DFG Deutsche Forschungsgemeinschaft

CONACYT
Consejo Nacional de Ciencia y Tecnología

Electroweak Precision Tests of the SM

Jens Erler

JGU & Helmholtz Institute Mainz (on leave from IF-UNAM)

PHOTON 2019 - International Conference on the Structure and the Interactions of the Photon

3-7 June 2019

INFN - LNF, Frascati

Satellite Workshop:
Photon Physics and Simulation at Hadron Colliders
6-7 June 2019

INSTITUTO Ð FÍSICA · UNAM 80 AÑOS 1938-2018

PDG particle data group

Outline

- *Weak mixing angle*
  global survey of $\sin^2\theta_W$ determinations
- *Theoretical uncertainties*
  correlations in precision observables
- *Vacuum polarizations in global fits*
  $\alpha(M_Z)$ $\sin^2\theta_W(0)$ $g_\mu-2$ $m_{c,b}$
- *Fit results*
- *Conclusions and outlook*

Weak mixing angle: global survey of $\sin^2\theta_W$ determinations

$$Z = \cos\theta_W W_3 - \sin\theta_W B$$
$$A = \sin\theta_W W_3 + \cos\theta_W B$$

$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \frac{M_W^2}{M_Z^2}$$

Why pushing $\sin^2\theta_W$?

- compute $\sin^2\theta_W$ from α, G_F and M_Z
- then measure $\sin^2\theta_W$ and M_W

➡ doubly over-constrained system at sub-‰ precision

- $\delta M_W \sim 15$ MeV $\leftrightarrow$ $\delta\sin^2\theta_W \sim 0.00029$ but complementary
- key test of EW symmetry breaking sector
- comparisons of different measurements, scales, and initial or final states provide window to physics beyond the SM

➡ global analysis

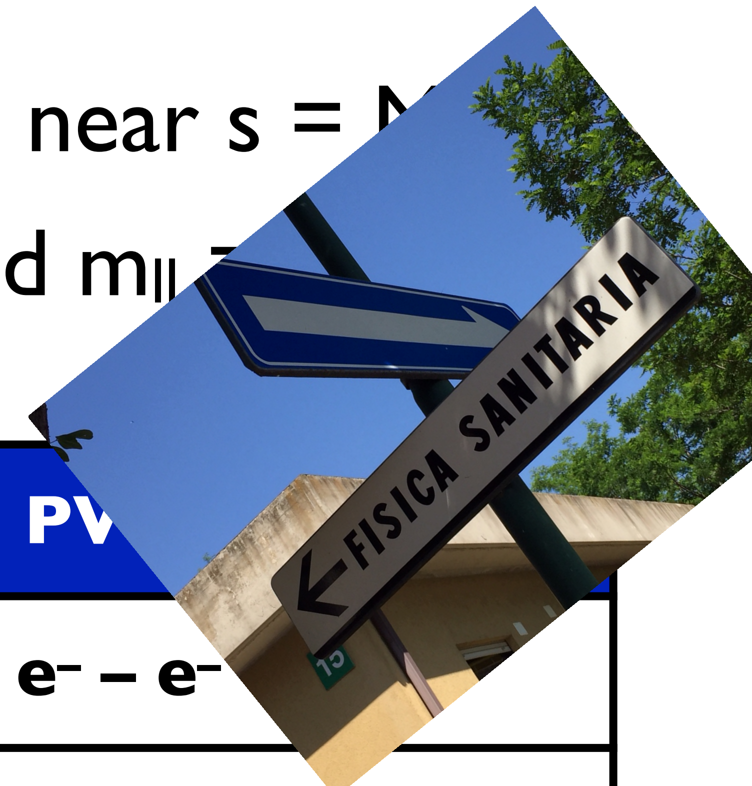
$\sin^2\theta_W(0)$: approaches

- tuning in on the Z resonance
  - FB and LR asymmetries in e^+e^- annihilation near $s = M_Z^2$
  - FB asymmetries in pp ($p\bar{p}$) Drell-Yan around $m_{ll} = M_Z$

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

$\sin^2\theta_W(0)$: approaches

- tuning in on the Z resonance
  - FB and LR asymmetries in e^+e^- annihilation near s =
  - FB asymmetries in pp ($p\bar{p}$) Drell-Yan around m_{ll}



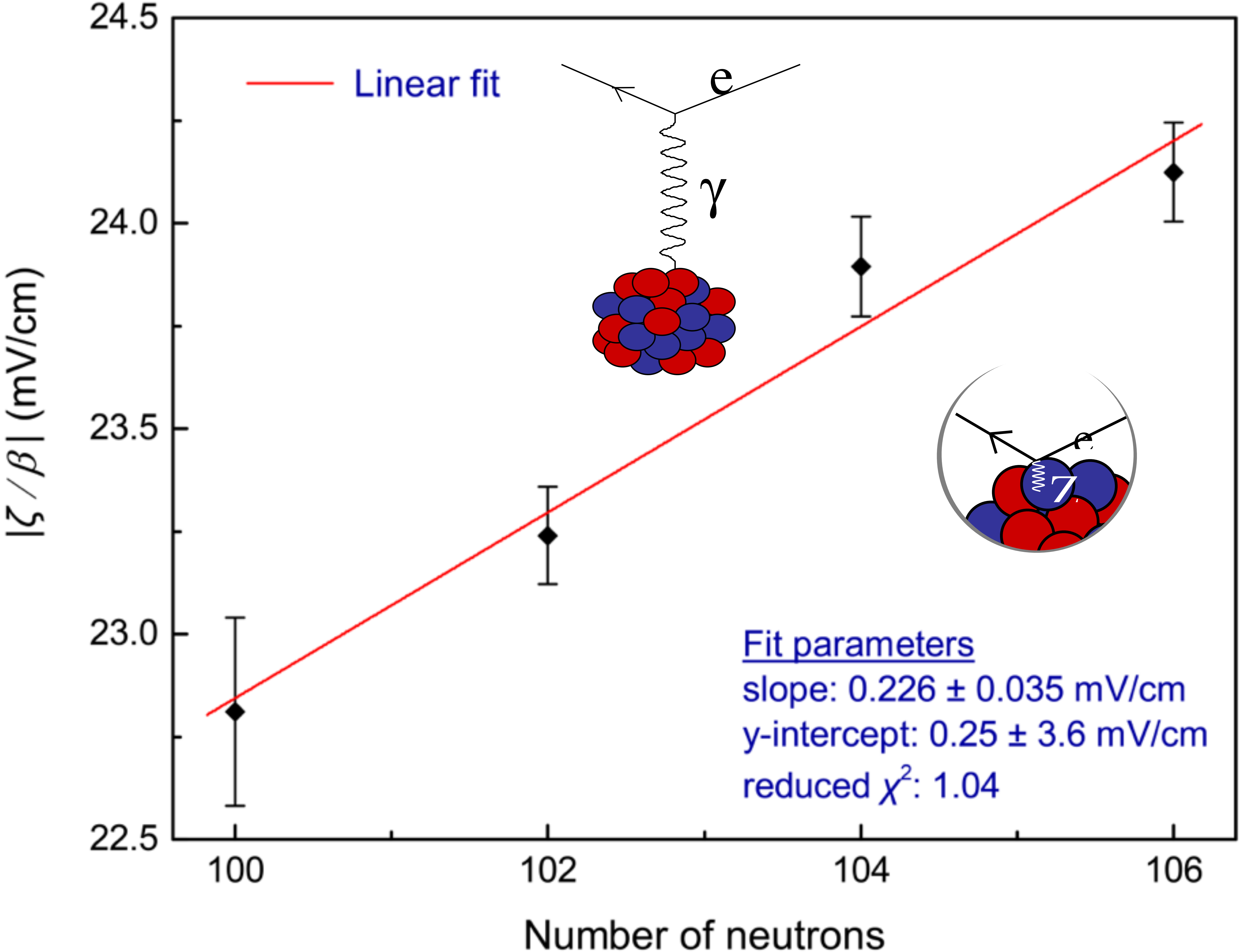
	ν scattering	PV
leptonic	$\nu_\mu - e^-$	$e^- - e^-$
DIS	heavy nuclei (NuTeV)	deuteron (PVDIS, SoLID)
elastic	CEvNS (COHERENT)	proton, ^{12}C (Qweak, P2)
APV	heavy alkali atoms and ions	isotope ratios (Mainz)

$\sin^2\theta_W(0)$: approaches

- tuning in on the Z resonance
  - FB and LR asymmetries in e^+e^- anni... $s = M$...
  - FB asymmetries in pp (p... ...an around m_{ll} = ...

very recent first measurements

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

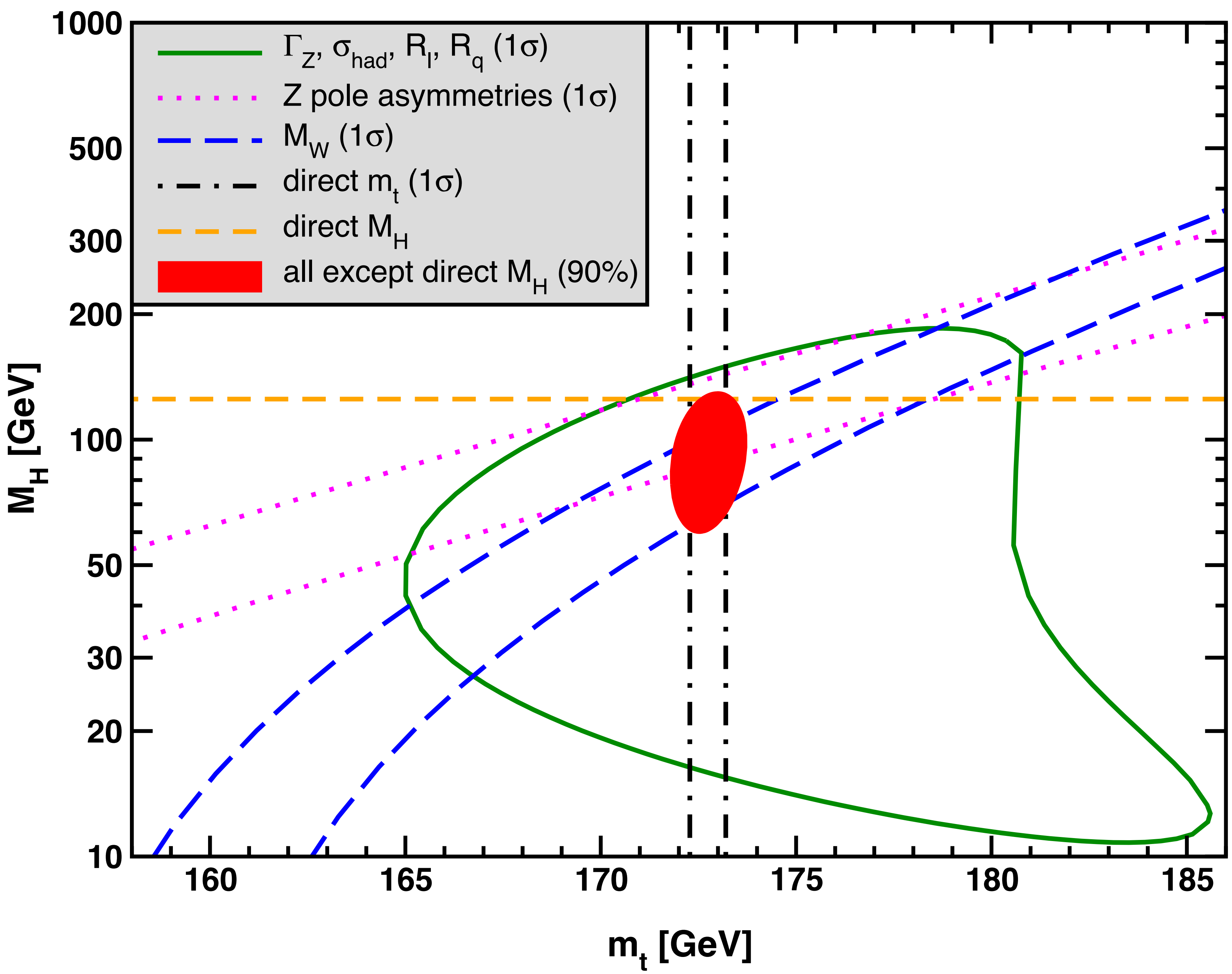


Linear fit
e
γ
e
γ
Fit parameters
slope: 0.226 ± 0.035 mV/cm
y-intercept: 0.25 ± 3.6 mV/cm
reduced χ²: 1.04
24.5
24.0
23.5
23.0
22.5
|ζ / β| (mV/cm)
100
102
104
106
Number of neutrons

Weak mixing angle: complementarity

- $M_W \leftrightarrow \sin^2\theta_W \leftrightarrow G_F$: high precision tests of electroweak symmetry breaking (doubly over-constrained after Higgs discovery)
- Z pole ↔ low energy: new physics in loops (Z couplings) ↔ at tree level (e.g. Z′ bosons or new operators)
- high ↔ low energy: running weak mixing angle
- ^{12}C & APV (single) ↔ p & APV (ratios): low energy running, S ↔ T
- all: cross-check of systematic and theoretical uncertainty estimates (keeps everyone honest)

$M_H - m_t$



indirect m_t:
176.4 ± 1.8 GeV
(2.0 σ high)

indirect M_H:
90^{+17}_{-15} GeV
(1.9 σ low)

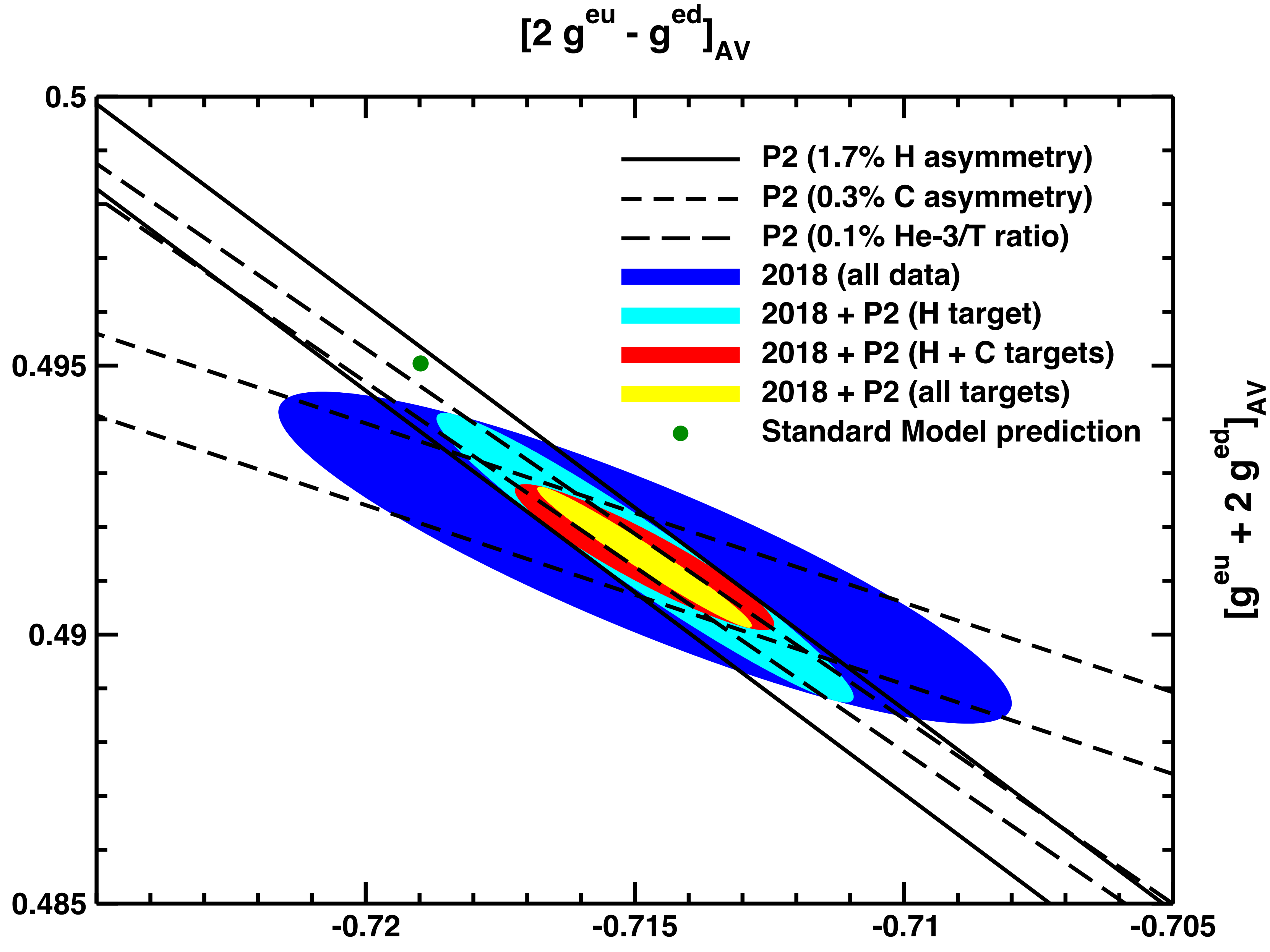
incl. theory error:

indirect M_H:
91^{+18}_{-16} GeV
(1.8 σ low)

Weak mixing angle: complementarity

- **$M_W \leftrightarrow \sin^2\theta_W \leftrightarrow G_F$:** high precision tests of electroweak symmetry breaking (doubly over-constrained after Higgs discovery)
- **Z pole ↔ low energy:** new physics in loops (**Z** couplings) ↔ at tree level (e.g. **Z′** bosons or new operators)
- **high ↔ low energy:** running weak mixing angle
- **^{12}C & APV (single) ↔ p & APV (ratios):** low energy running, **S** ↔ **T**
- **all:** cross-check of systematic and theoretical uncertainty estimates (keeps everyone honest)

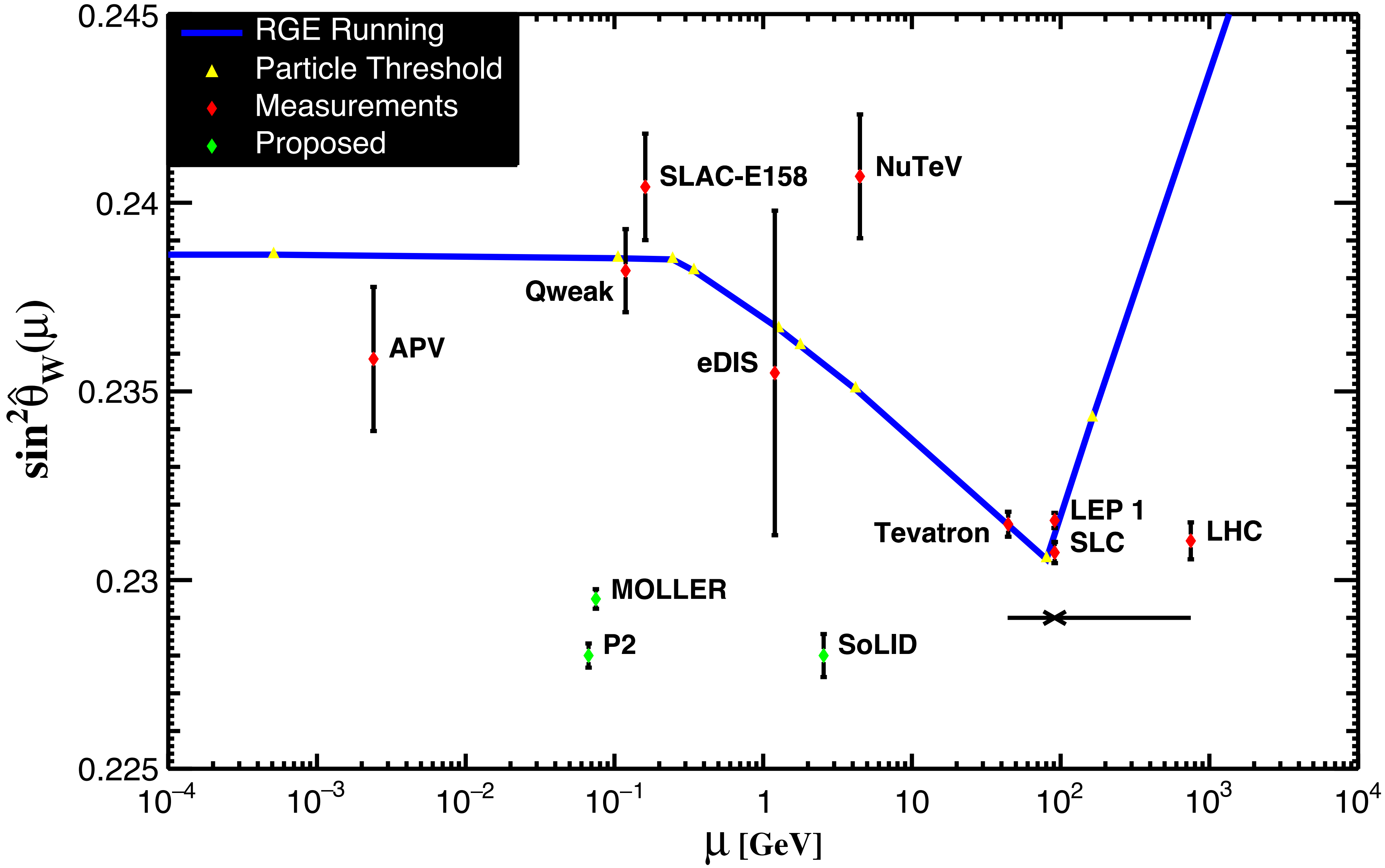
Effective couplings



Weak mixing angle: complementarity

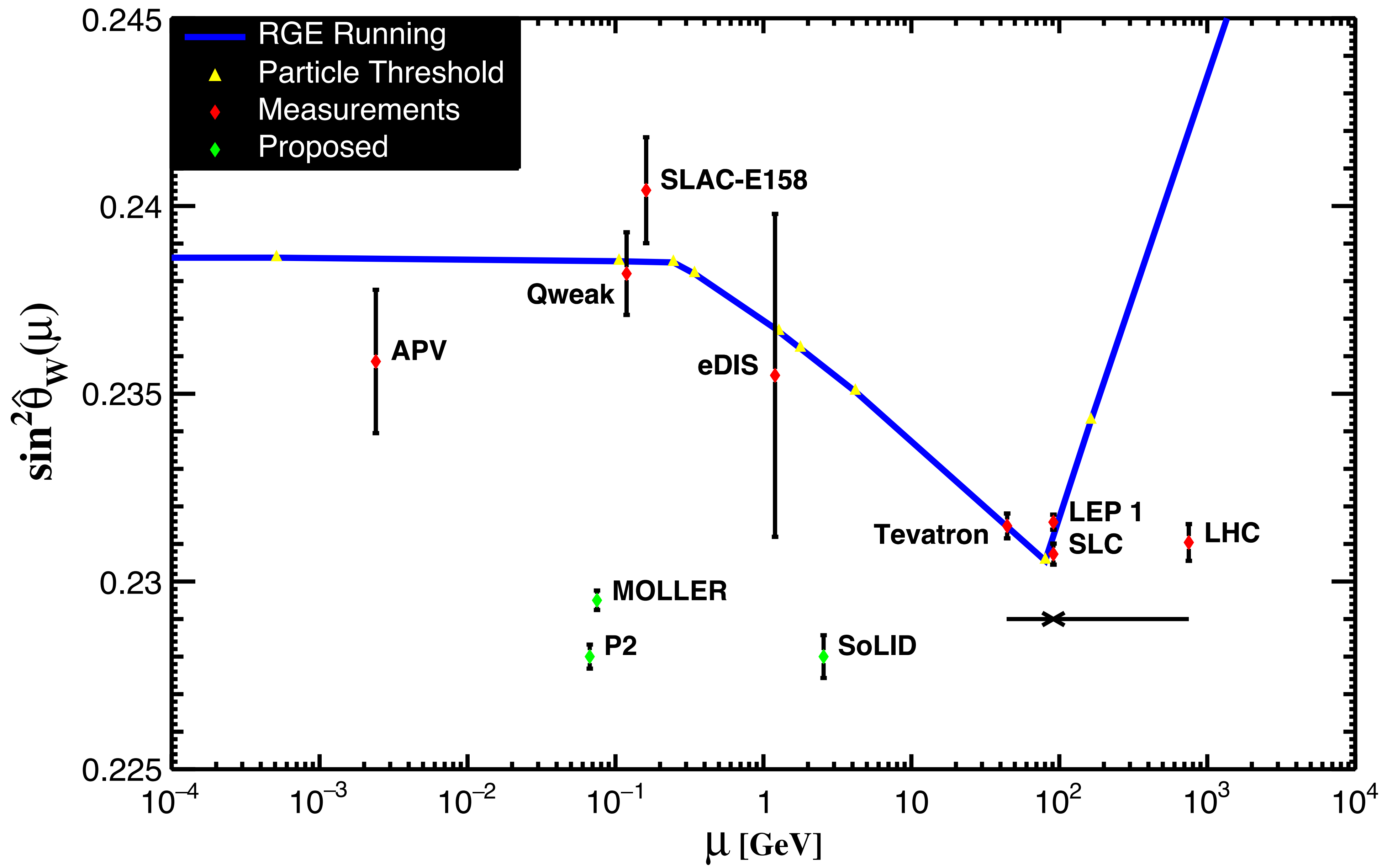
- **$M_W \leftrightarrow \sin^2\theta_W \leftrightarrow G_F$:** high precision tests of electroweak symmetry breaking (doubly over-constrained after Higgs discovery)
- **Z pole ↔ low energy:** new physics in loops (**Z** couplings) ↔ at tree level (e.g. **Z′** bosons or new operators)
- **high ↔ low energy:** running weak mixing angle
- **^{12}C & APV (single) ↔ p & APV (ratios):** low energy running, **S** ↔ **T**
- **all:** cross-check of systematic and theoretical uncertainty estimates (keeps everyone honest)

$\sin^2\theta_W(\mu)$



Ferro-Hernández & JE, JHEP 03 (2018)

$\sin^2\theta_W(\mu)$

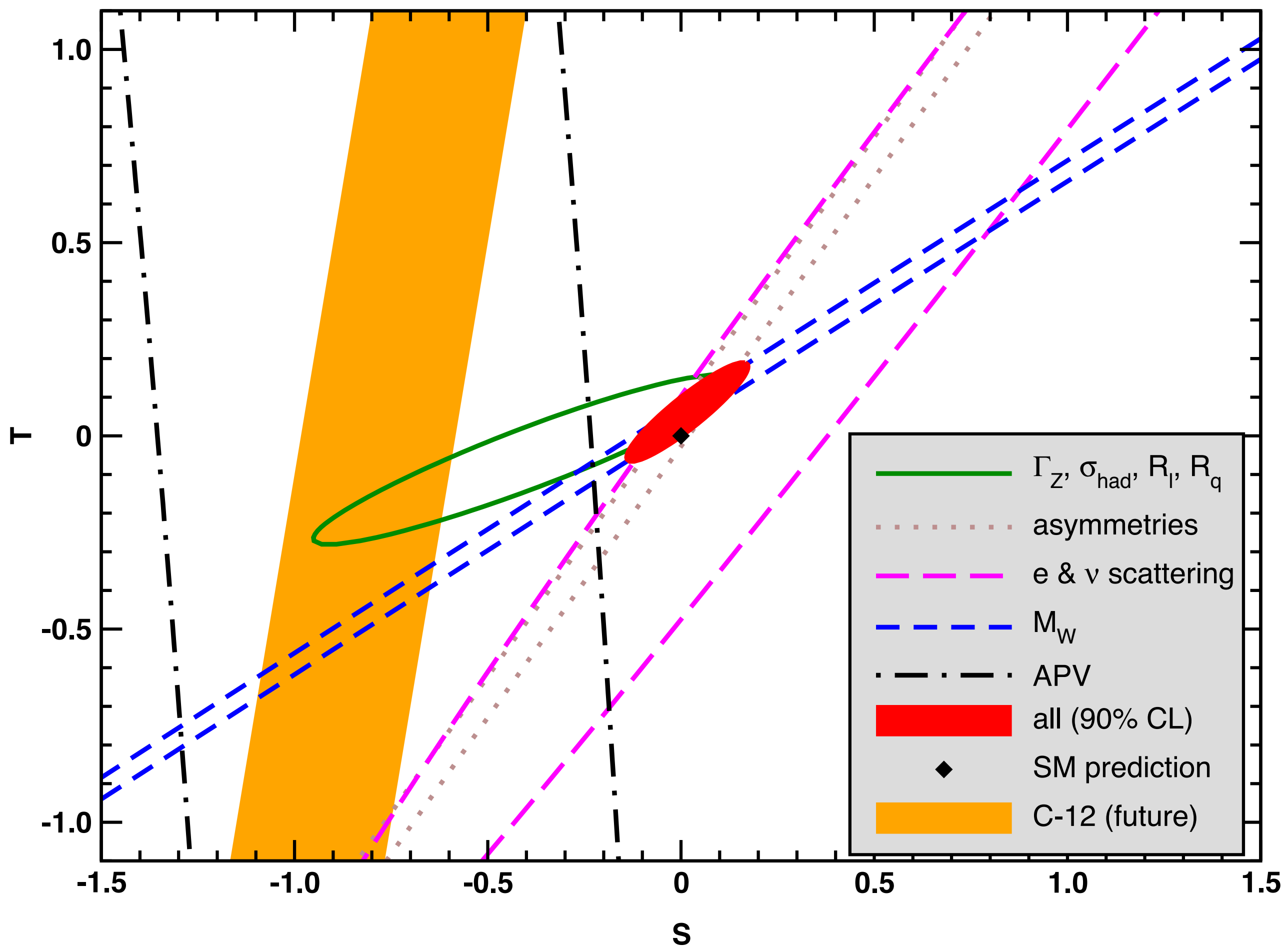


Ferro-Hernández & JE, JHEP 03 (2018)

Weak mixing angle: complementarity

- **$M_W \leftrightarrow \sin^2\theta_W \leftrightarrow G_F$:** high precision tests of electroweak symmetry breaking (doubly over-constrained after Higgs discovery)
- **Z pole ↔ low energy:** new physics in loops (**Z** couplings) ↔ at tree level (e.g. **Z′** bosons or new operators)
- **high ↔ low energy:** running weak mixing angle
- **^{12}C & APV (single) ↔ p & APV (ratios):** low energy running, **S** ↔ **T**
- **all:** cross-check of systematic and theoretical uncertainty estimates (keeps everyone honest)

S and T



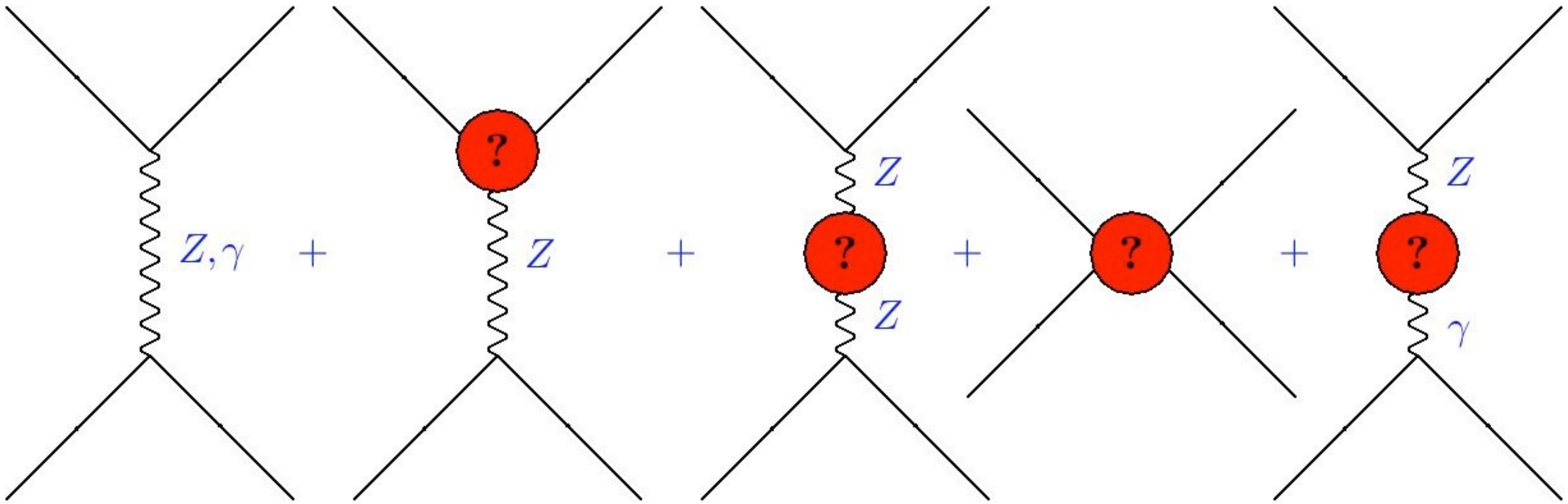
S	0.02 ± 0.07
T	0.06 ± 0.06
$\Delta\chi^2$	– 4.2

- $M_{KK} \gtrsim 3.2$ TeV in warped extra dimension models
- $M_V \gtrsim 4$ TeV in minimal composite Higgs models ***Freitas & JE, PDG (2018)***

Weak mixing angle: complementarity

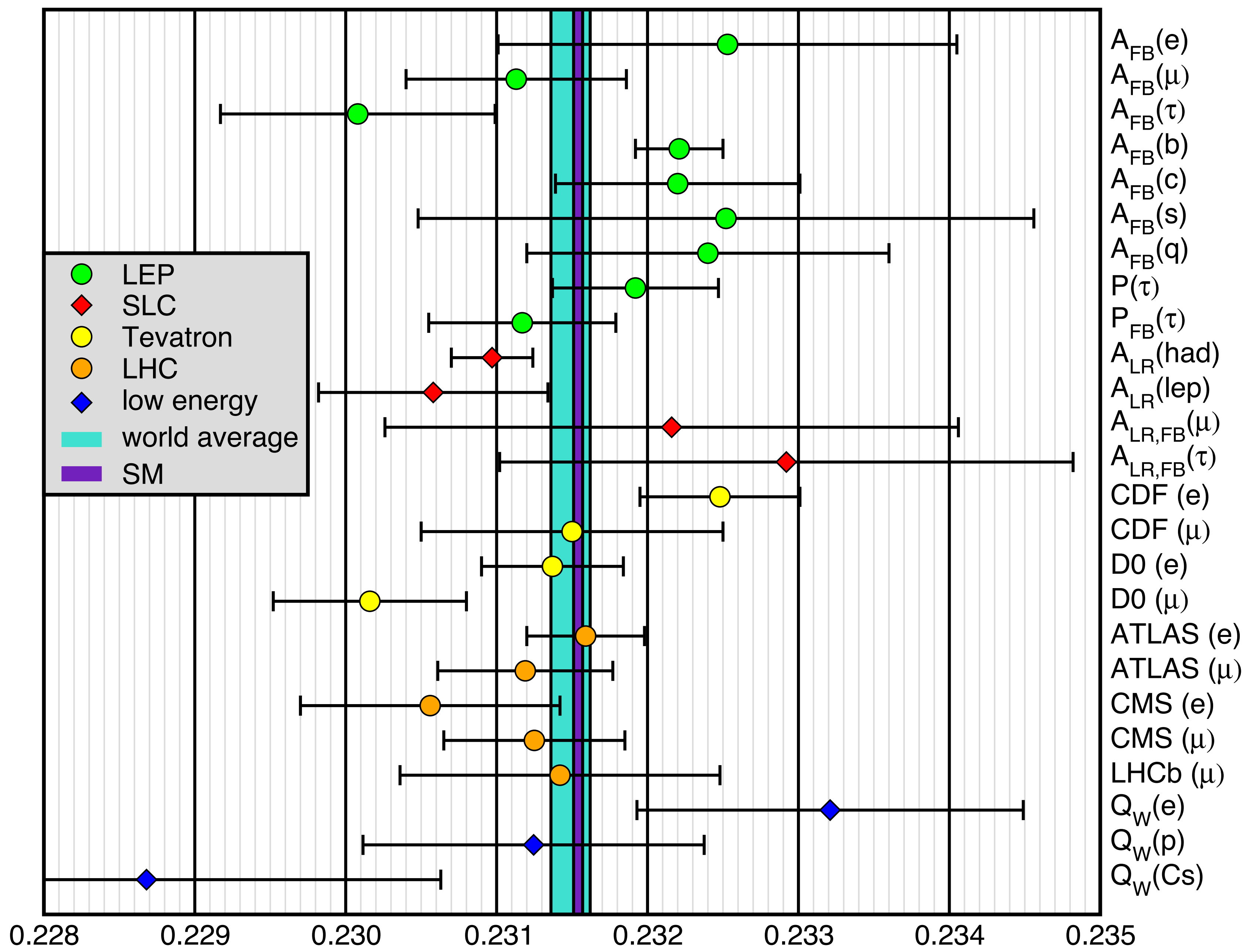
- $M_W \leftrightarrow \sin^2\theta_W \leftrightarrow G_F$: high precision tests of electroweak symmetry breaking (doubly over-constrained after Higgs discovery)
- Z pole ↔ low energy: new physics in loops (Z couplings) ↔ at tree level (e.g. Z′ bosons or new operators)
- high ↔ low energy: running weak mixing angle
- ^{12}C & APV (single) ↔ p & APV (ratios): low energy running, S ↔ T
- all: cross-check of systematic and theoretical uncertainty estimates (keeps everyone honest)

$\sin^2\theta_W$ beyond the SM



- Z-Z′ mixing: modification of Z vector coupling
- oblique parameters: STU (also need M_W and Γ_Z)
- new amplitudes: off- versus on-Z pole measurements (e.g. Z′)
- dark Z: renormalization group evolution (running)

$\sin^2\theta_W$ measurements



LEP & SLC:

0.23153 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23131 ± 0.00033

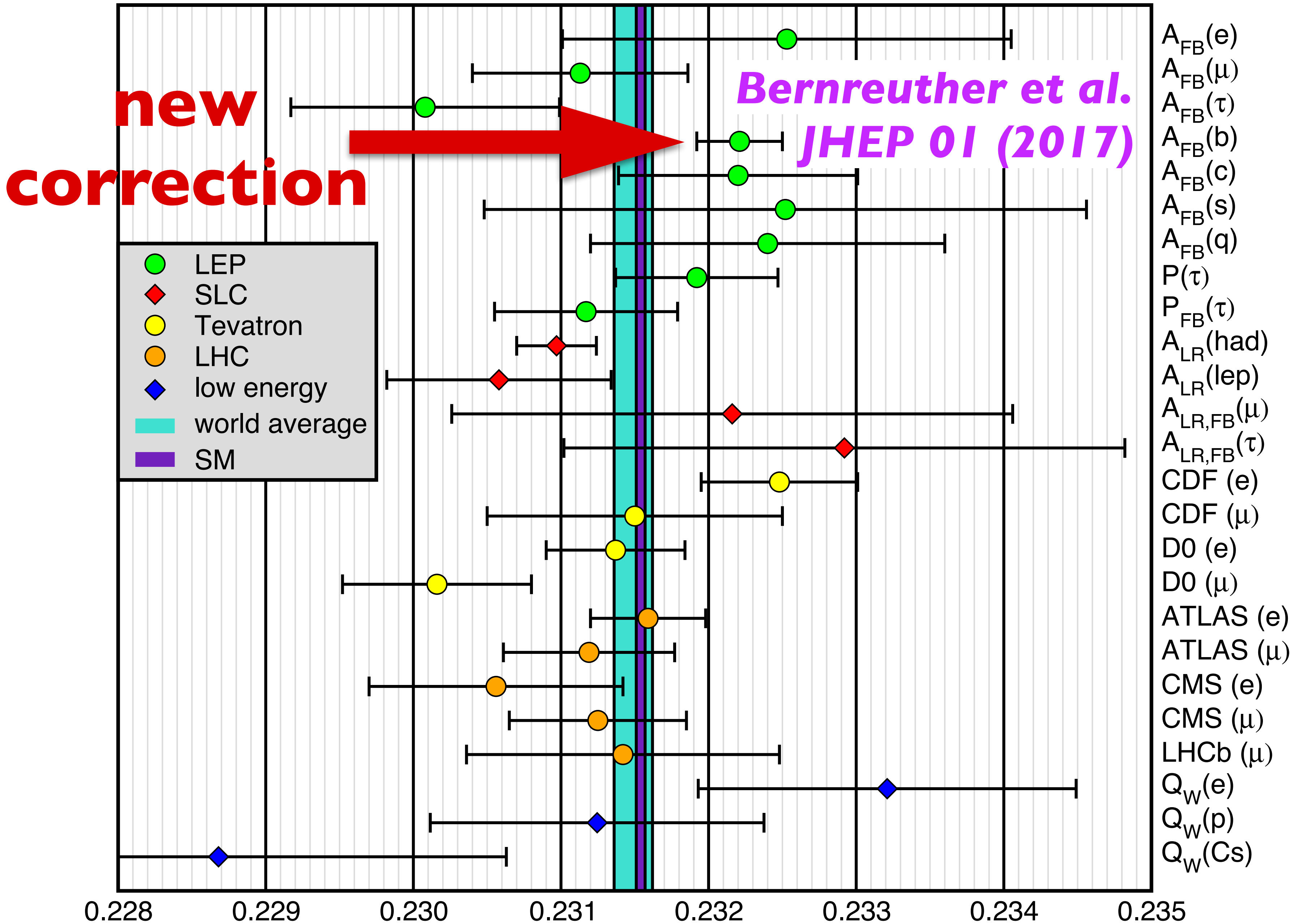
average direct

0.23149 ± 0.00013

global fit

0.23153 ± 0.00004

$\sin^2\theta_W$ measurements



LEP & SLC:

0.23153 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23131 ± 0.00033

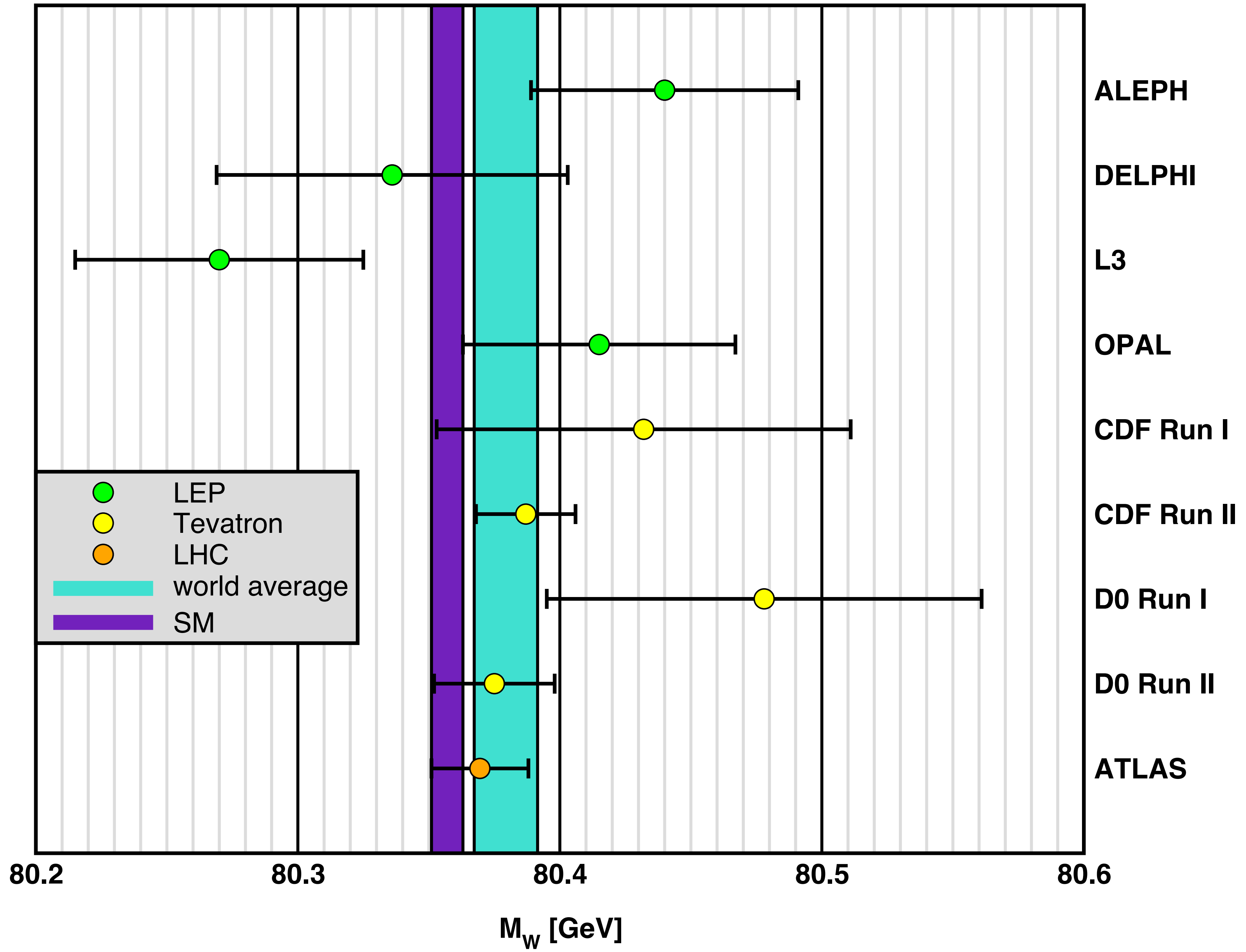
average direct

0.23149 ± 0.00013

global fit

0.23153 ± 0.00004

M_W measurements



average direct

80.379 ± 0.012 GeV

indirect

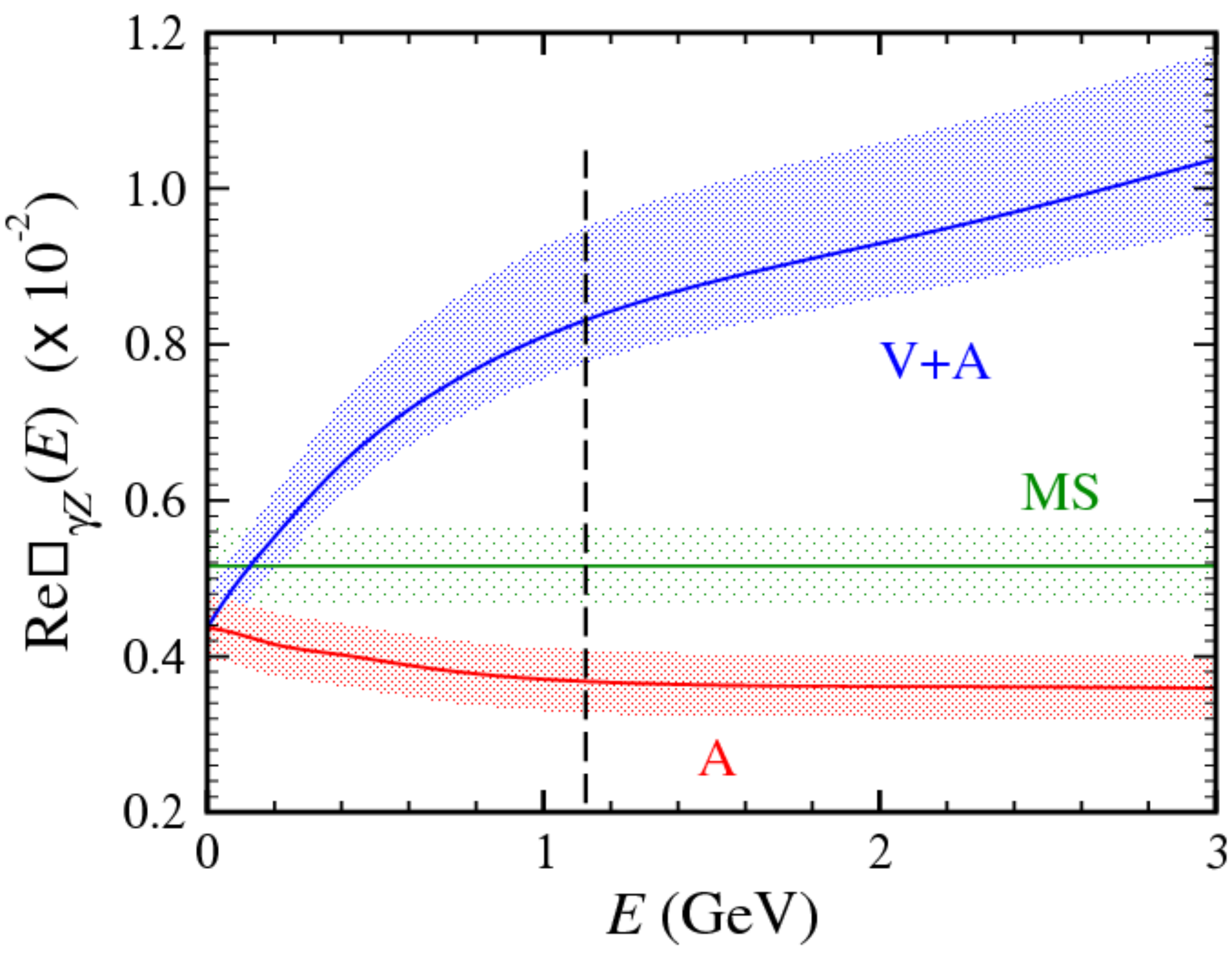
80.357 ± 0.006 GeV

(incl. correlated theory errors)

Theoretical uncertainties: correlations in precision observables

Theory issues in PVES

- need full 1-loop QED under experiment-specific conditions
- box diagrams (γZ-box)
- enhanced 2-loop electroweak (γWW-double box)
- running mixing angle (see later)
- unknown neutron distribution (neutron skin)



Theory issues for W & Z self-energies

- loop factors including enhancement factors such as $N_C = N_F = 3$ or $\sin^{-2}\theta_W \approx m_t^2/M_W^2 \approx 4$ amount to
  - 0.020 (QED)
  - 0.116 (QCD)
  - 0.032 (CC)
  - 0.029 (NC)
- parametrized by
  - $\Delta S_Z = \pm 0.0034$ (may be combined with $\Delta\alpha_{had}$),
  - $\Delta T = \pm 0.0073$ (t-b doublet)
  - $\Delta U = S_W - S_Z = \pm 0.0051$
- assuming ΔS_Z, ΔT and ΔU to be sufficiently different (uncorrelated) induces theory correlations between different observables **Schott & JE, PPNP 106 (2019)**

Vacuum polarizations in global fits:

$\alpha(M_Z)$ $\sin^2\theta_W(0)$ $g_\mu - 2$ $m_{b,c}$

$\alpha(M_Z)$

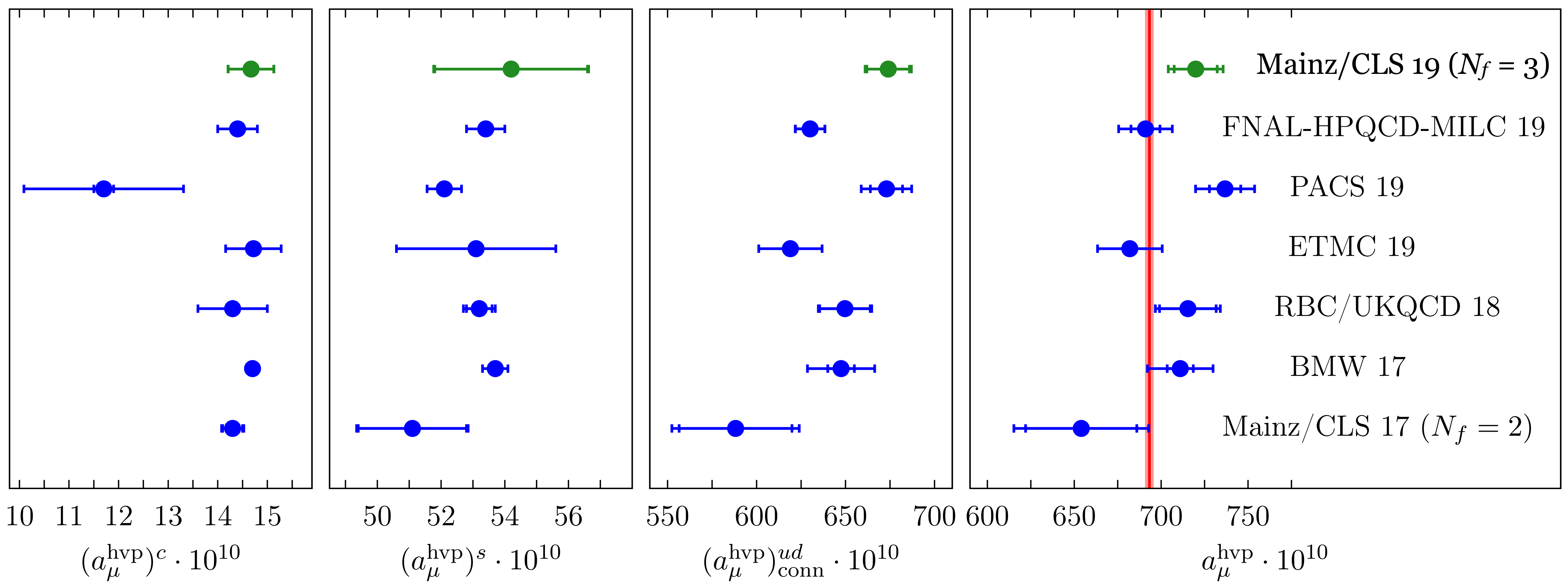
- Dispersive approach: integral over $\sigma(e^+e^- \to$ hadrons) and τ-decay data
- $\alpha^{-1}(M_Z) = 128.947 \pm 0.012$ ***Davier et al., EPJC 77 (2017)***
- $\alpha^{-1}(M_Z) = 128.958 \pm 0.016$ ***Jegerlehner, arXiv:1711.06089***
- $\alpha^{-1}(M_Z) = 128.946 \pm 0.015$ ***Keshavarzi et al., PRD 97 (2018)***
- $\alpha^{-1}(M_Z) = 128.949 \pm 0.010$ ***Ferro-Hernández & JE, JHEP 03 (2018)***
  - This value is converted from the $\overline{MS}$ scheme and uses both e^+e^- annihilation and τ decay spectral functions
    Davier et al., EPJC 77 (2017)
  - PQCD for $\sqrt{s} > 2$ GeV (using $\bar{m}_c$ & $\bar{m}_b$)
- (anti)correlation with $g_\mu - 2$ at two (three) loop order and with $\sin^2\theta_W(0)$

$g_\mu - 2$

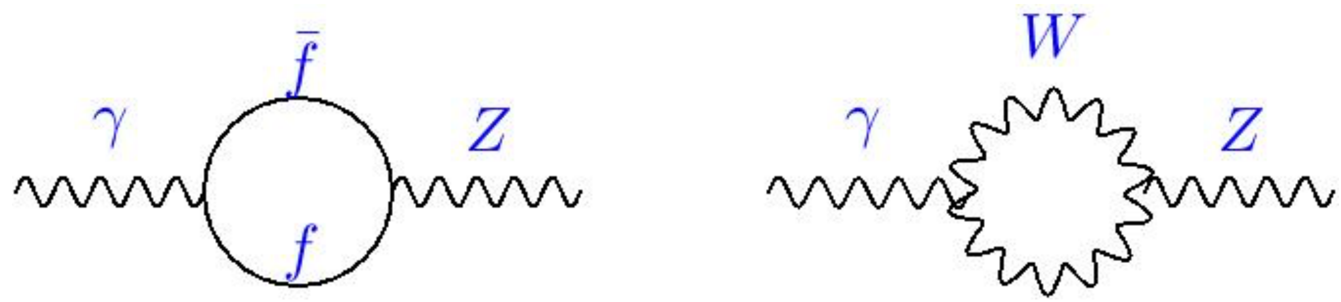
PQCD: *Luo & JE, PRL 87 (2001)*

$(a_\mu^{hvp})^c = (14.6 \pm 0.5_{theory} \pm 0.2_{mc} \pm 0.1_{\alpha s})\times 10^{-10}$ $(a_\mu^{hvp})^b = 0.3\times 10^{-10}$

Lattice gauge theory: *A. Gérardin et al., arXiv:1904.03120*



$\sin^2\theta_W(0)$ and $\Delta\alpha(M_Z)$



$$\mu^2 \frac{d\hat{v}_f}{d\mu^2} = \frac{\hat{\alpha} Q_f}{24\pi} \left[\sum_i K_i \gamma_i \hat{v}_i Q_i + 12\sigma \left(\sum_q Q_q \right) \left(\sum_q \hat{v}_q \right) \right]$$

$$\mu^2 \frac{d\hat{\alpha}}{d\mu^2} = \frac{\hat{\alpha}^2}{\pi} \left[\frac{1}{24} \sum_i K_i \gamma_i Q_i^2 + \sigma \left(\sum_q Q_q \right)^2 \right]$$

- coupled system of differential equations ***Ramsey-Musolf & JE, PRD 72 (2005)***
- $\Delta\alpha(M_Z)_{had}$ errors in $\sin^2\theta_W(0) = \kappa(0) \sin^2\theta_W(M_Z)$ add since $M_Z^2 \propto g_Z^2(M_Z)\, v^2 \propto [\alpha / s^2_W\, c^2_W](M_Z)\, G_F^{-1}$

$\sin^2\theta_W(0)$: result

source	uncertainty in $\sin^2\theta_W(0)$
$\Delta\alpha^{(3)}(2\text{ GeV})$	1.2×10^{-5}
flavor separation	1.0×10^{-5}
isospin breaking	0.7×10^{-5}
singlet contribution	0.3×10^{-5}
PQCD	0.6×10^{-5}
Total	1.8×10^{-5}

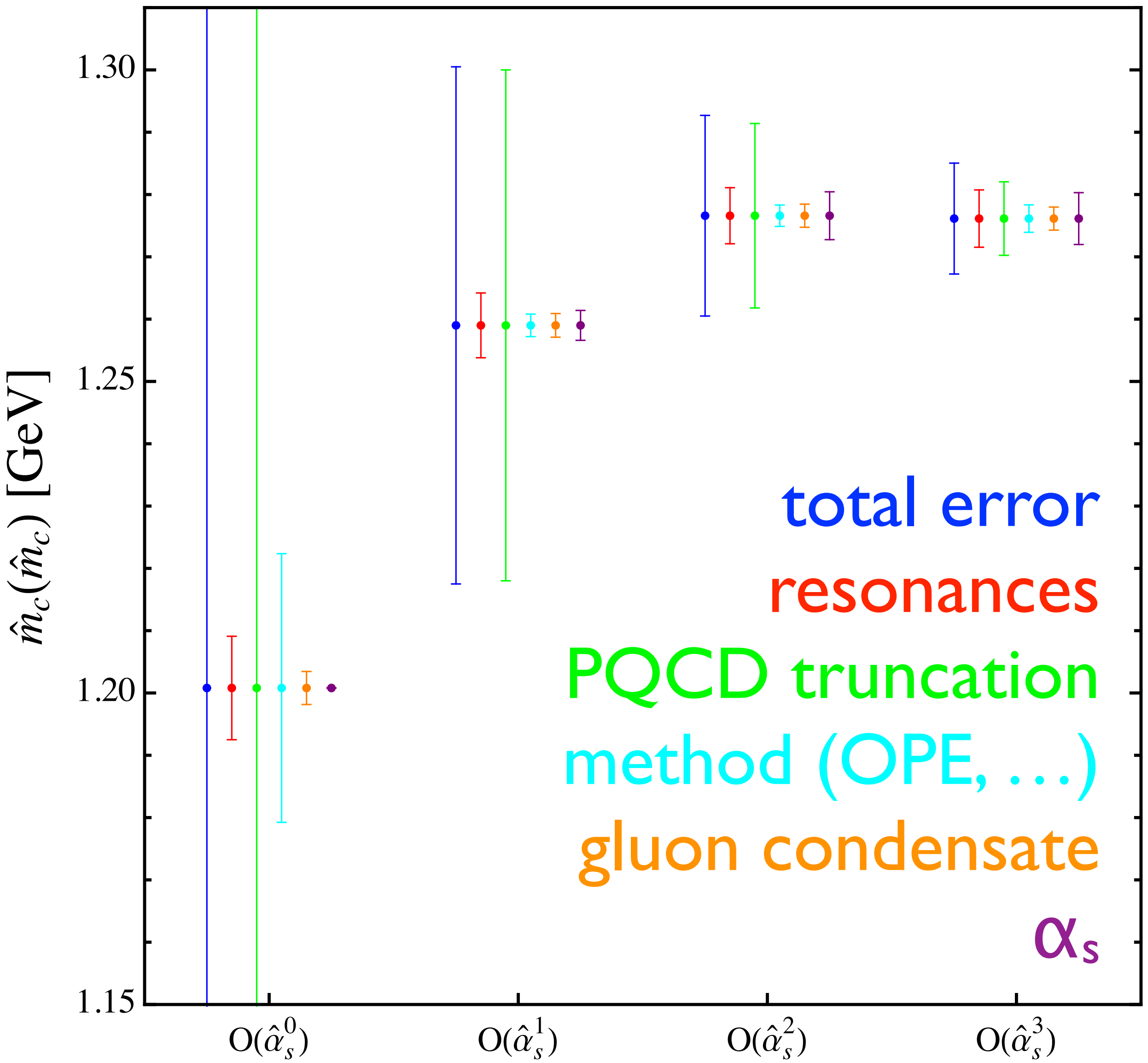
➡ $\sin^2\theta_W(0) = 0.23861 \pm 0.00005_{\text{Z-pole}} \pm 0.00002_{\text{theory}} \pm 0.00001_{\alpha_s}$

Ferro-Hernández & JE, JHEP 03 (2018); Freitas & JE, PDG (2018)

errors from m_c and m_b negligible, because…

$\overline{m}_c(\overline{m}_c)$

- derived from another set of dispersion integrals
- input: electronic widths of J/ψ and ψ(2S)
- continuum contribution from self-consistency between sum rules



- $\overline{m}_c(\overline{m}_c)$ = 1272 ± 8 + 2616 [$\overline{\alpha}_s(M_Z)$ – 0.1182] MeV

Masjuan, Spiesberger & JE, EPJC 77 (2017)

Fit Results

Performed with package GAPP
(Global Analysis of Particle Properties)

Standard global fit

M_H	125.14 ± 0.15 GeV
M_Z	91.1884 ± 0.0020 GeV
$\overline{m}_b(\overline{m}_b)$	4.180 ± 0.021 GeV
$\Delta\alpha_{had}^{(3)}(2\text{ GeV})$	$(59.0 \pm 0.5)\times10^{-4}$

$\overline{m}_t(\overline{m}_t)$	163.28 ± 0.44 GeV	1.00	–0.13	–0.28
$\overline{m}_c(\overline{m}_c)$	1.275 ± 0.009 GeV	–0.13	1.00	0.45
$\alpha_S(M_Z)$	0.1187 ± 0.0016	–0.28	0.45	1.00

other correlations small

Freitas & JE, PDG 2018

ρ_0 fit

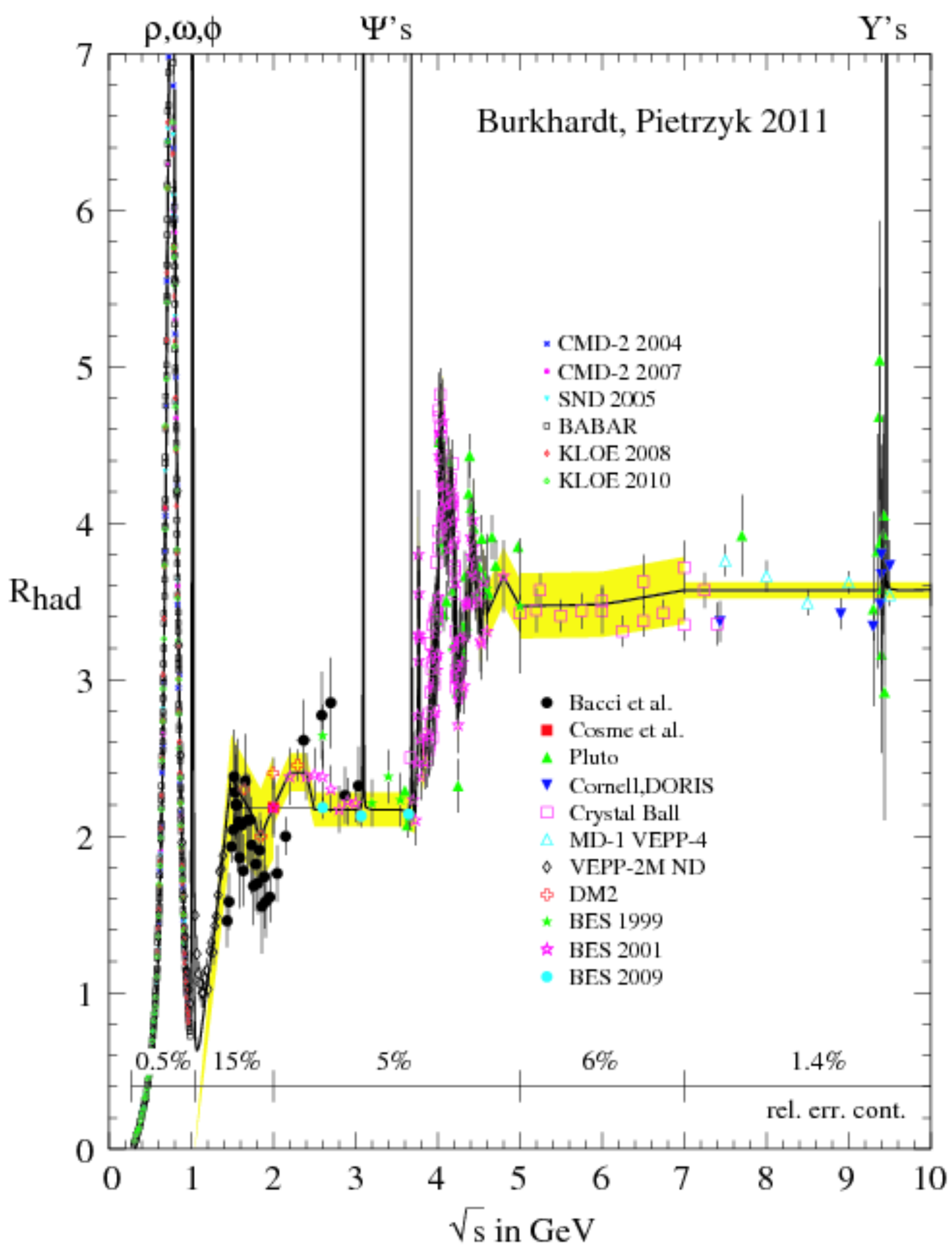
- $\Delta\rho_0 = G_F \sum_i C_i / (8\sqrt{2}\pi^2)\, \Delta m_i^2$
  - where $\Delta m_i^2 \geq (m_1 - m_2)^2$
  - despite appearance there is decoupling (see-saw type suppression of Δm_i^2)
- $\rho_0 = 1.00039 \pm 0.00019$ (2.0 σ)
  - $(16\text{ GeV})^2 \leq \sum_i C_i/3\, \Delta m_i^2 \leq (48\text{ GeV})^2$ @ 90% CL
  - Y = 0 Higgs triplet VEVs v_3 strongly disfavored ($\rho_0 < 1$)
  - consistent with |Y| = 1 Higgs triplets if $v_3 \sim 0.01\, v_2$

Conclusions and outlook

- LHC & low-energy experiments approaching LEP precision in **$\sin^2\theta_W$**
- new players:
  - coherent ν-scattering
  - ultra-high precision PVES
  - APV isotope ratios
- at ultra-high precision not only theoretical uncertainties are relevant, but also their correlations (hard to estimate)
  - example: vacuum polarization uncertainties enter correlated in an increasing number of quantities

Backups

m_c



- α(M_Z) and sin²θ_W(0): can use PQCD for heavy quark contribution if masses are known.
- g–2: c quark contribution to muon g–2 similar to γ×γ; ± 70 MeV uncertainty in m_c induces an error of $\pm 1.6 \times 10^{-10}$ comparable to the projected errors for the FNAL and J-PARC experiments.
- Yukawa coupling – mass relation (in single Higgs doublet SM): $\Delta m_b = \pm 9$ MeV and $\Delta m_c = \pm 8$ MeV to match precision from HiggsBRs @ FCC-ee
- QCD sum rule: $m_c = 1272 \pm 8$ MeV
  Masjuan, Spiesberger & JE, EPJC 77 (2017)
  (expect about twice the error for m_b)

m_t measurements

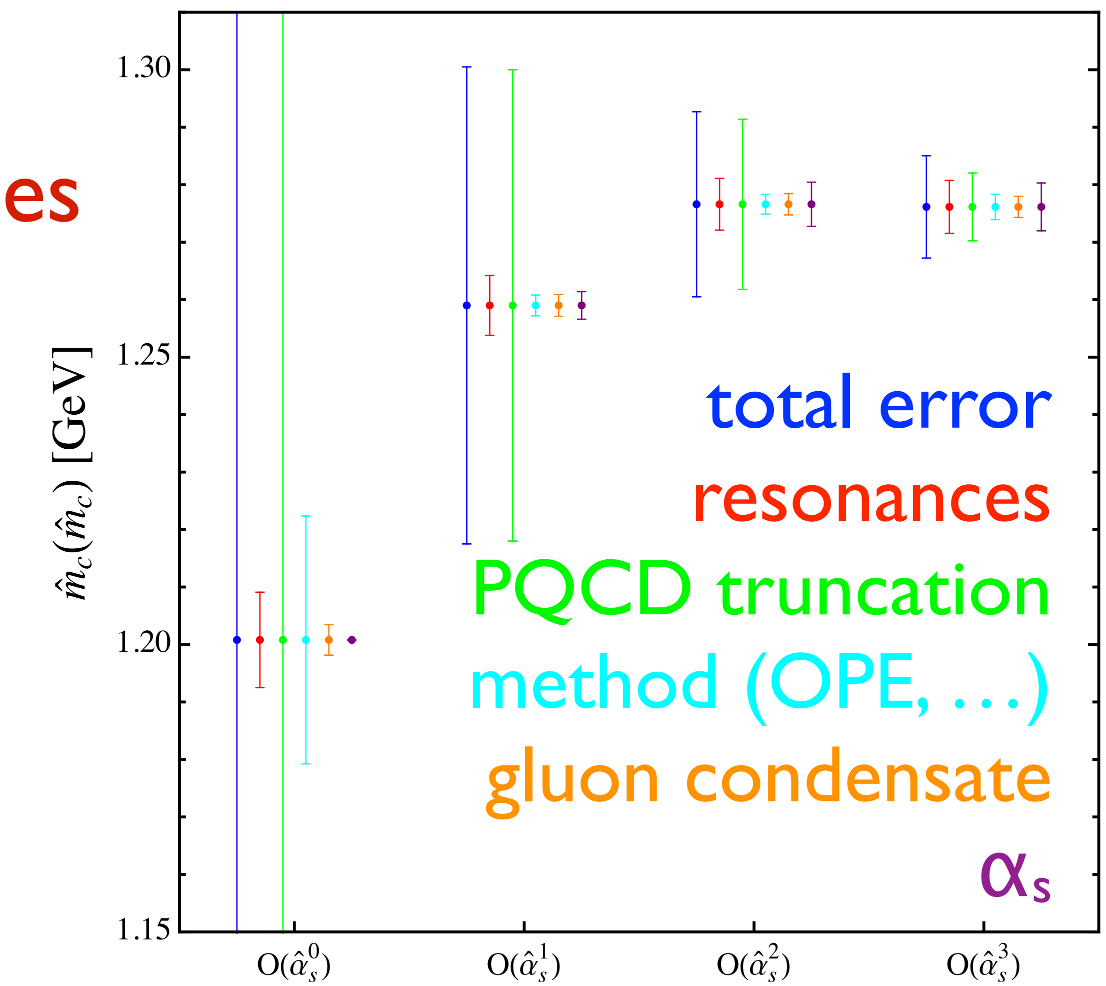
	central	statistical	systematic	total
Tevatron	174.30	0.35	0.54	0.64
ATLAS	172.51	0.27	0.42	0.50
CMS	172.43	0.13	0.46	0.48
CMS Run 2	172.25	0.08	0.62	0.63
grand average	172.74	0.11	0.31	0.33

JE, EPJC 75 (2015)

- $m_t = 172.74 \pm 0.25_{uncorr.} \pm 0.21_{corr.} \pm 0.32_{QCD}$ GeV = 172.74 ± 0.46 GeV
- somewhat larger shifts and smaller errors conceivable in the future
  Butenschoen et al., PRL 117 (2016); Andreassen & Schwartz, JHEP 10 (2017)
- 2.8 σ discrepancy between lepton + jet channels from DØ and CMS Run 2
- indirectly from EW fit: $m_t = 176.4 \pm 1.8$ GeV (2 σ) *Freitas & JE (PDG 2018)*

Features of our approach

- only experimental input: electronic widths of J/ψ and ψ(2S)
- continuum contribution from self-consistency between sum rules
- include $\mathcal{M}_0$ → stronger (milder) sensitivity to continuum (m_c)
- quark-hadron duality needed only in finite region (not locally)



- $\overline{m}_c(\overline{m}_c) = 1272 \pm 8 + 2616\,[\overline{\alpha}_s(M_Z) - 0.1182]$ MeV

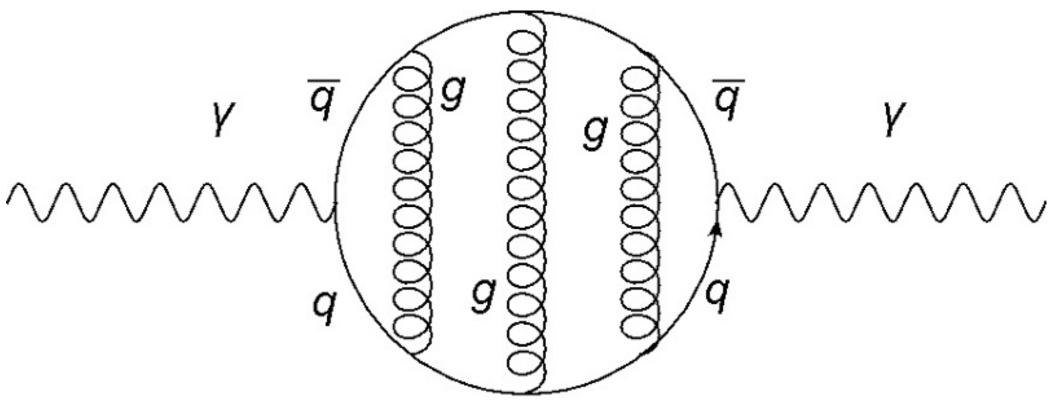
Masjuan, Spiesberger & JE, EPJC 77 (2017)

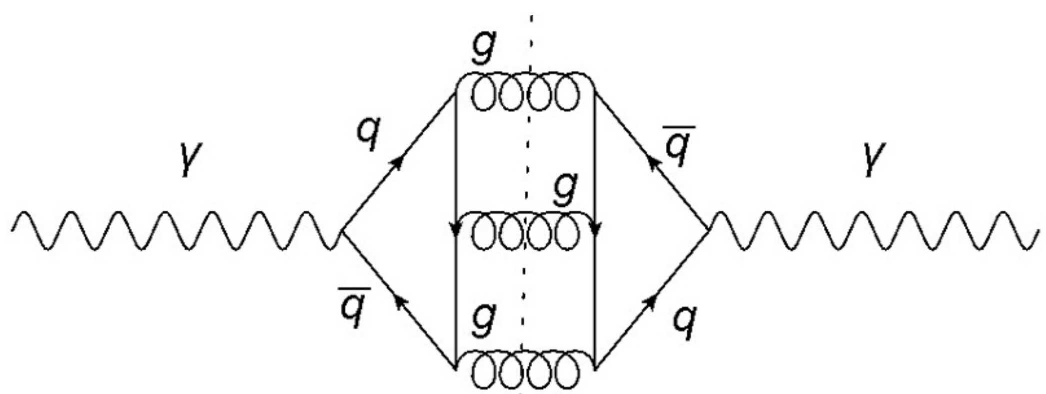
$\sin^2\theta_W(0)$: flavor separation

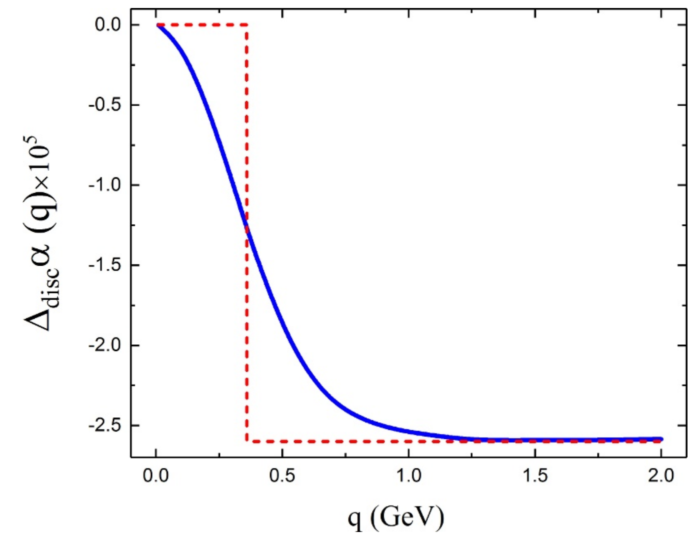
strange quark external current	ambiguous external current
Φ	$K\bar{K}$ (non – Φ)
$K\bar{K}\pi$ [almost saturated by $\Phi(1680)$]	$K\bar{K}2\pi$, $K\bar{K}3\pi$
$\eta\Phi$	$K\bar{K}\eta$, $K\bar{K}\omega$

- use of result for $\alpha(2\text{ GeV})$ also needs isolation of strange contribution $\Delta_s\alpha$
- left column assignment assumes OZI rule
- expect right column to originate mostly from strange current ($m_s > m_{u,d}$)
- quantify expectation using averaged $\Delta_s(g_\mu-2)$ from lattices as Bayesian prior
  RBC/UKQCD, JHEP 04 (2016); HPQCD, PRD 89 (2014)
- $\Delta_s\alpha(1.8\text{ GeV}) = (7.09 \pm 0.32)\times10^{-4}$ (threshold mass $\bar{m}_s = 342$ MeV $\approx \bar{m}_s^{disc}$)

$\sin^2\theta_W(0)$: singlet separation







Ferro-Hernández & JE, JHEP 03 (2018)

adapted from lattice g_μ–2 calculation

RBC/UKQCD, PRL 116 (2016)

- use of result for α(2 GeV) needs singlet piece isolation $\Delta_{disc}\,\alpha$(2 GeV)
- then $\Delta_{disc}\,\bar{s}^2 = (\bar{s}^2 \pm 1/20)\ \Delta_{disc}\,\alpha(2\text{ GeV}) = (-6 \pm 3)\times 10^{-6}$
- step function ⇒ singlet threshold mass $\bar{m}_s^{disc} \approx 350$ MeV

S fit

- S parameter rules out QCD-like technicolor models
- S also constrains extra degenerate fermion families:

➡ $N_F = 2.75 \pm 0.14$ (assuming $T = U = 0$)

- compare with $N_\nu = 2.991 \pm 0.007$ from Γ_Z

STU fit

$\sin^2\theta_W(M_Z)$	0.23113 ± 0.00014
$\alpha_S(M_Z)$	0.1189 ± 0.0016

S	0.02 ± 0.10	1.00	0.92	–0.66
T	0.07 ± 0.12	0.92	1.00	–0.86
U	0.00 ± 0.09	–0.66	–0.86	1.00

- $M_{KK} \gtrsim 3.2$ TeV in warped extra dimension models
- $M_V \gtrsim 4$ TeV in minimal composite Higgs models ***Freitas & JE (PDG 2018)***