LFC24 Fundamental Interactions at Future Colliders
September 17, 2024

Present and Future of Electroweak Precision Tests

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Introduction

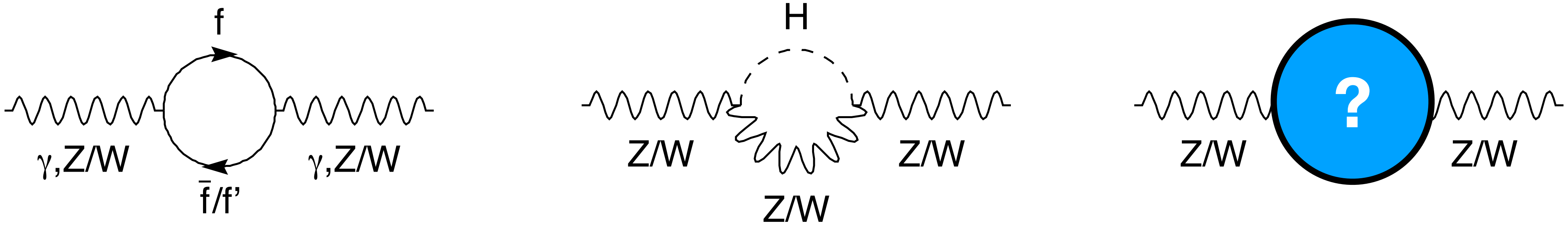
- The Standard Model is the most successful theory we have in particle physics:

  To a large extent this is known thanks to the Electroweak Precision Tests (Comparison of SM with the so-called Electroweak Precision Observables)

- Electroweak Precision Observables (EWPO)
  - Traditionally EWPO refers to a set of observables that, interpreted within the SM, allows the determination of the Z & W properties
  - Their measurements, mostly from LEP/SLD but also Tevatron/LHC, are some of the most precise we have, in many cases at per mile level

- Enough to test the quantum structure of the SM to the 2-loop level!

- The importance of precision: The more we have, the farther we can go in testing the limits of the Standard Model $\Longrightarrow$ Indirect search of New Physics



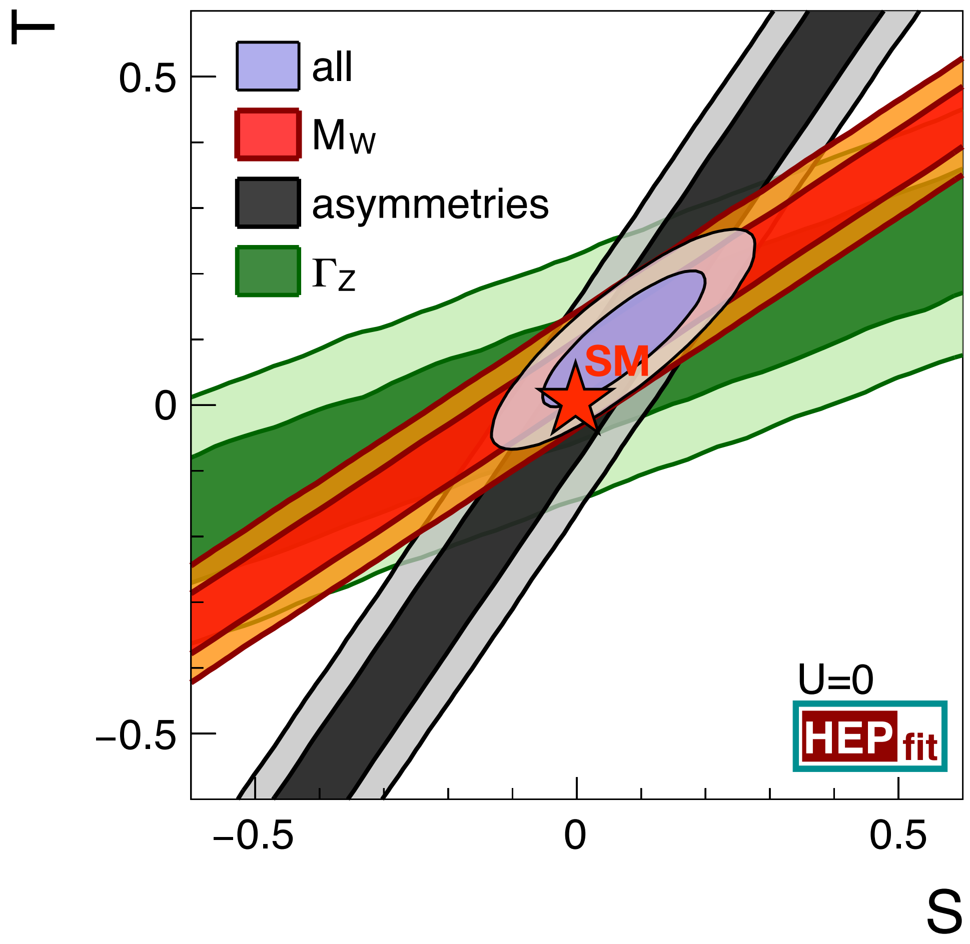
Separate SM vs NP: Precision means both experimental and theoretical!

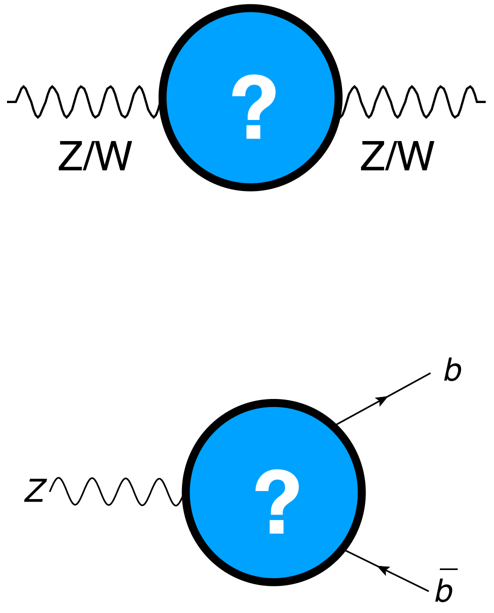
Introduction

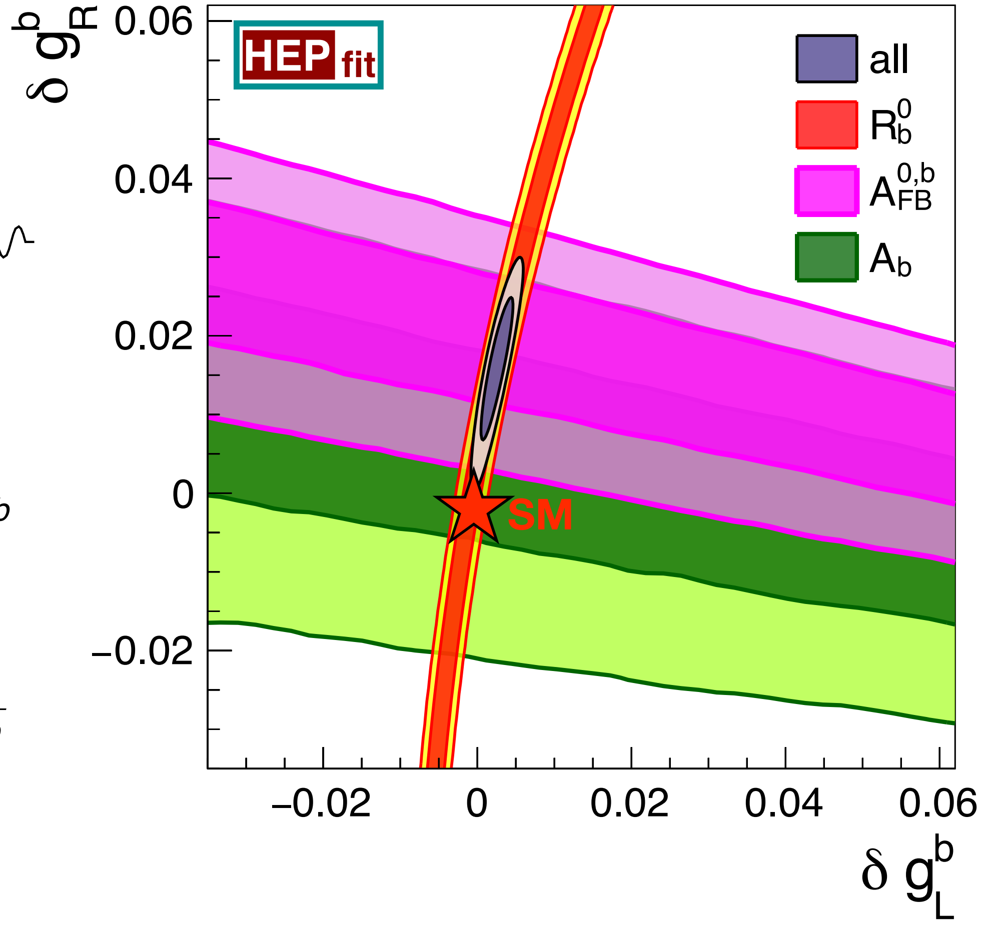
EW precision measurements as complement to high-energy collider searches

2012: All SM parameters are known

EWPO even more relevant after the Higgs discovery in the search of new physics







Agreement/deviation with/wrt SM predictions gives information (constraints/evidence) about new physics

Precision means both experimental and theoretical!

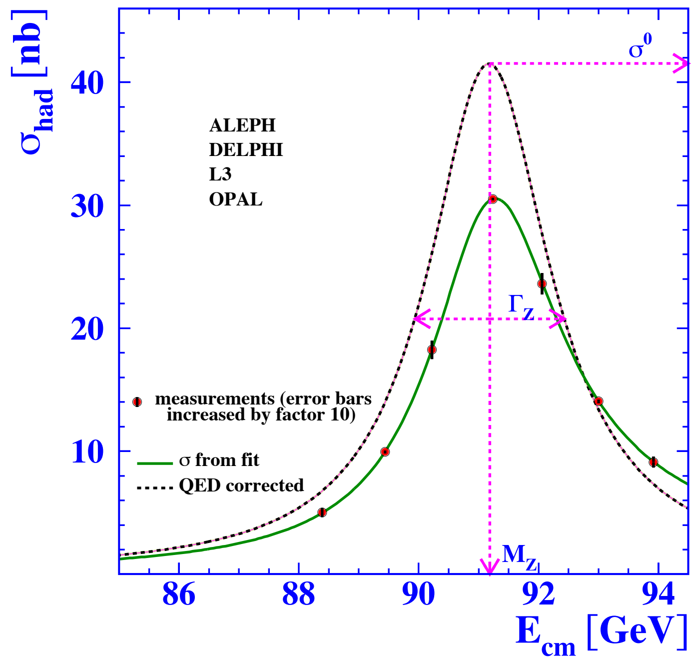
Status of
Electroweak Precision Observables

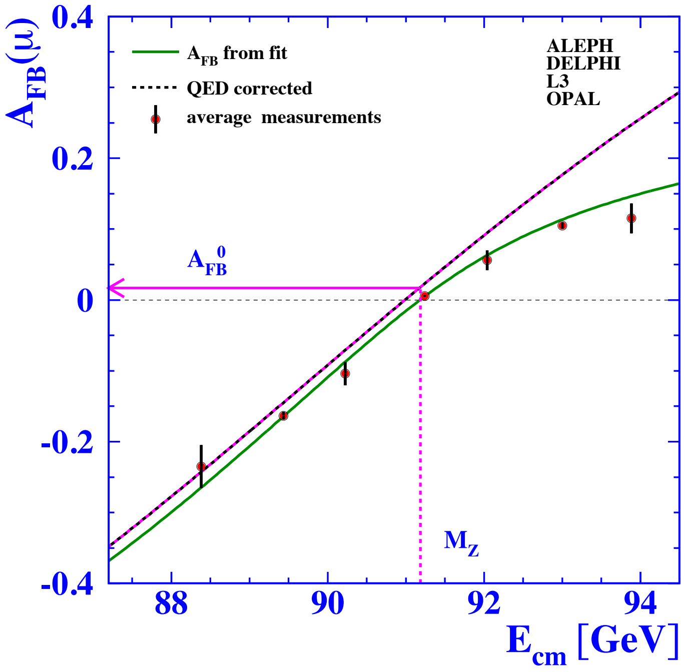
Electroweak precision observables: Z-pole

- Z pole observables: mainly coming from the LEP/SLC era

$$\boxed{M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P_\tau^{\rm pol},\ A_f,\ A^{0,f}_{FB},\ R^0_f}$$

Z-pole obs.
(LEP/SLC)
$0.002\text{-}O(1)\%$





LEP and SLD Collaborations, arXiv: 0509008 [hep-ex]

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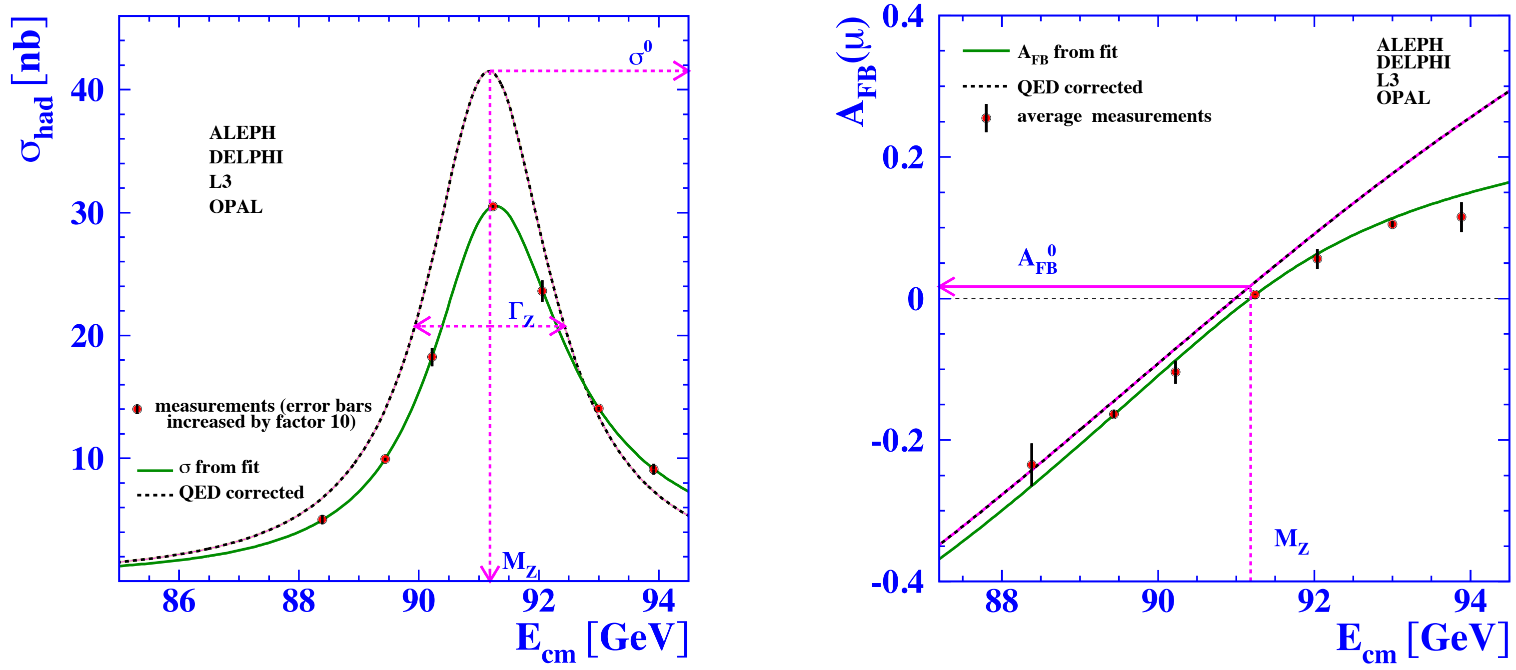


LEP and SLD Collaborations, arXiv: 0509008 [hep-ex]

Results depend on measuring precisely the integrated luminosity (L)
Obtained via low-angle Bhabha scattering (known to 0.061% during LEP era)

- Recently revisited using updated (more accurate) prediction of Bhabha process:
  - ✓ New corrections decrease the Bhabha cross section by 0.048% (uncertainty 0.037%) **P. Janot, S. Jadach, Phys.Lett.B 803 (2020) 135319**

$\sigma_{\rm Bhabha}$ ↘ ➡ L ↗ ➡ Measured $\sigma_{\rm had}$ ↘

Electroweak precision observables: Z-pole

- Z pole observables: mainly coming from the LEP/SLC era

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$

Z-pole obs. (LEP/SLC)

0.002-$\mathcal{O}(1)\%$

Z -lineshape observables

Observable	Experimental
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010

$\longrightarrow$

91.1875 ± 0.0021
2.4955 ± 0.0023
41.4802 ± 0.0325
20.767 ± 0.025
0.0171 ± 0.0010

0.002% - 5% precision

The updated results remove past tension with SM in the value of the effective # of ν : N_ν

$$R^0_{\rm inv} = \left(\frac{12\pi R^0_\ell}{\sigma^0_{\rm had} M_Z^2}\right)^{\frac{1}{2}} - R^0_\ell - (3+\delta_\tau) = N_\nu \left(\frac{\Gamma_{\nu\bar{\nu}}}{\Gamma_{\ell\ell}}\right)_{\rm SM}$$

$$N_\nu = 2.9840 \pm 0.0082 \ \ (\sim 2\sigma) \longrightarrow N_\nu = 2.9963 \pm 0.0074 \ \ (0.5\sigma)$$

Electroweak precision observables: Z-pole

- Z pole observables: Heavy flavor measurements from LEP/SLC

$$\boldsymbol{M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f}$$

Z-pole obs.
(LEP/SLC)
0.002-$\mathcal{O}(1)$%

LEP/SLD combination		$R^0_{\rm b}$	$R^0_{\rm c}$	$A^{0,\,\rm b}_{\rm FB}$	$A^{0,\,\rm c}_{\rm FB}$	$\mathcal{A}_{\rm b}$	$\mathcal{A}_{\rm c}$
$R^0_{\rm b}$	0.21629 ± 0.00066	1.00					
$R^0_{\rm c}$	0.1721 ± 0.0030	-0.18	1.00				
$A^{0,\,\rm b}_{\rm FB}$	0.0996 ± 0.0016	-0.10	0.04	1.00			
$A^{0,\,\rm c}_{\rm FB}$	0.0707 ± 0.0035	0.07	-0.06	0.15	1.00		
$\mathcal{A}_{\rm b}$	0.923 ± 0.020	-0.08	0.04	0.06	-0.02	1.00	
$\mathcal{A}_{\rm c}$	0.670 ± 0.027	0.04	-0.06	0.01	0.04	0.11	1.00

0.3%, 2-5% Precision

- A_{FB}^b also revisited recently, including:

D. D'Enterria, C. Yan, arXiv: 2011.00530 [hep-ph]

✓ Reassessment of QCD uncertainties using modern Parton showers (Pythia 8)

✓ NNLO (2-loop) massive b-quark corrections

$$A^{0,b}_{\rm FB} = 0.0992 \pm 0.0016 \longrightarrow 0.0996 \pm 0.0016$$

(Stat dominated)

✓ New corrections tend to reduce the discrepancy with the SM

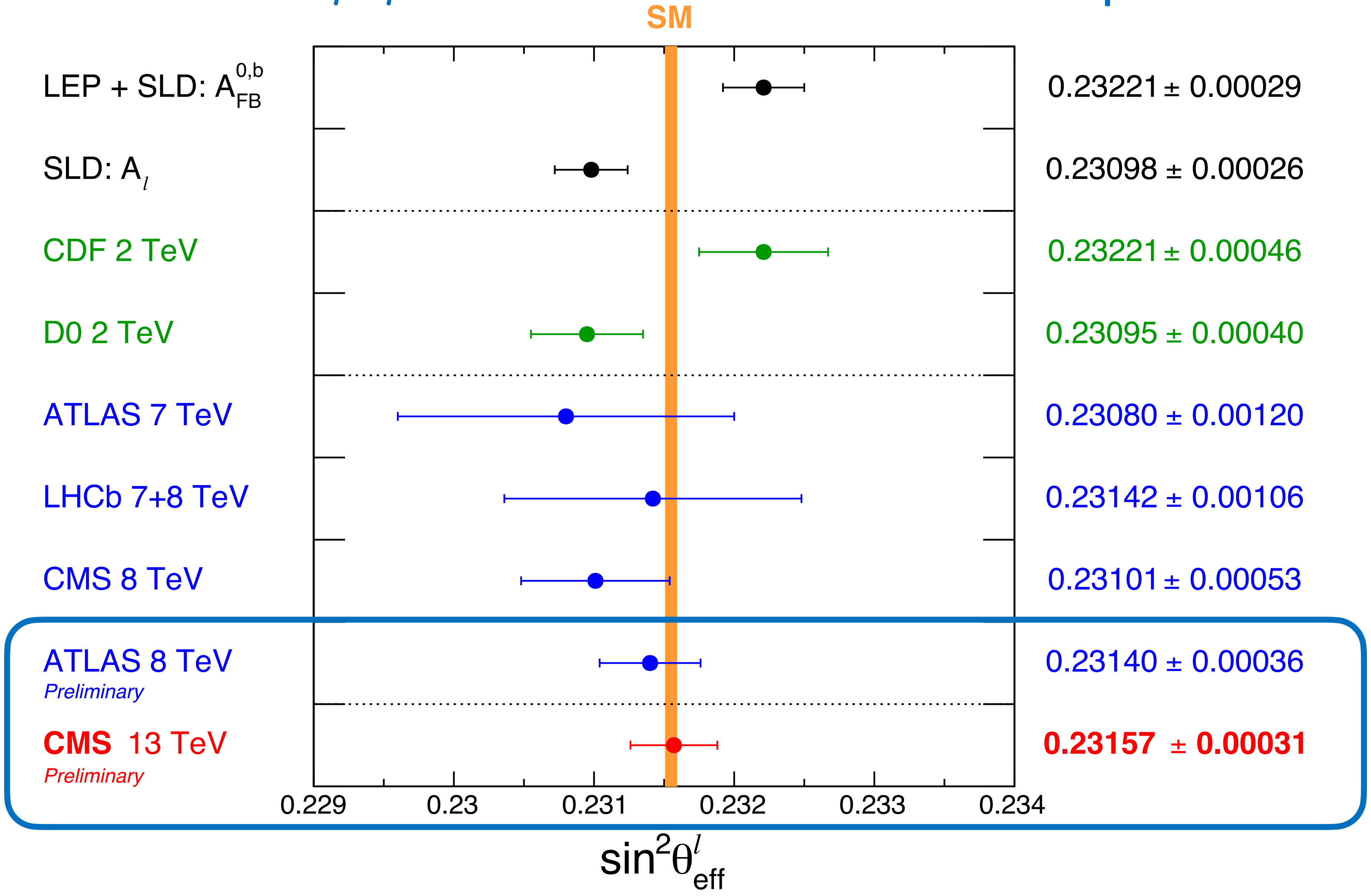
Electroweak precision observables: Z-pole

- Effective weak mixing angle at hadron colliders:
  - ✓ LEP/SLC determination from fermion asymmetries A_f/A_{FB}^f:

$$\sin^2\theta_{\rm eff}^{\rm lept}\Big|_{\rm LEP+SLC} = 0.23151 \pm 0.00016$$

0.07% Precision

  - ✓ Hadron colliders can measure same quantity via A_{FB} in Drell-Yan for e^+e^- and $\mu^+\mu^-$ final states, with invariant dilepton masses around M_Z



Measurement	$\sin^2\theta^l_{\rm eff}$
LEP + SLD: $A_{FB}^{0,b}$	0.23221 ± 0.00029
SLD: A_l	0.23098 ± 0.00026
CDF 2 TeV	0.23221 ± 0.00046
D0 2 TeV	0.23095 ± 0.00040
ATLAS 7 TeV	0.23080 ± 0.00120
LHCb 7+8 TeV	0.23142 ± 0.00106
CMS 8 TeV	0.23101 ± 0.00053
ATLAS 8 TeV *Preliminary*	0.23140 ± 0.00036
CMS 13 TeV *Preliminary*	**0.23157 ± 0.00031**

ATLAS/CMS measurements with uncertainty comparable to individual LEP/SLC (+ consistent with each other)

Electroweak precision observables: Z-pole

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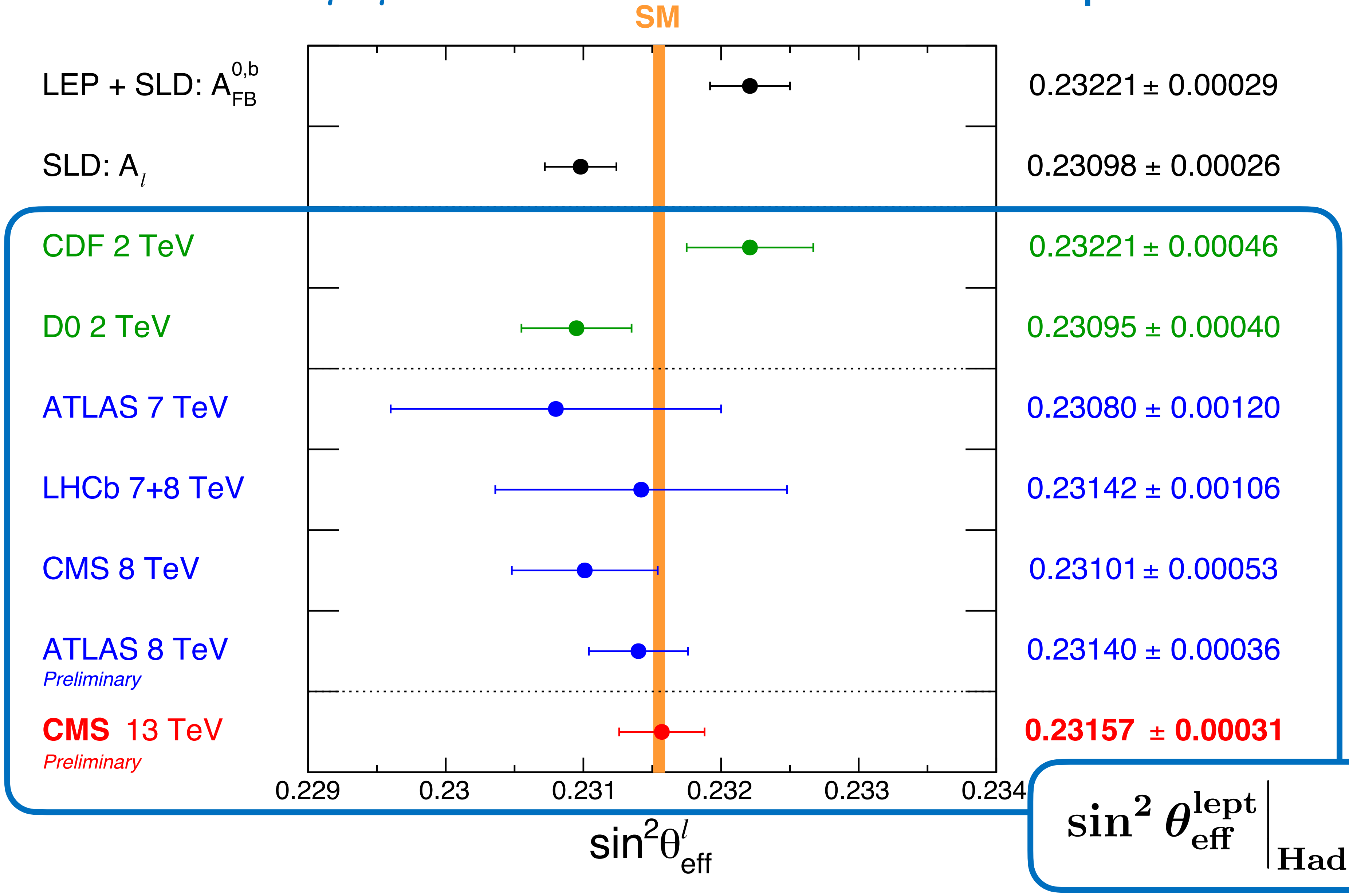


$$\sin^2\theta_{\rm eff}^{\rm lept}\Big|_{\rm Had.Coll.} = 0.23146 \pm 0.00021$$

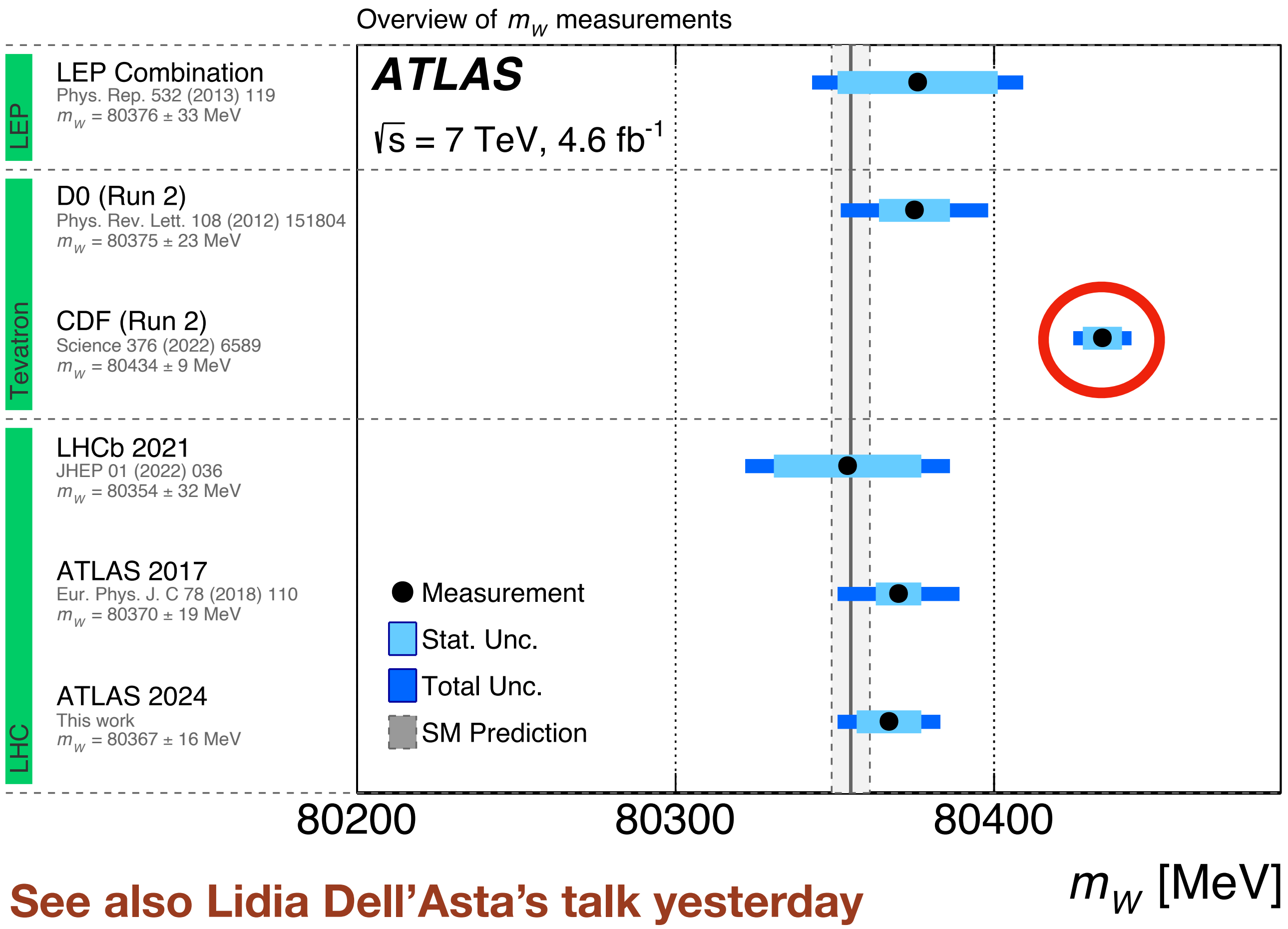
Electroweak precision observables: W properties

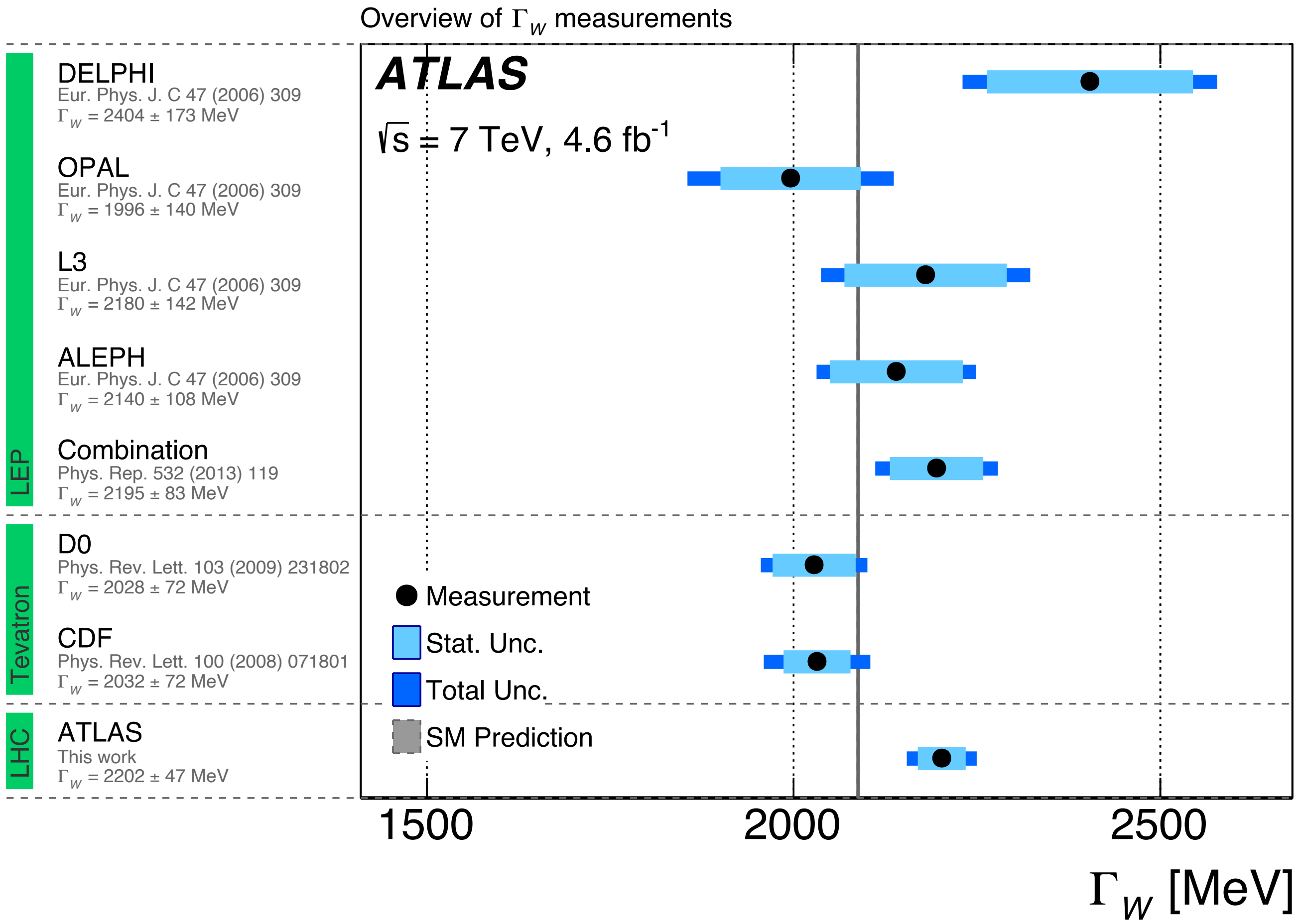
- Experimental measurements of M_W and Γ_W:

To be updated with CMS results in ~1h

$$\boxed{M_W,\ \Gamma_W,\ \mathrm{BR}_{W\to\ell\nu}}$$

W obs. (LEP2/Hadron Coll.)
$0.02\text{-}\mathcal{O}(1)\%$





See also Lidia Dell'Asta's talk yesterday

2024 PDG Combination:

$$M_W = 80.360 \pm 0.012\ \mathrm{GeV} \quad \text{~0.015\%}$$
$$\Gamma_W = 2.136 \pm 0.032\ \mathrm{GeV} \quad \text{~1.5\%}$$

CDF (adjusted to PDF CT18)

$$M_W^{\mathrm{CDF}} = 80.432 \pm 0.016\ \mathrm{GeV}$$

~4 σ tension with other measurements

See also S. Amoroso et al., arXiv: 2308.09417 [hep-ex]

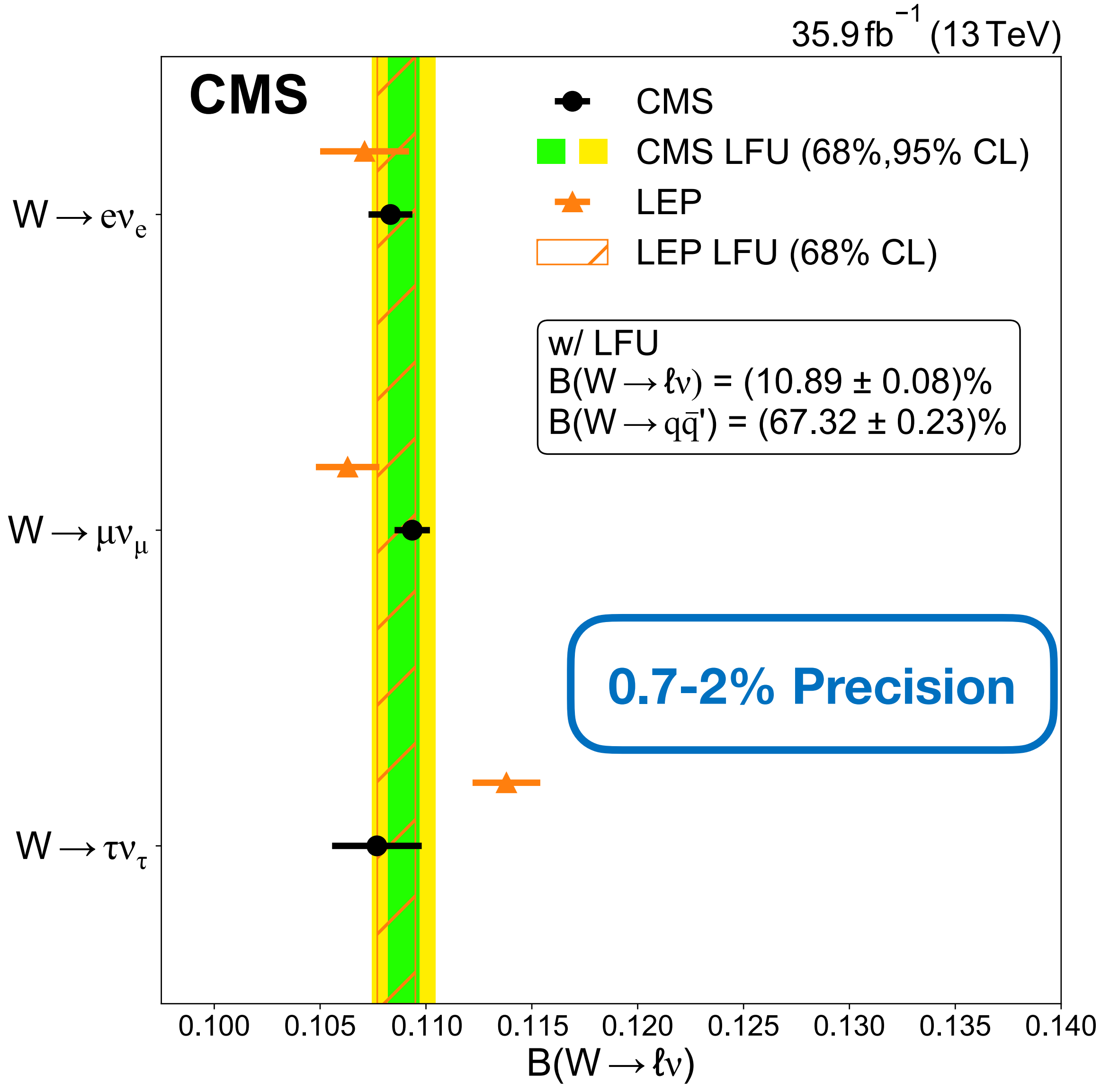
Electroweak precision observables: W properties

- Experimental measurements of W Branching ratios: LEP2 vs CMS

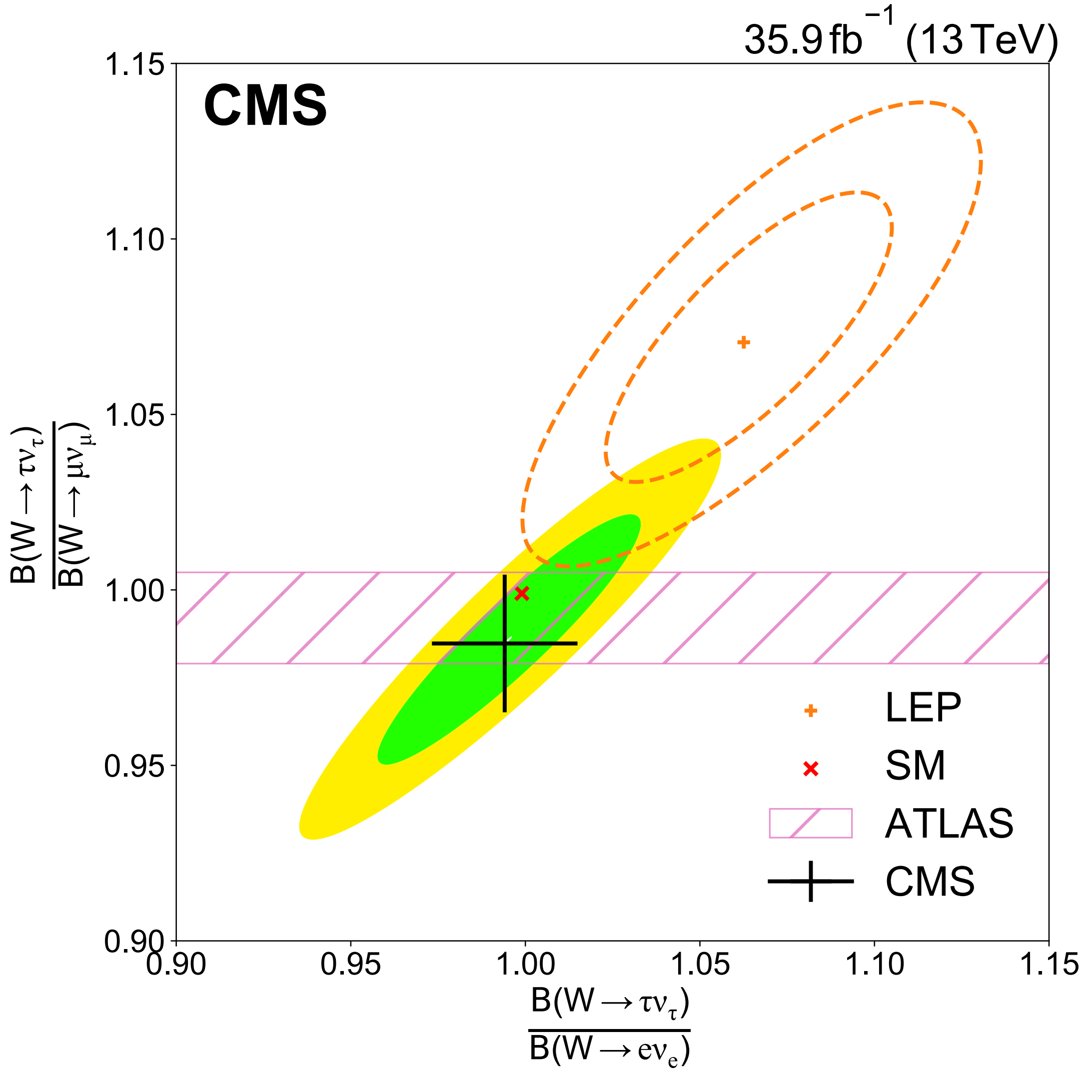
$$\boxed{M_W,\ \Gamma_W,\ \mathrm{BR}_{W\to\ell\nu}}$$

W obs. (LEP2/Hadron Coll.)
0.02-$\mathcal{O}(1)$%

Similar systematics but CMS 3-10 times more precise statistically → 1.5 x better for e/μ, similar for τ



0.7-2% Precision



CMS collaboration, arXiv: 2201.07861 [hep-ex]

CMS not only more precise than LEP2 but also no sign of tension in τ channel

EWPO: Status of SM predictions

- **Standard Model** inputs: α scheme

$$\{G_F,\ \alpha(M_Z^2),\ \alpha_s(M_Z^2),\ M_Z,\ M_H,\ m_t\}$$

- Fermi constant (G_F) and α(0) known with much higher precision than any EWPO such that their uncertainty can be neglected in EW precision tests.

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Constrained by Low E had Data/Lattice

$$\Delta\alpha_{\rm had}^{(5)}(M_Z^2) = 0.02766 \pm 0.00010$$

0.4 % precision

Dominated by Lattice

$$\alpha_s(M_Z^2)\big|_{\rm PDG\ 2023} = 0.1180 \pm 0.0009$$

0.8 % precision

LEP Z pole

$$M_Z|_{\rm LEP} = 91.1875 \pm 0.0021\ {\rm GeV}$$

0.002 % precision

Combination of ATLAS and CMS determinations (H→4ℓ, γγ)

$$M_H = 125.10 \pm 0.09\ {\rm GeV}$$

0.1 % precision

PDG combination: Tevatron, LHC Run 1/2

$$m_t = 172.61 \pm 0.25|_{\rm exp} \pm 0.52|_{\rm th.}\ \ {\rm GeV}$$

0.3 % precision

Comparison of EWPO with SM predictions (EW fit) is overconstrained

EWPO: Status of SM predictions

- State-of-the-art of SM theory calculations of EWPO:
  - ✓ Γ_W : Only EW one loop
    D.Y. Bardin, P.K. Khristova, O. Fedorenko, Nucl. Phys B197 (1982) 1-44
    D.Y. Bardin, S. Riemann, T. Riemann, Z. Phys C32 (1986) 121-125
  - ✓ M_W : Full EW 2-loop corr. + leading 3-loop & some 4-loop
    M. Awramik, M. Czakon, A. Freitas, G. Weiglein, Phys. Rev D69 (2004) 053006
  - ✓ $\sin^2\theta^f_{\rm Eff}$ (light ferm): Full EW 2-loop corr. + leading higher order
    M. Awramik, M. Czakon, A. Freitas, JHEP 0611 (2006) 048
    M. Awramik, M. Czakon, A. Freitas, B.A. Kniehl, Nucl. Phys. B813 (2009) 174-187
  - ✓ Γ^f_Z : Full 2-loop EW corr. + leading higher order
    I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, Phys. Lett. B 783 (2018) 86-94
  - ✓ $\sin^2\theta^b_{\rm Eff}$: Full 2-loop EW corr. + leading higher order
    I. Dubovyk, A. Freitas, J. Gluza, T. Riemann, J. Usovitsch, Phys. Lett. B 762 (2016) 184-189
  - ✓ Leading 3-loop EW fermionic corrections
    L. Cheng, A. Freitas, JHEP 07 (2020) 210

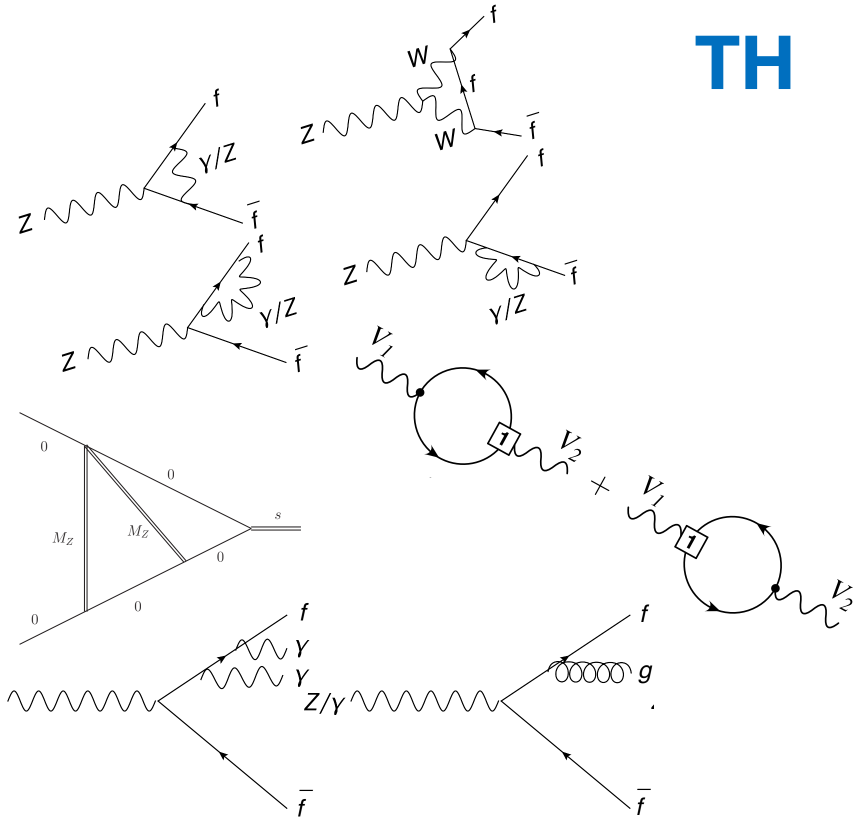
- Experimental vs. Theoretical uncertainties:

	$M_{\rm W}$	$\Gamma_{\rm Z}$	$\sigma^0_{\rm had}$	$R_{\rm b}$	$\sin^2\theta^\ell_{\rm eff}$
Exp. error	15 MeV	2.3 MeV	37 pb	6.6×10^{-4}	1.6×10^{-4}
Theory error	4 MeV	0.5 MeV	6 pb	1.5×10^{-4}	0.5×10^{-4}

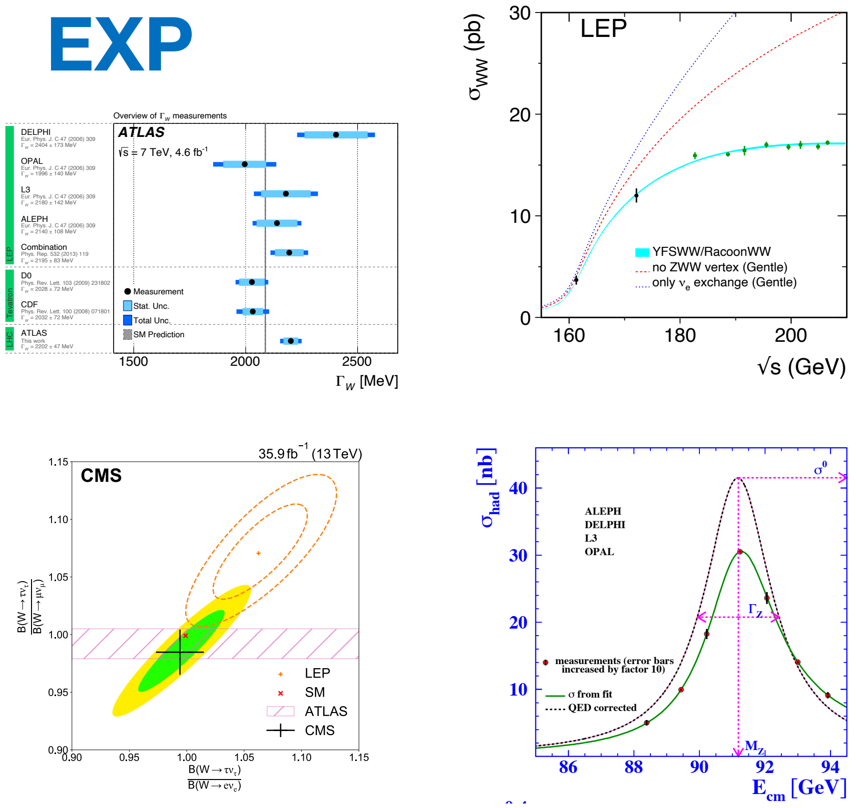
A. Freitas, PoS(LL2014)050 [arXiv: 1406.6980]

The Standard Model Electroweak fit

TH



EXP



Everything automatized in several codes in the "market"

$$\chi^2 = \sum_{ij}(O_i^{\rm Exp} - O_i^{\rm SM}(\theta_{\rm SM},\nu))(V^{-1})_{ij}(O_j^{\rm Exp} - O_j^{\rm SM}(\theta_{\rm SM},\nu))$$

+ statistical framework

<u>Global EW fit</u>

Model parameters

Goodness-of-fit, Tensions,…

The Standard Model EW fit

From*:

JB et al. , Phys. Rev. D 106, 033003 (2022)

JB, M. Pierini, L. Reina, L. Silvestrini, Phys. Rev. Lett. 129, 271801 (2022)

***Do not include a few of the latest updates discussed before but impact in the results is small**

The Standard Model Electroweak fit

- Reported here using the observables assuming Lepton Flavor Universality

Global SM EW fit (*standard* scenario)

	Measurement	Posterior	Individual Prediction	1D Pull	nD Pull
$\alpha_s(M_Z^2)$	0.1177 ± 0.0010	0.11792 ± 0.00094	0.1198 ± 0.0028	-0.7	
$\Delta\alpha_{\rm had}^{(5)}(M_Z^2)$	0.02766 ± 0.00010	0.027627 ± 0.000096	0.02717 ± 0.00037	1.3	
M_Z [GeV]	91.1875 ± 0.0021	91.1883 ± 0.0021	91.2047 ± 0.0088	-1.9	
m_t [GeV]	172.58 ± 0.45	172.75 ± 0.44	176.2 ± 2.0	-1.8	
m_H [GeV]	125.21 ± 0.12	125.21 ± 0.12	108.3 ± 11.7	1.3	
M_W [GeV]	80.379 ± 0.012	80.3591 ± 0.0052	80.3545 ± 0.0057	1.8	
Γ_W [GeV]	2.085 ± 0.042	2.08827 ± 0.00055	2.08829 ± 0.00056	-0.1	
${\rm BR}_{W\to\ell\bar\nu_\ell}$	0.10860 ± 0.00090	0.108381 ± 0.000022	0.108380 ± 0.000022	0.2	
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	0.2324 ± 0.0012	0.231509 ± 0.000056	0.231506 ± 0.000056	0.7	
$P_\tau^{\rm pol} = \mathcal{A}_\ell$	0.1465 ± 0.0033	0.14712 ± 0.00044 $[0.14625, 0.14799]$	0.14713 ± 0.00045 $[0.14626, 0.14801]$	-0.2	
Γ_Z [GeV]	2.4955 ± 0.0023	2.49443 ± 0.00065	2.49423 ± 0.00069	0.5	1.0
σ_h^0 [nb]	41.480 ± 0.033	41.4908 ± 0.0076	41.4927 ± 0.0079	-0.4	
R_ℓ^0	20.767 ± 0.025	20.7493 ± 0.0080	20.7462 ± 0.0087	0.8	
$A_{\rm FB}^{0,\ell}$	0.0171 ± 0.0010	0.016234 ± 0.000098	0.016225 ± 0.000097	0.9	
$\mathcal{A}_\ell$ (SLD)	0.1513 ± 0.0021	0.14712 ± 0.00044	0.14713 ± 0.00046	1.9	1.3
R_b^0	0.21629 ± 0.00066	0.215878 ± 0.000100	0.21587 ± 0.00010	0.6	
R_c^0	0.1721 ± 0.0030	0.172205 ± 0.000054	0.172206 ± 0.000053	0.0	
$A_{\rm FB}^{0,b}$	0.0996 ± 0.0016	0.10314 ± 0.00031	0.10315 ± 0.00033	-2.2	
$A_{\rm FB}^{0,c}$	0.0707 ± 0.0035	0.07369 ± 0.00023	0.07370 ± 0.00024	-0.9	
$\mathcal{A}_b$	0.923 ± 0.020	0.934738 ± 0.000040	0.934739 ± 0.000040	-0.6	
$\mathcal{A}_c$	0.670 ± 0.027	0.66782 ± 0.00022	0.66783 ± 0.00022	0.0	
$\mathcal{A}_s$	0.895 ± 0.091	0.935651 ± 0.000040	0.935651 ± 0.000040	-0.4	
$\sin^2\theta_{\rm eff}^{\rm lept}$ (HC)	0.23143 ± 0.00025	0.231509 ± 0.000056	0.231512 ± 0.000057	-0.3	
R_{uc}	0.1660 ± 0.0090	0.172227 ± 0.000032	0.172228 ± 0.000032	-0.7	

(Excluding $M_W^{\rm CDF}$)

"Posterior": The full fit results

"Indirect/Prediction":
Drop each (set of correlated) observable(s) at a time → fit → predict the removed observable

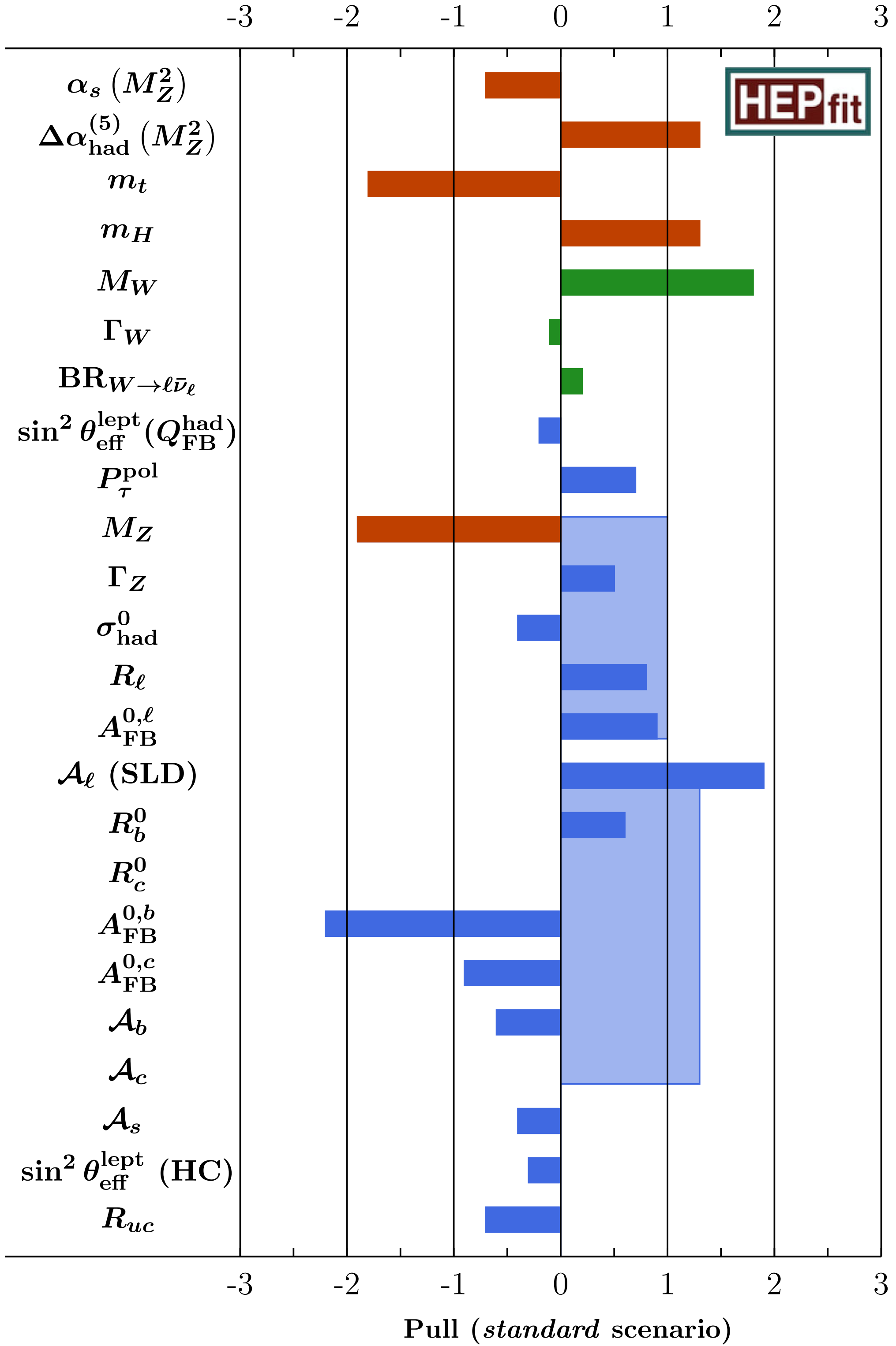
"1D pull":
Individual pull for each observable

"nD pull":
Global pull for sets of correlated observables

The Standard Model Electroweak fit

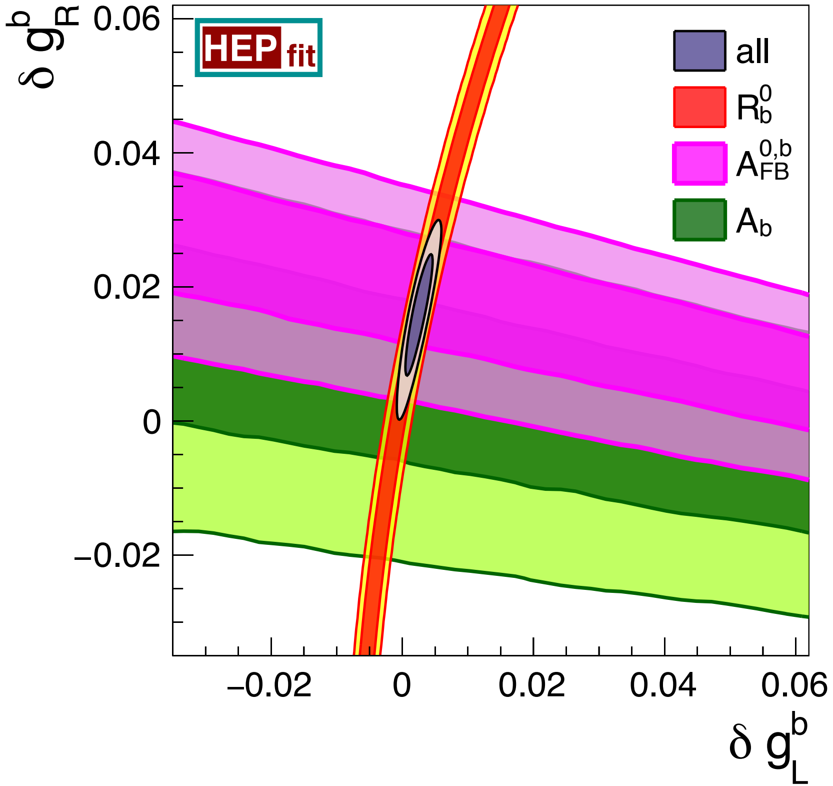
- Tensions in the Standard Model electroweak fit (Excluding the M_W^{CDF}):

Individual Predictions



The only persistent "anomaly" (>2σ) in the EW fit is A_{FB}^b

Interesting? Maybe… (3rd family)



Statistically significant? Not so much…

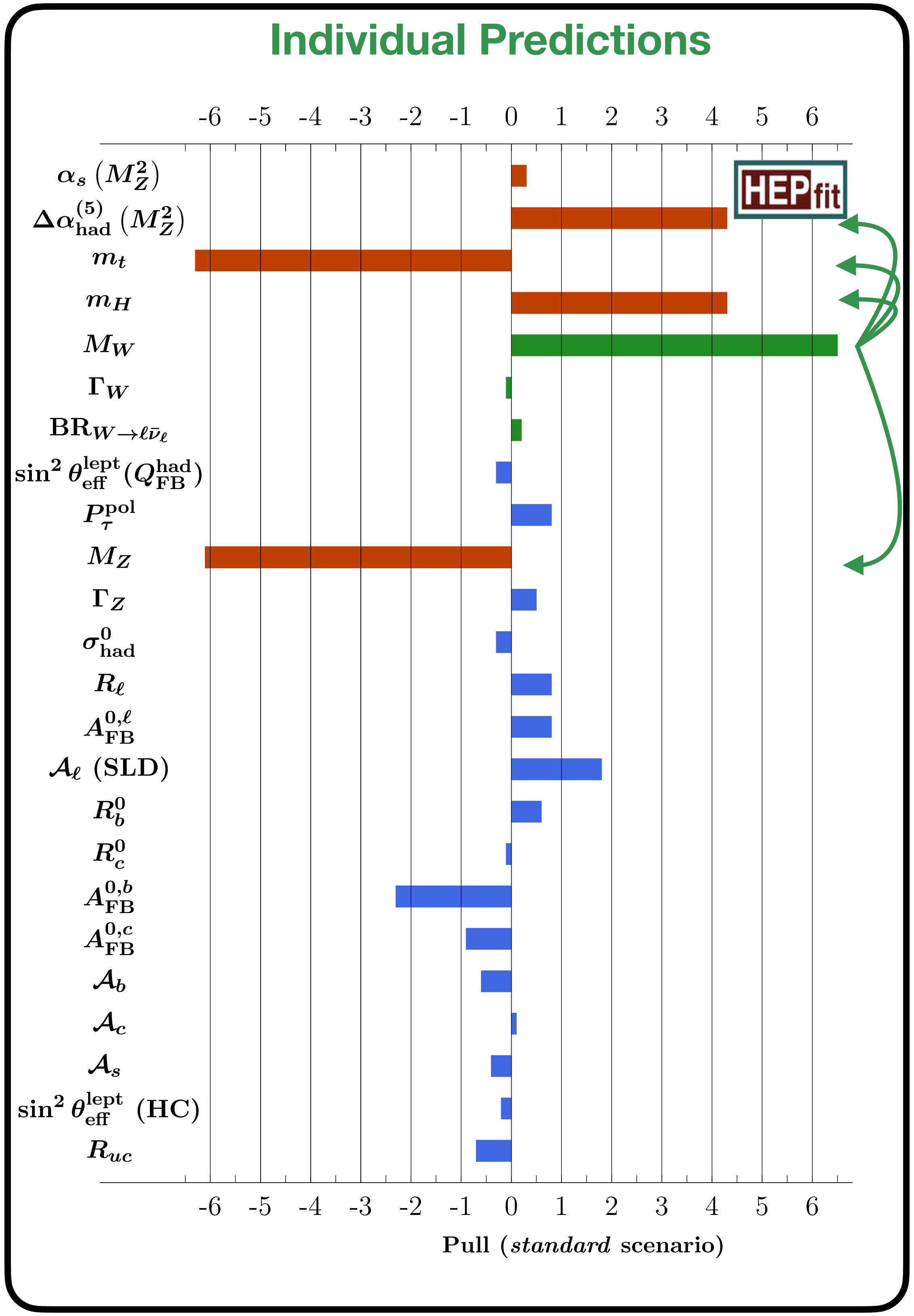
Global p-value of the fit

p-value: 0.53 (0.6 σ)

Excellent overall agreement of data with SM predictions to the level of 2-loop corrections

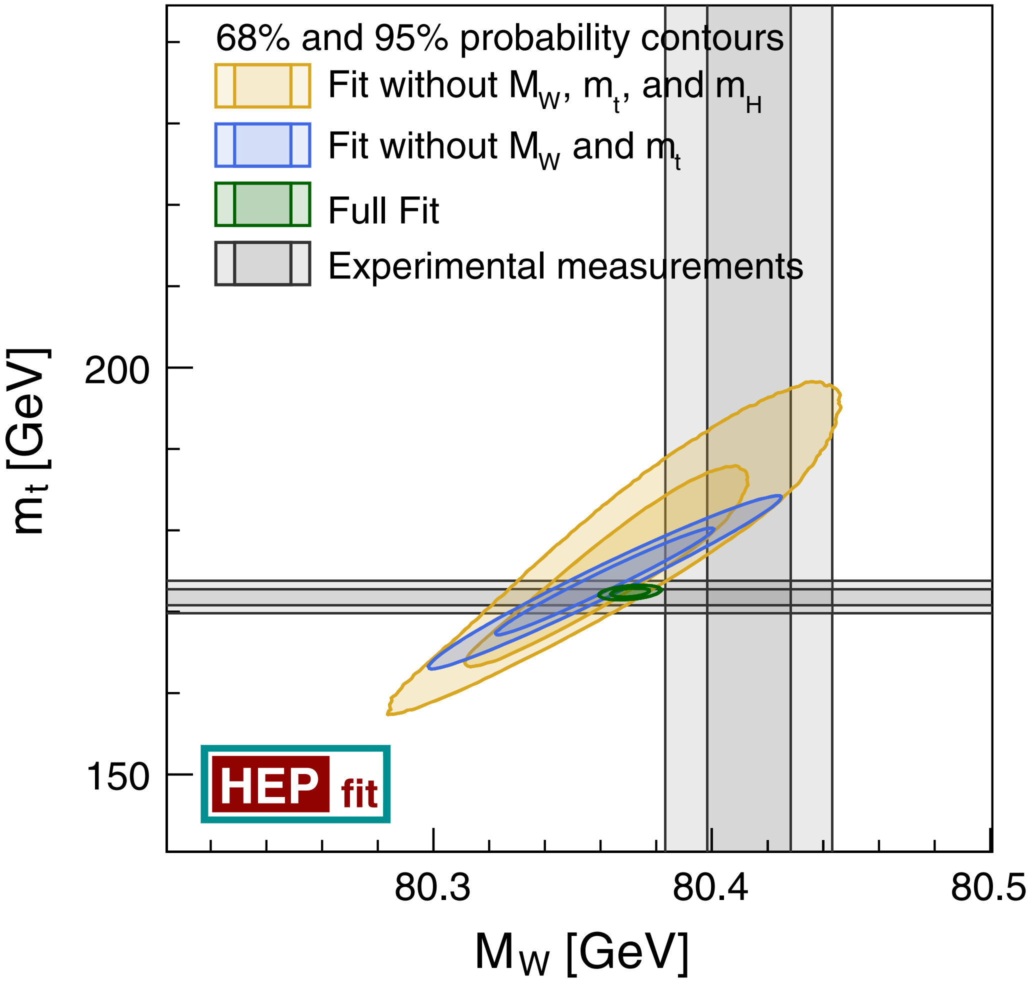
The Standard Model Electroweak fit

- Tensions in the Standard Model electroweak fit:


Individual Predictions

Impact of M_W on indirect determination of SM inputs

Including the M_W^{CDF} in the analysis



~7 σ discrepancy between CDF value and SM prediction (excluding it from the fit)

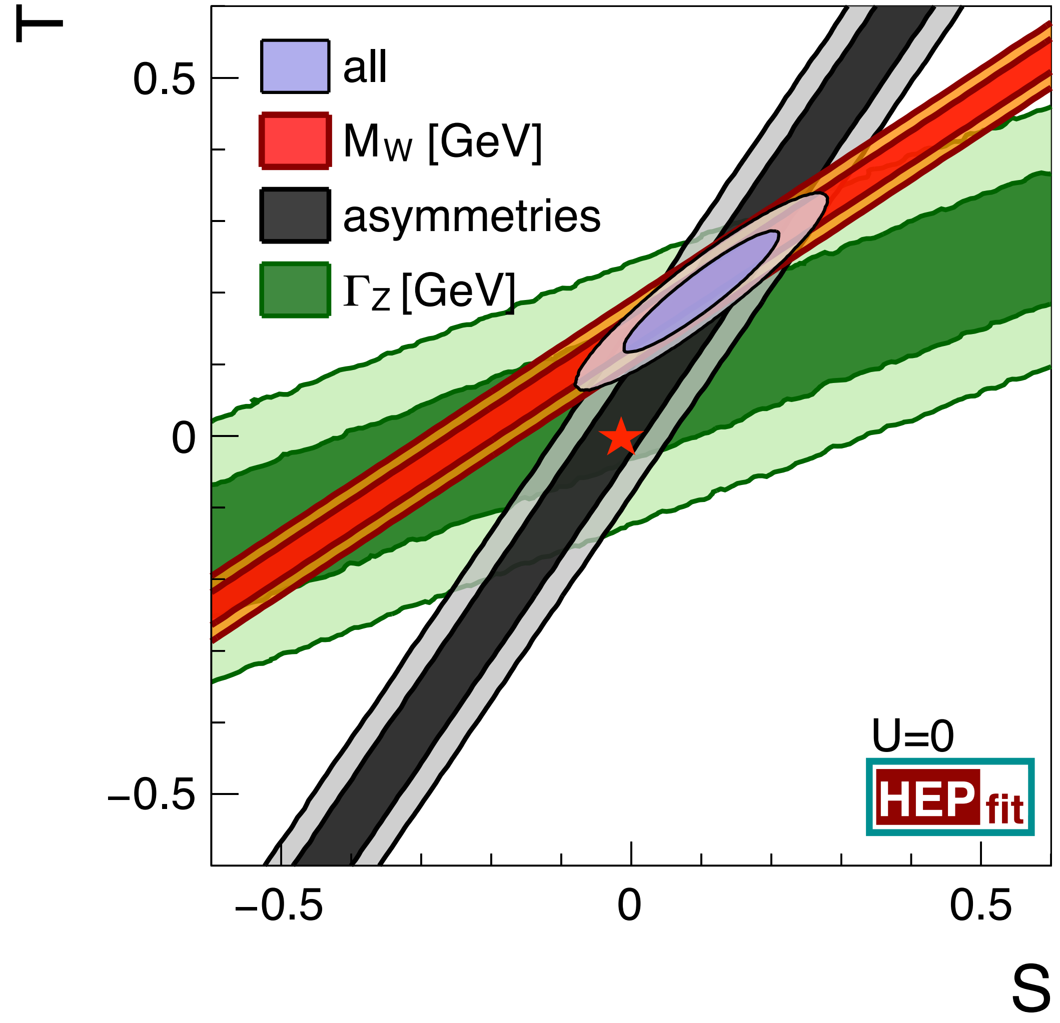
Global p-value: 2.5×10^{-5}

Overall tension in the SM fit: 4.2 σ

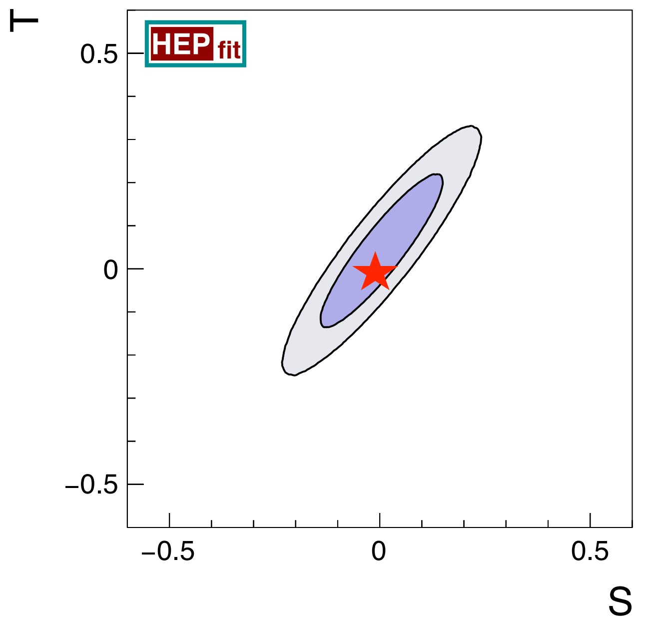
Oblique STU Electroweak fit

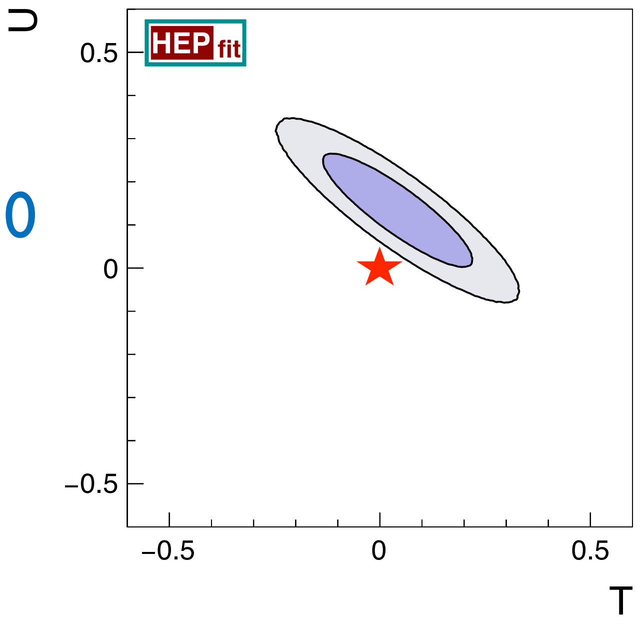
- New physics contributing only to gauge boson self-energies. Typically referred as "oblique" corrections (***S*, *T*, *U***)

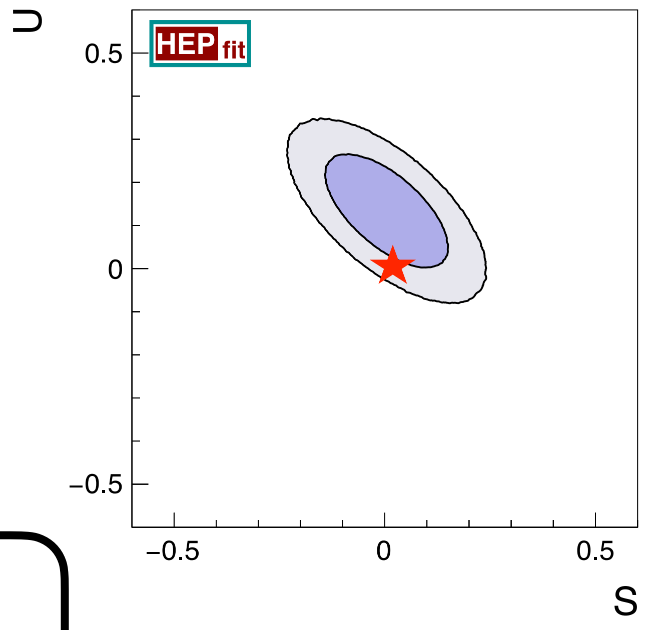
Explained by positive S,T (U=0)



Or large U
with S,T compatible with 0







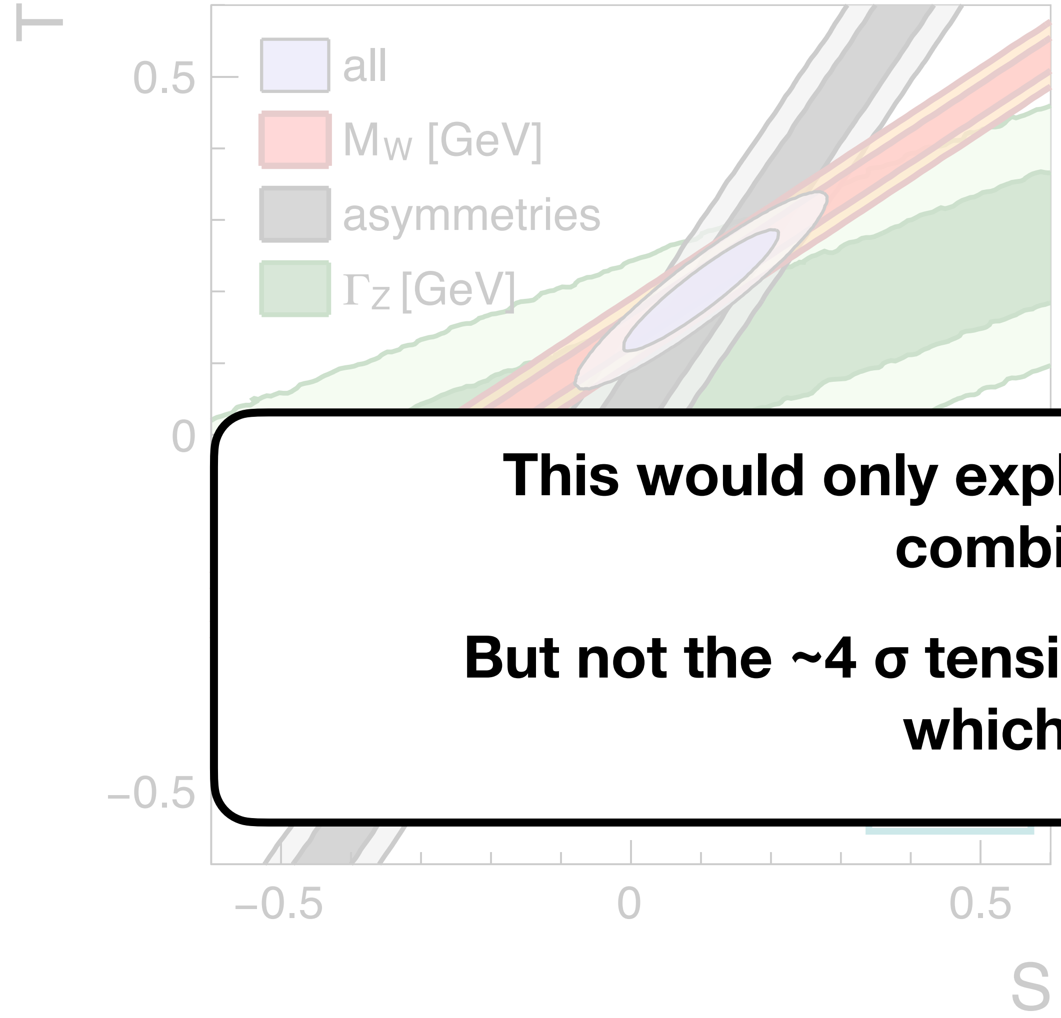
	Result	Correlation		Result	Correlation		
	$(\mathrm{IC}_{\mathrm{ST}}/\mathrm{IC}_{\mathrm{SM}} = 25.0/80.2)$			$(\mathrm{IC}_{\mathrm{STU}}/\mathrm{IC}_{\mathrm{SM}} = 25.3/80.2)$			
S	0.100 ± 0.073	1.00		0.005 ± 0.096	1.00		
T	0.202 ± 0.056	0.93	1.00	0.040 ± 0.120	0.91	1.00	
U	–	–	–	0.134 ± 0.087	-0.65	-0.88	1.00

$$\left(\mathrm{IC} \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}\right)$$

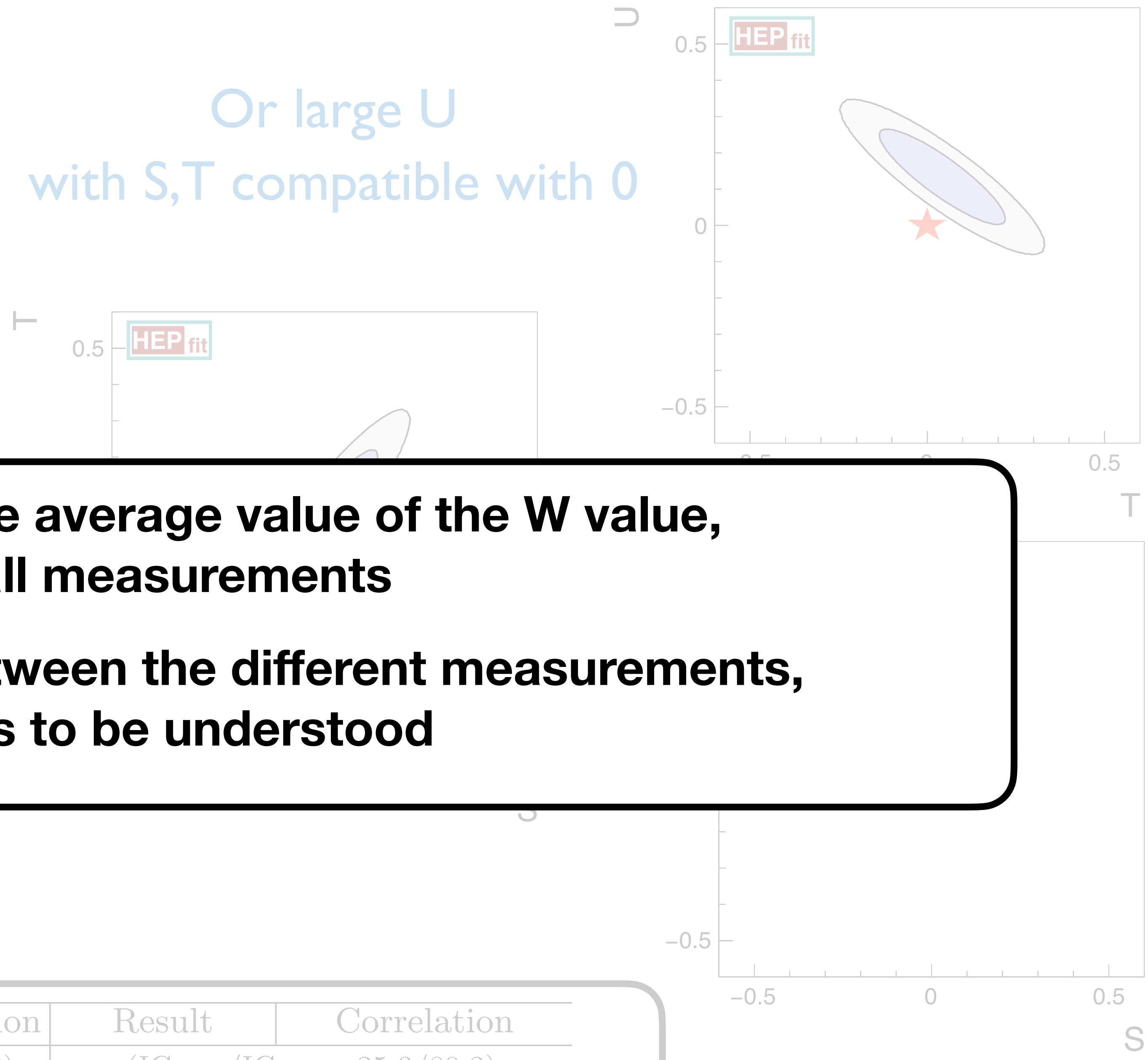
Oblique STU Electroweak fit

- New physics contributing only to gauge boson self-energies. Typically referred as "oblique" corrections (***S*, *T*, *U***)

Explained by positive S,T (U=0)



Or large U
with S,T compatible with 0



This would only explain the average value of the W value, combining all measurements

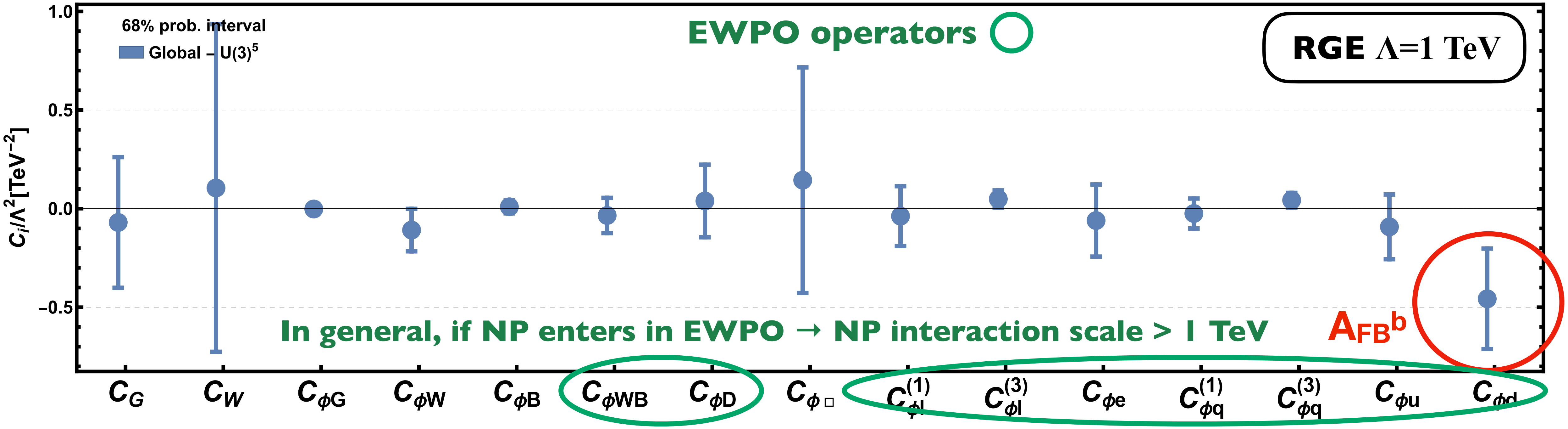
But not the ~4 σ tension between the different measurements, which needs to be understood

	Result	Correlation		Result	Correlation		
	$(\mathrm{IC}_{ST}/\mathrm{IC}_{SM} = 25.0/80.2)$			$(\mathrm{IC}_{STU}/\mathrm{IC}_{SM} = 25.3/80.2)$			
S	0.100 ± 0.073	1.00		0.005 ± 0.096	1.00		
T	0.202 ± 0.056	0.93	1.00	0.040 ± 0.120	0.91	1.00	
U	–	–	–	0.134 ± 0.087	−0.65	−0.88	1.00

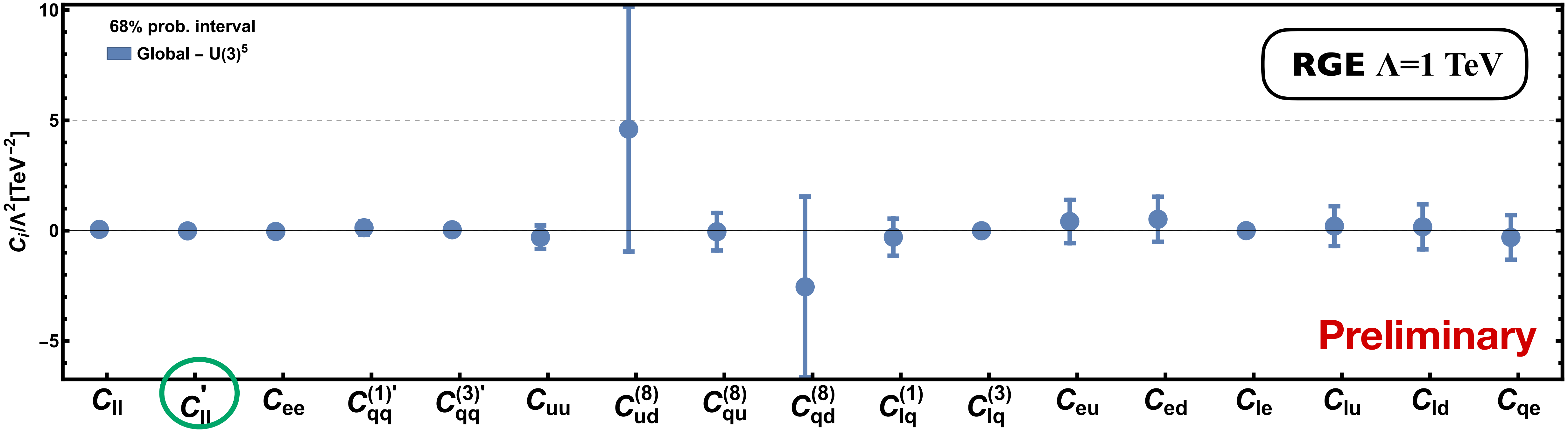
$$\left(\mathrm{IC} \equiv -2\overline{\log \mathcal{L}} + 4\sigma^2_{\log \mathcal{L}}\right)$$

The SMEFT global fit

- Example: **CP-even + U(3)^5** flavor symmetric fit (Ignoring CDF W mass)
  - Fit to EWPO+diBoson+Higgs+Top → Closed fit with 32 operators (Warsaw)



In general, if NP enters in EWPO → NP interaction scale > 1 TeV



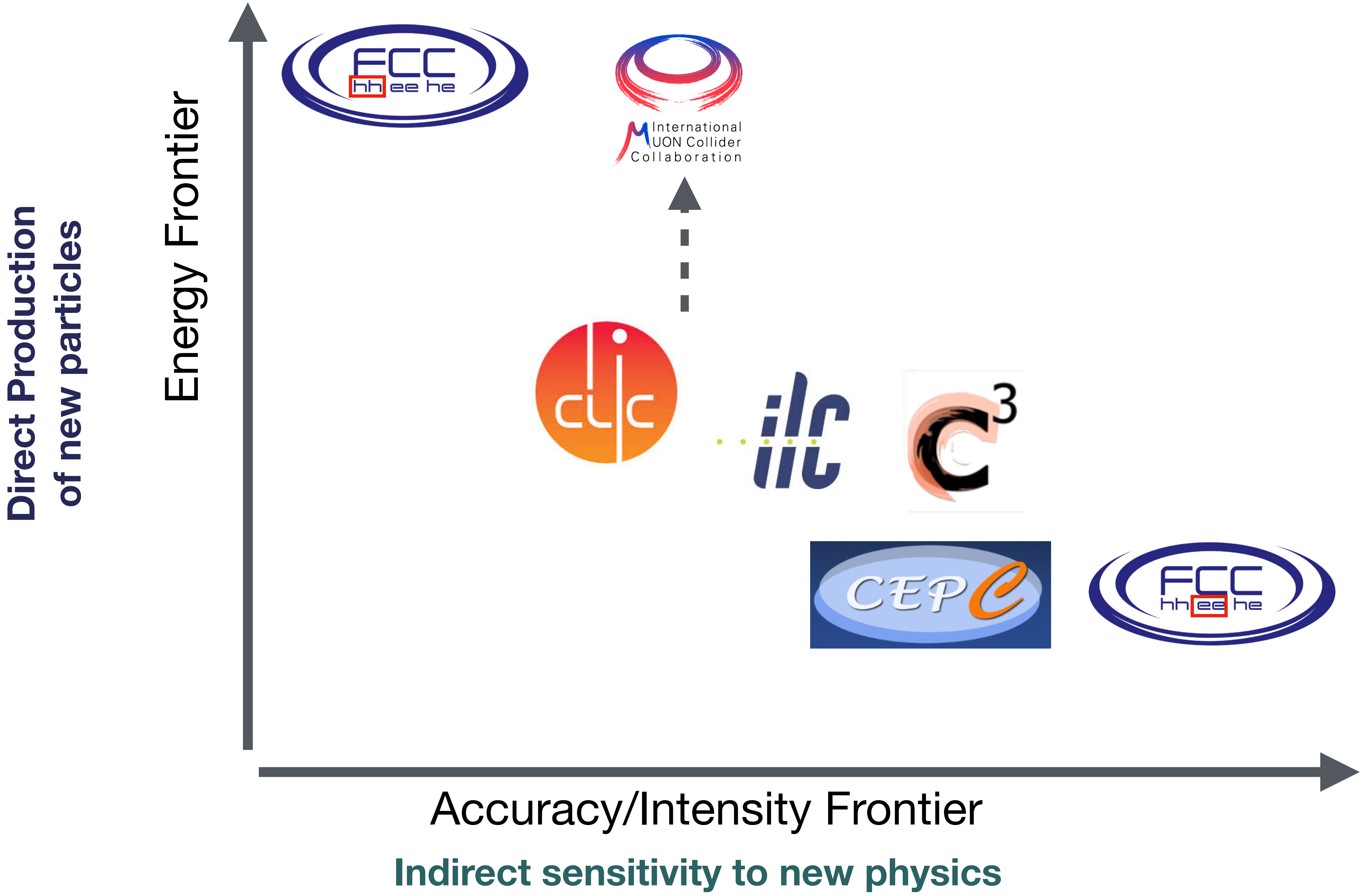
Preliminary

Electroweak Precision Physics

At Future Colliders

EW precision at future e^+e^- colliders

- Future collider projects: The Intensity/Energy frontier



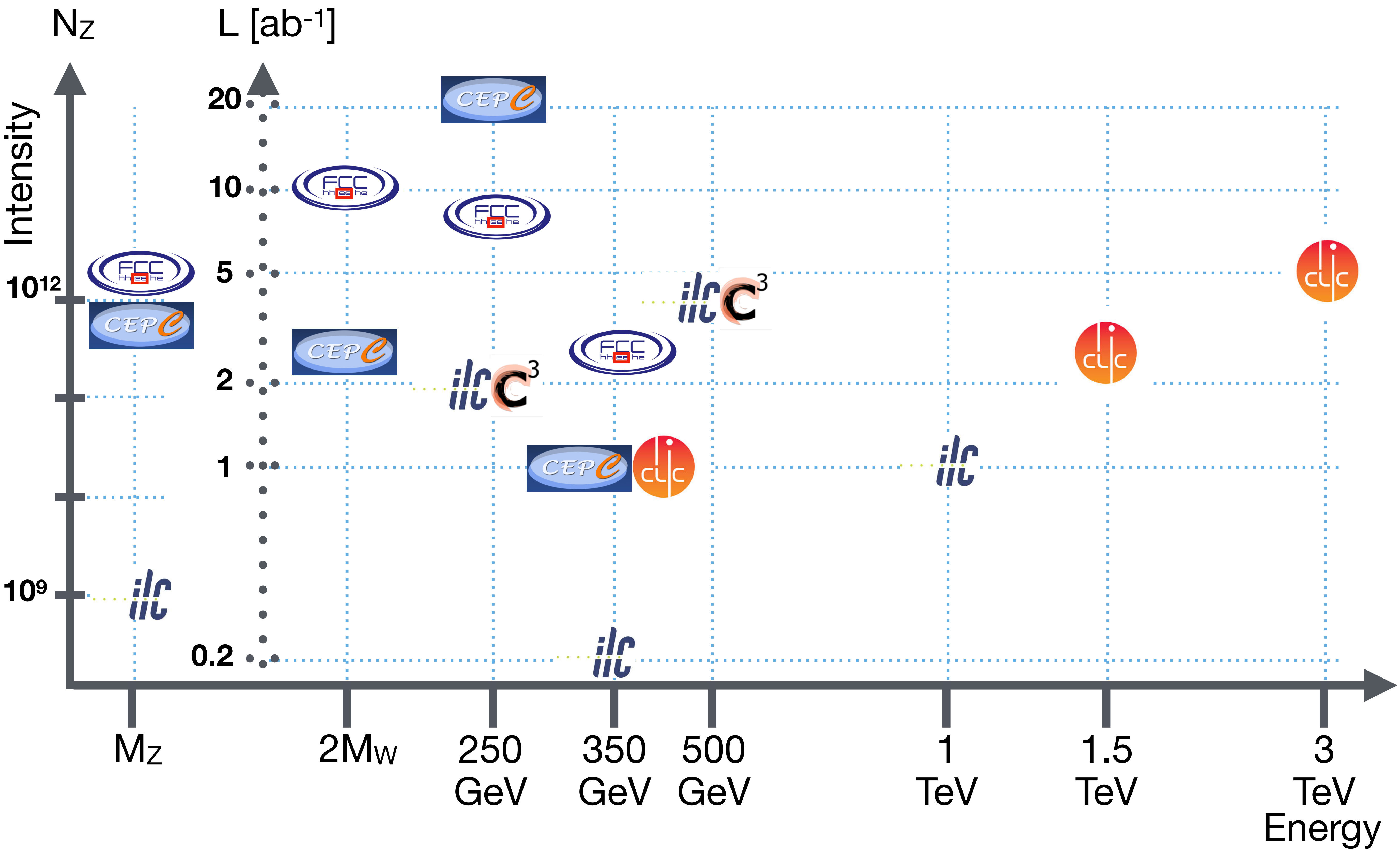
Direct Production of new particles

Energy Frontier

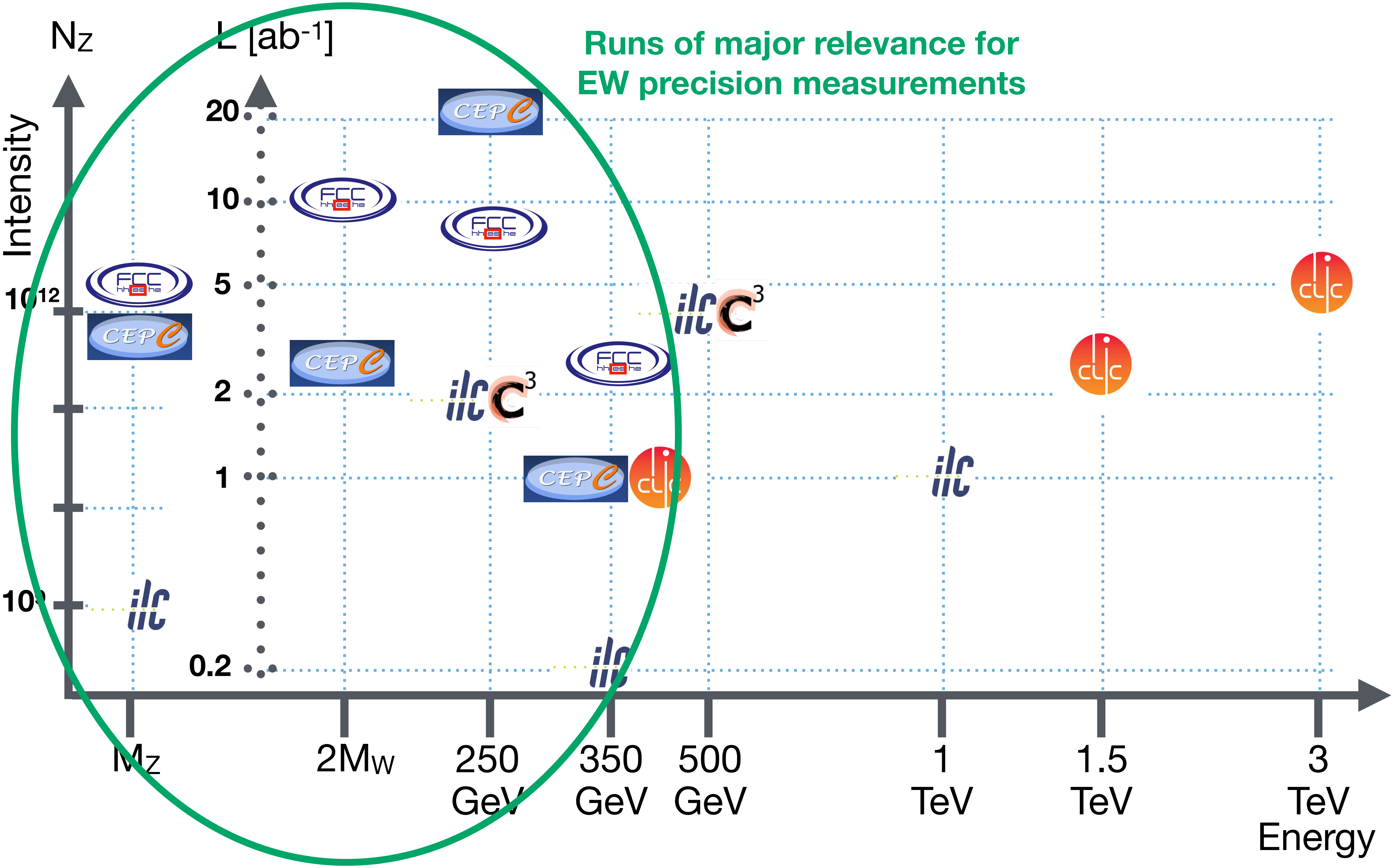
Accuracy/Intensity Frontier

Indirect sensitivity to new physics

EW precision at future e⁺e⁻ colliders



EW precision at future e^+e^- colliders



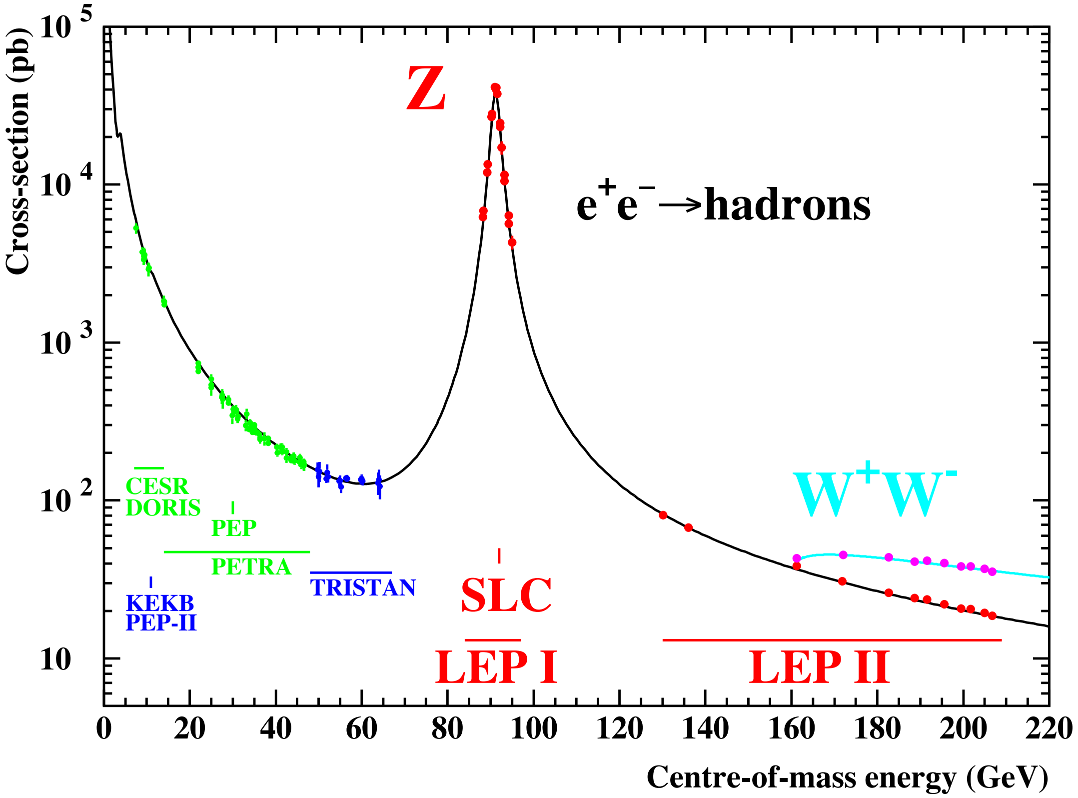
Runs of major relevance for EW precision measurements

EW precision at future e^+e^- colliders

- More than Higgs factories: Future e^+e^- colliders will also help us improve our knowledge of the EW interactions:
  - Improved Z pole run:
    - LEP/SLC: ~10^7 Z → O(0.1-1%)
    - FCCee/CEPC: 10^{12} Z
    - ILC (GigaZ): 10^9 Z (with polarization)

Z-pole EWPO:

$$M_Z,\ \Gamma_Z,\ \sigma^0_{\rm had},\ \sin^2\theta^{\rm lept}_{\rm Eff},\ P^{\rm pol}_\tau,\ A_f,\ A^{0,f}_{FB},\ R^0_f$$



- Z-pole measurements are also possible during the Higgs factory phase (√s ~250 GeV) via radiative return to the Z resonance

$$e^+e^- \to \gamma Z$$

ILC 250 with 2 ab^{-1}: 77 (12) million hadronic (leptonic) Zs
5 (100) times more statistics than LEP (SLC)!

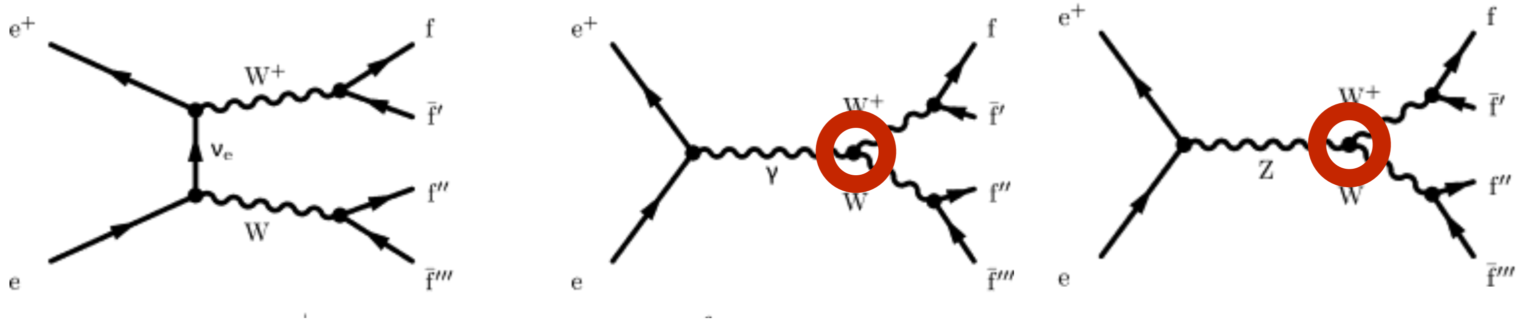
K. Fuji et al. , arXiv: 1908.11299 [hep-ex]
T. Mizuno, K. Fuji, J. Tian, arXiv: 2203.07944 [hep-ph]

EW precision at future e^+e^- colliders

- More than Higgs factories: Future e^+e^- colliders will also help us improve our knowledge of the EW interactions:

  ✓ WW production at 161 GeV and above: W mass and width, BRs, aTGCs, …

$e^+e^- \to W^+W^-$

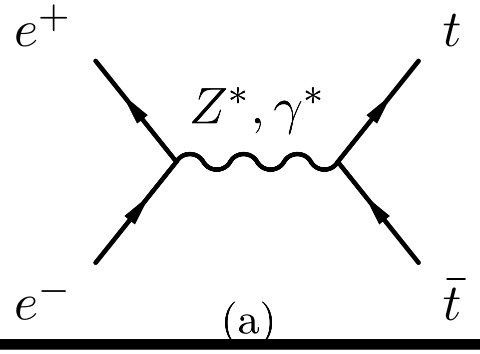


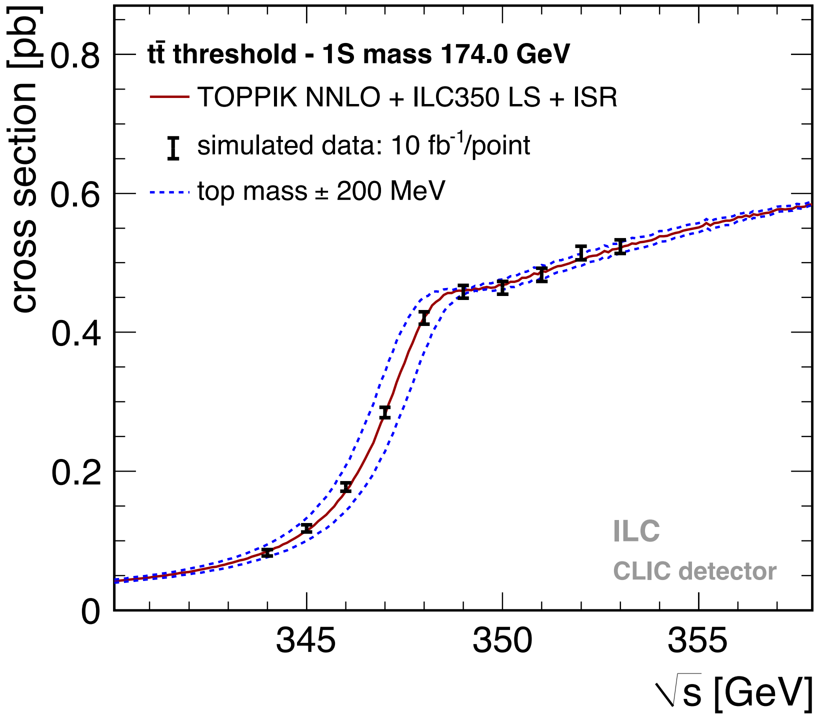
$$\boxed{\Delta M_W:\quad 12\text{ MeV}\longrightarrow\lesssim 1\text{ MeV}}$$

  ✓ 350/365 GeV: Clean production of top pairs around threshold

  → Multipoint scan ~350 GeV to determine m_t

$e^+e^- \to t\bar{t}$





$$\boxed{\Delta m_t:\quad \sim 400\text{ MeV}\longrightarrow\sim 20\text{ MeV}}$$

→365 GeV: Top interactions

EW precision at future e^+e^- colliders: Experiment

Quantity	current	ILC250	ILC-GigaZ	FCC-ee$^{\text{2IPs}}$	CEPC	CLIC380
$\Delta\alpha(m_Z)^{-1}$ $(\times 10^3)$	17.8^*	17.8^*		3.8 (1.2)	17.8^*	
Δm_W (MeV)	12^*	0.5 (2.4)		0.25 (0.3)	0.35 (0.3)	
Δm_Z (MeV)	2.1^*	0.7 (0.2)	0.2	0.004 (0.1)	0.005 (0.1)	2.1^*
Δm_H (MeV)	170^*	14		2.5 (2)	5.9	78
$\Delta\Gamma_W$ (MeV)	42^*	2		1.2 (0.3)	1.8 (0.9)	
$\Delta\Gamma_Z$ (MeV)	2.3^*	1.5 (0.2)	0.12	0.004 (0.025)	0.005 (0.025)	2.3^*
ΔA_e $(\times 10^5)$	190^*	14 (4.5)	1.5 (8)	0.7 (2)	1.5	64
ΔA_μ $(\times 10^5)$	1500^*	82 (4.5)	3 (8)	2.3 (2.2)	3.0 (1.8)	400
ΔA_τ $(\times 10^5)$	400^*	86 (4.5)	3 (8)	0.5 (20)	1.2 (6.9)	570
ΔA_b $(\times 10^5)$	2000^*	53 (35)	9 (50)	2.4 (21)	3 (21)	380
ΔA_c $(\times 10^5)$	2700^*	140 (25)	20 (37)	20 (15)	6 (30)	200
$\Delta\sigma^0_{\text{had}}$ (pb)	37^*			0.035 (4)	0.05 (2)	37^*
δR_e $(\times 10^3)$	2.4^*	0.5 (1.0)	0.2 (0.5)	0.004 (0.3)	0.003 (0.2)	2.7
δR_μ $(\times 10^3)$	1.6^*	0.5 (1.0)	0.2 (0.2)	0.003 (0.05)	0.003 (0.1)	2.7
δR_τ $(\times 10^3)$	2.2^*	0.6 (1.0)	0.2 (0.4)	0.003 (0.1)	0.003 (0.1)	6
δR_b $(\times 10^3)$	3.0^*	0.4 (1.0)	0.04 (0.7)	0.0014 (< 0.3)	0.005 (0.2)	1.8
$\delta R_c(\times 10^3)$	17^*	0.6 (5.0)	0.2 (3.0)	0.015 (1.5)	0.02 (1)	5.6

Improvement ranges from 1 to 2 orders of magnitude for the most relevant observables of the EW fit

Snowmass 2021

EW precision at future e+e- colliders: Experiment

Quantity	Current	HL-LHC	FCC-ee (2IPs)	CEPC	ILC		CLIC	
					Giga-Z	250 GeV	Giga-Z	380 GeV
δm_{top} [MeV]	~500 $^{a)}$	~400 $^{a)}$	20 $^{b)}$	–	–	17 $^{b)}$	–	20-22 $^{b)}$
δM_Z [MeV]	2.1	–	0.1	0.5	–	–	–	–
$\delta\Gamma_Z$ [MeV]	2.3	–	0.1	0.5	1	–	1	–
$\delta\Gamma_{Z\to\text{had}}$ [MeV]	2.0	–	–	–	0.7	–	0.7	–
$\delta\sigma^0_{\text{had}}$ [pb]	37	–	4	5	–	–	–	–
δM_W [MeV]	12	7	0.7	1.0 (2-3) $^{c)}$	–	2.4 $^{d)}$	–	2.5
$\delta\Gamma_W$ [MeV]	42	–	1.5	3	–	–	–	–
δA^c_{FB} [10^{-4}]	500	–	80 $^{f)}$	30 $^{f)}$	–	–	–	–
δR_e [10^{-4}]	24	–	3	2.4	5.4	11	4.2	27
δR_μ [10^{-4}]	16	–	0.5	1	2.8	11	2.2	27
δR_τ [10^{-4}]	22	–	1	1.5	4.5	12	4.3	60
δR_b [10^{-4}]	31	–	2	2	7	11	7	18
δR_c [10^{-4}]	170	–	10	10	30	50	23	56

Example: FCCee (4 IPs)

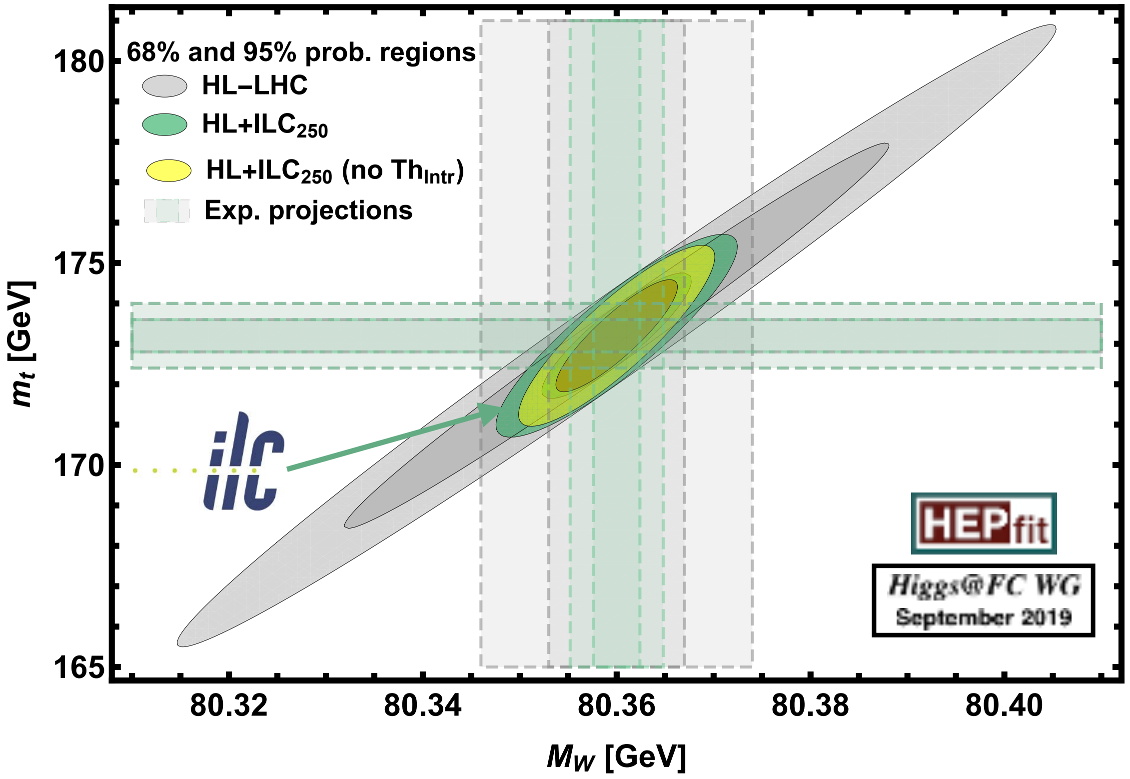
$$
\begin{aligned}
\Delta\Gamma_Z:&\quad 2300\text{ KeV} \longrightarrow 25\text{ KeV} \quad (4(\text{stat})\oplus 25(\text{sys}))\\
\Delta M_W:&\quad 15\text{ MeV} \longrightarrow 0.5\text{ MeV} \quad (0.25(\text{stat})\oplus 0.3(\text{sys}))\\
\Delta\sin^2\theta^\ell_{\text{eff}}(\times 10^6):&\quad 160 \longrightarrow 3 \quad (2(\text{stat})\oplus 2.4(\text{sys}))\\
\Delta A^b_{FB}(\times 10^4):&\quad 16 \longrightarrow 1\text{-}3 \quad (0.02(\text{stat})\oplus 1\text{-}3(\text{sys}))
\end{aligned}
$$

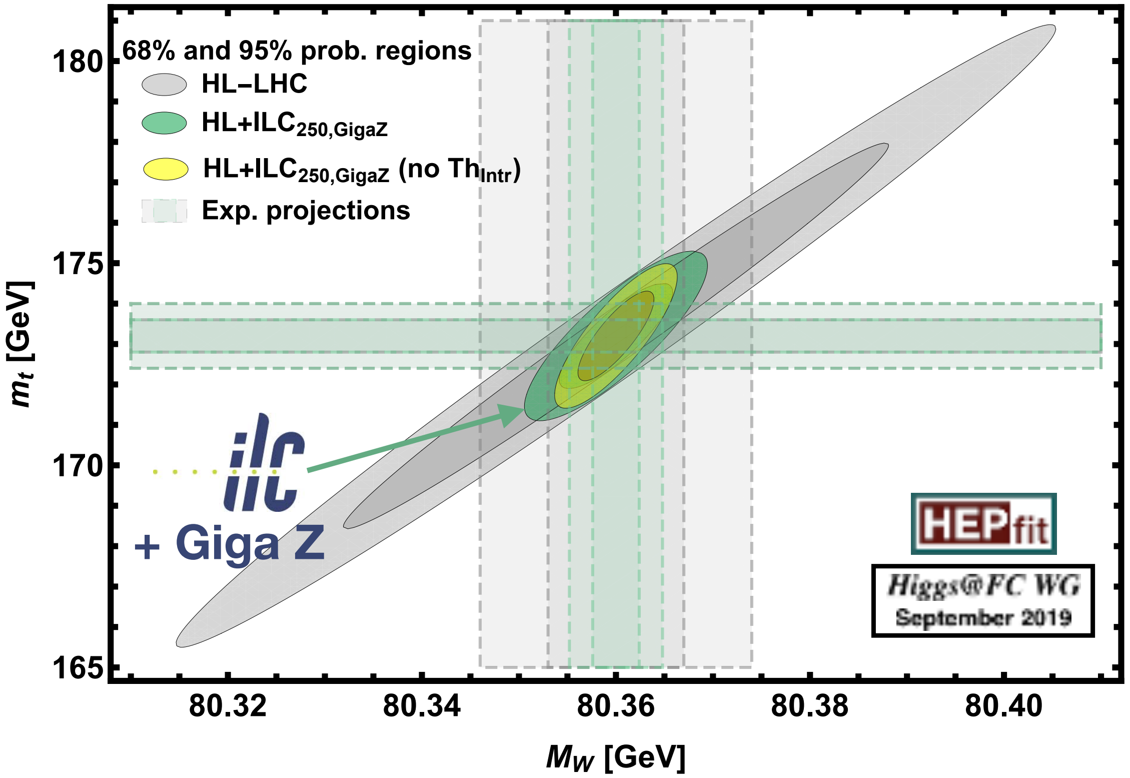
Tera Z: Typically Stats < Sys

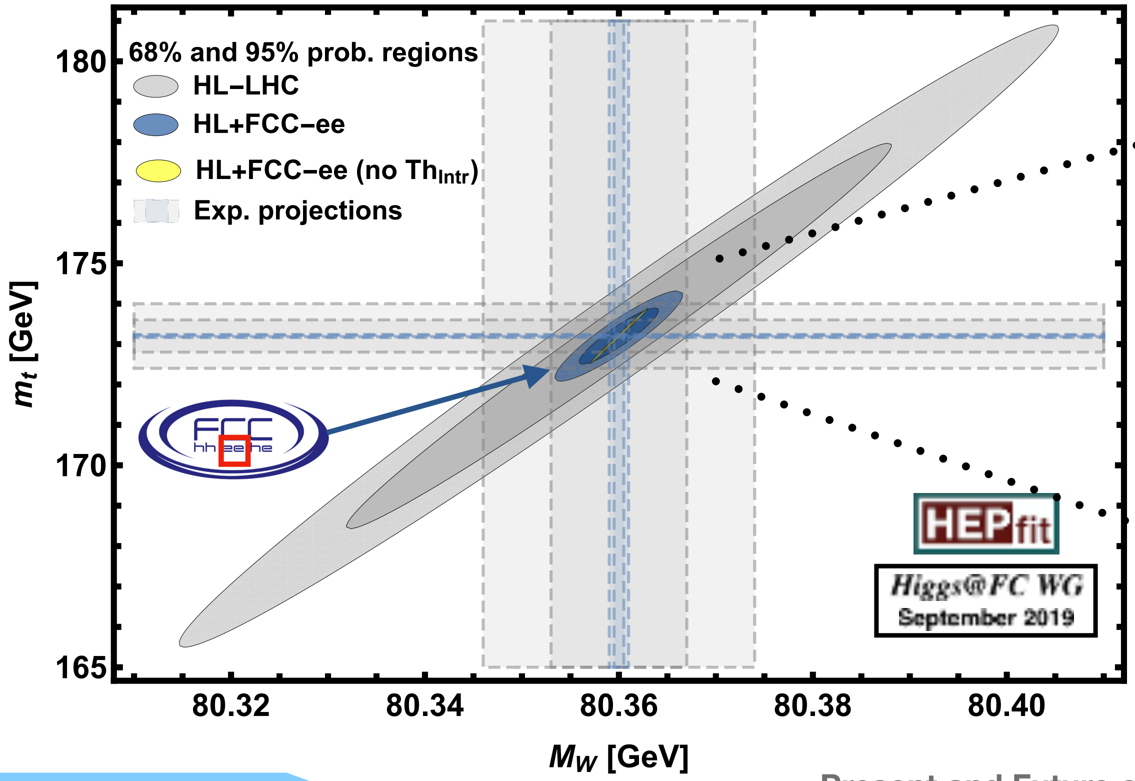
Improvement ranges from 1 to 2 orders of magnitude for the most relevant observables of the EW fit

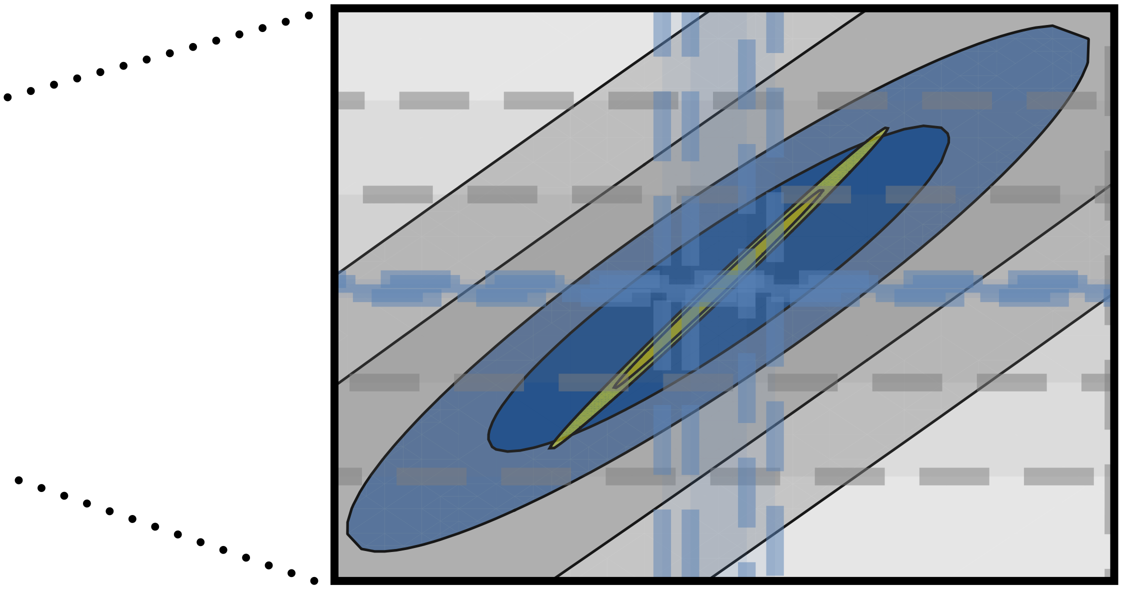
EW precision at future e^+e^- colliders: Experiment

- Consistency tests of the EW sector: HL-LHC vs. Giga Z vs. Tera Z







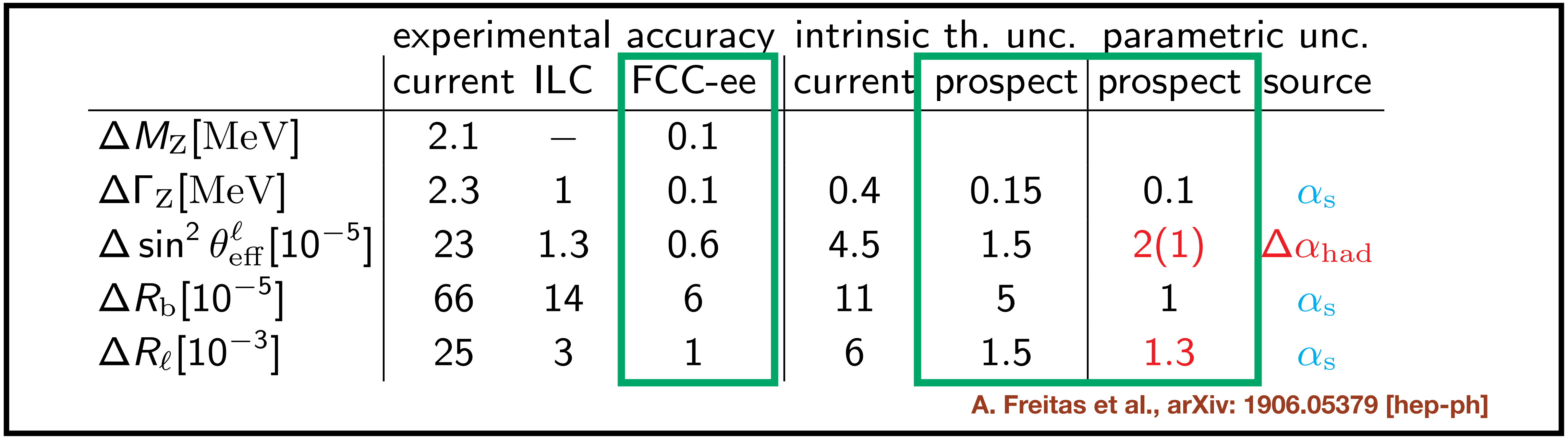


JB et al., JHEP 01 (2020) 139

Theory Challenges at the precision frontier

- Proper interpretation of precision measurements require precision theory
    - The goal of improved precision measurements is to learn about new physics ⇒ We need to distinguish between new physics (signal) and SM (background)

- We need to have very good control of the background so its uncertainties do not affect the new physics interpretation



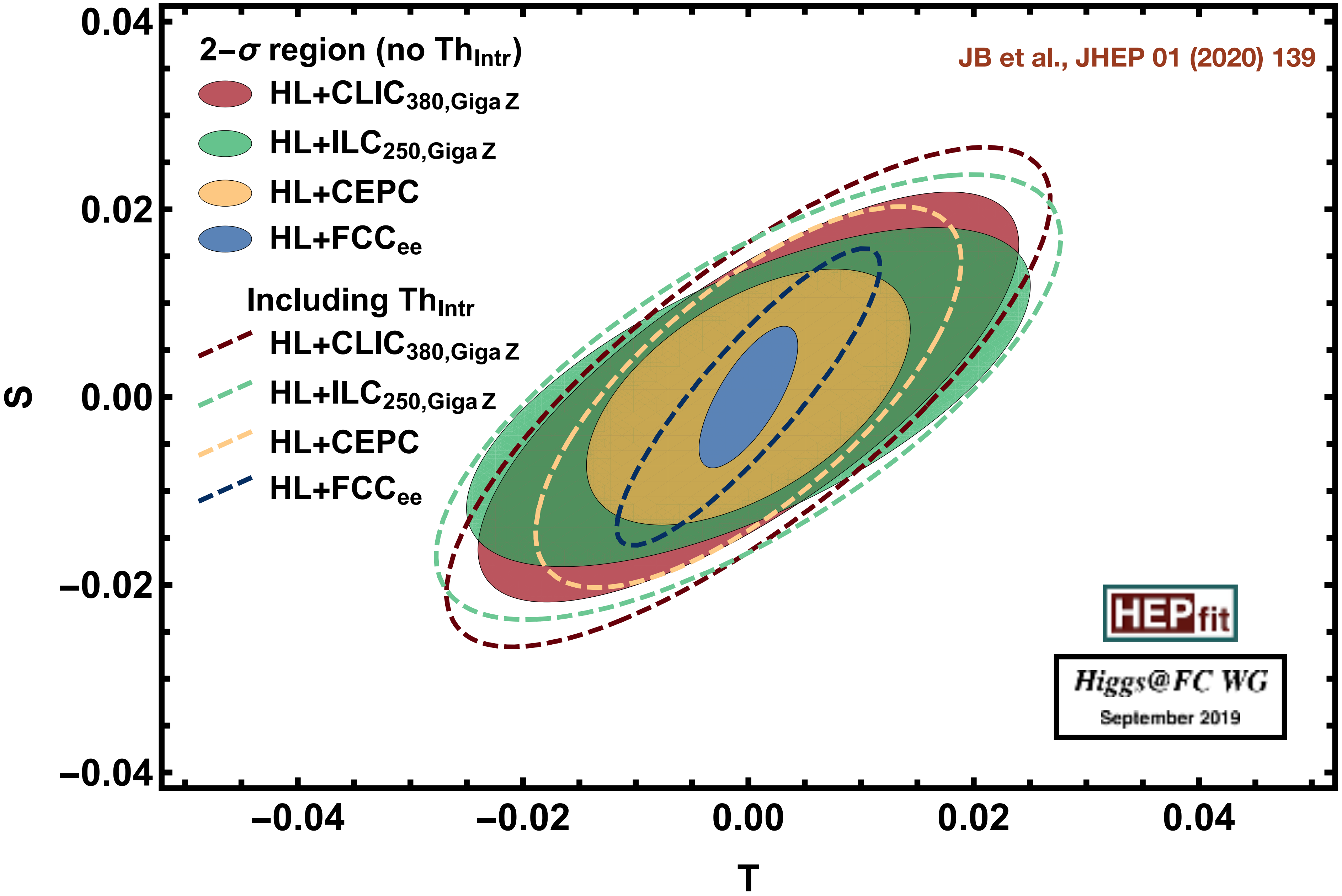
	experimental accuracy			intrinsic th. unc.		parametric unc.	
	current	ILC	FCC-ee	current	prospect	prospect	source
ΔM_Z[MeV]	2.1	—	0.1				
$\Delta\Gamma_Z$[MeV]	2.3	1	0.1	0.4	0.15	0.1	α_s
$\Delta \sin^2\theta^{\ell}_{\rm eff}[10^{-5}]$	23	1.3	0.6	4.5	1.5	2(1)	$\Delta\alpha_{\rm had}$
$\Delta R_b[10^{-5}]$	66	14	6	11	5	1	α_s
$\Delta R_\ell[10^{-3}]$	25	3	1	6	1.5	1.3	α_s

A. Freitas et al., arXiv: 1906.05379 [hep-ph]

- Theory challenges: Future projections assume full EW & QCD-EW 3-loop + leading 4 loop (Y_t enhanced) are computed by the time of future e+e-
    - ✓ Enough only to lower theory uncertainty to the experimental level

Theory Challenges at the precision frontier

- Precision Experiment vs. Theory: Impact of SM theory uncertainties



- Even accounting for future progress, SM theory uncertainties will have an impact on BSM interpretation of EWPO

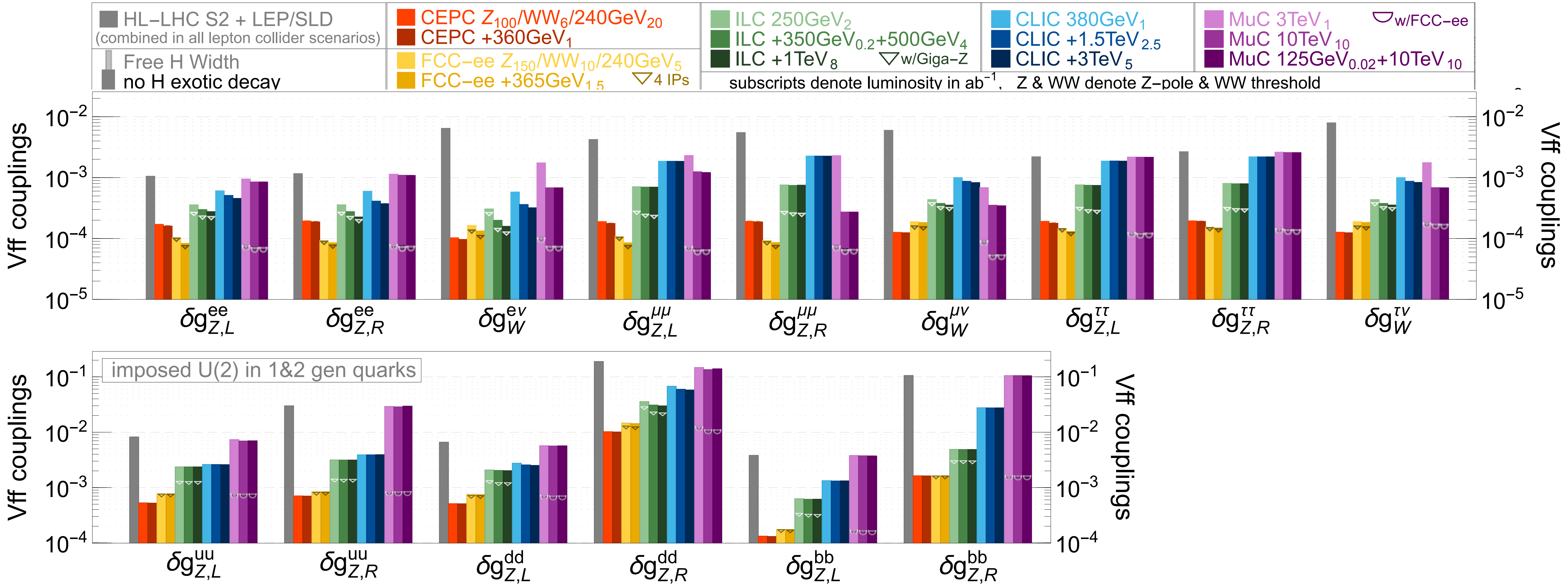
- Parametric uncertainties expected to have similar effect ($\alpha_{\rm em} \rightarrow A_l \rightarrow S$ par.)

Global SMEFT constraints at Future Colliders

- Example: SMEFT at HL-LHC vs FCCee: Sensitivity improvement

Modifications of SM interactions

precision reach on effective couplings from SMEFT global fit



Effective EW couplings

$$\Gamma_{Z\to e^+e^-} = \frac{\alpha\, M_Z}{6\sin^2\theta_w \cos^2\theta_w}\left(|g^{\rm eff}_{Zee,L}|^2 + |g^{\rm eff}_{Zee,R}|^2\right), \qquad A_e = \frac{|g^{\rm eff}_{Zee,L}|^2 - |g^{\rm eff}_{Zee,R}|^2}{|g^{\rm eff}_{Zee,L}|^2 + |g^{\rm eff}_{Zee,R}|^2}.$$

Snowmass 2021: JB et al., arXiv: 2206.08326

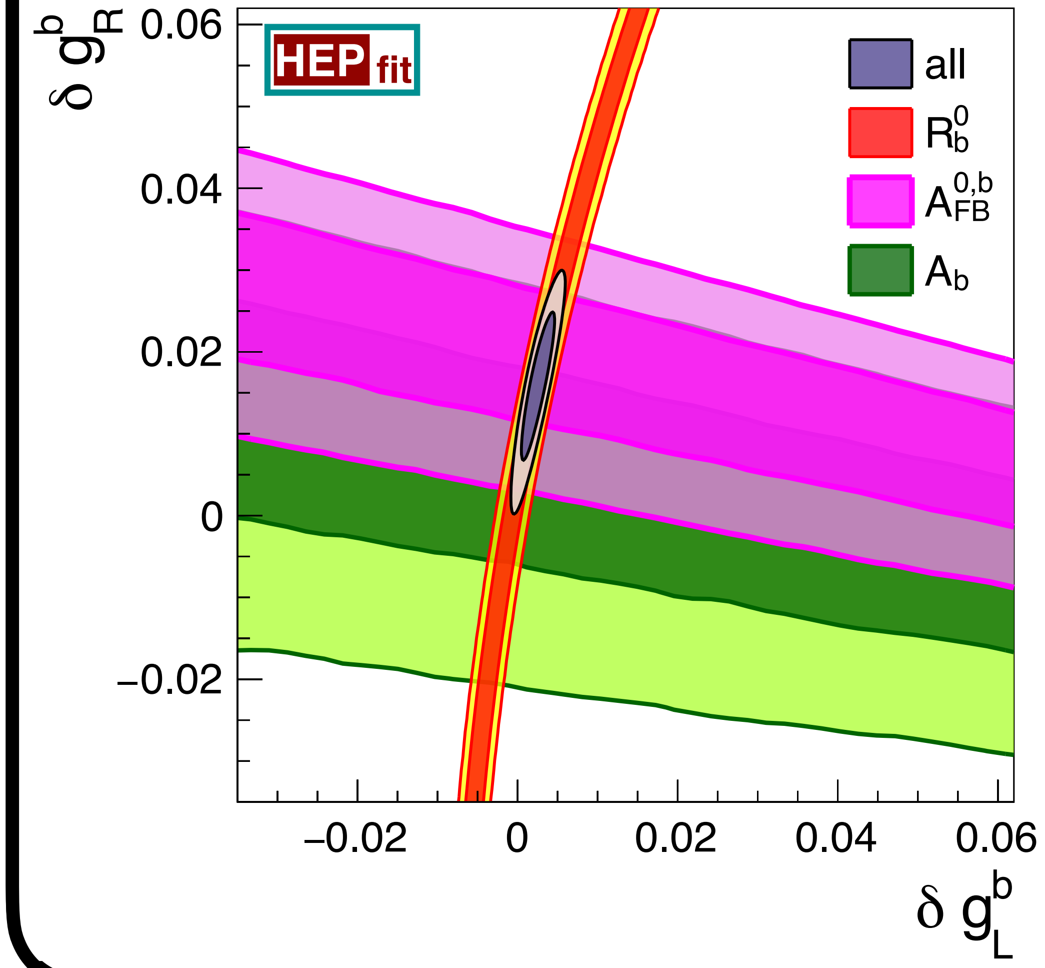
Global SMEFT constraints at Future Colliders

- Example: SMEFT at HL-LHC vs FCCee: Sensitivity improvement

Modifications of SM interactions

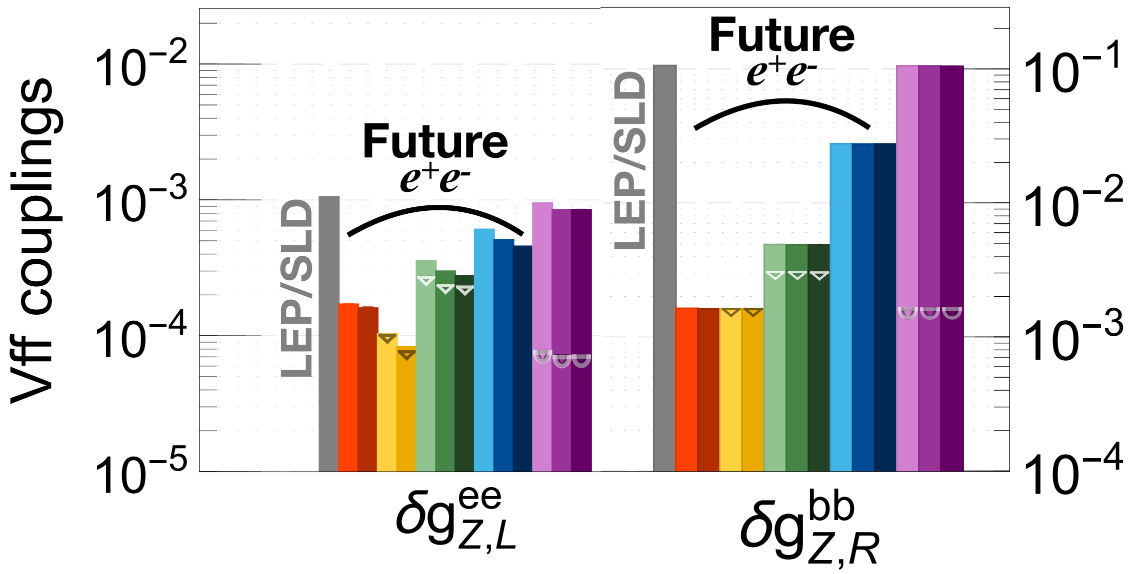
Any future e^+e^- factory can solve the puzzles of the current EW fit

Forward-Backward Asymmetry
Bottom quark



Future e^+e^- improves LEP/SLD EW precision typically by a factor ~10

Tera Z/Giga Z/Rad. return$_{250}$: Enough to clarify current tensions in EW fit: A_{FB}^b



But in general clear advantage for Tera Z: Sensitivity to O(0.01%) BSM effects in several couplings

EW couplings $6\sin^2\theta_w\cos^2\theta_w$ $|g_{Zee,L}|^2 + |g_{Zee,R}|^2$

Vff couplings

Snowmass 2021: JB et al., arXiv: 2206.08326

Global SMEFT constraints at Future Colliders

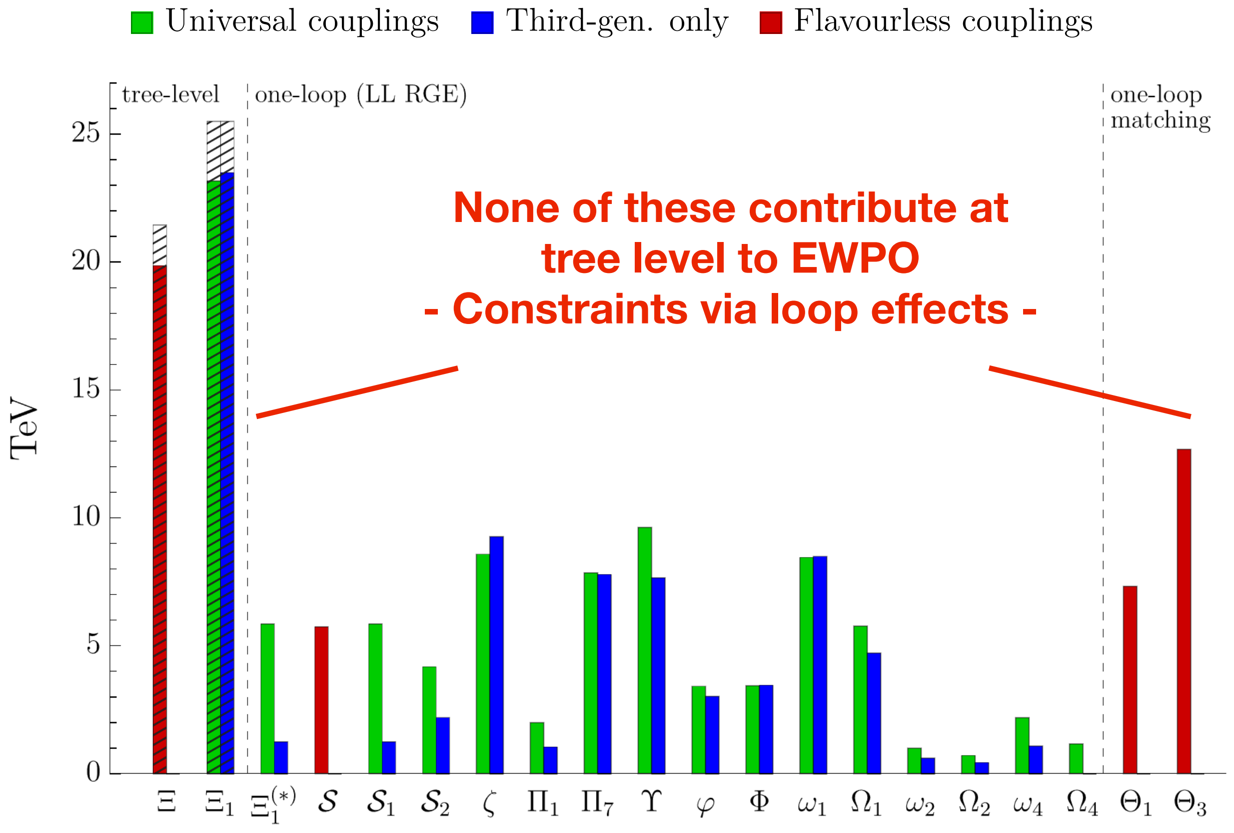
- Example: SMEFT at HL-LHC vs FCCee: Sensitivity improvement

Modifications of SM interactions

Vff couplings

Future e^+e^- EW measurements: What can we learn with this precision?

Strong constraints on new particles even if these do not correct EWPO at LO

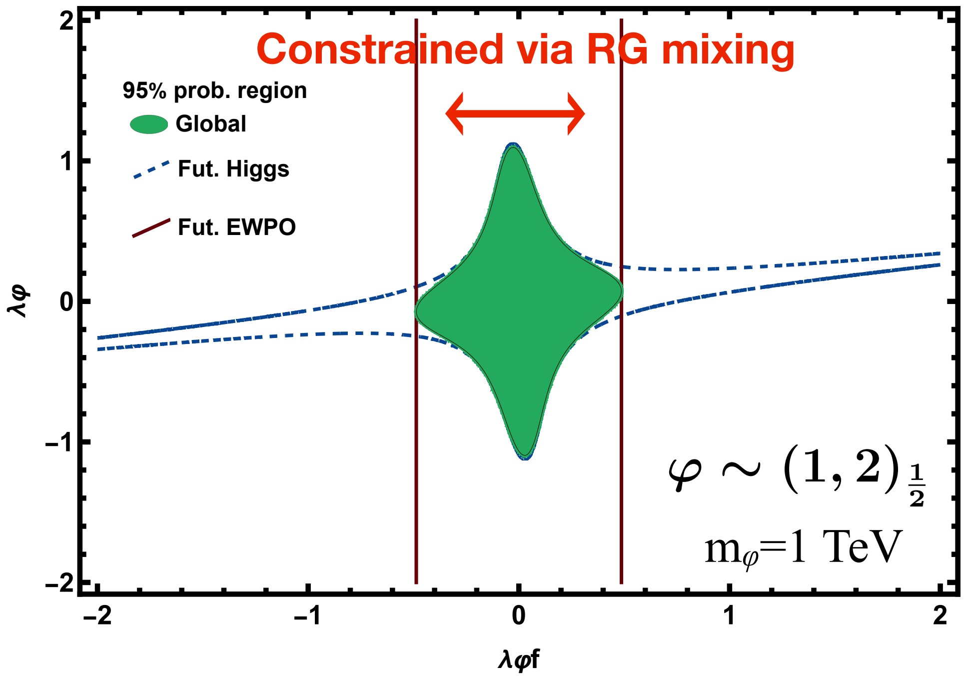


None of these contribute at tree level to EWPO
- Constraints via loop effects -

New scalars contributing to d6 SMEFT at tree level

L. Allwicher, M. McCullough, S. Renner, arXiv:2408.03992 [hep-ph]

$$\Delta\mathcal{L}_{\varphi-\mathrm{SM}} = -\lambda_\varphi(\varphi^\dagger\phi)(\phi^\dagger\phi)$$
$$-\lambda_{\varphi f}(y_e\varphi^\dagger\bar{e}_R l_L + y_d\varphi^\dagger\bar{d}_R q_L + y_u\varphi^\dagger i\sigma_2\bar{q}_L^T u_R) + \mathrm{h.c.}$$



Constrained via RG mixing

Complementarity between EWPO & Higgs

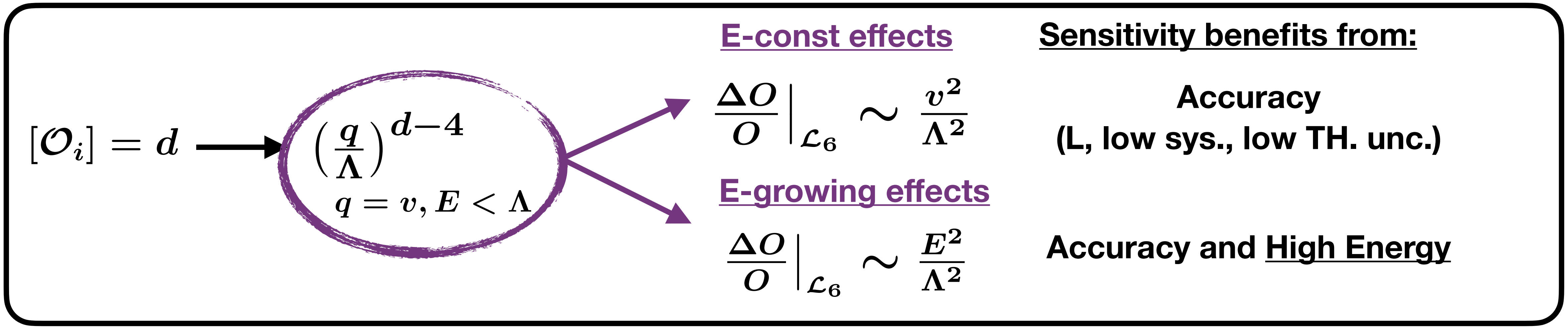
JB, PRELIMINARY

EW couplings $6\sin^2\theta_w\cos^2\theta_w$ $|g_{Zee,L}|^2+|g_{Zee,R}|^2$

Snowmass 2021: JB et al., arXiv: 2206.08326

Electroweak Precision Test at High-E Future Colliders

- Continuing with the interpretation within the EFT, the sensitivity to BSM effects benefits not only from experimental precision but also from access to high-E:



$[\mathcal{O}_i] = d \longrightarrow \left(\frac{q}{\Lambda}\right)^{d-4}$

$q = v, E < \Lambda$

E-const effects

$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{v^2}{\Lambda^2}$$

E-growing effects

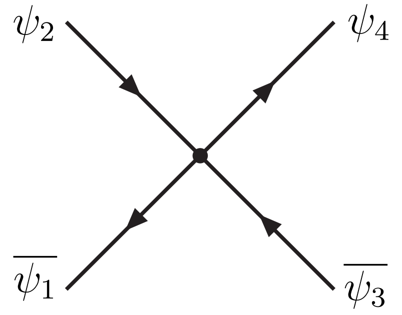
$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{E^2}{\Lambda^2}$$

Sensitivity benefits from:

Accuracy
(L, low sys., low TH. unc.)

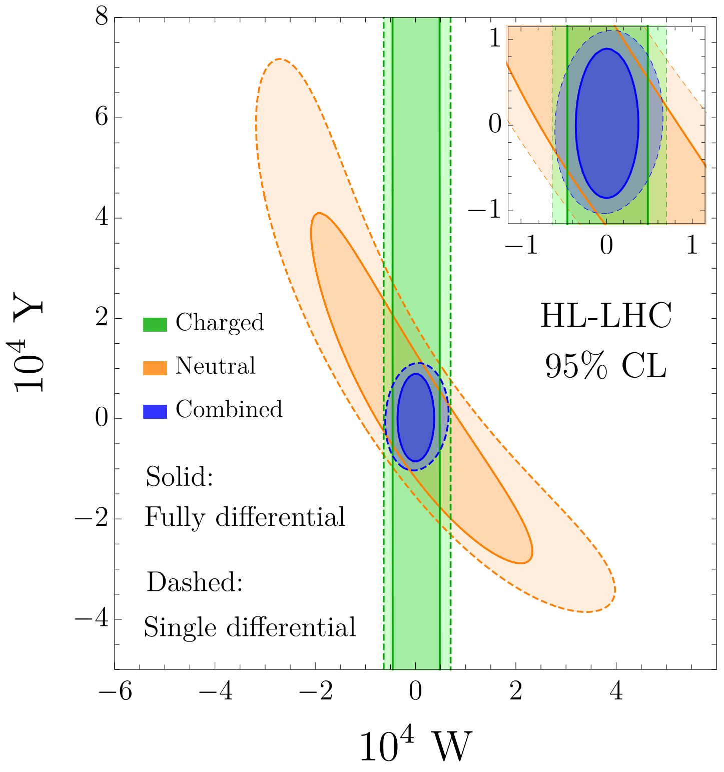
Accuracy and High Energy

- Example: HL-LHC 2→2 fermion processes

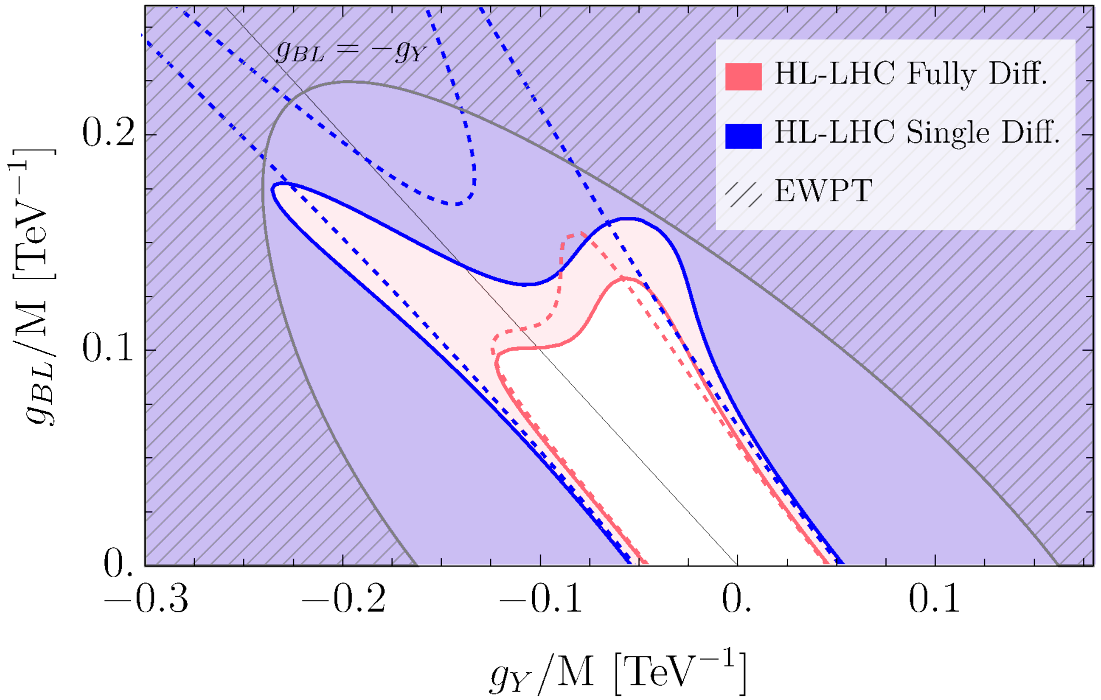


$$\left.\frac{\Delta O}{O}\right|_{\mathcal{L}_6} \sim \frac{E^2}{\Lambda^2}$$

In NC and CC DY



G. Panico, L. Ricci, A. Wulzer, JHEP 07 (2021) 086



Minimal *Z'* models

Electroweak Precision Test at High-E Future Colliders

- Within the context of Future Lepton Colliders, this is of special relevance for high-energy (multi-TeV) muon colliders

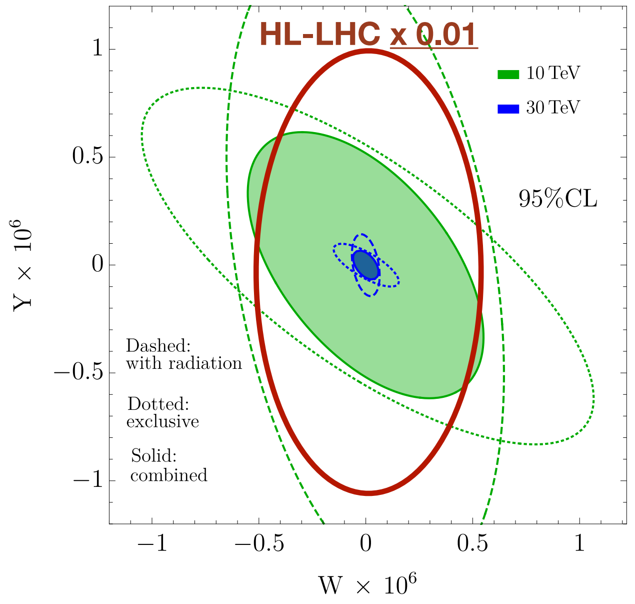
S. Chen et al. , JHEP 05 (2022) 180

W & Y parameters in 2→2 fermion processes

$$O_{2W} = (D_\mu W^{\mu\nu,a})^2 \qquad O_{2B} = (\partial_\mu B^{\mu\nu})^2 \quad \longrightarrow \quad J_L^{a,\mu} J_{L,\mu}^a \qquad J_L^{a,\mu} = \frac{1}{2}\sum_f \bar{f}\gamma^\mu\sigma^a f + \ldots \qquad J_Y^\mu J_{Y,\mu} \qquad J_Y^\mu = \sum_f Y_f \bar{f}\gamma^\mu f + \ldots$$

Induce 4-fermion operators:

Contribution to cross section for $\sim \dfrac{\boldsymbol{E^2}}{\boldsymbol{\Lambda^2}}$

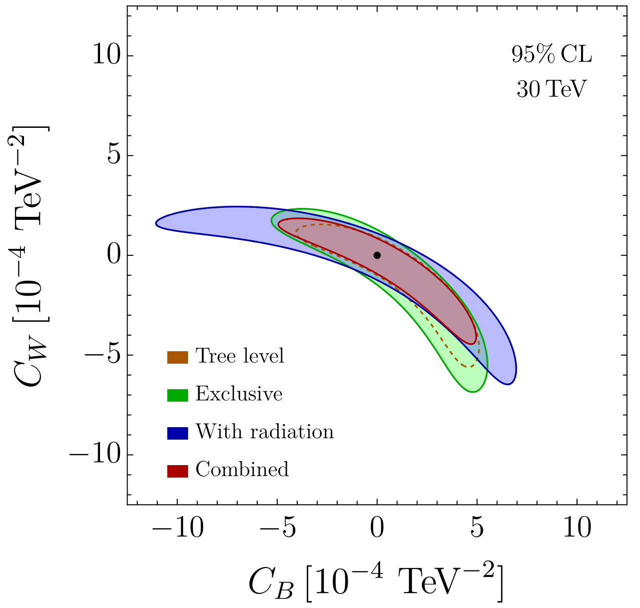


Vector bosons and Higgs production (*Zh, WW, Wh, WZ*)

$$O_W = \frac{ig}{2}(H^\dagger\sigma^a \overleftrightarrow{D}_\mu H) D^\nu W^a_{\mu\nu} \qquad O_B = \frac{ig'}{2}(H^\dagger \overleftrightarrow{D}_\mu H)\partial^\nu B_{\mu\nu} \quad \longrightarrow \quad \frac{g^2}{4}(H^\dagger i\overleftrightarrow{D}_\mu \sigma^a H)(\bar{L}_L\gamma^\mu\sigma^a L_L) + \ldots \qquad -\frac{g'^2}{4}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{L}_L\gamma^\mu L_L) - \frac{g'^2}{2}(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_R\gamma^\mu l_R) + \ldots$$

Induce *VHff* operators:

Contribution to cross section $\sim \dfrac{\boldsymbol{E^2}}{\boldsymbol{\Lambda^2}}$



$$\frac{\mu\text{coll}_{10\text{ TeV}}}{\mu\text{coll}_{30\text{ TeV}}} \sim 10$$

Summary

Summary

- EW precision tests have been traditionally a powerful tool to validate the SM description of electroweak interactions and constrain new physics
- Current precision established the need for precision calculations, testing the SM to the level of quantum corrections (2-loops)
- While the SM global EW fit is "dominated" by measurements at previous lepton colliders (LEP/SLD), it also receives important information from hadron colliders (Tevatron, LHC):
  - ✓ Some input parameters can only be measured there (Top and Higgs masses)
  - ✓ In some cases better precision: W mass
  - ✓ Plus some measurements of the neutral current are starting to compete with the LEP/SLC precision
- (If we ignore M_W from CDF) No statistically significant deviation in the SM EW fit, though interesting tensions still present (A_{FB}^b)
  - ✓ Strong constraints on new physics affecting the EW sector!!! (Sensitivity to new physics ~few TeV, depending on new physics couplings)

Summary

- Future e^+e^- colliders like any of the proposed Higgs factories would be capable of significantly improving our knowledge of the EW sector
  - ✓ Different ways of improving the precision of EWPO:
    - ▸ Run at Z-pole (Tera Z/Giga Z)
    - ▸ Measurements at Higgs factory run (250 GeV) via radiative return to Z
  - ✓ Higgs factory runs (250 and 350 GeV) → Improvement in W and Top-quark mass precision
- Typically, one order of magnitude improvement in sensitivity to new physics…
- …But requires a substantial improvement in SM theory calculations to match the expected experimental precision of EWPO
  - ✓ Challenging but needed so SM theory is not a bottleneck for new physics interpretations
- High Energy Future Colliders (e.g. Muon colliders) also benefit of the high-E reach to provide other interesting EW measurements beyond EWPO, and strong BSM sensitivity without relying crucially on EXP precision

Backup slides

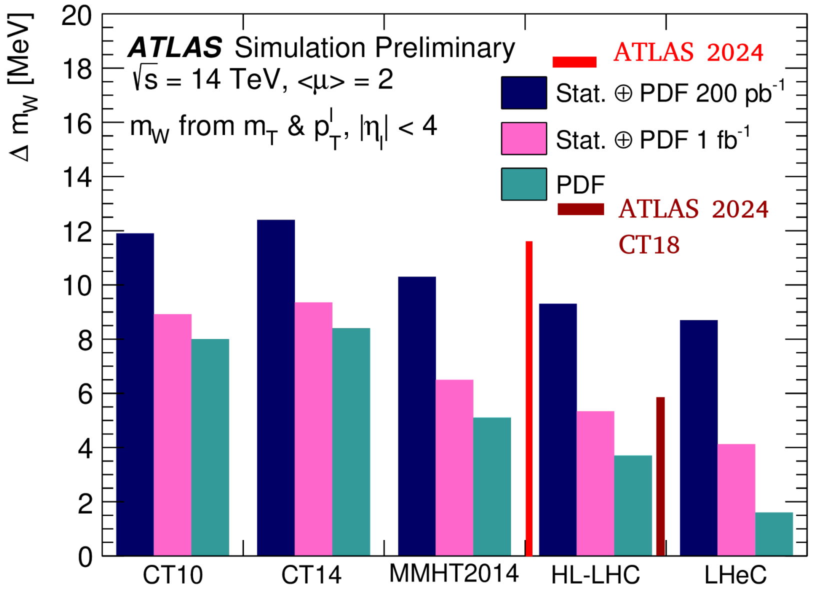
Electroweak precision observables at the HL-LHC

- **W mass** at HL-LHC

ATLAS 2024 (CT18): $m_W = 80366.5 \pm 9.8\,(\mathrm{stat.}) \pm 12.5\,(\mathrm{syst.})$ MeV

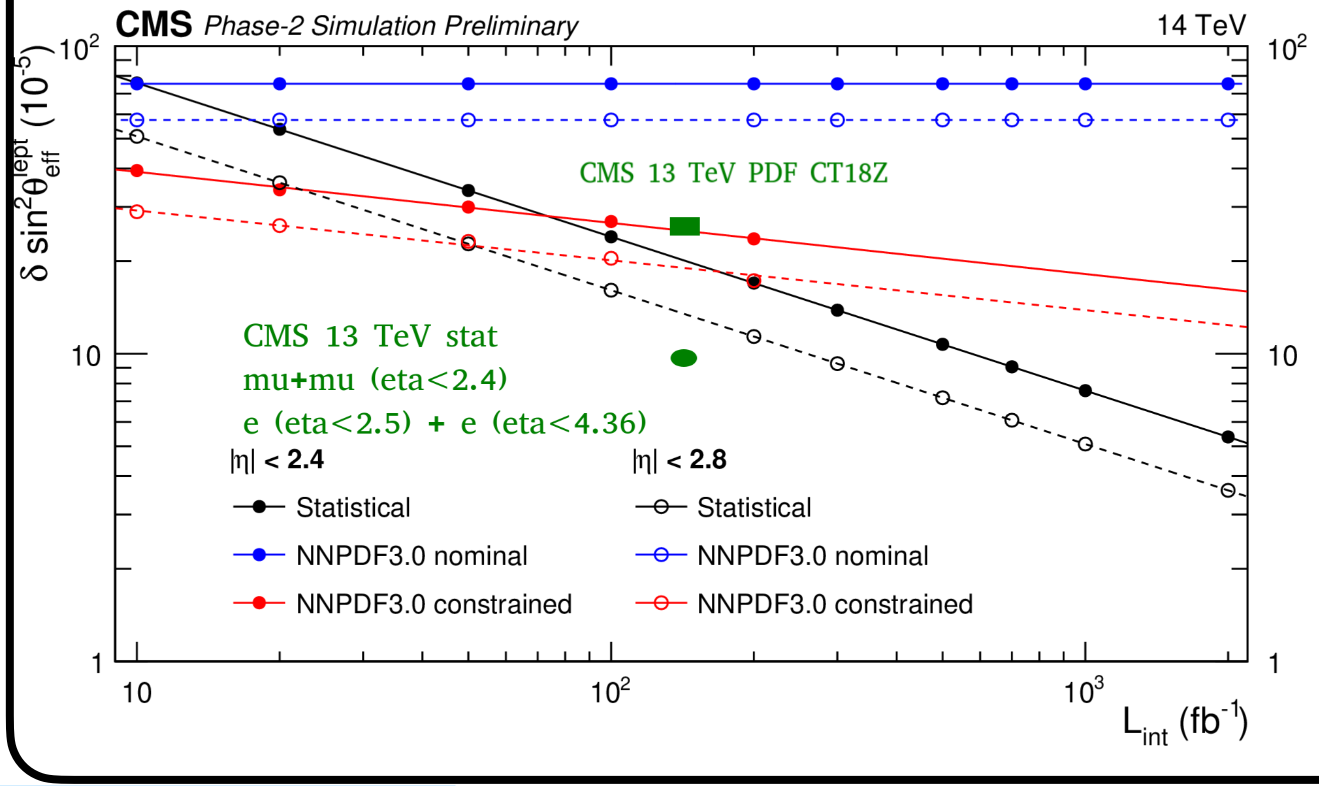
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_{T}	Lumi	Γ_W	PS
p_{T}^{ℓ}	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_{T}	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

HLLHC will benefit from improved lepton acceptance
Final precision will largely depend on PDFs and amount of data



- **Effective weak mixing angle** at HL-LHC

CMS 2024: $sin^2\theta^{\ell}_{\mathrm{eff}} = 0.23157 \pm 0.00010\,(\mathrm{stat}) \pm 0.00015\,(\mathrm{exp}) \pm 0.00009\,(\mathrm{theo}) \pm 0.00027\,(\mathrm{PDF})$



	ATLAS $\sqrt{s} = 8$ TeV	ATLAS $\sqrt{s} = 14$ TeV	ATLAS $\sqrt{s} = 14$ TeV
$\mathcal{L}$ [fb^{-1}]	20	3000	3000
PDF set	MMHT14	CT14	PDF4LHC15$_{HL-LHC}$
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ [$\times 10^{-5}$]	23140	23153	23153
Stat.	± 21	± 4	± 4
PDFs	± 24	± 16	± 13
Experimental Syst.	± 9	± 8	± 6
Other Syst.	± 13	-	-
Total	± 36	± 18	± 15

Final precision at the LEP/SLD level

(Depending again on PDFs)

Snowmass 2021: ATLAS-PHYS-PUB-2022-018/CMS PAS FTR-22-001

Electroweak precision observables at the HL-LHC

- **EWPO** at HL-LHC: Impact on EWPO fit

SM EW fit

Including expected HLLHC improvements on:

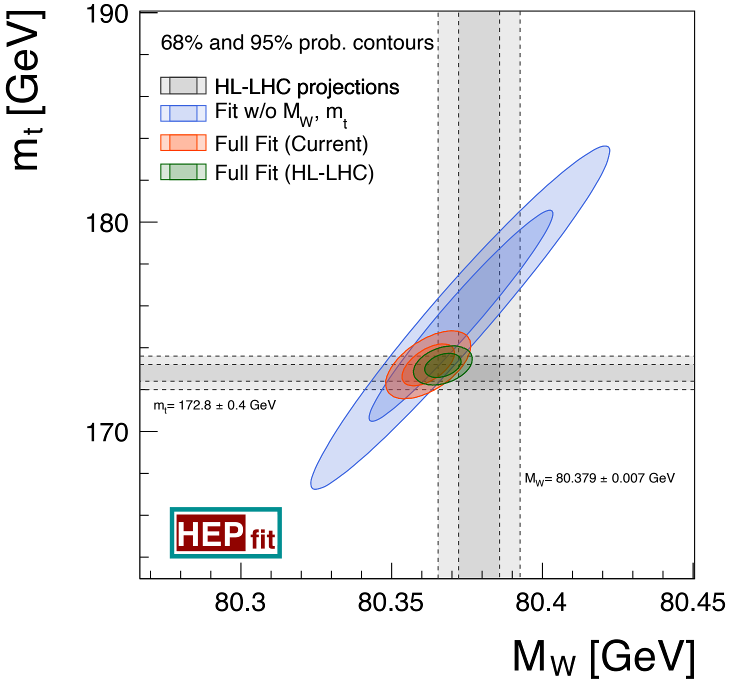
-W mass

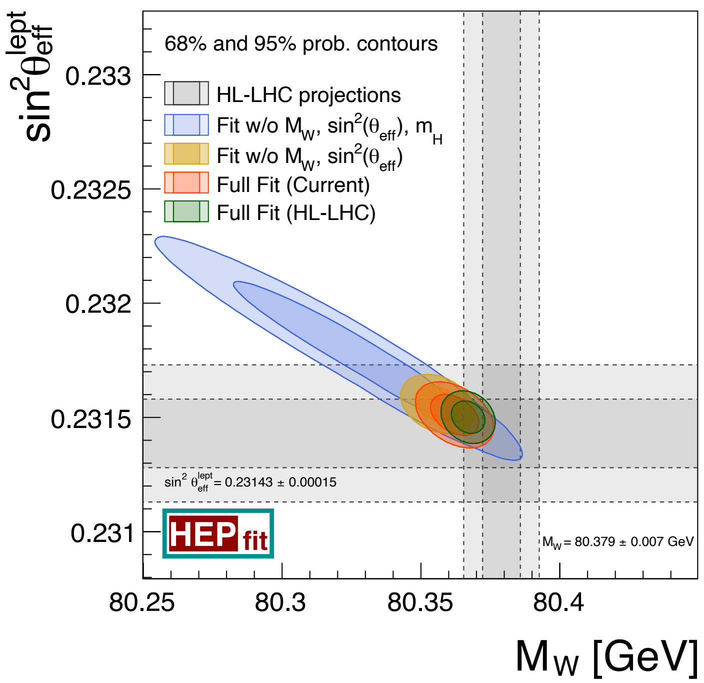
- Effective angle

- Top Quark mass

Only small effect compared to 2016 SM EW fit

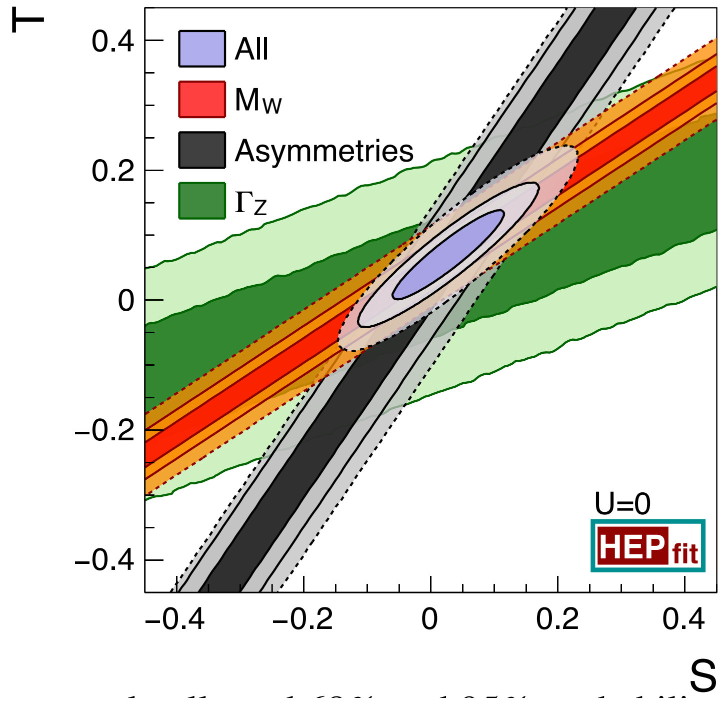
arXiv: 1902.04070





Oblique parameters STU

	Result	Correlation Matrix			Precision at HL-LHC
S	0.04 ± 0.10	1.00			0.09
T	0.08 ± 0.12	0.90	1.00		0.12
U	0.00 ± 0.09	-0.62	-0.84	1.00	0.08
S	0.04 ± 0.08	1.00			0.06
T	0.08 ± 0.06	0.90	1.00		0.05
$(U = 0)$					



arXiv: 1902.04070