The Global Electroweak Fit

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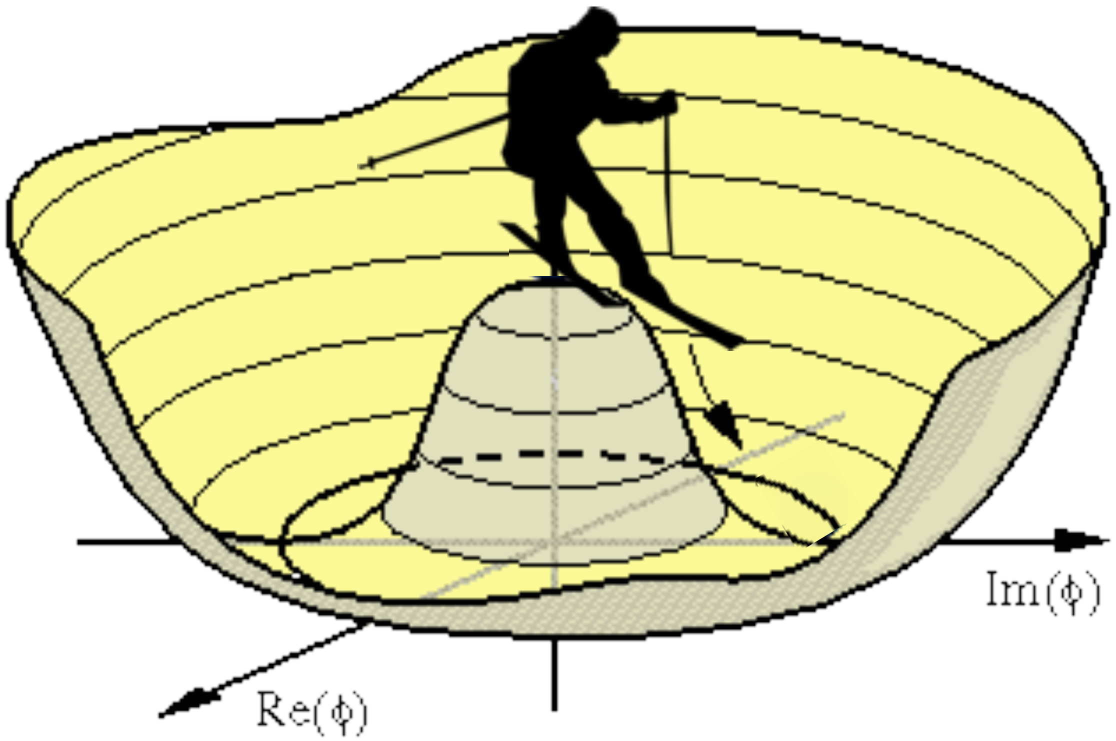
for the Gfitter group

50th Rencontres de Moriond EW

La Thuile, March 14 - 21, 2015



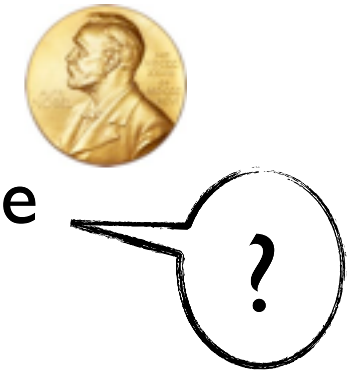
G fitter

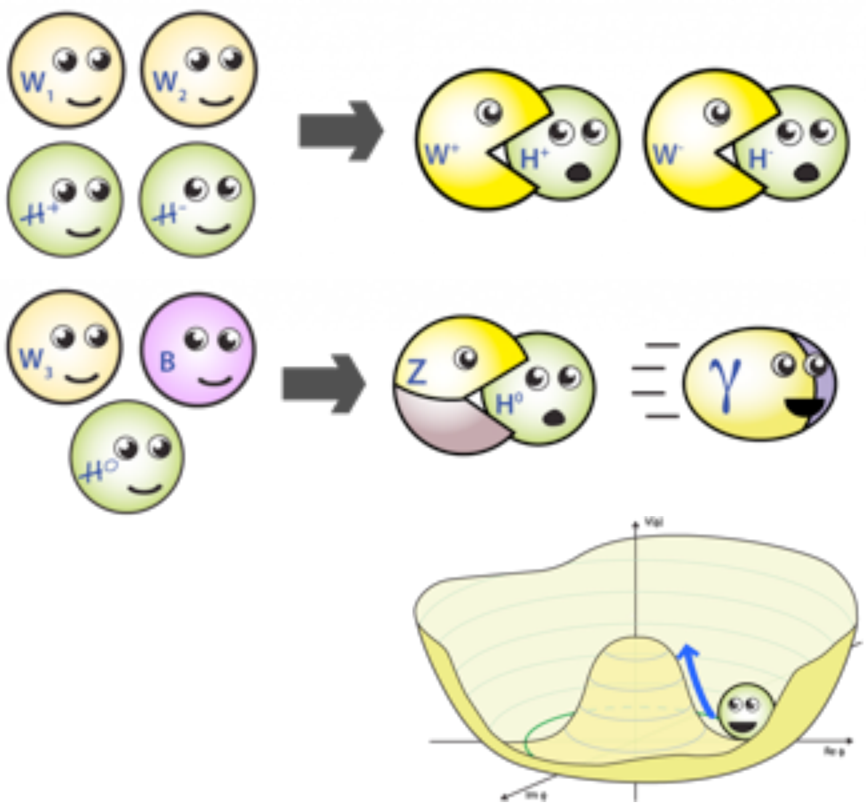
The Gfitter group: M. Baak (CERN), J. Cùth (Univ. of Mainz), J. Haller (Univ. Hamburg), A. Hoecker (CERN), R. K. (Univ. Hamburg), K. Mönig (DESY), T. Peiffer (Univ. Hamburg), M. Schott (Univ. of Mainz), J. Stelzer (Univ. of Michigan)

Introduction

The H discovery

- something to celebrate
- something to contemplate





[Philip Tanedo, quantumdiaries.org]

The SM incorporates the minimal version of the scalar sector

- is there a single Higgs doublet?

The electroweak fit is a powerful tool to study the scalar sector from all perspectives

- in the SM
- modified H couplings
- test extensions of the scalar sector

The Electroweak Sector of the SM

Electroweak sector given by 3 parameters

- once v, g, g’ are known, all other parameters are fixed

$$M_W = \frac{v|g|}{2}$$

$$M_Z = \frac{v\sqrt{g^2 + g'^2}}{2}$$

$$\cos\theta_W = \frac{M_W}{M_Z}$$

Use the three most precise parameters

- α : $\Delta\alpha/\alpha = 3\times10^{-10}$
- G_F : $\Delta G_F/G_F = 5\times10^{-7}$
- M_Z : $\Delta M_Z/M_Z = 2\times10^{-5}$
- measure more than the minimal set of parameters to test the theory!

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

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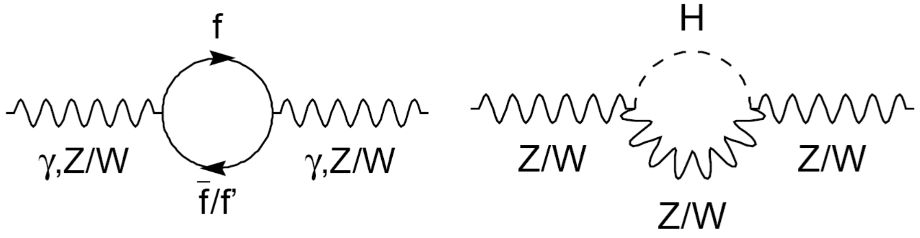
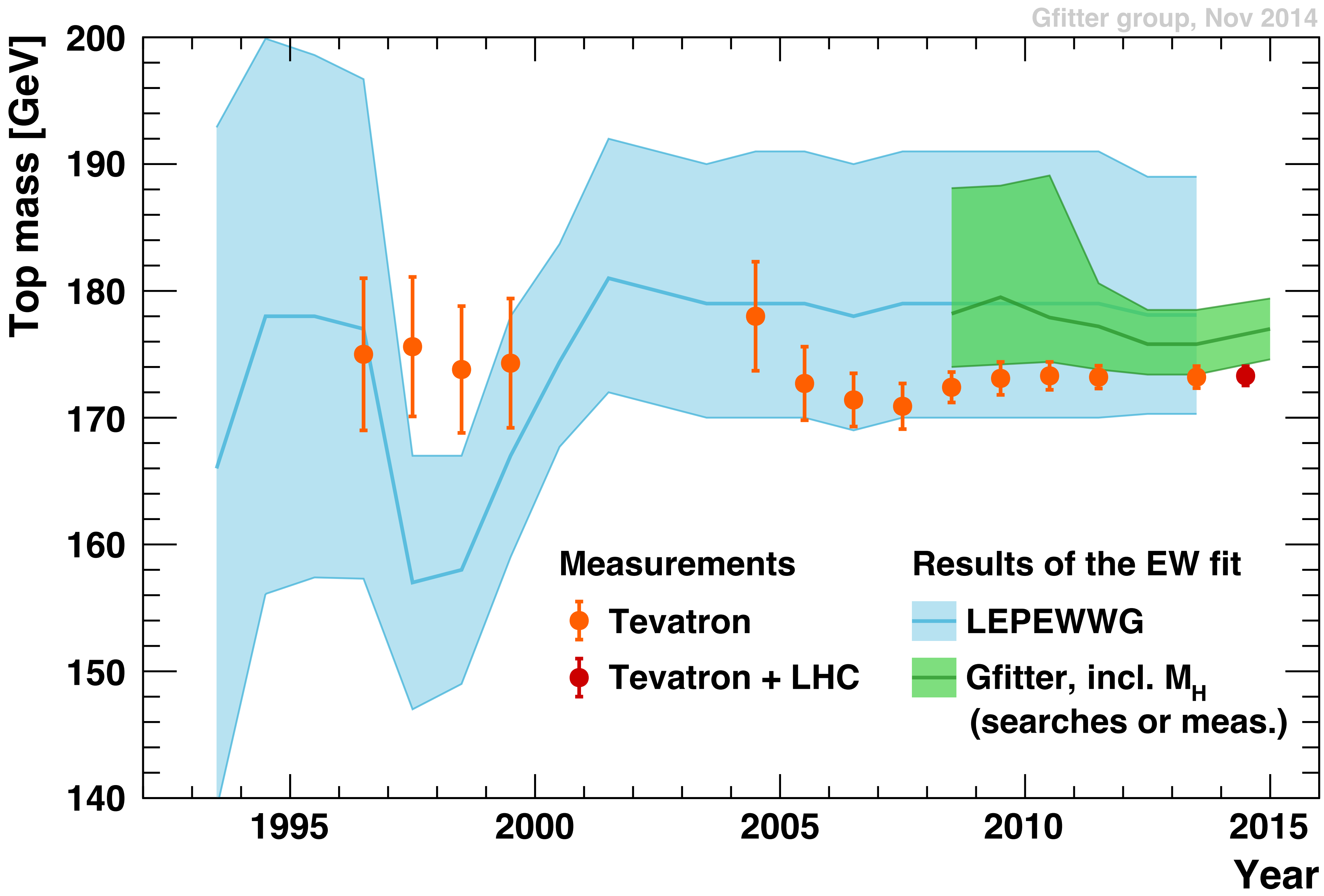
Radiative corrections



- modification of propagators and vertices
- electroweak form factors ρ, κ, Δr
  - depend on all parameters of the theory (m_t, M_H, α_s...)

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

Top Quark Mass from Loop Effects



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

The Electroweak Fit

Disclaimer:

- there are several groups who routinely perform the electroweak fit
- there are small differences in the methodology, the results agree very well
- I will focus on results from the Gfitter group [Gfitter group, EPJC 74, 3046 (2014)]

Experimental Input

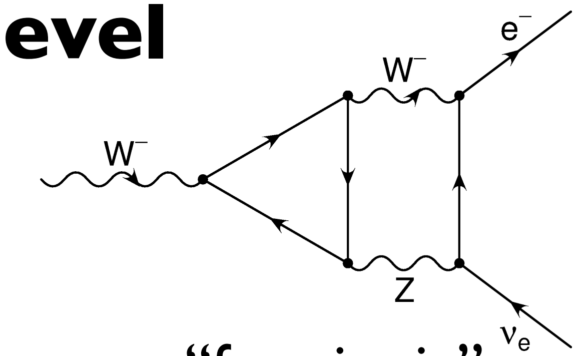
Fit is overconstrained

- all free parameters measured ($\alpha_s(M_Z)$ unconstrained in fit)
  - most input from e^+e^- colliders
    - M_Z : 0.002%
  - but crucial input from hadron colliders:
    - m_t : 0.4%
    - M_W : 0.02%
    - M_H : 0.2%
  - remarkable precision (<1%)
- require precision calculations

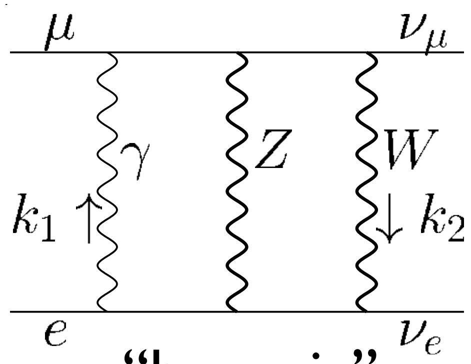
M_H [GeV]	125.14 ± 0.24	LHC
M_W [GeV]	80.385 ± 0.015	Tev.
Γ_W [GeV]	2.085 ± 0.042	
M_Z [GeV]	91.1875 ± 0.0021	
Γ_Z [GeV]	2.4952 ± 0.0023	
$\sigma^0_{\rm had}$ [nb]	41.540 ± 0.037	LEP
R^0_ℓ	20.767 ± 0.025	
$A^{0,\ell}_{\rm FB}$	0.0171 ± 0.0010	
A_ℓ $^{(\star)}$	0.1499 ± 0.0018	SLD
$\sin^2\theta^\ell_{\rm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

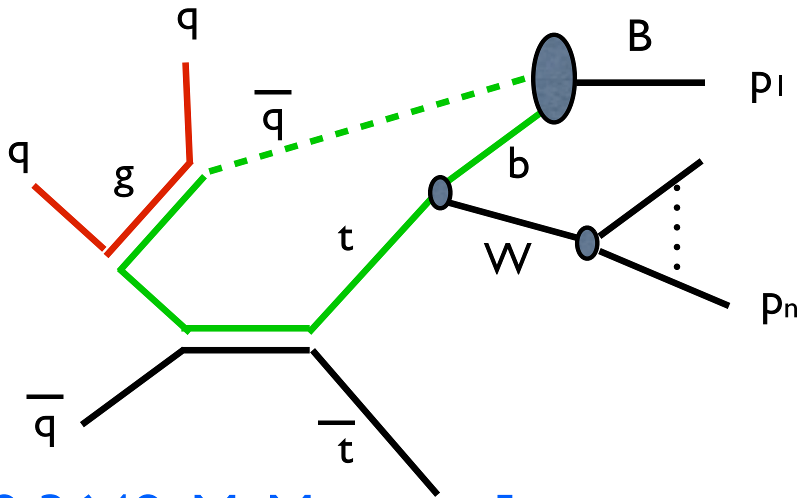
NEW

- **Radiator functions**: QCD corrections at N^{3}LO
  [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]

  - kin 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)

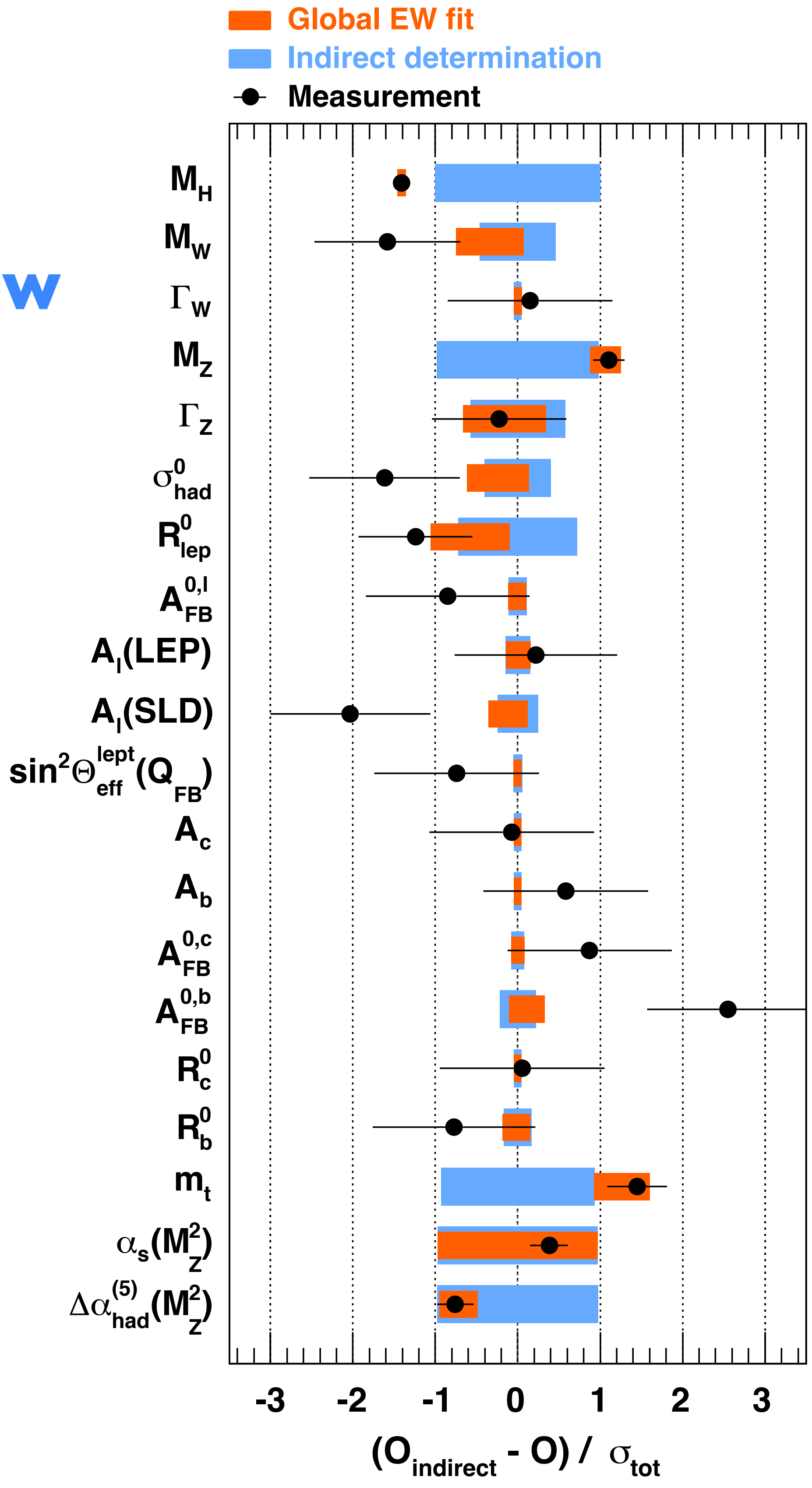
SM Fit Results

black: direct measurement (data)

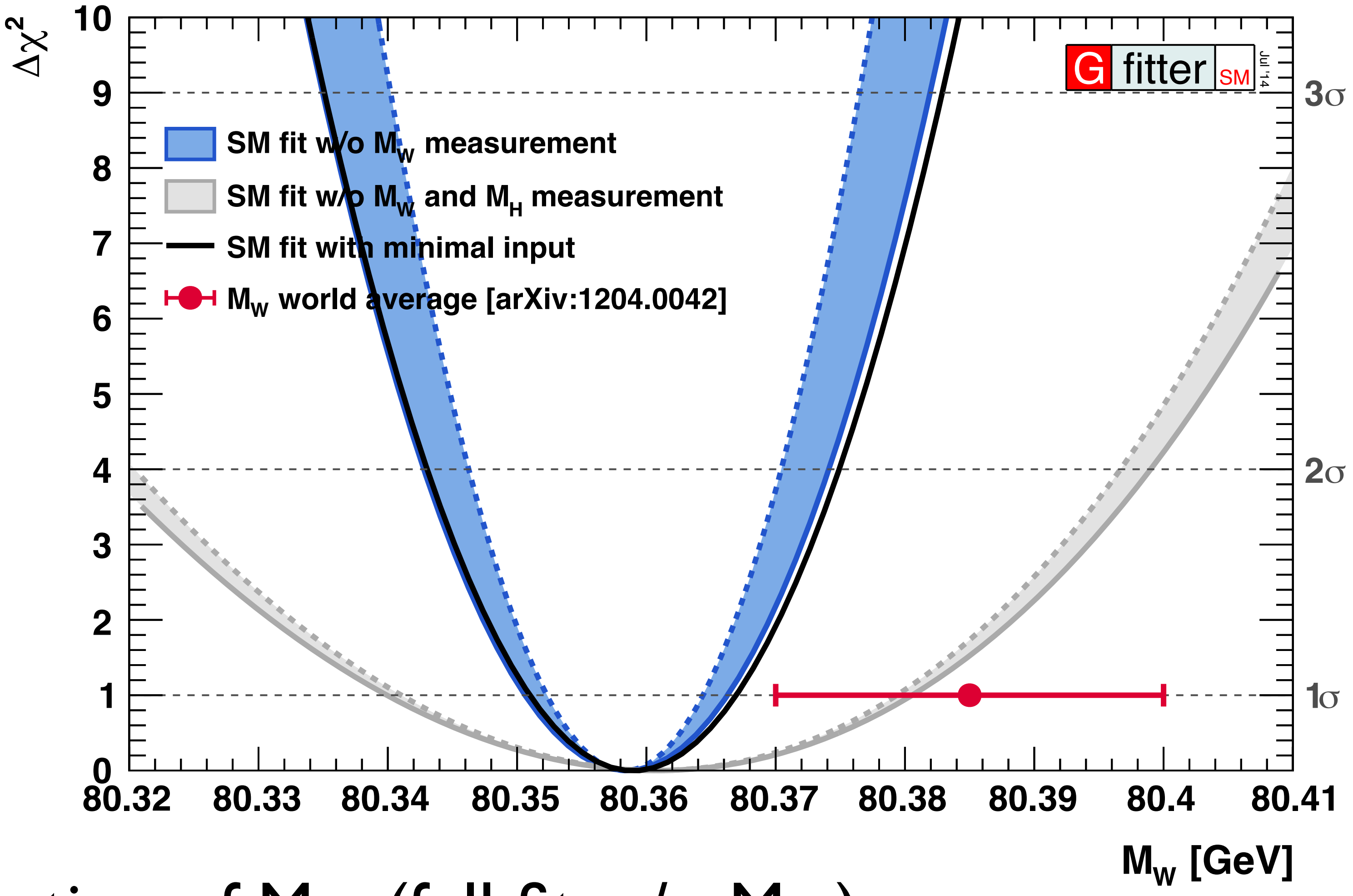
orange: full fit

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}(Z widths 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



Indirect determination of W mass



$\Delta\chi^2$ profile vs M_W

- 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):

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

more precise than direct measurement (15 MeV)

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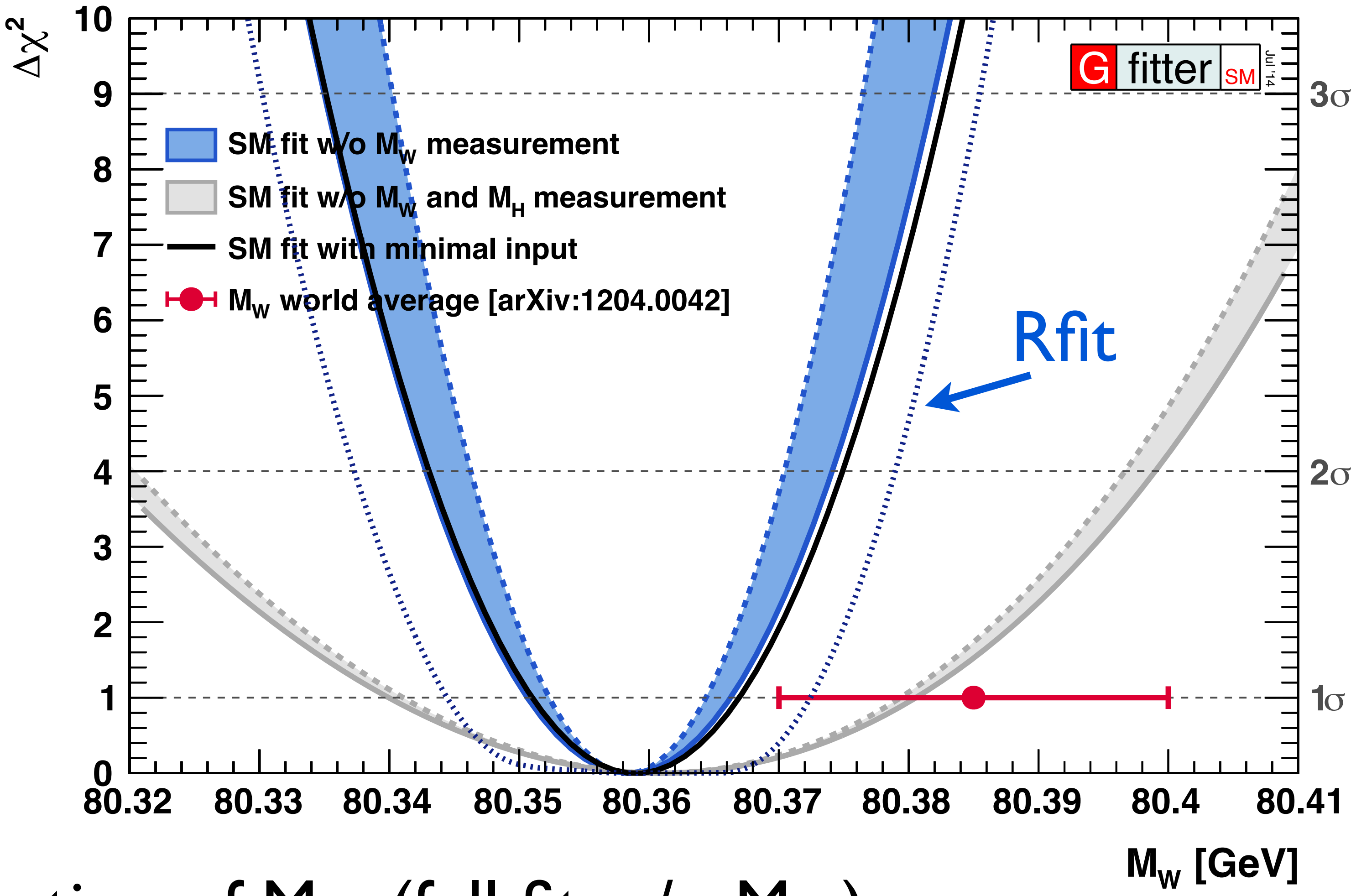

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&= 80.358 \pm 0.008_{\text{tot}} \ \text{GeV}
\end{aligned}
$$

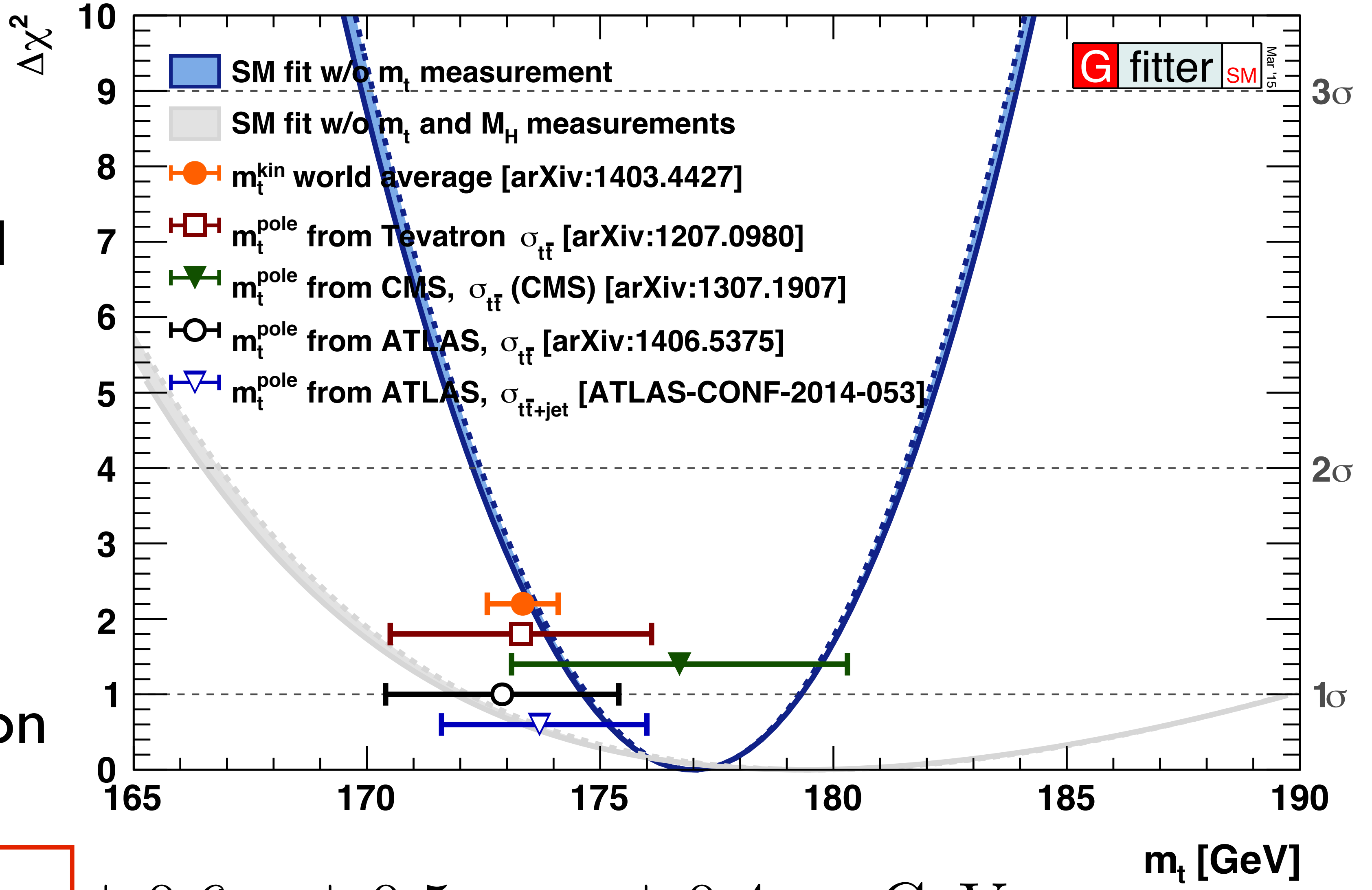
(δm_t (1 GeV): ±9 MeV, Rfit: ±13 MeV)

more precise than direct measurement (15 MeV)

Indirect determination of m_t

$\Delta\chi^2$ profile vs m_t

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

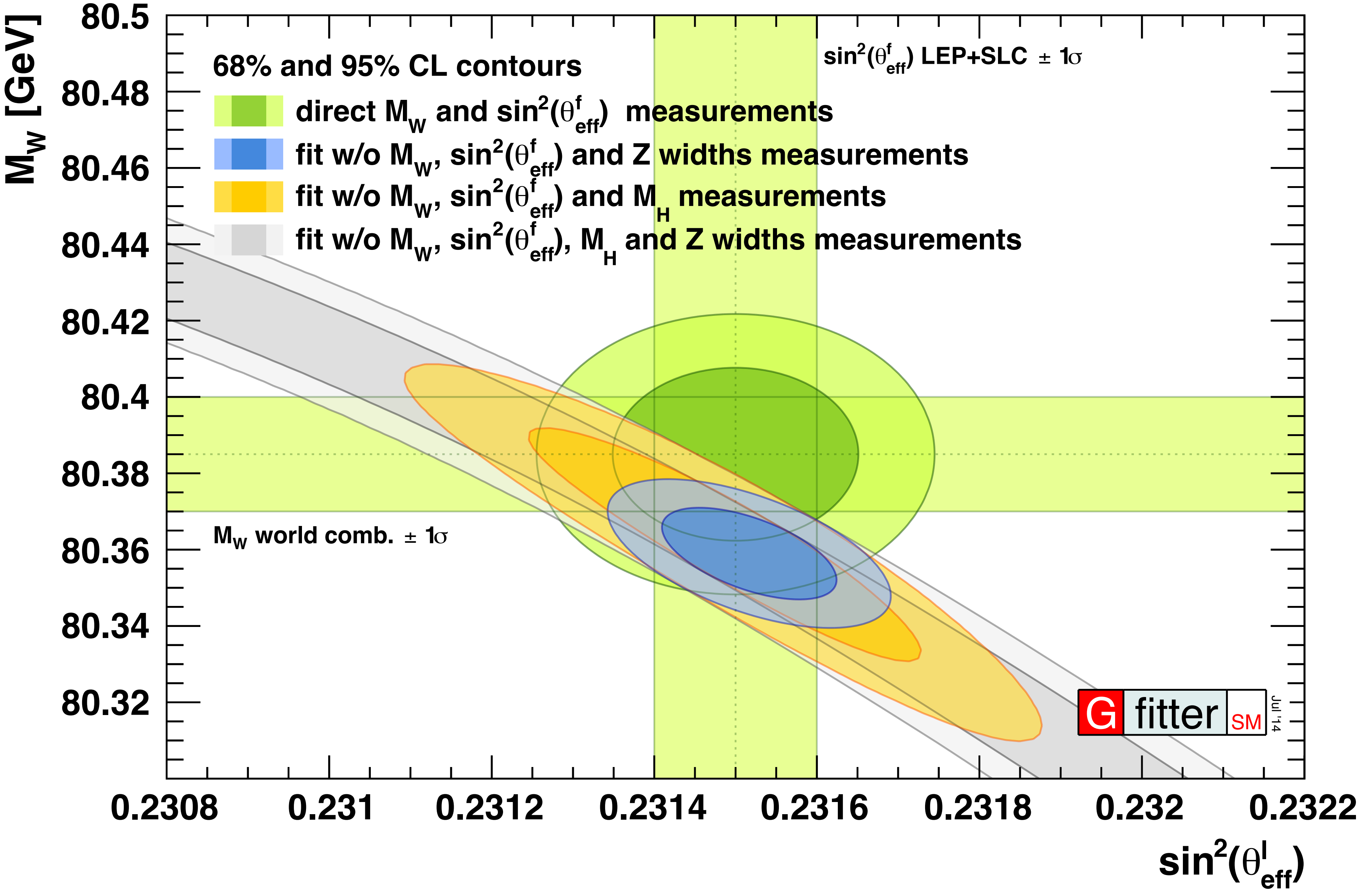


$$m_t = 177.0 \pm \boxed{2.3_{M_W,\,\sin^2\theta^f_{\rm eff}}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\rm had}} \pm 0.4_{M_Z}\ \text{GeV}$$

$$= \underline{177.0 \pm 2.4_{\rm exp} \pm 0.5_{\rm theo}\ \text{GeV}}$$

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

State of the SM: M_W vs $\sin^2\theta^l_{eff}$



sensitive probes of new physics

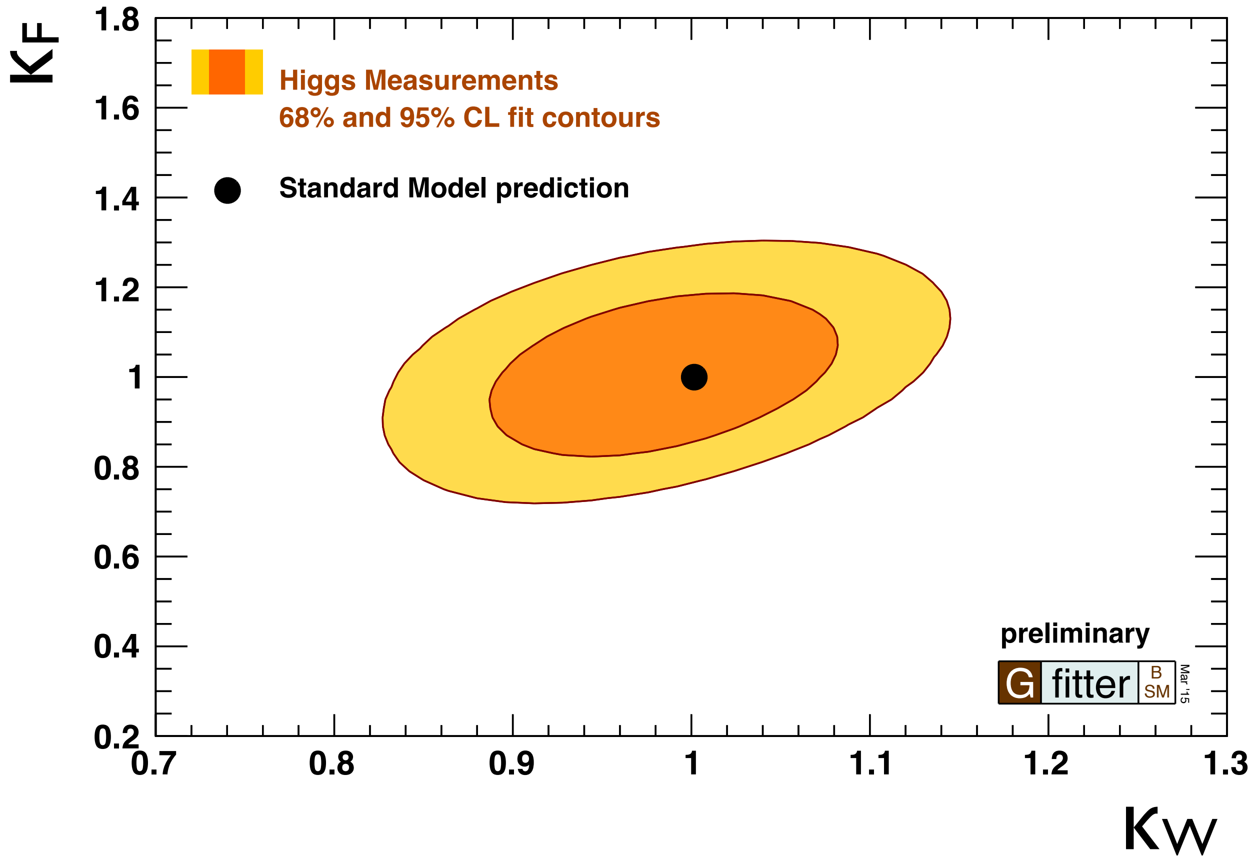
- significant reduction of parameter space due to knowledge of M_H
- predictions are more precise than the direct measurements

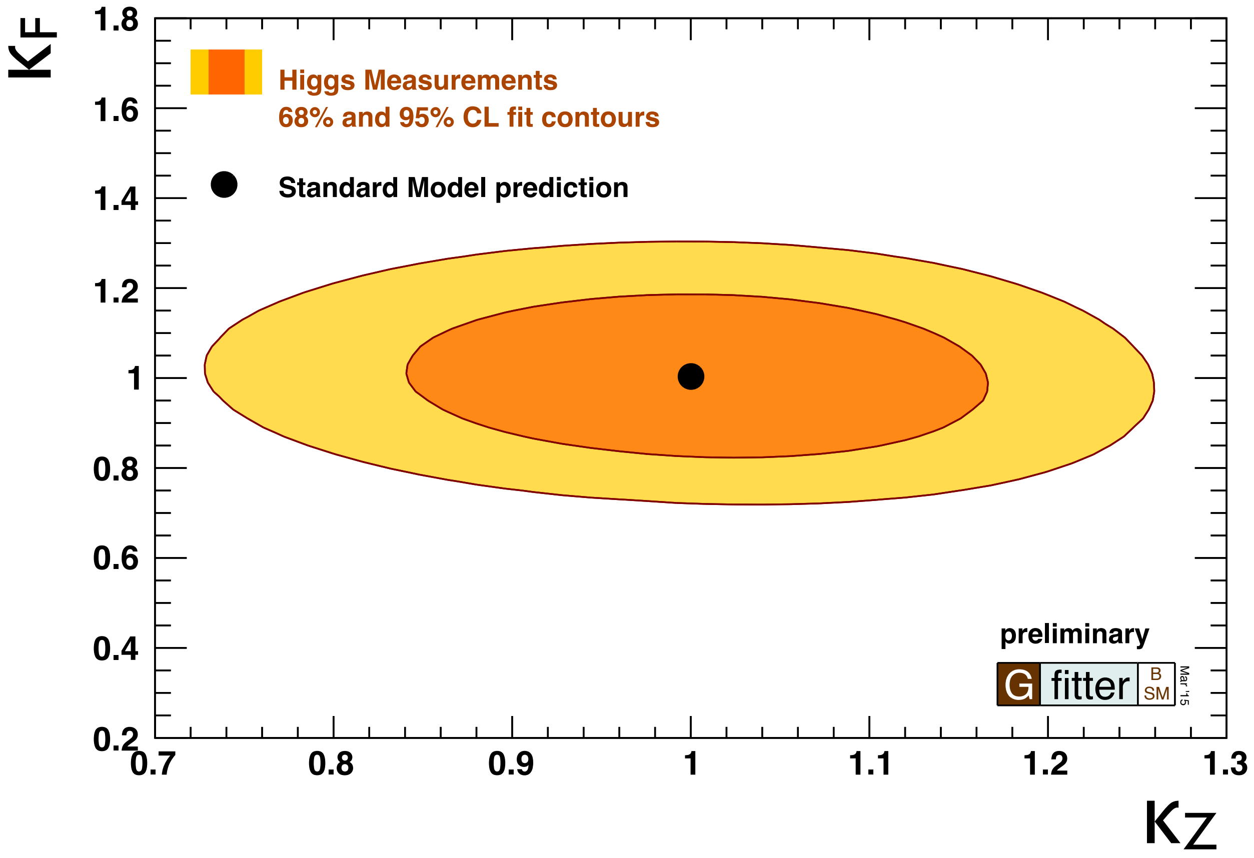
The Scalar Sector

Tree Level Higgs Couplings

[talk by Michael Duehrssen]

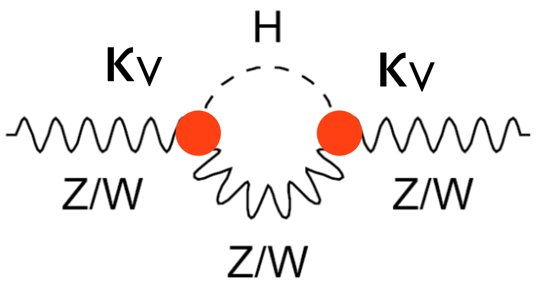
- study of potential deviations of Higgs couplings from SM
- leading corrections only, parametrize deviations with effective couplings
- LHC and Tevatron data included using HiggsSignals [P. Bechtle et al., JHEP11, 039 (2014)]





- no BSM contributions on tree-level to fermion or vector-boson coupling
- stronger constraints on κ_W than on κ_Z
- custodial symmetry holds, $\kappa_W = \kappa_Z = \kappa_V$

Constraints from EWPD

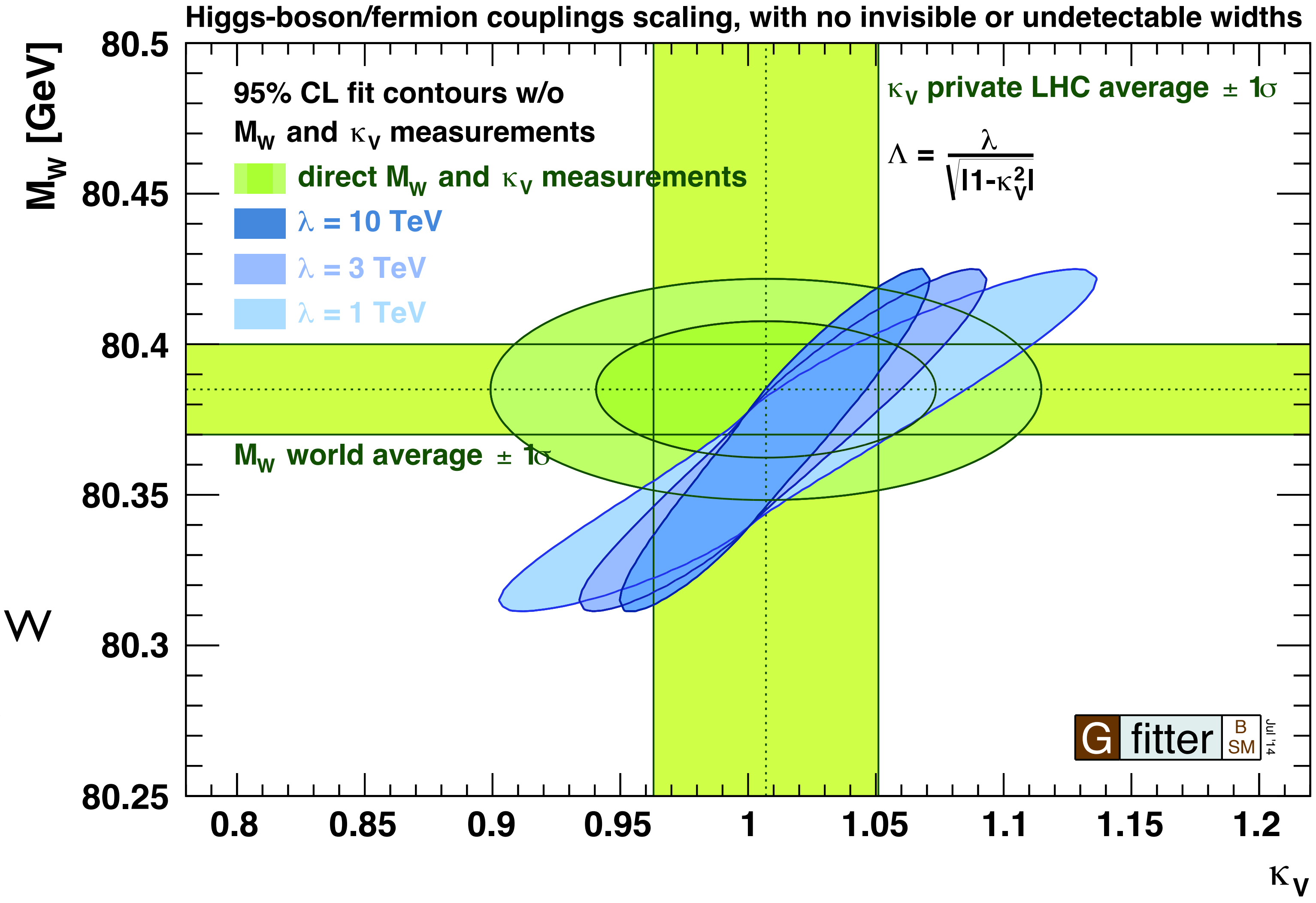


- consider specific model in “κ parametrisation”:
  - scaling of Higgs-vector boson (κV) and Higgs-fermion couplings (κF), with no invisible/undetectable widths
- main effect on EWPD due to modified Higgs coupling to gauge bosons (κV) [Espinosa et al. arXiv:1202.3697, Falkowski et al. arXiv:1303.1812], etc

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

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

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



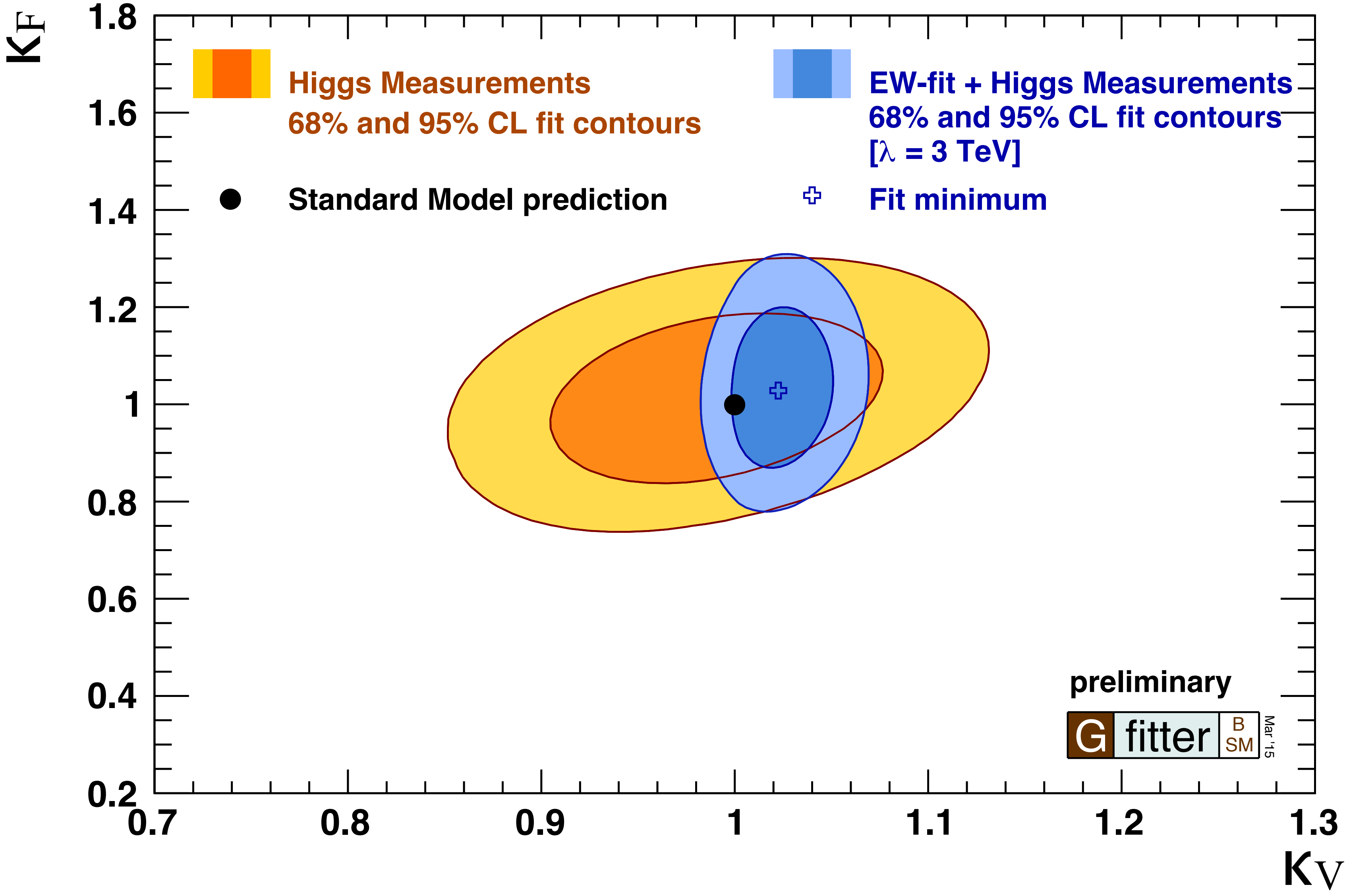
- correlation between κV and MW
  - slightly smaller values of MW preferred

Higgs Coupling Results

Higgs coupling measurements:

- κ_V = 0.99 ± 0.08
- κ_F = 1.01 ± 0.17

- **Combined result:**
- κ_V = 1.03 ± 0.02 (λ = 3 TeV)
- implies NP-scale of $\Lambda \geq$ 13 TeV



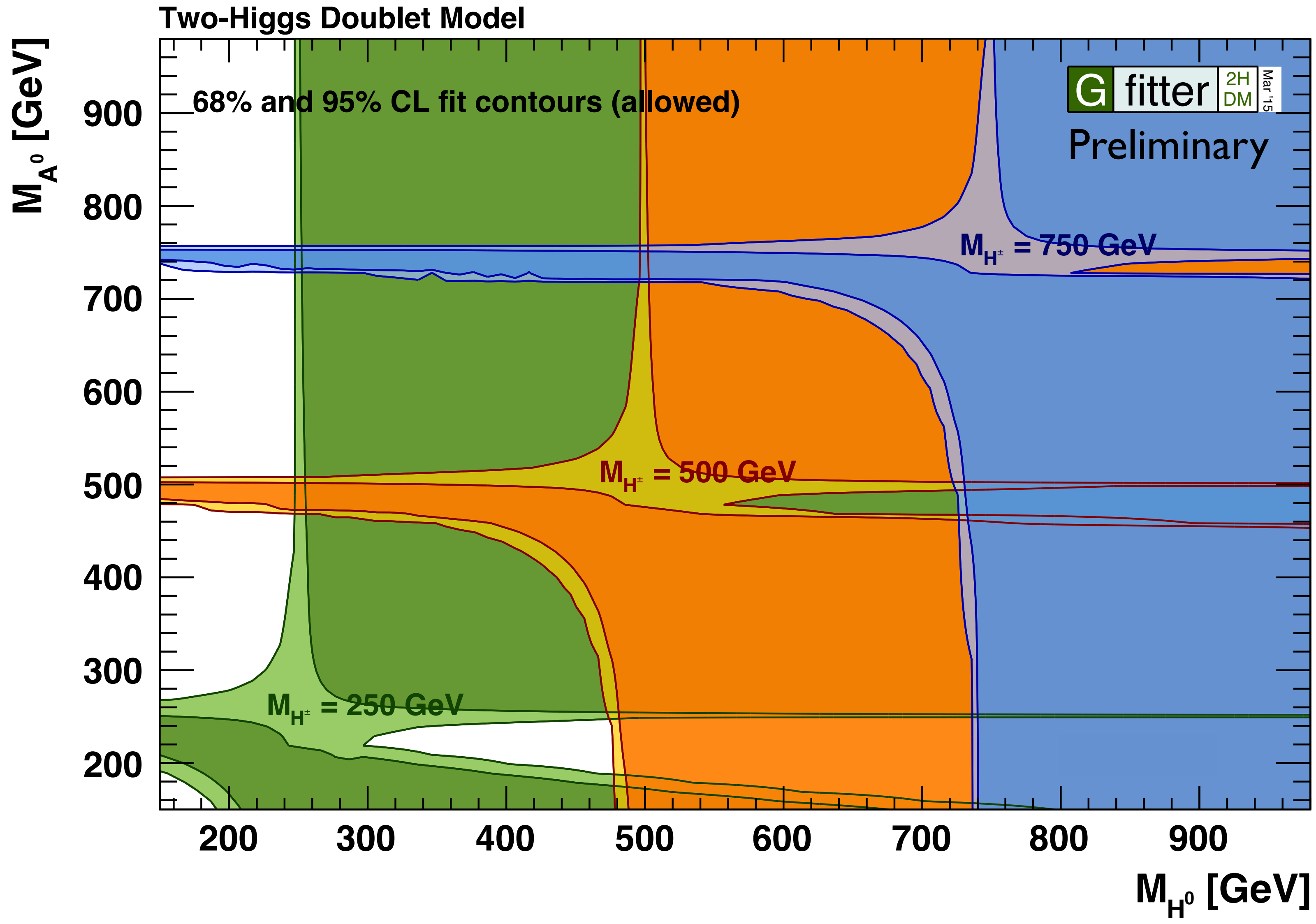
- some dependency for κ_V in central value [1.02-1.04] and error [0.02-0.03] on cut-off scale λ [1-10 TeV]
  - EW fit sofar more precise result for κ_V than current LHC experiments
  - EW fit has positive deviation of κ_V from 1.0
    - many BSM models: κ_V < 1

Two Higgs Doublet Models

[talk by Alejandro Celis]

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

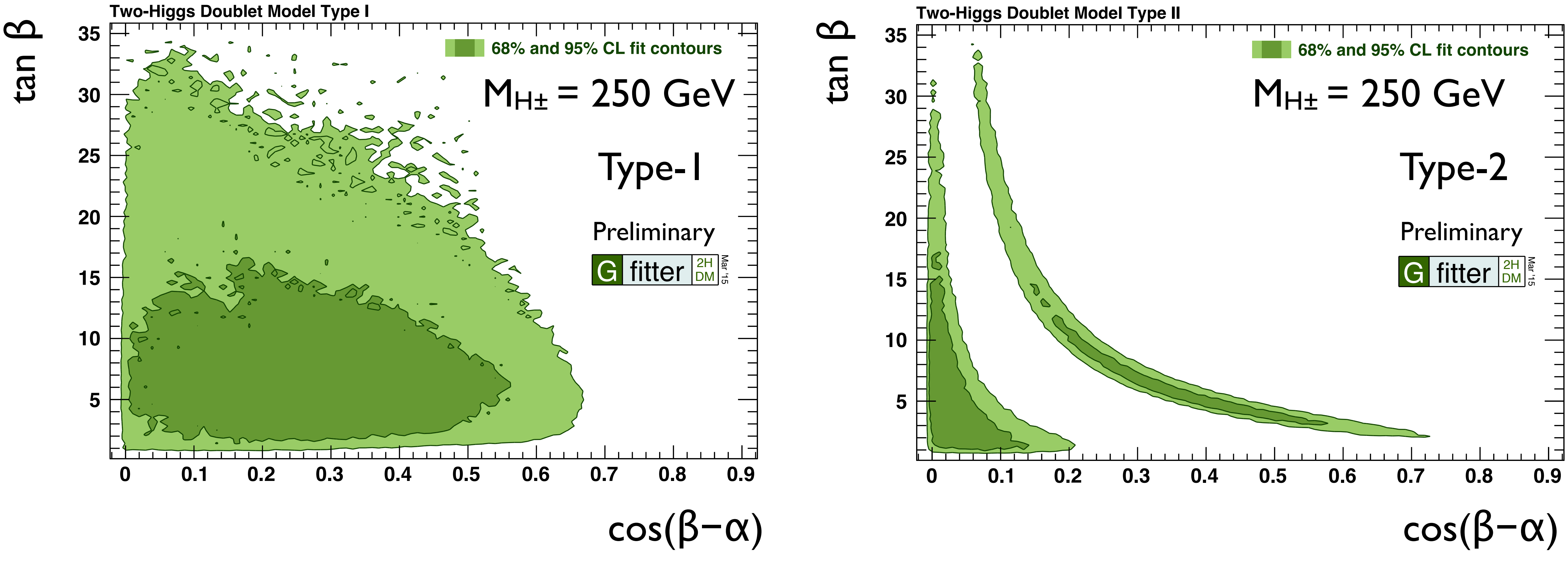
	Type I and Type II
Higgs	C_V
h	$\sin(\beta - \alpha)$
H	$\cos(\beta - \alpha)$
A	0



- 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

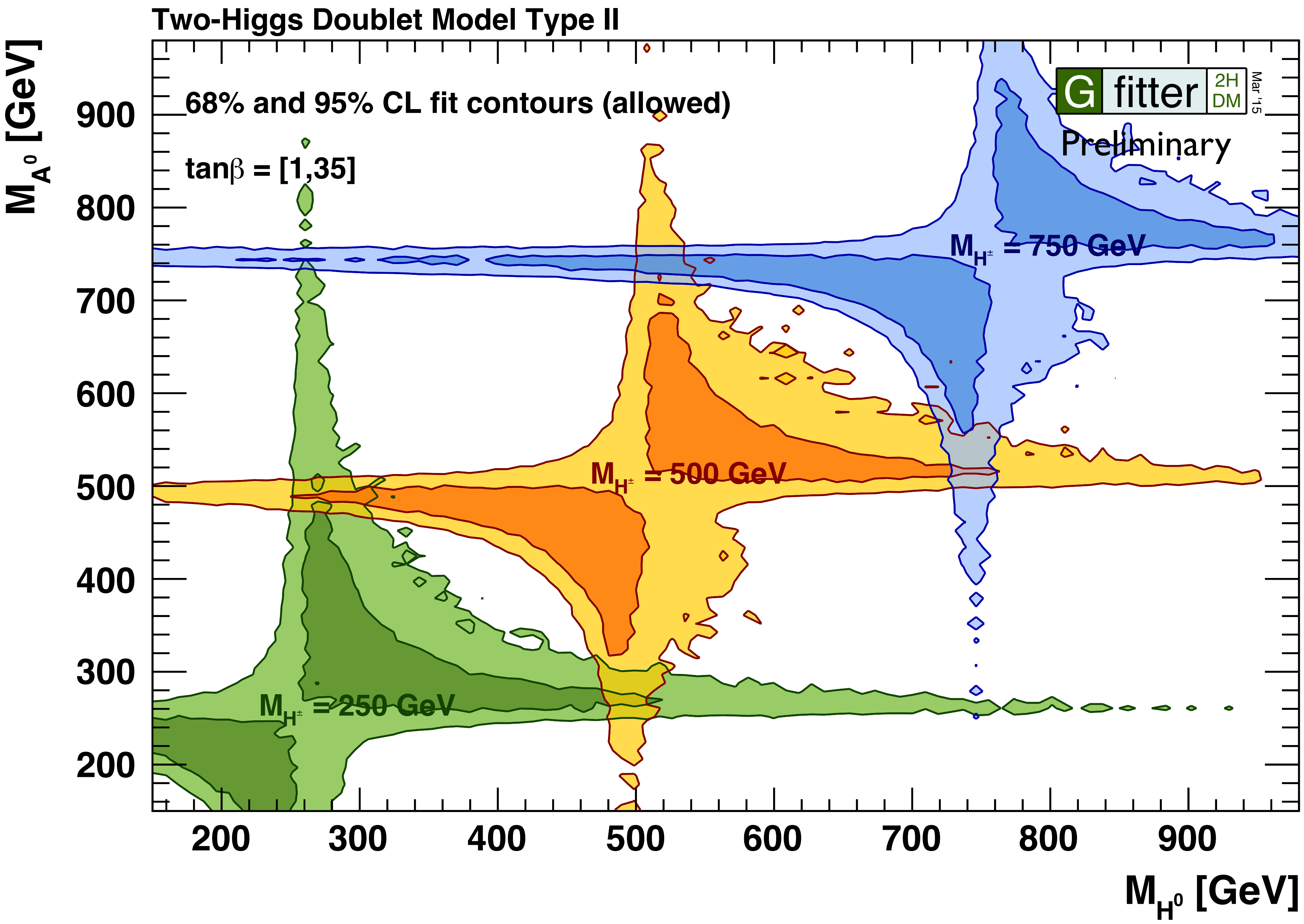
2HDM and H Coupling Measurements

- 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]



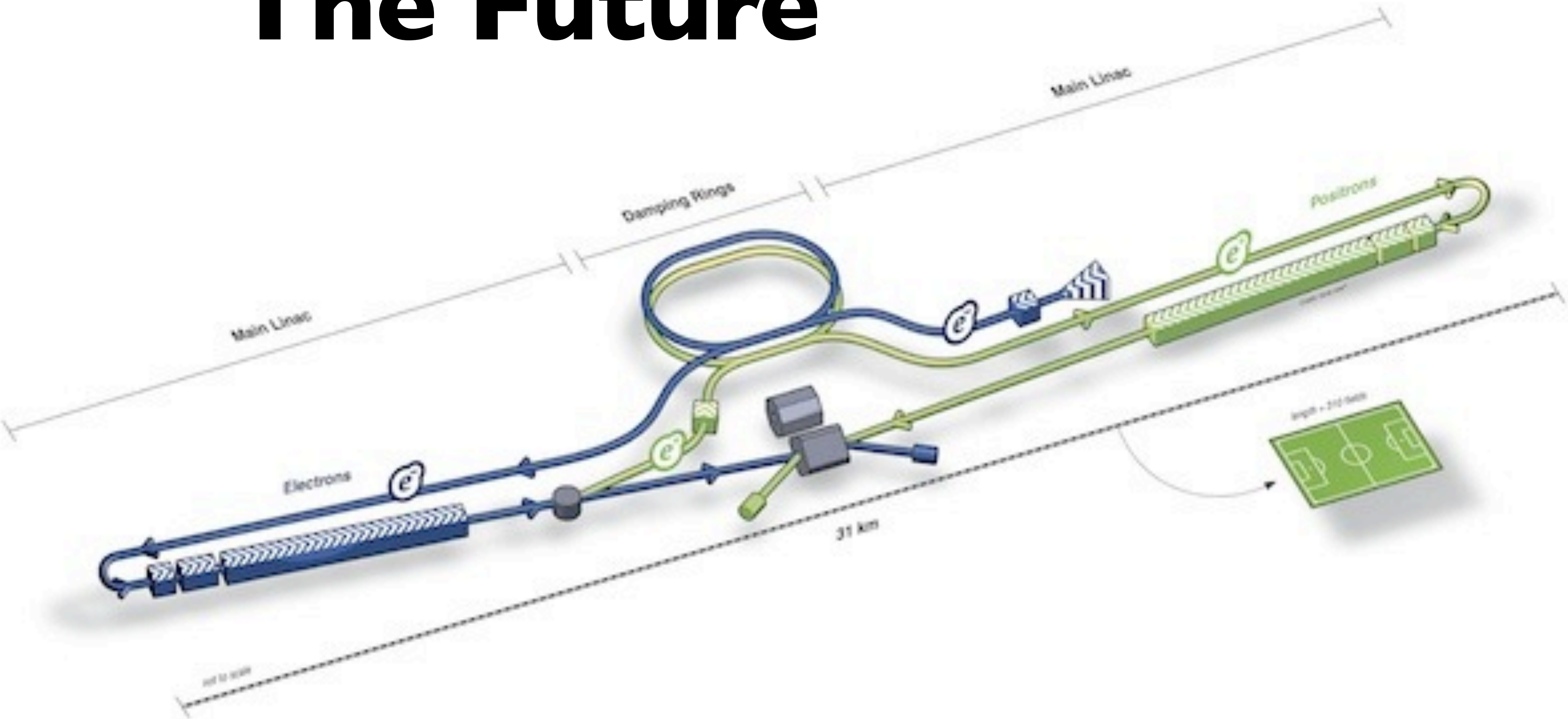
- additional constraints from flavour data
  - $B \to X_s \gamma$: $\tan\beta > 1$
  - $B_s \to \mu\mu$: constraints depending on M_H and $M_{H\pm}$

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 [talks by Paolo Meridani, Mario Pelliccioni]

The Future

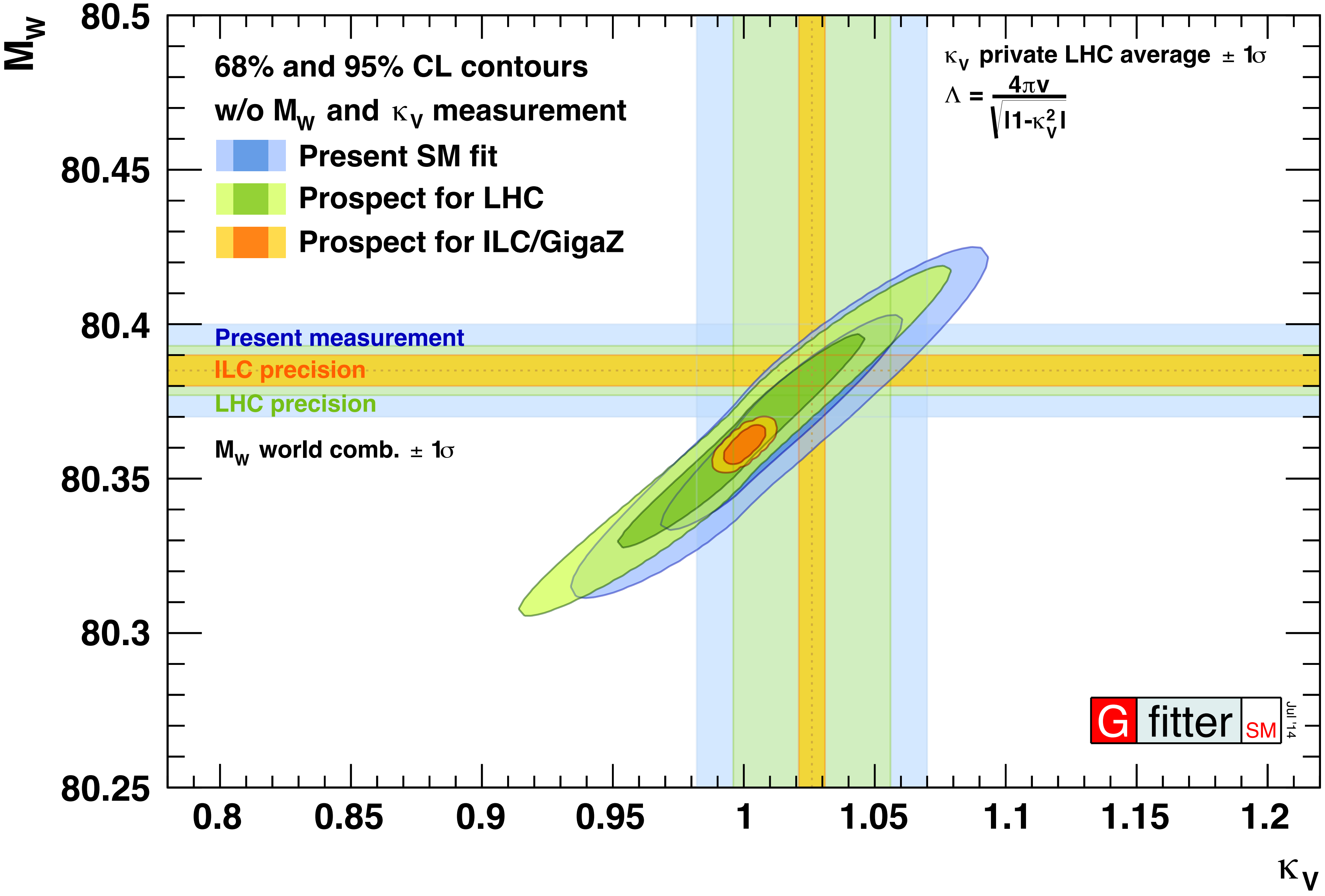

Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km
not to scale

Future Improvements

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	→	5		5	low energy data, better α_s
R^0_l $[10^{-3}]$	25		25	→	4	high statistics on Z-pole
κ_V $(\lambda = 3\,\mathrm{TeV})$	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 EW calculations!
  - exception: $\delta_{\rm theo}\, m_t$ (LHC) = 0.25 GeV (factor 2)

Prospects of EW Fit

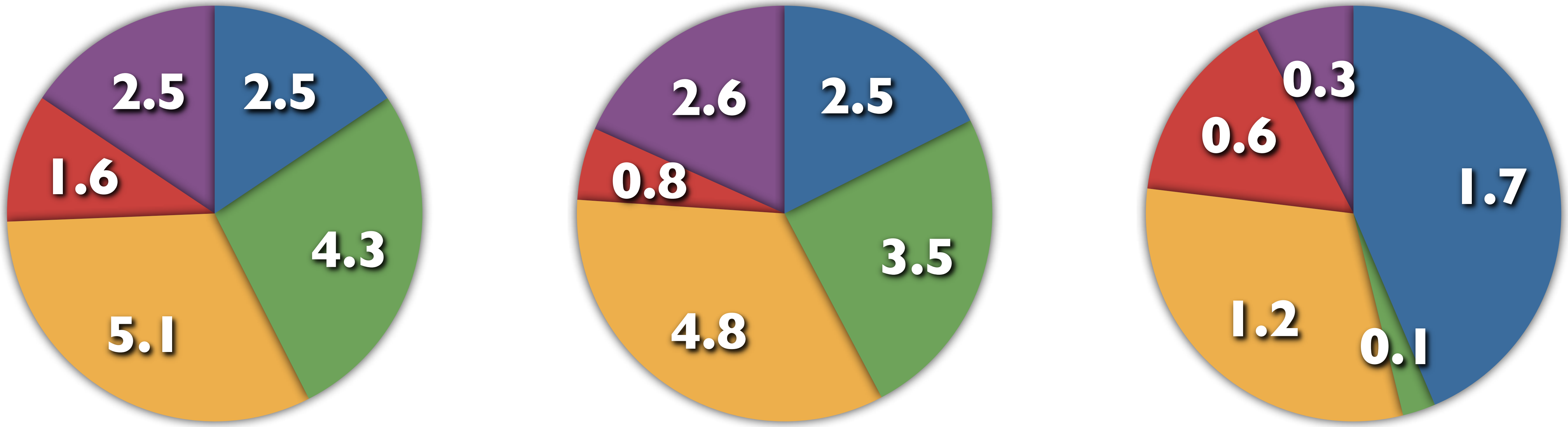


- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP

M_W : Impact of Uncertainties

	Today	**LHC-300**	**ILC/GigaZ**
δ_{meas} =	15 MeV	8 MeV	5 MeV
δ_{fit} =	8 MeV	6 MeV	2 MeV

● δM_Z ● δm_{top} ● $\delta \sin^2(\theta^l_{eff})$ ● $\delta \Delta\alpha_{had}$ ● $\delta\alpha_s$



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

- ILC/GigaZ: impact δM_Z of will become important again!

Summary

Huge success of the SM

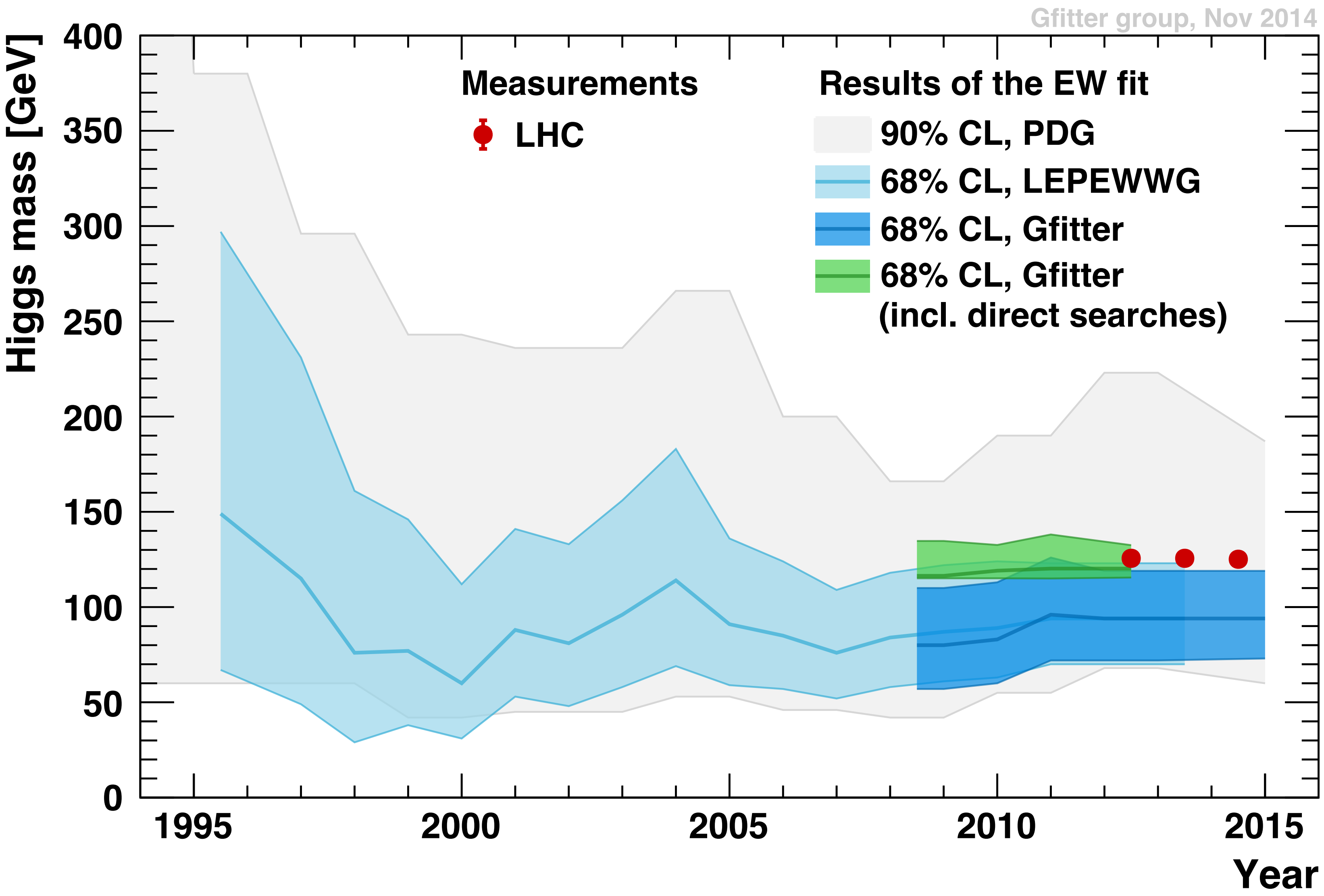
- EW fit is a powerful tool to study the scalar sector of the SM
  - impact on SM observables
  - modifications of H couplings
  - BSM extensions

We cannot know M_W and $\sin^2\theta^l_{eff}$ precise enough

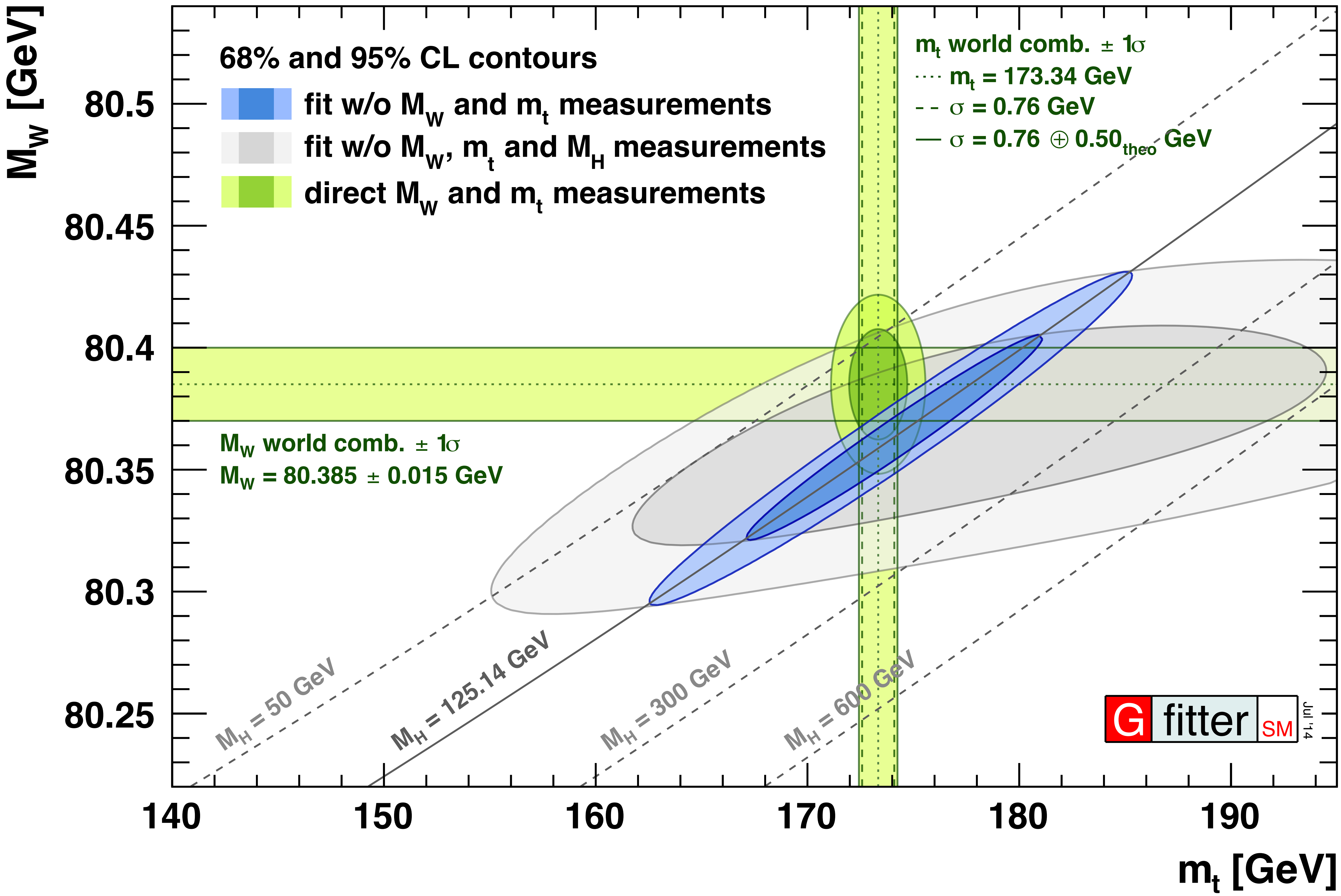
(theoretically and experimentally)

G fitter

www.cern.ch/gfitter



Thank You For Your Attention!



Additional Material

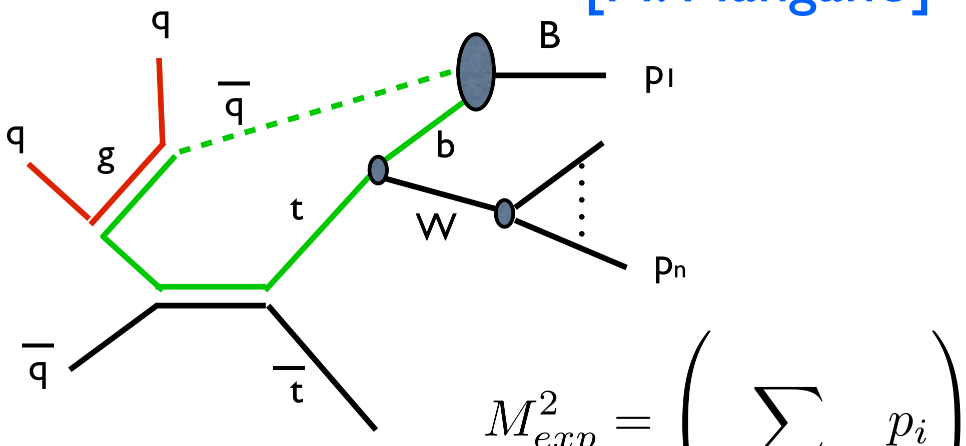
Interpreteation of m_t measurements

Accuracy of m_t ?

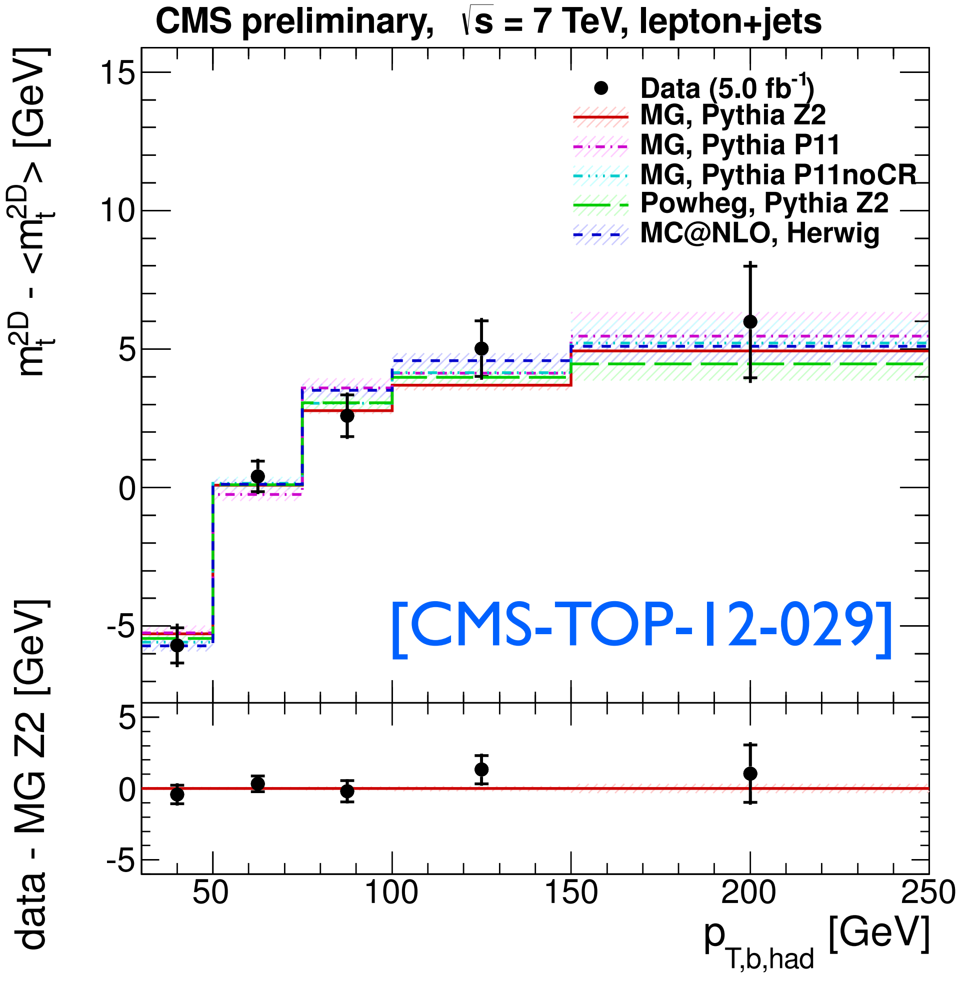
- kinematic top mass definition
  - factorization: hard function, universal jet-function, non-pert. soft function [Moch et al, arXiv:1405.4781]
  - MC mass is (may be) related to the low scale short-distance mass in the jet function
  - but: no quantitative statement available
  - relating m_t^{kin} to m_t^{pole} : $\Delta m_t \geq \Lambda_{QCD}$
- colour structure and hadronisation
  - partly included in experimental uncertainties
  - study on kinematic dependencies of m_t
- calculating $m_t(m_t)$ from m_t^{pole}
  - QCD (three-loop): $\Delta m_t \approx 0.02$ GeV
  - EW (two-loop): $\Delta m_t \approx 0.1$ GeV

[Kniehl et al., arXiv:1401.1844]

[M. Mangano]

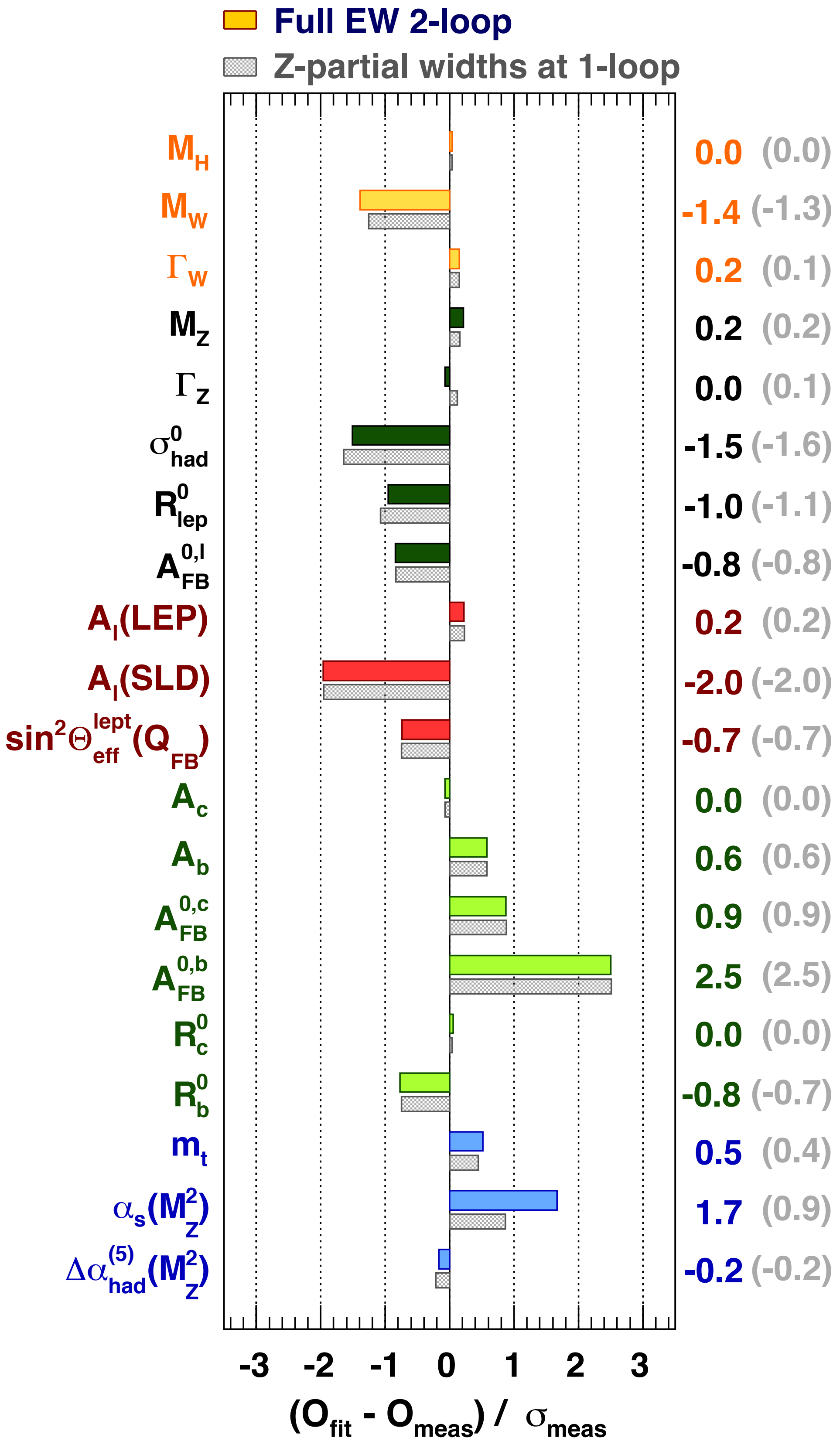


$$M_{exp}^2 = \left(\sum_{i=1,\dots,n} p_i \right)^2$$



[CMS-TOP-12-029]

SM Fit Results



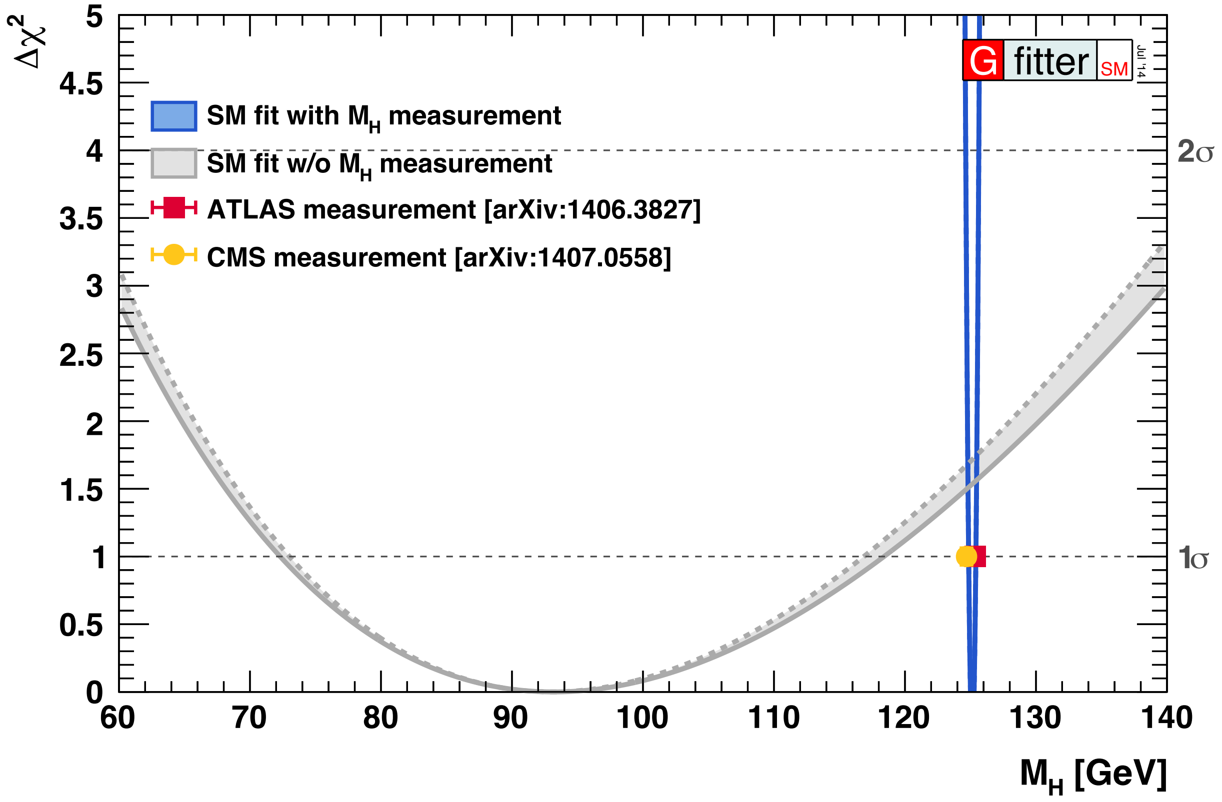
- no individual value exceeds 3σ
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ

    → largest contribution to χ^2
- Small pulls for M_H, M_Z, m_c, m_b
  - input accuracies exceed fit requirements
- Goodness of fit, p-value:

  χ^2_{min}= 17.8 Prob(χ^2_{min}, 14) = **21%**

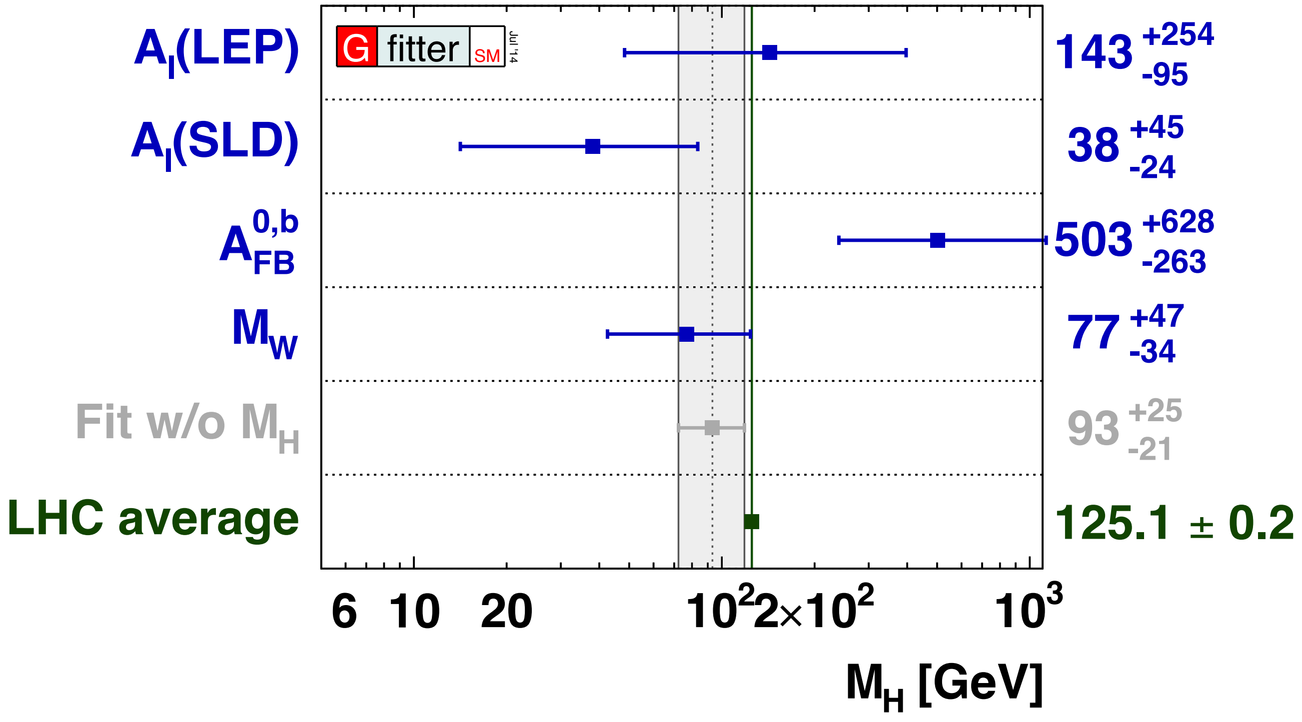
  Pseudo experiments: 21 ± 2 (theo)%
- Small changes from switching between 1 and 2-loop calc. for partial Z widths and small M_W correction:
  - χ^2_{min}(Z widths in 1-loop) = 18.0
  - χ^2_{min}(no $O(\alpha m_t \alpha_s^3)$ M_W correction) = 17.4
  - χ^2_{min}(no theory uncertainties) = 18.2

Higgs results



$\Delta\chi^2$ profile vs 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



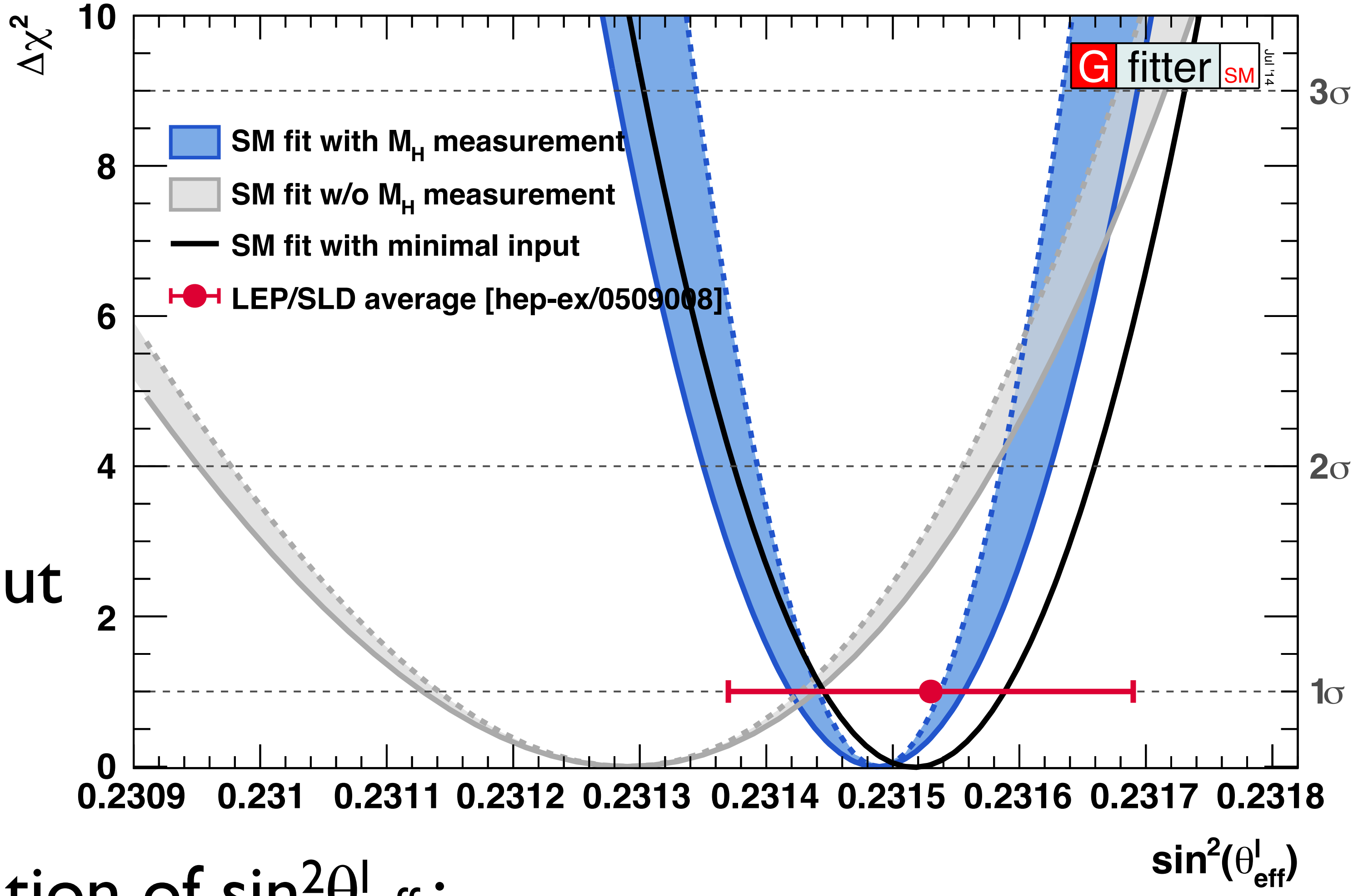
impact of most sensitive observables

- 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

The effective weak mixing angle

$\Delta\chi^2$ profile vs $\sin^2\theta^l_{\mathrm{eff}}$

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



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

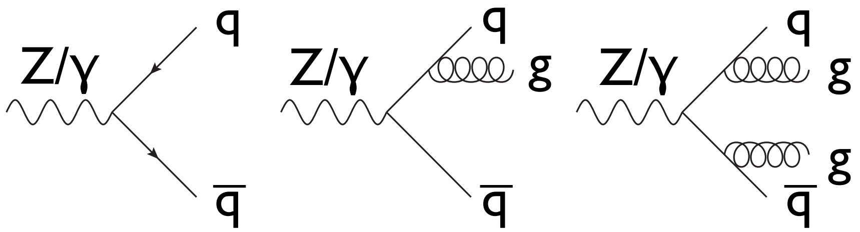
$$\begin{aligned}\sin^2\theta^{\ell}_{\mathrm{eff}} &= 0.231488 \pm \boxed{0.000024_{m_t}} \pm 0.000016_{\delta_{\mathrm{theo}} m_t} \pm 0.000015_{M_Z} \pm \boxed{0.000035_{\Delta\alpha_{\mathrm{had}}}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm \boxed{0.000047_{\delta_{\mathrm{theo}}\,\sin^2\theta^f_{\mathrm{eff}}}}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

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

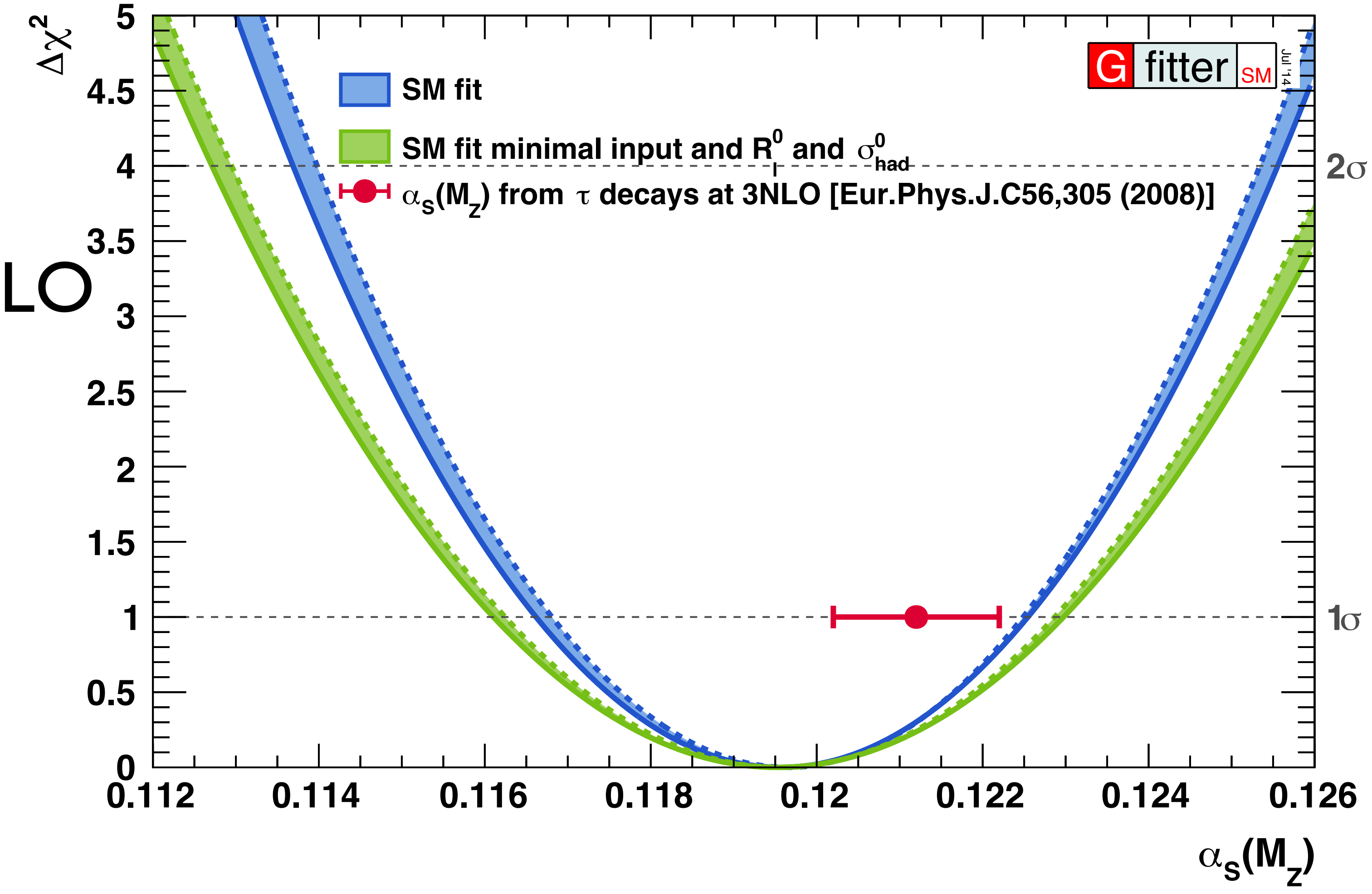
The strong coupling $\alpha_s(M_Z)$

$\Delta\chi^2$ profile vs $\alpha_s(M_Z)$

- determination of α_s at full NNLO and partial NNNLO
- also shown: minimal input with two most sensitive measurements: R_l, σ^0_{had}



- M_H has no (visible) impact

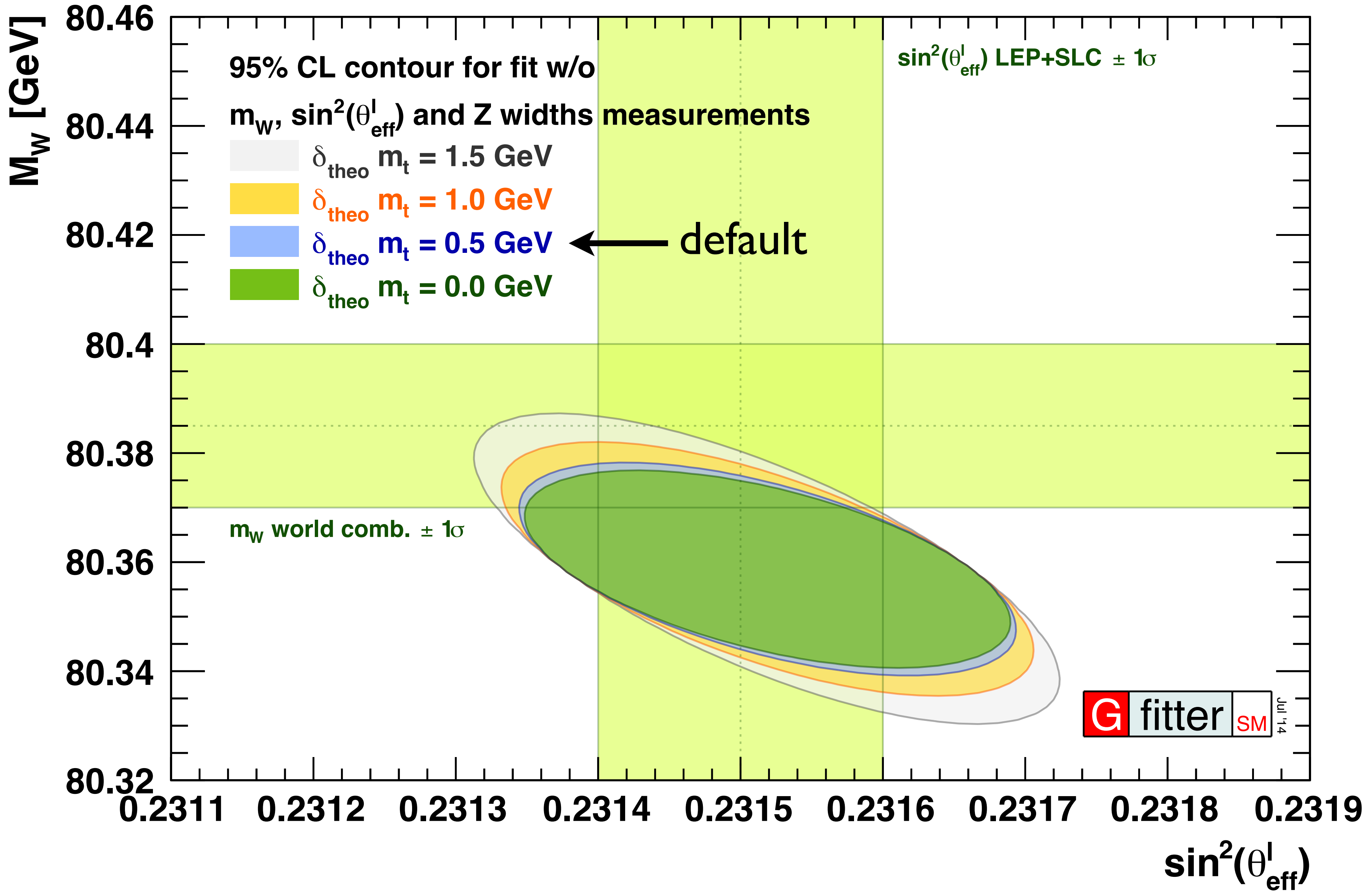


$$\begin{aligned}\alpha_s(M_Z^2) &= 0.1196 \pm 0.0028_{\,\text{exp}} \pm \boxed{0.0006_{\delta_\text{theo}\mathcal{R}_{V,A}} \pm 0.0006_{\delta_\text{theo}\Gamma_i} \pm 0.0002_{\delta_\text{theo}\sigma^0_\text{had}}} \\ &= \underline{0.1196 \pm 0.0030_{\,\text{tot}}}\end{aligned}$$

More accurate estimation of theo. uncertainties (previously: δ_{theo} = 0.0001 from scale variations)

good agreement with WA, dominated by exp. uncertainty

Theoretical uncertainty on m_t



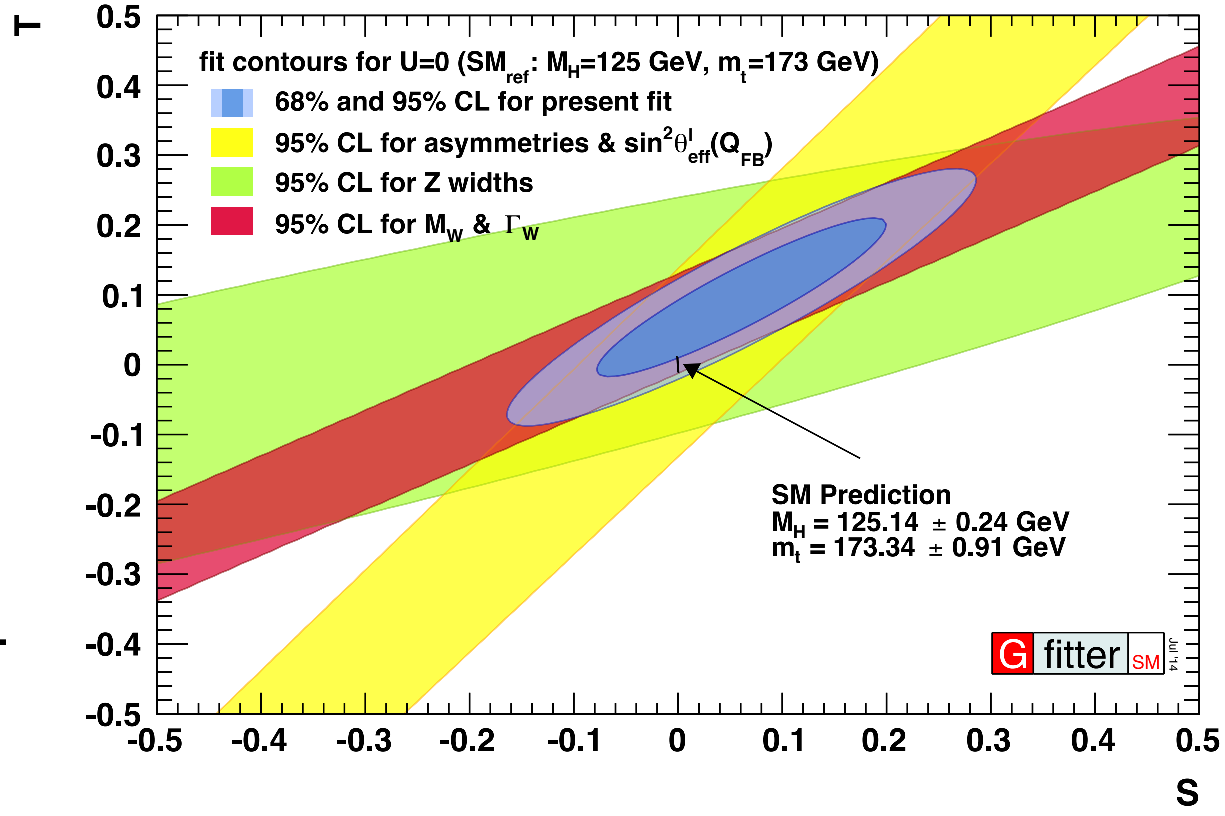
impact of variation in δ_{theo} m_t between 0 and 1.5 GeV

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

Constraints on BSM models

- if energy scale of NP is high, BSM physics could appear dominantly through vacuum polarisation corrections

stronger constraints with U = 0:



- described by STU parameters
  [Peskin and Takeuchi, Phys. Rev. D46, 1 (1991)]

- SM: M_H = 125 GeV, m_t = 173 GeV
  this defines (S,T,U) = (0,0,0)

- S, T depend logarithmically on MH

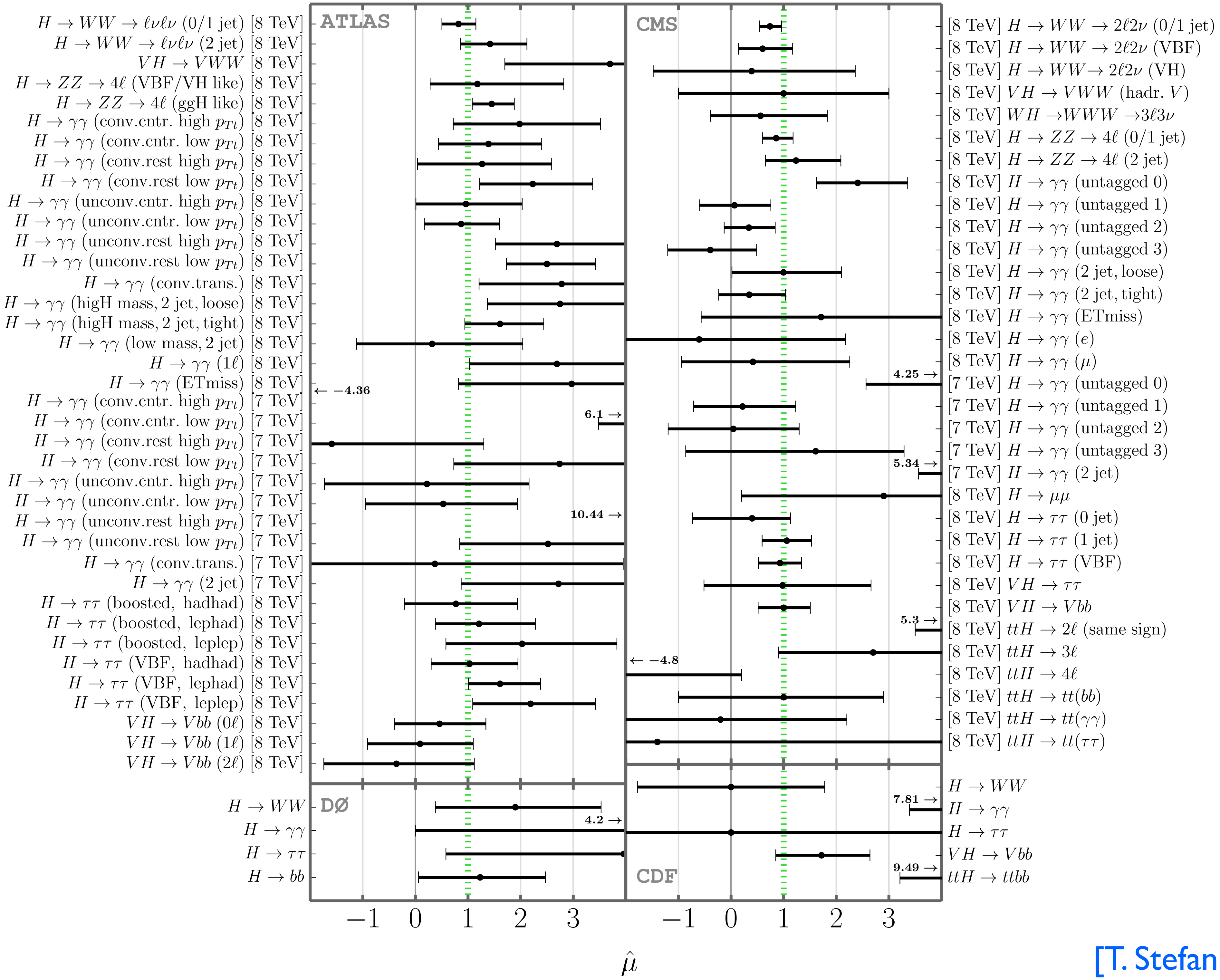
- Fit result:
  S = 0.05 ± 0.11
  T = 0.09 ± 0.13
  U = 0.01 ± 0.11

	S	T	U
S	1	+0.90	-0.59
T		1	-0.83
U			1

- no indication for new physics
- use this to constrain parameter space in BSM models

Measurements in HiggsSignals 1.2

in total: 80 signal rate + 4 mass measurements

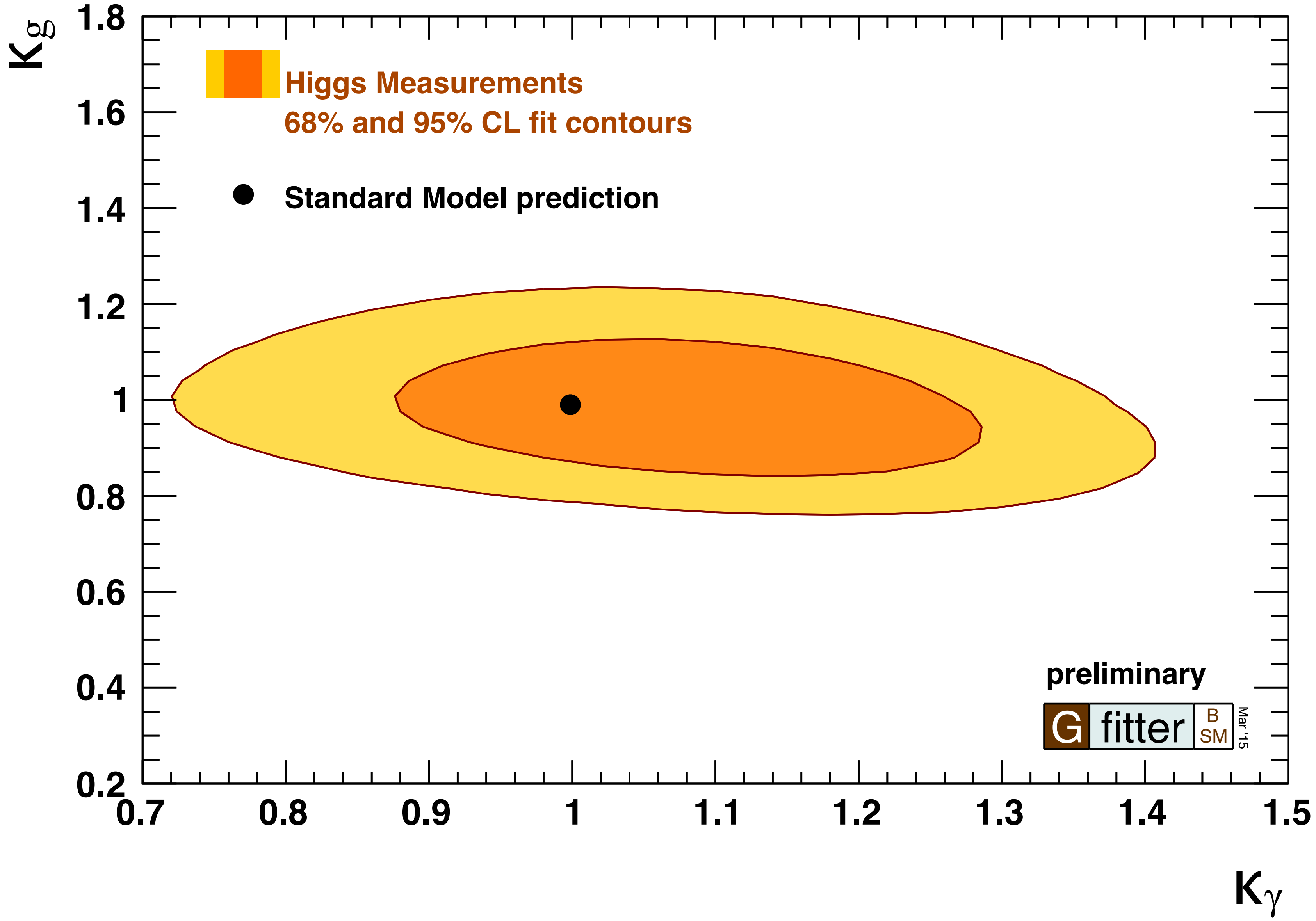


[T. Stefaniak, Nov 2014]

Higgs Couplings in Loops

- New physics may show up in loops, contributing to gg and $\gamma\gamma$ channels
- Charged SUSY particles or additional charged scalars

- Neglect modifications to tree level couplings
- Simultaneous fit:
  - $\kappa_g = 0.99 \pm 0.15$
  - $\kappa_\gamma = 1.08 \pm 0.21$



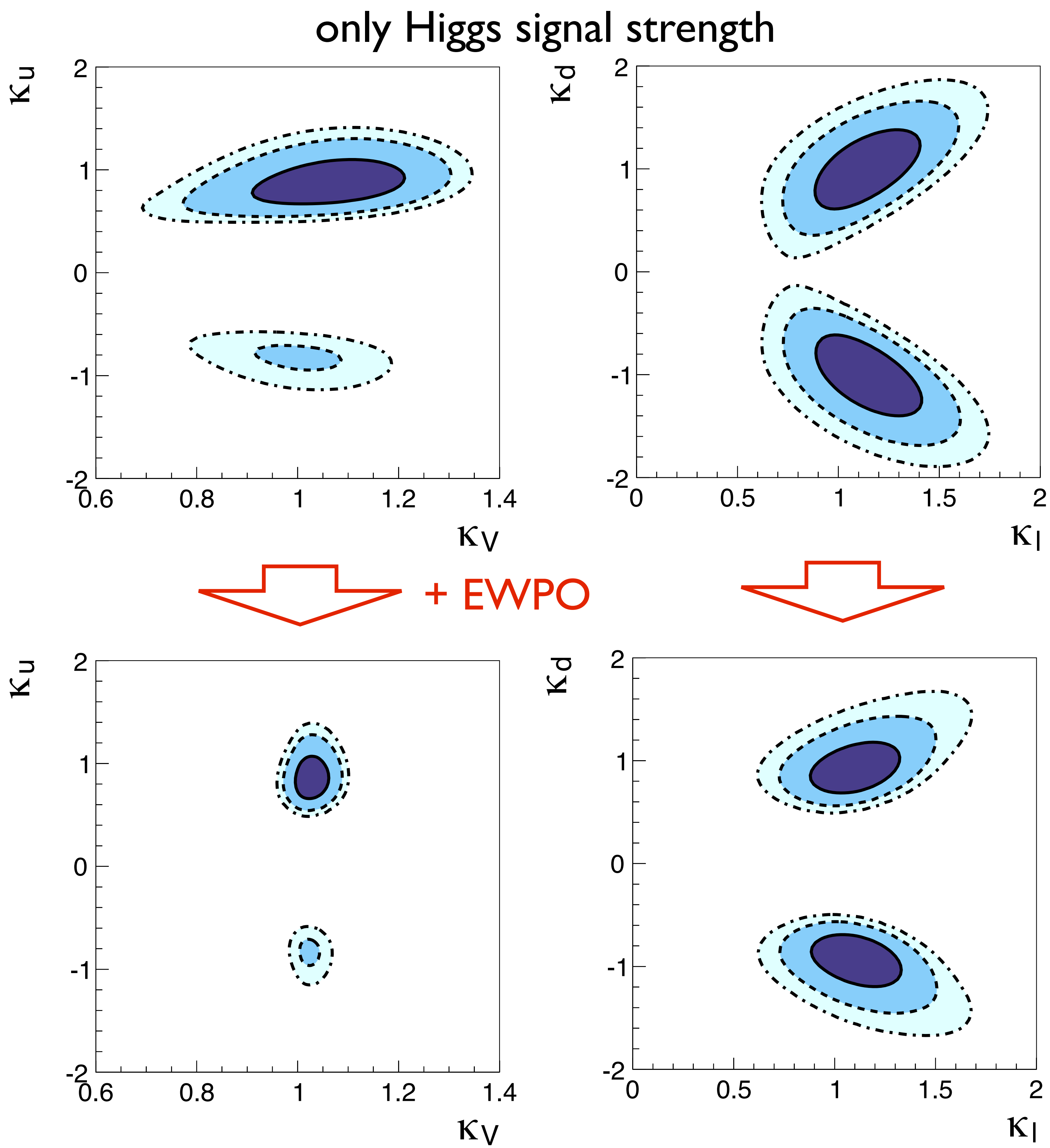
Higgs coupling results

- allowing for different couplings to up- and down-type quarks κ_u and κ_d

- stricter constraints due to EWPO, some gain also in the fermion sector

	68%	95%	Correlations			
κ_V	1.03 ± 0.02	[0.99, 1.07]	1.00			
κ_ℓ	1.10 ± 0.14	[0.82, 1.38]	0.14	1.00		
κ_u	0.88 ± 0.12	[0.66, 1.15]	0.09	0.23	1.00	
κ_d	0.92 ± 0.15	[0.65, 1.26]	0.28	0.35	0.81	1.00

- also possible to constrain coefficients of dimension-6 operators



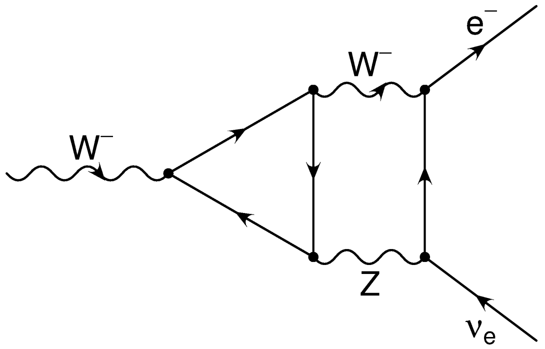
[Marco Ciuchini et al, arXiv:1410.6940]

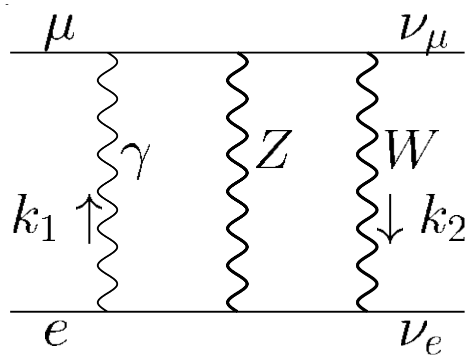
Calculation of M_W

- Full EW one- and two-loop calculation of fermionic and bosonic contributions
- One- and two-loop QCD corrections and leading terms of higher order corrections
- Results for Δr include terms of order $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{\mathrm{ferm}})$, $O(\alpha^2_{\mathrm{bos}})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- Uncertainty estimate:
  - missing terms of order $O(\alpha^2\alpha_s)$: about 3 MeV (from $O(\alpha^2\alpha_s m_t^4)$)
  - electroweak three-loop correction $O(\alpha^3)$: < 2 MeV
  - three-loop QCD corrections $O(\alpha\alpha_s^3)$: < 2 MeV
  - Total: $\delta M_W \approx$ 4 MeV

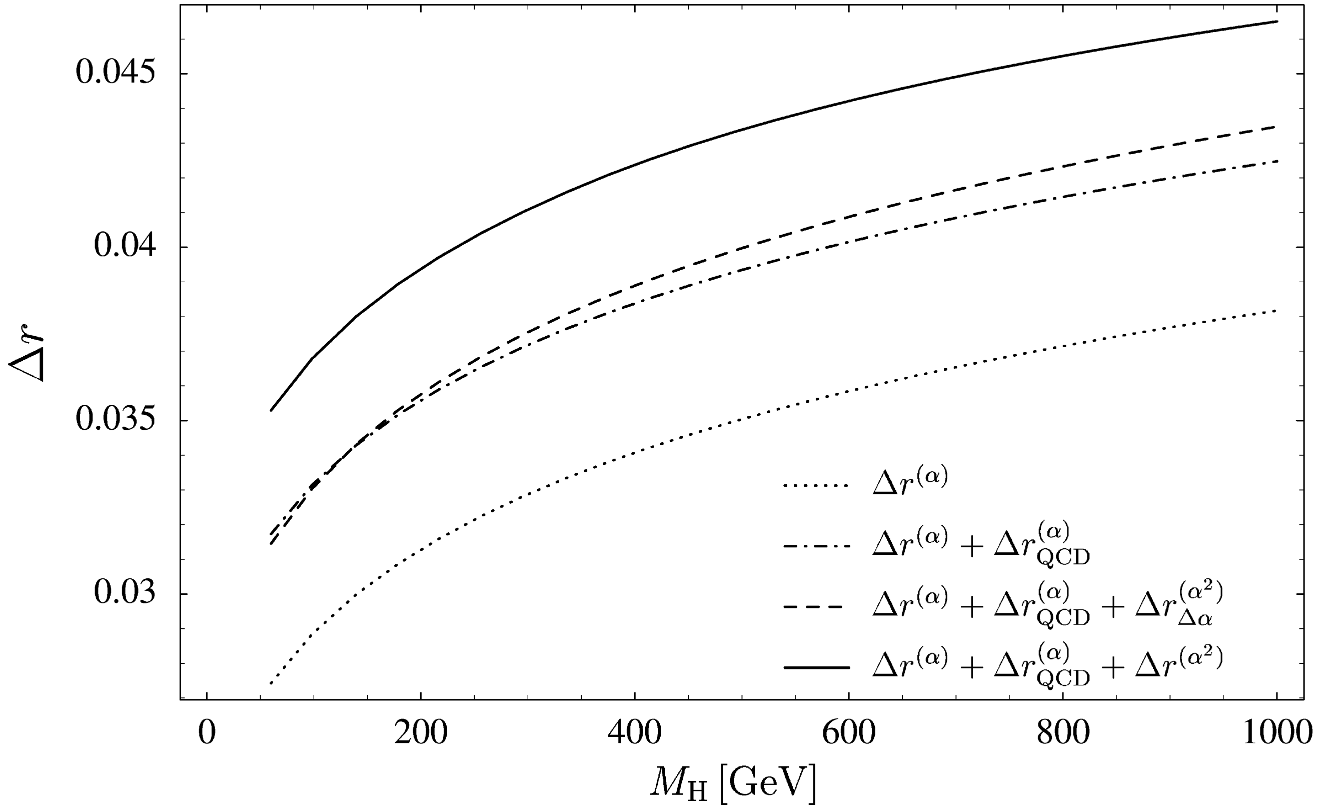
[M Awramik et al., Phys. Rev. D69, 053006 (2004)]

[M Awramik et al., Phys. Rev. Lett. 89, 241801 (2002)]





A Freitas et al., Phys. Lett. B495, 338 (2000)]



Calculation of $\sin^2(\theta^l_{\mathrm{eff}})$

- Effective mixing angle:

$$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}} = \left(1 - M_{\mathrm{W}}^2/M_{\mathrm{Z}}^2\right)(1+\Delta\kappa)$$

- Two-loop EW and QCD correction to $\Delta\kappa$ known, leading terms of higher order QCD corrections
- fermionic two-loop correction about 10^{-3}, whereas bosonic one 10^{-5}
- Uncertainty estimate obtained with different methods, geometric progression:

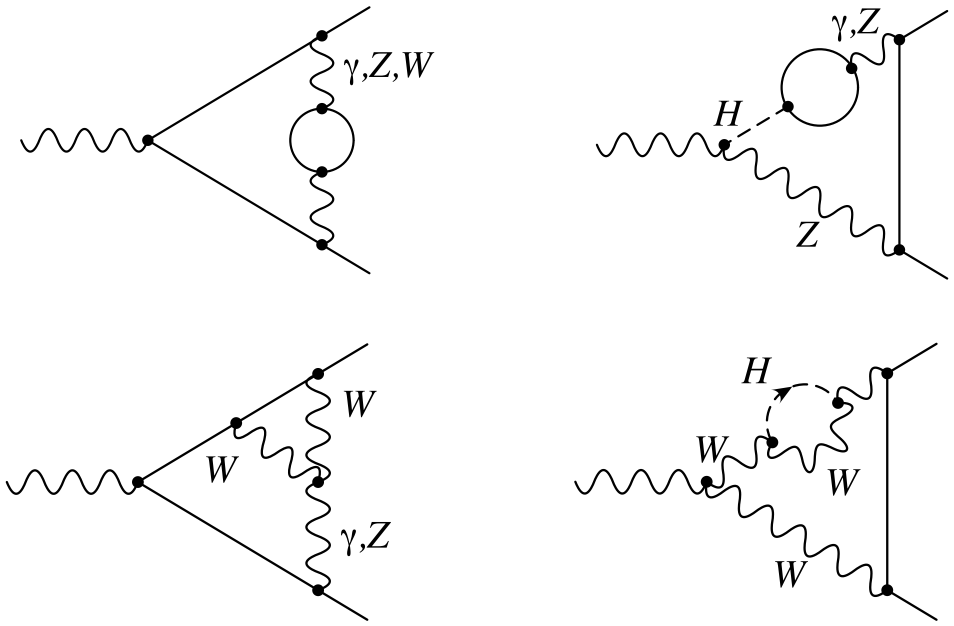
$$\mathcal{O}(\alpha^2\alpha_{\mathrm{s}}) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_{\mathrm{s}}).$$

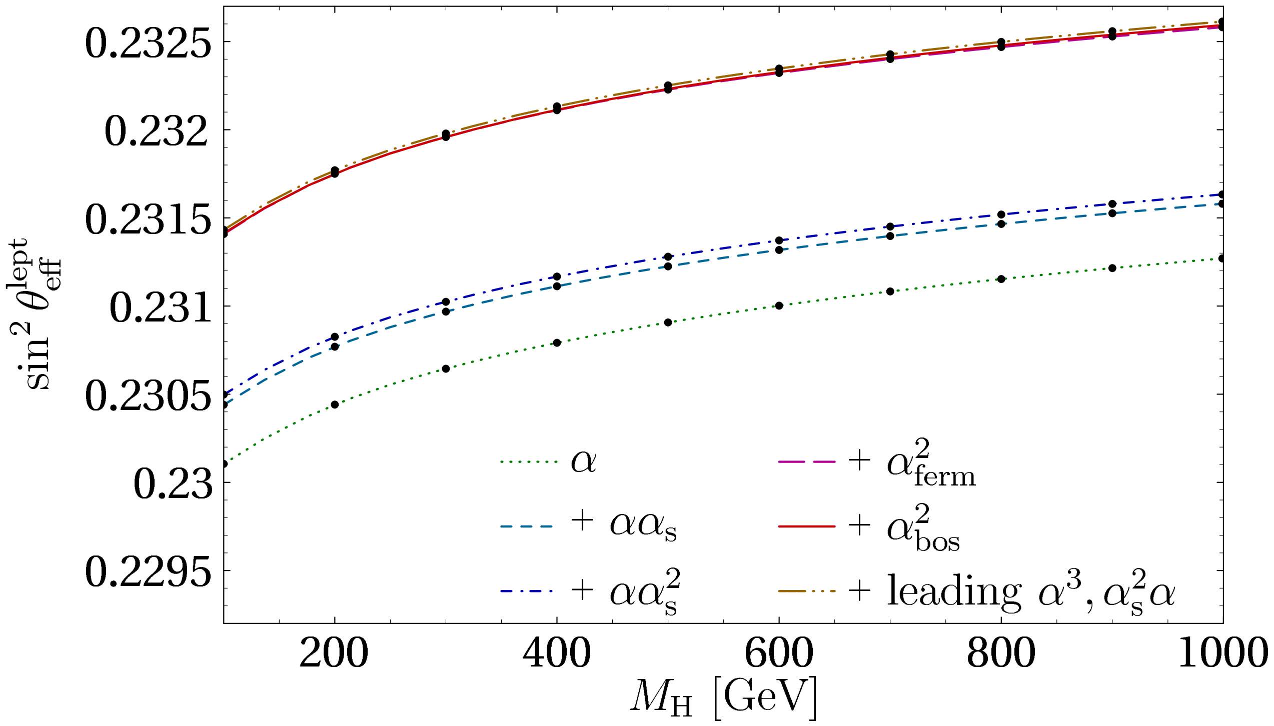
$\mathcal{O}(\alpha^2\alpha_{\mathrm{s}})$ beyond leading m_{t}^4	$3.3\ldots2.8\times10^{-5}$
$\mathcal{O}(\alpha\alpha_{\mathrm{s}}^3)$	$1.5\ldots1.4$
$\mathcal{O}(\alpha^3)$ beyond leading m_{t}^6	$2.5\ldots3.5$

Total: $\delta\sin^2\theta^l_{\mathrm{eff}} \approx 4.7\ 10^{-5}$

[M Awramik et al, Phys. Rev. Lett. 93, 201805 (2004)]

[M Awramik et al., JHEP 11, 048 (2006)]



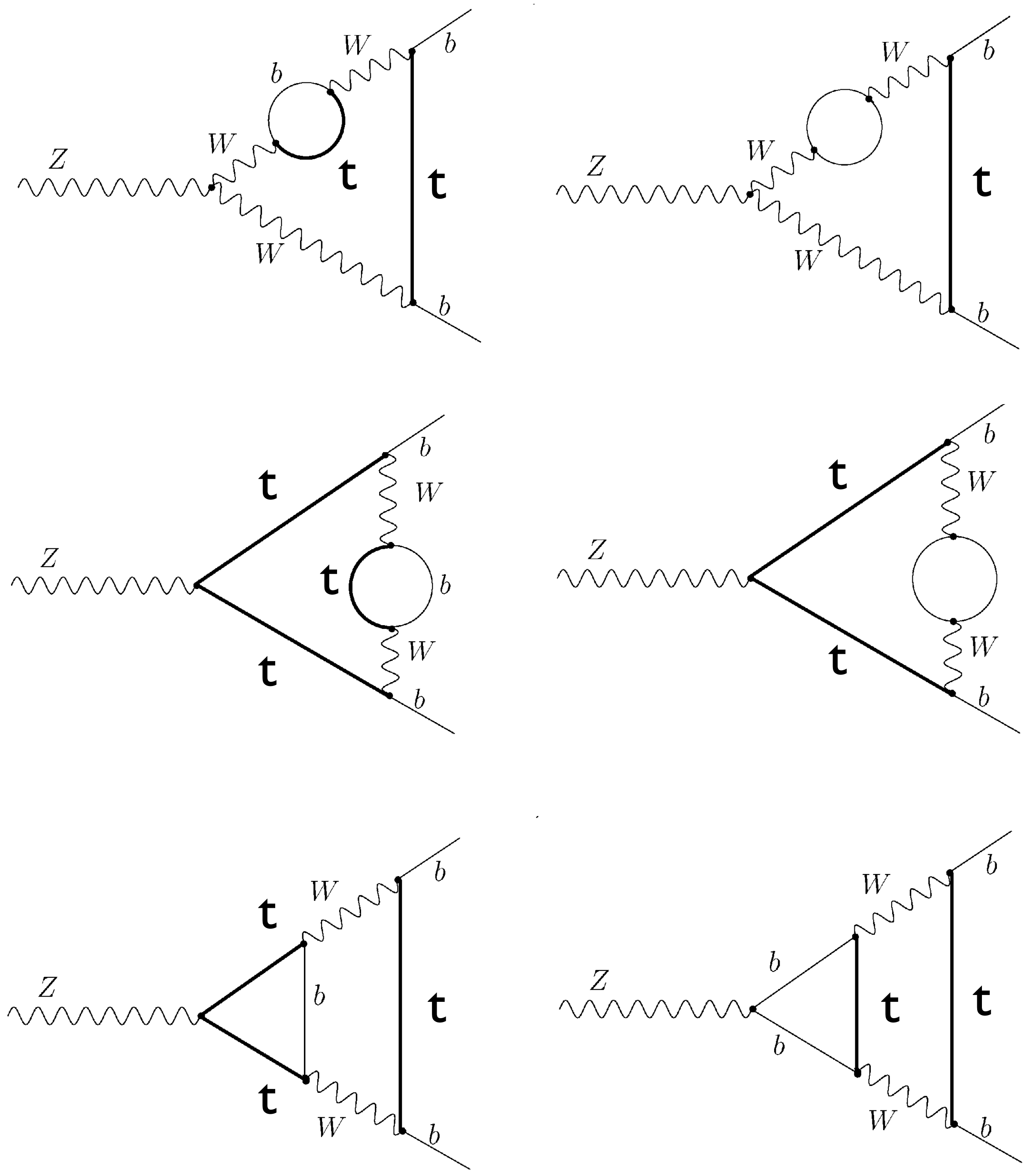


Calculation of $\sin^2(\theta^{bb}_{\mathrm{eff}})$

[M Awramik et al, Nucl. Phys. B813, 174 (2009)]

- Calculation of $\sin^2\theta_{\mathrm{eff}}$ for b-quarks more involved, because of top quark propagators in the $Z \to b\bar{b}$ vertex
- Investigation of known discrepancy between $\sin^2\theta_{\mathrm{eff}}$ from leptonic and hadronic asymmetry measurements
- Two-loop EW correction only recently completed, effect of $O(10^{-4})$
- Now $\sin^2\theta^{bb}_{\mathrm{eff}}$ known at the same order as $\sin^2\theta_{\mathrm{eff}}$ for leptons and light quarks
- Uncertainty assumed to be of same size as for $\sin^2\theta_{\mathrm{eff}}$:

$$\delta\sin^2\theta^{bb}_{\mathrm{eff}} \approx 4.7\ 10^{-5}$$



Calculation of R^0_b

[A. Freitas et al., JHEP 1208, 050 (2012)
Erratum ibid. 1305 (2013) 074]

Full two-loop calculation of $Z \rightarrow b\bar{b}$

- The branching ratio $R^0{}_b$: partial decay width of $Z \rightarrow b\bar{b}$ and $Z \rightarrow q\bar{q}$

$$R_b \equiv \frac{\Gamma_b}{\Gamma_{\text{had}}} = \frac{\Gamma_b}{\Gamma_d + \Gamma_u + \Gamma_s + \Gamma_c + \Gamma_b} = \frac{1}{1 + 2(\Gamma_d + \Gamma_u)/\Gamma_b}$$

- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}{}_{\text{eff}}$
  → cross-check the two results, found good agreement

- Two-loop corrections small compared to experimental uncertainty ($6.6 \cdot 10^{-4}$)

	1-loop EW and QCD correction to FSR	2-loop EW correction	2-loop EW and 2+3-loop QCD correction to FSR	1+2-loop QCD correction to gauge boson selfenergies
M_{H} [GeV]	$\mathcal{O}(\alpha) + \text{FSR}_{\alpha,\alpha_{\text{s}},\alpha_{\text{s}}^2}$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\text{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\text{ferm}}) + \text{FSR}_{\alpha_{\text{s}}^3,\alpha\alpha_{\text{s}},m_b^2\alpha_{\text{s}},m_b^4}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_{\text{s}},\alpha\alpha_{\text{s}}^2)$ $[10^{-4}]$
100	-35.66	-0.856	-2.496	-0.407
200	-35.85	-0.851	-2.488	-0.407
400	-36.09	-0.846	-2.479	-0.406

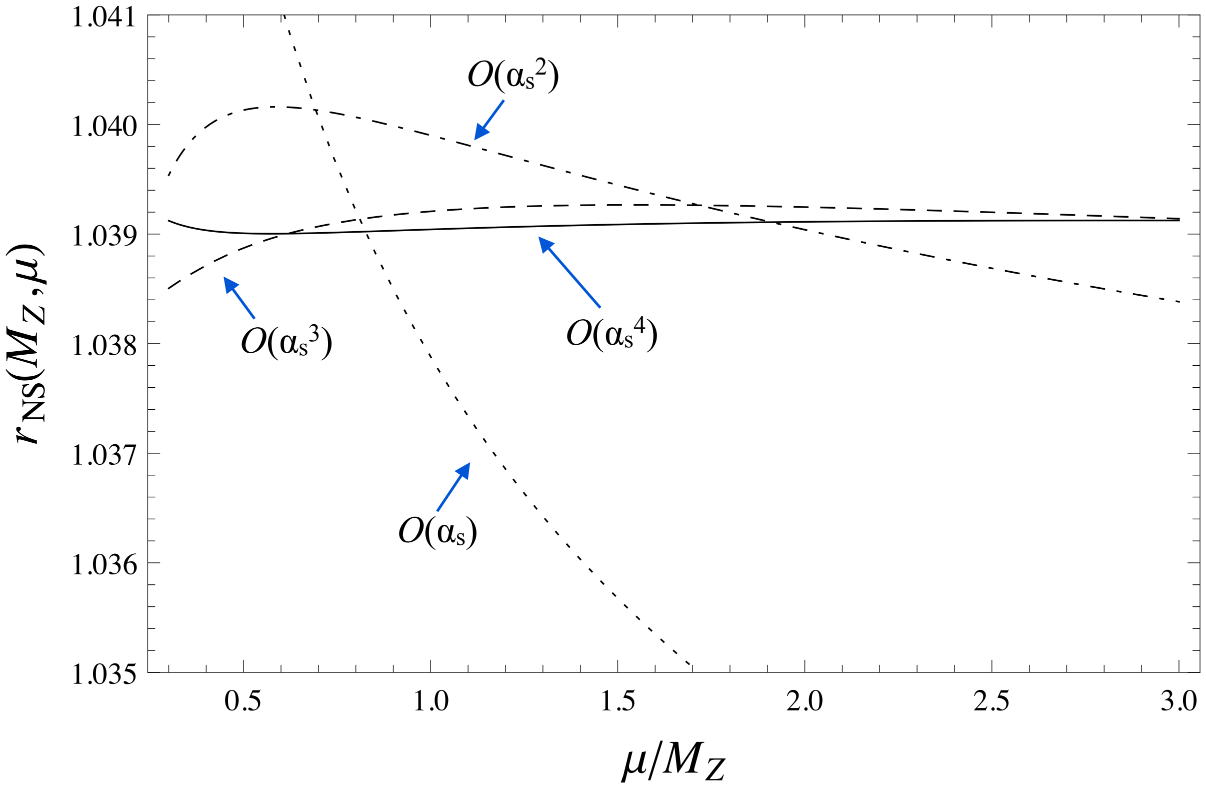
Radiator Functions

- Partial widths are defined inclusively: they contain QCD and QED contributions
- Corrections can be expressed as radiator functions $R_{A,f}$ and $R_{V,f}$

$$\Gamma_{f\bar{f}} = N_c^f \frac{G_F M_Z^3}{6\sqrt{2}\pi} \left(|g_{A,f}|^2 R_{A,f} + |g_{V,f}|^2 R_{V,f} \right)^2$$

[D. Bardin, G. Passarino, "The Standard Model in the Making", Clarendon Press (1999)]

- High sensitivity to the strong coupling α_s
- Full four-loop calculation of QCD Adler function available (N^{3}LO)
- Much reduced scale dependence
- Theoretical uncertainty of 0.1 MeV, compare to experimental uncertainty of 2.0 MeV



[P. Baikov et al., Phys. Rev. Lett. 108, 222003 (2012)]
[P. Baikov et al Phys. Rev. Lett. 104, 132004 (2010)]

Modified Higgs Couplings

Study of potential deviations of Higgs couplings from SM

$$L_V = \frac{h}{v}\left(2\kappa_V m_W^2 W_\mu W^\mu + \kappa_V m_Z^2 Z_\mu Z^\mu\right)$$

$$L_F = -\frac{h}{v}\left(\kappa_F m_t \bar{t}t + \kappa_F m_b \bar{b}b + \kappa_F m_\tau \bar{\tau}\tau\right)$$

- BSM modelled as extension of SM through effective Lagrangian
  - Leading corrections only
- Benchmark model:
  - Scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F)
  - No additional loops in the production or decay of the Higgs, no invisible Higgs decays and undetectable width
- Main effect on EWPO due to modified Higgs coupling to gauge bosons (κ_V)
  - Involving the longitudinal d.o.f.
- Most BSM models: $\kappa_V < 1$
- Additional Higgses typically give positive contribution to M_W