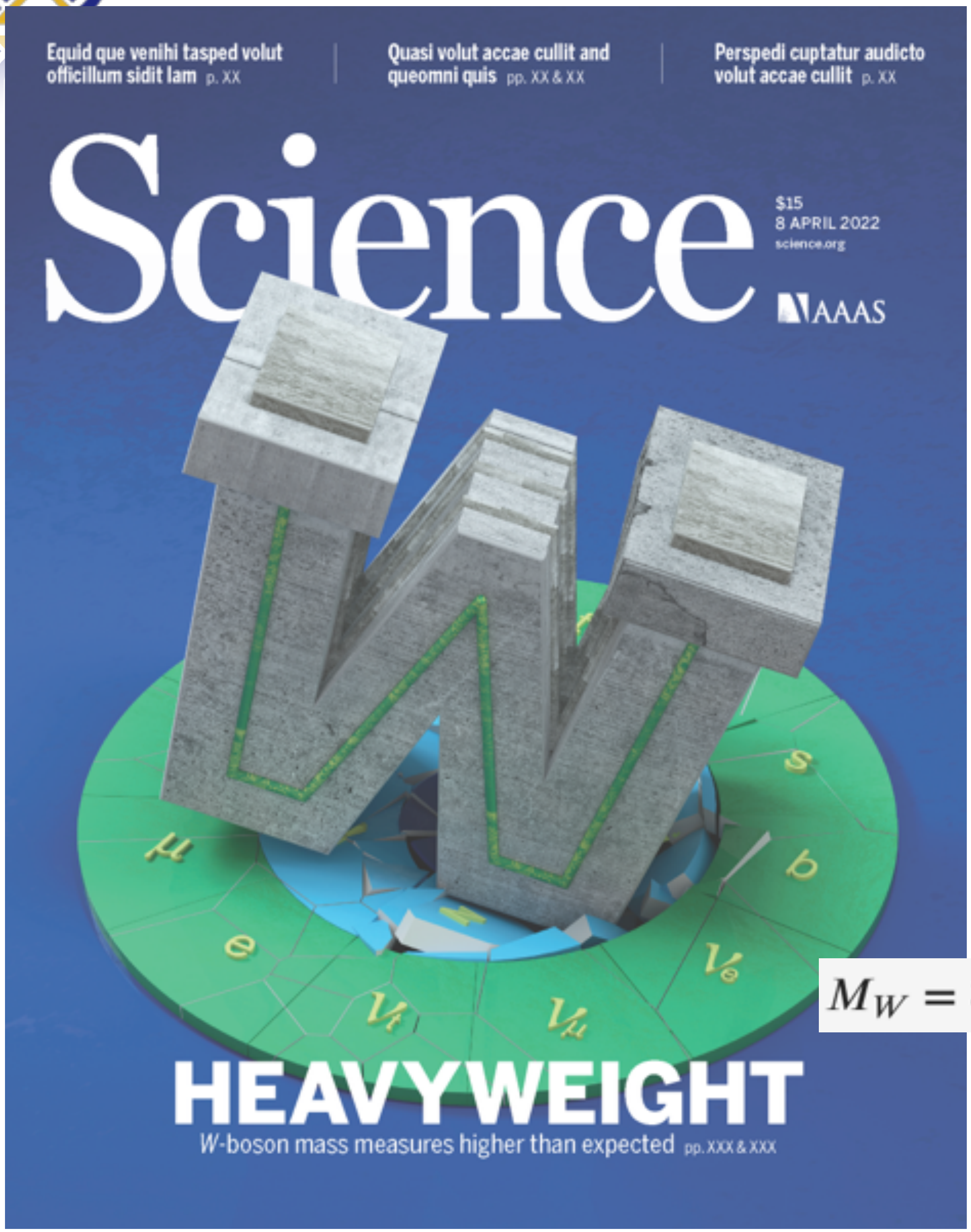
KIAS Workshop on ``**Physics beyond the SM in light of the CDF W boson mass anomaly**'', June 2022

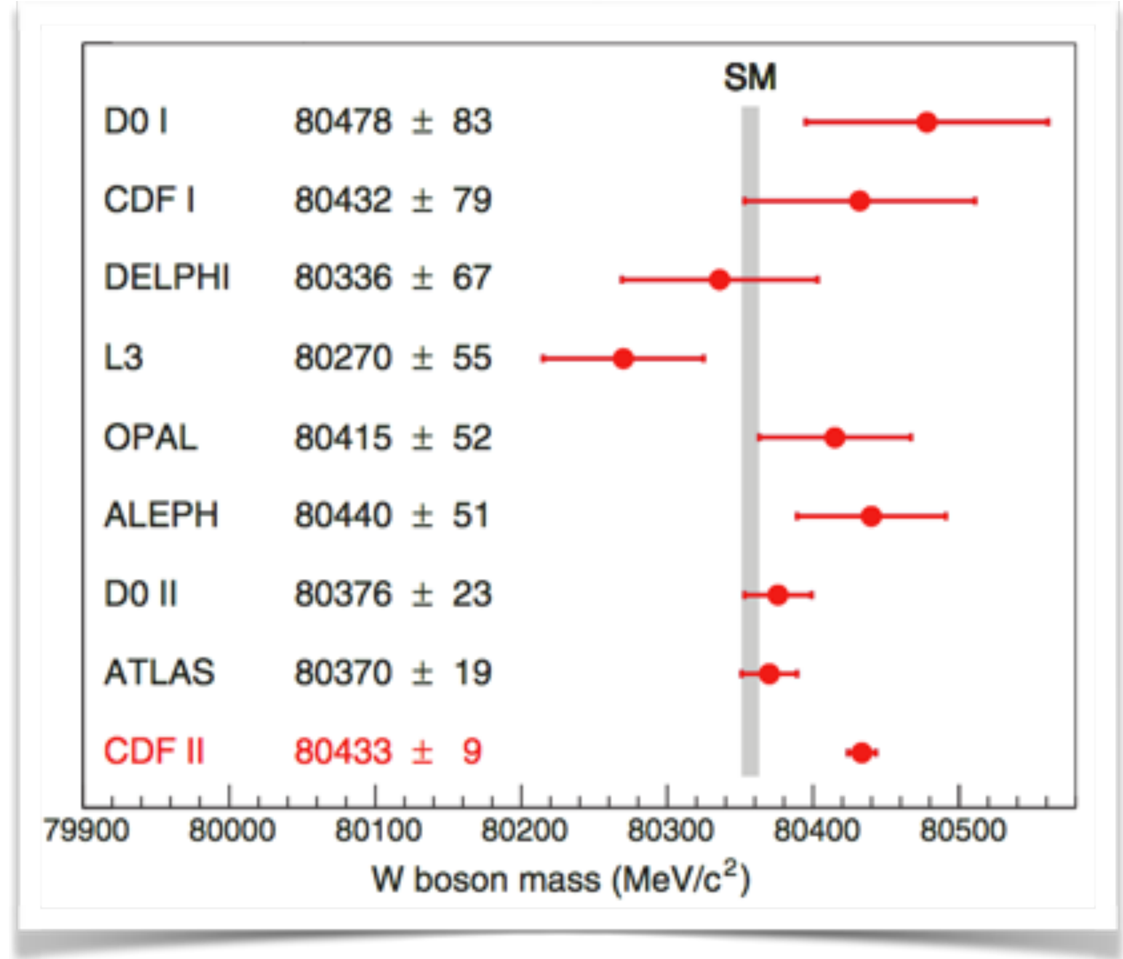
W-boson mass, SMEFT and Future Tests at e+e- Collider

Tao Liu (HKUST)

Based on arXiv:2204.04805, with Ji-Ji Fan, Ling-Feng Li, Kun-Feng Lyu

CDF II W-Boson Mass





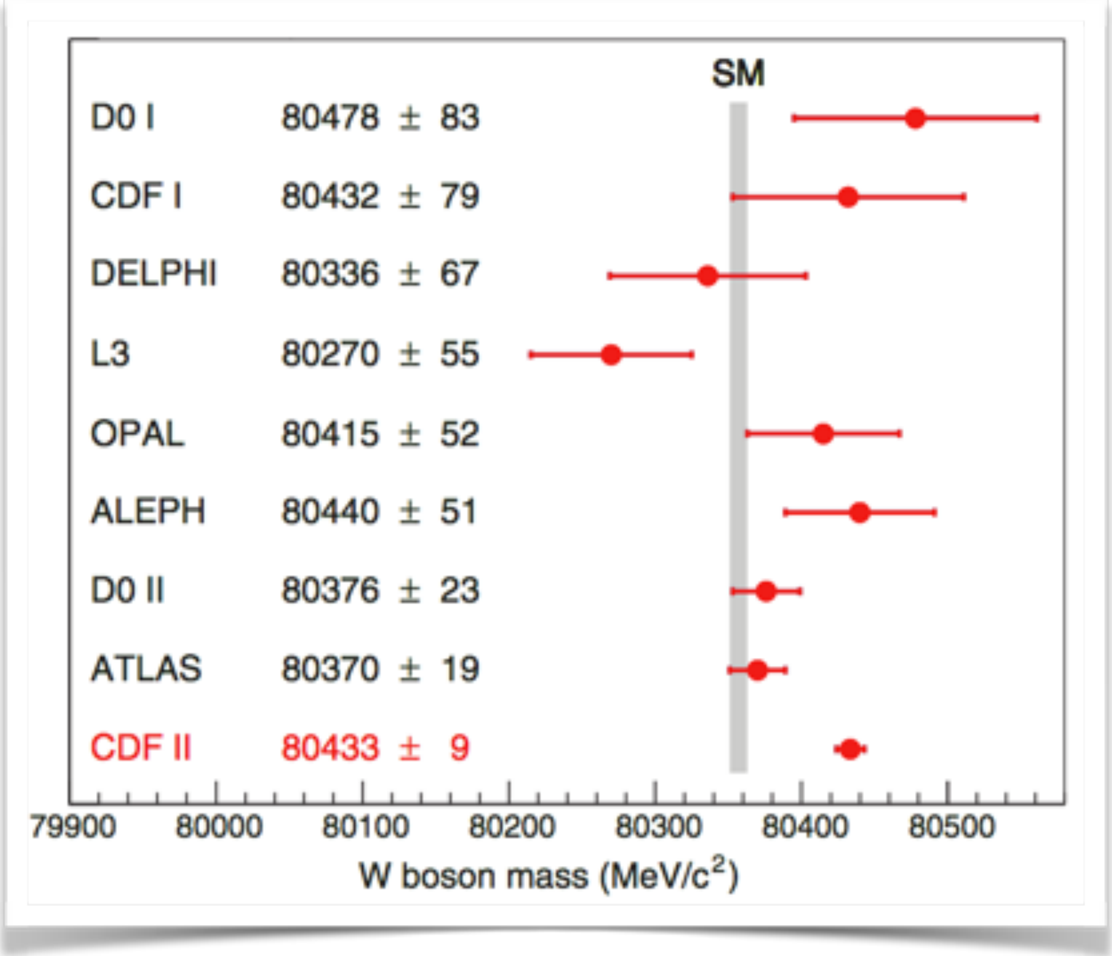
[Science 376 (2022)]

$$M_W = 80{,}433.5 \pm 6.4_{\mathrm{stat}} \pm 6.9_{\mathrm{syst}} = 80{,}433.5 \pm 9.4\ \mathrm{MeV}/c^2$$

VS.

$$M_W = 80{,}357 \pm 4_{\mathrm{inputs}} \pm 4_{\mathrm{theory}}\ \mathrm{MeV}$$

CDF II W-Boson Mass



[Science 376 (2022)]

While making any NP-interpretation, one needs to be cautious, given that significant tension exists between this CDF II result and the direct measurements performed by the D0 collaboration at the Tevatron and the ATLAS/LHCb collaboration at the Large Hadron Collider (LHC) and especially the latter ones are in good agreement with the SM prediction

6D SMEFT

Consider totally six self-contained operators in relation to EWPOs

$$\mathcal{O}_{WB} = gg' H^\dagger \sigma^a H W^a_{\mu\nu} B^{\mu\nu}, \qquad \mathcal{O}_T = \frac{1}{2}(H^\dagger \overleftrightarrow{D}_\mu H)^2,$$
$$\mathcal{O}_L^{(3)l} = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L), \qquad \mathcal{O}_{LL}^{(3)l} = (\bar{L}_L \gamma_\mu \sigma^a L_L)(\bar{L}_L \gamma^\mu \sigma^a L_L),$$
$$\mathcal{O}_L^l = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L), \qquad \mathcal{O}_R^e = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{l}_R \gamma^\mu l_R).$$

Fit with W-boson mass (CDF/PDG), the EWPOs, and one Higgs observable

$$R_b = \frac{\Gamma_b}{\Gamma_{\rm had}}, \quad R_\ell = \frac{\Gamma_{\rm had}}{\Gamma_\ell}, \quad A_f, \quad A_{FB}^f = \frac{3}{4} A_e A_f \quad (f = b, \ell),$$
$$\sin^2\theta_{\rm eff}^{\rm lep} = \frac{1}{4}\left(1 - \frac{g_V^l}{g_A^l}\right), \quad \Gamma_Z, \quad \sigma_{\rm had}^0 = \frac{12\pi}{m_Z^2} \frac{\Gamma_e \Gamma_{\rm had}}{\Gamma_Z^2}, \quad \Gamma_W, \quad {\rm BR}_{W\to{\rm had}}$$

6D SMEFT

$$\frac{\Delta\mathcal{O}}{\mathcal{O}} = C_{\mathcal{O}}^{WB}\frac{c_{WB}}{\Lambda^2} + C_{\mathcal{O}}^{T}\frac{c_T}{\Lambda^2} + C_{\mathcal{O}}^{3L}\frac{c_L^{(3)l}}{\Lambda^2} + C_{\mathcal{O}}^{3LL}\frac{c_{LL}^{(3)l}}{\Lambda^2} + C_{\mathcal{O}}^{L}\frac{c_L^l}{\Lambda^2} + C_{\mathcal{O}}^{R}\frac{c_R^e}{\Lambda^2}$$

$\mathcal{O}$	$C_{\mathcal{O}}^{WB}$	$C_{\mathcal{O}}^{T}$	$C_{\mathcal{O}}^{3L}$	$C_{\mathcal{O}}^{3LL}$	$C_{\mathcal{O}}^{L}$	$C_{\mathcal{O}}^{R}$
m_W	-0.0111	0.0433	-0.0264	0.0264	/	/
A_b	-0.00781	0.0142	-0.0285	0.0285	/	/
R_b	0.00189	-0.00345	0.00691	-0.00691	/	/
R_ℓ	-0.00969	0.0177	-0.159	0.0353	-0.124	0.109
A_{FB}^{ℓ}	-1.01	1.84	-2.41	3.69	1.28	1.46
A_ℓ	-0.583	1.06	-1.38	2.13	0.739	0.843
A_{FB}^{b}	-0.625	1.14	-1.50	2.28	0.784	0.894
Γ_Z	-0.0112	0.079	-0.121	0.158	-0.0113	-0.0113
$\sigma_{\rm had}^0$	0.00142	-0.00259	0.0572	-0.00519	0.152	-0.0895
Γ_W	-0.0322	0.126	-0.174	0.193	/	/
$\mathrm{BR}_{W\to\mathrm{had}}$	/	/	-0.0200	/	/	/
$\sin^2\theta_{\rm eff}^{\rm lep}$	0.0483	-0.0881	0.115	-0.176	-0.0612	-0.0698
$\mu_{ggh}^{\gamma\gamma}/\mu_{\rm SM}$	5.8	/	/	/	/	/

2D Marginalization

- Case (1): $\mathcal{O}_{WB}$ and $\mathcal{O}_T$ only

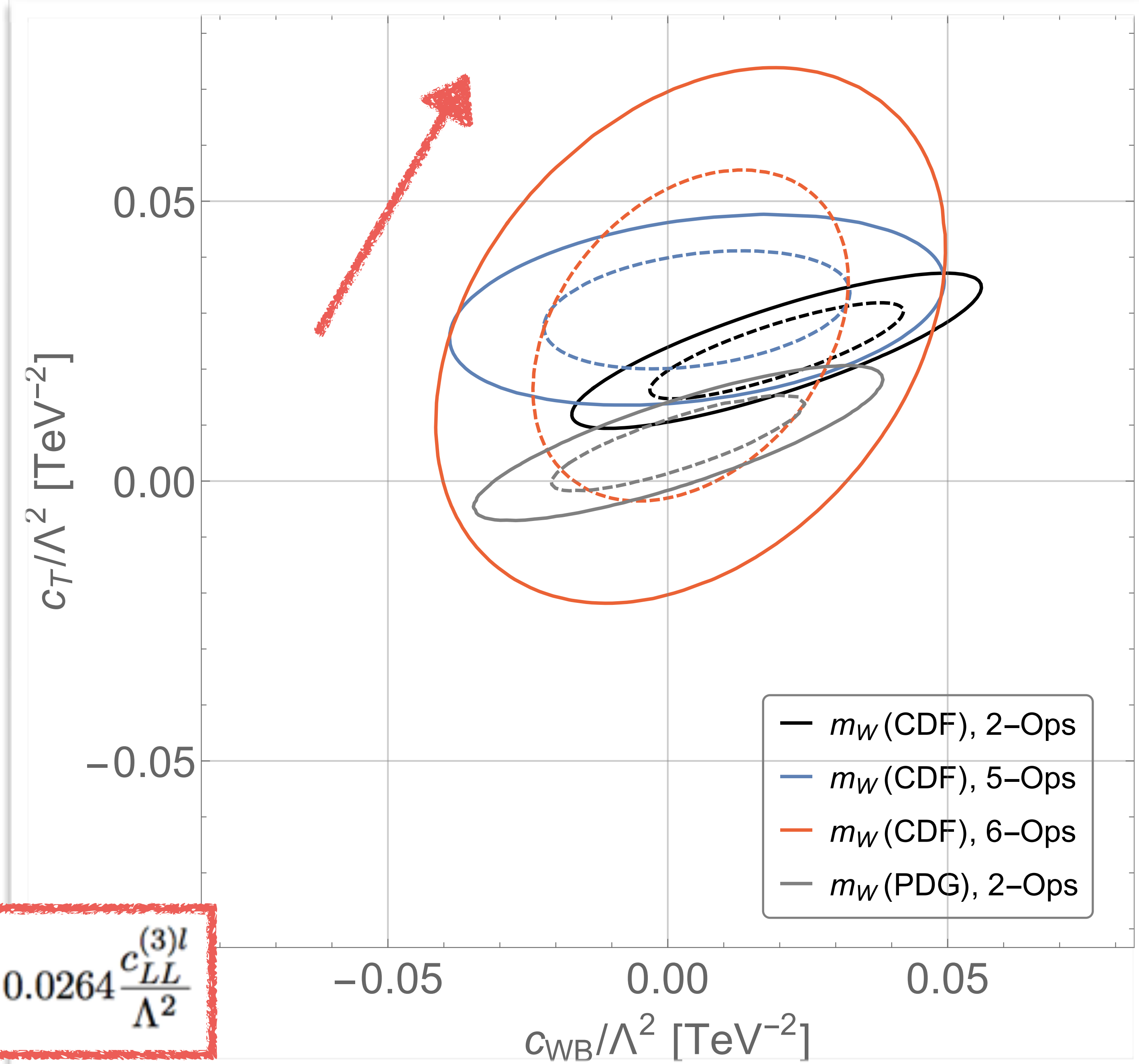
$$S = 16\pi \frac{c_{WB}\, v^2}{\Lambda^2} \approx 3 c_{WB} \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

$$T = \frac{c_T}{\alpha} \frac{v^2}{\Lambda^2} \approx 7.7 c_T \left(\frac{\text{TeV}}{\Lambda}\right)^2$$

- Case (2): five operators except $\mathcal{O}_R^e$
- Case (3): all six operators

To fit the CRF mW, T ~ 0.1 is favored!

$$\frac{\Delta m_W}{m_W} = -0.0111 \frac{c_{WB}}{\Lambda^2} + 0.0433 \frac{c_T}{\Lambda^2} - 0.0264 \frac{c_L^{(3)l}}{\Lambda^2} + 0.0264 \frac{c_{LL}^{(3)l}}{\Lambda^2}$$



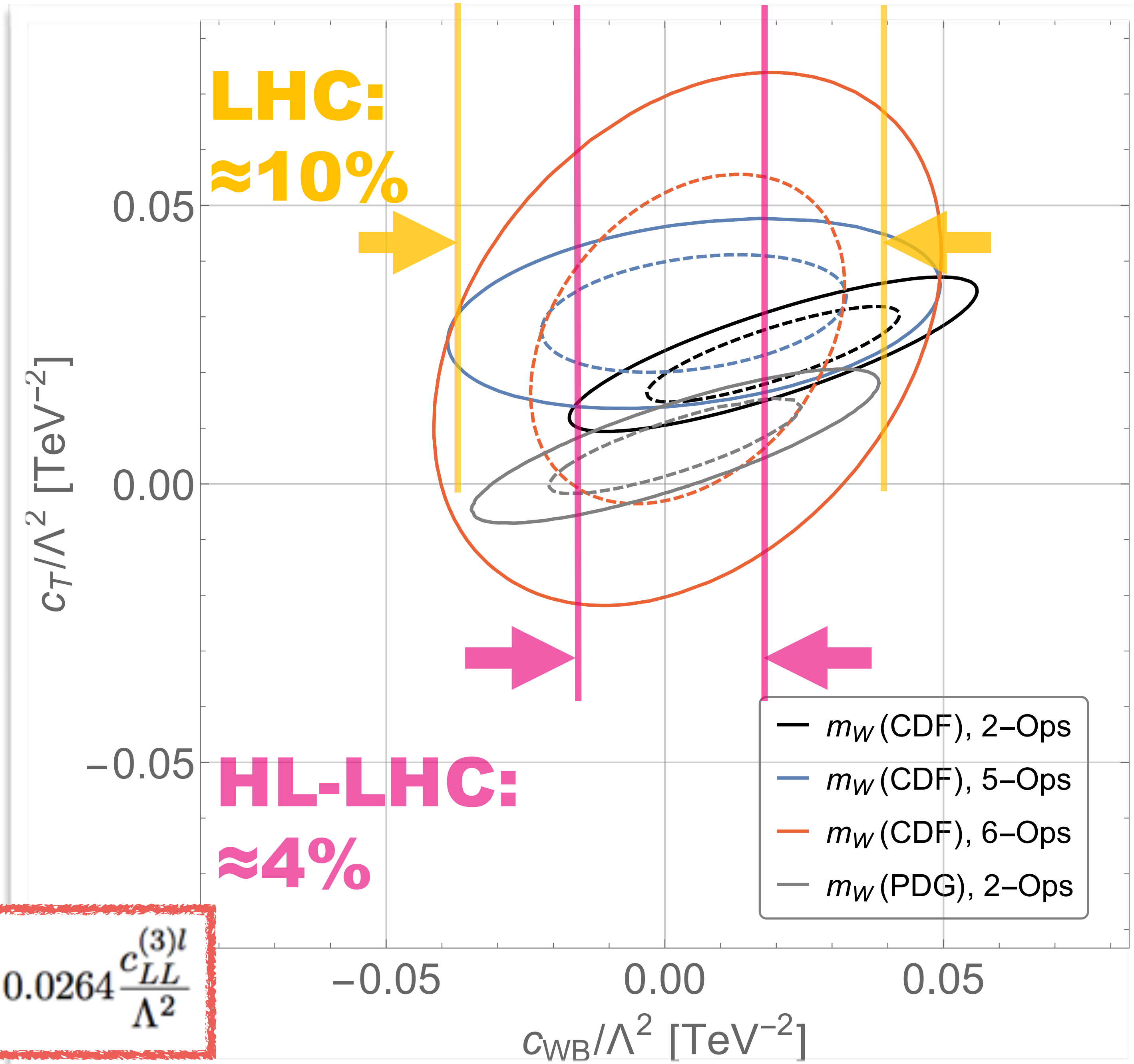
2D Marginalization

- Include the signal strength of Higgs di-photon decay to constrain O_{WB}

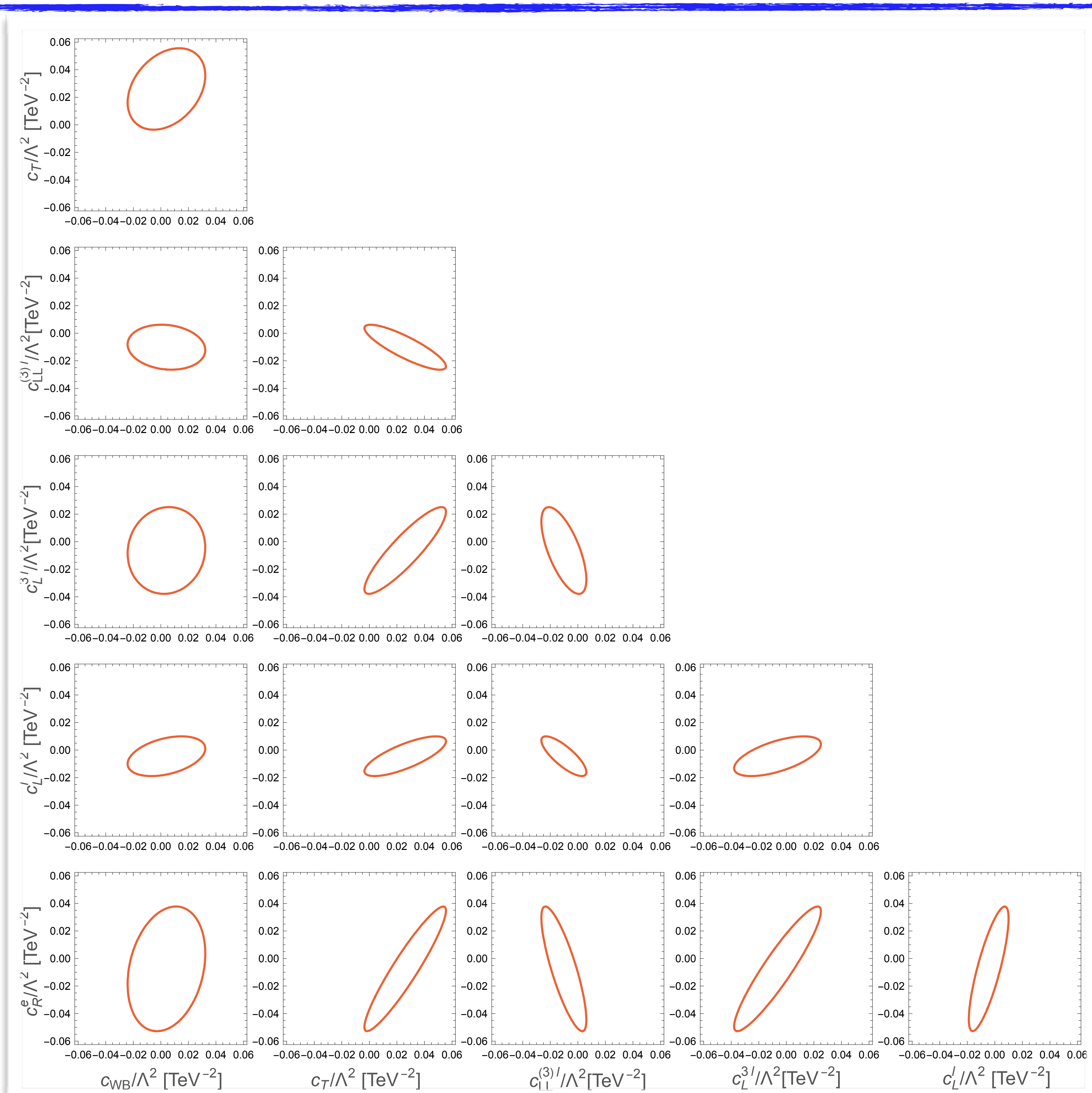
$$\frac{\mu^{\gamma\gamma}_{ggh}}{\mu_{\rm SM}} = \frac{5.8}{\Lambda^2} C_{WB}$$

- Help to constrain O_T to some extent

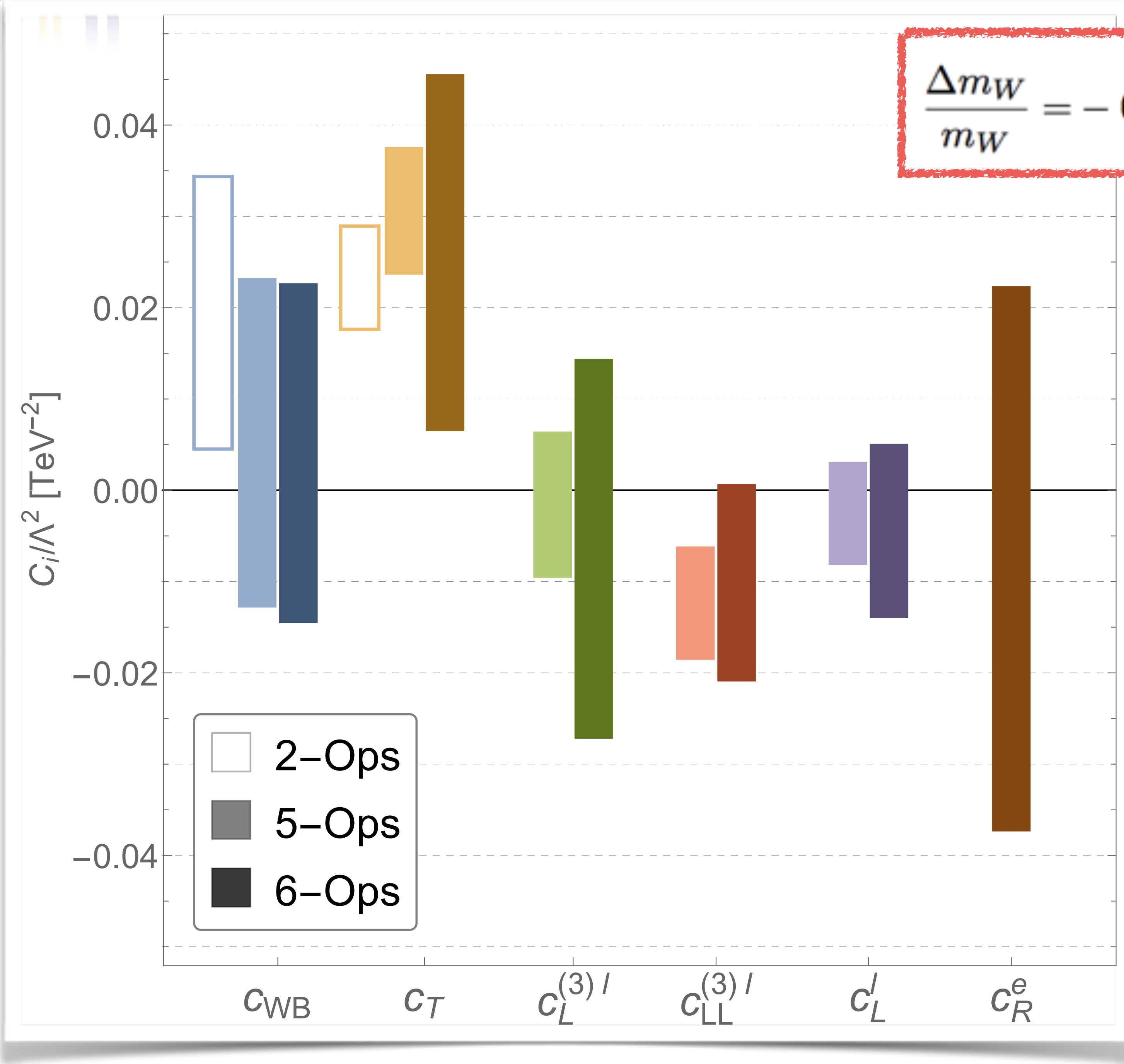
$$\boxed{\frac{\Delta m_W}{m_W} = -0.0111\frac{c_{WB}}{\Lambda^2} + 0.0433\frac{c_T}{\Lambda^2} - 0.0264\frac{c_L^{(3)l}}{\Lambda^2} + 0.0264\frac{c_{LL}^{(3)l}}{\Lambda^2}}$$



2D Marginalization: Case (3)



1D Marginalization



$$\frac{\Delta m_W}{m_W} = -0.0111\frac{c_{WB}}{\Lambda^2} + 0.0433\frac{c_T}{\Lambda^2} - 0.0264\frac{c_L^{(3)l}}{\Lambda^2} + 0.0264\frac{c_{LL}^{(3)l}}{\Lambda^2}$$

A positive C_T is strongly favored: at 68% C.L.

$$C_T > (0.005 - 0.015) \times \frac{\Lambda^2}{\mathrm{TeV}^2}$$

- Tree-level NP ($C_T \sim \mathcal{O}(1)$):

$$\Lambda \lesssim \mathcal{O}(10)\mathrm{TeV}$$

- Loop-level NP ($C_T \sim \mathcal{O}(10^{-2})$):

$$\Lambda \lesssim \mathcal{O}(1)\mathrm{TeV}$$

One Representative NP Scenario

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = \frac{\sum_i \left[4T_i(T_i+1) - Y_i^2\right] |v_i|^2 c_i}{\sum_i 2Y_i^2 |v_i|^2}$$

T_i : SU(2)$_L$ isospin
Y_i : hypercharge
v_i : v.e.v.
c_i : 1 for complex representation
1/2 for real representation

- T=0 (or rho=1): NP with $4T_i(T_i+1) = 3Y_i^2$
  - SM + singlet (1,1,0)
  - SM + doublet (0,2,1)
- T>0 (or rho>1): NP with $4T_i(T_i+1) > 3Y_i^2$
  - SM + A hypercharge-free triplet (Σ) (1,3,0)

$$\mathcal{L} \supset -\lambda H^\dagger \Sigma H \ - \frac{\lambda_3}{2}(H^\dagger H)\Sigma\Sigma, \ \Rightarrow \ T \simeq \frac{1}{\alpha}\frac{2\langle\Sigma\rangle^2}{v^2}$$

Best-fit Point

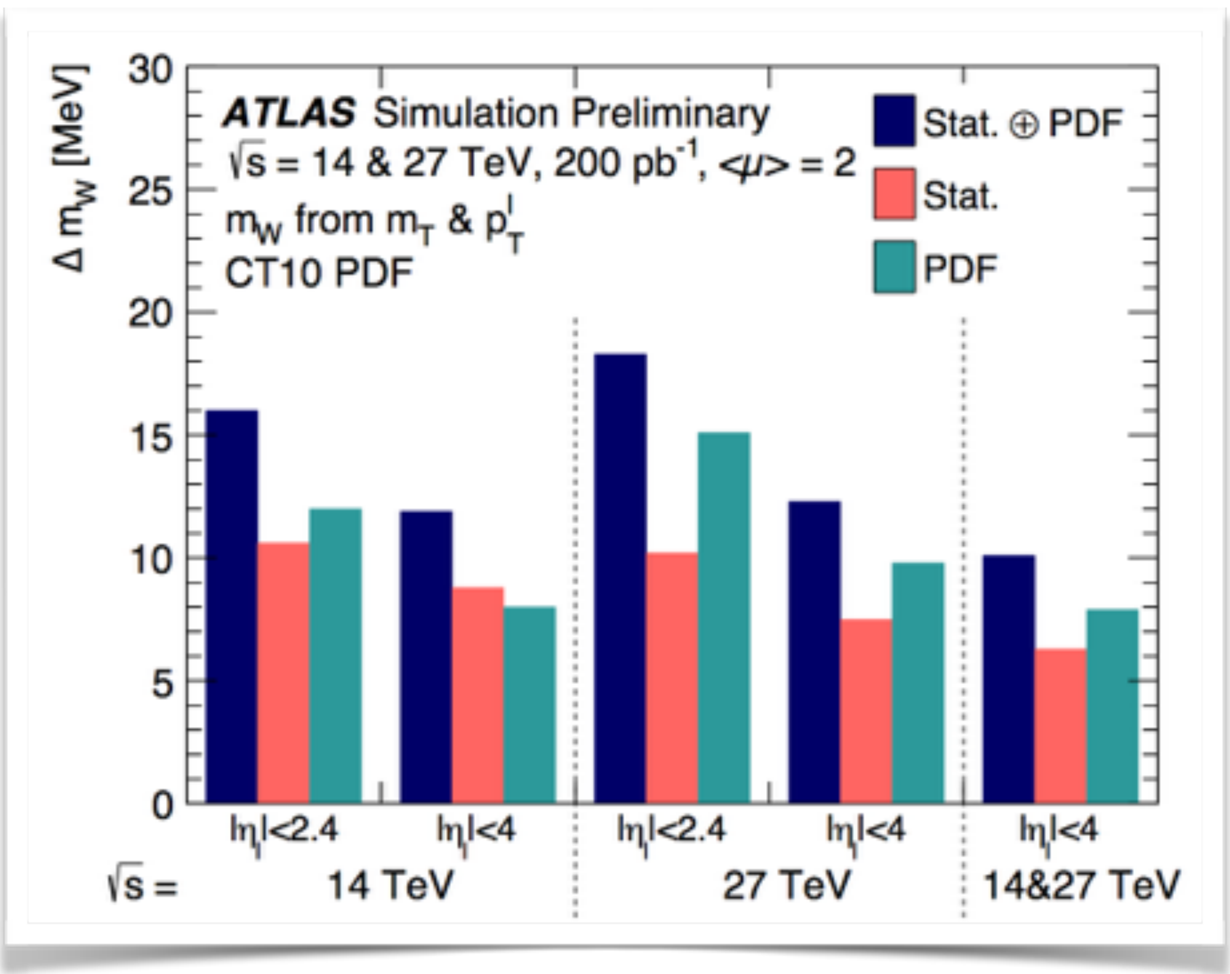
Observables	Case (1)	Case (2)	Case (3)	Experimental Measurement
m_W(GeV)	80.4182	80.4335	80.4335	80.4335 ± 0.0094 [21]
A_b	0.934895	0.93481	0.934944	0.923 ± 0.020 [5, 19]
A_ℓ (P_τ)	0.14889	0.14744	0.14736	0.1465 ± 0.0033 [5, 19]
A_ℓ (SLD)	0.14889	0.14744	0.14736	0.1513 ± 0.0021 [5, 19]
R_b	0.21587	0.21588	0.21587	0.21629 ± 0.00066 [5, 19]
R_ℓ	20.7510	20.7592	20.7634	20.767 ± 0.025 [5, 19]
$A_{\rm FB}^b$	0.10448	0.10340	0.10335	0.0996 ± 0.0016 [5, 19]
$A_{\rm FB}^\ell$	0.01657	0.01629	0.01627	0.0171 ± 0.0010 [5, 19]
Γ_Z(GeV)	2.49818	2.49515	2.49537	2.4955 ± 0.0023 [5]
$\sigma^0_{\rm had}$(nb)	41.4915	41.4729	41.4771	41.480 ± 0.033 [22]
Γ_W(GeV)	2.09262	2.09109	2.09261	2.085 ± 0.042 [5]
${\rm BR}_{W\to{\rm had}}$	0.6748	0.6748	0.6749	0.6741 ± 0.0021 [5]
$\sin^2\theta_{\rm eff}^{\rm lep}(10^{-5})$	23127.7	23146.6	23147.7	(23143 ± 25) [6]
$\mu_{ggh}^{\gamma\gamma}/\mu_{\rm SM}$	1.11	1.03	1.02	1.02 ± 0.11 [23]
χ^2/D.O.F	1.38	1.20	1.34	

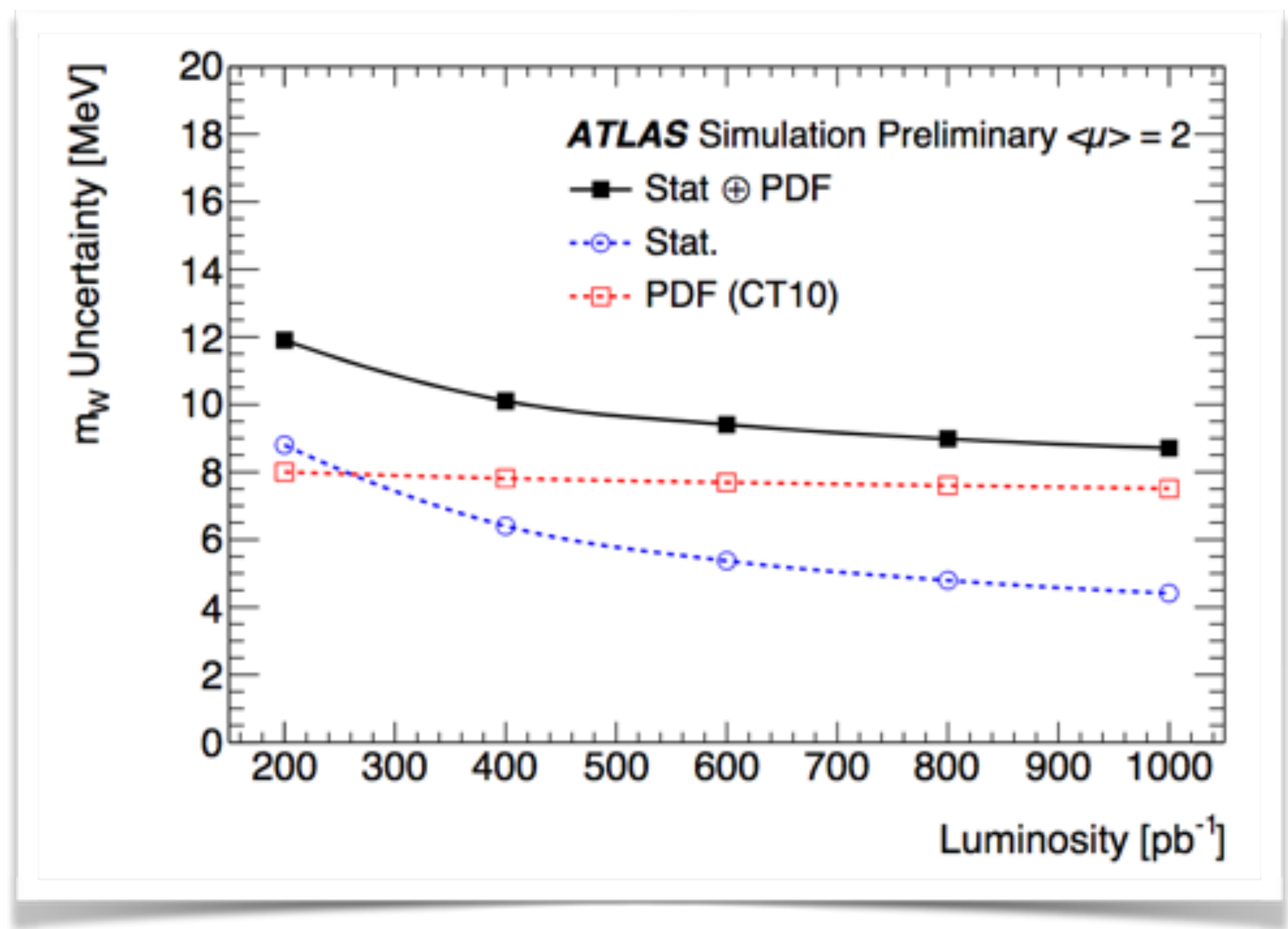
Mw is always well-fit, hence driving the whole fit

More operators may not yield a better fit

W-boson Mass at (HL-)LHC

- Highly challenging in normal environment: systematics such as pileups takes over, making the kinematics reconstruction of W events inaccurate
- Special run with low ins-L and low pile-up: low detector occupancy => optimal reconstruction of missing pT, PDF + Stat becomes dominant



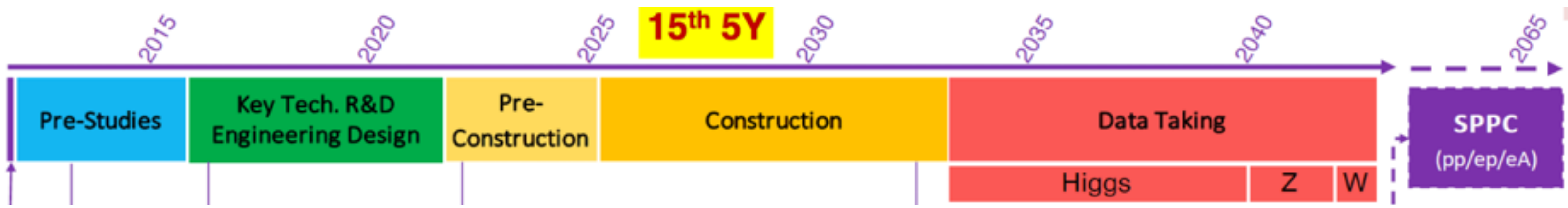


[ATL-PHYS-PUB-2018-026]

Future e+e- Collider

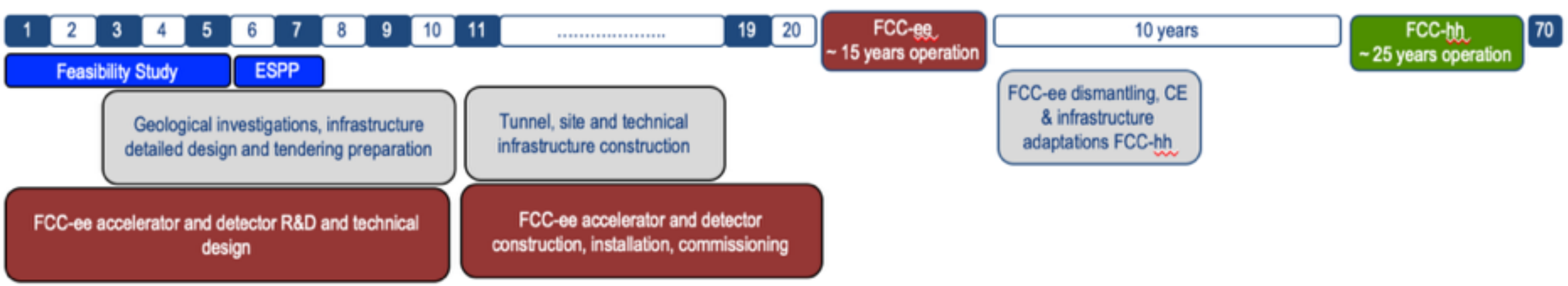
Defines the precision frontier of next decades in Higgs and electroweak physics and has an inborn advantage to measure W-boson mass.

Roadmap of CEPC-SppC/FCC



[From Xinchou Lou, HKUST IAS HEP program (2022)]

2020 +



[From Frank Zimmermann, HKUST IAS HEP program (2022)]

Operation Modes of CEPC/FCC-ee

CEPC Operation mode		ZH	Z	W⁺W⁻	ttbar (new)
$\sqrt{s}$ [GeV]		~ 240	~ 91.2	~ 160	~ 360
Run time [years]		7	2	1	~7.7
CDR	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	3	32	10	
	$\int L\,dt$ [ab^{-1}, 2 IPs]	5.6	16	2.6	
	Event yields [2 IPs]	1×10^6	7×10^{11}	2×10^7	
Latest	L / IP [$\times 10^{34}$ cm^{-2}s^{-1}]	5.0	115	15.4	0.5
	$\int L\,dt$ [ab^{-1}, 2 IPs]	9.3	57.5	4.0	1.0
	Event yields [2 IPs]	1.7×10^6	2.5×10^{12}	3×10^7	3×10^5

[From Xinchou Lou, HKUST IAS HEP program (2022)]

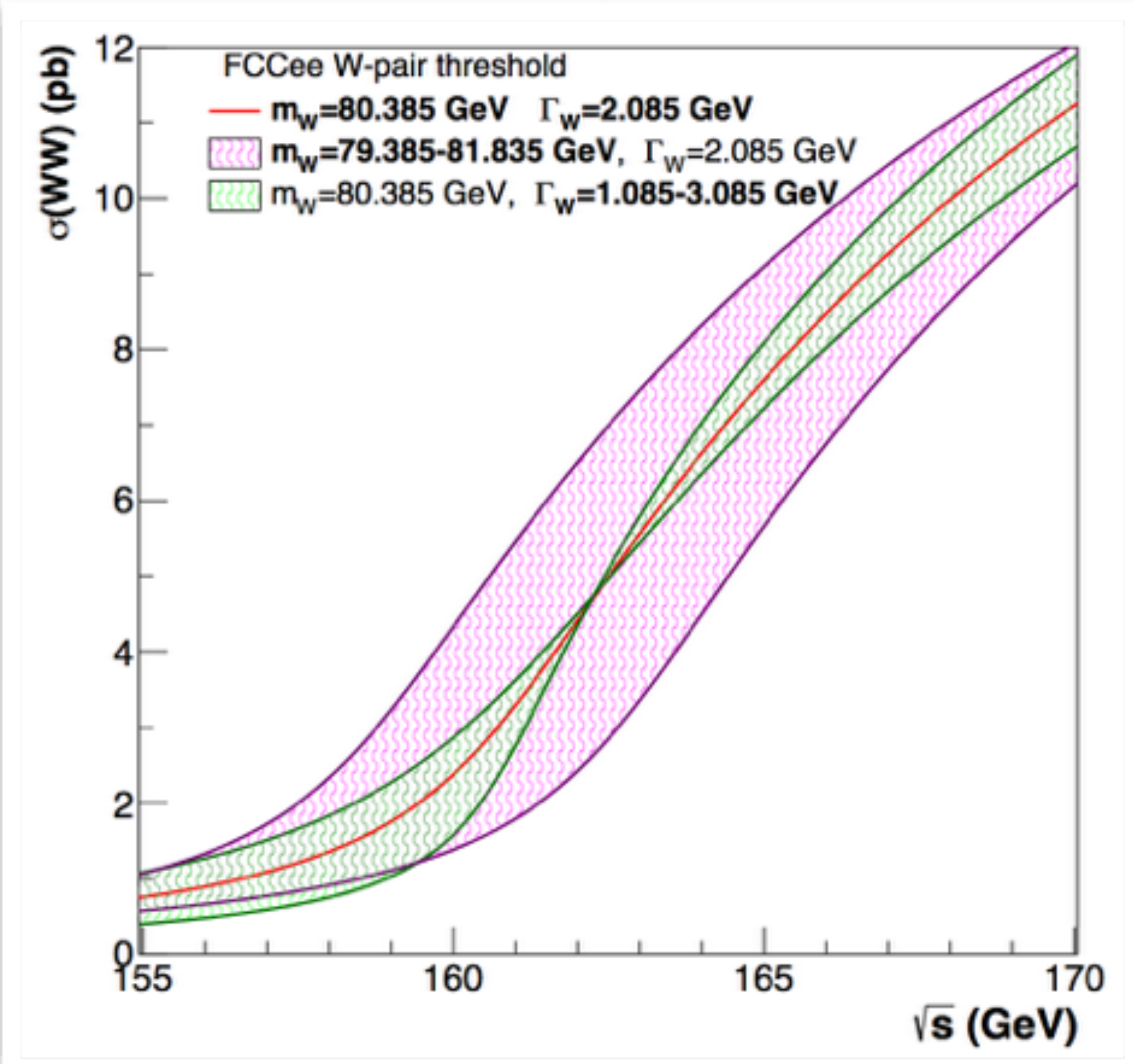
FCC-ee collider parameters

K. Oide

	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1400	135	26.7	5.0
number bunches/beam	8800	1120	336	42
bunch intensity [10^{11}]	2.76	2.29	1.51	2.26
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.48/0	4.0/7.67
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.15	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
ontal geometric emittance [nm]	0.71	2.17	0.64	1.49
al geom. emittance [pm]	1.42	4.34	1.29	2.98
ontal rms IP spot size [μm]	10	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.32 / 15.2	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54
luminosity per IP [10^{34} cm^{-2}s^{-1}]	181	17.3	7.2	1.25
total integrated luminosity / year [ab^{-1}/yr]	86	8	3.4	0.6
beam lifetime rad Bhabha / BS [min]	19 / ?	20 / ?	10 / 19	12 46

[From Frank Zimmermann,
HKUST IAS HEP program (2022)]

Methods of Measuring W-boson Mass at e+e- Collider



- Threshold scan: relies on rapid rise of the W-pair production near its kinematic threshold.
  - Simple and clean: involving event selection and counting only
  - 12/ab data equally shared between 157.5-162.5 GeV => $\Delta M_W \sim 0.5\mathrm{MeV}$ (stat)
- Kinematic reconstruction: exploits the W-pair final state reconstruction and kinematic fit.
  - Less influenced by statistical uncertainty
  - Combining data at WW threshold and 240-365 GeV => $\Delta M_W \sim 0.5\mathrm{MeV}$ (stat)

[FCC CDR, vol. 1]

Methods of Measuring W-boson Mass at e+e- Collider

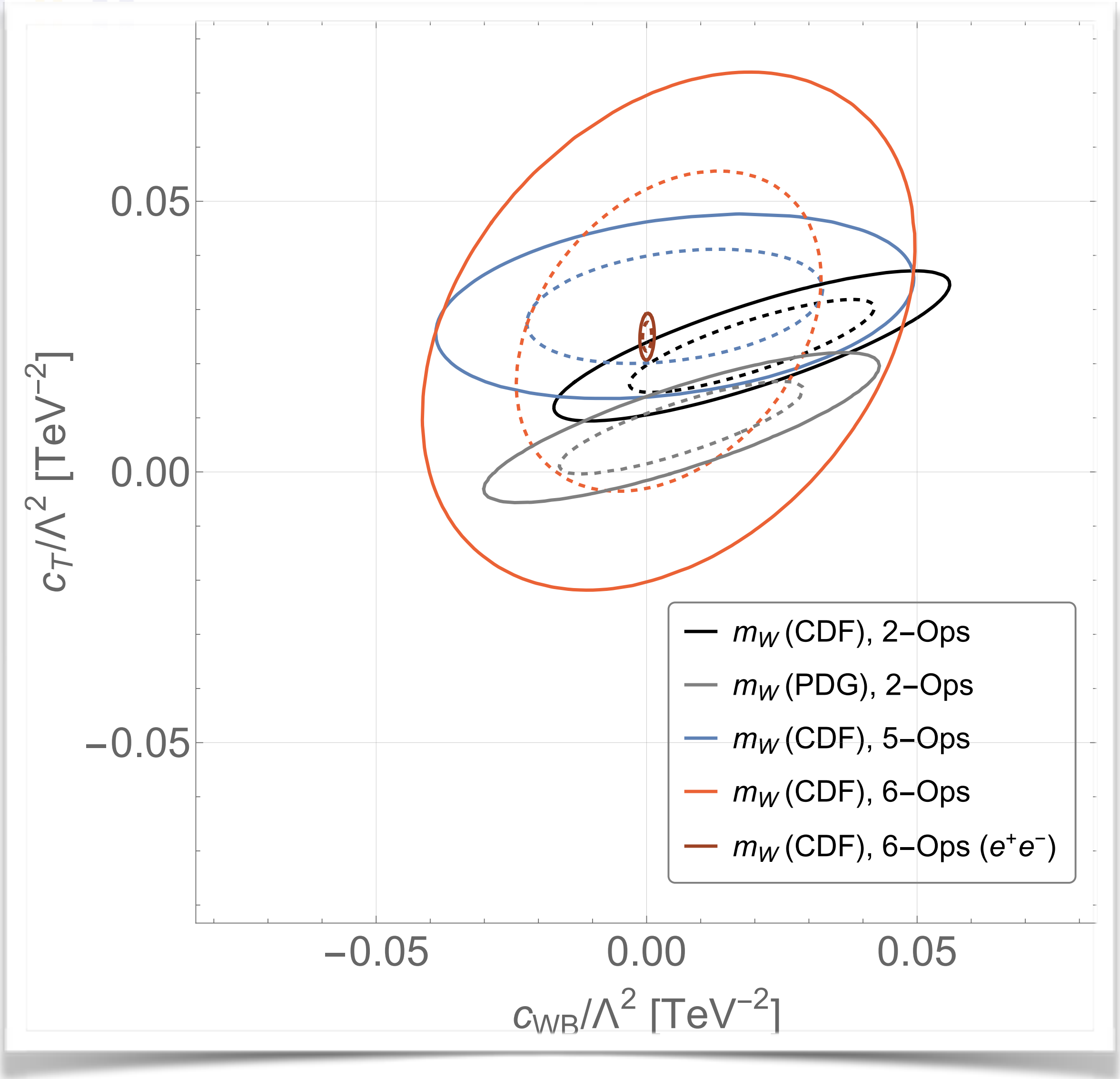
Observable	LEP precision	CEPC precision	CEPC runs	CEPC $\int \mathcal{L}dt$
m_Z	2.1 MeV	0.5 MeV	Z pole	8 ab^{-1}
Γ_Z	2.3 MeV	0.5 MeV	Z pole	8 ab^{-1}
$A_{FB}^{0,b}$	0.0016	0.0001	Z pole	8 ab^{-1}
$A_{FB}^{0,\mu}$	0.0013	0.00005	Z pole	8 ab^{-1}
$A_{FB}^{0,e}$	0.0025	0.00008	Z pole	8 ab^{-1}
$\sin^2\theta_W^{\text{eff}}$	0.00016	0.00001	Z pole	8 ab^{-1}
R_b^0	0.00066	0.00004	Z pole	8 ab^{-1}
R_μ^0	0.025	0.002	Z pole	8 ab^{-1}
m_W	33 MeV	1 MeV	WW threshold	2.6 ab^{-1}
m_W	33 MeV	2–3 MeV	ZH run	5.6 ab^{-1}
N_ν	1.7%	0.05%	ZH run	5.6 ab^{-1}

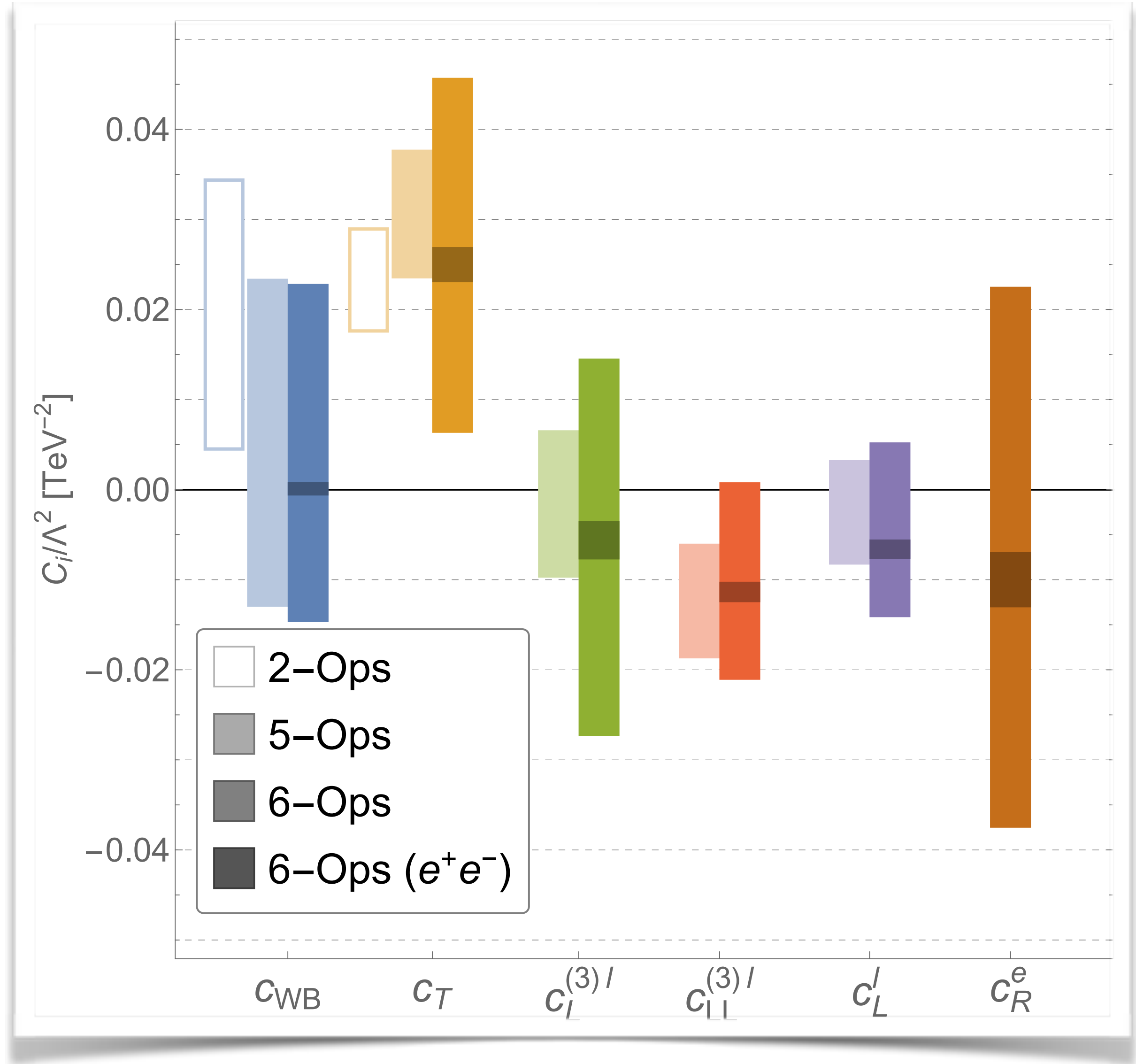
[CEPC CDR, vol. II]

[FCC CDR, vol. 1]

Observable	present value ± error	FCC-ee Stat.	FCC-ee Syst.	Comment and dominant exp. error
m_W (MeV)	80350 ± 15	0.6	0.3	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2085 ± 42	1.5	0.3	From WW threshold scan Beam energy calibration
$\alpha_s(m_W)(\times 10^4)$	1170 ± 420	3	small	from R_ℓ^W [43]
$N_\nu(\times 10^3)$	2920 ± 50	0.8	small	ratio of invis. to leptonic in radiative Z returns

W-boson Mass at Future e+e- Collider





Combination of the FCCee precisions and the current central values of the set of observables => CT can be tested with more than 10sigma away from its null limit

Theoretical Uncertainties

Quantity	FCC-ee	future parametric unc.	Main source
M_W [MeV]	$0.5 - 1$	1 (0.6)	$\delta(\Delta\alpha)$
$\sin^2\theta^{\ell}_{\rm eff}$ [10^{-5}]	0.6	2 (1)	$\delta(\Delta\alpha)$
Γ_Z [MeV]	0.1	0.1 (0.06)	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3 (0.7)	$\delta\alpha_s$

Quantity	FCC-ee	Current intrinsic error		Projected intrinsic error
M_W [MeV]	0.5–1[‡]	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^{\ell}_{\rm eff}$ [10^{-5}]	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.4	$(\alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.15
R_b [10^{-5}]	6	11	$(\alpha^3, \alpha^2\alpha_s)$	5
R_l [10^{-3}]	1	6	$(\alpha^3, \alpha^2\alpha_s)$	1.5

[A. Freitas, S. Heinemeyer et. al., 1906.05379]

Question: Can the theory interpretation of m_W catch-up with the experiment progress by the time of the future e+e- collider runs?

Summary

- In the SMEFT, an upward shift of mW is mainly driven by the O_T operator
- The favored NP scale could be within the reach of current and near-future LHC searches
  - Tree-level NP: $\Lambda \lesssim \mathcal{O}(10)\mathrm{TeV}$
  - Loop-level NP: $\Lambda \lesssim \mathcal{O}(1)\mathrm{TeV}$
- Future e+e- colliders have an inborn advantage to measure W physics and test the relevant SMEFT
- We need to be open for all possibilities, to finally reveal the truth on this anomaly … …

大學教育資助委員會
University Grants Committee

AoE under grant No. AoE/P-404/18-3

GRF under grant No. 16305219

Thank you!