Theoretical Implications of Precision Measurements

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Outline

- Old Physics Implications: the electroweak global fit
- Key Observables
- New Physics Implications
- Conclusions

Old Physics Implications:
the electroweak global fit
(PDG 2016 & some 2017 updates)

Birthdays

- October 17: 50 years of Standard Model (immortal?)
- July 4: 5 years of Higgs

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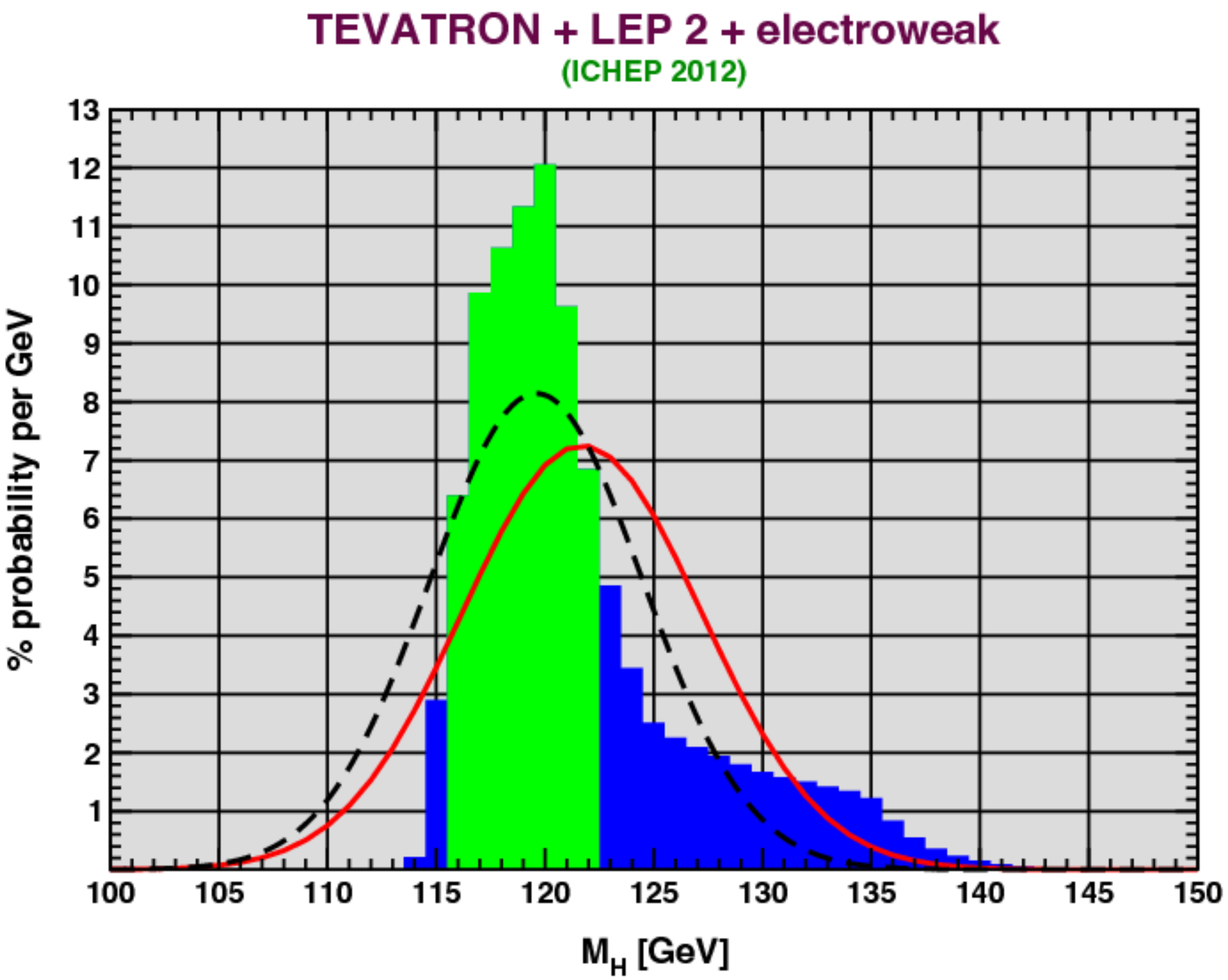
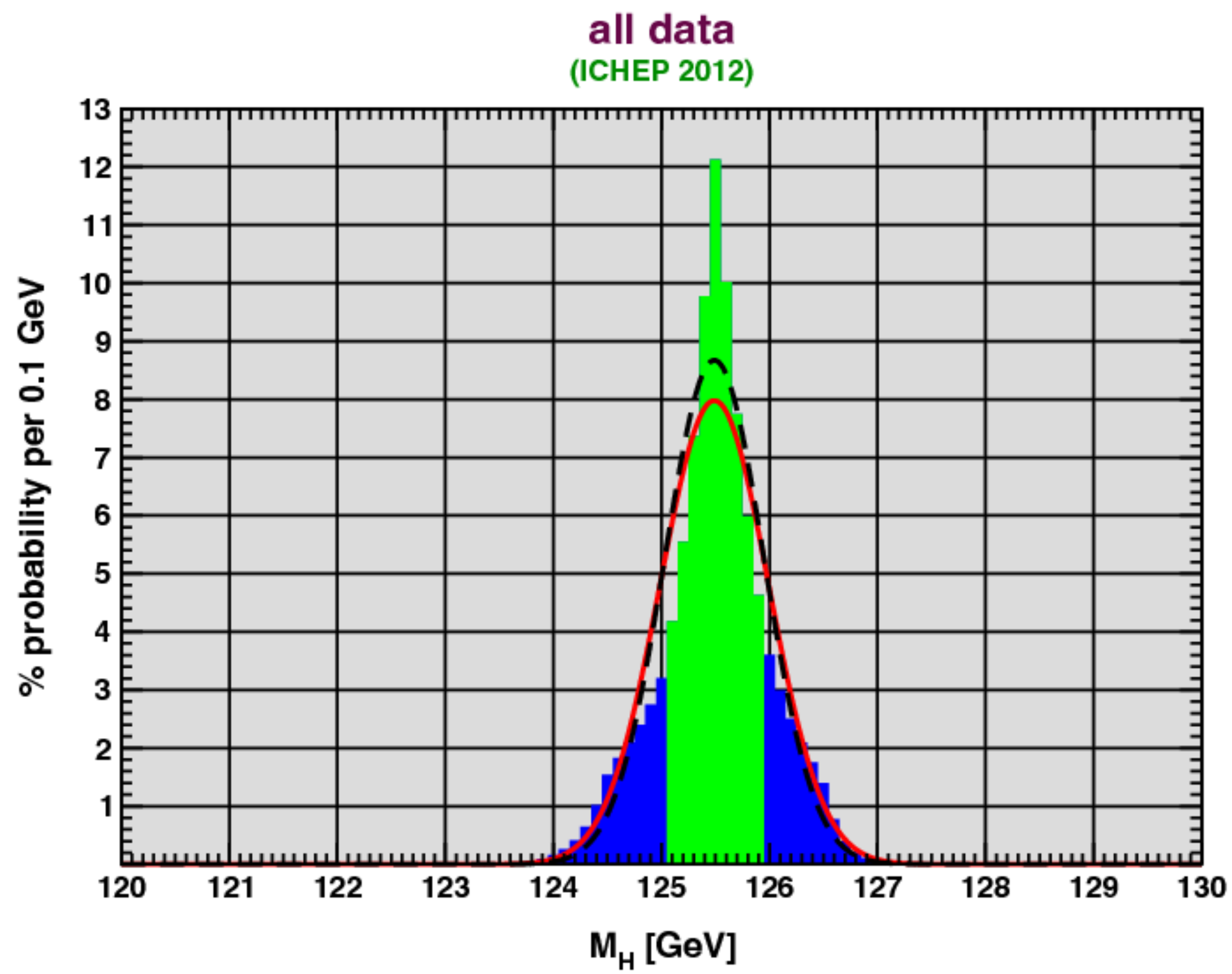




Introduction: The electroweak fit

- 5 inputs needed to fix the bosonic sector of the SM:
  SU(3) × SU(2) × U(1) gauge couplings and 2 Higgs parameters

- fine structure constant: α e.g. from the Rydberg constant (leaves g_e–2 as derived quantity and extra SM test)

- Fermi constant: G_F from PSI (muon lifetime)

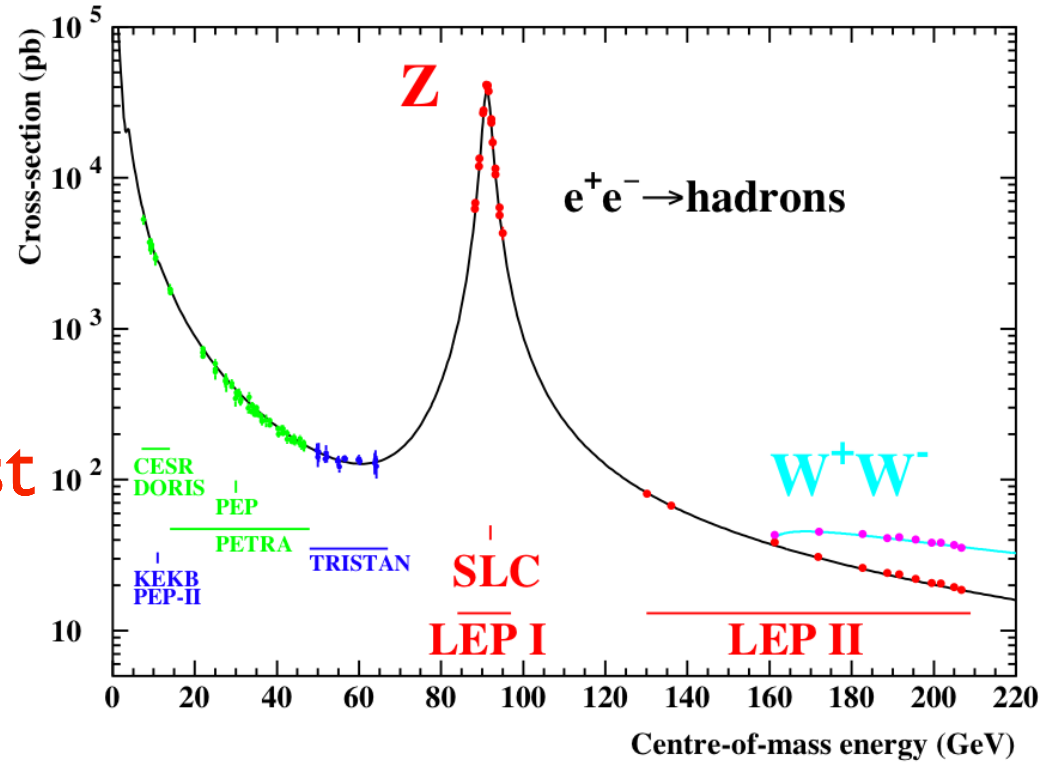
- Z mass: M_Z from LEP

- Higgs mass: M_H from the LHC

- strong coupling constant: $\alpha_s(M_Z)$ is fit output ☛

Weak probes of the strong coupling

- Z width, height and BRs: only α_s constraint not limited by theory
  - $\alpha_s(M_Z) = 0.1203 \pm 0.0028$
  - $N_\nu = 2.992 \pm 0.007$ ***Freitas, JE 2016***



- W width: $1^{st} + 2^{nd}$ row CKM unitarity test
- τ lifetime & BRs:
  - α_s at the verge of a perturbative breakdown: FOPT vs. CIPT
  - $\alpha_s(m_\tau) = 0.314^{+0.016}_{-0.013}$ and $\alpha_s(M_Z) = 0.1174^{+0.0019}_{-0.0017}$
- electroweak fit $\Longrightarrow$ $\alpha_s(M_Z) = 0.1182 \pm 0.0016$ ***Freitas, JE (PDG 2016)***

Top quark mass

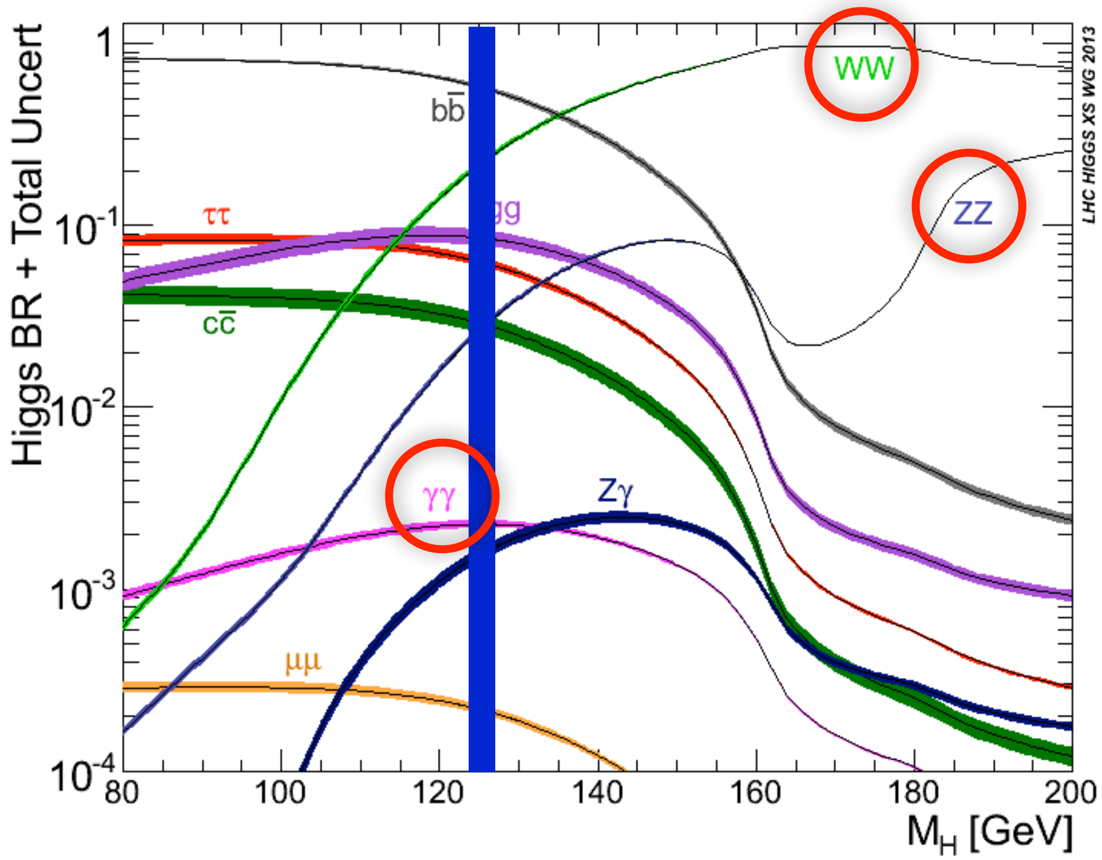
	central value	statistical error	systematic error	total error
ATLAS	172.84	0.34	0.61	0.70
Tevatron	174.30	0.35	0.54	0.64
CMS	172.43	0.13	0.46	0.48
grand average	172.97	0.13	0.38	0.41

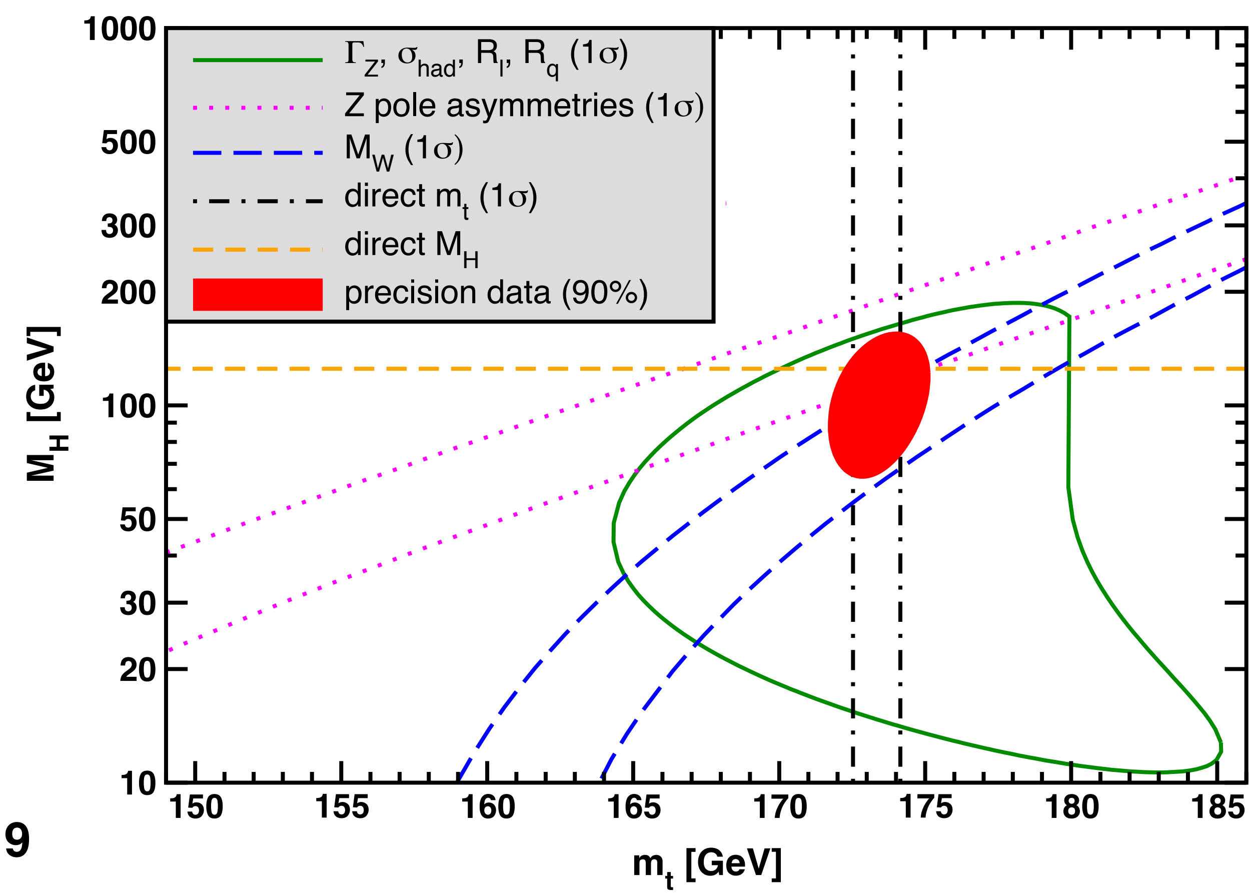
JE, Eur. Phys. J. C 75 (2015)

- $m_t = 172.97 \pm 0.28_{\text{uncorr.}} \pm 0.29_{\text{corr.}} \pm 0.50_{\text{QCD}}$ GeV
- future reduction of QCD error at hadron colliders to 70 MeV?
- change from previous $m_t = 173.34 \pm 0.81$ GeV $\Longrightarrow \Delta M_H = -3$ GeV
- indirectly from EW fit: $m_t = 176.7 \pm 2.1$ GeV ***Freitas, JE (PDG 2016)***

M_H

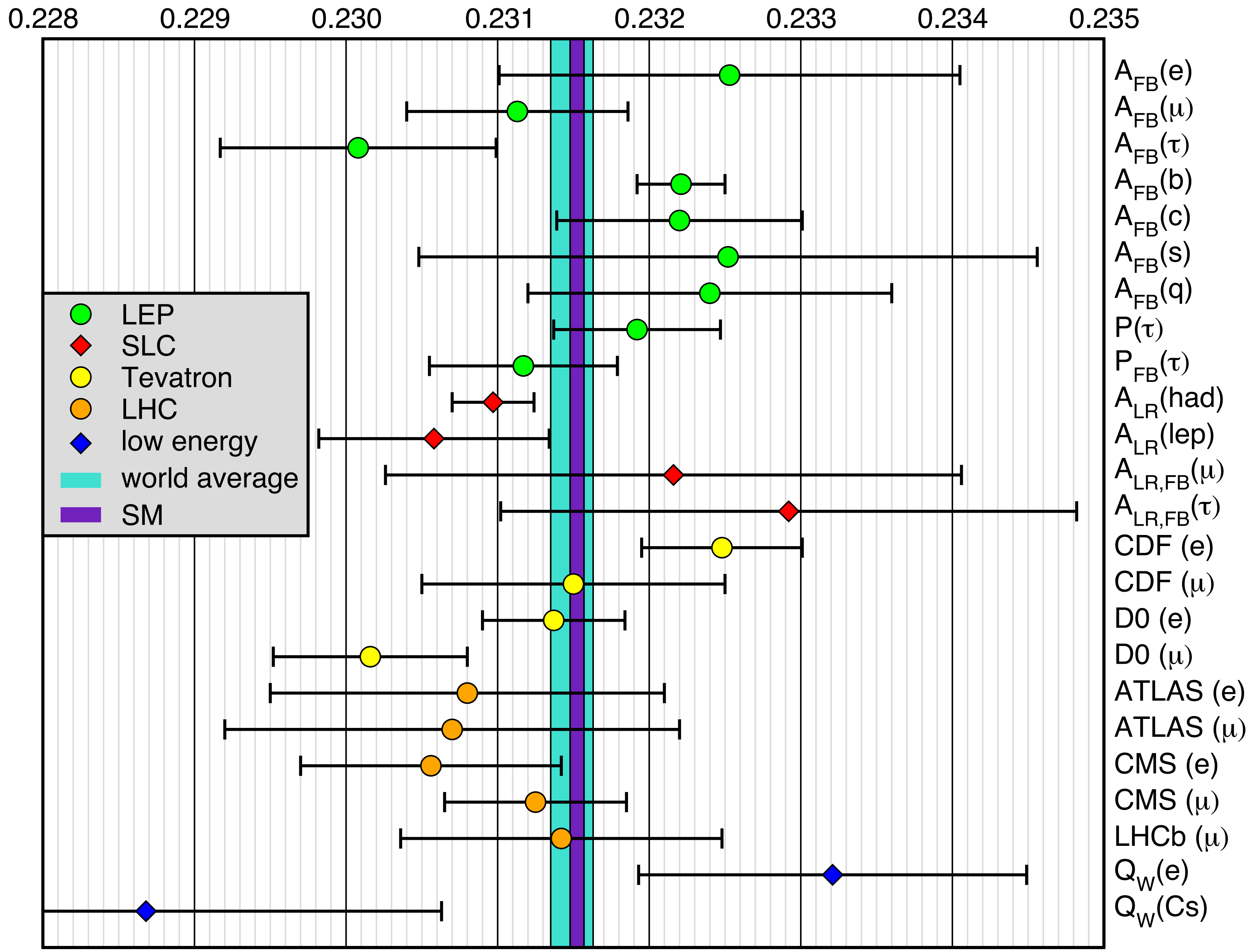
event kinematics ATLAS, CMS 2015	**125.09 ± 0.24 GeV**
Higgs BRs Freitas, JE (PDG 2016)	**126.1 ± 1.9 GeV**
Electroweak fit (2017)	**90^{+18}_{-16} GeV**

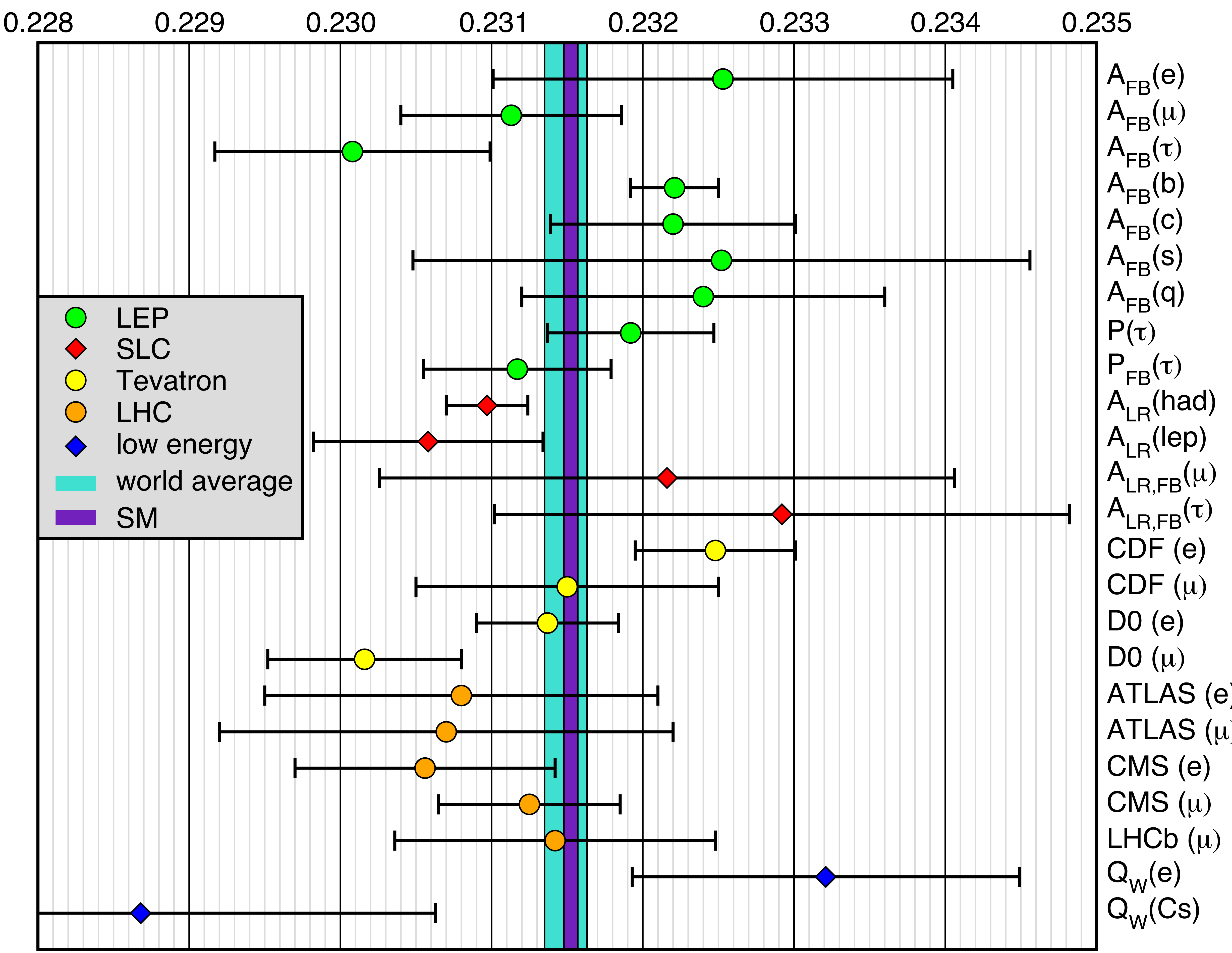




Key Observables

Weak Mixing Angle ($\sin^2\theta_W$)

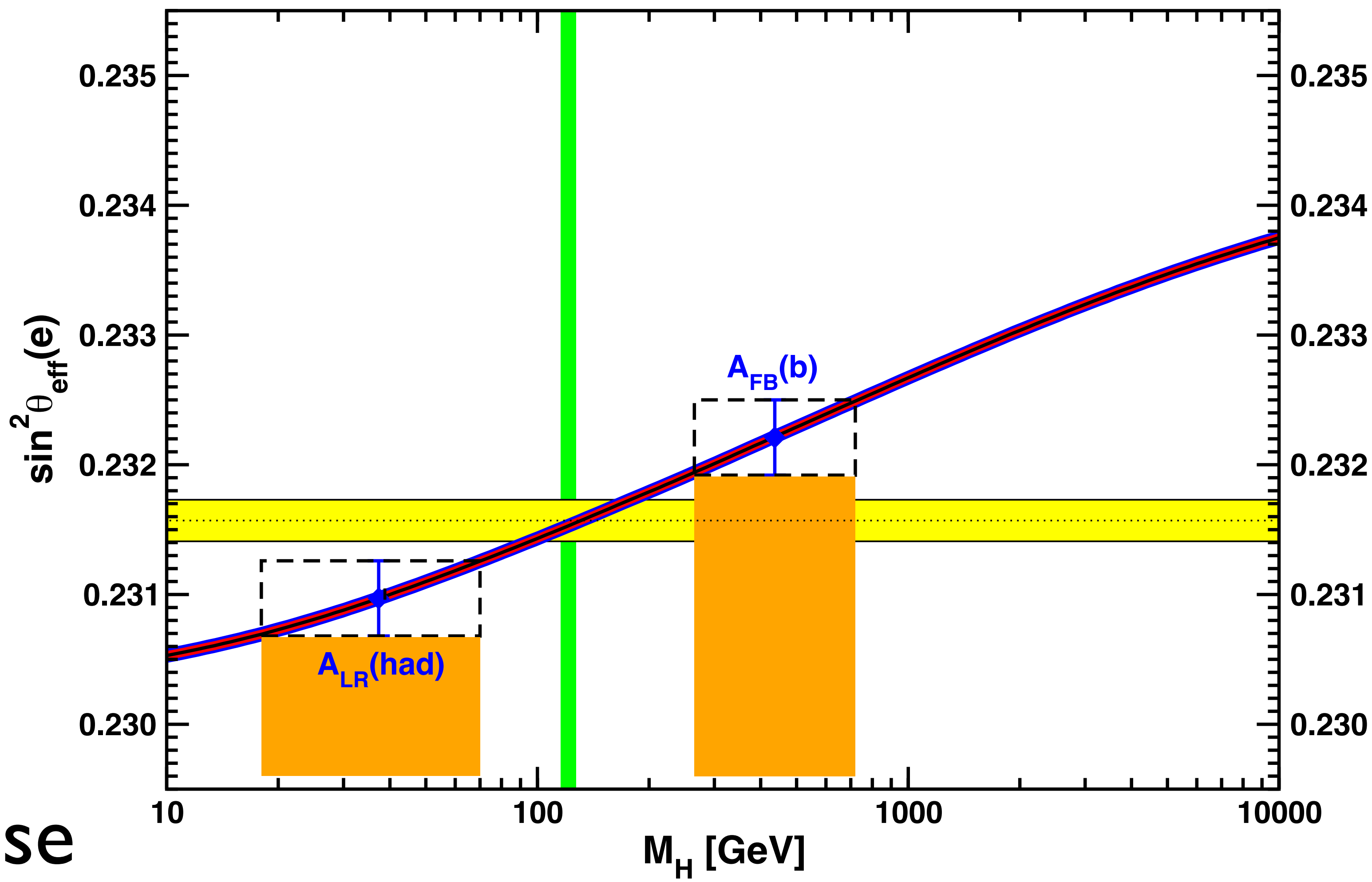




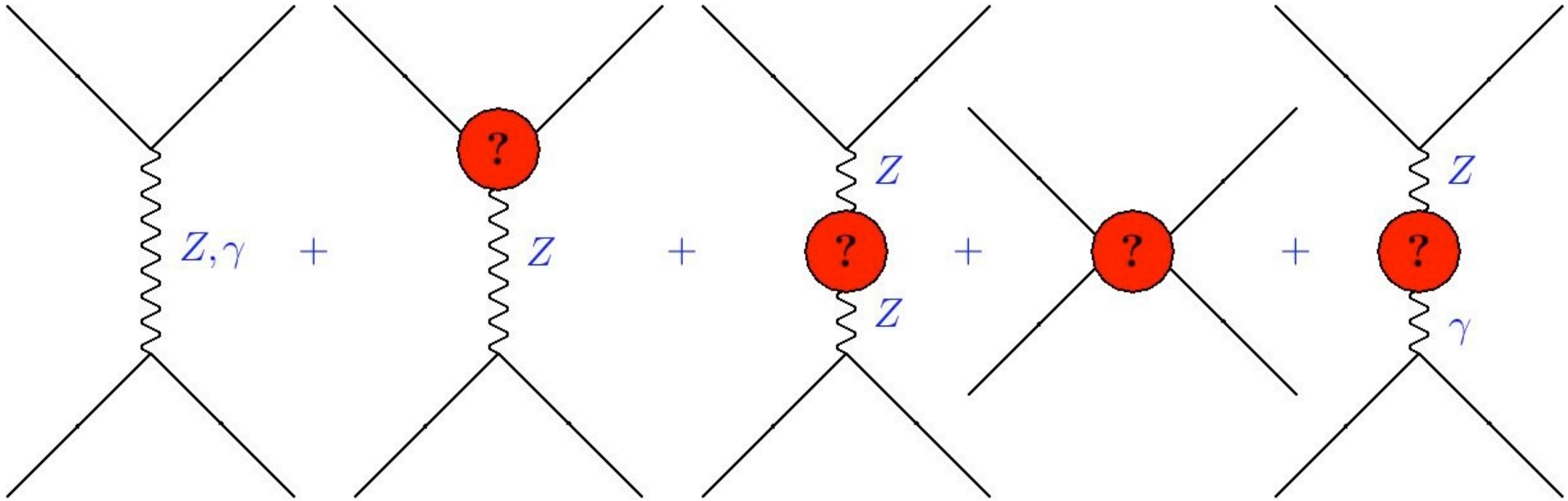
0.228
0.229
0.230
0.231
0.232
0.233
0.234
0.235
A_FB(e)
A_FB(μ)
A_FB(τ)
A_FB(b)
A_FB(c)
A_FB(s)
A_FB(q)
P(τ)
P_FB(τ)
A_LR(had)
A_LR(lep)
A_LR,FB(μ)
A_LR,FB(τ)
CDF (e)
CDF (μ)
D0 (e)
D0 (μ)
ATLAS (e)
ATLAS (μ)
CMS (e)
CMS (μ)
LHCb (μ)
Q_W(e)
Q_W(Cs)
LEP
SLC
Tevatron
LHC
low energy
world average
SM

$\sin^2\theta_W$ within the SM

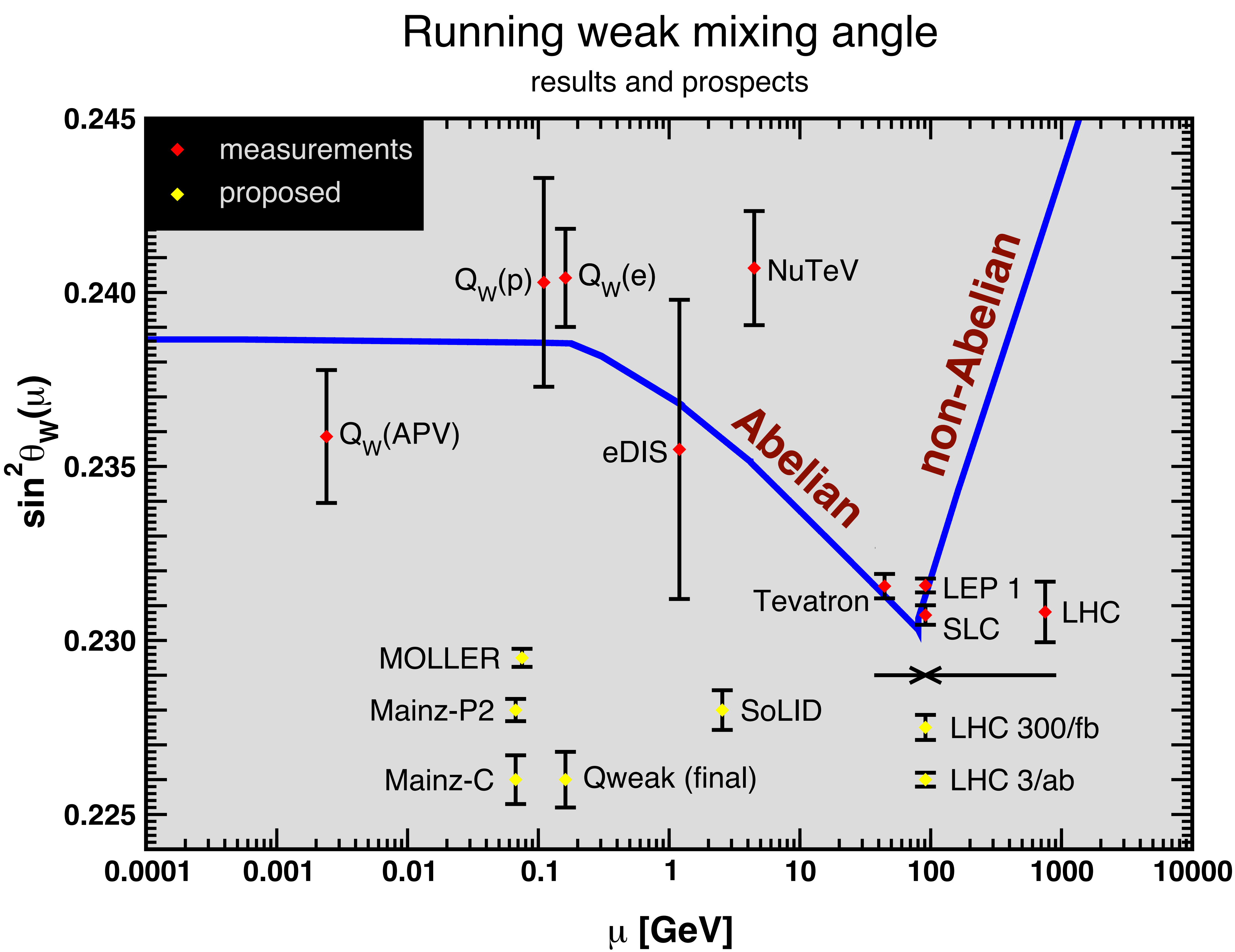
- $\sin^2\theta_W$ & M_W most precise derived quantities in EW sector:
  - Standard Model: key test of EW symmetry breaking
  - Higgs sector: predict M_H and compare with LHC
  - 3 σ conflict: between most precise LEP and SLC results



$\sin^2\theta_W$ beyond the SM

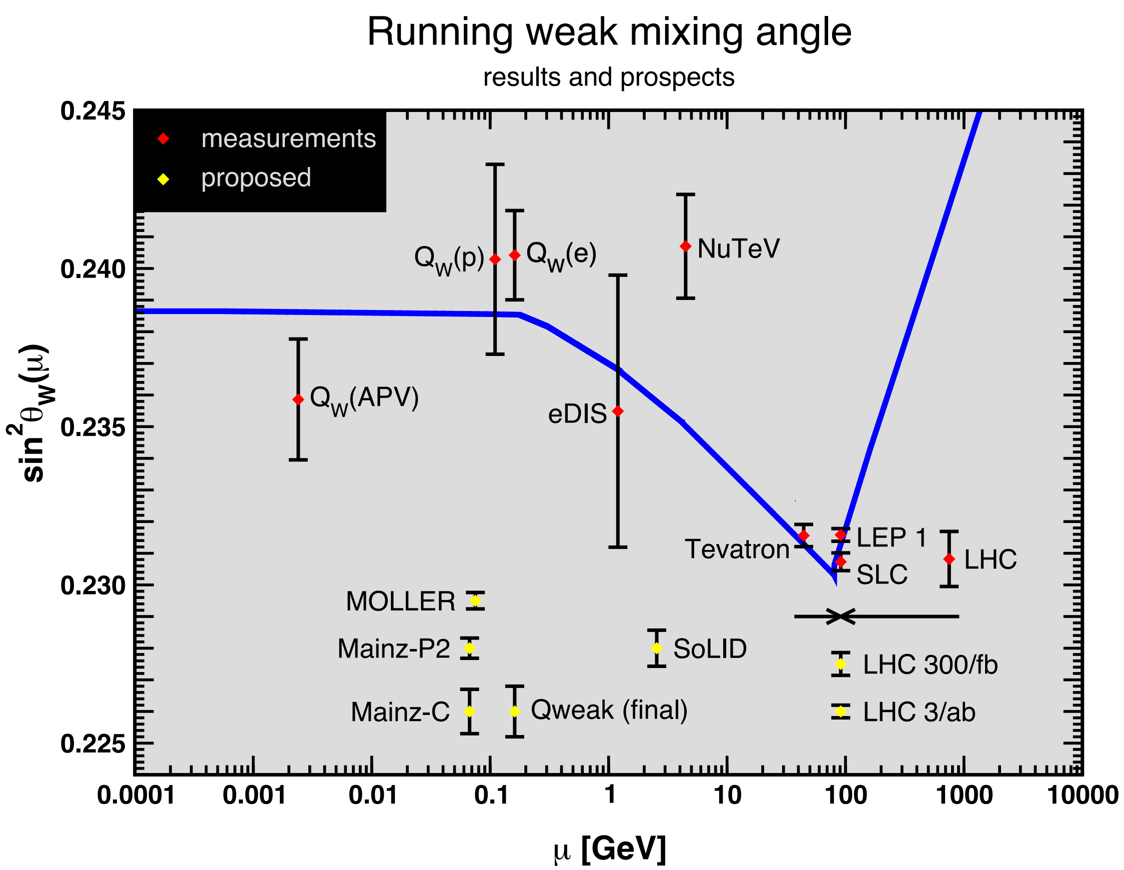


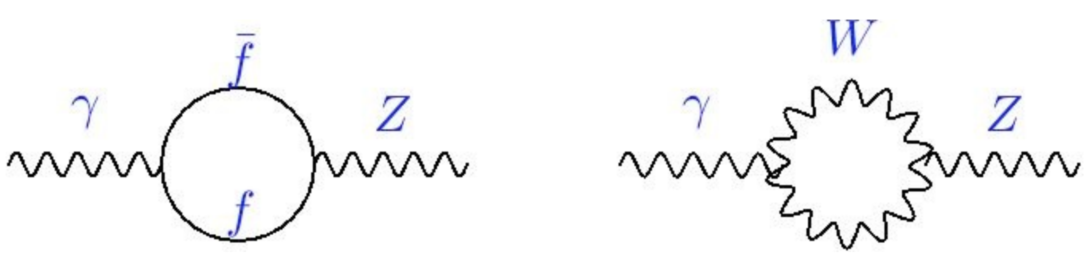
- Z-Z′ mixing: modification of Z vector coupling
- oblique parameters: STU (also need M_W and Γ_Z)
- new amplitudes: off- versus on-Z pole measurements (e.g. Z′)
- dark Z: renormalization group evolution (running)



Running weak mixing angle
results and prospects
measurements
proposed
0.245
0.240
0.235
0.230
0.225
$\sin^2\theta_W(\mu)$
$Q_W(p)$
$Q_W(e)$
NuTeV
$Q_W(APV)$
eDIS
Abelian
non-Abelian
Tevatron
LEP 1
SLC
LHC
MOLLER
Mainz-P2
SoLID
LHC 300/fb
Mainz-C
Qweak (final)
LHC 3/ab
0.0001
0.001
0.01
0.1
1
10
100
1000
10000
μ [GeV]

$\sin^2\bar{\theta}_W(0)$

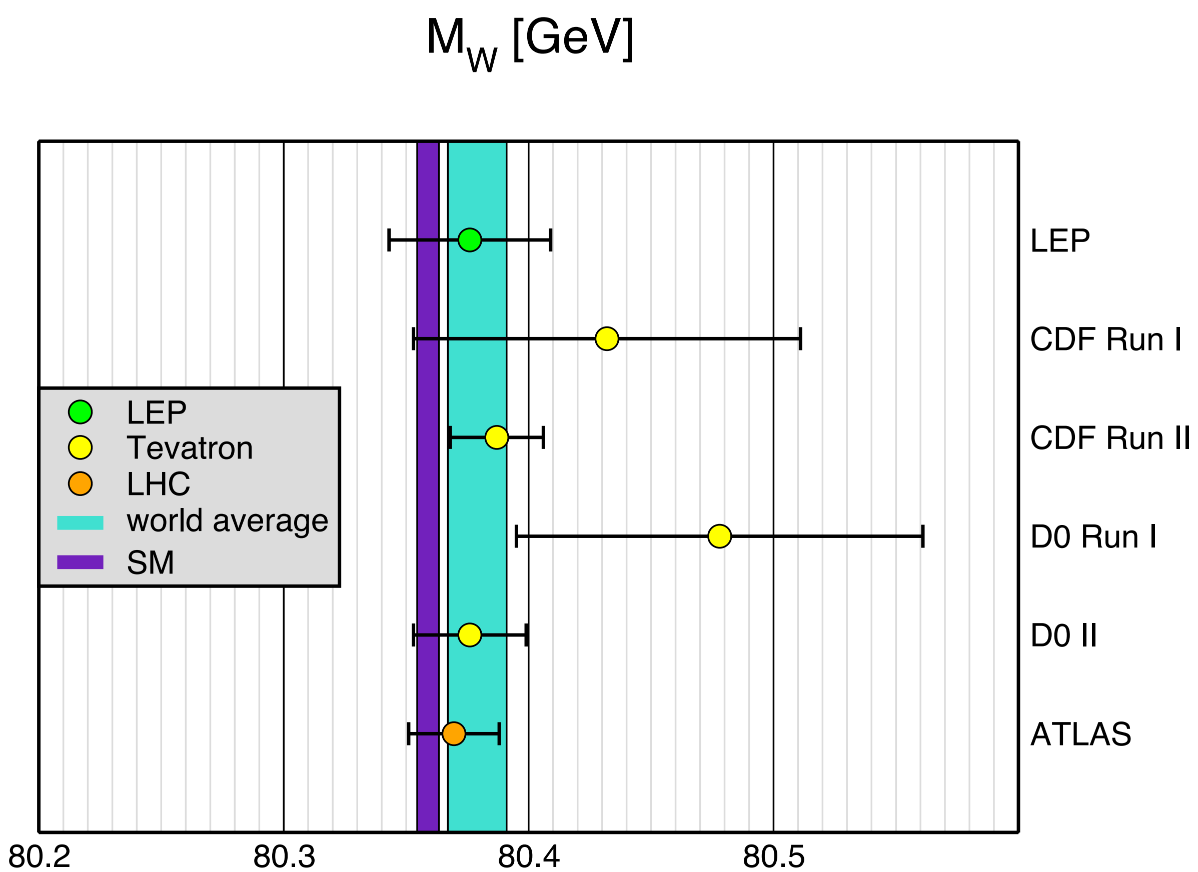




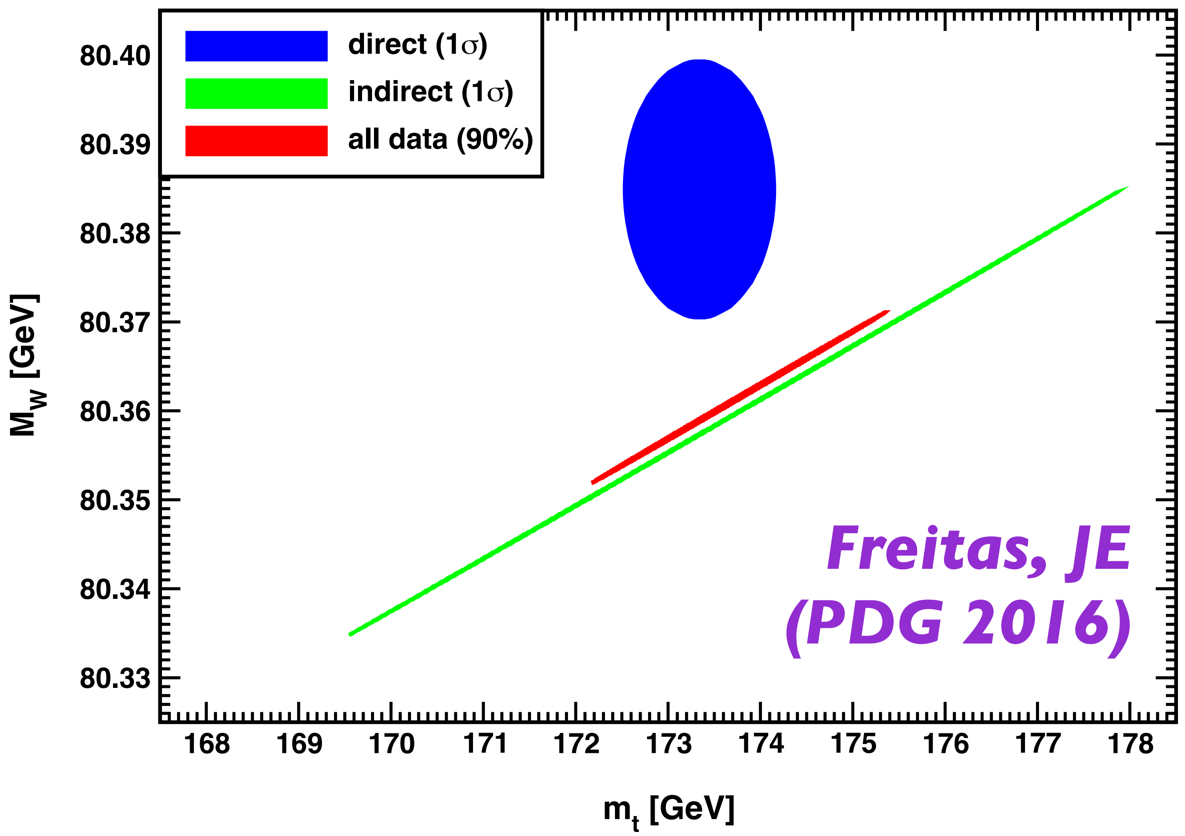
Rodolfo Ferro, JE
(update in preparation)

- use PQCD where possible (m_c and m_b needed)
- where not, relate to dispersion relation result for running α where possible
- flavor separation: construction of upper and lower limits on strange quark contribution
- singlet separation: adaptation of lattice result for $g_\mu-2$

M_W

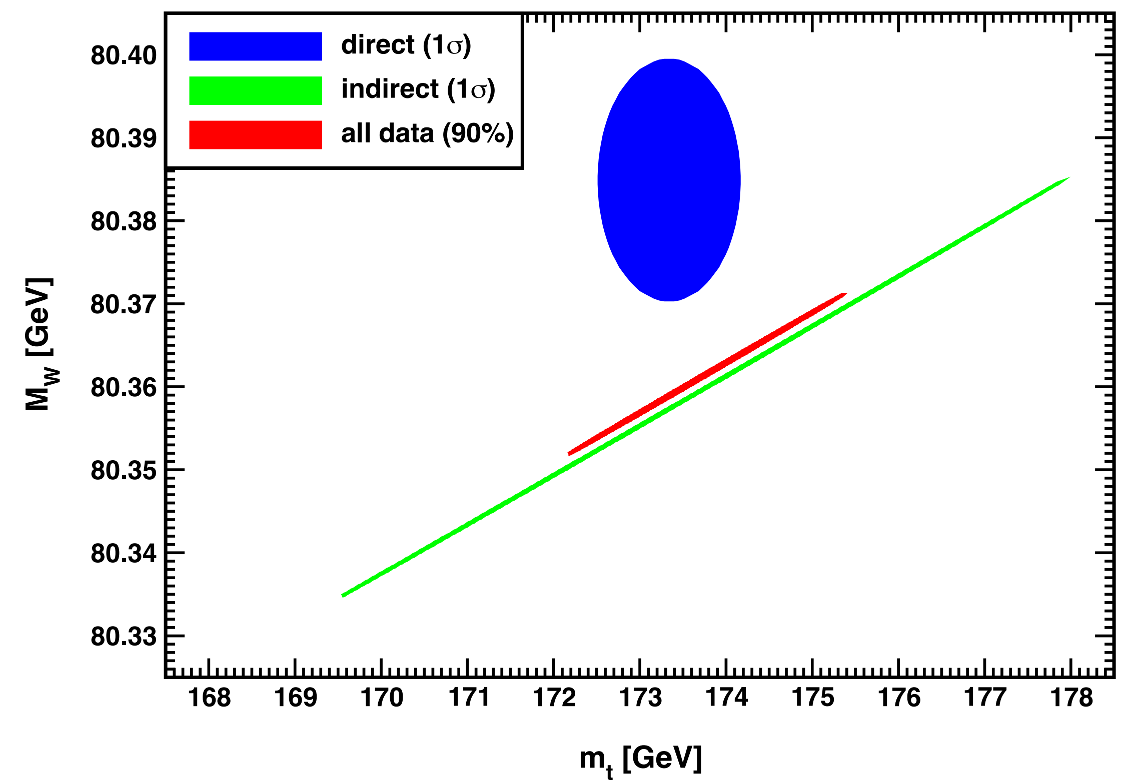


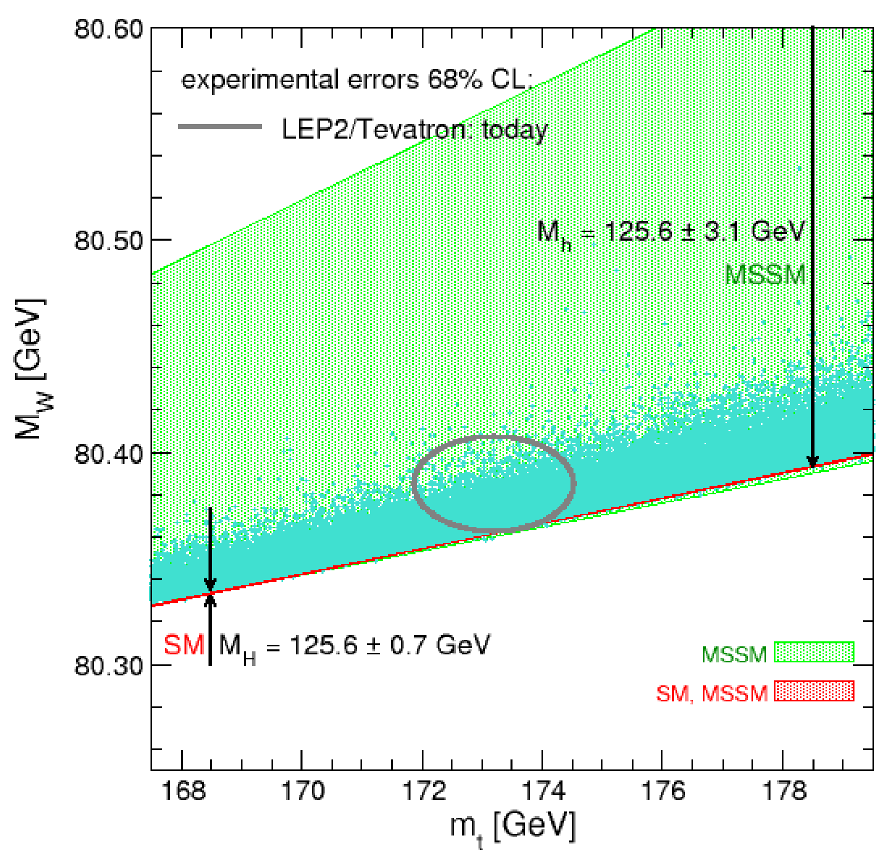
M_W [GeV]
LEP
CDF Run I
CDF Run II
D0 Run I
D0 II
ATLAS
LEP
Tevatron
LHC
world average
SM
80.2
80.3
80.4
80.5

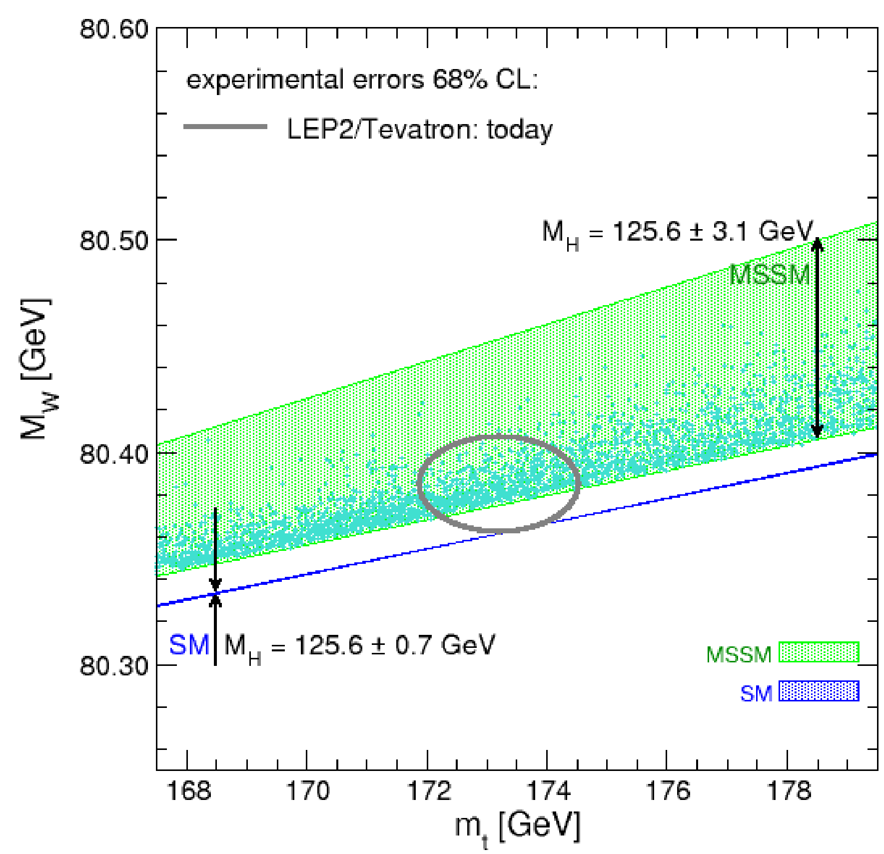


direct (1σ)
indirect (1σ)
all data (90%)
M_W [GeV]
m_t [GeV]
Freitas, JE
(PDG 2016)
80.40
80.39
80.38
80.37
80.36
80.35
80.34
80.33
168
169
170
171
172
173
174
175
176
177
178

M_W in the MSSM



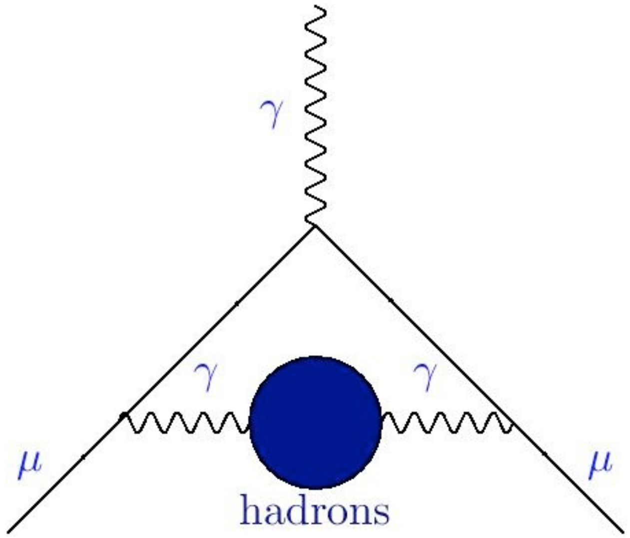




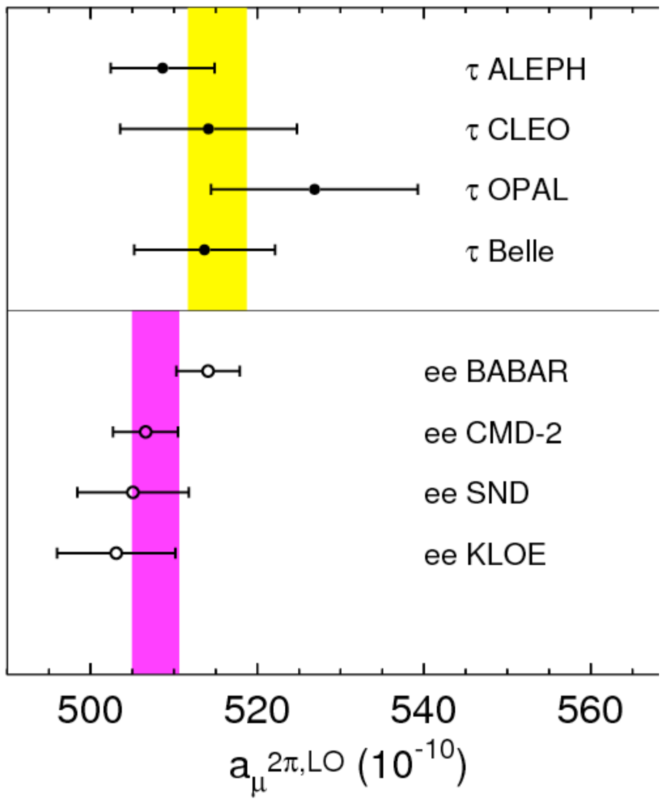
Heinemeyer, Hollik, Weiglein, Zeune 2013

$g_\mu - 2$

- $a_\mu \equiv (1165920.91 \pm 0.63)\times10^{-9}$ ***BNL-E821 2004***
- SM: $a_\mu = (1165917.63 \pm 0.46)\times10^{-9}$ (4.2 σ)
- hadronic vacuum polarization (VP):
  use data + PQCD ***Luo, JE 2002***
  (m_c and m_b needed)



Davier et al. 2011



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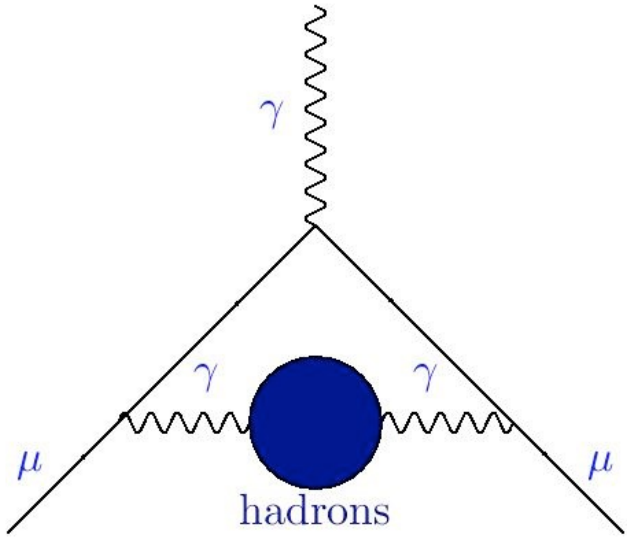
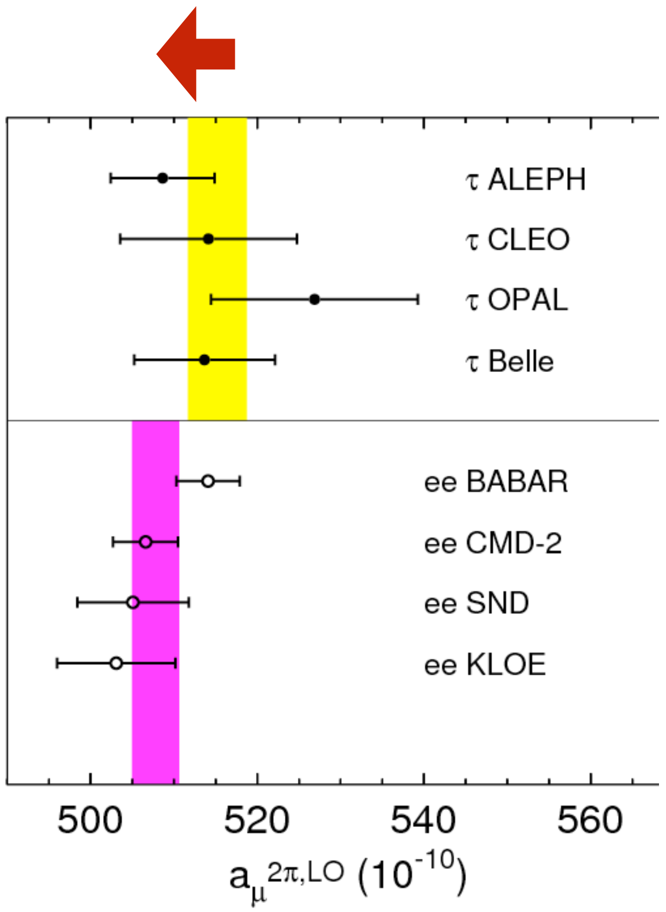
  (m_c and m_b needed)

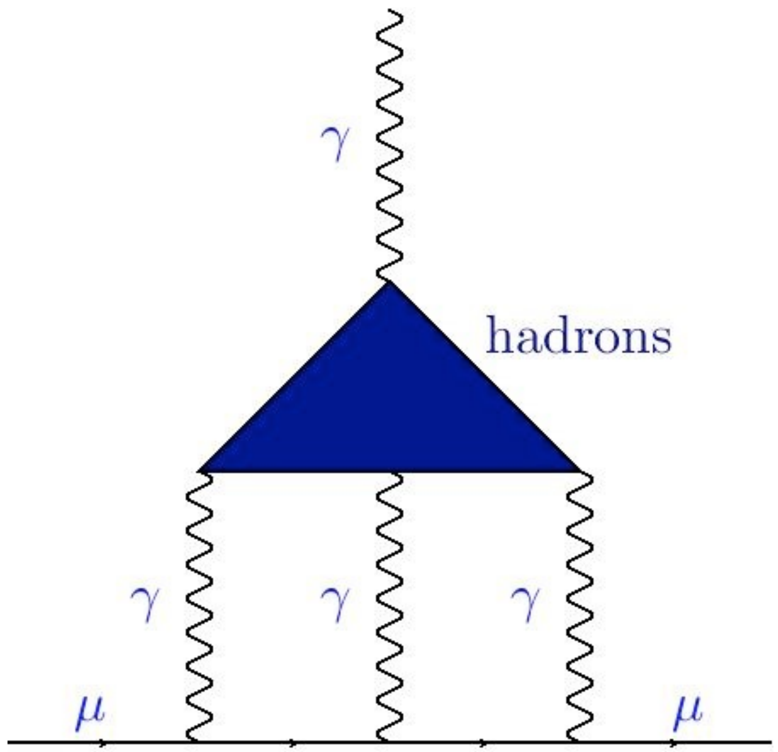
- consistency between experimental
  $B(\tau^- \to \nu\, \pi^0 \pi^-)$ and prediction from
  e^+e^- and CVC after accounting for
  γ-ρ mixing ***Jegerlehner, Szafron 2011***





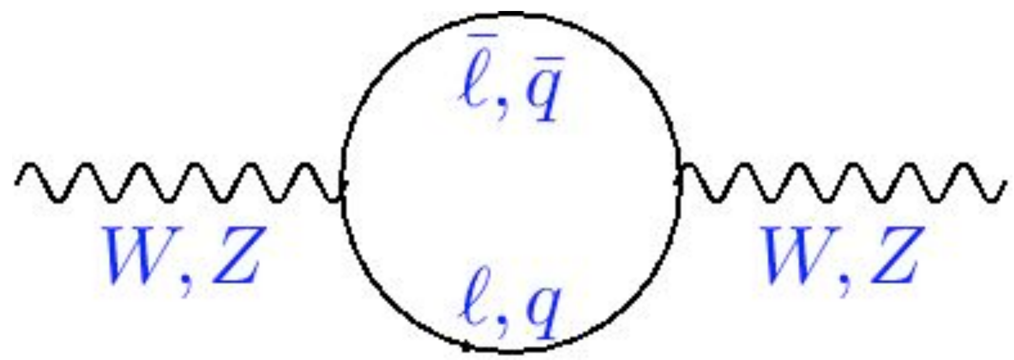
$g_\mu - 2$ theory prospects

- VP in space-like region from Bhabba ***Carloni Calame et al. 2015*** and μe-scattering ***Abbiendi et al. 2016*** using $a_\mu^{had} = \alpha/\pi \int dx\,(1-x)\,\Delta\alpha_{had}[x^2 m_\mu^2/(x-1)]$ ***Lautrup et al. 1972***
- hadronic $\gamma\times\gamma$ error: $\pm 0.32\times 10^{-9}$ (30%)
- lattice:
  - 5% statistical error (systematic error under investigation) ***Blum et al. 2015***
  - only quark-connected diagrams
  - cross-check: calculation of muonic $\gamma\times\gamma$ agrees within 2%
  - VP: also few % errors (~1 year to achieve sub-%?)



New Physics Implications

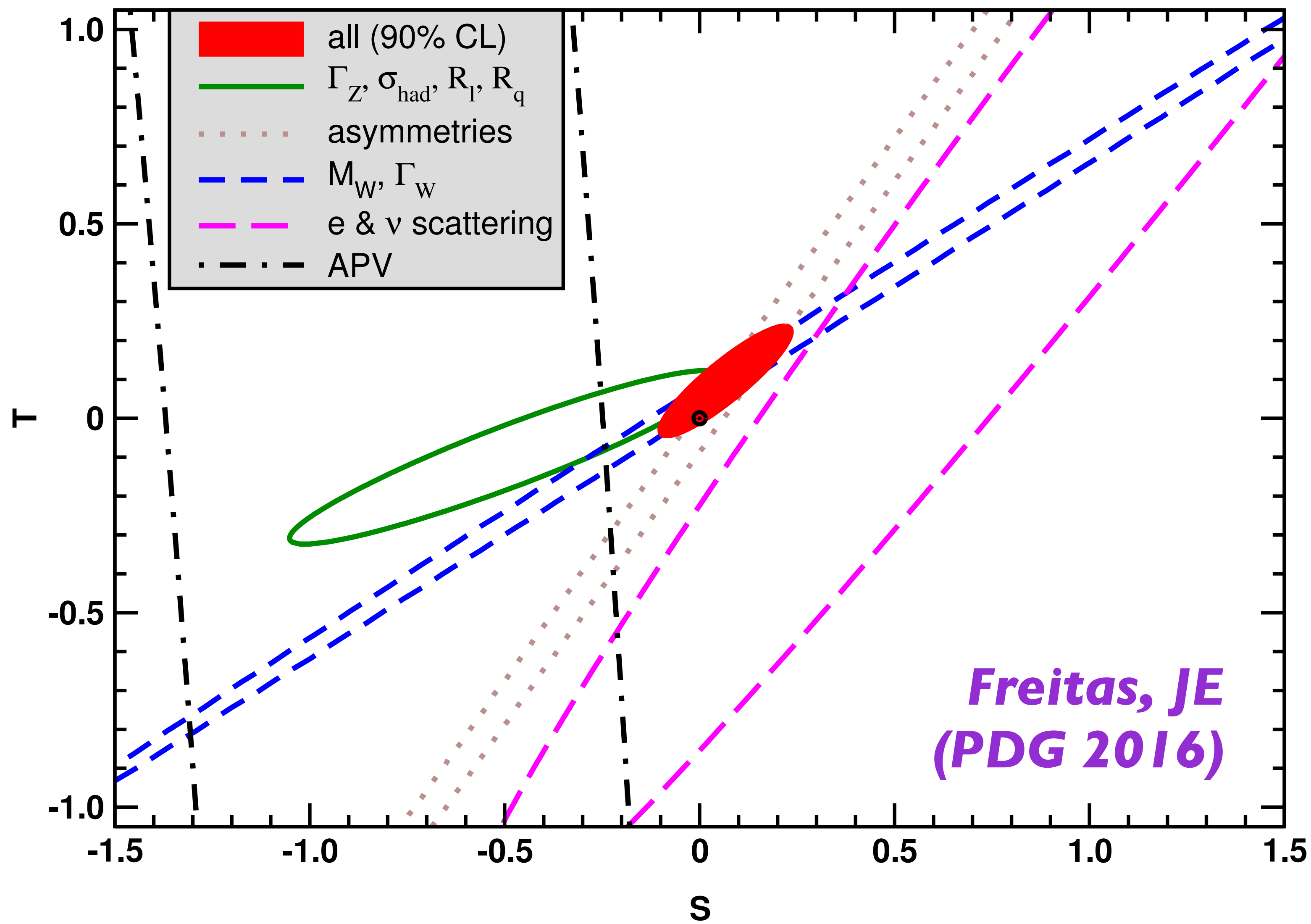
Oblique physics beyond the SM



- STU describe corrections to gauge-boson self-energies
- T breaks custodial SO(4)
- a multiplet of heavy degenerate chiral fermions contributes $\Delta S = N_C / 3\pi \sum_i [t_{3L}{}^i - t_{3R}{}^i]^2$
- extra degenerate fermion family yields $\Delta S = 2/3\pi \approx 0.21$
- S and T (U) correspond to dimension 6 (8) operators

Non-degenerate doublets (T)

- $\Delta\rho_0 = G_F \Sigma_i C_i / (8 \sqrt{2} \pi^2) \Delta m_i^2$
- where $\Delta m_i^2 \geq (m_1 - m_2)^2$
- despite appearance there is decoupling (see-saw type suppression of Δm_i^2)
- summer 2017 update: $\rho_0 = 1.00039 \pm 0.00019$ ($2.0\ \sigma$)
- $(15\ \text{GeV})^2 \leq \Sigma_i C_i /3\ \Delta m_i^2 \leq (47\ \text{GeV})^2$ @ 90%CL
- CEPC can measure T within ± 0.00008



S and T

- ρ_0 (T) constrains VEVs of higher dimensional Higgs representations to ≲ 10 GeV
- S rules out:
  - QCD-like technicolor
  - degenerate 4th generation

	2017 update	CEPC
S	0.06 ± 0.08	± 0.014
T	0.09 ± 0.06	± 0.017
$\Delta\chi^2$	–4.0	?

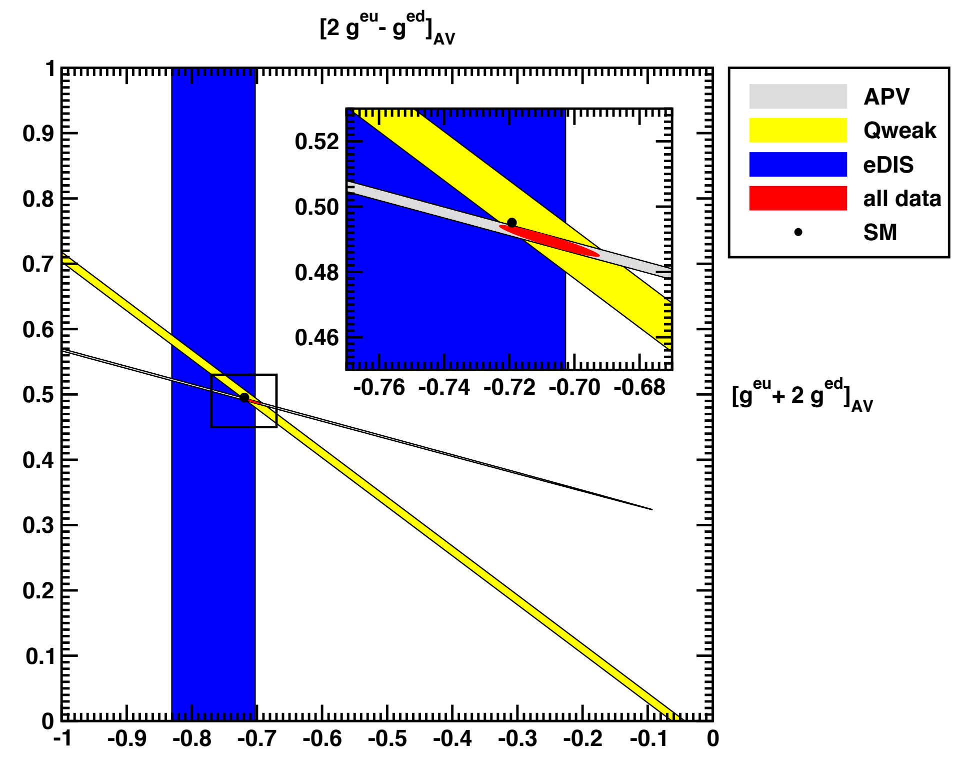
Non-oblique parameters

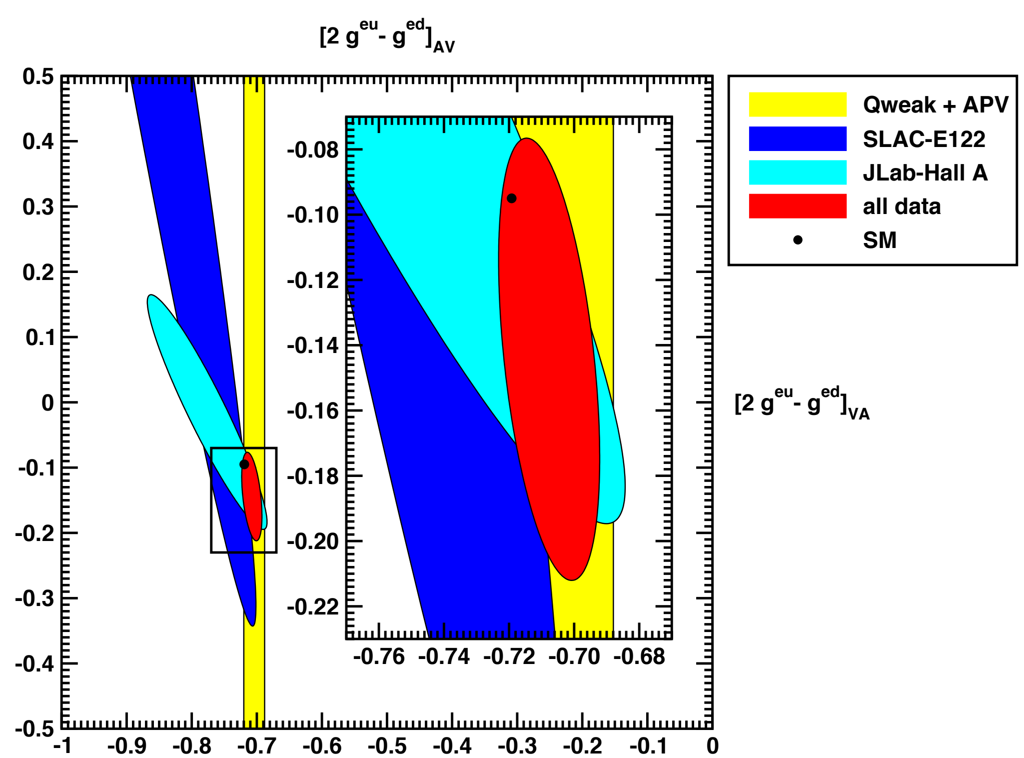
- long-standing deviation in $A_{FB}(b)$ from LEP 1
- currently: $\rho_b = 0.056 \pm 0.020$ $\kappa_b = 0.182 \pm 0.068$ (2.7 σ)

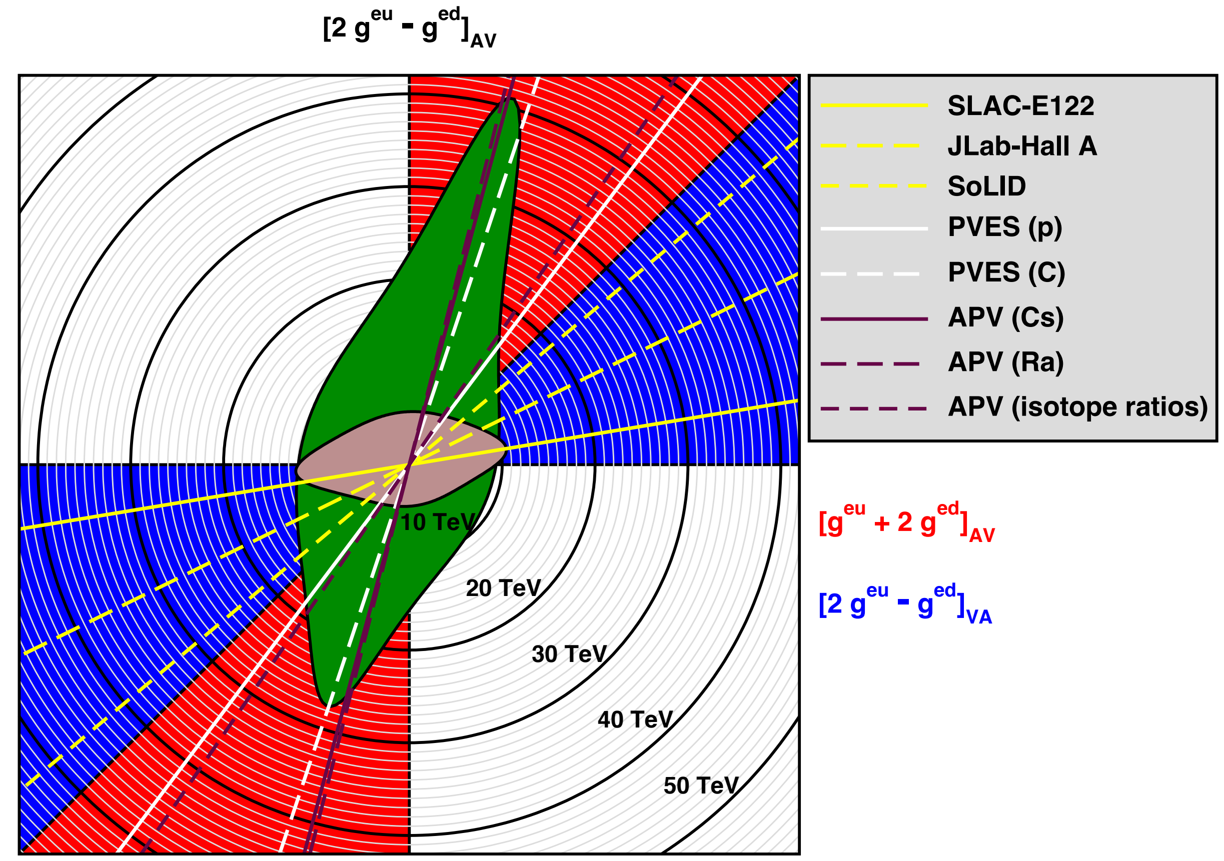
  Freitas, JE (PDG 2016)

  - difficult to explain without affecting / tuning R_b
- CEPC: $\rho_b \rightarrow \pm 0.005$ $\kappa_b \rightarrow \pm 0.007$
- Results virtually independent of STU (fixed or floating)

Compositeness scales from low energies







Conclusions

- SM almost 50 but in remarkable health!
- SM over-constrained: derived quantities like M_W, $\sin^2\theta_W$, $g_\mu - 2$ and weak charges computed and measured
- Precision in $\sin^2\theta_W$ (A_{FB}) & M_W and future $Q_W(e)$ & $Q_W(p)$ measurements challenge theory → needs major global effort
- indirect M_H: 1.9 σ below direct
- ρ-parameter: 2.0 σ high in SM + ρ fit (S = U = 0)
- Contact interactions: compare $\sin^2\theta_W$ at low Q^2 with Z-pole and test Λ_{new} up to $\mathcal{O}$(50 TeV) in the case of strong coupling

Backup

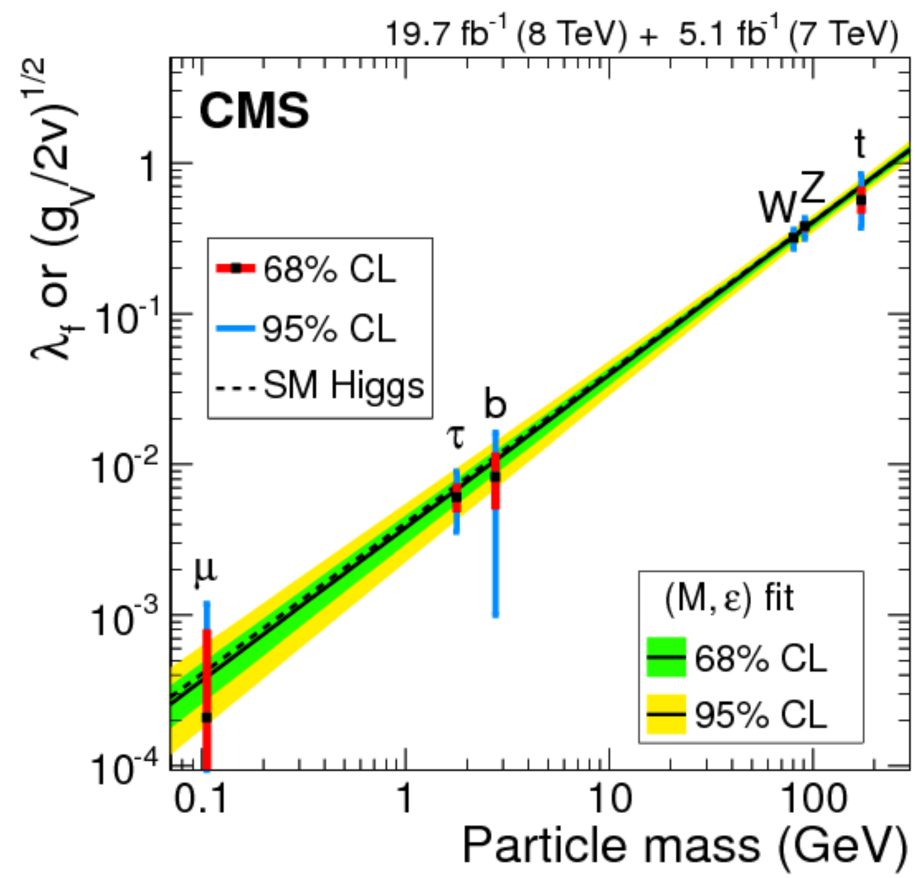
Lab	experiment	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new}
	APV ^{133}Cs	0.58 %	0.0019	32.3 TeV
SLAC	E158	14 %	0.0013	17.0 TeV
Jefferson Lab	Qweak I	19 %	0.0030	17.0 TeV
Jefferson Lab	PVDIS	4.5 %	0.0051	7.6 TeV
Jefferson Lab	Qweak final	4.5 %	0.0008	33 TeV
Jefferson Lab	SoLID	0.6 %	0.00057	22 TeV
Jefferson Lab	MOLLER	2.3 %	0.00026	39 TeV
JGU	P2	1.7 %	0.00032	52 TeV
JGU	PVES ^{12}C	0.3 %	0.0007	49 TeV
university of groningen	APV ^{225}Ra	0.5 %	0.0018	34 TeV
university of groningen	APV ^{213}Ra/^{225}Ra	0.1 %	0.0037	16 TeV
Belle II	Belle II	0.14 %	—	33 TeV
CERN	CEPC / FCC	?	?	?

Charm and bottom quark masses

- $g_\mu - 2$: c quark and γ×γ effects comparable; ± 70 MeV in m_c would induce an error of $\pm 1.6 \times 10^{-10}$ — comparable to projections for FNAL & J-PARC

- $\alpha(M_Z)$ & $\sin^2\theta_W(0)$: PQCD for heavy quark contributions if masses known

- Yukawa coupling – mass relation: $\Delta m_b = \pm 9$ MeV & $\Delta m_c = \pm 8$ MeV to match future precision in HiggsBRs (FCC-ee & CEPC)



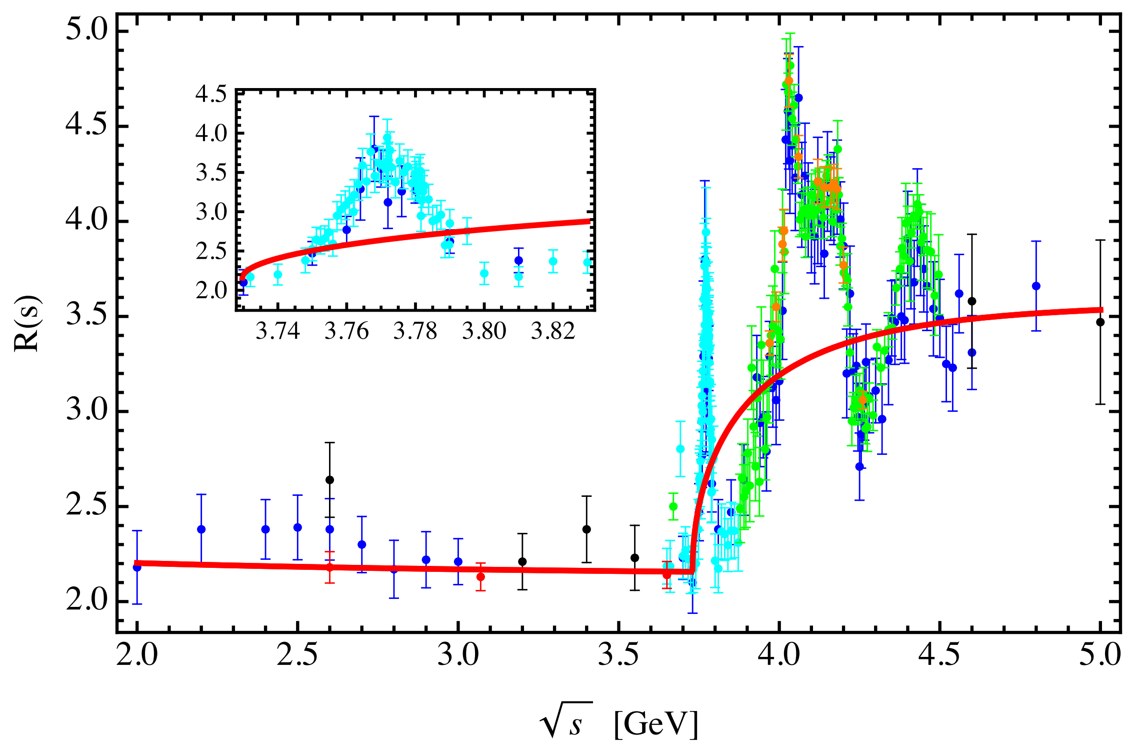
Relativistic sum rule formalism

$$12\pi^2 \frac{\hat{\Pi}_q(0) - \hat{\Pi}_q(-t)}{t} = \int_{4\hat{m}_q^2}^{\infty} \frac{\mathrm{d}s}{s} \frac{R_q(s)}{s+t}$$

- QCD sum rule of moments of vector current correlator Π_q
- pQCD to $\mathcal{O}(\alpha_S^3)$ ***Chetyrkin, Kühn, Sturm 2006; Boughezal, Czakon, Schutzmeier 2006; Kniehl, Kotikov 2006; Maier, Maierhofer, Marquard 2008; Maier, Maierhofer, Marquard, Smirnov 2010***
- $t \to 0 \Rightarrow$ 1st moment sum rule $\mathcal{M}_1$
- differentiating $\Rightarrow$ higher moments $\mathcal{M}_n$ ***Novikov et al. 1978***
- $t \to \infty \Rightarrow$ 0th moment sum rule $\mathcal{M}_0$ ***JE, Luo 2003***
- regularization: subtract $R_c(s) = 4/3\ \lambda_1(s)$ at $m_c = 0$

Features of our approach

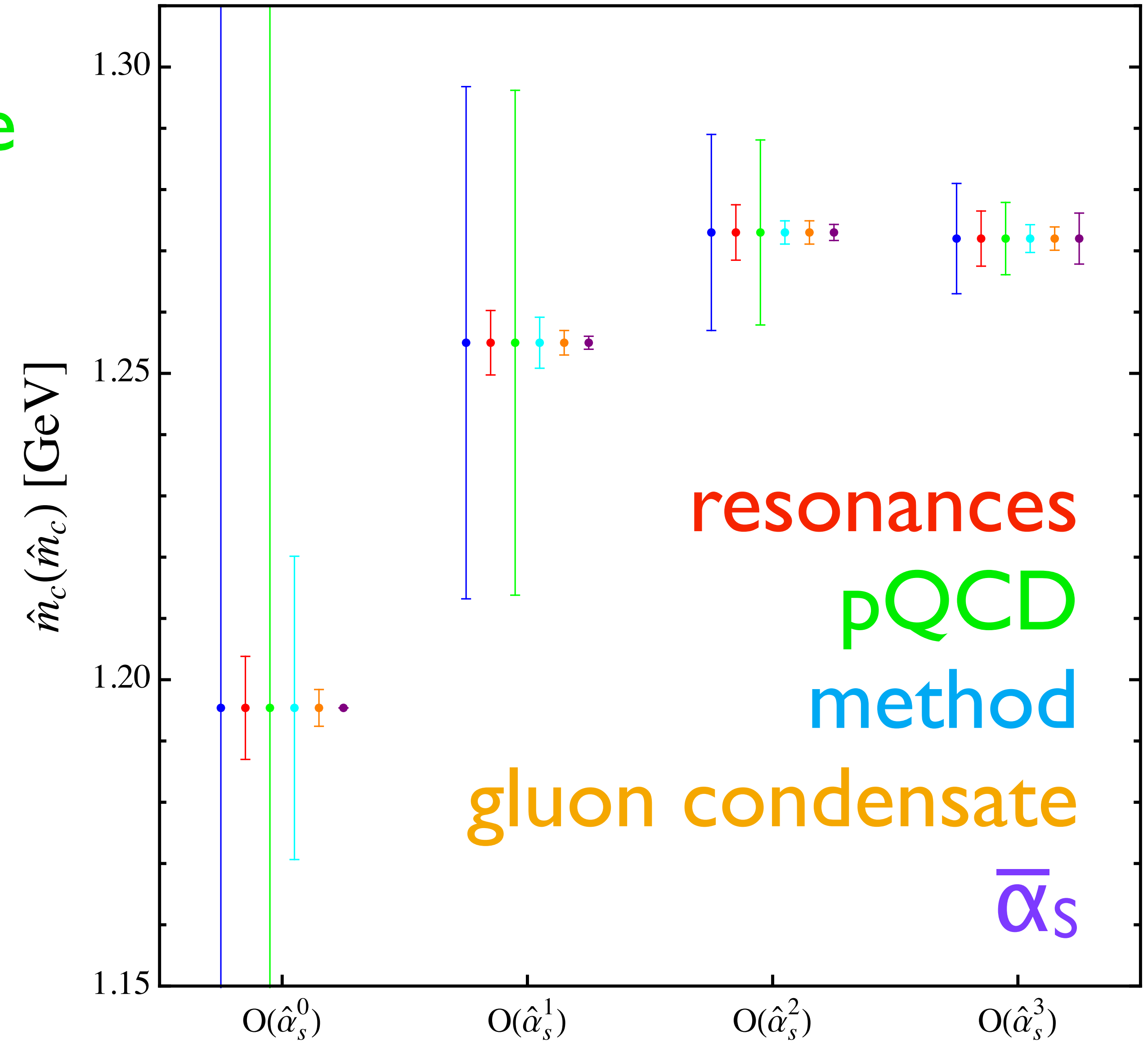
- only experimental input: electronic widths of J/ψ and ψ(2S)
- continuum contribution from self-consistency between sum rules
- include $\mathscr{M}_0$ → stronger (milder) sensitivity to continuum (m_c)
- quark-hadron duality needed only in finite region (not locally)



$$\bar{m}_c(\bar{m}_c) = 1272 \pm 8 + 2616\,[\bar{\alpha}_s(M_Z) - 0.1182]\ \text{MeV}$$

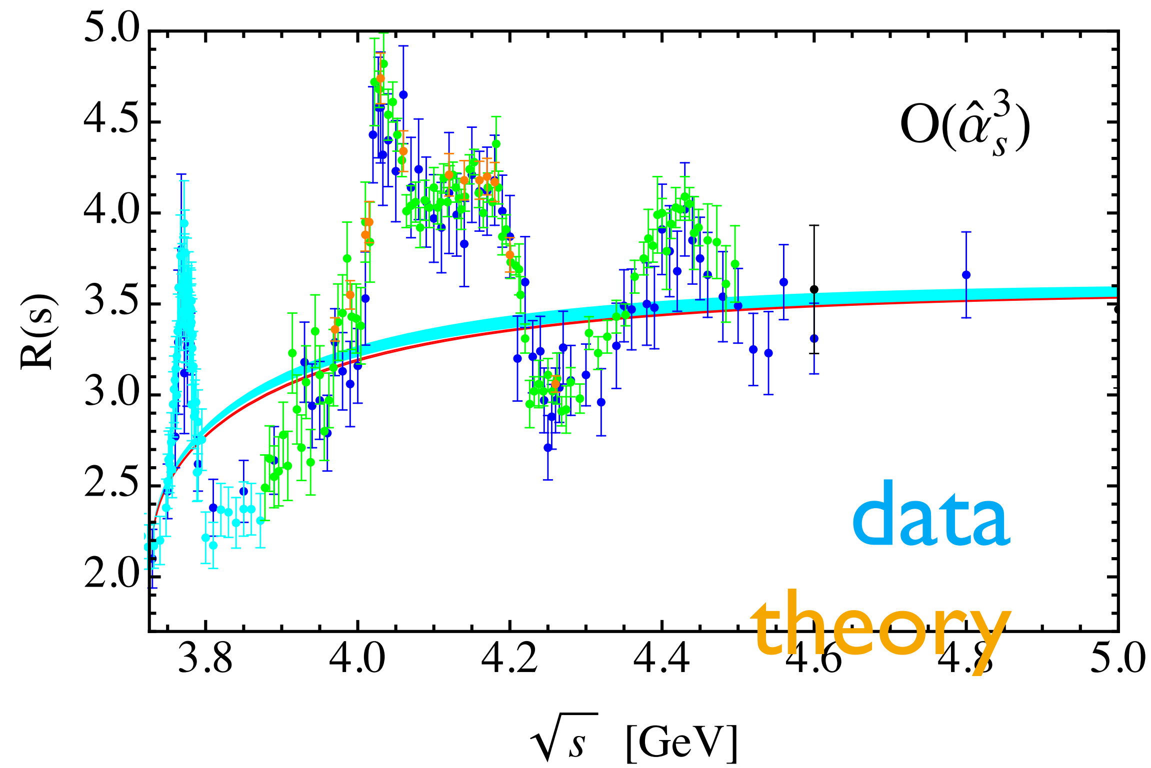
Error calibration

- experimental input error
- truncation error (we use more conservative estimate than taking last computed term)
- we use $e^+ e^- \to$ hadron data to control method (higher order in OPE & quark-hadron duality violations)
- parametric uncertainty (100%)
- $\overline{\alpha}_S(M_Z) = 0.1182 \pm 0.0016$



Continuum

- $R_c^{cont} = 4/3\ \lambda_1(s)\ [\ 1 - 4\ \overline{m}^2(2M_D)/s'\ ]^{1/2}\ [\ 1 + 2\ \lambda_3\ \overline{m}^2(2M_D)/s'\ ]$
- $s' \equiv s + 4\ [\ \overline{m}^2(2M) - M^2\ ]$
- λ_1 known asymptotic behaviour
- λ_3 free parameter (expect ≈ 1)
- $\mathcal{M}_0$ & $\mathcal{M}_2 \Longrightarrow \lambda_3 = 1.23(6)$



- removing background from light quarks and singlet contributions from ***Crystal Ball***, ***BES*** & ***CLEO*** data $\Longrightarrow \lambda_3 = 1.34(17)$
- fit normalization of sub-continuum data to pQCD $\Longrightarrow \lambda_3 = 1.15(16)$

Recent m_c determinations