Global Vision of Electroweak Measurements

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Workshop on
Ultimate Precision at Hadron Colliders
Institut Pascal (Université Paris-Saclay)
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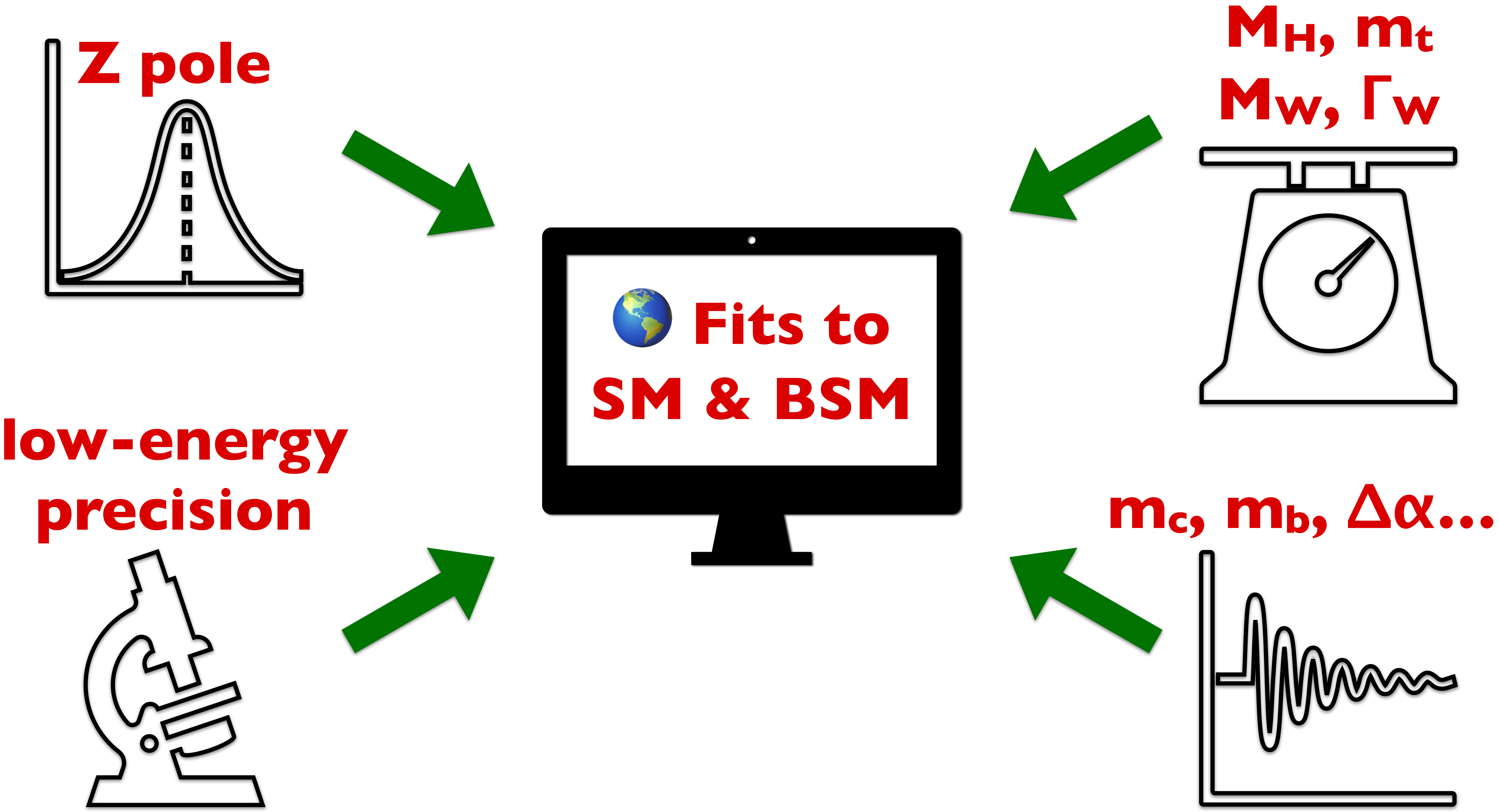

Z pole
M_H, m_t
M_W, Γ_W
Fits to
SM & BSM
low-energy
precision
m_c, m_b, $\Delta\alpha$...

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

Outline

- *$\sin^2\theta_W$*
  - news on $A_{FB}(b)$ and APV
  - Tevatron and LHC
  - Qweak, CEνNS & APV isotope chains
- *heavy weights*
  - M_W
  - m_t
  - M_H
- *α_s*
  - LEP luminosity → σ_{had} & Γ_Z
  - τ decays
- *conclusions and outlook*

$$\sin^2\theta_W$$

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)

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recent first measurements

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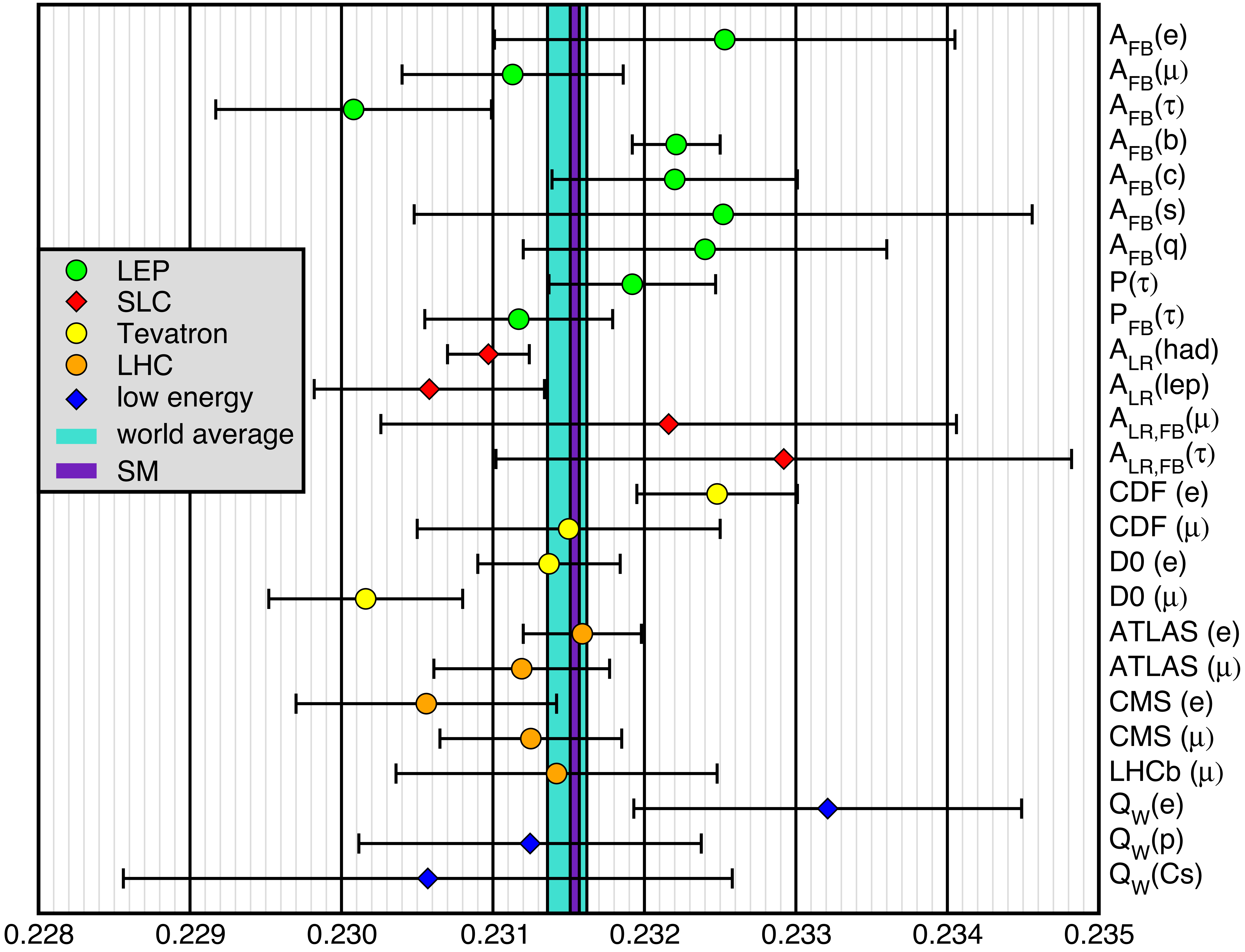
$\sin^2\theta_W$ measurements



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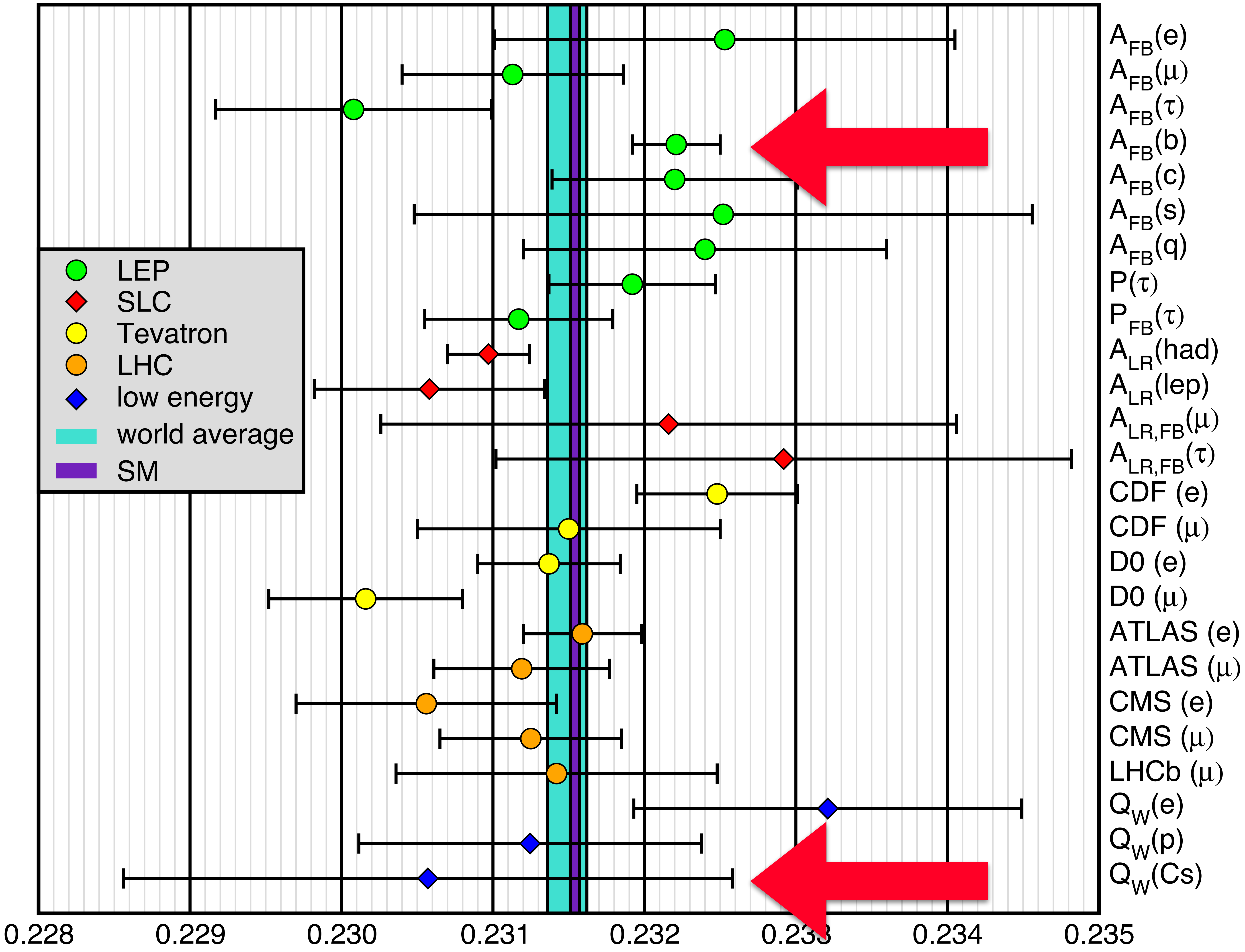


$A_{FB}(q) = \frac{3}{4} A_e A_q$

A_b (A_c) 78 (10) times less sensitive to $\sin^2\theta_W$ than A_e

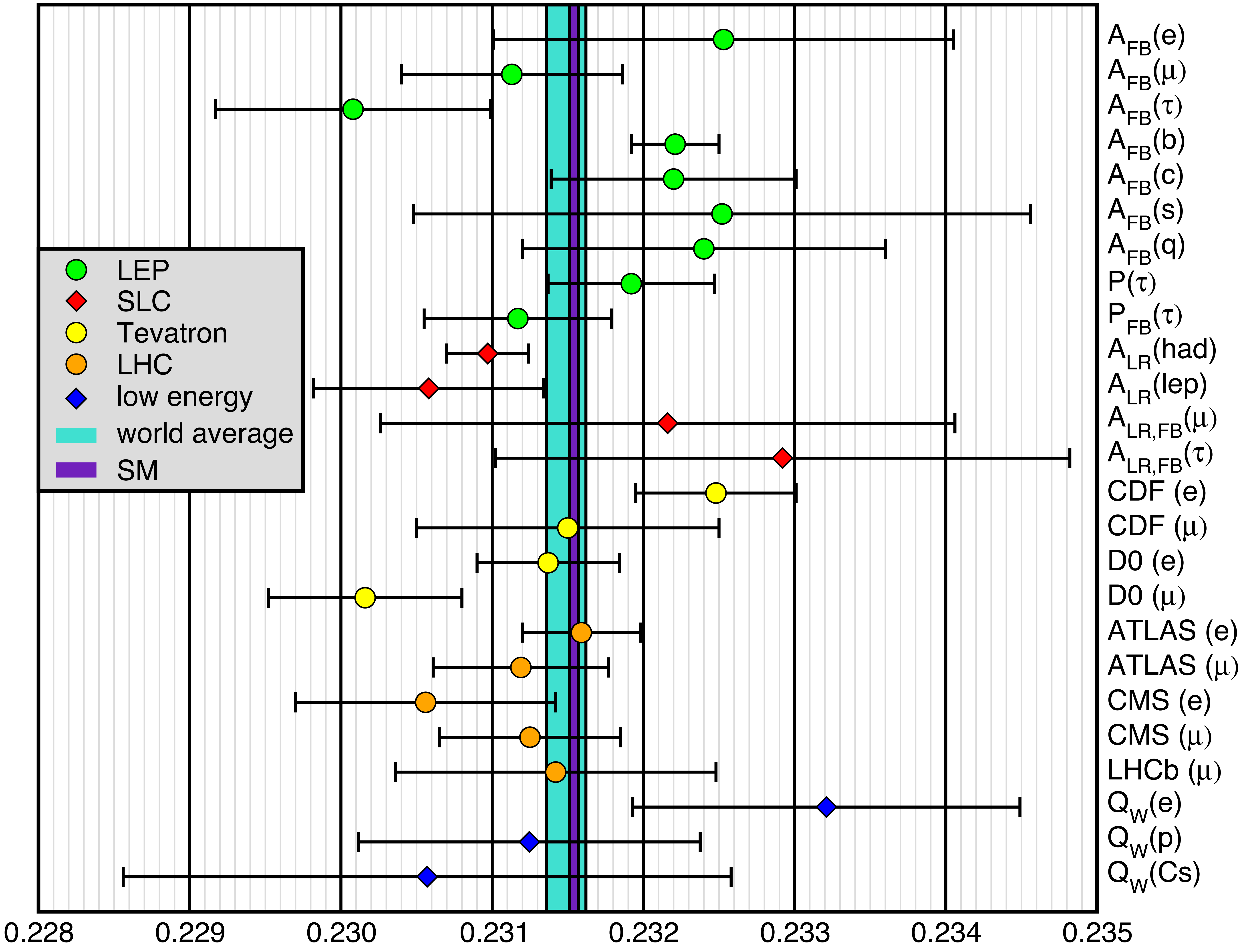
2-loop QCD correction with $m_b \neq 0$

Bernreuther et al. arXiv:1611.07942

new measured transition vector polarizability

Tho et al. arXiv:1905.02768

$\sin^2\theta_W$ measurements



LEP & SLC:

0.23153 ± 0.00016

Tevatron:

0.23148 ± 0.00033

LHC:

0.23131 ± 0.00033

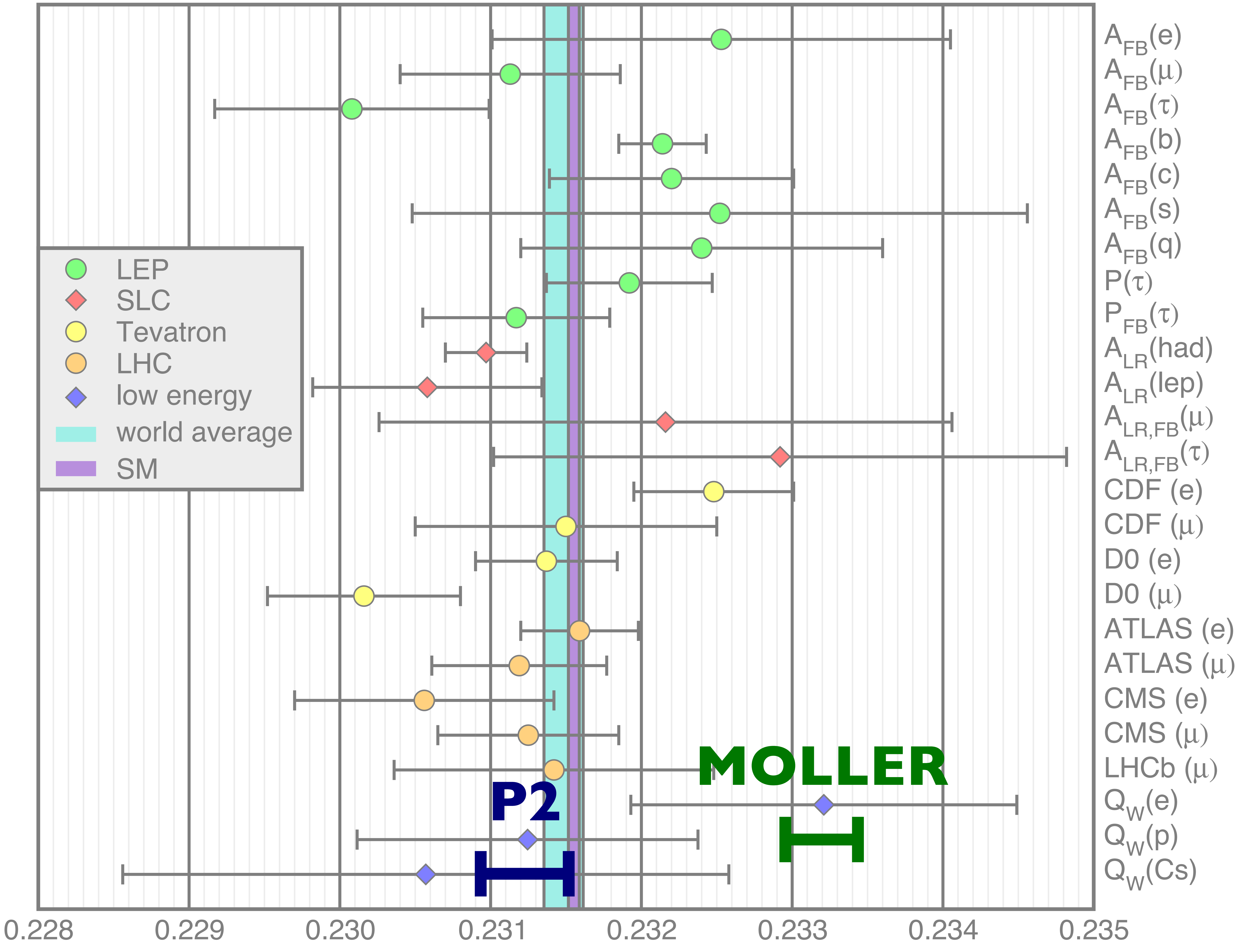
average direct

0.23149 ± 0.00013

global fit

0.23153 ± 0.00004

$\sin^2\theta_W$ measurements



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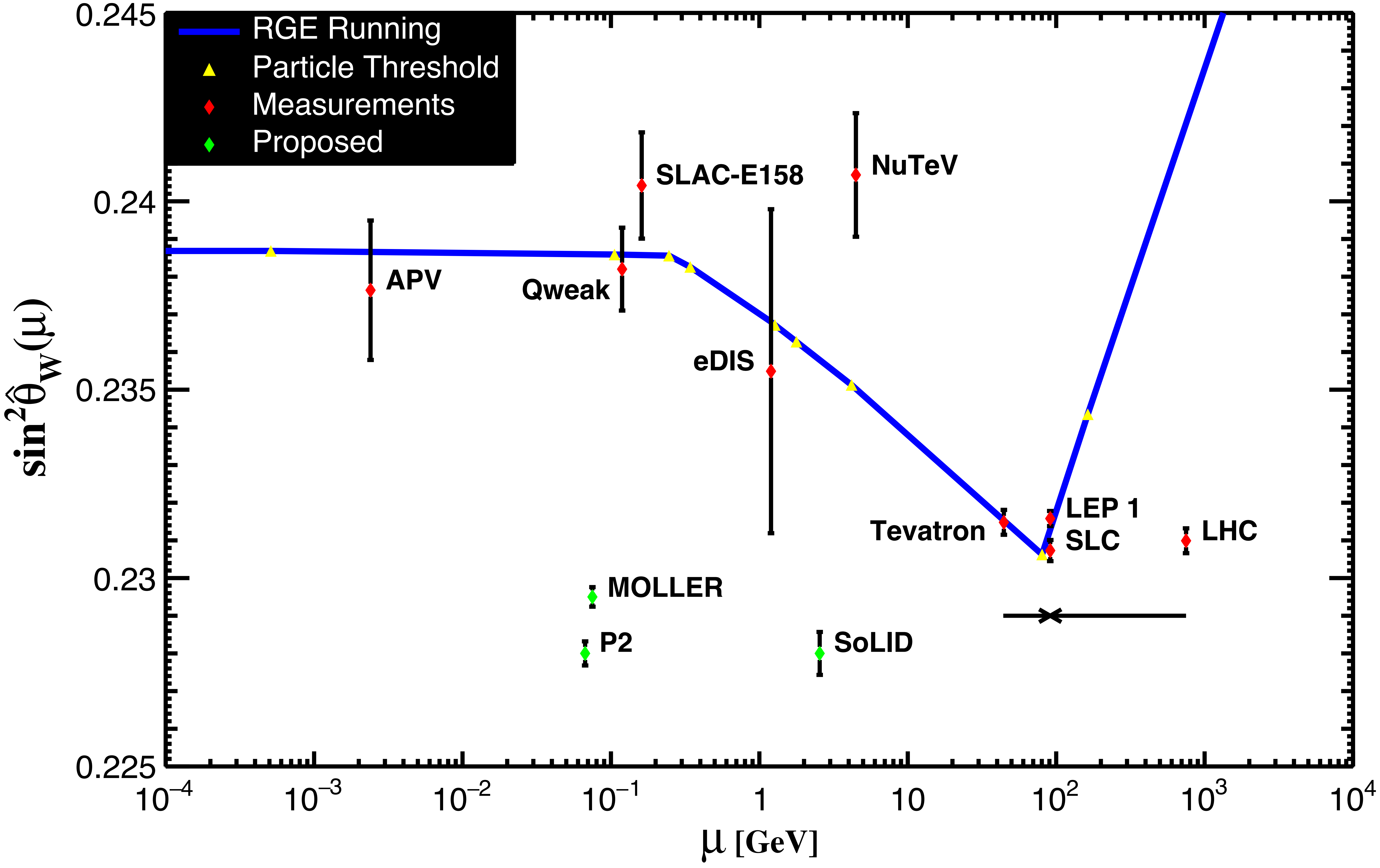
Running weak mixing angle

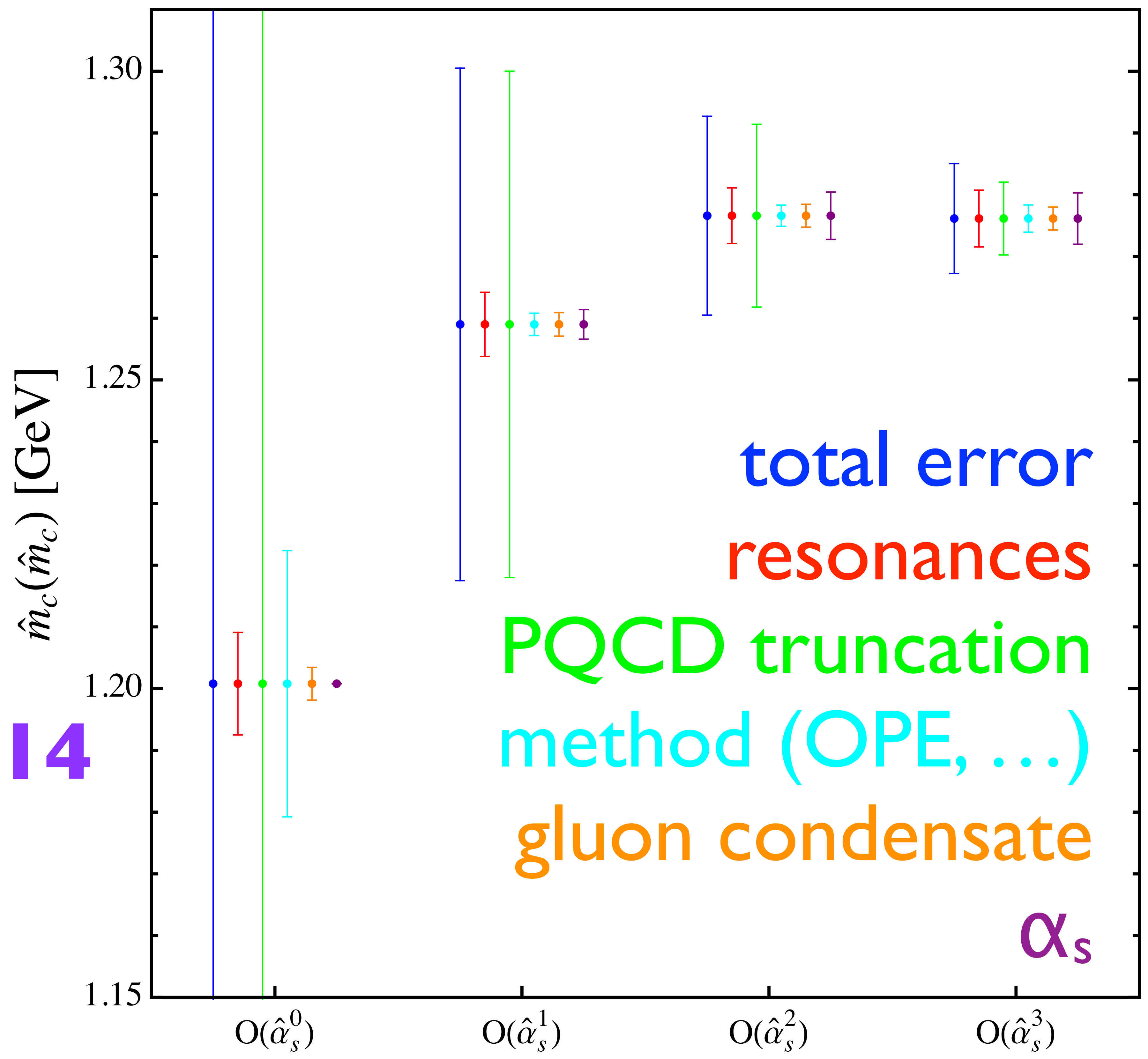


Ferro-Hernández & JE arXiv:1712.09146

$m_c(m_c)$

- 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:1610.08531



Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

$E_e = 1149$ MeV

$|Q| = 158$ MeV ($\theta = 7.9°$)

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

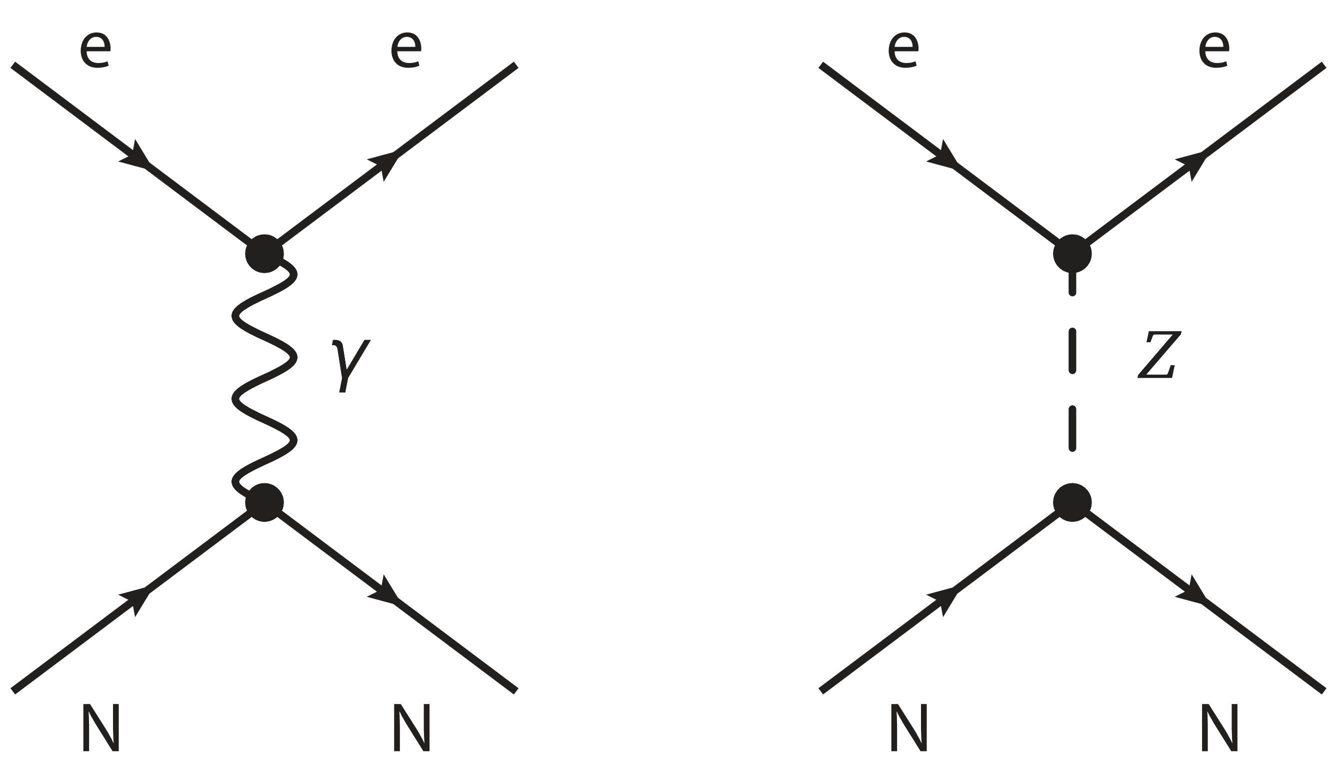
$\Delta A_{PV} = \pm\ 4.1\%$

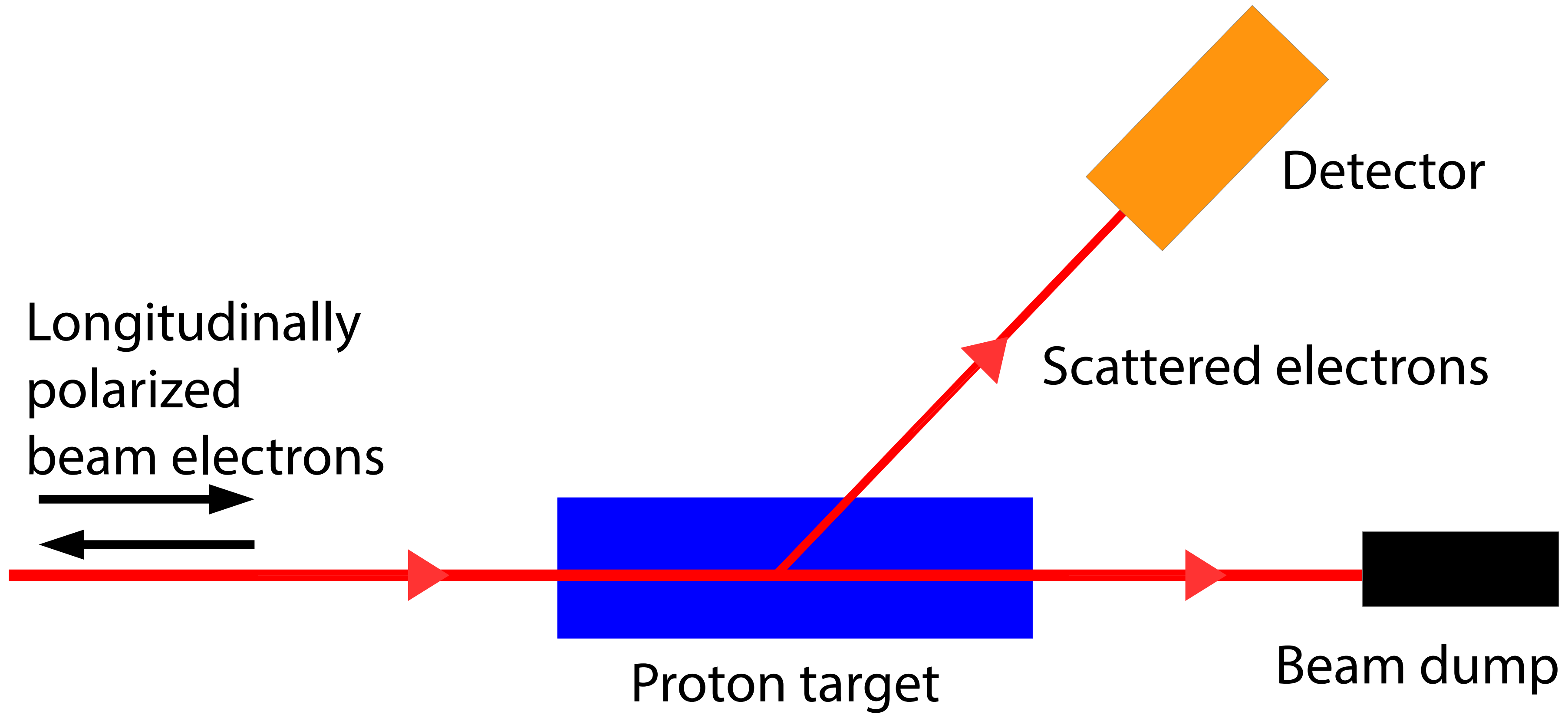
$\Delta Q_W(p) = \pm\ 6.25\%$

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

FFs from fit to ep asymmetries

arXiv:1905.08283





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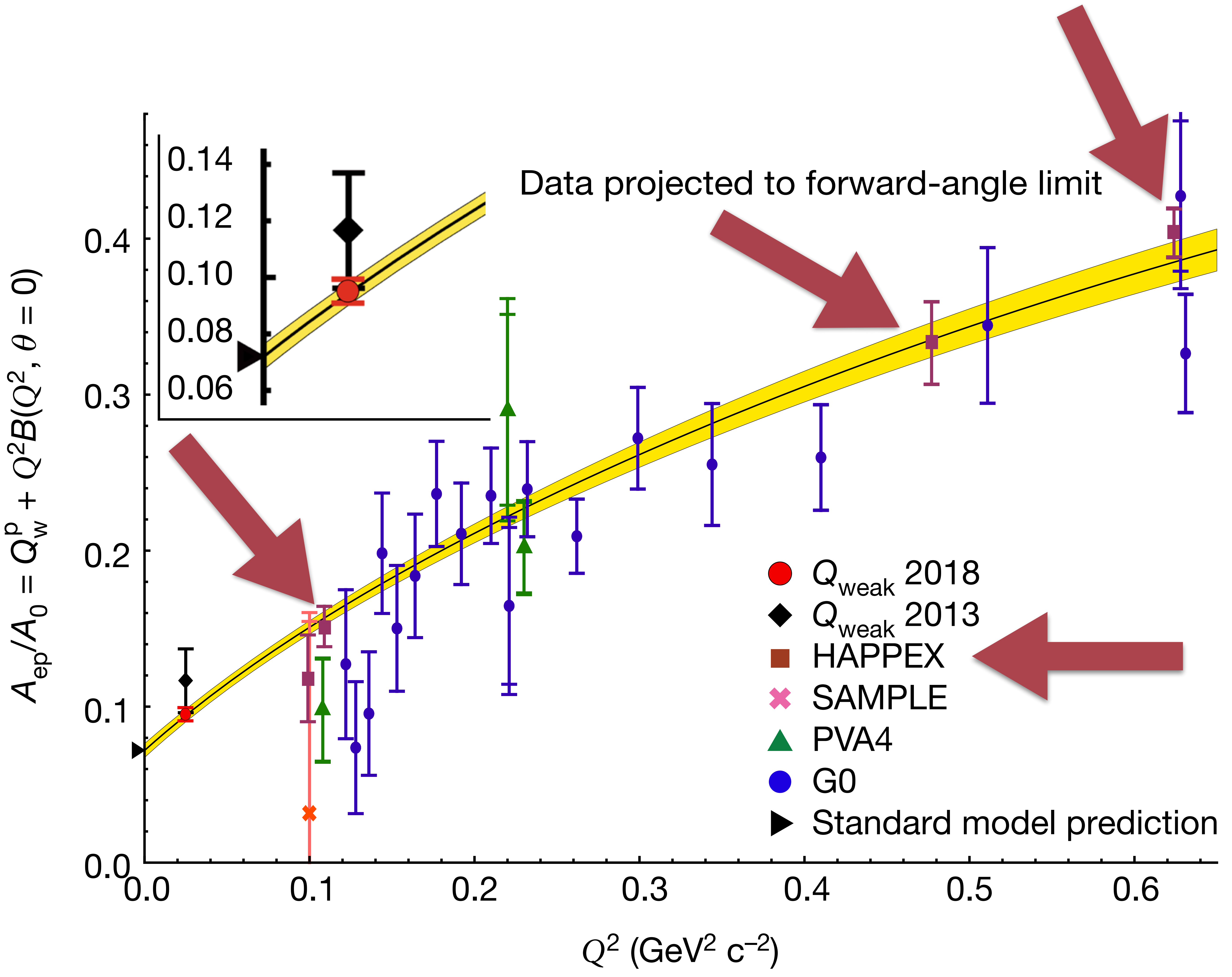
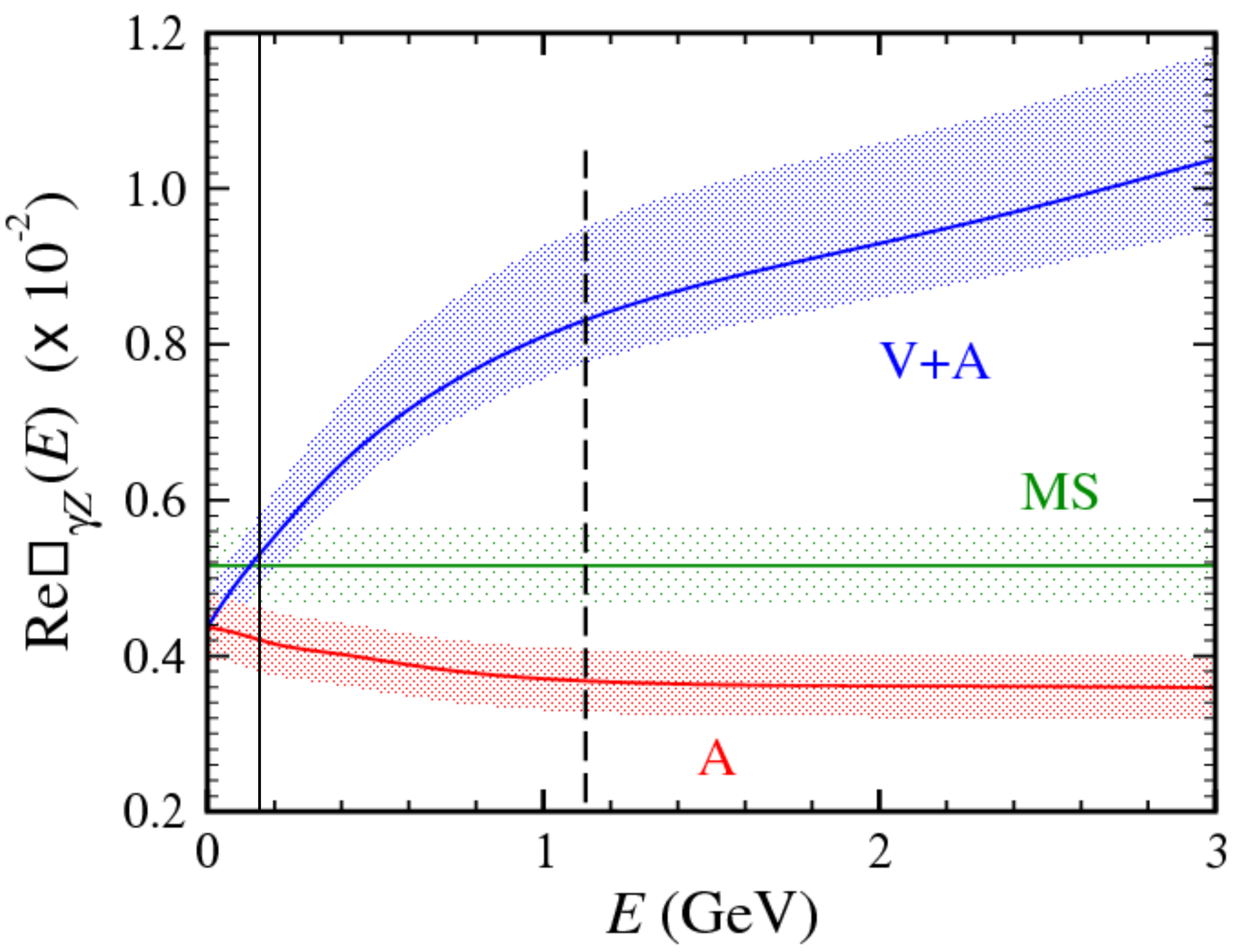


Theory issues in PVES

* 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
JE et al., arXiv:1907.07928

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
$\lvert Q \rvert$ = 158 MeV	$\lvert Q \rvert$ = 68 MeV	$A_{PV} = 6 \times 10^{-7}$
$A_{PV} = 2.3 \times 10^{-7}$	$A_{PV} = 4 \times 10^{-8}$	$\Delta A_{PV} = \pm\ 0.3\%$
$\Delta A_{PV} = \pm\ 4.1\%$	$\Delta A_{PV} = \pm\ 1.4\%$	$\Delta Q_W(^{12}C) = \pm\ 0.3\%$
$\Delta Q_W(p) = \pm\ 6.25\%$	$\Delta Q_W(p) = \pm\ 1.83\%$	$\Delta \sin^2\theta_W = \pm\ 0.0007$
$\sin^2\theta_W = 0.2383 \pm 0.0011$	$\Delta \sin^2\theta_W = \pm\ 0.00033$	proton skin?
FFs from fit	FFs from backward angles	only one FF
arXiv:1905.08283	**arXiv:1802.04759**	**arXiv:1802.04759**

Parity Violating e^- Scattering (PVES) — Møller

E158 @ SLC (SLAC)

hydrogen (completed)

E_e = 45 & 48 GeV

$|Q|$ = 161 MeV

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

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

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

$\sin^2\theta_W = 0.2397 \pm 0.0013$

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) — DIS

<u>E122 @ SLAC</u>

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)

<u>PVDIS @ CEBAF</u>

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

<u>SoLID @ CEBAF</u>

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

Atomic parity violation in an isotope chain

AG Budker @ JGU Mainz

Ytterbium

$^{170}Yb - {}^{176}Yb$

± 0.5% per isotope

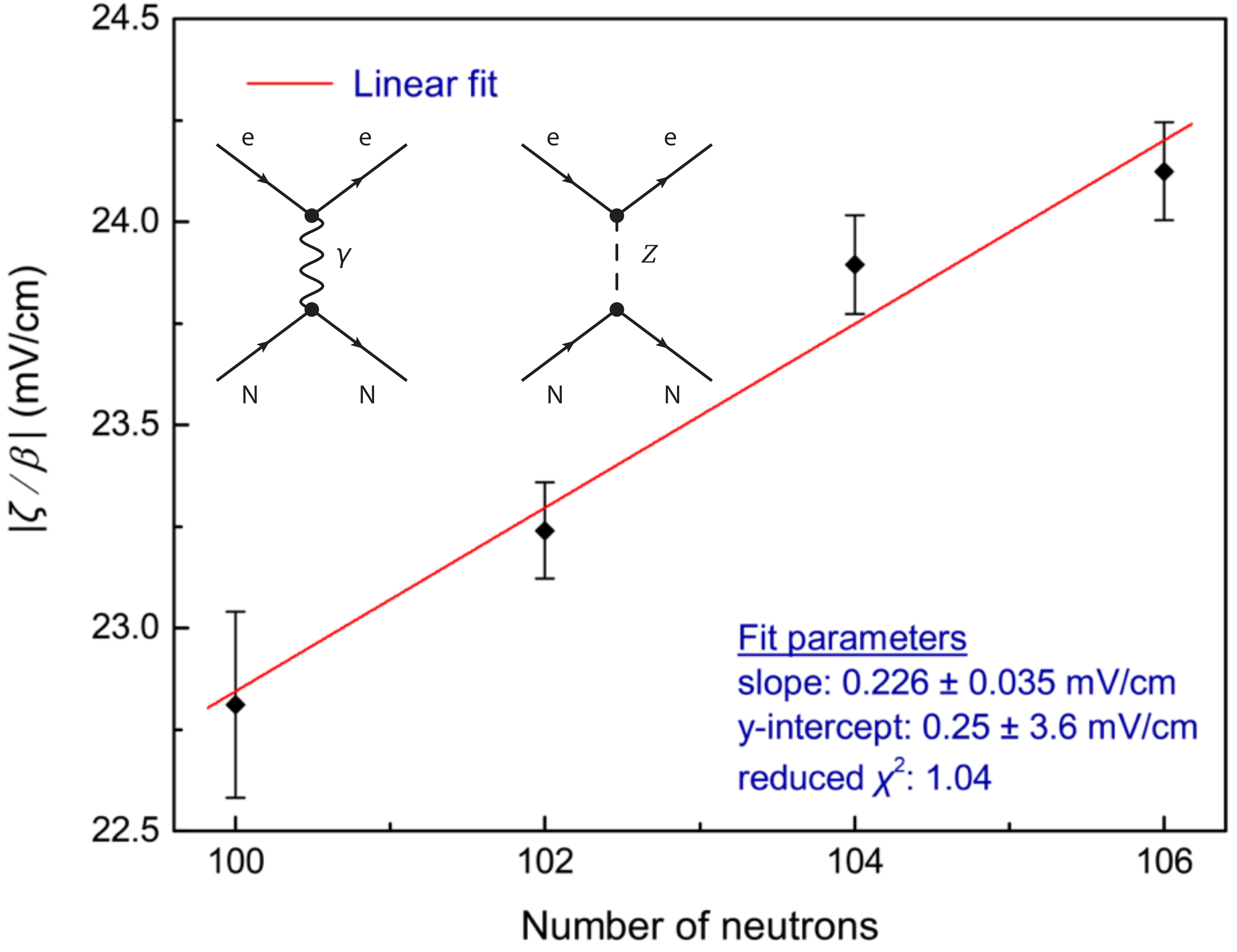
± 100% error in $\sin^2\theta_W$

constraints on Z´ with M < 100 keV

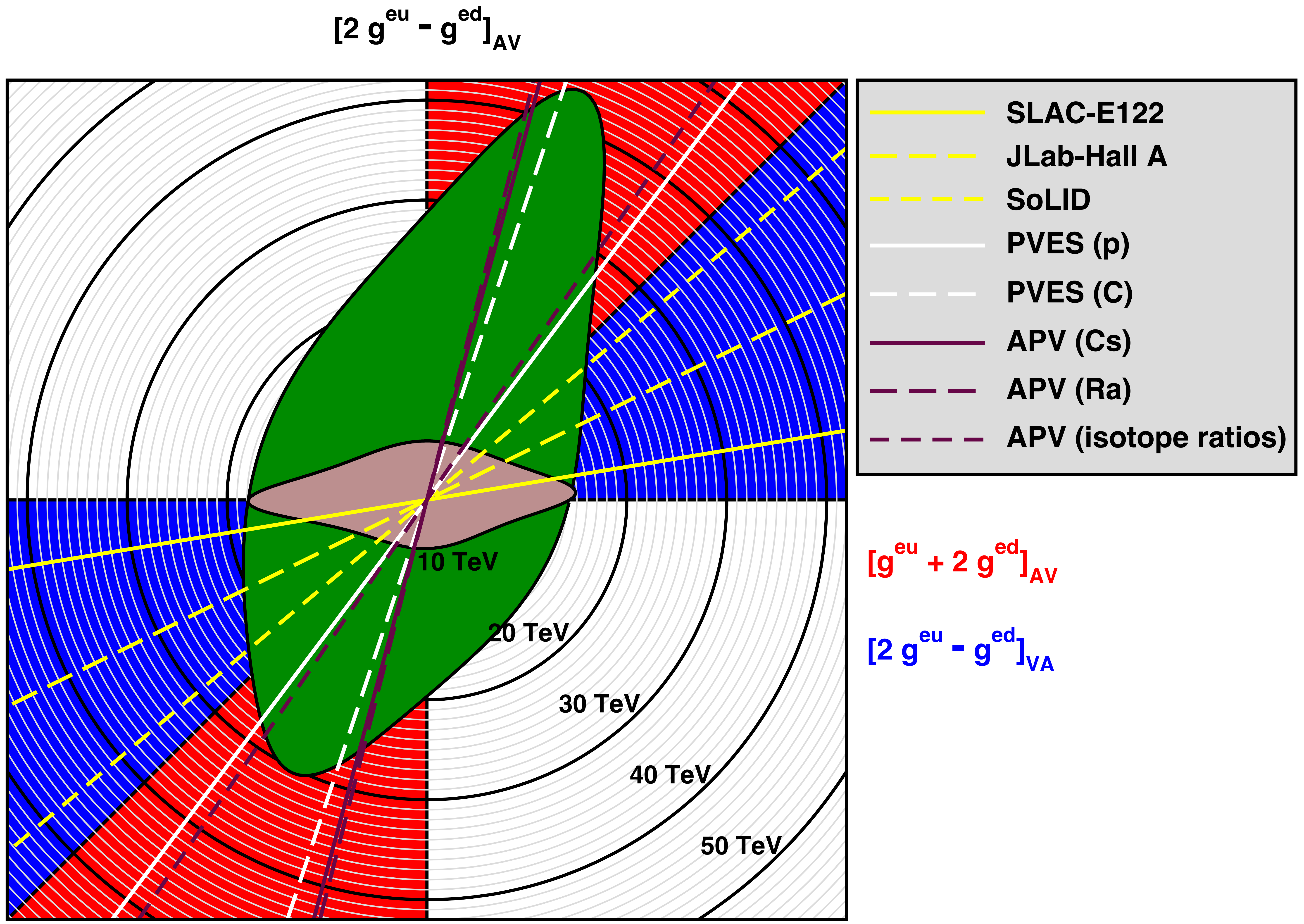
$\sin^2\theta_W = 0.258 \pm 0.052$

neutron skin?

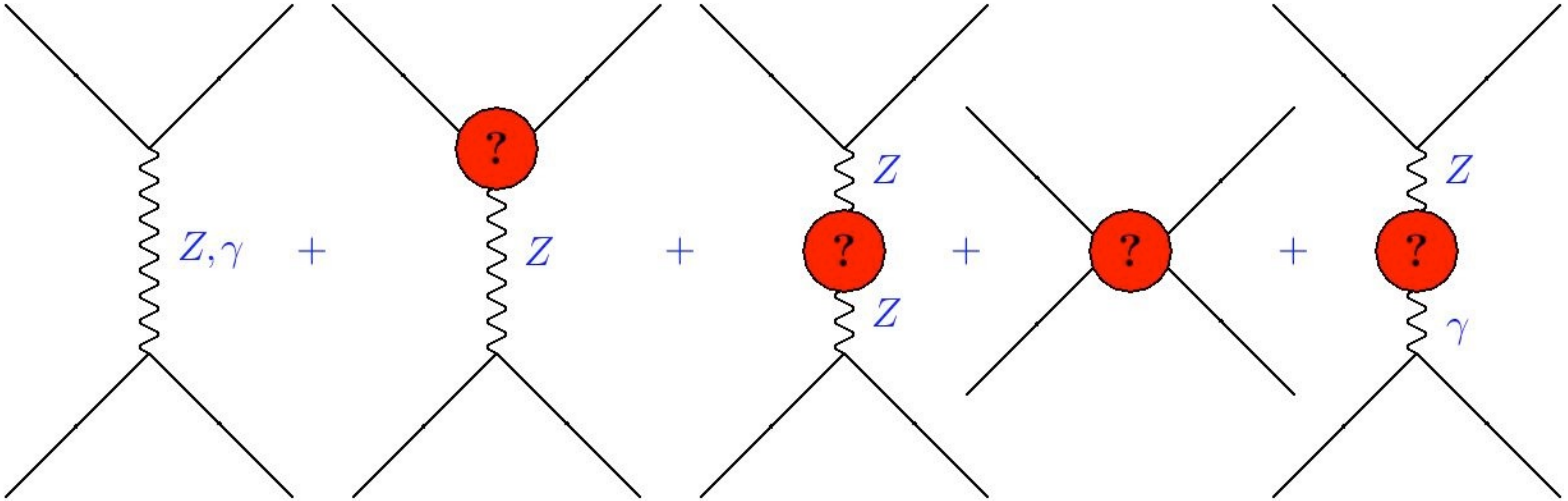
arXiv:1804.05747



Scale exclusions post Qweak



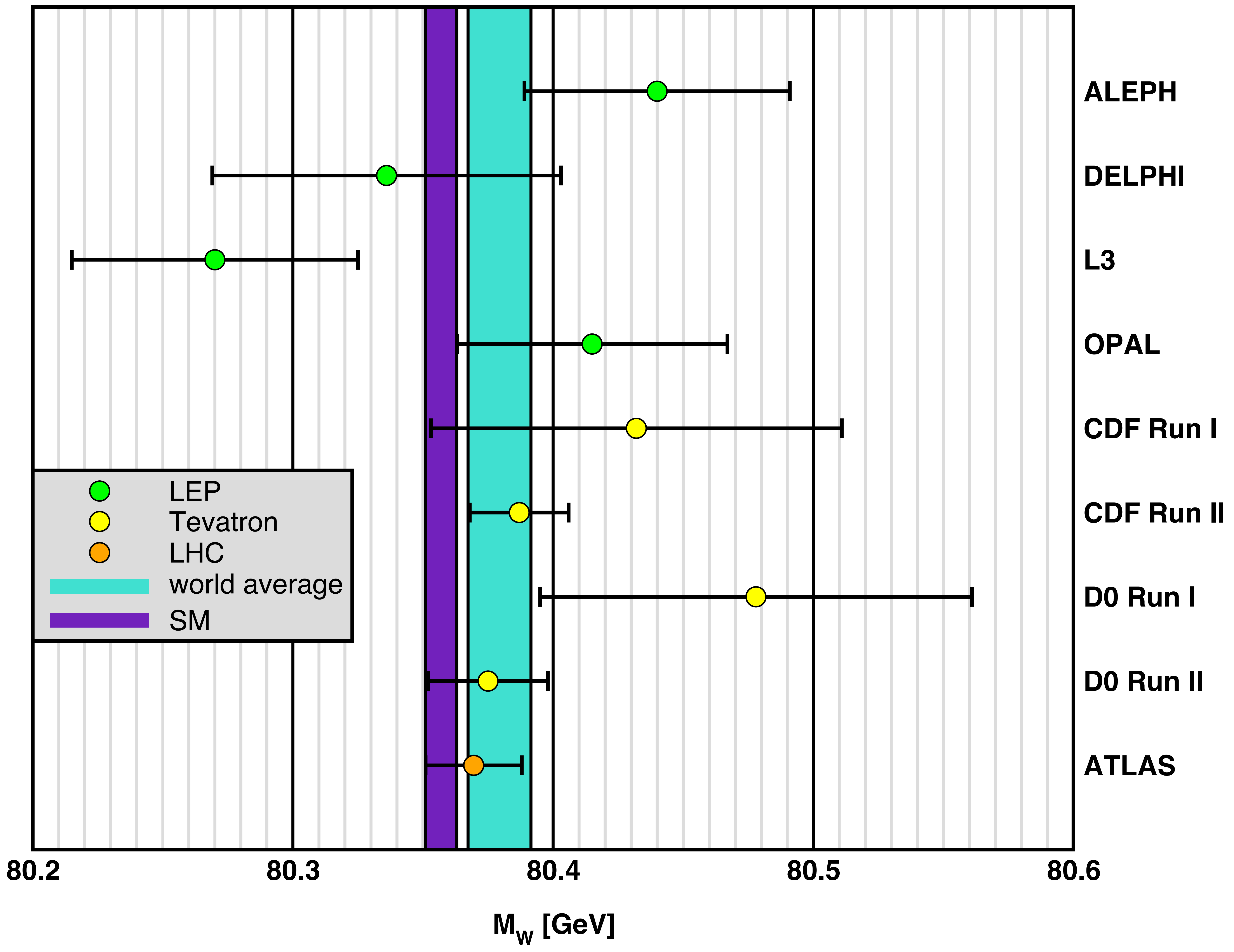
Discriminating new physics



- 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. heavy Z′)
- dark Z: renormalization group evolution (low versus very low energy measurements)

heavy weights

W boson mass measurements



average direct

80.379 ± 0.012 GeV

indirect

80.352 ± 0.006 GeV

(2.0 σ low)

including

m_t^{pole} from X-sections

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_t^{MC} measurements

	central	statistical	systematic	total error	arXiv
Tevatron	174.30	0.35	0.54	0.64	1608.01881
ATLAS Run 1	172.69	0.25	0.41	0.48	1810.01772
CMS Run 1	172.43	0.13	0.46	0.48	1509.04044
CMS Run 2	172.26	0.07	0.61	0.61	1812.10534
average	**172.8**	**0.11**	**0.29**	**0.31**	

* for stat.-syst. total error separation, see **JE, arXiv:1507.08210**
* 2.8 σ discrepancy between lepton + jet channels from DØ and CMS Run 2
* $m_t^{pole} = 172.80 \pm 0.25_{uncorr.} \pm 0.17_{corr.} \pm 0.32_{QCD}$ GeV $+ \Delta_{MC} = 172.80 \pm 0.44$ GeV $+ \Delta_{MC}$
* Δ_{MC}: uncertainty & non-universal shift (?) of order $\alpha_s(Q_0)\, Q_0$; $Q_0 \simeq \Gamma_t \Rightarrow \Delta_{MC} \sim 0.54$ GeV
* for a review, see ***G. Corcella, arXiv:1903.06574***

m_t^{pole} measurements

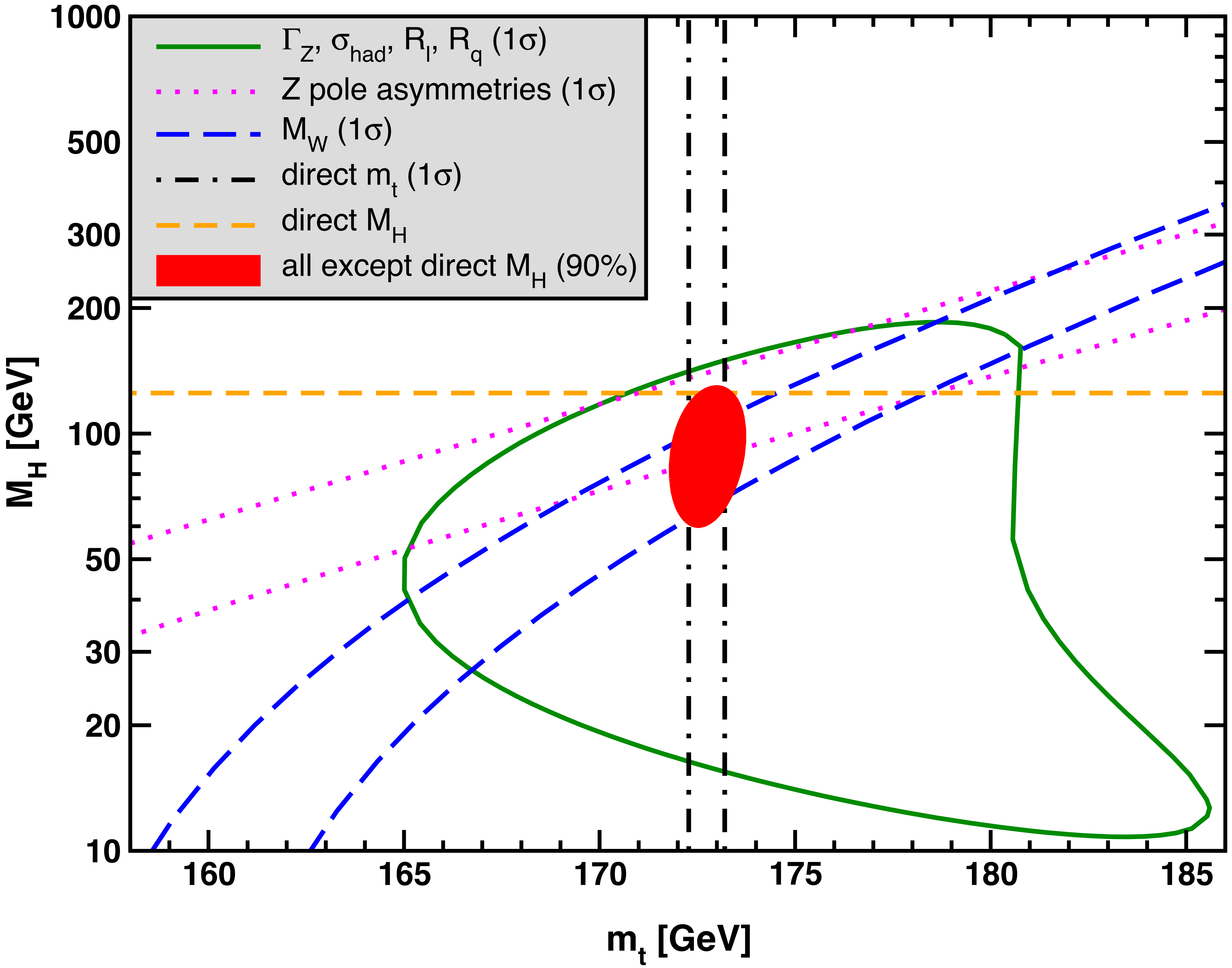
	X-section	m_t^{pole} (GeV)	$\alpha_s(M_Z)$	corr.	arXiv
CMS Run 2	$t\bar{t}$	170.5 ± 0.8	$0.1135^{+0.0021}_{-0.0017}$	$\rho_{\alpha,m} = 0.3$	1904.05237
CMS Run 2	$t\bar{t}$	171.1 ± 0.8	0.119 ± 0.001		adjusted
ATLAS Run 1	$t\bar{t}$ + 1-jet	$171.1^{+1.2}_{-1.1}$	0.119 ± 0.001		1905.02302

* these are differential cross-section at NLO
* total cross-sections currently give larger errors ≳ 2 GeV

M_H fits

	m_t (GeV)	M_H (GeV)	χ^2/d.o.f.
no external m_t	$173.2^{+6.5}_{-5.3}$	91^{+73}_{-38}	35.6/39
m_t^{MC} (Δ_{MC} = 0)	172.8 ± 0.44	88^{+18}_{-16}	35.7/40
m_t^{MC} (Δ_{MC} = 0 ± 0.54 GeV)	172.8 ± 0.7	88^{+19}_{-16}	35.7/40
m_t^{MC} (Δ_{MC} = 0.54 ± 0.54 GeV)	173.3 ± 0.7	92^{+20}_{-16}	35.6/40
m_t^{pole}	171.6 ± 0.7	79^{+17}_{-15}	36.0/41
m_t^{MC} (Δ_{MC} = 0 ± 0.54 GeV) + m_t^{pole}	172.2 ± 0.48	83^{+17}_{-15}	37.6/42
m_t^{MC} (Δ_{MC} = 0.54 ± 0.54 GeV) + m_t^{pole}	172.4 ± 0.48	85^{+17}_{-16}	39.3/42

$M_H - m_t$



indirect m_t

176.4 ± 1.9 GeV

(1.9 σ high)

including

correlated theory errors

α_s

α_s from the Z pole

for massless quarks

$$R_V^q = R_A^q = 1 + \frac{\alpha_s(M_Z)}{\pi} + 1.409\frac{\alpha_s^2}{\pi^2} - 12.77\frac{\alpha_s^3}{\pi^3} - 80.0\frac{\alpha_s^4}{\pi^4} + Q_q^2\left[\frac{3}{4} - \frac{\alpha_s}{4\pi} - \left(1.106 + \frac{3}{32}Q_q^2\right)\frac{\alpha}{\pi}\right]\frac{\alpha(M_Z)}{\pi}$$

after large (top quark driven) singlet corrections (Z boson only) starting at order α_s

$$\Gamma_Z^{\text{had}} \propto \rho\left(1 + \frac{\alpha_s(M_Z)}{\pi} + 0.79\frac{\alpha_s^2}{\pi^2} - 15.52\frac{\alpha_s^3}{\pi^3} - 69.3\frac{\alpha_s^4}{\pi^4}\right)$$

$$\delta_{\text{PQCD}} \approx \pm\frac{\alpha_s^5}{\pi^5}\frac{(80.0)^2}{12.77\pi - 80.0\alpha_s} = \pm 6\times 10^{-5} \Longrightarrow \delta_{\text{PQCD}}\alpha_s \approx \pm 0.0002$$

$$\mathcal{O}(\alpha_s^5) + \mathcal{O}(\alpha\alpha_s^5) + \mathcal{O}(\alpha^2\alpha_s) \Longrightarrow \delta_{\text{PQCD+mixed}}\alpha_s \approx \pm 0.0004\ (\textbf{negligible})$$

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Schott & JE, arXiv:1902.05142

α_s from the Z pole

observable	$\alpha_s(M_Z)$	change	χ^2/d.o.f.
$\Gamma_Z = 2495.5 \pm 2.3$ MeV	0.1215 ± 0.0048	+0.0006	
$\sigma_{had} = 41.501 \pm 0.037$ nb	0.1201 ± 0.0065	+0.0131	
$R_e = 20.804 \pm 0.050$	0.1295 ± 0.0082	—	
$R_\mu = 20.785 \pm 0.033$	0.1264 ± 0.0054	—	
$R_\tau = 20.764 \pm 0.045$	0.1157 ± 0.0072	—	
combination	0.1228 ± 0.0028	+0.0021	2.4/4
Z-pole + M_H	0.1224 ± 0.0027	+0.0017	18.6/23
global fit ex. τ decays	0.1214 ± 0.0026	+0.0019	38.3/40

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

α_s from τ decays

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

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

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

* charm, bottom and strange mass effects not shown but included
  Larin, van Ritbergen & Vermaseren, hep-ph/9411260
* $\mathcal{B}_\tau{}^s$ = 0.0292 ± 0.0004 ($\Delta S = -1$) **PDG 2018**
* $S(m_\tau, M_Z)$ = 1.01907 ± 0.0003 **JE, hep-ph/0211345**

α_s from τ decays

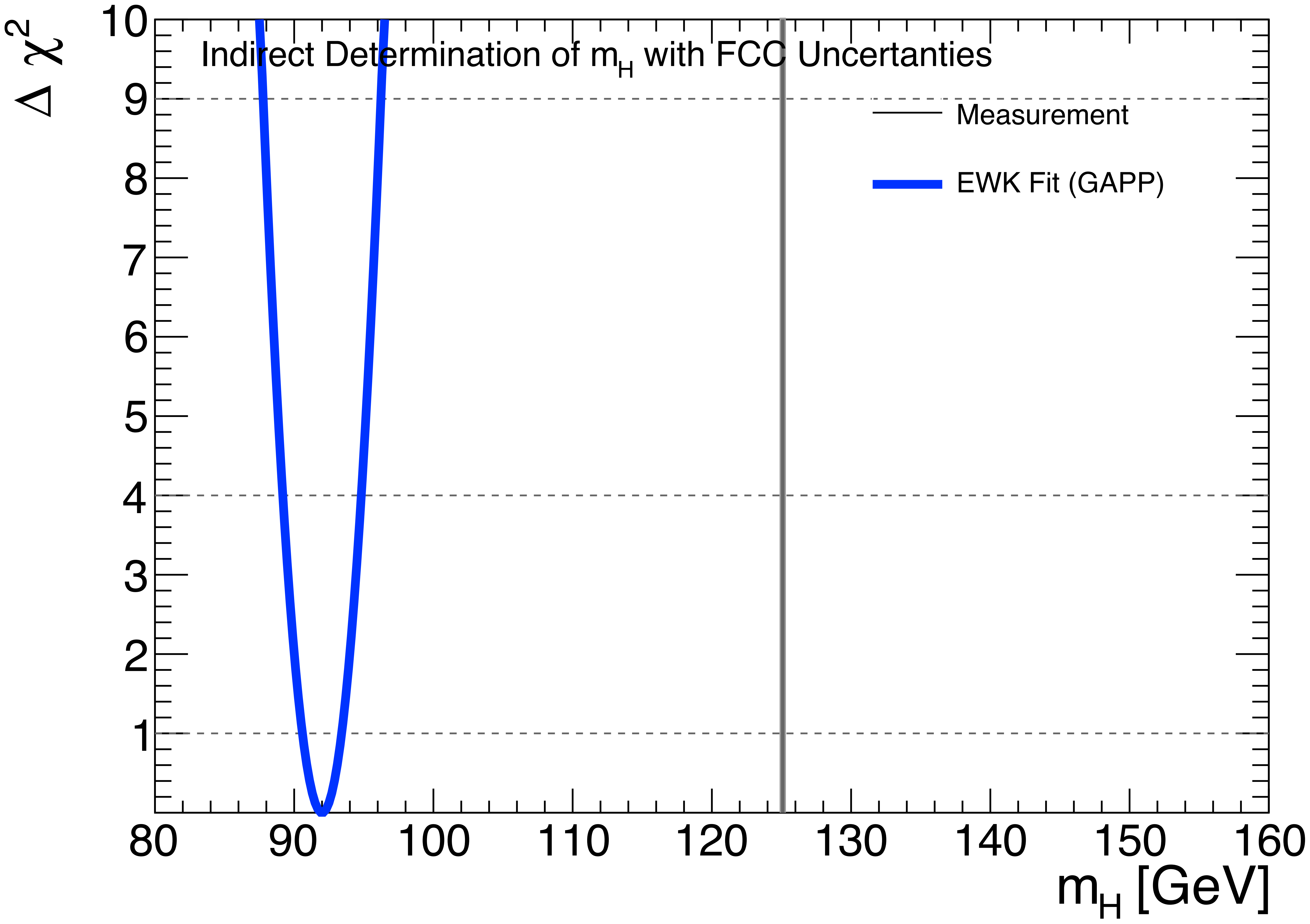
* $\delta_{NP} = 0.003 \pm 0.009$ (both within OPE & OPE breaking) based on (FOPT)
  * $\delta_{NP} = -0.004 \pm 0.012$ (OPAL data) **Boito et al., arXiv:1203.3146**
  * $\delta_{NP} = \ \ 0.020 \pm 0.009$ (ALEPH data) **Boito et al., arXiv:1410.3528**
  * $\delta_{NP} = -0.0064 \pm 0.0013$ (ALEPH data) **Davier et al., arXiv:1312.1501**
  * $\delta_{NP} = -0.006 \pm 0.009$ (ALEPH data) **Pich & Rodríguez-Sánchez, arXiv:1605.06830**
* dominant error from PQCD truncation (FOPT vs. CIPT vs. geometric continuation)
  * $\alpha_s^{(3)}(m_\tau) = 0.317^{+0.013}_{-0.011}$ (PQCD) $\pm\, 0.009 = 0.317^{+0.016}_{-0.014}$
  * $\alpha_s^{(4)}(m_\tau) = 0.323^{+0.014}_{-0.011}$ (PQCD) $\pm\, 0.009 = 0.323^{+0.017}_{-0.014}$
  * $\boldsymbol{\alpha_s^{(5)}(M_Z) = 0.1184^{+0.0017}_{-0.0014}}$ **(PQCD)** $\boldsymbol{\pm\, 0.0011 = 0.1184^{+0.0020}_{-0.0018}}$
  * updated from **Luo & JE, hep-ph/0207114** **in** **Freitas & JE, PDG 2018**
  * **global electroweak fit:** $\boldsymbol{\alpha_s^{(5)}(M_Z) = 0.1195^{+0.0017}_{-0.0016}}$ (m_t^{MC} only)

N_ν

	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**

outlook

M_H at the FCC–ee



indirect

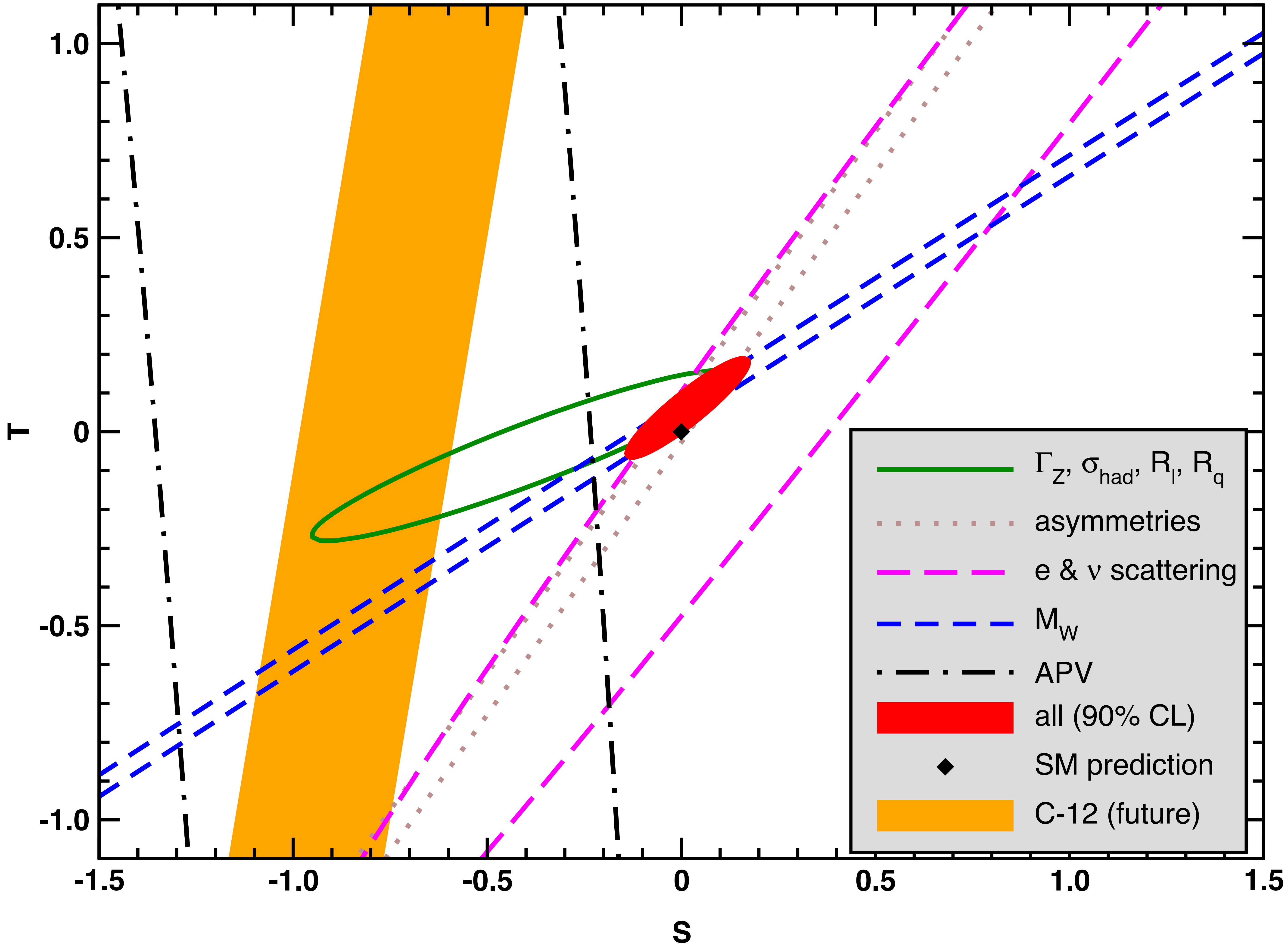
$\Delta M_H = \pm$ 1.4 GeV

$\Delta M_W = \pm$ 0.2 MeV

(theory errors ignored)

Blondel et al. arXiv:1905.05078

S and T

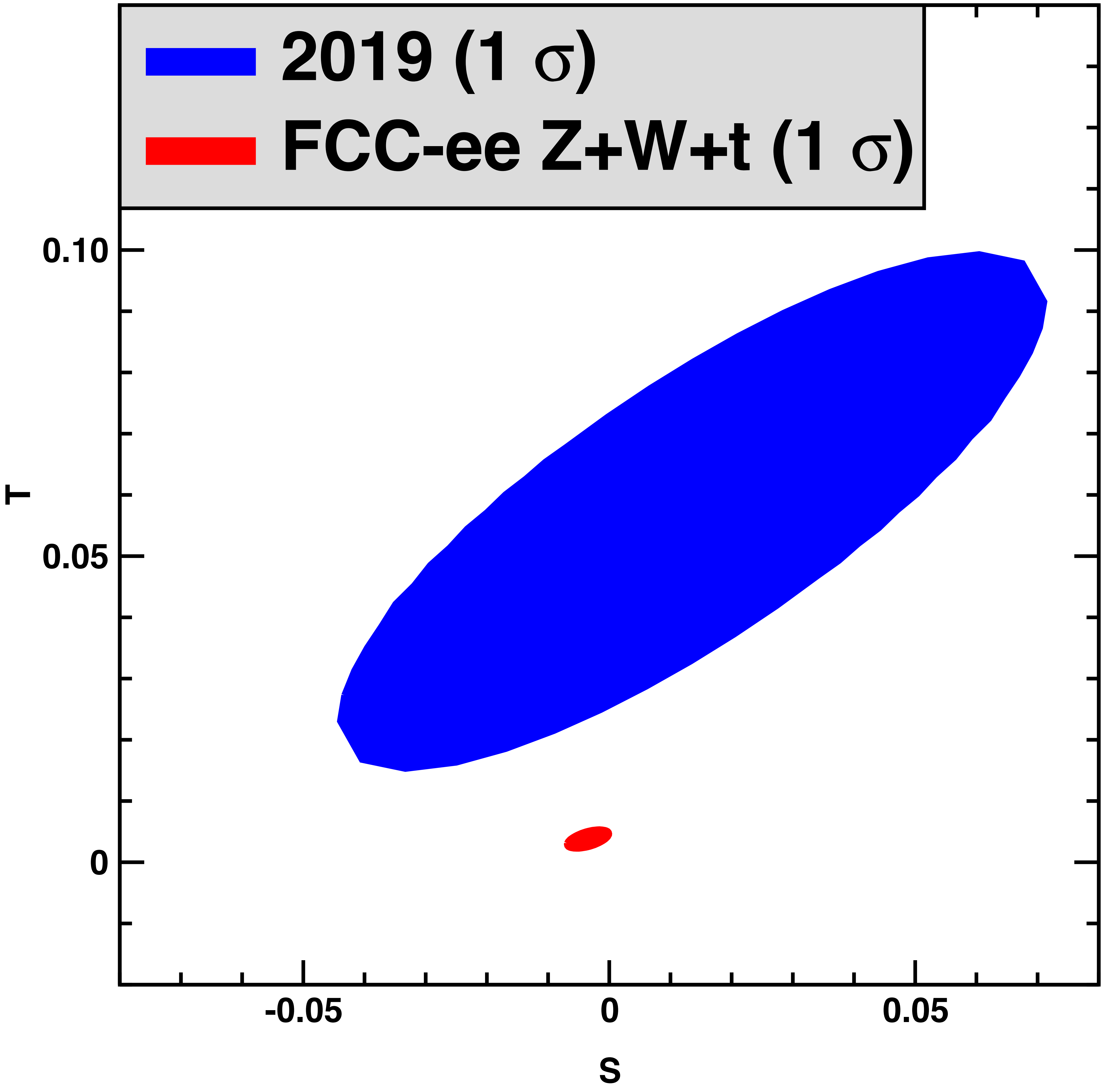


S	0.02 ± 0.07
T	0.06 ± 0.06
$\Delta\chi^2$	– 4.2

- $M_{KK} \gtrsim 3.2$ 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
Blondel et al., arXiv:1905.05078
except $\Delta\Gamma_Z$ = 100 MeV → 25 MeV

(theory uncertainties ignored)

Summary

* *new developments:*
  * LEP luminosity update
  * high precision PVES
  * APV isotope ratios and coherent elastic ν-scattering
  * changes in $A_{FB}(b)$ from LEP and $Q_W(Cs)$ from APV
  * precise m_t from $t\bar{t}$ production X-sections
* *future developments:*
  * ultra-high precision PVES (MOLLER and P2)
  * a leap in precision can be expected from future lepton colliders

backup

Coherent Elastic ν Nucleus Scattering (CEνNS)

COHERENT @ SNS

CsI

$E_\nu \approx 16 - 53$ MeV

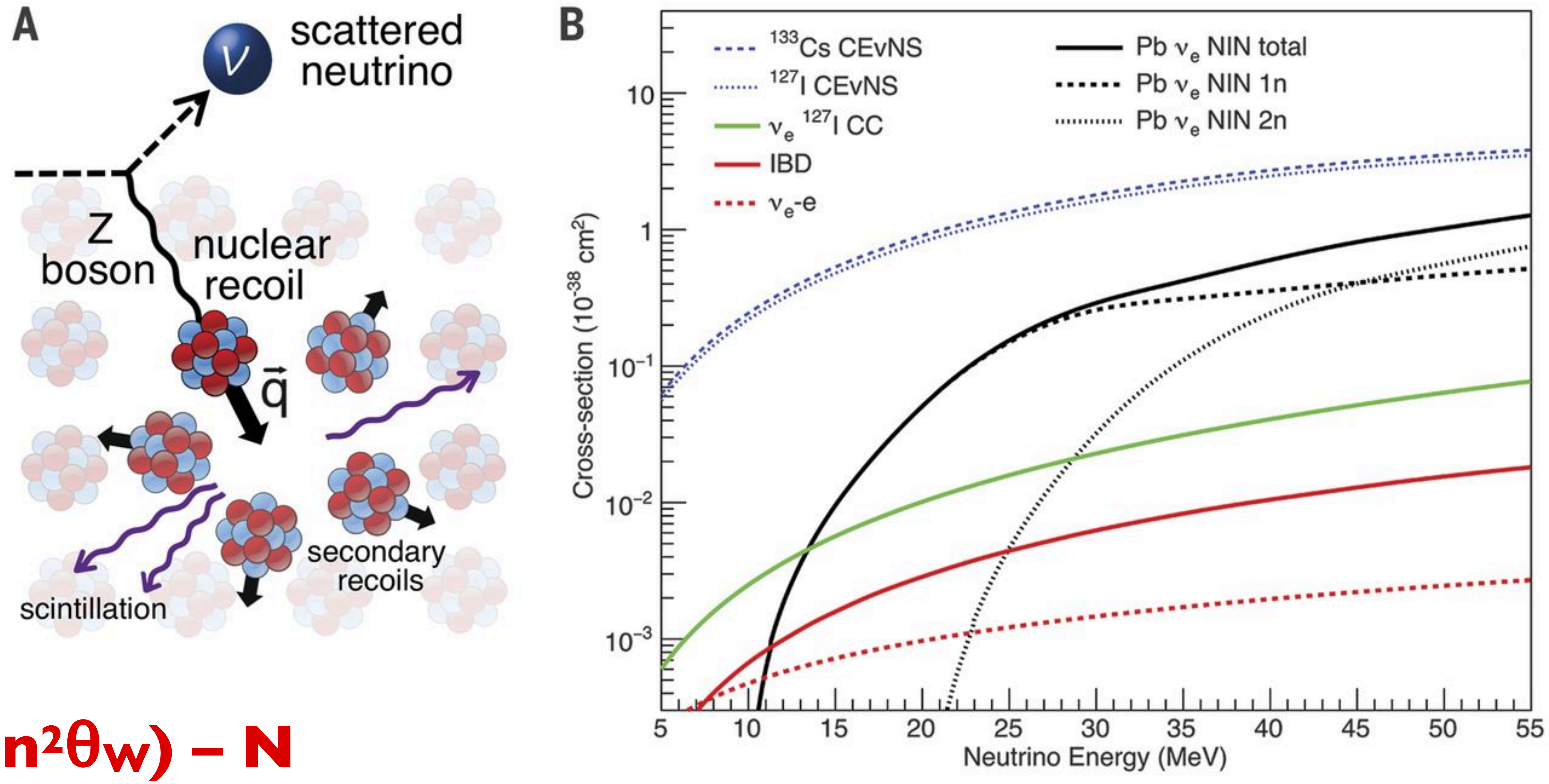
$\sigma \sim Q_W^2$

134 ± 22 events

constraints on NSI

neutron skin?

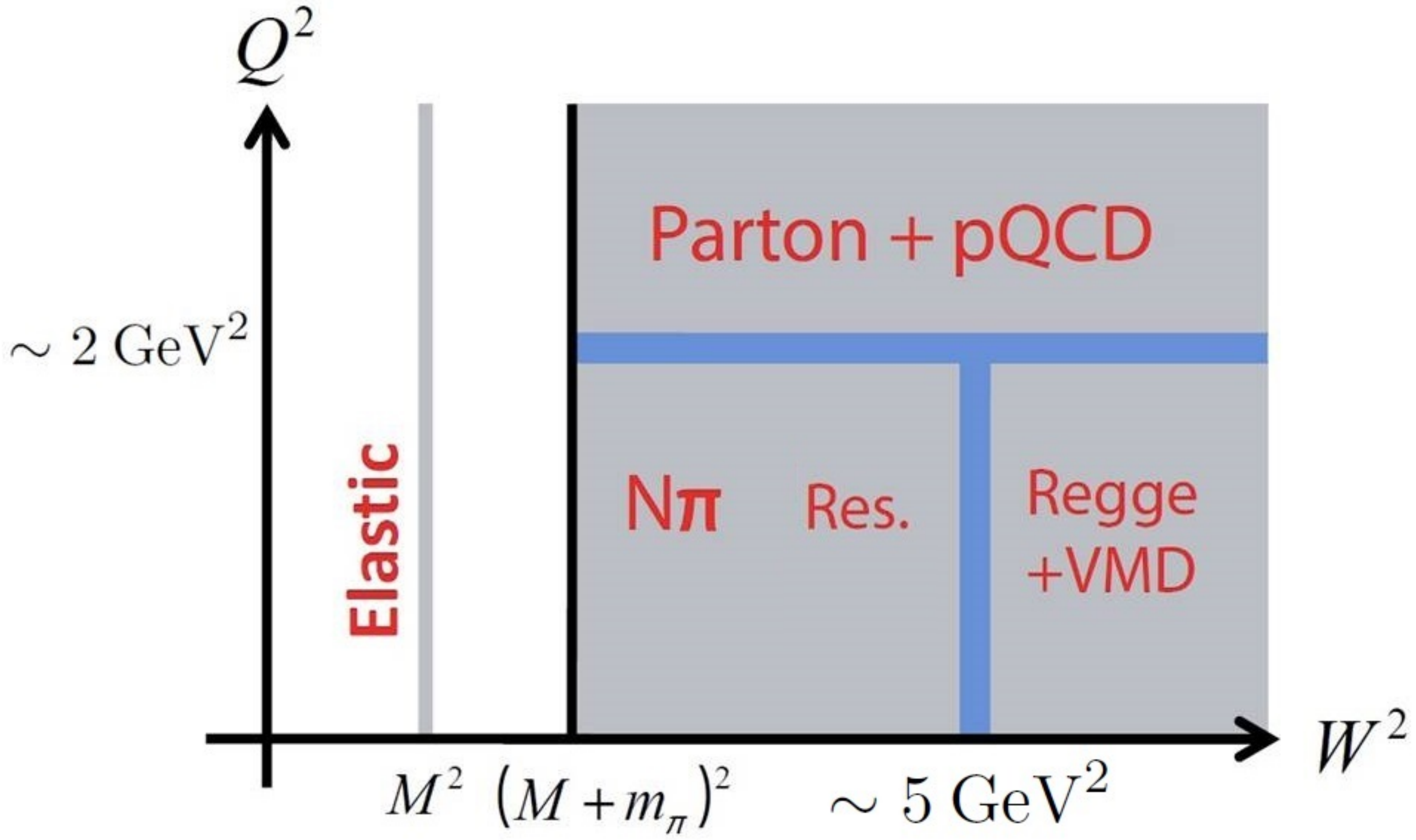
arXiv:1708.01294

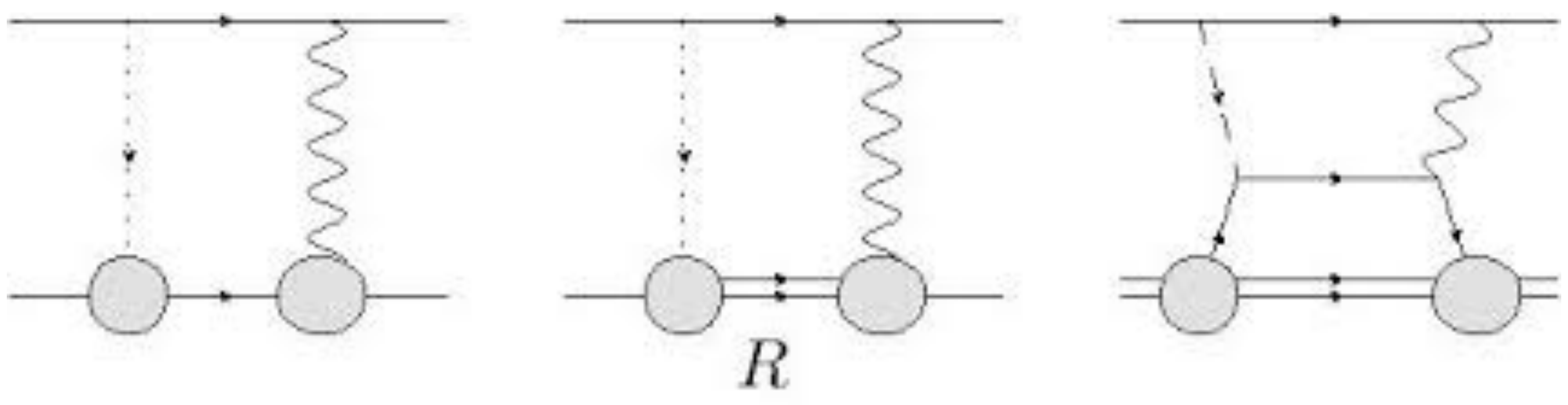


$$Q_W(N,Z) = Z\,(1 - 4\sin^2\theta_W) - N$$

Axial γZ-box

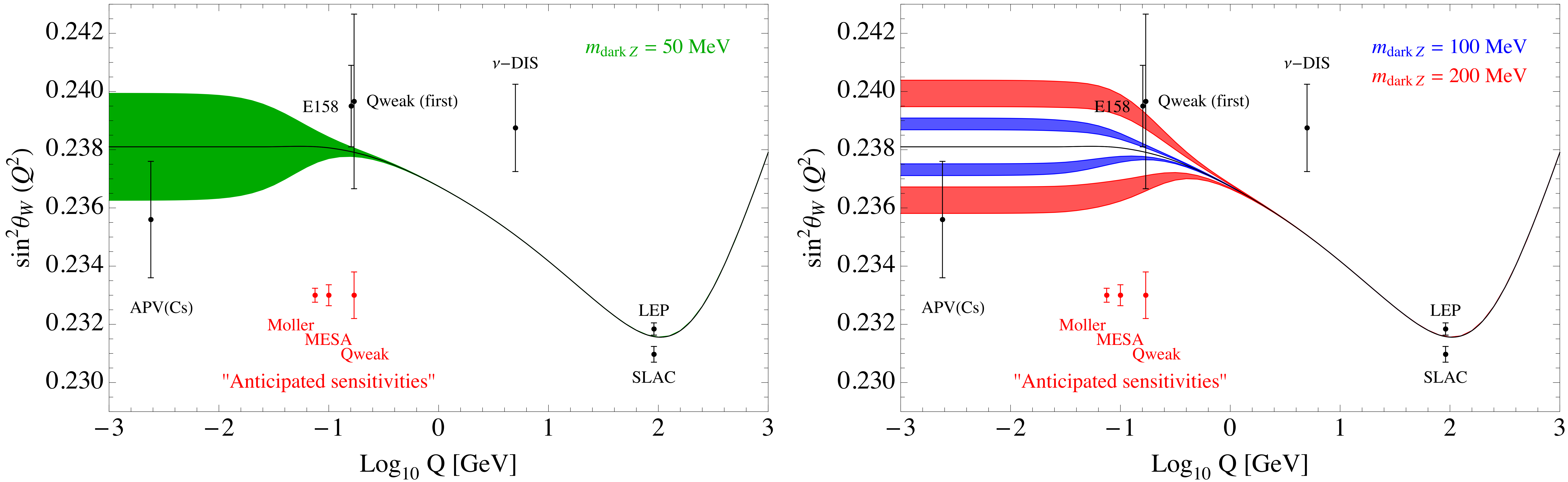
- largest contribution from DIS region
- largest uncertainty from Regge-VMD model
- non-vanishing at $E_e = 0$ (affects APV)
- total error now at $2{\times}10^{-4}$ (0.3%) level





JE et al., arXiv:1907.07928

The dark Z′ (Z_d)



- Z_d = dark γ (kinetic mixing term ∝ ε ≪ 1) + extra Higgs (Z-Z′ mass mixing term ∝ ε_Z ≪ 1)
- $g_\mu - 2 \propto \varepsilon^2 \alpha$: need invisible Z_d decay & cancellation in K → π + inv. (but <u>wrong sign</u> in g_e-2!)
- $\Delta\sin^2\theta_W(Q^2) = -\varepsilon\varepsilon_Z M_Z^2/(M_{Z'}^2 + Q^2)\sin 2\theta_W/2$ **Davoudiasl et al., arXiv:1402.3620**

Simple models

* Leptoquarks: large effects in $Q_W(p)$ and $Q_W(n)$ possible, $Q_W(e)$ unaffected

* SUSY loops: $Q_W(e)$ and $Q_W(p)$ strongly correlated (through oblique effects in $\sin^2\theta_W$), relatively small shifts in $Q_W(n)$ (box graphs numerically small)

* RPV SUSY: slepton exchange affects all Q_W (also CC) through G_F, squarks mimic leptoquarks, overall $Q_W(p)$ and $Q_W(e)$ tend to shift with opposite sign
  Kurylov, Ramsey-Musolf & JE, hep-ph/0302149

* E_6 Z': $Q_W(e)$ and $Q_W(p)$ shift together (also in chiral SUSY models **JE, hep-ph/0006051**), $Q_W(n)$ independent (with kinetic mixing ∃ two independent $U(1)'$ charge parameters), no more preference for Z-Z' mixing after LEP lumi update
  Voutsinas et al., arXiv:1908.01704

New Physics scales Λ_{NP} (95% CL)

	precision	$\Delta\sin^2\theta_W$	Λ_{NP}		precision	$\Delta\sin^2\theta_W$	Λ_{NP}
E158	14%	0.0013	17.0 TeV	MOLLER	2.4%	0.00028	38 TeV
PVDIS	4.1%	0.0043	7.8 TeV	SoLID	0.6%	0.00057	22 TeV
Qweak	6.3%	0.0011	27.8 TeV	P2	1.83%	0.00033	51 TeV
				P2 ^{12}C	0.3%	0.0007	49 TeV
APV ^{133}Cs	0.58%	0.0019	32.3 TeV	APV ^{225}Ra	0.5%	0.0018	34 TeV
^{176}Yb / ^{170}Yb	0.78%	0.052	4.3 TeV	^{225}Ra / ^{213}Ra	0.1%	0.0037	16 TeV