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Electroweak Fits in the Standard Model and Beyond

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on behalf of the Gfitter collaboration

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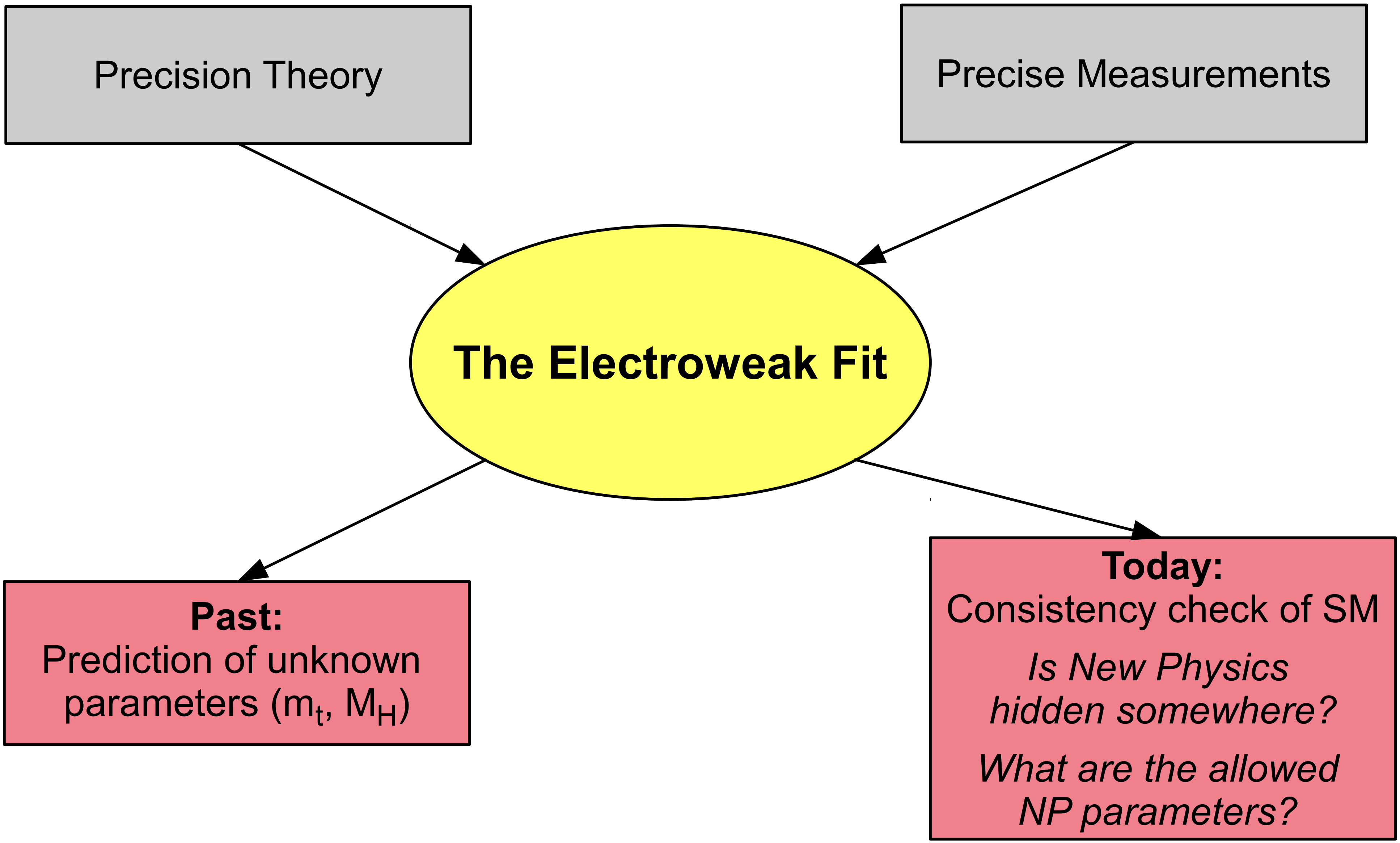
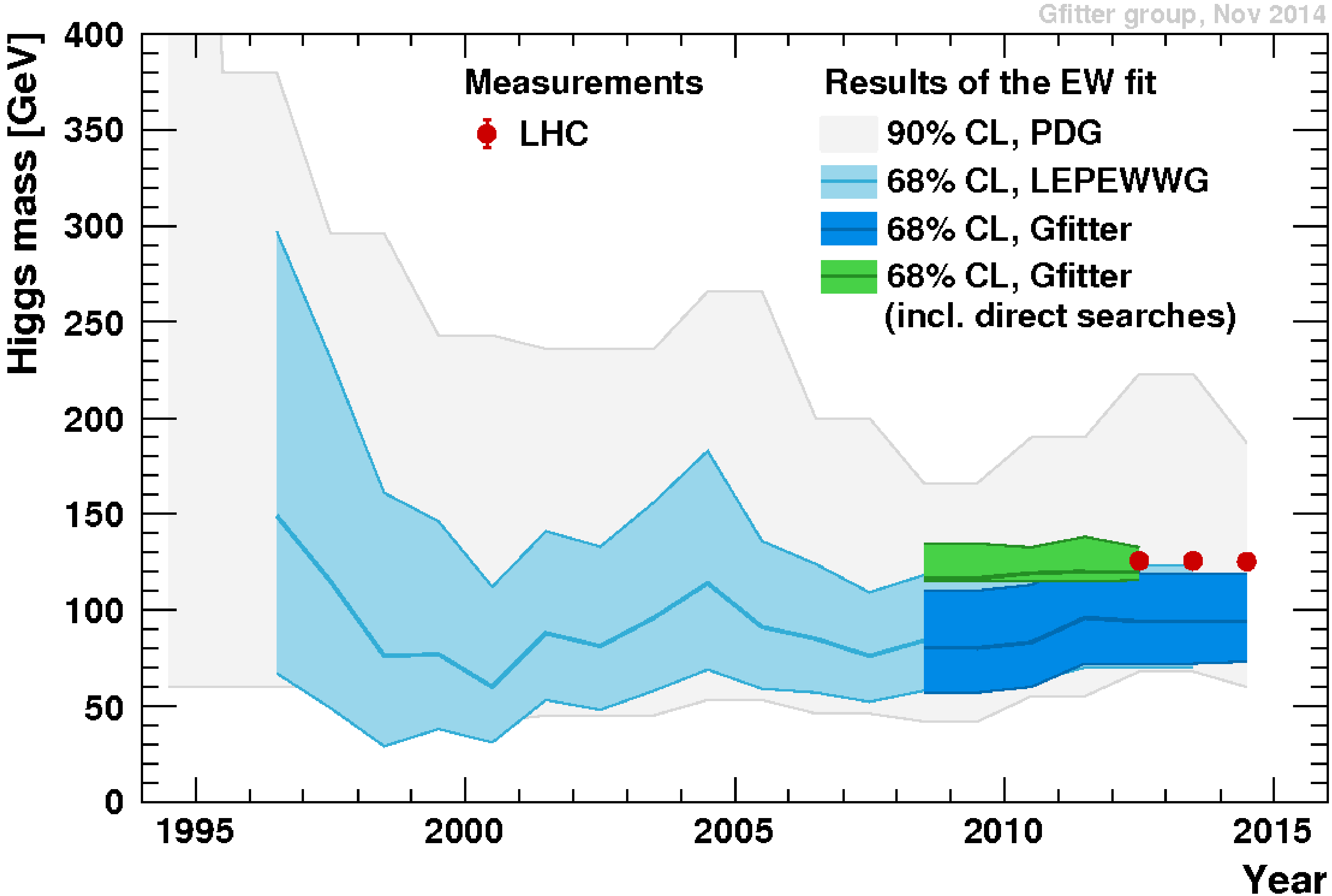
Precision theory for precise measurements
Quy-Nhon

26.09.2016

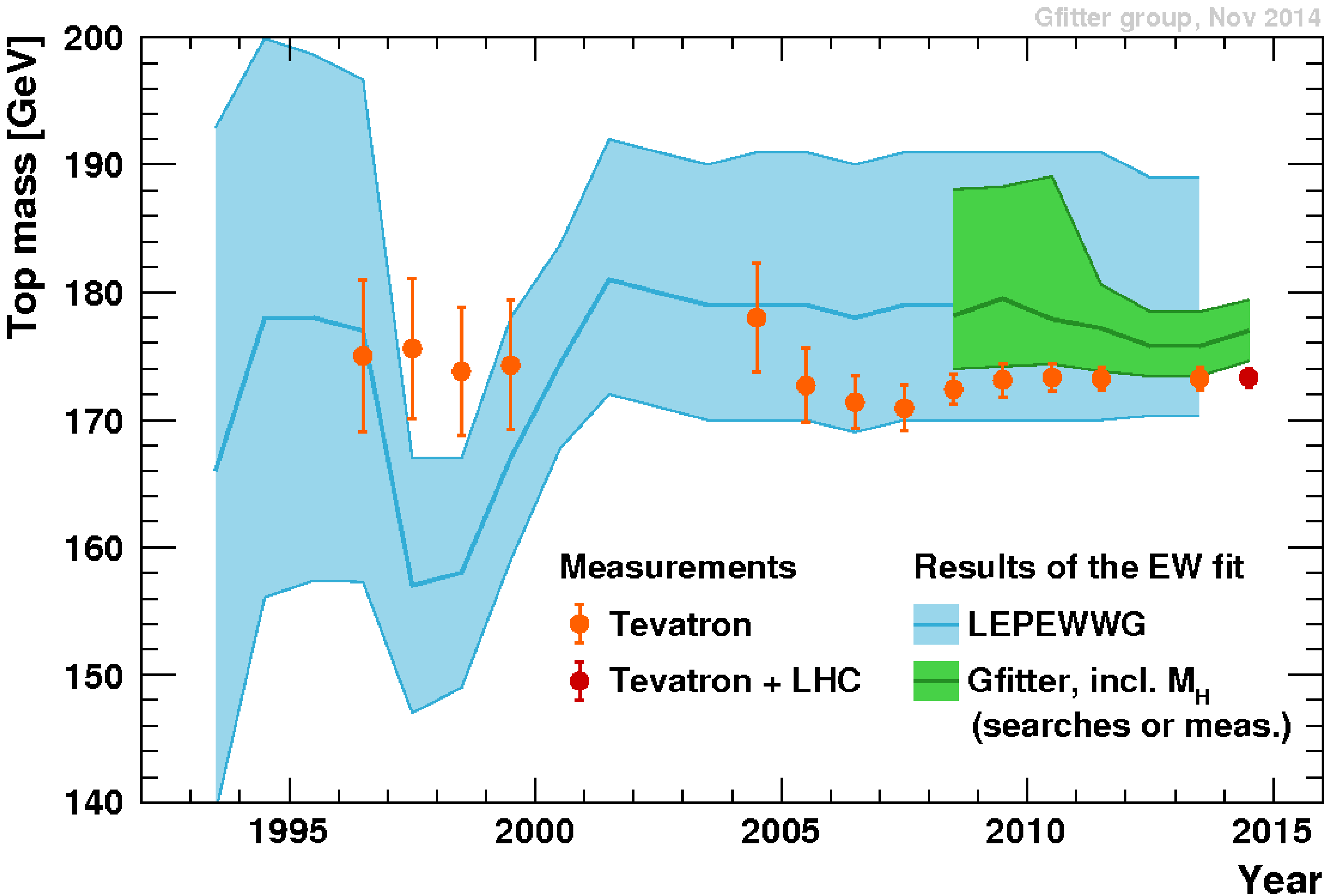
Overview


Precision Theory
Precise Measurements
The Electroweak Fit
Past:
Prediction of unknown parameters (m_t, M_H)
Today:
Consistency check of SM
Is New Physics hidden somewhere?
What are the allowed NP parameters?

Higgs Mass


Gfitter group, Nov 2014
Higgs mass [GeV]
400
350
300
250
200
150
100
50
0
1995
2000
2005
2010
2015
Year
Measurements
LHC
Results of the EW fit
90% CL, PDG
68% CL, LEPEWWG
68% CL, Gfitter
68% CL, Gfitter
(incl. direct searches)

Top Quark Mass



Content

The electroweak fit of the SM

New physics constraints

Example: The 2-Higgs-Doublet Model (2HDM)

Future Colliders

The Electroweak Fit

- Gauge & scalar sector is determined by 4 parameters (choose α, G_F, M_Z, M_H)

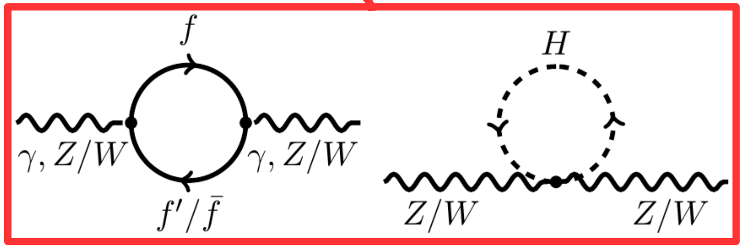
- Other parameters and observables related by theory

$$\sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2} \qquad M_W^2 \sin^2\theta_W = \frac{\pi\alpha}{\sqrt{2}\,G_F}$$

→ over-constrained theory

- Other SM parameters (quark masses, M_H, α_S) enter by radiative corrections

$$M_W^2 = \frac{M_Z^2}{2}\left(1 + \sqrt{1 - \frac{\sqrt{8}\,\pi\alpha(1 + \Delta r)}{G_F M_Z^2}}\right)$$



$$\sin^2\theta_{\mathrm{eff}}^f = \kappa_Z^f \sin^2\theta_W \qquad g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\mathrm{eff}}^f\right) \qquad g_{A,f} = \sqrt{\rho_Z^f}\, I_3^f$$

- G_F known with high precision → not varied in the fit

Theoretical Input

- Consistent set of full EW 2-loop calculations is available:
  - $\sin^2\Theta^f_{eff}$: effective weak mixing angle (from ratio g_V/g_A)
    (M. Awramik et al., PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009))
  - M_W: mass of the W boson, includes QCD corrections at 4-loop level
    (M. Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002))
  - Γ_f: partial widths of the Z boson (A. Freitas, JHEP 04, 070 (2014))
  - Radiator functions to Γ_f: QED and QCD corrections up to N^3LO
    (Baikov et al., PRL 108, 222003 (2012))
  - (Γ_W: width of the W boson, only 1-loop EW corrections included
    (Cho et al., JHEP 1111, 068 (2011))
- Estimate uncertainties due to unknown higher orders (using a geometric series):

$\delta_{\rm theo} M_W$	4 MeV	$\delta_{\rm theo}\Gamma_{u,c}$	0.12 MeV
$\delta_{\rm theo}\sin^2\theta^f_{\rm eff}$	$4.7\cdot 10^{-5}$	$\delta_{\rm theo}\Gamma_b$	0.21 MeV
$\delta_{\rm theo}\Gamma_{e,\mu,\tau}$	0.012 MeV	$\delta_{\rm theo}\sigma^0_{\rm had}$	6 pb
$\delta_{\rm theo}\Gamma_\nu$	0.014 MeV	$\delta_{\rm theo}\mathcal{R}_{V,A}$	$\sim\mathcal{O}(\alpha_s^4)$
$\delta_{\rm theo}\Gamma_{d,s}$	0.09 MeV	$\delta_{\rm theo} m_t$	0.5 GeV

Uncertainty on m_t: Relation between m_{pole} and measured mass

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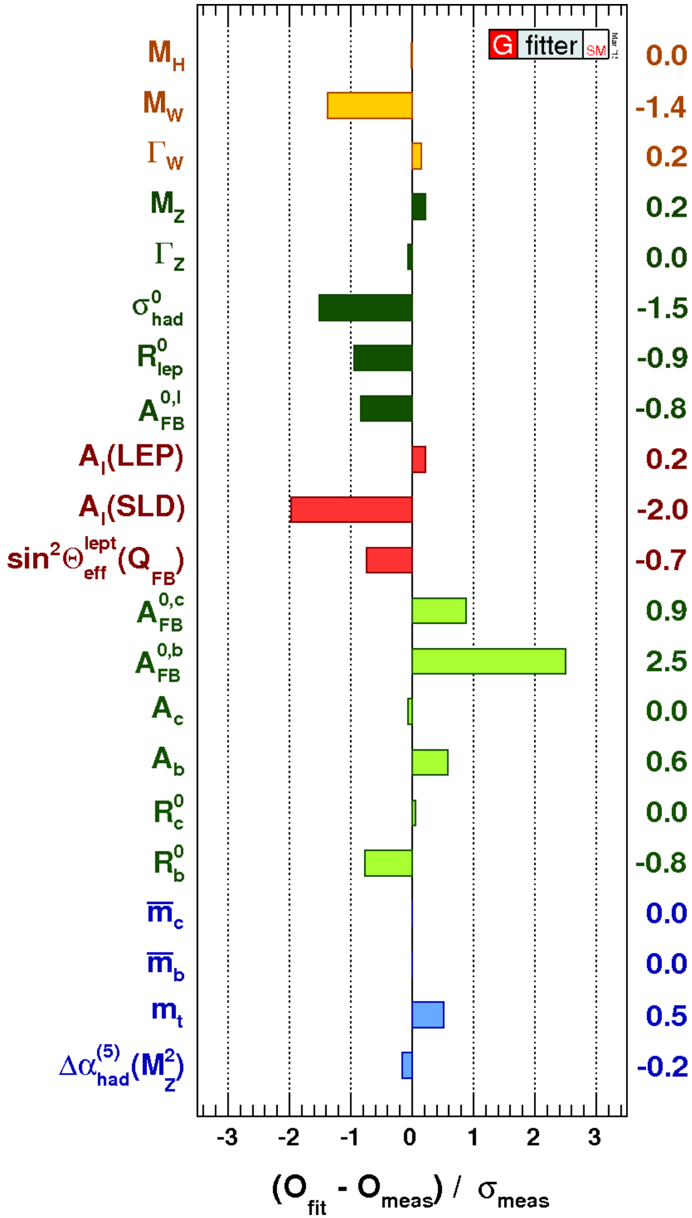
Experimental Input

Gfitter

- All SM parameters measured in experiments
- Input from e^+e^- colliders (LEP+SLC):
  - M_Z, M_W, Γ_W, Γ_Z
  - forward-backward asymmetries
  - partial-Z-width ratios R
- Input from hadron colliders (LHC+Tevatron):
  - M_W, Γ_W
  - M_H
  - m_t
- $\alpha_s(M_Z^2)$ enters the fit as free parameter
- Evolution of α parameterized with $\Delta\alpha^{(5)}_{had}$

M_H [GeV]	125.14 ± 0.24
M_W [GeV]	80.385 ± 0.015
Γ_W [GeV]	2.085 ± 0.042
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010
A_ℓ	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$
m_t [GeV]	173.34 ± 0.76
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2757 ± 10

Results

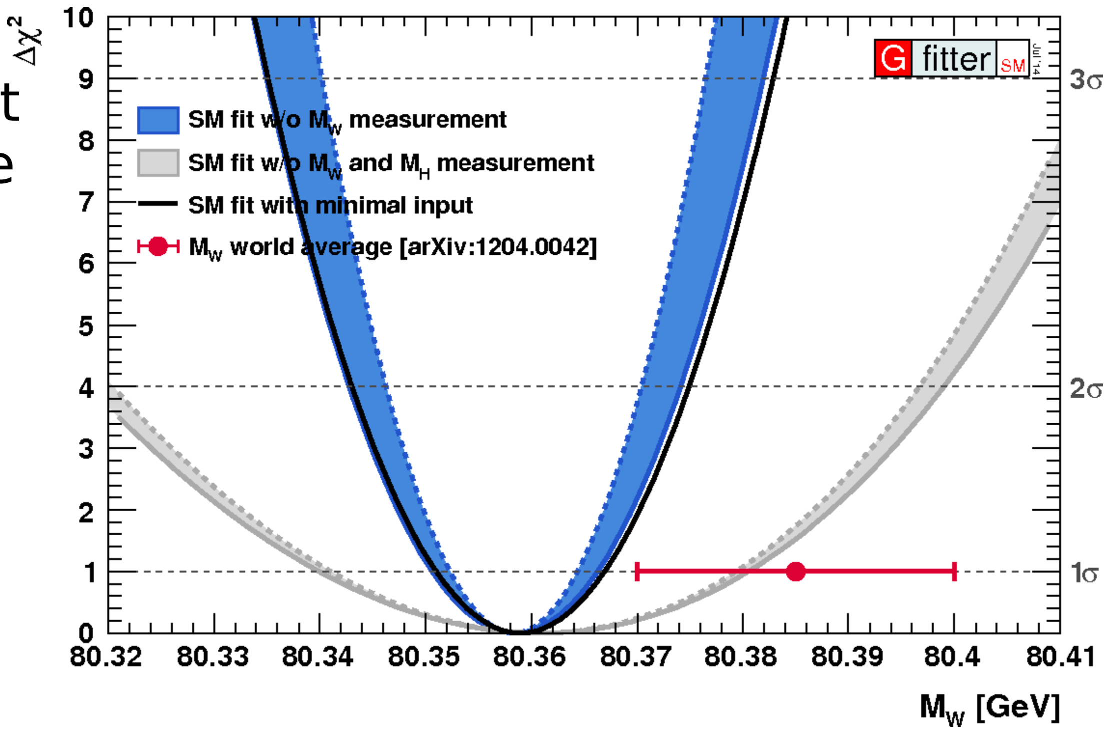


- Global χ^2=17.8 (for ndof = 14), p-value=0.21
- Predictions consistent with measurements
- Largest deviation for $A_{FB}^{0,b}$ ~ 2.5σ

Indirect Determination

- Perform fit without including direct measurement of observable in the fit

- Indirect determination of M_W more precise than direct measurement



$$M_W = 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W} \text{ GeV},$$

$$= 80.358 \pm 0.008_{\rm tot} \text{ GeV}.$$

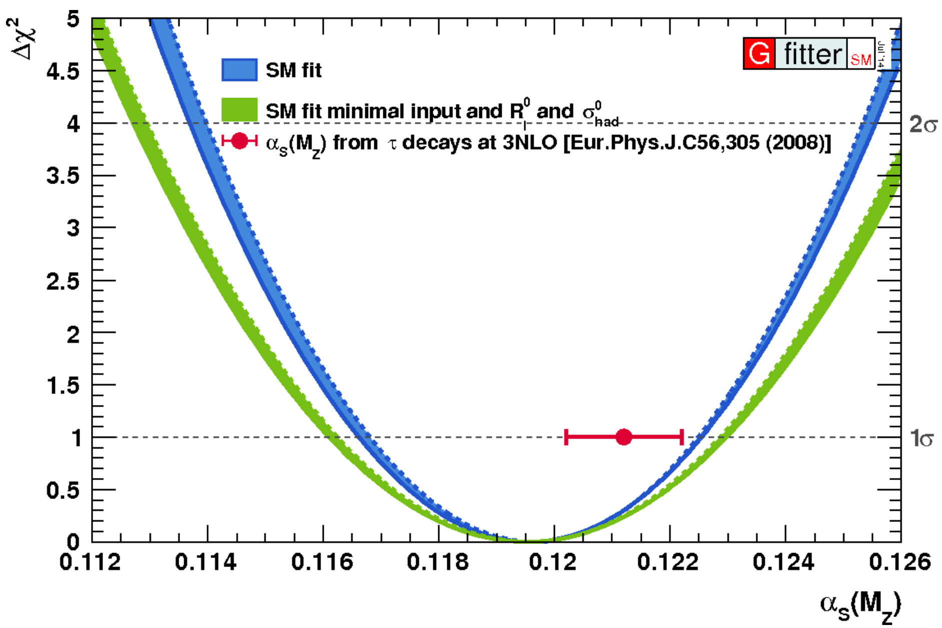
compared to world average:
80.385 ± 0.015 GeV
(difference of 1.6 σ)

Strong Coupling

Sensitive variables of the EW data to α_S:

- $R^0_{lep}=\Gamma_{had}/\Gamma_{lep}$ → $\alpha_S=0.1221(41)$
- Hadronic pole cross section σ^0_{had} → $\alpha_S=0.1055(70)$
- Total width Γ_Z → $\alpha_S=0.1182(46)$

$$\alpha_s(m_Z^2) = 0.1196 \pm 0.0028_{\rm exp} \pm 0.0006_{\rm QCD} \pm 0.0006_{\rm EW} = 0.1196 \pm 0.0030$$



Γ_Z might be affected by unknown New Physics contributions

→ Include Γ_{inv} as additional parameter in the fit:

$$\alpha_S(m_Z^2) = 0.1186 \pm 0.0034$$

$$\Gamma_{\rm inv} = 503.0 \pm 2.5 {\rm MeV}$$

(PDG value: Γ_{inv} = 499.0 ± 1.5 MeV)

Indirect Determination

Other indirect determinations:

$$M_H = 93^{+25}_{-21}\,\text{GeV}$$

direct value: 125.09 ± 0.24 GeV

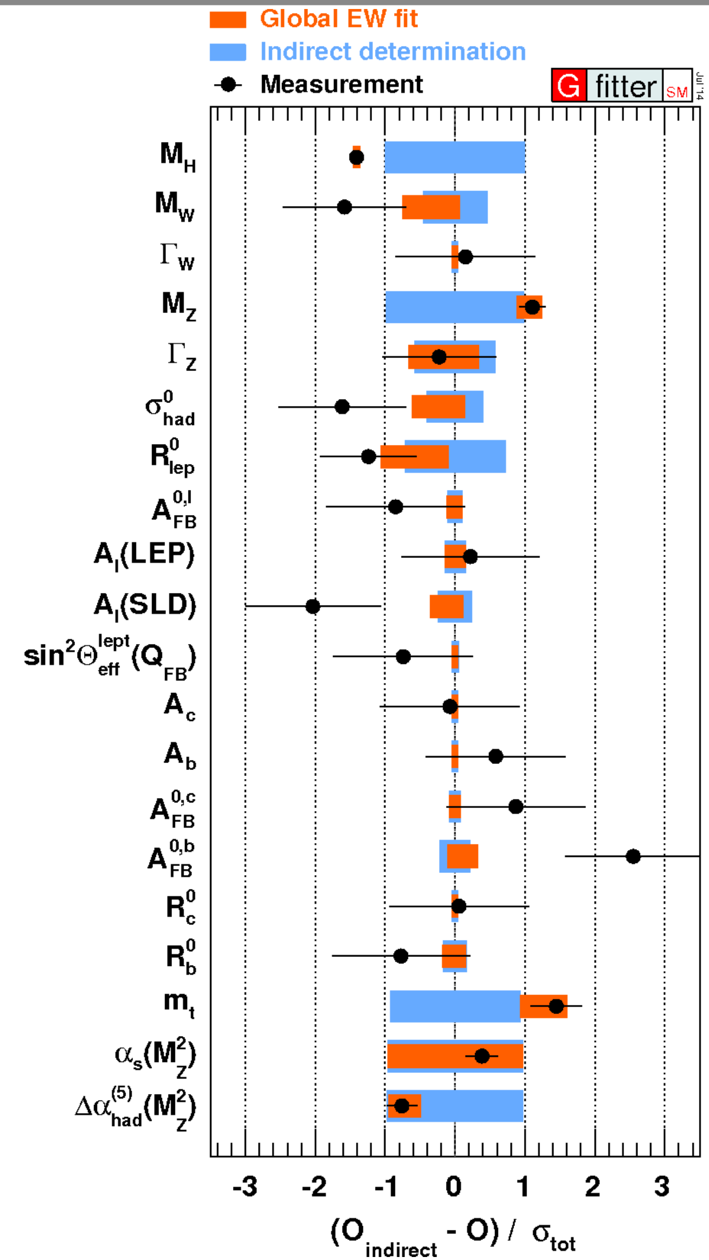
$$m_t = 177.0^{+2.3}_{-2.4}\,\text{GeV}$$

direct value: 173.34 ± 0.76 GeV

direct value from cross section:

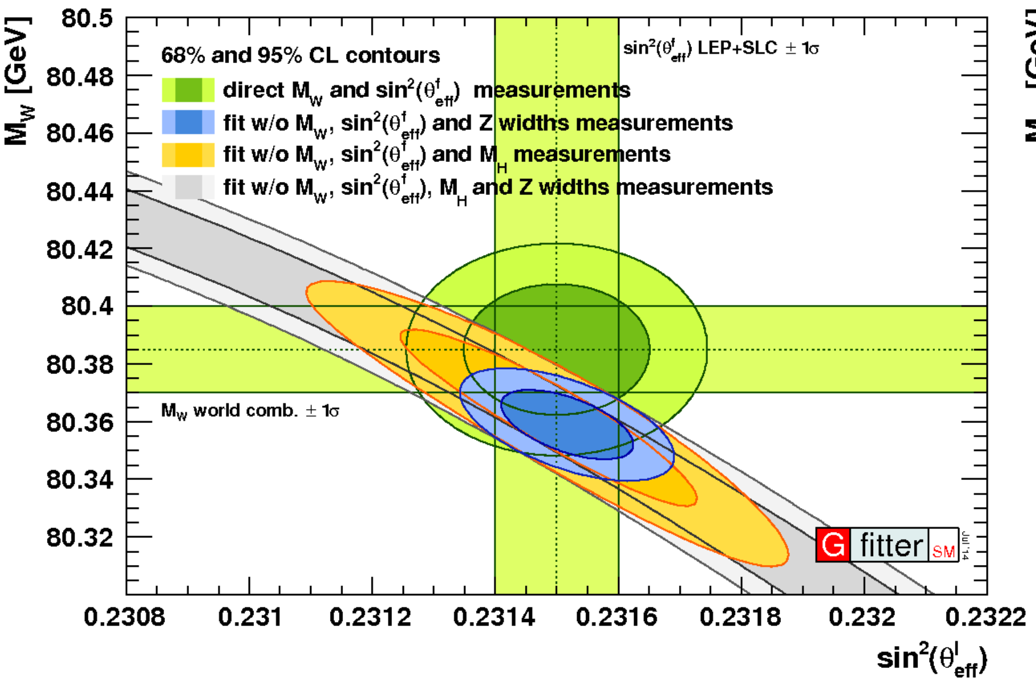
173.68 ± 0.20 (stat) + 1.58 -0.97 (syst) GeV

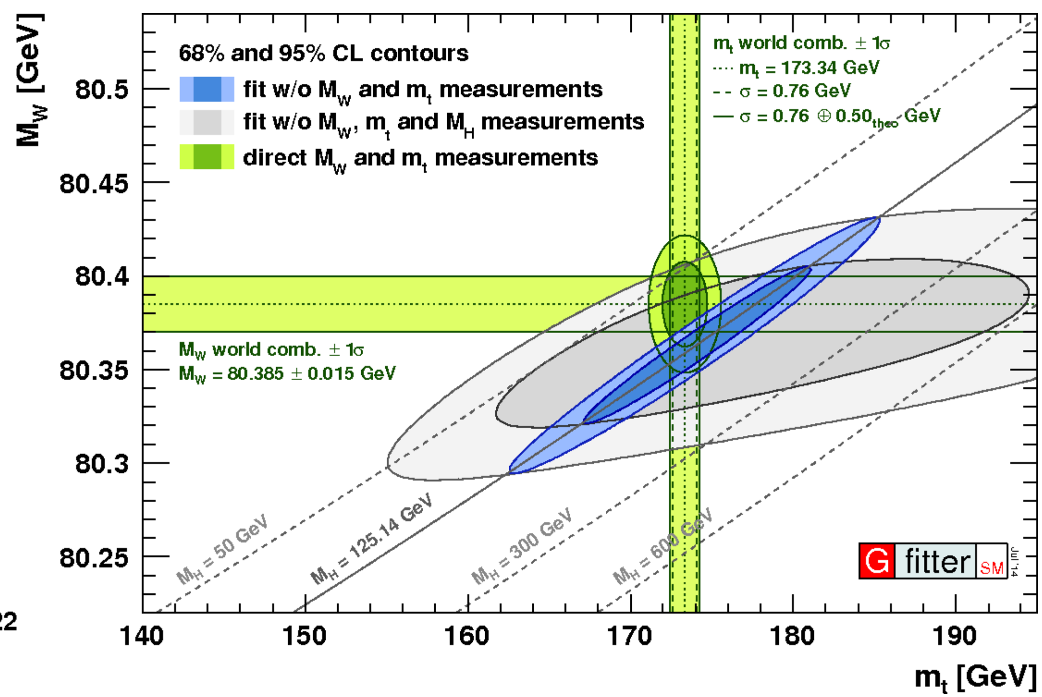
(arXiv:1603.06536)



2D Scans

- Testing simultaneously two sensitive observables to New Physics effects
- Determine χ^2 for each point in 2D space





- Increased precision due to knowledge of M_H
- Good consistency of SM predictions and measurements

Oblique Parameters

New Physics in electroweak sector parameterized with 3 parameters:

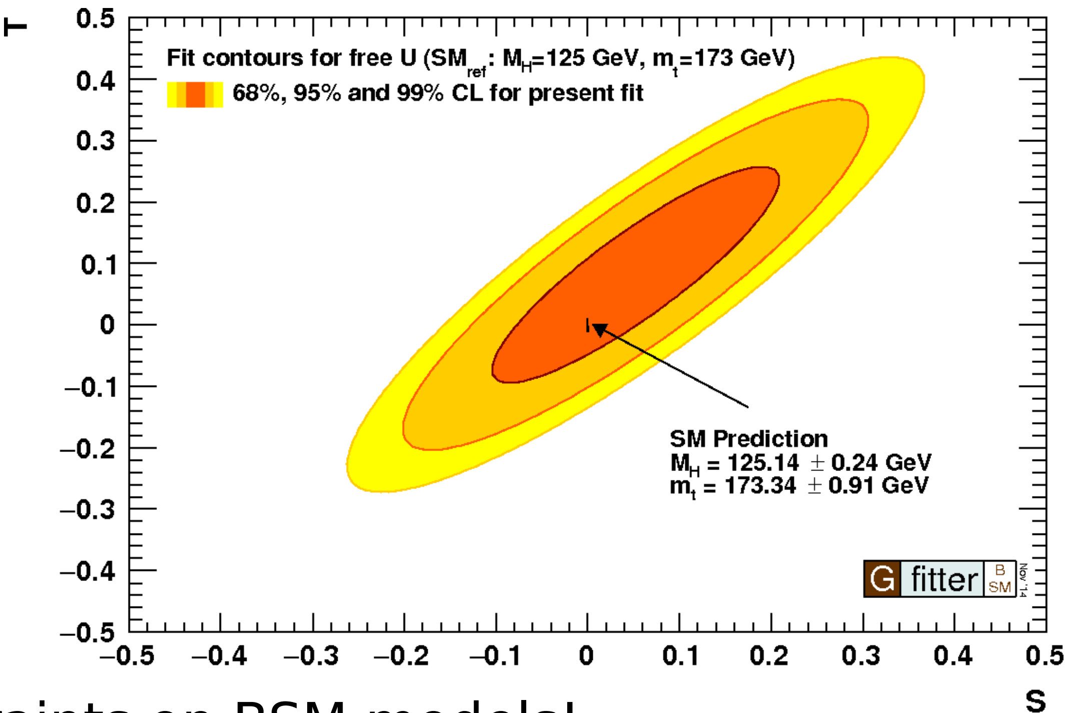
- S: changes to neutral currents
- T: changes to difference between charged and neutral currents
- U: changes to W width and mass

In SM: S=T=U=0

Fit result (for fixed M_H=125 GeV and m_t=173 GeV):

$$S = 0.05 \pm 0.11$$
$$T = 0.09 \pm 0.13$$
$$U = 0.01 \pm 0.11$$

(with large correlations)



No hint for New Physics but constraints on BSM models!

Example: 2HDM

The 2-Higgs-Doublet Model

- Simple extension of the SM Higgs sector
- One additional Higgs doublet → 5 Higgs bosons:

  h_0, H_0, A_0, H^+, H^-
- Additional free parameters:
  - $\tan\beta = v_2/v_1$
  - α: mixing angle of the neutral Higgs fields
  - M_{12}^2: mass parameter of the mixed term $\Phi_1^\dagger\Phi_2$, soft breaking scale

How is parameter space constrained by precision measurements?

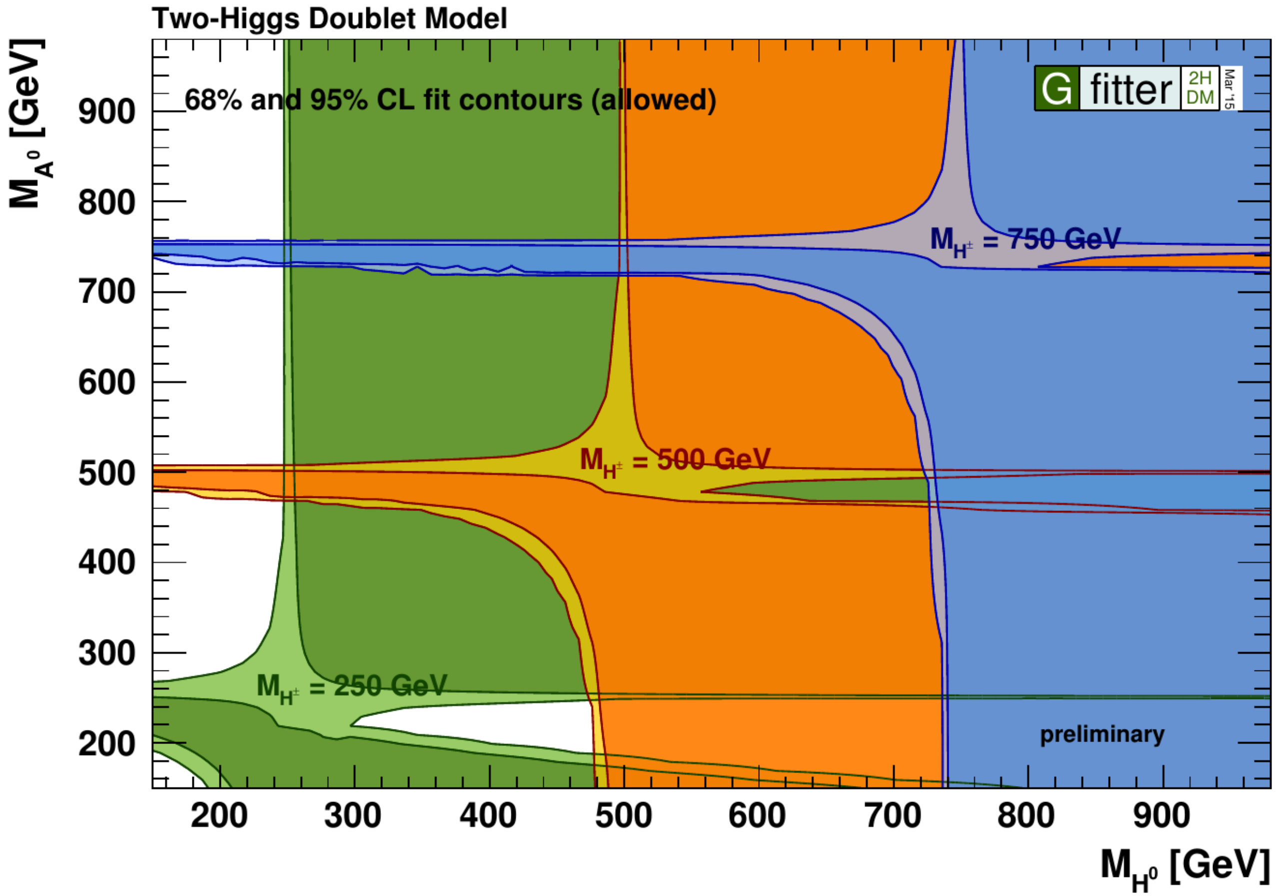
2HDM: Types

Four CP conserving types of the 2HDM with different Yukawa couplings:

- **Type I:**
  - Only one Higgs doublet couples to fermions
- **Type II:**
  - One Higgs couples to up-type quarks and leptons
  - Second Higgs couples to down-type quarks and leptons
- **Lepton specific:**
  - As type I model, but with leptons coupling to other Higgs doublet than the quarks
- **Flipped:**
  - As type II, but with couplings of up- and down-type exchanged

2HDM: EW Constraints

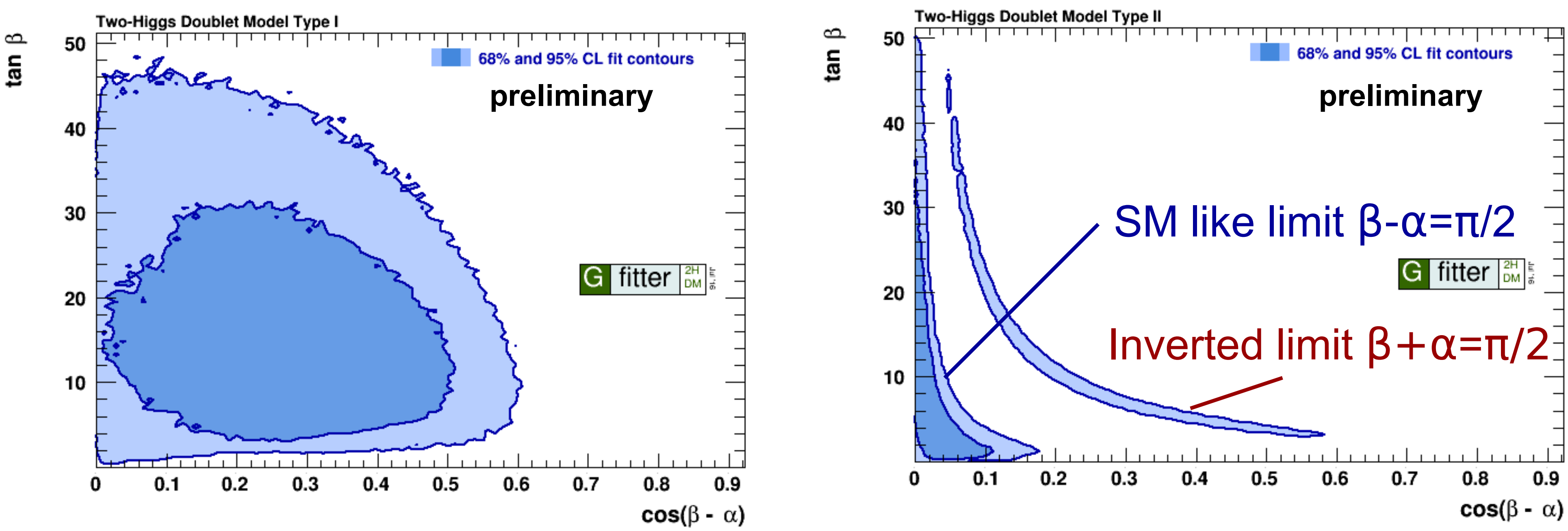
- Use STU formalism to constrain 2HDM
- Assume: discovered 125 GeV Higgs boson is light h_0
- Keep tan β and α free (not constraint by EW data)



Only weak constraints on mass ratios from electroweak data

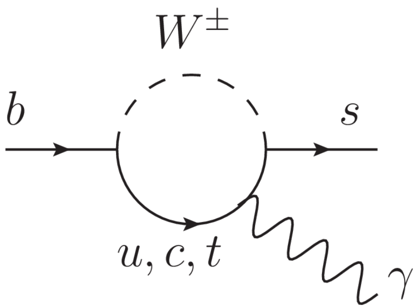
2HDM: Higgs BRs

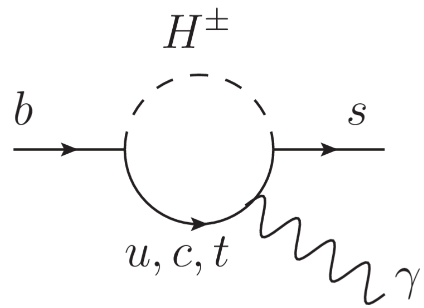
- Measured Higgs branching ratios can constrain 2HDM
- Predictions for Higgs BRs from 2HDMC (D. Eriksson et al., CPC 181, 189 (2010))
- Importance sampling algorithm MultiNest (F. Feroz et al., arXiv:1306.2144) used to scan parameter space



2HDM: Flavor

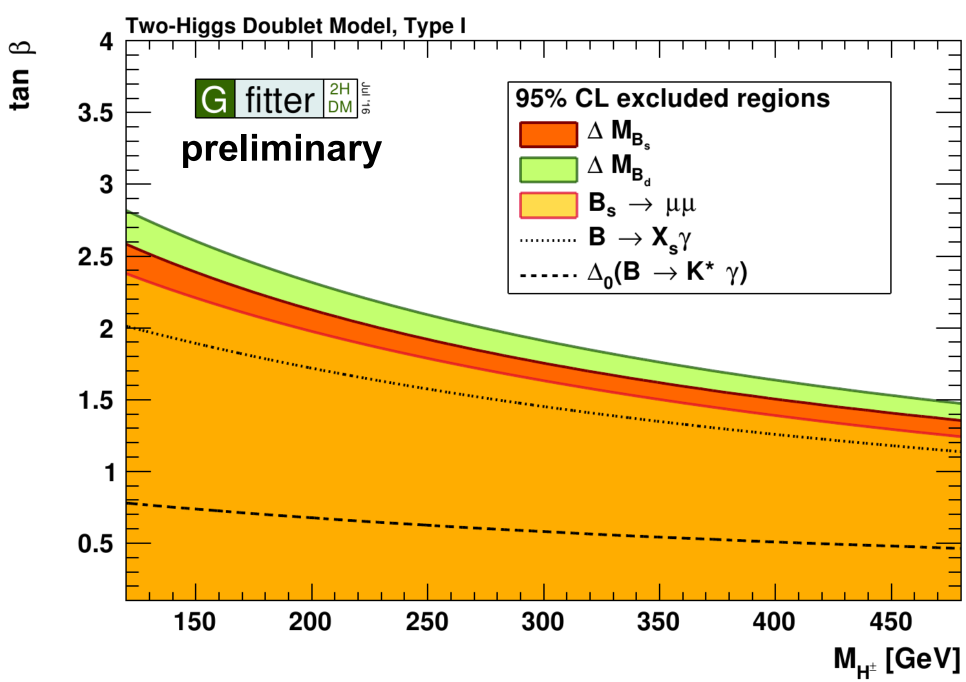
Flavor observables may be affected by charged Higgs contributions

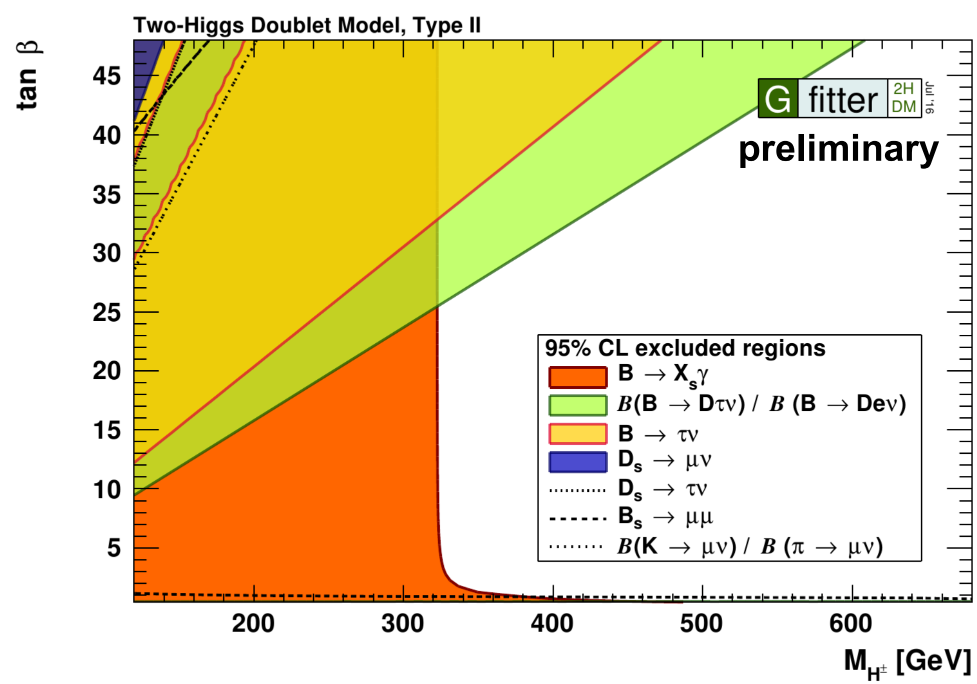




F. Mahmoudi, CPC 180, 1579 (2009)
M. Misiak et al., PRL 114, 221801 (2015)
T. Hermann, M. Misiak, M. Steinhauser, JHEP 11, 036 (2012)

Requires precise theory predictions and CKM matrix elements (CKMfitter)





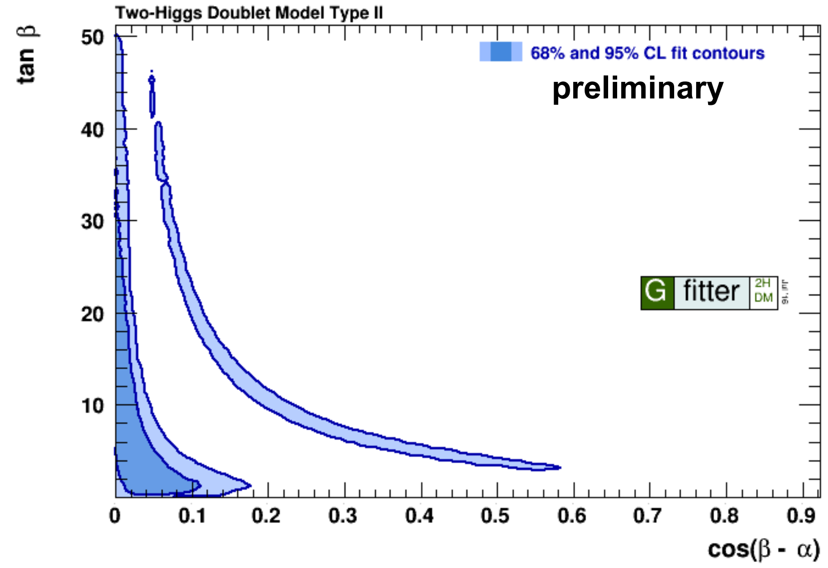
Limit on $M(H^{\pm})$ from $b \to s+\gamma$ only in Type II 2HDM

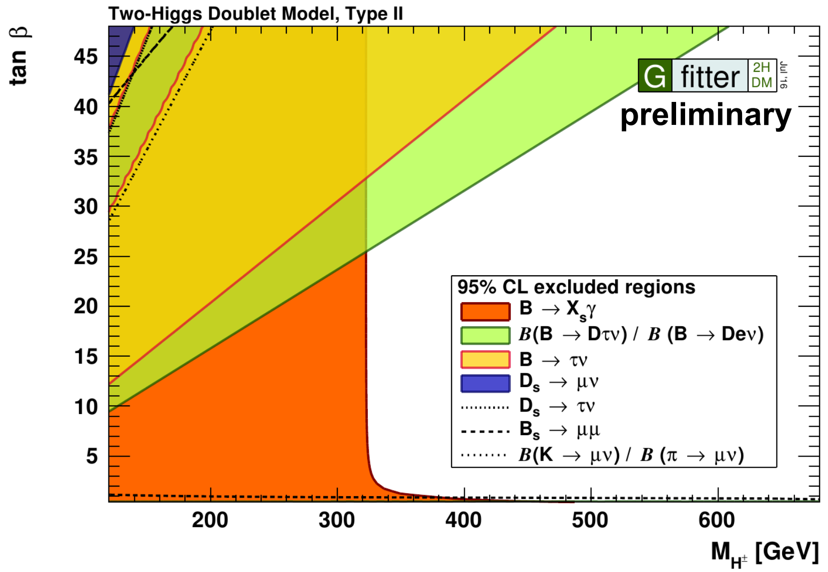
Summary: 2HDM

Two-Higgs-Doublet model constrained by:

- Electroweak precision data
- Higgs coupling measurements
- Flavor data

Combination of all available data allows to derive tight constrains on allowed parameter space





Future Colliders

- LHC and future electron colliders could improve EW measurements
- **Future LHC:**
  - Run 2 and 3 data
  - 300 fb^{-1}
  - More precise t, H and W masses
- **ILC:**
  - WW, $t\bar{t}$ threshold scans

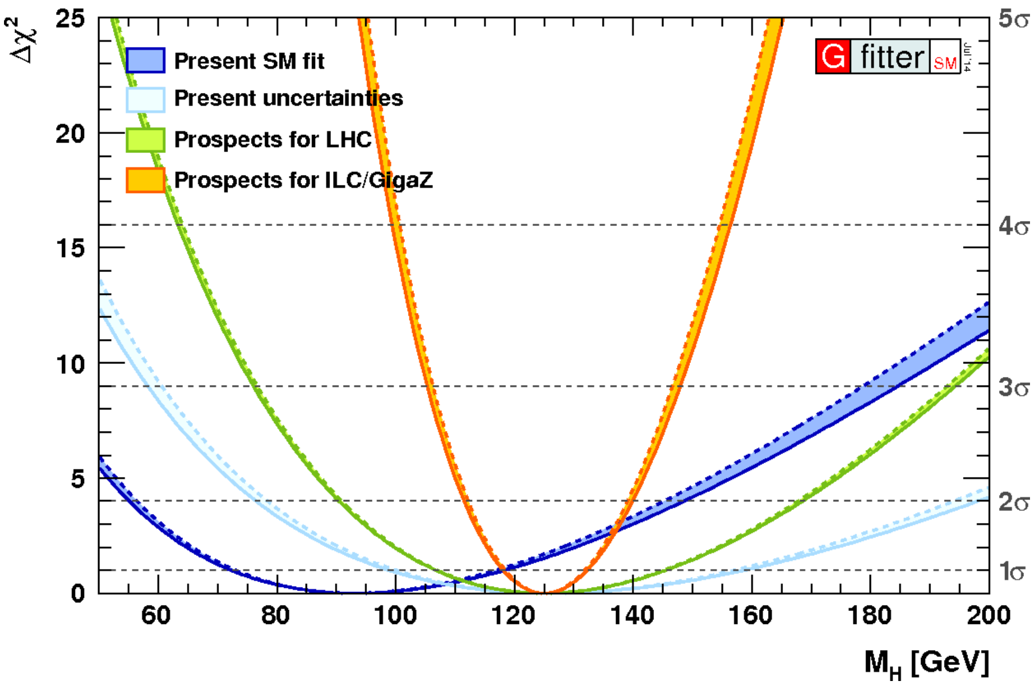
    → t and W masses with high precision
  - GigaZ:

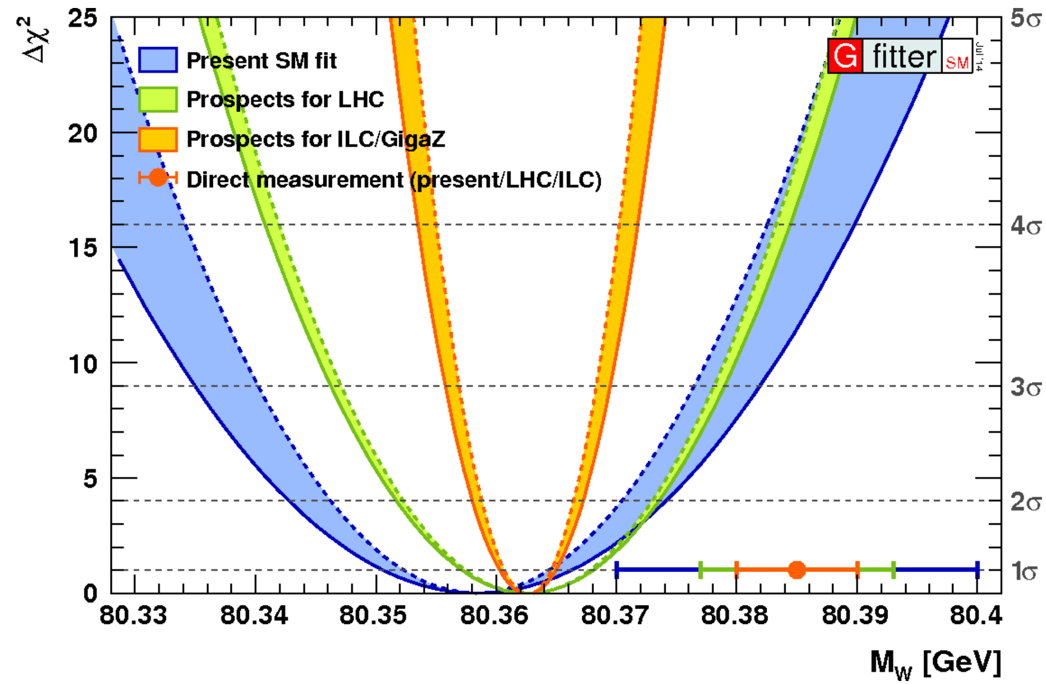
    → Z pole measurements
- Reduced theory uncertainties from 3-loop calculations

  → assume $\delta_{theo} M_W$ and $\delta_{theo} \sin^2\Theta^f_{eff}$ reduced by factor 4-5

Parameter	Present	LHC	ILC/GigaZ
M_H [GeV]	0.2	< 0.1	< 0.1
M_W [MeV]	15	8	5
M_Z [MeV]	2.1	2.1	2.1
m_t [GeV]	0.8	0.6	0.1
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	16	16	1.3
$\Delta\alpha^5_{\rm had}(M_Z^2)$ $[10^{-5}]$	10	4.7	4.7
R^0_l $[10^{-3}]$	25	25	4

Future Masses

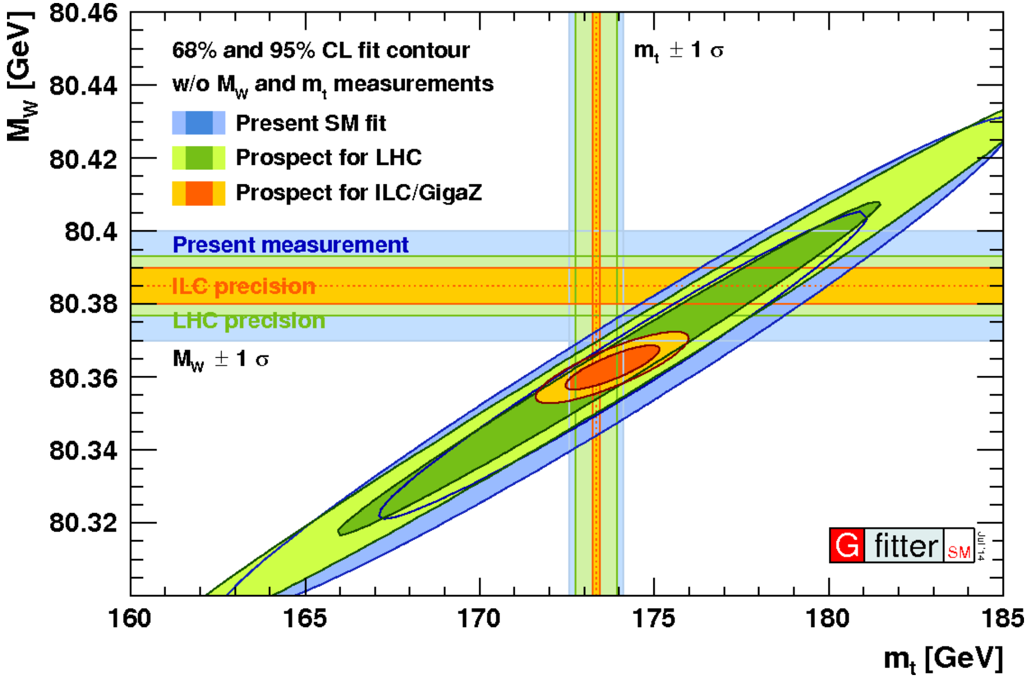


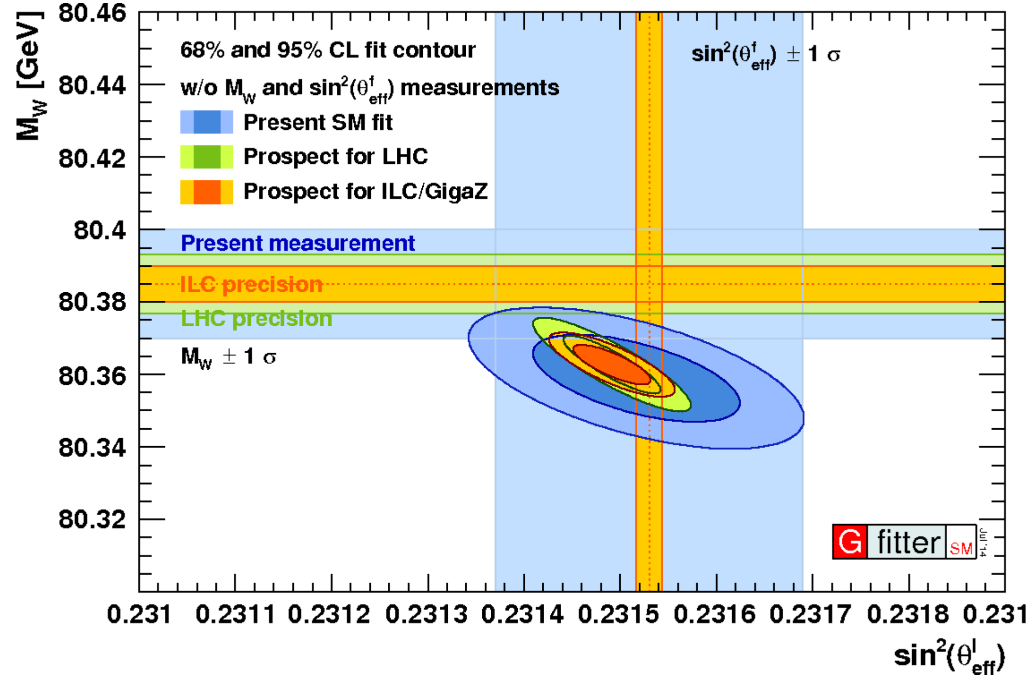


- Central values adjusted to reproduce M_H=125 GeV
- Expected uncertainty of 7 GeV for ILC
- Indirect determination of M_H will not compete with direct measurement

- Expected uncertainty of direct and indirect M_W determination improved by factor ~3.
- For unchanged central values: 3σ discrepancy possible

Future 2D Scans

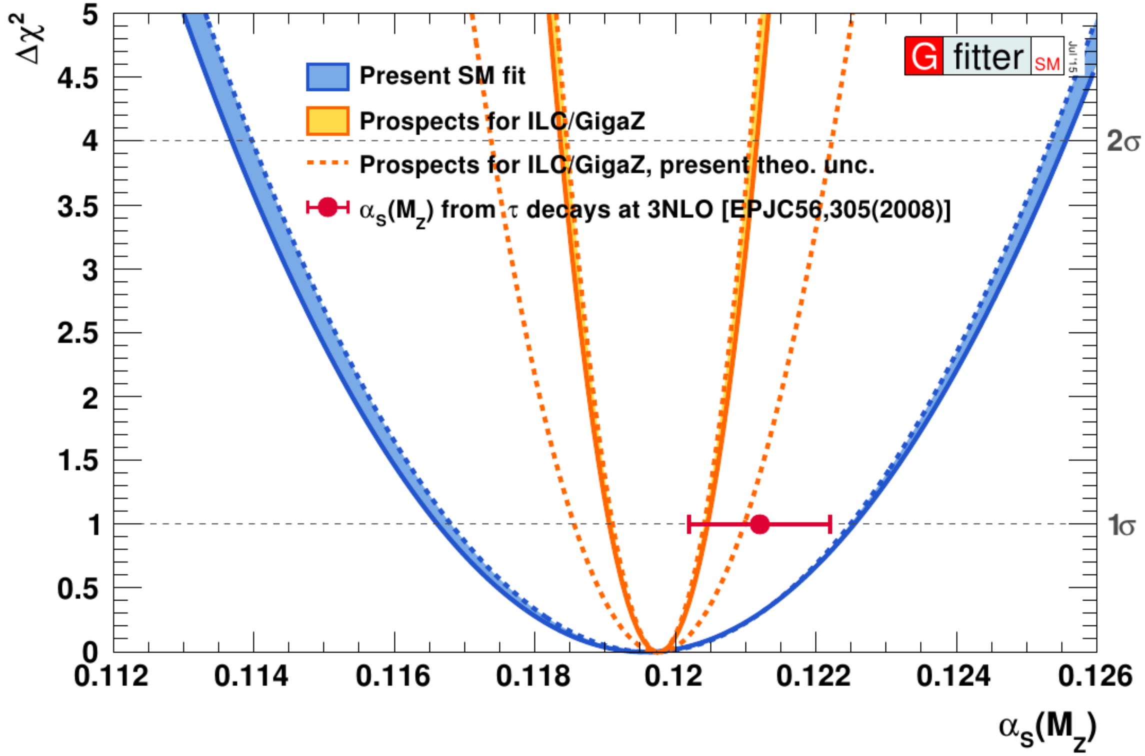




- m_t assumed to be measured with 0.1 GeV precision at ILC
- Indirect measurement of m_t with precision below 1 GeV reachable

- Improvements on m_t and $\Delta\alpha^{(5)}_{had}$ could lead to improved determination of weak mixing angle by factor 3 already with more LHC data
- Direct measurement at ILC will gain more than factor 10 in precision

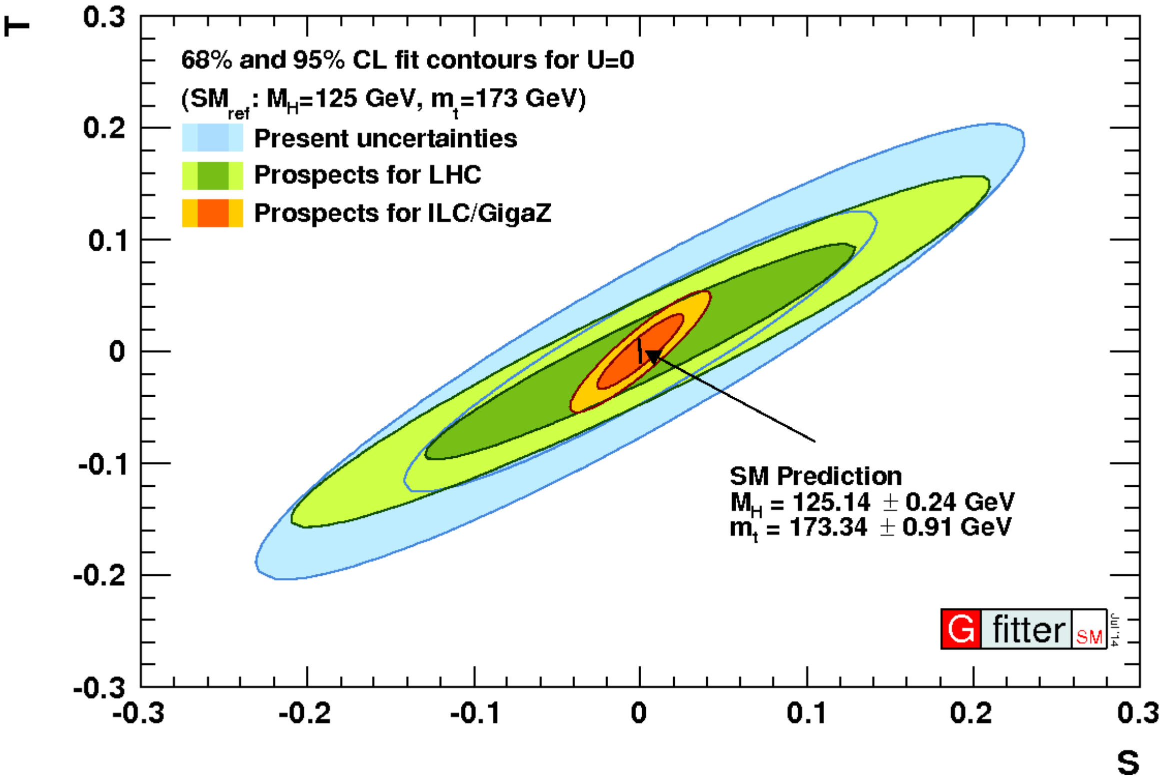
Prospect for α_S



Better measurement of masses at ILC and reduced theory uncertainties might lead to uncertainty on α_S of:

$$\begin{aligned}\Delta\alpha_s &= 0.00065_{\text{exp}} \oplus 0.00023_{\text{QCD}} \oplus 0.00025_{\text{EW}} \\ &= 0.00070\end{aligned}$$

Prospect for STU



- Central values adjusted to reproduce M_H=125 GeV for future scenarios, U=0
- Only minor improvement with expected LHC data
- Expected improvement of factor 3 to 4 at ILC

Conclusion

Electroweak fit: combination of precision theory with precise measurements

- Probes SM at high precision
- Combination of EW and Higgs data can be used to constrain New Physics
- So far: consistency of all SM measurements

Outlook:

- LHC and future e^+e^- colliders could improve measurements
- Looking forward to new W mass measurements from LHC and Tevatron
- EW fit important to test SM with ultra-high precision in the future

BACKUP

Fit Results

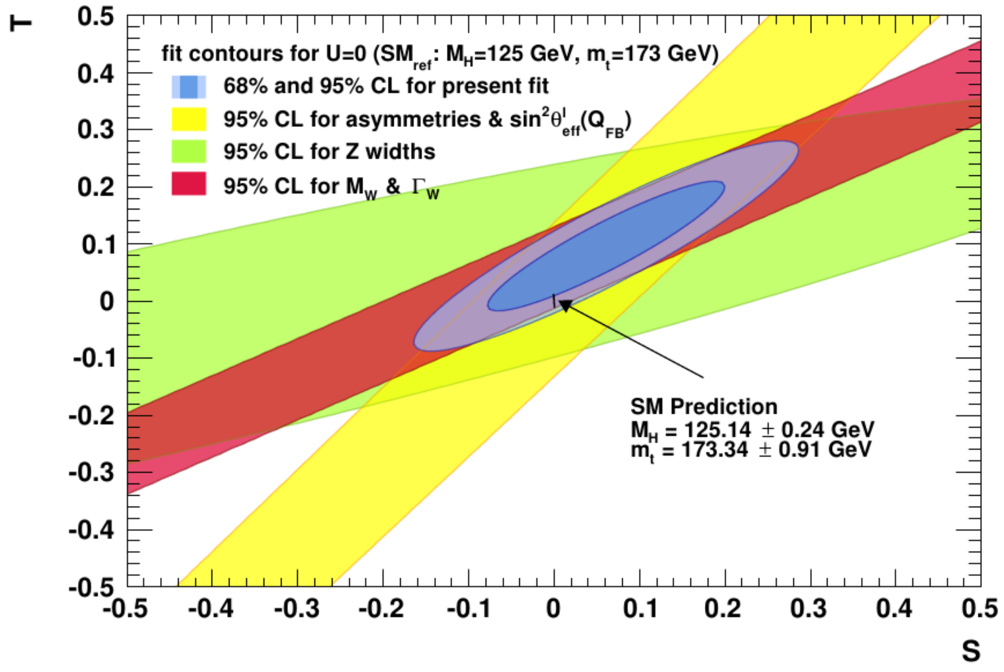
Parameter	Input value	Free in fit	Fit Result	w/o exp. input in line	w/o exp. input in line, no theo. unc
M_H [GeV]$^{(\circ)}$	125.14 ± 0.24	yes	125.14 ± 0.24	93^{+25}_{-21}	93^{+24}_{-20}
M_W [GeV]	80.385 ± 0.015	–	80.364 ± 0.007	80.358 ± 0.008	80.358 ± 0.006
Γ_W [GeV]	2.085 ± 0.042	–	2.091 ± 0.001	2.091 ± 0.001	2.091 ± 0.001
M_Z [GeV]	91.1875 ± 0.0021	yes	91.1880 ± 0.0021	91.200 ± 0.011	91.2000 ± 0.010
Γ_Z [GeV]	2.4952 ± 0.0023	–	2.4950 ± 0.0014	2.4946 ± 0.0016	2.4945 ± 0.0016
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	–	41.484 ± 0.015	41.475 ± 0.016	41.474 ± 0.015
R^0_ℓ	20.767 ± 0.025	–	20.743 ± 0.017	20.722 ± 0.026	20.721 ± 0.026
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	–	0.01626 ± 0.0001	0.01625 ± 0.0001	0.01625 ± 0.0001
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	–	0.1472 ± 0.0005	0.1472 ± 0.0005	0.1472 ± 0.0004
$\sin^2\theta^\ell_{\rm eff}(Q_{\rm FB})$	0.2324 ± 0.0012	–	0.23150 ± 0.00006	0.23149 ± 0.00007	0.23150 ± 0.00005
A_c	0.670 ± 0.027	–	0.6680 ± 0.00022	0.6680 ± 0.00022	0.6680 ± 0.00016
A_b	0.923 ± 0.020	–	0.93463 ± 0.00004	0.93463 ± 0.00004	0.93463 ± 0.00003
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	–	0.0738 ± 0.0003	0.0738 ± 0.0003	0.0738 ± 0.0002
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	–	0.1032 ± 0.0004	0.1034 ± 0.0004	0.1033 ± 0.0003
R^0_c	0.1721 ± 0.0030	–	$0.17226^{+0.00009}_{-0.00008}$	0.17226 ± 0.00008	0.17226 ± 0.00006
R^0_b	0.21629 ± 0.00066	–	0.21578 ± 0.00011	0.21577 ± 0.00011	0.21577 ± 0.00004
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	yes	$1.27^{+0.07}_{-0.11}$	–	–
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	yes	$4.20^{+0.17}_{-0.07}$	–	–
m_t [GeV]	173.34 ± 0.76	yes	$173.81 \pm 0.85^{(\bigtriangledown)}$	$177.0^{+2.3}_{-2.4}{}^{(\bigtriangledown)}$	177.0 ± 2.3
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	2757 ± 10	yes	2756 ± 10	2723 ± 44	2722 ± 42
$\alpha_s(M_Z^2)$	–	yes	0.1196 ± 0.0030	0.1196 ± 0.0030	0.1196 ± 0.0028

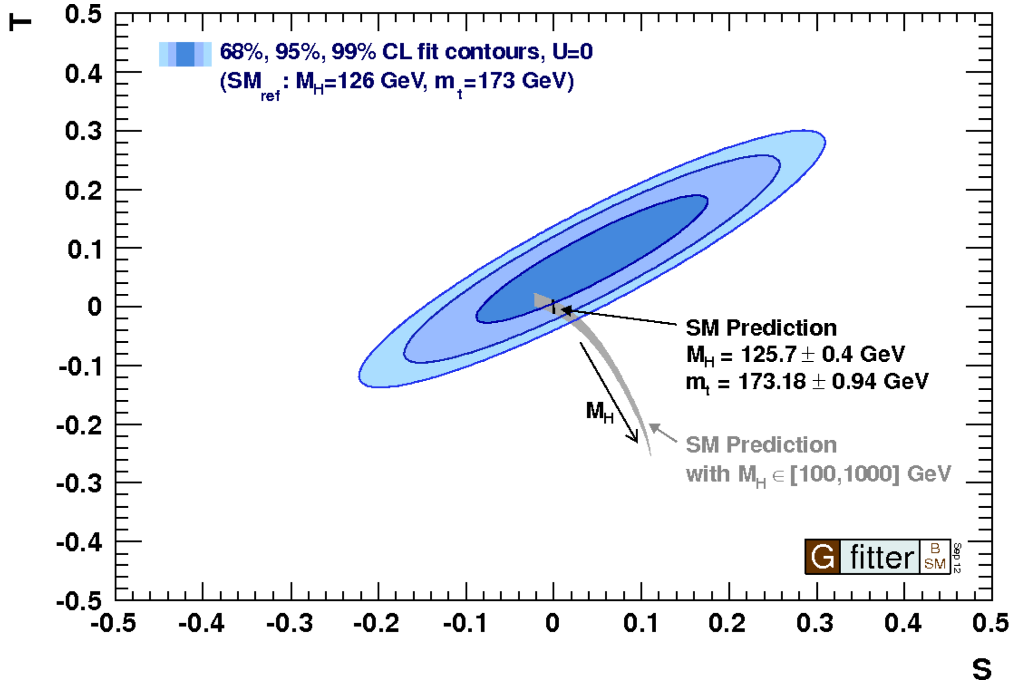
$^{(\circ)}$Average of the ATLAS and CMS measurements assuming no correlation of the systematic uncertainties.
$^{(\star)}$Average of the LEP and SLD A_ℓ measurements, used as two measurements in the fit.
$^{(\bigtriangledown)}$The theoretical top mass uncertainty of 0.5 GeV is excluded.
$^{(\dagger)}$In units of 10^{-5}.
$^{(\triangle)}$Rescaled due to α_s dependence.

STU scans

Correlations between S,T and U:

	S	T	U
S	1	0.891	-0.540
T		1	-0.803
U			1





2HDM Types

Parameterization for various 2HDMs (taken from arXiv:1106.0034)

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Future Colliders

Parameter	δ_{meas}	$\delta_{\text{fit}}^{\text{tot}}$	$\delta_{\text{fit}}^{\text{theo}}$	$\delta_{\text{fit}}^{\text{exp}}$	Experimental uncertainty source [$\pm 1\sigma$] δM_W	δM_Z	δm_t	$\delta \sin^2\theta^f_{\text{eff}}$	$\delta \Delta\alpha_{\text{had}}$	$\delta \alpha_S$
Present uncertainties										
M_H [GeV]	0.2	$^{+33}_{-27}$	$^{+10}_{-8}$	$^{+31}_{-26}$	$^{+28}_{-23}$	$^{+5}_{-4}$	$^{+10}_{-7}$	$^{+29}_{-23}$	$^{+7}_{-5}$	$^{+4}_{-3}$
M_W [MeV]	15	7.8	5.0	6.0	–	2.5	4.3	5.1	1.6	2.5
M_Z [MeV]	2.1	12.0	3.7	11.4	10.5	–	3.5	11.2	2.2	1.4
m_t [GeV]	0.8	2.5	0.6	2.4	2.3	0.4	–	2.3	0.5	0.6
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	16	6.6	4.9	4.5	3.7	1.2	2.0	–	3.4	1.2
$\Delta\alpha_{\text{had}}$ $^{(\circ)}$	10	44	13	42	31	6	10	41	–	2
LHC prospects										
M_H [GeV]	< 0.1	$^{+21}_{-18}$	$^{+4}_{-3}$	$^{+20}_{-18}$	$^{+17}_{-14}$	$^{+6}_{-5}$	$^{+8}_{-7}$	$^{+18}_{-16}$	$^{+3}_{-2}$	$^{+5}_{-4}$
M_W [MeV]	8	5.5	1.8	5.2	–	2.5	3.5	4.8	0.8	2.6
M_Z [MeV]	2.1	7.2	1.4	7.0	6.0	–	2.8	5.9	0.8	1.9
m_t [GeV]	0.6	1.5	0.2	1.5	1.3	0.4	–	1.2	0.2	0.5
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	16	3.0	1.1	2.8	2.5	1.1	1.4	–	1.5	0.9
$\Delta\alpha_{\text{had}}$ $^{(\circ)}$	4.7	36	6	36	25	9	12	35	–	5
ILC/GigaZ prospects										
M_H [GeV]	< 0.1	$^{+7.3}_{-6.9}$	$^{+2.5}_{-2.4}$	$^{+6.8}_{-6.5}$	$^{+2.5}_{-3.6}$	$^{+4.3}_{-4.0}$	$^{+0.3}_{-0.2}$	$^{+3.4}_{-2.9}$	$^{+4.3}_{-4.0}$	$^{+0.3}_{-0.3}$
M_W [MeV]	5	2.3	1.3	1.9	–	1.7	0.1	1.2	0.6	0.3
M_Z [MeV]	2.1	2.7	1.0	2.5	2.4	–	0.1	1.3	1.9	0.2
m_t [GeV]	0.1	0.8	0.2	0.7	0.6	0.5	–	0.3	0.4	0.2
$\sin^2\theta^\ell_{\text{eff}}$ $^{(\circ)}$	1.3	2.3	1.0	2.0	1.7	1.2	0.1	–	1.5	0.1
$\Delta\alpha_{\text{had}}$ $^{(\circ)}$	4.7	6.4	3.0	5.6	2.6	4.2	0.2	3.8	–	0.2

$^{(\circ)}$In units of 10^{-5}. $^{(\star)}$In units of 10^{-4}