Deutsche Forschungsgemeinschaft

PDG particle data group

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(on leave from IF-UNAM)

Precision electroweak physics with low energy measurements

Instituto de Física · UNAM 80 años 1938-2018

CONACYT Consejo Nacional de Ciencia y Tecnología

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

Complementary physics

High-energy precision tests

EW symmetry breaking

Collider searches

new particles & states

M_W
$\sin^2\theta_W$
Z & H properties
top quark properties

Low-energy precision tests

new amplitudes

Flavor physics

symmetries and conservation laws

polarized e^- scattering
ν scattering
atomic parity violation
lepton properties

Outline

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

Weak Mixing Angle

Weak mixing angle at tree level

doubly over-constrained system

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

$$M_W = \frac{g}{2} v \Longrightarrow \sin^2\theta_W = \frac{\pi\alpha(M_W)}{\sqrt{2} G_F M_W^2} \Longrightarrow \theta_W = 28.68^\circ$$

$$M_Z^2 = \frac{g^2 + g'^2}{2} v^2 \Longrightarrow \sin^2 2\theta_W = \frac{\sqrt{8}\pi\alpha(M_Z)}{G_F M_Z^2} \Longrightarrow \theta_W = 28.90^\circ$$

$$\theta_W = \arccos\frac{M_W}{M_Z} = 28.18^\circ$$

only 1 relation if $\alpha(M_Z)$ would not be known (currently induces 3 MeV error)

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

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

Weak mixing angle approaches

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recent first measurements

	ν scattering	[illegible] 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)
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Coherent Elastic ν Nucleus Scattering (CEνNS)

COHERENT @ SNS

CsI

$E_\nu \approx 16 - 53$ MeV

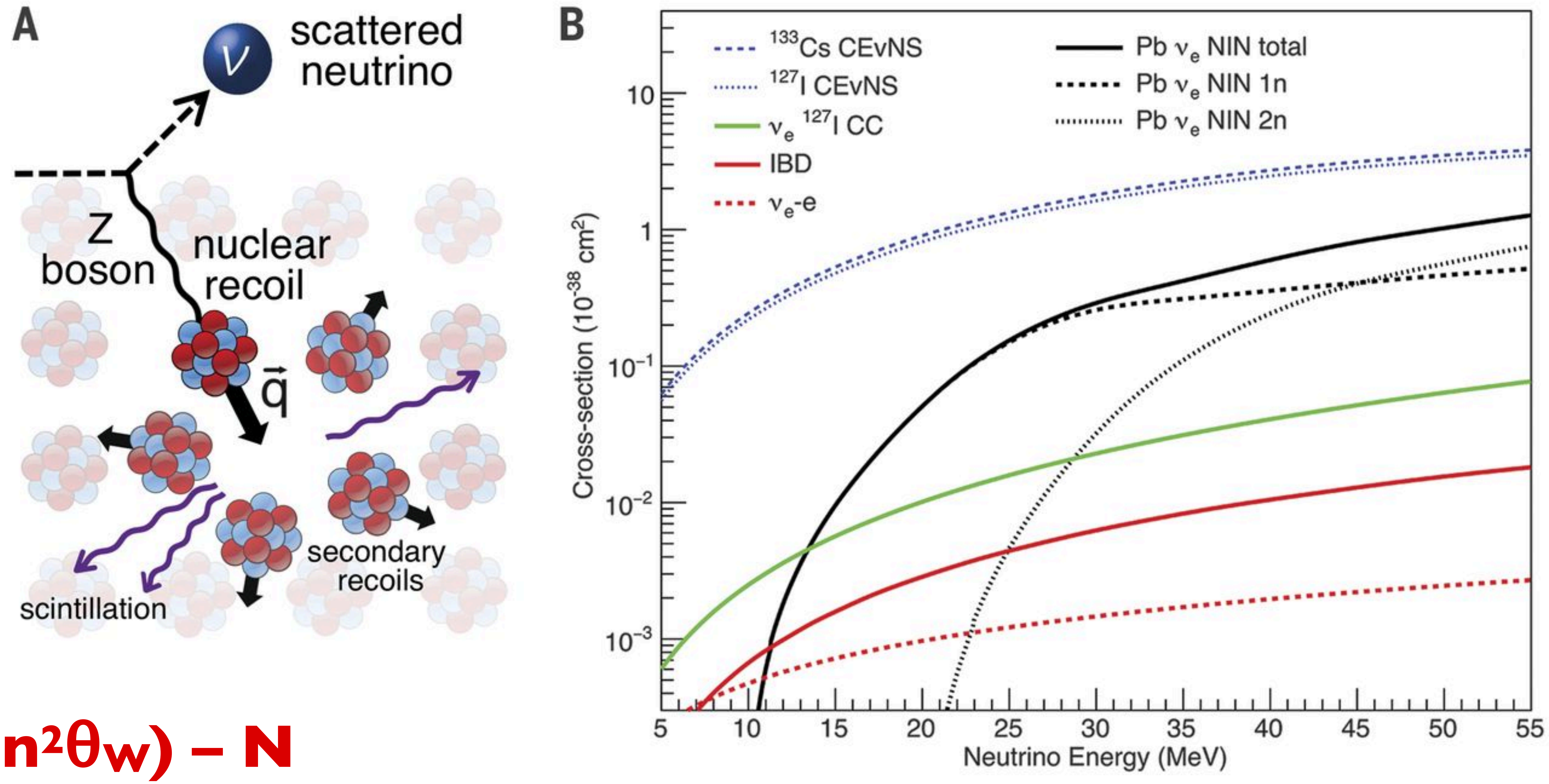
$\sigma \sim Q_W^2$

134 ± 22 events

constraints on NSI

neutron skin?

arXiv:1708.01294



$$Q_W(N,Z) = Z\,(1 - 4\sin^2\theta_W) - N$$

Atomic parity violation in an isotope chain

AG Budker @ JGU Mainz

Ytterbium

^{170}Yb – ^{176}Yb

± 0.5% per isotope

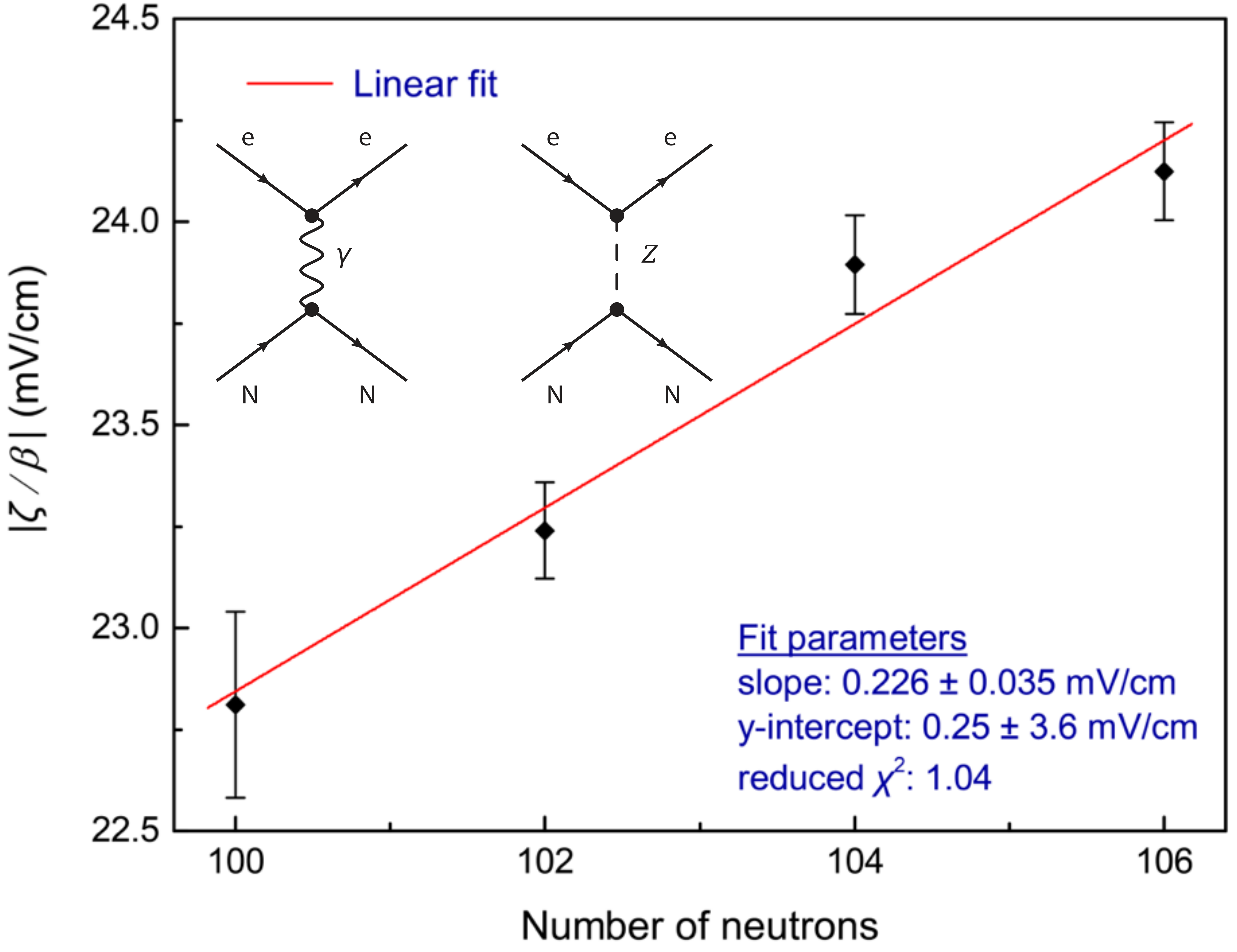
± 100% error in $\sin^2\theta_W$

constraints on Z´ with M < 100 keV

$\Delta\sin^2\theta_W$ = ± 0.2

neutron skin?

arXiv:1804.05747



Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1165 MeV

$|Q|$ = 158 MeV

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

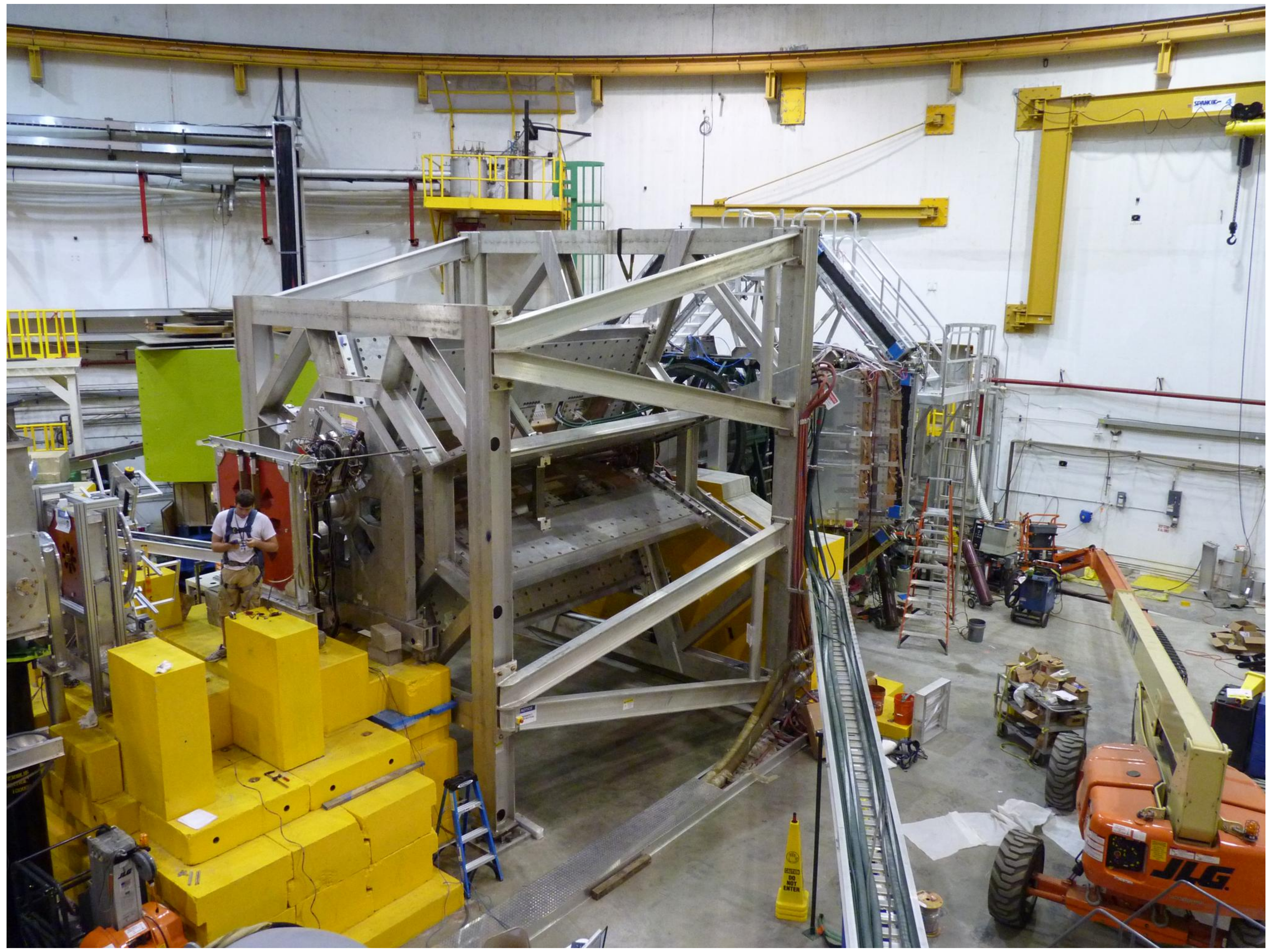
$\Delta A_{PV} = \pm\ 4.1\%$

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

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

FFs from fit to ep asymmetries

arXiv:1905.08283



Parity Violating e⁻ Scattering (PVES) — Elastic

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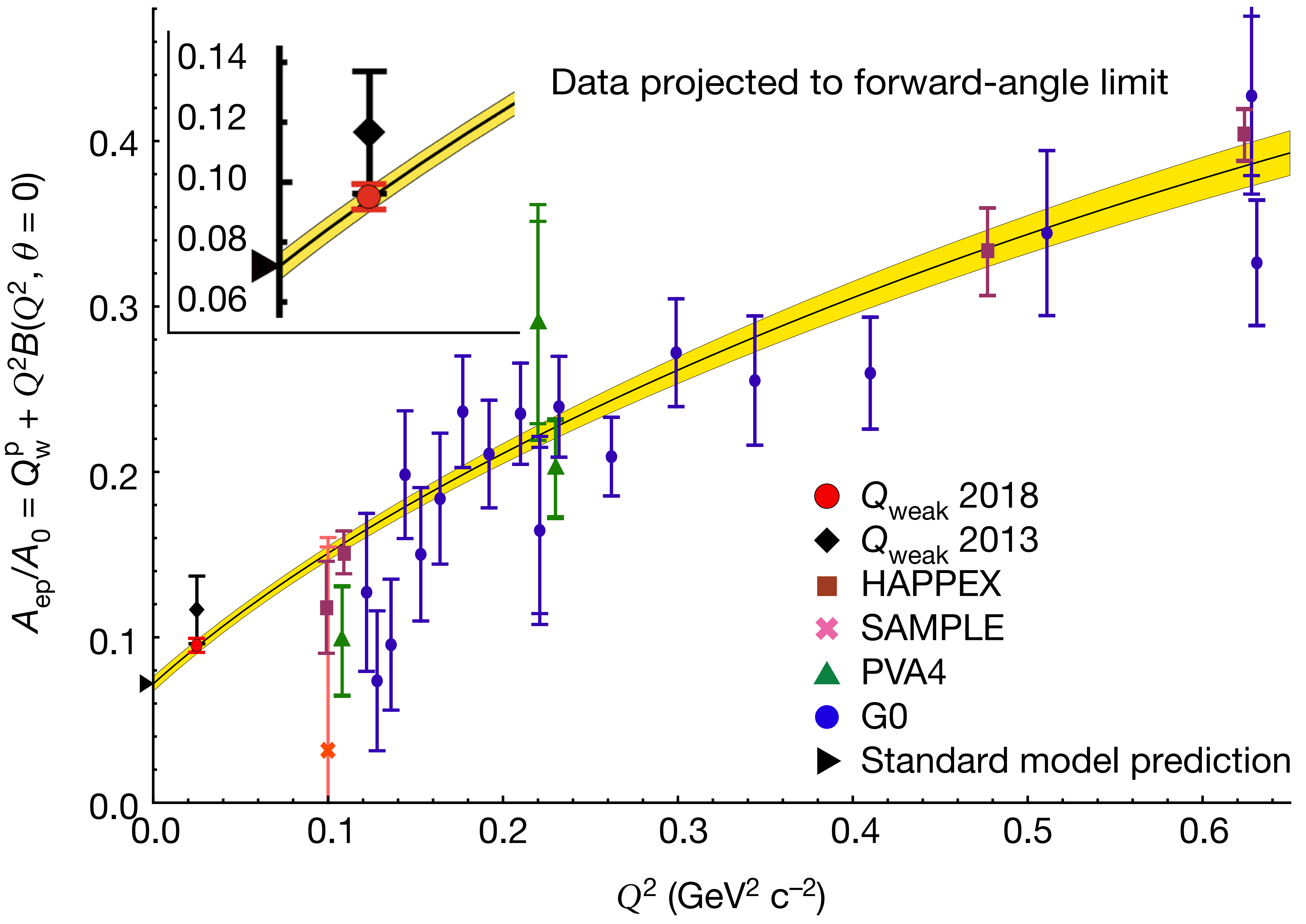
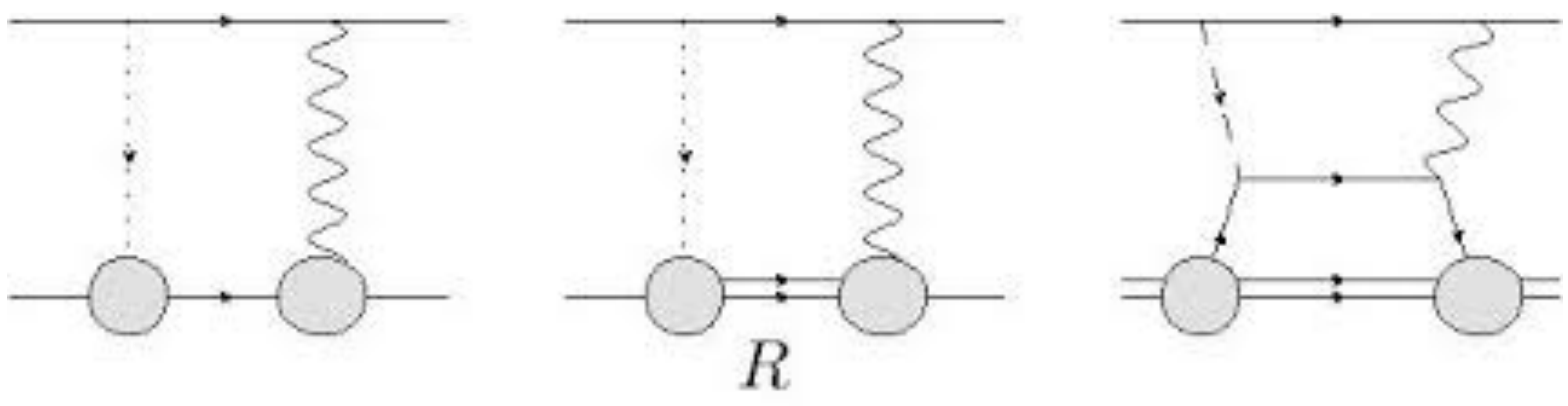
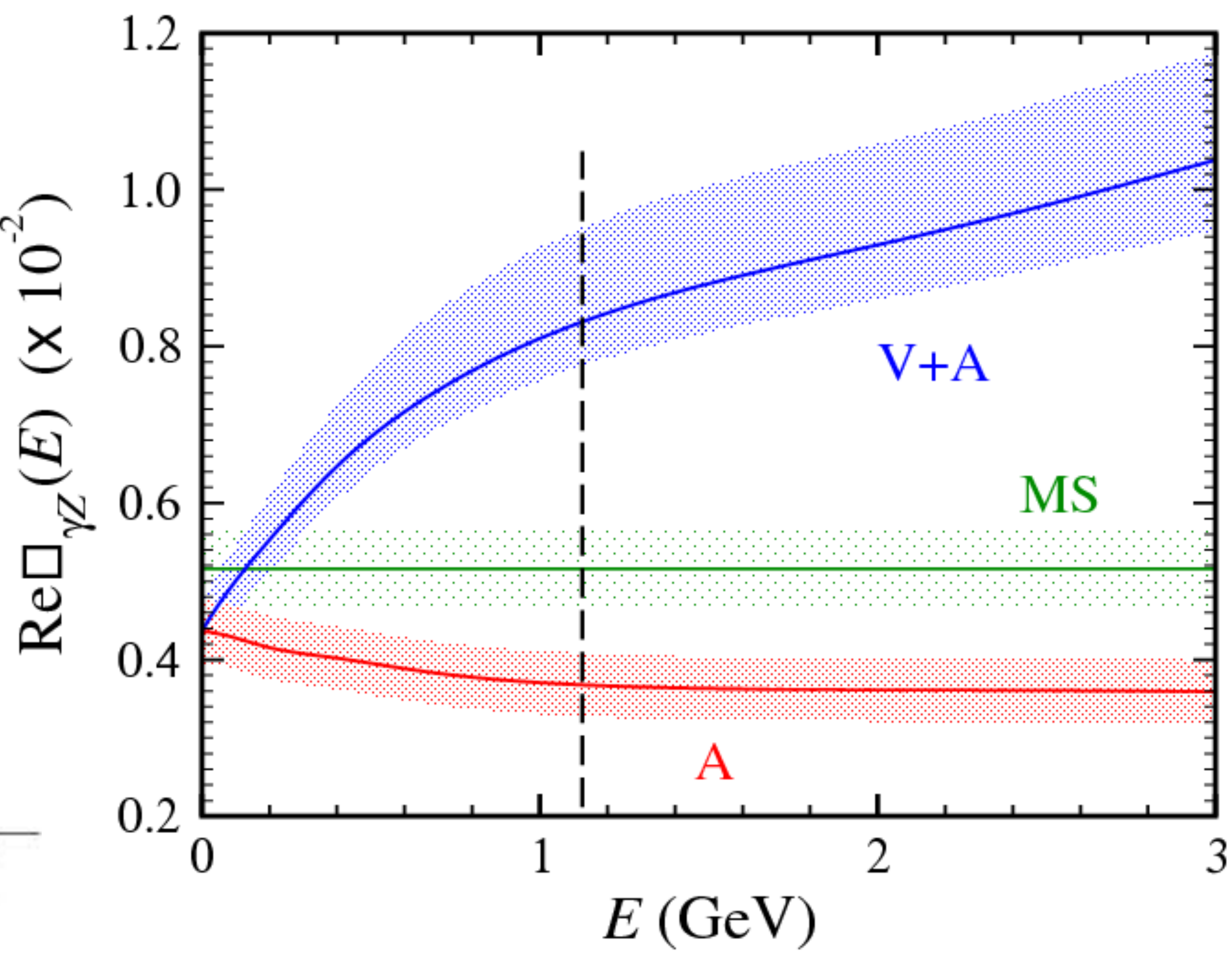


Theory issues in PVES

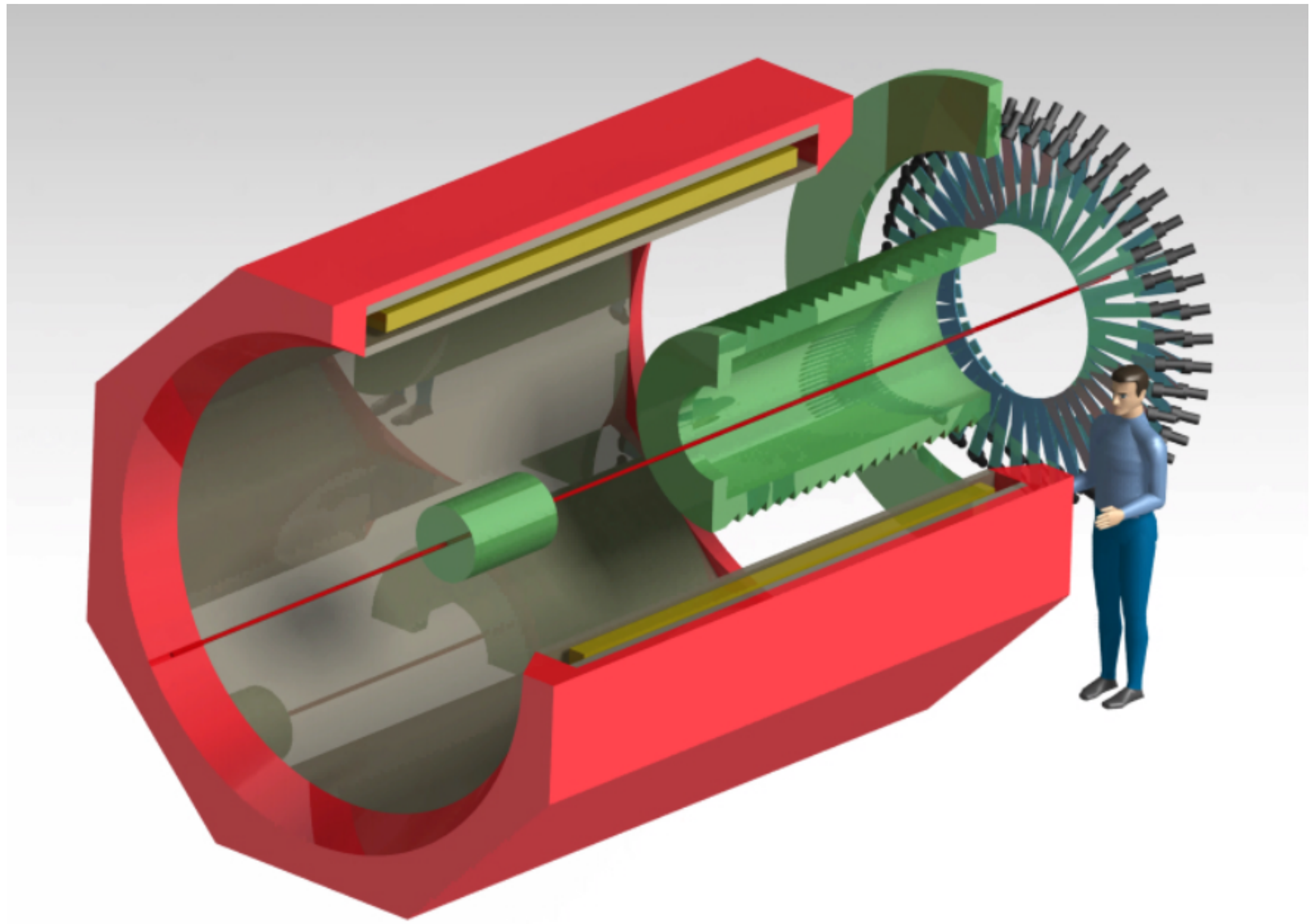
* need full 1-loop QED under experiment-specific conditions
* box diagrams (γZ-box)
* enhanced 2-loop electroweak (γWW-double box)
* running weak mixing angle (see later)
* unknown neutron distribution (neutron skin for heavier nuclei)





Blunden et al., arXiv:1102.5334

Parity Violating e^- Scattering (PVES) — Elastic



P2 @ MESA (JGU Mainz)

hydrogen (CDR)

E_e = 155 MeV

$|Q|$ = 67 MeV

$A_{PV} = 4 \times 10^{-8}$

$\Delta A_{PV} = \pm\ 1.4\%$

$\Delta Q_W(p) = \pm\ 1.83\%$

$\Delta \sin^2\theta_W = \pm\ 0.00033$

FFs from backward angle data

arXiv:1802.04759

Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

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E_e = 1165 MeV

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P2 @ MESA (JGU Mainz)

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E_e = 150 MeV

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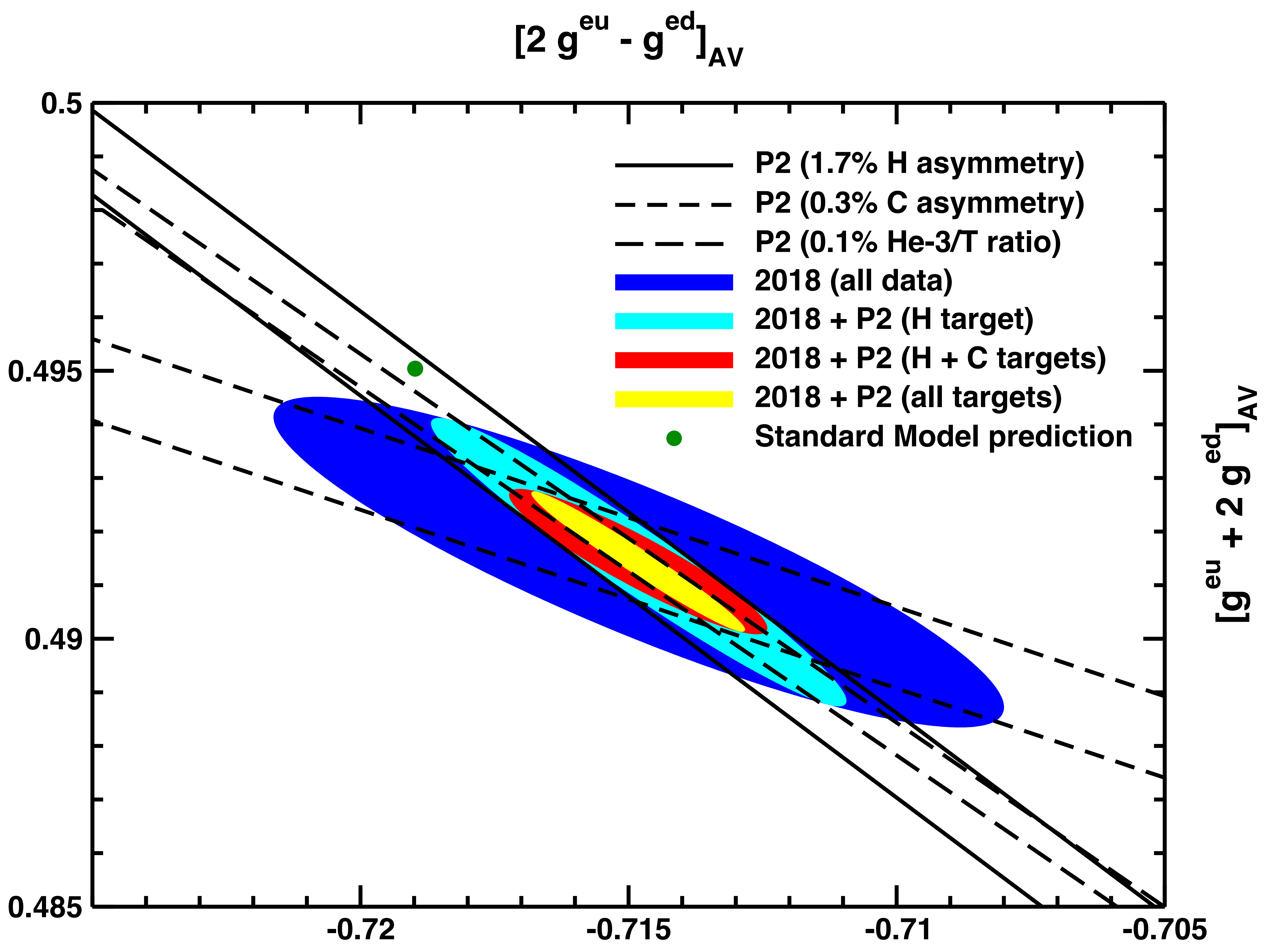
FFs from backward angle data

arXiv:1802.04759

Effective couplings (Wilson coefficients)



Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF

H (completed)

E_e = 1165 MeV

$|Q|$ = 158 MeV

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

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

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

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

FFs from fit

arXiv:1905.08283

P2 @ MESA

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$\Delta A_{PV} = \pm 1.4\%$

$\Delta Q_W(p) = \pm 1.83\%$

$\Delta \sin^2\theta_W = \pm 0.00033$

FFs from backward angles

arXiv:1802.04759

P2 @ MESA

^{12}C (CDR)

E_e = 150 MeV

$A_{PV} = 6 \times 10^{-7}$

$\Delta A_{PV} = \pm 0.3\%$

$\Delta Q_W(^{12}C) = \pm 0.3\%$

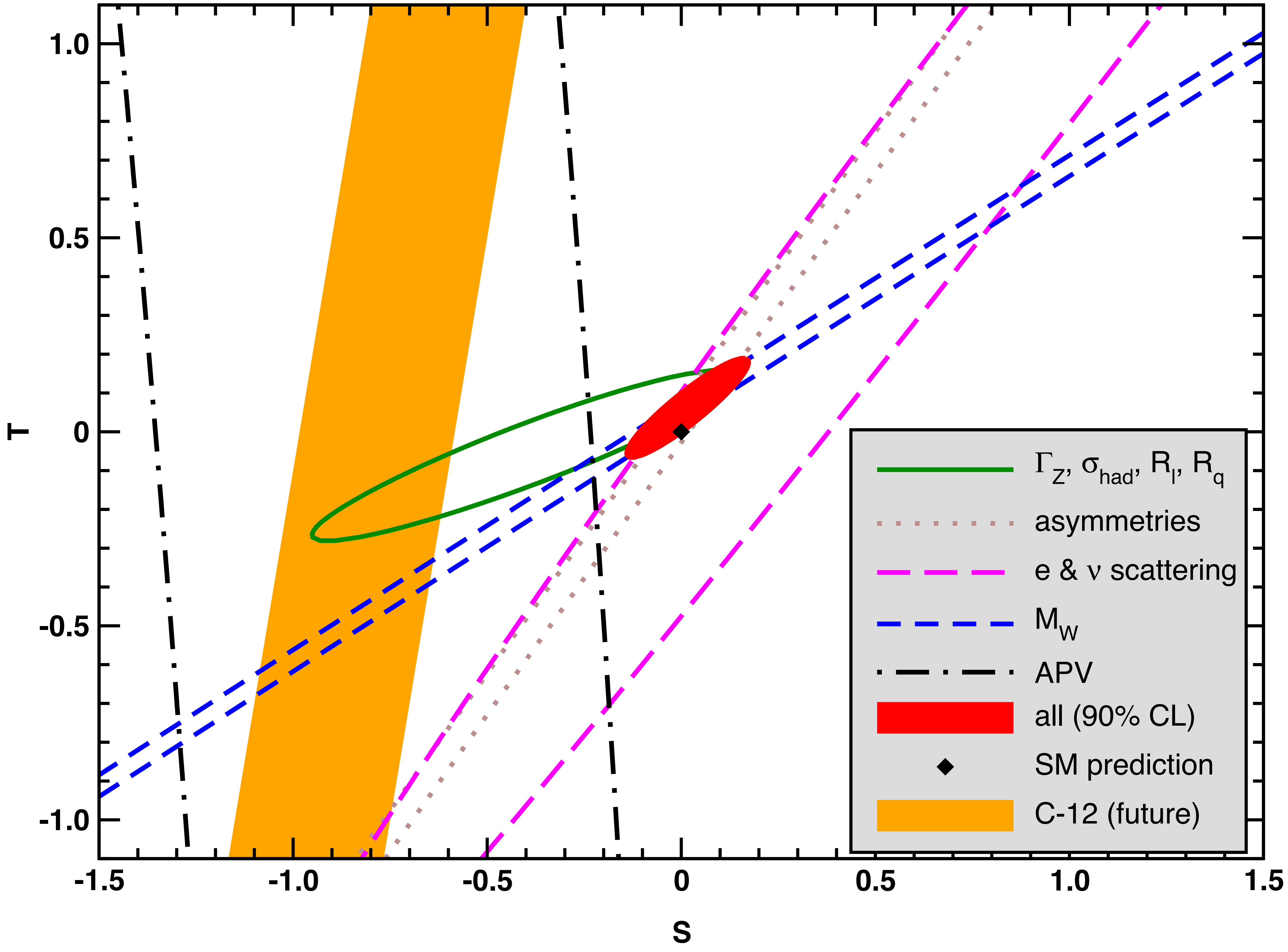
$\Delta \sin^2\theta_W = \pm 0.0007$

neutron skin?

only one FF

arXiv:1802.04759

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)

Parity Violating e⁻ Scattering (PVES) — DIS

E122 @ SLAC

D (completed)

$|Q| = 0.96 – 1.40$ GeV

$A_{PV} = 1.2 \times 10^{-4}$

$\Delta A_{PV} = \pm 8\%$

$\Delta \sin^2\theta_W = \pm 0.011$

PLB 84, 524 (1979)

PVDIS @ CEBAF

D (completed)

$|Q| = 1.04$ & 1.38 GeV

$A_{PV} = 1.6 \times 10^{-4}$

$\Delta A_{PV} = \pm 4.4\%$

$\Delta \sin^2\theta_W = \pm 0.0051$

arXiv:1411.3200

SoLID @ CEBAF

D (pre-CDR)

$|Q| = 2.1 – 3.1$ GeV

$A_{PV} = 8 \times 10^{-4}$

$\Delta A_{PV} = \pm 0.6\%$

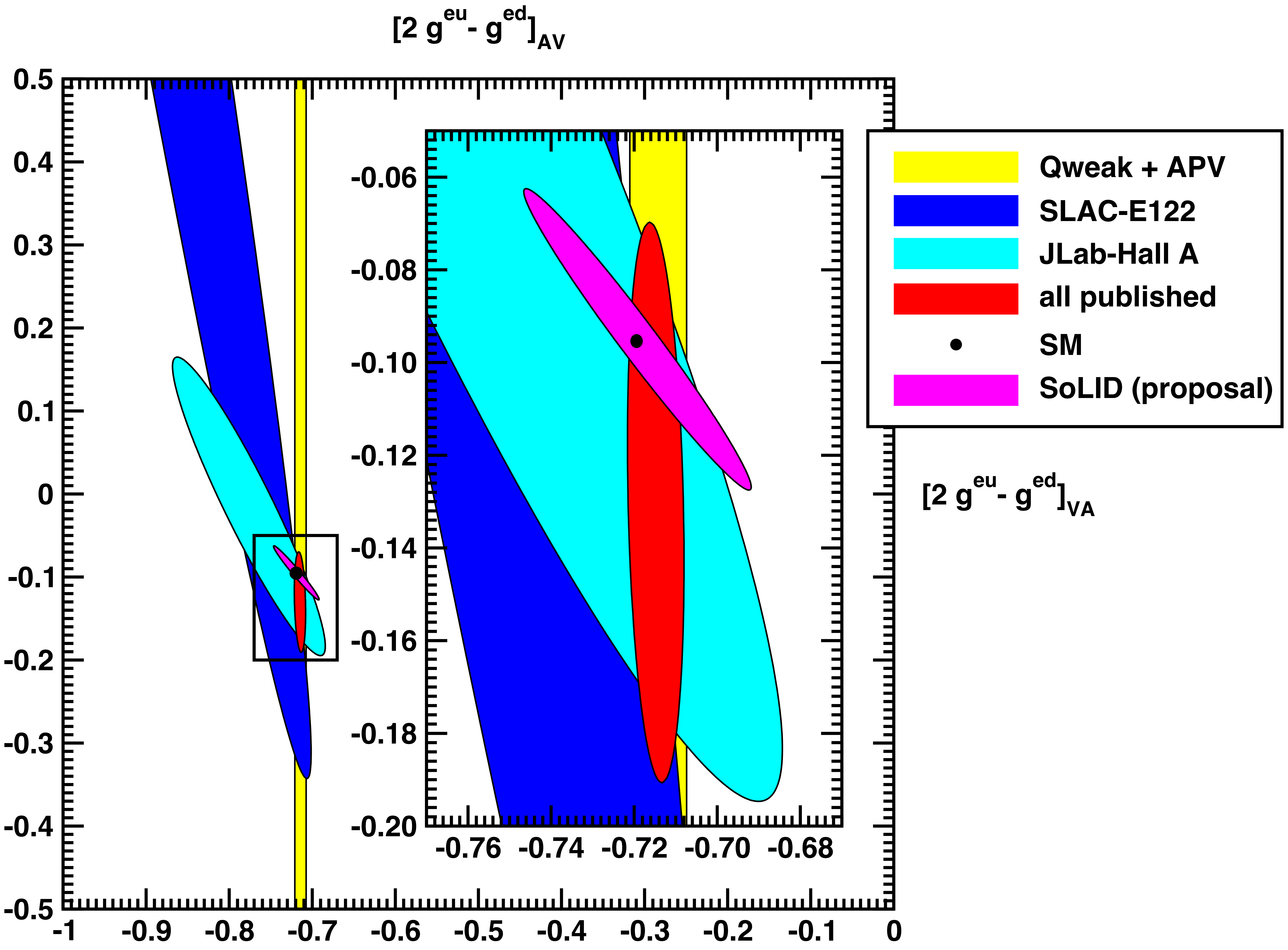
$\Delta \sin^2\theta_W = \pm 0.00057$

Higher twist?

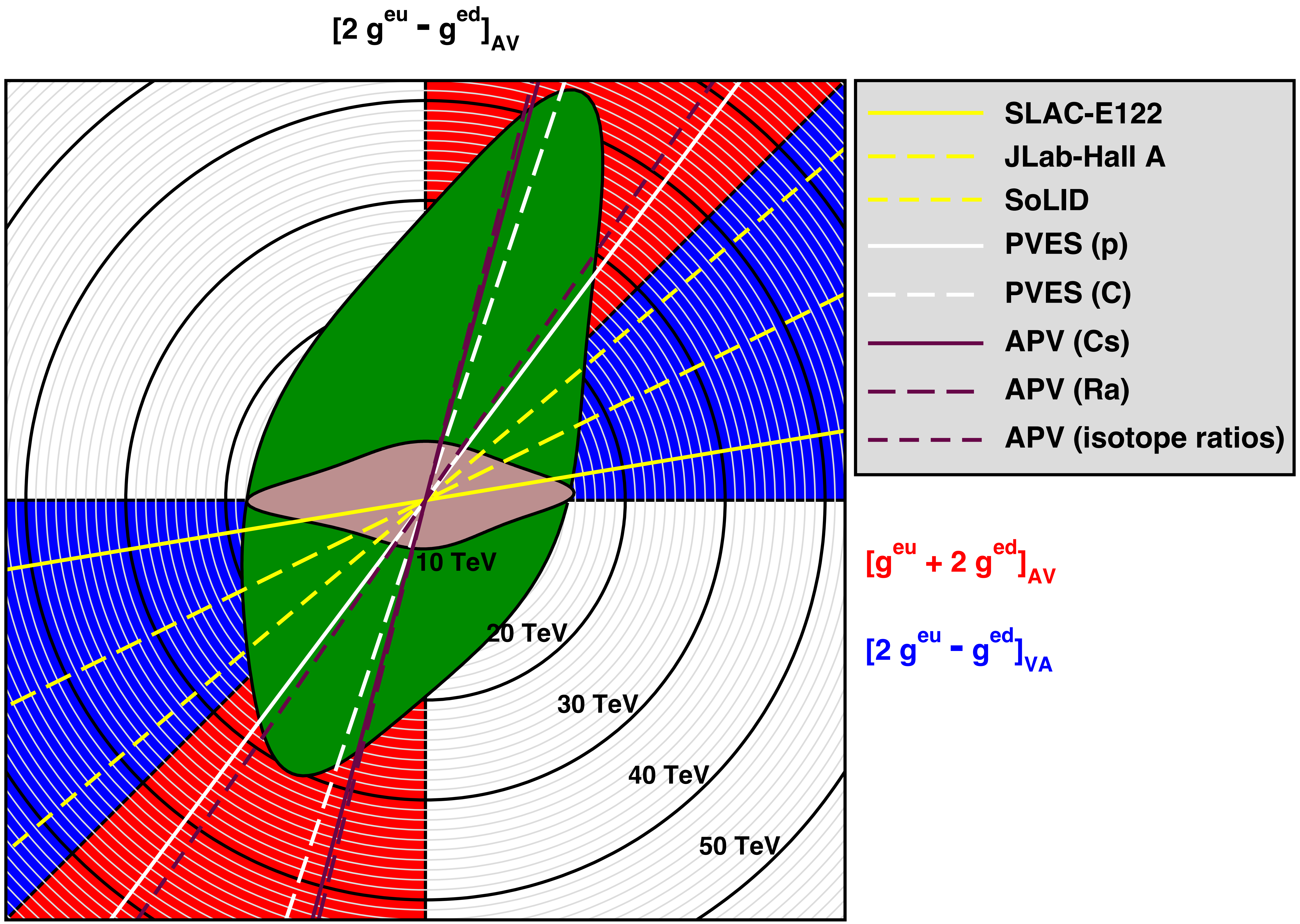
Isospin violation?

arXiv:1810.00989

Effective couplings (Wilson coefficients)



Scale exclusions post Qweak



Parity Violating e^- Scattering (PVES) — Møller

E158 @ SLC (SLAC)

hydrogen (completed)

E_e = 45 & 48 GeV

$|Q|$ = 161 MeV

$A_{PV} = 1.31 \times 10^{-7}$

$\Delta A_{PV} = \pm$ 13%

$\Delta Q_W(e) = \pm$ 13%

$\Delta \sin^2\theta_W = \pm 0.0013$

hep-ex/0504049

MOLLER @ CEBAF (JLab)

hydrogen (proposal)

E_e = 11.0 GeV

$|Q|$ = 76 MeV

$A_{PV} = 3.3 \times 10^{-8}$

$\Delta A_{PV} = \pm$ 2.4%

$\Delta Q_W(e) = \pm$ 2.4%

$\Delta \sin^2\theta_W = \pm 0.00027$

arXiv:1411.4088

Parity Violating e⁻ Scattering (PVES) — Møller

<u>E158 @ SLC (SLAC)</u>

hydrogen (completed)

E_e = 45 & 48 GeV

$|Q|$ = 161 MeV

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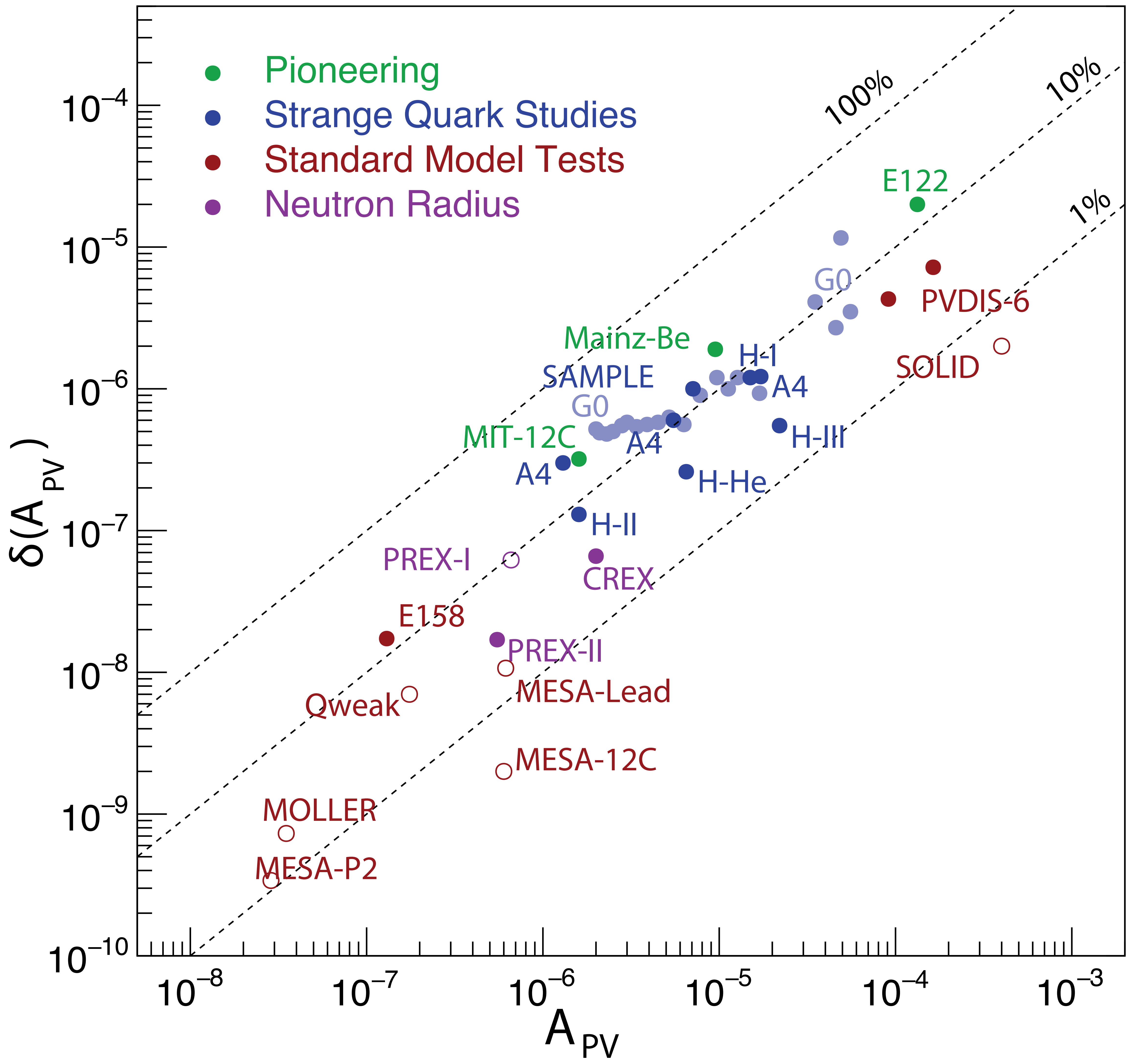
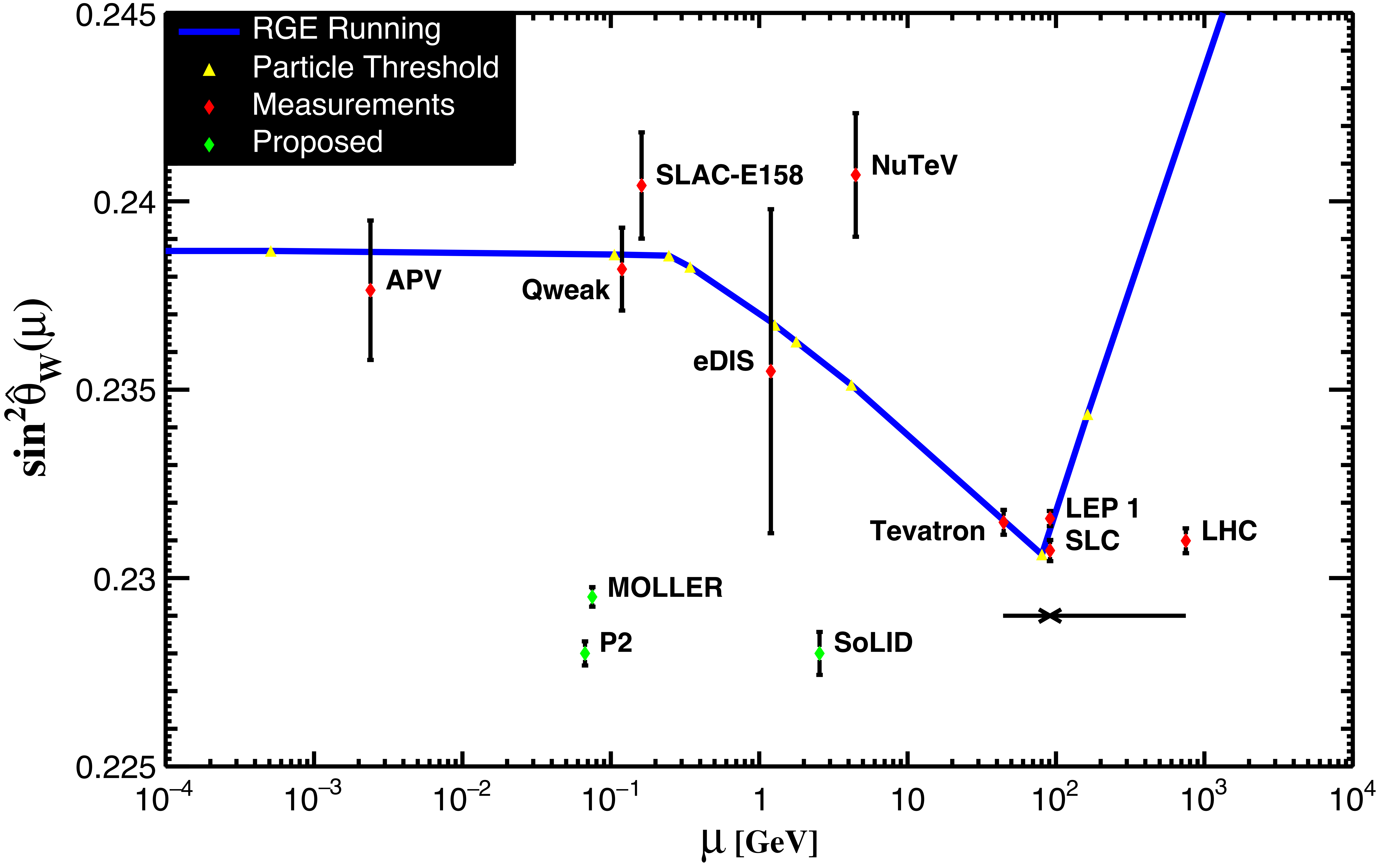
arXiv:1411.4088

PVES history

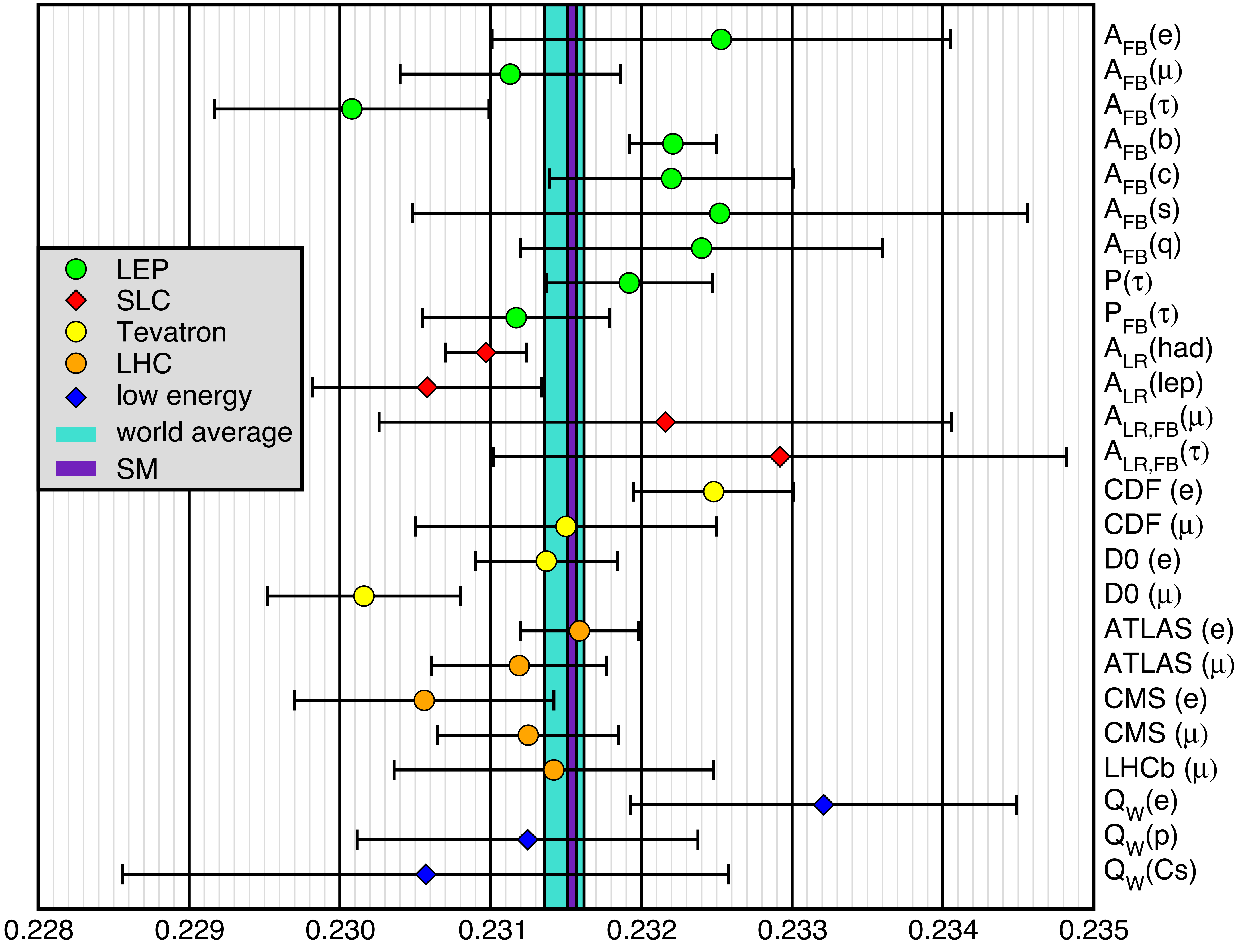


Running weak mixing angle

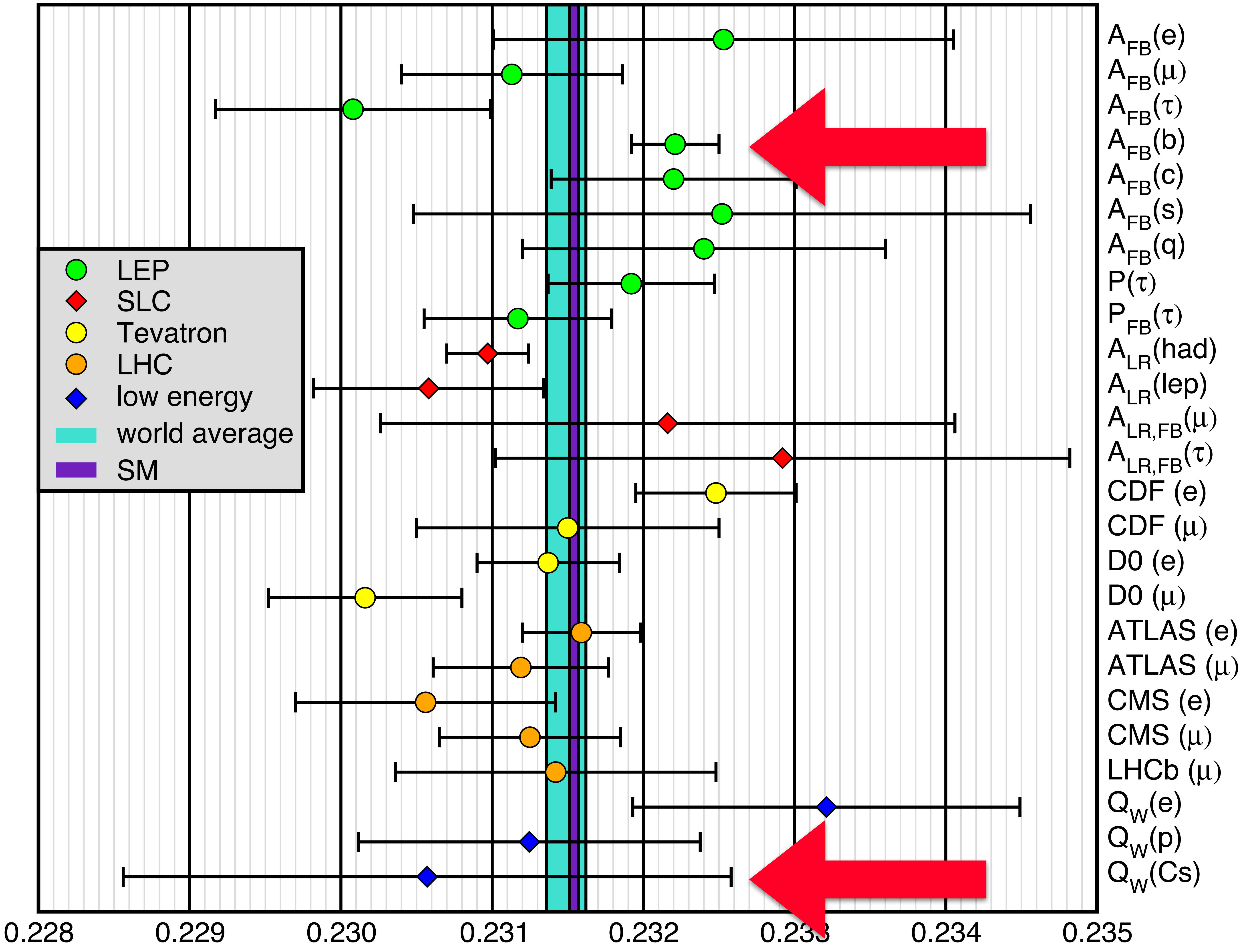


Ferro-Hernández & JE
arXiv:1712.09146

Weak mixing angle measurements



Weak mixing angle measurements



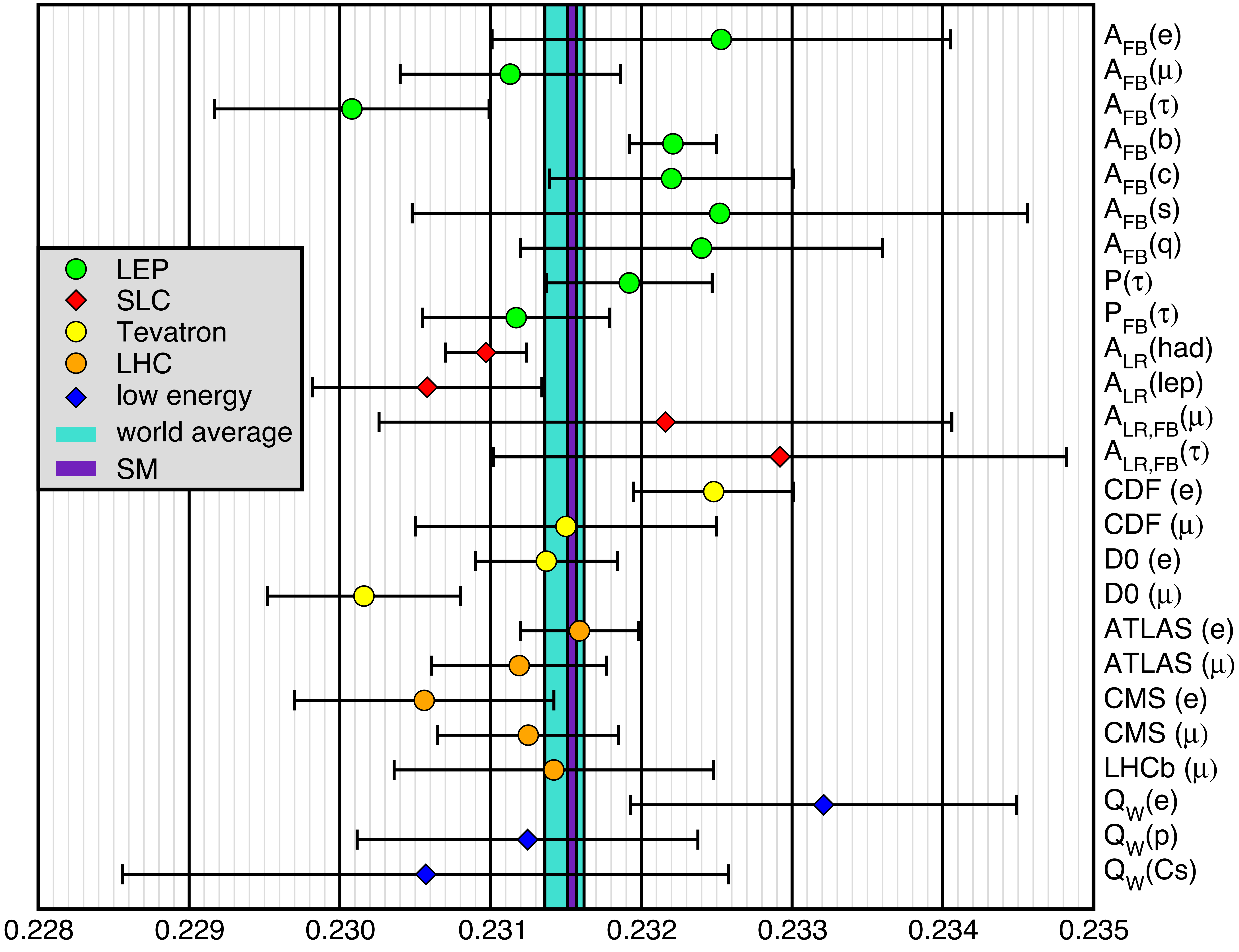
2-loop QCD correction
with $m_b \neq 0$

Bernreuther et al.
arXiv:1611.07942

new measured
transition vector polarizability

Tho et al.
arXiv:1905.02768

Weak mixing angle measurements



LEP & SLC:

0.23153 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23131 ± 0.00033

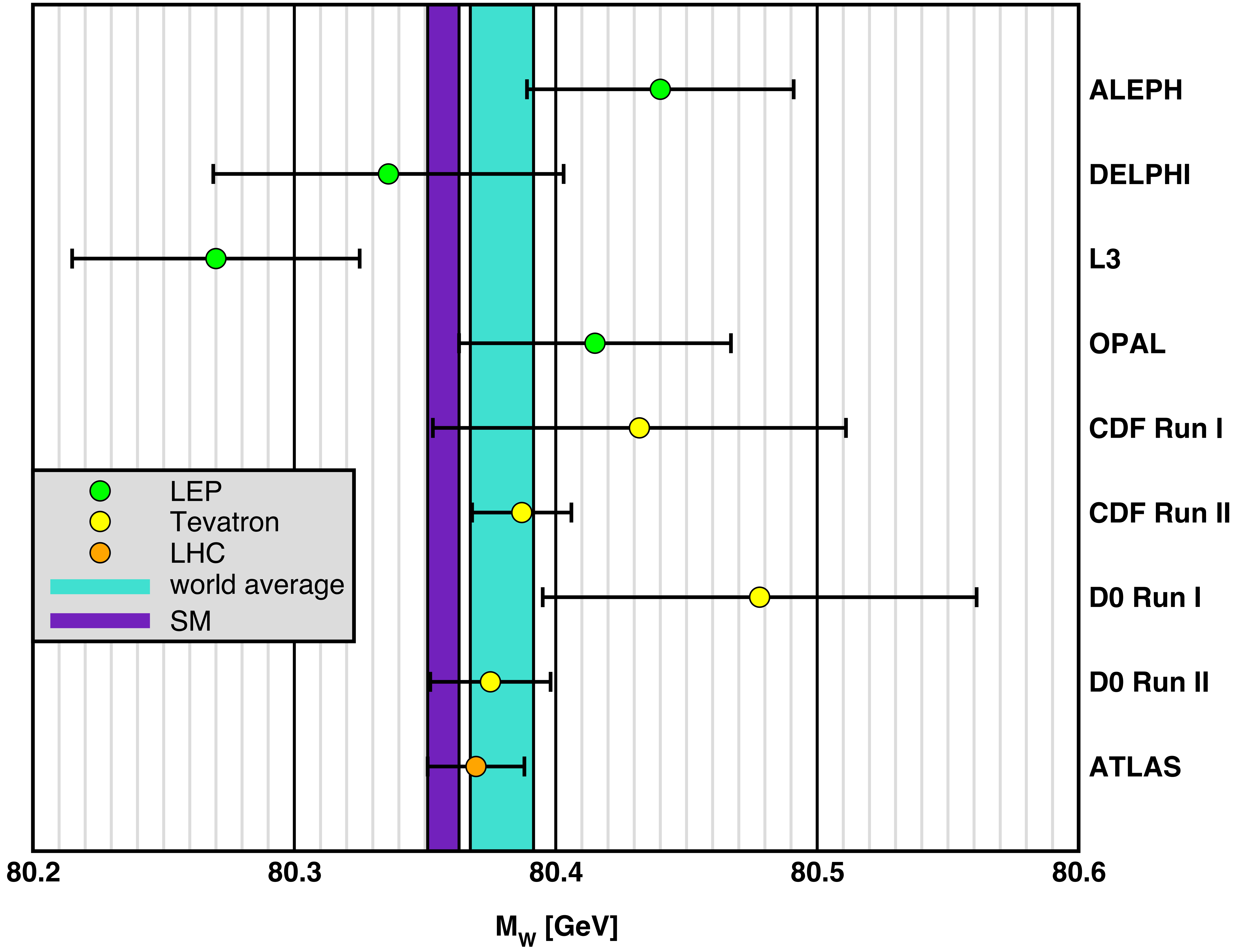
average direct

0.23149 ± 0.00013

global fit

0.23153 ± 0.00004

W boson mass measurements



average direct

80.379 ± 0.012 GeV

indirect

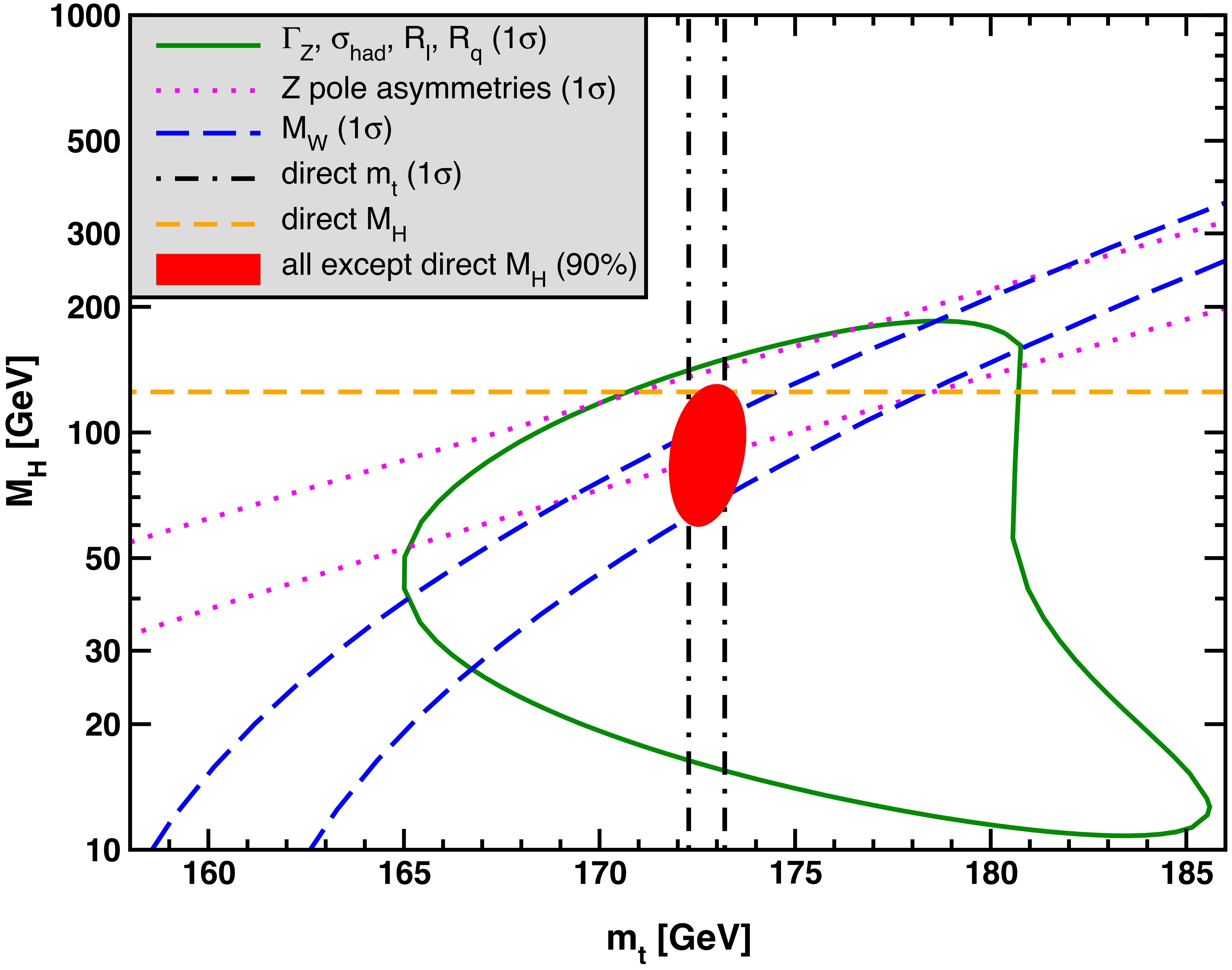
80.357 ± 0.006 GeV

including
correlated theory errors

Theoretical uncertainties and correlations

* loop factors including enhancement factors $N_C = N_F = 3$ or $\sin^{-2}\theta_W \approx m_t^2/M_W^2 \approx 4$:
  * $8\,\alpha(M_W)/\pi = 0.020$ (QED)
  * $3\,\alpha_s(M_W)/\pi = 0.116$ (QCD)
  * $3\,\alpha(M_W)/\pi\,\sin^2\theta_W(M_W) = 0.032$ (CC)
  * $(3 - 6\,s^2_W + 8\,s^4_W)/\pi\,s^2_W\,c^2_W = 0.029$ (NC)
    * $\Delta S_Z = \pm\,0.0034$ (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, arXiv:1902.05142**

$M_H - m_t$



indirect m_t

176.4 ± 1.8 GeV (2.0 σ high)

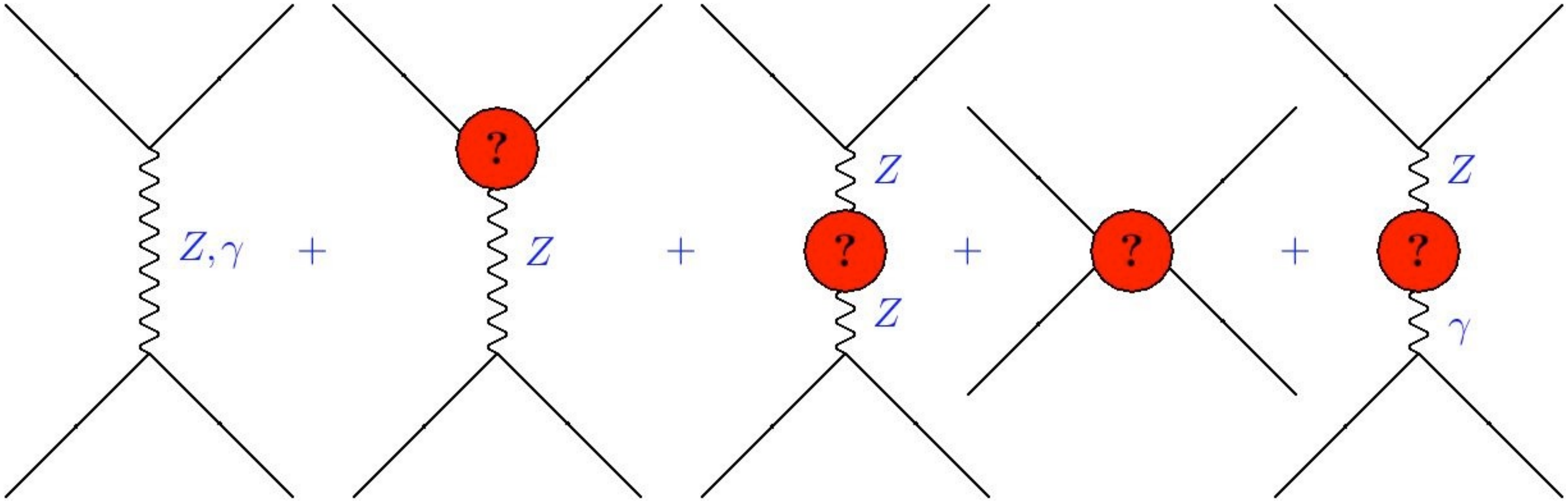
indirect M_H

90^{+17}_{-15} GeV (1.9 σ low)

including theory error

91^{+18}_{-16} GeV (1.8 σ low)

Beyond the SM

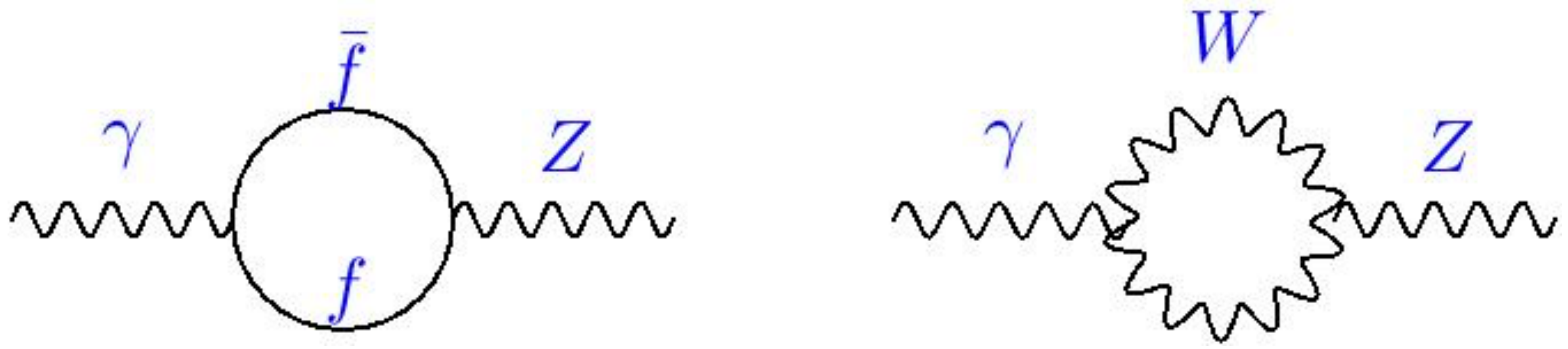


* Z-Z′ mixing: modification of Z vector coupling
* oblique parameters: STU (also need M_W and Γ_Z)
* new amplitudes: off- versus on-Z pole measurements (e.g. Z′)
* dark Z: renormalization group evolution (running)

Vacuum Polarization in Global Fits

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

$\sin^2\theta_W(0)$ 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 equations **Ramsey-Musolf & JE, hep-ph/0409169**
- $\Delta\alpha(M_Z)_{had}$ errors in $\sin^2\theta_W(0) = \kappa(0) \sin^2\theta_W(M_Z)$ add because

  $M_Z^2 \sim g_Z^2(M_Z)\, v^2 \sim [\alpha / s^2_W\, c^2_W](M_Z)\, G_F^{-1}$

$\alpha(M_Z)$

* Dispersive approach: integral over $\sigma(e^+e^- \to \text{hadrons})$ and τ-decay data
  * $\alpha^{-1}(M_Z) = 128.947 \pm 0.012$ **Davier et al., arXiv:1706.09436**
  * $\alpha^{-1}(M_Z) = 128.958 \pm 0.016$ **Jegerlehner, arXiv:1711.06089**
  * $\alpha^{-1}(M_Z) = 128.946 \pm 0.015$ **Keshavarzi et al., arXiv:1802.02995**
* **$\alpha^{-1}(M_Z) = 128.949 \pm 0.010$** **Ferro-Hernández & JE, arXiv:1712.09146**
  * converted from the $\overline{MS}$ scheme and uses e^+e^- annihilation and τ spectral functions
  * 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 $\sin^2\theta_W(0)$

$m_c(m_c)$

* only experimental input:
  electronic widths of J/ψ and ψ(2S)

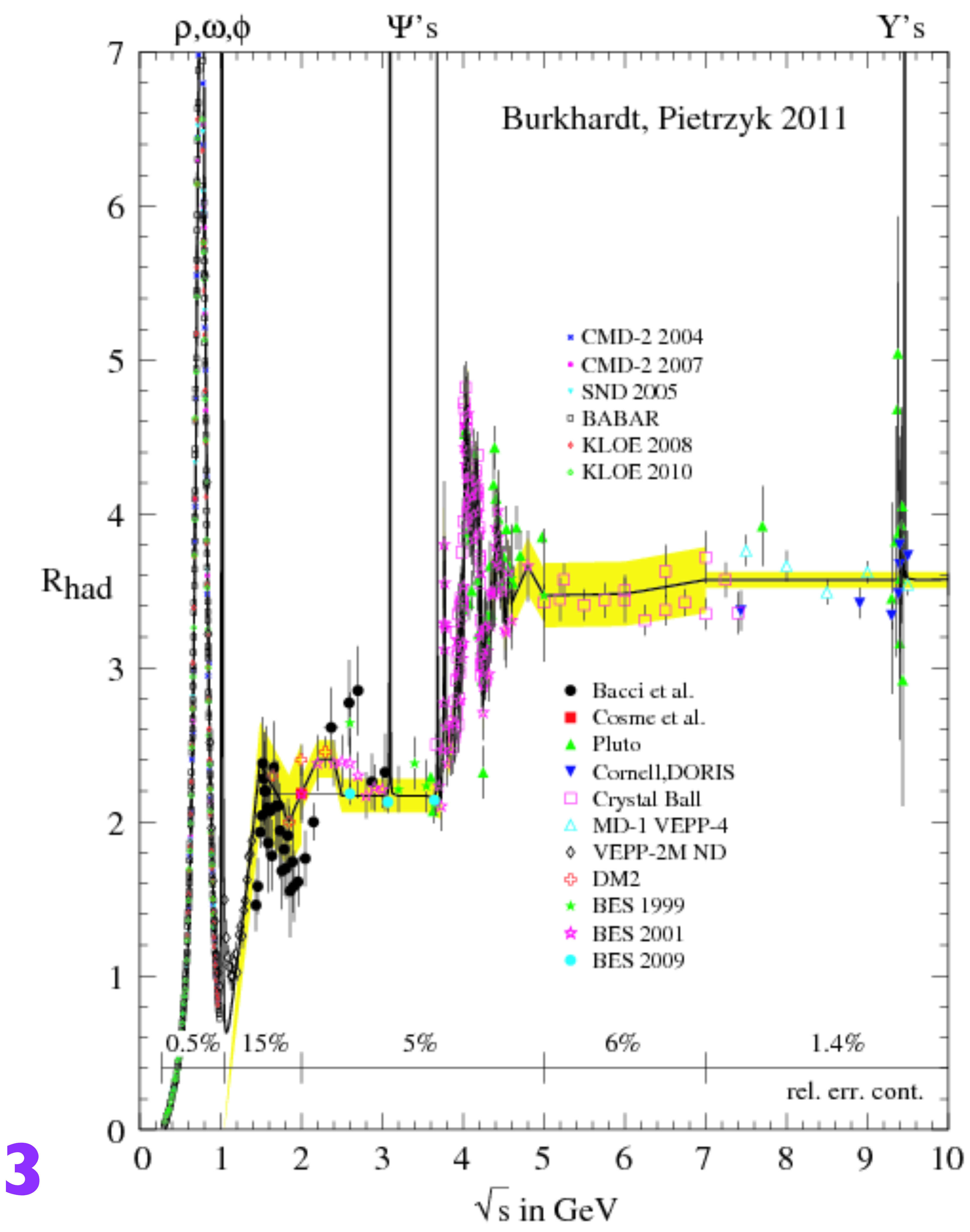
* continuum contribution from
  self-consistency between sum rules
  → continuum over-constrained

* include $\mathcal{M}_0$ → stronger (milder) sensitivity
  to continuum (m_c) **Luo & JE, hep-ph/0207114**

* 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, arXiv:1610.0853



$m_c(m_c)$

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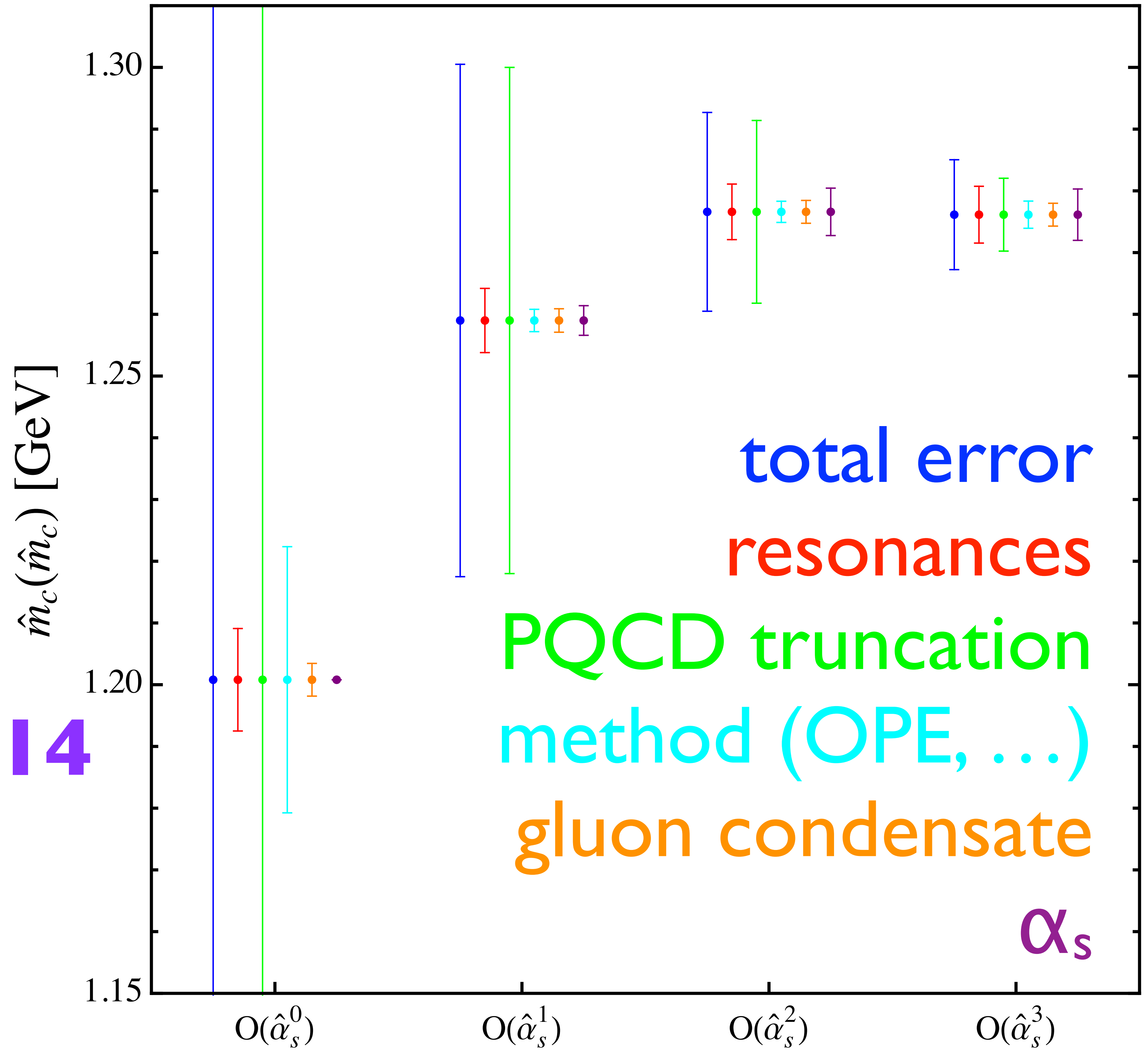
  Masjuan, Spiesberger & JE, arXiv:1610.08531



$\sin^2\theta_W(0)$

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}

Ferro-Hernández & JE arXiv:1712.09146

Freitas & JE PDG (2018)

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

(errors from m_c and m_b negligible)

$g_\mu - 2$

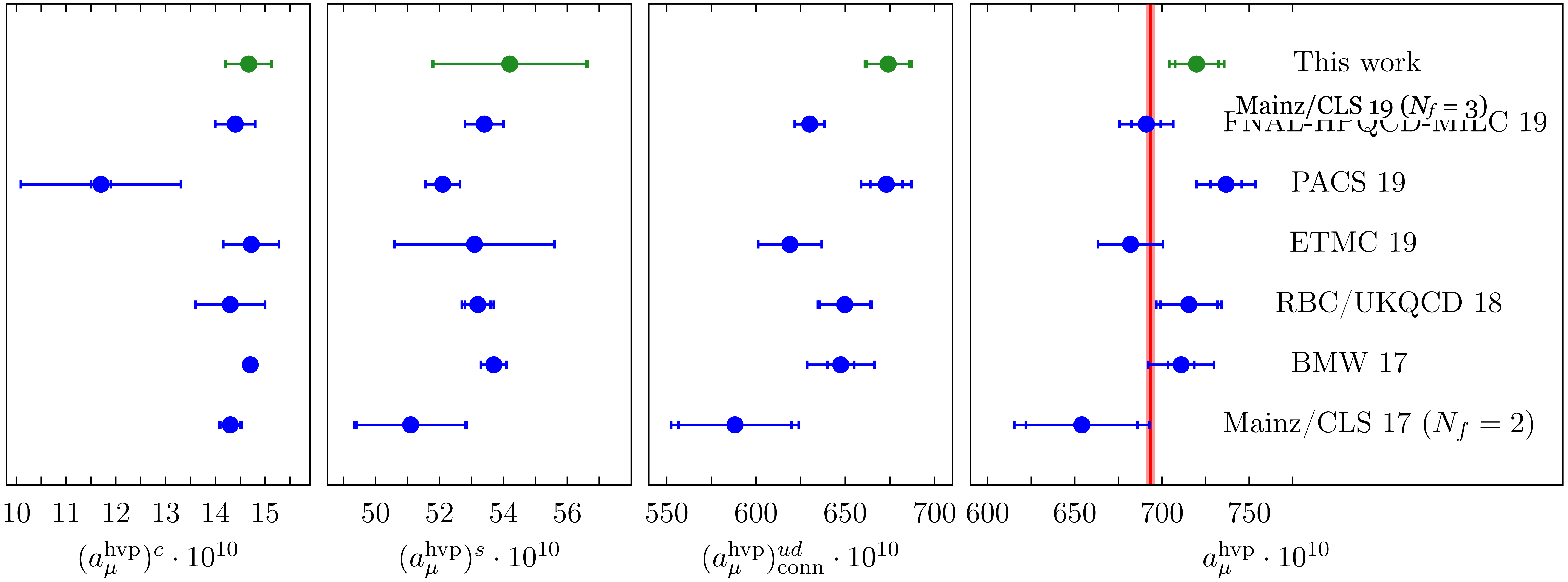
PQCD: $(a_\mu^{hvp})^c = (14.6 \pm 0.5_{theory} \pm 0.2_{mc} \pm 0.1_{\alpha s})\times 10^{-10}$

$(a_\mu^{hvp})^b = 0.3\times 10^{-10}$

Luo & JE, hep-ph/0101010

Lattice gauge theory:

A. Gérardin et al., arXiv:1904.03120



Conclusions and outlook

* new players:
  * coherent ν-scattering
  * ultra-high precision PVES
  * APV isotope ratios
* ultra-high precision frontier $\Longrightarrow$ fields merge (incl. theory communities):
  * collider physics
  * ν-physics
  * nuclear physics (anapole moments)
  * astrophysics (neutron skins)
  * atomic physics (APV, proton radius)
  * lattice gauge theory (vacuum polarization, …)

Backups

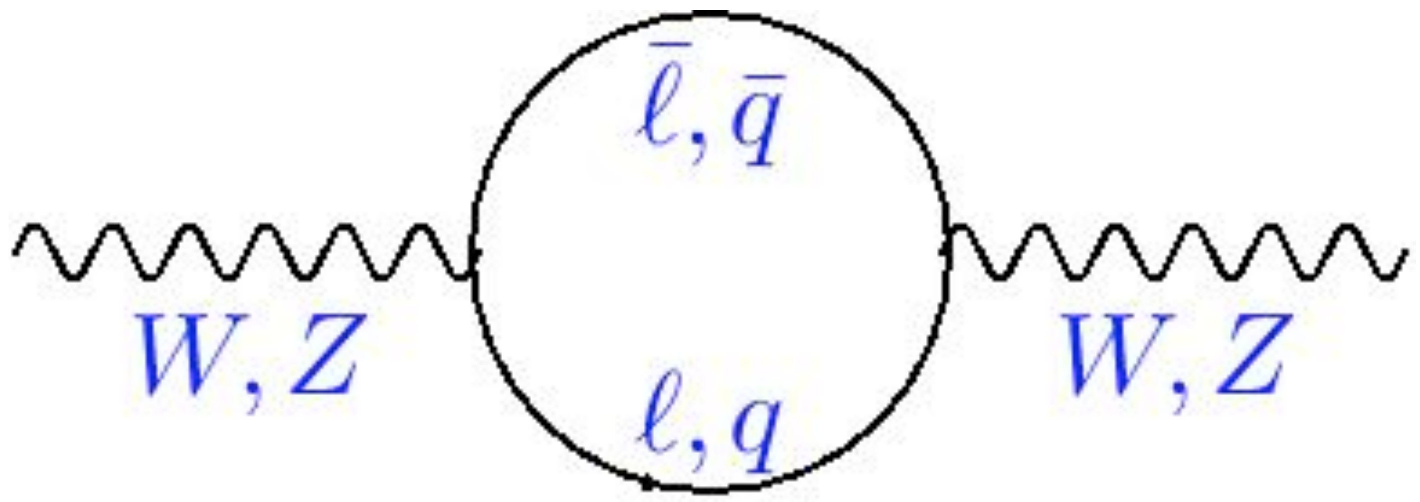
Standard global fit

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		
$\Delta\alpha_{had}^{(3)}(2\ \mathrm{GeV})$		$(59.0 \pm 0.5)\times 10^{-4}$		
$\overline{m}_t(\overline{m}_t)$	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

Oblique physics beyond the SM



- STU describe corrections to gauge-boson self-energies
- T breaks custodial SO(4)
- a multiplet of heavy degenerate chiral fermions contributes $\Delta S = N_C/3\pi \sum_i [t_{3L}^i - t_{3R}^i]^2$
- extra degenerate fermion family yields $\Delta S = 2/3\pi \approx 0.21$
- S and T (U) correspond to dimension 6 (8) operators

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 $v_3 \sim 0.01\ v_2$

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			
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)***

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)

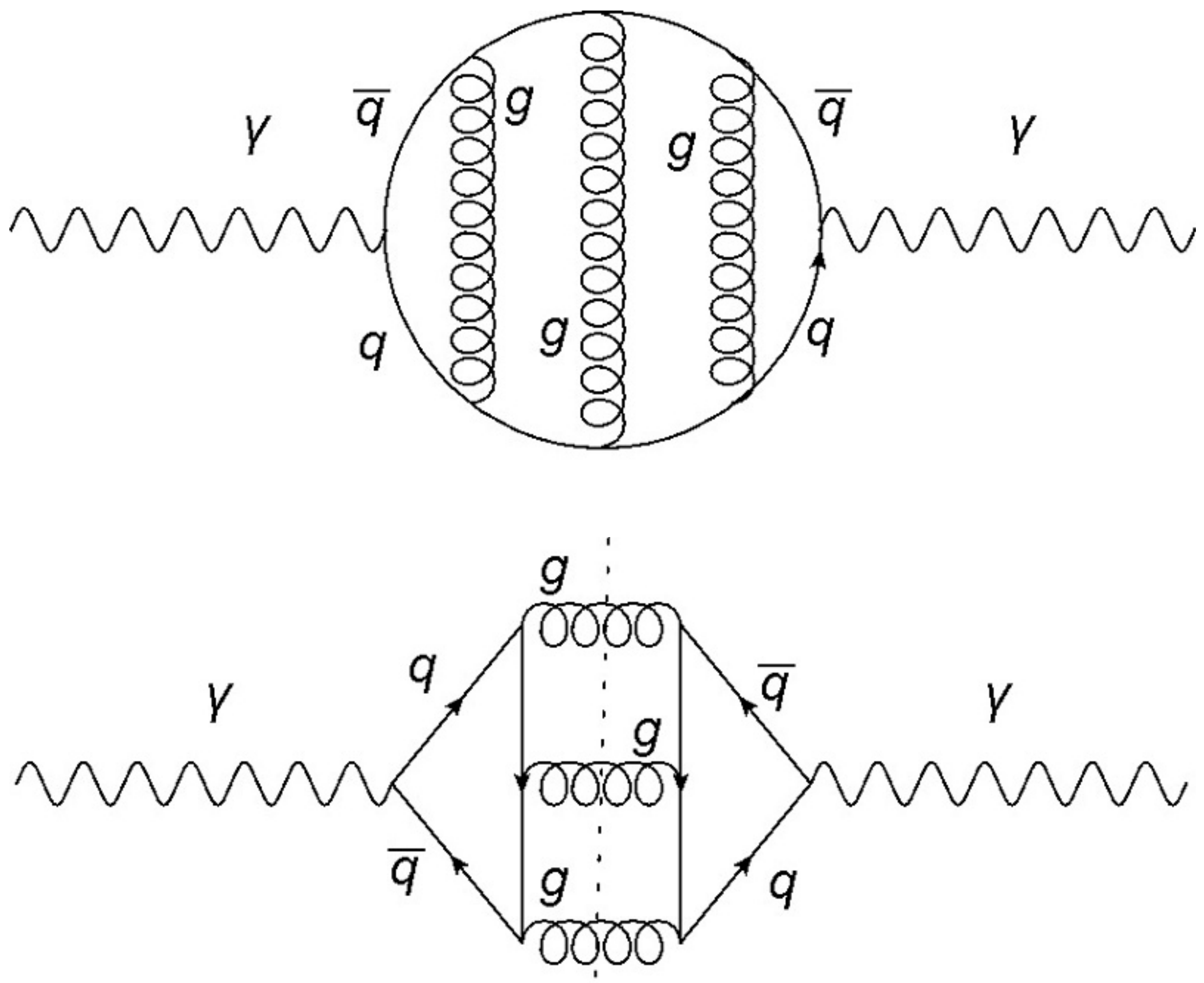
- $m_t = 172.74 \pm 0.25_{\text{uncorr.}} \pm 0.21_{\text{corr.}} \pm 0.32_{\text{QCD}}$ GeV = 172.74 ± 0.46 GeV
- somewhat larger shifts and smaller errors conceivable in the future
  Butenschoen et al., PRL 117 (2016); Andreassen & Schwartz, JHEP 10 (2017)
- 2.8 σ discrepancy between lepton + jet channels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

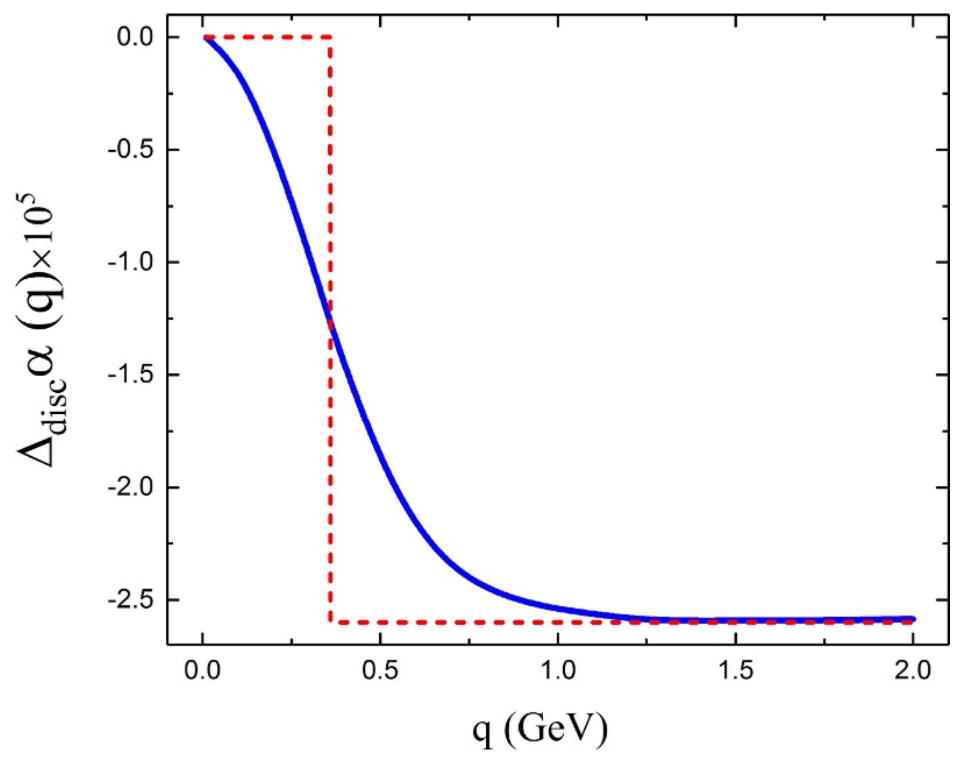
$\sin^2\theta_W(0)$: flavor separation

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 $\alpha(2\text{ GeV})$ needs singlet piece isolation $\Delta_{disc}\,\alpha(2\text{ GeV})$
- 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 $\Rightarrow$ singlet threshold mass $\bar{m}_s^{disc} \approx 350$ MeV

α_s from τ decays

$$\tau_\tau = \hbar \frac{1 - \mathcal{B}_\tau^s}{\Gamma_\tau^e + \Gamma_\tau^\mu + \Gamma_\tau^{ud}} = 290.75 \pm 0.36 \text{ fs},$$

$$\Gamma_\tau^{ud} = \frac{G_F^2 m_\tau^5 |V_{ud}|^2}{64\pi^3} S(m_\tau, M_Z) \left(1 + \frac{3}{5}\frac{m_\tau^2 - m_\mu^2}{M_W^2}\right) \times$$

$$\left[1 + \frac{\alpha_s(m_\tau)}{\pi} + 5.202\frac{\alpha_s^2}{\pi^2} + 26.37\frac{\alpha_s^3}{\pi^3} + 127.1\frac{\alpha_s^4}{\pi^4} + \frac{\hat{\alpha}}{\pi}\left(\frac{85}{24} - \frac{\pi^2}{2}\right) + \delta_{\text{NP}}\right]$$

- τ_τ result includes leptonic branching ratios
- $\mathcal{B}_\tau^s$ = 0.0292 ± 0.0004 ($\Delta S = -1$) *PDG 2018*
- $S(m_\tau, M_Z)$ = 1.01907 ± 0.0003 *JE, Rev. Mex. Fis. 50 (2004)*
- δ_{NP} = 0.003 ± 0.009 (within OPE & OPE breaking) based on (controversial) *Boito et al., PRD 85 (2012) & PRD 91 (2015); Davier et al., EPJC 74 (2014); Pich & Rodríguez-Sánchez, PRD 94 (2016)*

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- dominant uncertainty from PQCD truncation (FOPT vs. CIPT vs. geometric continuation)
- $\alpha_S^{(4)}(m_\tau) = 0.323^{+0.018}_{-0.014}$
- $\alpha_S^{(5)}(M_Z) = 0.1184^{+0.0020}_{-0.0018}$
- updated from ***Luo & JE, PLB 558 (2003)*** in ***Freitas & JE (PDG 2018)***