σ_1	$\mathcal{B}$	$\mathcal{W}$
Spin	0	0	1/2	1/2	1	1
$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{\mathrm{U}(1)_Y}$	$(1,1)_1$	$(1,3)_1$	$(1,1)_{-1}$	$(1,3)_{-1}$	$(1,1)_0$	$(1,3)_0$

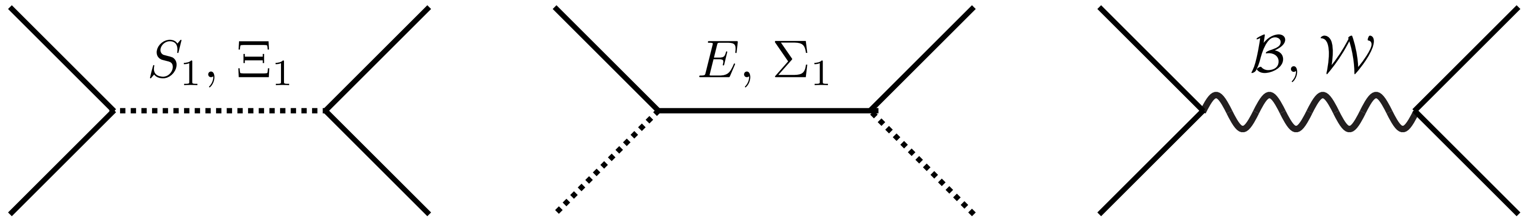
$Y = Q - T_L'^3$

✦ These fields can have couplings with left-handed leptons.

✦ Singlet scalar $(1,1)_0$ and triplet lepton $(1,3)_0$ are not considered, since the are likely to generate too large neutrino masses by seesaw mechanisms.

✦ C_{ll} and/or $C_{\phi l}^{(3)}$ are generated at tree level.

	S_1	Ξ_1	E	Σ_1	$\mathcal{B}$	$\mathcal{W}$
$C_{\ell\ell}$	✓	✓	—	—	✓	✓
$C_{\phi\ell}^{(3)}$	—	—	✓	✓	—	—



Scalar extension

S_1	Ξ_1
$(1,1)_1$	$(1,3)_1$

- S_1 and Ξ_1 have Yukawa interactions with left-handed leptons:

$$-\mathcal{L}_{\rm int} = (y_{S_1})_{ij} S_1^\dagger (\bar{\ell}_i i\sigma^2 \ell_j^c) + (y_{\Xi_1})_{ij} \Xi_1^{a\dagger} (\bar{\ell}_i \sigma^a i\sigma^2 \ell_j^c) + \text{h.c.}$$

- y_{S1} and $y_{\Xi 1}$ are anti-symmetric and symmetric in flavor space, respectively.

- We neglect Ξ_1-H-H coupling, since they are generically independent of the above Yukawa interactions and irrelevant to δG_F.

- S_1 and Ξ_1 contribute to $(C_{ll})_{1221}$ negatively and positively, respectively.

$$(C_{\ell\ell})_{1221} = -\frac{\left|(y_{S_1})_{12}\right|^2}{M_{S_1}^2} + \frac{\left|(y_{\Xi_1})_{12}\right|^2}{M_{\Xi_1}^2}$$

S_1	Ξ_1
0	0
$(1,1)_1$	$(1,3)_1$

- Ξ_1 can be a source of CDF anomaly.

Vector extension

$\mathcal{B}$	$\mathcal{W}$
$(1,1)_0$	$(1,3)_0$

✦ *B* and *W* have following interactions with left-handed leptons:

$$-\mathcal{L}_{\rm int} = (g_{\mathcal{B}})_{ij}\mathcal{B}_\mu(\bar{\ell}_i\gamma^\mu\ell_j) + \frac{1}{2}(g_{\mathcal{W}})_{ij}\mathcal{W}^a_\mu(\bar{\ell}_i\sigma^a\gamma^\mu\ell_j)$$

✦ We do not assume any mechanism to generate vector-boson masses or any UV realization of the model.

✦ We don't consider interactions of *B* and *W* with other SM fields, since they are irrelevant to δG_F.

✦ *W* can give positive contribution to $(C_{ll})_{1221}$:

$$(C_{\ell\ell})_{1221} = -\frac{\left|(g_{\mathcal{B}})_{12}\right|^2}{2M_{\mathcal{B}}^2} - \frac{(g_{\mathcal{W}})_{11}(g_{\mathcal{W}})_{22}}{4M_{\mathcal{W}}^2} + \frac{\left|(g_{\mathcal{W}})_{12}\right|^2}{8M_{\mathcal{W}}^2}$$

✦ *W* can be a source of CDF anomaly.

Fermion extension

E	Σ_1
$(1,1)_{-1}$	$(1,3)_{-1}$

✦ *E* and *Σ₁* have Yukawa interactions with left-handed leptons:

$$-\mathcal{L}_{\rm int} = (\lambda_E)_i\, \bar{E}_R\, \phi^\dagger \ell_i + \frac{1}{2}(\lambda_{\Sigma_1})_i\, \bar{\Sigma}^a_{1R}\, \phi^\dagger \sigma^a \ell_i + \mathrm{h.c.}$$

✦ They are assumed to have vector-like masses ($M_E,\, M_{\Sigma_1} \gg v$).

✦ Operators $O_{e\phi}$ and $O_{\phi l}^{(1)}$ are generated in addition to $O_{\phi l}^{(3)}$:

$$(C_{e\phi})_{ij} = (y_\ell)^*_{jk}\left[\frac{(\lambda_E)_k(\lambda_E)^*_i}{2M_E^2} + \frac{(\lambda_{\Sigma_1})_k(\lambda_{\Sigma_1})^*_i}{8M_{\Sigma_1}^2}\right]$$

$$(C^{(1)}_{\phi\ell})_{ij} = -\frac{(\lambda_E)_j(\lambda_E)^*_i}{4M_E^2} - \frac{3(\lambda_{\Sigma_1})_j(\lambda_{\Sigma_1})^*_i}{16M_{\Sigma_1}^2}$$

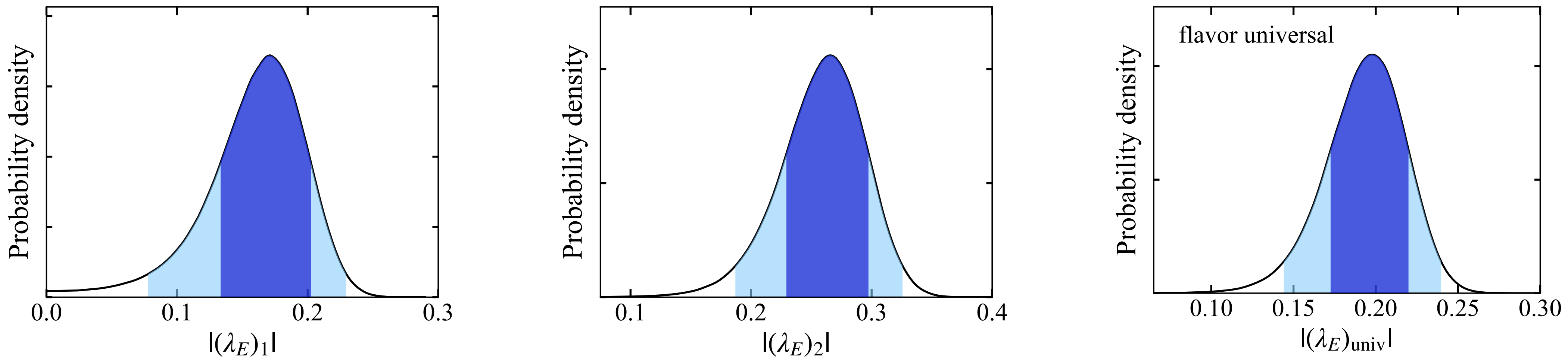
$$(C^{(3)}_{\phi\ell})_{ij} = -\frac{(\lambda_E)_j(\lambda_E)^*_i}{4M_E^2} + \frac{(\lambda_{\Sigma_1})_j(\lambda_{\Sigma_1})^*_i}{16M_{\Sigma_1}^2} \;\Rightarrow\; (C^{(3)}_{\phi\ell})_{11,22} = -\frac{\left|(\lambda_E)_{1,2}\right|^2}{4M_E^2} + \frac{\left|(\lambda_{\Sigma_1})_{1,2}\right|^2}{16M_{\Sigma_1}^2}$$

$$(\mathcal{O}_{e\phi})_{ij} = (\phi^\dagger\phi)(\bar{\ell}_i\phi\, e_{Rj})$$
$$(\mathcal{O}^{(1)}_{\phi\ell})_{ij} = (\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{\ell}_i\gamma^\mu\ell_j)$$
$$(\mathcal{O}^{(3)}_{\phi\ell})_{ij} = (\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{\ell}_i\gamma^\mu\sigma^a\ell_j)$$

✦ *E* can be a source of CDF anomaly.

Fermion extension

- ✦ $C_{\phi l}^{(1)}$ and $C_{\phi l}^{(3)}$ contribute to EW precision observables.
- ✦ EW precision fits give constraints on λ_E for M_E=1 TeV:



$$\left|(\lambda_E)_1\right| < \left|(\lambda_E)_2\right|$$

- ✦ $C_{e\phi}$ affects signal strengths of Higgs decays ($h \to e_i^+ e_j^-$), but they are much weaker than experimental sensitivities.
- ✦ Muon g-2 anomaly can be explained by introducing extra lepton, $\Delta_1 \sim (1,2)_{-1/2}$ or $\Delta_3 \sim (1,2)_{-3/2}$, in addition to E.

M.Endo and SM, 2005.03933

NP scale

✦ scalar Ξ_1=(1,3)$_1$

$$0.14 < \frac{|(y_{\Xi_1})_{12}|}{M_{\Xi_1}} < 0.17 \ \ \mathrm{TeV}^{-1} \quad \Rightarrow \quad M_{\Xi_1} \sim 6-7 \ \mathrm{TeV} \quad \text{for} \ \ |(y_{\Xi_1})_{12}| \sim 1$$

✦ vector W=(1,3)$_0$ *c.f.* Bound from muonium-antimuonium oscillation is much weaker.

$$0.27 < \frac{\mathcal{G}_{\mathcal{W}}}{M_{\mathcal{W}}} < 0.35 \ \ \mathrm{TeV}^{-1}, \quad 0.38 < \frac{(g_{\mathcal{W}})_{12}}{M_{\mathcal{W}}} < 0.49 \ \ \mathrm{TeV}^{-1}$$

$$\mathcal{G}_{\mathcal{W}} = \sqrt{-(g_{\mathcal{W}})_{11}(g_{\mathcal{W}})_{22}} \quad \Rightarrow \quad M_{\mathcal{W}} \sim 2-4 \ \mathrm{TeV} \quad \text{for} \ \ \mathcal{G}_{\mathcal{W}}, \ |(g_{\mathcal{W}})_{12}| \sim 1$$

✦ fermion E=(1,1)$_{-1}$

$$0.13 < |(\lambda_E)_1| < 0.20 \quad \Rightarrow \quad M_E \sim 5-7 \ \mathrm{TeV} \quad \text{for} \ \ |(\lambda_E)_1| \sim 1$$

$$0.23 < |(\lambda_E)_2| < 0.30 \quad \Rightarrow \quad M_E \sim 3-4 \ \mathrm{TeV} \quad \text{for} \ \ |(\lambda_E)_2| \sim 1$$

$$0.17 < |(\lambda_E)_{\mathrm{univ}}| < 0.22 \quad \Rightarrow \quad M_E \sim 5-6 \ \mathrm{TeV} \quad \text{for} \ \ |(\lambda_E)_{\mathrm{univ}}| \sim 1$$

Summary

- New CDF measurement of MW disagrees with SM predictions as well as previous measurements.
- CDF anomaly can be explained well by non-zero *T* parameter.
- We studied non-oblique NP scenarios that affect Fermi constant G_F.
- CDF anomaly corresponds to positive (negative) shift in C_{ll} ($C_{\phi l}^{(3)}$).
- Ξ_1, *E* and *W* at multi-TeV scale can relax the anomaly.

	S_1	Ξ_1	E	Σ_1	$\mathcal{B}$	$\mathcal{W}$
Spin	0	0	1/2	1/2	1	1
$(\mathrm{SU}(3)_c, \mathrm{SU}(2)_L)_{\mathrm{U}(1)_Y}$	$(1,1)_1$	$(1,3)_1$	$(1,1)_{-1}$	$(1,3)_{-1}$	$(1,1)_0$	$(1,3)_0$
CDF M_W	—	✓	✓	—	—	✓