Deutsche Forschungsgemeinschaft

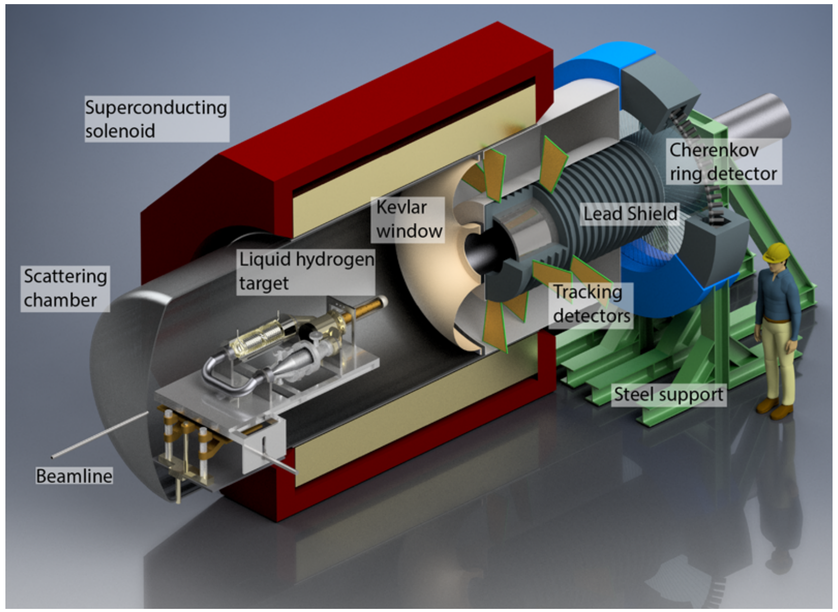
PDG particle data group

Jens Erler

JGU & Helmholtz Institute Mainz

(on leave from IF-UNAM)

The proton's weak charge



Workshop on *New physics at the low-energy precision frontier*

LPT Orsay, September 16–20, 2019

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

Outline

* *Measurements*
  * the past: JLab–Qweak
  * the future: JGU–P2
* *Higher-order corrections*
  * 1-loop radiative corrections
  * the weak mixing angle at low energy
  * form factors
  * the γZ box
* *Beyond the Standard Model*
  * model-independent constraints
  * constraints on simple models
* *Related experiments*
  * other targets
  * other projectiles
  * DIS
  * APV
* *Conclusions*

Measurements

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

* tuning in on the Z resonance
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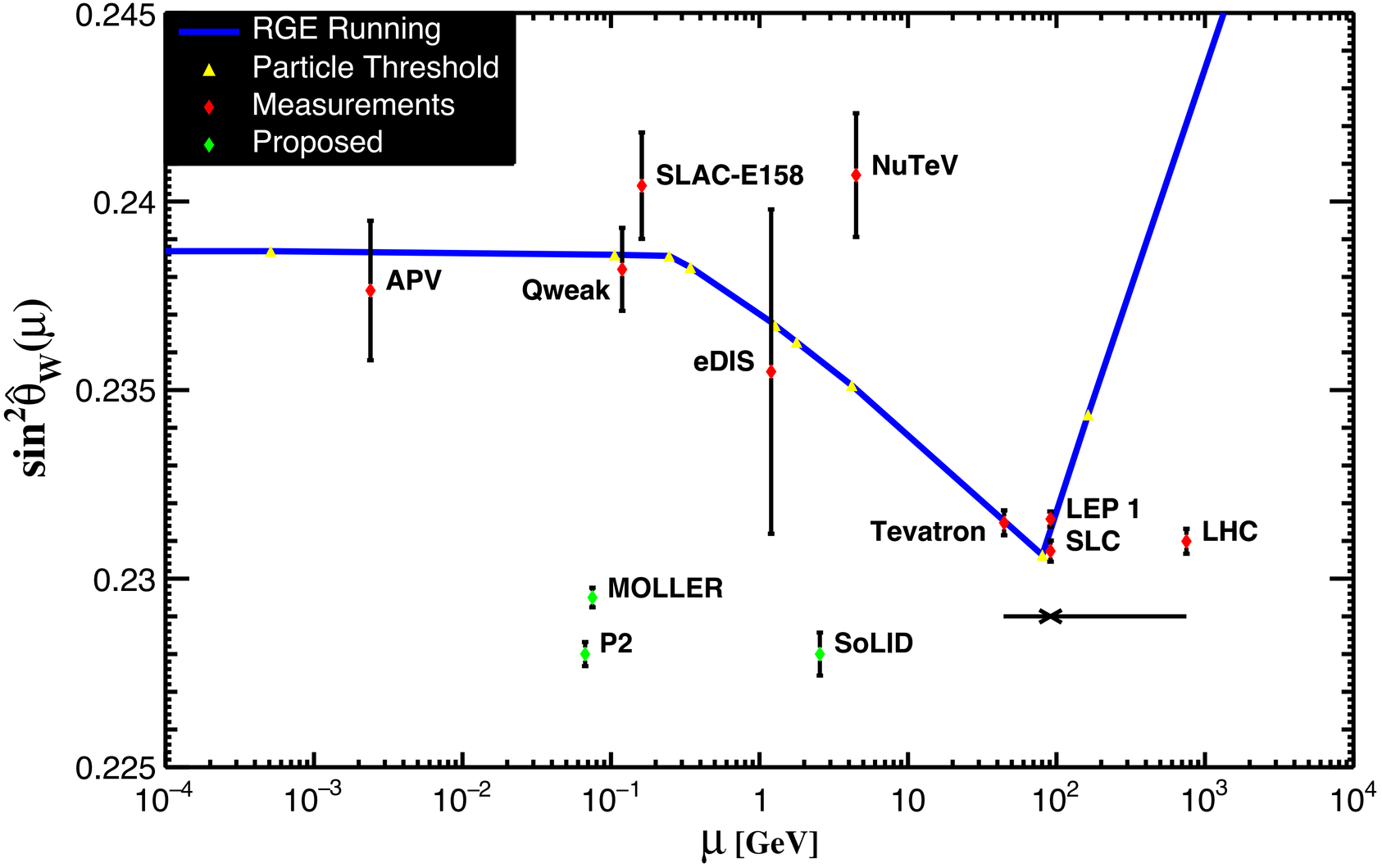
recent first measurements

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

Running weak mixing angle



Ferro-Hernández & JE arXiv:1712.09146

Weak charge of a nucleus

$$Q_W(N,Z) \approx -2\,(Z\, g_{AV}^{ep} + N\, g_{AV}^{en}) \approx Z\,(1 - 4\sin^2\theta_W) - N$$

$$Q_W(p) \approx -4\, g_{AV}^{ep} - 2\, g_{AV}^{en} \approx 1 - 4\sin^2\theta_W$$

$$g_{AV}^{ep} = 2\, g_{AV}^{eu} + g_{AV}^{ed}$$

$$g_{AV}^{en} = g_{AV}^{eu} + 2\, g_{AV}^{ed}$$

Coherent elastic ν nucleus scattering (CEνNS) ~ $G_F^2\, Q^4\, Q_W^2$

Parity violating elastic e^- scattering (PVES) ~ $G_F\, Q^2\, Q_W$

special case of proton: Z = 1, N = 0

➡ extra sensitivity to weak mixing angle and new physics

need small Q^2 to suppress form factor effects

not too small to maintain measurable cross section (asymmetry)

Parity violating asymmetry (Qweak)

after EM radiative corrections and accounting for signal dilutions and false or background process asymmetries

$A_{msr} = P_e A_{LR}$

(41.2 ± 2.3) %

P_e = 87.66 ± 1.05 % (Run I) P_e = 88.71 ± 0.55 % (Run II)

$A_{LR} = (226.5 \pm 7.3_{stat} \pm 5.8_{syst}) \times 10^{-9}$

$$A_{LR} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = -\frac{2 m_p E_e}{v^2} \frac{g_{AV}^{ep}}{4\pi\alpha} \left[y + \mathcal{O}(y^2) \right]$$

average $y \equiv 1 - E_e'/E_e$ = 0.0115 (average scattering angle θ = 7.9°)

$O(y^2)$-terms from vector, strange and axial form factors

for **P2: (35.2 ± 0.5)%** for scattering angles in the window θ = (35 ± 20)° (average y = 0.0157)

Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 MeV

|Q| = 158 MeV (θ = 7.9°)

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

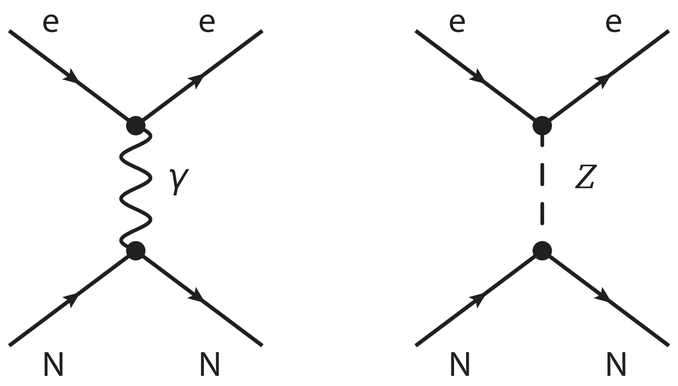
$\Delta A_{PV} = \pm 4.1\%$

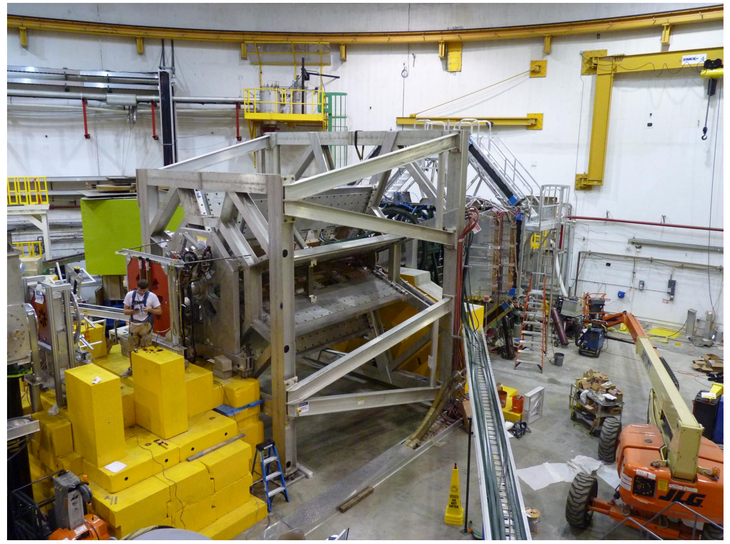
$\Delta Q_W(p) = \pm 6.25\%$

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

FFs from fit to ep asymmetries

arXiv:1905.08283





Parity Violating e⁻ Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 MeV

|Q| = 158 MeV (θ = 7.9°)

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

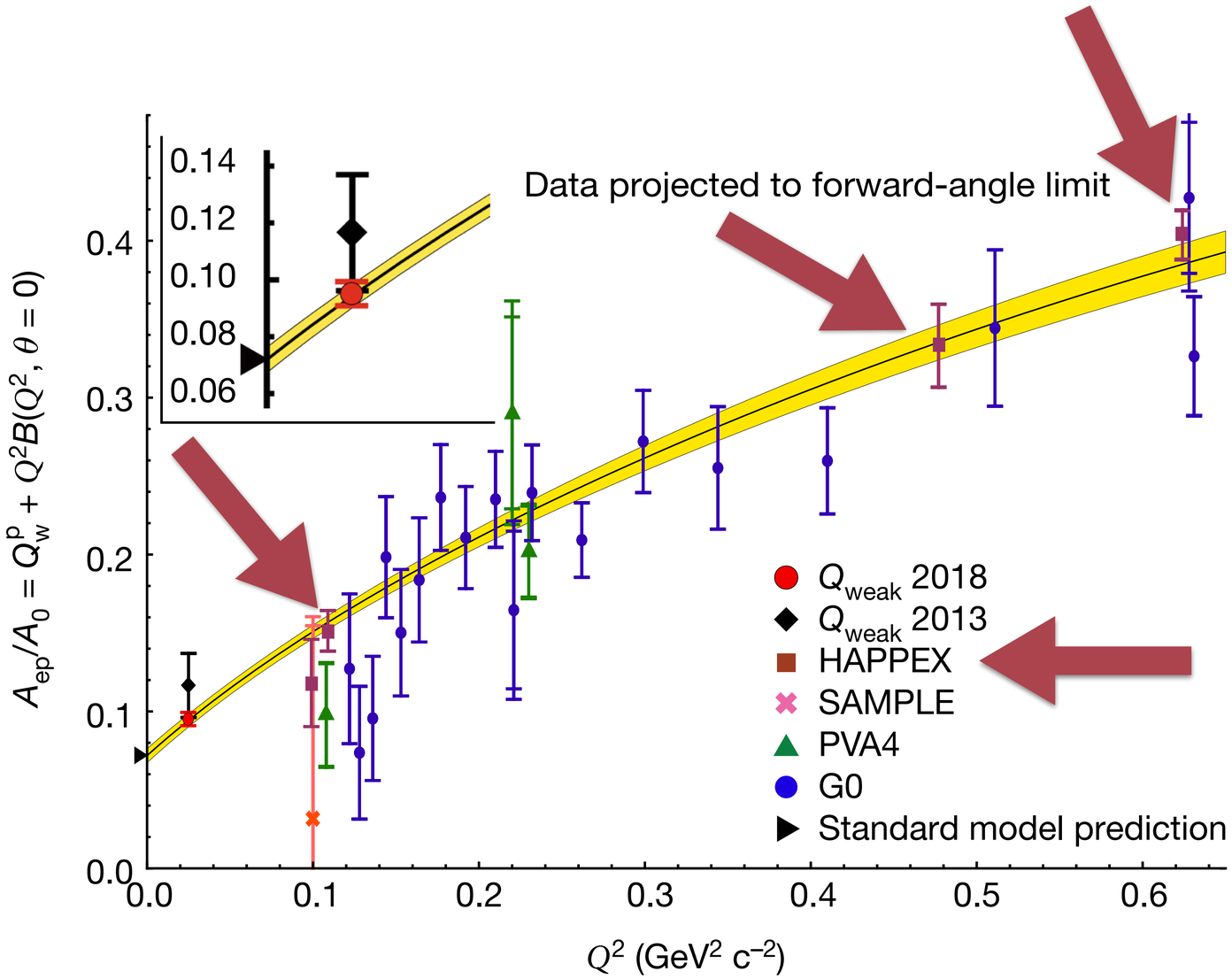
$\Delta A_{PV} = \pm 4.1\%$

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

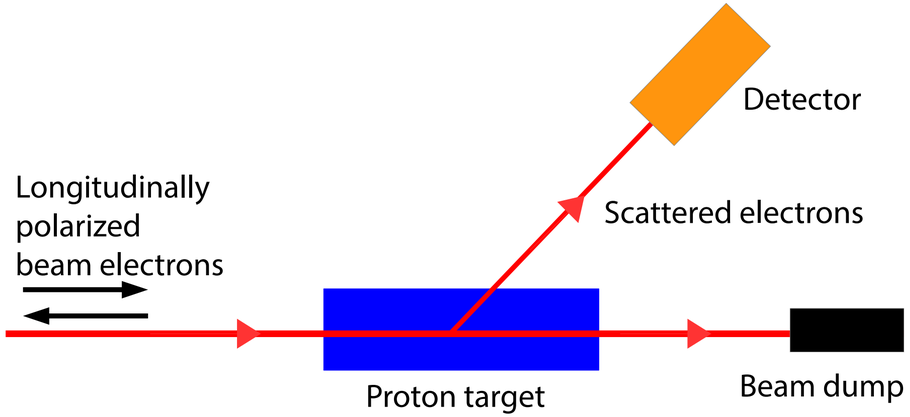
(± 5.3% with lattice input)

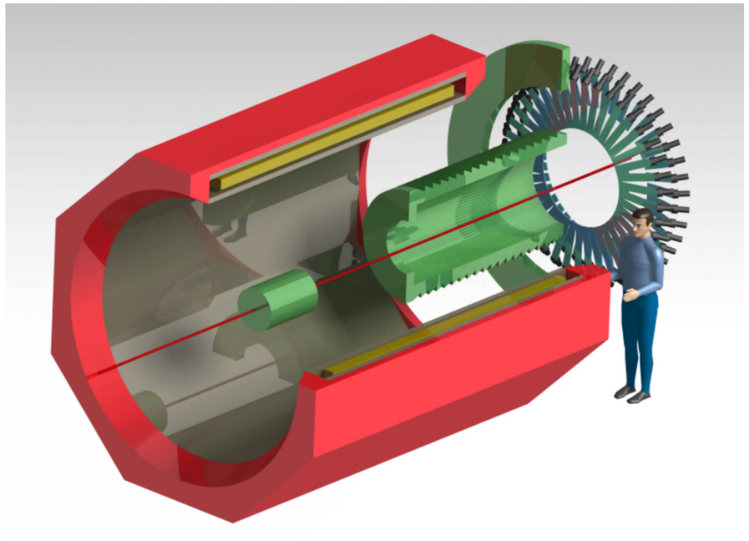
FFs from fit to ep asymmetries

arXiv:1905.08283



Parity Violating e^- Scattering (PVES) — Elastic





<u>P2 @ MESA (JGU Mainz)</u>

hydrogen (CDR)

E_e = 155 MeV

$|Q|$ = 68 MeV (θ = 35° ± 20°)

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

ΔA_{PV} = ± 1.4%

$\Delta Q_W(p)$ = ± 1.83%

$\Delta \sin^2\theta_W$ = ± 0.00033

FFs from backward angle data

arXiv:1802.04759

Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1165 MeV

|Q| = 158 MeV

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

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

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

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

FFs from fit to ep asymmetries

arXiv:1905.08283

P2 @ MESA (JGU Mainz)

hydrogen (CDR)

E_e = 150 MeV

|Q| = 68 MeV

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

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

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

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

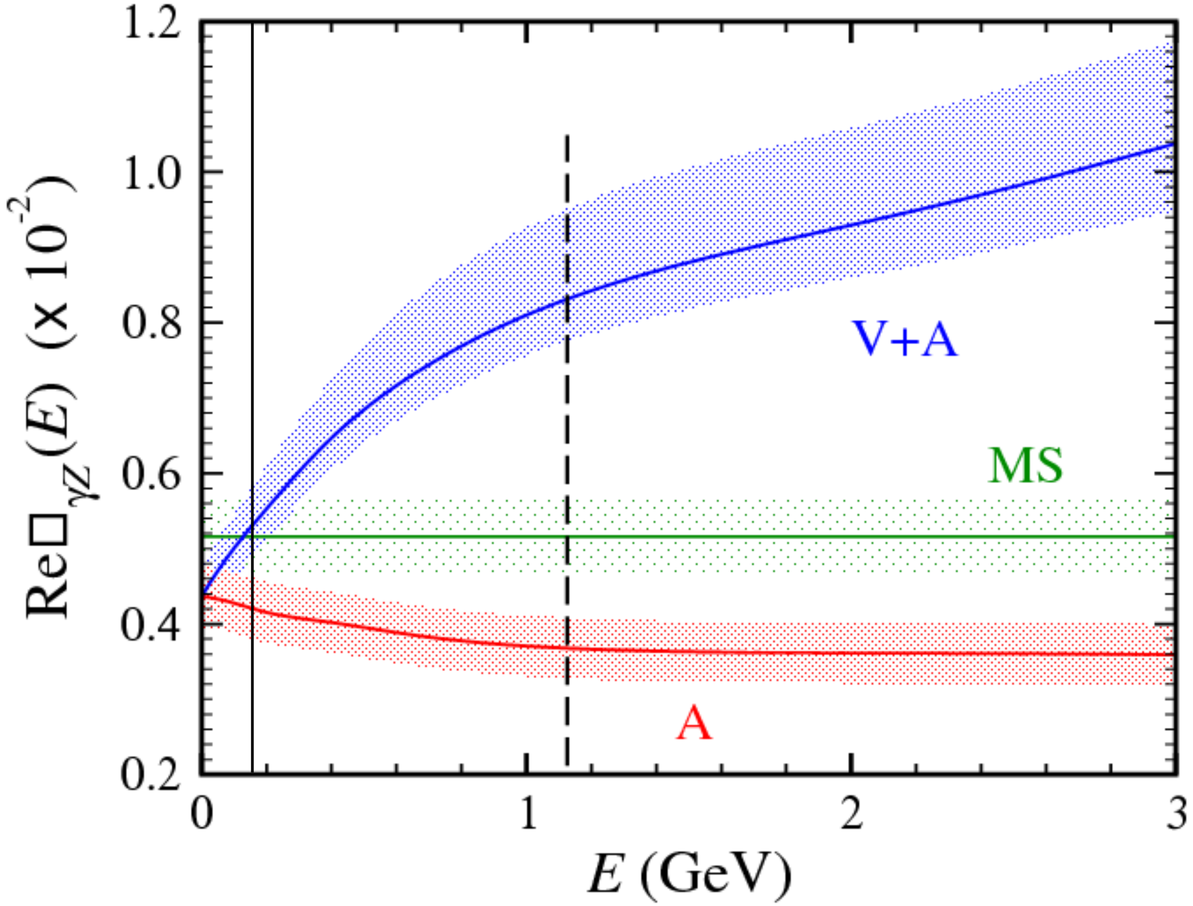
FFs from backward angle data

arXiv:1802.04759

Higher-order corrections

Theory issues in PVES

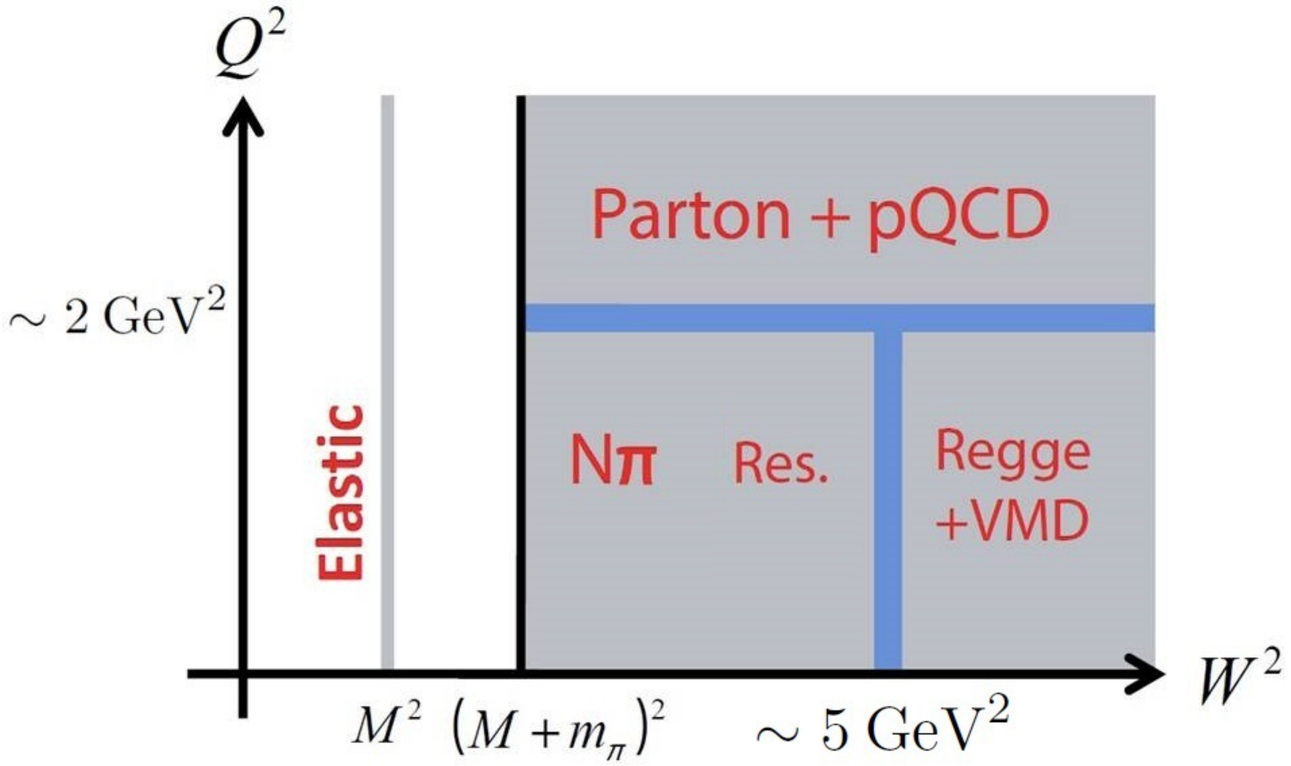
* 1-loop radiative corrections from **Marciano & Sirlin PRD27 (1983) 552; JE & Ramsey-Musolf hep-ph/0302149**
* WW box enhanced by ×7 relative to Møller scattering
* γZ-box uncertainty
* enhanced 2-loop electroweak (γWW-double box)
* running weak mixing angle (see later)
* unknown neutron distribution (neutron skin for heavier nuclei)

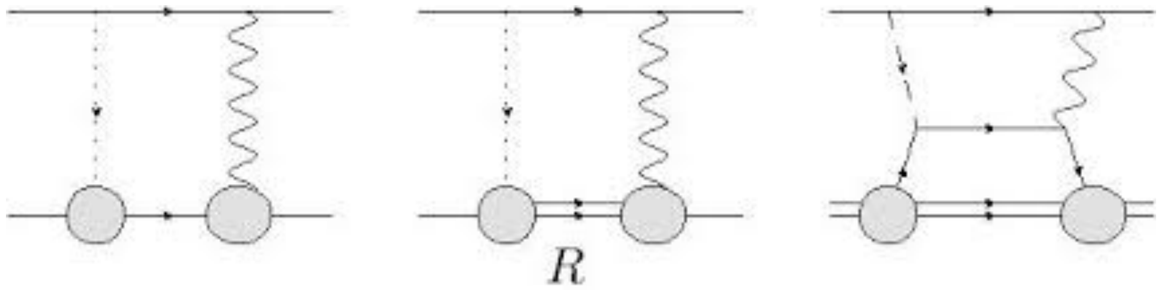


Blunden et al., arXiv:1102.5334

Axial box

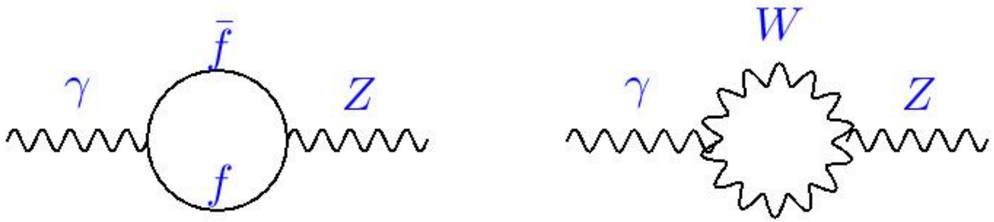
* largest contribution from DIS region
* largest uncertainty from Regge-VMD model
* non-vanishing at $E_e = 0$ (affects APV)
* total error now at 2×10^{-4} (0.3%) level





JE et al., arXiv:1907.07928

$\sin^2\theta_W(0)$ 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

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

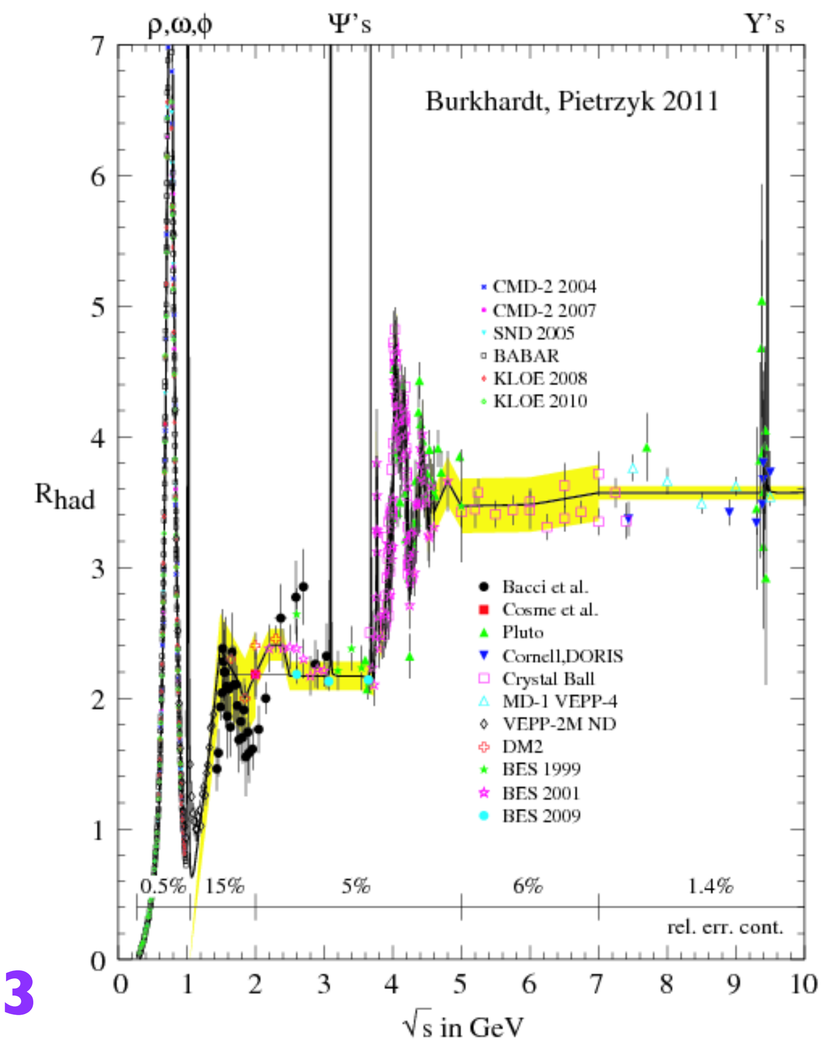
$\alpha(M_Z)$

* 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 $\overline{m}_c$ & $\overline{m}_b$)
  * (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



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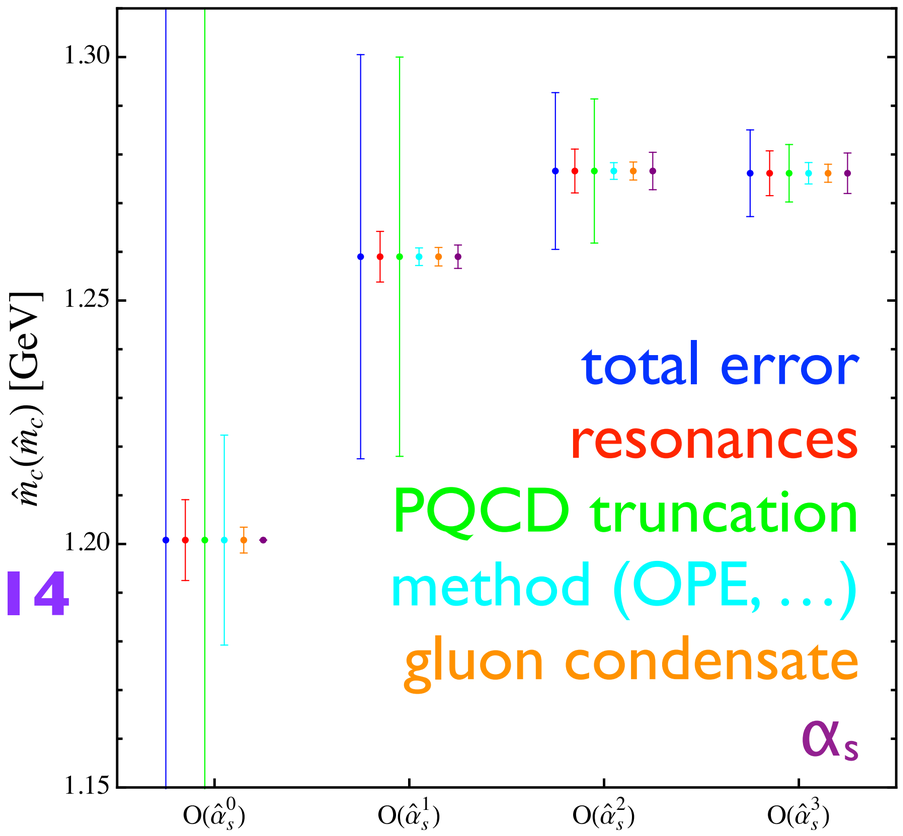
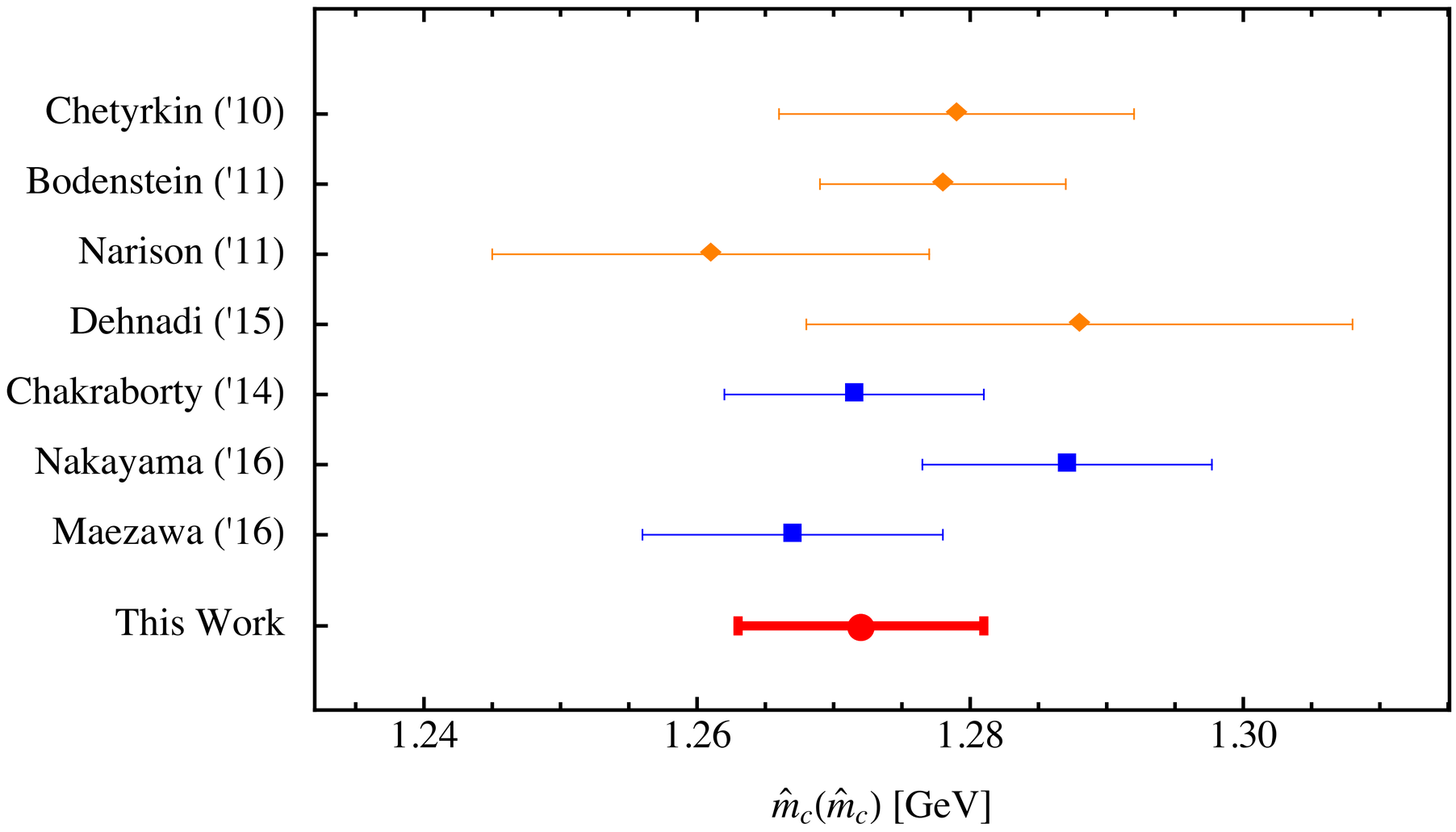
  Masjuan, Spiesberger & JE, arXiv:1610.08531



$m_c(m_c)$ comparison



$g_\mu - 2$

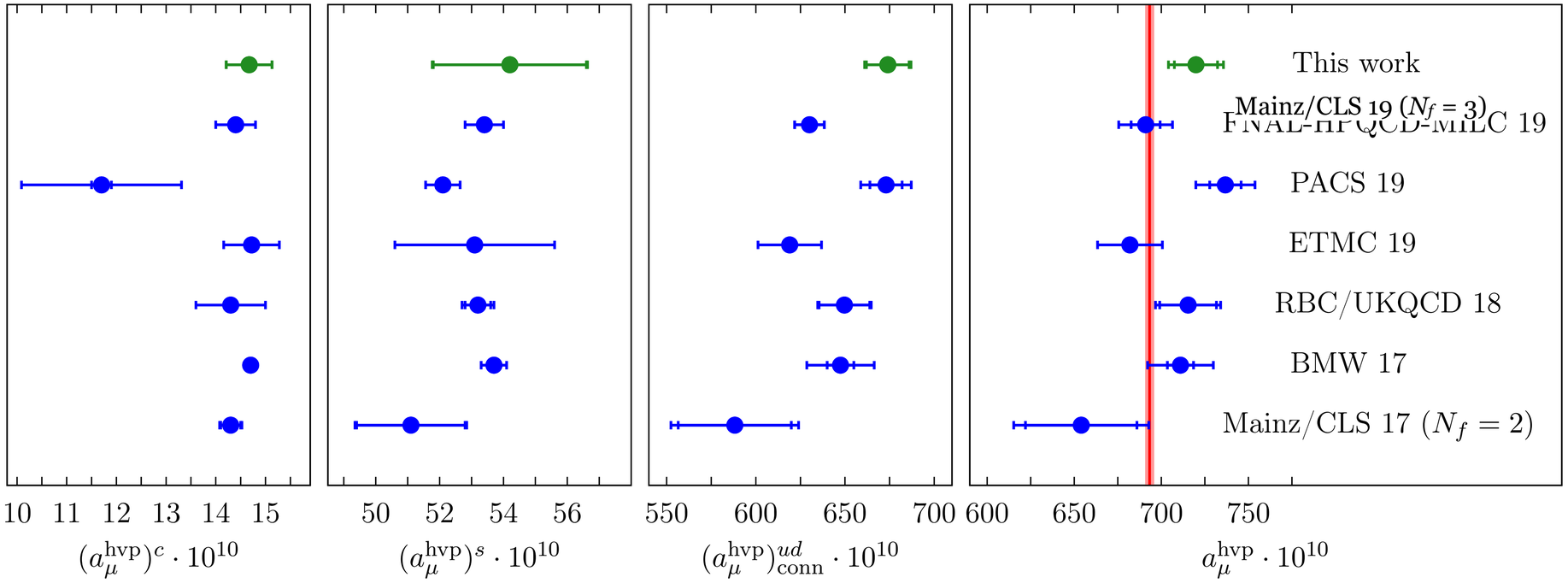
PQCD: $(a_\mu^{hvp})^c = (14.6 \pm 0.5_{theory} \pm 0.2_{mc} \pm 0.1_{\alpha s}) \times 10^{-10}$

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

Luo & JE, hep-ph/0101010

Lattice gauge theory:

Gérardin et al., arXiv:1904.03120



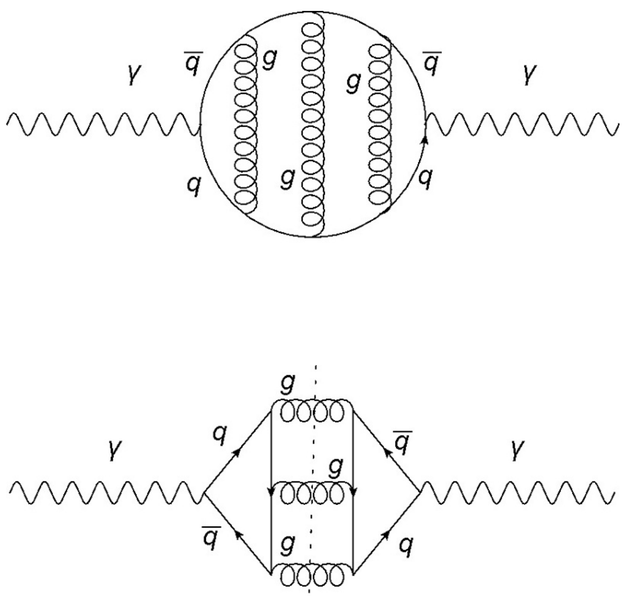
$\sin^2\theta_W(0)$: flavor separation

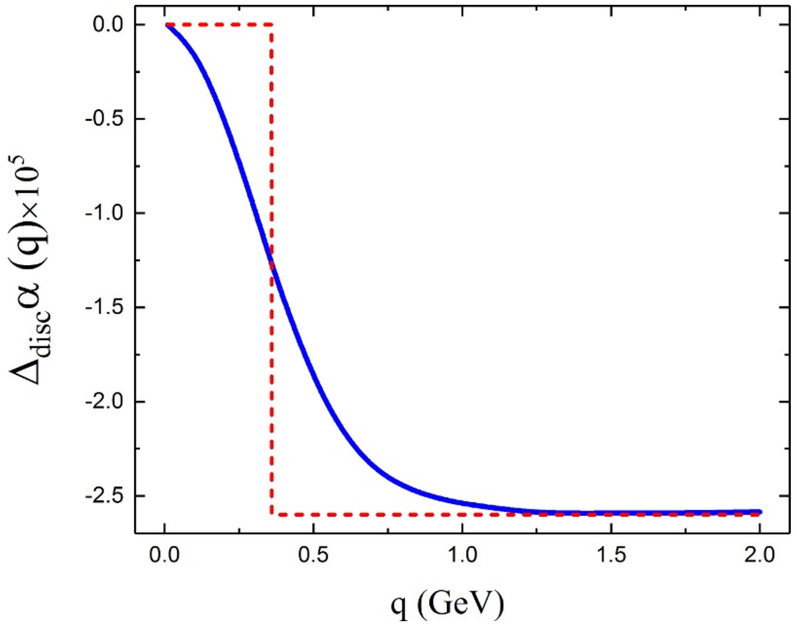
strange quark external current	ambiguous external current
Φ	$K\bar{K}$ (non – Φ)
$K\bar{K}\pi$ [almost saturated by $\Phi(1680)$]	$K\bar{K}2\pi$, $K\bar{K}3\pi$
$\eta\Phi$	$K\bar{K}\eta$, $K\bar{K}\omega$

* 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, arXiv:1602.01767; HPQCD, arXiv:1403.1778
* $\Delta_s\alpha(1.8\text{ GeV}) = (7.09 \pm 0.32)\times10^{-4}$ (threshold mass $\bar{m}_s = 342\text{ MeV} \approx \bar{m}_s^{disc}$)

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





JE & Ferro-Hernández
arXiv:1712.09146

adapted from lattice g_μ–2 calculation
RBC/UKQCD
arXiv:1512.09054

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

$\sin^2\theta_W(0)$

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

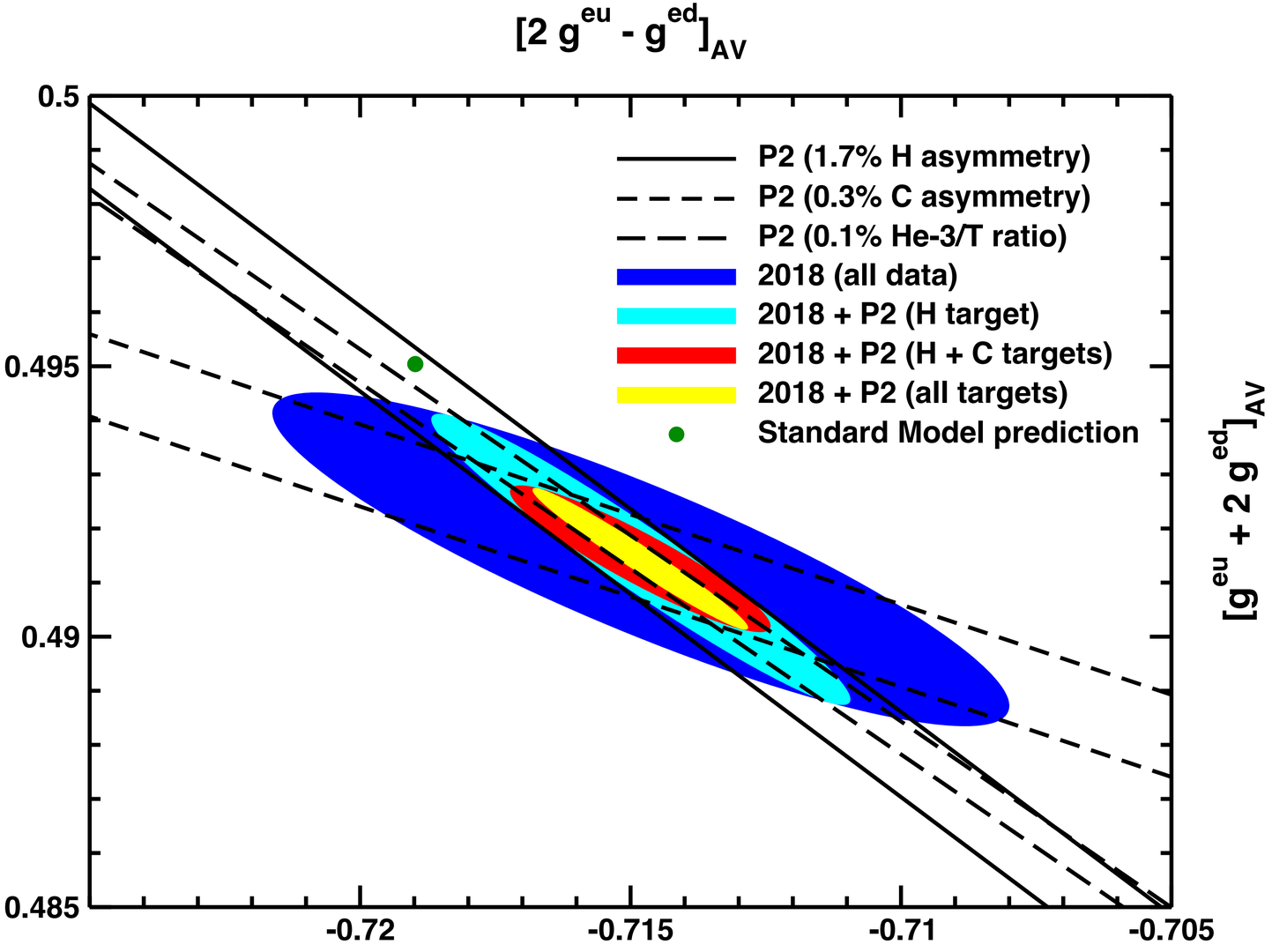
Freitas & JE PDG (2018)

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

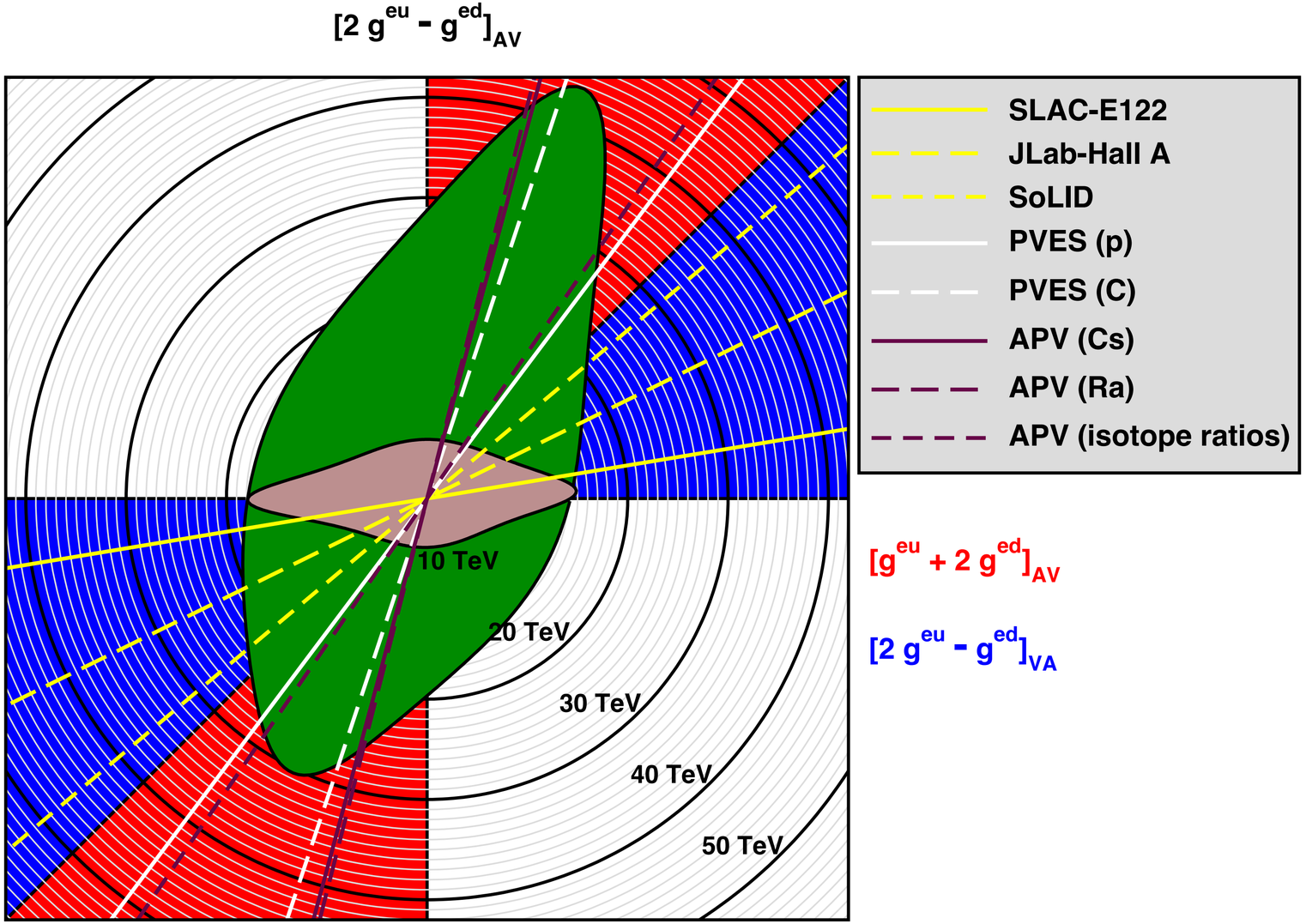
(errors from m_c and m_b negligible)

Beyond the Standard Model

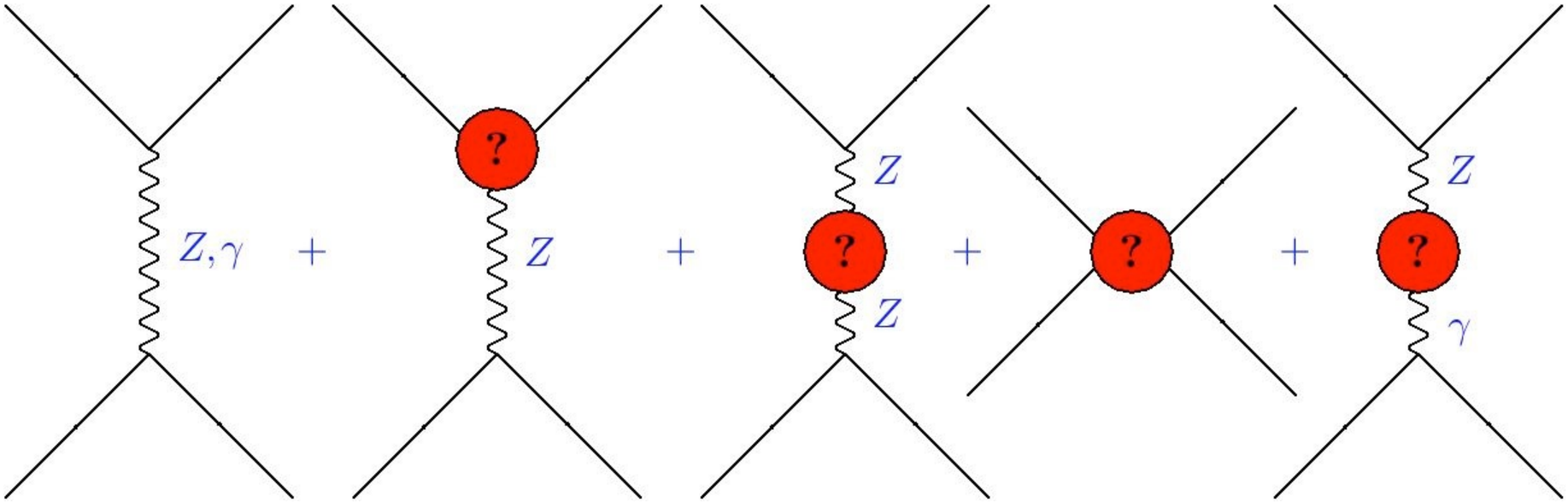
Effective couplings (Wilson coefficients)



Scale exclusions post Qweak



Beyond the SM



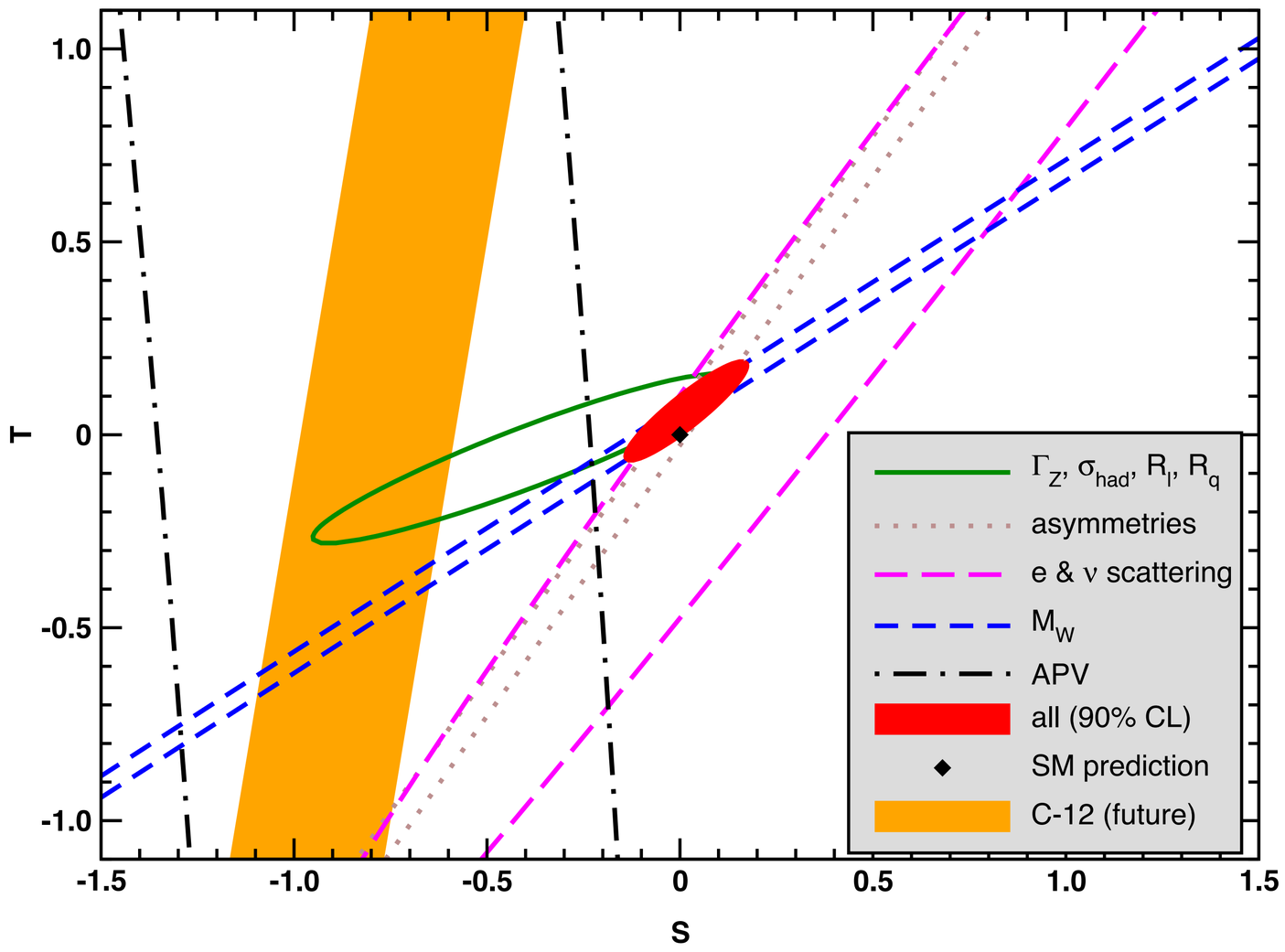
* Z-Z′ mixing: modification of Z vector coupling
* oblique parameters: STU (also need M_W and Γ_Z)
* new amplitudes: off- versus on-Z pole measurements (e.g. Z′)
* dark Z: renormalization group evolution (running)

Related experiments

Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF	**P2 @ MESA**	**P2 @ MESA**
H (completed)	H (CDR)	^{12}C (CDR)
E_e = 1149 MeV	E_e = 155 MeV	E_e = 150 MeV
$\|Q\|$ = 158 MeV	$\|Q\|$ = 68 MeV	$A_{PV} = 6 \times 10^{-7}$
$A_{PV} = 2.3 \times 10^{-7}$	$A_{PV} = 4 \times 10^{-8}$	$\Delta A_{PV} = \pm 0.3\%$
$\Delta A_{PV} = \pm 4.1\%$	$\Delta A_{PV} = \pm 1.4\%$	$\Delta Q_W(^{12}C) = \pm 0.3\%$
$\Delta Q_W(p) = \pm 6.25\%$	$\Delta Q_W(p) = \pm 1.83\%$	$\Delta \sin^2\theta_W = \pm 0.0007$
$\Delta \sin^2\theta_W = \pm 0.0011$	$\Delta \sin^2\theta_W = \pm 0.00033$	neutron skin?
FFs from fit	FFs from backward angles	only one FF
arXiv:1905.08283	**arXiv:1802.04759**	**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

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

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

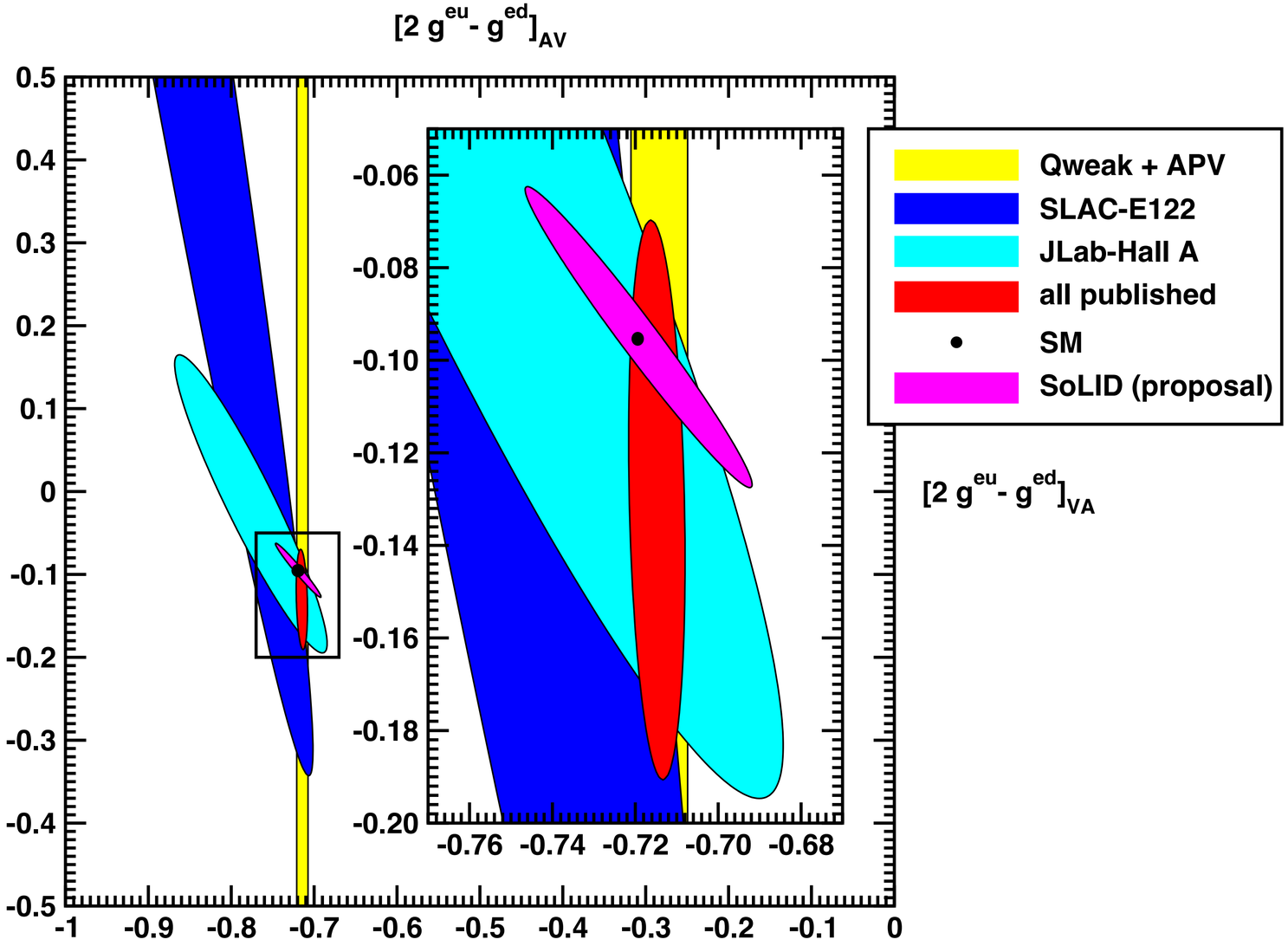
$\Delta \sin^2\theta_W = \pm 0.00057$

Higher twist?

Isospin violation?

arXiv:1810.00989

Effective couplings (Wilson coefficients)



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

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

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

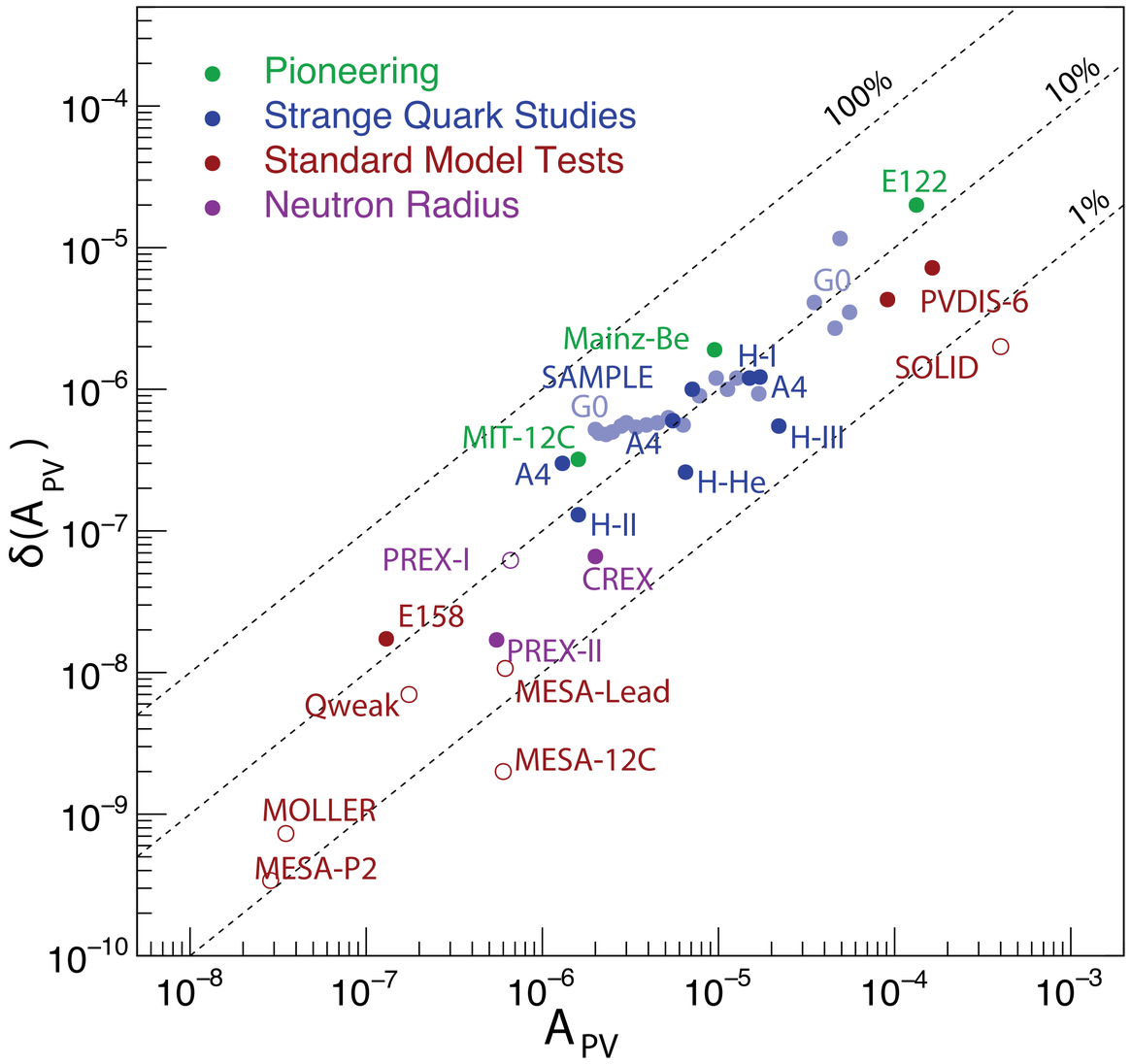
$\Delta A_{PV} = \pm 2.4\%$

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

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

arXiv:1411.4088

PVES history



Coherent Elastic ν Nucleus Scattering (CEνNS)

COHERENT @ SNS

CsI

$E_\nu \approx 16 - 53$ MeV

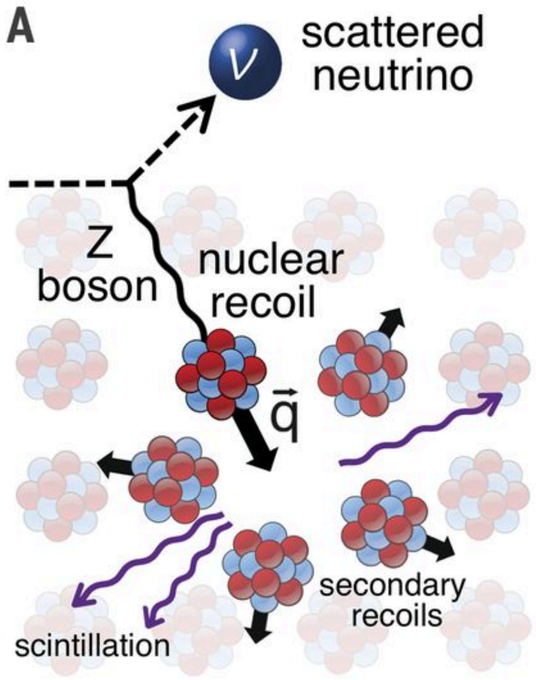
$\sigma \sim Q_W^2$

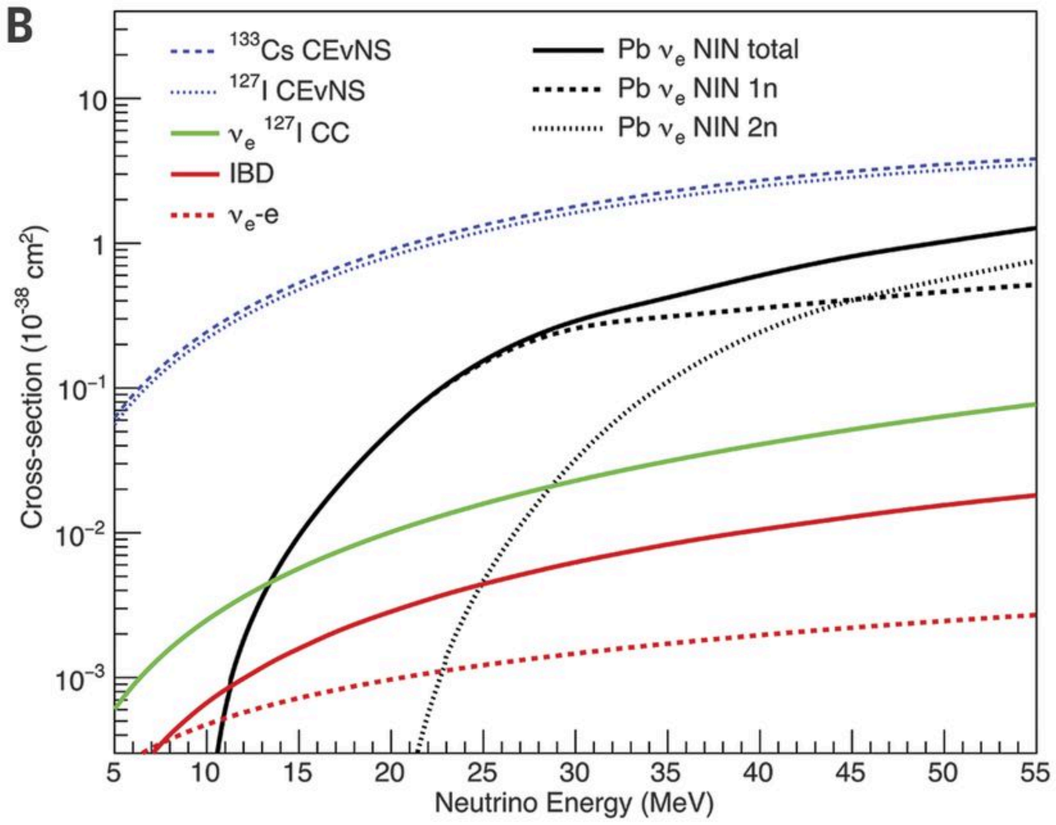
134 ± 22 events

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

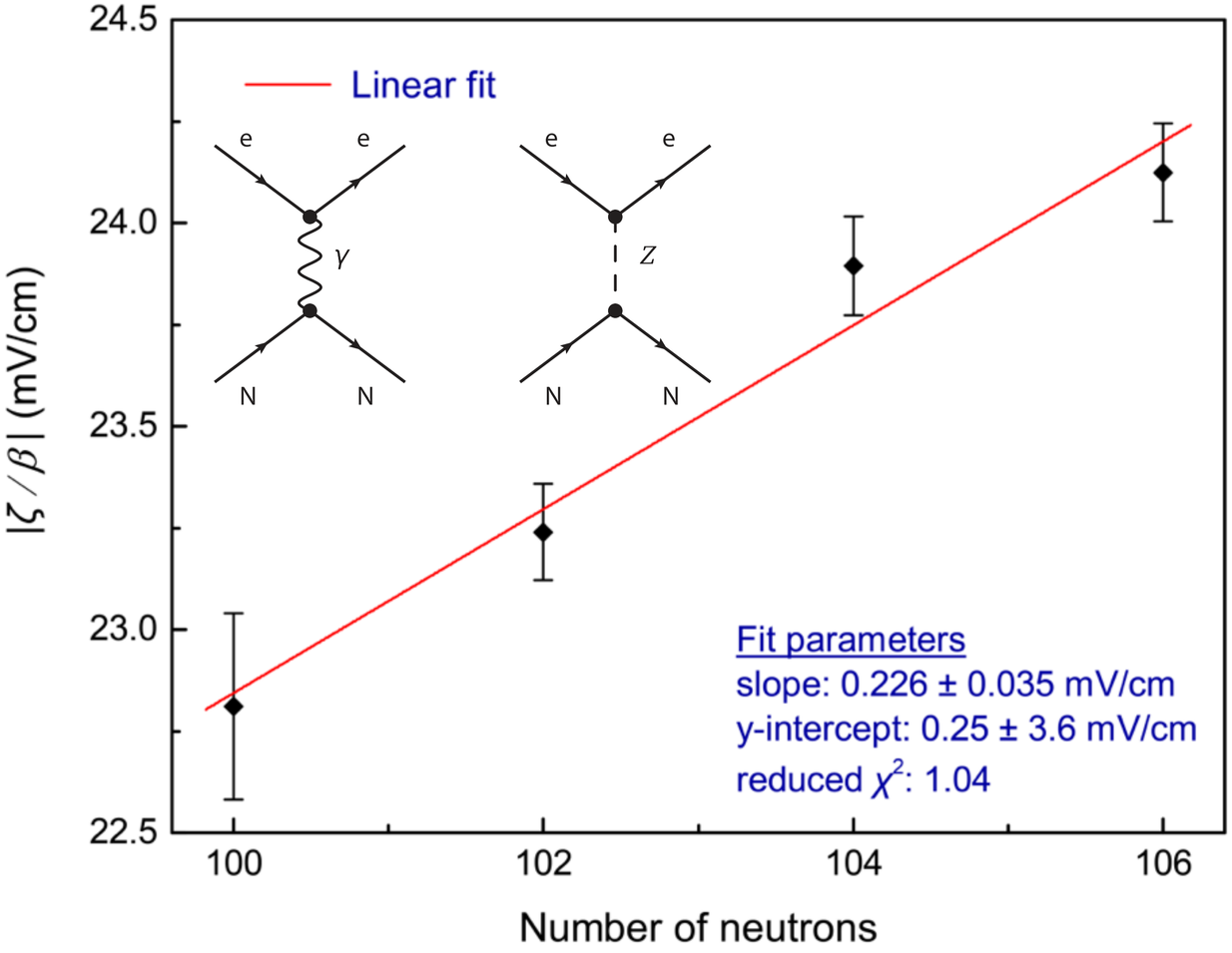
± 100% error in $\sin^2\theta_W$

constraints on Z´ with M < 100 keV

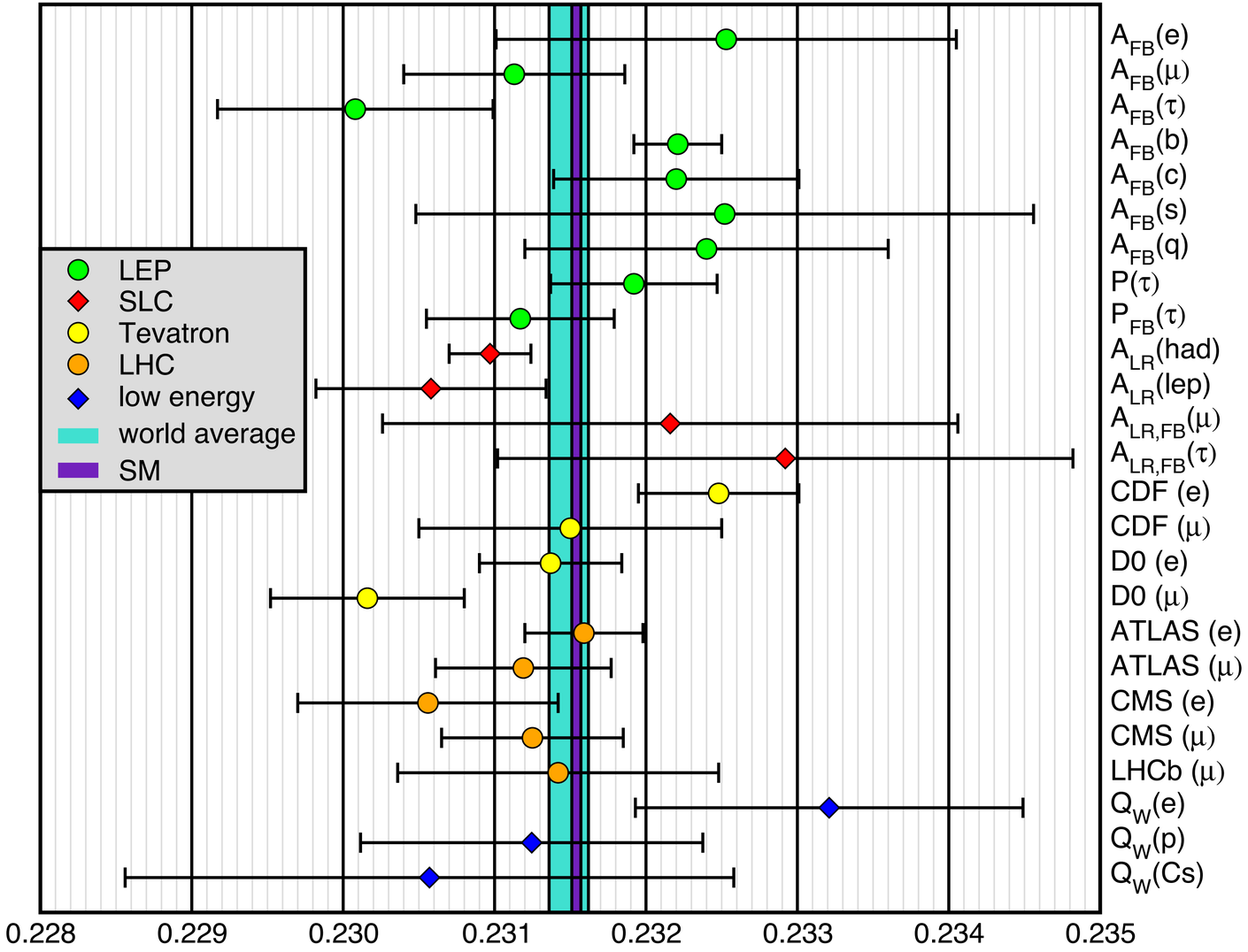
$\Delta\sin^2\theta_W = \pm 0.2$

neutron skin?

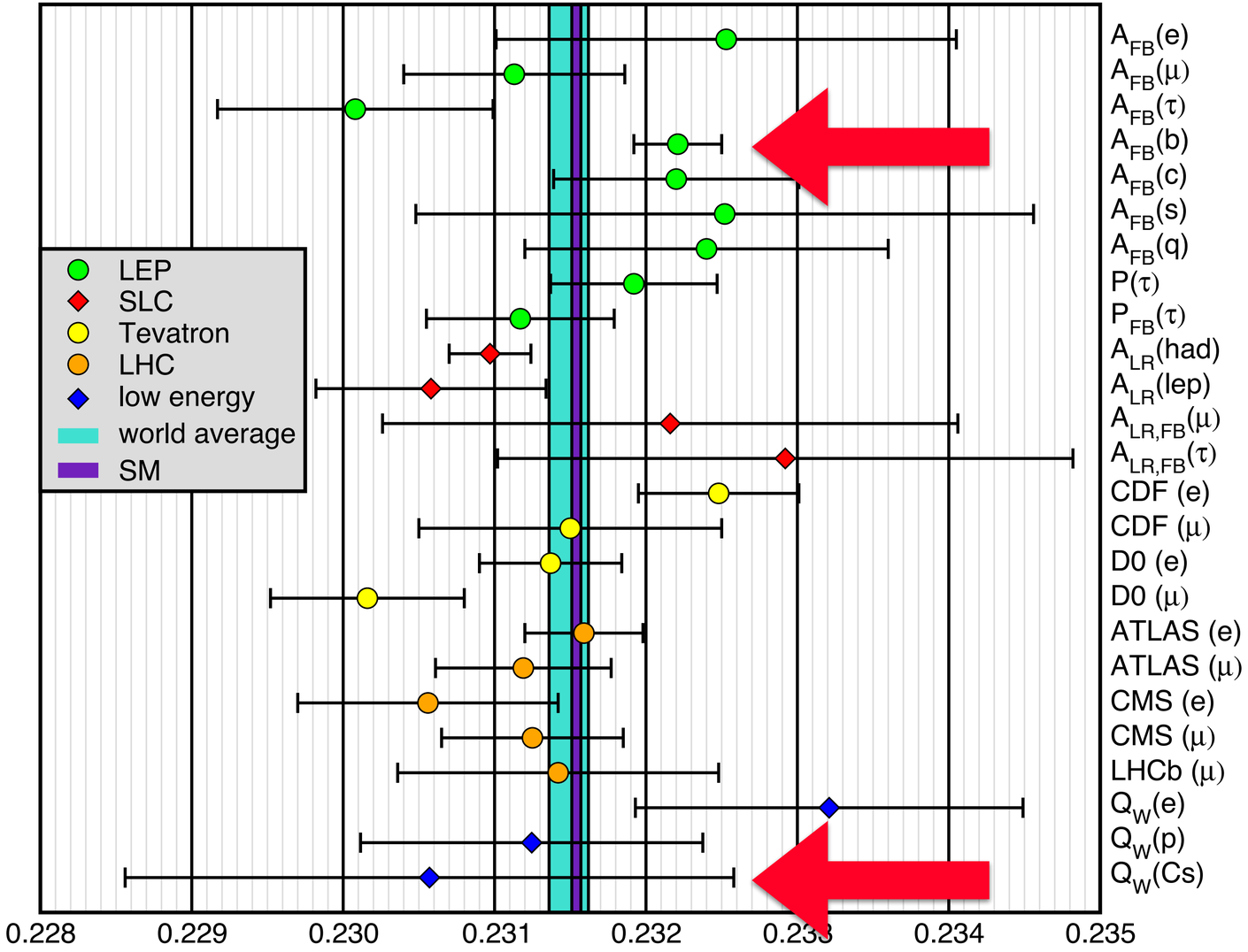
arXiv:1804.05747



Weak mixing angle measurements



Weak mixing angle measurements



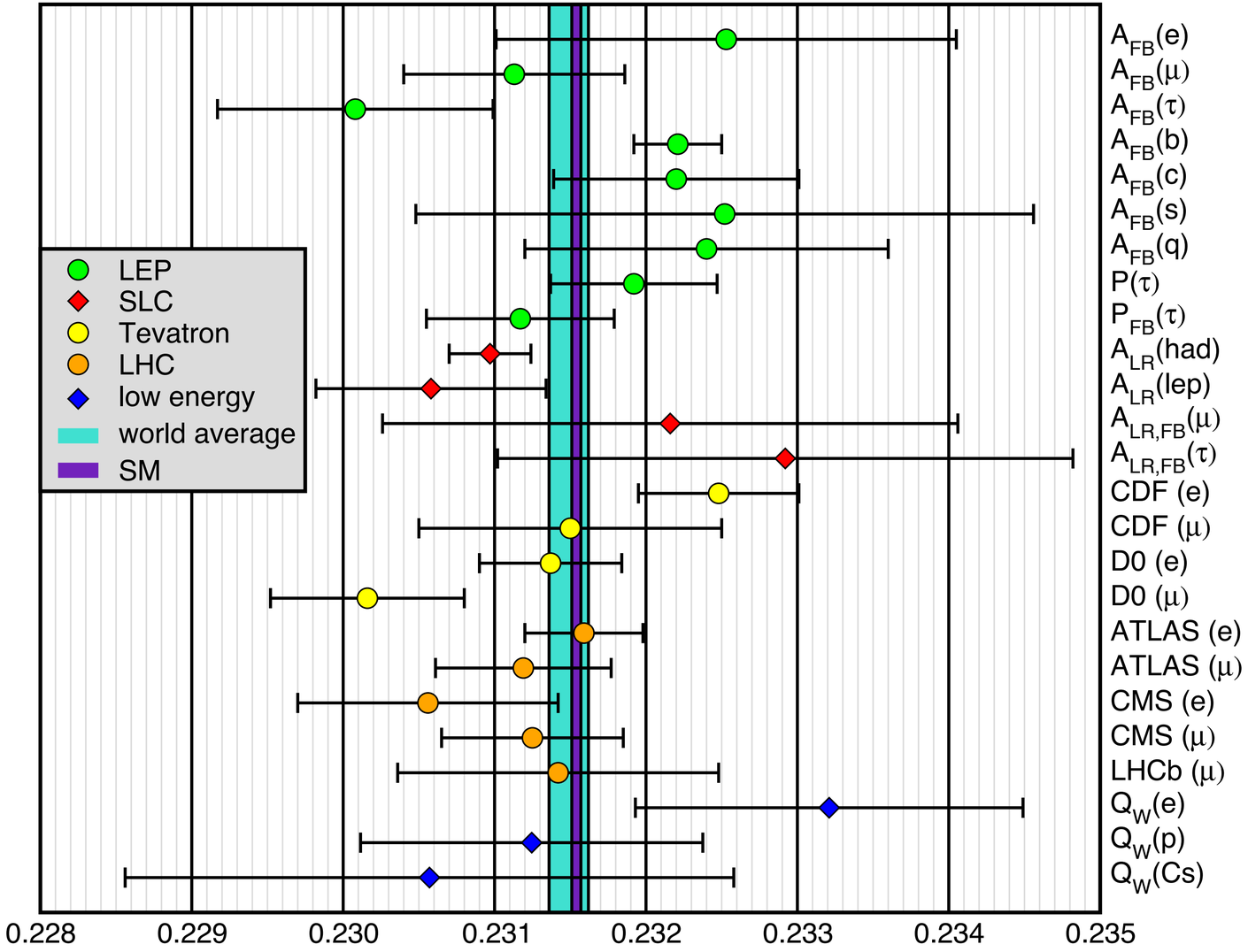
2-loop QCD correction with $m_b \neq 0$

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

Conclusions

Summary and conclusions

* first measurement of proton's weak charge by Qweak@JLab
* ultra-high precision measurement anticipated at P2@MESA-Mainz
* theory needs refinements
  * ideally full two-loop calculation
  * enhanced three-loop effects
  * γZ-box (vector) improvement
  * correction to asymmetry under experiment specific conditions
  * but **no showstoppers**