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Electroweak Standard Model & Constraints on New Physics

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Cluster of Excellence PRISMA++

Overview

* The weak mixing angle
    * History, impact and status
    * Low-energy measurements
* The bigger picture
    * Hadronic vacuum polarization: $\alpha(M_Z)$, $g-2$, and $\sin^2\theta_W(0)$
    * Latest developments: M_Z (*CDF* and *LHCb*), M_W (*CDF* and *CMS*), Γ_W (update)
    * α_S and N_ν
    * $\overline{m}_c(\overline{m}_c)$ and $\overline{m}_b(\overline{m}_b)$
* Beyond the SM (SMEFT)
* Conclusions

Standard Model Particles and Helicities

ν_τ ±½	τ^- ±½	τ^+ ±½	t ±½	t ±½	t ±½	$\bar{t}$ ±½	$\bar{t}$ ±½	$\bar{t}$ ±½	b ±½	b ±½	b ±½	$\bar{b}$ ±½	$\bar{b}$ ±½	$\bar{b}$ ±½
ν_μ ±½	μ^- ±½	μ^+ ±½	c ±½	c ±½	c ±½	$\bar{c}$ ±½	$\bar{c}$ ±½	$\bar{c}$ ±½	s ±½	s ±½	s ±½	$\bar{s}$ ±½	$\bar{s}$ ±½	$\bar{s}$ ±½
ν_e ±½	e^- ±½	e^+ ±½	u ±½	u ±½	u ±½	$\bar{u}$ ±½	$\bar{u}$ ±½	$\bar{u}$ ±½	d ±½	d ±½	d ±½	$\bar{d}$ ±½	$\bar{d}$ ±½	$\bar{d}$ ±½
H 0	$H^\pm$ 0	Z ±1	W^- ±1	W^+ ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	γ ±1	G ±2

(before electroweak symmetry breaking)

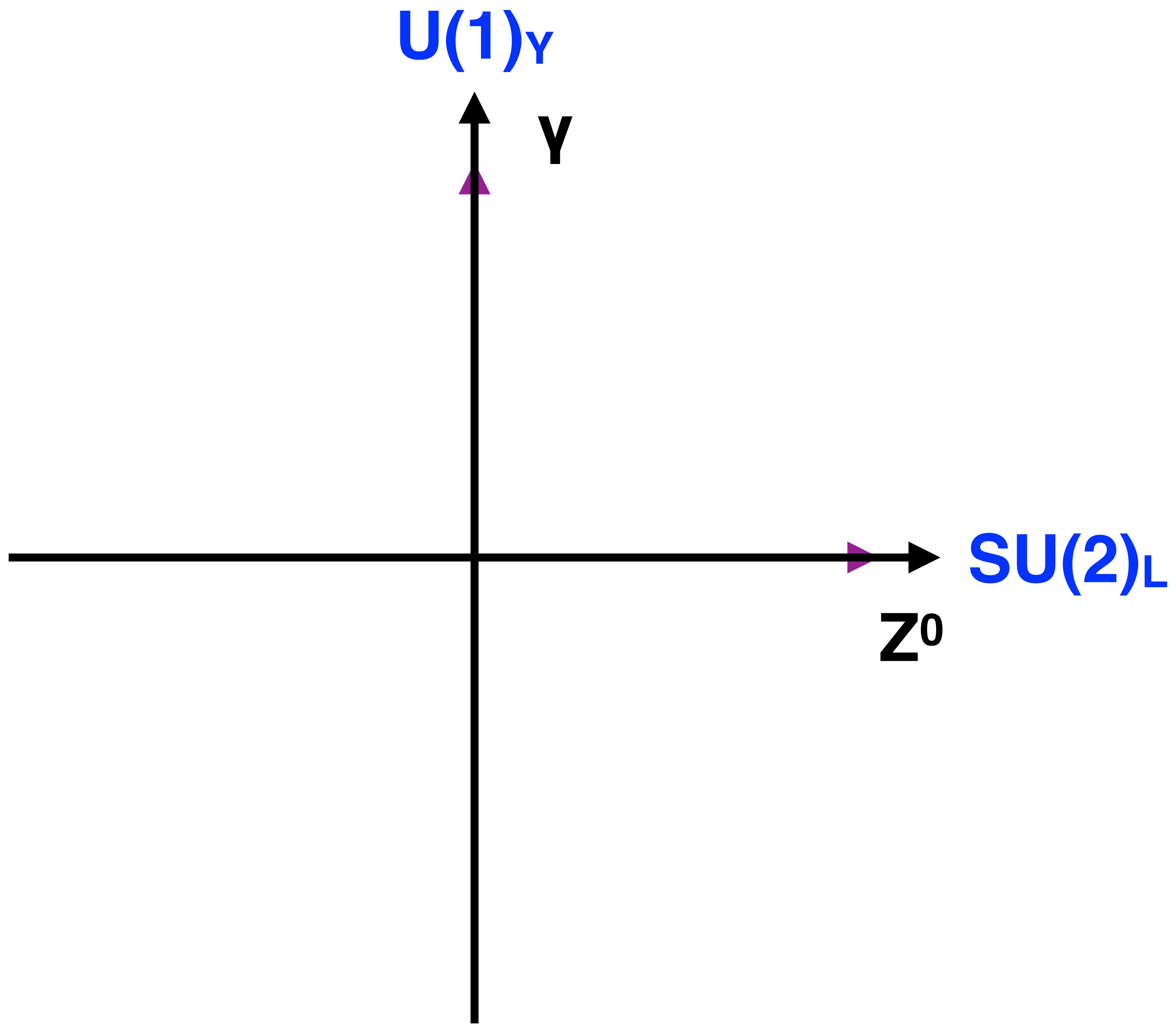
Standard Model Particles and Helicities

ν_τ ±½	τ^- ±½	τ^+ ±½	t ±½	t ±½	t ±½	$\bar{t}$ ±½	$\bar{t}$ ±½	$\bar{t}$ ±½	b ±½	b ±½	b ±½	$\bar{b}$ ±½	$\bar{b}$ ±½	$\bar{b}$ ±½
ν_μ ±½	μ^- ±½	μ^+ ±½	c ±½	c ±½	c ±½	$\bar{c}$ ±½	$\bar{c}$ ±½	$\bar{c}$ ±½	s ±½	s ±½	s ±½	$\bar{s}$ ±½	$\bar{s}$ ±½	$\bar{s}$ ±½
ν_e ±½	e^- ±½	e^+ ±½	u ±½	u ±½	u ±½	$\bar{u}$ ±½	$\bar{u}$ ±½	$\bar{u}$ ±½	d ±½	d ±½	d ±½	$\bar{d}$ ±½	$\bar{d}$ ±½	$\bar{d}$ ±½
H 0	$H^\pm$ 0	Z ±1	W^- ±1	W^+ ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	g ±1	γ ±1	G ±2

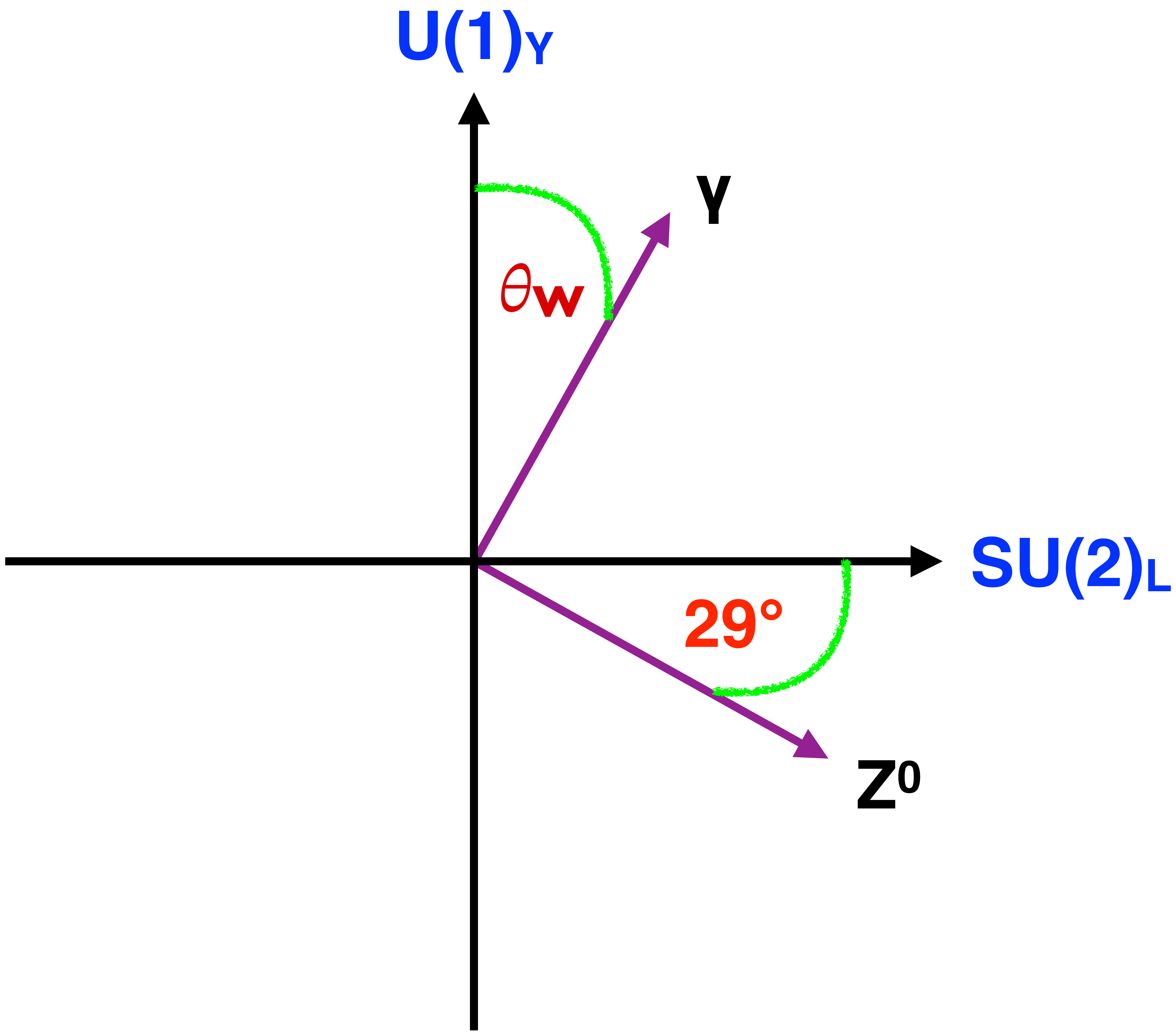
do not discriminate against anybody
based solely on the value of their spin!


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

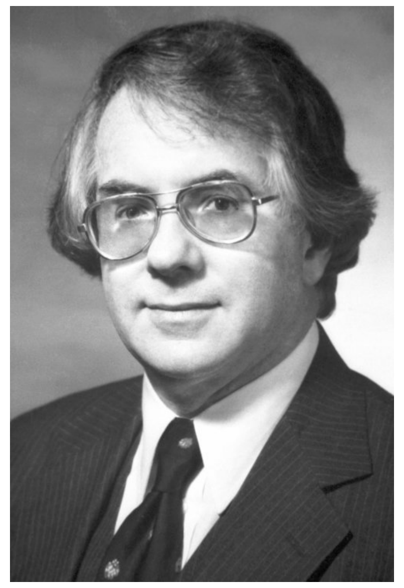
$\sin^2\theta_W$



$\sin^2\theta_W$



The E = mc² of the SM

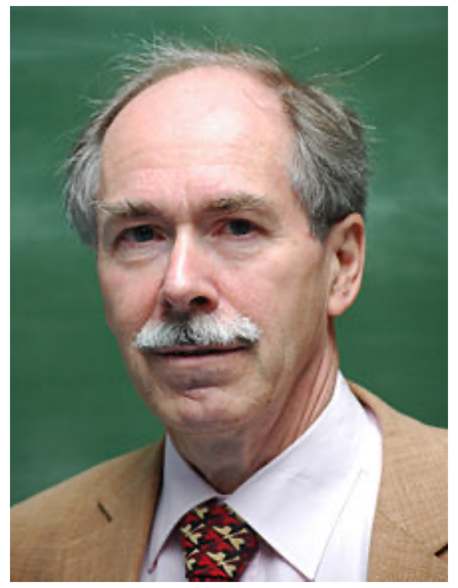
$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \frac{M_W^2}{M_Z^2} = \frac{\pi\alpha}{\sqrt{2}G_F M_W^2}$$

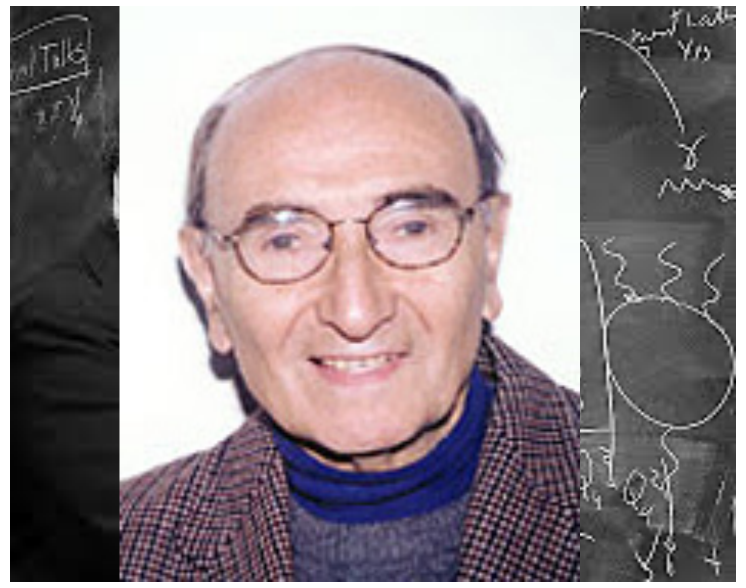
Radiative corrections

$$\propto \frac{\alpha m_t^2}{M_W^2}$$

$$\Delta\hat{\alpha} + \ldots$$

$$\frac{\sin^2\theta^e_{\rm eff}}{1+\Delta\hat{k}} = \frac{\hat{g}'^2}{\hat{g}^2+\hat{g}'^2} = 1 - \frac{(1-\Delta\hat{\rho})M_W^2}{M_Z^2} = \frac{\pi\alpha}{(1-\Delta\hat{r})\sqrt{2}G_F M_W^2}$$




Why we need to know $\sin^2\theta_W$ as *precisely as possible*

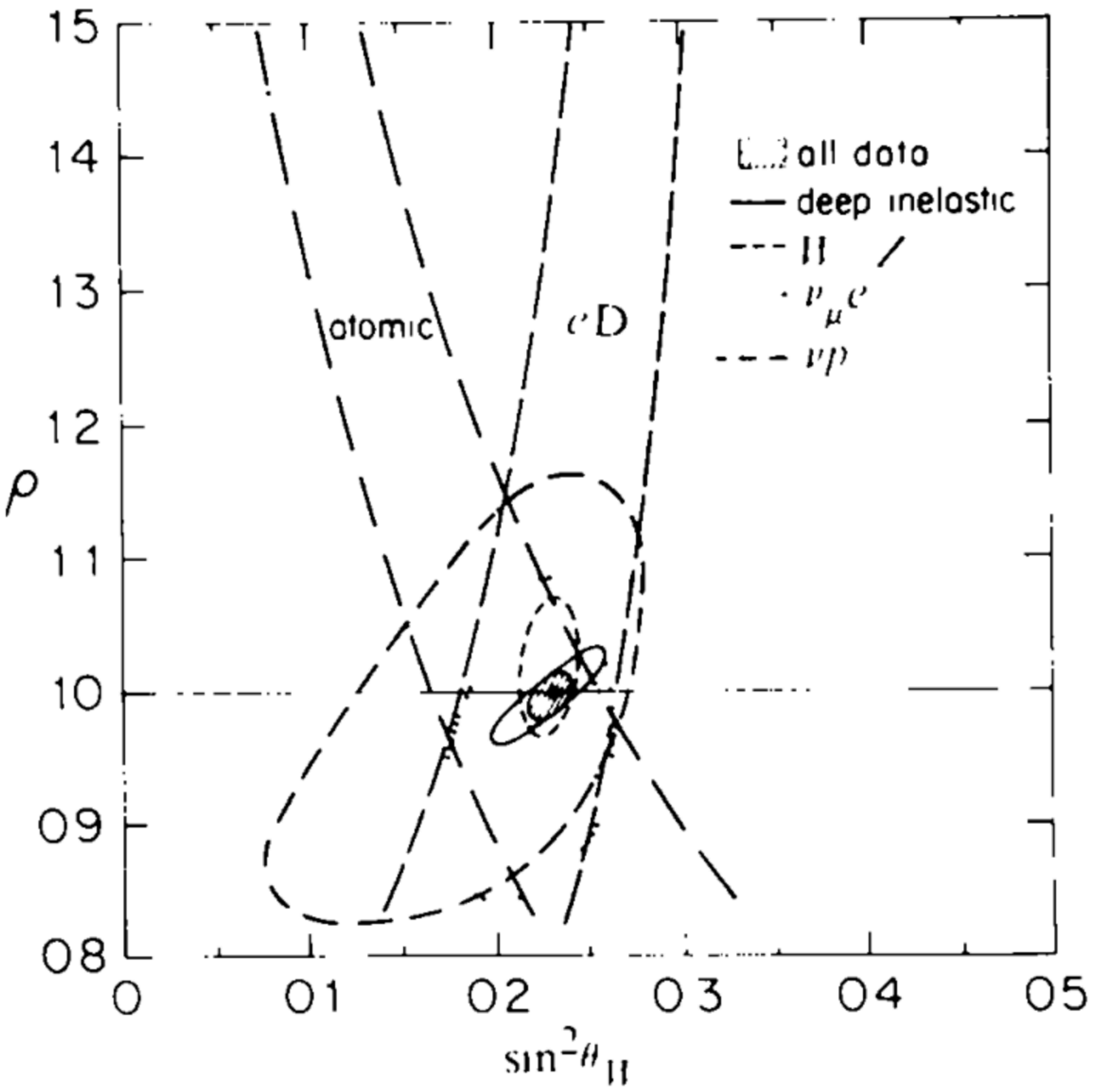
* Weak mixing angle is crucial!
  * Impact within the Standard Model (SM):
    * even before electroweak (EW) spontaneous symmetry breaking (SSB): test of gauge coupling unification (GUTs)
    * after SSB: with Fermi constant G_F from muon lifetime, $\sin^2\theta_W \Longrightarrow$ Z boson mass (M_Z)
    * with M_Z from *UA1* & *UA2* @ *SPS* (CERN), $\sin^2\theta_W \Longrightarrow$ simple Higgs structure ($\rho_0 = 1$)
    * with $\rho_0 = 1$, $\sin^2\theta_W$ + other Z pole observables (*LEP* & *SLC*) $\Longrightarrow$ top quark mass (m_t)
    * with m_t from *CDF* & *DØ* @ *Tevatron* (FNAL), $\sin^2\theta_W \Longrightarrow$ Higgs boson mass (M_H)

Why we need to know $\sin^2\theta_W$ as *precisely as possible*

$$G = G_\mu = (1.16632 \pm 0.00002) \times 10^{-5}\ \text{GeV}^{-2}$$ Refs. 3,8 ;

$$\sin^2\theta_W = 0.224 \pm 0.019, \quad \rho = 0.992 \pm 0.020$$
$$\sin^2\theta_W = 0.229 \pm 0.010, \quad \rho \equiv 1\ \text{(fixed)}$$ Ref. 9 .

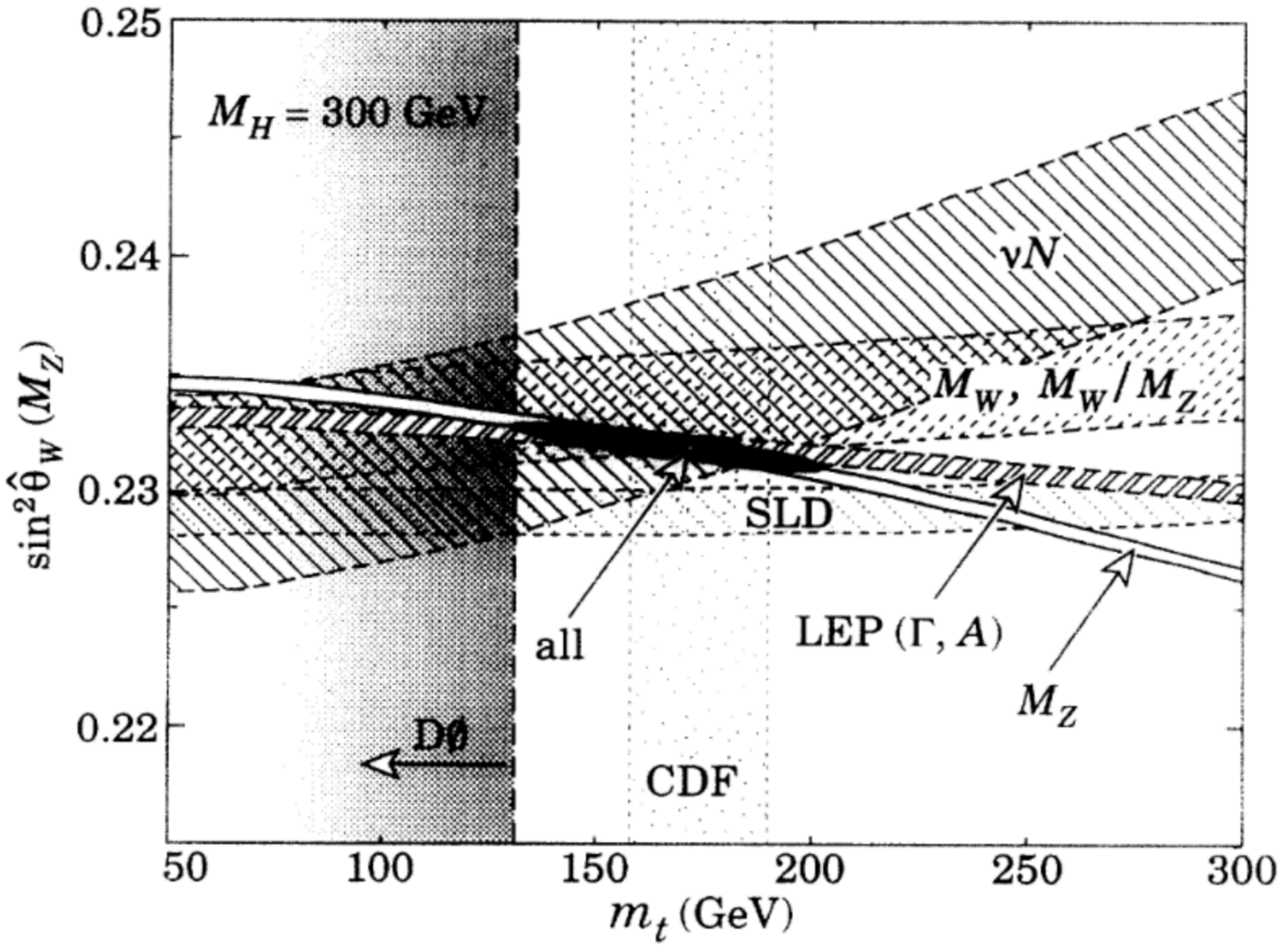
The resulting mass estimates for $W^\pm$ and Z are $M_W = 37.3\ \text{GeV}/\sin\theta_W = 77.9 \pm 1.7$ GeV, and $M_Z = 88.8 \pm 1.4$ GeV, where the numerical values are obtained using the simplest Higgs structure ($\rho \equiv 1$). Electroweak radiative corrections to these estimates may be as large as 5%.[10]



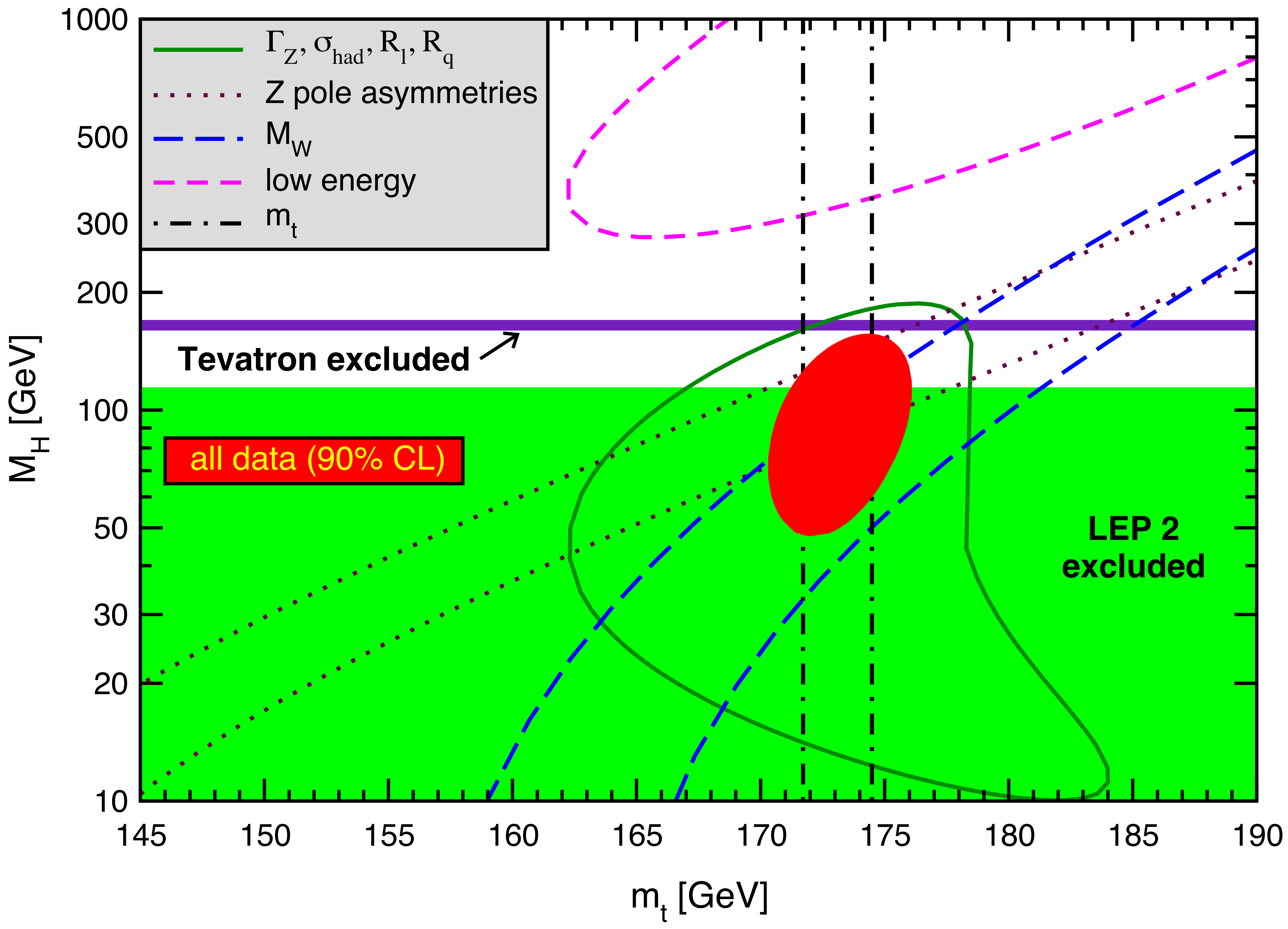
PDG 1982

Paul Langacker (PDG 1988)

Why we need to know $\sin^2\theta_W$ as *precisely as possible*

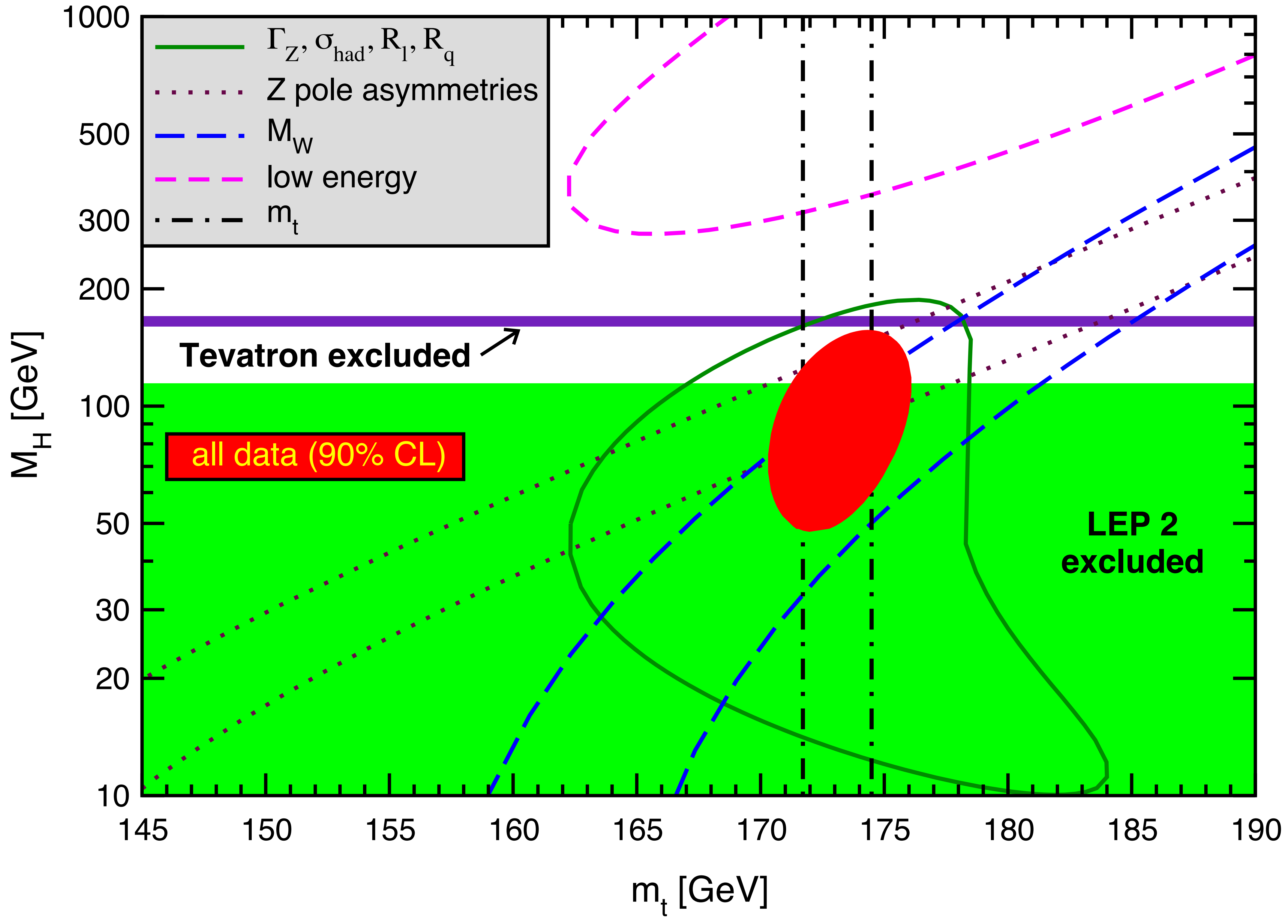


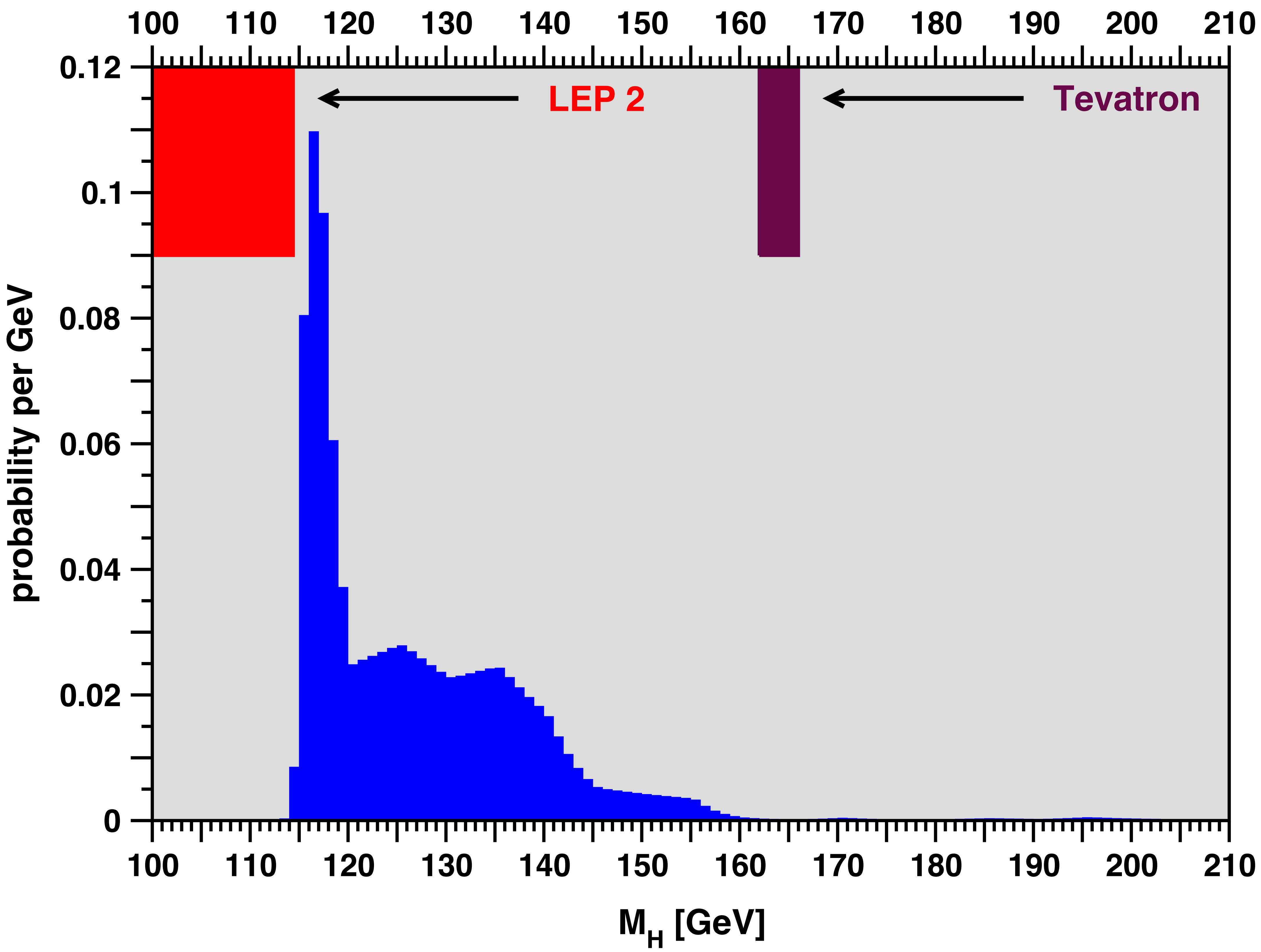
Paul Langacker, JE (PDG 1994)



JE, Paul Langacker (PDG 2010)

Why we need to know $\sin^2\theta_W$ as *precisely as possible*

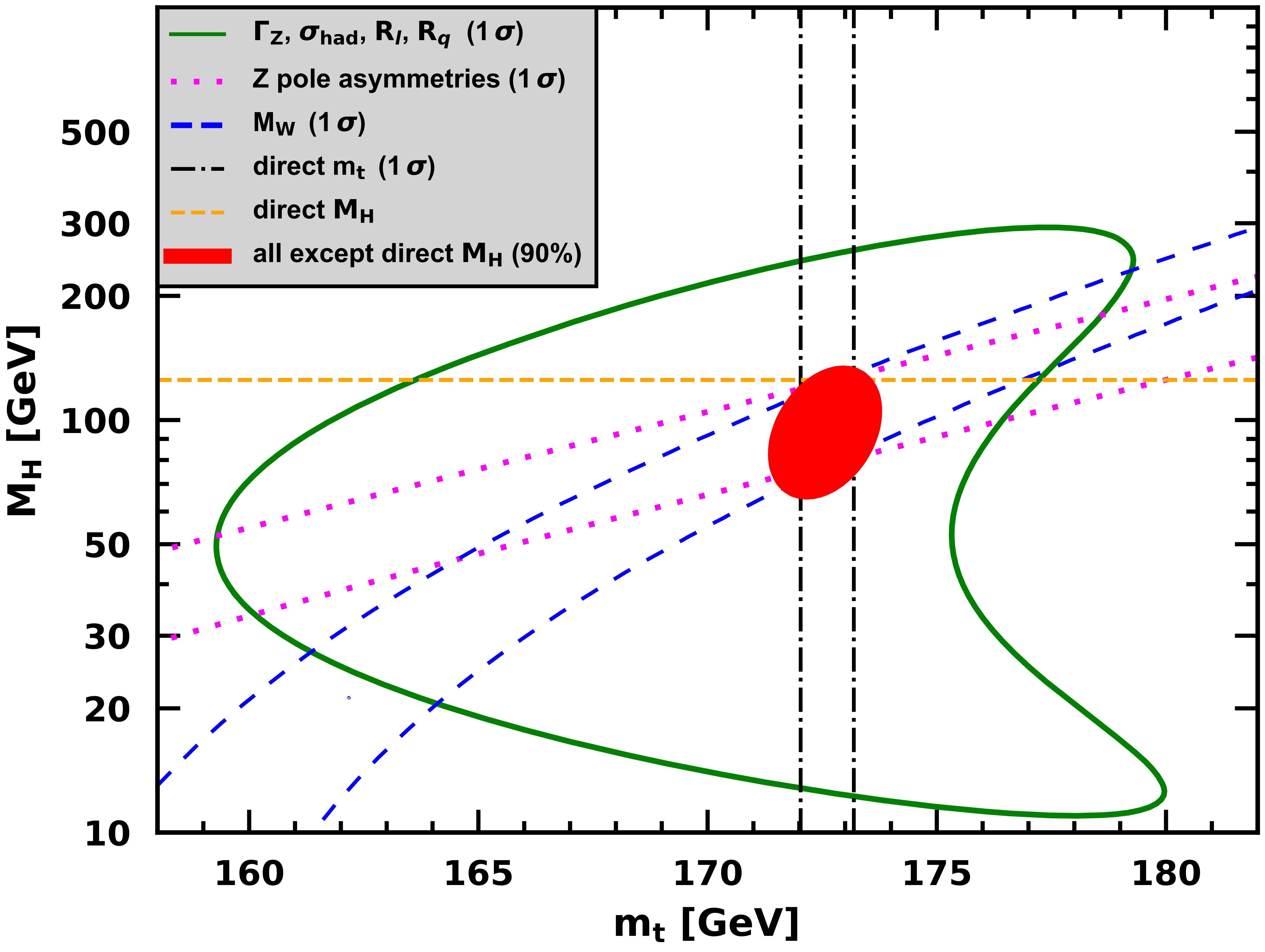




Paul Langacker, JE (PDG 2010)

JE, arXiv 1002.1320 [hep-ph]

$M_H - m_t$



$\chi^2/\text{d.o.f.} = 45.5/48$
(p-value = 57%)

M_H = 97 (99)$^{+15}_{-14}$ GeV
indirect (including Γ_H)

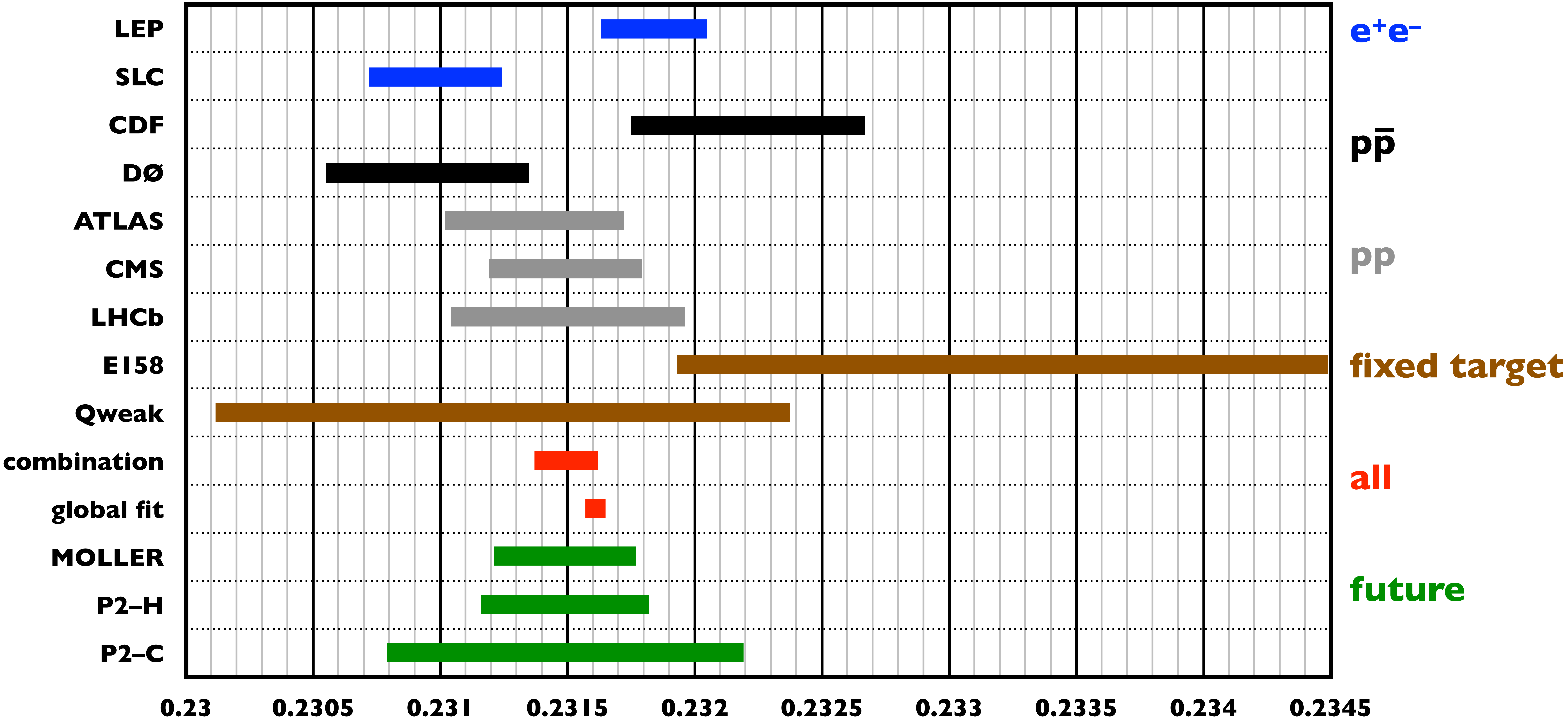
1.7 σ below

M_H = 125.10 ± 0.09 GeV
(LHC)

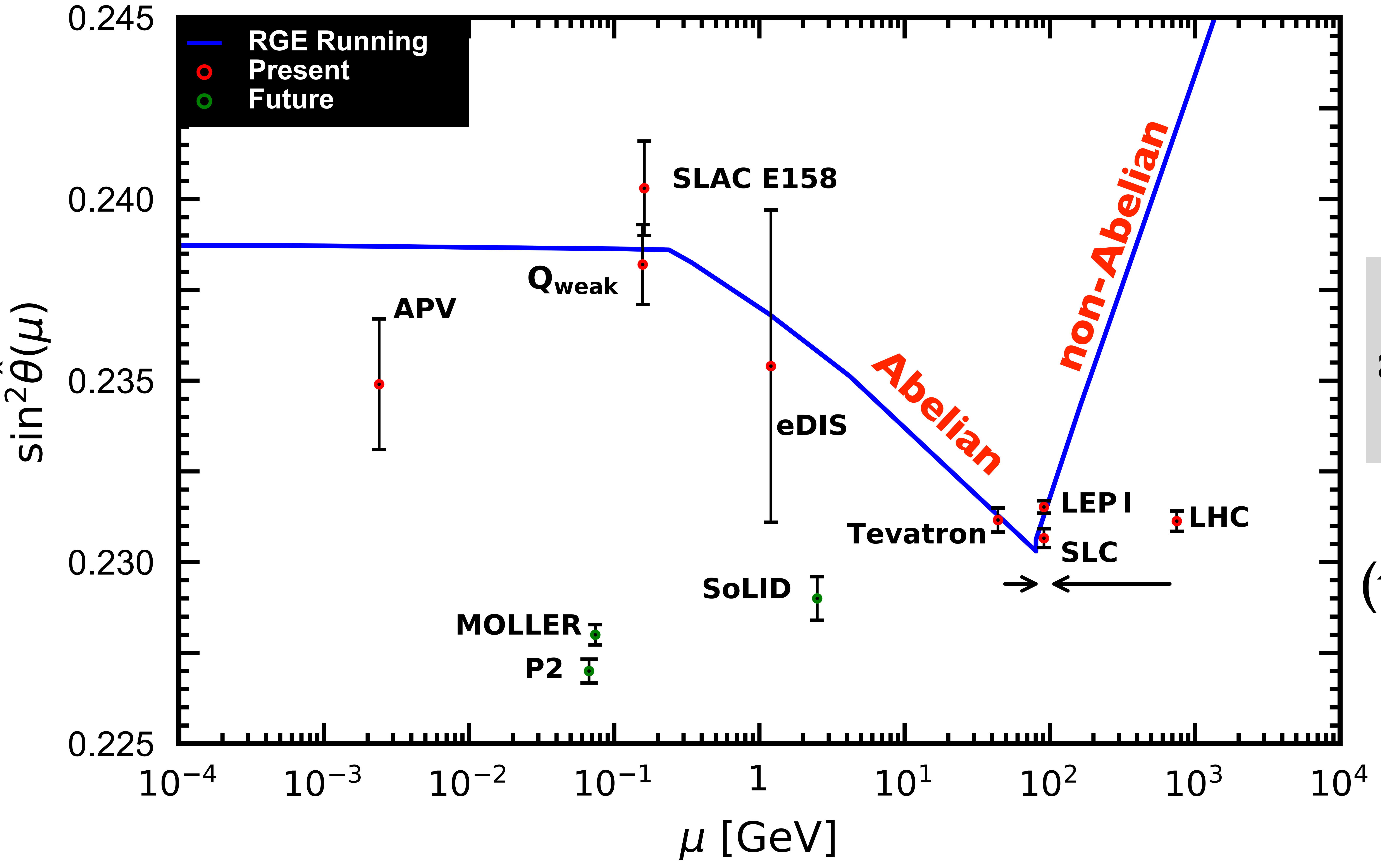
MOLLER & P2 will reduce asymmetry band by ~15%

Freitas & JE, PDG (2024)
figure: Rodolfo Ferro

Status of $\sin^2\theta^{\ell}_{\text{eff}}$ (= LEP definition)



Running $\overline{\text{MS}}$ weak mixing angle



updated from
Ferro-Hernández & JE
arXiv:1712.09146

MOLLER & P2 will measure a radiative correction factor to ≲ 3% uncertainty!

(theory ahead of experiment)

Low-energy measurements of $\sin^2\theta^{\ell}_{\mathrm{eff}}$

	ν scattering	PVES
leptonic	$\nu_\mu - e^-$	$e^- - e^-$ (E158, MOLLER)
DIS	heavy nuclei (NuTeV)	deuteron (E122, PVDIS, SoLID)
elastic	CEvNS: COHERENT (accelerator) XENONnT & PandaX (solar) CONUS+ (reactor)	proton (Qweak, P2) ^{12}C (P2)
APV	heavy alkali (type) atoms and ions	isotope ratios (Mainz)

mentioned in 1979 Nobel committee press release as "of special interest"

recent first measurements

upcoming measurements

Parity Violating e⁻ Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 MeV

|Q| = 158 MeV (θ = 7.9°)

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

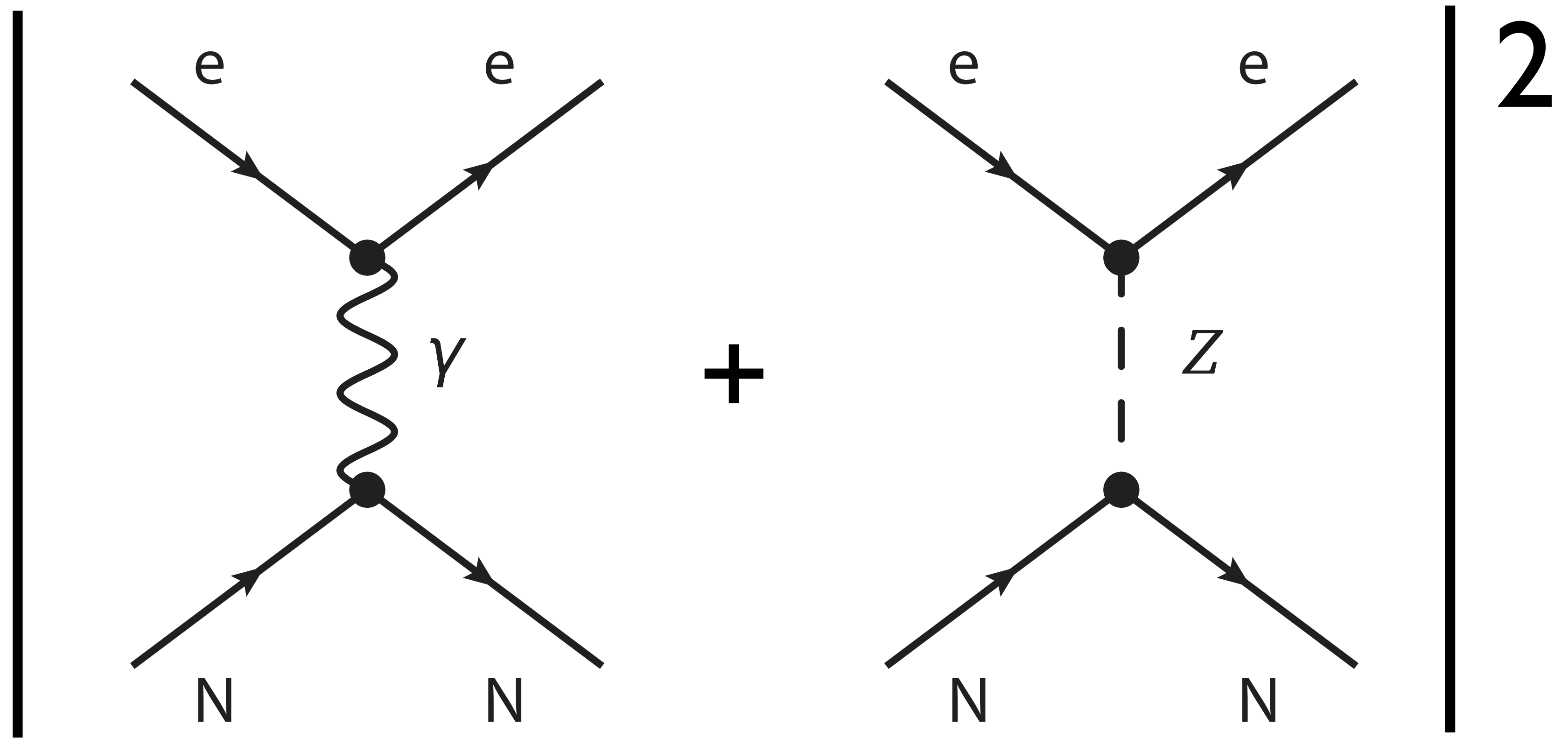
$\Delta A_{PV} = \pm 4.1\%$

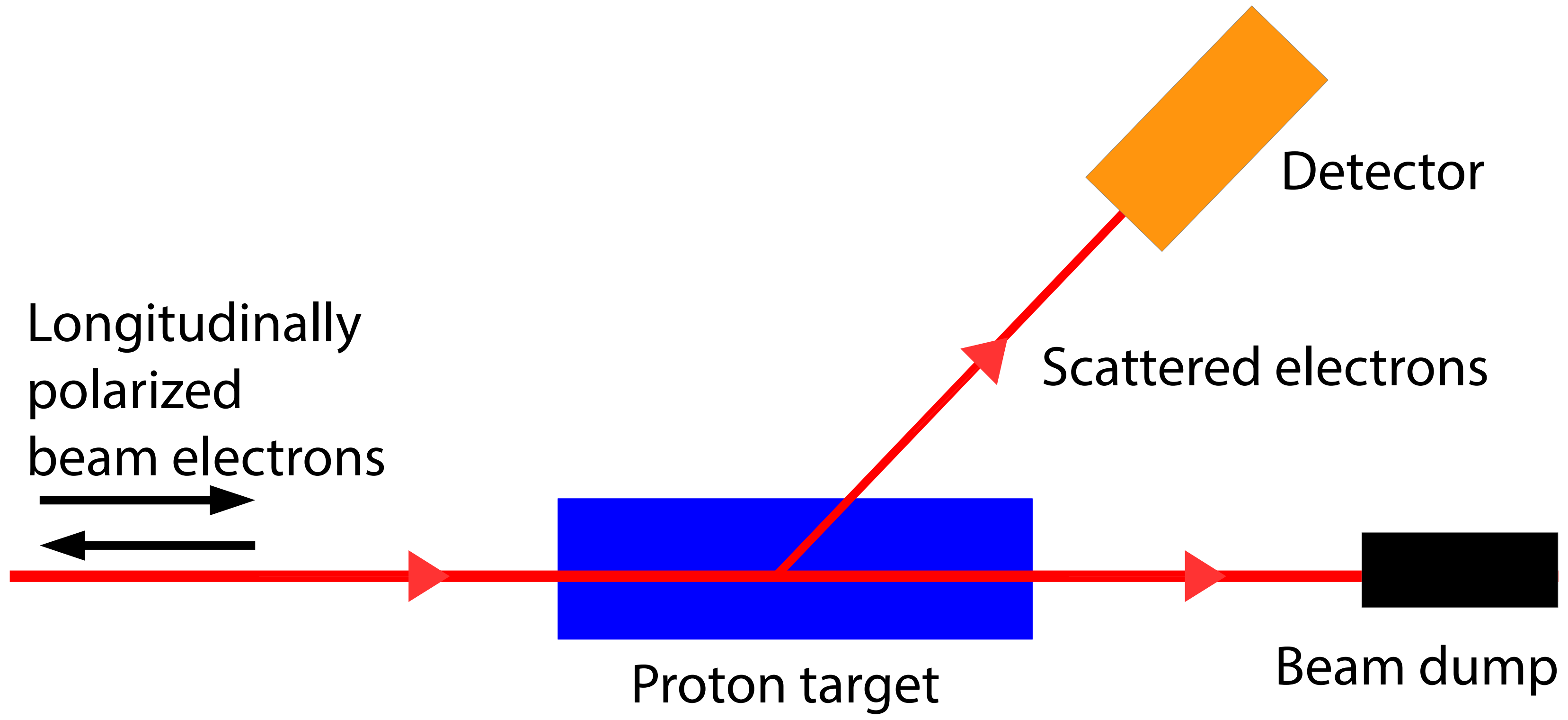
$\Delta Q_W(p) = \pm 6.25\%$

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

FFs from fit to ep asymmetries

arXiv:1905.08283





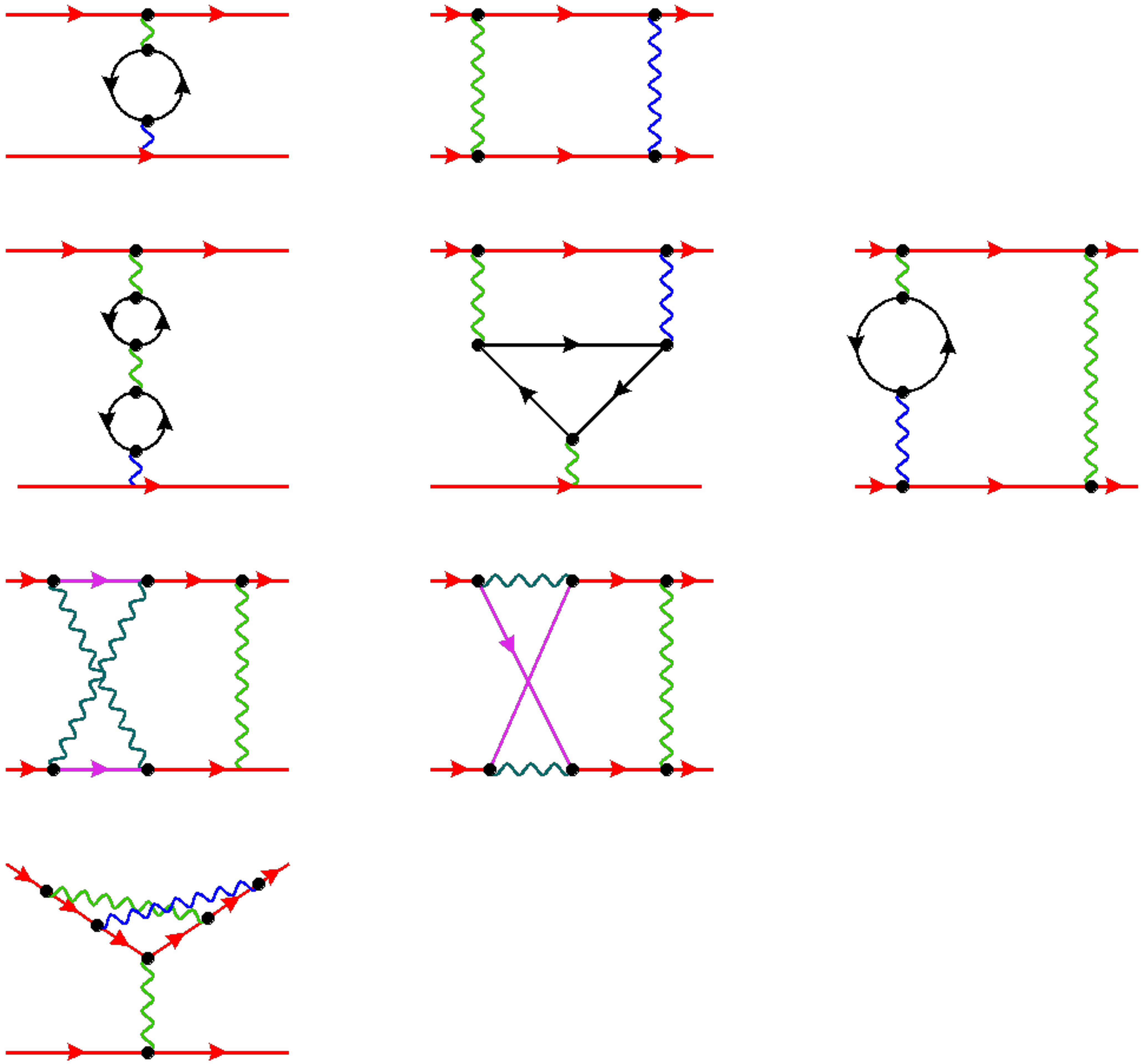
$$A_{PV} = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} \sim \frac{Q^2}{e^2 v^2} \sim 10^{-4}\, Q^2\ [\mathrm{GeV}^2]$$

Electroweak Radiative Correction for MOLLER and P2

1-loop

2-loop

incomplete



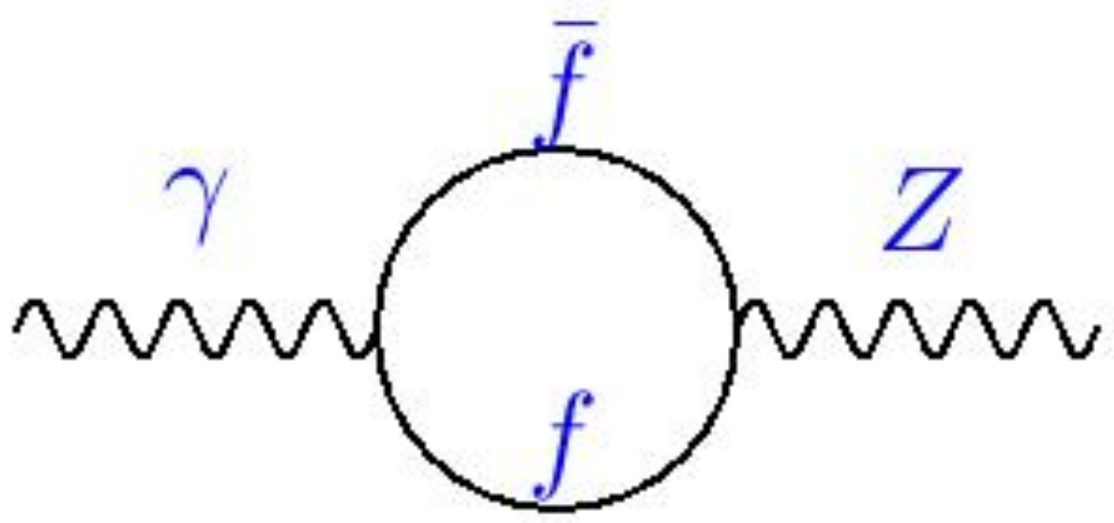
Parity violating asymmetry of the proton

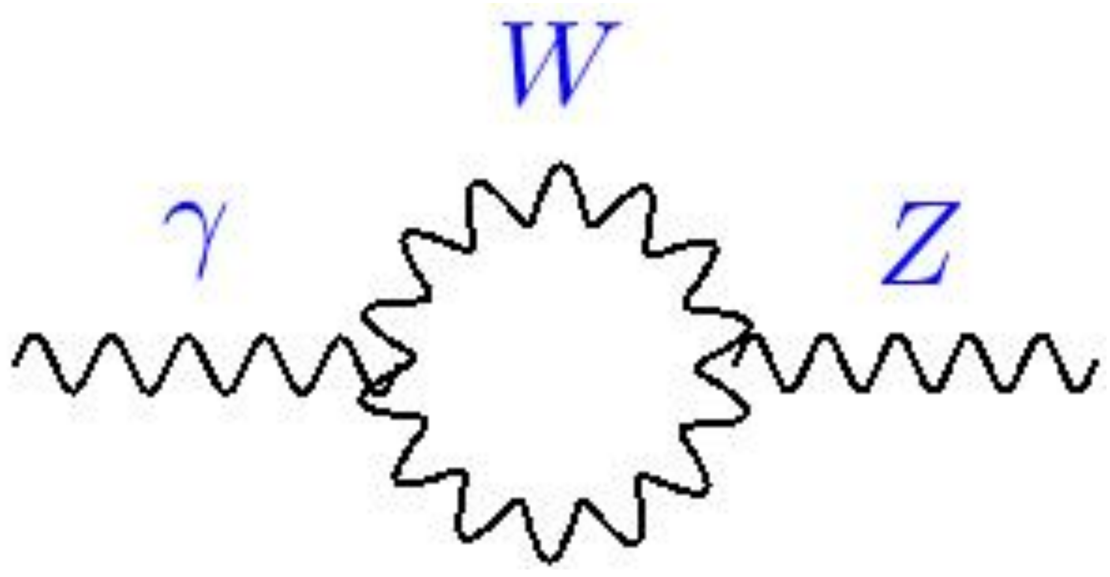
$$A_p^{PV} = -\frac{G_F}{4\sqrt{2}\pi\alpha} Q^2 \left[Q_W^p - F\left(Q^2\right) \right] \longrightarrow \boxed{F\left(Q^2\right) = F^{EM}\left(Q^2\right) + F^A\left(Q^2\right) + F^S\left(Q^2\right) + F^{u,d}\left(Q^2\right)}$$

* EM FF F^{EM} – world data
* strange FF F^S – lattice QCD
* isospin breaking FF $F^{u,d}$ – χPT & lattice
* axial FF F^A – backward angle kinematics

➜ **Rolando Martínez** (PhD student)

$\sin^2\theta_W(0)$





* Work in MS-bar scheme
* RGE for α: $\mu^2\, d\alpha/d\mu^2 \equiv \alpha/24\pi \sum_k N_C^k\, \gamma^k\, (Q^k)^2$
* RGE for v_i: $\bar{X} \equiv \sum_i NC^i\, \gamma^i\, \overline{v}^i\, Q^i \Longrightarrow d\bar{X}/\bar{X} = d\alpha/\alpha$
* running of α e^+e^- and/or τ data $\Rightarrow$ running of $\sin^2\bar{\theta}_W$ if

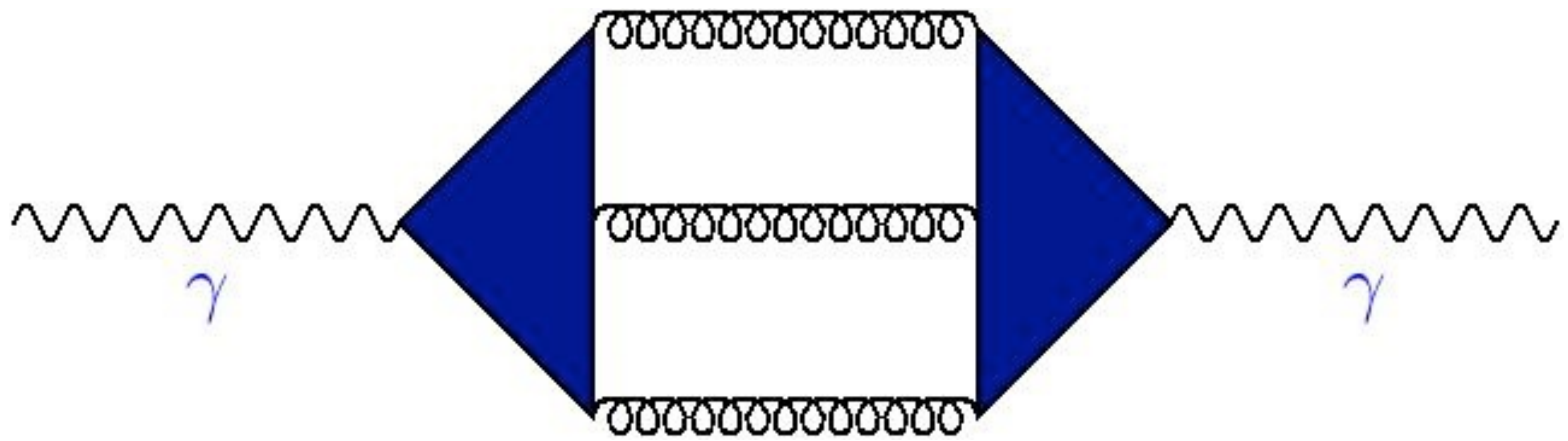
  either no mass threshold is crossed

  or perturbation theory applies ($W^\pm$, leptons, b & c quarks)

  or all coefficient are equal (RGE factorizes) like for (d,s)

  or there is a symmetry like $SU(2)_I$ or $SU(3)_F$

Threshold Mass Trick



only problem area: u vs. (d,s) or s vs. (u,d) ($m_s \neq m_d \approx m_u$)

strategy: define threshold masses, $\bar{m}_q = \frac{1}{2}\, \xi_q\, M_{1S}$ ($0 \leq \xi_q \leq 1$)

expect: $\xi_b > \xi_c > \xi_s > \xi_d > \xi_u$

compute $\bar{m}_b$ and $\bar{m}_c$ in perturbative QCD $\Longrightarrow$ $\xi_b > \xi_c$ (✓)

heavy quark limit for $\bar{m}_s$: $\xi_s \rightarrow \xi_c \Longrightarrow \bar{m}_s < 387$ MeV

$SU(3)_F$ limit: $\xi_s \rightarrow \xi_d \approx \xi_u$ + dispersion result for $\Delta\alpha^{(3)}(\bar{m}_c)$

$\sin^2\theta_W(0)$

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)

The bigger picture

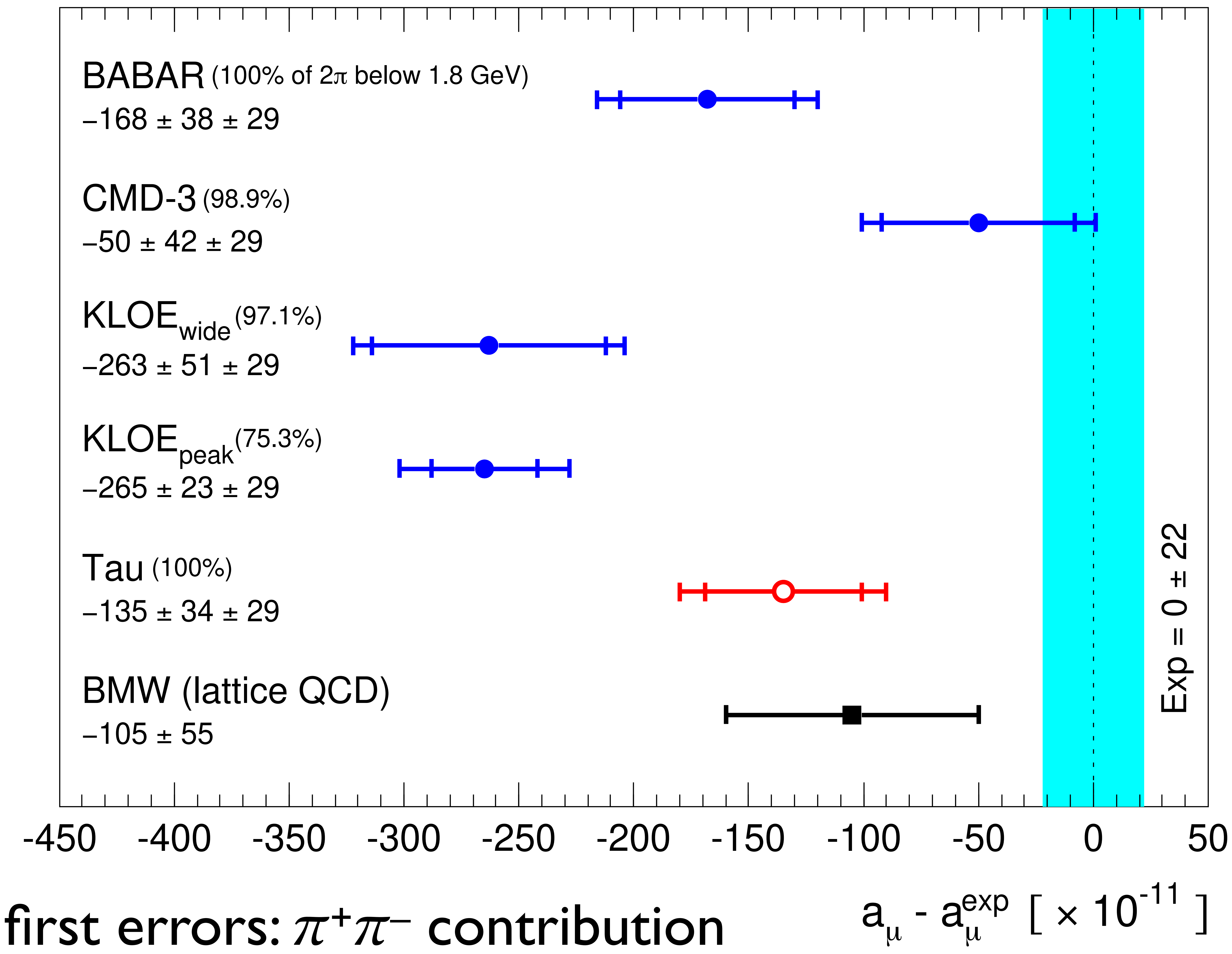
Heavy quark masses from a pair of sum rules

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

$$\overline{m}_b(\overline{m}_b) = 4180 + \ 109\ [\alpha_s(M_Z) - 0.1182] \pm 8\ \text{MeV}$$

source	uncertainty [MeV]	comment
electronic widths of resonance (exp)	4.5	3.2
continuum region (exp)	1.7	1.0
calibration (theory – exp)	1.5	3.5
perturbative truncation (moments)	5.9	6.3
gluon condensate	1.9	< 0.2
TOTAL	8.0	8.0

Hadronic vacuum polarization



first errors: $\pi^+\pi^-$ contribution

BaBar and earlier data based on
Davier et al. arXiv:1908.00921

CMD–3 and figure from
Davier et al., arXiv:2312.02053

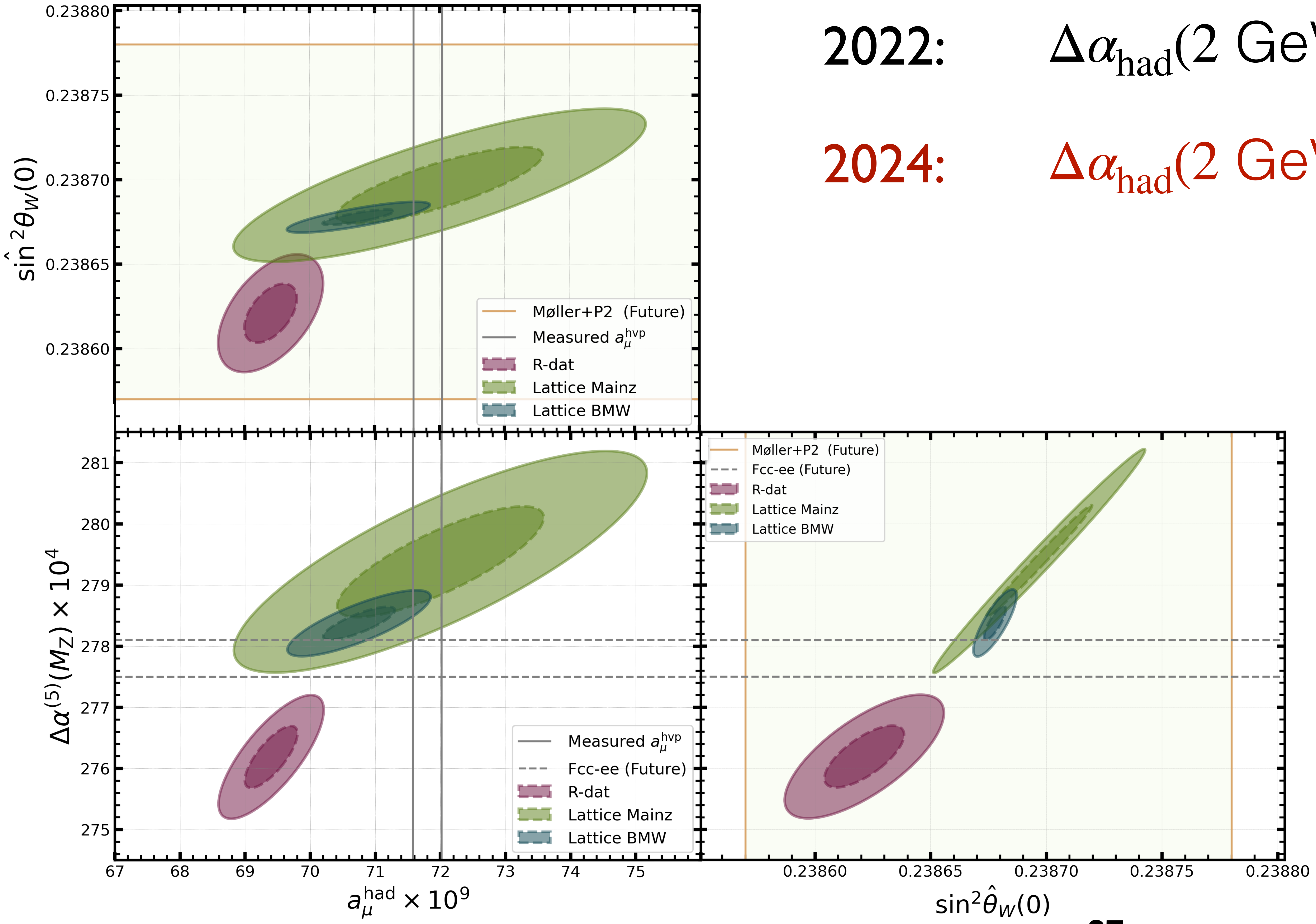
KLOE based on
Davier et al. arXiv:1908.00921

after isospin rotation according to
Davier et al., arXiv:2312.02053

Borsanyi et al., arXiv:2002.12347

$\Delta\alpha$ from Cè et al., arXiv:2203.08676
also enters through correlations

g_μ–2, $\alpha(M_Z)$ and $\sin^2\theta_W(0)$



2022: $\Delta\alpha_{\rm had}(2\ {\rm GeV}) = (58.84 \pm 0.51) \times 10^{-4}$

2024: $\Delta\alpha_{\rm had}(2\ {\rm GeV}) = (60.30 \pm 0.43) \times 10^{-4}$

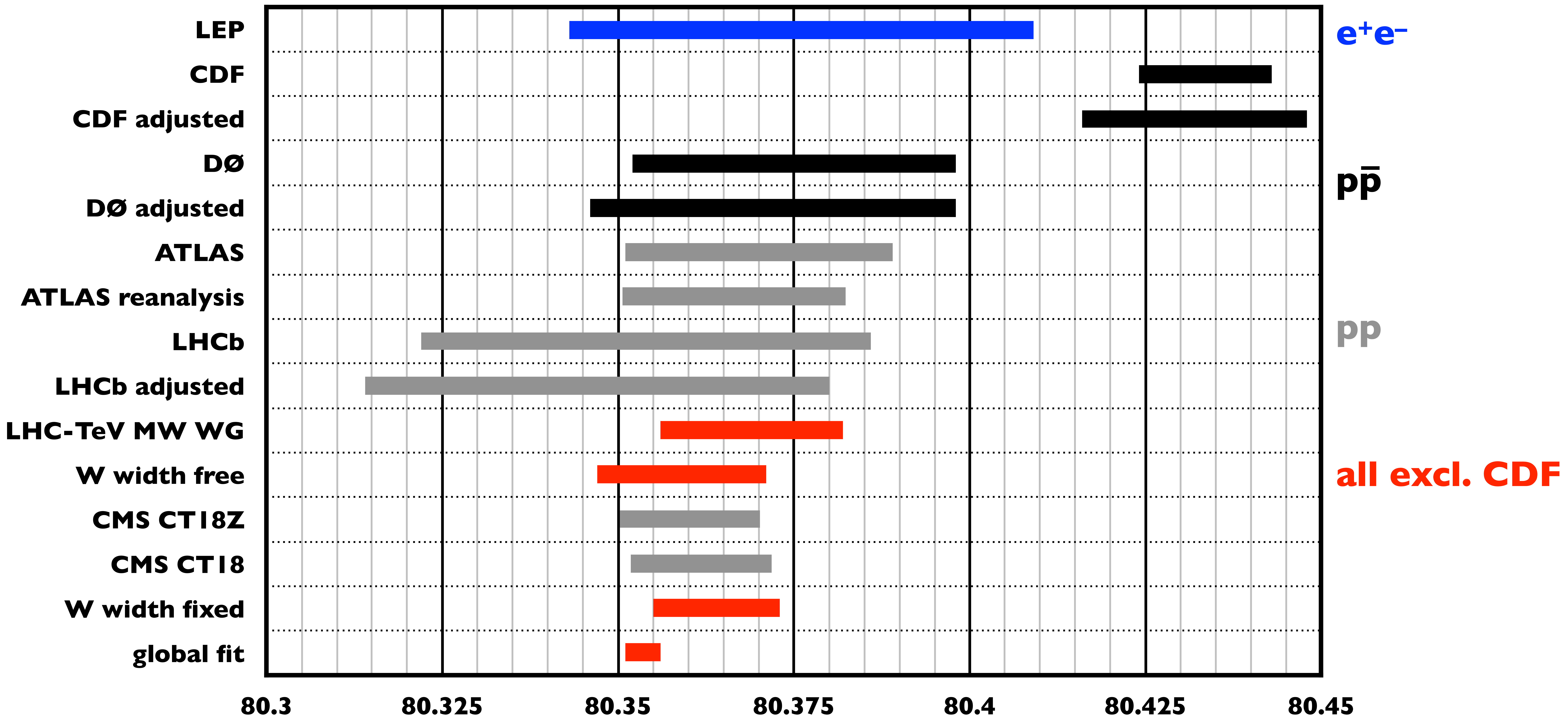
Freitas & JE, PDG (2024)

$\Delta M_W = -\,2.7$ MeV

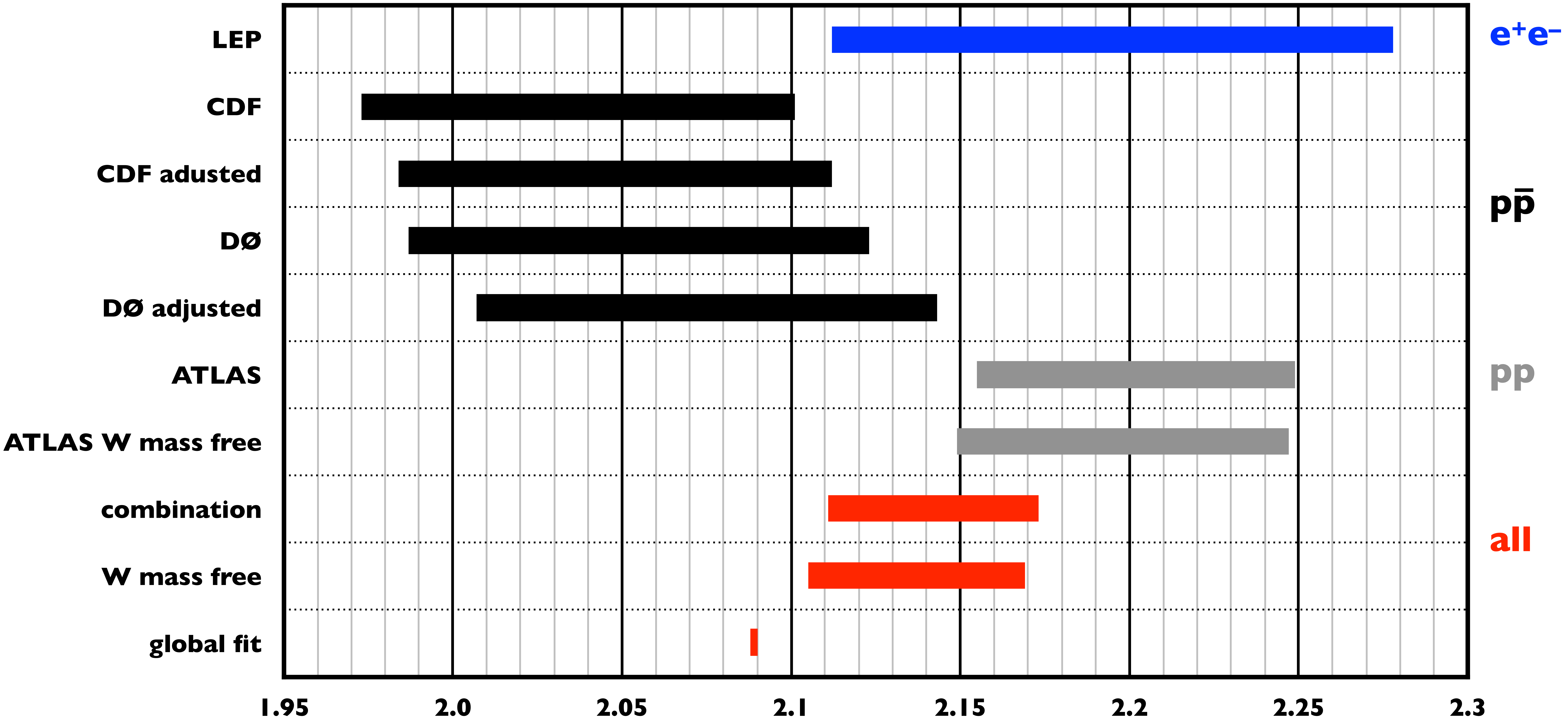
$\Delta M_H = -\,7.0$ MeV

Ferro-Hernàndez, Kuberski & JE, arXiv:2406.16691

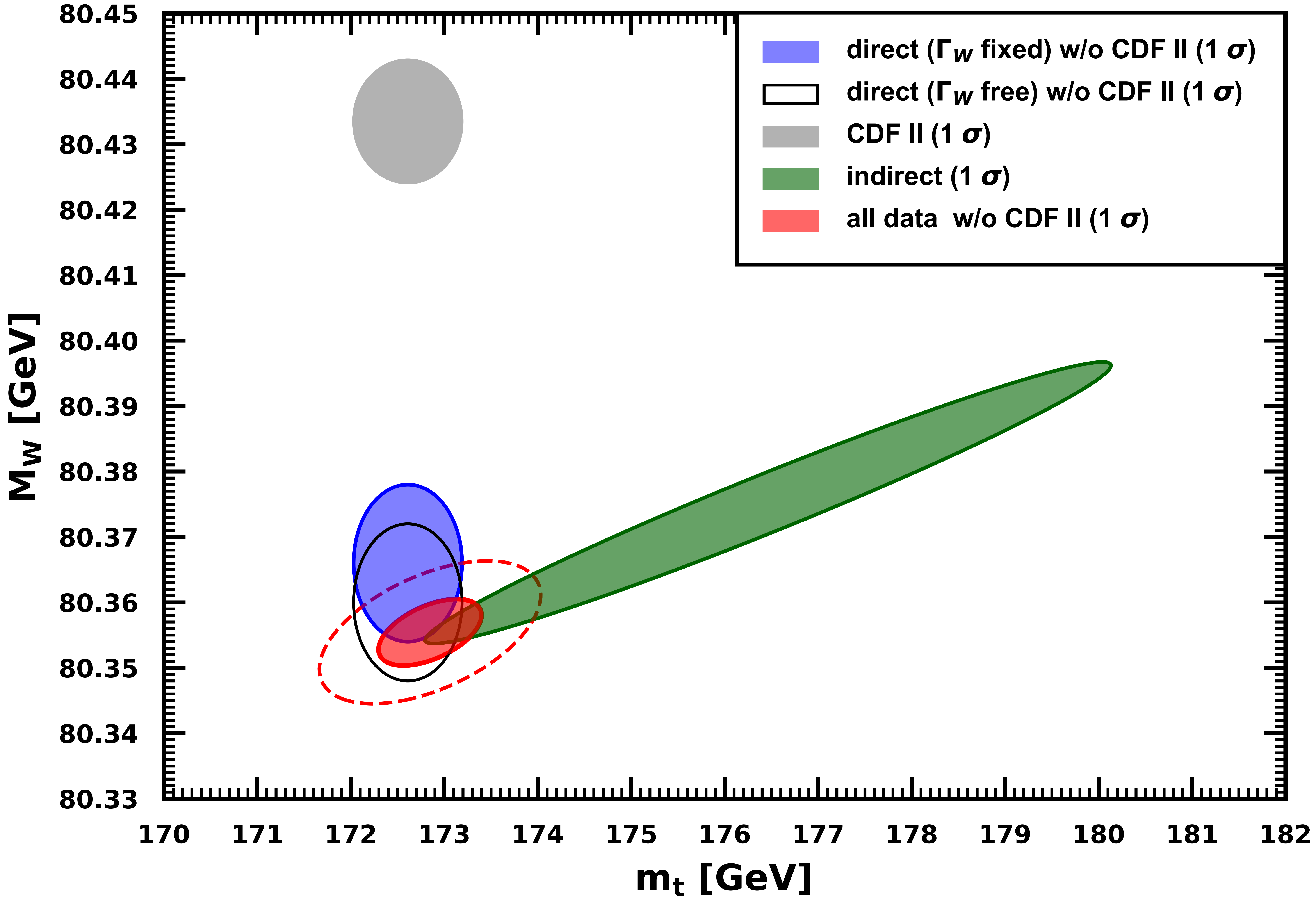
Status of M_W [GeV]



Status of Γ_W [GeV]



$M_W - m_t$



m_t = 174.8 ± 1.4 GeV (indirect)

1.5 σ above

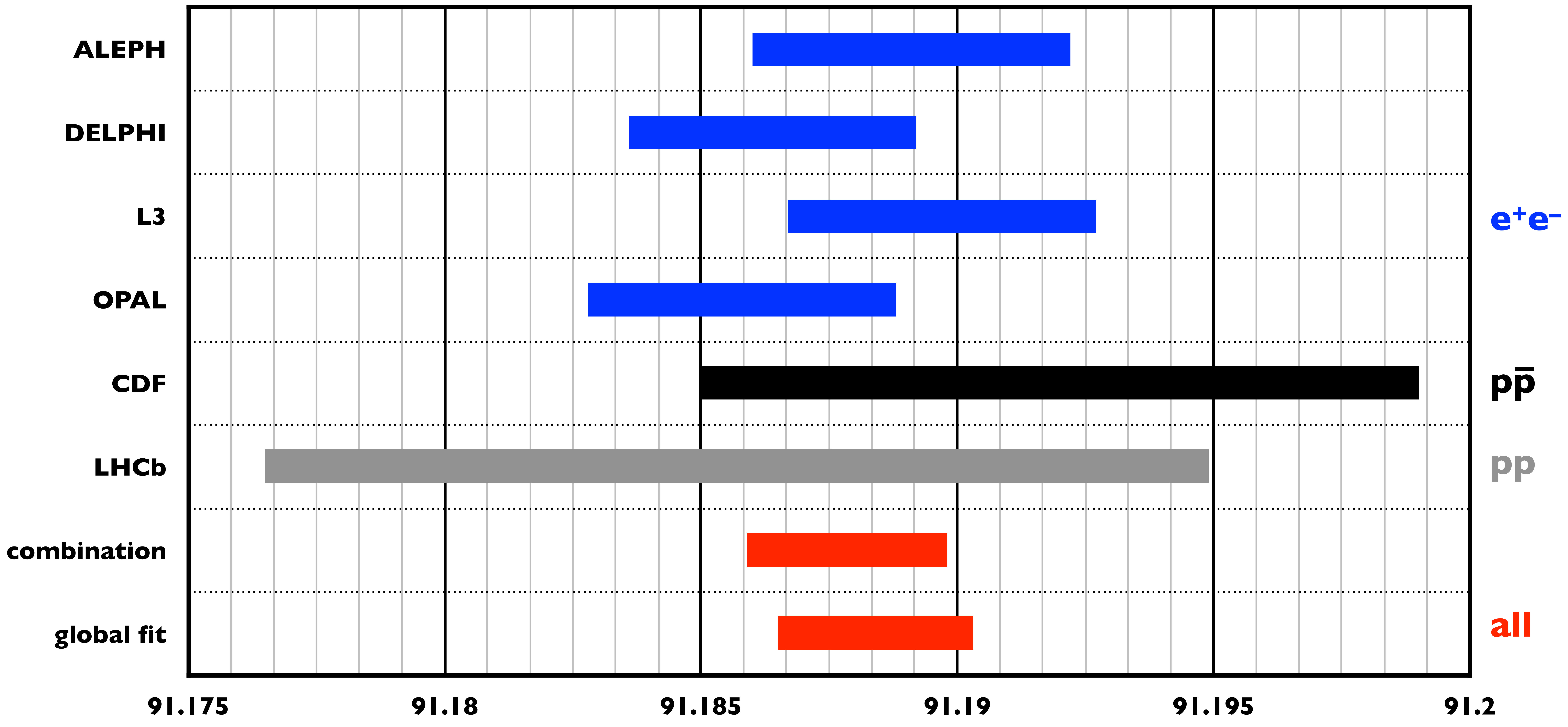
m_t = 172.61 ± 0.58 GeV (Tevatron + LHC)

M_W = 80353 ± 6 MeV (indirect)

M_W = 80364 ± 9 MeV (direct)

Freitas & JE, PDG (2024)
figure: Rodolfo Ferro

Status of M_Z [GeV]



M_Z improvement @ the LHC?

- today (LEP 1): $M_Z = 91.1876 \pm 0.0021$ GeV (resonant depolarization)

  ➟ M_H (indirect) $= 92^{+19}_{-17}$ GeV

  M_H (direct) $= 125.14 \pm 0.15$ GeV (1.5 σ tension)

- assuming: $M_Z = 91.1897 \pm 0.001$ GeV from LHC (1σ higher)

  ➟ ΔM_H (indirect) $= 3.3$ GeV

  ➟ non-negligible impact

  ➟ important cross-check for LEP energy calibration

  (corrections for sun, moon, water level in lake Geneva, trains…)

  what if something was missed?

α_s from the Z pole

observable	$\alpha_s(M_Z)$	comment
$\Gamma_Z = 2495.5 \pm 2.3$ MeV	0.1215 ± 0.0048	update: $\Gamma_Z = +0.3$ MeV
$\sigma_{had} = 41.481 \pm 0.033$ nb	0.1201 ± 0.0065	update: $\Delta\sigma_{had} = -60$ pb
$R_e = \Gamma_{had}/\Gamma_e = 20.804 \pm 0.050$	0.1295 ± 0.0082	
$R_\mu = \Gamma_{had}/\Gamma_\mu = 20.784 \pm 0.034$	0.1264 ± 0.0054	$m_\mu \neq 0$
$R_\tau = \Gamma_{had}/\Gamma_\tau = 20.764 \pm 0.045$	0.1157 ± 0.0072	$m_\tau \neq 0$
$B_W(had) = 0.6736 \pm 0.0018$	0.098 ± 0.025	recent (LEP 2 + CMS)
combination	0.1223 ± 0.0028	future lepton collider ~ 10^{-4}
global electroweak fit	0.1211 ± 0.0025	excludes τ decays & $g_\mu-2$

electromagnetic beam-beam effects
improved Bhabha X section (luminosity)

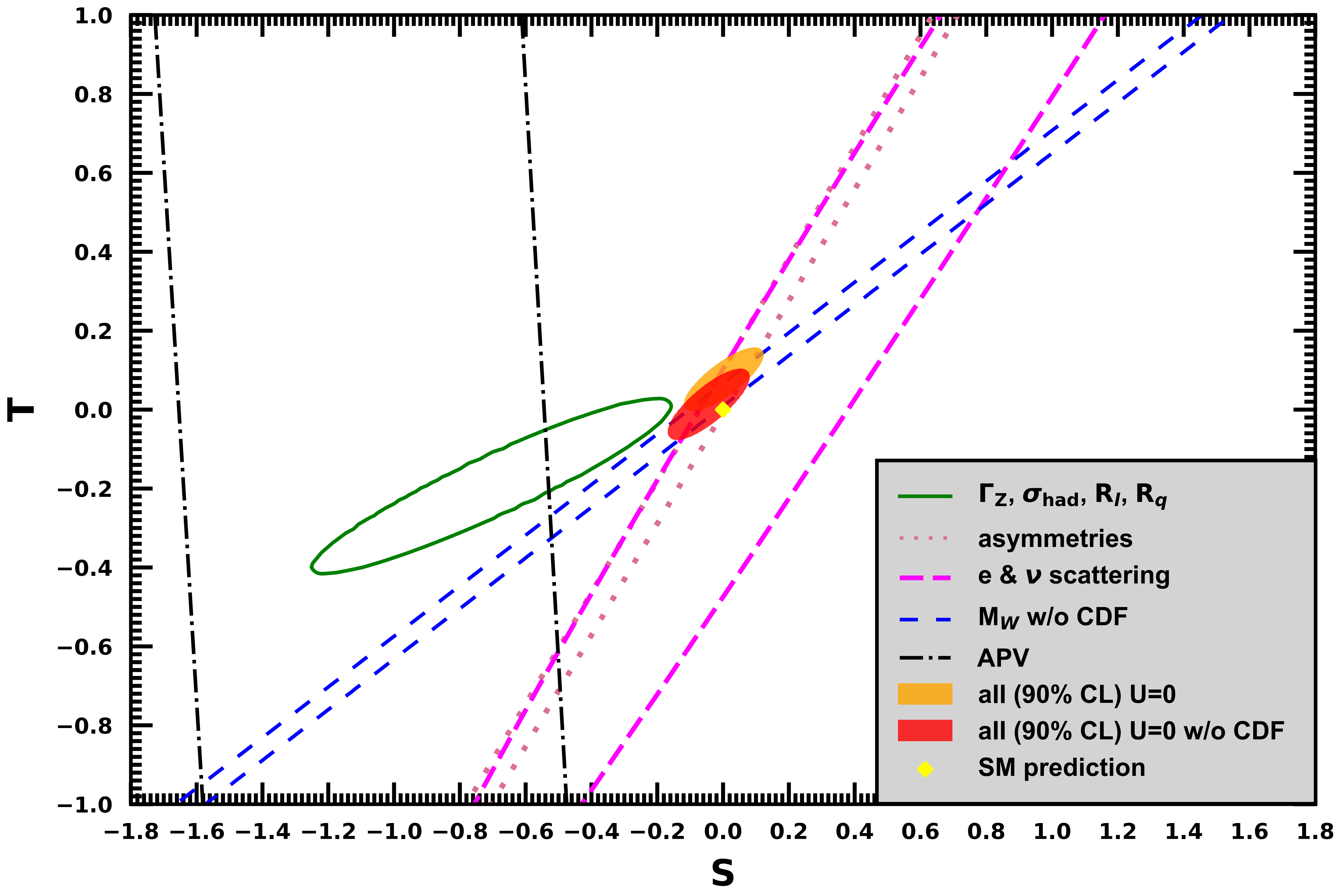
Voutsinas et al., arXiv:1908.01704
Janot & Jadach, arXiv:1912.02067

α_s

observable	$\alpha_s(M_Z)$	comment
global electroweak fit	0.1211 ± 0.0025	excludes τ decays & g_μ–2
τ decays	0.1171 ± 0.0018	low scale (FOPT)
heavy quarkonia	0.1181 ± 0.0037	
PDF fits	0.1161 ± 0.0022	
jets and shapes in e^+e^- annihilation	0.1189 ± 0.0037	non-MC methods
hadron colliders	0.1170 ± 0.0025	
lattice	0.1183 ± 0.0007	FLAG average

Beyond the Standard Model

S – T 2024



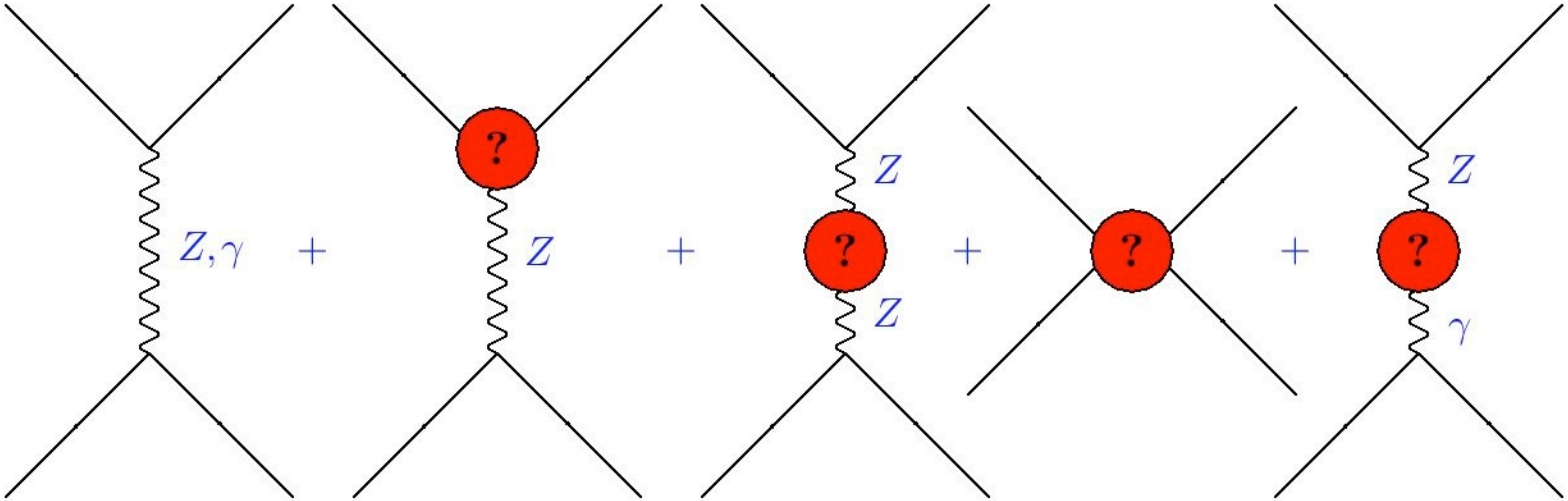
Freitas & JE, PDG (2024)
figure: Rodolfo Ferro

S	–0.06 ± 0.07
T	–0.01 ± 0.05

S	0 (fixed)
T	+0.03 ± 0.02

$$(2\ \mathrm{GeV})^2 < \sum_i \frac{N_C^i}{3} \Delta m_i^2 < (44\ \mathrm{GeV})^2$$

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)

Standard Model Effective Field Theory (SMEFT)

	$N_f = 3$	$N_f = 1$	bosonic	ψ^2	ψ^4 ($\Delta B = 0$)	ψ^4 ($\Delta B \neq 0$)	
D = 0	1	1	1	–	–	–	$\Lambda_C \neq 0$
D = 1	–	–	–	–	–	–	
D = 2	1	1	1	–	–	–	$M_H \neq 0$
D = 3	–	–	–	–	–	–	
D = 4	55	7	1	6	–	–	**SM**
D = 5	12	2	–	12	–	–	$m_\nu \neq 0$
D = 6	3045	84	15	31	30	8	
D = 7	1542	30	–	10	12	8	**BSM**
D = 8	44807	993	89	386	420	98	

Henning et al., arXiv:1512.03433

SMEFT–84: *independent parameters* @ dimension 6

9 + 6 bosonic
(e.g. S and T)

29 + 9 fermionic

19 + 12 mixed
("single current")

CP-conserving

CP-violating

3 L^4 + (10 + 3) L^2Q^2 + (4 + 4) LQ^3 ($\Delta B \neq 0$) + (12 + 2) Q^4

$$\psi_V = \bar{\psi}\gamma^\mu\psi$$

$$\psi_A = \bar{\psi}\gamma^\mu\gamma^5\psi$$

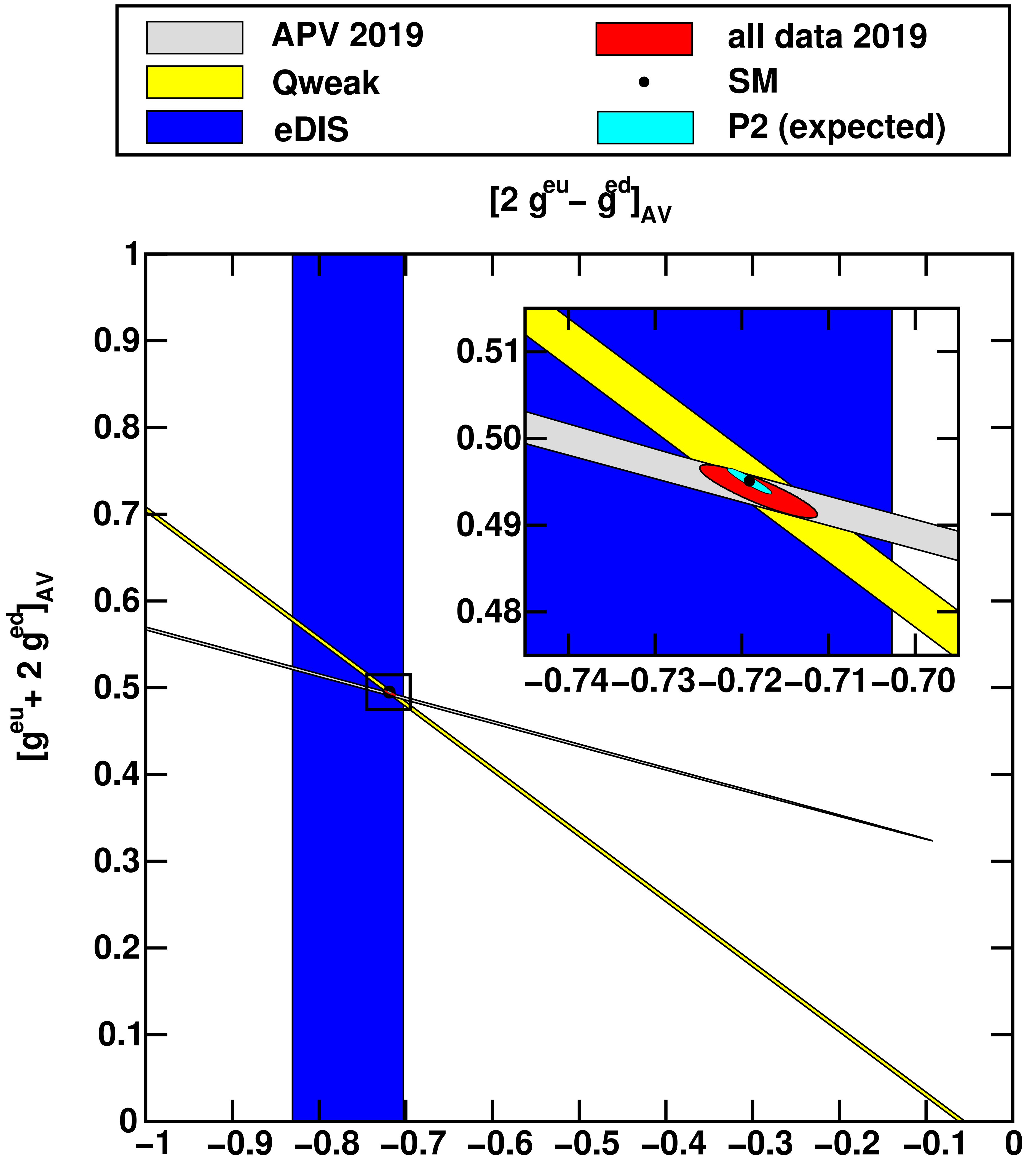
$e_V e_V$ + $e_A e_V$ [MOLLER] + $e_A e_A$

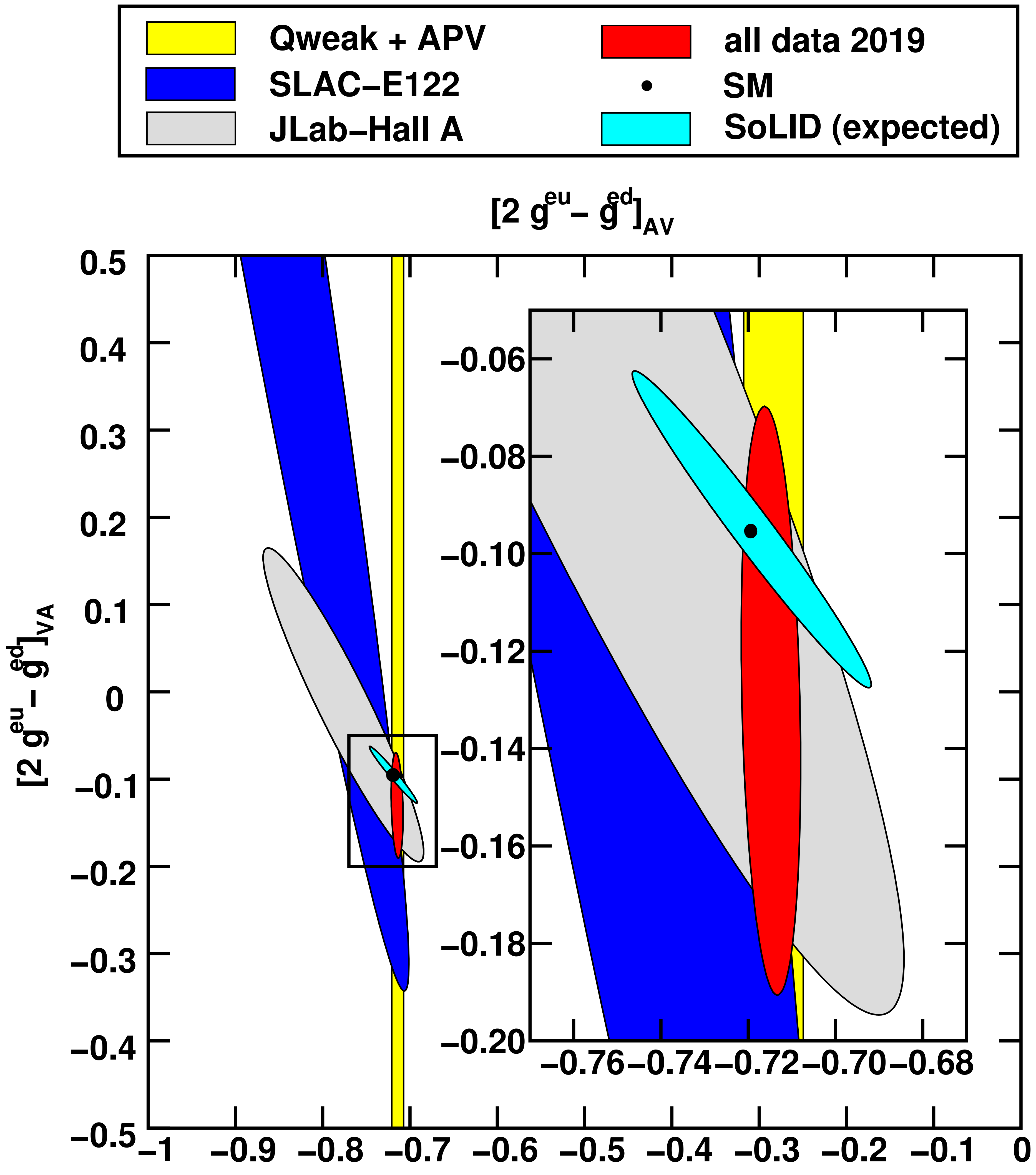
7 vector and axial-vector combinations + (2 + 2) scalar + (1 + 1) tensor

2 $e_V q_V$ (C_0) + 2 $e_A q_V$ (C_1) [APV, Qweak, P2] + 2 $e_V q_A$ (C_2) [eDIS] + 2 $e_A q_A$ (C_3) [eDIS]

–1 constraint: $\bar{u}_L\gamma^\mu u_L\bar{e}_R\gamma_\mu e_R$ not independent of $\bar{d}_L\gamma^\mu d_L\bar{e}_R\gamma_\mu e_R$

Parity-violating 4-fermion electron-quark couplings

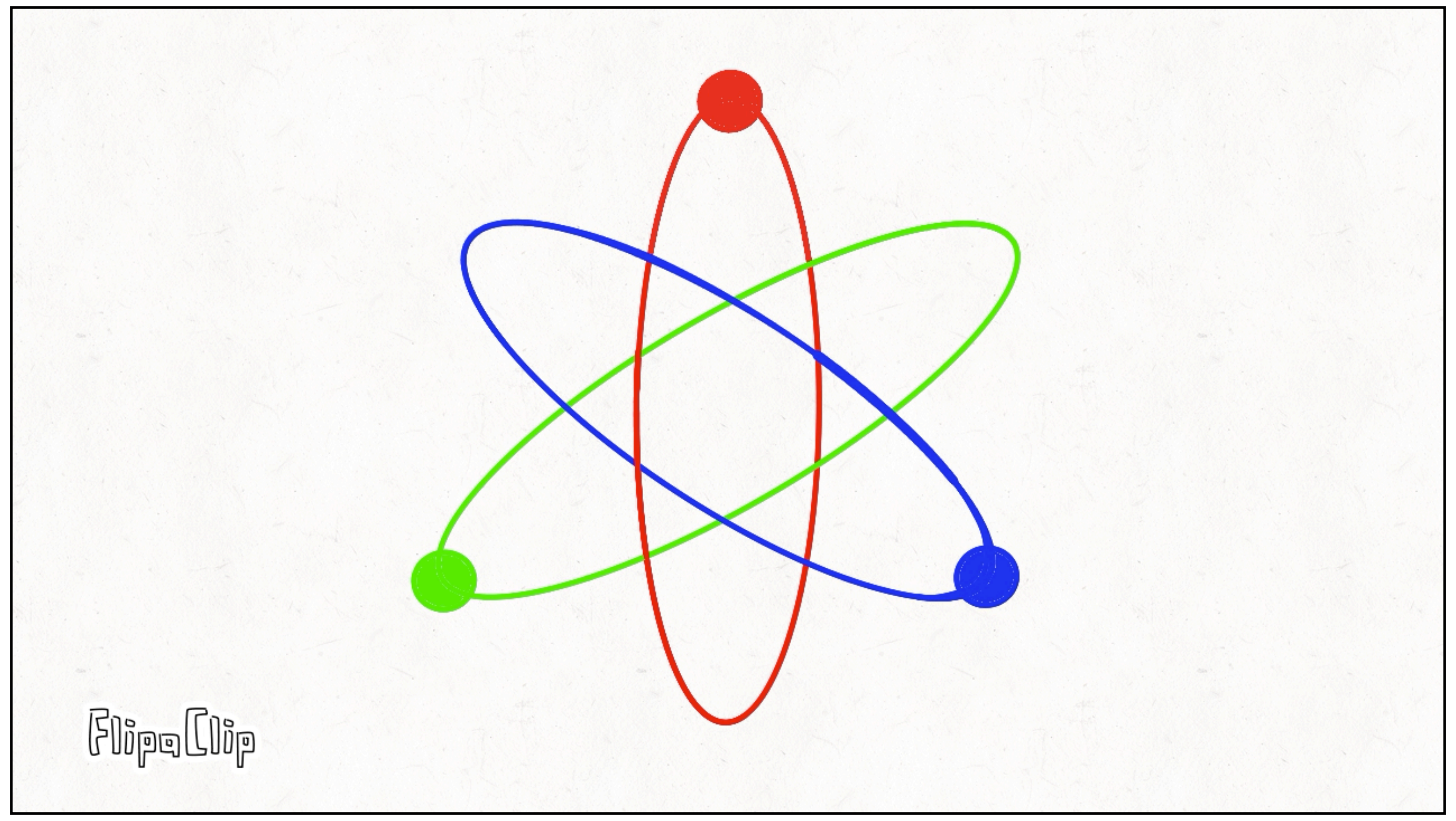




Conclusions

- *after 50+ years of electroweak precision physics, still no conclusive evidence for BSM*
  - hadronic vacuum polarization from lattice QCD solved g–2 discrepancy

    impacts interpretation of other precision observables
  - *CDF* M_W result ~ 7 σ higher than other measurements (not understood)
  - *LEP* luminosity update confirms N_ν = 3 active neutrinos, but α_s somewhat high
  - reliable bottom and charm quark masses from (relativistic) QCD sum rules
- *outlook*
  - upcoming measurements of the weak mixing angle
  - high precision PVES (*P2, MOLLER, SoLID*) competitive alternatives to high energy frontier
  - complementary in terms of experimental systematics as well as BSM tests
  - leap in precision expected from future lepton collider(s): *ILC, CEPC, FCC–ee, CLIC, μ collider*



Thank You