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

# Status and Prospects for Standard Model Fits

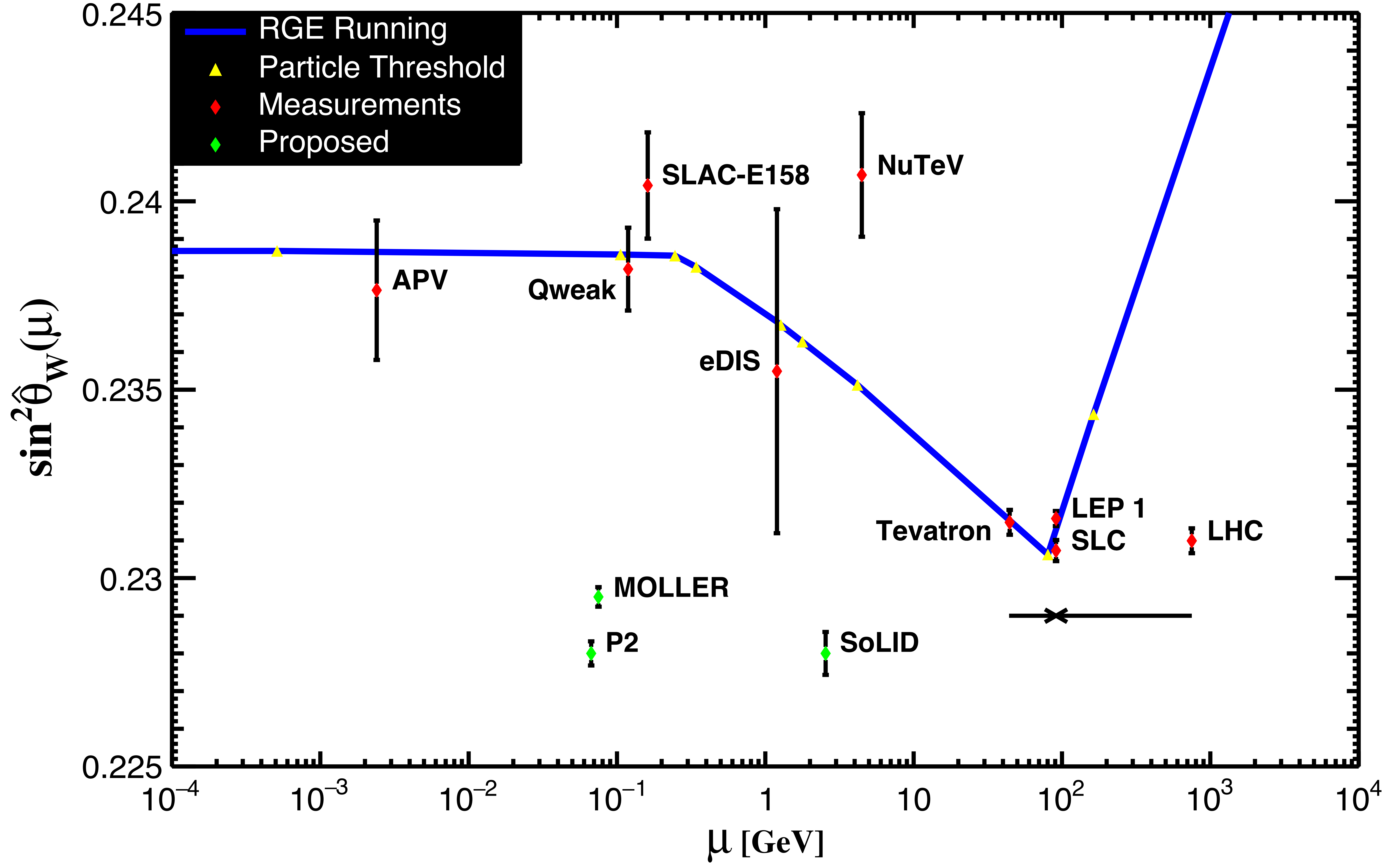
LFC19:
Strong dynamics for physics within and beyond the Standard Model at LHC and Future Colliders
ECT* Trento, September 9–13, 2019

# Outline

* *News on $\sin^2\theta_W$ and related experiments:*
    * first measurements
    * updated extractions
* *Electroweak fits:*
    * Results
    * Theoretical uncertainties and correlations
    * FCC–ee
* *Conclusions and outlook*

# *News on $\sin^2\theta_W$ and related experiments*

# Running weak mixing angle





**Ferro-Hernández & JE**
**arXiv:1712.09146**

# 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
    * 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 | parity-violating electron 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) |

# Coherent Elastic ν Nucleus Scattering (CEνNS)

**COHERENT @ SNS**

CsI

$E_\nu \approx 16 - 53$ MeV

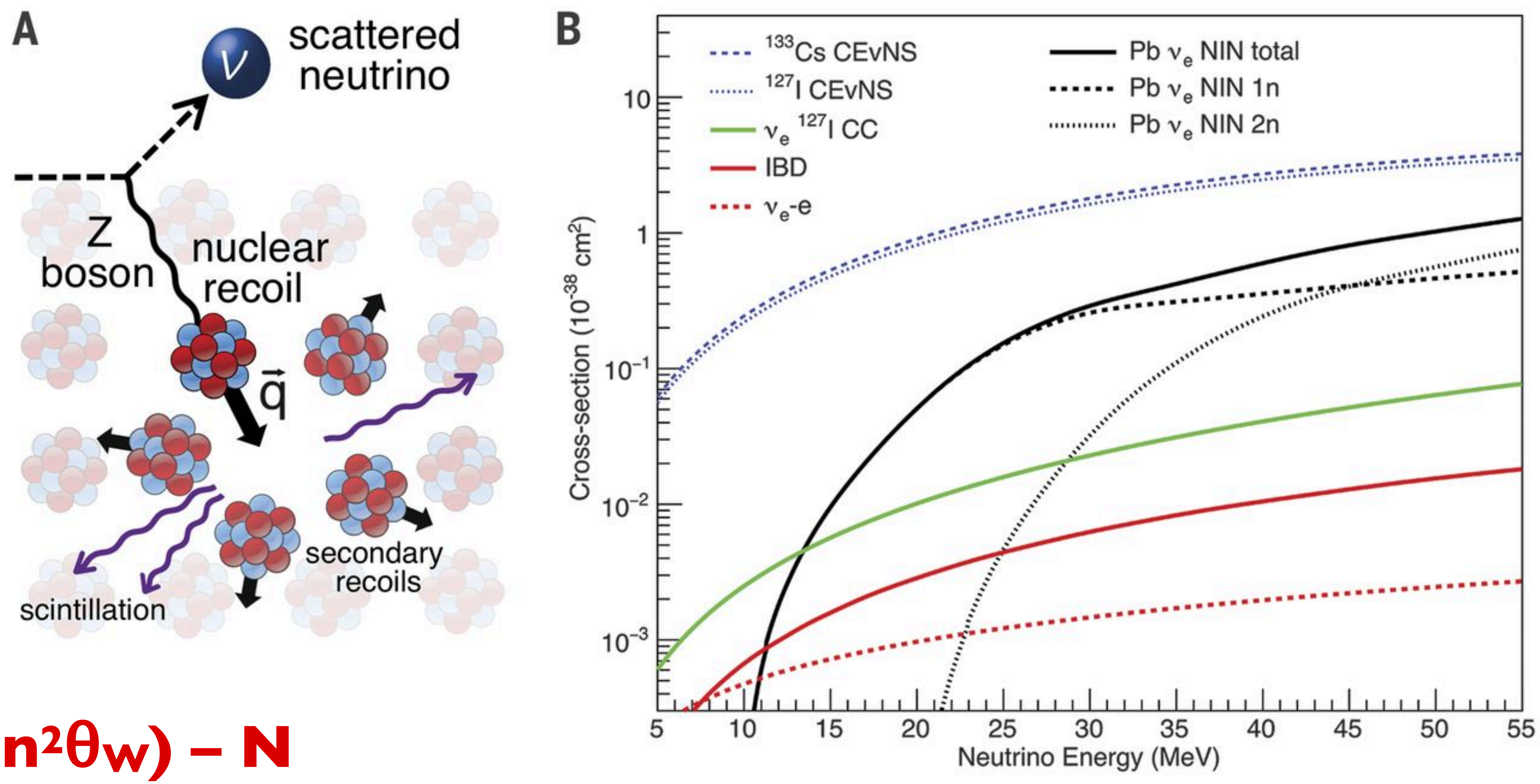
$\sigma \sim Q_W^2$

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

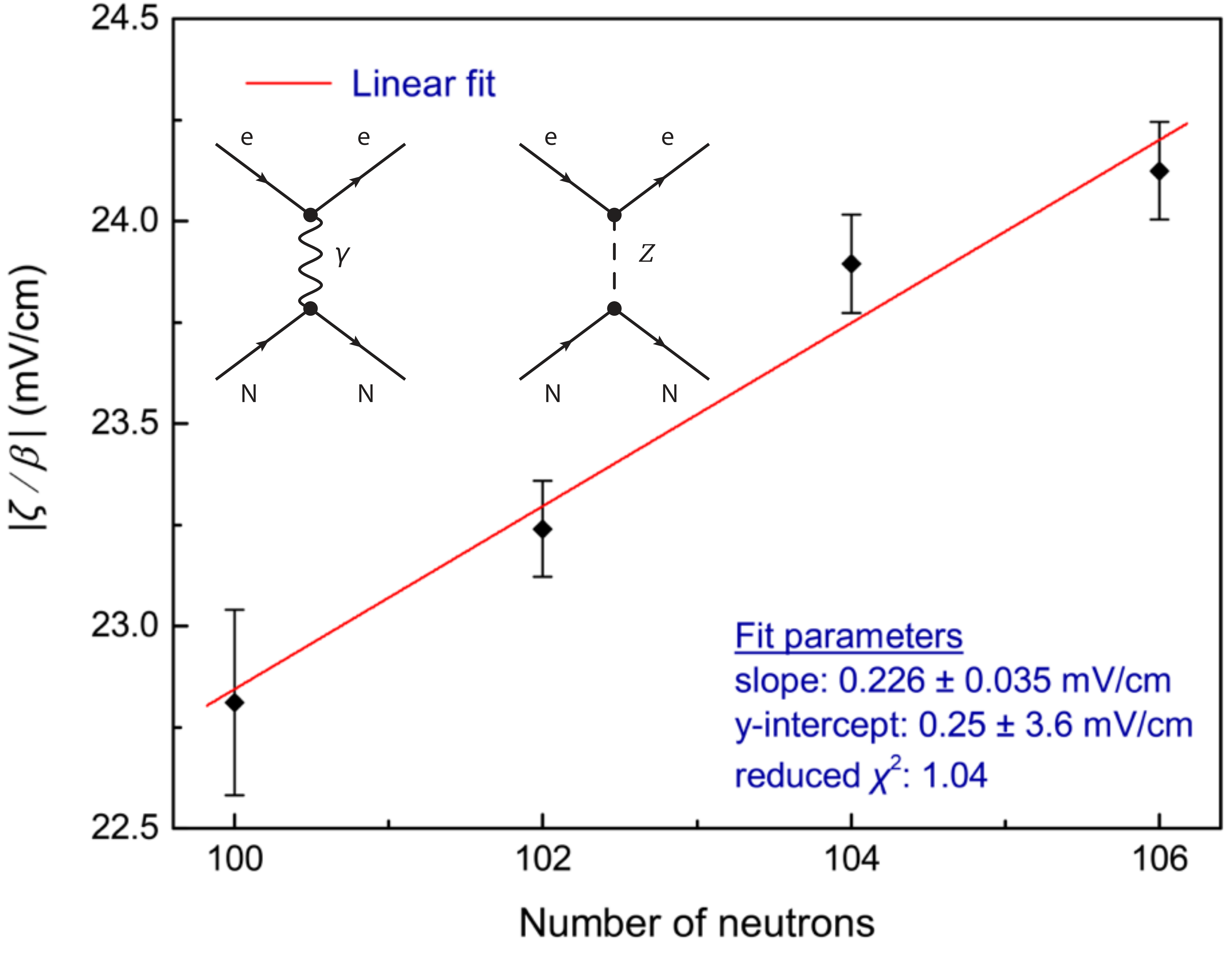
± 100% error in $\sin^2\theta_W$

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

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

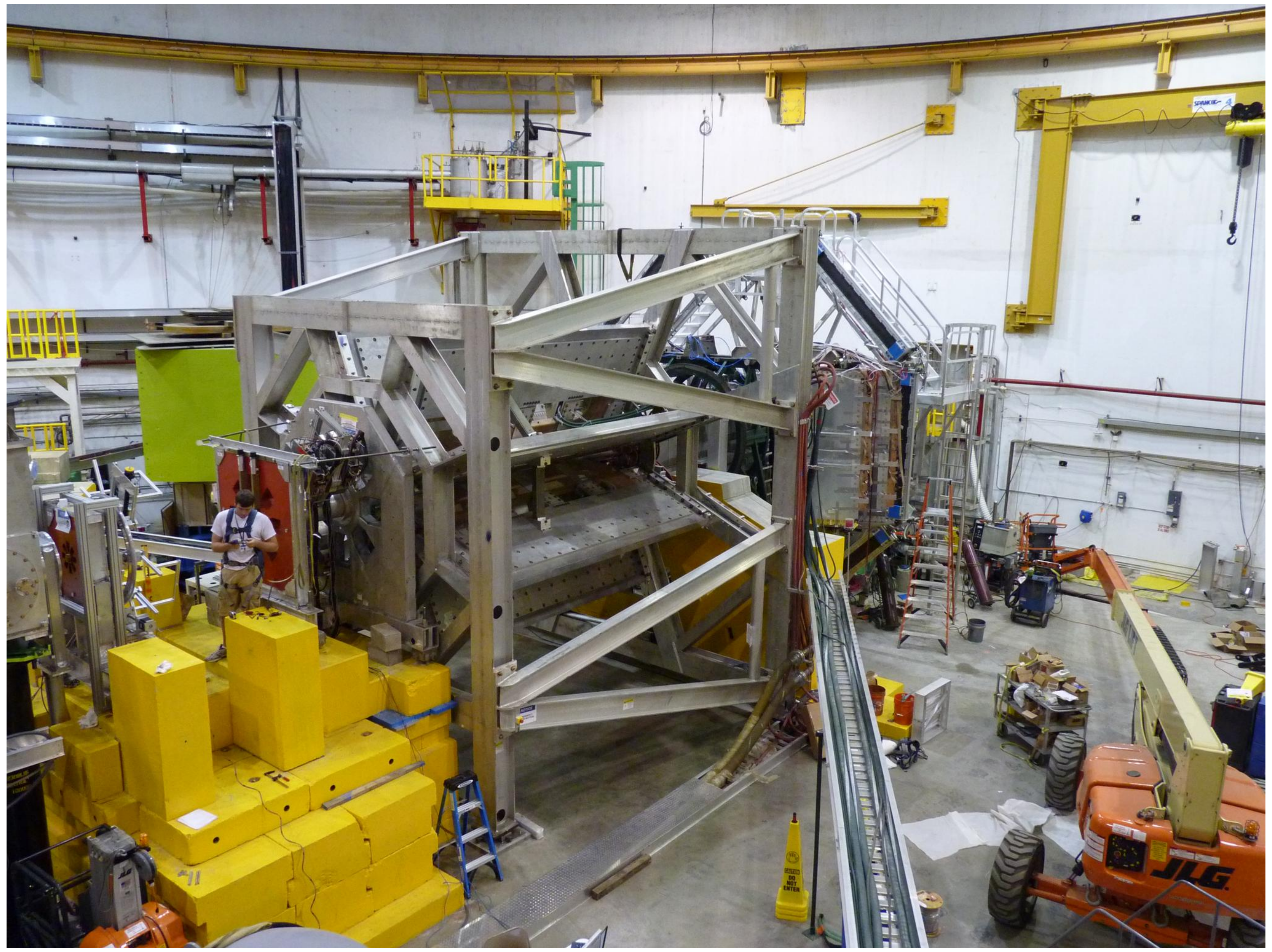
$\Delta A_{PV} = \pm 4.1\%$

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

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

FFs from fit to ep asymmetries

**arXiv:1905.08283**



# Parity Violating e⁻ Scattering (PVES) — Elastic

**Qweak @ CEBAF (JLab)**

hydrogen (completed)

$E_e$ = 1165 MeV

|Q| = 158 MeV

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

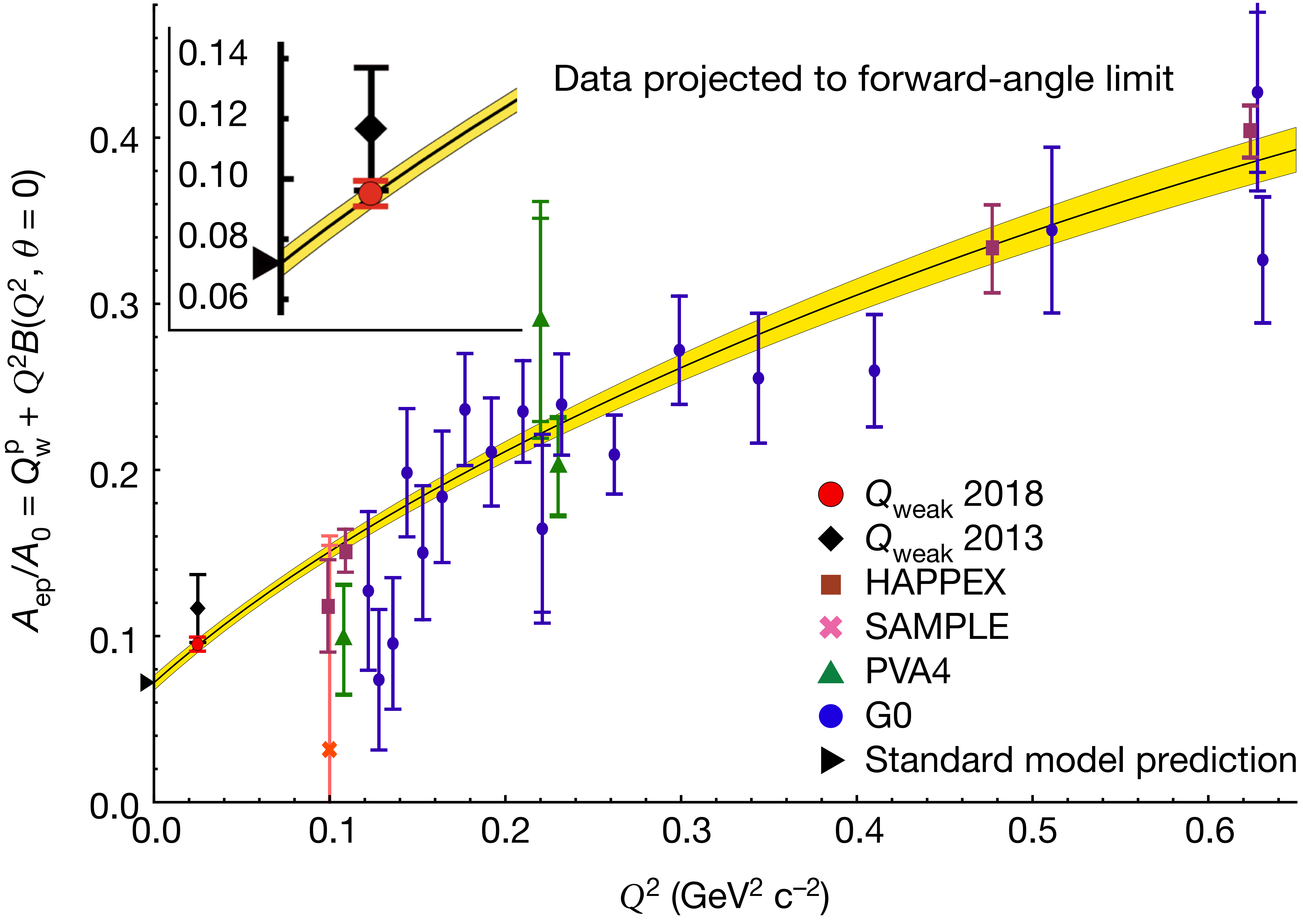
$\Delta A_{PV}$ = ± 4.1%

$\Delta Q_W(p)$ = ± 6.25%

$\Delta \sin^2\theta_W$ = ± 0.0011

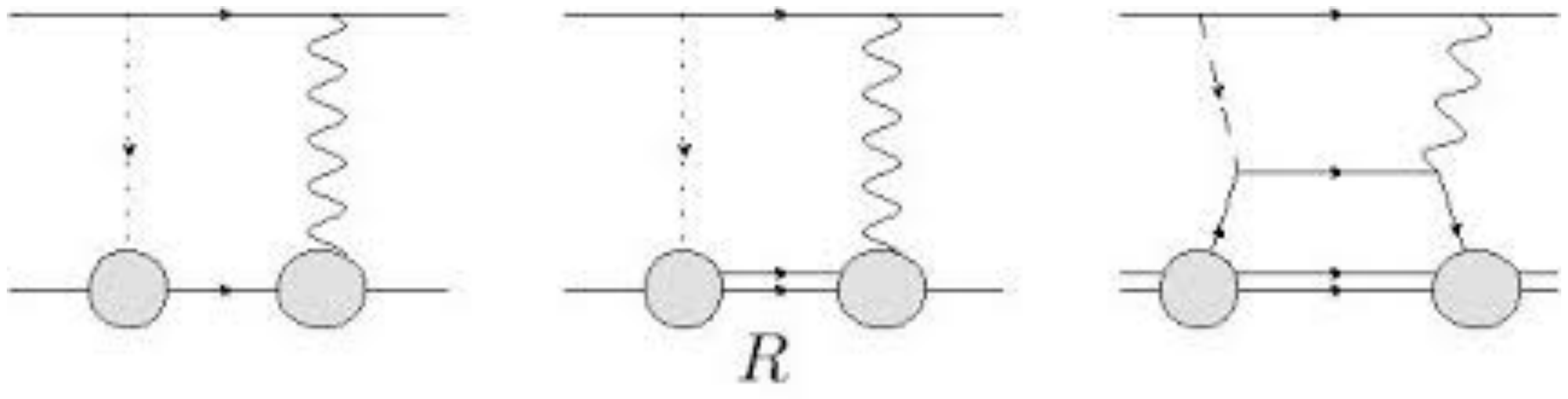
FFs from fit to ep asymmetries

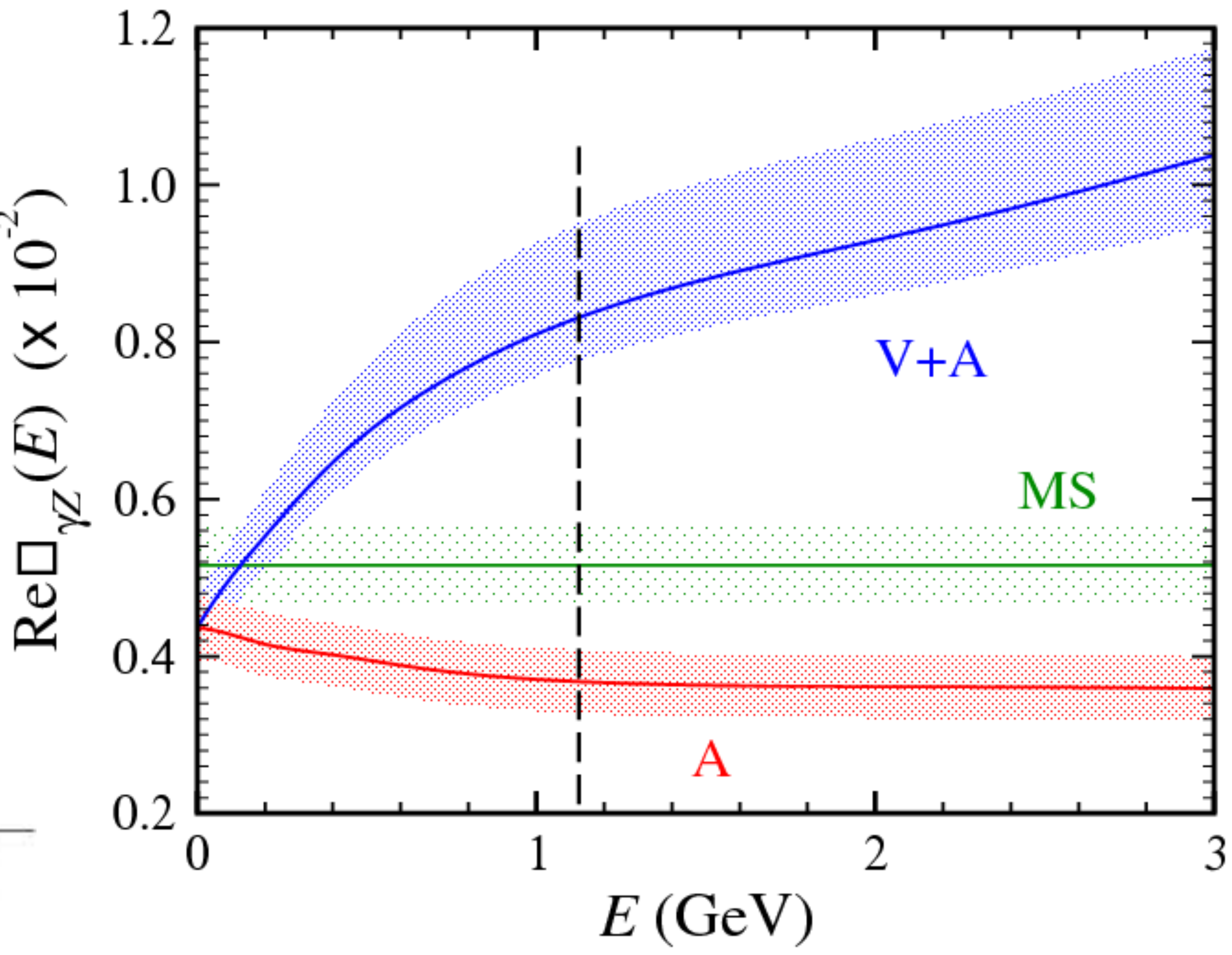
**arXiv:1905.08283**



# Theory issues in PVES

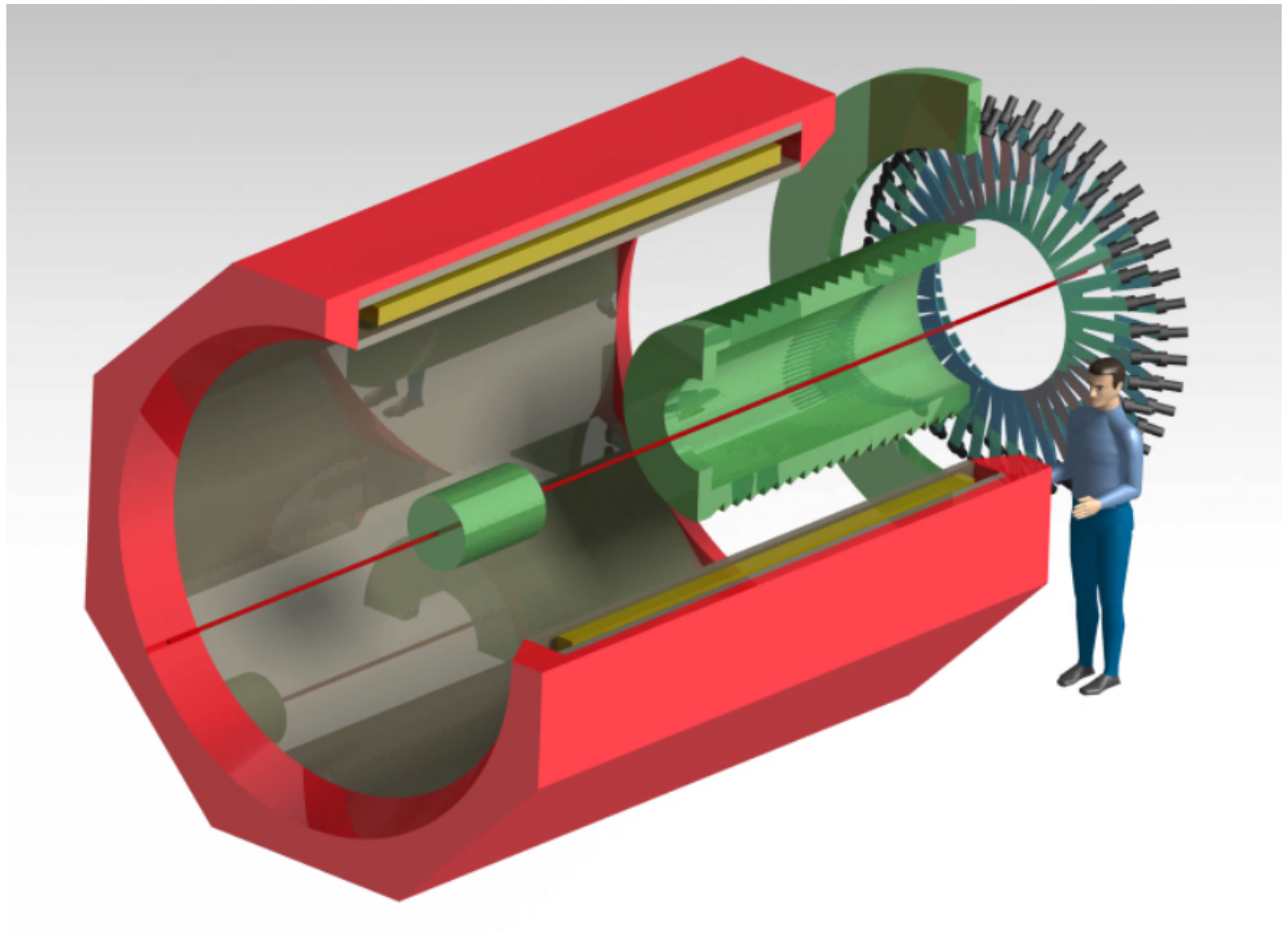
* need full 1-loop QED under experiment-specific conditions
* box diagrams (γZ-box)
* enhanced 2-loop electroweak (γWW-double box)
* running weak mixing angle
* unknown neutron distribution (neutron skin for heavier nuclei)




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

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

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

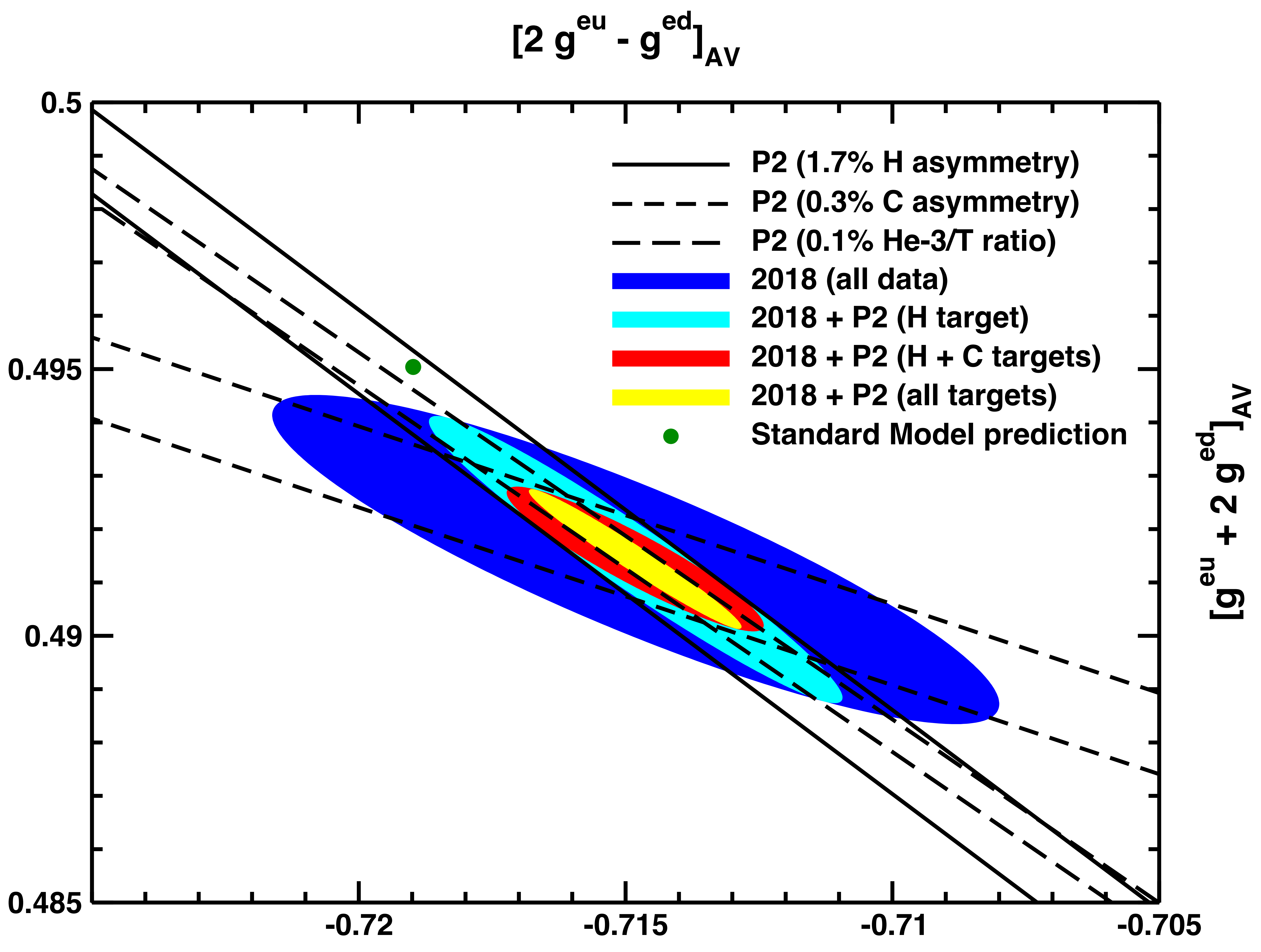
$\Delta Q_W(p) = \pm\ 1.83\%$

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

FFs from backward angle data

**arXiv:1802.04759**

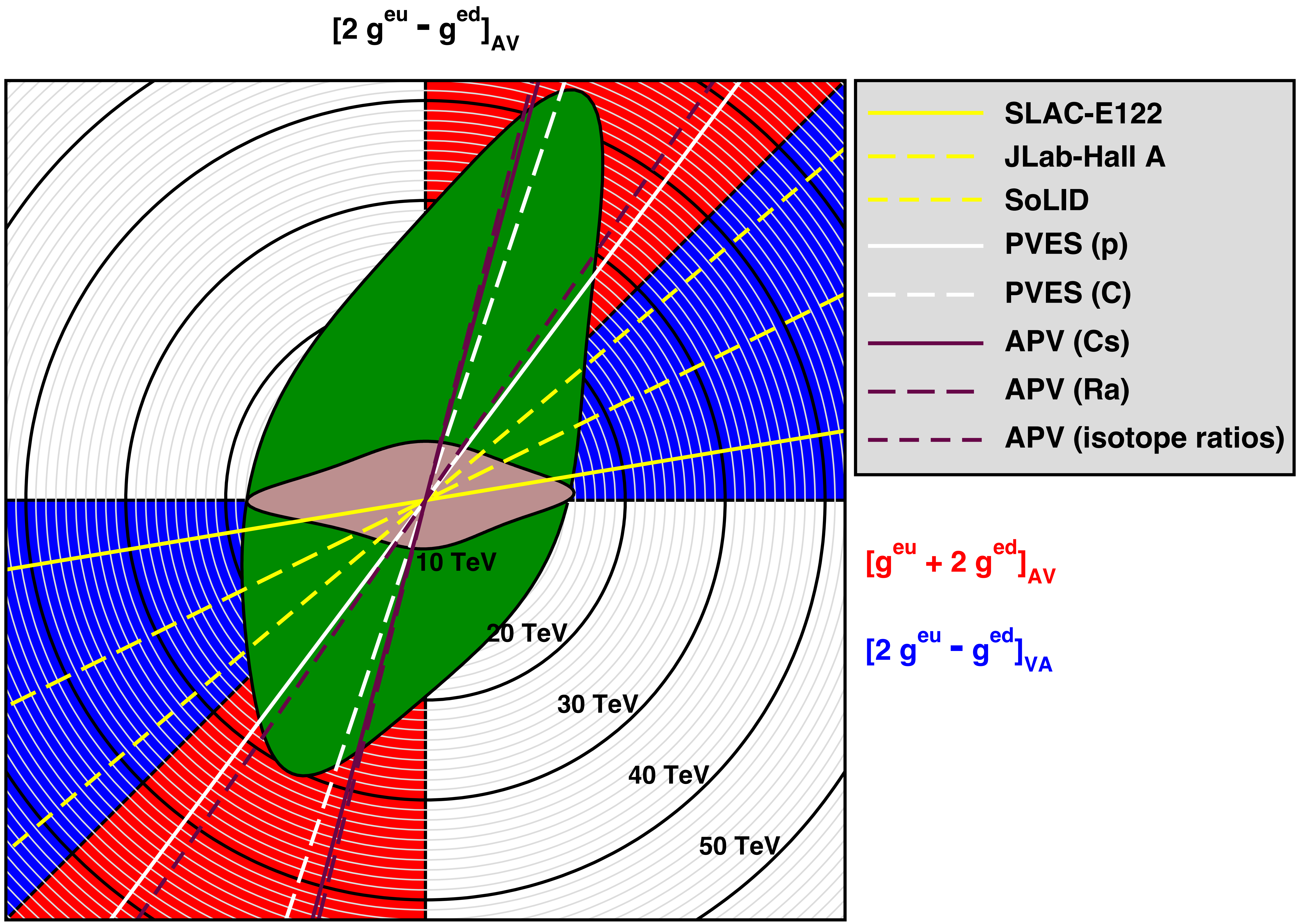
# Effective couplings (Wilson coefficients)



# Parity Violating $e^-$ Scattering (PVES) — Elastic

| **Qweak @ CEBAF** | **P2 @ MESA** | **P2 @ MESA** |
| --- | --- | --- |
| H (completed) | H (CDR) | $^{12}C$ (CDR) |
| $E_e$ = 1165 MeV | $E_e$ = 155 MeV | $E_e$ = 150 MeV |
| $\|Q\|$ = 158 MeV | $\|Q\|$ = 67 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** |

# Scale exclusions post Qweak




PRISMA+

# 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

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

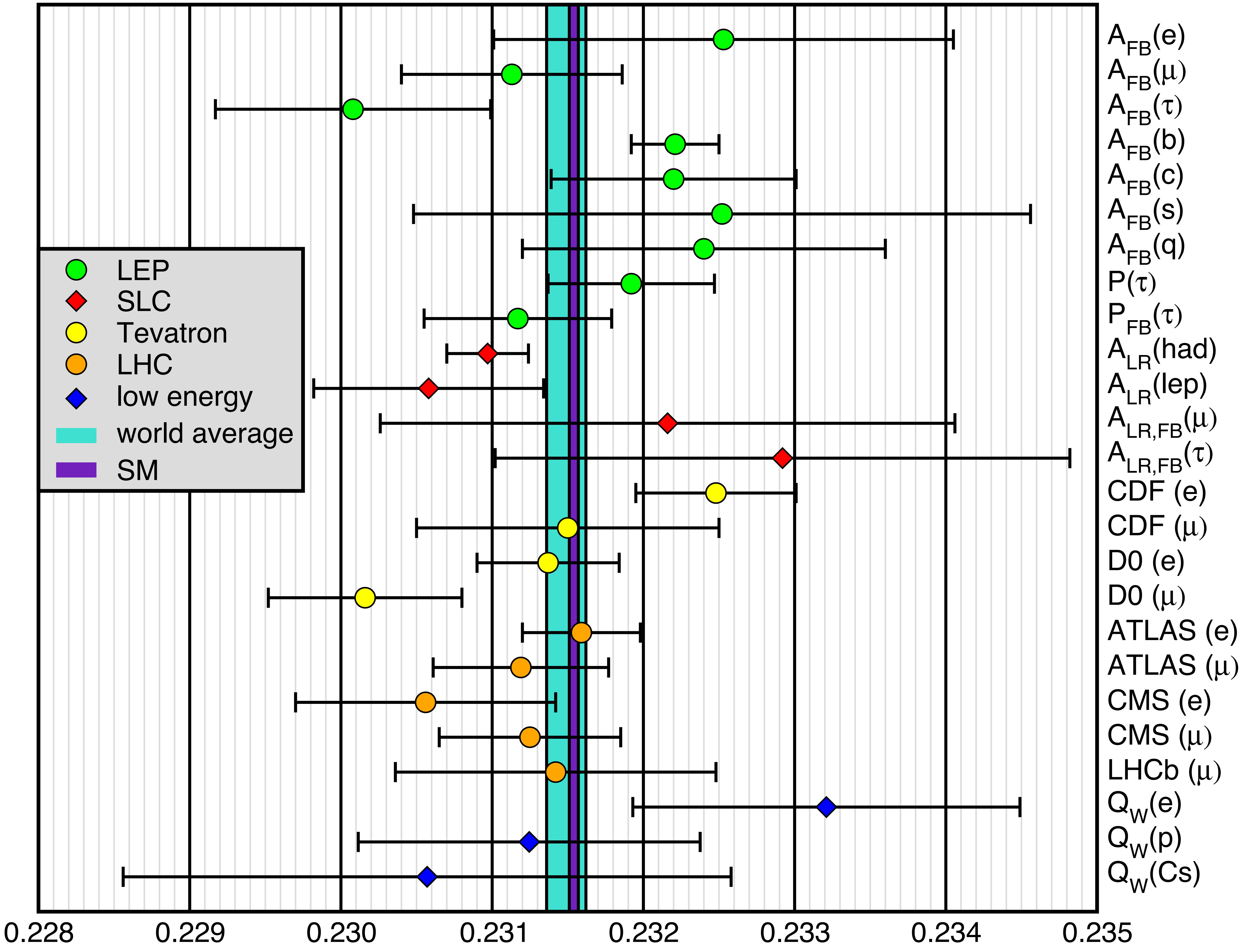
$\Delta A_{PV} = \pm 2.4\%$

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

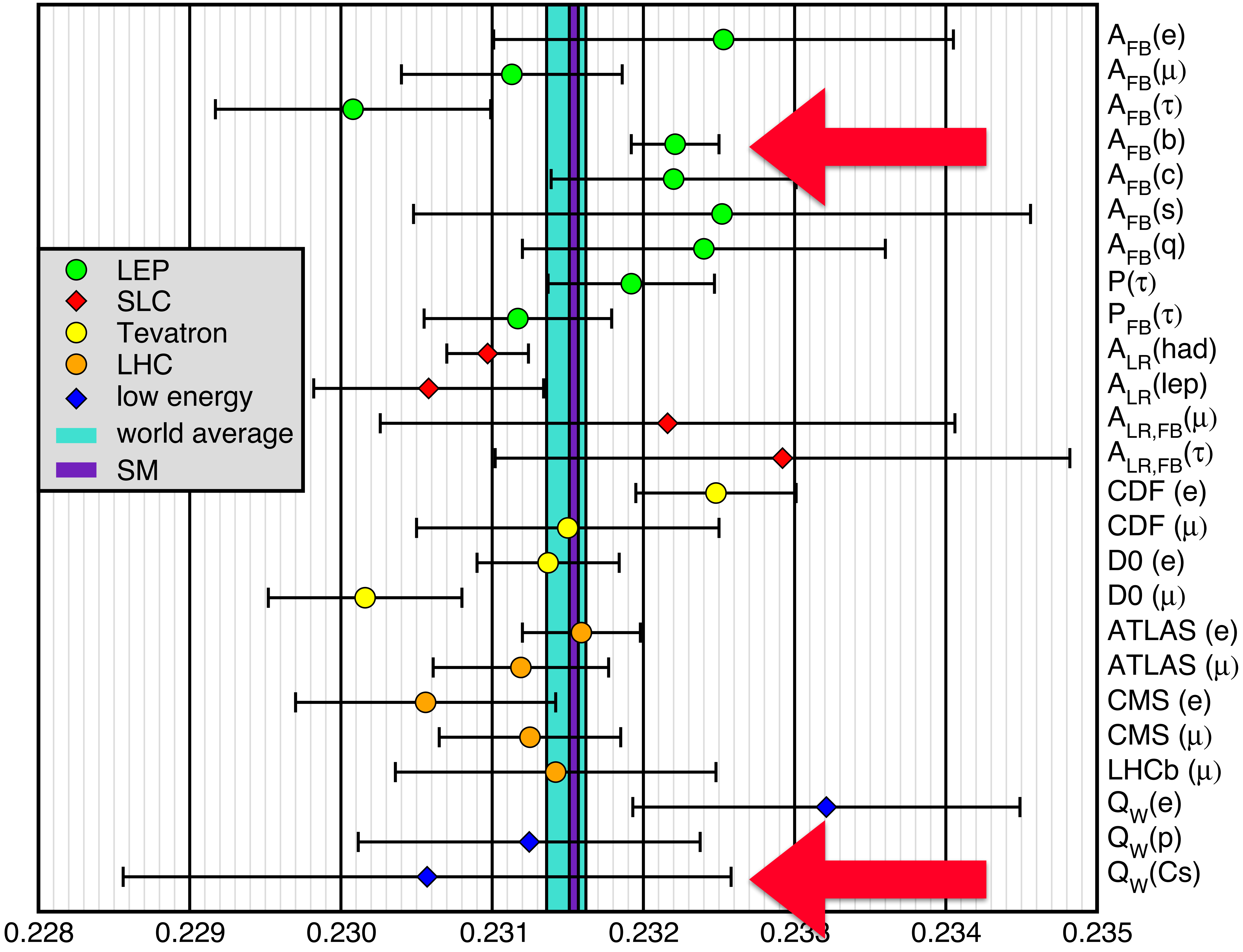
$\Delta \sin^2\theta_W = \pm 0.00027$

**arXiv:1411.4088**

# 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

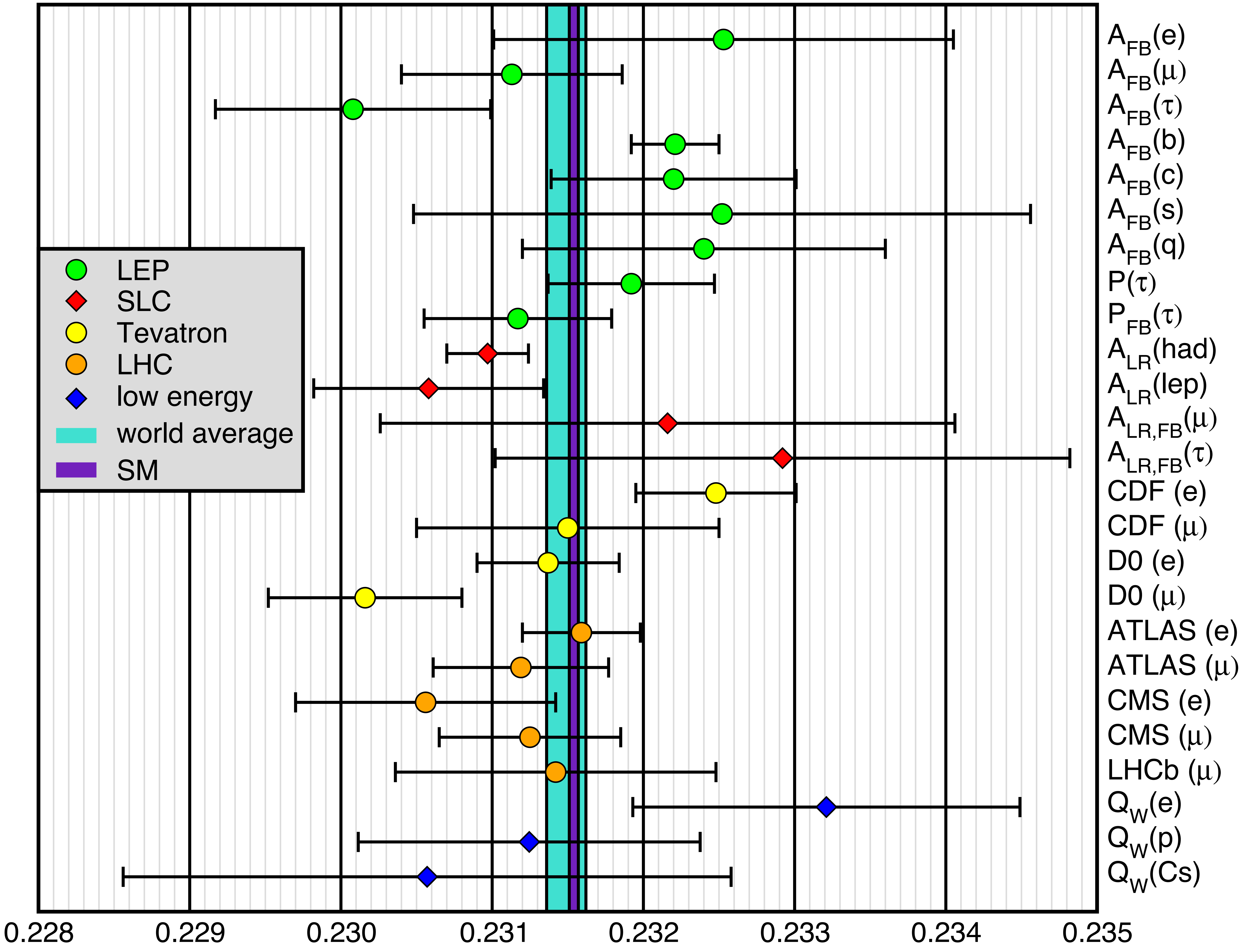
**Tho et al.**
**arXiv:1905.02768**

# *Electroweak fits*

# Global electroweak fits

* *Various groups, programs, approaches, renormalization schemes:*
  * *GAPP* ($\overline{\text{MS}}$ scheme, FORTRAN, options for BSM fits, used for PDG)
    **JE, hep-ph/0005084**
  * *Gfitter* (on-shell scheme, C++)
    **Flächer et al., arXiv:0811.0009**
  * *HEPfit* (on-shell scheme, allows fit to Wilson coefficients)
    **de Blas et al., arXiv:1608.01509**
  * *ZFITTER* (on-shell scheme, FORTRAN, used for LEPEWWG)
    **Bardin et al., hep-ph/9412201**

# Weak mixing angle measurements




**LEP & SLC:**

**0.23153 ± 0.00016**

**Tevatron:**

**0.23148 ± 0.00033**

**LHC:**

**0.23131 ± 0.00033**

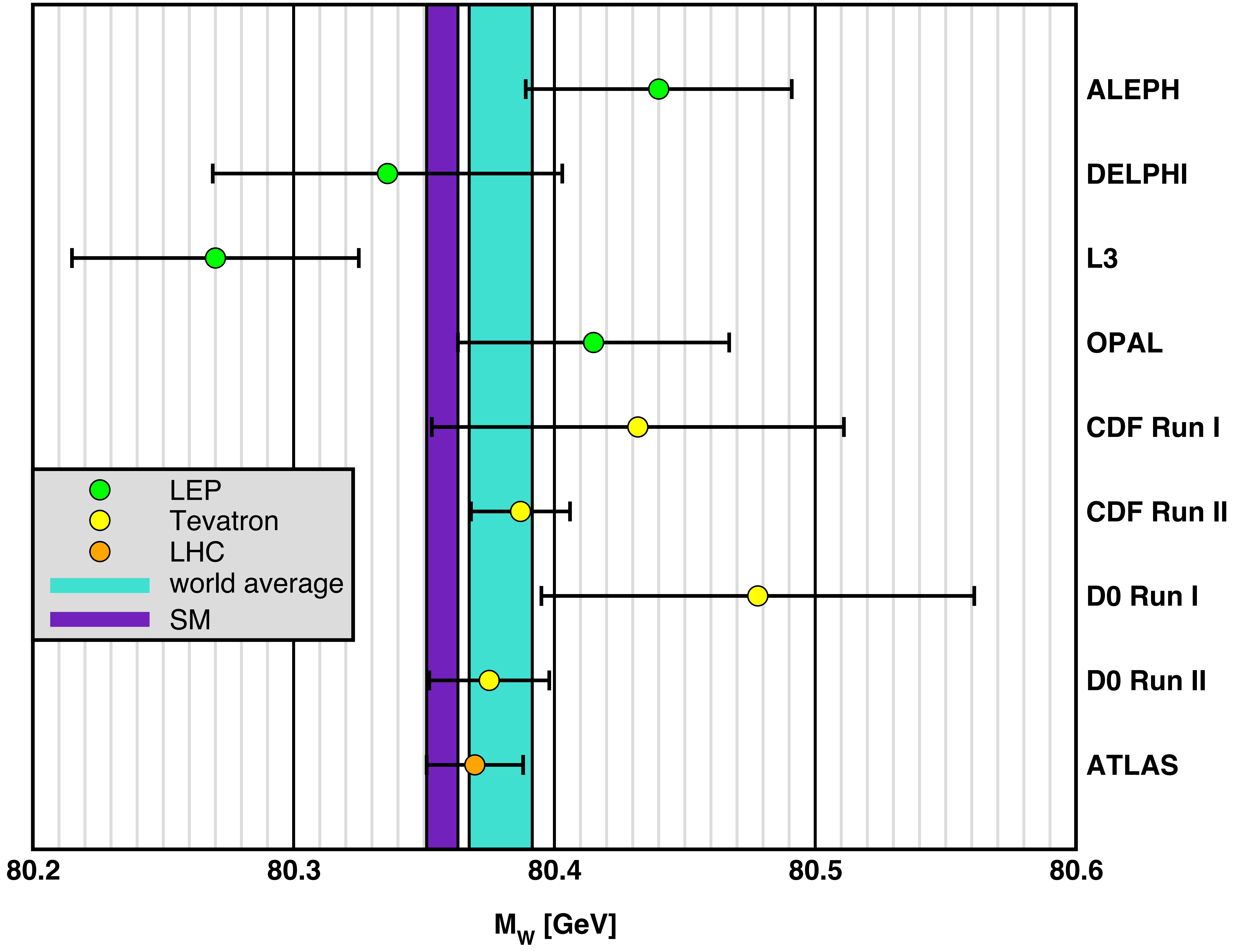
**average direct**

**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)

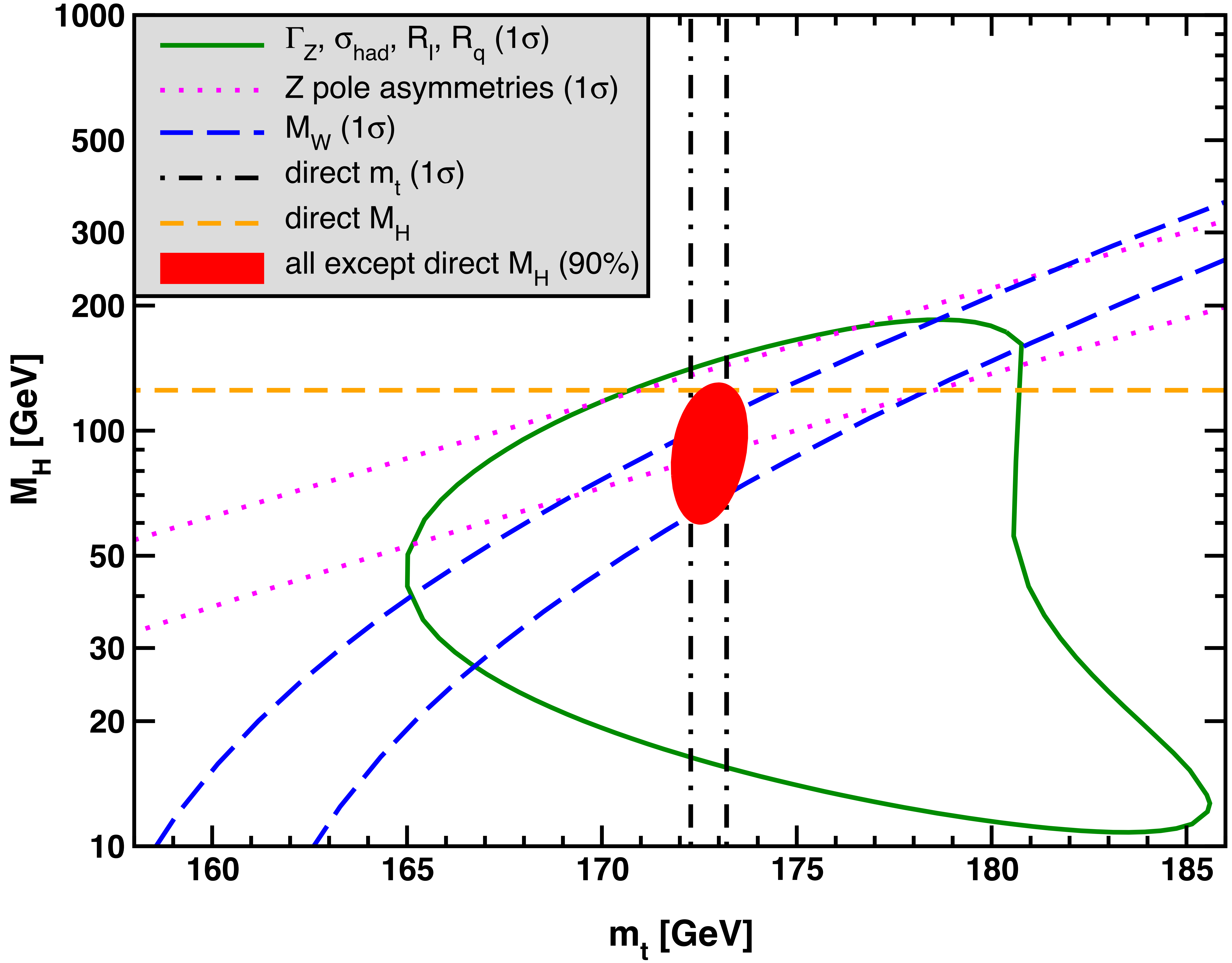
  }

    - $\Delta S_Z = \pm\,0.0034$ (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 $\Delta S_Z$, $\Delta T$ and $\Delta U$ to be sufficiently different (uncorrelated) induces theory correlations between different observables **Schott & JE, arXiv:1902.05142**

# $\alpha(M_Z)$

* Dispersive approach: integral over $\sigma(e^+e^- \to \text{hadrons})$ and $\tau$-decay data
  * $\alpha^{-1}(M_Z) = 128.958 \pm 0.016$ **Jegerlehner, arXiv:1711.06089**
  * $\alpha^{-1}(M_Z) = 128.946 \pm 0.015$ **Keshavarzi et al., arXiv:1802.02995**
  * $\alpha^{-1}(M_Z) = 128.946 \pm 0.013$ **Davier et al., arXiv:1908.00921**
* **$\alpha^{-1}(M_Z) = 128.949 \pm 0.010$** **Ferro-Hernández & JE, arXiv:1712.09146**
  * converted from the $\overline{MS}$ scheme and uses $e^+e^-$ annihilation and $\tau$ 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 $\sin^2\theta_W(0)$

# $M_H - m_t$




**indirect $m_t$**

**176.4 ± 1.8 GeV (2.0 σ high)**

**indirect $M_H$**

**$90^{+17}_{-15}$ GeV (1.9 σ low)**

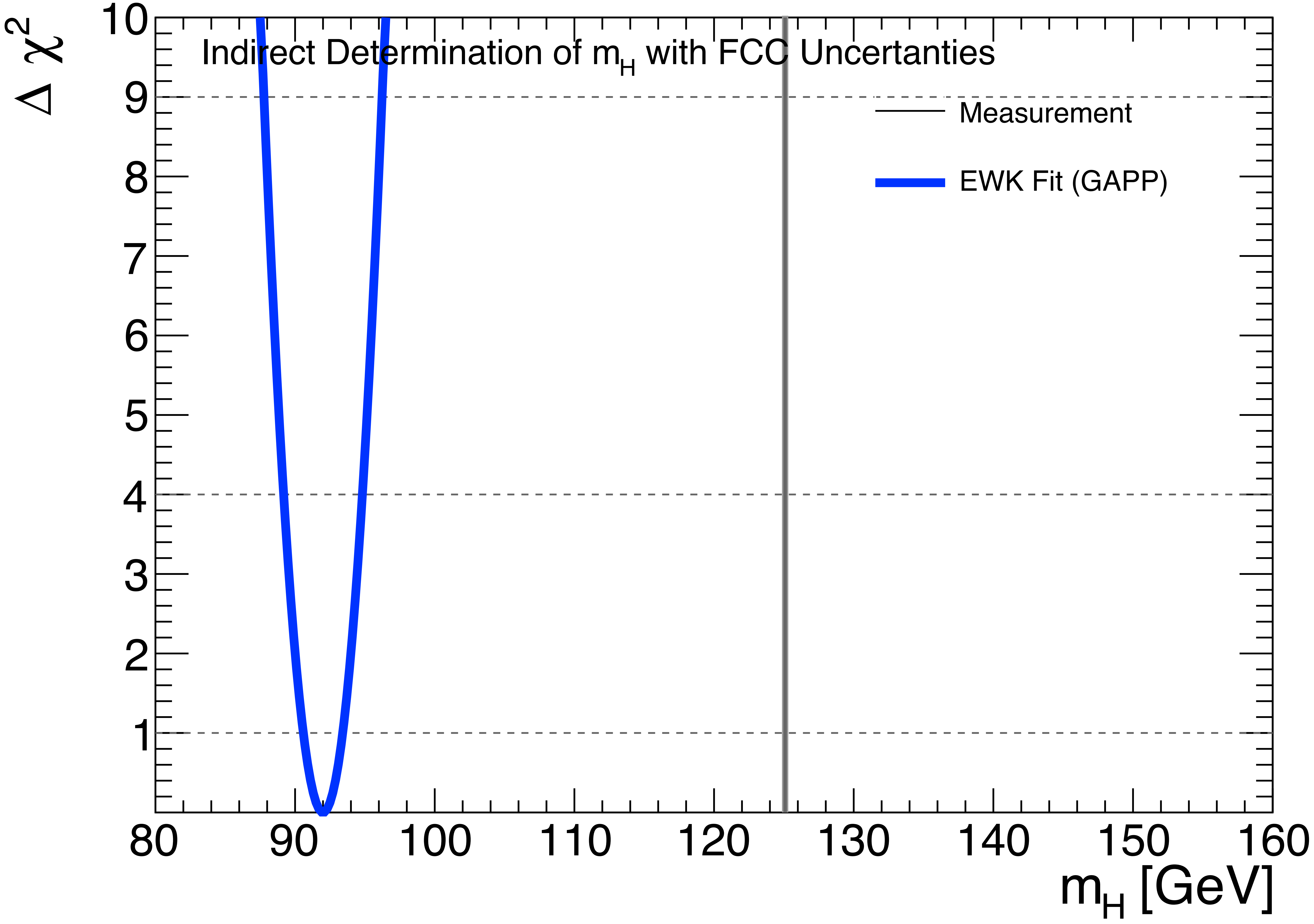
**including theory error**

**$91^{+18}_{-16}$ GeV (1.8 σ low)**

using $m_t^{pole}$ = 170.5 ± 0.8 GeV from **CMS arXiv:1905.08283** instead (see **Davide Melini** on Wednesday morning)

**$74^{+16}_{-14}$ GeV (2.7 σ low)**

# $M_H$ at the FCC–ee




**indirect**

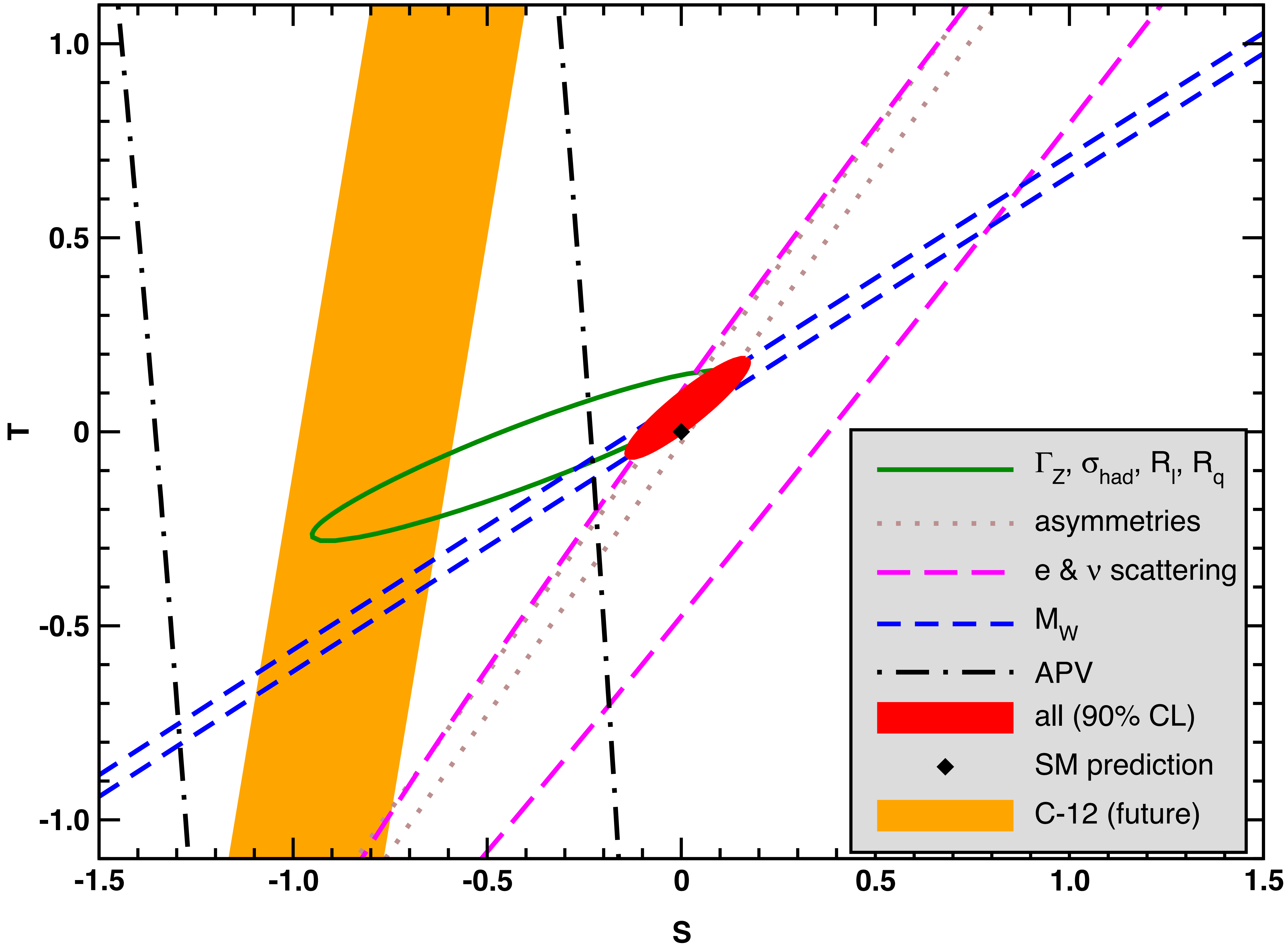
$\Delta M_H = \pm\ 1.4$ GeV

$\Delta M_W = \pm\ 0.2$ MeV

(theory errors ignored)

**Blondel et al., arXiv:1905.05078**

# S and T

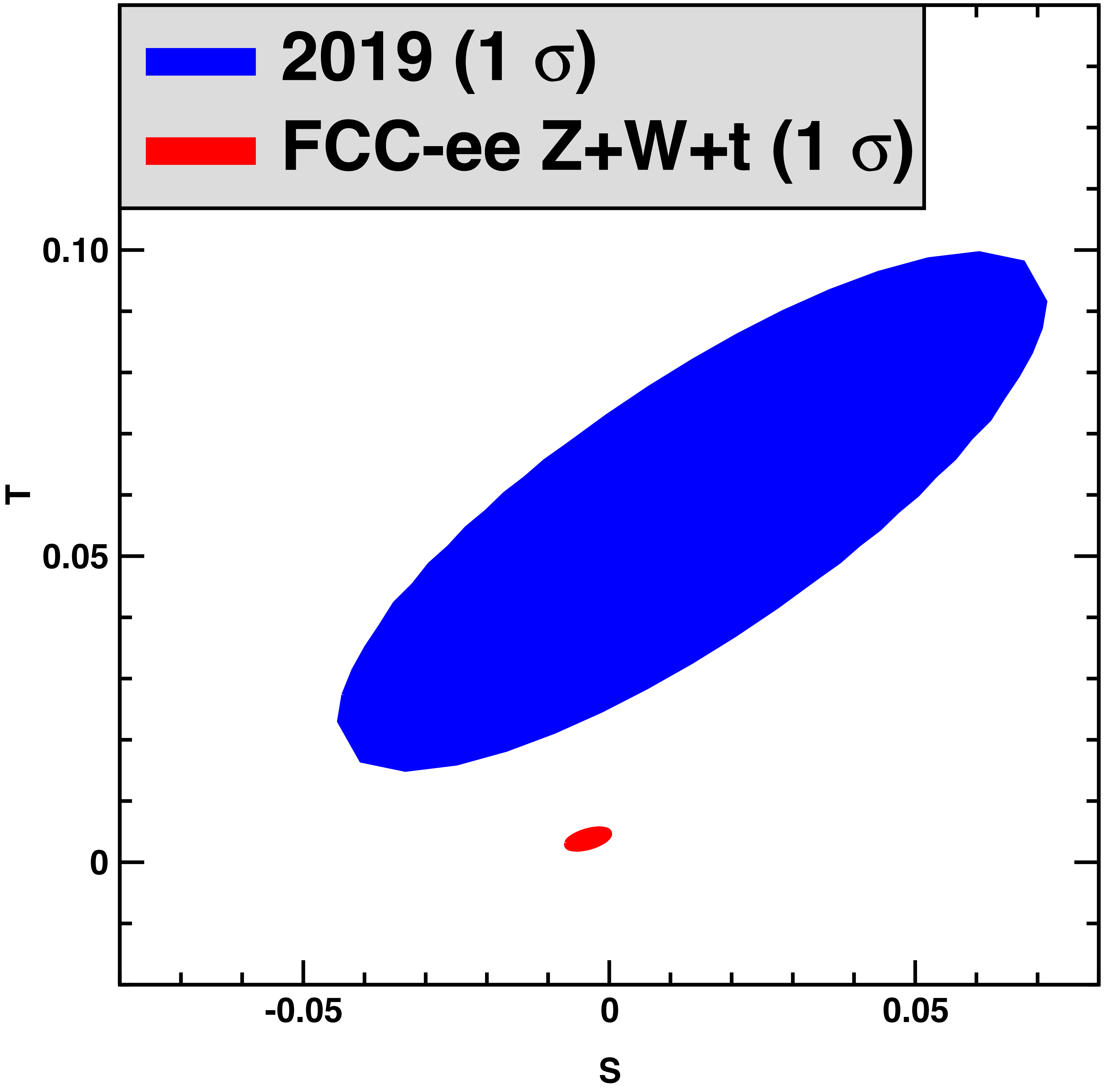



| | |
|---|---|
| S | 0.02 ± 0.07 |
| T | 0.06 ± 0.06 |
| $\Delta\chi^2$ | – 4.2 |

- $M_{KK} \gtrsim$ 3.2 TeV in warped extra dimension models
- $M_V \gtrsim$ 4 TeV in minimal composite Higgs models

**Freitas & JE**
**PDG (2018)**

# 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
**Franco Bedeschi** on Monday afternoon
except $\Delta\Gamma_Z$ = 100 MeV → 25 MeV

(theory uncertainties ignored)

# Summary

* *new developments:*
  * coherent $\nu$-scattering
  * high precision PVES
  * APV isotope ratios
  * change in $A_{FB}(b)$ from LEP
  * change $Q_W(Cs)$ from APV
* *future developments:*
  * ultra-high precision PVES (MOLLER and P2)
  * a leap in precision can be expected from future lepton colliders