Deutsche Forschungsgemeinschaft

PDG particle data group

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Fundamental Parameters from Electroweak Fits

Workshop on
Determination of Fundamental QCD Parameters
***ICTP–SAIFR*, São Paulo, September 30–October 4, 2019**

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CONACYT Consejo Nacional de Ciencia y Tecnología

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


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

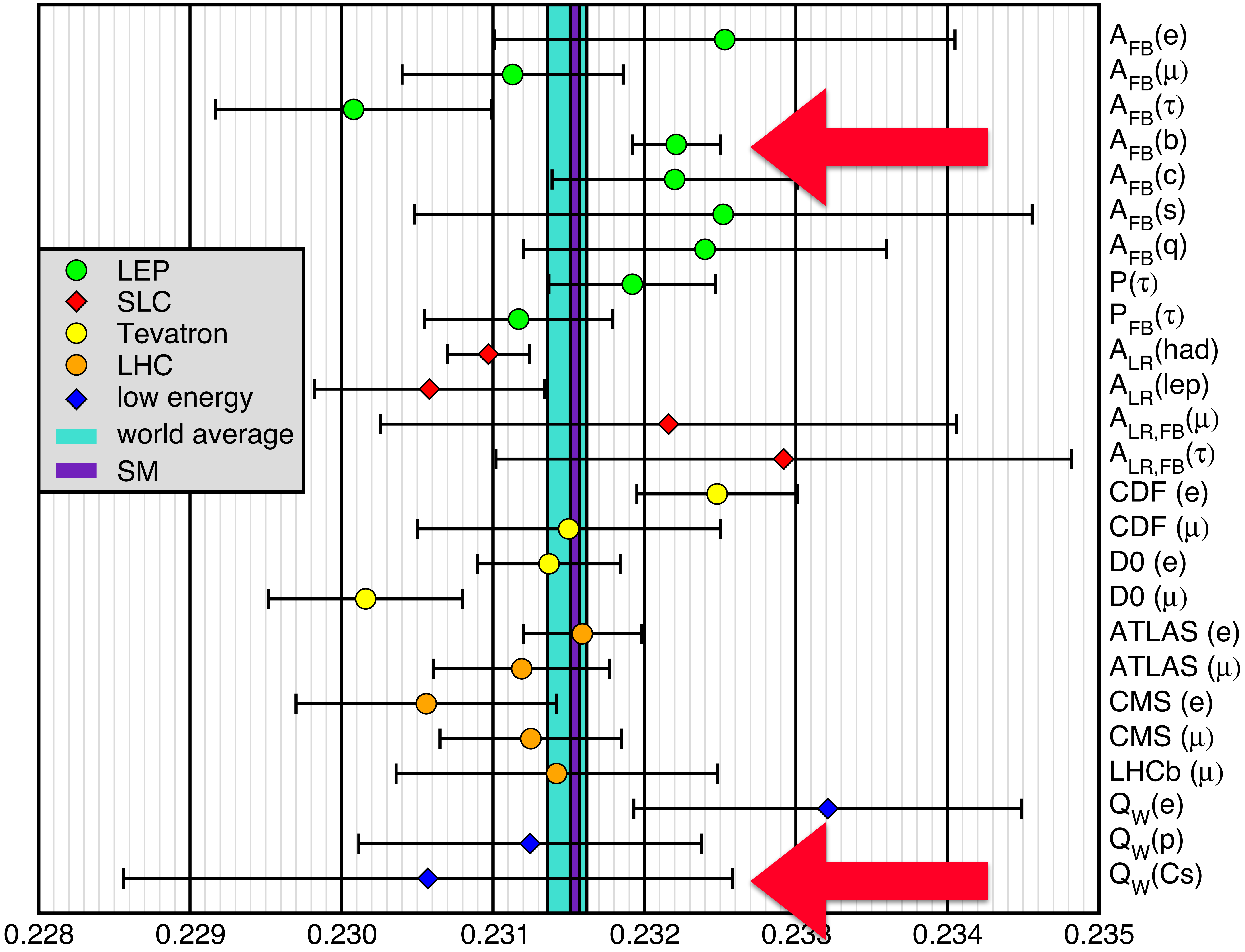
* *Various groups, programs, approaches, renormalization schemes:*
  * *GAPP* ($\overline{\text{MS}}$ scheme, FORTRAN, options for BSM fits, used for PDG)
    JE, hep-ph/0005084
  * *Gfitter* (on-shell scheme, C++)
    Flächer et al., arXiv:0811.0009
  * *HEPfit* (on-shell scheme, allows fit to Wilson 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
* *heavy weights*
  * M_W
  * m_t
  * M_H
* α_s
  * LEP luminosity → σ_{had} & Γ_Z
  * τ decays
* *outlook*
  * parity violating electron scattering
  * FCC-ee

$\sin^2\theta_W$

Weak mixing angle measurements



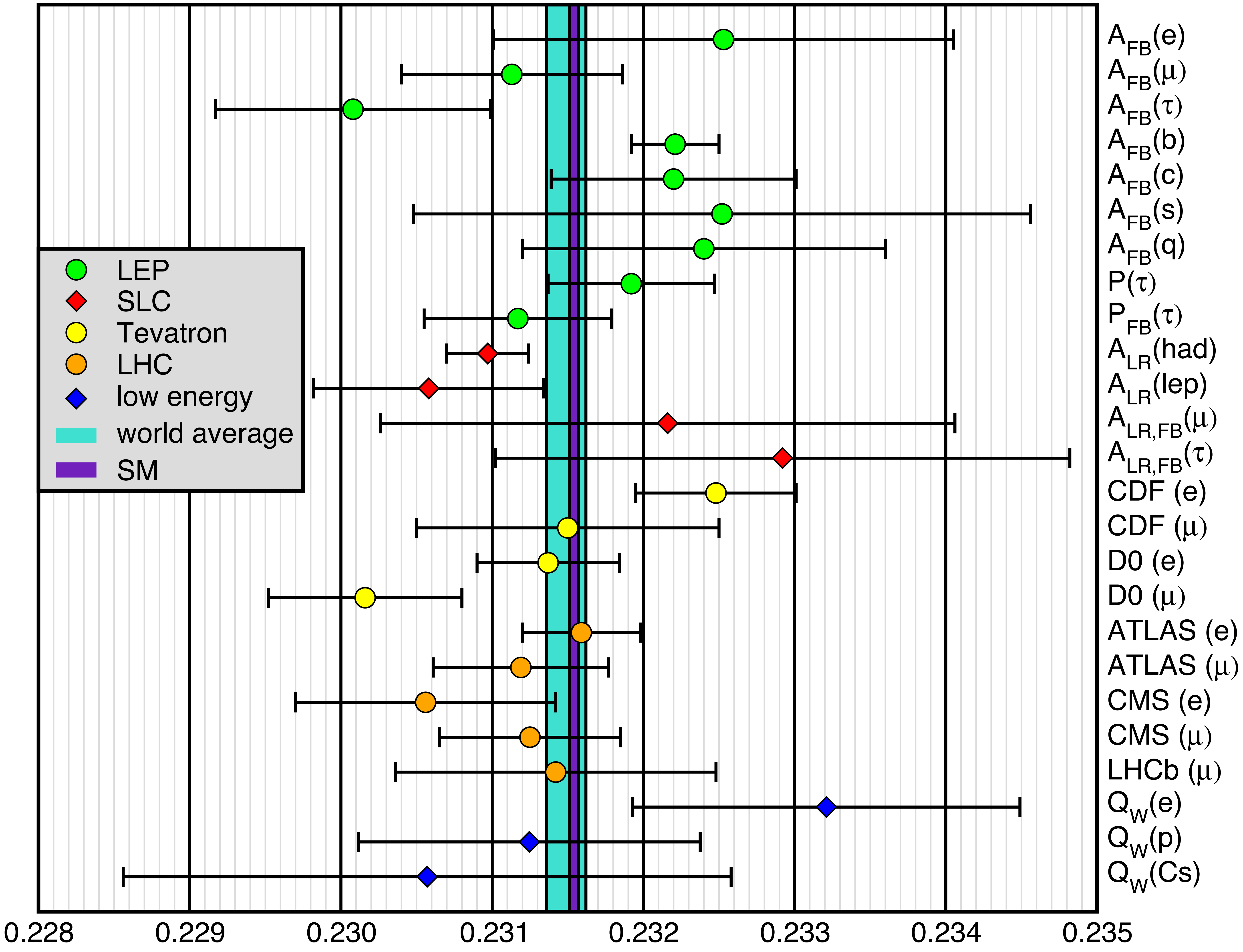
2-loop QCD correction with $m_b \neq 0$

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

Parity Violating e⁻ Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 MeV

|Q| = 158 MeV

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

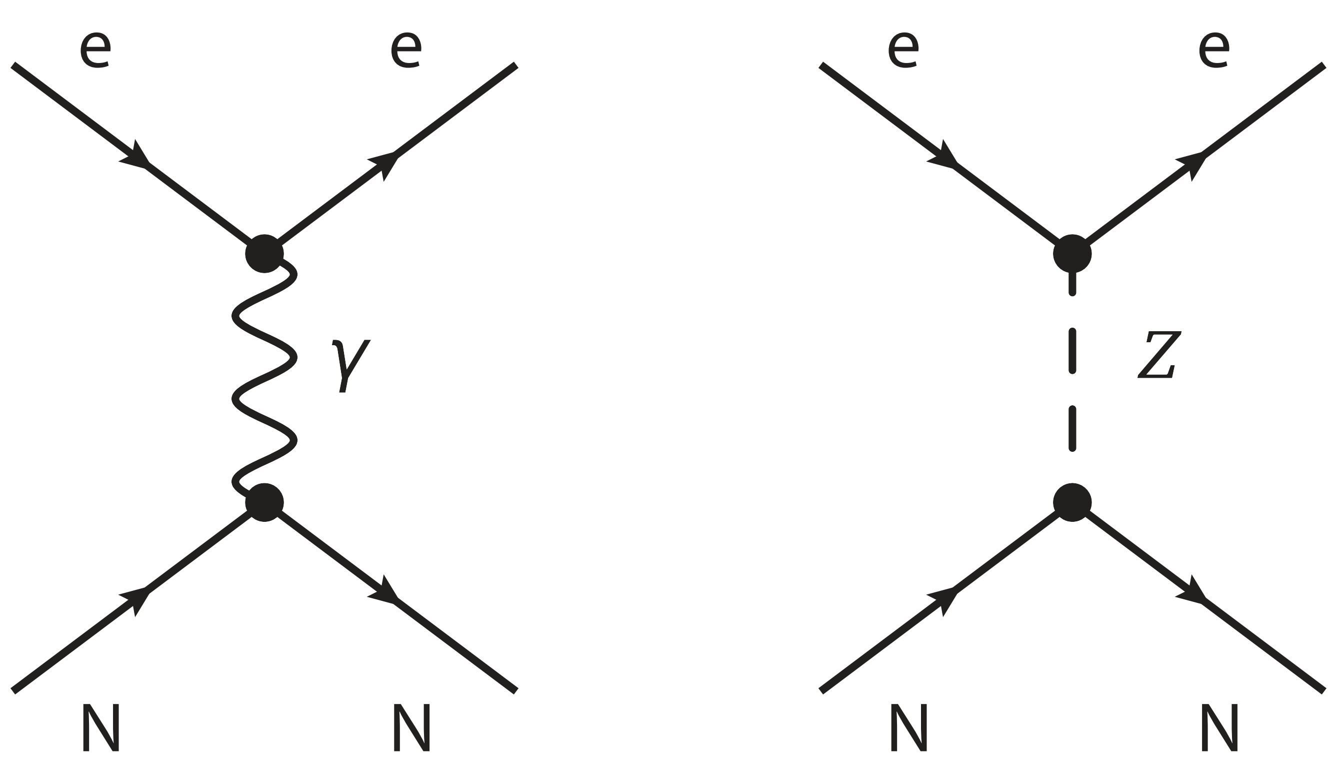
$\Delta A_{PV} = \pm\ 4.1\%$

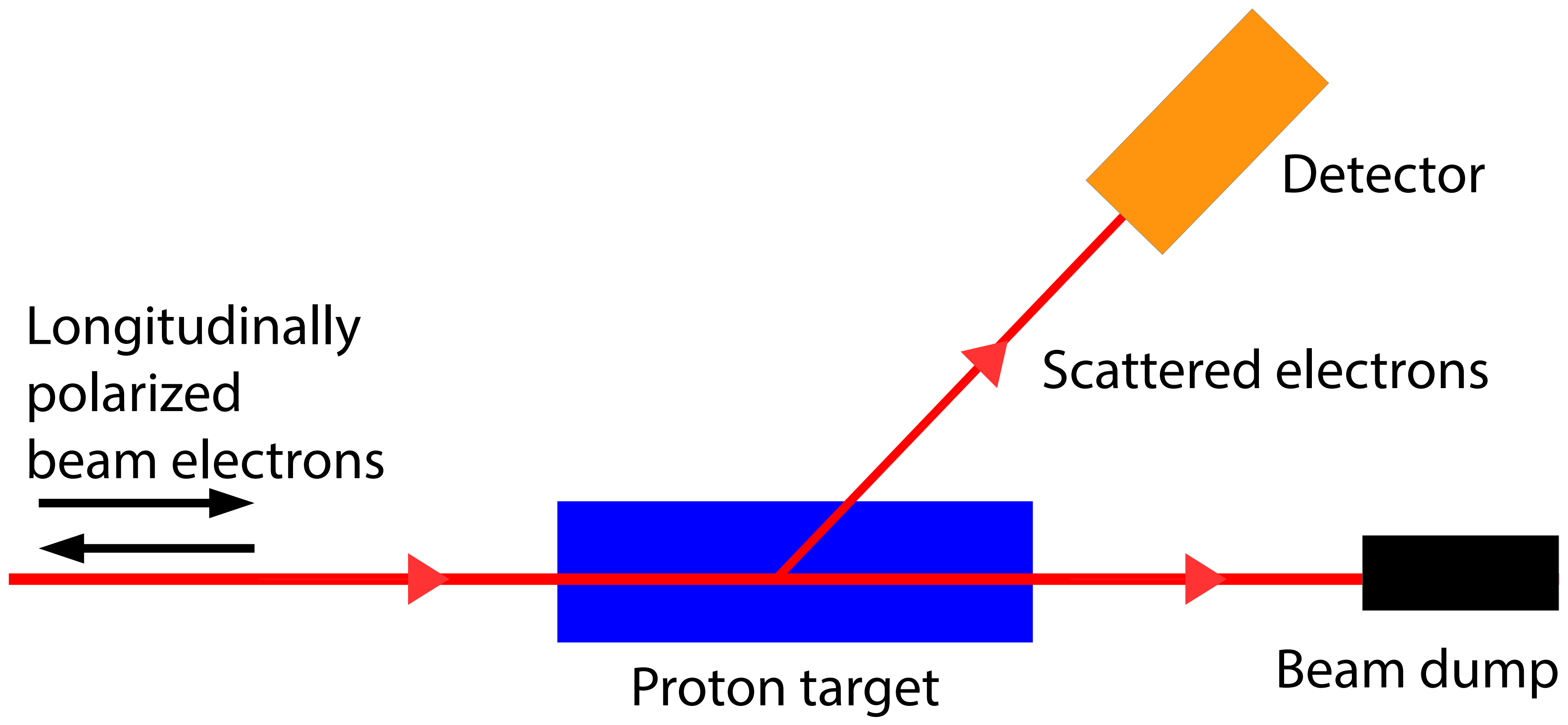
$\Delta Q_W(p) = \pm\ 6.25\%$

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

FFs from fit to ep asymmetries

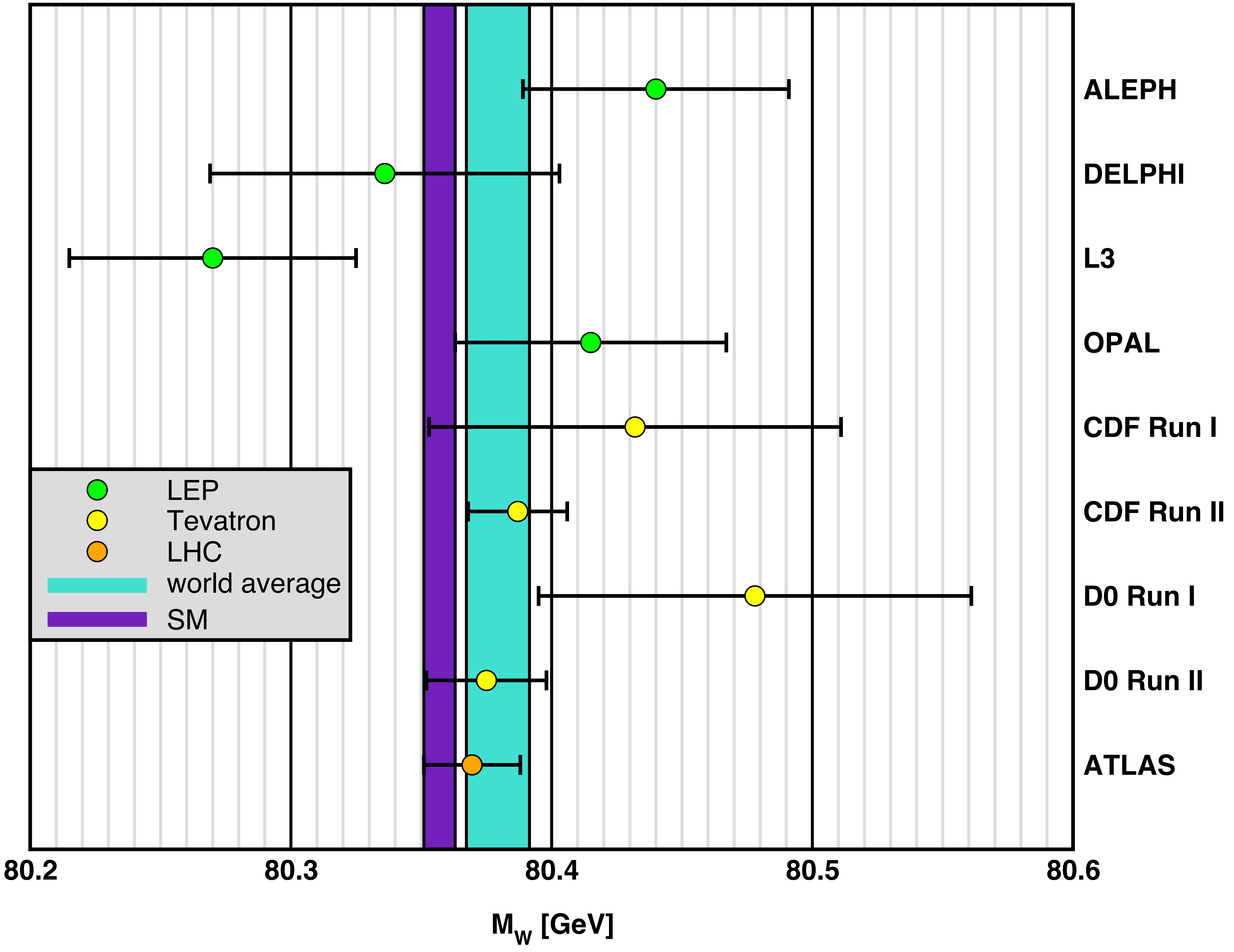
arXiv:1905.08283





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

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 + Δ_{MC} = 172.80 ± 0.44 GeV + Δ_{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
ATLAS Run 1	$t\bar{t}$ + 1-jet	$171.1^{+1.2}_{-1.1}$	0.119 ± 0.001		1905.02302

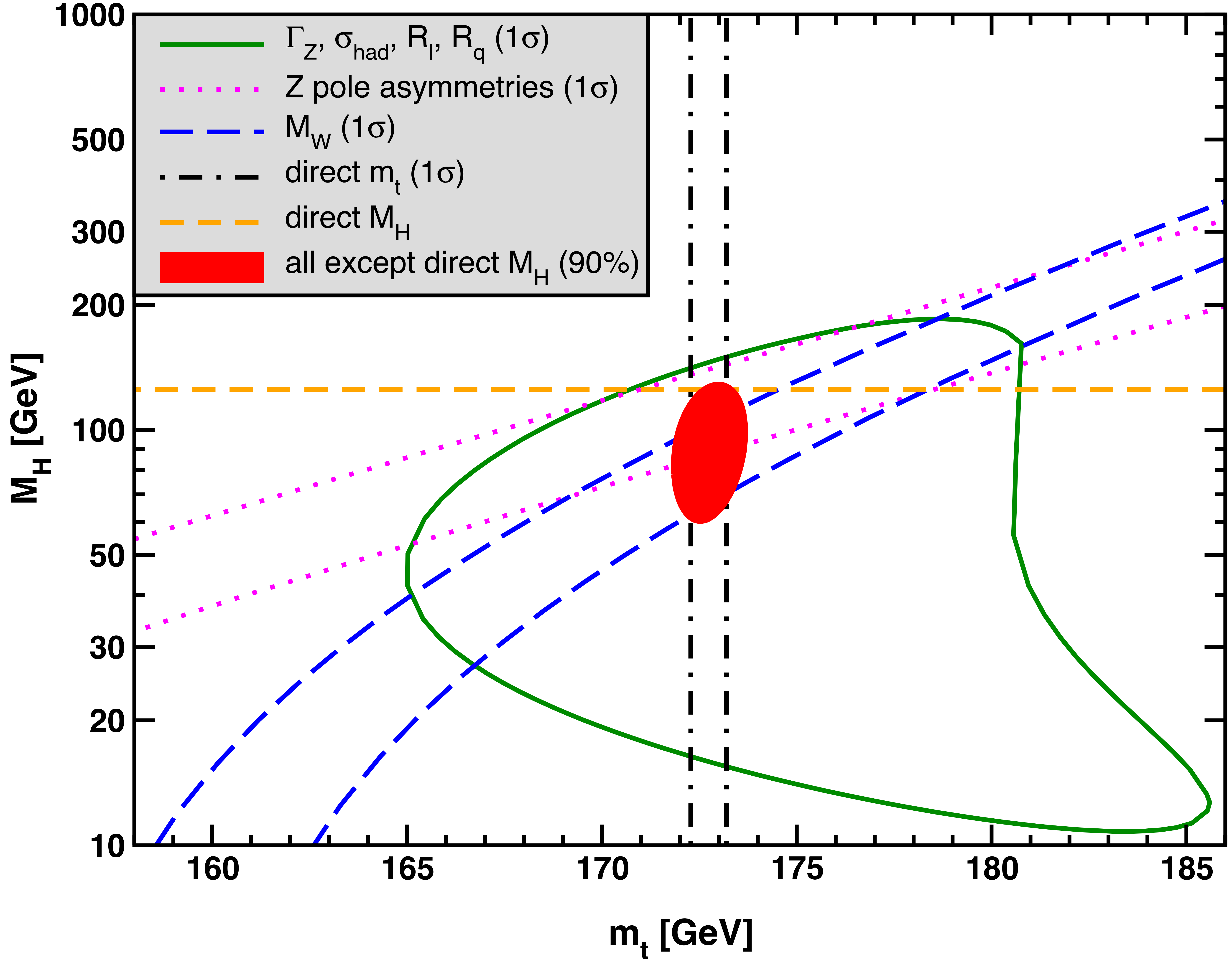
* these are <u>differential</u> cross-section at NLO
* <u>total</u> cross-sections currently give larger errors $\gtrsim$ 2 GeV

M_H fits

	m_t (GeV)	M_H (GeV)	χ^2/d.o.f.
no external m_t	$174.3^{+6.8}_{-5.6}$	102^{+83}_{-43}	37.2/39
m_t^{MC} (Δ_{MC} = 0)	172.8 ± 0.44	89^{+18}_{-15}	37.3/40
m_t^{MC} (Δ_{MC} = 0 ± 0.54 GeV)	172.8 ± 0.7	89^{+19}_{-16}	37.3/40
m_t^{MC} (Δ_{MC} = 0.54 ± 0.54 GeV)	173.4 ± 0.7	94^{+19}_{-17}	37.2/40
m_t^{pole}	171.0 ± 0.6	79^{+17}_{-14}	43.7/42
m_t^{MC} (Δ_{MC} = 0 ± 0.54 GeV) + m_t^{pole}	171.8 ± 0.47	85^{+17}_{-15}	47.2/43
m_t^{MC} (Δ_{MC} = 0.54 ± 0.54 GeV) + m_t^{pole}	172.1 ± 0.47	87^{+17}_{-16}	49.7/43

in the last fit: $\alpha_s(M_Z) = 0.1175 \pm 0.0011$

$M_H - m_t$



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

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

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

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

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 ± 0.0047	+0.0006	
$\sigma_{had} = 41.501 \pm 0.037$ nb	0.1148 ± 0.0073	+0.0078	
$R_e = 20.804 \pm 0.050$	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	0.1221 ± 0.0028	+0.0014	3.3/4
Z-pole + M_H	0.1219 ± 0.0027	+0.0012	19.1/23
global fit ex. τ decays	0.1207 ± 0.0026	+0.0012	40.4/40

change: $\Delta\sigma_{had} = -40$ pb, $\Delta\Gamma_Z = +0.3$ MeV **Voutsinas et al., arXiv:1908.01704**

α_s from τ decays

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

$$\Gamma_\tau^{ud} = \frac{G_F^2 m_\tau^5 |V_{ud}|^2}{64\pi^3} S(m_\tau, M_Z) \left(1 + \frac{3}{5}\frac{m_\tau^2 - m_\mu^2}{M_W^2}\right) \times$$
$$\left[1 + \frac{\alpha_s^{(3)}(m_\tau)}{\pi} + 5.202\,\frac{\alpha_s^2}{\pi^2} + 26.37\,\frac{\alpha_s^3}{\pi^3} + 127.1\,\frac{\alpha_s^4}{\pi^4} + \frac{\hat{\alpha}^{(3)}(m_\tau)}{\pi}\left(\frac{85}{24} - \frac{\pi^2}{2}\right) + \delta_{\mathrm{NP}}\right]$$

* charm, bottom and strange mass effects not shown but included
  Larin, van Ritbergen & Vermaseren, hep-ph/9411260
* $\mathcal{B}_\tau{}^s = 0.0292 \pm 0.0004$ ($\Delta S = -1$) **PDG 2018**
* $S(m_\tau, M_Z) = 1.01907 \pm 0.0003$ **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:** $\boldsymbol{\alpha_s^{(5)}(M_Z) = 0.1192^{+0.0017}_{-0.0015}}$ (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 **Voutsinas et al. arXiv:1908.01704**	2.998 ± 0.007	luminosity update
		3.001 ± 0.007	precise $t\bar{t}$ X-sections

Global electroweak fit (incl. m_t^{pole} from X-sections)

M_H	125.14 ± 0.15 GeV
M_Z	91.1884 ± 0.0020 GeV
$\overline{m}_b(\overline{m}_b)$	4.180 ± 0.021 GeV
$\Delta\alpha_{had}^{(3)}(2\ \mathrm{GeV})$	$(59.0 \pm 0.5)\times 10^{-4}$

$\overline{m}_t(\overline{m}_t)$	162.53 ± 0.43 GeV	1.00	–0.04	–0.10
$\overline{m}_c(\overline{m}_c)$	1.272 ± 0.009 GeV	–0.04	1.00	0.35
$\alpha_S(M_Z)$	0.1173 ± 0.0011	–0.10	0.35	1.00

$\chi^2/\mathrm{d.o.f.} = 51.9/44$

outlook

Parity Violating e^- Scattering (PVES) — Elastic

Qweak @ CEBAF (JLab)

hydrogen (completed)

E_e = 1149 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 = 155 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

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

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

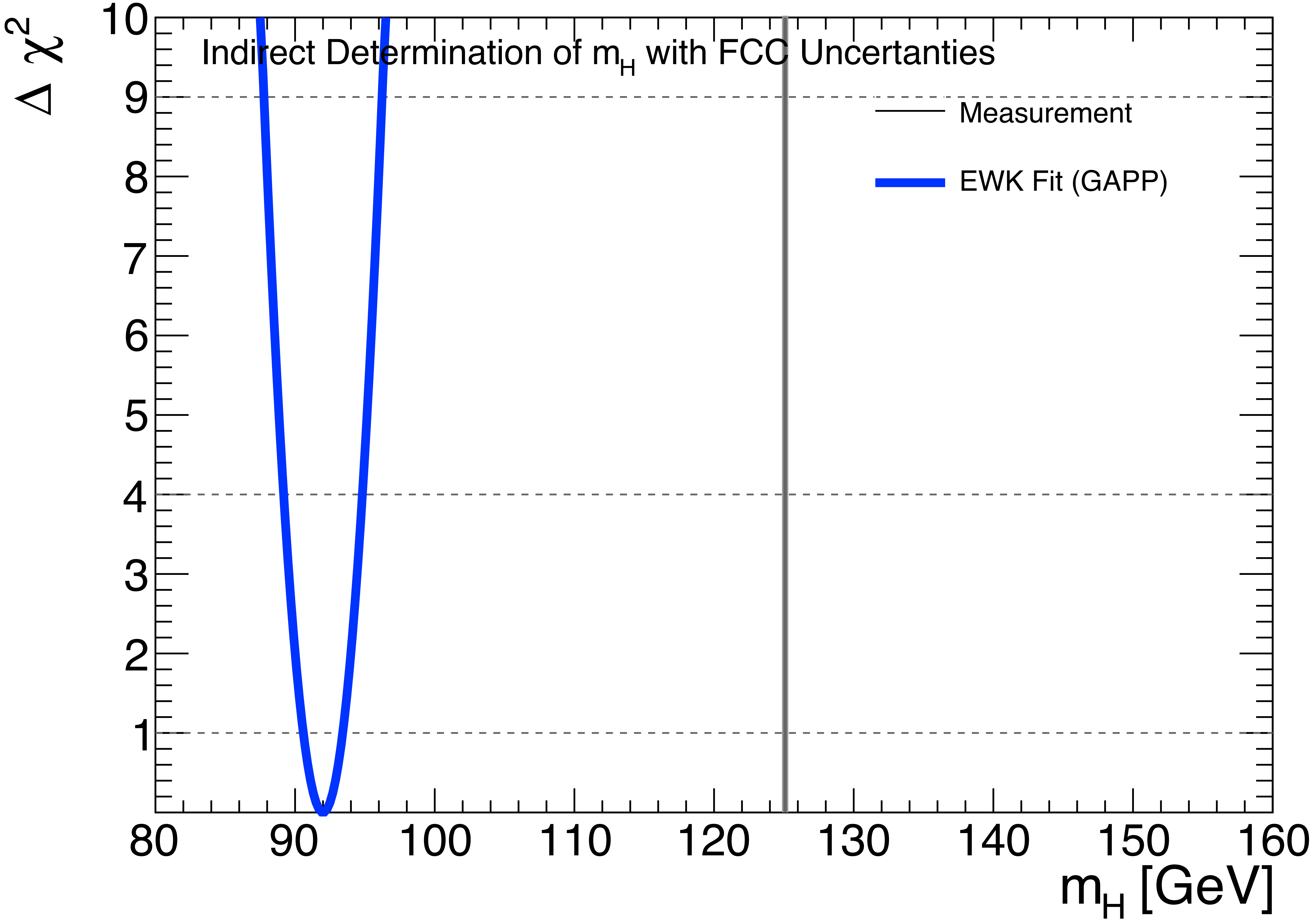
$\Delta A_{PV} = \pm 2.4\%$

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

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

arXiv:1411.4088

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

Summary

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