Electroweak Precision Observables: Theory Status

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FCC-ee physics WG2: Precision EW Calculations

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Contributors (so far): *M. Beneke, A. Blondel, A. Hoang, P. Janot, J. Reuter, C. Schwinn, S. Weinzierl, . . .*

1. Introduction
2. Electroweak Precision Observables
3. Status

(FCC-ee) Future ⇒ second talk

1. Introduction

Experimental situation:

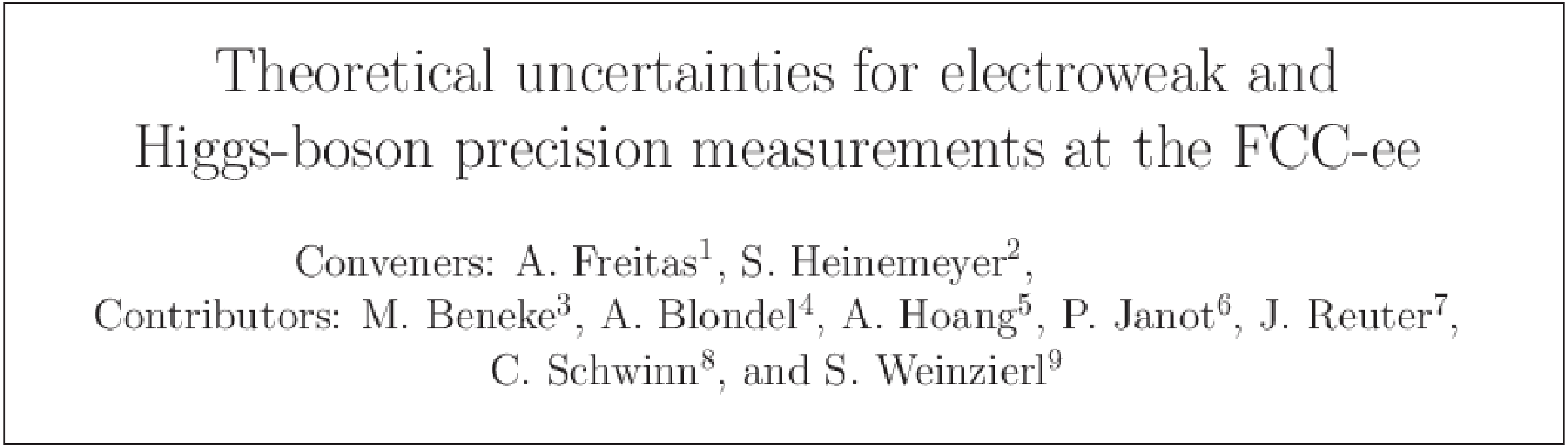
LHC/ILC/FCC-ee/CEPC/... will provide (high!) accuracy measurements!

Theory situation:

- Measurements are performed using theory predictions
- measured observables have to be compared with theoretical predictions (in various models: SM, MSSM, ...)

Full uncertainty is given by the (linear) sum of experimental and theoretical uncertainties!

FCC-ee physics WG2 – Precision EW Calculations: Write-up



Theoretical uncertainties for electroweak and
Higgs-boson precision measurements at the FCC-ee

Conveners: A. Freitas[1], S. Heinemeyer[2],
Contributors: M. Beneke[3], A. Blondel[4], A. Hoang[5], P. Janot[6], J. Reuter[7],
C. Schwinn[8], and S. Weinzierl[9]

⇒ will go into CDR!

⇒ should be taken into account by other (exp) groups!

⇒ Here: current status of EWPO TH calculations

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W
   → at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $e^+e^- \to W^+W^-$
   → better than then "pure" experimental precision

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Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\rm had}$, . . .

Options for the evaluation of intrinsic uncertainties:

1. Determine all prefactors of a certain diagram class (couplings, group factors, multiplicities, mass ratios) and assume the loop is $\mathcal{O}(1)$

2. Take the known contribution at n-loop and $(n-1)$-loop and thus estimate the $n+1$-loop contribution:

$$\frac{(n+1)^{\text{(estimated)}}}{n^{\text{(known)}}} \approx \frac{n^{\text{(known)}}}{(n-1)^{\text{(known)}}}$$

   ⇒ simplified example! Has to be done
   "coupling constant by coupling constant"

3. Variation of $\mu^{\overline{\text{MS}}}$ (QCD!, EW?)

4. Compare different renormalizations

⇒ Mostly used here: 1 & 2

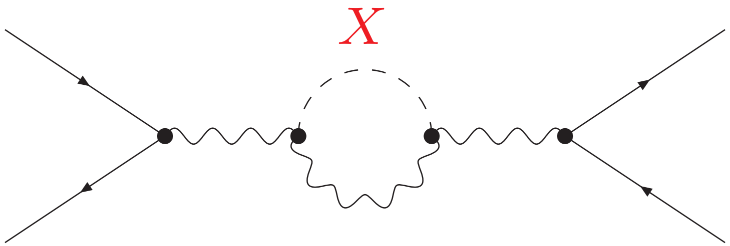
2. Electroweak Precision Observables

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\mathrm{eff}}, a_\mu, \ M_h$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H, BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

$\Rightarrow$ only models “ready” so far: SM, MSSM

The EWPO:

M_W (best from threshold scan)

$$\sigma^0_{\text{had}} = \sum_q \sigma_q(M_Z^2),$$

$$\Gamma_Z = \sum_f \Gamma[Z \to f\bar{f}], \qquad \text{(from a fit to } \sigma_f(s) \text{ at various values of } s\text{)}$$

$$R_\ell = \left[\textstyle\sum_q \sigma_q(M_Z^2)\right] / \sigma_\ell(M_Z^2), \qquad (\ell = e, \mu, \tau)$$

$$R_q = \sigma_q(M_Z^2) / \left[\textstyle\sum_q \sigma_q(M_Z^2)\right], \qquad (q = b, c)$$

$$A^f_{\text{FB}} = \frac{\sigma_f(\theta < \frac{\pi}{2}) - \sigma_f(\theta > \frac{\pi}{2})}{\sigma_f(\theta < \frac{\pi}{2}) + \sigma_f(\theta > \frac{\pi}{2})} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

$$A^f_{\text{LR}} = \frac{\sigma_f(P_e < 0) - \sigma_f(P_e > 0)}{\sigma_f(P_e < 0) + \sigma_f(P_e > 0)} \equiv \mathcal{A}_e|P_e|$$

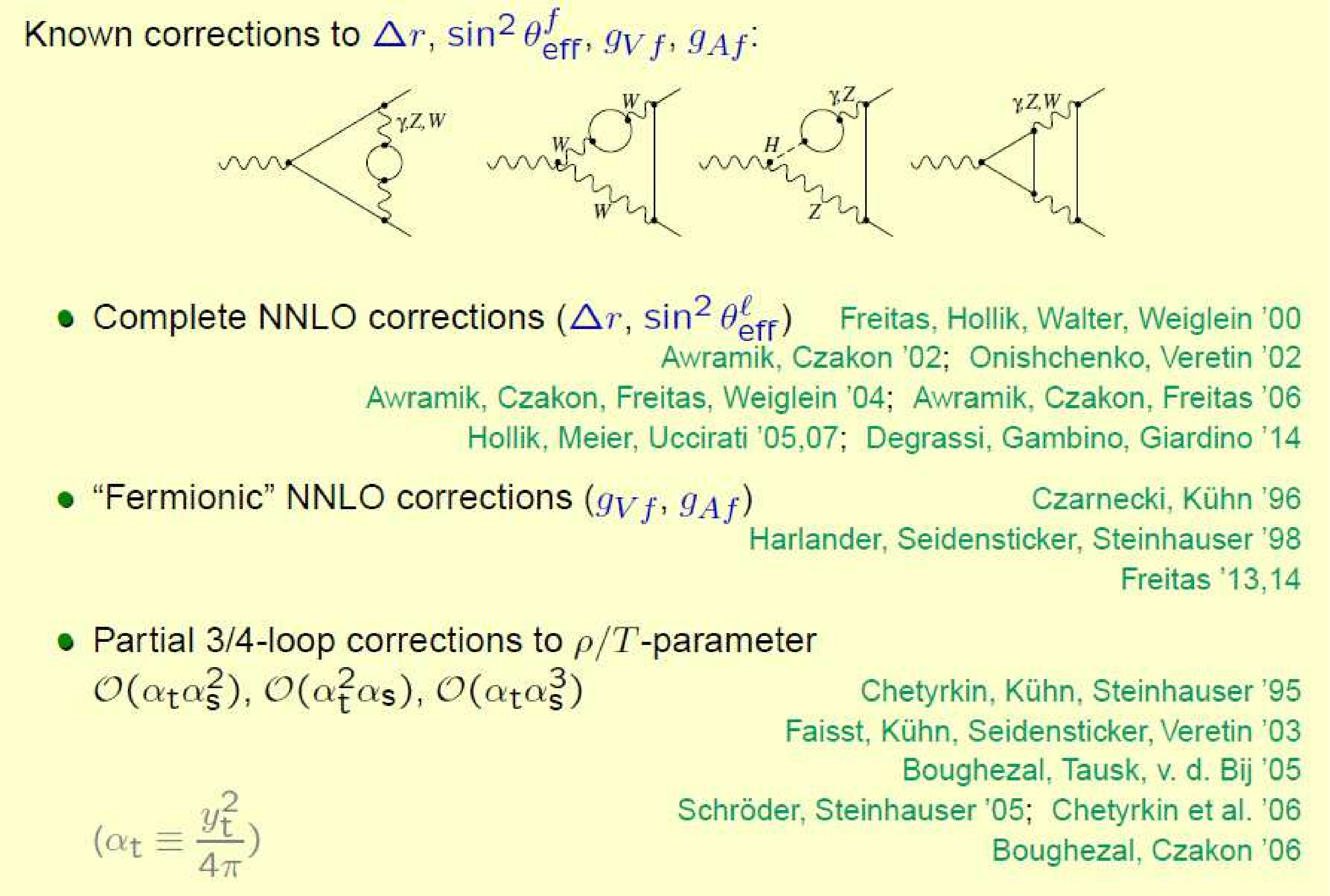
$$\mathcal{A}_f = 2\frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2} = \frac{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2} \quad (f = \ell, b, \ldots)$$

3. Status

⇒ see also Janusz' talk!

Existing higher-order corrections to the EWPO

[*taken from A. Freitas '16*]



Known corrections to Δr, $\sin^2\theta^f_{\rm eff}$, g_{Vf}, g_{Af}:

- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\rm eff}$) Freitas, Hollik, Walter, Weiglein '00
  Awramik, Czakon '02; Onishchenko, Veretin '02
  Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
  Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14
- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14
- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ Chetyrkin, Kühn, Steinhauser '95
  Faisst, Kühn, Seidensticker, Veretin '03
  Boughezal, Tausk, v. d. Bij '05
  Schröder, Steinhauser '05; Chetyrkin et al. '06
  Boughezal, Czakon '06

  ($\alpha_t \equiv \frac{y_t^2}{4\pi}$)

Intrinsic uncertainties:

Quantity	current experimental unc.	current intrinsic unc.	
M_W [MeV]	15	4	$(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^\ell_{\text{eff}}$ $[10^{-5}]$	16	4.5	$(\alpha^3, \alpha^2\alpha_s)$
Γ_Z [MeV]	2.3	0.5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$
R_b $[10^{-5}]$	66	15	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$
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Parametric uncertainties:

Quantity	$\delta m_t = 0.9$ GeV	$\delta(\Delta\alpha_{\mathrm{had}}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
$\delta M_W^{\mathrm{para}}$ [MeV]	5.5	2	2.5
$\delta\sin^2\theta^{\ell,\mathrm{para}}_{\mathrm{eff}}$ $[10^{-5}]$	3.0	3.6	1.4

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⇒ Current intrinsic/parametric uncertainties are substantially smaller than current experimental uncertainties :-)

Additional uncertainty for M_W from threshold scan:

Not only $e^+e^- \to W^{(*)}W^{(*)}$, but $e^+e^- \to WW \to$ 4f needed

Current status:

full one-loop for $2 \to 4$ process

[*A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99-'02*]

⇒ extraction of M_W at the level of $\sim$ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

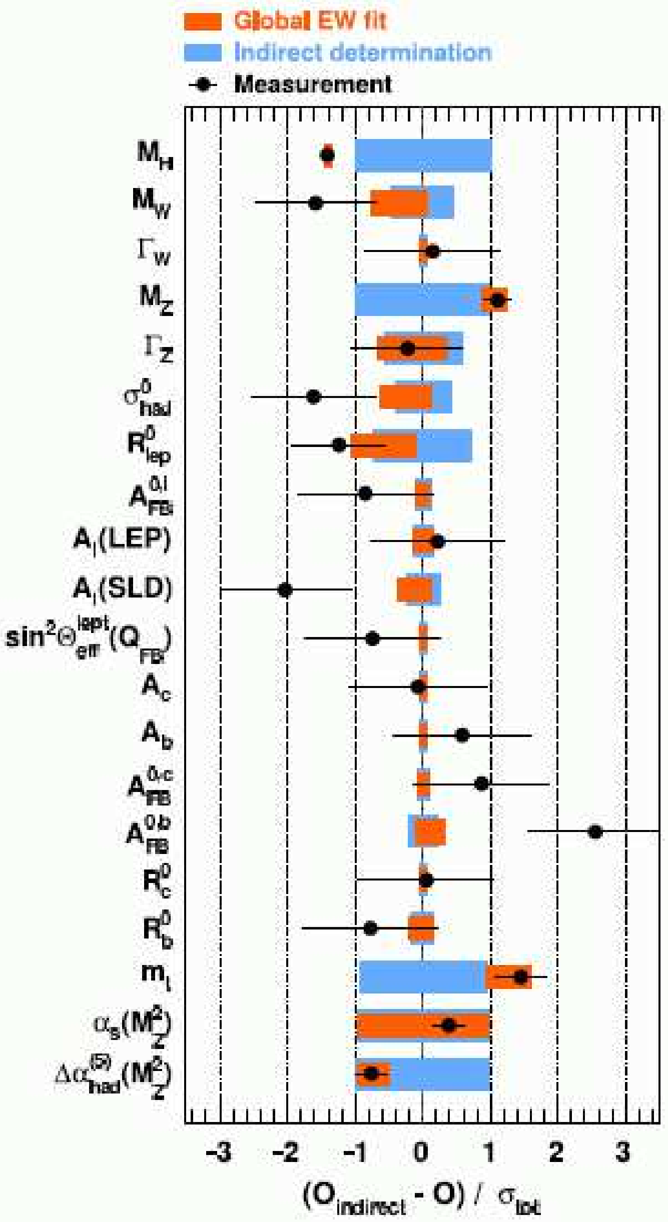
[*Actis, Beneke, Falgari, Schwinn '08*]

⇒ impact on M_W at the level of $\sim$ 3 MeV

⇒ well under control for LEP data

Overview about all EWPO:

[*taken from A. Freitas '16*]



Surprisingly good agreement:

χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

Most quantities measured with 1%–0.1% precision

GFitter coll. '14

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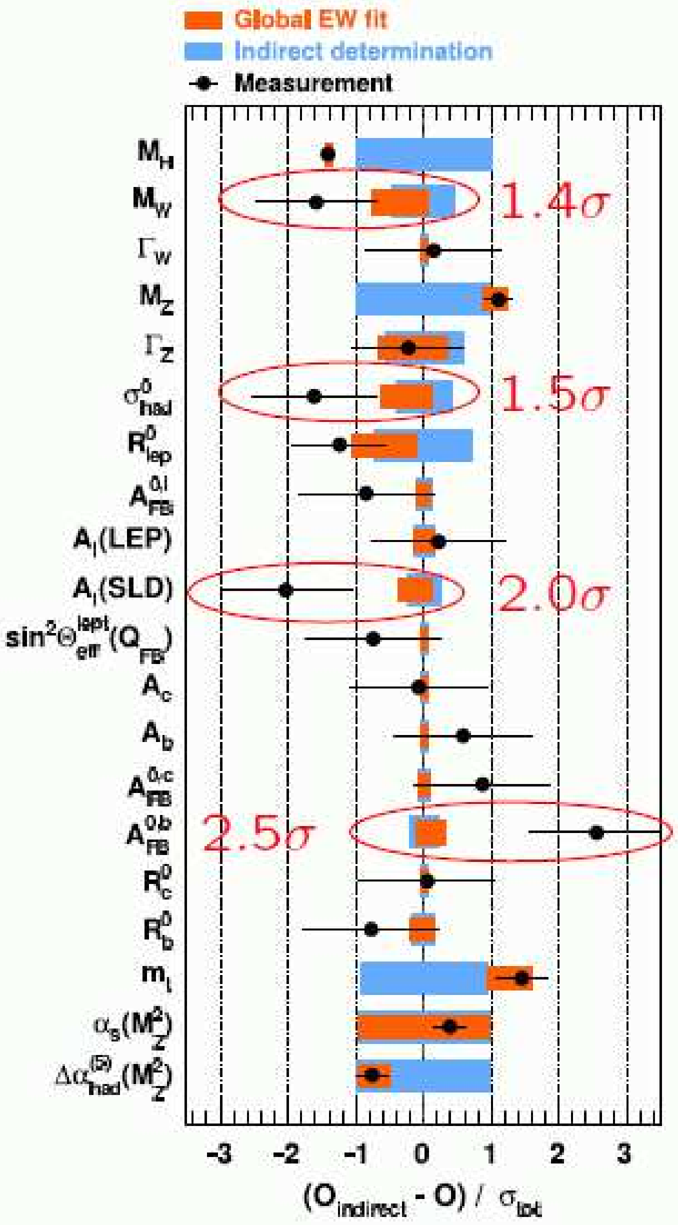

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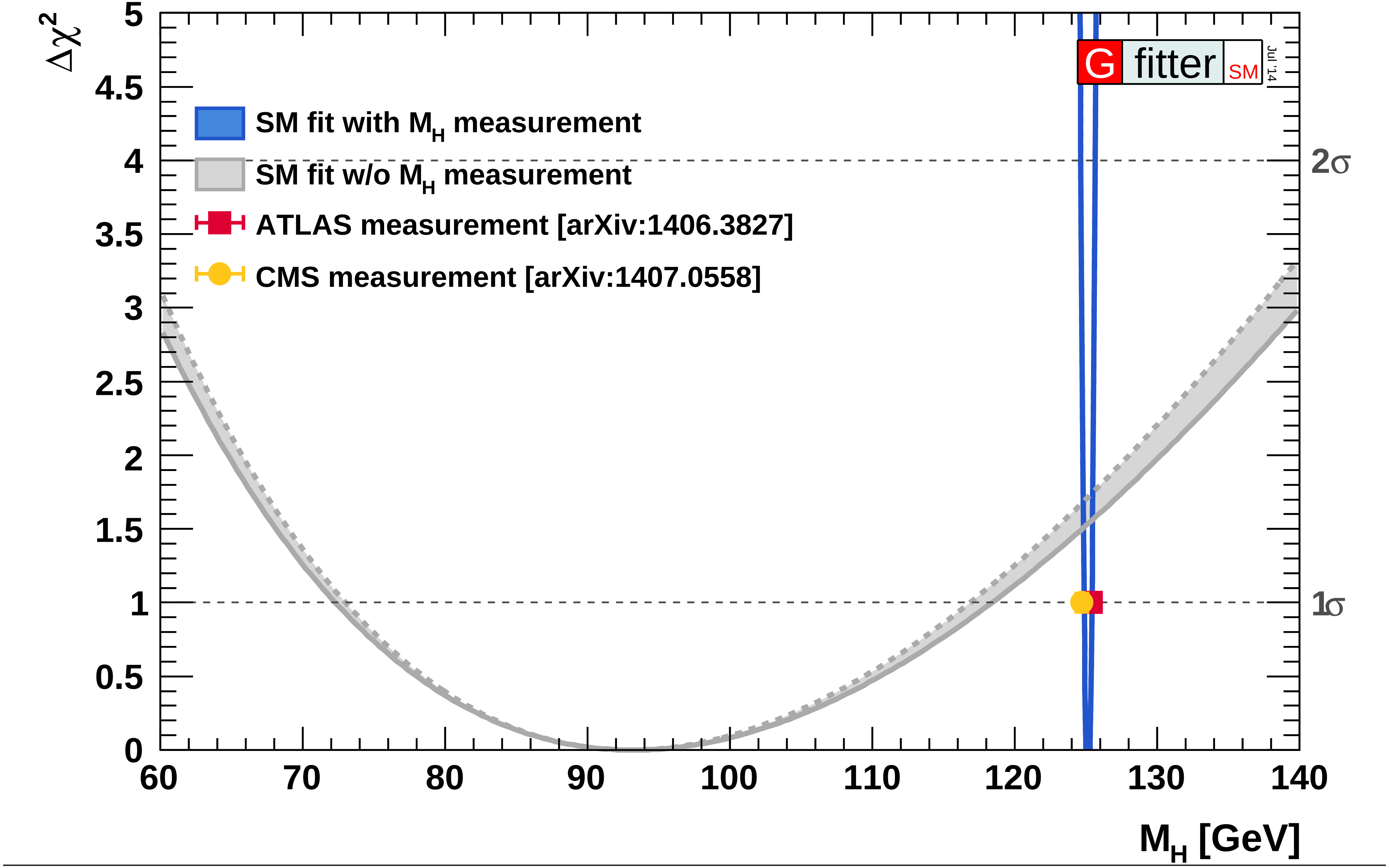
A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

GFitter coll. '14

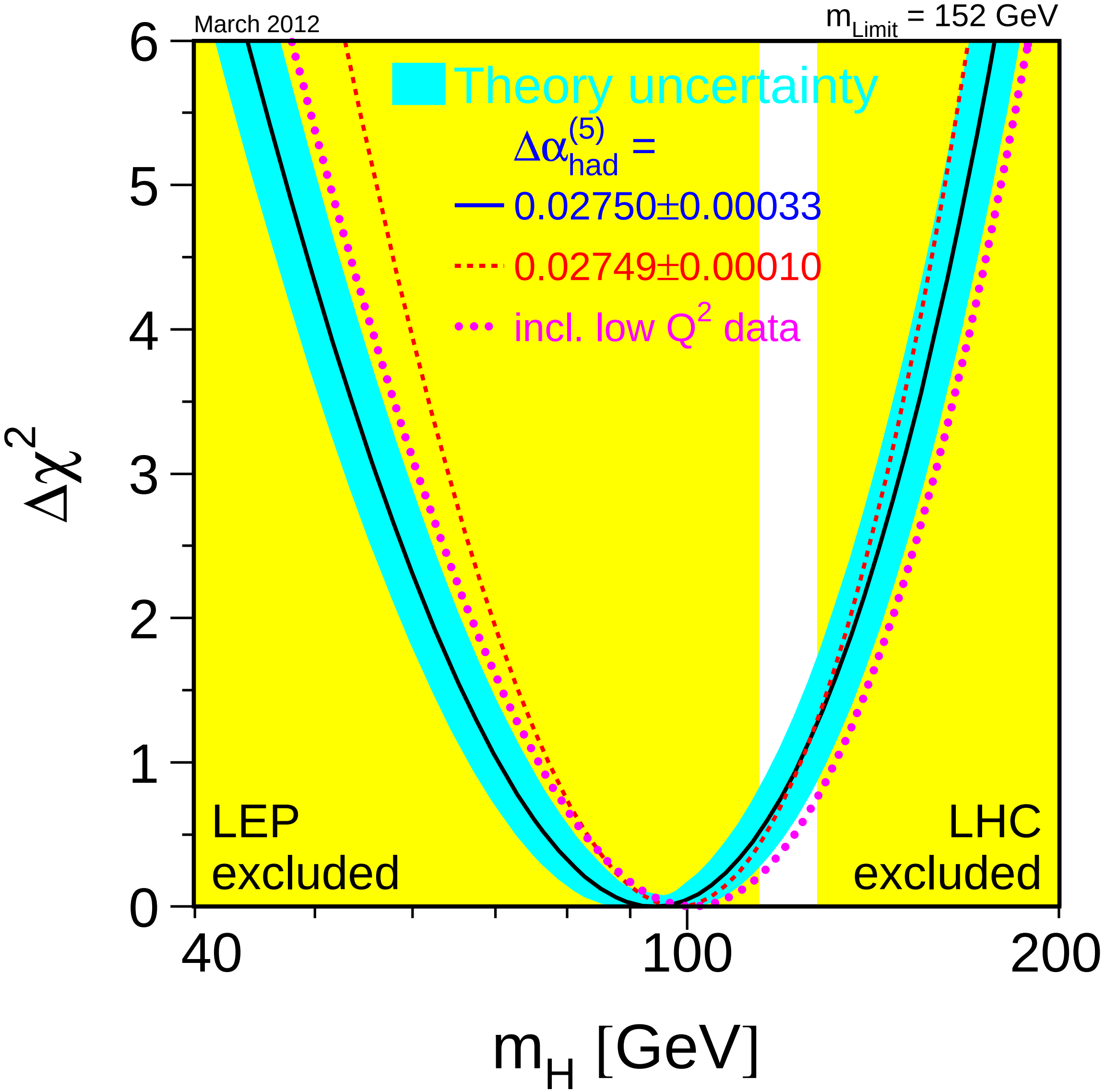
Current fit to M_H:

[GFitter '14]



Current fit to M_H:

[LEPEWWG '12]



One more word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of EWPO can be obtained.

We know that BSM physics must exist! (DM, gravity, . . .)

As soon as BSM physics will be discovered, an evaluation of the EWPO in any preferred BSM model will be necessary.

The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.