News From The Global Electroweak Fit

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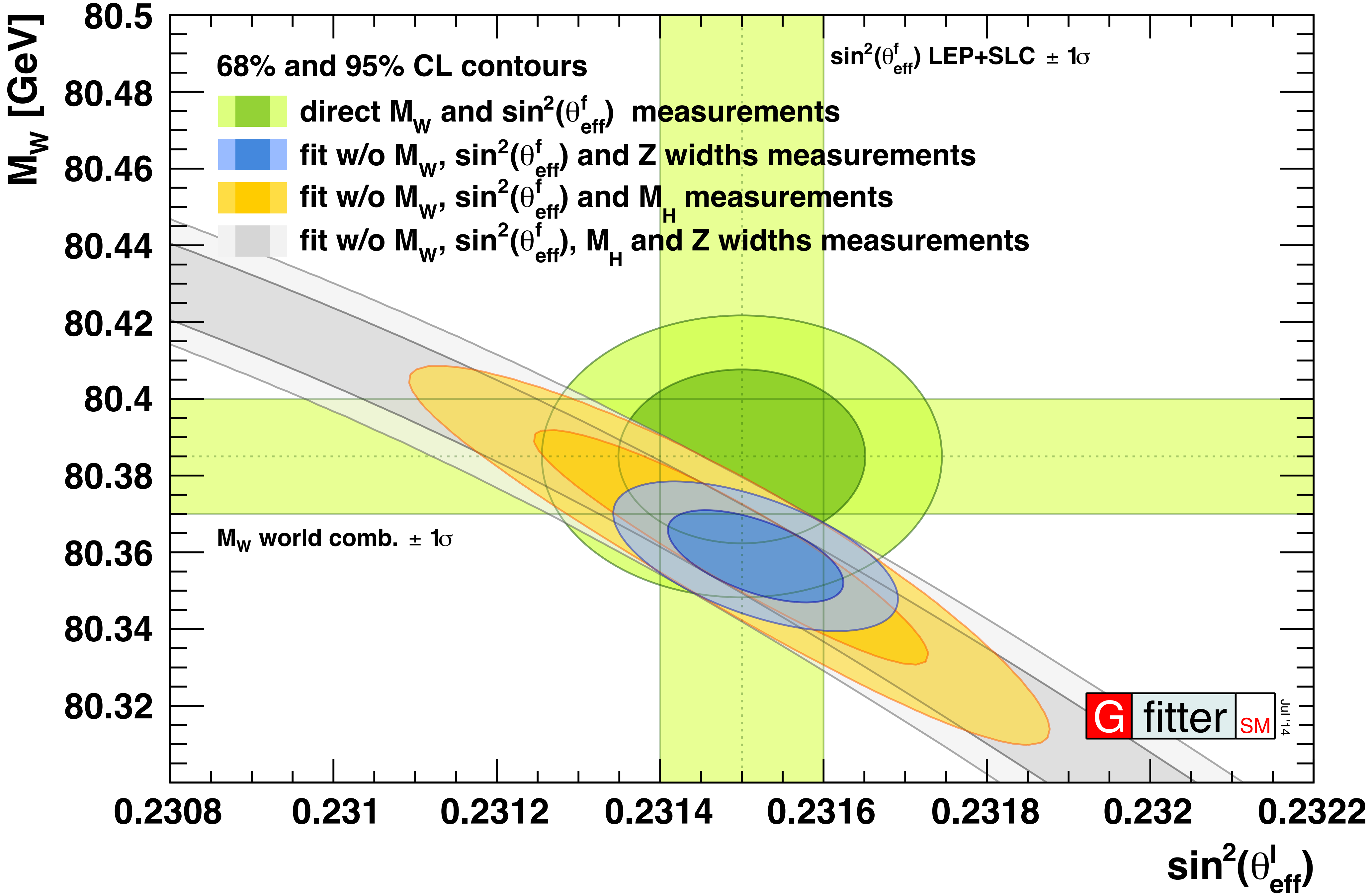
for the Gfitter group

Higgs Hunting
LAL, August 1st, 2015

Gfitter

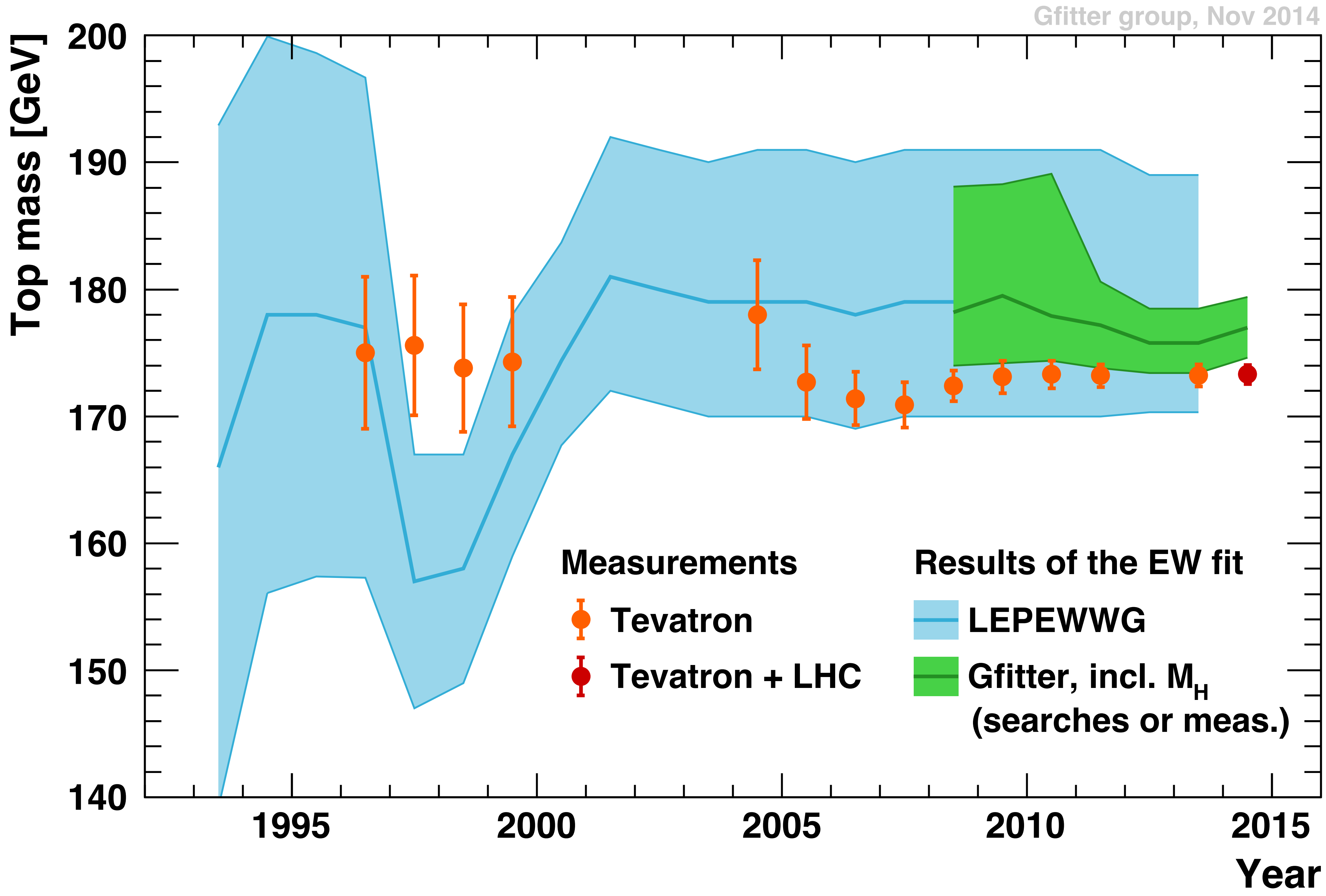
The Gfitter group: M. Baak (CERN), J. Cùth (Univ. of Mainz), J. Haller (Univ. Hamburg), A. Hoecker (CERN), R. K. (Univ. Hamburg), K. Mönig (DESY), T. Peiffer (Univ. Hamburg), M. Schott (Univ. of Mainz), J. Stelzer (Univ. of Michigan)

State of the Standard Model



(see also talk by Tongguang Cheng)

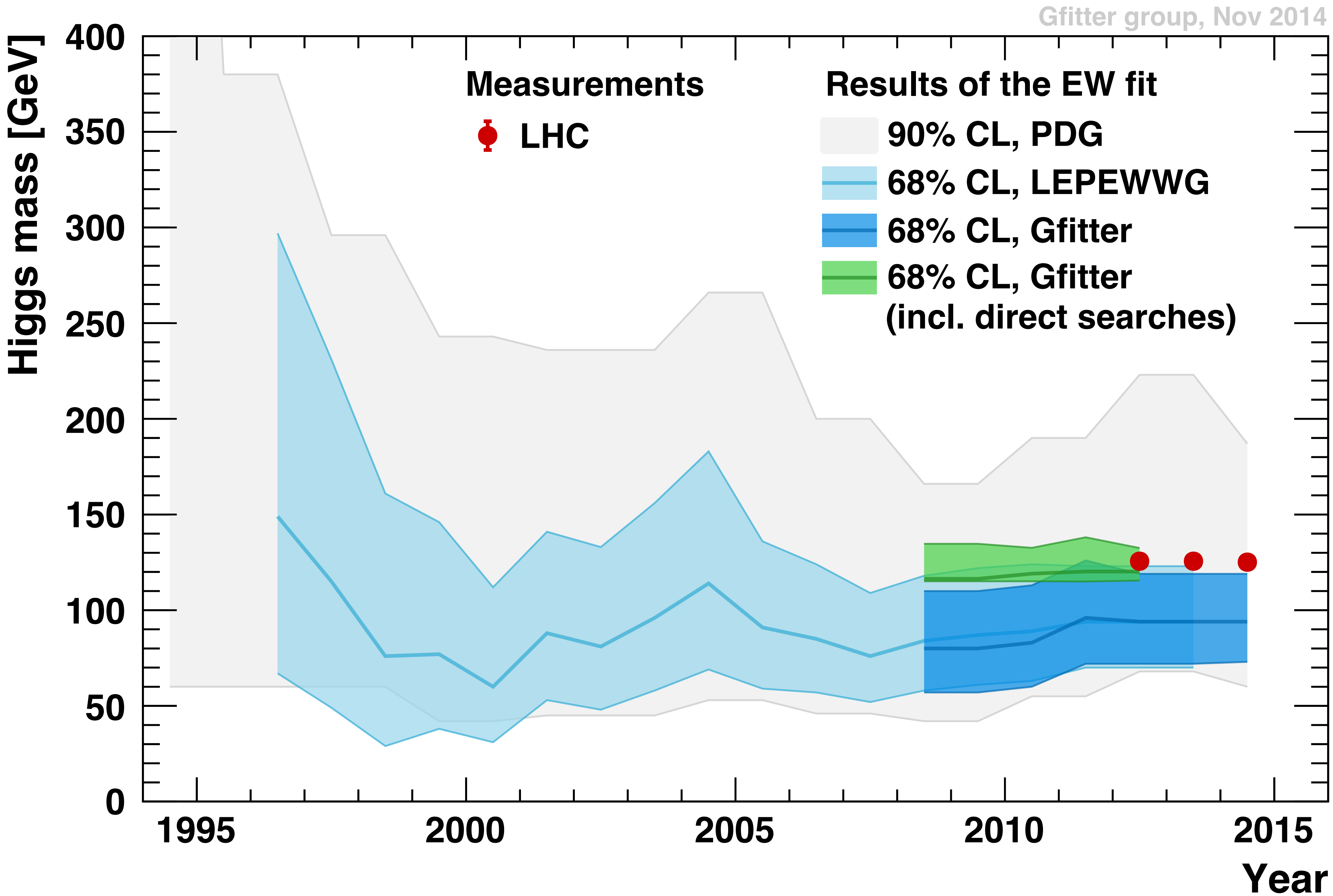
Prediction of Top Quark Mass



- m_t predictions from loop effects since 1990
- official LEPEWWG fit since 1993
- the fits have always been able to predict m_t correctly!

What precision is needed to see significant deviations between measurements and predictions?

Prediction of Higgs Mass



- M_H predictions from loop effects since the discovery of the top quark 1995
- weaker constraints than for m_t because of logarithmic dependence
- still, the fits have always predicted M_H correctly!

Again: what precision should we strive for? What are the major challenges?

Experimental Input

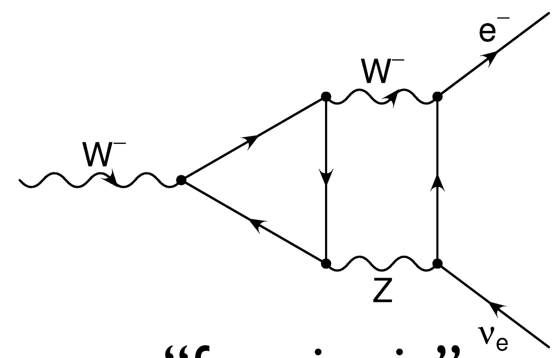
Fit is overconstrained

- all free parameters measured ($\alpha_s(M_Z)$ unconstrained in fit)
  - most input from e^+e^- colliders
    - M_Z : $2\cdot 10^{-5}$
  - but crucial input from hadron colliders:
    - m_t : $4\cdot 10^{-3}$
    - M_H : $2\cdot 10^{-3}$
    - M_W : $2\cdot 10^{-4}$
  - remarkable precision (<1%)
- require precision calculations

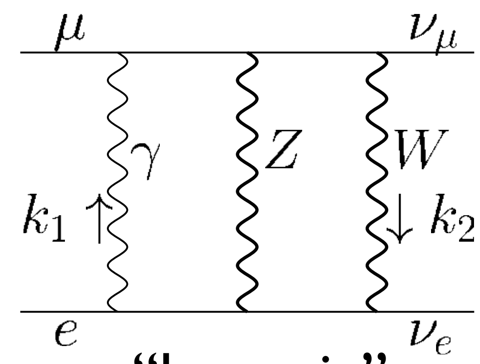
M_H [GeV]	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	Tev.
M_Z [GeV]	91.1875 ± 0.0021	LEP
Γ_Z [GeV]	2.4952 ± 0.0023	LEP
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	LEP
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	LEP
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	LEP, SLD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

Calculations

All observables calculated at 2-loop level



"fermionic"



"bosonic"

- **M_W** : full EW one- and two-loop calculation of fermionic and bosonic contributions
  [M Awramik et al., PRD 69, 053006 (2004), PRL 89, 241801 (2002)]
  + 4-loop QCD correction [Chetyrkin et al., PRL 97, 102003 (2006)]
- **$\sin^2\theta^l_{eff}$** : same order as M_W, calculations for leptons and all quark flavours
  [M Awramik et al, PRL 93, 201805 (2004), JHEP 11, 048 (2006), Nucl. Phys. B813, 174 (2009)]
- **partial widths Γ_f** : fermionic corrections in two-loop for all flavours (includes predictions for σ^0_{had}) [A. Freitas, JHEP04, 070 (2014)]

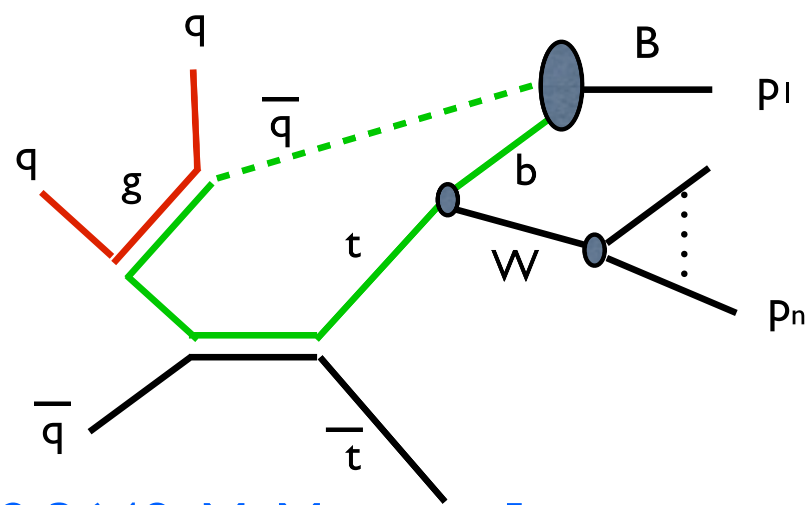
NEW

- **Radiator functions**: QCD corrections at N^3LO
  [Baikov et al., PRL 108, 222003 (2012)]
- **Γ_W** : only one-loop EW corrections available, negligible impact on fit
  [Cho et al, JHEP 1111, 068 (2011)]
- **all calculations**: one- and two-loop QCD corrections and leading terms of higher order corrections

Theoretical Uncertainties

- estimated using a geometric series ($a_n = a\, r^n$), example: $\mathcal{O}(\alpha^2\alpha_s) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\mathcal{O}(\alpha\alpha_s)$
  - similar results from scale variations
- reasonable estimates for all observables
- exception: m_t !

$$M^2_{exp} = \left(\sum_{i=1,\dots,n} p_i\right)^2$$



[A. Hoang arXiv:1412.3649, M. Mangano]

  - MC definition, relation to m^{pole} unknown
  - uncertainties from colour structure, hadronisation and $m^{pole} \rightarrow m_t(m_t)$ smaller

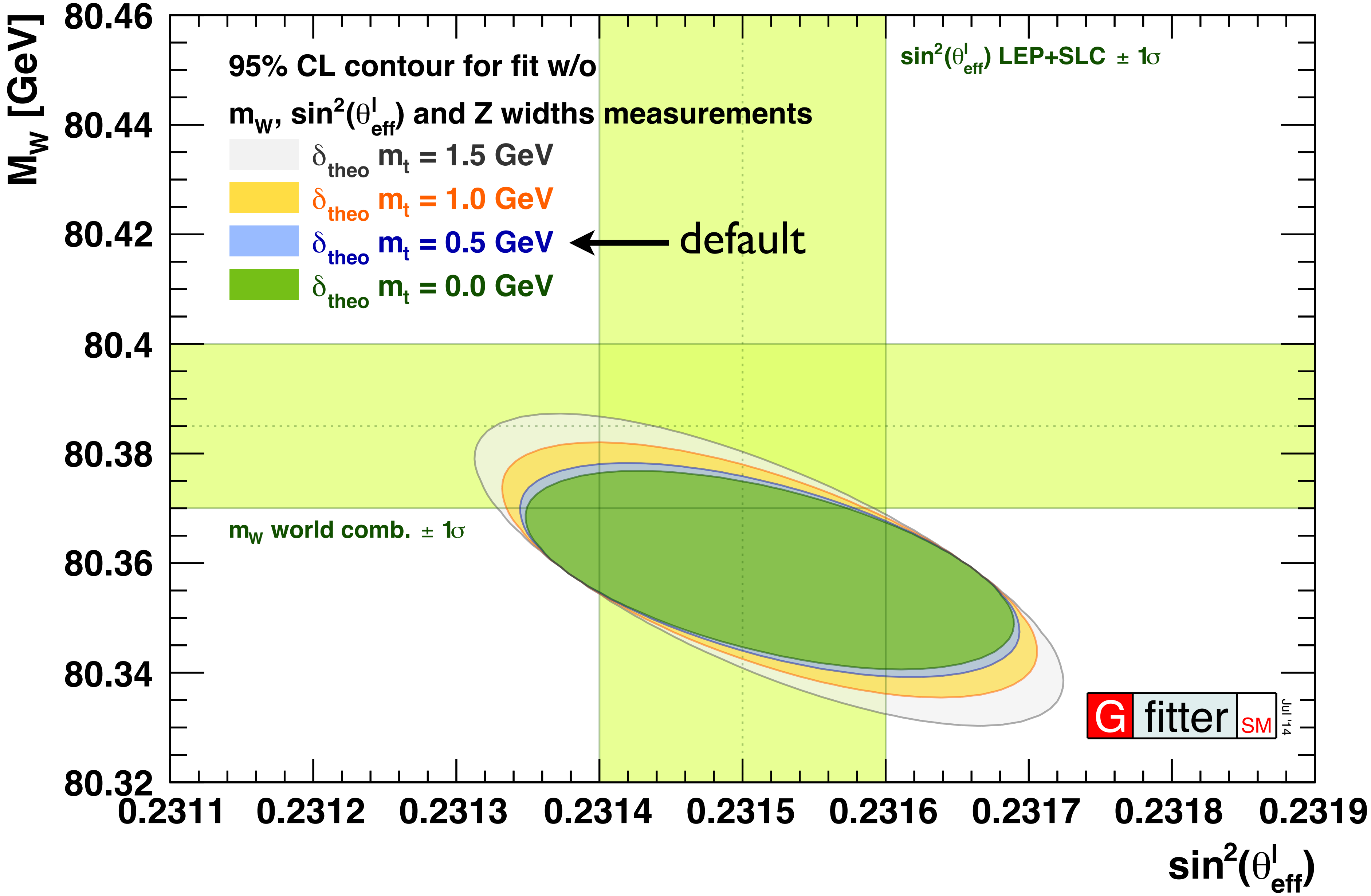
important

Observable	Exp. error	Theo. error
M_W	15 MeV	4 MeV
$\sin^2\theta^l_{\text{eff}}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
σ^0_{had}	37 pb	6 pb
R^0_b	$6.6 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
m_t	0.76 GeV	0.5 GeV

new in fit

- 10 additional free parameters, Gaussian likelihood
- important missing higher order terms:
  - $O(\alpha^2\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{bos})$ (in some cases), $O(\alpha^3)$, $O(\alpha_s^5)$ (rad. functions)

Theoretical uncertainty on m_t



impact of variation in δ_{theo} m_t between 0 and 1.5 GeV

- better assessment of uncertainty on m_t important for the fit
- uncertainty of 0.5 GeV small impact on result

Future Improvements

LHC = LHC with 300 fb^{-1}
ILC/GigaZ = future e$^+$e$^-$ collider, option to run on Z-pole (w polarized beams)

Parameter	Present		LHC		ILC/GigaZ	
M_H [GeV]	0.2	→	< 0.1		< 0.1	
M_W [MeV]	15	→	8	→	5	WW threshold
M_Z [MeV]	2.1		2.1		2.1	
m_t [GeV]	0.8	→	0.6	→	0.1	$t\bar{t}$ threshold scan
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	16		16	→	1.3	$\delta A^{0,f}_{LR}$: $10^{-3} \rightarrow 10^{-4}$
$\Delta\alpha^5_{\rm had}(M_Z^2)$ [10^{-5}]	10	→	4		4	low energy data, better α_s
R^0_l [10^{-3}]	25		25	→	4	high statistics on Z-pole
κ_V (λ = 3 TeV)	0.05	→	0.03	→	0.01	direct measurement of BRs

- theoretical uncertainties reduced by a factor of 4 (esp. M_W and $\sin^2\theta^l_{\rm eff}$)
  - implies three-loop calculations!
  - exception: $\delta_{\rm theo}\, m_t$ (LHC) = 0.25 GeV (factor 2)
- central values of input measurements adjusted to M_H = 125 GeV

[Baak et al, arXiv:1310.6708]

[Gfitter, arXiv:1407.3792]

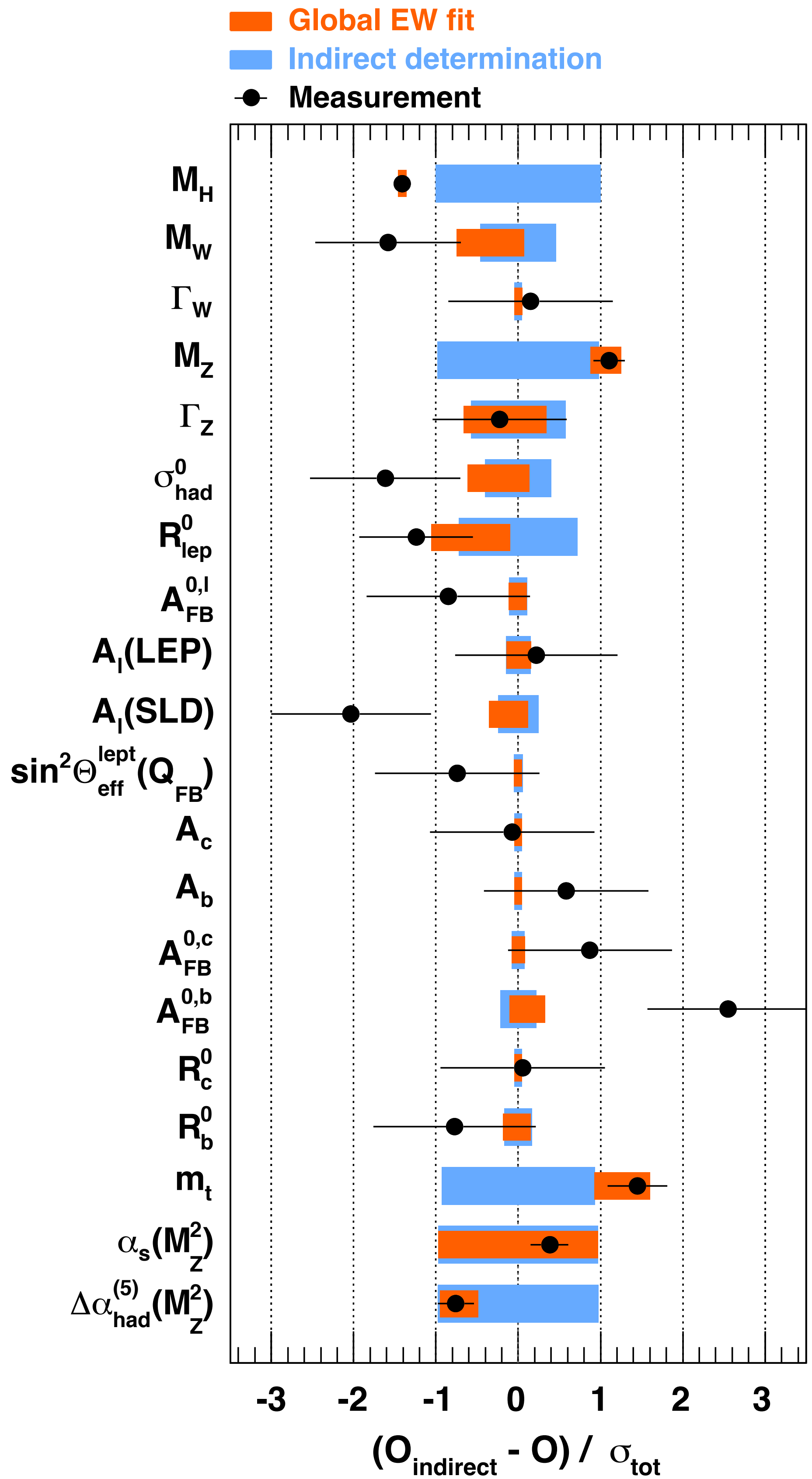
SM Fit Results

black: direct measurement (data)

orange: full fit

light-blue: fit excluding input from row

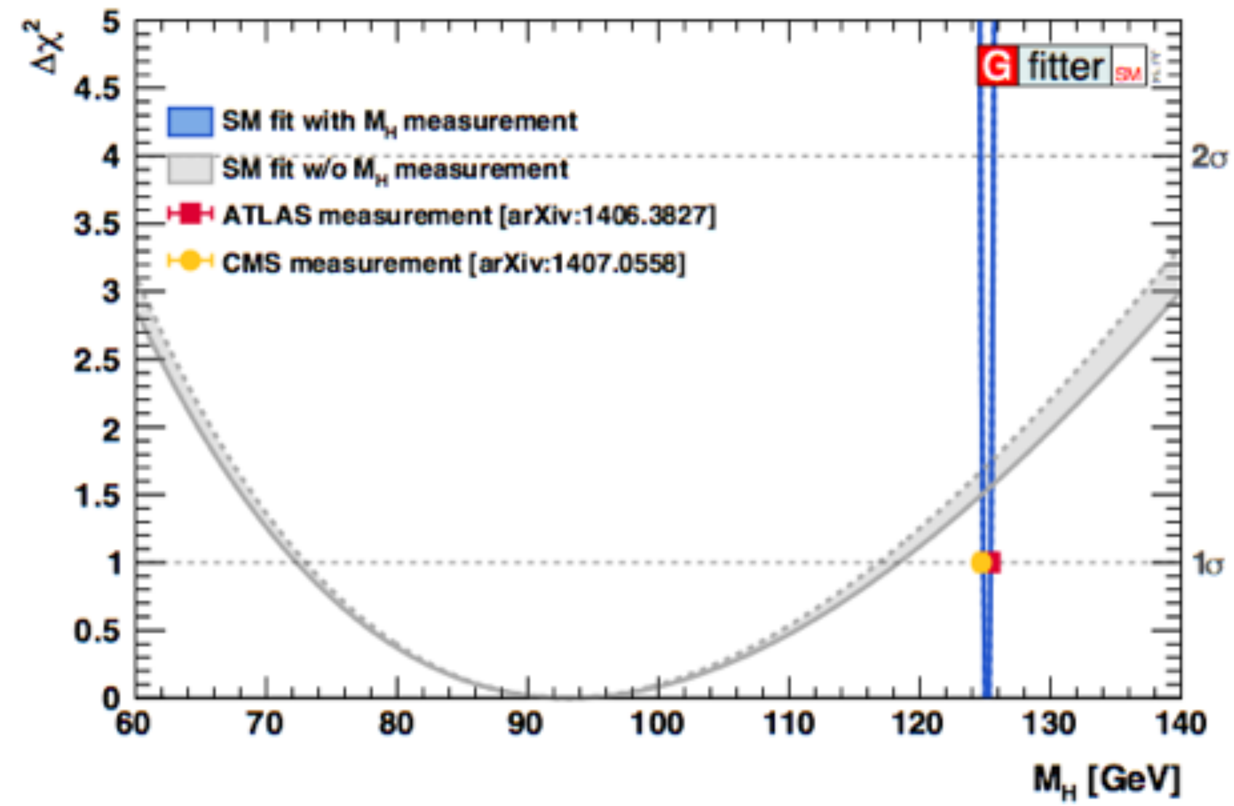
- goodness of fit, p-value:
  χ^2_{min}= **17.8** Prob(χ^2_{min}, 14) = **21%**
  Pseudo experiments: 21 ± 2 (theo)%
  - χ^2_{min}(Γ_i in 1-loop) = 18.0
  - χ^2_{min}(no theory uncertainties) = 18.2
- no individual value exceeds 3σ
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ
    → largest contribution to χ^2
- small pulls for M_H, M_Z
  - input accuracies exceed fit requirements



Present Results: Higgs

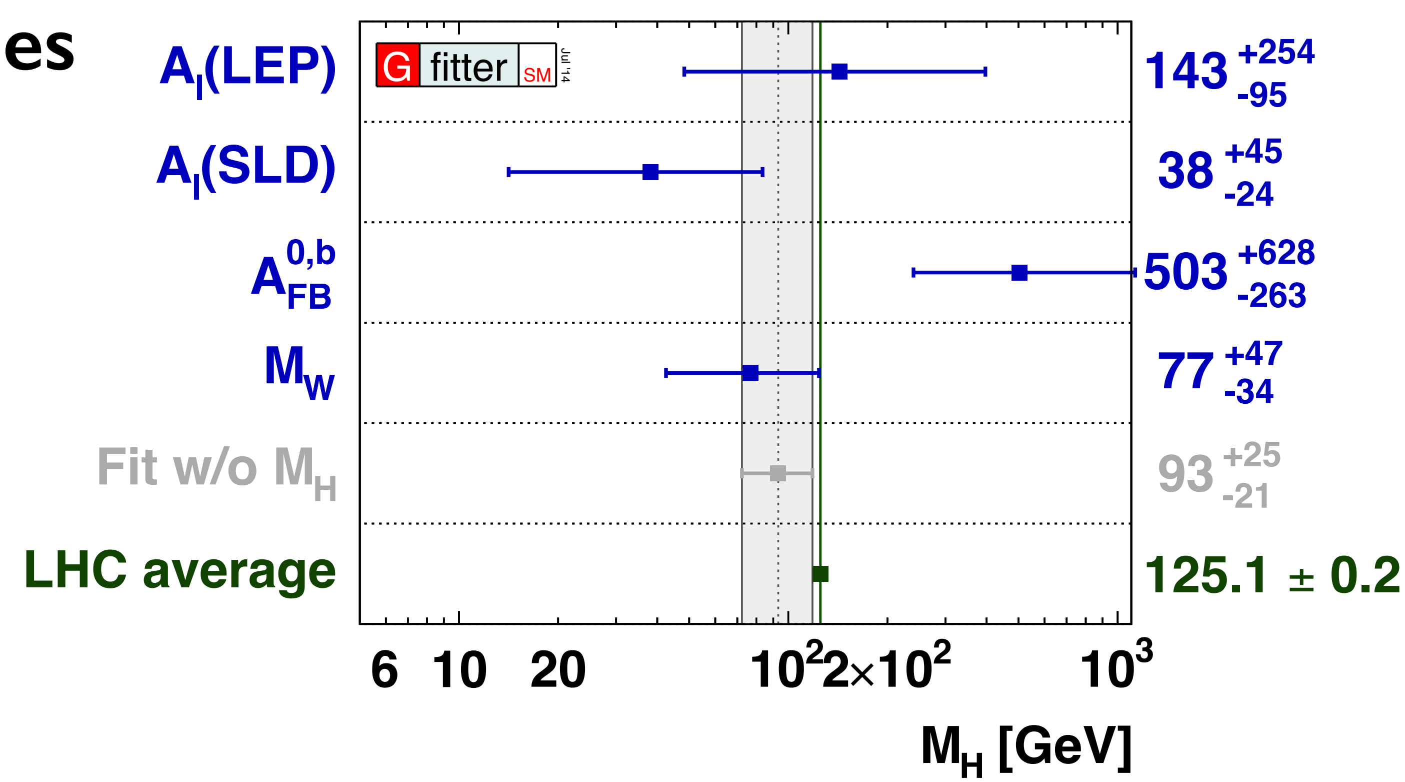
Determination of M_H

- grey band: fit without M_H measurement
  - $M_H = 93^{+25}_{-21}$ GeV
  - consistent with measurement at **1.3σ**
- blue line: full SM fit

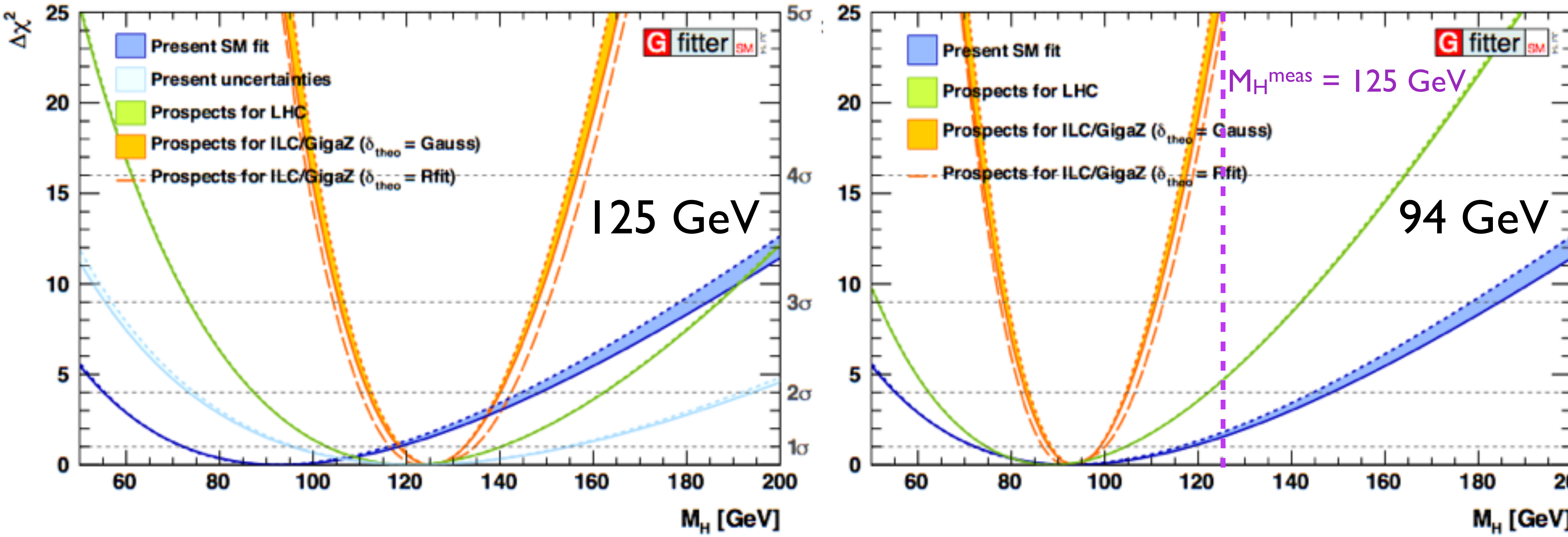


Impact of most sensitive observables

- determination of M_H, removing all sensitive observables except the given one
- known tension (3σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible



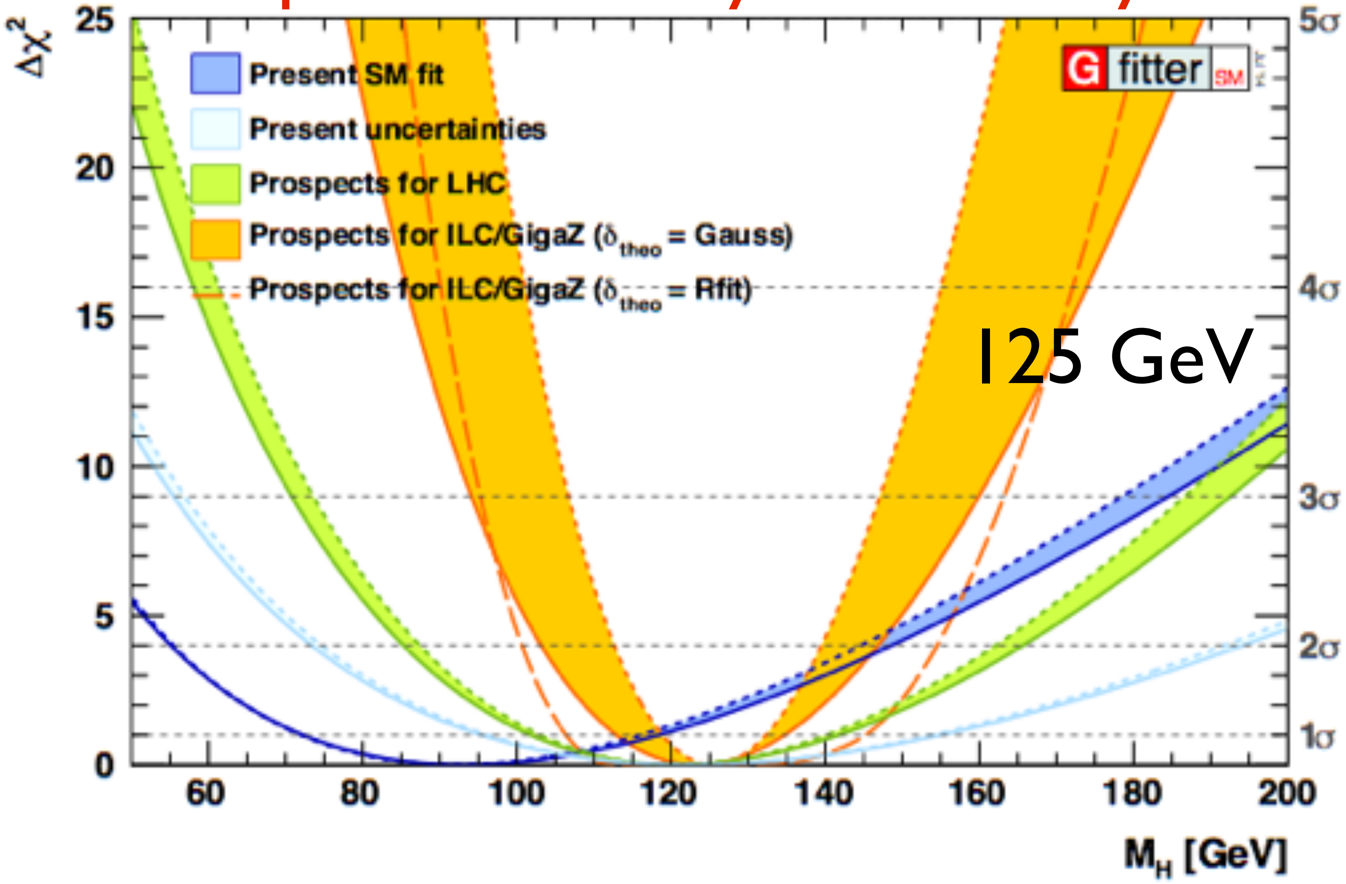
Future: Higgs Mass



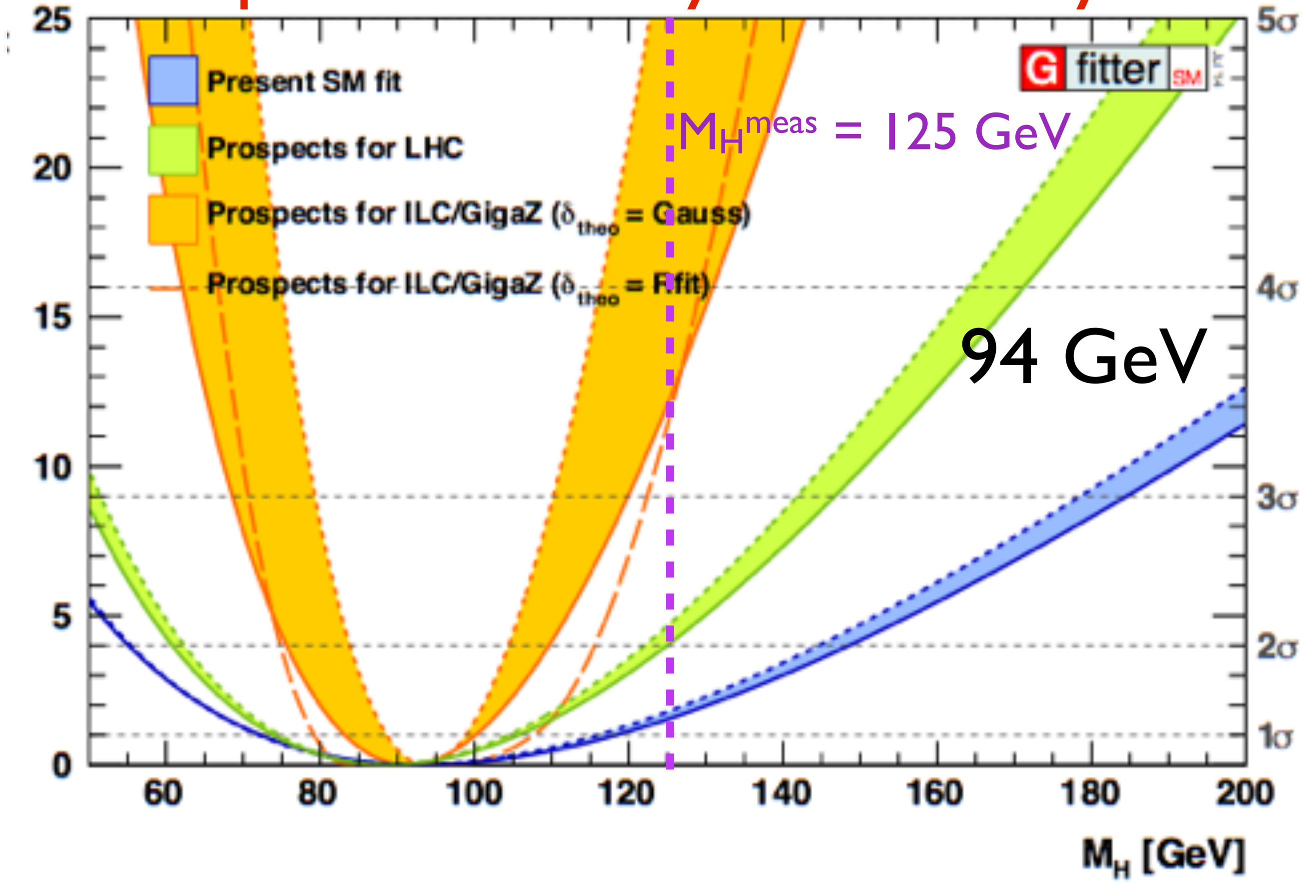
- Logarithmic dependency on M_H → cannot compete with direct M_H meas.
  - no theory uncertainty: $M_H = 125 \pm 7$ GeV
  - future theory uncertainty (Rfit): $M_H = 125^{+10}_{-9}$ GeV
  - present day theory uncertainty: $M_H = 125^{+20}_{-17}$ GeV
- If EWPO central values unchanged (94 GeV), ~5σ discrepancy with measured Higgs mass

Future: Higgs Mass

present theory uncertainty



present theory uncertainty



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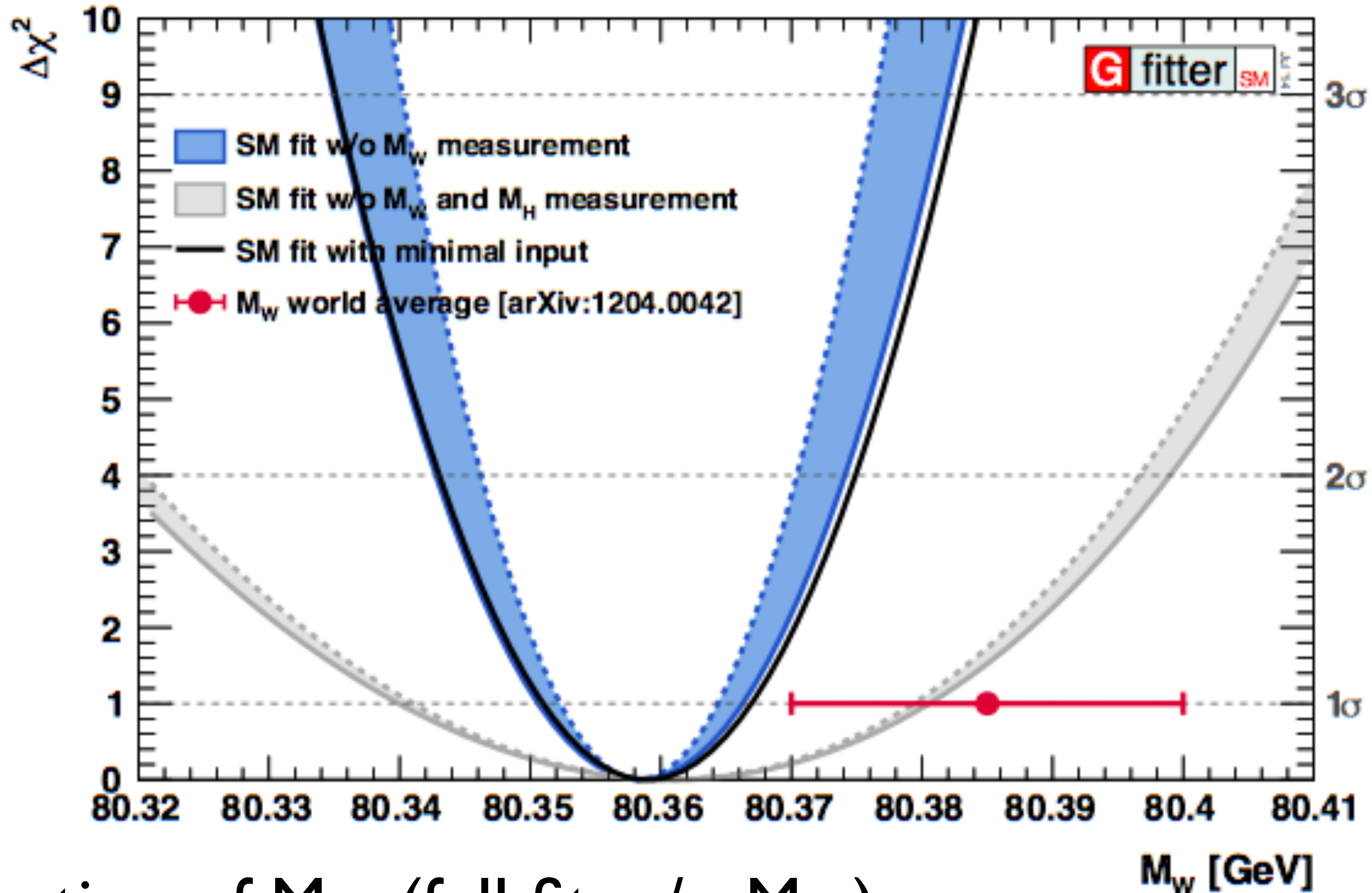
- If EWPO central values unchanged (94 GeV), ~5σ discrepancy with measured Higgs mass compromised by present theory uncertainty!

Indirect determination of W mass

- also shown: SM fit with minimal input: M_Z, G_F, $\Delta\alpha_{had}^{(5)}(M_Z)$, $\alpha_s(M_Z)$, M_H, and fermion masses
  - good consistency
- M_H measurement allows for precise constraint on M_W
  - agreement at **1.4σ**



- fit result for indirect determination of M_W (full fit w/o M_W):

$$
\begin{aligned}
M_W &= 80.3584 \pm 0.0046_{m_t} \pm 0.0030_{\delta_{\rm theo} m_t} \pm 0.0026_{M_Z} \pm 0.0018_{\Delta\alpha_{\rm had}} \\
&\quad \pm 0.0020_{\alpha_S} \pm 0.0001_{M_H} \pm 0.0040_{\delta_{\rm theo} M_W}\ \mathrm{GeV} \\
&= 80.358 \pm 0.008_{\rm tot}\ \mathrm{GeV}
\end{aligned}
$$

more precise than direct measurement (15 MeV)

Indirect determination of W mass

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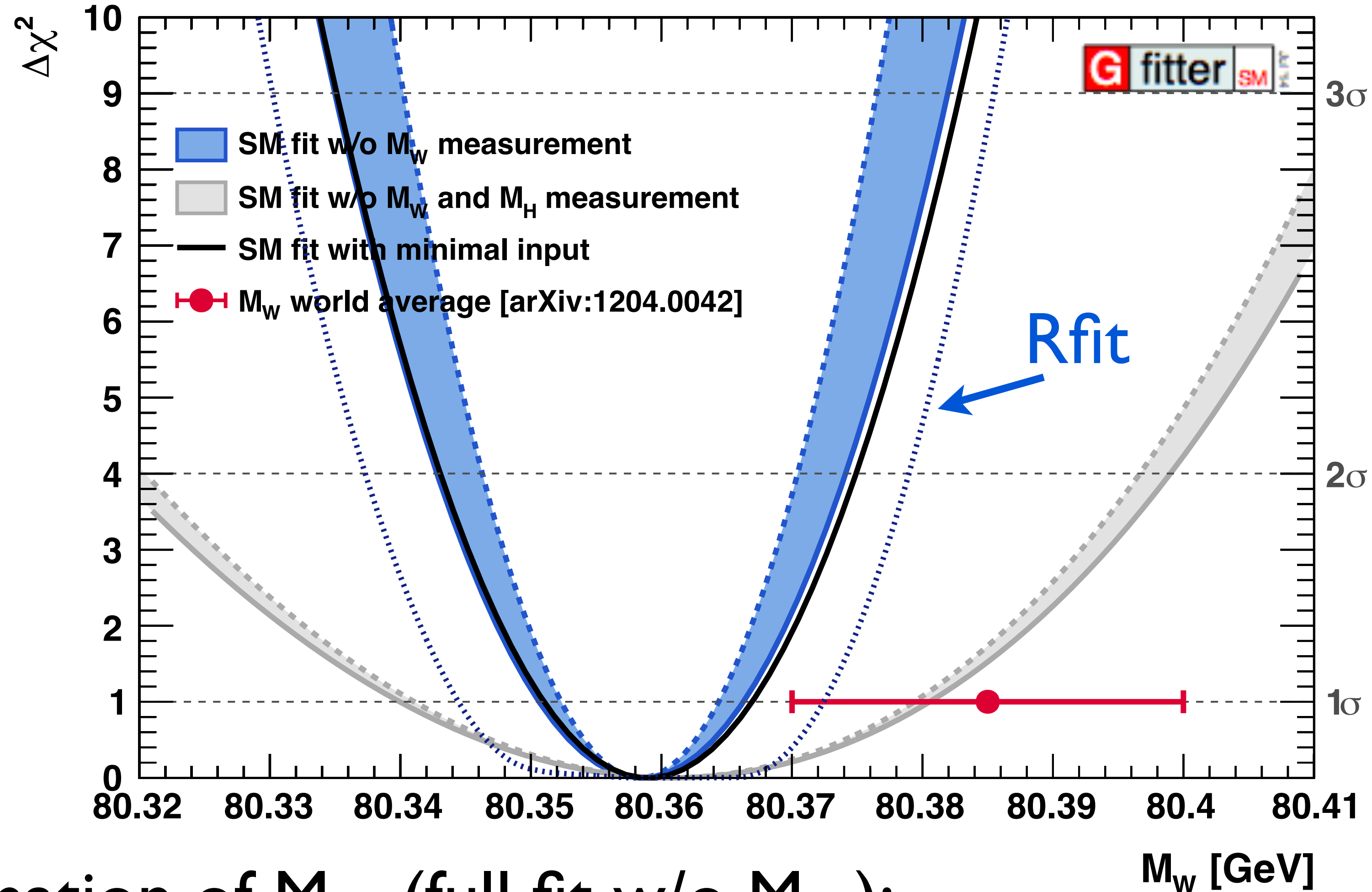

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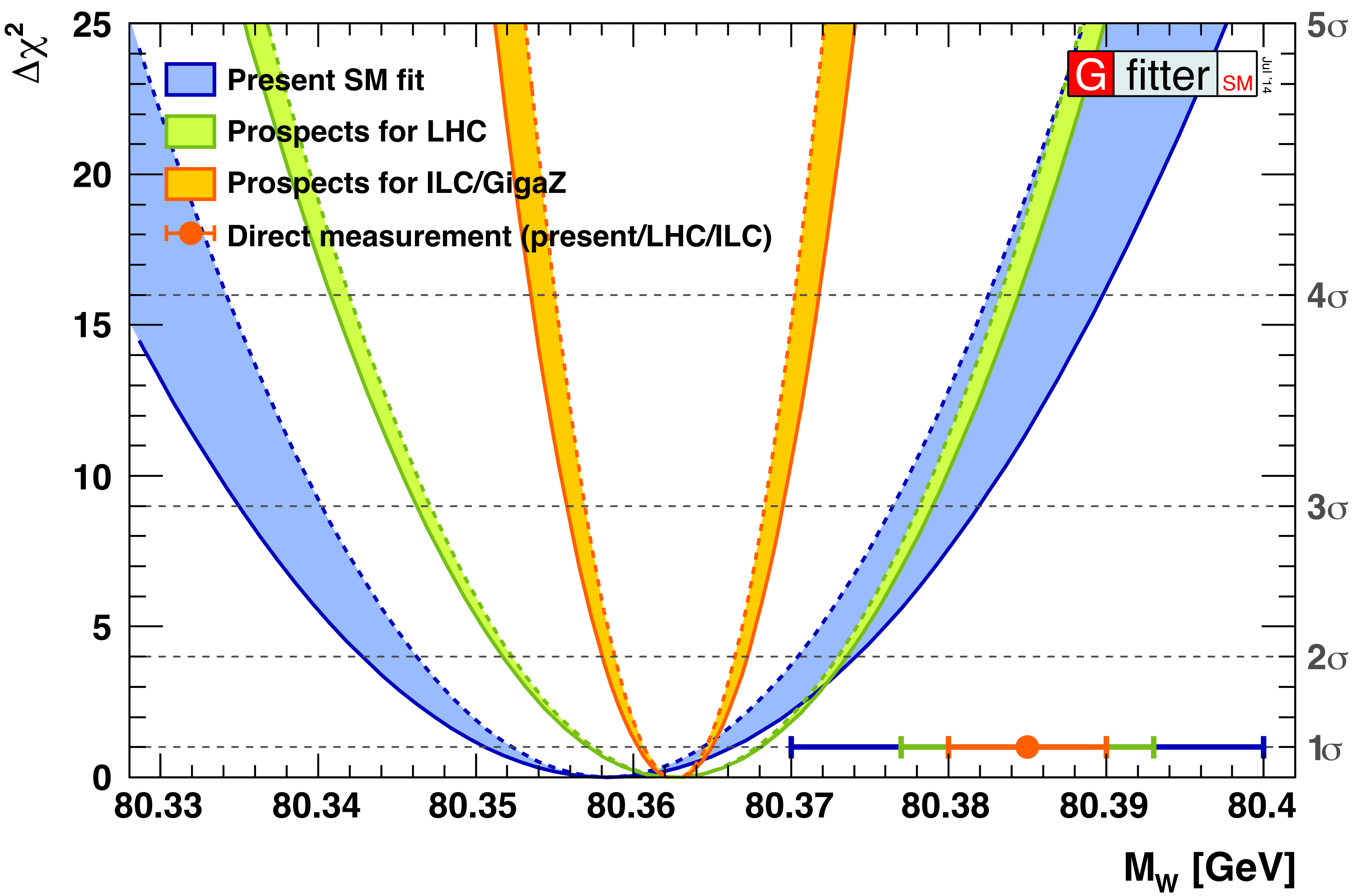
$$= 80.358 \pm 0.008_{\rm tot}\ \text{GeV}$$

(δm_t (1 GeV): ±9 MeV, Rfit: ±13 MeV)

more precise than direct measurement (15 MeV)

Future: M_W



LHC-300 Scenario

- moderate improvement (~30%) of indirect constraint
  - theoretical uncertainties already important

ILC Scenario

- improvement of factor 3 possible, similar to direct measurement

Fit Results:

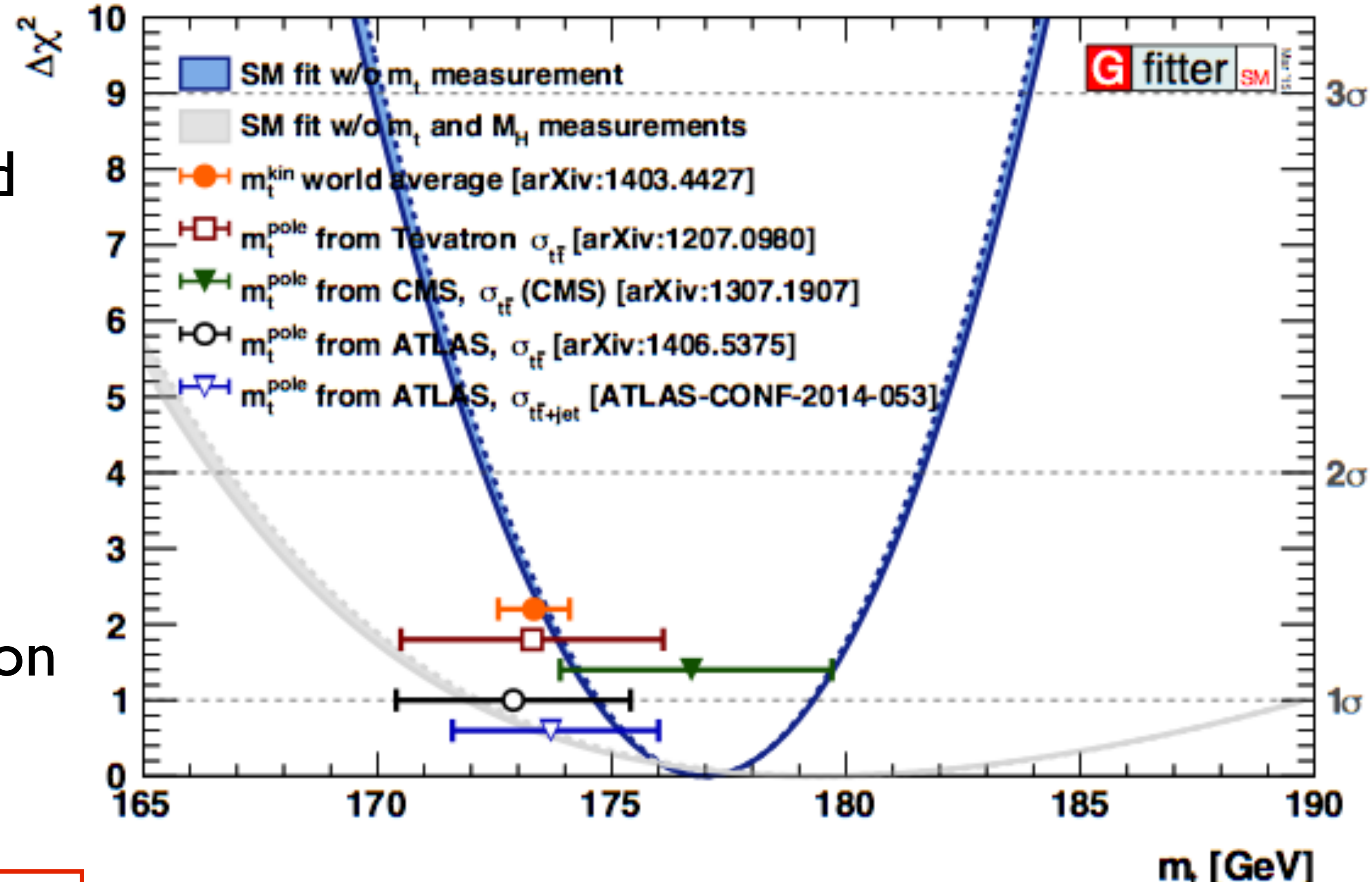
$$\delta M_W = 1.7_{M_Z} \oplus 0.1_{m_t} \oplus 1.2_{\sin^2\theta^f_{\rm eff}} \oplus 0.6_{\Delta\alpha_{\rm had}} \oplus 0.3_{\alpha_s}\ \text{MeV}$$

$$\delta M_W = 1.3_{\rm theo} \oplus 1.9_{\rm exp}\ \text{MeV} = 2.3_{\rm tot}\ \text{MeV}$$

Measurement uncertainty for ILC: 5 MeV

Indirect determination of m_t

- determination of m_t from Z-pole data (fully obtained from rad. corrections $\sim m_t^2$)
- alternative to direct measurements
- M_H allows for significantly more precise determination of m_t



$$m_t = 177.0 \pm 2.3_{M_W,\,\sin^2\theta^f_{\rm eff}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\rm had}} \pm 0.4_{M_Z}\ \text{GeV}$$
$$= 177.0 \pm 2.4_{\rm exp} \pm 0.5_{\rm theo}\ \text{GeV}$$

- similar precision as determination from $\sigma_{t\bar{t}}$, good agreement
- dominated by experimental precision

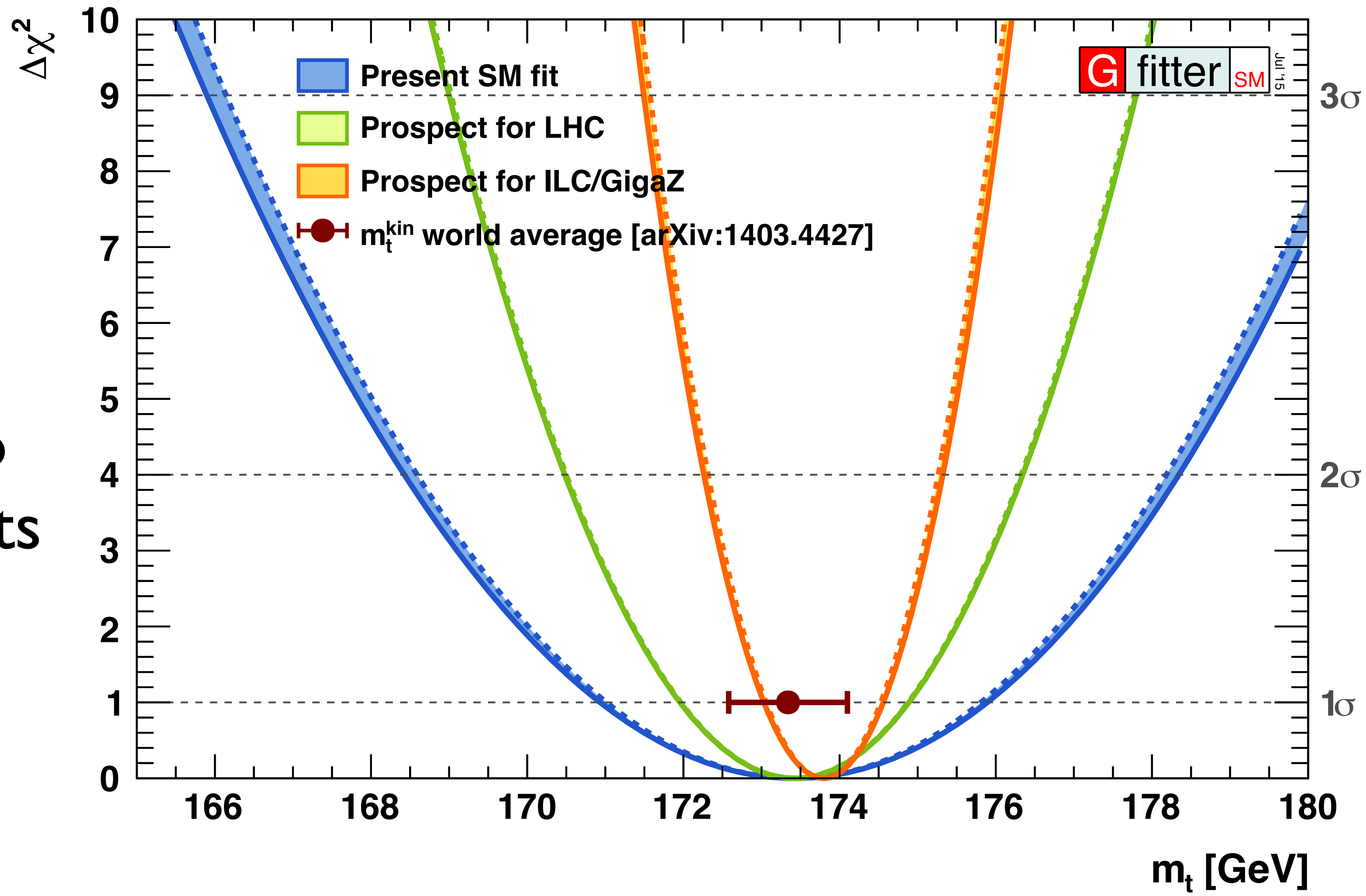
Future: Top Quark Mass

LHC-300 Scenario

- improvement due to improved precision on M_W

ILC Scenario

- Comparable precision due to M_W and $\sin^2\theta^l_{eff}$ measurements (M_W: δm_t = 1 GeV
$\sin^2\theta^l_{eff}$: δm_t = 0.9 GeV)



Fit Results:

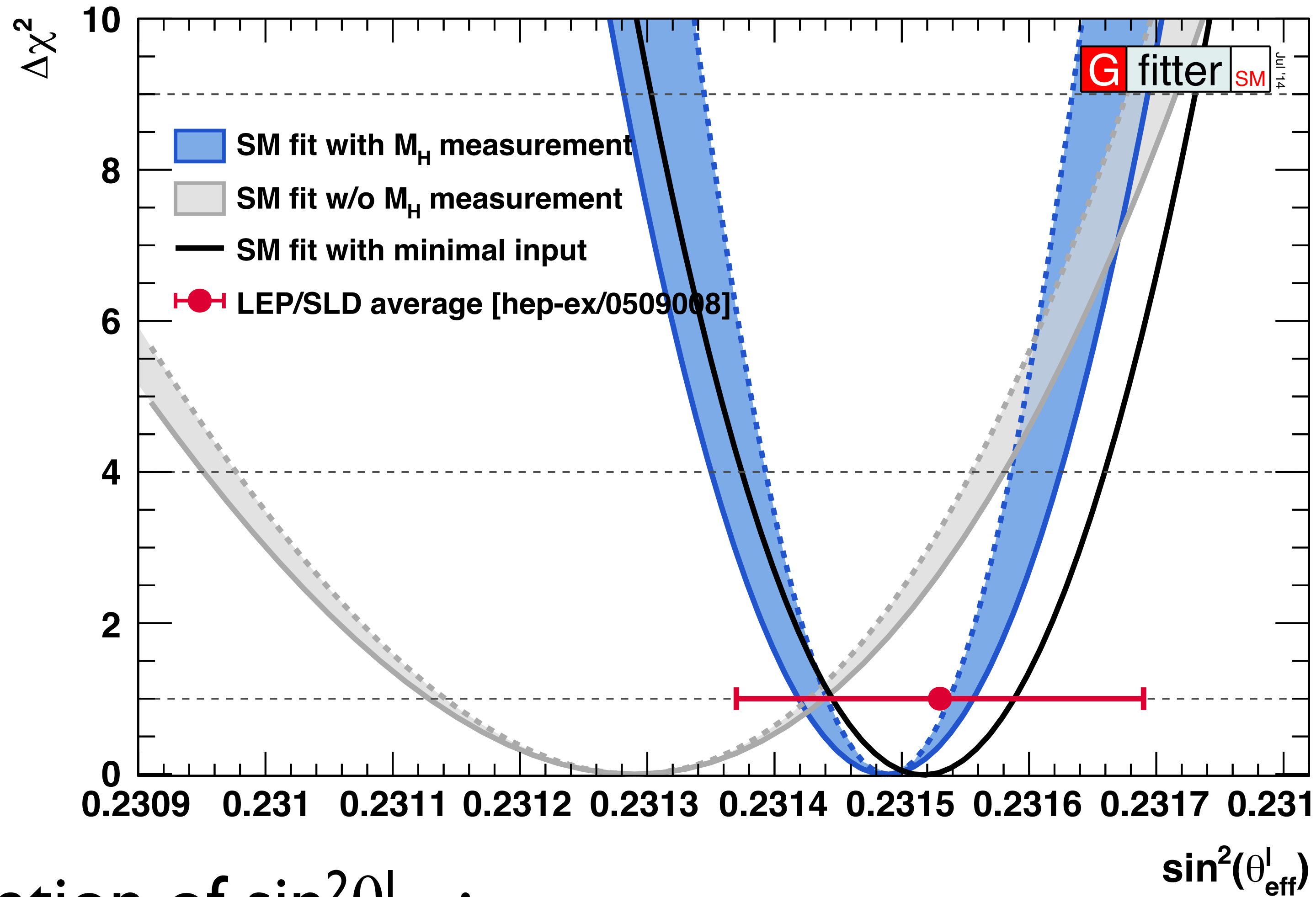
$$\delta m_t = 0.6_{M_W} \oplus 0.5_{M_Z} \oplus 0.3_{\sin^2\theta^f_{\rm eff}} \oplus 0.4_{\Delta\alpha_{\rm had}} \oplus 0.2_{\alpha_s}\ \mathrm{GeV}$$

$$\delta m_t = 0.2_{\rm theo} \oplus 0.7_{\rm exp}\ \mathrm{GeV} = 0.8_{\rm tot}\ \mathrm{GeV}$$

- similar precision as present world average of m_t^{kin} from hadron colliders
- still dominated by experimental precision

Present: Effective Weak Mixing Angle

- all measurements directly sensitive to $\sin^2\theta^l_{eff}$ removed from fit (asymmetries, partial widths)
  - good agreement with minimal input
- M_H measurement allows for precise constraint



- fit result for indirect determination of $\sin^2\theta^l_{eff}$:

$$\begin{aligned}\sin^2\theta^\ell_{\rm eff} &= 0.231488 \pm 0.000024_{m_t} \pm 0.000016_{\delta_{\rm theo} m_t} \pm 0.000015_{M_Z} \pm 0.000035_{\Delta\alpha_{\rm had}} \\ &\quad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm 0.000047_{\delta_{\rm theo}\sin^2\theta^f_{\rm eff}} \\ &= 0.23149 \pm 0.00007_{\rm tot}\end{aligned}$$

more precise than determination from LEP/SLD (1.6×10^{-4})

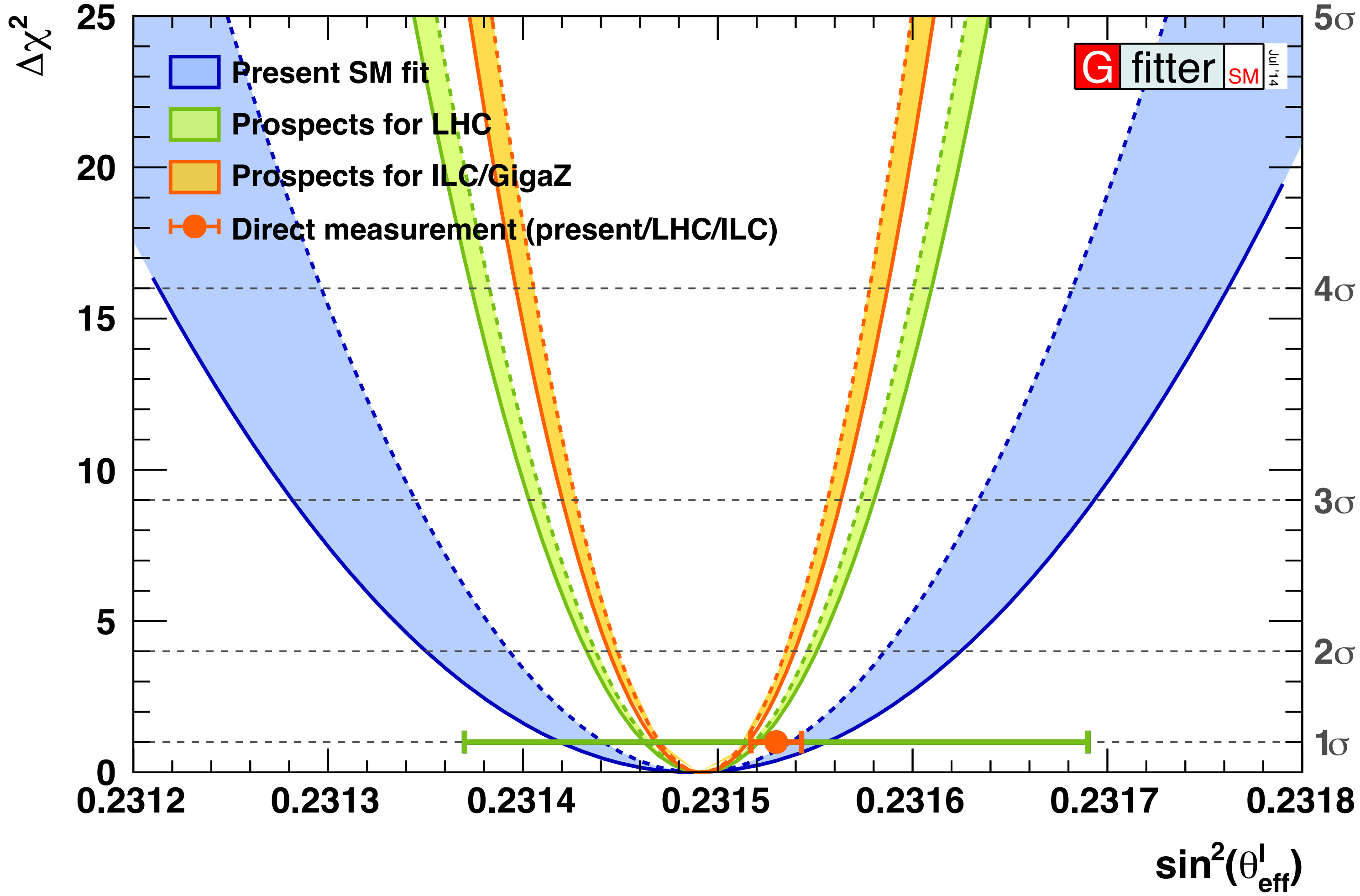
Future: Effective Weak Mixing Angle

LHC-300 Scenario

- large improvement of indirect constraint
  - compromised by today's theoretical uncertainties

ILC Scenario

- Indirect constraint and direct measurement comparable precision



Fit Results:

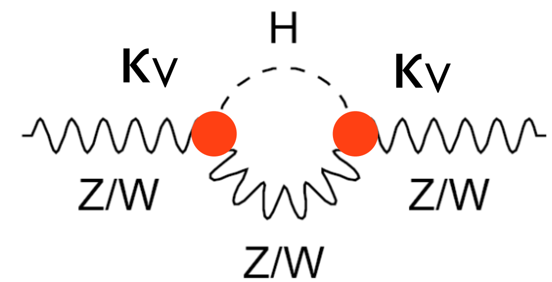
$$\delta \sin^2 \theta^f_{\text{eff}} = (1.7_{M_W} \oplus 1.2_{M_Z} \oplus 0.1_{m_t} \oplus 1.5_{\Delta\alpha_{\text{had}}} \oplus 0.1_{\alpha_s}) \cdot 10^{-5}$$

$$\delta \sin^2 \theta^f_{\text{eff}} = (1.0_{\text{theo}} \oplus 2.0_{\text{exp}}) \cdot 10^{-5} = (2.3_{\text{tot}}) \cdot 10^{-5}$$

Measurement uncertainty for ILC: $1.3 \cdot 10^{-5}$

Coupling Constraints from EWPO

- consider specific model in κ parametrisation:
  - scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F), with no invisible/undetectable widths



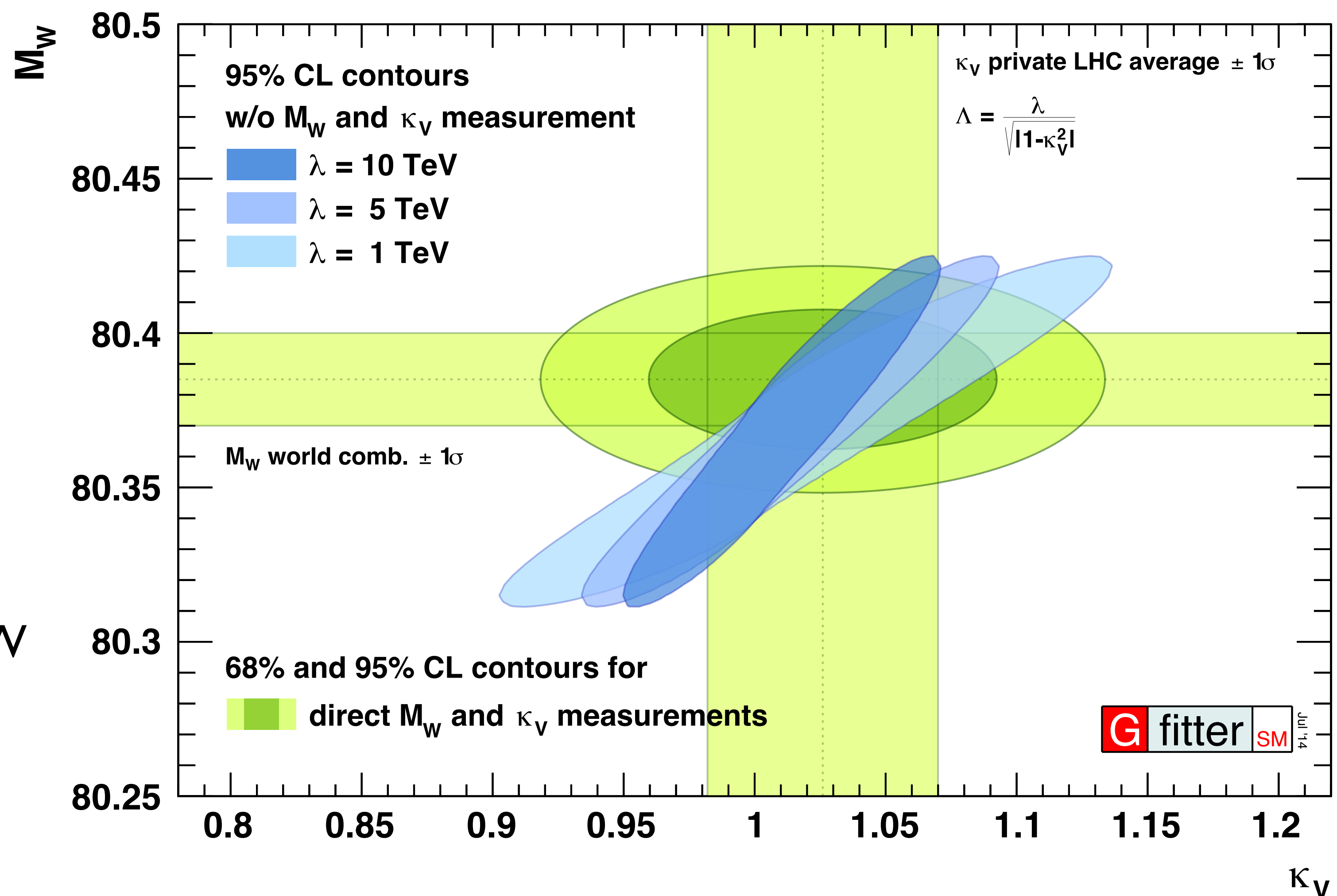
- main effect on EWPD due to modified Higgs coupling to gauge bosons (κ_V)
  [Espinosa et al. arXiv:1202.3697, Falkowski et al. arXiv:1303.1812], etc

$$S = \frac{1}{12\pi}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}$$

$$T = -\frac{3}{16\pi\cos^2\theta^\ell_{\rm eff}}(1-\kappa_V^2)\ln\frac{\Lambda^2}{M_H^2}$$

$$\Lambda = \frac{\lambda}{\sqrt{|1-\kappa_V^2|}}$$

- correlation between κ_V and M_W
  - slightly smaller values of M_W preferred

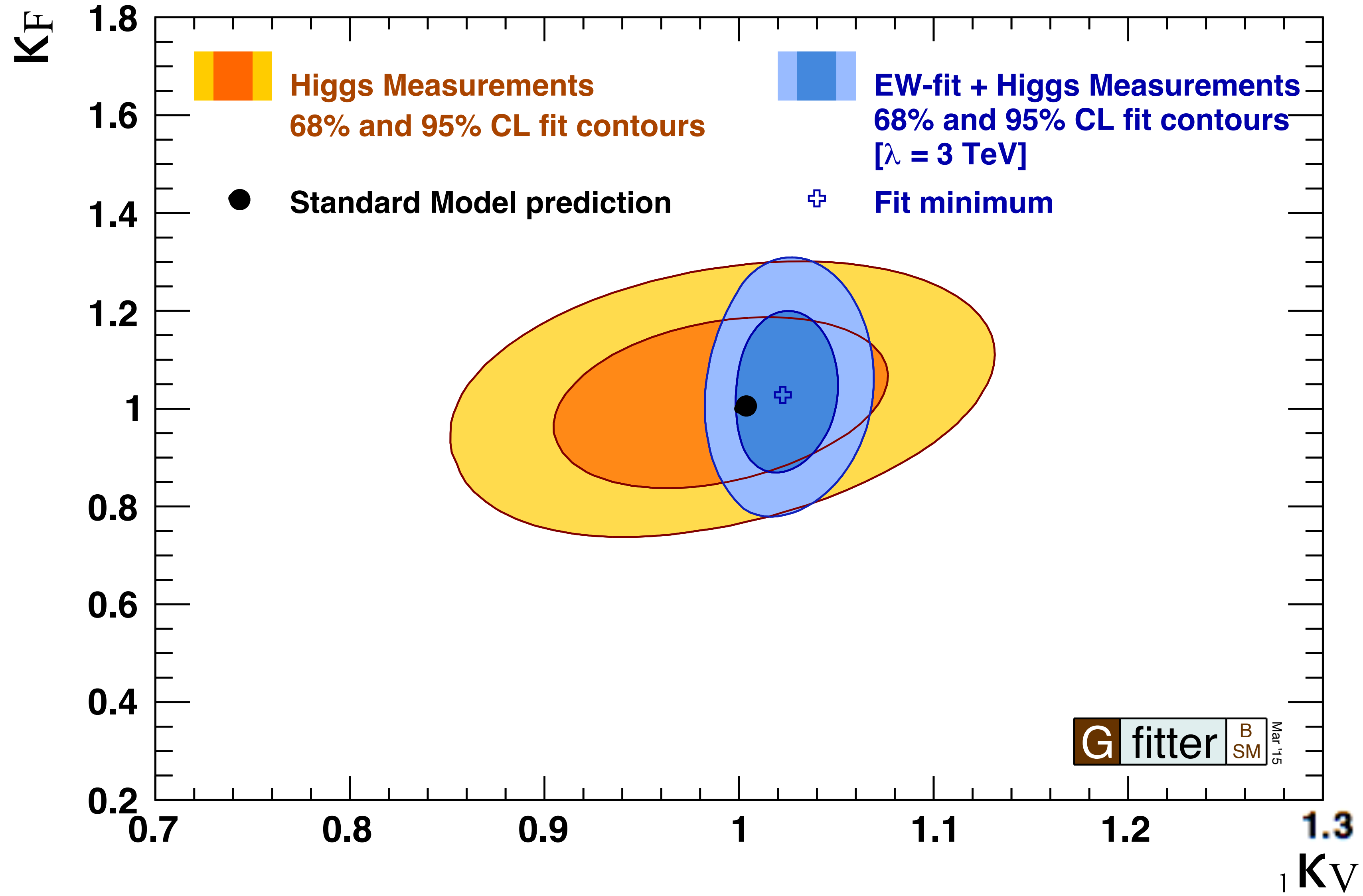


Higgs Coupling Results

Higgs coupling measurements:

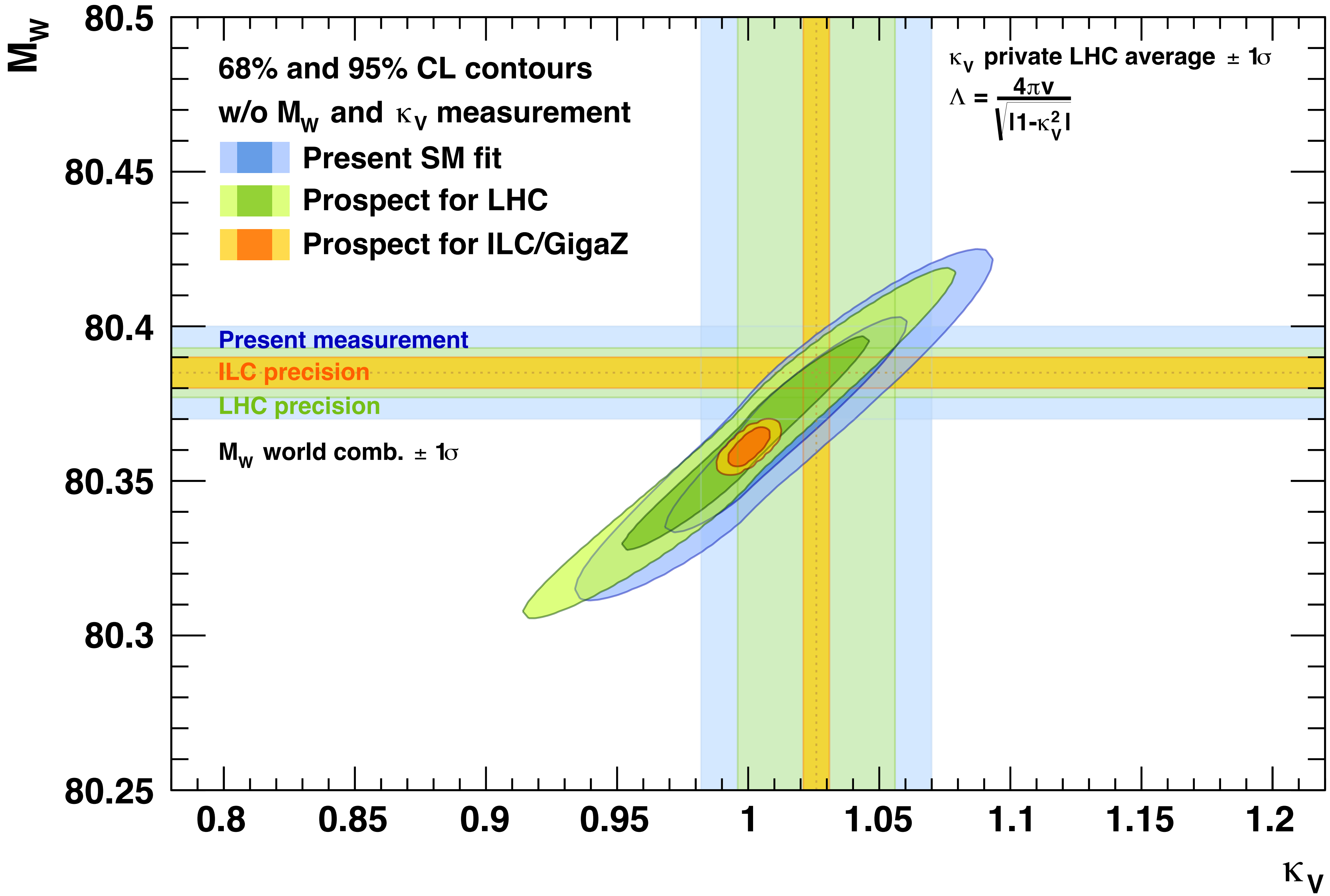
- $\kappa_V = 0.99 \pm 0.08$
- $\kappa_F = 1.01 \pm 0.17$

- **Combined result:**
- $\kappa_V = 1.03 \pm 0.02$ ($\lambda = 3$ TeV)
- implies NP-scale of $\Lambda \geq 13$ TeV



- some dependency for κ_V in central value [1.02-1.04] and error [0.02-0.03] on cut-off scale λ [1-10 TeV]
  - EW fit sofar more precise result for κ_V than current LHC experiments
  - EW fit has positive deviation of κ_V from 1.0
    - many BSM models: $\kappa_V < 1$

Prospects of EW Fit



- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP

Summary of Indirect Predictions

Parameter	Experimental input $[\pm 1\sigma_{\rm exp}]$ Present	LHC	ILC/GigaZ	Indirect determination $[\pm 1\sigma_{\rm exp}, \pm 1\sigma_{\rm theo}]$ Present	LHC	ILC/GigaZ
M_H [GeV]	0.2	< 0.1	< 0.1	$^{+31}_{-26}, ^{+10}_{-8}$	$^{+20}_{-18}, ^{+3.9}_{-3.2}$	$^{+6.8}_{-6.5}, ^{+2.5}_{-2.4}$
M_W [MeV]	15	8	5	6.0, 5.0	5.2, 1.8	1.9, 1.3
M_Z [MeV]	2.1	2.1	2.1	11, 4	7.0, 1.4	2.5, 1.0
m_t [GeV]	0.8	0.6	0.1	2.4, 0.6	1.5, 0.2	0.7, 0.2
$\sin^2\theta^\ell_{\rm eff}$ $[10^{-5}]$	16	16	1.3	4.5, 4.9	2.8, 1.1	2.0, 1.0
$\Delta\alpha^5_{\rm had}(M_Z^2)$ $[10^{-5}]$	10	4.7	4.7	42, 13	36, 6	5.6, 3.0
R^0_l $[10^{-3}]$	25	25	4	–	–	–
$\alpha_S(M_Z^2)$ $[10^{-4}]$	–	–	–	40, 10	39, 7	6.4, 6.9
$S\vert_{U=0}$	–	–	–	0.094, 0.027	0.086, 0.006	0.017, 0.006
$T\vert_{U=0}$	–	–	–	0.083, 0.023	0.064, 0.005	0.022, 0.005
κ_V ($\lambda = 3$ TeV)	0.05	0.03	0.01	0.02	0.02	0.01

Summary of Indirect Predictions

	Experimental input [$\pm 1\sigma_{\rm exp}$]			Indirect determination [$\pm 1\sigma_{\rm exp}, \pm 1\sigma_{\rm theo}$]		
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M_W [MeV]	15	8	5	6.0, 5.0	5.2, 1.8	1.9, 1.3
M_Z [MeV]	2.1	2.1	2.1	11, 4	7.0, 1.4	2.5, 1.0
m_t [GeV]	0.8	0.6	0.1	2.4, 0.6	1.5, 0.2	0.7, 0.2
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	16	16	1.3	4.5, 4.9	2.8, 1.1	2.0, 1.0
$\Delta\alpha^5_{\rm had}(M_Z^2)$ [10^{-5}]	10	4.7	4.7	42, 13	36, 6	5.6, 3.0
R^0_l [10^{-3}]	25	25	4	–	–	–
$\alpha_S(M_Z^2)$ [10^{-4}]	–	–	–	40, 10	39, 7	6.4, 6.9
$S\|_{U=0}$	–	–	–	0.094, 0.027	0.086, 0.006	0.017, 0.006
$T\|_{U=0}$	–	–	–	0.083, 0.023	0.064, 0.005	0.022, 0.005
κ_V ($\lambda = 3$ TeV)	0.05	0.03	0.01	0.02	0.02	0.01

- Theory uncertainty needs to be reduced if we want to achieve the ultimate precision with the LHC!
- Future e^+e^- collider: fantastic possibilities for consistency tests of the SM on loop level and NP constraints

Summary

Uncertainties on M_W

Today

δ_{meas} = 15 MeV

δ_{fit} = 8 MeV

δ_{fit}^{theo} = 5 MeV

LHC-300

δ_{meas} = 8 MeV

δ_{fit} = 6 MeV

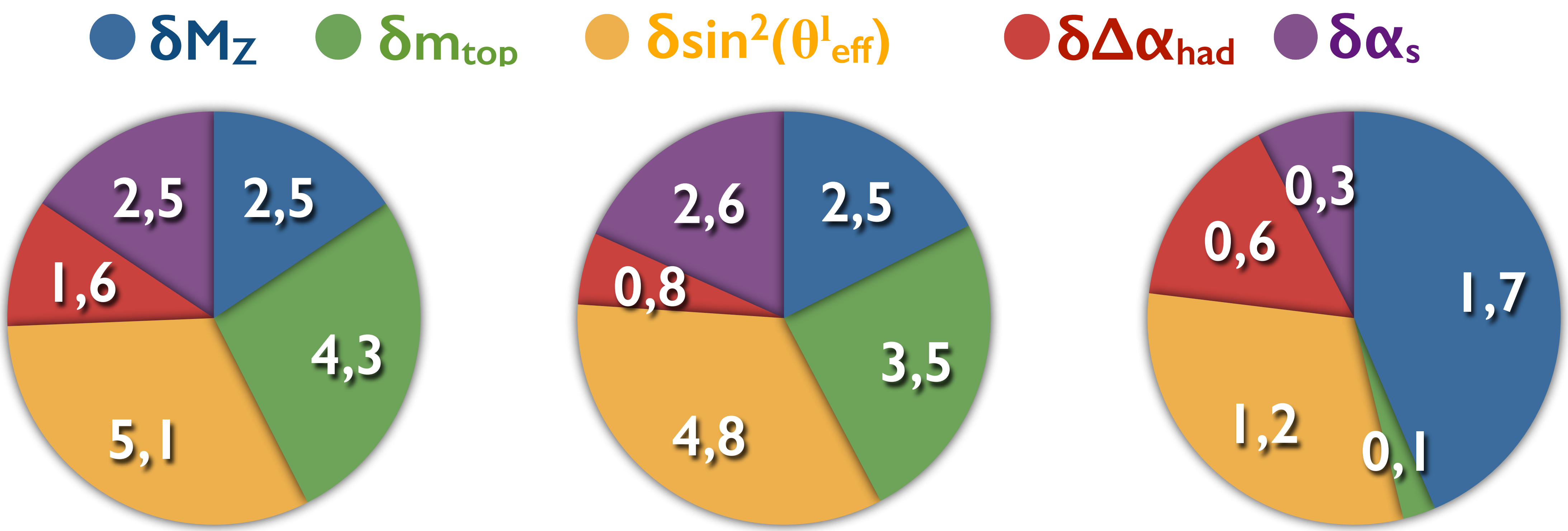
δ_{fit}^{theo} = 2 MeV

ILC/GigaZ

δ_{meas} = 5 MeV

δ_{fit} = 2 MeV

δ_{fit}^{theo} = 1 MeV



Impact of individual uncertainties on δM_W in fit (numbers in MeV)

Improved theoretical precision needed already for the LHC-300!

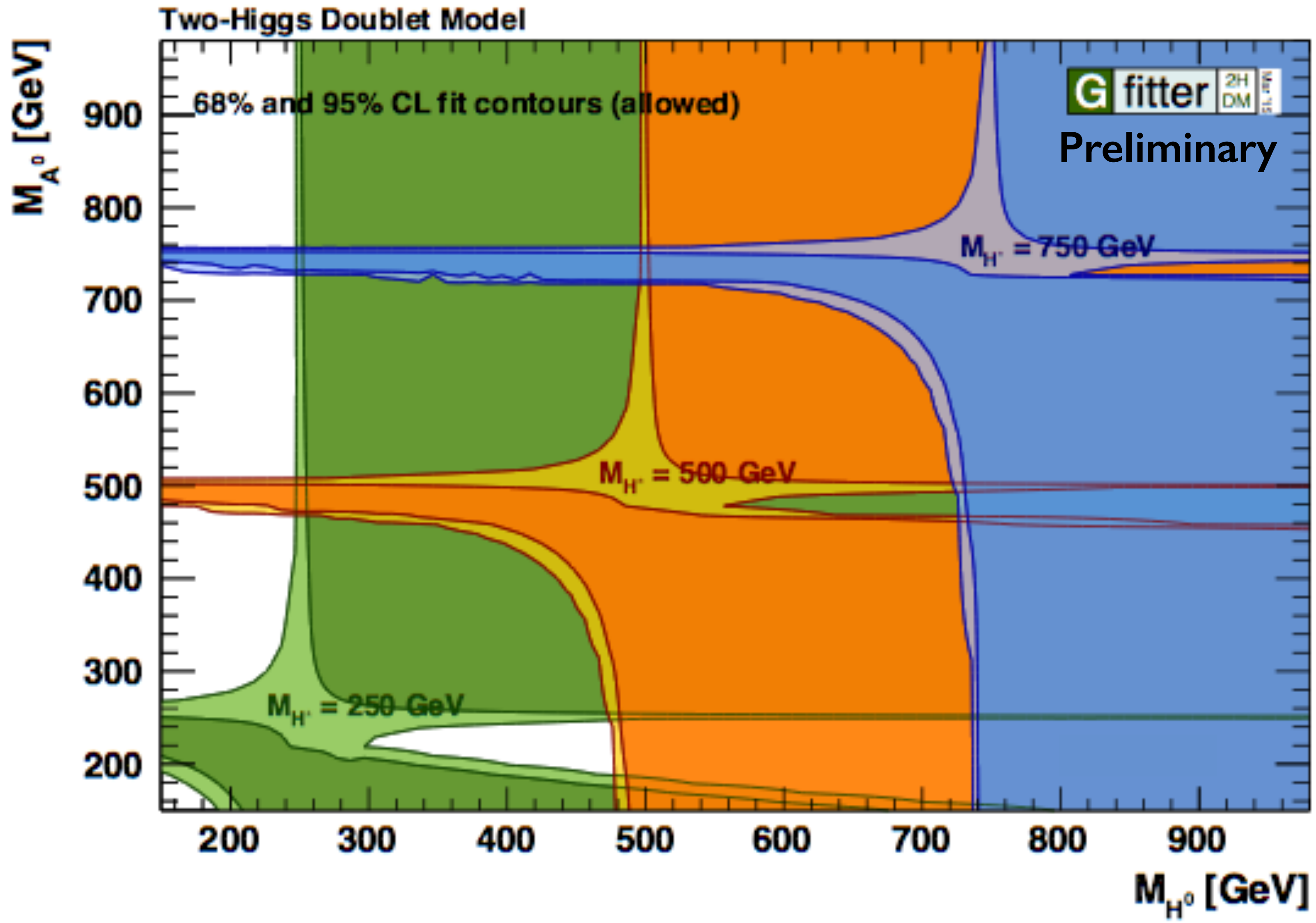
Additional Material

Two Higgs Doublet Models

(see talk by M. Beckingham)

- extend the scalar sector by another doublet
- studies of Z_2 Type-1 and Type-2 2HDMs
  - difference in the coupling to down-type quarks
  - Type-2 related to MSSM, but less constrained

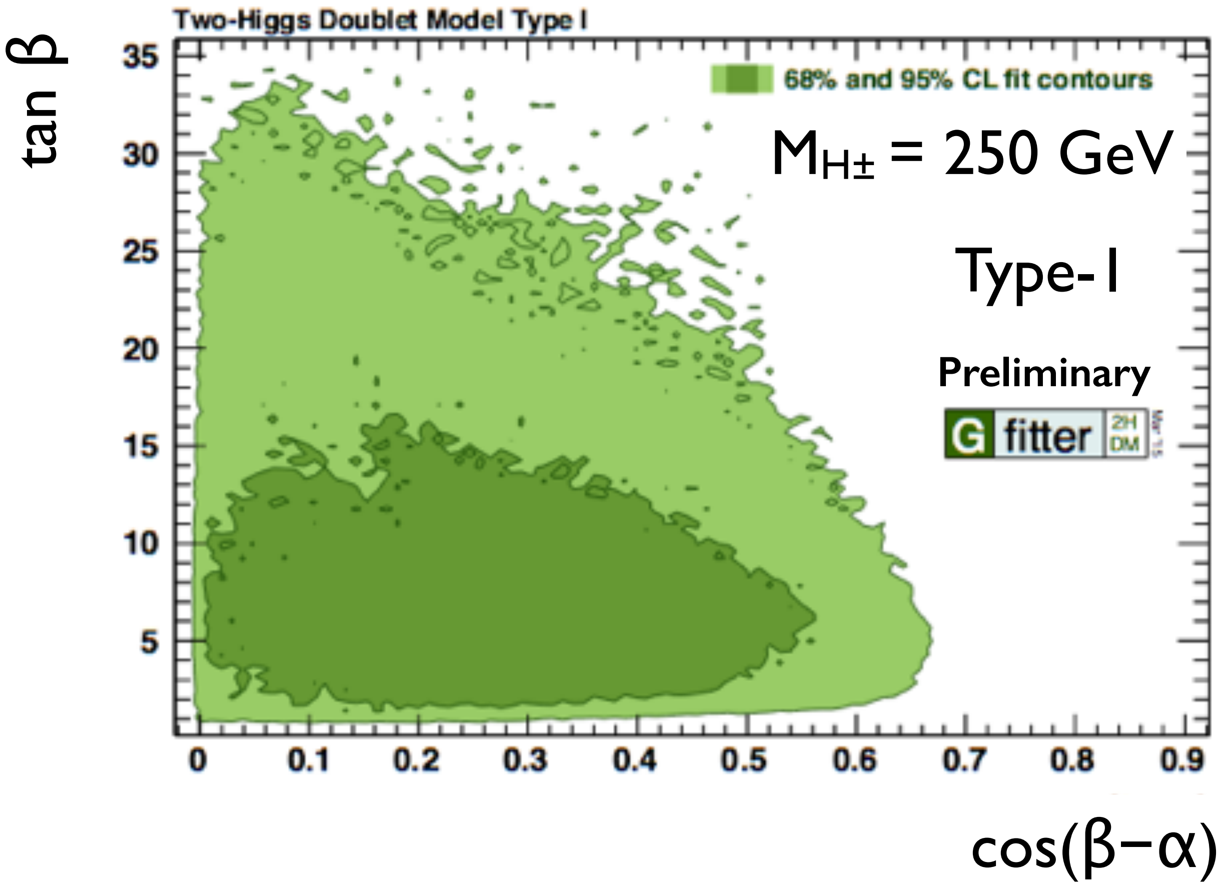
	Type I and Type II
Higgs	C_V
h	$\sin(\beta - \alpha)$
H	$\cos(\beta - \alpha)$
A	0

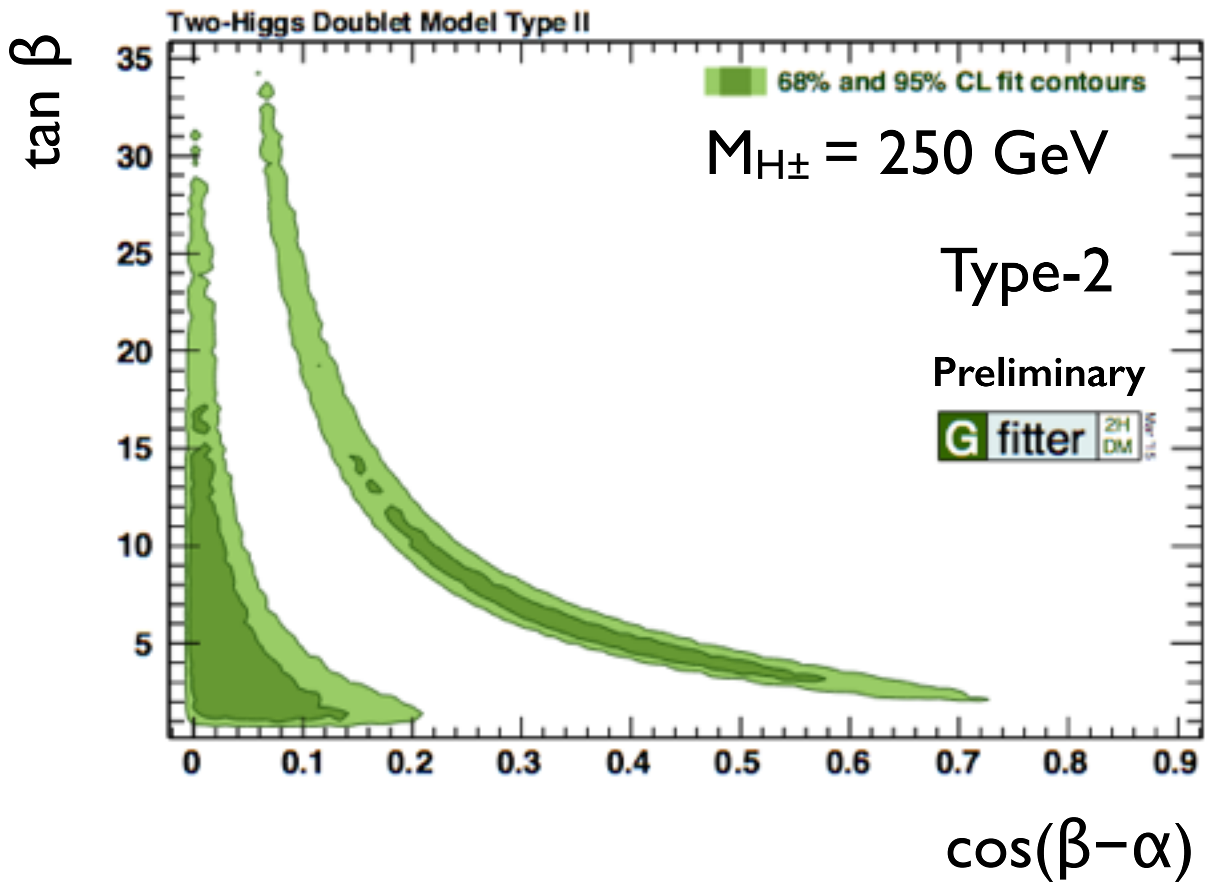


- constraints derived from EWPD using S,T,U formalism
- lightest scalar M_h = 125.1 GeV
- weak constraints on masses, since $\tan\beta$ and $\cos(\beta-\alpha)$ are unconstrained

2HDM and H Coupling Measurements

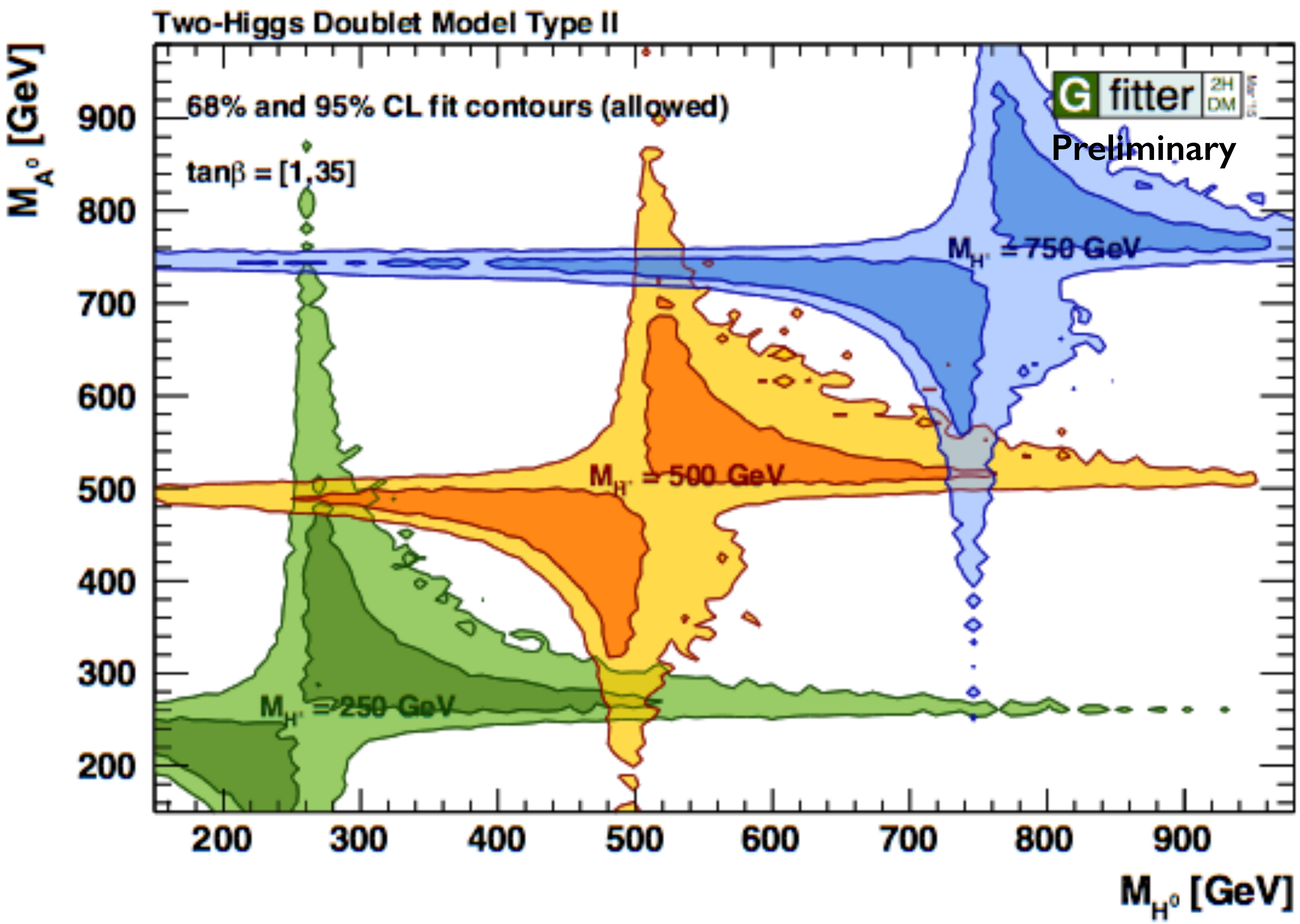
- coupling measurements place important constraints on 2HDMs
- predictions of BRs using 2HDMC [D. Eriksson et al., CPC 181, 189 (2010)]
- 7 additional, unconstraint parameters (4 masses, 2 angles, soft breaking scale): importance sampling with MultiNest [F. Feroz et al., arXiv:1306.2144]





- additional constraints from flavour data
  - $B \to X_s \gamma$: $\tan\beta > 1$
  - $B_s \to \mu\mu$: constraints depending on M_H and $M_{H\pm}$

Global Fit to 2HDM of Type-2



- for given $M_{H\pm}$ tight constraints from H coupling measurements and EWPD
- expect improvement from direct searches at the LHC