The Higgs boson through the lens of precision e^+e^- data

Roman Kogler

60th Rencontres de Moriond

21 March, 2026

The Gfitter group:
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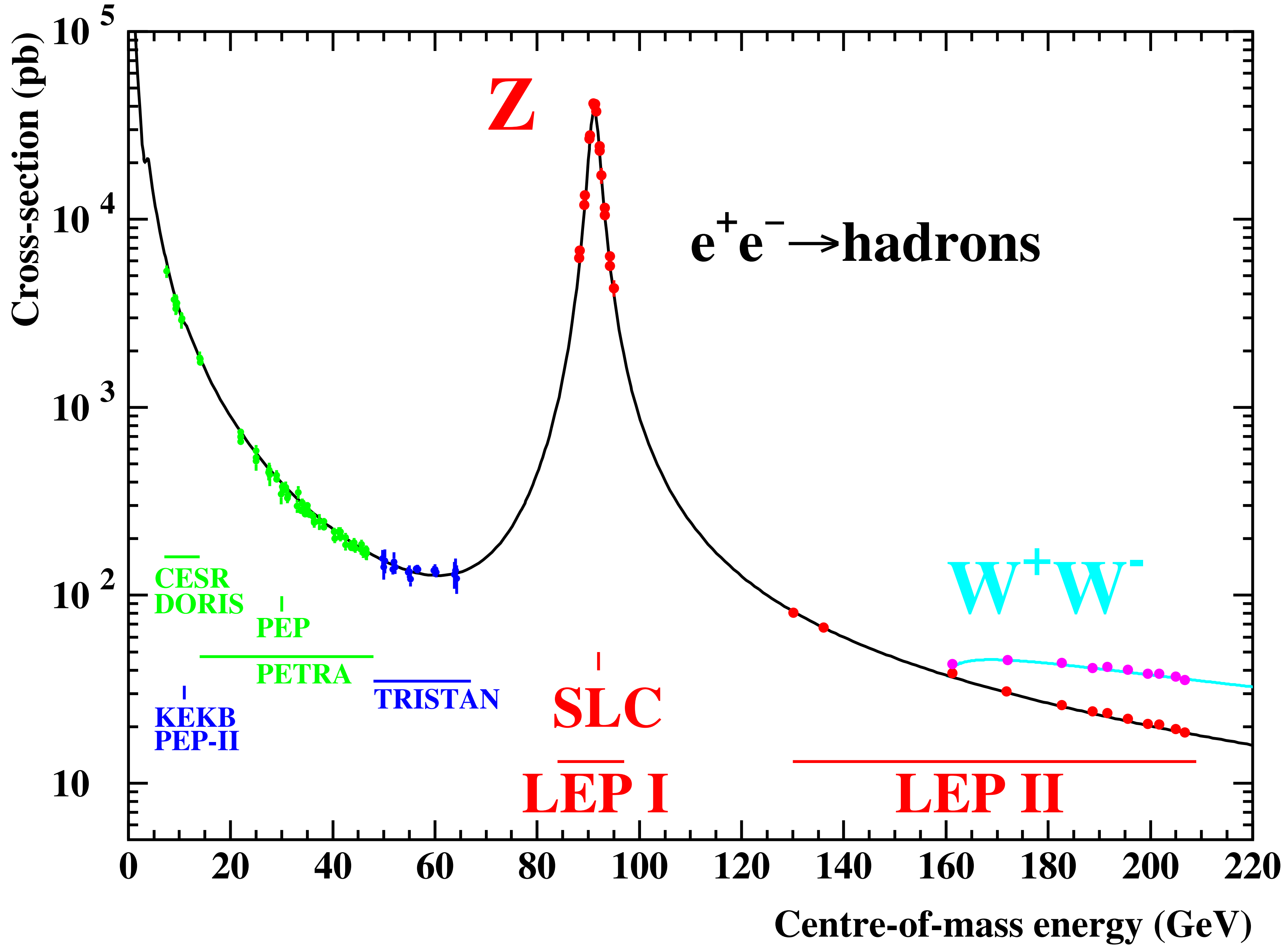
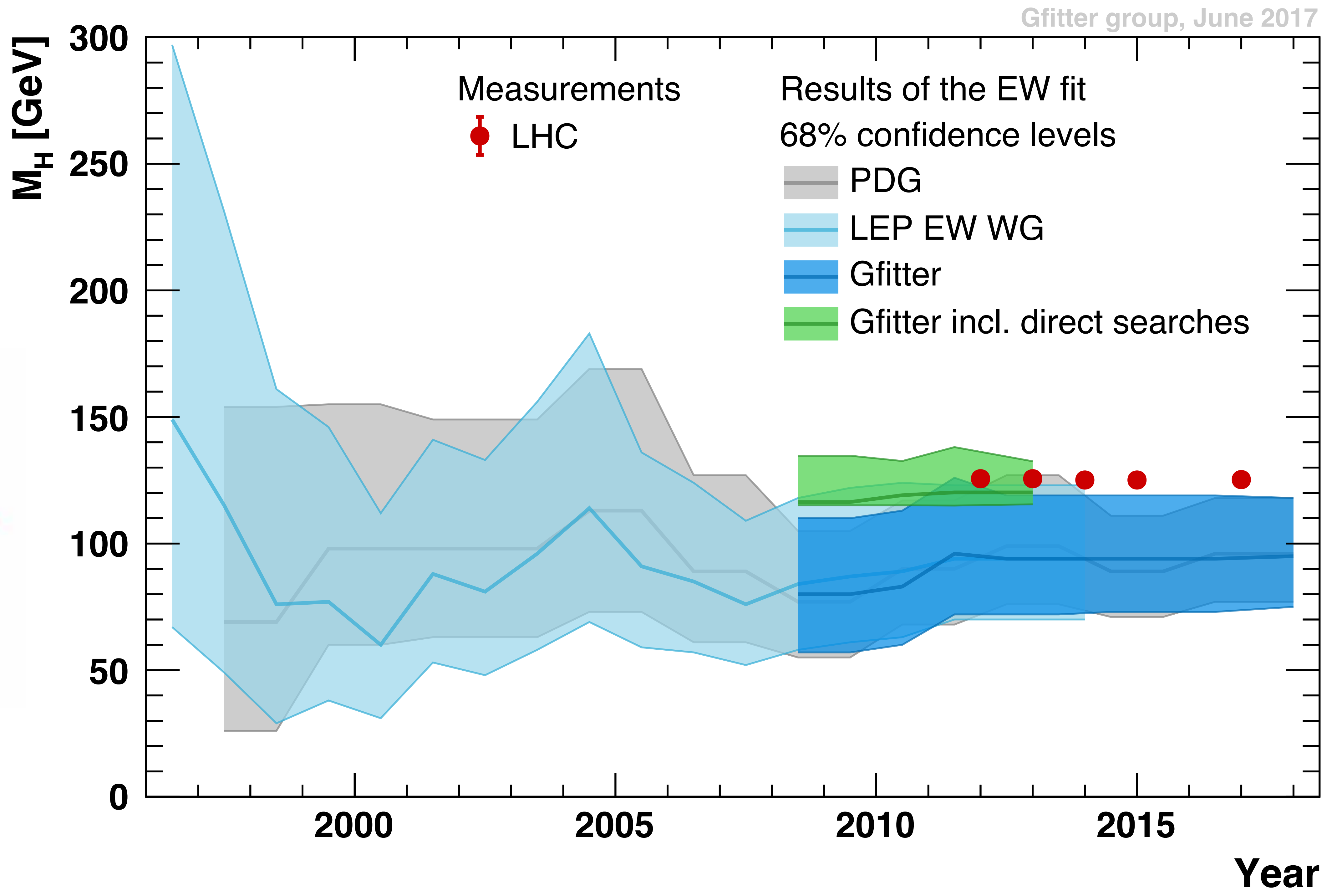
The Global EW Fit

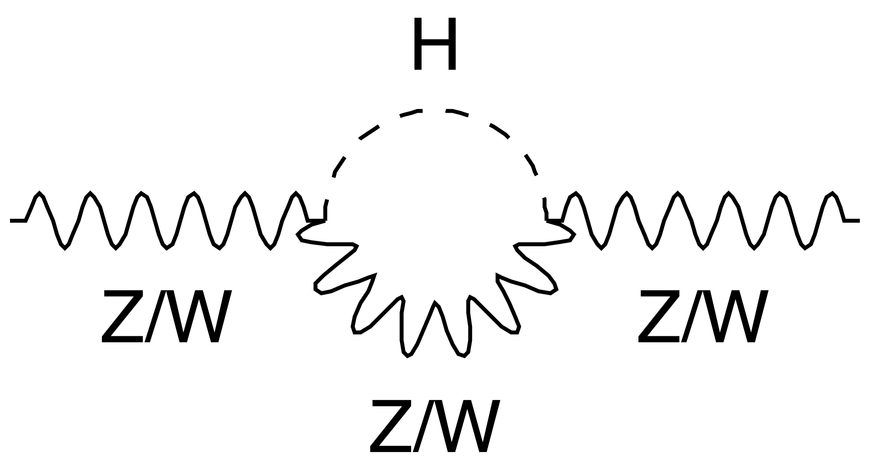
Precision data (EWPO)



Predictions and SM consistency tests

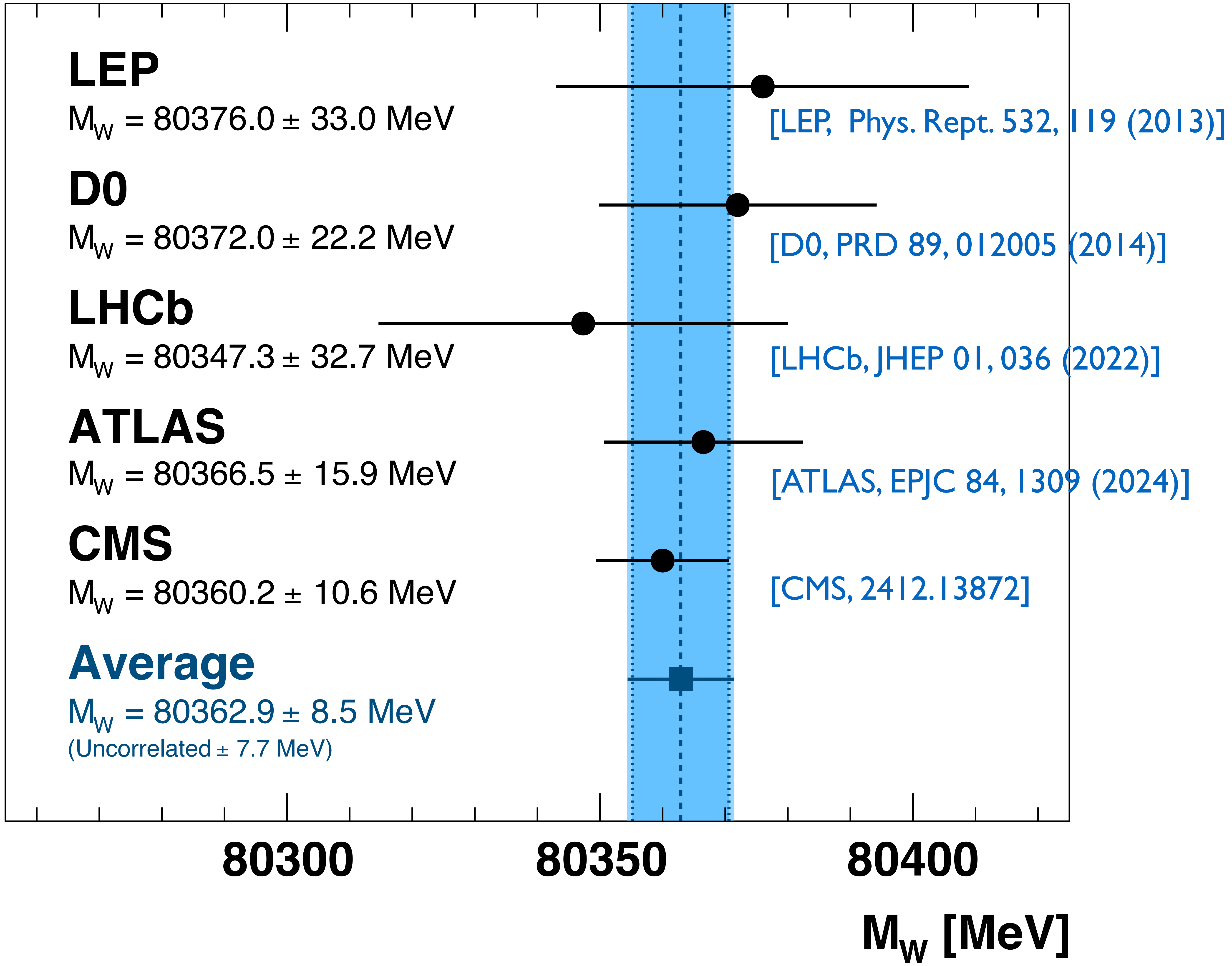


Precision calculations (NNLO and higher)



$$\propto \ln \frac{M_H^2}{M_W^2}$$

W Mass



- Combination following LHC-TeV MW Working Group
  [MW WG, EPJC 84, 451 (2024)]
- Values adjusted to CT18
- Correlations accounted for
- $\chi 2/\mathrm{ndf} = 0.7 / 5$

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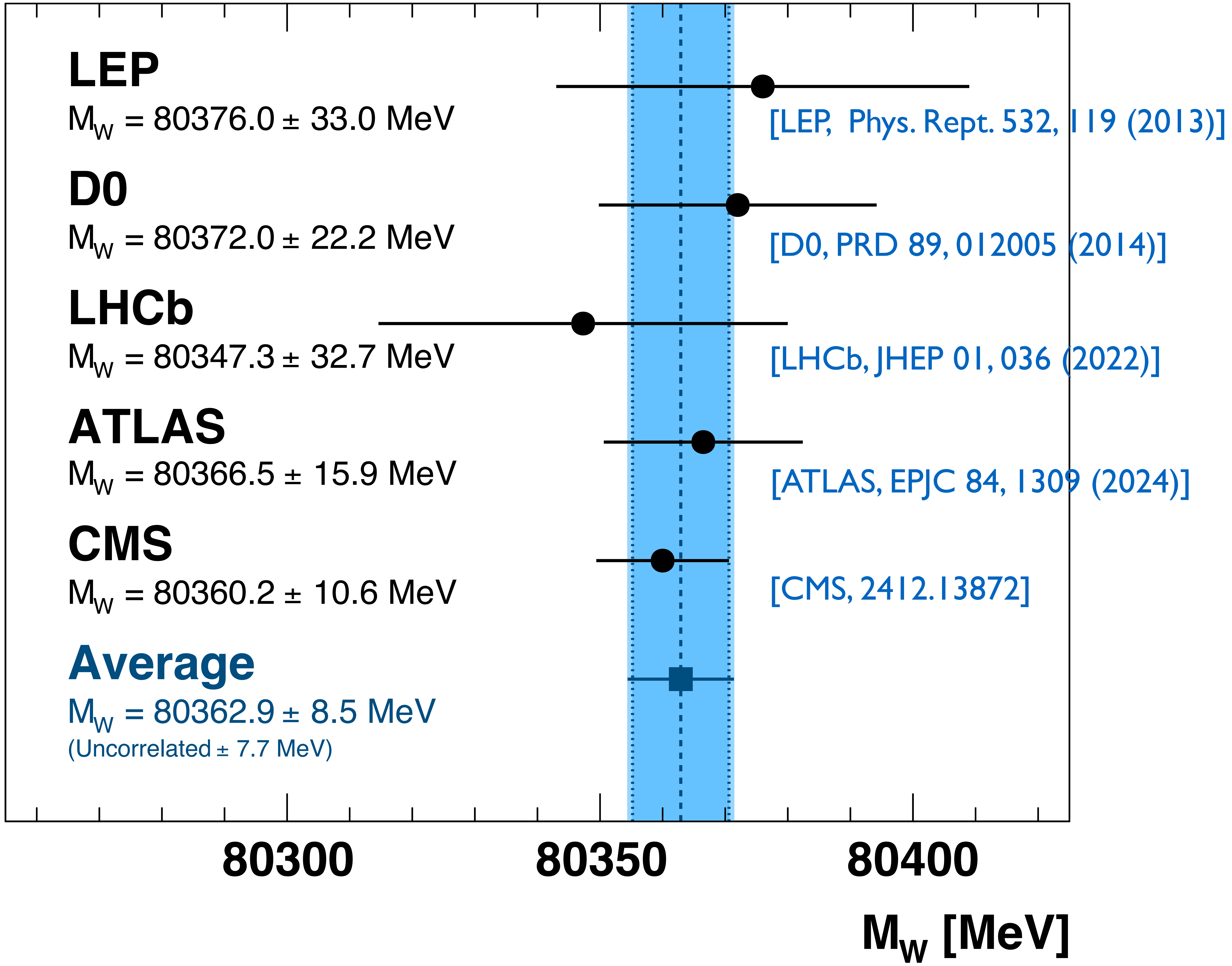

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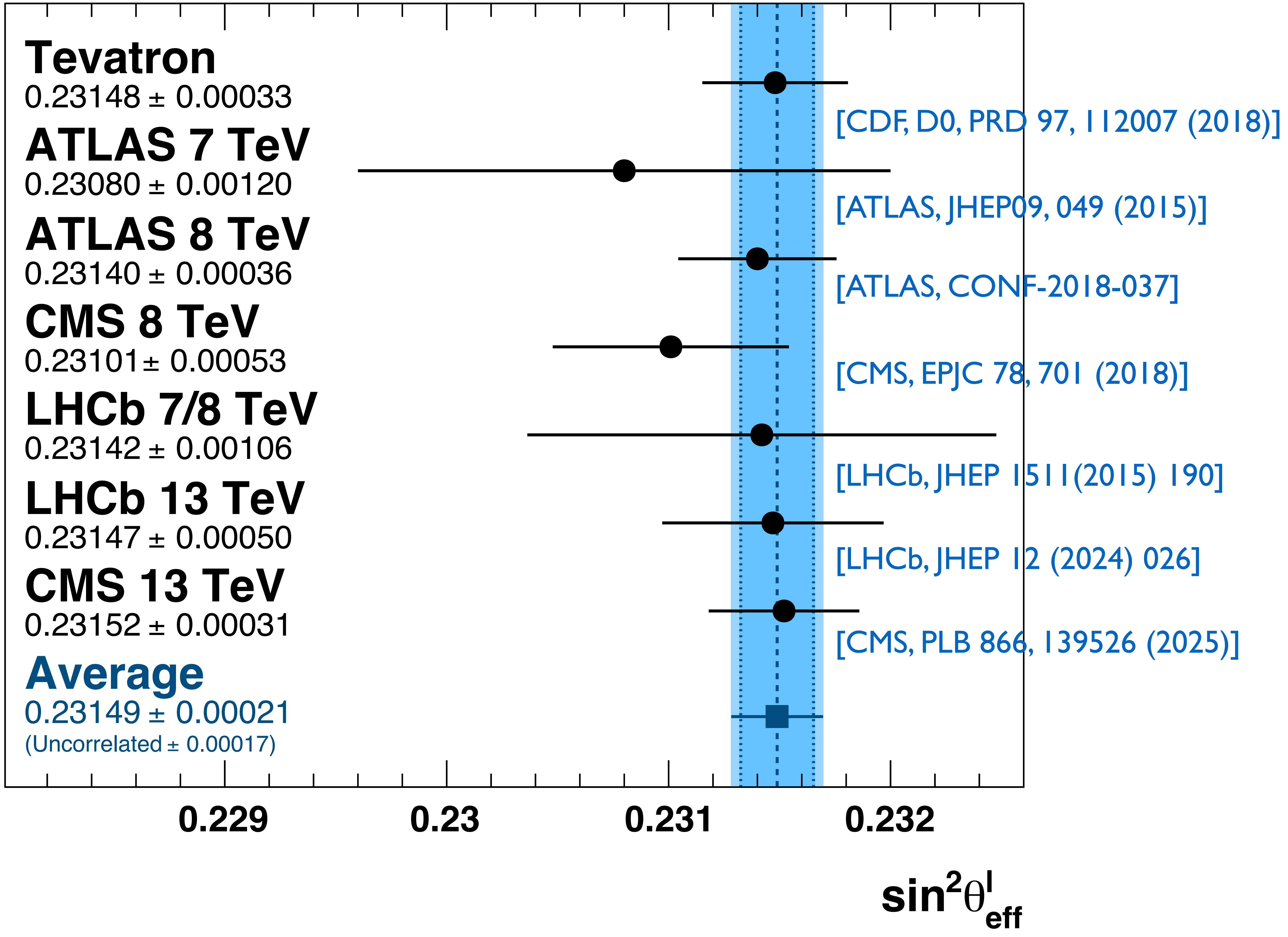
Precision on m_W:
15 MeV (2015)
8.5 MeV (today)

(about 10 years ago: envisioned 8 MeV for LHC Run 3)

Effective weak mixing angle $\sin^2(\theta^\ell_{eff})$



Combination performed using assumptions and variations of PDF and model uncertainties

$\chi^2/\text{ndf} = 1.3 / 6$

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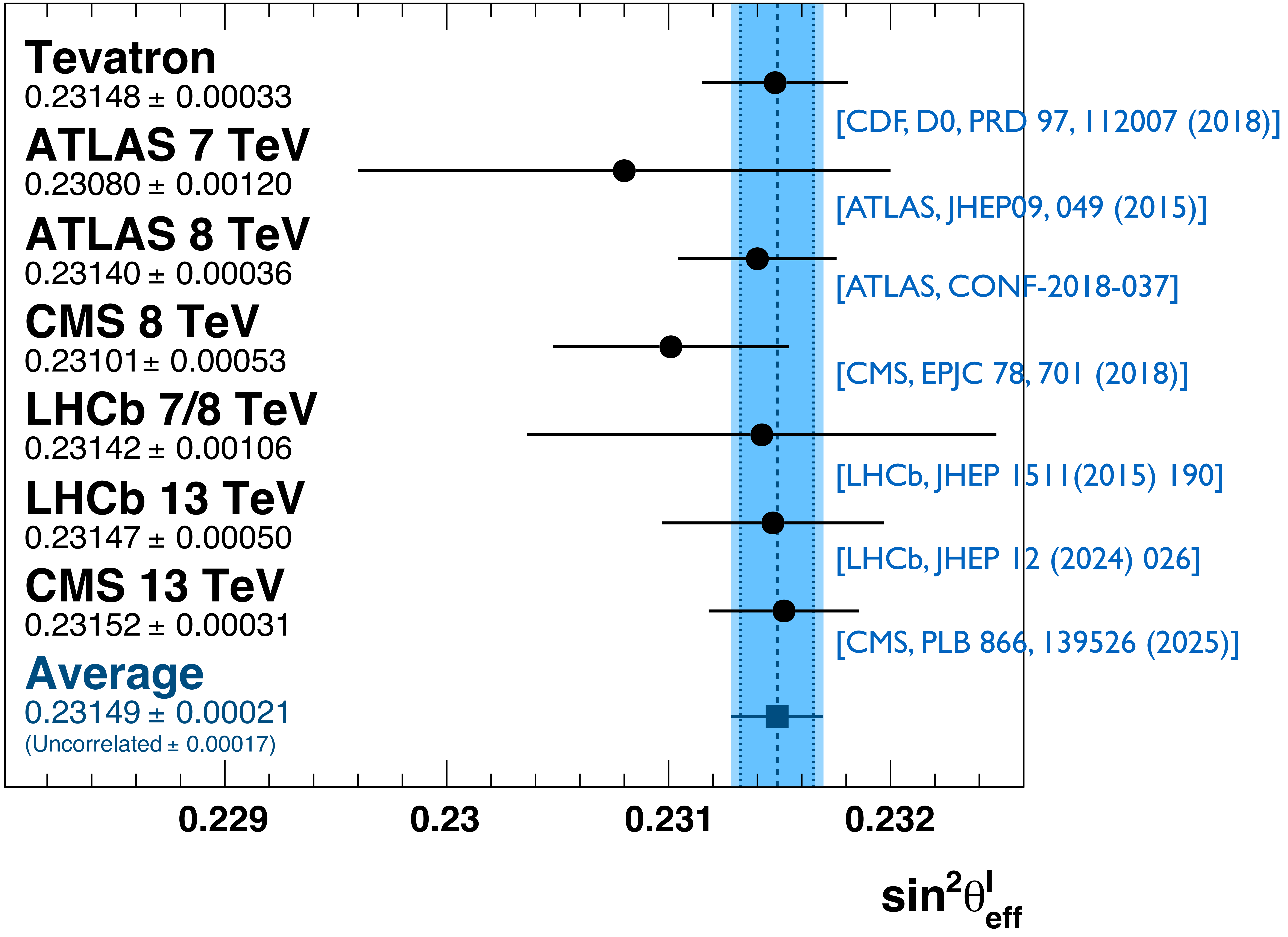


Combination performed using assumptions and variations of PDF and model uncertainties

$\chi^2/\text{ndf} = 1.3 / 6$

LHC measurements now competitive with Tevatron

Comparison:
LEP/SLD: 0.23153 ± 0.00016
(included in fit through asymmetries)

[LEP, SLD, Phys. Rep. 427, 257 (2006)]

SM Fit Results

Recent updates

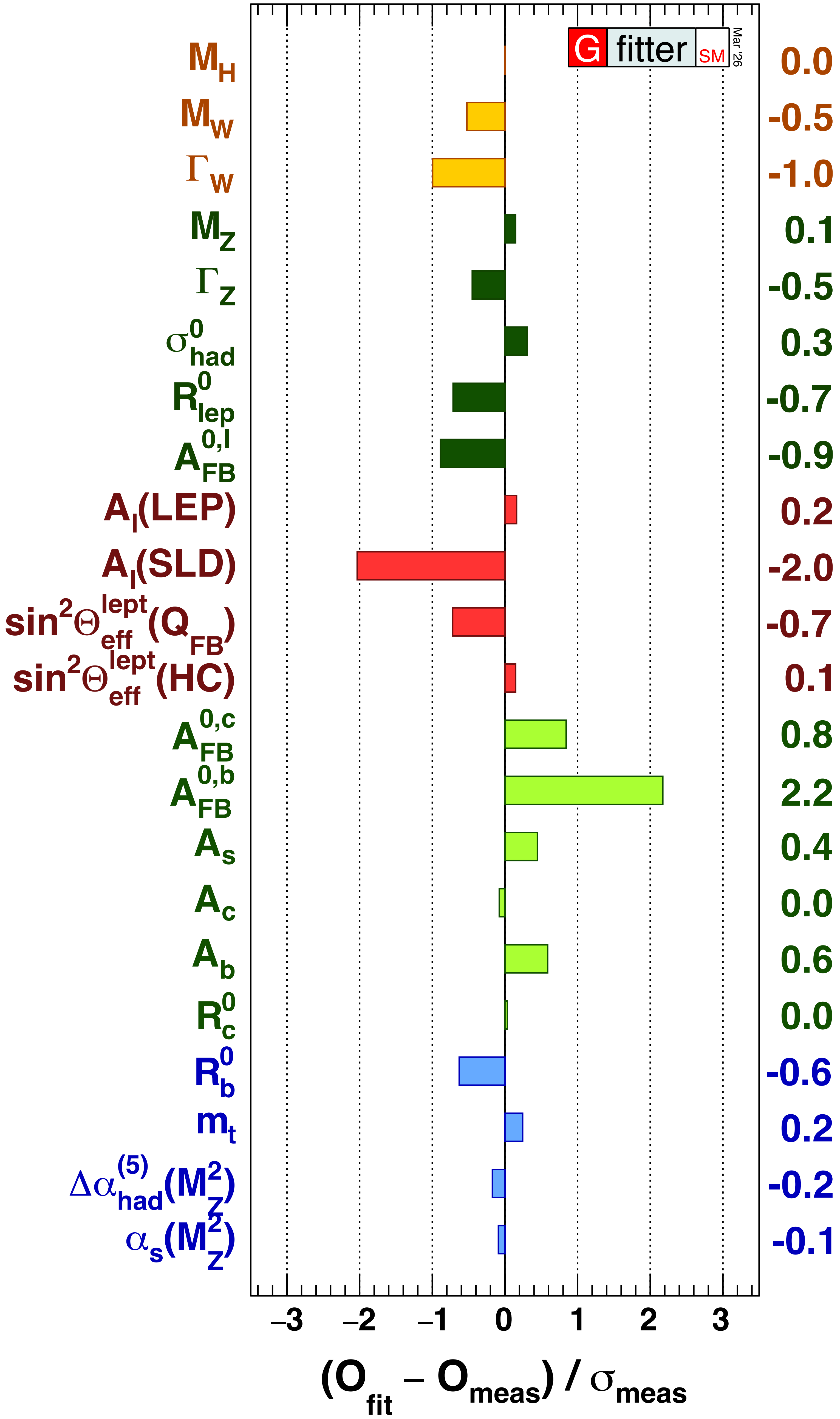
- Updated calculations of beam-beam effects on the LEP luminosity [Voutsinas et al, PLB 800, 135068 (2020)]
- Updated Bhabha cross section [Janot, Jadach, PLB 803, 135319 (2020)]

Good fit quality

- χ^2 / ndf = 13.6 / 16, p-value = 0.63
  - χ^2 (2018) = 18.6
  - χ^2 (2012) = 21.8

Indirect predictions:

- $m_H = 110\ ^{+20}_{-17}$ GeV
- $m_W = 80.356 \pm 0.006$ GeV
- $m_t = 173.7 \pm 1.6$ GeV
- $\alpha_S(M_Z) = 0.1200 \pm 0.0028$



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SM gets healthier with age

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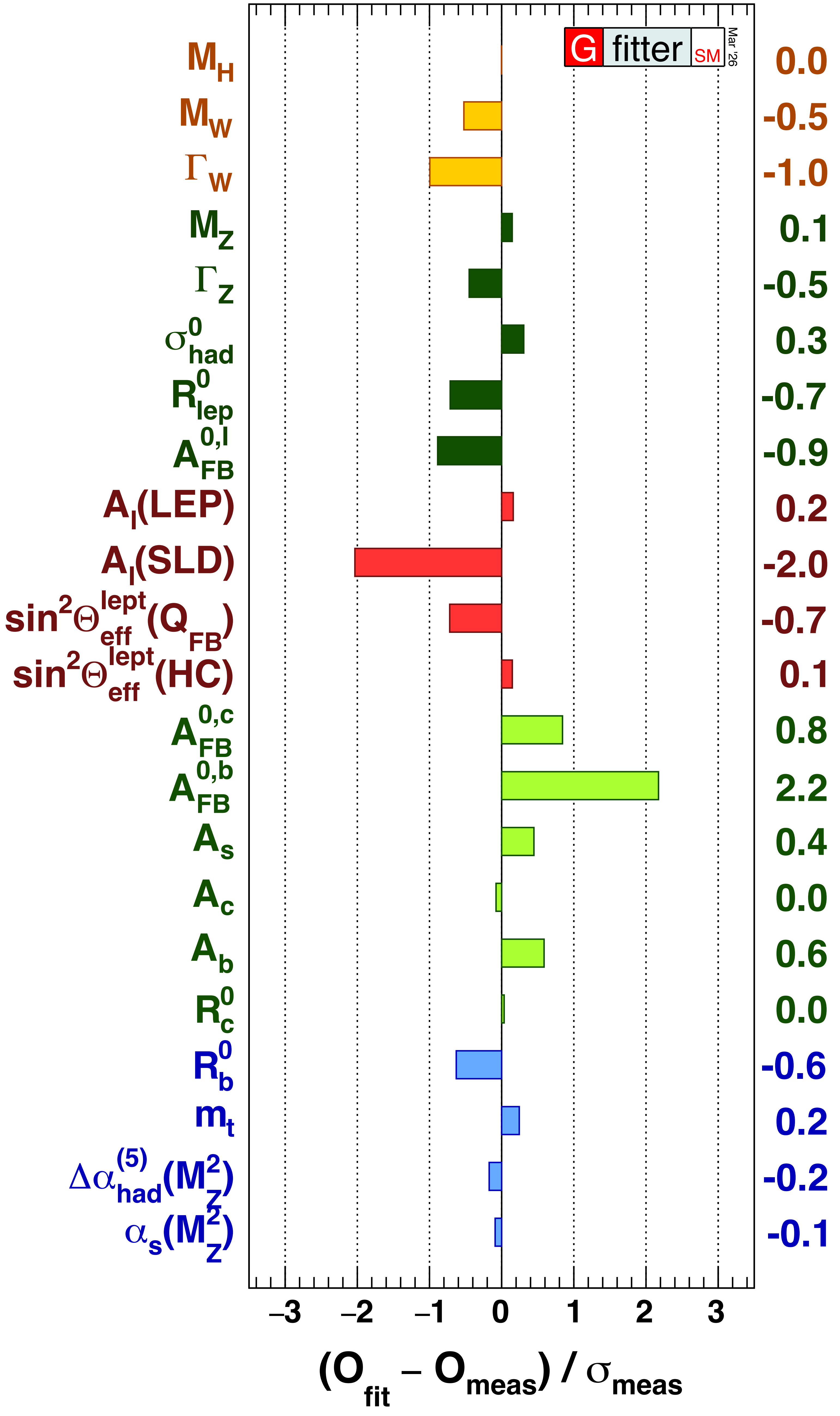
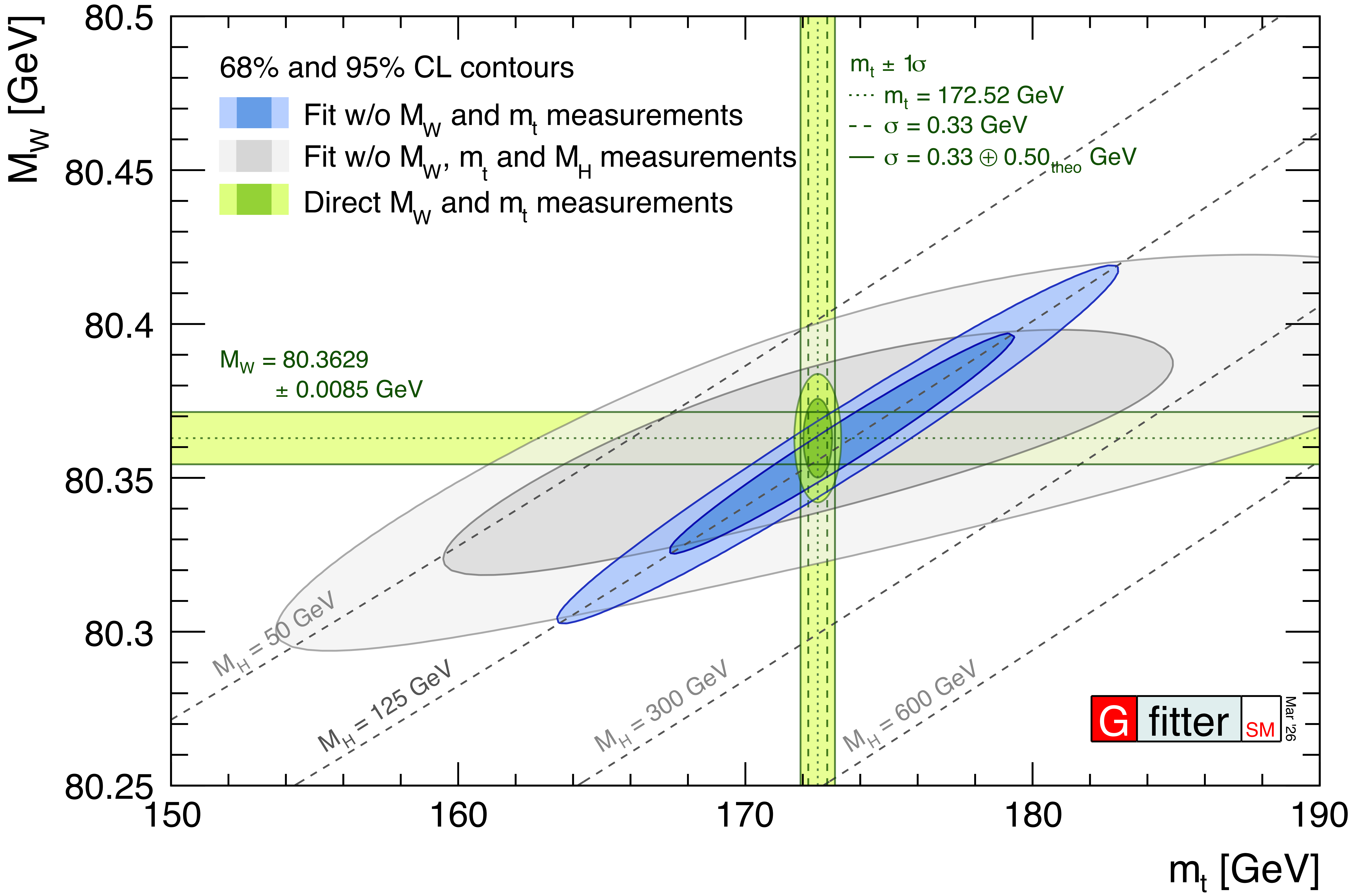
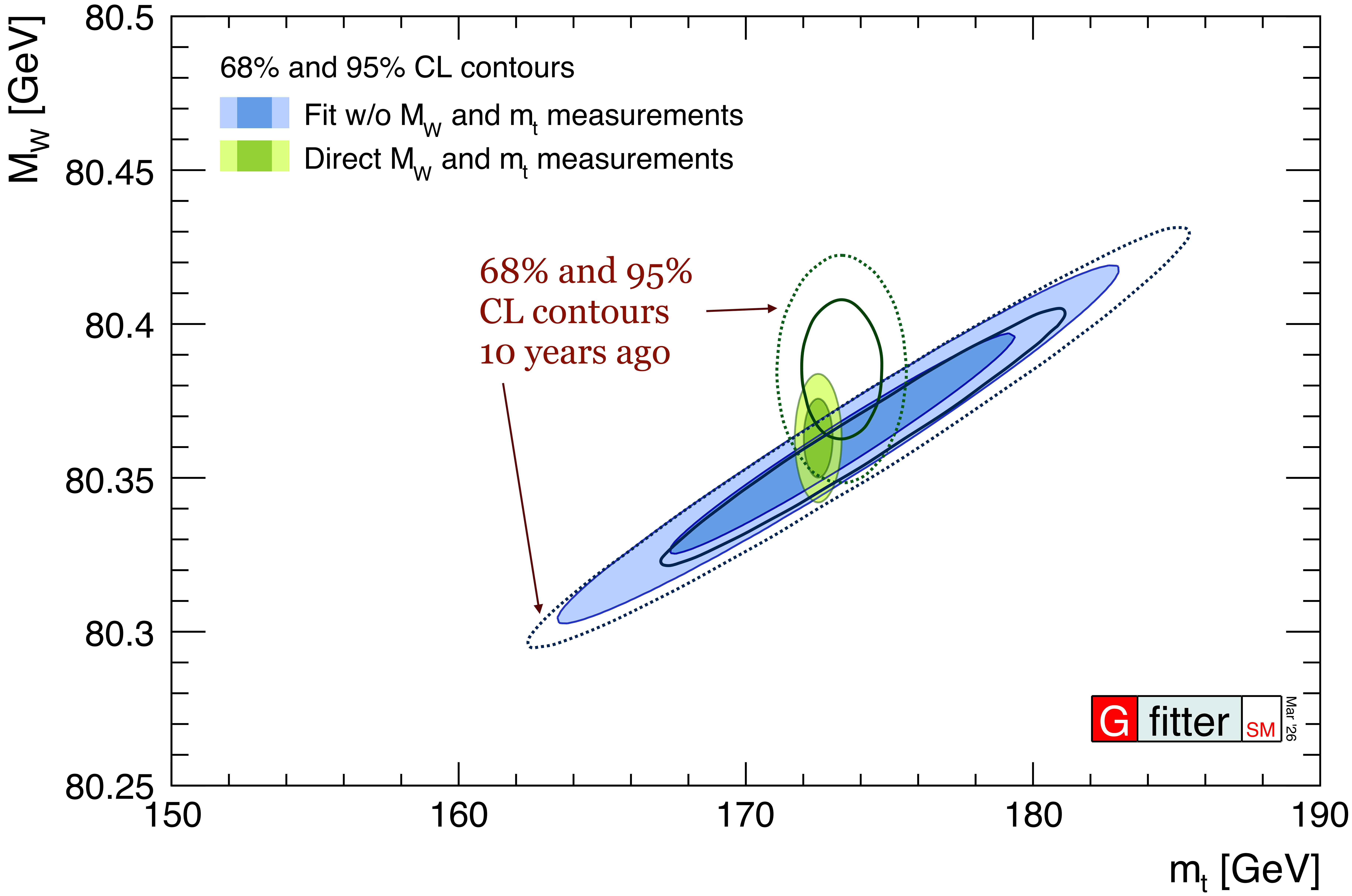




68% and 95% CL contours
Fit w/o M_W and m_t measurements
Fit w/o M_W, m_t and M_H measurements
Direct M_W and m_t measurements
m_t ± 1σ
m_t = 172.52 GeV
σ = 0.33 GeV
σ = 0.33 ⊕ 0.50_theo GeV
M_W = 80.3629
± 0.0085 GeV
M_H = 50 GeV
M_H = 125 GeV
M_H = 300 GeV
M_H = 600 GeV
G fitter SM
Mar '26
M_W [GeV]
m_t [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
150
160
170
180
190



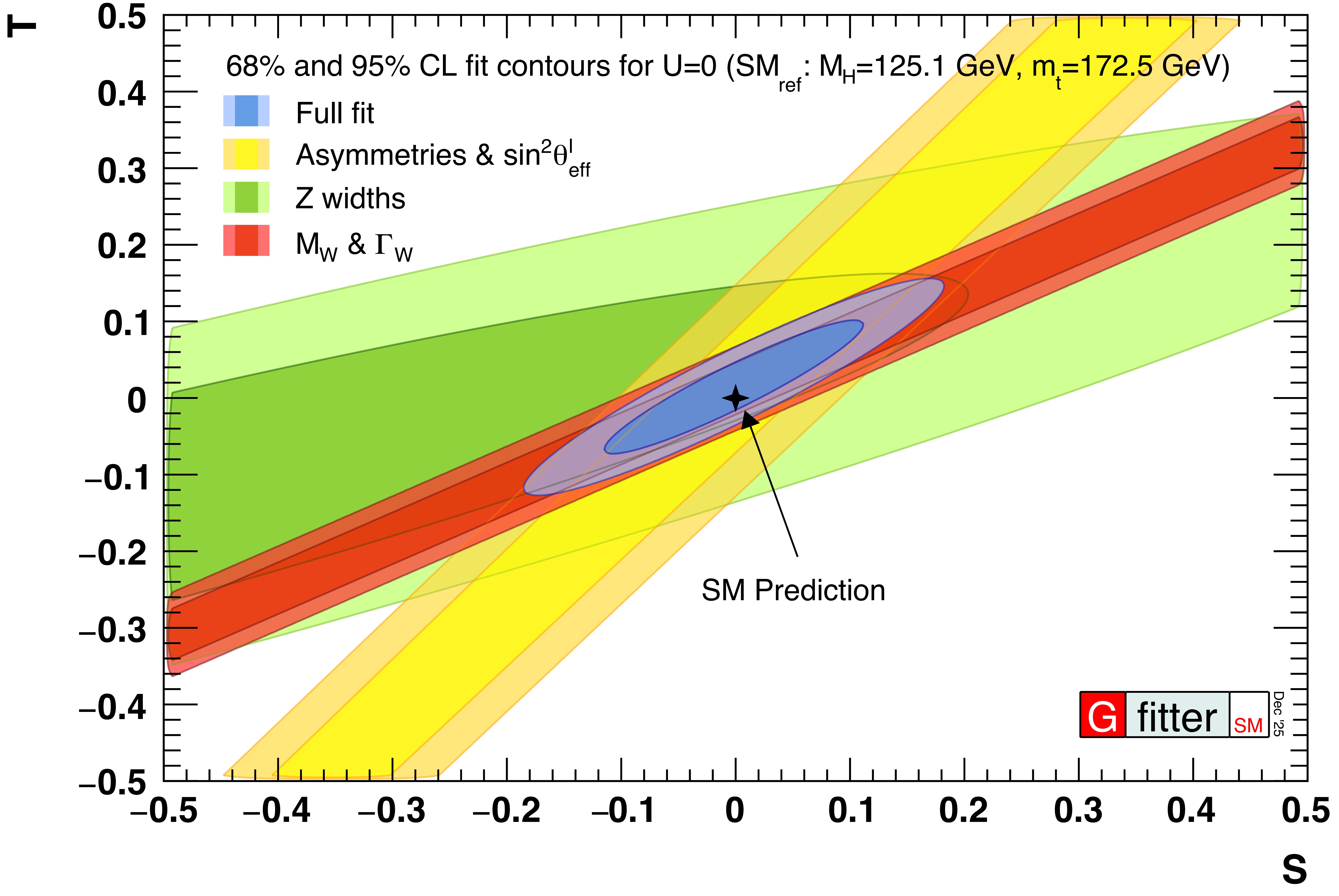
68% and 95% CL contours
Fit w/o M_W and m_t measurements
Direct M_W and m_t measurements
68% and 95%
CL contours
10 years ago
M_W [GeV]
80.5
80.45
80.4
80.35
80.3
80.25
150
160
170
180
190
m_t [GeV]
G fitter SM
Mar '26

BSM in the loops: Oblique Parameters

Constrain heavy BSM physics ($M > M_Z$) through its effects on vacuum polarisation diagrams

- Universal modifications to light-particle scattering
  - Oblique Parameters S, T, U

- Neutral current interactions: S, T
- Charged current: U



The Higgs Boson Width

$$\text{(ATLAS)} \quad \Gamma_H = 4.3^{+2.7}_{-1.9} \; [4.1^{+3.5}_{-3.4} \text{ (exp)}] \text{ MeV}$$

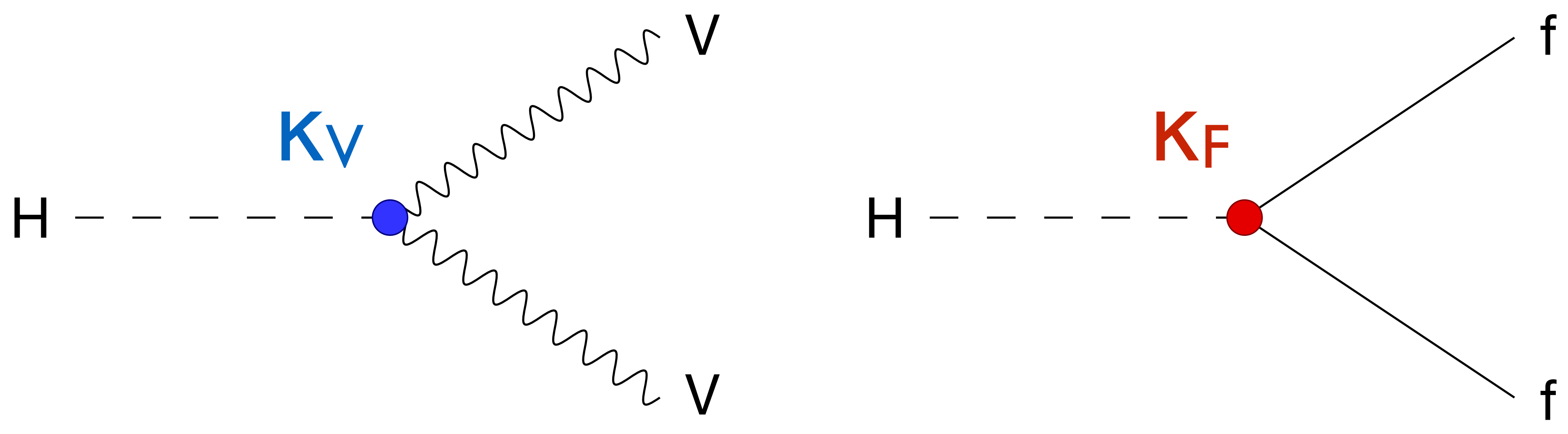
$$\text{(CMS)} \quad \Gamma_H = 3.0^{+2.0}_{-1.5} \; [4.1 \pm 3.5 \text{ (exp)}] \text{ MeV}$$

[PDG 2025]

The Higgs-κ Framework

Modification of SM Higgs couplings

- Parameterised through κ_i modifiers
- Defined through partial widths $\Gamma_i = \kappa_i^2 \Gamma_i^{SM}$



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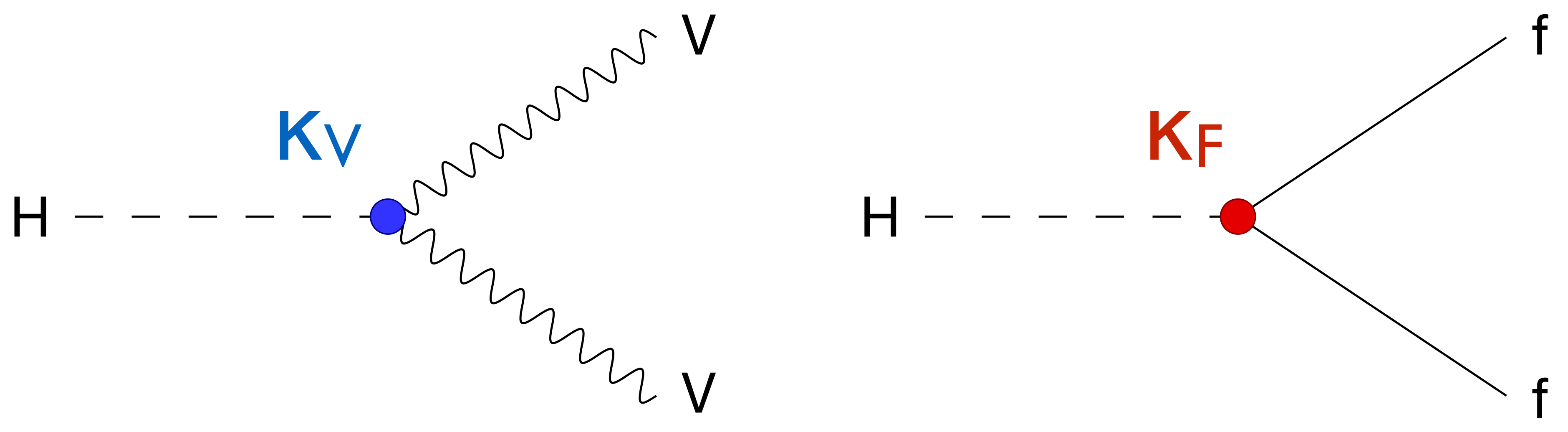
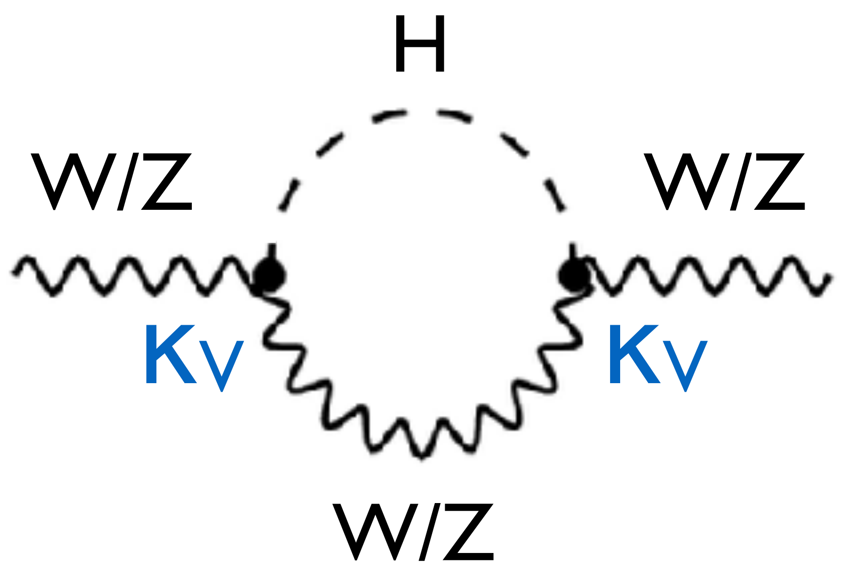


- If couplings get modified, it's BSM physics and would show up in oblique corrections:



$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_H^2}\right)$$

$$T = -\frac{3}{16\pi c_W^2}(1-\kappa_V^2)\ln\left(\frac{\Lambda^2}{m_H^2}\right)$$

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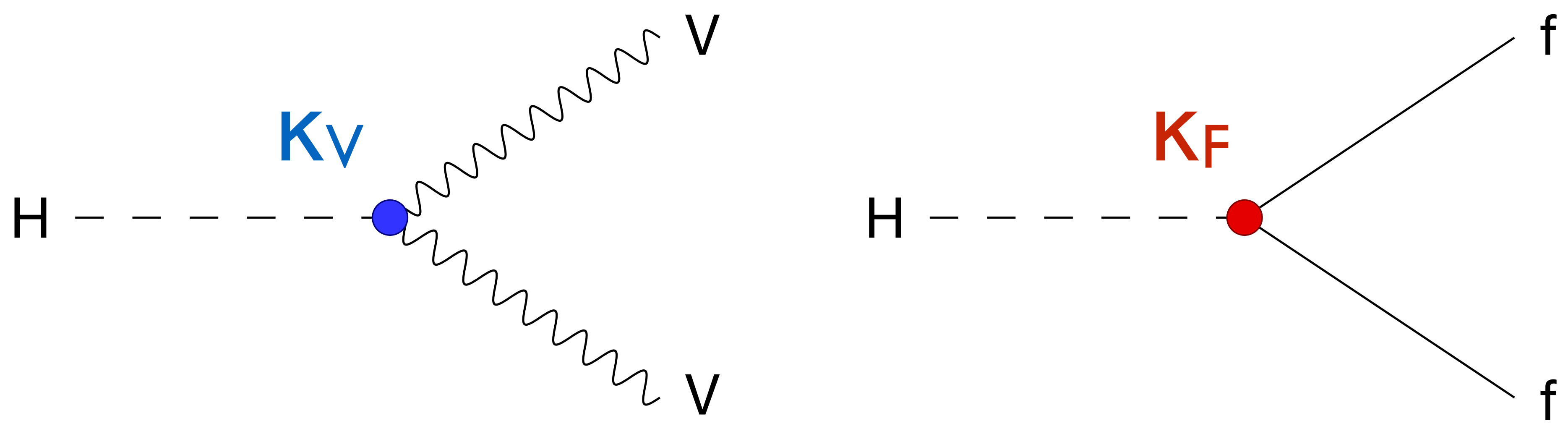

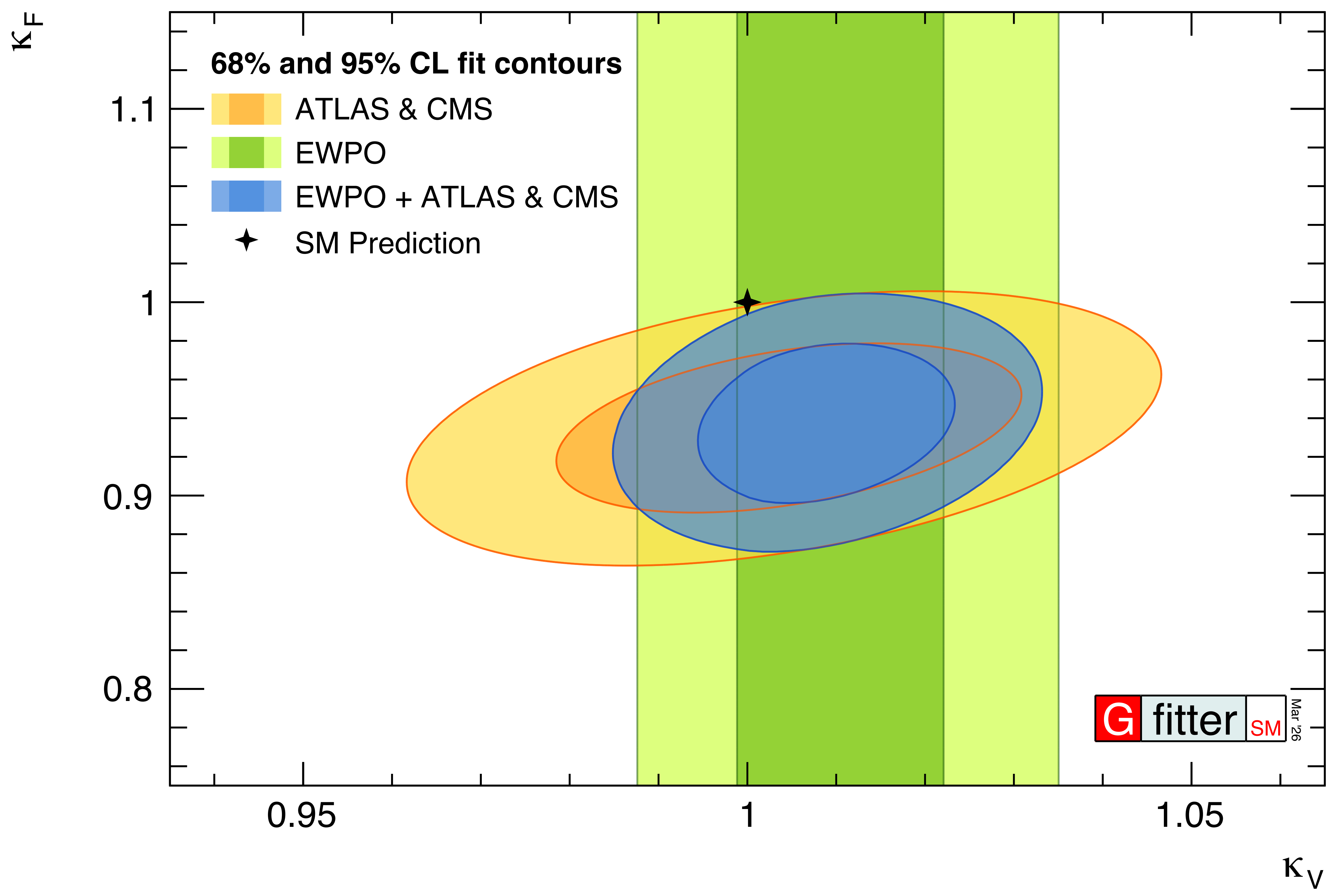

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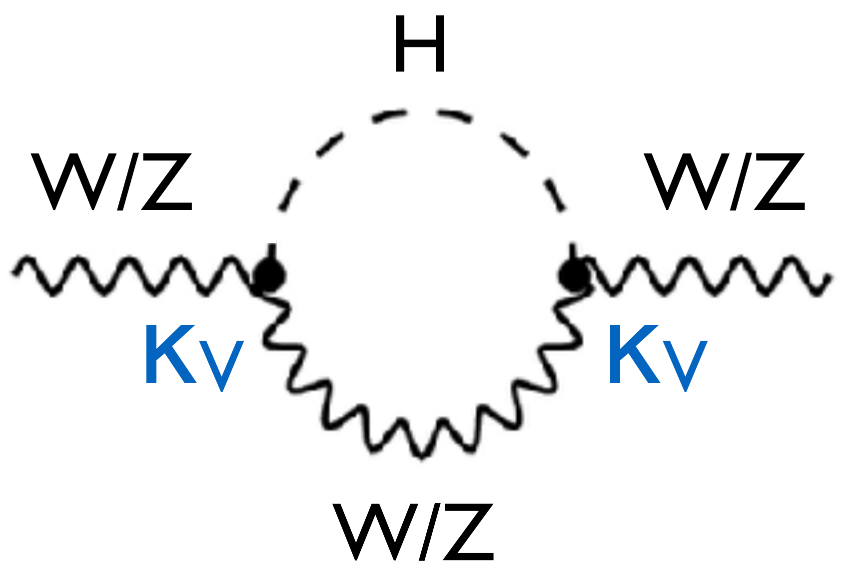

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$\kappa_V = 1.010 \pm 0.012$ (EWPO only)

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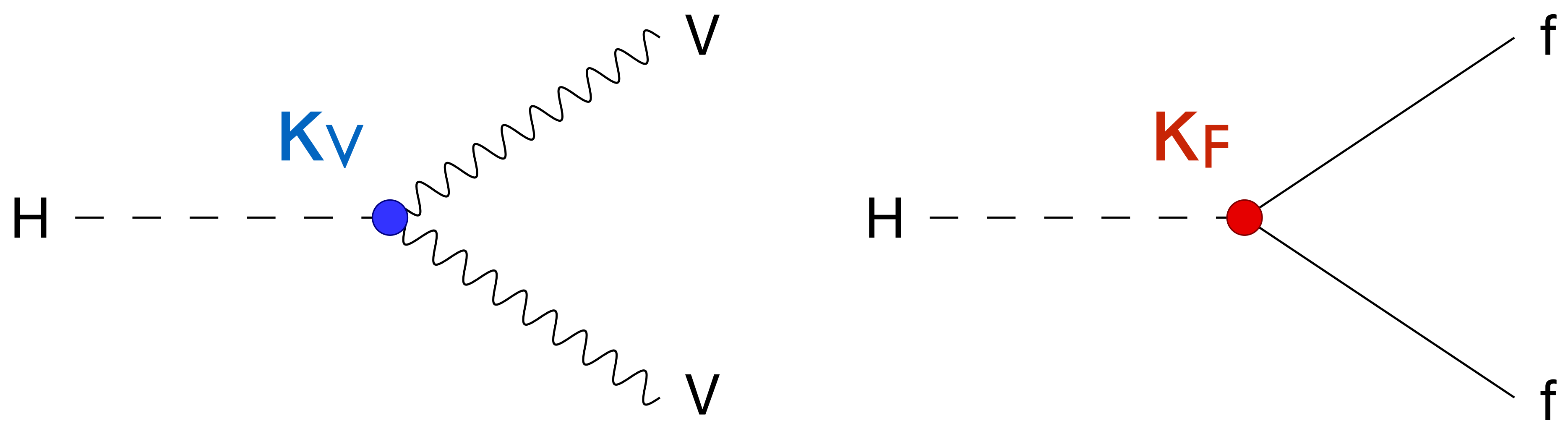

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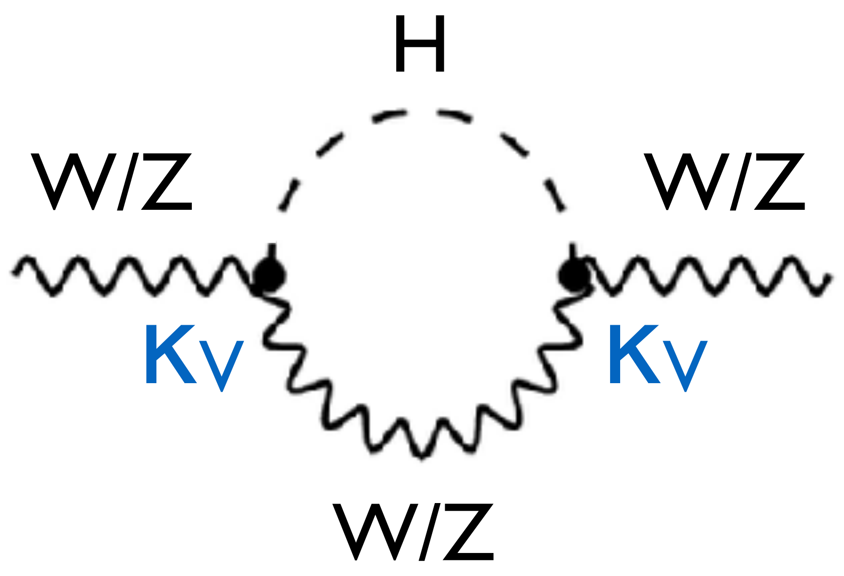

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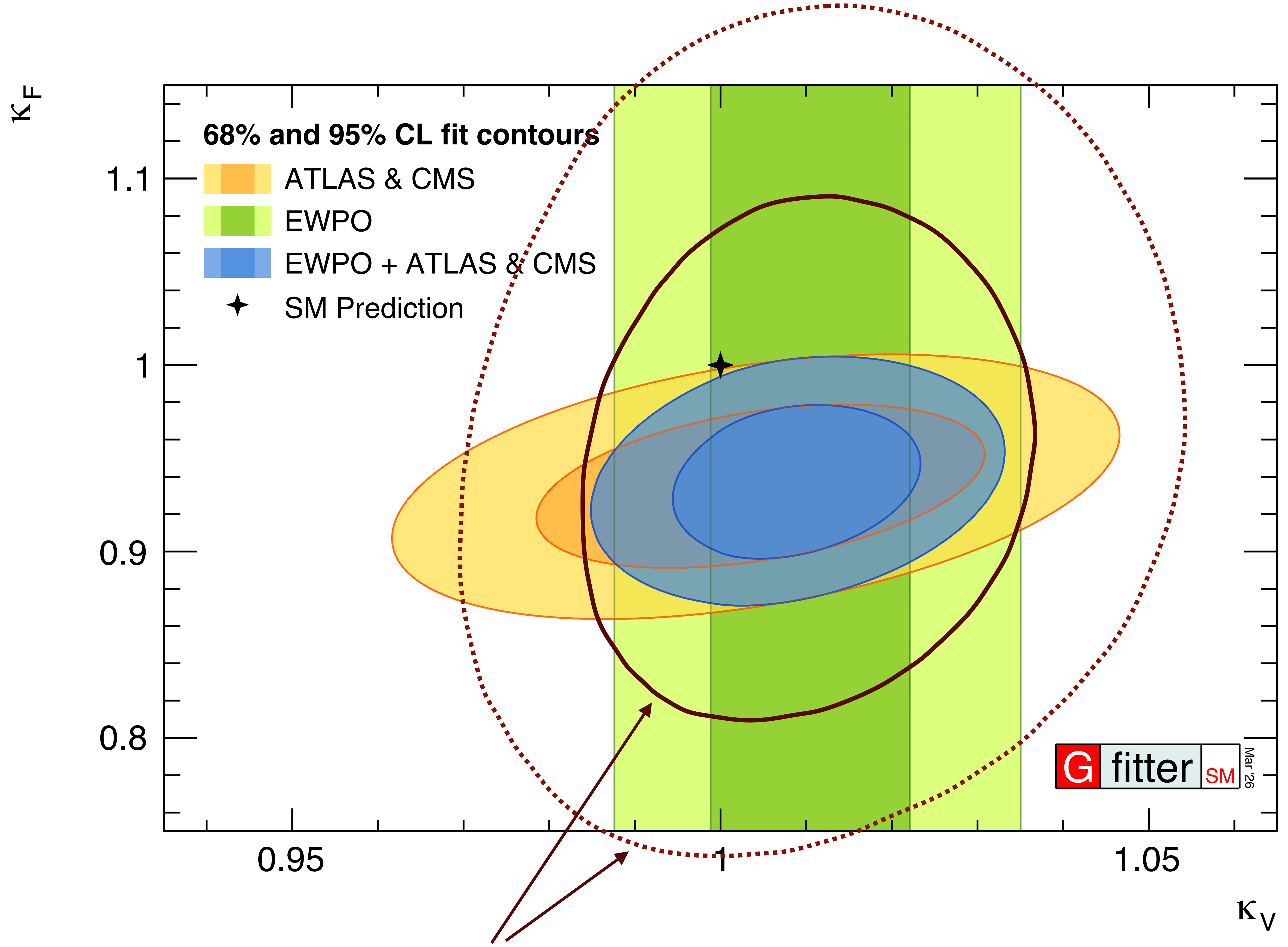

68% and 96% CL contours 10 years ago

Higgs Signal Strengths

General parameterisation:

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$ with total width modifier $\kappa_H^2 = \frac{\Gamma_H}{\Gamma_{H,\mathrm{SM}}}$

$$\mu_i^f \equiv \frac{\sigma \cdot \mathrm{BR}}{\sigma_{\mathrm{SM}} \cdot \mathrm{BR}_{\mathrm{SM}}} = \frac{\kappa_i^2 \cdot \kappa_f^2}{\kappa_H^2}$$

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- With $\kappa_Z = \kappa_W = \kappa_V$, we can write

$$\mu_{\mathrm{VBF}}^{WW} = \mu_{\mathrm{VBF}}^{ZZ} = \mu_{VH}^{WW} = \mu_{VH}^{ZZ} = \frac{\kappa_V^4}{\kappa_H^2}$$

← Obtain the total H width through HVV coupling by combining EWPO and ATLAS & CMS Higgs data

- Adding more data, use κ_g, κ_γ, κ_τ, and κ_V

$$\mu_{\mathrm{VBF}}^{VV} = \frac{\mu_{\mathrm{ggF}}^{VV} \mu_{\mathrm{VBF}}^{jj}}{\mu_{\mathrm{ggF}}^{jj}}, jj = \gamma\gamma, \tau\tau$$

(same for VH)

← Effective couplings: Model-independent determination of H width including loop effects

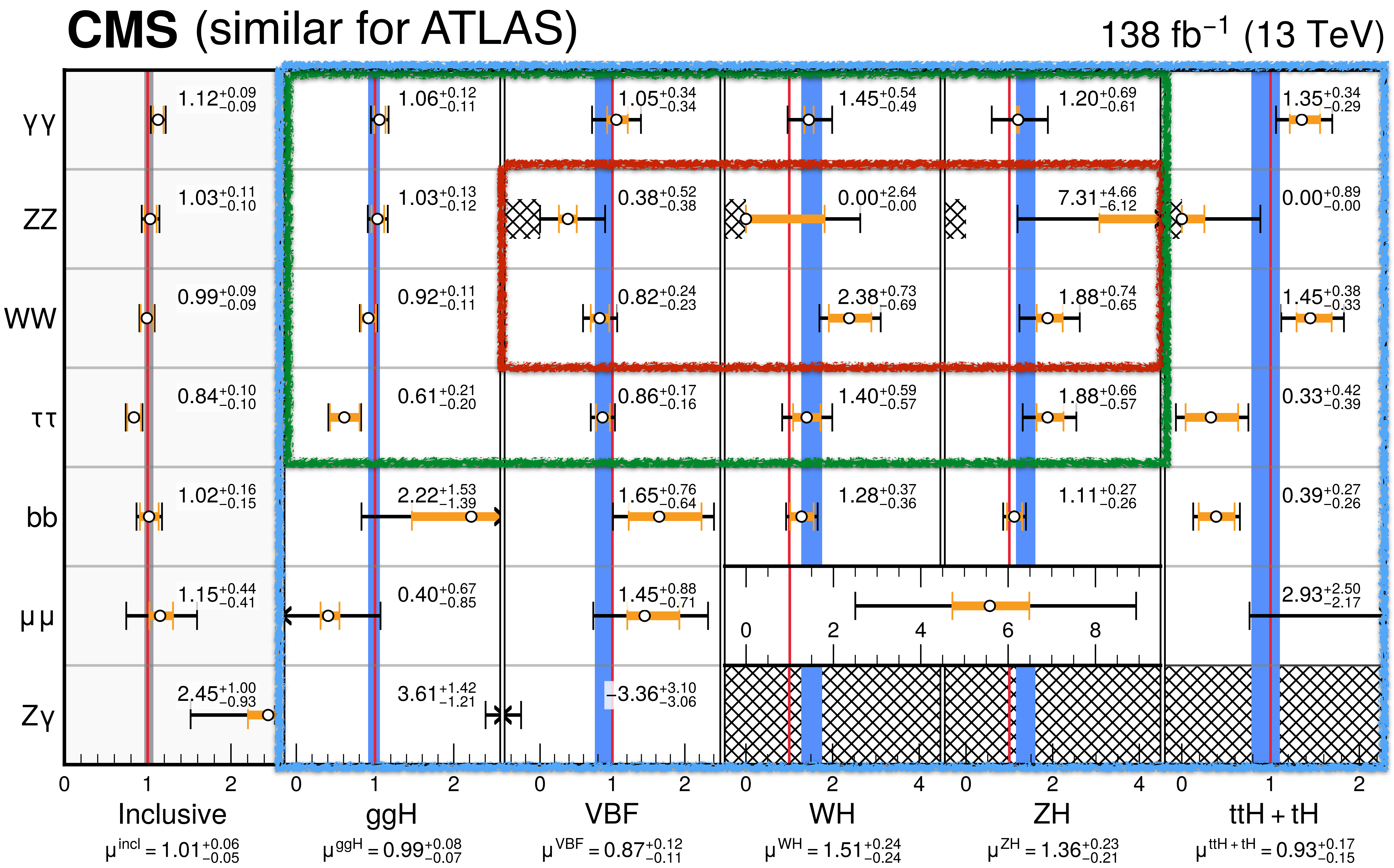
Higgs Signal Strengths

Use latest ATLAS and CMS Run-2 Higgs combinations

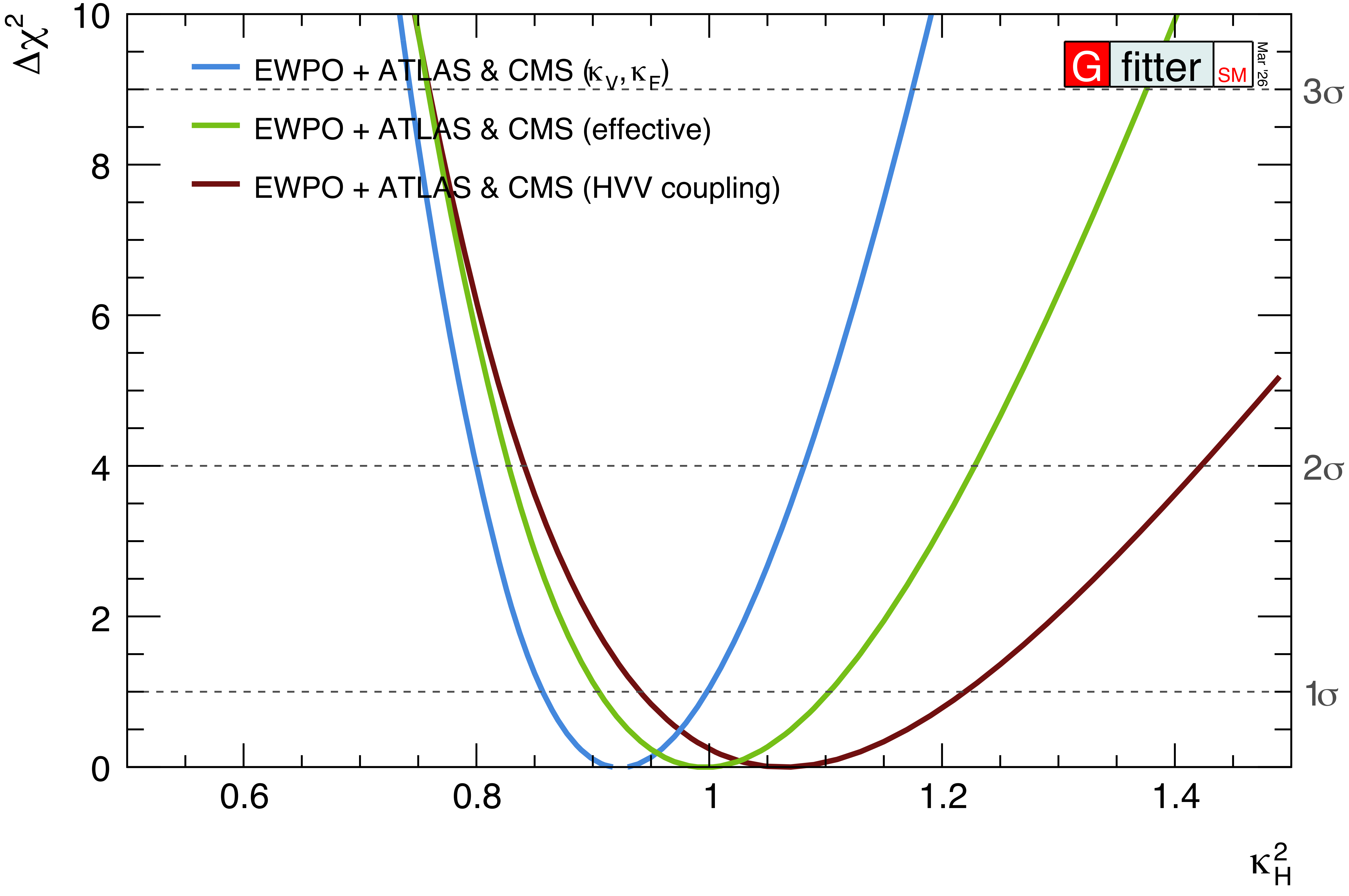
- [CMS, 2602.18611]
- [ATLAS, CONF-2025-006]
- Correlations between μ_{ij} taken into account

Three sets of measurements, corresponding to the parameterisations:

- HVV
- Effective (incl. κ_g, κ_γ)
- Resolved (κ_V, κ_F)



Width of the Higgs Boson



HVV coupling-only:

$$\Gamma_H = 4.36\ ^{+0.64}_{-0.51}\ \text{MeV}$$

χ^2 / ndf = 28.8 / 28

Effective parameterisation:

$$\Gamma_H = 4.09\ ^{+0.44}_{-0.37}\ \text{MeV} \quad (\delta\Gamma_H \approx 10\%)$$

χ^2 / ndf = 45.9 / 44

All measurements (resolved parameterisation κ_V, κ_F):

$$\Gamma_H = 3.79\ ^{+0.31}_{-0.27}\ \text{MeV}$$

χ^2 / ndf = 72.9 / 76

$(\Gamma_H^{SM} = 4.1\ \text{MeV})$

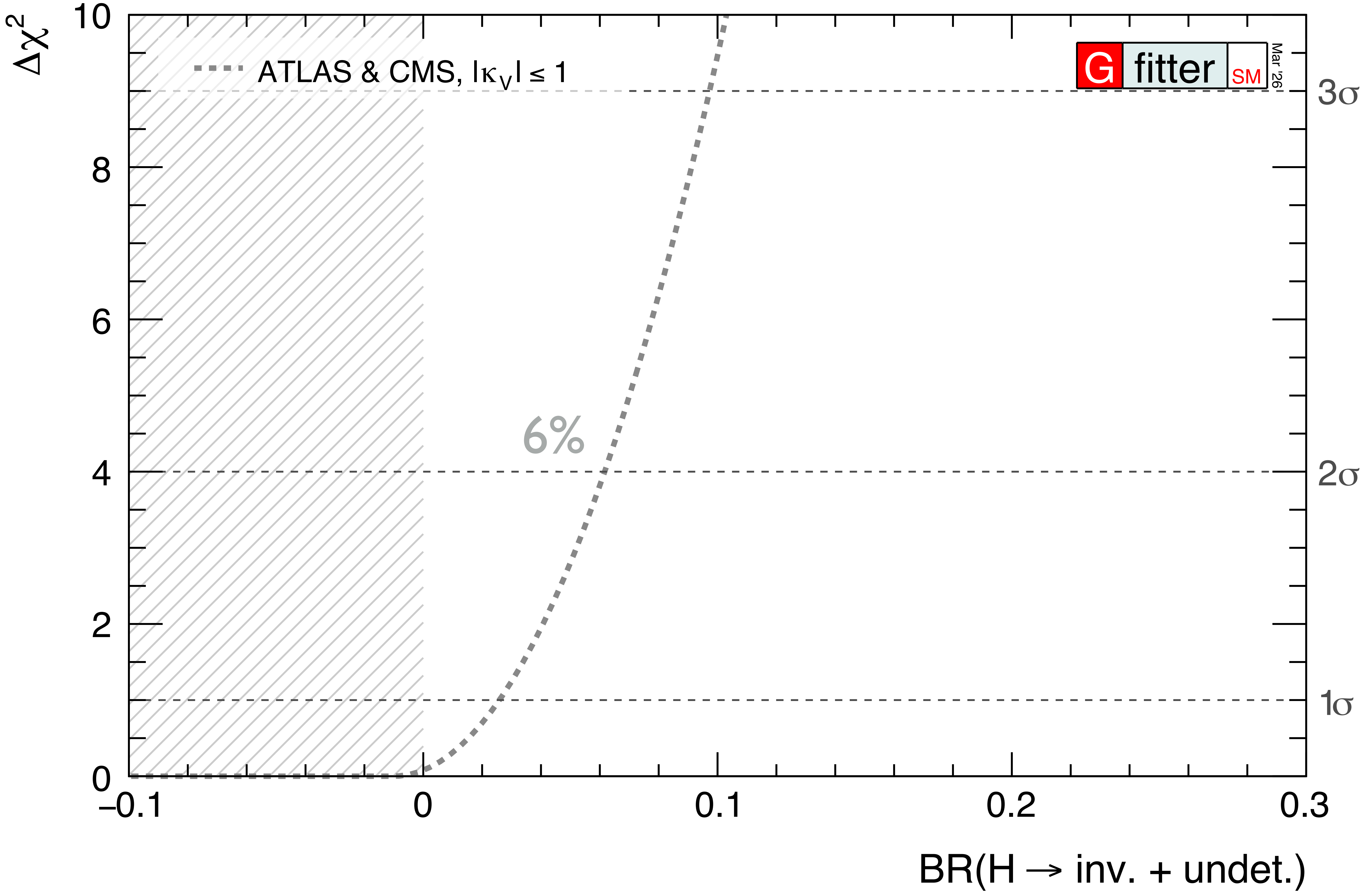
The Invisible and Undetectable Higgs

Define BR(H→BSM) through

$$BR(H \to \text{BSM}) = \frac{\Gamma_{\text{BSM}}}{\Gamma_H}$$

where $\Gamma_H = \Gamma(\kappa) + \Gamma_{\text{BSM}}$

the visible widths are scaled with κ_i



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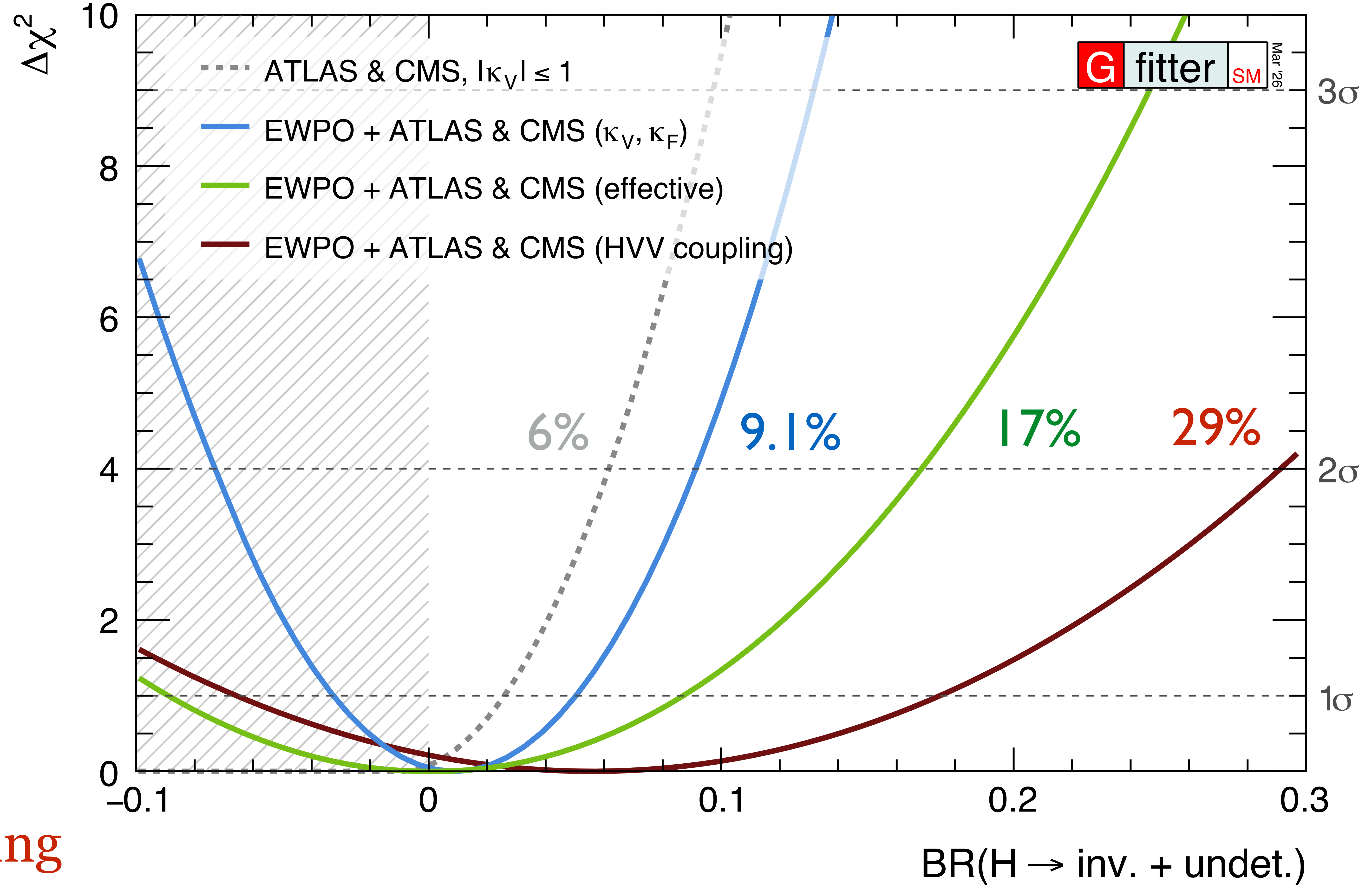
the visible widths are scaled with κ_i

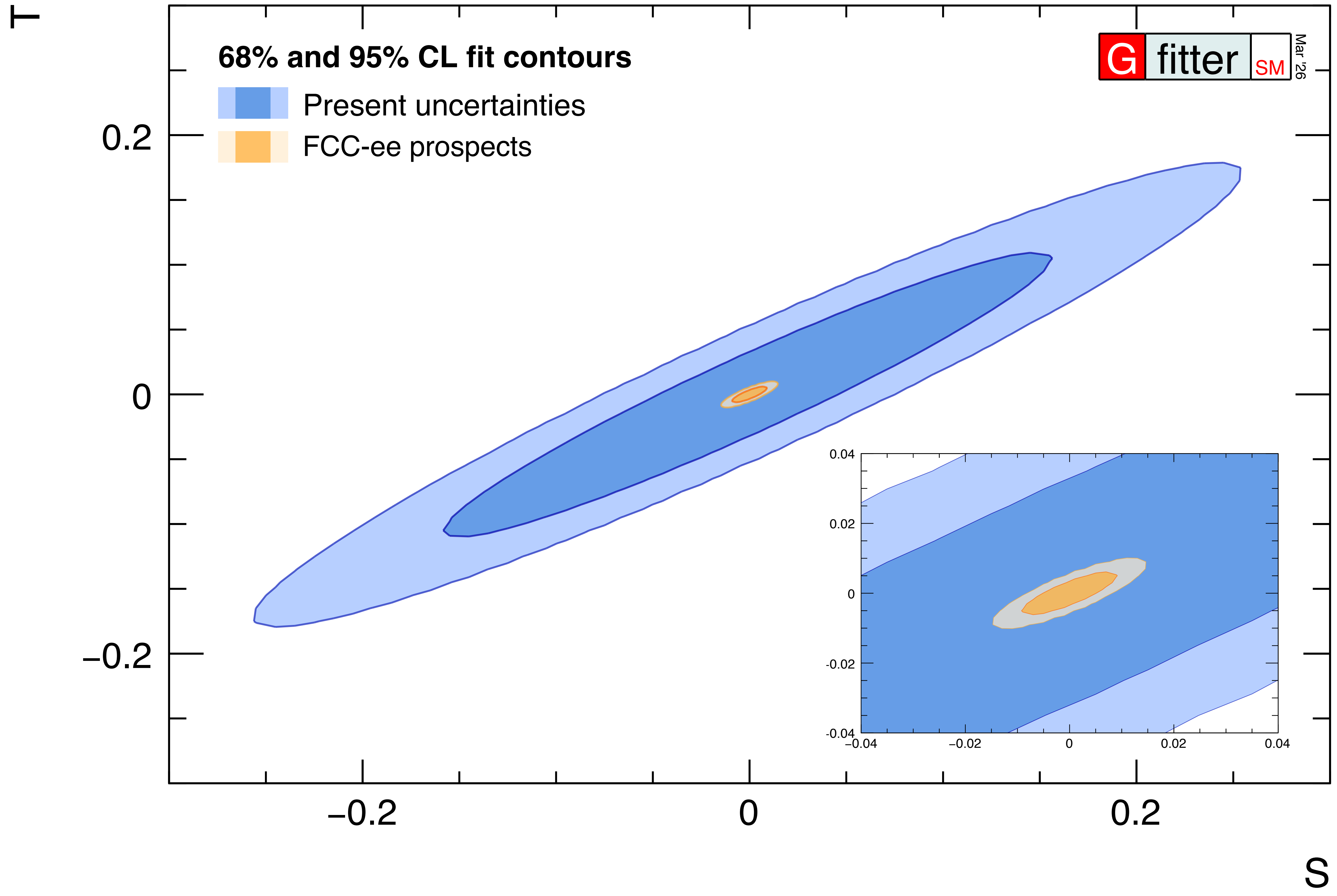
- Constraint on κ_V from EWPO
  - Less model-dependent than $\kappa_V \leq 1$
  - Constrain Γ_{BSM} using μs only
- 95% CL limits:

  $BR(H \to \text{BSM}) < 0.29$ for HVV coupling

  $BR(H \to \text{BSM}) < 0.17$ for effective coupling



Future: FCC-ee



Estimate precision of FCC-ee

- Uncertainties in EWPOs and Higgs boson measurements
  - Physics Briefing Book [ESPP, CERN YRM 8 (2025)]
  - Higgs at future colliders and updates
    [J de Blas et al., JHEP 01, 139 (2020)]
    [M Selvaggi et al., ESPP Input (2025)]
- Assume *conservative* theory uncertainties

Parameter	Present		FCC-ee	
	indirect	direct	indirect	direct
δm_t [GeV]	±1.6	±0.6	±0.1	±0.04
δM_H [GeV]	$^{+22}_{-19}$	±0.1	$^{+2.4}_{-2.3}$	±0.004
δM_W [MeV]	±6	±8.5	±1.1	±0.24
$\delta \sin^2\theta^{\ell}_{\mathrm{eff}}$ $(\times10^{-5})$	±5	±16	±2	±0.1
$\delta\alpha_s(M_Z^2)$ $(\times10^{-2})$	±28	±9	±1.2	
$\delta\Delta\alpha_{\mathrm{had}}(M_Z^2)$ $(\times10^{-5})$	±33	±10	±3	±3

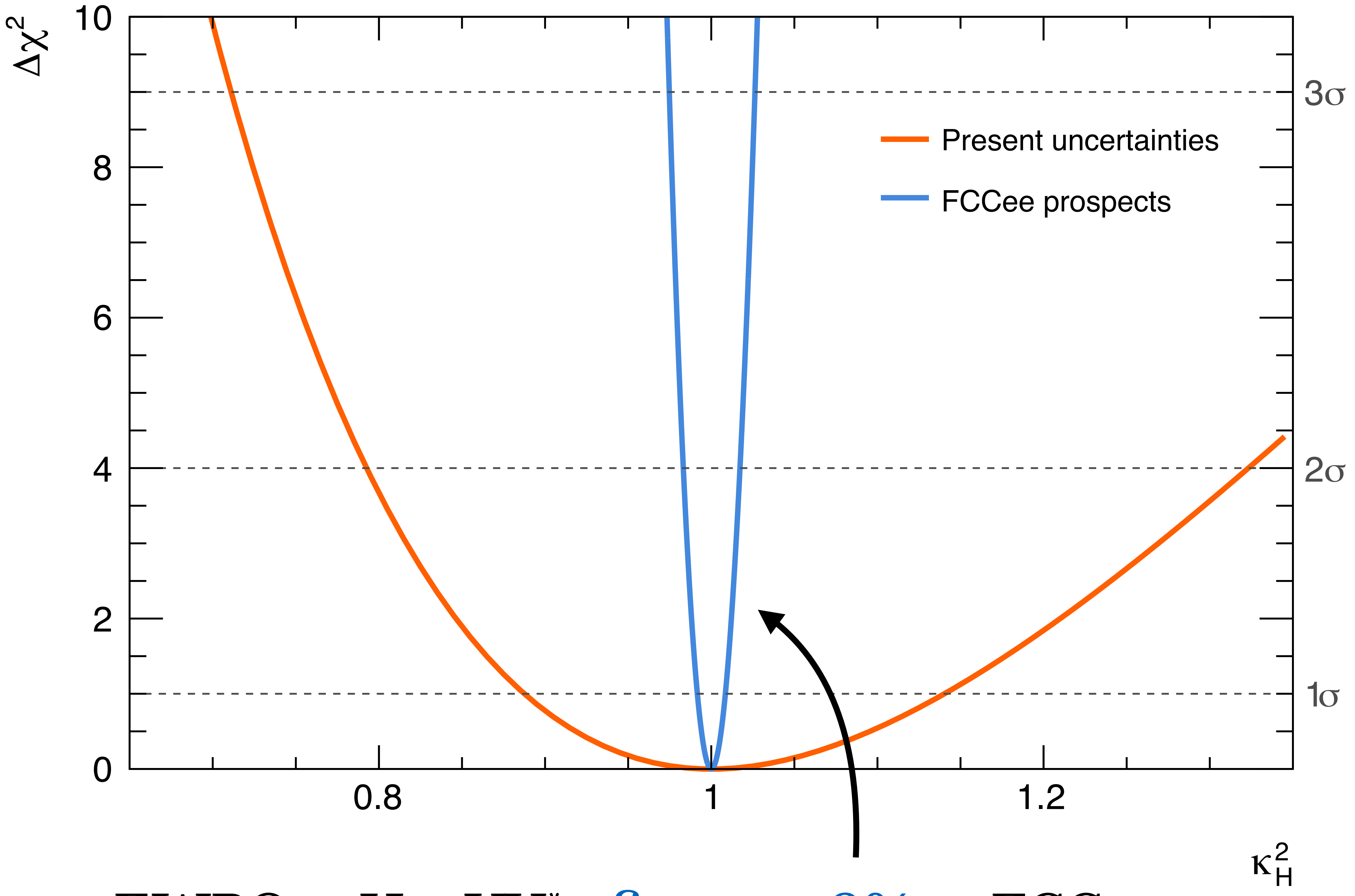
Γ_H at the FCC-ee

HVV coupling from EWPO

- $\delta\kappa_V$ = 0.1%
  - $\mathcal{O}(10)$ improvement to present
- Combine $\delta\kappa_V$ constraint with ZH(WW) and ZH(ZZ) measurements at FCC-ee

$\sqrt{s}$	240 **GeV**	
channel	**ZH**	**WW → H**
ZH → any	±0.31	
γH → any	±150	
H → bb	±0.21	±1.9
H → cc	±1.6	±19
H → ss	±120	±990
H → gg	±0.80	±5.5
H → $\tau\tau$	±0.58	
H → $\mu\mu$	±11	
H → WW*	±0.80	
H → ZZ*	±2.5	
H → $\gamma\gamma$	±3.6	
H → Zγ	±11.8	

[M Selvaggi et al., ESPP Input (2025)]



EWPO + H→VV*: $\delta\kappa_H$ = 0.8% at FCC-ee

Recoil-mass technique: $\delta\Gamma_H \approx$ 1 %

[A Blondel, P Janot, EPJ Plus 137, 92 (2022)]

Summary

SM is healthier than ever

- While we have the highest precision we have ever had
- SM predicts M_H = 110 ± 18 GeV

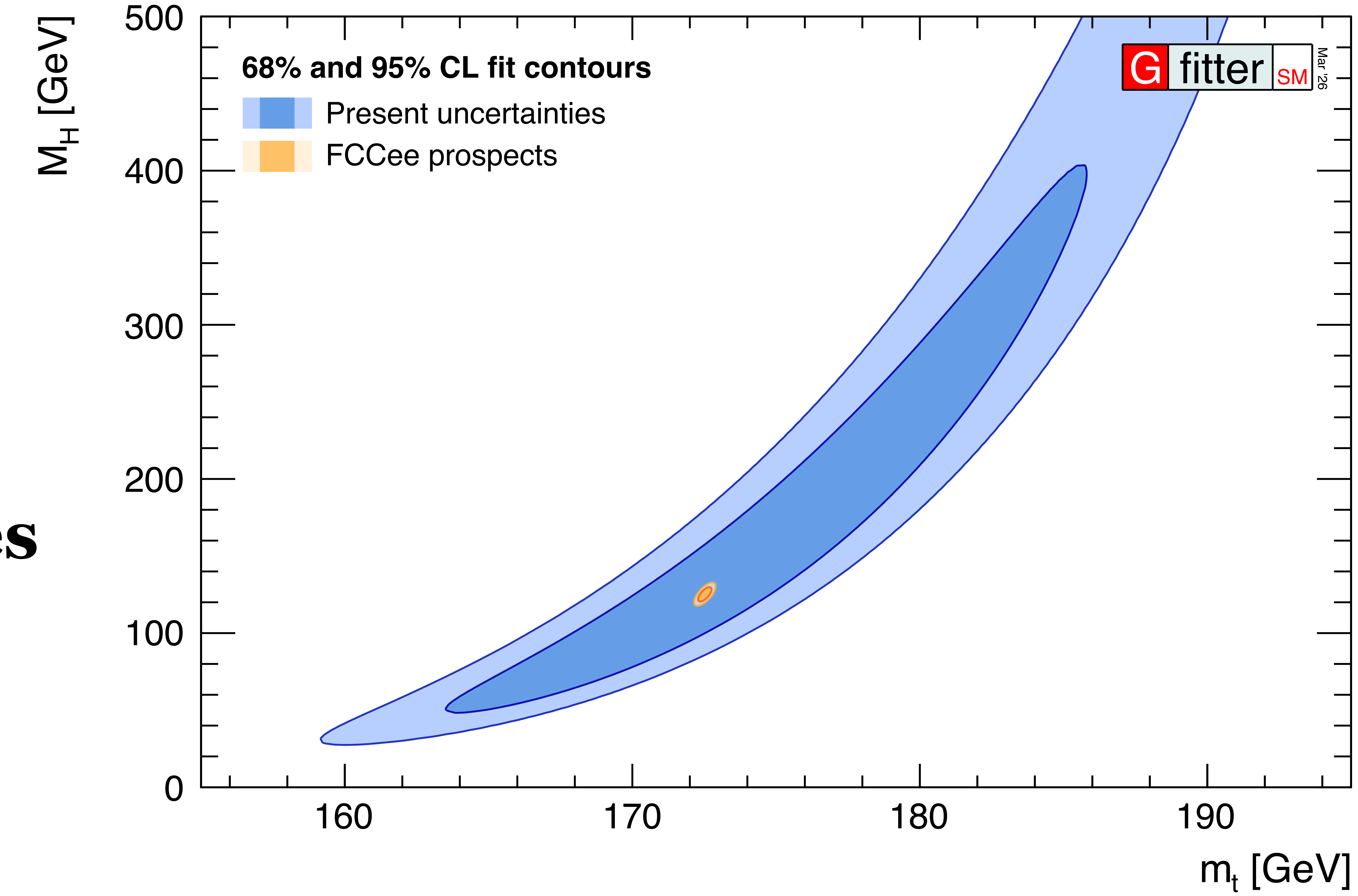
EWPO and LHC Higgs measurements

- HVV coupling known to 1% precision
- $\delta\Gamma_H \approx$ 10% with minimal assumptions!
- BR(H → inv. + undet.) < 17% at 95% CL

FCC-ee provides extraordinary capabilities

- HVV coupling with 0.1% from EWPO
- Indirect constraint on Γ_H about 1%

(conservative estimates)



Additional Material

Effective Weak Mixing Angle Combination

Combination of $\sin^2(\theta^{\ell}_{eff})$ measurements:

+ Tevatron combination [1801.06283]
+ ATLAS 7 TeV (1503.03709)
+ ATLAS 8 TeV (ATLAS-CONF-2018-037)
+ CMS 8 TeV [1806.00863]
+ LHCb 7+8 TeV [1509.07645]
+ *LHCb 13 TeV [2410.02502]*
+ *CMS 13 TeV [2408.07622]*

Assumptions

Correlate PDF unc: 100% between ATLAS/CMS
50-75% for different $\sqrt{s}$ at LHC
25% between Tev/ATLAS-CMS
0-25% between LHCb/ATLAS-CMS
0% between Tev/LHCb

$$\sin^2(\theta^{\ell}_{eff}) = 0.23149 \pm 0.00021 \quad (\chi^2/\text{ndf} = 1.3/6)$$

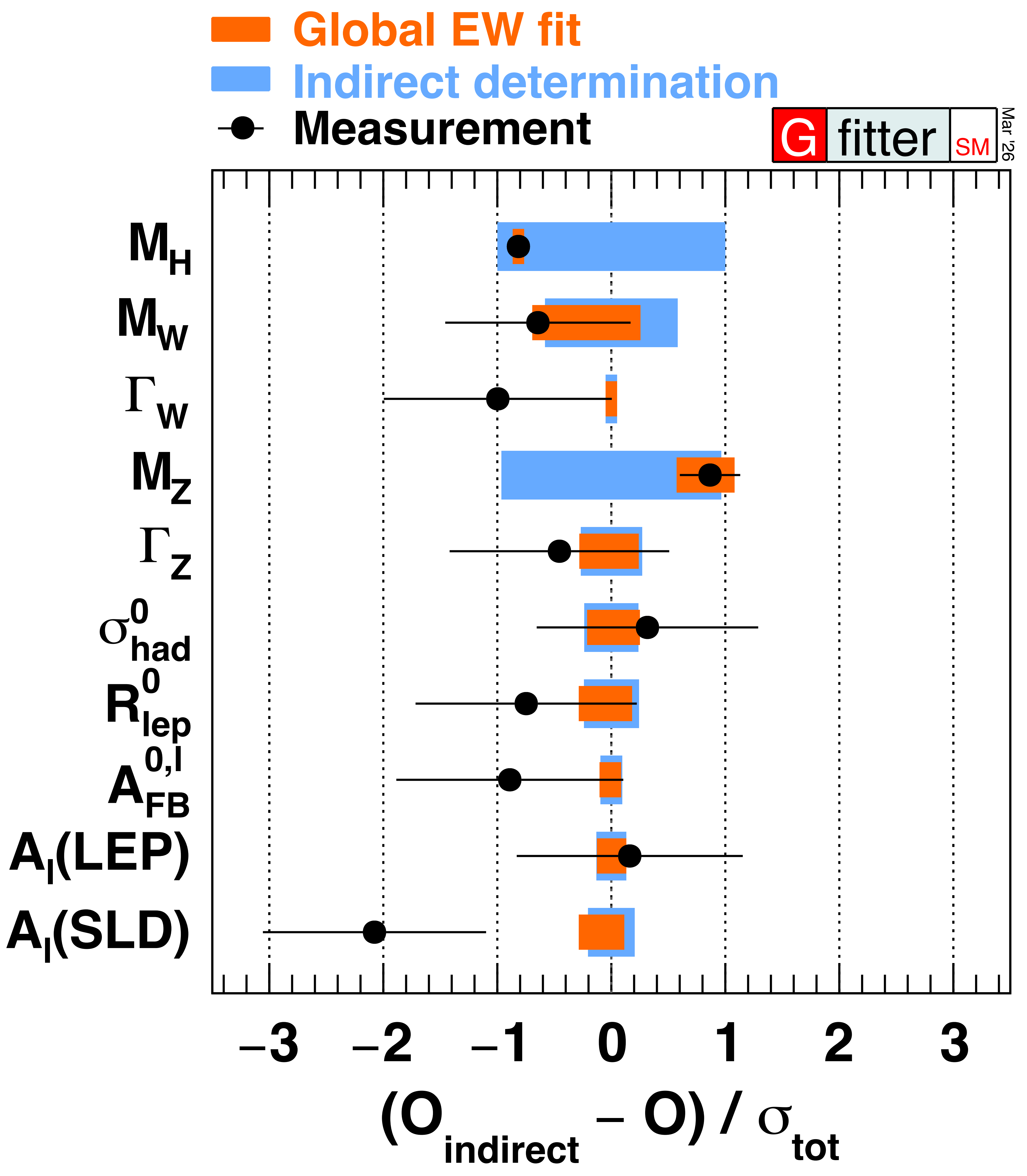
Uncertainty of 0.00017 for no correlation

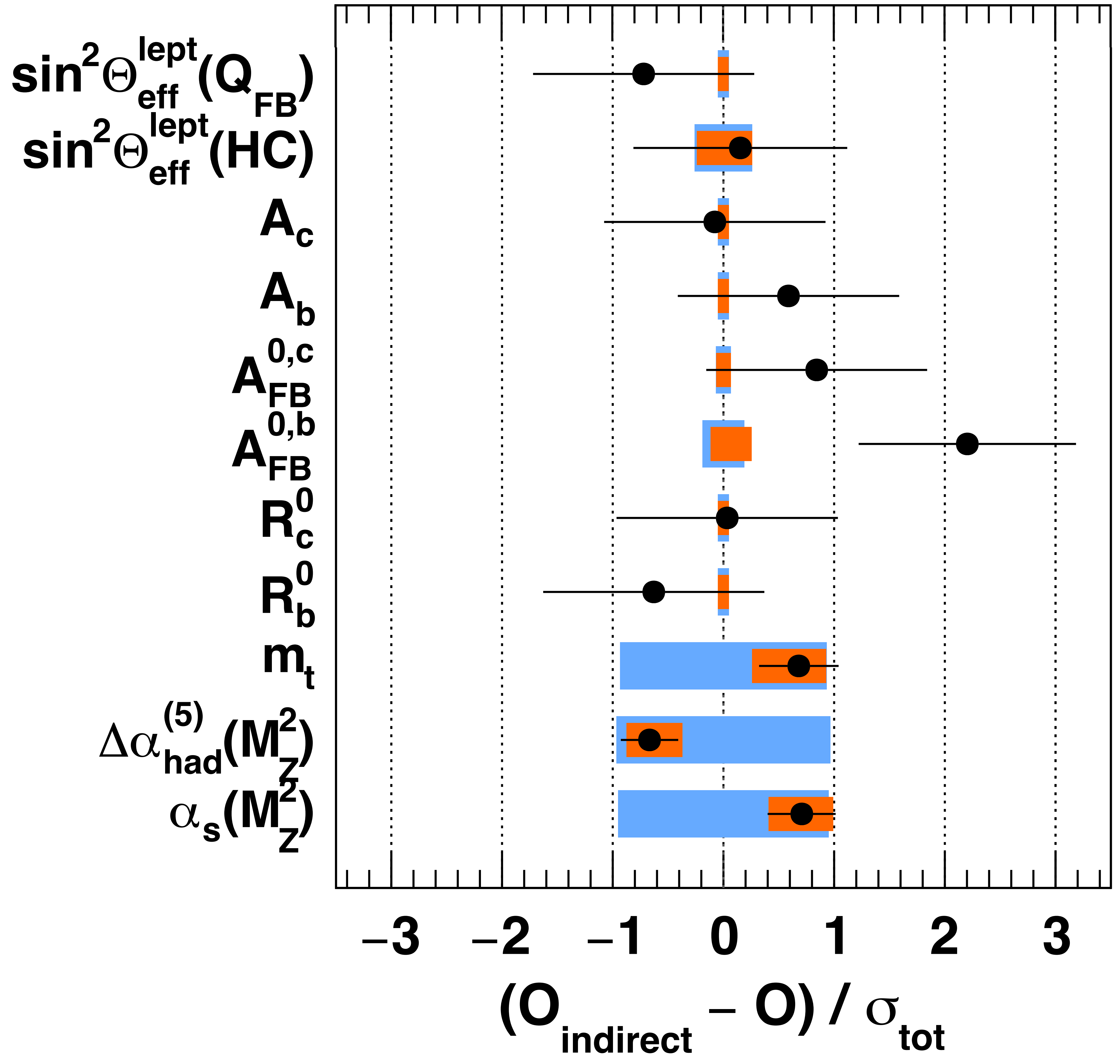
Complete SM Fit Results

Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]	125.1 ± 0.1	yes	$125.1^{+0.1}_{-0.1}$	$110.1^{+19.5}_{-17.2}$	$110.3^{+17.2}_{-15.4}$
M_W [GeV]	80.363 ± 0.009	–	80.358 ± 0.005	80.356 ± 0.006	80.356 ± 0.004
Γ_W [GeV]	2.140 ± 0.050	–	2.090 ± 0.001	2.090 ± 0.001	2.090 ± 0.000
M_Z [GeV]	91.1880 ± 0.0020	yes	91.1883 ± 0.0019	91.1945 ± 0.0073	91.1944 ± 0.0064
Γ_Z [GeV]	2.4955 ± 0.0023	–	2.4945 ± 0.0006	2.4944 ± 0.0006	2.4944 ± 0.0005
$\sigma^0_{\rm had}$ [nb]	41.480 ± 0.033	–	41.490 ± 0.008	41.491 ± 0.008	41.491 ± 0.005
R^0_ℓ	20.767 ± 0.025	–	20.749 ± 0.006	20.748 ± 0.006	20.748 ± 0.005
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01621 ± 0.0001	0.01621 ± 0.0001	0.01620 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1470 ± 0.0004	0.1470 ± 0.0004	0.1470 ± 0.0003
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23152 ± 0.00005	0.23152 ± 0.00005	0.23152 ± 0.00003
$\sin^2\theta^\ell_{\rm eff}$(HC)	0.23149 ± 0.00021	–	0.23152 ± 0.00005	0.23152 ± 0.00006	0.23153 ± 0.00003
A_s	0.895 ± 0.091	–	0.9357 ± 0.00003	0.9357 ± 0.00003	0.9357 ± 0.00002
A_c	0.670 ± 0.027	–	0.6679 ± 0.00019	0.6679 ± 0.00019	0.6679 ± 0.00012
A_b	0.923 ± 0.020	–	0.93475 ± 0.00003	0.93475 ± 0.00003	0.93475 ± 0.00002
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0737 ± 0.0002	0.0737 ± 0.0002	0.0736 ± 0.0001
$A^{0,b}_{\rm FB}$	0.0996 ± 0.0016	–	0.1031 ± 0.0003	0.1032 ± 0.0003	0.1031 ± 0.0002
R^0_c	0.1721 ± 0.0030	–	0.17220 ± 0.00003	0.17220 ± 0.00003	0.17220 ± 0.00002
R^0_b	0.21629 ± 0.00066	–	0.21587 ± 0.00003	0.21587 ± 0.00003	0.21588 ± 0.00001
$\overline{m}_c$ [GeV]	1.273 ± 0.003	yes	1.273 ± 0.003	–	–
$\overline{m}_b$ [GeV]	4.183 ± 0.004	yes	4.183 ± 0.004	–	–
m_t [GeV]$^{(\triangledown)}$	172.52 ± 0.60	yes	172.67 ± 0.56	$173.66\,^{+1.55}_{-1.56}$	$173.67\,^{+1.43}_{-1.44}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$ $^{(\dagger\triangle)}$	2758 ± 10	yes	2757 ± 9	2735 ± 34	2735 ± 30
$\alpha_s(M_Z^2)$	0.1177 ± 0.0009	yes	0.1179 ± 0.0009	0.1200 ± 0.0028	0.1198 ± 0.0027

$^{(\star)}$Average of LEP ($A_\ell = 0.1465 \pm 0.0033$) and SLD ($A_\ell = 0.1513 \pm 0.0021$) measurements, used as two measurements in the fit. The fit w/o the LEP (SLD) measurement gives $A_\ell = 0.1470 \pm 0.0004$ ($A_\ell = 0.1468 \pm 0.0004$). $^{(\triangledown)}$Combination of experimental (0.331059 GeV) and theory uncertainty (0.5 GeV).$^{(\dagger)}$In units of 10^{-5}. $^{(\triangle)}$Rescaled due to α_s dependency.

Complete SM Fit Results

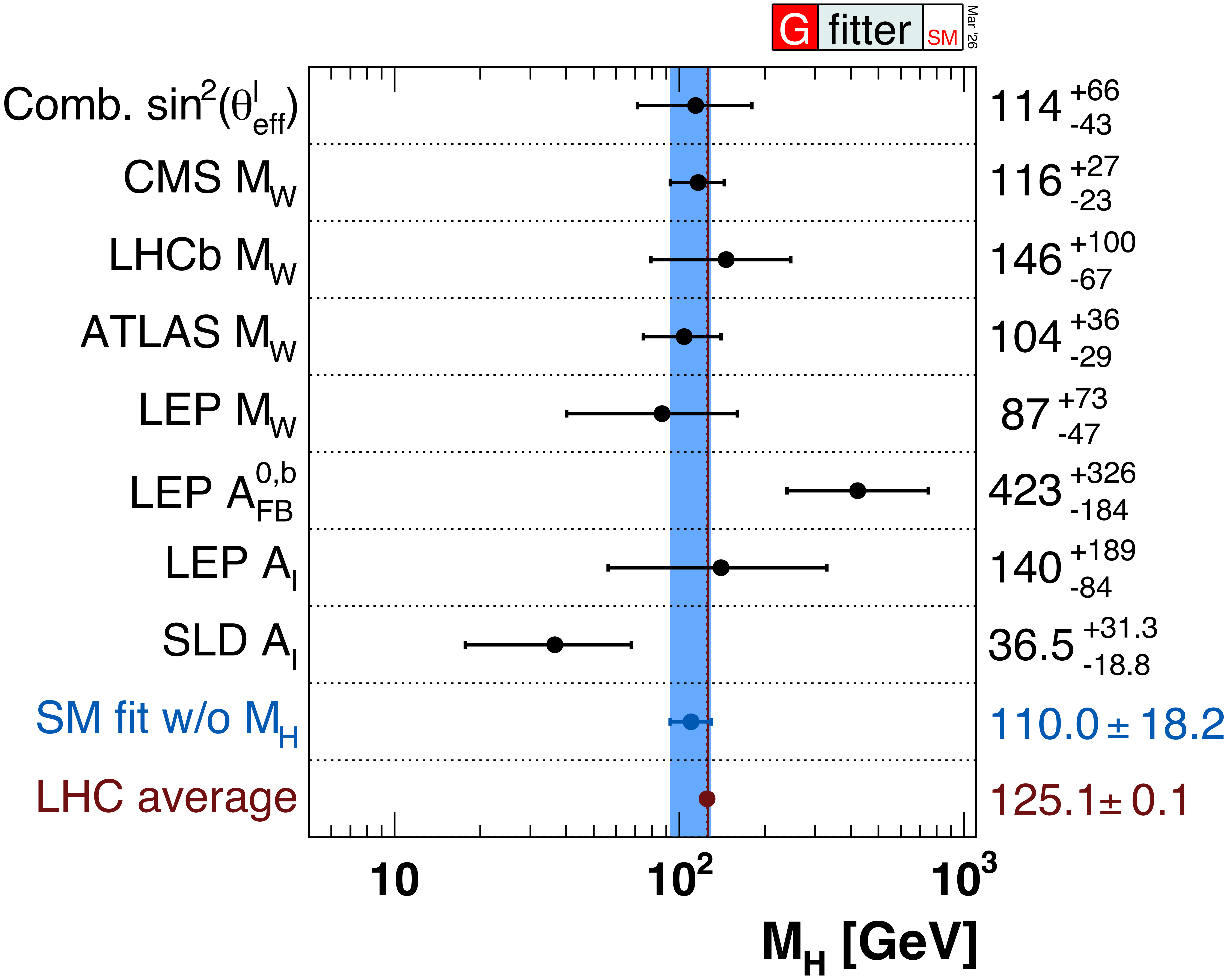




Predicting M_H

Prediction of MH with only a single observable

- weak mixing angle and M_W predict M_H to be closer to 125 GeV than before
- long-standing tension between A^{0}_{bFB} and A_ℓ(SLD) visible



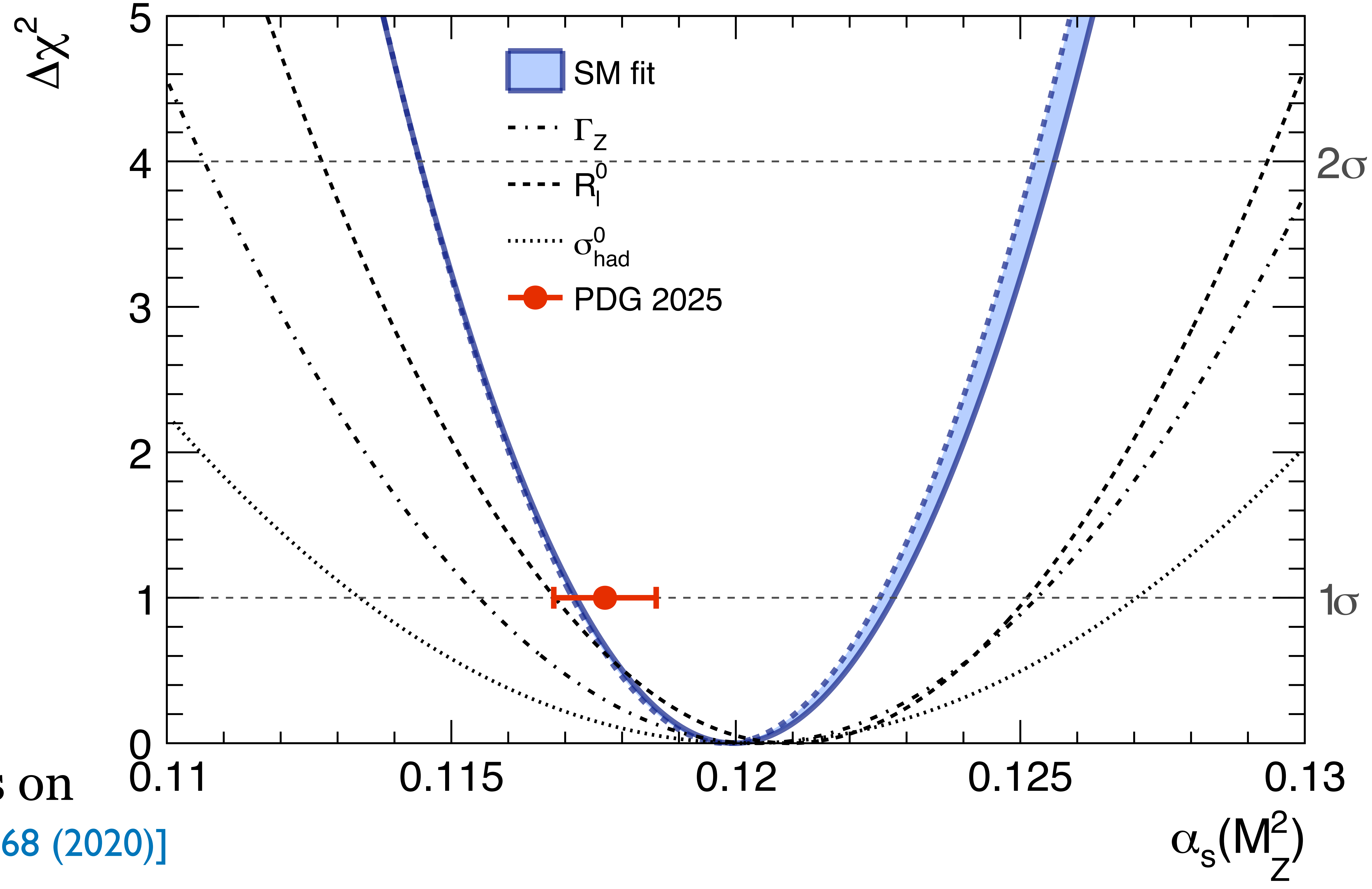
α_S Consistency Improved

Complete fit:

$$\alpha_s(M_Z^2) = 0.1200 \pm 0.0028$$

Individual fits:

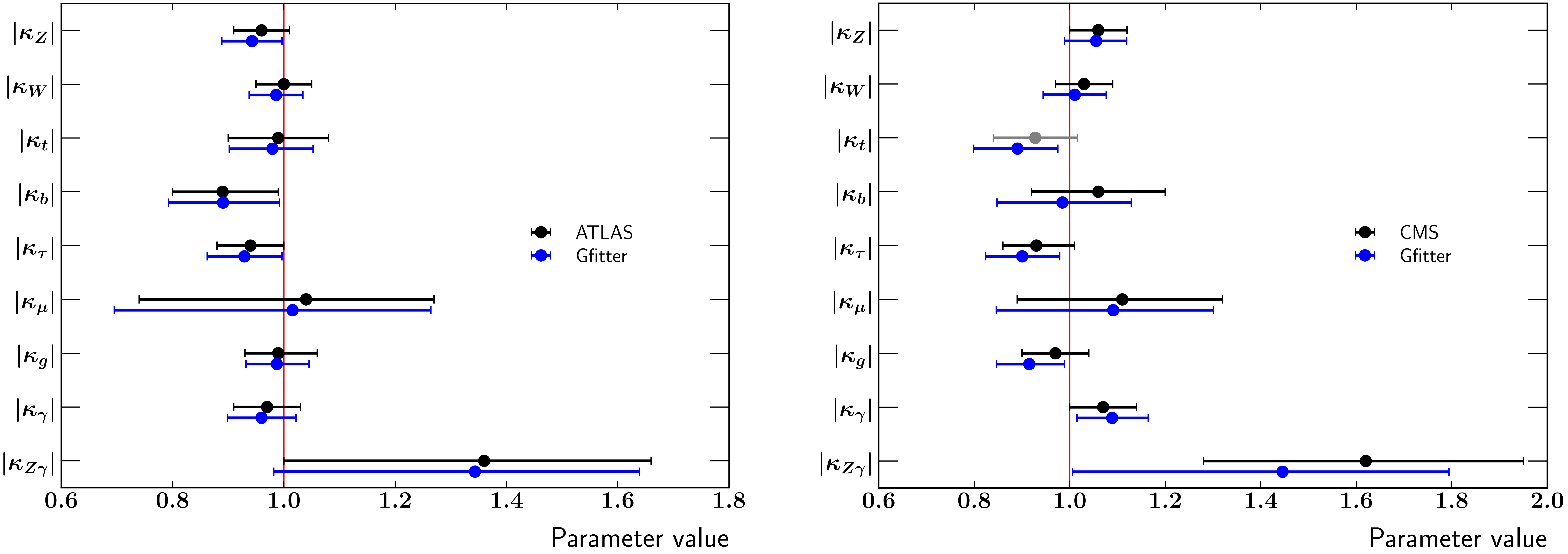
$$R_\ell : \alpha_s(M_Z^2) = 0.1211 \pm 0.0042\,,$$
$$\Gamma_Z : \alpha_s(M_Z^2) = 0.1214 \pm 0.0049\,,$$
$$\sigma_{\rm had} : \alpha_s(M_Z^2) = 0.1199 \pm 0.0068\,,$$



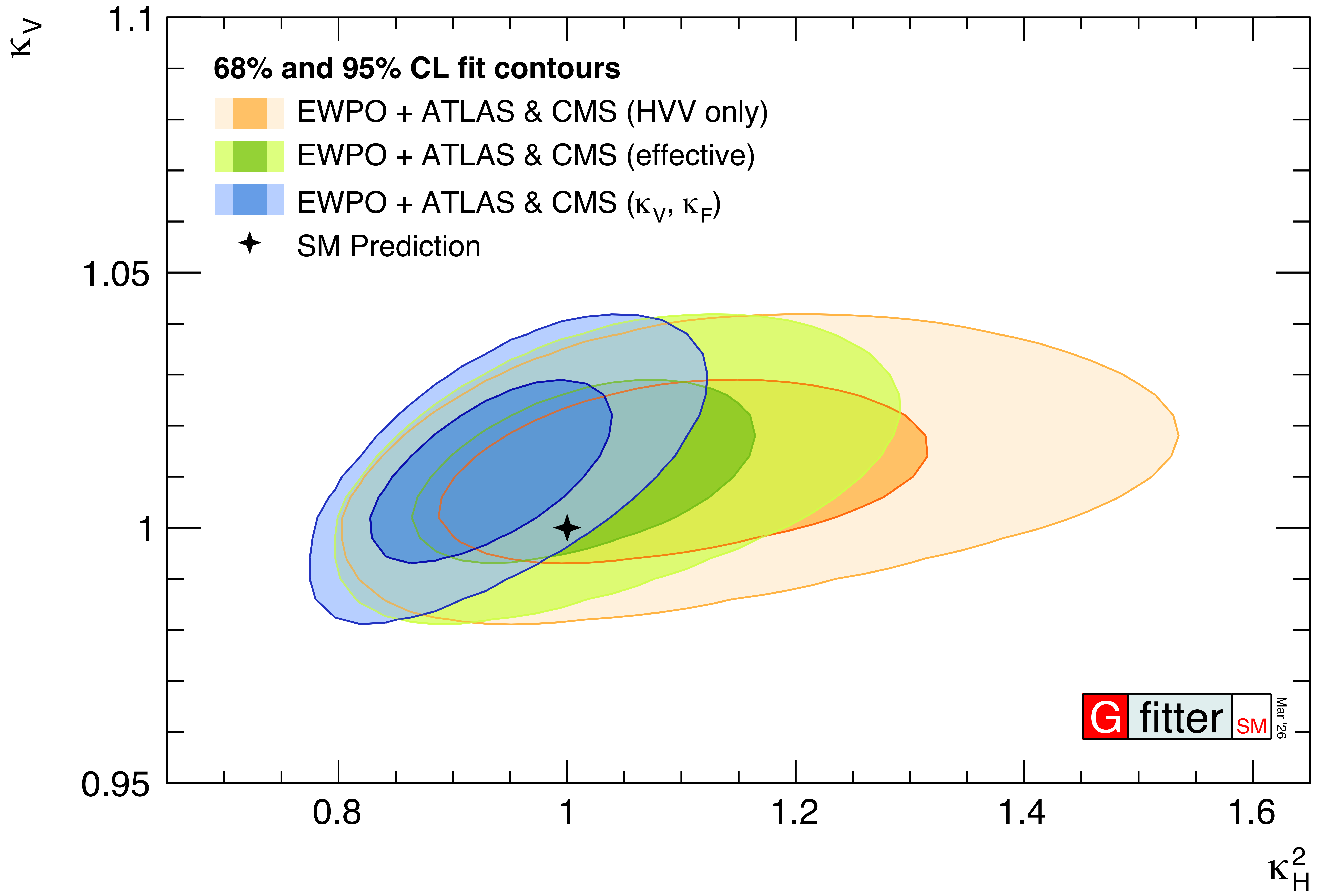
Because of

- Updated calculations of beam-beam effects on the LEP luminosity [Voutsinas et al, PLB 800, 135068 (2020)]
- Updated Bhabha cross section [Janot, Jadach, PLB 803 (2020) 135319]

κ Consistency Check



The Higgs Boson Width



FCCee Fit Setup

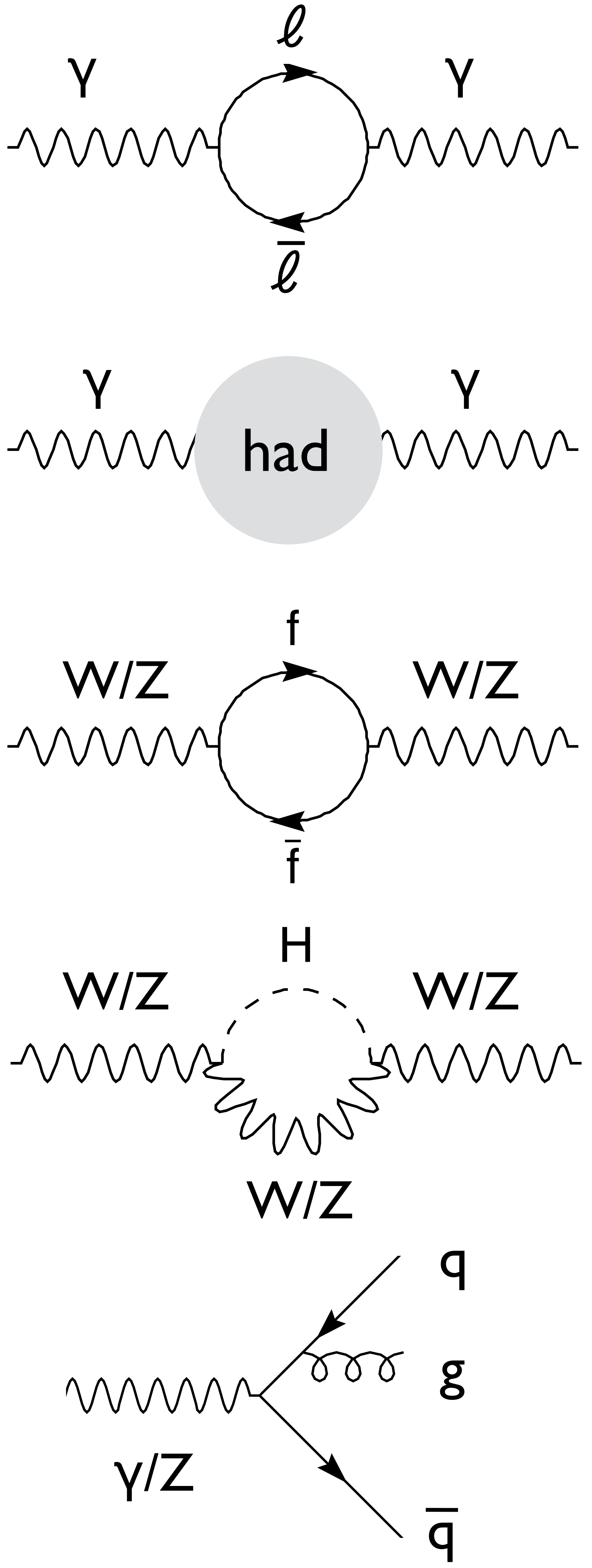
- Use EWPO uncertainty estimates from Physics Briefing Book
  [ESPP, CERN YRM 8 (2025)]
- Add projections for m_H and m_t
- Adjust central values of EWPO for perfect fit with $\chi^2 = 0$
- Conservative theory uncertainty estimates, about 1/4 of present uncertainties
- Estimate present uncertainties with same setup, but current uncertainties in EWPO

Observable	Current	FCC-ee
Δm_Z (keV)	2000	4 (100)
$\Delta\Gamma_Z$ (keV)	2300	4 (12)
δR_μ ($\times 10^{-6}$) $R_\mu \equiv \frac{\Gamma_{had}}{\Gamma_\mu}$	1600	2.4 (2.3)
δR_b ($\times 10^{-6}$) $R_b \equiv \frac{\Gamma_b}{\Gamma_{had}}$	3300	1.2 (1.6)
$\Delta \sin^2\theta_W$ ($\times 10^6$)	130	0.4 (0.5)
$\Delta\alpha(m_Z)^{-1}$ ($\times 10^3$)	14	0.8, 3.8
Δm_W (keV)	9900	180 (160)
$\Delta\Gamma_W$ (keV)	42000	270 (200)

Radiative Corrections

Modifications of Propagators and Vertices

- QED corrections
  - leptonic loop insertions
    - calculable to high precision
  - quark loop insertions (hadronic)
    - partially not calculable in pure pQCD
- Weak corrections
  - Insertion of fermion loops
    - high sensitivity to m_f (if $m_f \gg m_W$)
  - Insertion of boson loops
    - logarithmic sensitivity to M_H
- QCD corrections
  - Sensitivity to strong coupling
    - numerically small contribution $(1 + \alpha_s/\pi)$



$\propto \alpha \ln \frac{s}{m_\ell^2}$

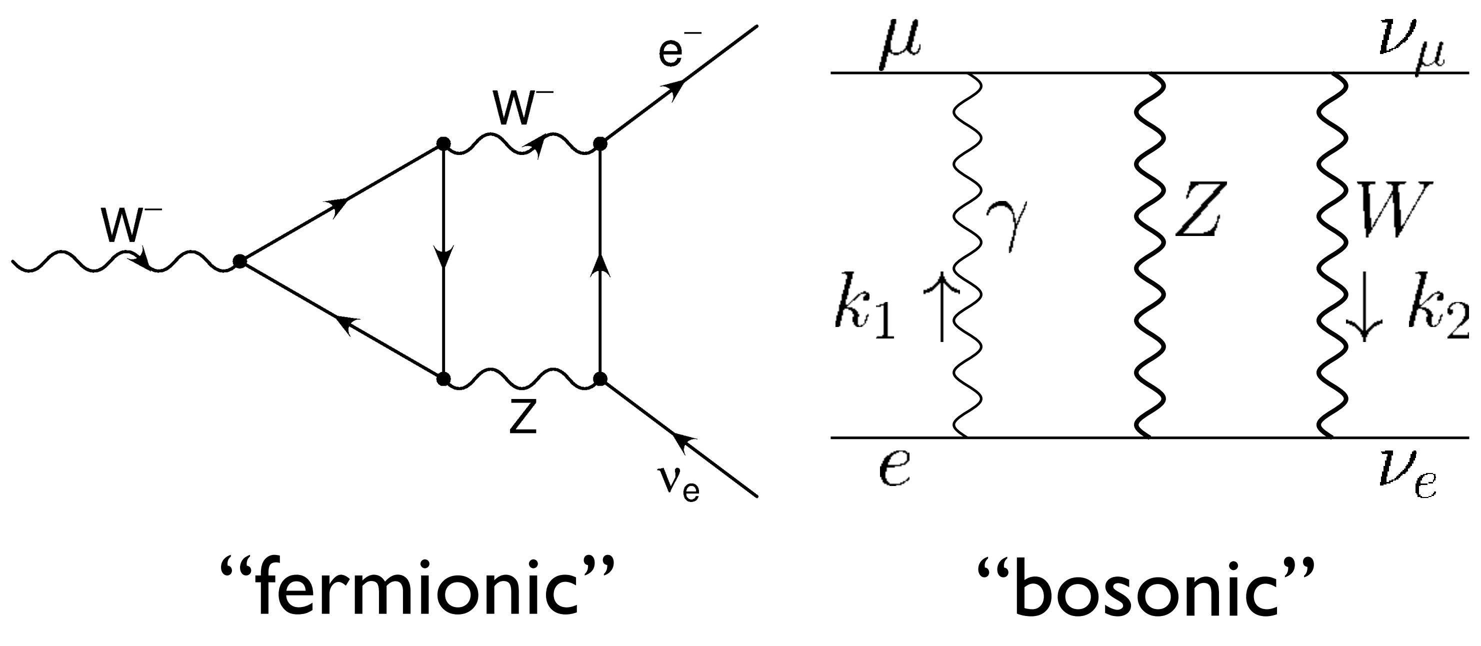
$\propto \Delta\alpha_{\rm had}(s)$

$\propto N_C m_f^2$

$\propto \ln \frac{M_H^2}{M_W^2}$

$\propto \alpha_s(s)$

Precision Calculations



All observables calculated at 2-loop level

- **M_W** : full EW one- and two-loop calculation of fermionic and bosonic contributions
  [Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002)]
  + 4-loop QCD correction [Chetyrkin et al., PRL 97, 102003 (2006)]
- **$\sin^2\theta^f_{eff}$** : same order as M_W, calculations for leptons and all quark flavours
  [Awramik et al, PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009)]
- **Partial Z widths Γ_f** : bosonic+fermionic corrections in two loops for all flavours (includes predictions for σ^0_{had}) [A. Freitas et al, PLB 730, 50 (2014), JHEP04, 070 (2014), PLB 783, 86 (2018), JHEP 1908, 113 (2019), JHEP 07, 210 (2020)]
- **Radiator functions**: QCD corrections at N^3LO
  [Baikov et al., PRL 108, 222003 (2012)]
- **Γ_W** : one-loop EW corrections available, negligible impact on fit
  [Cho et al, JHEP 1111, 068 (2011)]
- **All calculations**: one- and two-loop QCD corrections and leading terms of higher order corrections

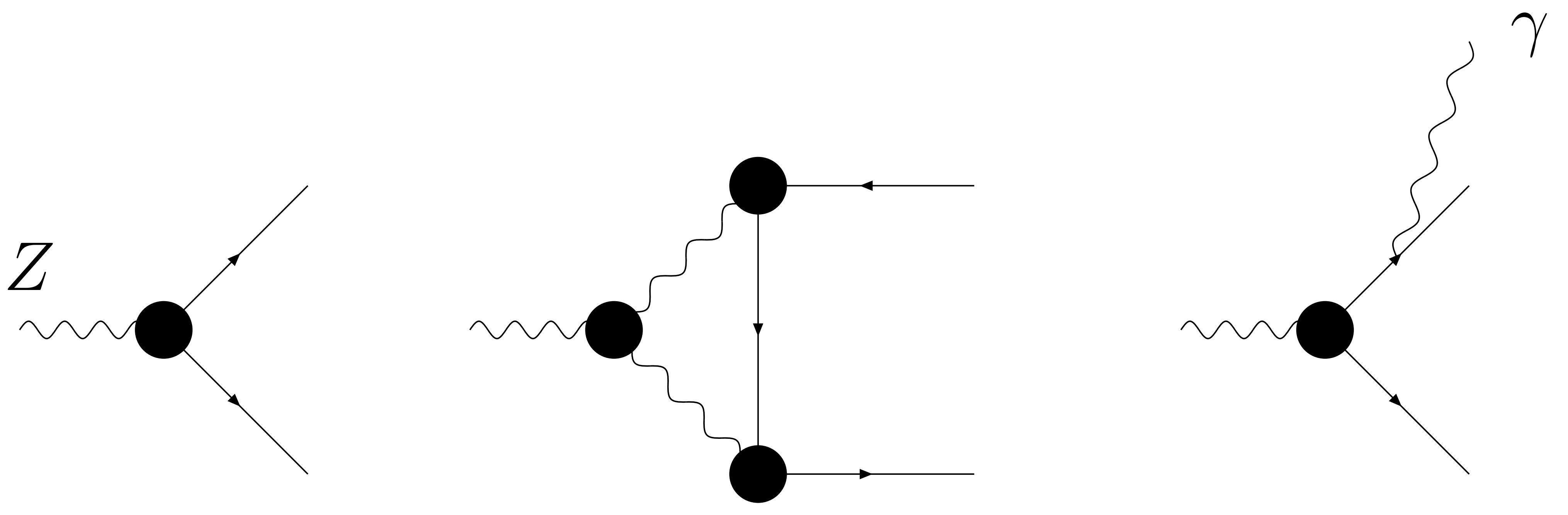
Theoretical Uncertainties

- Estimated using geometric series
  - $a_n = a\, r^n$,
    example: $$\mathcal{O}(\alpha^2\alpha_s) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_s)$$
  - similar results from scale variations
  - Reasonable estimates for all observables
- Exception: m_t !
  - MC parameter, translation to m_t^{pole} unknown
- 10 additional free parameters
  - Gaussian likelihood
- Important missing higher order terms:
  - $O(\alpha^2\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^3)$, $O(\alpha_s^5)$ (rad. functions)

important

Observable	Exp. error	Theo. error
M_W	8.5 MeV	4 MeV
$\sin^2\theta^l_{\rm eff}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\rm had}$	37 pb	6 pb
R^0_b	$6.6 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
m_t	0.33 GeV	0.5 GeV

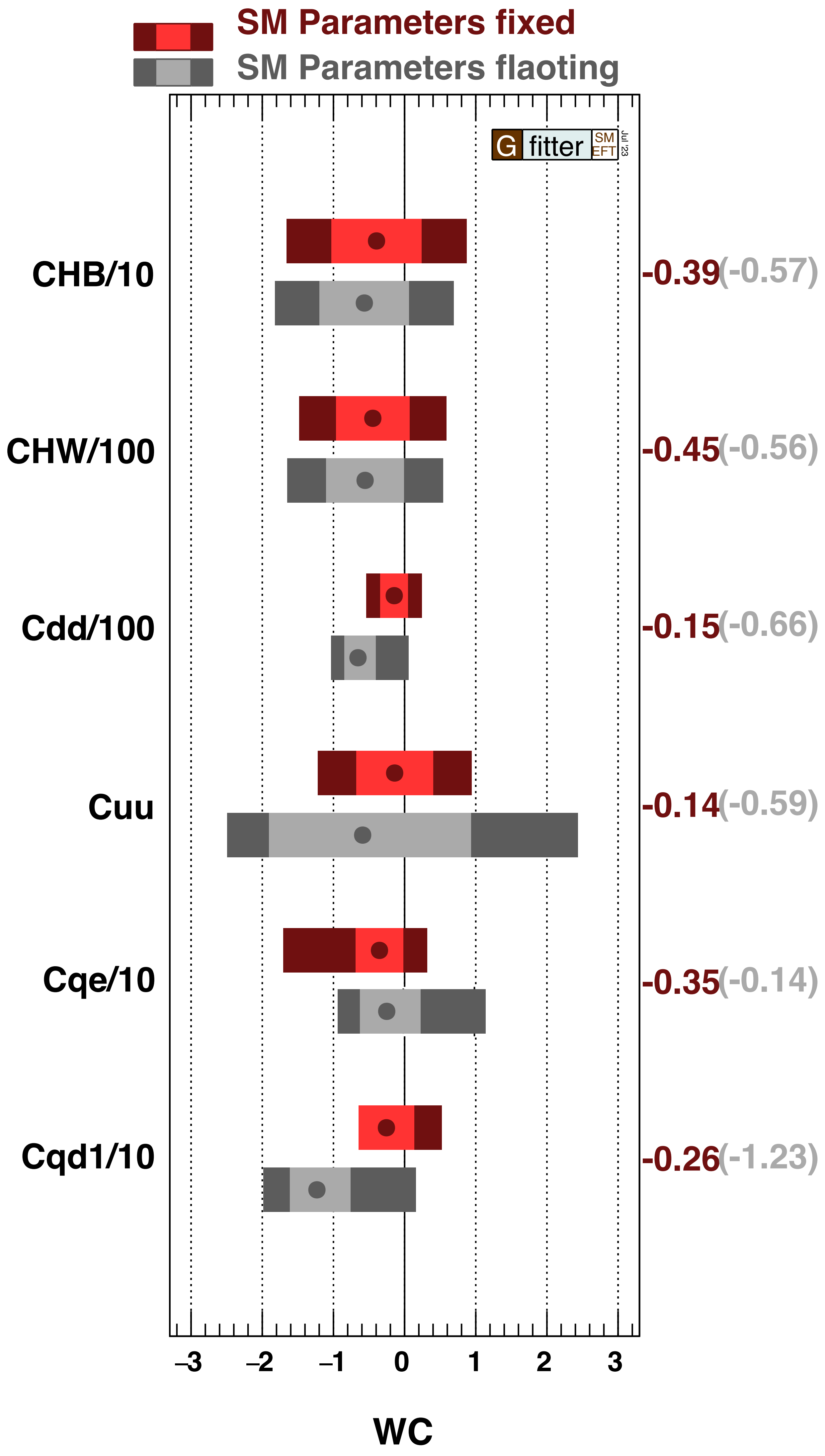
SMEFT Contributions



LO NLO virtual NLO real

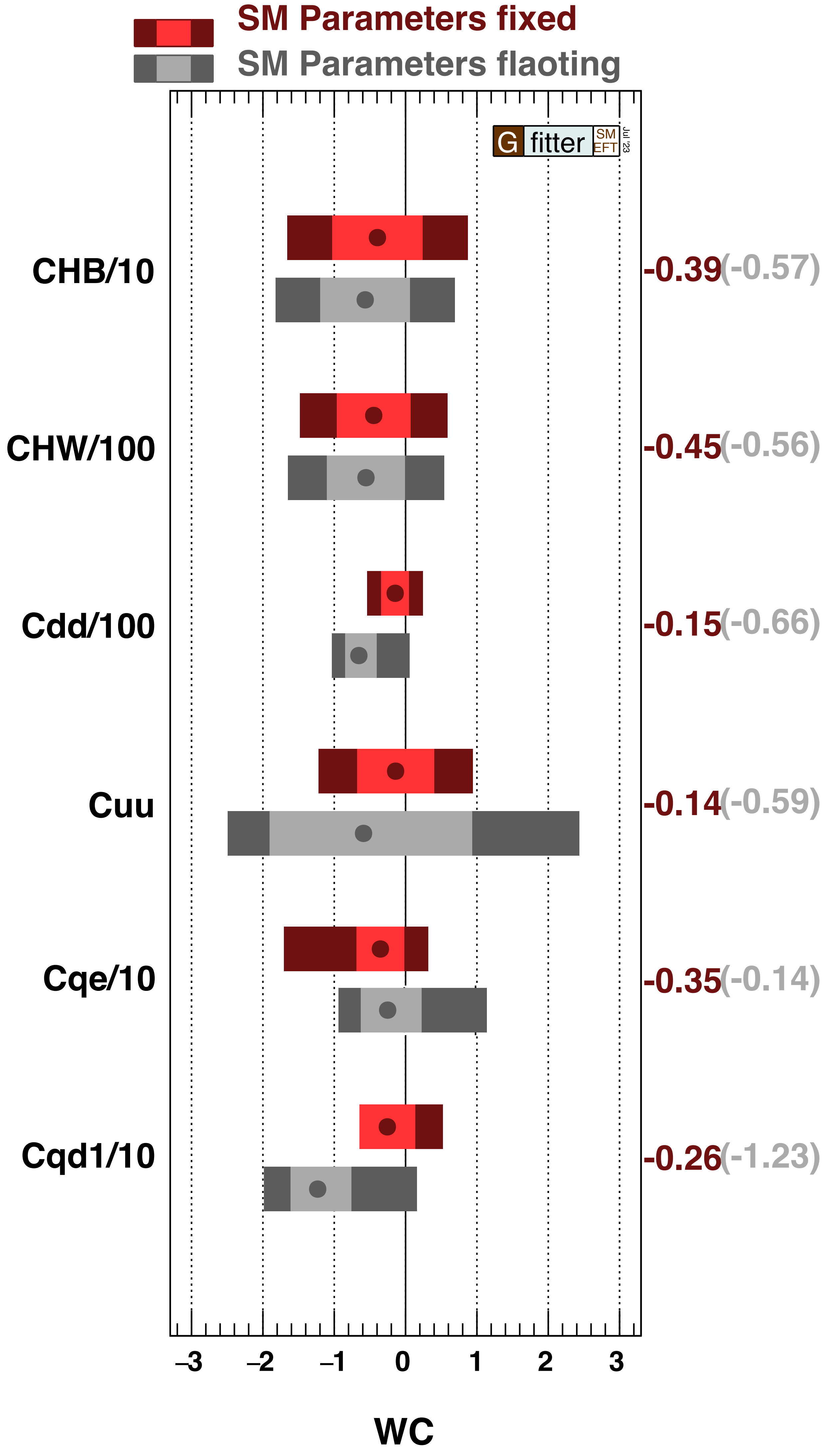
- Considering 32 flavour independent operators in Warsaw basis
  - 10 operators contributing at LO $\mathcal{O}_{ll}$, $\mathcal{O}_{HWB}$, $\mathcal{O}_{HD}$, $\mathcal{O}_{He}$, $\mathcal{O}_{Hd}$, $\mathcal{O}_{Hu}$, $\mathcal{O}_{Hq}^{(3)}$, $\mathcal{O}_{Hq}^{(1)}$, $\mathcal{O}_{Hl}^{(3)}$, $\mathcal{O}_{Hl}^{(1)}$
  - 22 operators contributing at NLO:
    - 4 bosonic operators: $\mathcal{O}_{\phi B}$, $\mathcal{O}_{\phi W}$, $\mathcal{O}_{\Box}$, $\mathcal{O}_{W}$
    - 2 2-fermion operators: $\mathcal{O}_{uB}[ij]$, $\mathcal{O}_{uW}[ij]$
    - 16 4-fermion operators: $\mathcal{O}_{ed}[ijkl]$, $\mathcal{O}_{ee}[ijkl]$, $\mathcal{O}_{eu}[ijkl]$, $\mathcal{O}_{lu}[ijkl]$, $\mathcal{O}_{ld}[ijkl]$, $\mathcal{O}_{le}[ijkl]$, $\mathcal{O}_{lq}^{(1)}[ijkl]$, $\mathcal{O}_{lq}^{(3)}[ijkl]$, $\mathcal{O}_{qe}[ijkl]$, $\mathcal{O}_{qd}^{(1)}[ijkl]$, $\mathcal{O}_{qq}^{(3)}[ijkl]$, $\mathcal{O}_{qq}^{(1)}[ijkl]$, $\mathcal{O}_{qu}^{(1)}[ijkl]$, $\mathcal{O}_{ud}^{(1)}[ijkl]$, $\mathcal{O}_{uu}[ijkl]$, $\mathcal{O}_{dd}[ijkl]$

SMEFT Fits



Effect of letting SM parameters floating in SMEFT fit

SMEFT Fits



Effect of letting SM parameters floating in SMEFT fit

Simultaneous fit of down-quark couplings