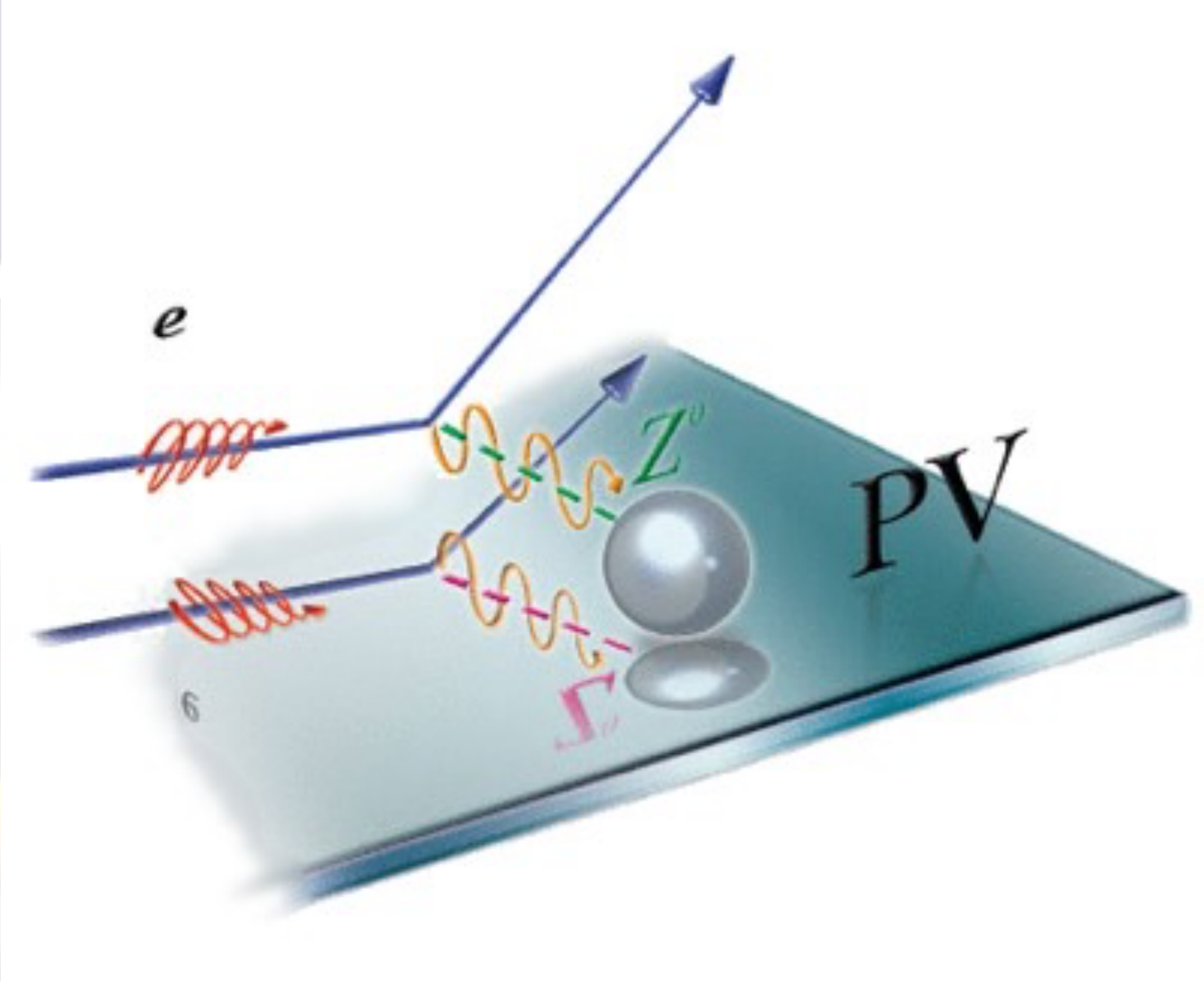
Deutsche Forschungsgemeinschaft
German Research Foundation

Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter



PDG particle data group

Electroweak precision tests of the SM: status and prospects

Jens Erler

JG|U

CONACYT Consejo Nacional de Ciencia y Tecnología

SoLID SOLENOIDAL LARGE INTENSITY DEVICE

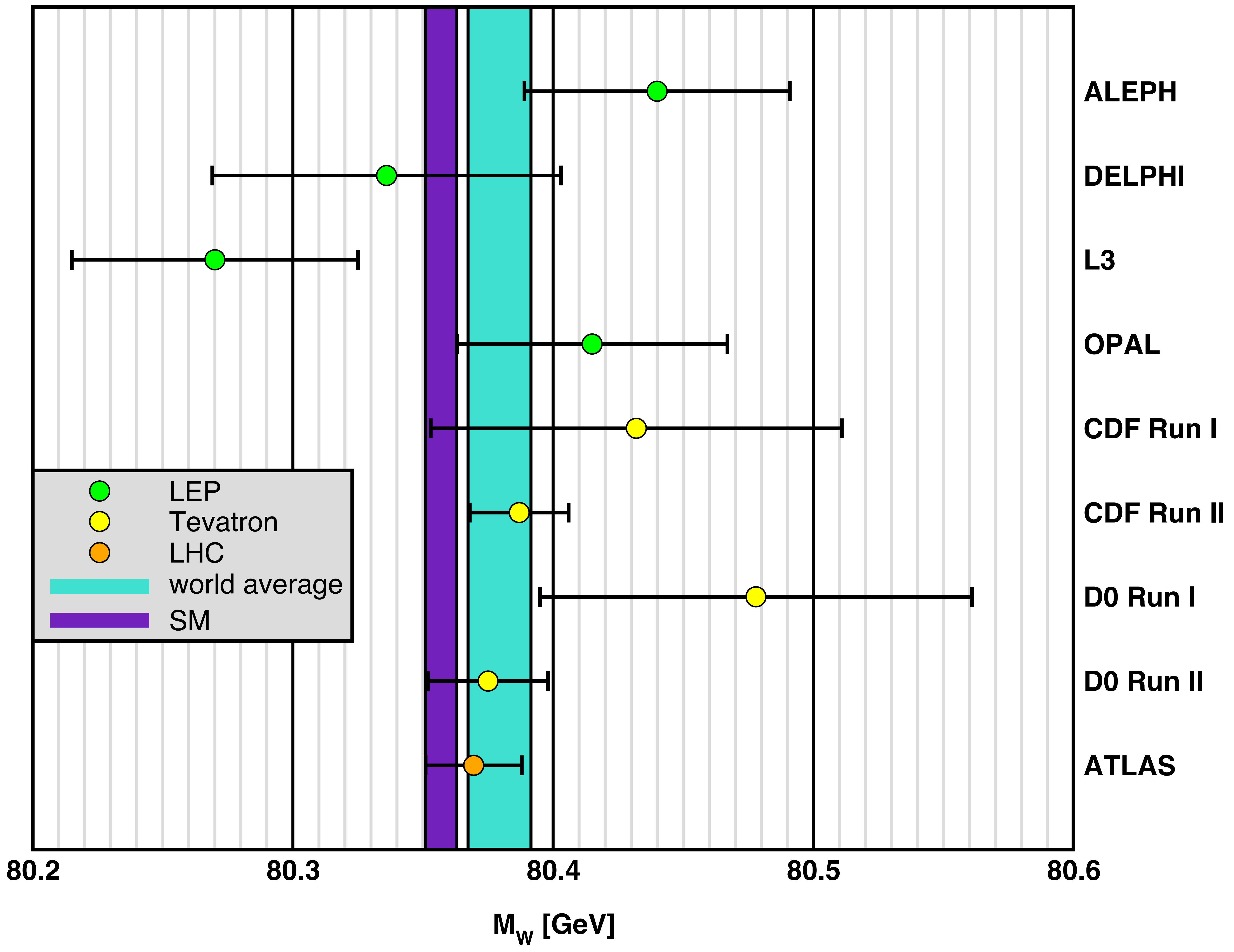
Les Rencontres de Physique de la Vallée d'Aoste, La Thuile, March 11, 2021

Electroweak precision physics

* The electroweak (EW) precision program started about 50 years ago
* M_W, M_Z, m_t, M_H (and m_c) have all been successfully predicted before their discoveries
* 2012 the Standard Model (SM) was completed …

  … and it is as successful as it is unsatisfactory (dark matter, naturalness, …)
* no new states discovered at the LHC yet, so perhaps they show up in EW physics first
* General remark: the higher the precision, the more physics issues will enter in the interpretation of precision measurements
* this is an obstacle when looking at single observables but is a feature in global analyses (across different observables and subfields of particle, nuclear and atomic physics)
* some tensions in g_μ–2, M_W, and the first row CKM matrix unitarity constraint

W boson mass



average direct

80.379 ± 0.012 GeV

indirect

80.357 ± 0.006 GeV

(1.7 σ low)

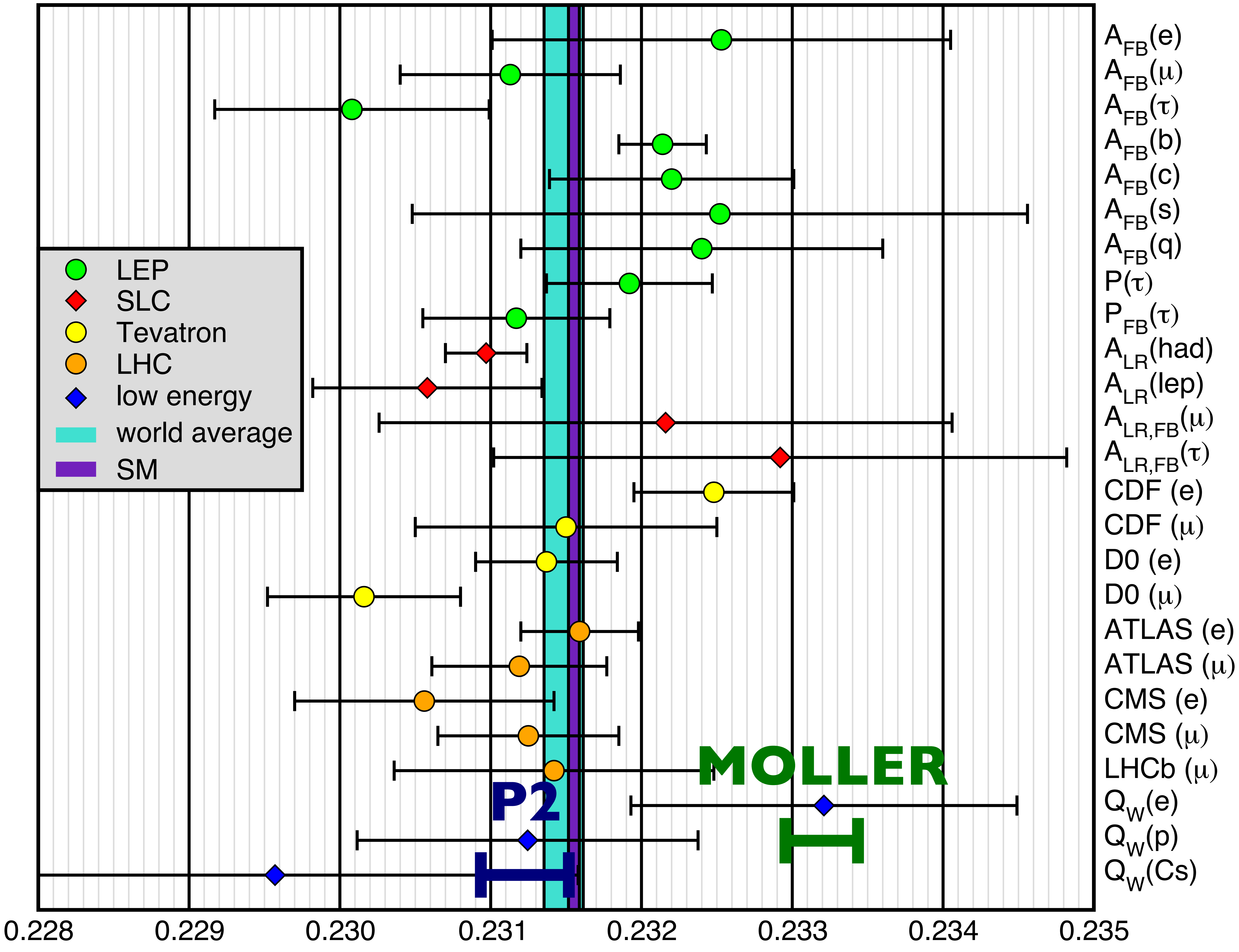
Weak mixing angle approaches

- tuning in on the Z resonance
  - leptonic and heavy quark FB asymmetries in e^+e^- annihilation near $s = M_Z^2$
  - leptonic FB asymmetries in pp ($p\bar{p}$) Drell-Yan in a window around $m_{ll} = M_Z$
  - LR asymmetry (SLC) and final state τ polarization (LEP) and their FB asymmetries

recent first measurements

	ν scattering	…tering (PVES)
leptonic	$\nu_\mu - e^-$	$e^- - e^-$
DIS	heavy nuclei (NuTeV)	deuteron (E–122, PVDIS, SoLID)
elastic	CEνNS (COHERENT)	proton, ^{12}C (Qweak, P2)
APV	heavy alkali atoms and ions	isotope ratios (Mainz)

Weak mixing angle measurements



LEP & SLC:

0.23151 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23129 ± 0.00033

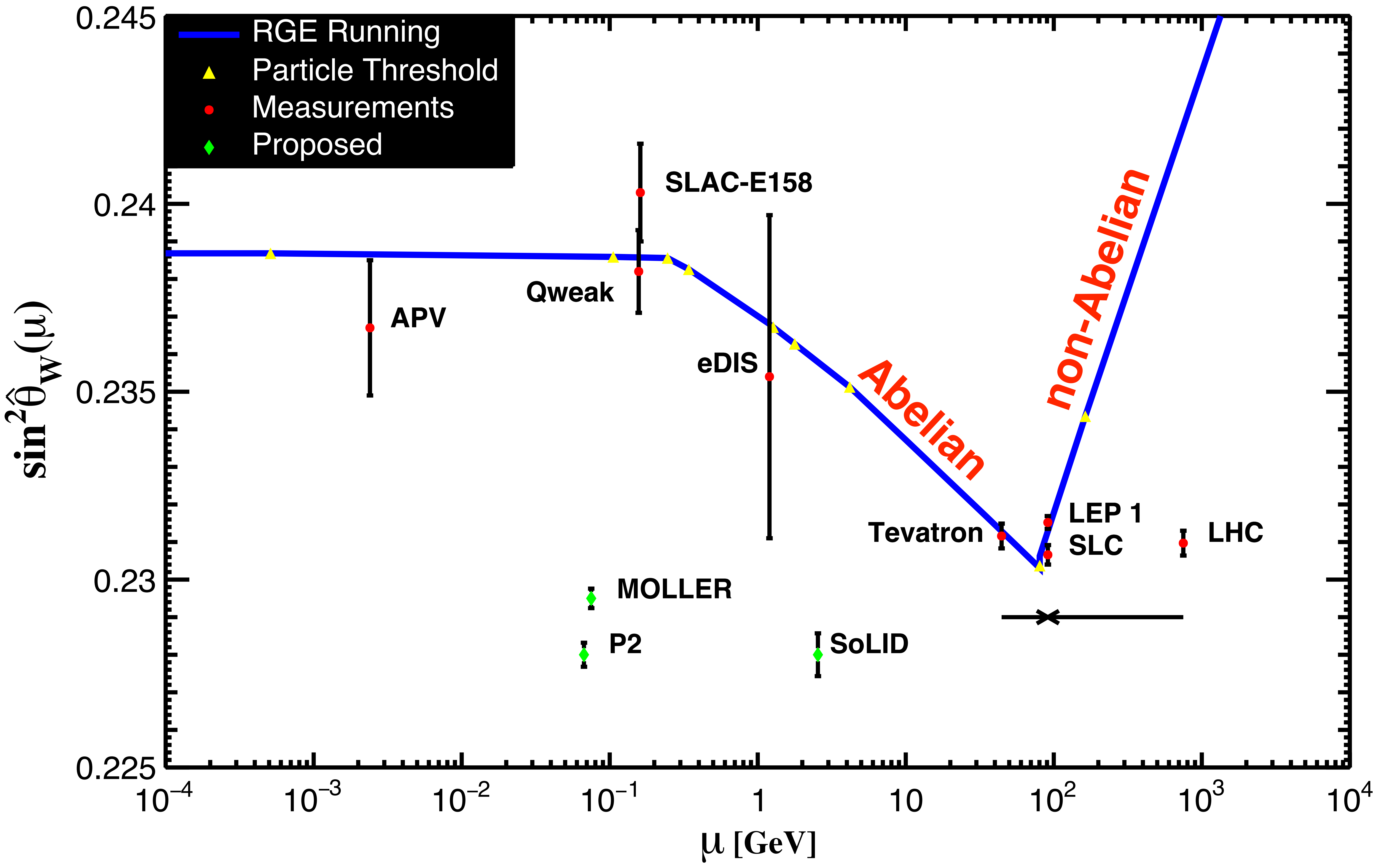
average direct

0.23148 ± 0.00013

global fit

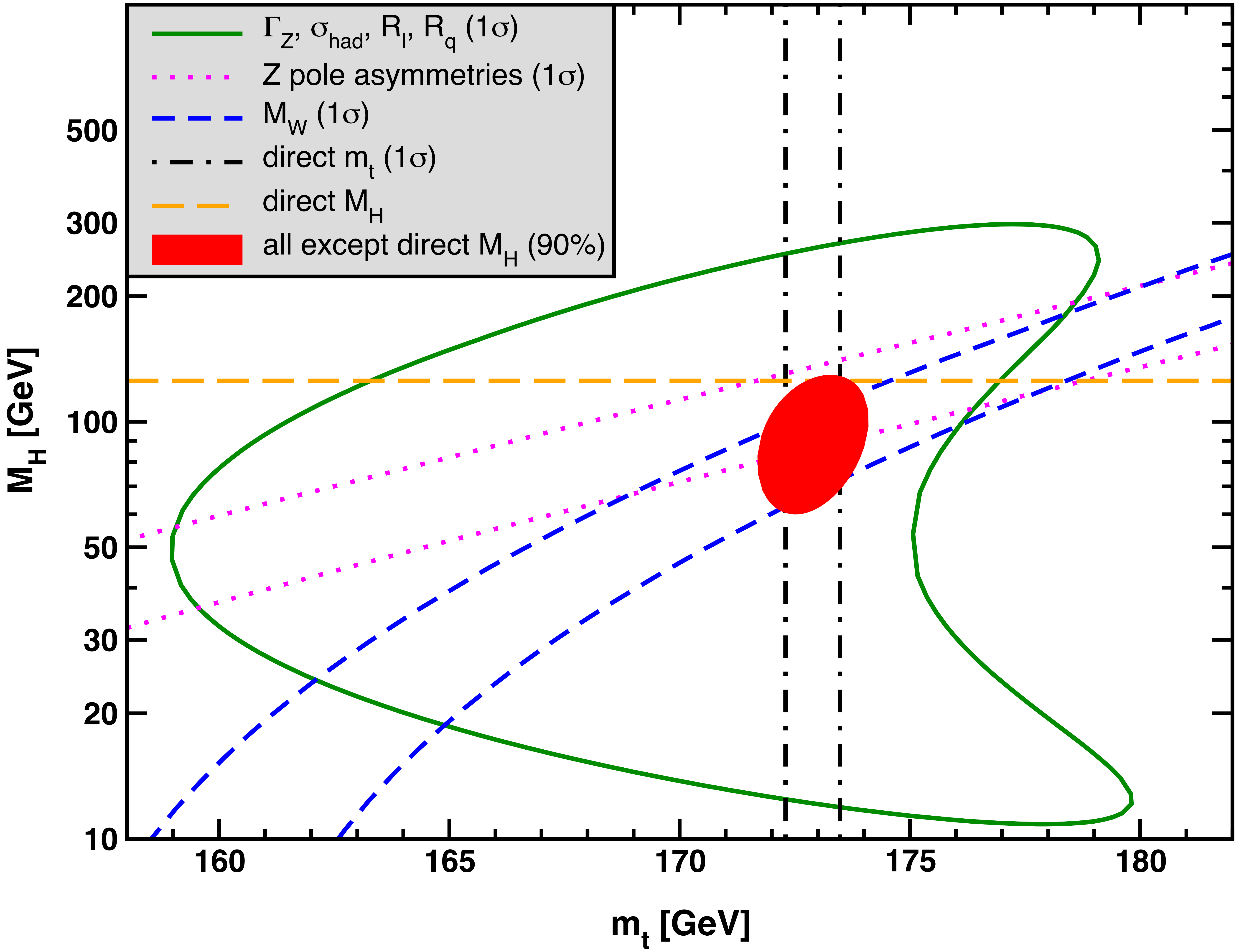
0.23153 ± 0.00004

Running weak mixing angle



Ferro-Hernández & JE, arXiv:1712.09146

M_H – m_t today



indirect m_t

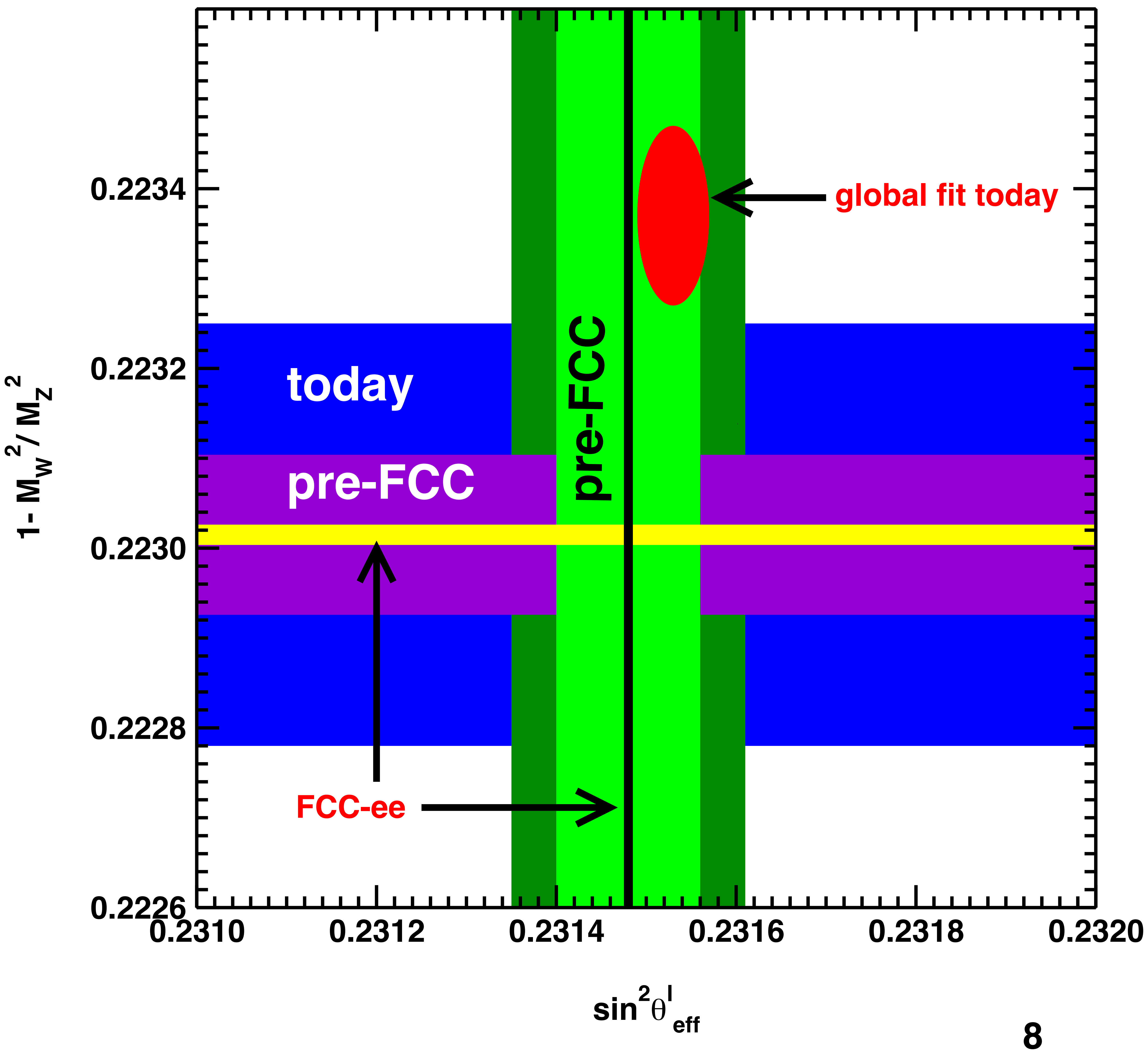
176.4 ± 1.9 GeV

(1.9 σ high)

including
correlated theory errors

Freitas & JE, PDG (2020)

on-shell *vs.* effective weak mixing angle



ΔM_W (LHC)

$\approx 3.8_{stat} + 3.8_{syst} + 3.8_{PDF}$ MeV

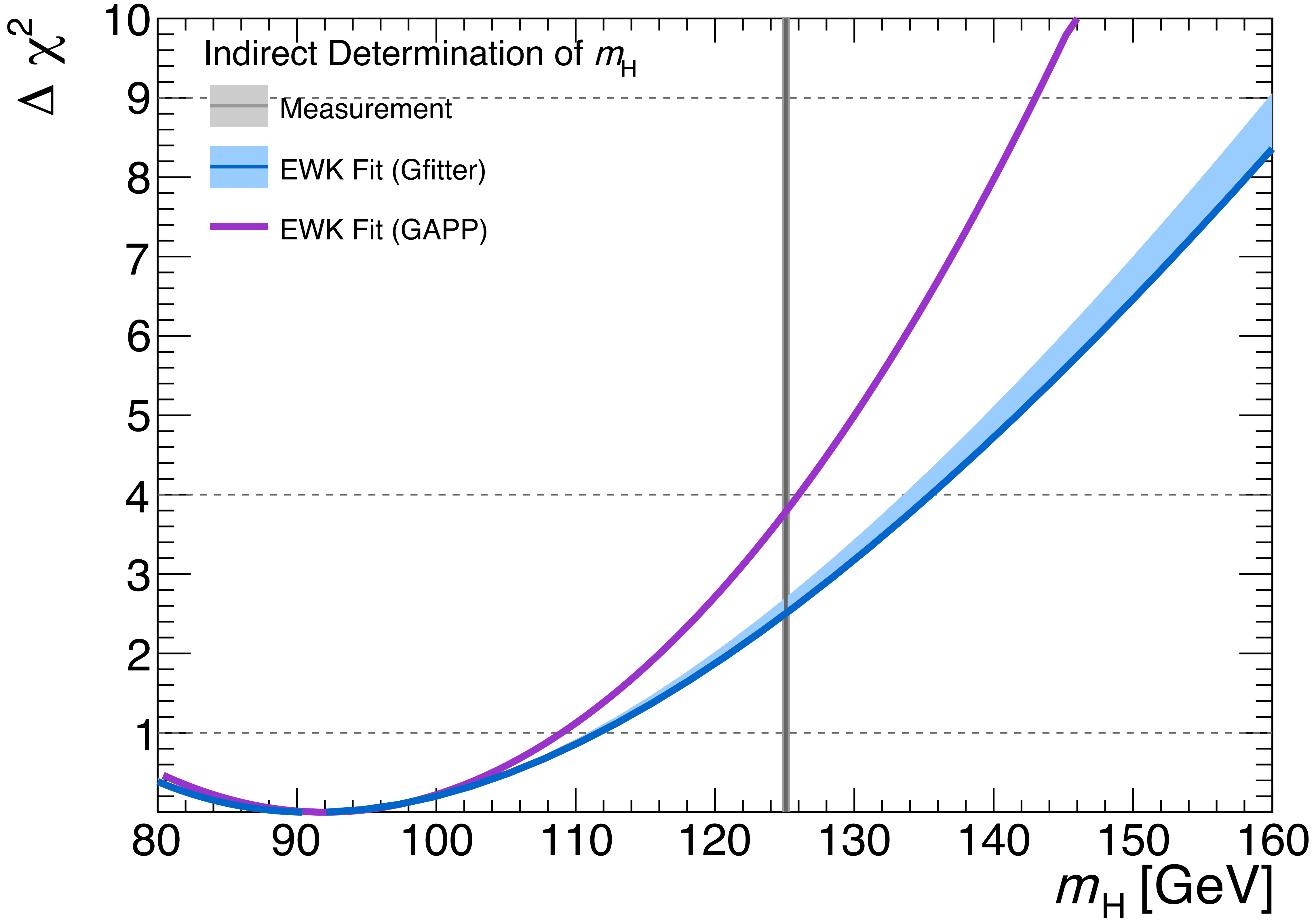
$\approx (5/3)^{1/2} \times 3.8$ MeV $\approx$ 5 MeV

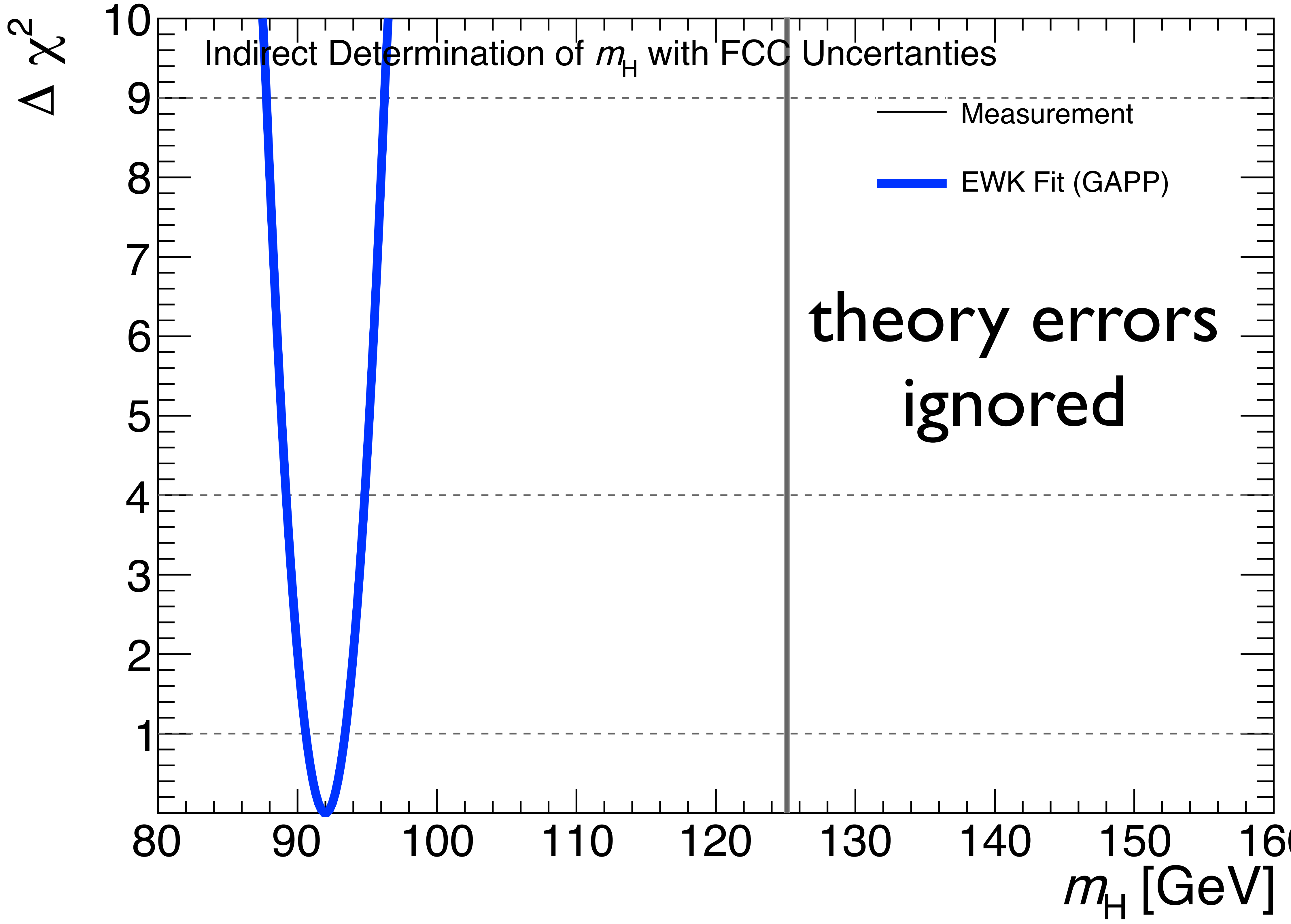
(for 3 detectors) based on

Azzi et al.
arXiv:1902.04070

$\Delta \sin^2\theta_W$ (LHC) $\approx 10^{-4}$

Higgs boson mass





Blondel et al.
arXiv:1905.05078

$\Delta M_H = \pm$ 1.4 GeV

($\Delta M_H = \pm$ 5.7 GeV with no theory improvement)

Parity Violating e⁻ Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 MeV

$|Q|$ = 158 MeV (θ = 7.9°)

$A_{PV} = 2.3 \times 10^{-7}$

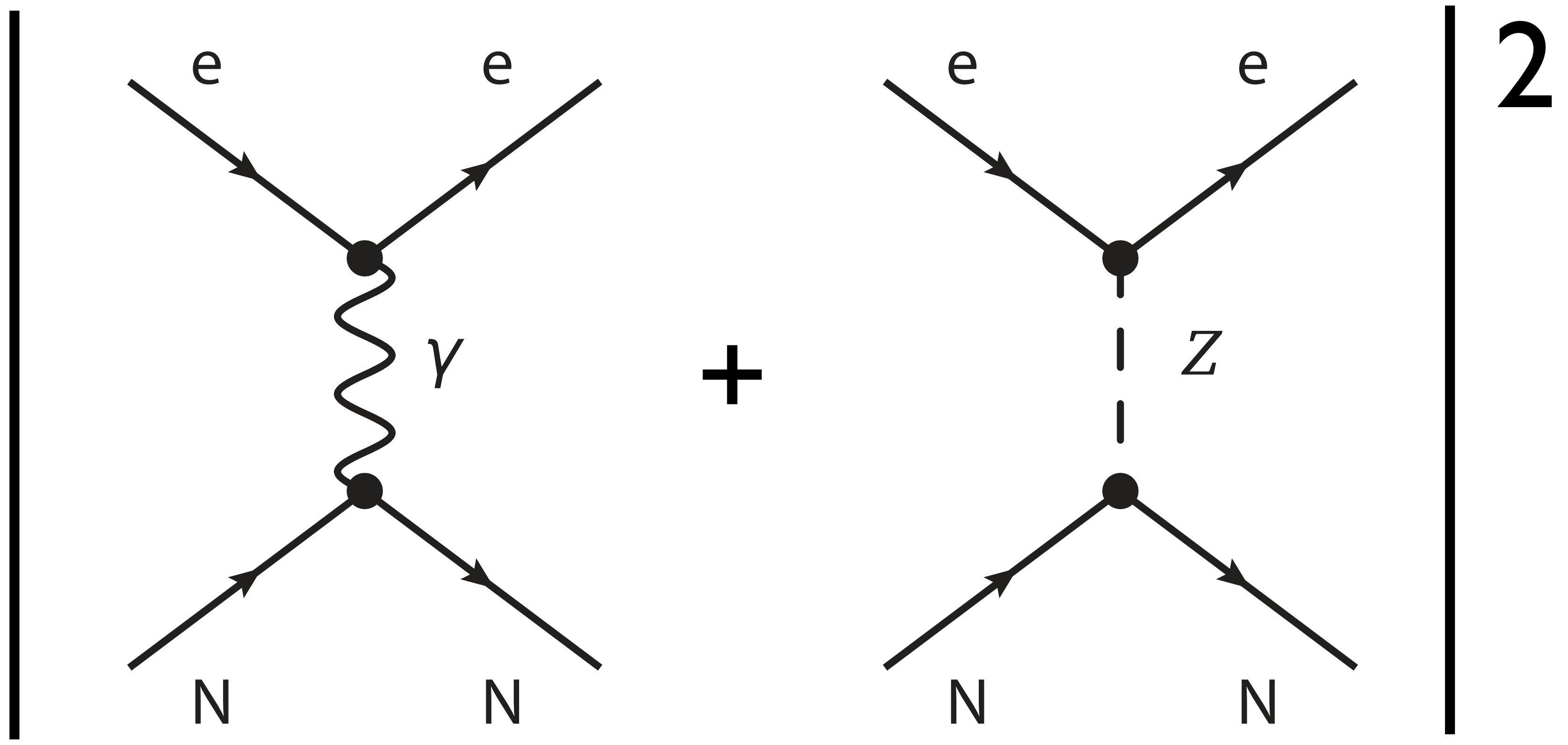
$\Delta A_{PV} = \pm\ 4.1\%$

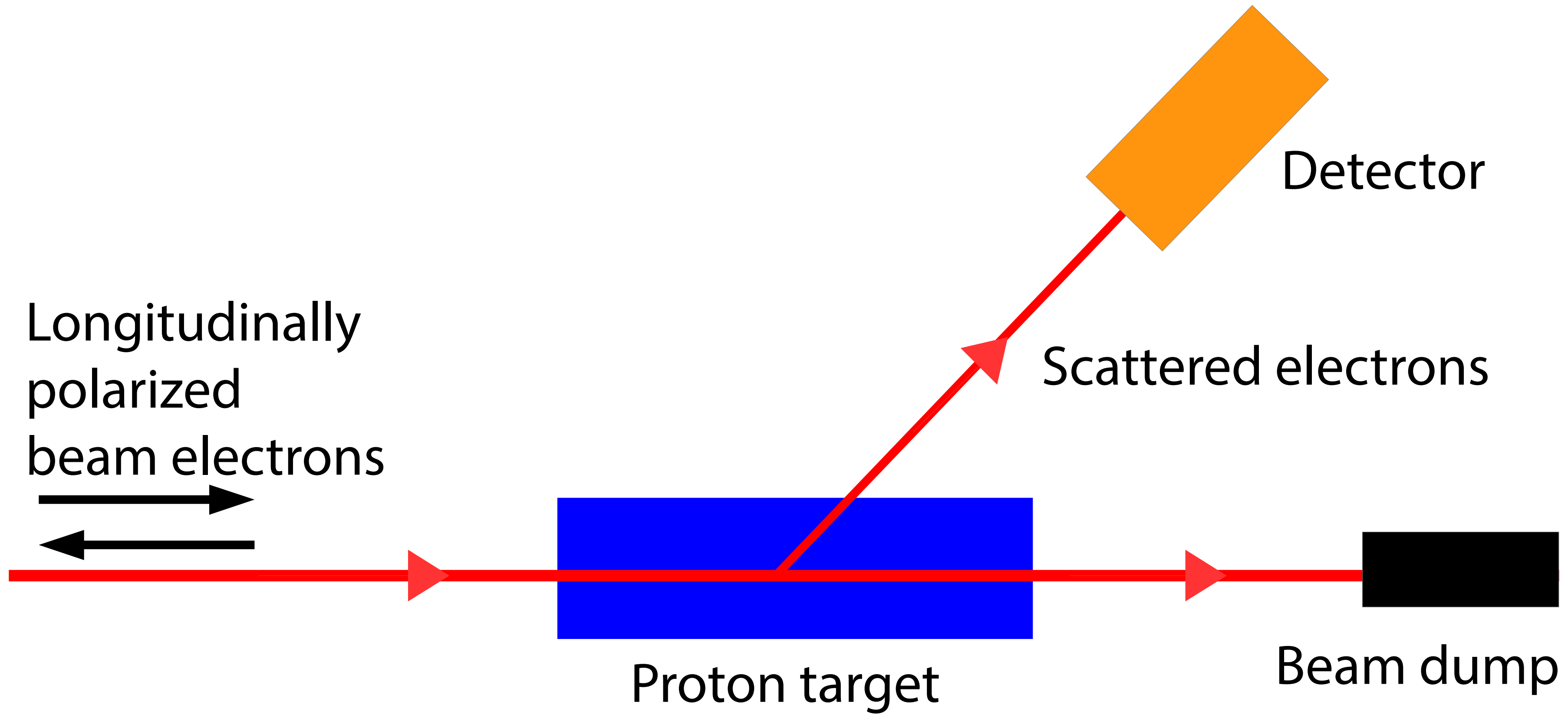
$\Delta Q_W(p) = \pm\ 6.25\%$

$\sin^2\theta_W = 0.2383 \pm 0.0011$

FFs from fit to ep asymmetries

arXiv:1905.08283





Standard Model Effective Field Theory (SMEFT)

	$N_f = 3$	$N_f = 1$	bosonic	ψ^2	ψ^4 ($\Delta B = 0$)	ψ^4 ($\Delta B \neq 0$)	
D = 0	1	1	1	–	–	–	$\Lambda_C \neq 0$
D = 1	–	–	–	–	–	–	
D = 2	1	1	1	–	–	–	$M_H \neq 0$
D = 3	–	–	–	–	–	–	
D = 4	55	7	1	6	–	–	**SM**
D = 5	12	2	–	12	–	–	$m_\nu \neq 0$
D = 6	3045	84	15	31	30	8	
D = 7	1542	30	–	10	12	8	**BSM**
D = 8	44807	993	89	386	420	98	

Henning et al., arXiv:1512.03433

SMEFT@ D = 6

38 four-Fermi-operators

↓

3 L^4 + 13 L^2Q^2 + 8 LQ^3 ($\Delta B \neq 0$) + 14 Q^4 operators

↓

$$\psi_V = \bar{\psi}\gamma^\mu\psi$$

$$\psi_A = \bar{\psi}\gamma^\mu\gamma^5\psi$$

3 L^4 = $e_V e_V$ + $e_A e_V$ *(MOLLER)* + $e_A e_A$

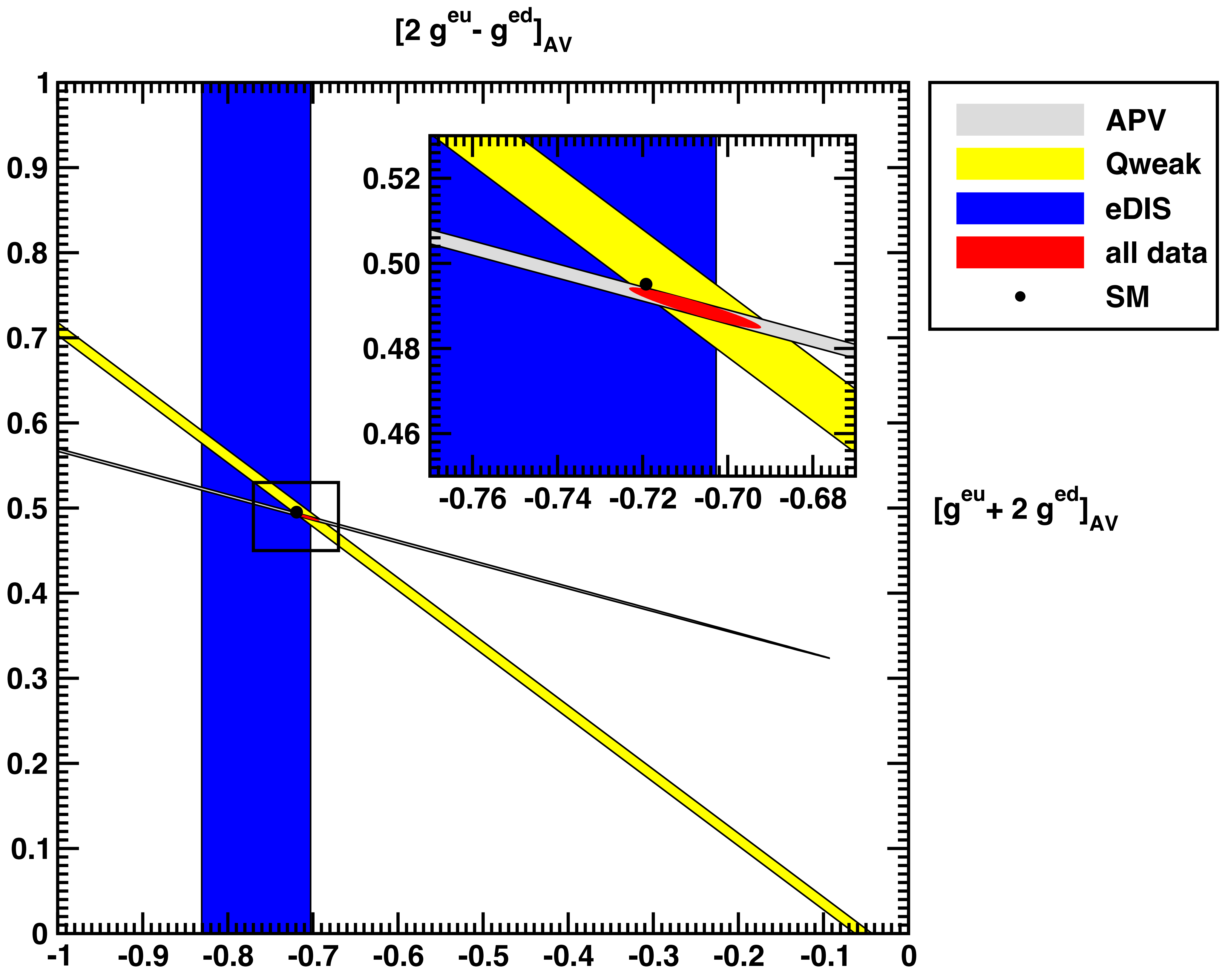
13 L^2Q^2 = 7 vector and axial-vector combinations + 4 scalar + 2 tensor

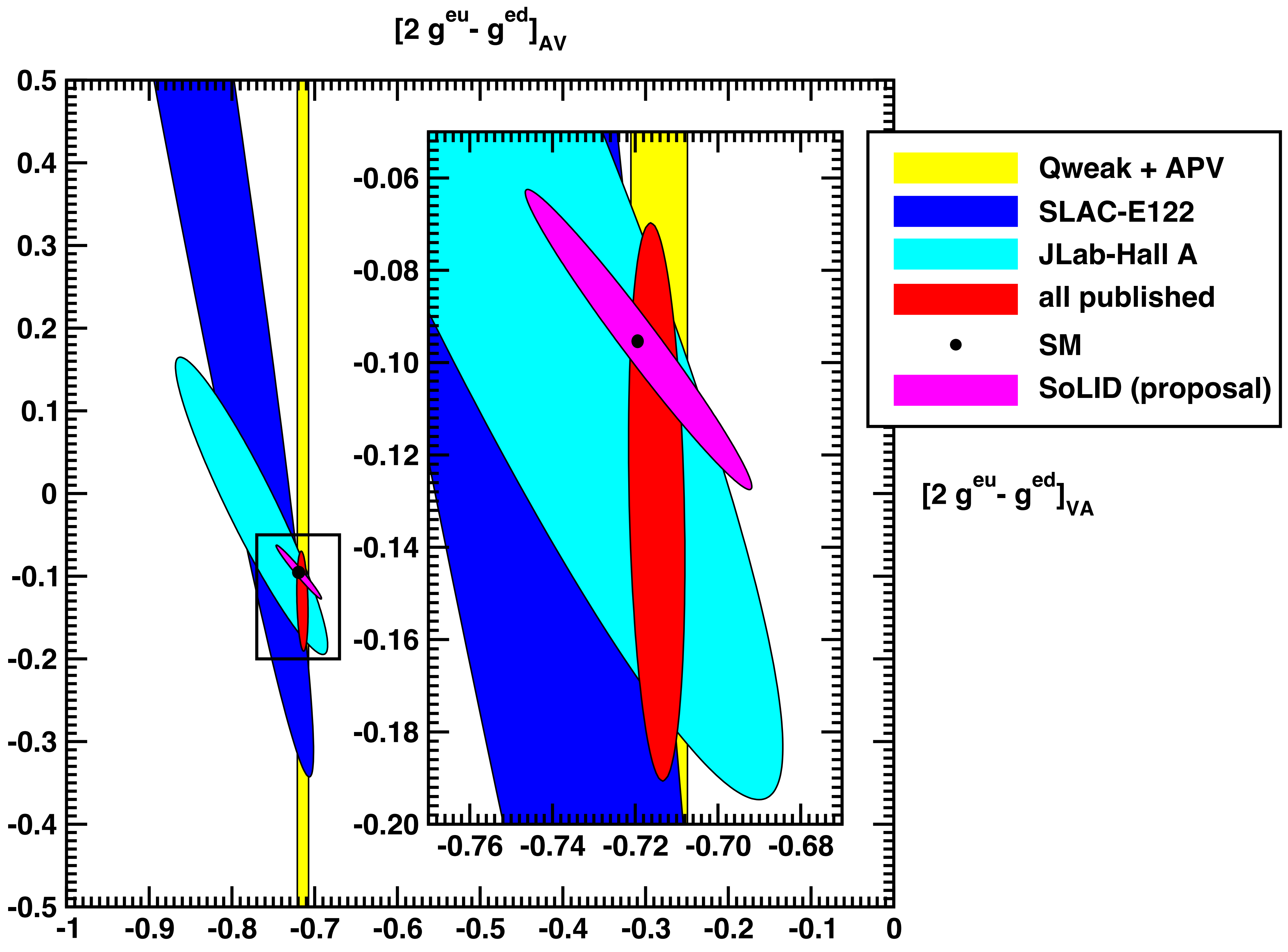
↓

2 $e_V q_V$ (C_0) + 2 $e_A q_V$ (C_1) *(APV, Qweak, P2)* + 2 $e_V q_A$ (C_2) *(SLAC-E122, PVDIS, SoLID)*

+ 2 $e_A q_A$ (C_3) *(e^+@SoLID)* −1 constraint: $(\bar{u}_L\gamma^\mu u_L - \bar{d}_L\gamma^\mu d_L)\bar{e}_R\gamma_\mu e_R = 0$

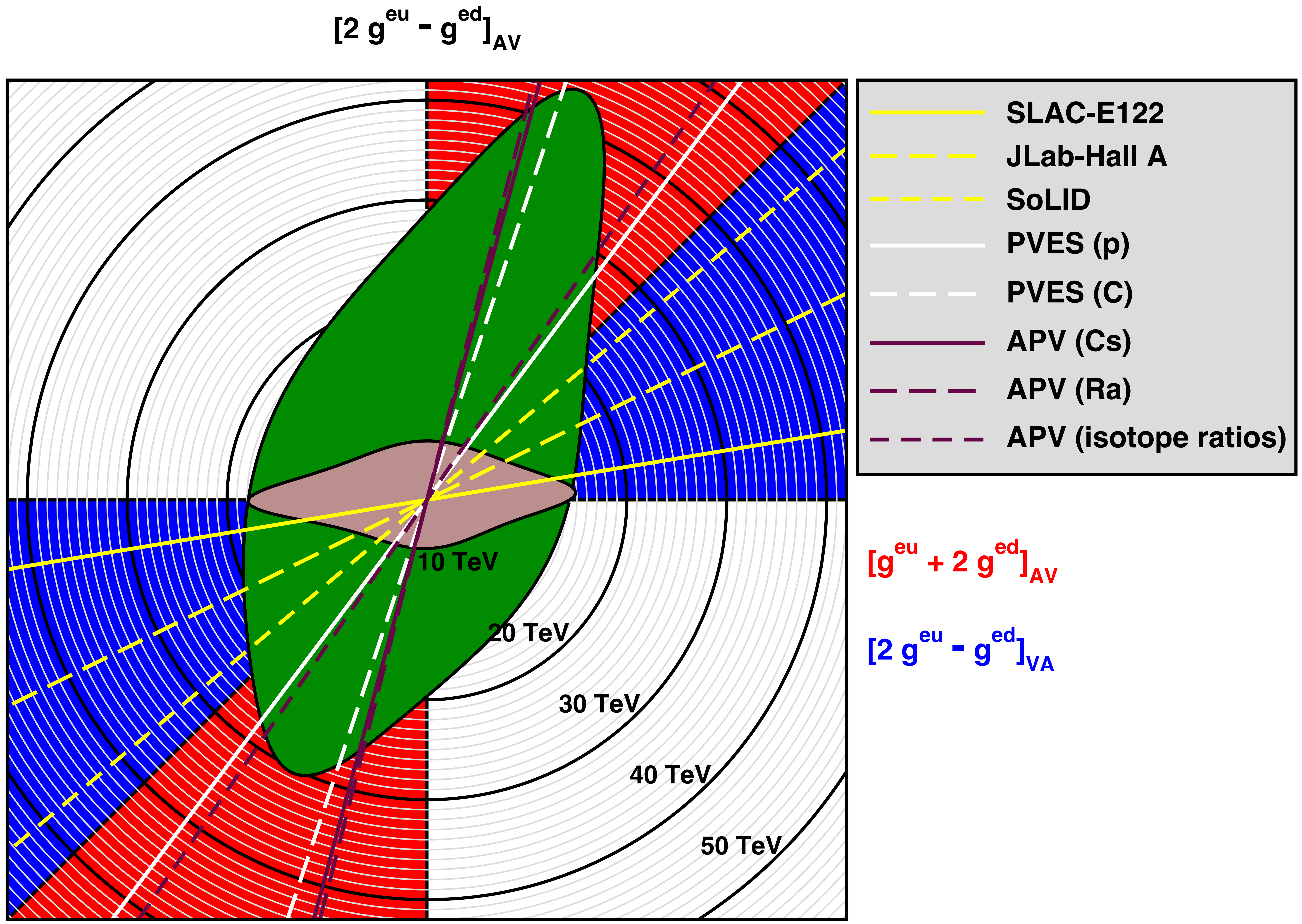
Parity-violating 4-fermion electron-quark couplings





JE et al., arXiv:1401.6199

Scale exclusions post Qweak

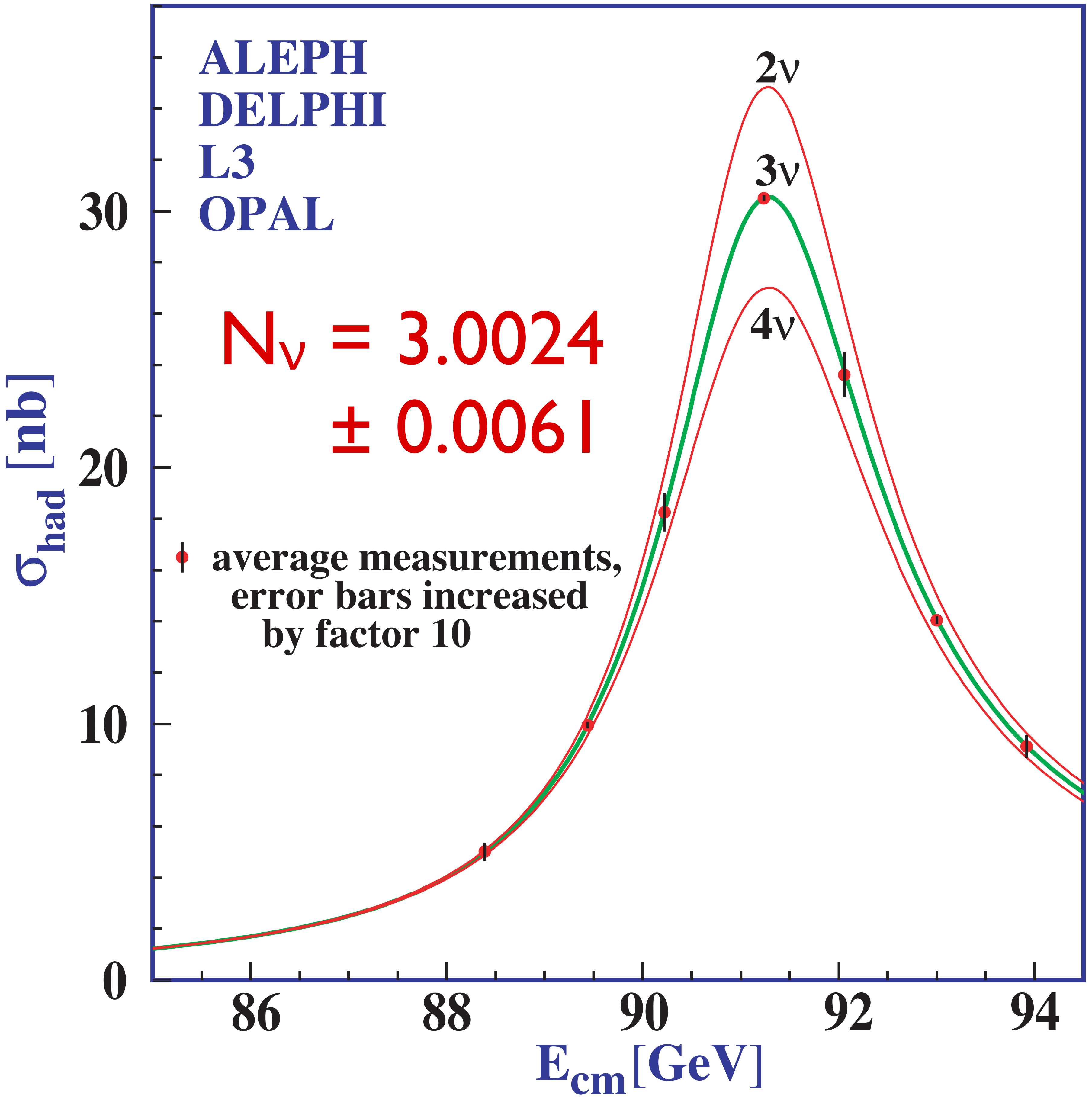


N_ν

year	from σ_{had}	global fit	development
2006	2.984 ± 0.008 **LEPEWWG hep-ex/0509008**	2.986 ± 0.007	CIPT for τ_τ
2010		2.991 ± 0.007	FOPT for τ_τ
2014		2.990 ± 0.007	Higgs discovery
2019	2.992 ± 0.008	2.998 ± 0.007	**Voutsinas et al. arXiv:1908.01704**
	2.9975 ± 0.0074	**3.0024 ± 0.0061**	**Janot & Jadach, arXiv:1912.02067**

α_s from the Z pole

observable	$\alpha_s(M_Z)$
Γ_Z = 2495.5 ± 2.3 MeV	0.1215 ± 0.0048
σ_{had} = 41.481 ± 0.033 nb	0.1201 ± 0.0065
R_e = 20.804 ± 0.050	0.1295 ± 0.0082
R_μ = 20.784 ± 0.034	0.1264 ± 0.0054
R_τ = 20.764 ± 0.045	0.1157 ± 0.0072
B_W(had) = 0.6741 ± 0.0027	0.104 ± 0.037
combination	0.1228 ± 0.0028
global fit	0.1185 ± 0.0016



change: $\Delta\sigma_{had}$ = –40 pb, $\Delta\Gamma_Z$ = ±0.3 MeV

additional change: $\Delta\sigma_{had}$ = –27 pb

Voutsinas et al., arXiv:1908.01704

Janot & Jadach, arXiv:1912.02067

α_s from the Z pole

observable	$\alpha_s(M_Z)$	FCC–ee	α_s@FCC–ee
Γ_Z = 2495.5 ± 2.3 MeV	0.1215 ± 0.0048	± 25 keV	± 0.00007
σ_{had} = 41.481 ± 0.033 nb	0.1201 ± 0.0065	± 4 pb	± 0.00064
R_e = 20.804 ± 0.050	0.1295 ± 0.0082		
R_μ = 20.784 ± 0.034	0.1264 ± 0.0054	ΔR_l = ± 0.0006	± 0.00010
R_τ = 20.764 ± 0.045	0.1157 ± 0.0072		
B_W(had) = 0.6741 ± 0.0027	0.104 ± 0.037	± 0.00002	± 0.00027
combination	0.1228 ± 0.0028		± 0.00006
global fit	0.1185 ± 0.0016		± 0.00005

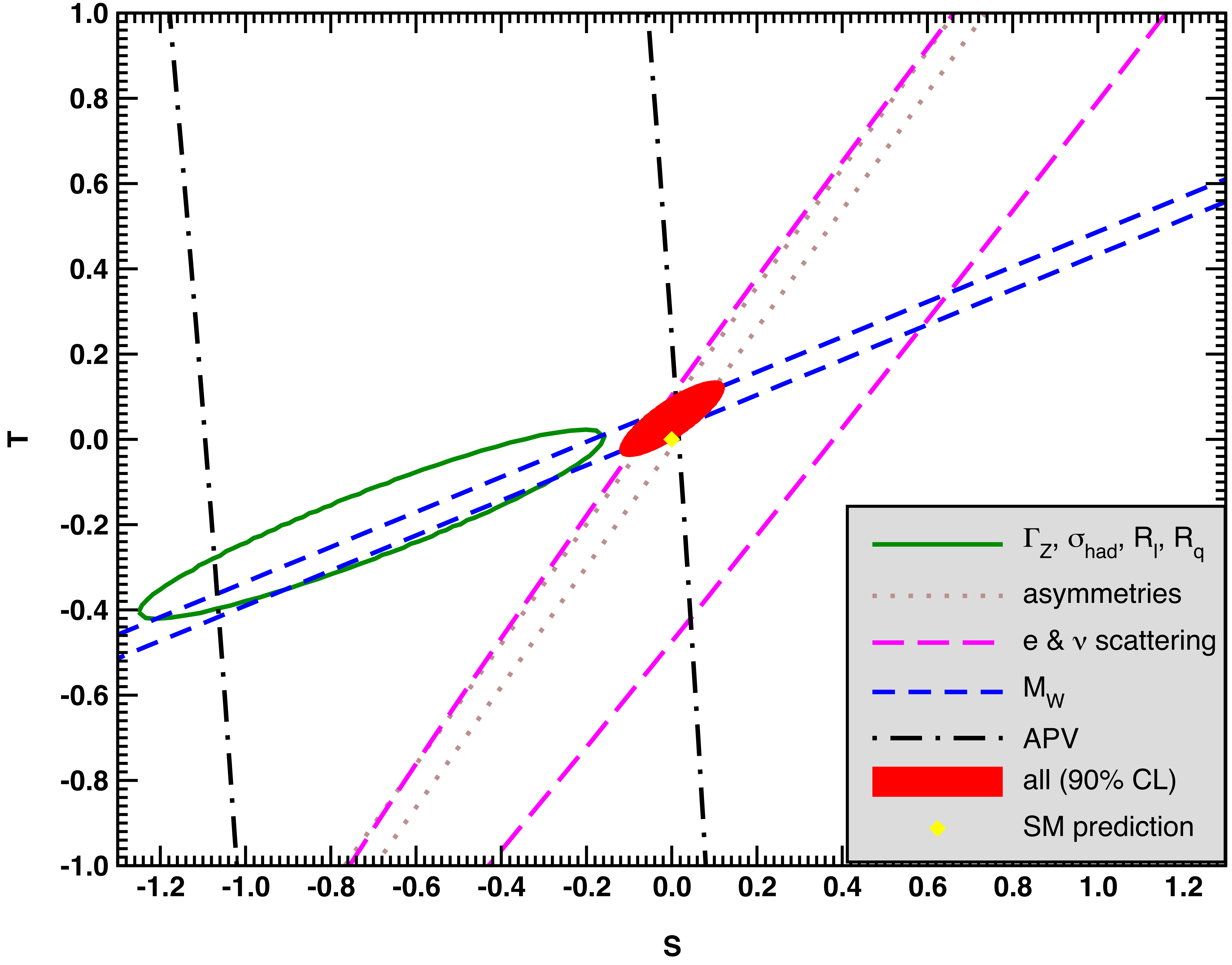
change: $\Delta\sigma_{had}$ = –40 pb, $\Delta\Gamma_Z$ = ±0.3 MeV

<u>additional change</u>: $\Delta\sigma_{had}$ = –27 pb

Voutsinas et al., arXiv:1908.01704

Janot & Jadach, arXiv:1912.02067

S and T

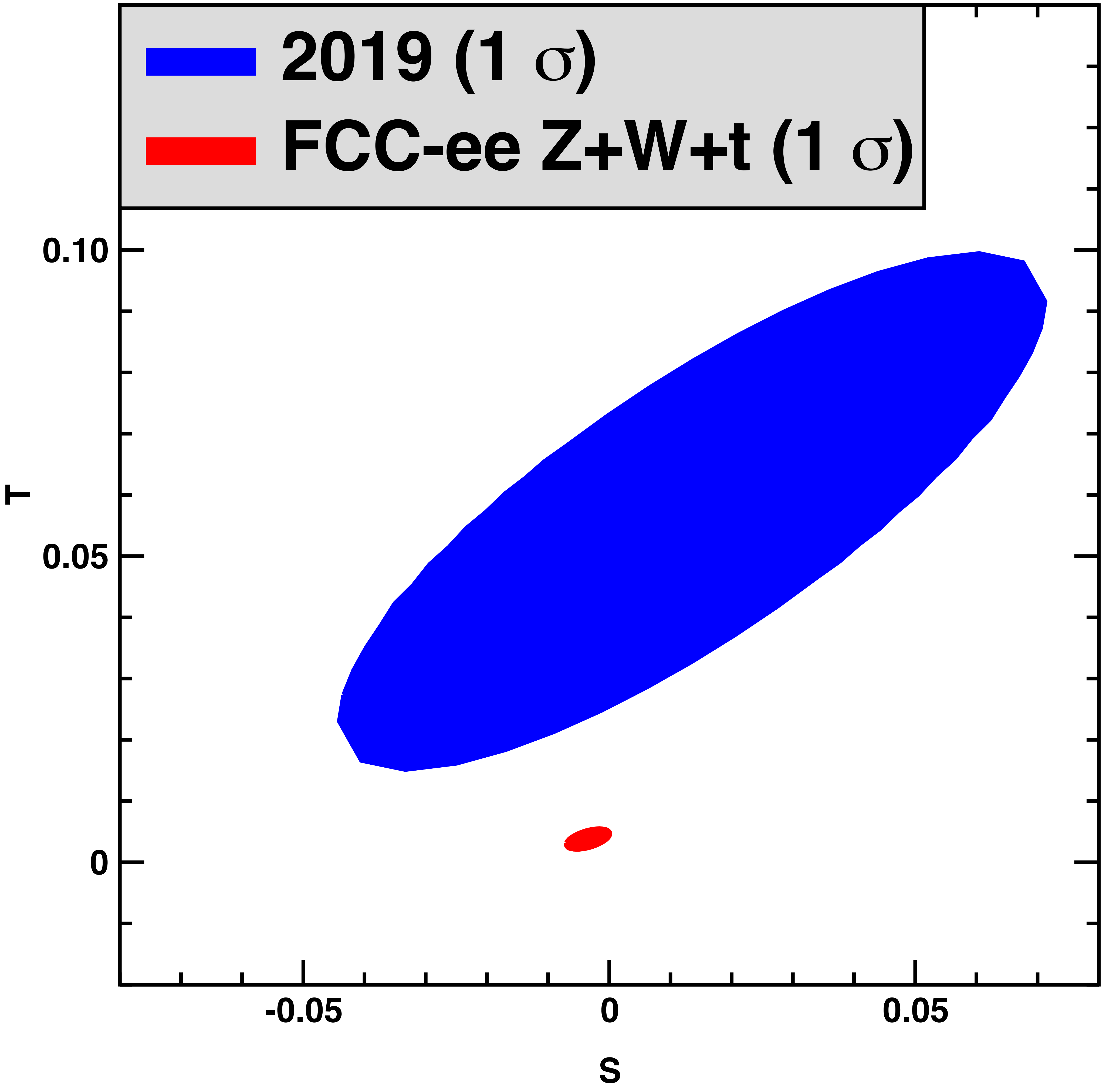


S	0.00 ± 0.07
T	0.05 ± 0.06
$\Delta\chi^2$	– 3.9

* $M_{KK} \gtrsim$ 3.6 TeV in warped extra dimension models
* $M_V \gtrsim$ 4 TeV in minimal composite Higgs models

Freitas & JE, PDG (2020)

S and T at the FCC–ee (and preliminary update)



S	0.01 ± 0.06	1.00	0.82
T	0.06 ± 0.04	0.82	1.00

S	± 0.0035	1.00	0.54
T	± 0.0016	0.54	1.00

FCC projections from
Blondel et al., arXiv:1905.05078
except $\Delta\Gamma_Z$ = 100 MeV → 25 MeV

(theory uncertainties ignored)

Conclusions

* *No conclusive evidence for physics beyond the SM found so far*
  * oblique parameters (STU…) more model-dependent and illustrative
  * SMEFT systematic and model-independent framework (if no new "light" states)
  * recent LEP luminosity update confirms $N_\nu = 3$ (<u>active</u> neutrinos), but α_s from electroweak processes now somewhat puzzling
  * many precise and complementary measurements of $\sin^2\theta_W$
* *future developments*
  * ultra-high precision PVES (MOLLER, P2 and SoLID) competitive alternatives to high energy frontier
  * a leap in precision can be expected from future lepton colliders ("Higgs factories") ILC, CEPC, FCC–ee, CLIC, muon collider

Thank You