Electroweak Physics

Jens Erler
IF-UNAM

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Outline

- Z boson: lineshape, decays, and the weak mixing angle
- W boson: mass, width, and branching ratios
- Top quark: mass uncertainty and impact on precision tests
- Charm and bottom quarks: mass uncertainties and impact
- Oblique parameters: current and future (FCC-ee as example)
- Contact interactions: low-energy measurements

Introduction

Most searches for Physics Beyond the Standard Model fall into one of three categories:

New phenomena: use shape and rates to distinguish from hopefully small background

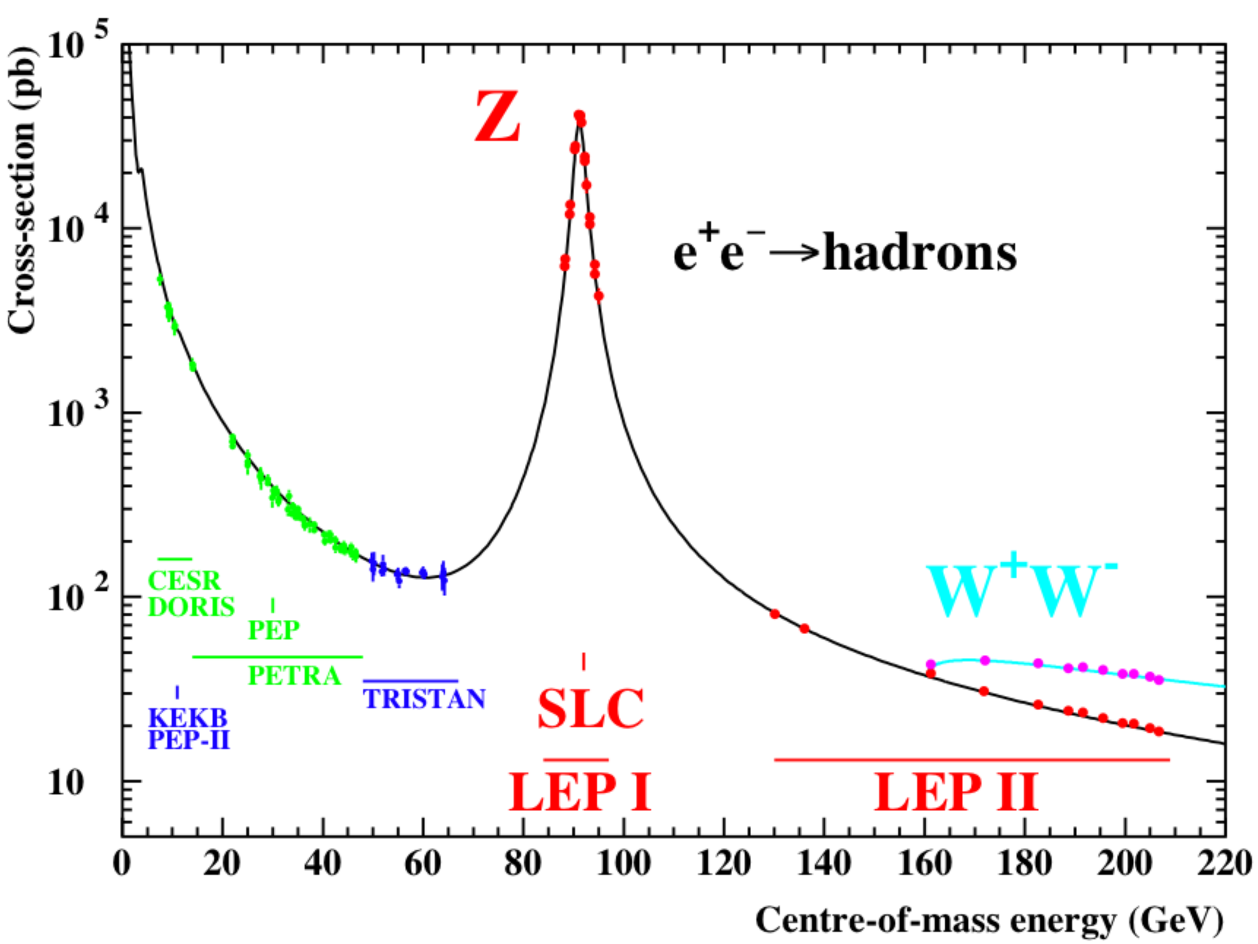
Rare or forbidden processes: few or even one event enough; vanishing or very small (reducible) background

Precision tests (this talk): small or tiny signal over SM "background" (irreducible but calculable); only insightful in greater context; need to know accuracy accurately

Electroweak fit

- input: need 4 input variables for EW sector of the SM: $SU(2)_L \times U(1)_Y$ gauge couplings and Higgs potential parameters.
- fine structure constant: α known to 6.6×10^{-10} from Rydberg constant (leaves g_e-2 as new physics constraint)
- Fermi constant: G_F known to 5.1×10^{-7} from muon lifetime
- Higgs mass: M_H^2 known to 3.8×10^{-3} from kinematic reconstruction, but enters only in loops (except total width)
- Z mass: M_Z^2 known to 4.6×10^{-5} from Z-lineshape
  ➡ induces largest input uncertainty

Z lineshape



- lineshape: cross section scans at circular lepton colliders (energy calibration through resonant spin depolarization)
- peak location = M_Z ➡ no longer negligible in $\sin^2\theta_W = 1 - M_W^2/M_Z^2$ if M_W improves
- height = peak cross section: for hadrons most precise and least correlated ➡ α_s
- ½ width @ ½ maximum = Γ_Z ➡ N_ν

Number of active neutrinos

currently:

$N_\nu = 2.992 \pm 0.007$

need to fix $\alpha_s = 0.1129$ to find $N_\nu = 3$, but this is a bad fit.

FCC-ee @ 91 GeV:
N_ν can be constrained to within $\pm$ 0.0006

FCC-ee @ 161 GeV:
the $Z\gamma$ final state would provide an additional constraint on N_ν of better than $\pm$ 0.0015

α_s

source	α_s	uncertainty	FCC
Z decays	0.1203	0.0028	0.00012
W decays	0.117	0.043	0.00018
τ decays	0.1174	$^{+0.0019}_{-0.0017}$	
deep inelastic	0.1156	0.0023	0.00018
jet-event shapes in	0.1169	0.0034	< 0.001
lattice	0.1187	0.0012	
world average	0.1181	0.0013	0.00009

needed for top threshold scan
& precision gauge coupling unification

Bethke, Dissertori, Salam 2015
JE, Freitas 2015
PDG 2016

W boson

- W width (direct and hadronic branching ratio): 1st + 2nd row CKM unitarity test and α_s determination
- leptonic W branching ratios: lepton universality tests
- W pair production: four-fermion operators (can use ZH threshold)
- W mass (kinematic reconstruction and W threshold scan): Currently most important SM test: $M_W = 80.385 \pm 0.015$ GeV from Tevatron & LEP 2 (combined with M_Z) ➡ $\sin^2\theta_W^{OS} \equiv 1 - M_W^2/M_Z^2 = 0.22290 \pm 0.00029$ and $M_H = 83^{+26}_{-22}$ GeV. M_W is easily affected by new physics in general and Higgs sector modification in particular, but needs m_t.

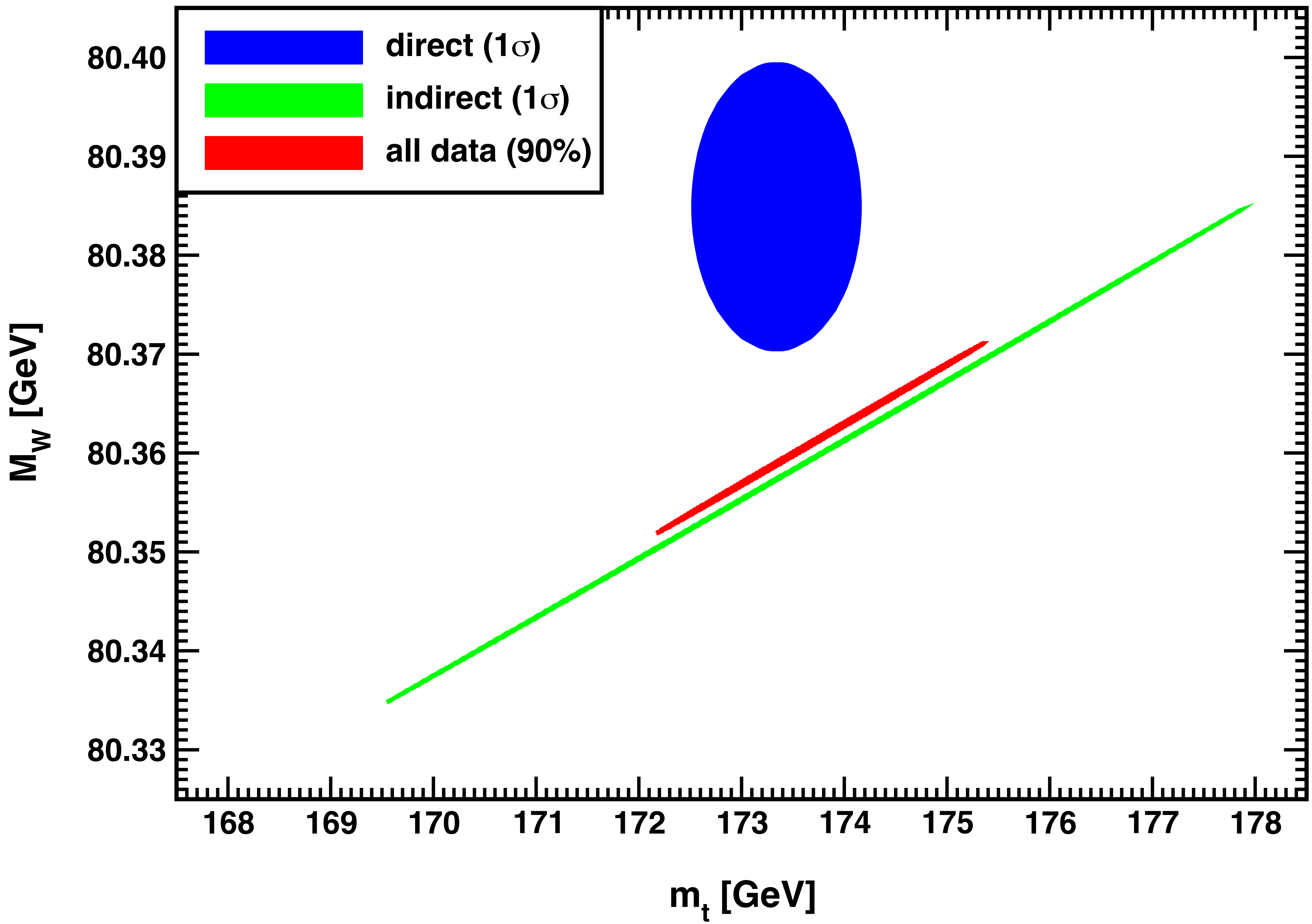
Top quark

- currently:
  $m_t = 173.34 \pm 0.64_{\text{exp.}} \pm 0.50_{\text{QCD}}$ GeV

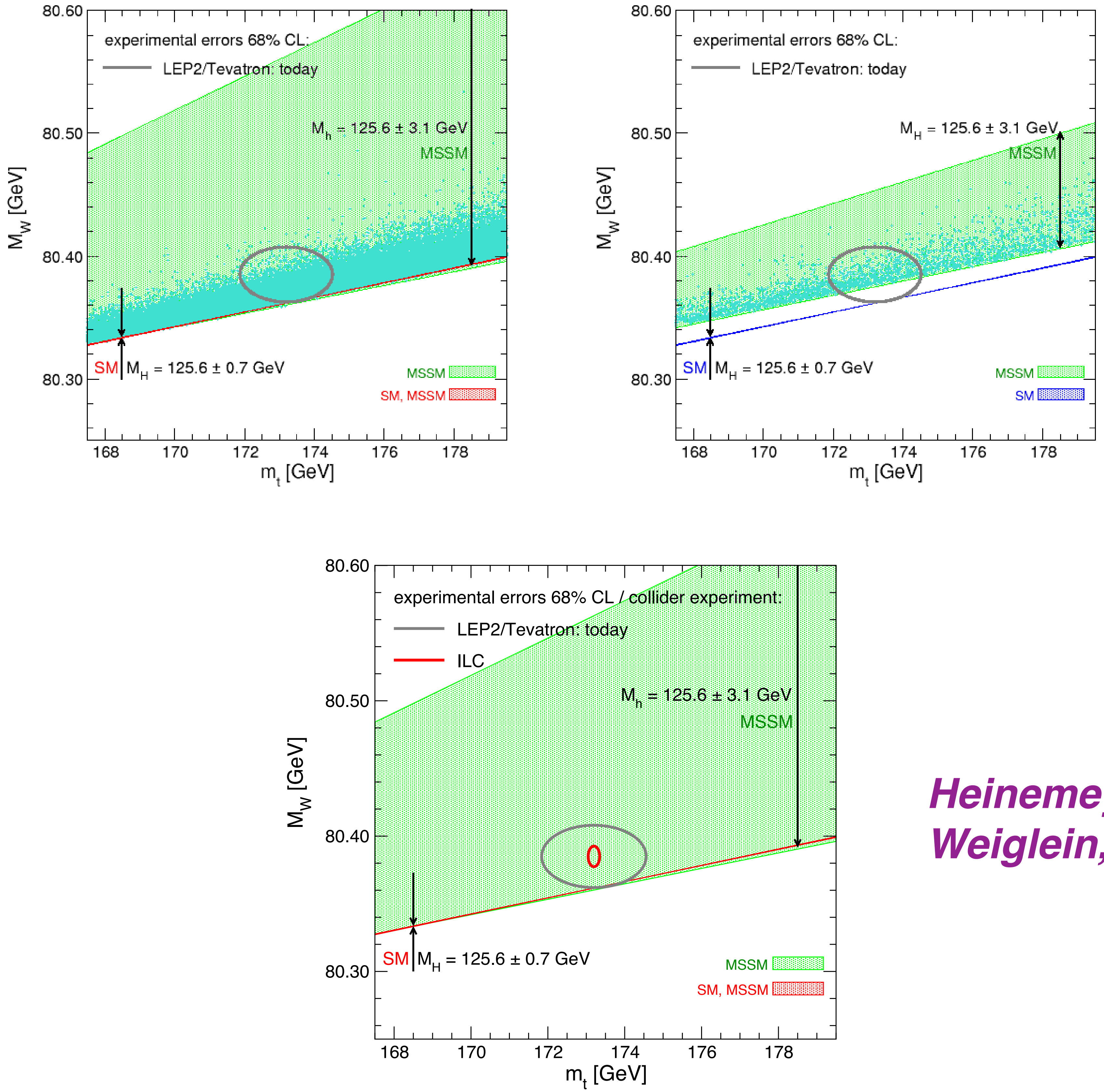
- experimentally:
  2.6 σ discrepancy between the two most precise measurements (the D0 and CMS lepton + jets channels)

- QCD uncertainty:
  from hadron collider extraction

- theoretically cleaner alternatives:
  $t\bar{t}$ production cross section
  $t\bar{t}$ threshold scan at a future lepton collider

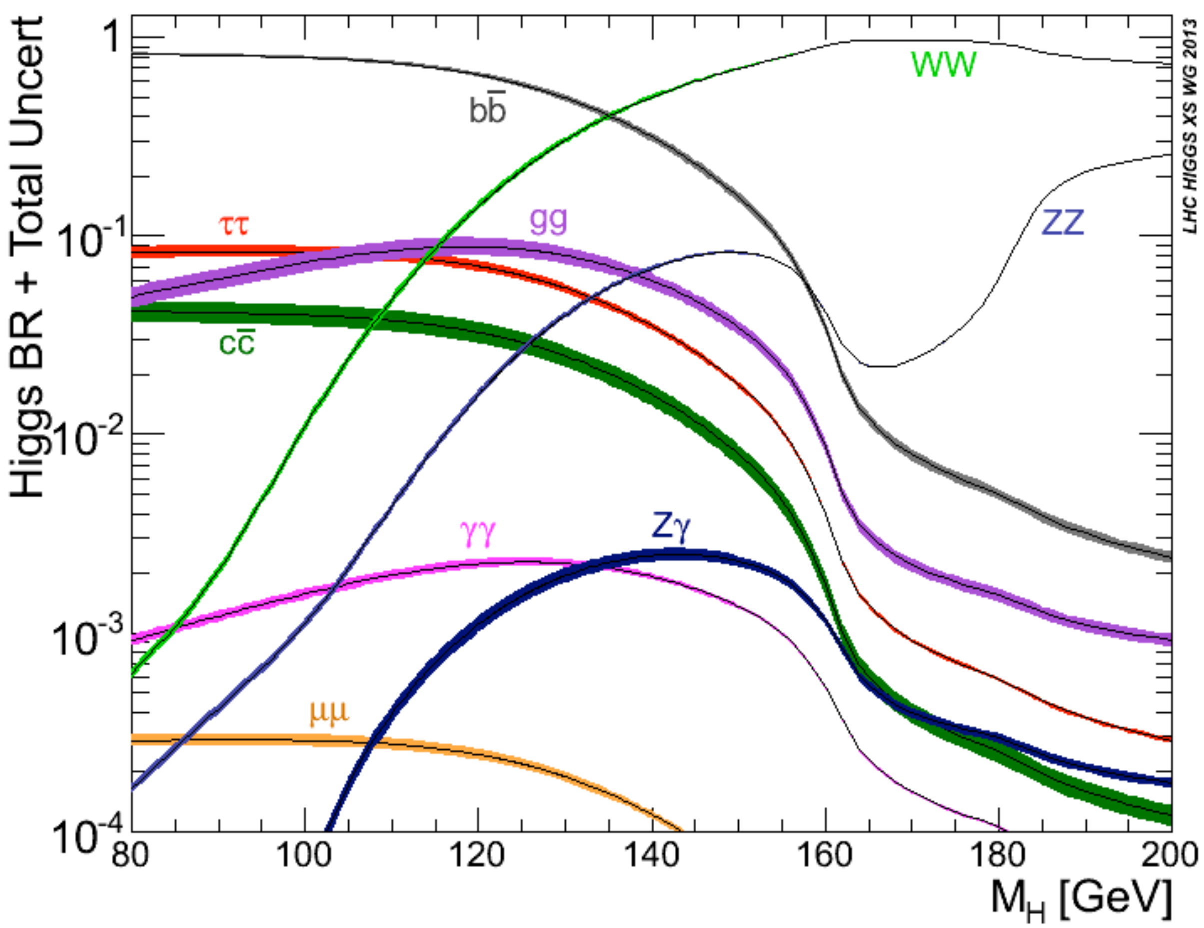


direct (1σ)
indirect (1σ)
all data (90%)
80.40
80.39
80.38
80.37
80.36
80.35
80.34
80.33
M_W [GeV]
168
169
170
171
172
173
174
175
176
177
178
m_t [GeV]



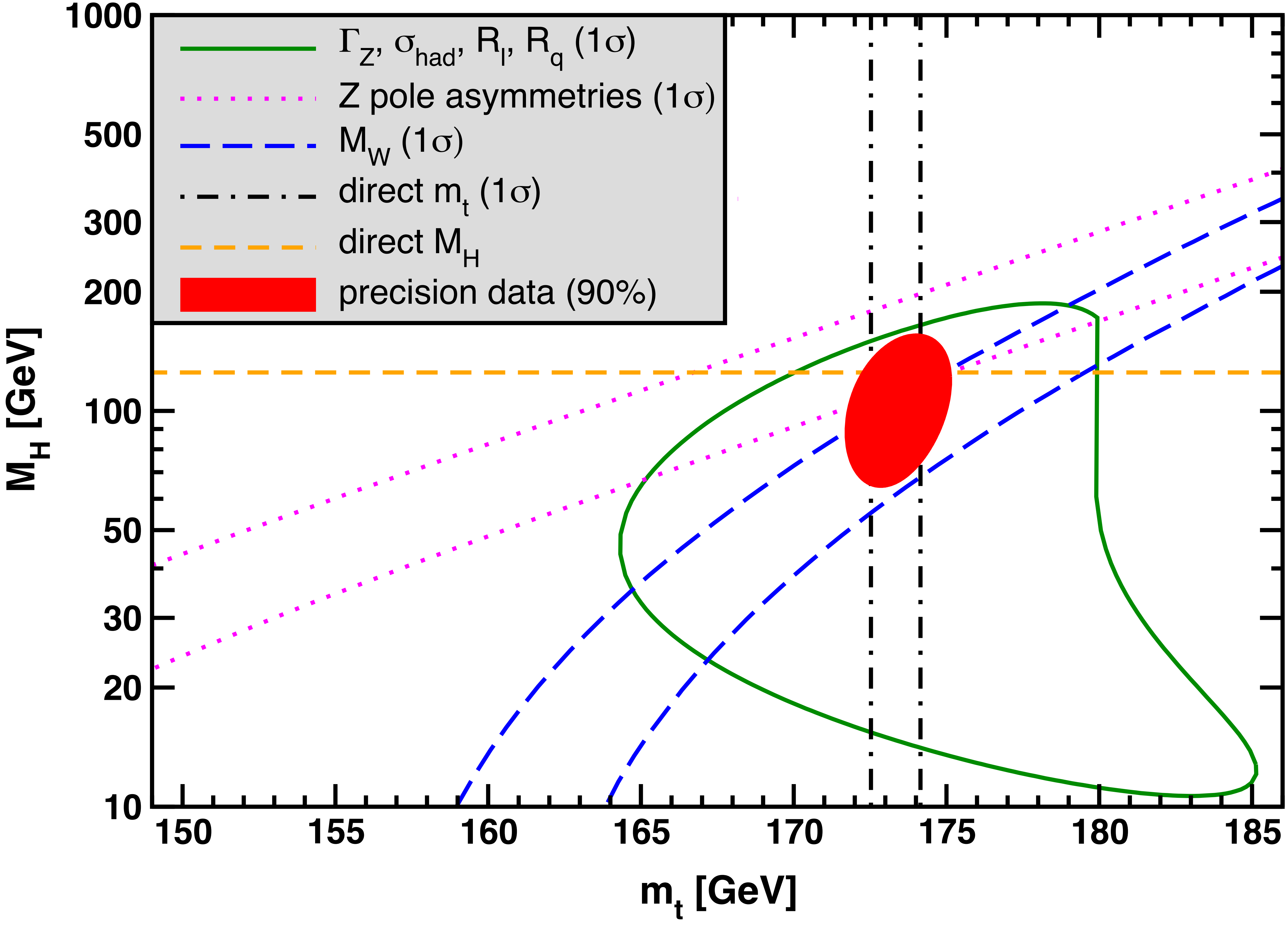
Heinemeyer, Hollik, Weiglein, Zeune 2013

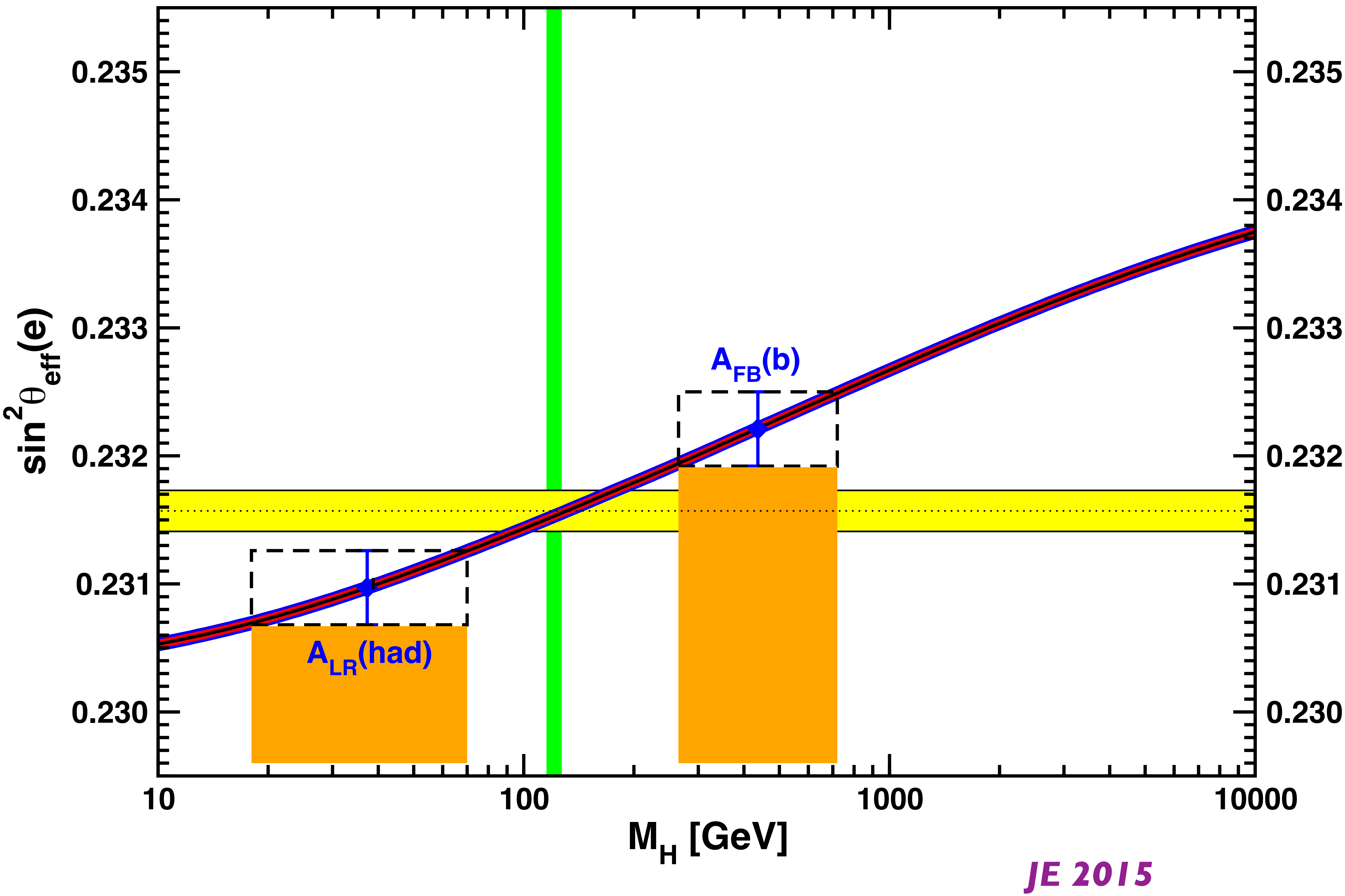
M_H



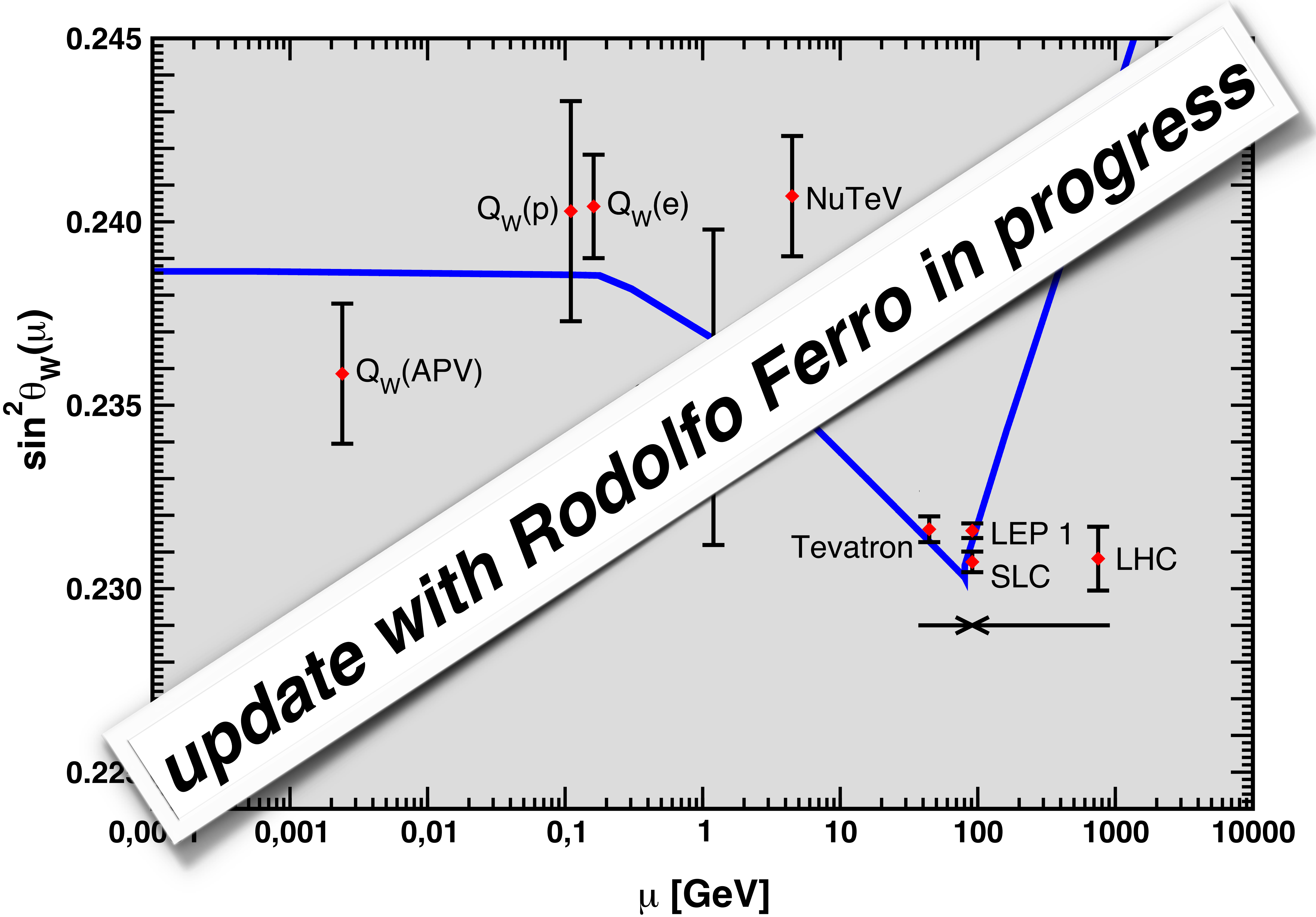
JE, Freitas 2015 (PDG 2016)

source	M_H	ΔM_H	FCC-ee
EW fit	96	$^{+22}_{-19}$	1.3
Higgs BRs	126.1	1.9	
direct	125.09	0.24	0.007
global fit	125.11	0.24	0.007

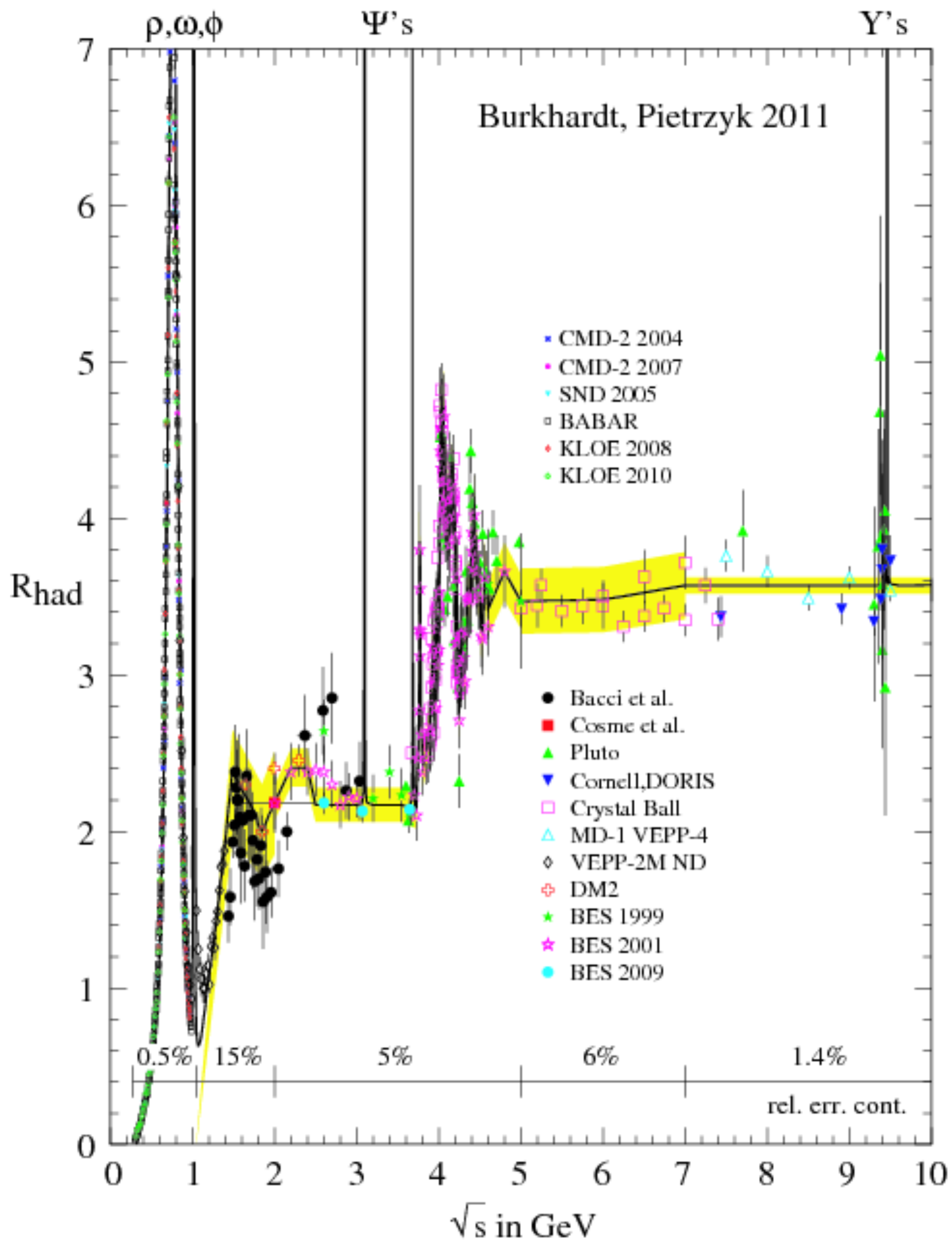

Γ_Z, σ_{had}, R_l, R_q (1σ)
Z pole asymmetries (1σ)
M_W (1σ)
direct m_t (1σ)
direct M_H
precision data (90%)
1000
500
300
200
100
50
30
20
10
150
155
160
165
170
175
180
185
M_H [GeV]
m_t [GeV]



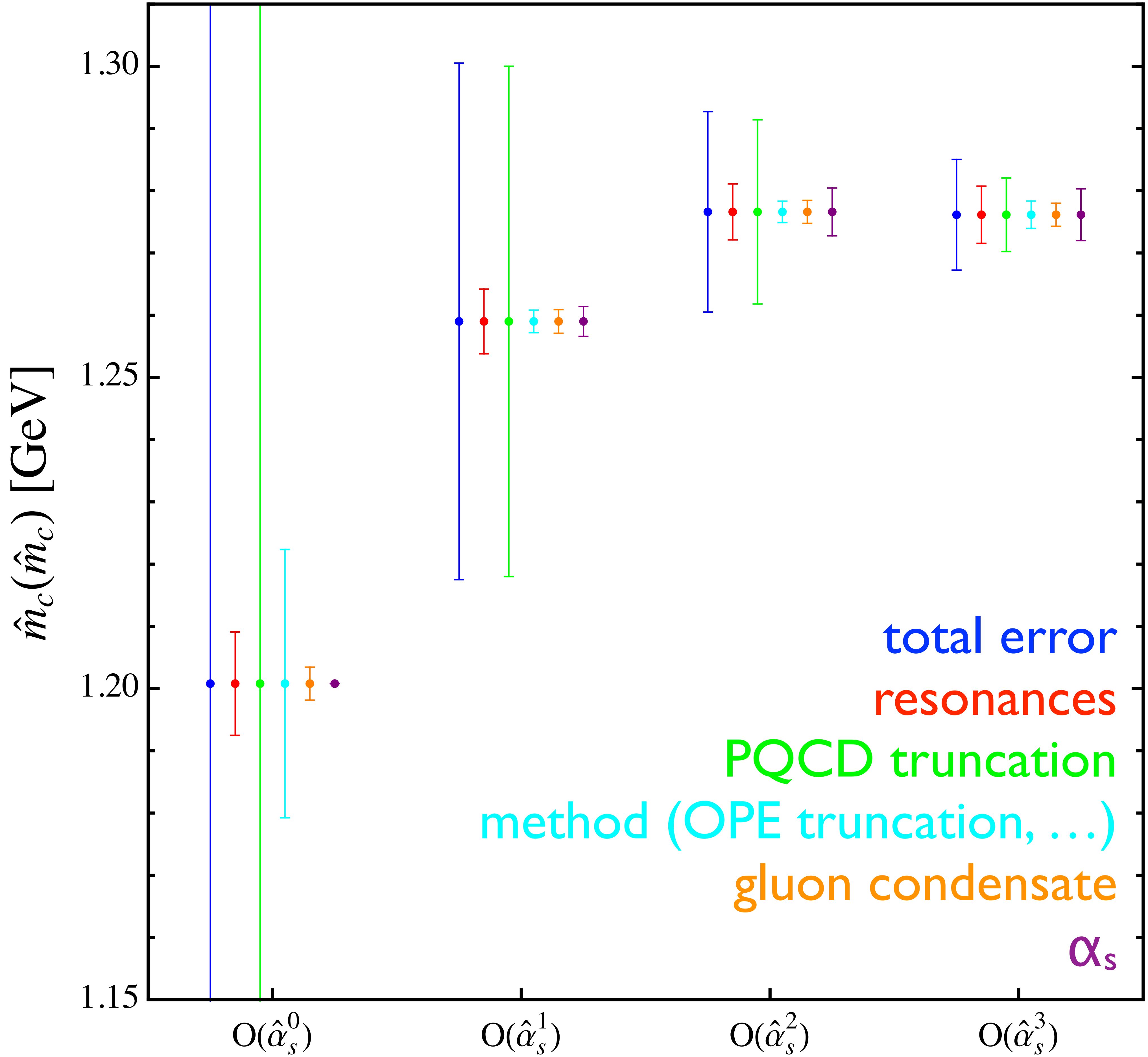
0.235
0.234
0.233
0.232
0.231
0.230
sin²θ_eff(e)
A_FB(b)
A_LR(had)
10
100
1000
10000
M_H [GeV]
JE 2015


update with Rodolfo Ferro in progress
0.245
0.240
0.235
0.230
0.22
$\sin^2\theta_W(\mu)$
$Q_W(p)$
$Q_W(e)$
NuTeV
$Q_W(APV)$
Tevatron
LEP 1
SLC
LHC
0,00
0,001
0,01
0,1
1
10
100
1000
10000
μ [GeV]

Charm and bottom quarks



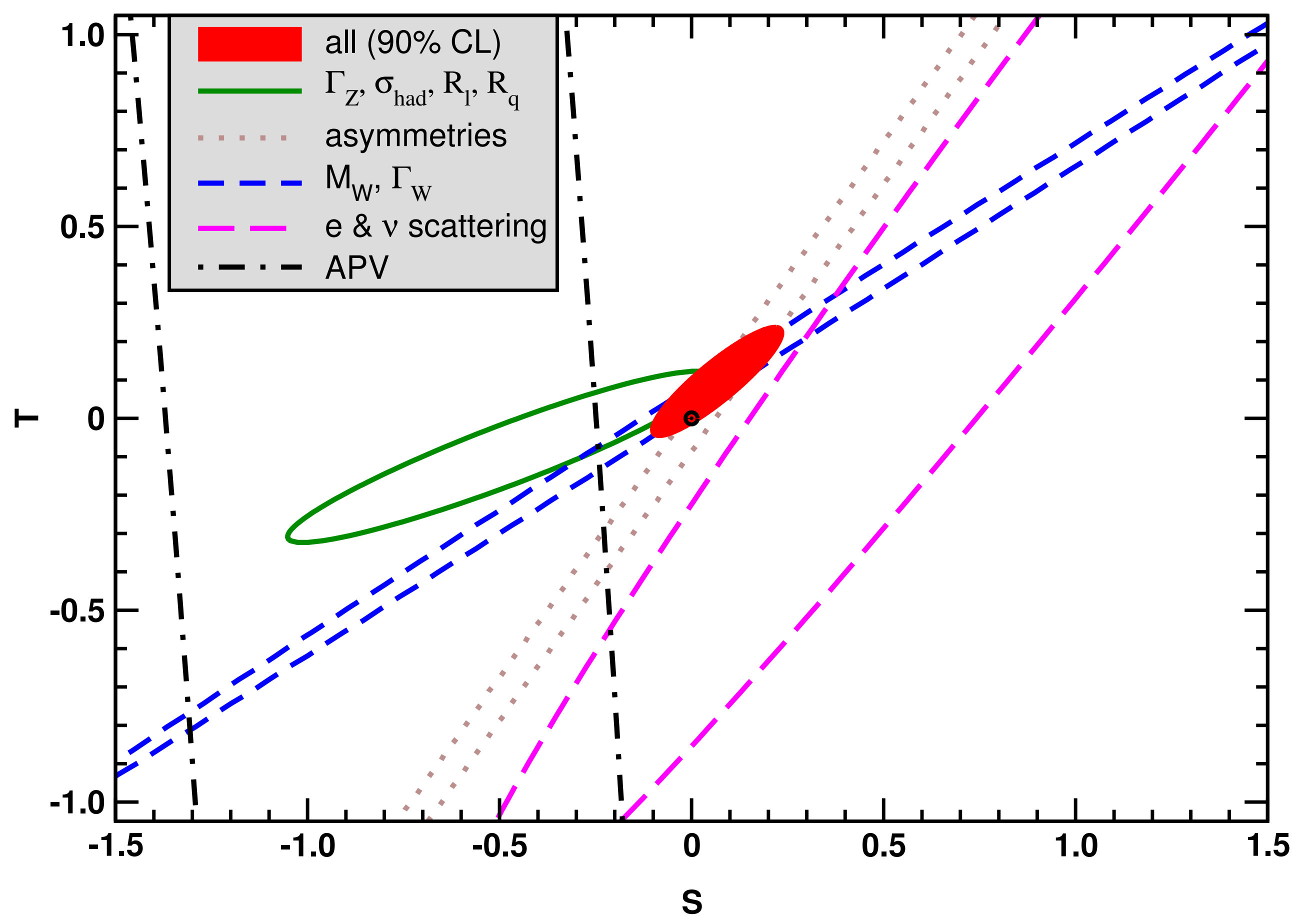
- $\alpha(M_Z)$ and $\sin^2\theta_W(0)$: can use PQCD for heavy quark contribution if masses known.
- g–2: c quark contribution to muon g–2 similar to $\gamma\times\gamma$; ± 70 MeV uncertainty in m_c induces an error of $\pm 1.6 \times 10^{-10}$ comparable to the projected errors for the FNAL and J-PARC experiments.
- Yukawa coupling – mass relation (in single Higgs doublet SM): $\Delta m_b = \pm 9$ MeV and $\Delta m_c = \pm 8$ MeV to match precision from HiggsBRs @ FCC-ee
- QCD sum rule: $m_c = 1272 \pm 8$ MeV
  Masjuan, Spiesberger, JE 2016
  (expect about twice the error for m_b)



JE, Masjuan, Spiesberger 2016

Implications of T (ρ_0) parameter

$\rho_0 \sim 1+\alpha T$



In SM: ρ_0 = 1
(custodial symmetry)

- ρ_0 would constrain VEVs of higher dimensional Higgs representations to ≲ 1 GeV
- Sensitivity to degenerate scalar EW doublets up to 2 TeV (using results based on EFT approach ***Henning, Lu, Murayama 2014***)
- Non-degenerate multiplets of heavy fermions or scalars

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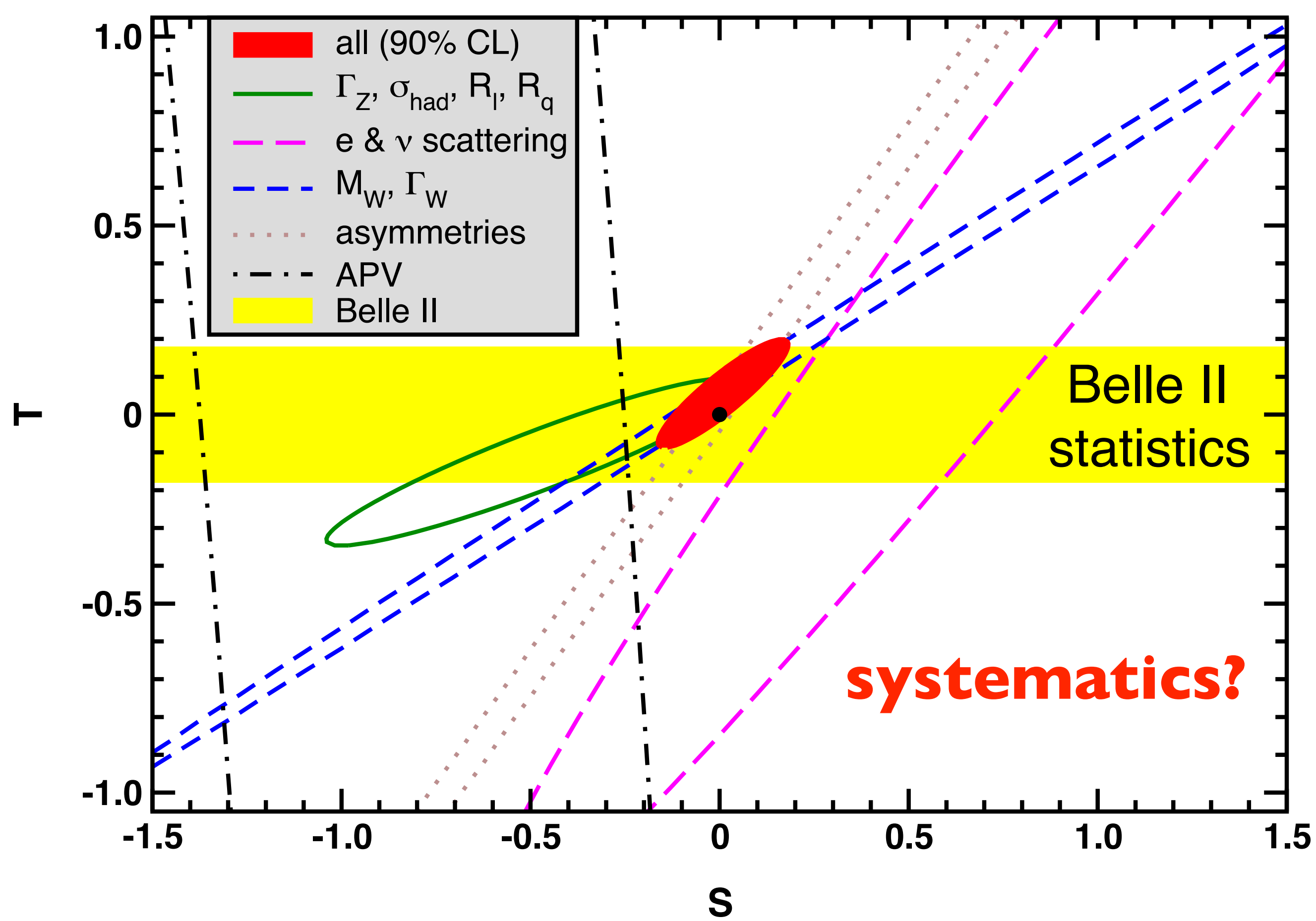

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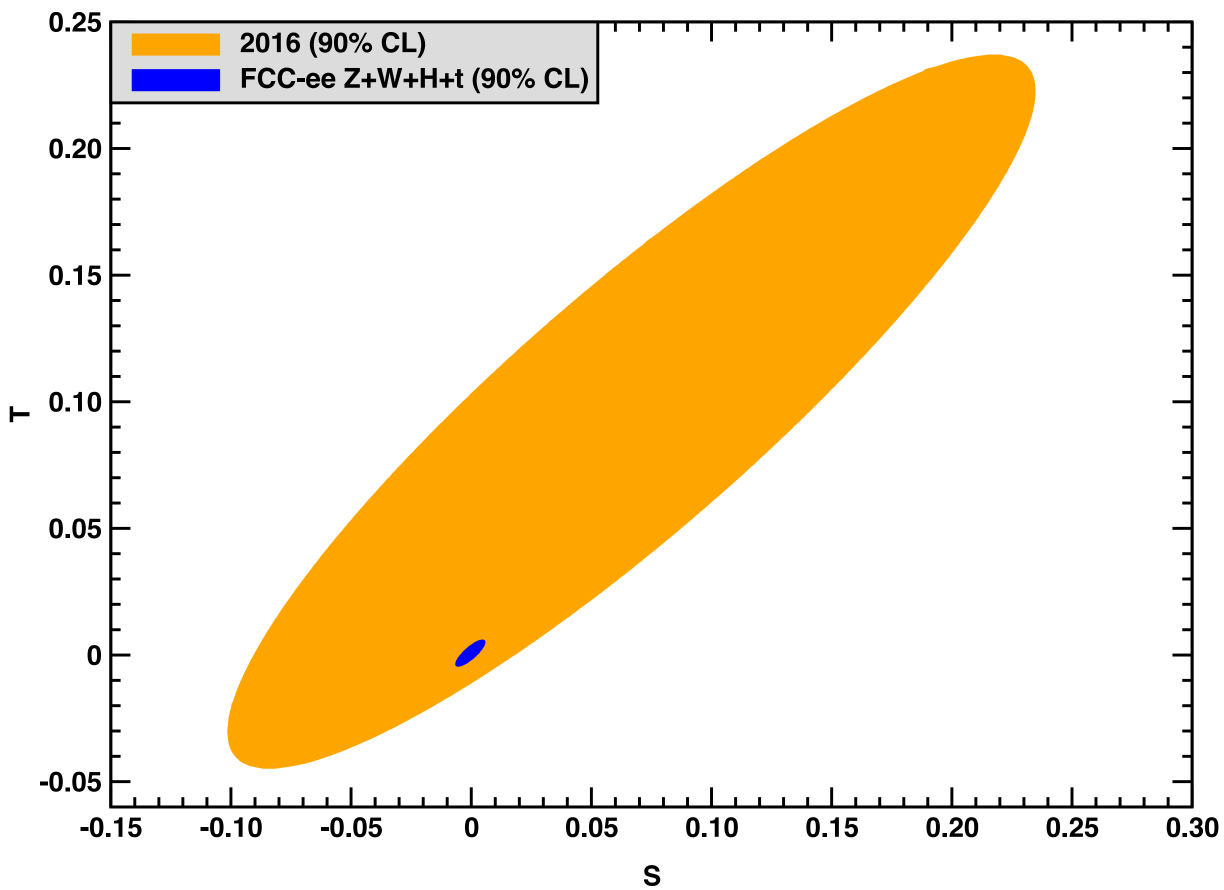
Non-degenerate multiplets of heavy fermions or scalars

- $\Delta\rho_0 = G_F \, \Sigma_i \, C_i \, / \, (8 \sqrt{2} \, \pi^2) \, \Delta m_i^2$ [$\Delta m_i^2 \geq (m_1 - m_2)^2$]
- despite appearance there is decoupling
  (see-saw type suppression of Δm_i^2)
- currently: $\Sigma_i \, C_i \, / \, 3 \, \Delta m_i^2 \leq (49 \text{ GeV})^2$
- assuming no SM deviation ($\rho_0 = 1 \pm 0.000012$)
  $\Longrightarrow$ FCC-ee: $\Sigma_i \, C_i \, / \, 3 \, \Delta m_i^2 \leq (8 \text{ GeV})^2$
- assuming central value unchanged from today ($\rho_0 = 1.00037 \pm 0.000012$)
  $\Longrightarrow$ FCC-ee: $\Sigma_i \, C_i \, / \, 3 \, \Delta m_i^2 = (34 \pm 1 \text{ GeV})^2$

STU



	current	FCC-ee
S	± 0.099	± 0.005
T	± 0.116	± 0.007
U	± 0.095	± 0.005
S	± 0.078	± 0.003
T	± 0.066	± 0.003
T	± 0.030	± 0.002

Low-energy measurements

Model independent new physics sensitivity

$$\mathcal{L}_{eq} = \left[\frac{G_F}{\sqrt{2}} g_{VA}^{eq}(\mathrm{SM}) + \frac{g^2}{\Lambda^2}\right] \bar{e}\gamma_\mu e\, \bar{q}\gamma^\mu\gamma^5 q$$

$$\frac{g^2}{\Lambda^2} = \frac{4\pi}{\Lambda^2} = \frac{\bar{g}_{VA}^{eq} - g_{VA}^{eq}(\mathrm{SM})}{2v^2}$$

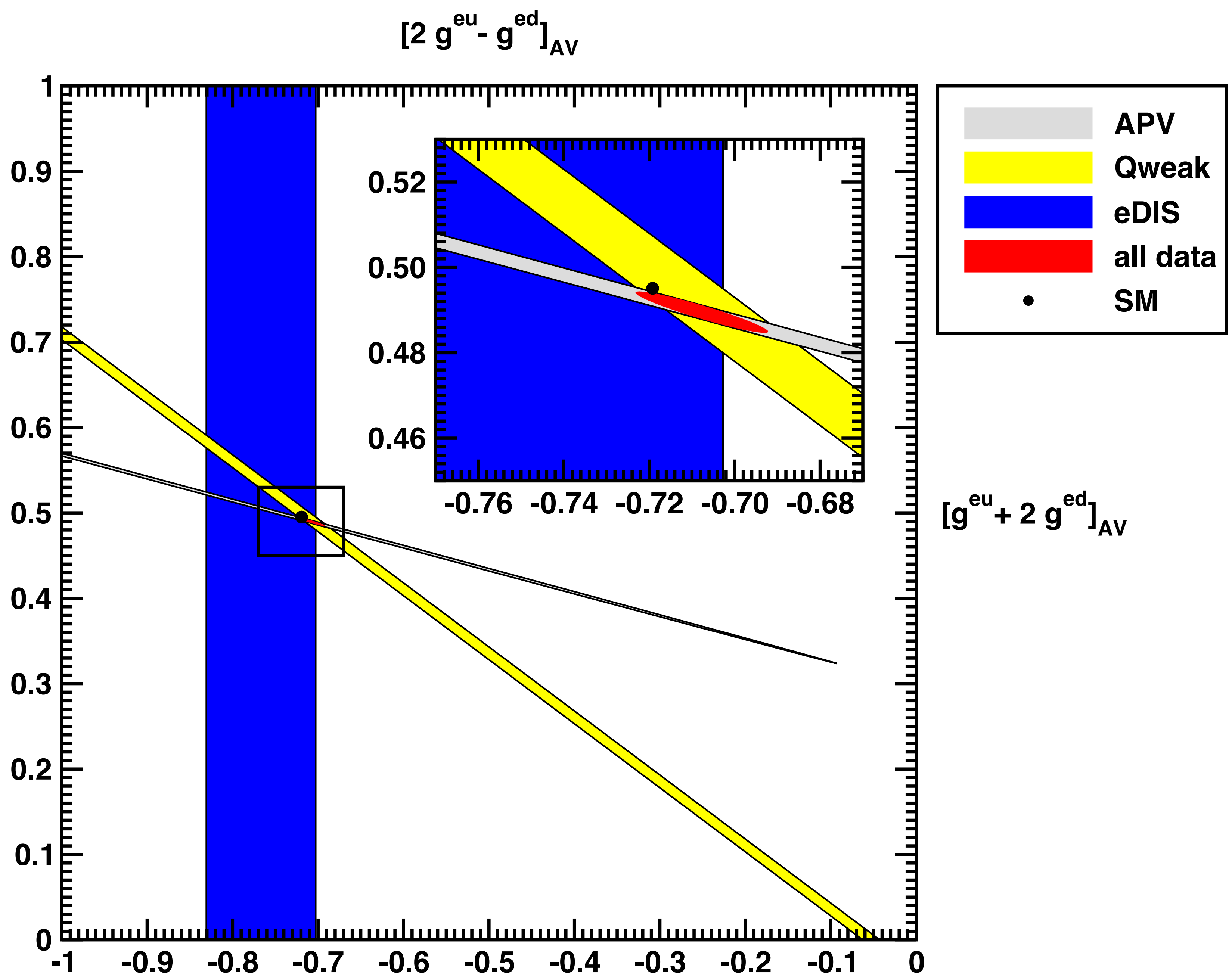
$g^2 = 4\pi$ (convention)

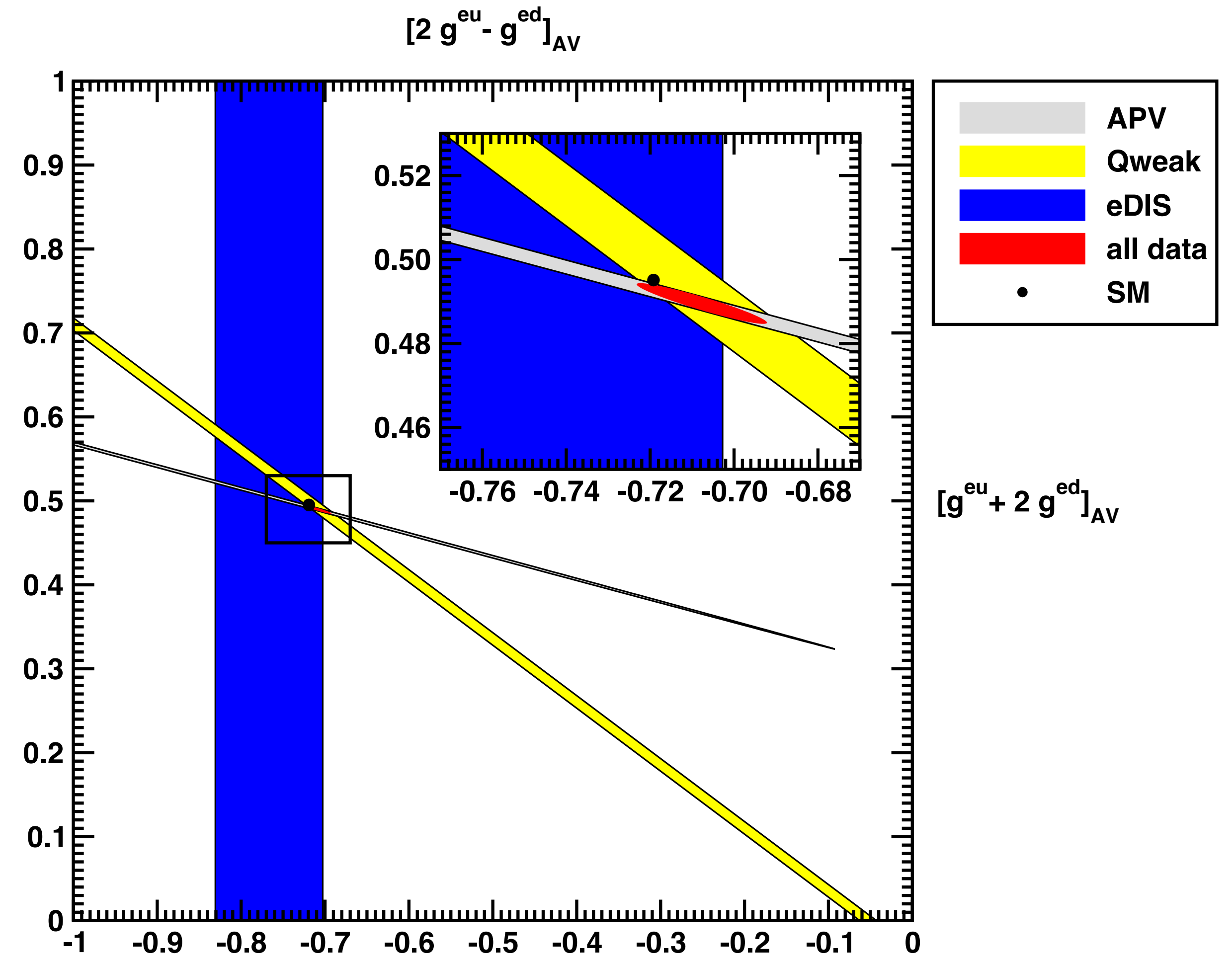
Customary to quote one-sided limits on Λ!

important metric:
generalization to other types of operators?

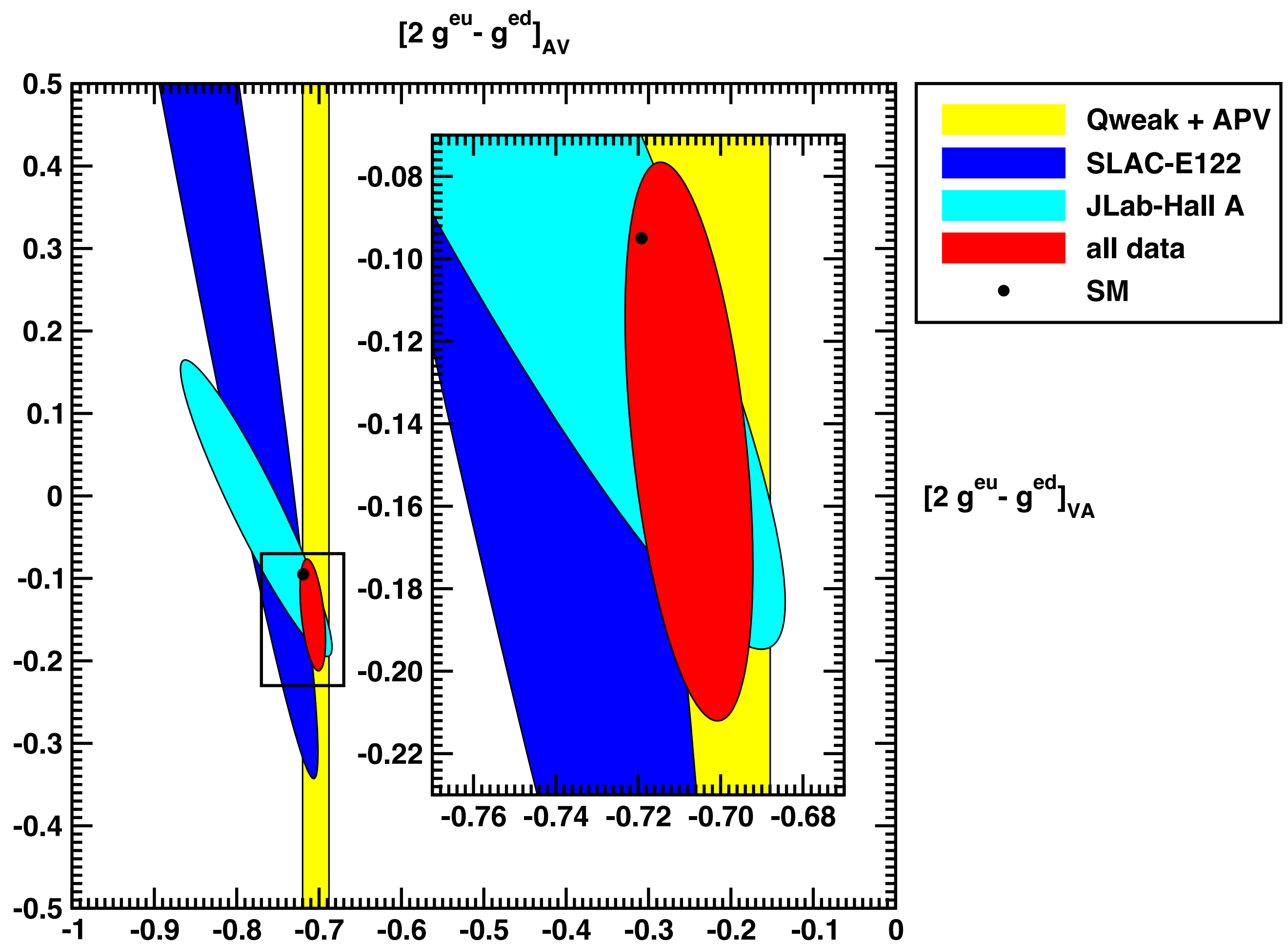
	precision	$\Delta \sin^2\bar{\theta}_W(0)$	Λ_{new} (expected)
APV ^{133}Cs	0.58 %	0.0019	32.3 TeV
E158	14%	0.0013	17.0 TeV
Qweak I	19%	0.0030	17.0 TeV
PVDIS	4.5%	0.0051	7.6 TeV
Qweak final	4.5%	0.0008	33 TeV
SoLID	0.6 %	0.00057	22 TeV
MOLLER	2.3 %	0.00026	39 TeV
P2	2.0 %	0.00036	49 TeV
PVES ^{12}C	0.3 %	0.0007	49 TeV
APV ^{225}Ra	0.5%	0.0018	34 TeV
APV ^{213}Ra/^{225}Ra	0.1%	0.0037	16 TeV
Belle II	0.14%	—	33 TeV
CEPC / FCC	?	?	?

PV (axial)-electron (vector)-quark couplings



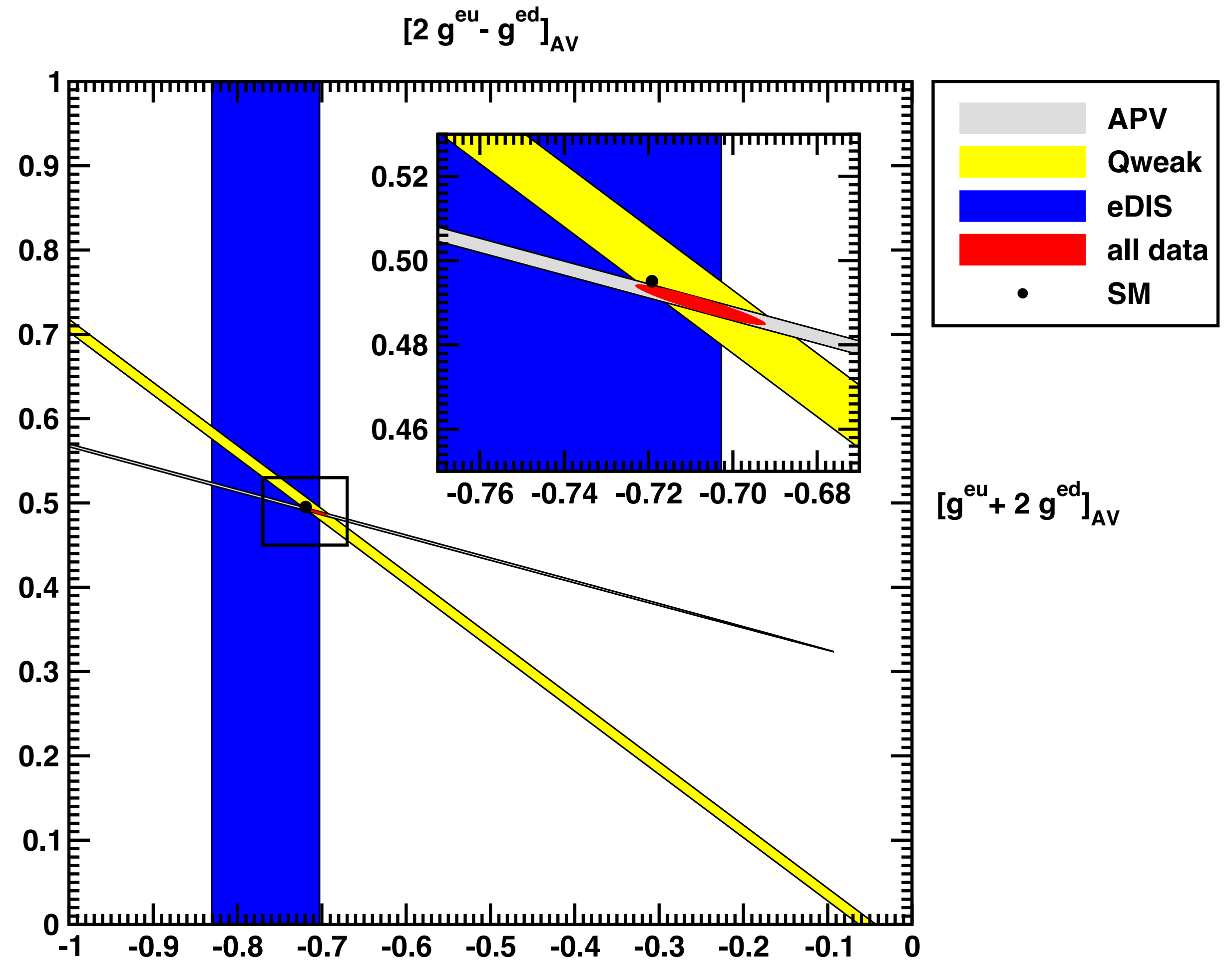


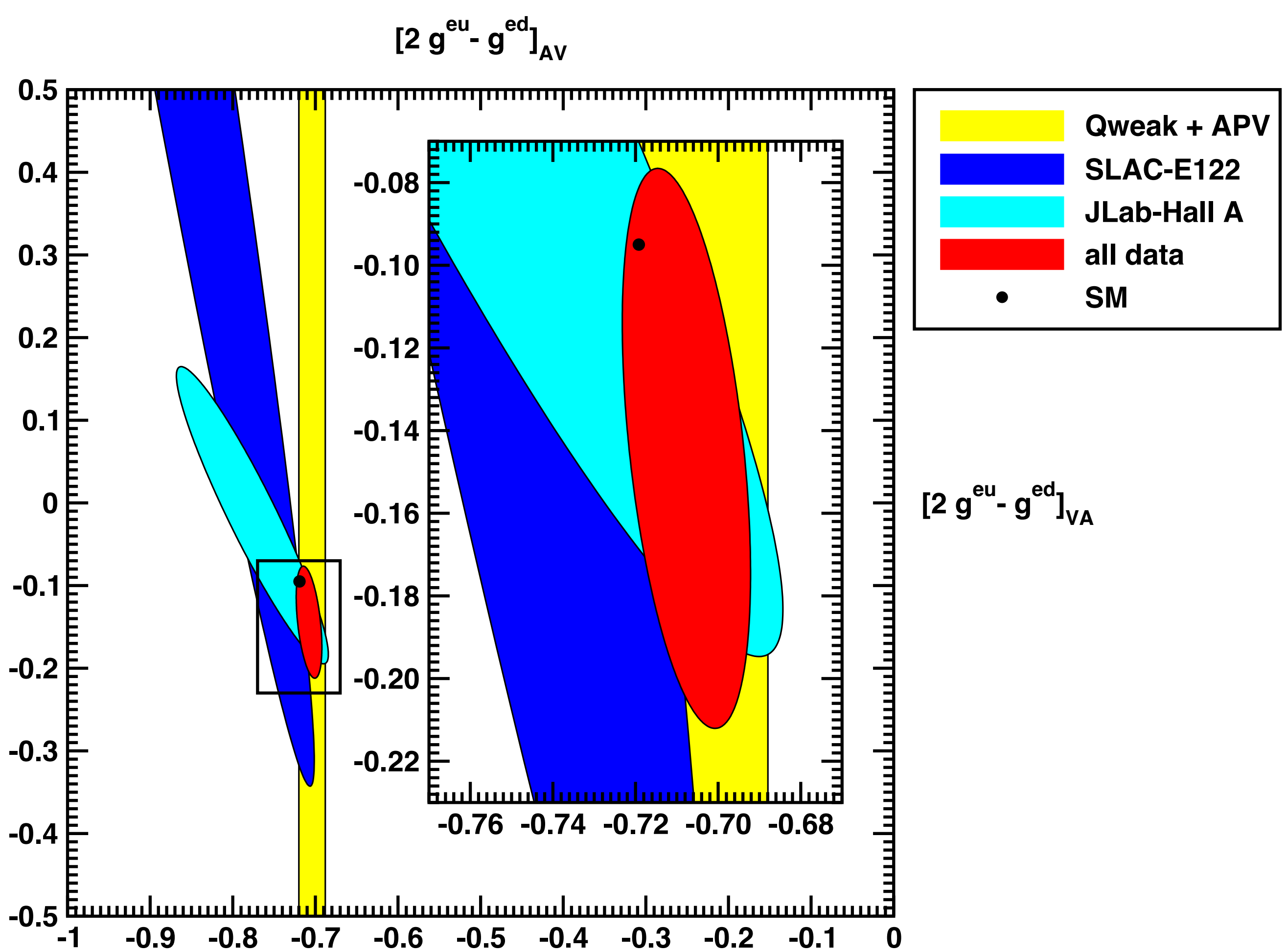
[2 g^eu - g^ed]_AV
APV
Qweak
eDIS
all data
SM
[g^eu + 2 g^ed]_AV

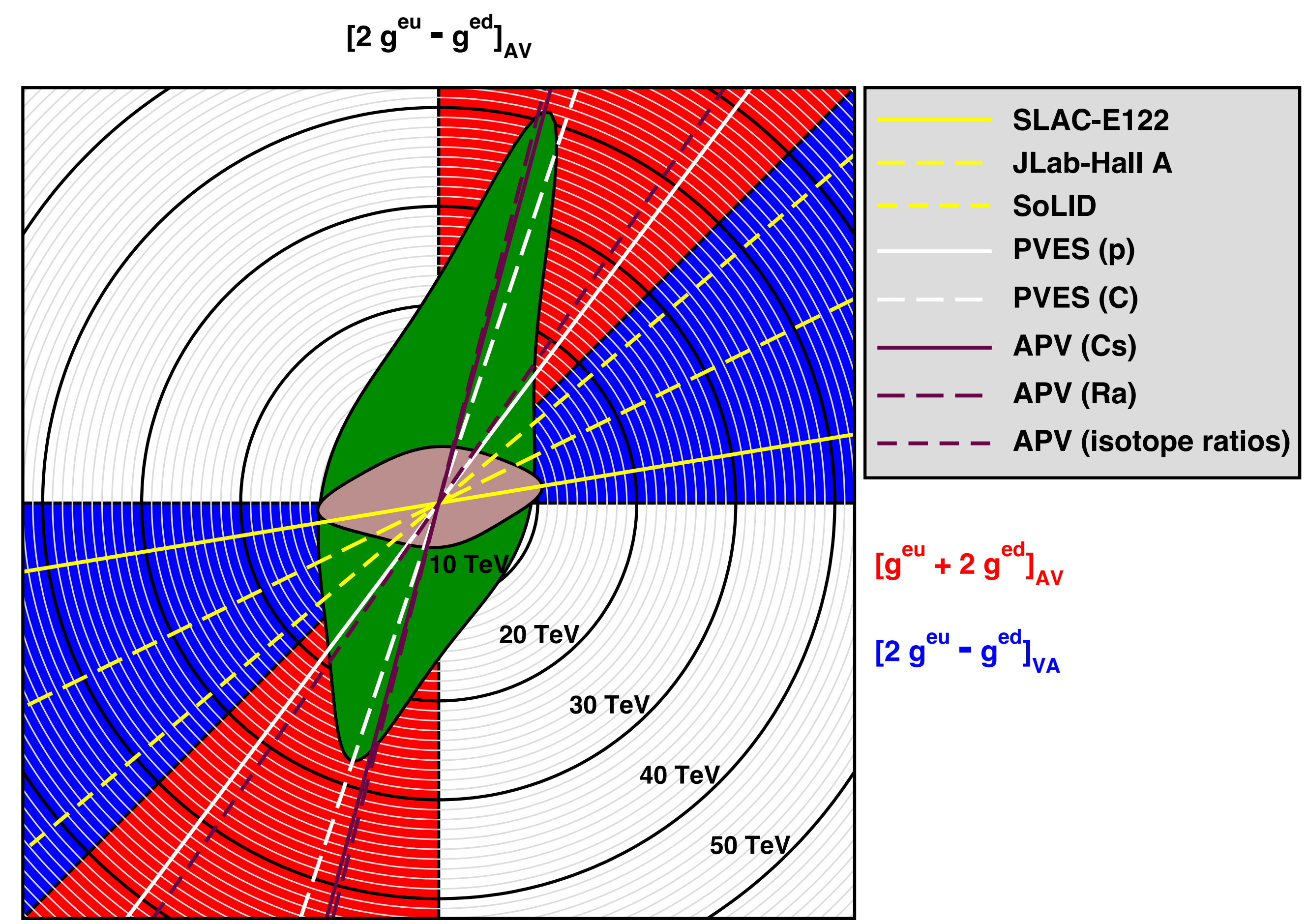


[2 g^eu - g^ed]_AV
Qweak + APV
SLAC-E122
JLab-Hall A
all data
SM
[2 g^eu - g^ed]_VA

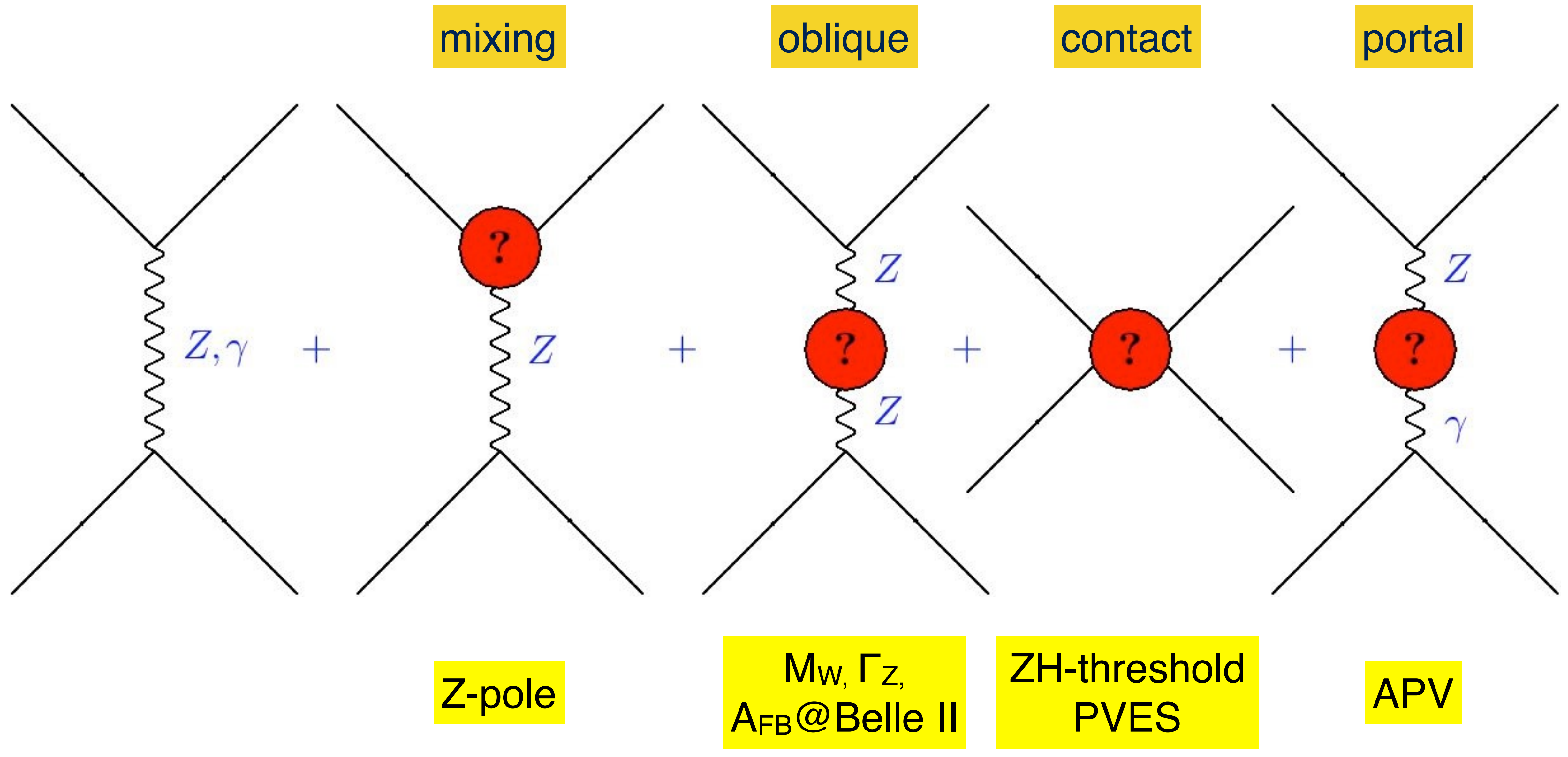
Compositeness scales







Discriminating between new physics



Summary

- fixing the SM: determine fundamental parameters like α_s
- testing the SM: CKM unitarity and fermion universality tests
- over-constraining the SM: compute and measure derived quantities like M_W, $\sin^2\theta_W$, g_μ–2 and weak charges
- GUTs: e.g. gauge & Yukawa-coupling ($b\tau$) unification
- model-independent constraints on new physics: e.g. oblique parameters or four-fermion operators
- models: extra fermions or scalars; supersymmetry, extra dimensions, compositeness, extended Higgs sector models, dark sector models, …

BACKUP

Uncertainties in precision observables

- statistical: straightforward to estimate and main reference when designing experiments; limited by beam time, luminosity, …; known error distribution
- systematic: difficult to estimate in general; can often be constrained by auxiliary measurements (which may themselves be statistical); sometimes unknown distribution but often approximately Gaussian
- theoretical: very difficult to estimate in general but can sometimes be systematically improved; usually unknown distribution
- model: (almost) unquantifiable; unknown distribution
- parametric: easy to determine; distribution may be complicated but can be taken into account exactly within global fits

Assumptions for FCC-ee

M_Z ± 2.1 MeV ➨ < 100 keV

Γ_Z ± 2.3 MeV ➨ < 100 keV

R_μ ± 0.025 ➨ < 0.001

R_b ± 0.00066 ➨ $< 6\times10^{-5}$

m_t ± 810 MeV (incl. QCD) ➨ ± 15 MeV

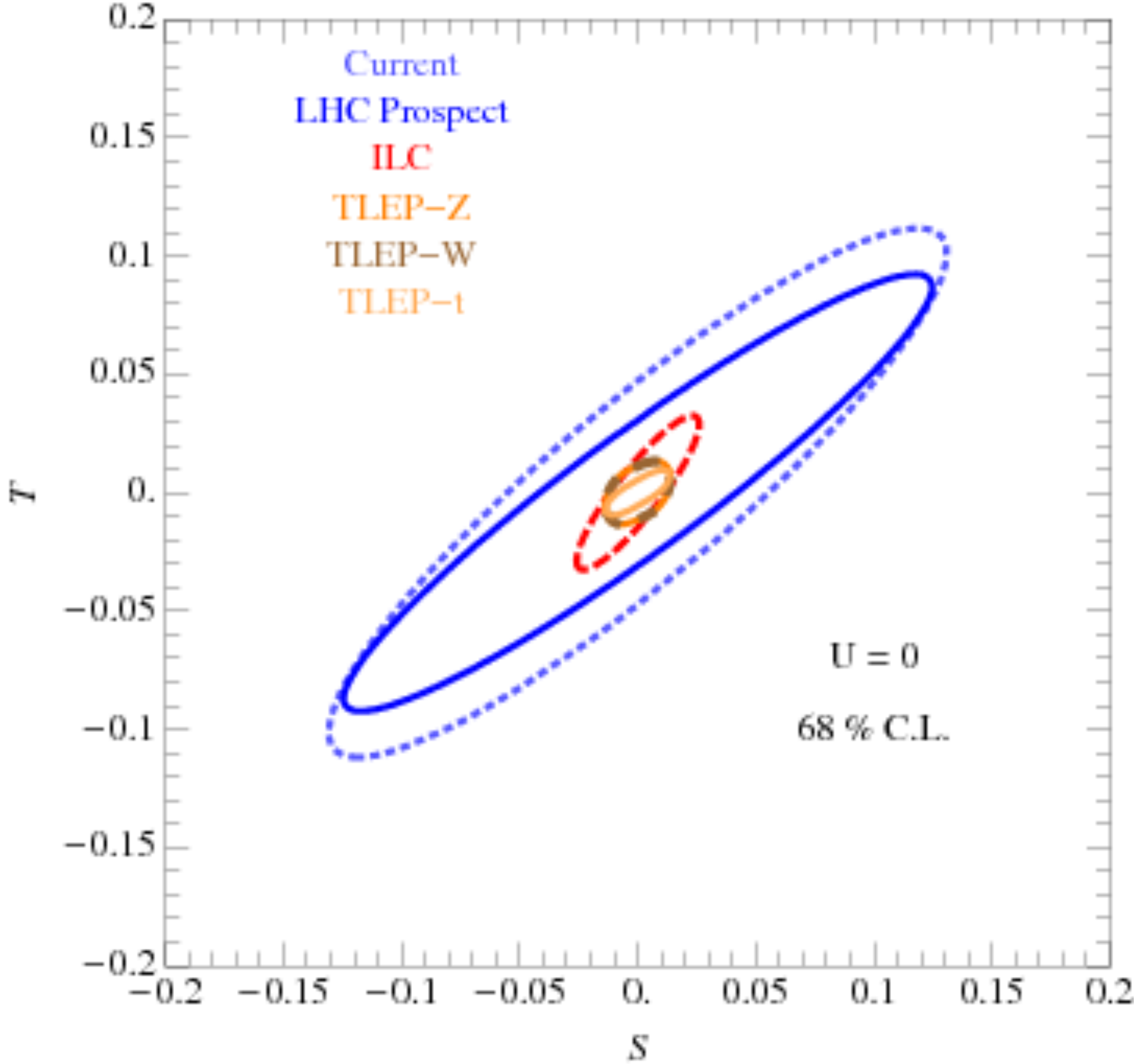
σ_{had} ± 37 pb ➨ ± 4 pb (assumes 0.01% luminosity error)

A_{LR} ± 0.0022 ➨ $\pm 2\times10^{-5}$ (needs 3-loop EW to be useful, 4-loop to match exp.)

$A_{LR}^{FB}(b)$ ± 0.020 ➨ ± 0.001 (using similar b-tagging improvements as for R_b)

M_W ± 33 MeV (LEP); ± 16 MeV (Tevatron) ➨ ± 0.6 MeV

Γ_W ± 42 MeV ➨ 1st + 2nd row CKM unitarity test



Fan, Reece, Wang
2014

Complementarity: Need EW precision measurements on and off the Z pole

on pole:
$\sin^2\theta_W$
STU
RPC SUSY
ZZ′

below pole (interference amplitude):
running $\sin^2\theta_W$ ("dark Z")
X parameter
RPV SUSY
νν ee, νν uu, νν dd 4-Fermi operators
parity-violating eeee, eeuu, eedd 4-Fermi operators

above pole:
eeff operators
incl. 2nd/3rd generation f and parity-conserving