EPIC 2024

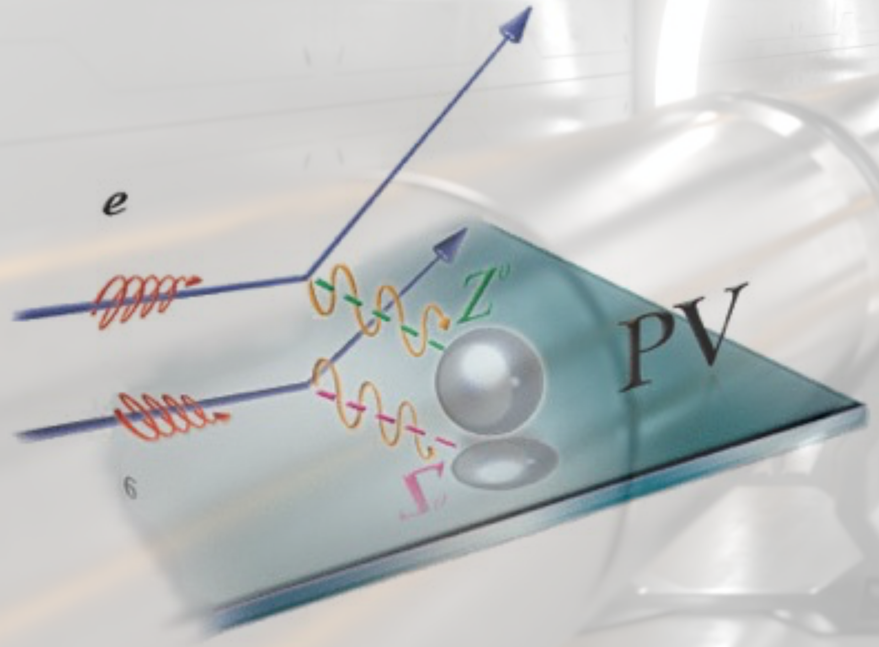
Calaserena Resort, Sardinia, Italy

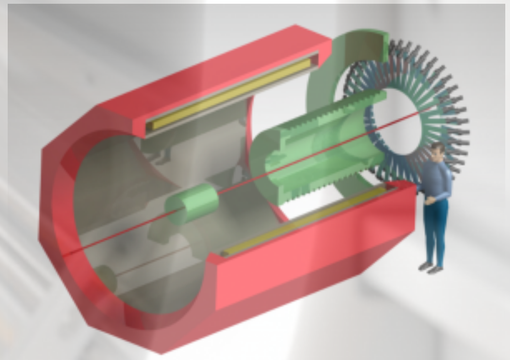
September 23, 2024

Electroweak fit

Jens Erler

JOHANNES GUTENBERG UNIVERSITÄT MAINZ





PDG particle data group

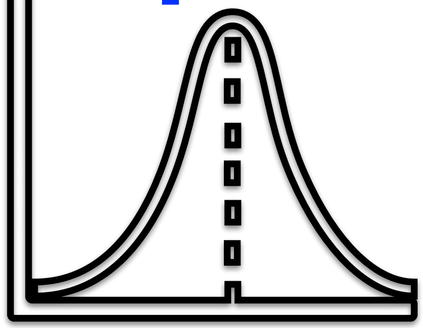
Cluster of Excellence PRISMA+ Precision Physics, Fundamental Interactions and Structure of Matter

Overview

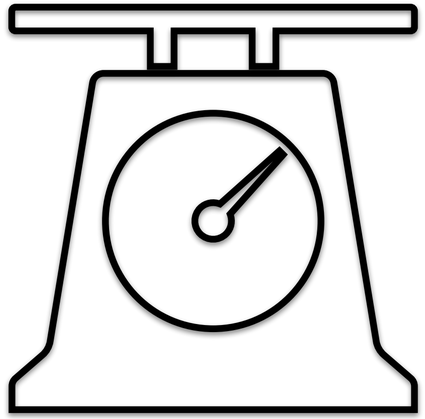
* Introduction
  * the over-constrained Standard Model
  * the weak mixing angle
* Latest developments
  * M_Z (CDF)
  * M_W (ATLAS and CDF)
  * Γ_W (update)
* Hadronic vacuum polarization
  * $\alpha(M_Z)$
  * $\sin^2\theta_W(0)$
  * g–2
* α_S and N_ν from the Z pole

The over-constrained SM

Z pole

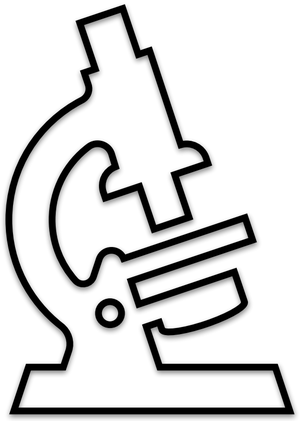


M_H, m_t
M_W, Γ_W

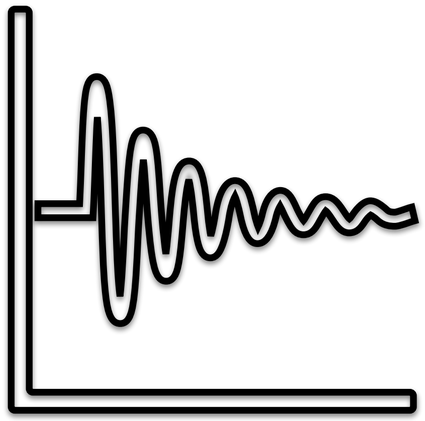


Fits to
SM & BSM

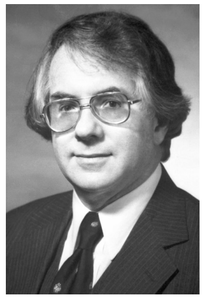
low-energy
precision



m_c, m_b, $\Delta\alpha$...



The E = mc² of the SM





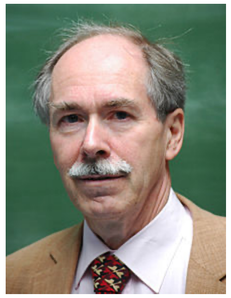
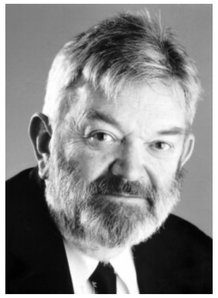
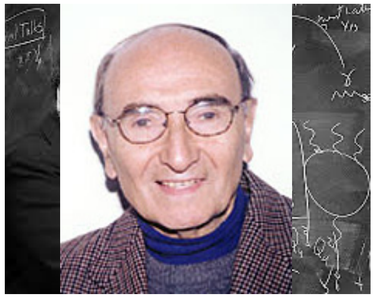
$$\sin^2\theta_W = \frac{g'^2}{g^2 + g'^2} = 1 - \frac{M_W^2}{M_Z^2} = \frac{\pi\alpha}{\sqrt{2}G_F M_W^2}$$

Radiative corrections

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

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

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


High-precision era

😀 Standard Model correct to lowest order and at the level of quantum corrections

➡️ Global analysis of precision observables at ultra-high precision

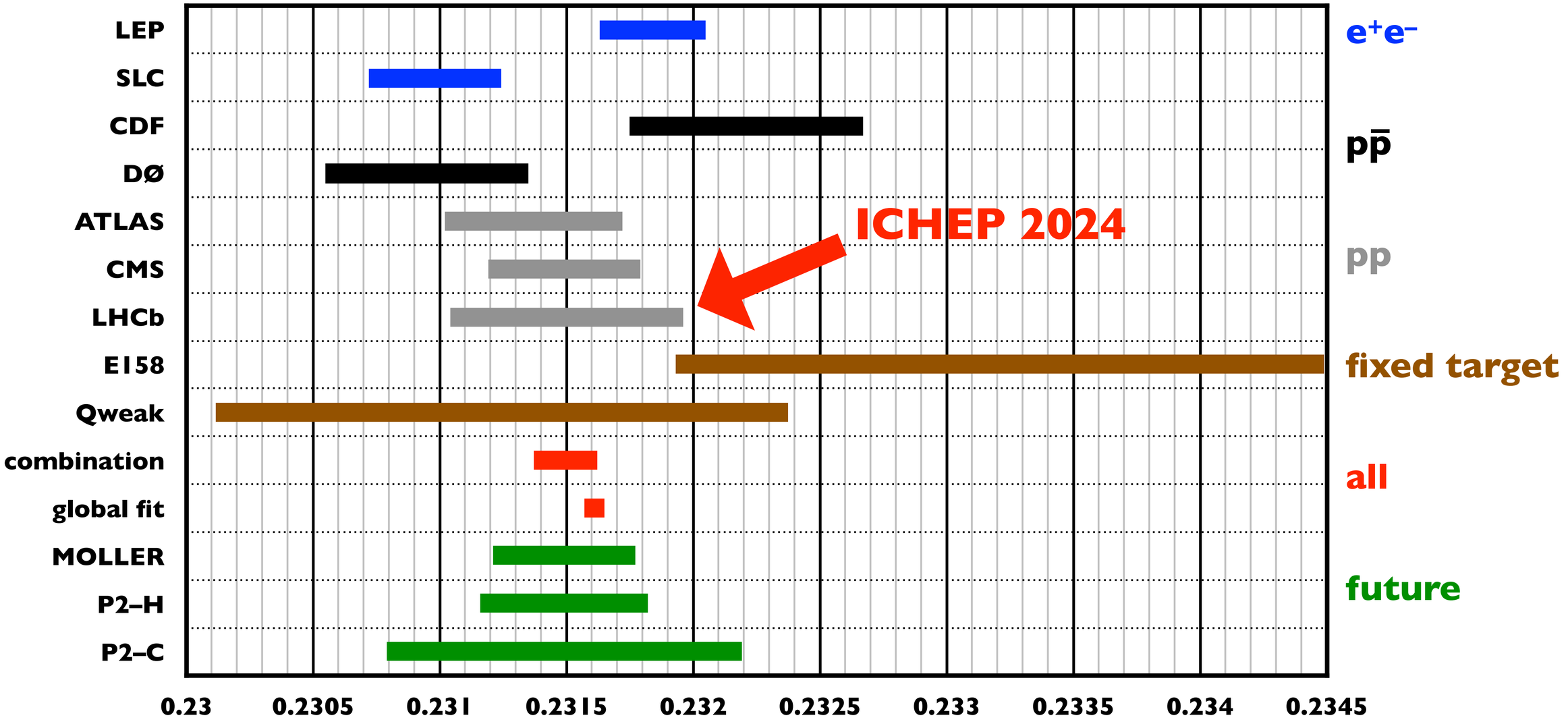
* General remark: the higher the precision, the more physics issues will enter in the interpretation of precision measurements

➡️ Atomic physics (e.g., transition matrix elements), nuclear physics (e.g., neutron skin), hadron physics (e.g., form factors), QCD (e.g., PDFs), QED (e.g., initial-state radiation)

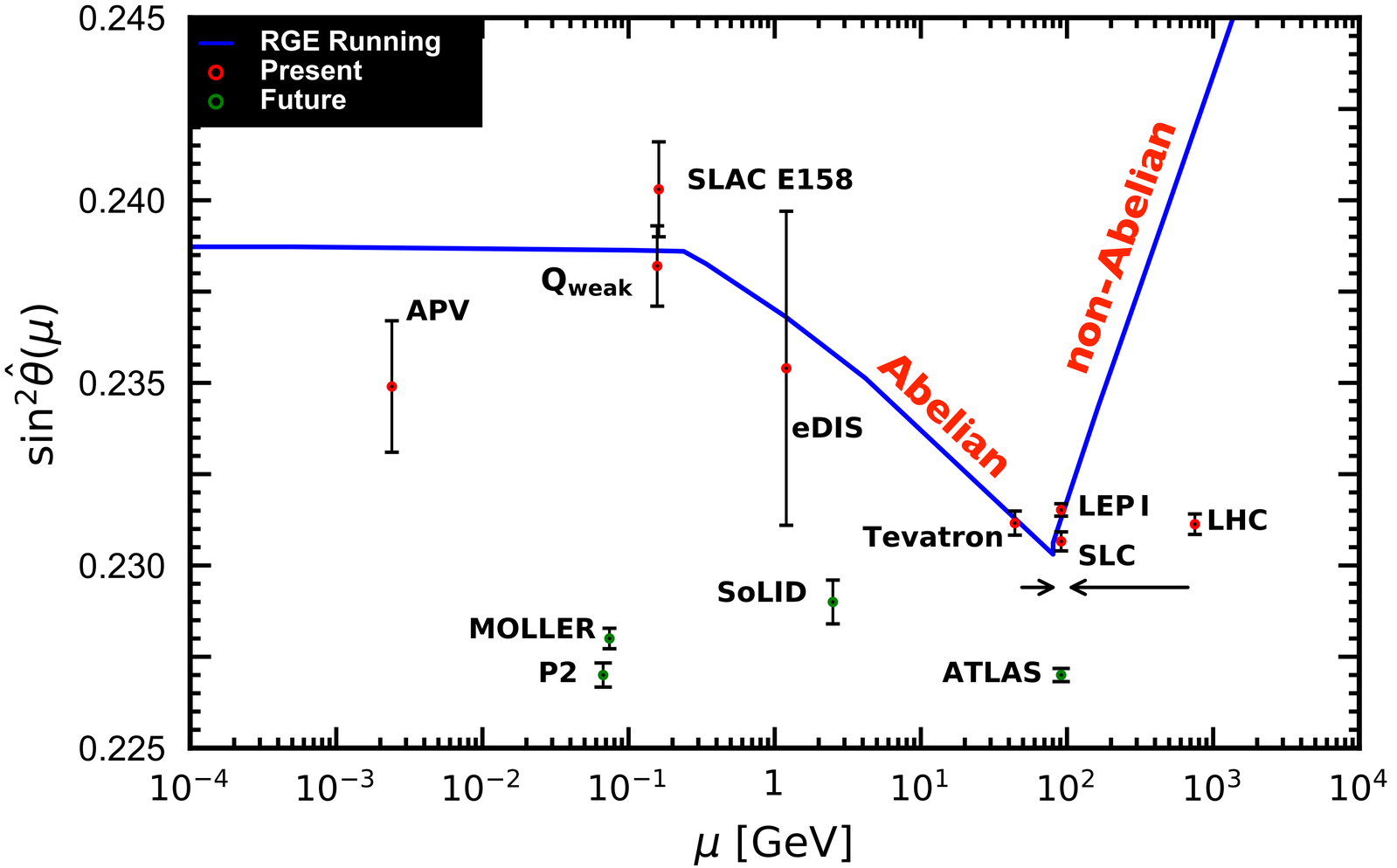
* Obstacle when looking at single observables

* A feature in global analyses:
Someones bottleneck may be somebody else's opportunity ➔ *this Workshop*

$\sin^2\theta^{\ell}_{\text{eff}}$ anno 2024



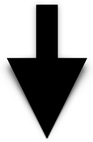
Running $\overline{\text{MS}}$ weak mixing angle



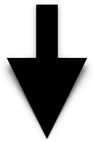
updated from
Ferro-Hernández & JE
arXiv:1712.09146

SMEFT@ D = 6

38 four-Fermi-operators



3 L^4 + 13 L^2Q^2 + 8 LQ^3 ($\Delta B \neq 0$) + 14 Q^4 operators



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

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

3 L^4 = e_Ve_V + e_Ae_V *(MOLLER)* + e_Ae_A

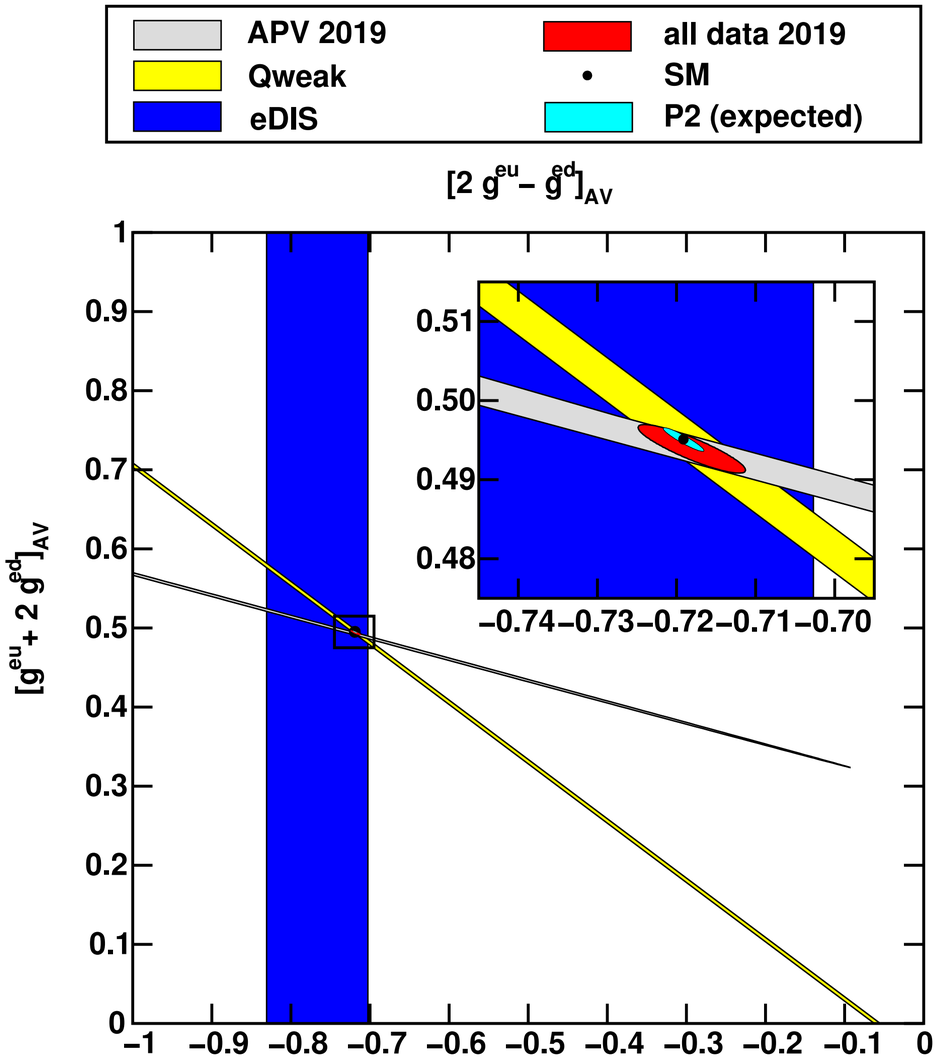
13 L^2Q^2 = 7 vector and axial-vector combinations + 4 scalar + 2 tensor

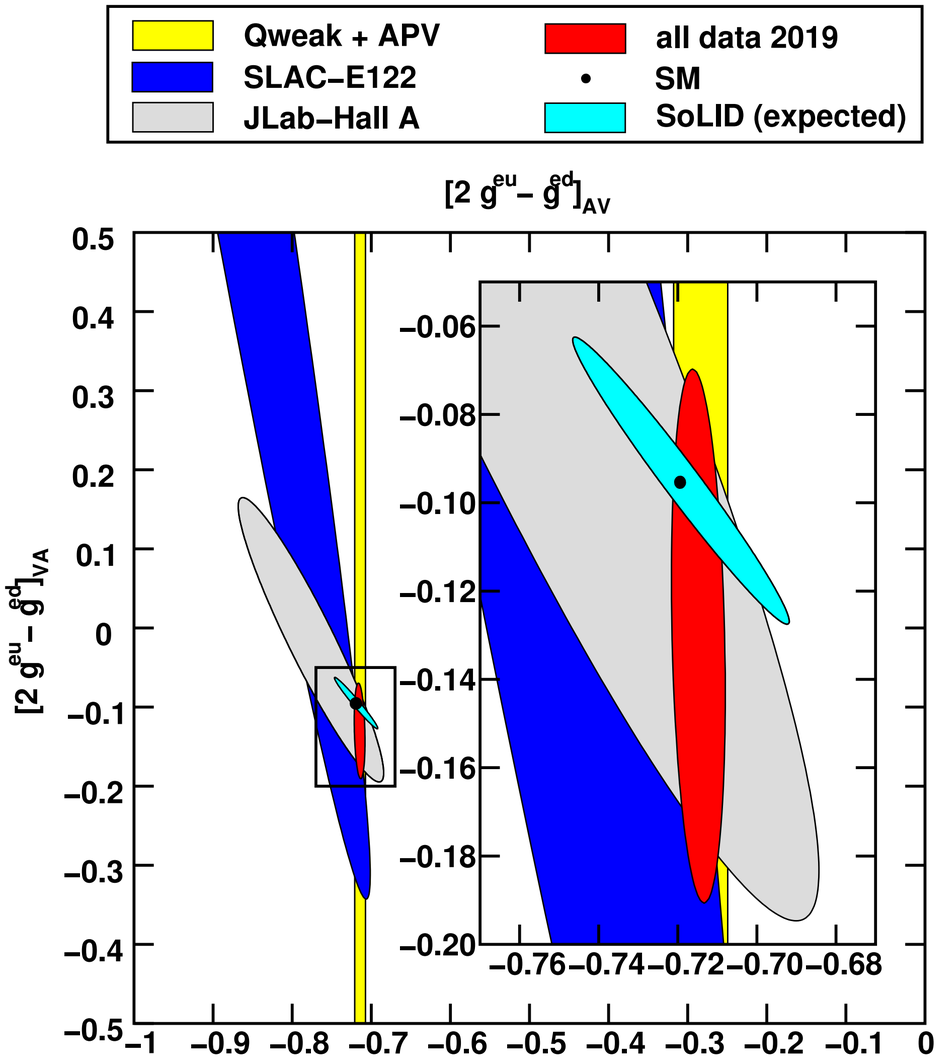
2 e_Vq_V (C_0) + 2 e_Aq_V (C_1) *(APV, Qweak, P2)* + 2 e_Vq_A (C_2) *(SLAC-E122, PVDIS, SoLID)*

+ 2 e_Aq_A (C_3) *(e+@SoLID)*

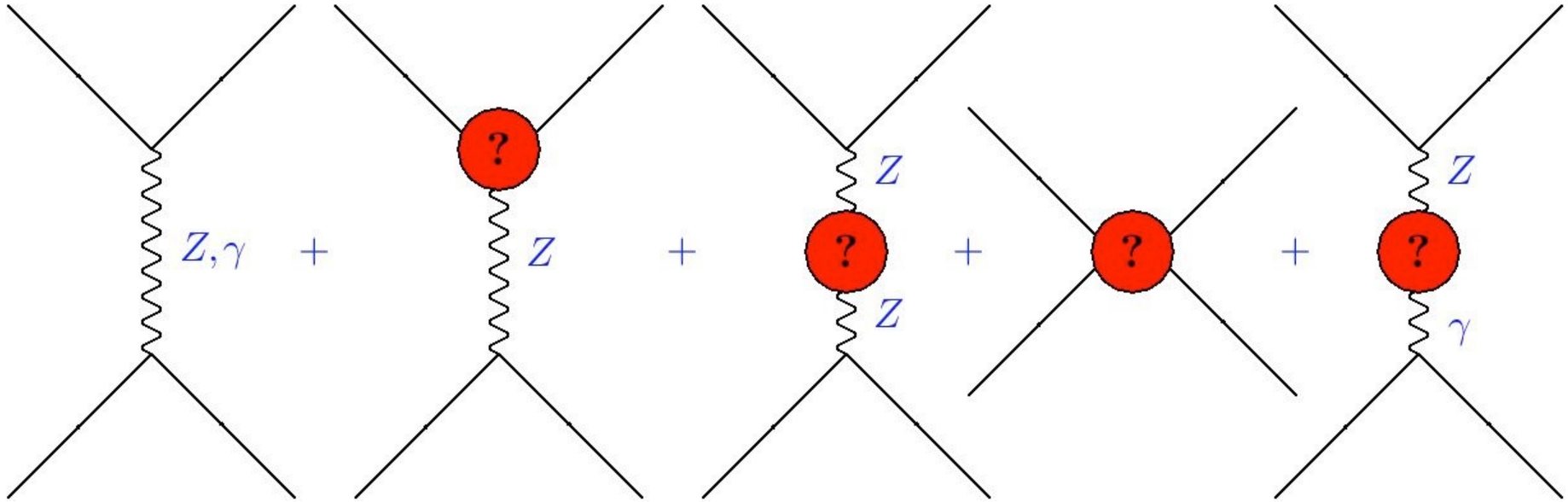
–1 constraint: $(\bar{u}_L\gamma^\mu u_L - \bar{d}_L\gamma^\mu d_L)\bar{e}_R\gamma_\mu e_R = 0$

Parity-violating 4-fermion electron-quark couplings





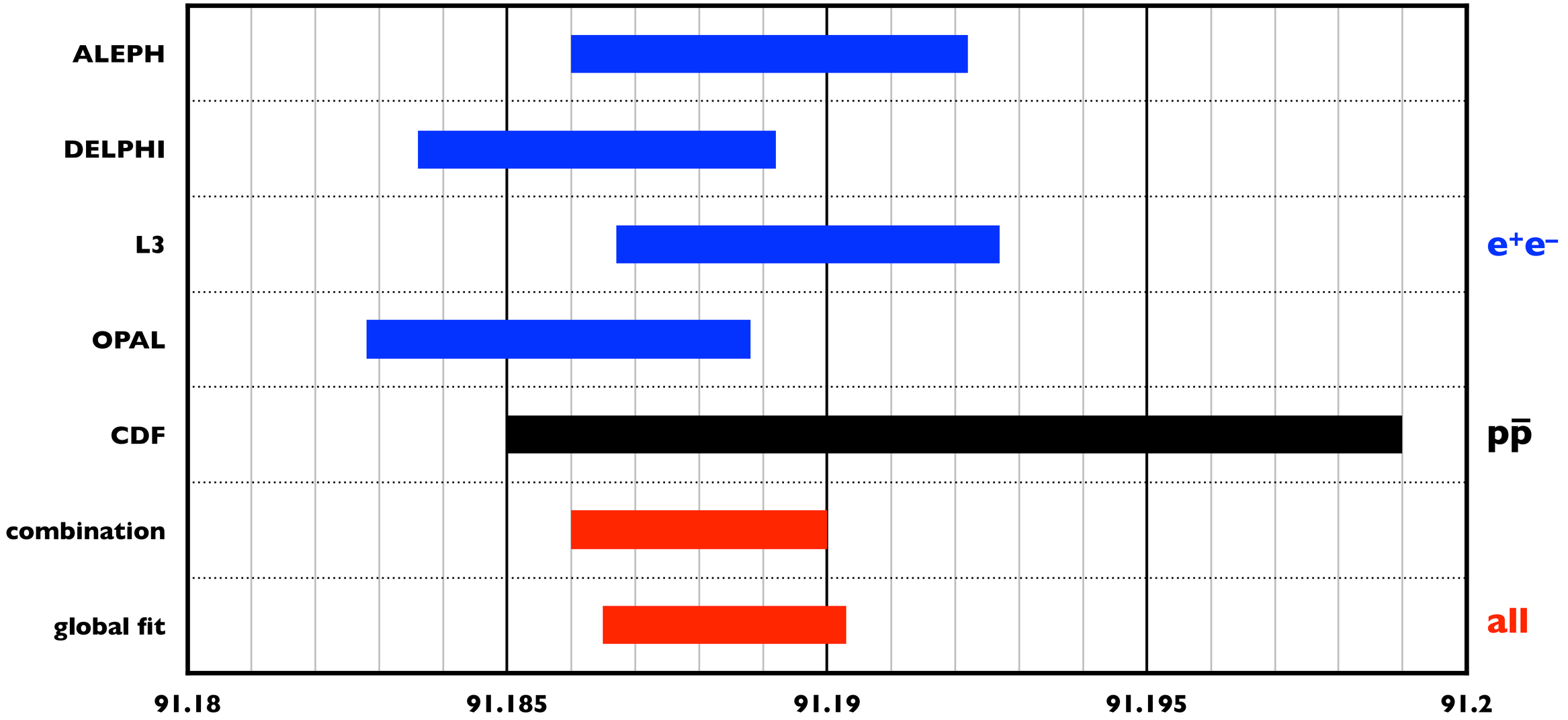
Discriminating new physics



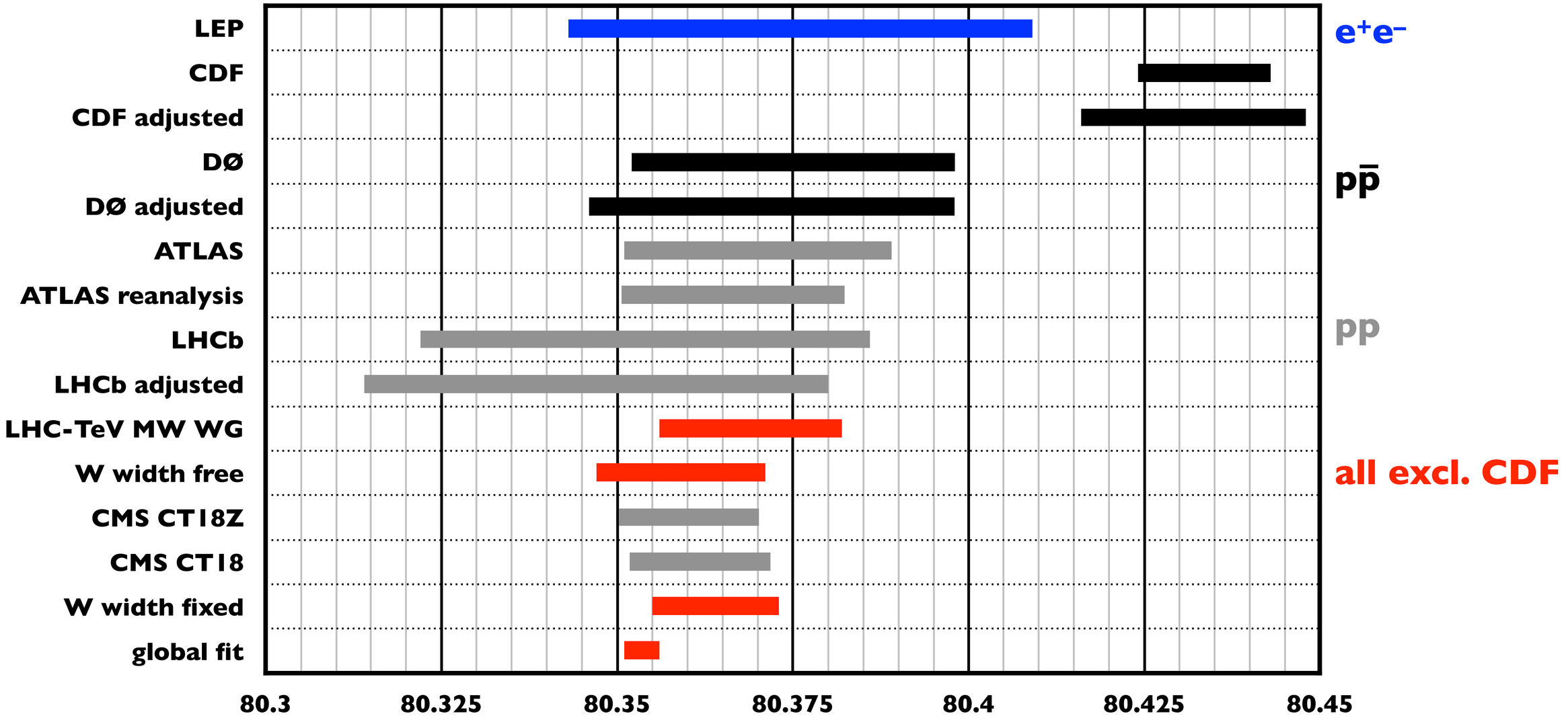
* Z-Z′ mixing: modification of Z vector coupling
* oblique parameters: STU (also need M_W and Γ_Z)
* new amplitudes: off- versus on-Z pole measurements (e.g. heavy Z′)
* dark Z: renormalization group evolution (low versus very low energy measurements)

Latest developments

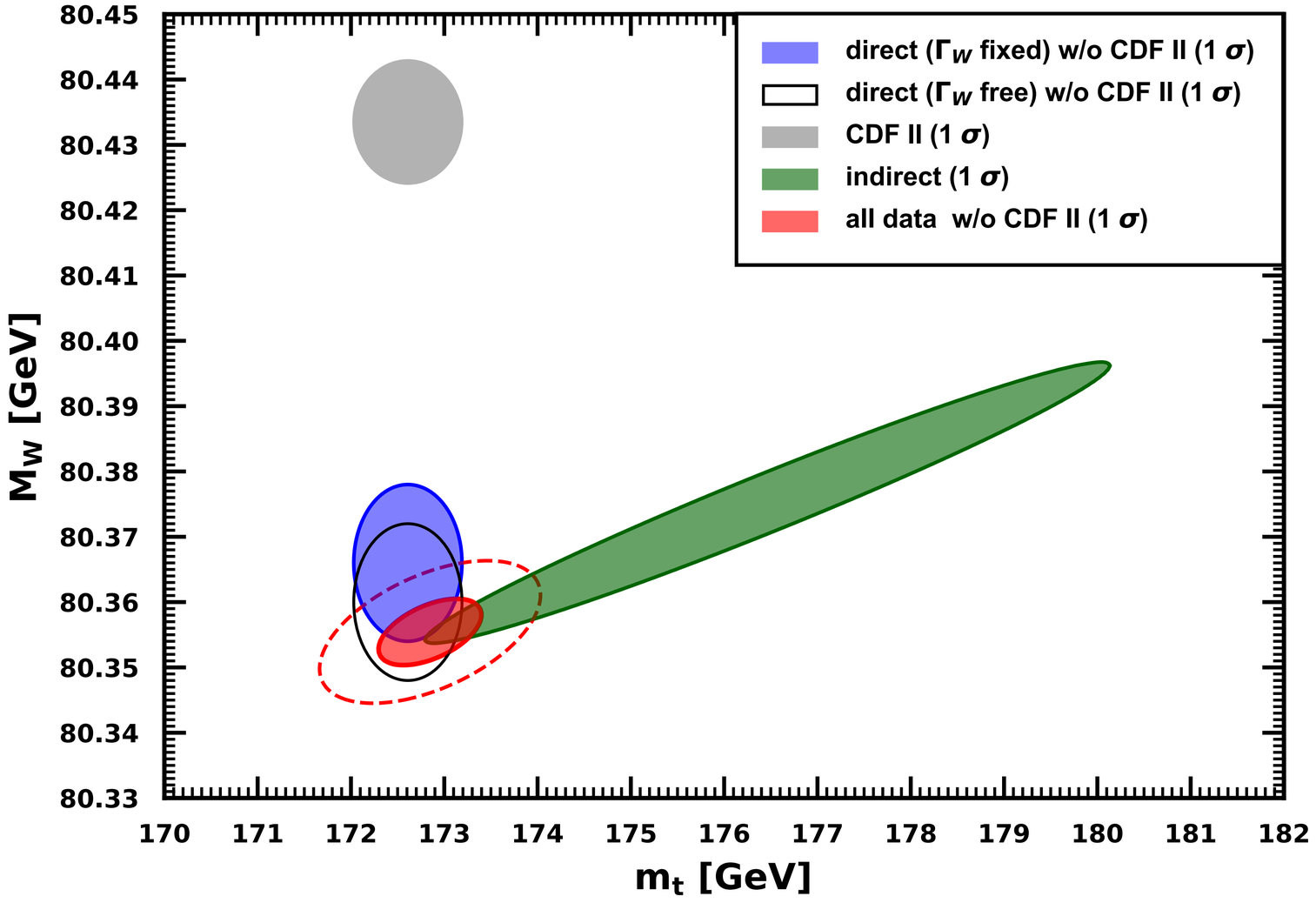
M_Z anno 2024 [GeV]



M_W anno 2024 [GeV]



$M_W - m_t$



m_t = 174.8 ± 1.4 GeV (indirect)

1.5 σ above

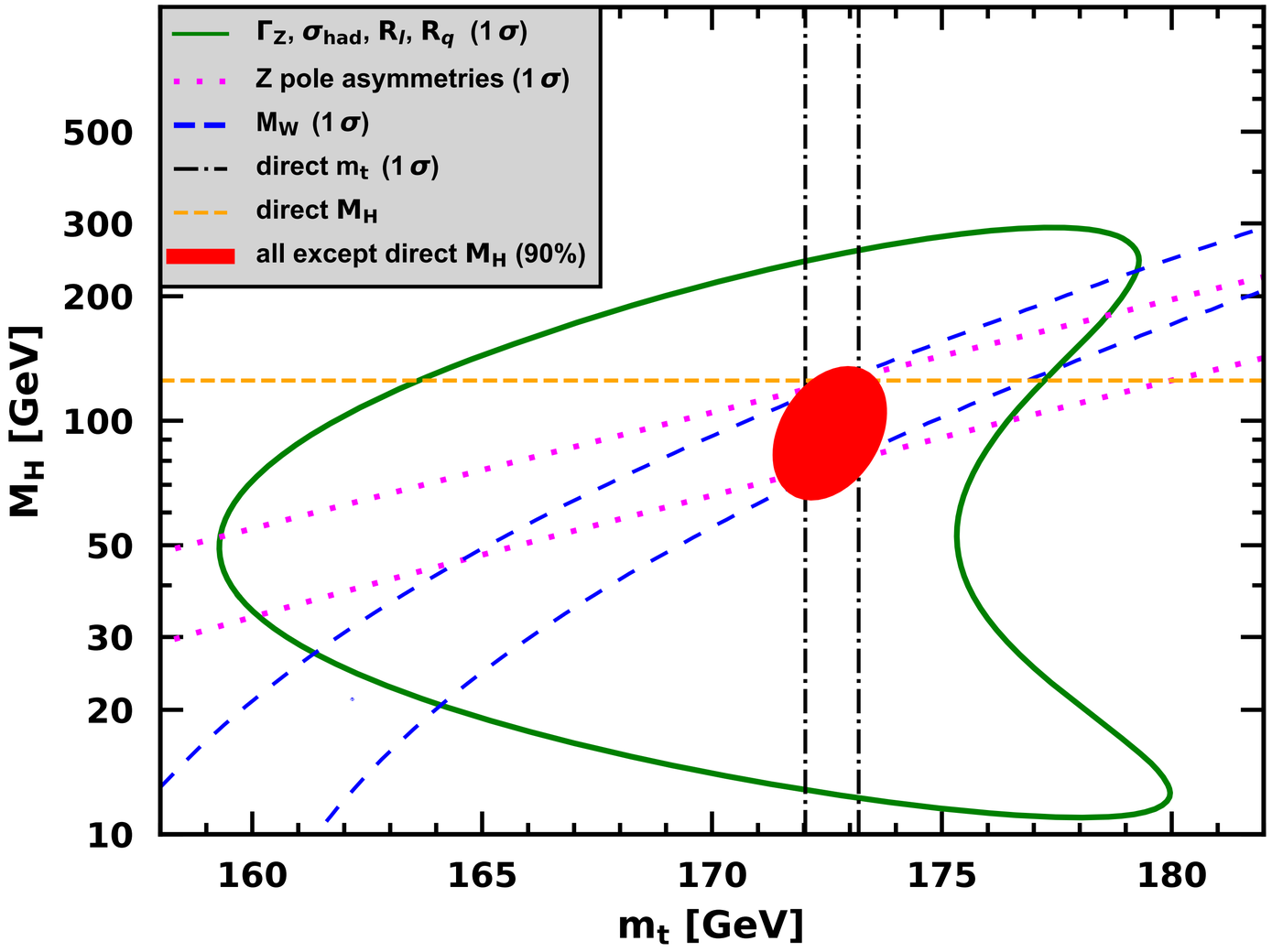
m_t = 172.61 ± 0.58 GeV (Tevatron + LHC)

M_W = 80353 ± 6 GeV (indirect)

M_W = 80364 ± 9 MeV (direct)

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

M_H – m_t EPIC update



χ^2/d.o.f. = 45.5/48

(p-value = 57%)

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

indirect (including Γ_H)

1.7 σ below

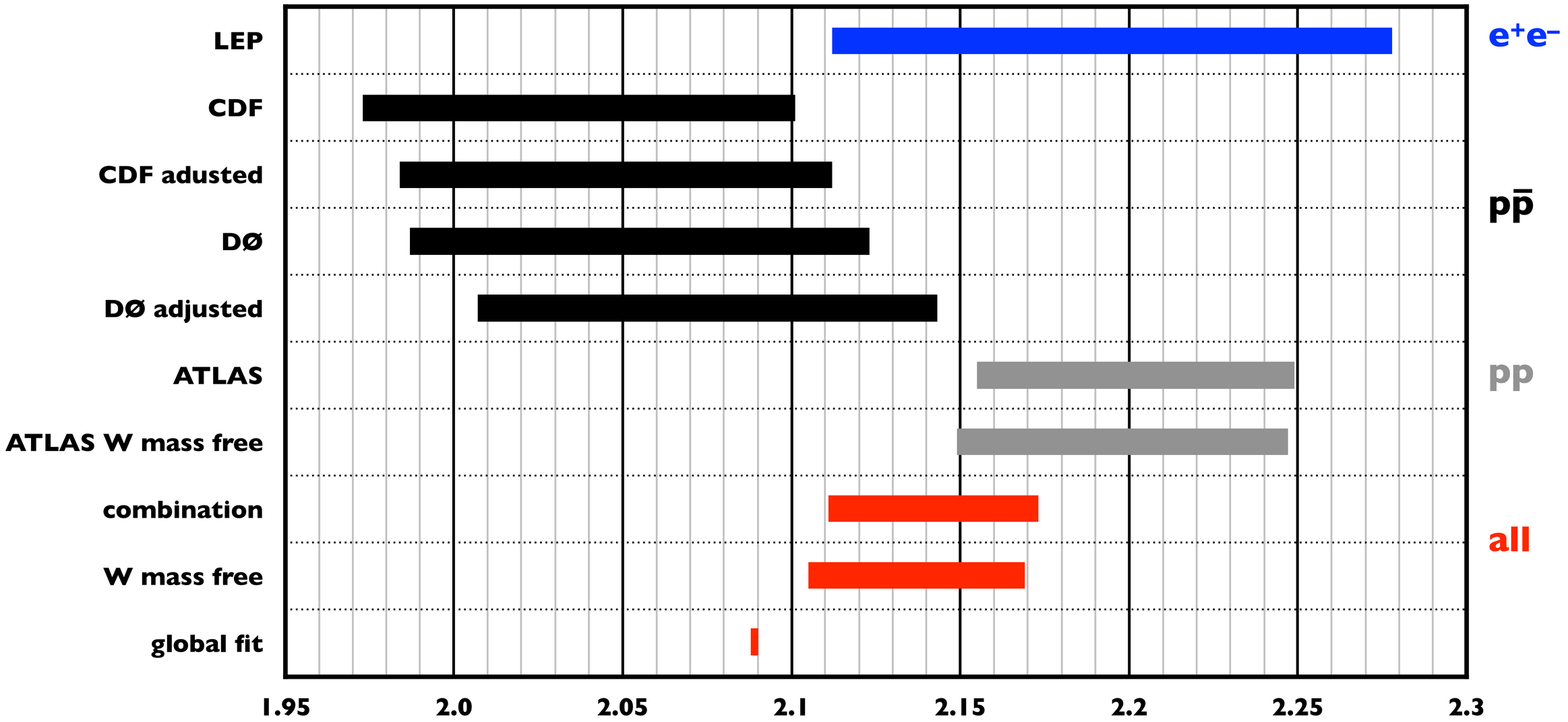
M_H = 125.10 ± 0.09 GeV

(LHC)

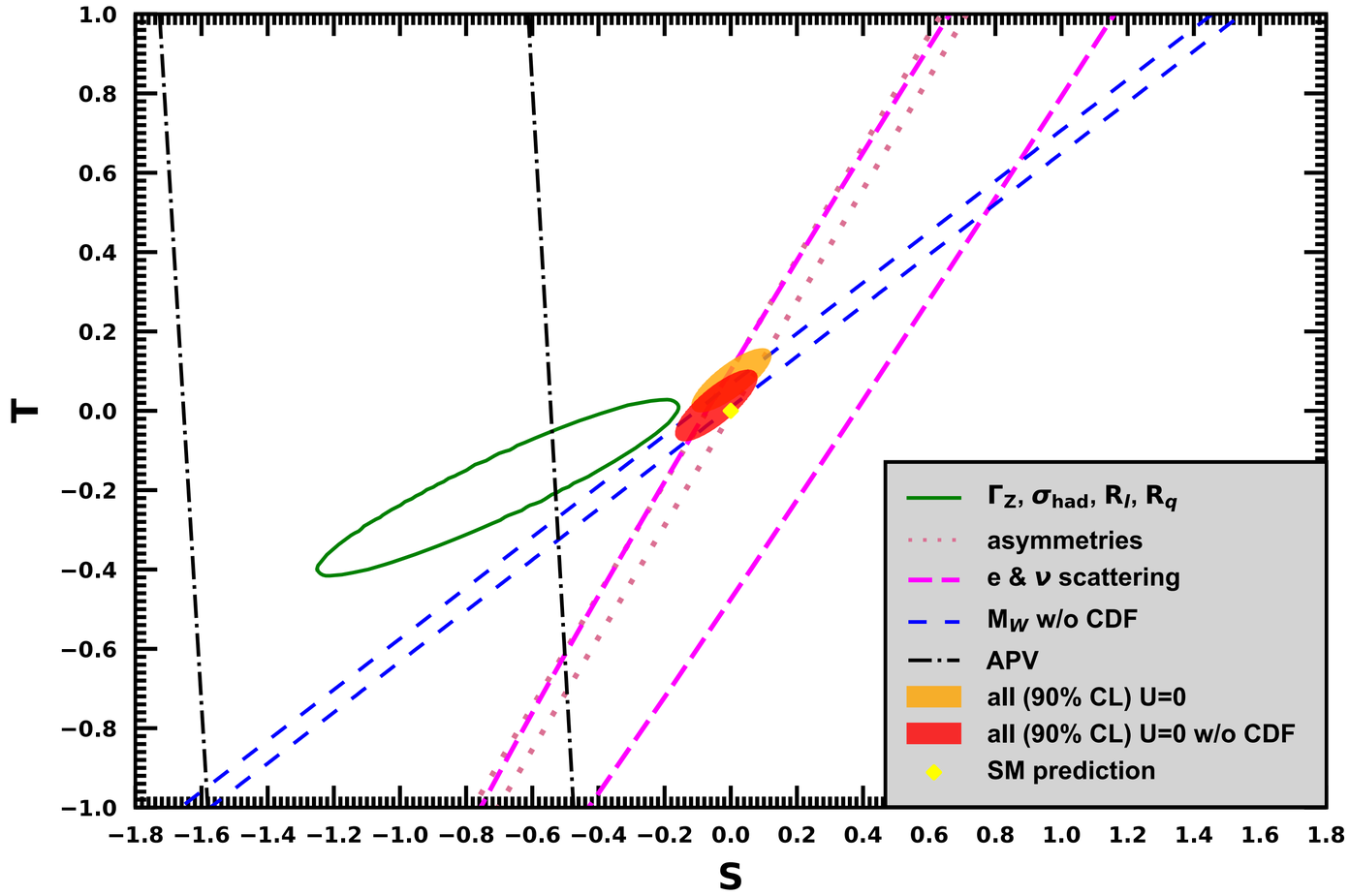
Freitas & JE, PDG (2024)

figure: Rodolfo Ferro

Γ_W anno 2024 [GeV]



S – T EPIC update



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

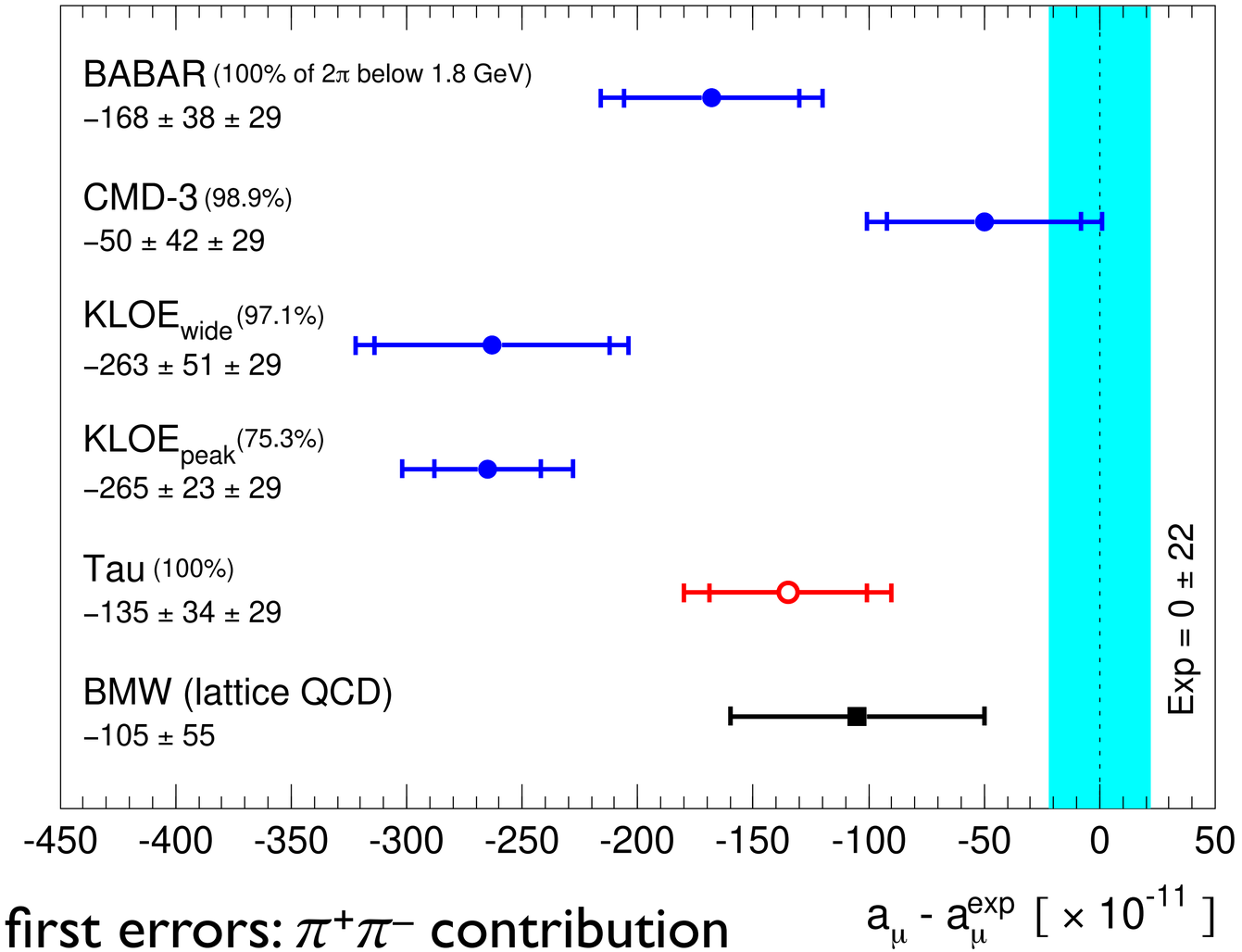
S	–0.06 ± 0.07
T	–0.01 ± 0.05

S	0 (fixed)
T	+0.03 ± 0.02

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

Hadronic vacuum polarization

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

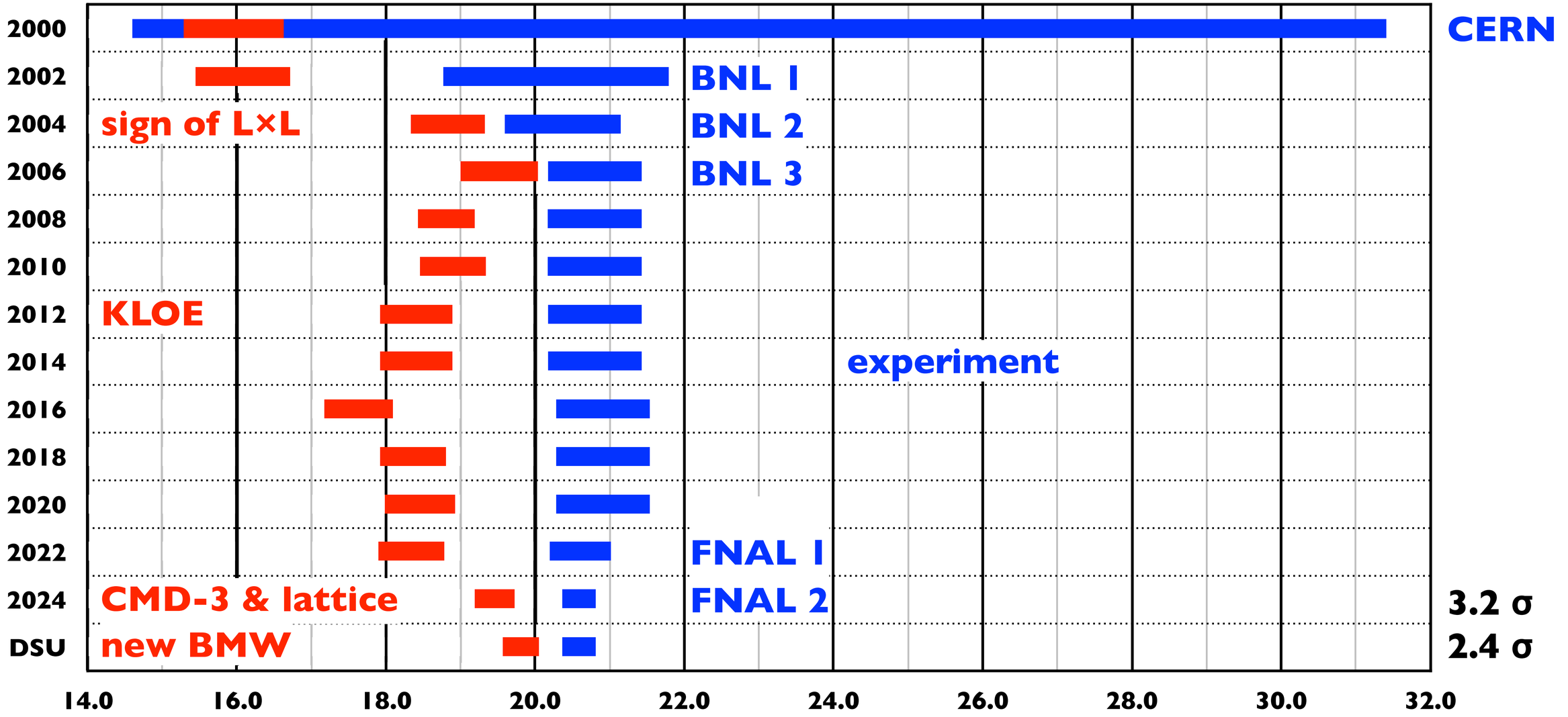
KLOE based on
Davier et al. arXiv:1908.00921

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

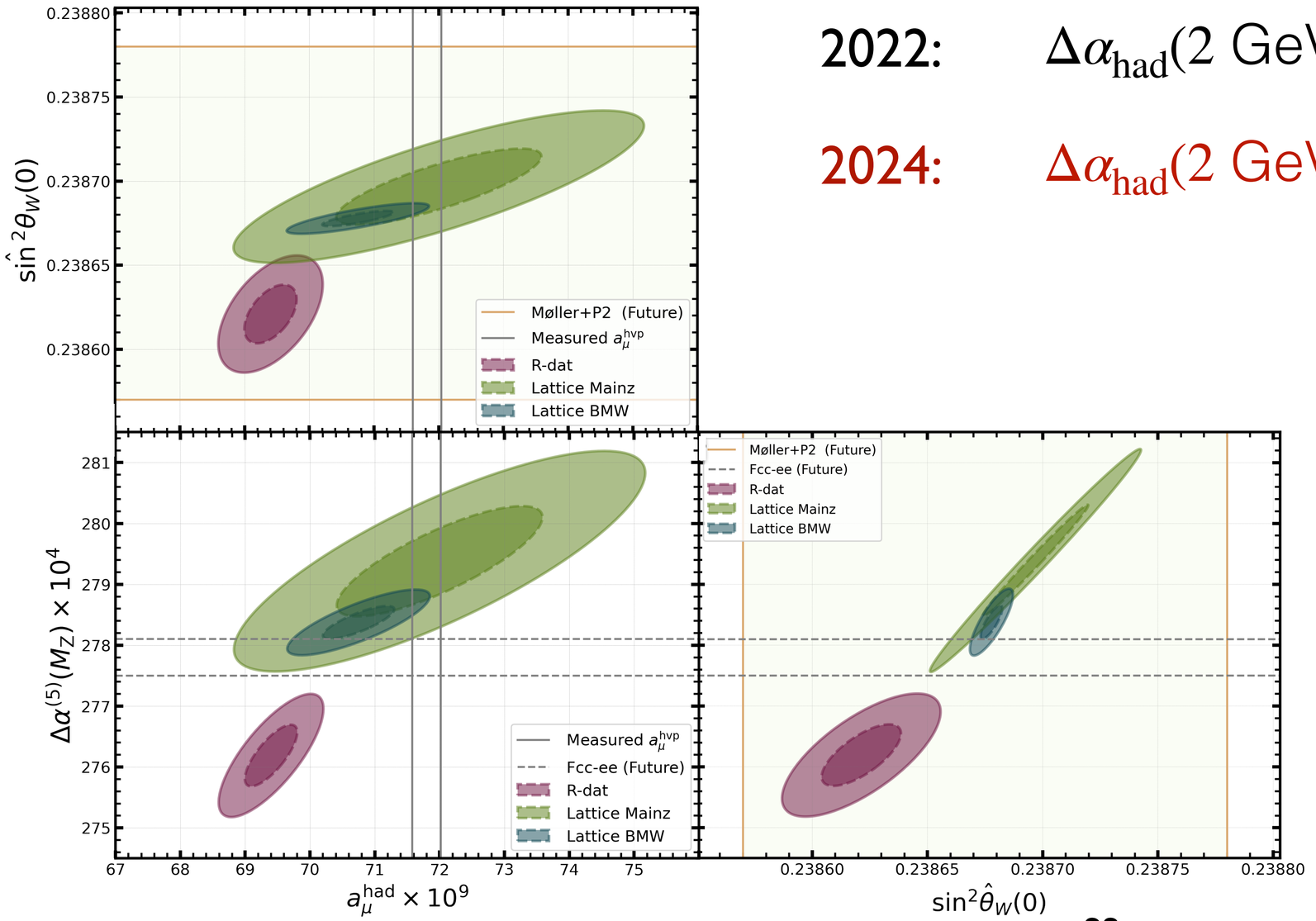
Borsanyi et al., arXiv:2002.12347

Δα from Cè et al., arXiv:2203.08676
also enters through correlations

chronology of a_μ [$\times 10^9$ – 1165900]



$g_\mu - 2$, $\alpha(M_Z)$ and $\sin^2\theta_W(0)$



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

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

$\Delta M_W = -2.7$ MeV

$\Delta M_H = -7.0$ MeV

Ferro-Hernàndez, Kuberski & JE, arXiv:2406.16691

. . . if there is time . . .

α_s from the Z pole

observable	$\alpha_s(M_Z)$	comment
Γ_Z = 2495.5 ± 2.3 MeV	0.1215 ± 0.0048	update: Γ_Z = +0.3 MeV
σ_{had} = 41.481 ± 0.033 nb	0.1201 ± 0.0065	update: $\Delta\sigma_{had}$ = –60 pb
$R_e = \Gamma_{had}/\Gamma_e$ = 20.804 ± 0.050	0.1295 ± 0.0082	
$R_\mu = \Gamma_{had}/\Gamma_\mu$ = 20.784 ± 0.034	0.1264 ± 0.0054	$m_\mu \neq 0$
$R_\tau = \Gamma_{had}/\Gamma_\tau$ = 20.764 ± 0.045	0.1157 ± 0.0072	$m_\tau \neq 0$
B_W(had) = 0.6736 ± 0.0018	0.098 ± 0.025	recent (LEP 2 + CMS)
combination	0.1223 ± 0.0028	future lepton collider ~ 10^{-4}
global fit	0.1185 ± 0.0016	includes τ decays

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

Voutsinas et al., arXiv:1908.01704

Janot & Jadach, arXiv:1912.02067

Conclusions

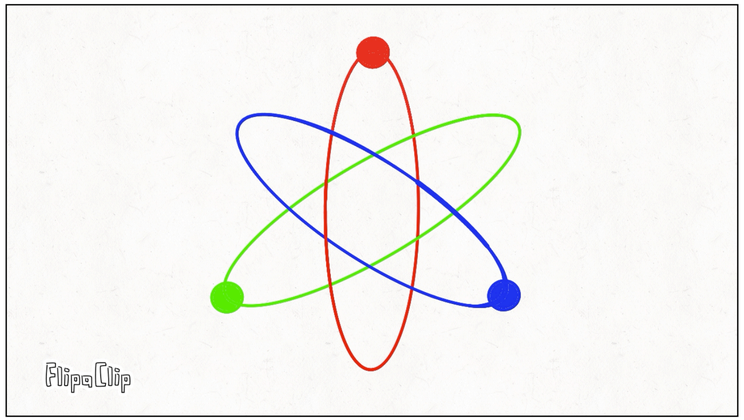
* *after more than 50 years of electroweak precision physics, still no conclusive evidence for BSM*
  * M_W, M_Z, m_t, M_H (and m_c) have all been successfully predicted before their discoveries
  * the infamous conflict in muon g–2 reduced to about 2.4 σ
  * recent *LEP* luminosity update confirms $N_\nu = 3$ active neutrinos, but α_s somewhat high
  * new CDF M_W result ~ 7 σ higher than other measurements !!!
* *outlook*
  * high precision PVES (*P2, MOLLER, SoLID*) competitive alternatives to high energy frontier
  * leap in precision expected from future lepton collider(s)
    ILC, CEPC, FCC–ee, CLIC, μ collider

Discussion Topics

* *How difficult would be the atomic theory calculation for the 7s to $6d_{3/2}$ transition in Ra^+?*
  What uncertainty could be expected?

* *Is the muon g–2 deviation gone (nominally 2.4 σ)?*
  Trust dispersion analysis or lattice?

* *What should be done about the M_W from CDF, given that their M_Z agrees well with LEP?*
  Are we central limit or even confirmation biased?



Thank You