The global electroweak fit in a new era of precision

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- Prerequisites and ingredients
- Results and status of the EW fit
- BSM constraints
- Future prospects

The Electroweak Sector of the SM

Electroweak interactions described by SU(2)×U(1)

- 4 gauge bosons: 3 massive ($Z, W^{\pm}$), 1 massless (γ)
- 1 scalar (H)
  - extremely successful theory
  - taught in each particle physics course

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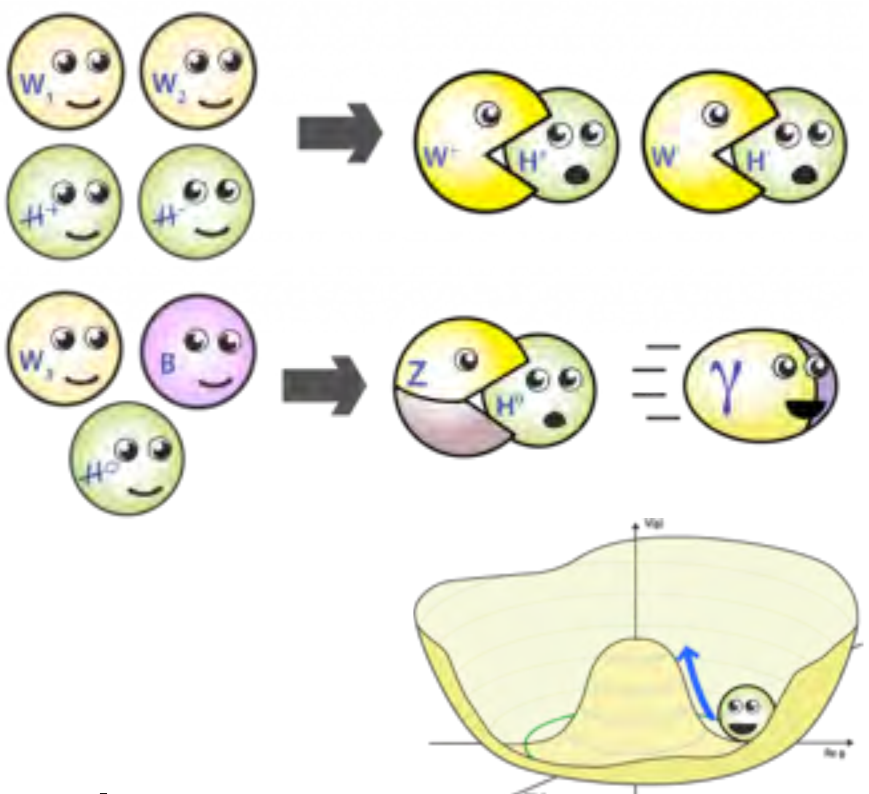
Let's take one step back...

- it's a complicated, highly non-trivial theory
  - massive gauge bosons
  - parity (and CP) violation
  - Higgs field, results in a scalar particle



[Philip Tanedo, quantumdiaries.org]

Why do we believe it?

- we physicists always had a hard time believing anything...
- we want to test the theory to ultimate precision!

The Electroweak Sector of the SM

Electroweak sector given by 3 parameters

- g, g' : coupling constants of $SU(2)_L$ and $U(1)_Y$
- v : vacuum expectation value
- weak mixing angle : fixed by the massless photon

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

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

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

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!

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

The Electroweak Sector of the SM

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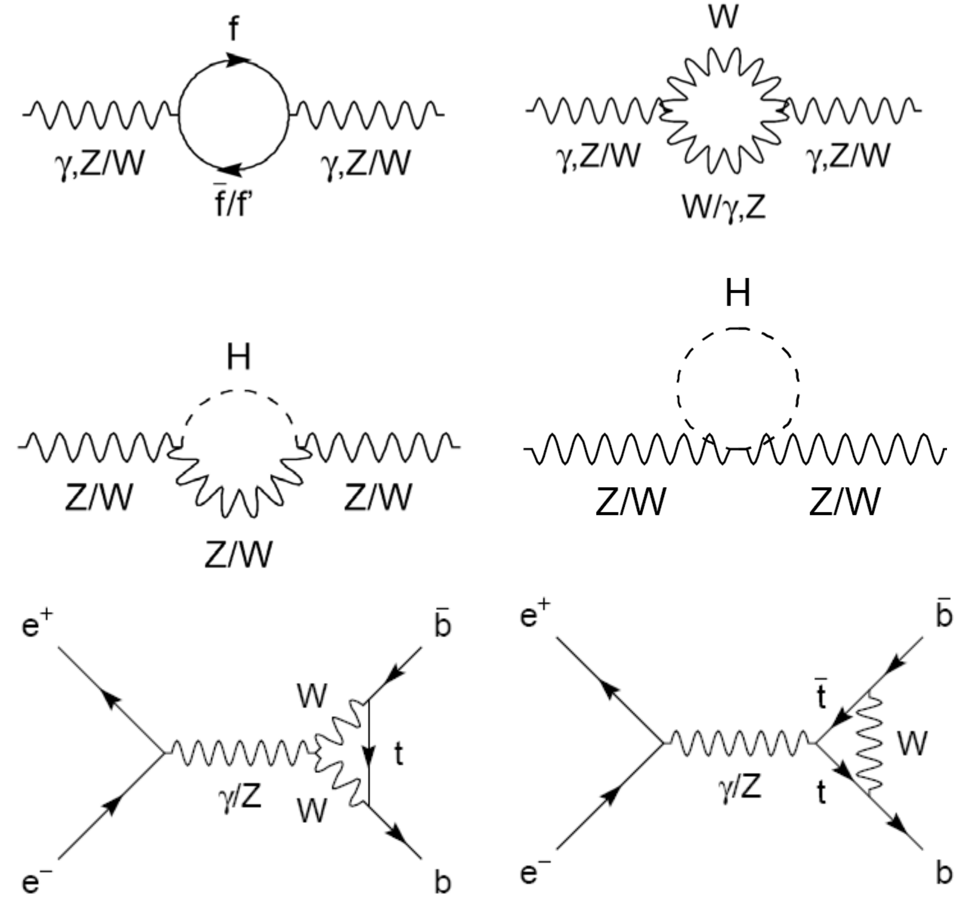
$$M_W^2 = \frac{M_Z^2}{2}\left(1+\sqrt{1-\frac{\sqrt{8}\pi\alpha}{G_F M_Z^2}}\right)$$

Calculate M_W and compare with experiment

- M_W(theo) = 80.939 ± 0.003 GeV
- M_W(exp) = 80.385 ± 0.015 GeV
- difference = 0.554 GeV ~ 35σ !! new physics?

Radiative Corrections

Modification of propagators and vertices



- Parametrisation of radiative corrections: electroweak form factors ρ, κ, Δr
- Effective couplings at the Z-pole:

$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\text{eff}}^f\right)$$

$$g_{A,f} = \sqrt{\rho_Z^f} I_3^f$$

$$\sin^2\theta_{\text{eff}}^f = \kappa_Z^f \sin^2\theta_W$$

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

- ρ, κ, Δr depend on all parameters of the theory (m_t, M_H, α_s...)

$$\Delta r = -\frac{3\alpha c_W^2}{16\pi s_W^4}\frac{m_t^2}{M_W^2} + \frac{11\alpha}{48\pi s_W^2}\ln\frac{M_H^2}{M_W^2} + \ldots$$

Free Parameters

EW sector

- G_F : $\Delta G_F/G_F = 5\times10^{-7}$
- M_Z : $\Delta M_Z/M_Z = 2\times10^{-5}$
- evolution of fine structure constant ($\Delta\alpha/\alpha = 3\times10^{-10}$) to scale s

$$\Delta\alpha(s) = \Delta\alpha_{\rm lep}(s) + \Delta\alpha^{(5)}_{\rm had}(s) + \Delta\alpha_{\rm top}(s)$$

relative precision = 1×10^{-6} | 2×10^{-4} | 1×10^{-7}

Fermion masses

- m_c, m_b : precision of about 7% and 1%, sufficient (see later)
- m_t crucial parameter, experimental precision of 0.5% (more later)

Strong sector

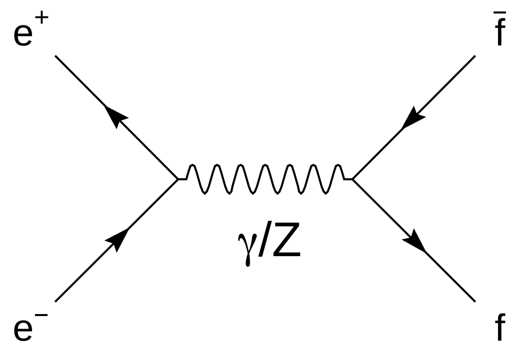
- α_s : can be constrained using Z-pole measurements

Higgs sector

- M_H : precision of LHC measurements is 0.3%

Measure more than minimal set to constrain the theory

Measurements at e⁺e⁻ Colliders



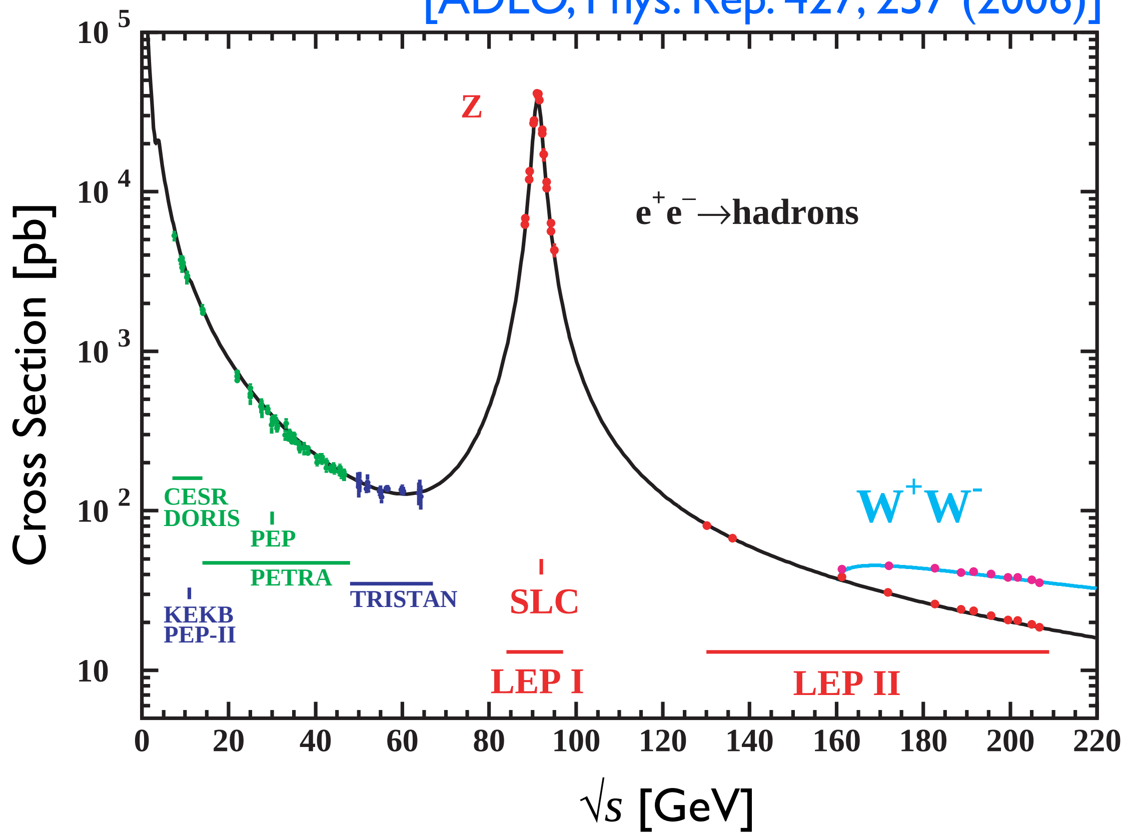
Z-pole measurements at LEP-1 and SLC

- LEP : running near the Z-pole, four experiments, 4×10^6 Zs / experiment
- SLC : one experiment, 500.000 Zs, polarized beams

Precision measurements

- exactly known initial state
- precise beam energy, $\Delta E_{beam} = \pm\ 0.2$ MeV

[ADLO, Phys. Rep. 427, 257 (2006)]



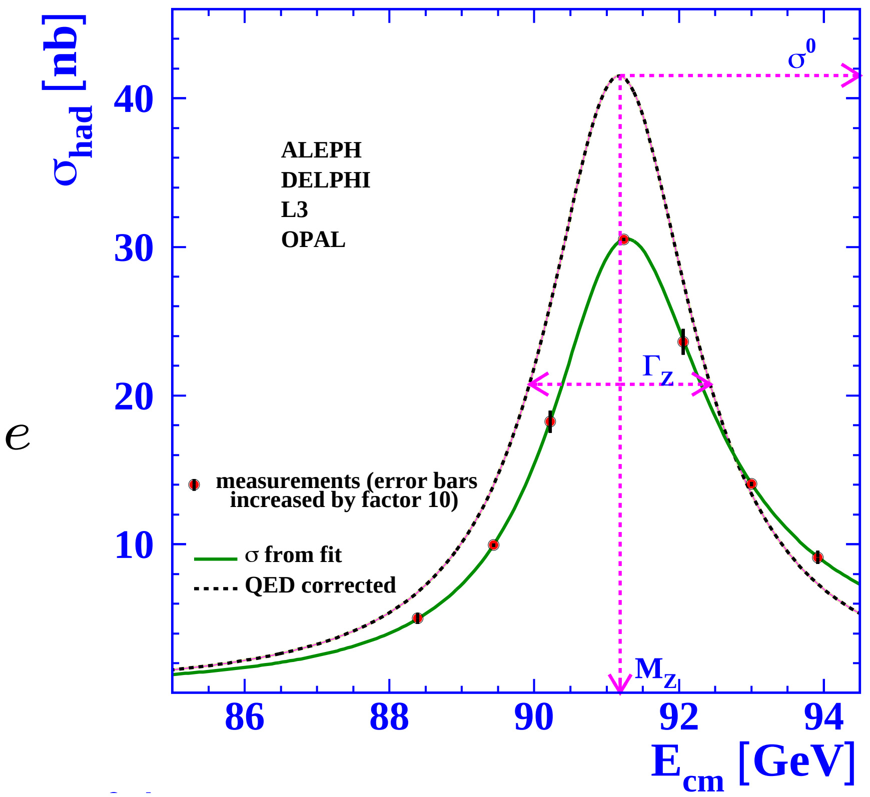
Cross section

- $$\sigma^Z_{f\bar{f}} = \sigma^0_{f\bar{f}} \frac{s\Gamma_Z^2}{(s-M_Z^2)^2 + s^2\Gamma_Z^2/M_Z^2} \frac{1}{R_{\mathrm{QED}}}$$

with $\sigma^0_{f\bar{f}} = \frac{12\pi}{M_Z^2}\frac{\Gamma_{ee}\Gamma_{f\bar{f}}}{\Gamma_Z^2}$ and $\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{\mathrm{had}} + \Gamma_{\mathrm{inv}}$

Observables

[ADLO, Phys. Rep. 427, 257 (2006)]



Minimal correlated set of parameters

- mass and total width of Z⁰ M_Z, Γ_Z
- hadronic pole cross section $\sigma^0_{\rm had}$
- leptonic decay ratios $R^0_\ell = R^0_e = \Gamma_{\rm had}/\Gamma_{ee}$
- hadronic width ratios $R^0_{c,b} = \Gamma_{c\bar{c},b\bar{b}}/\Gamma_{\rm had}$

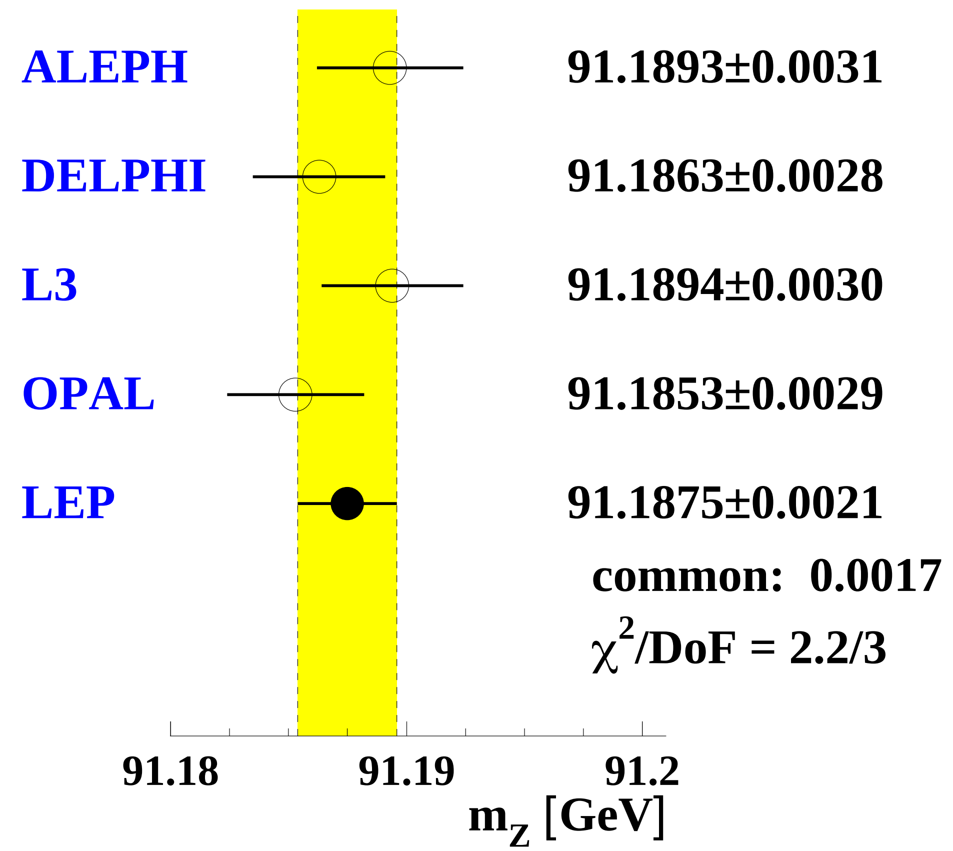
Asymmetries

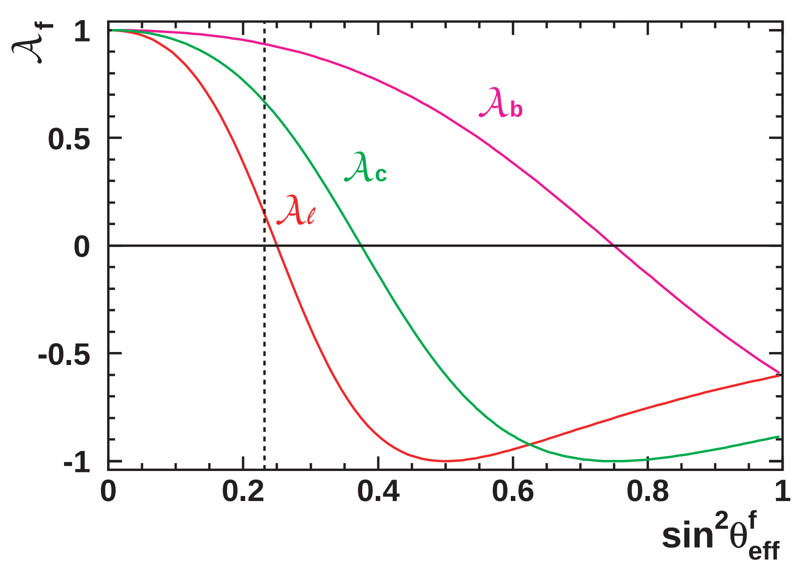
- $A_f = \dfrac{g^2_{L,f} - g^2_{R,f}}{g^2_{L,f} + g^2_{R,f}} = 2\dfrac{g_{V,f}/g_{A,f}}{1+(g_{V,f}/g_{A,f})^2}$ directly related to $\sin^2\theta^{f\bar{f}}_{\rm eff}$
- forward/backward asymmetry $A^f_{FB} = \dfrac{N^f_F - N^f_B}{N^f_F + N^f_B}$, $A^{0,f}_{FB} = \dfrac{3}{4}A_e A_f$
- left/right asymmetry $A^f_{LR} = \dfrac{N^f_L - N^f_R}{N^f_L + N^f_R}\dfrac{1}{\langle |P|_e \rangle}$

Measurements at the Z-Pole

[ADLO, Phys. Rep. 427, 257 (2006)]

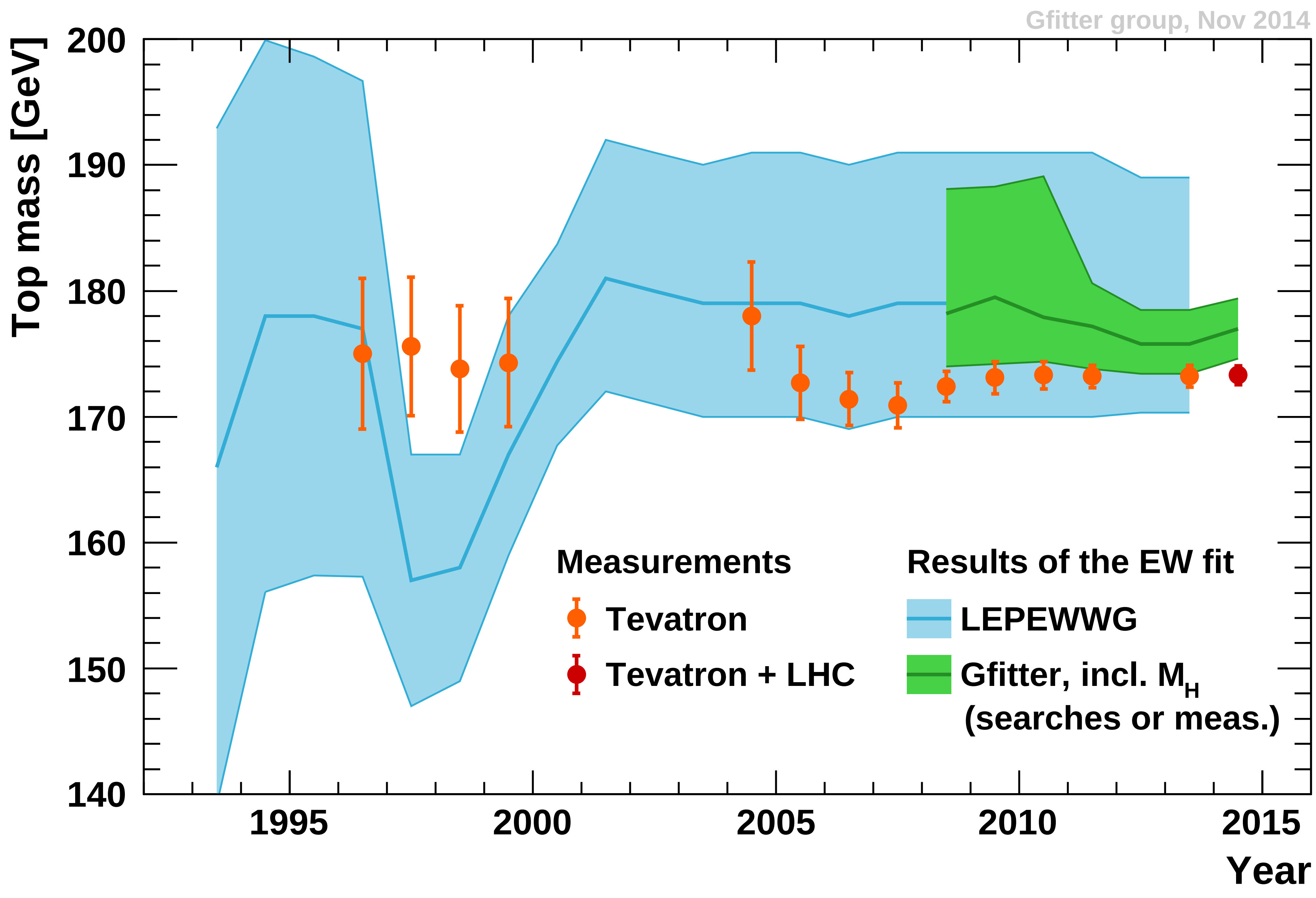
M_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R^0_ℓ	20.767 ± 0.025
$A^{0,\ell}_{\mathrm{FB}}$	0.0171 ± 0.0010
A_ℓ $^{(\star)}$	0.1499 ± 0.0018
$\sin^2\theta^\ell_{\mathrm{eff}}(Q_{\mathrm{FB}})$	0.2324 ± 0.0012
A_c	0.670 ± 0.027
A_b	0.923 ± 0.020
$A^{0,c}_{\mathrm{FB}}$	0.0707 ± 0.0035
$A^{0,b}_{\mathrm{FB}}$	0.0992 ± 0.0016
R^0_c	0.1721 ± 0.0030
R^0_b	0.21629 ± 0.00066





- precision of up to 0.002%!
- LEP/SLD measurements will stay the most precise for quite some time
- allow for precision tests of the SM and constrain new physics

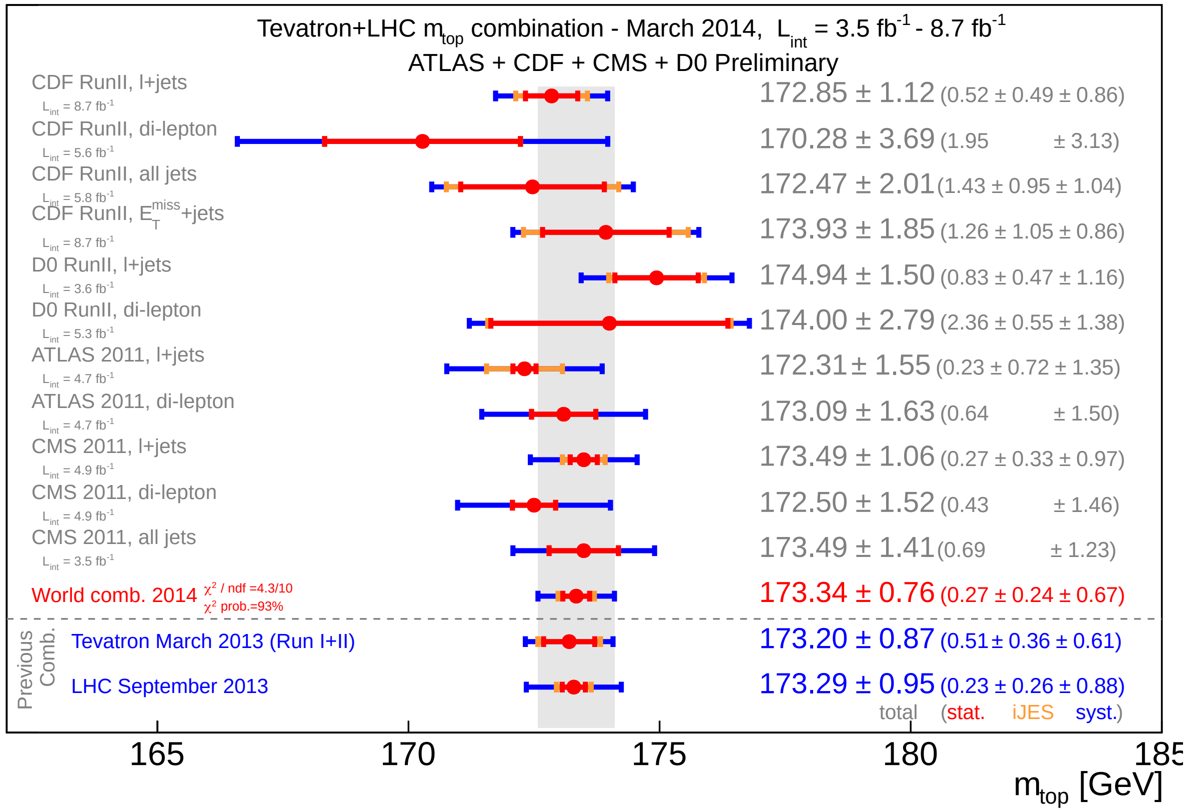
Prediction of top quark mass



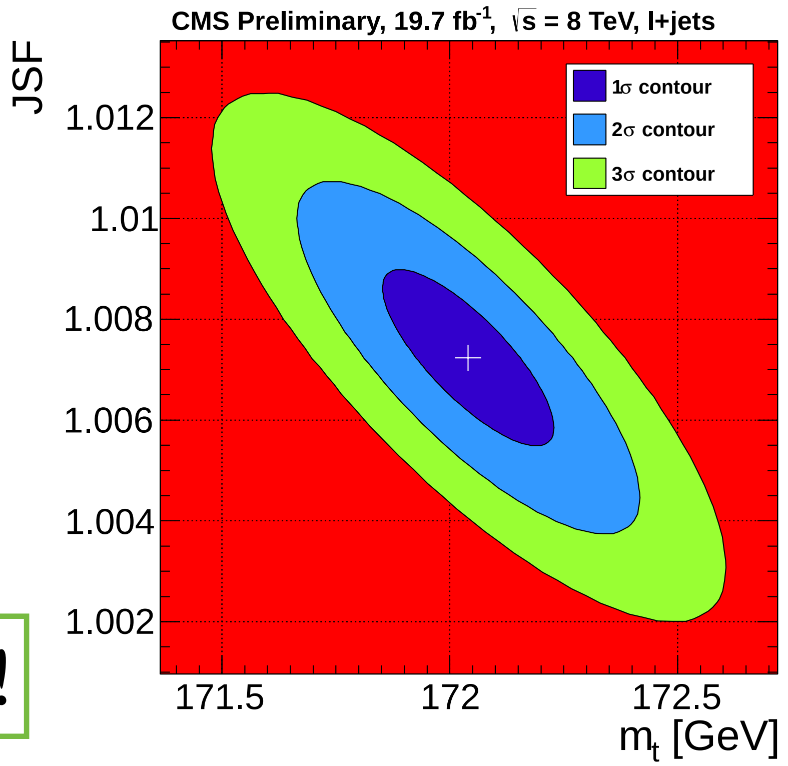
- m_t predictions from loop effects since 1990
- official LEPEWWG fit since 1993
- the fits have always been able to predict m_t correctly!

Measurements of m_t

[CDF, D0, ATLAS, CMS: arXiv:1403.4427]



- Tevatron pioneered measurements of a "kinematic" mass in t decays
- Tevatron
  - exceeding all expectations (expected precision: 2-3 GeV)
- LHC collaborations taking over
  - re-use of methods, high statistics
- world average: m_t = 173.34 ± 0.76 GeV
  - single best measurement in WA from CMS in l+jets channel
  - recently updated [CMS-PAS-TOP-14-001]
    m_t = 172.04 ± 0.19 (stat.+JES) ± 0.75 (syst.) GeV
    - crucial: JER, pile-up, flavour dependence of JES
- Tevatron 2014: Δm_t = 0.64 GeV [D0, CDF, arXiv:1407.2682]

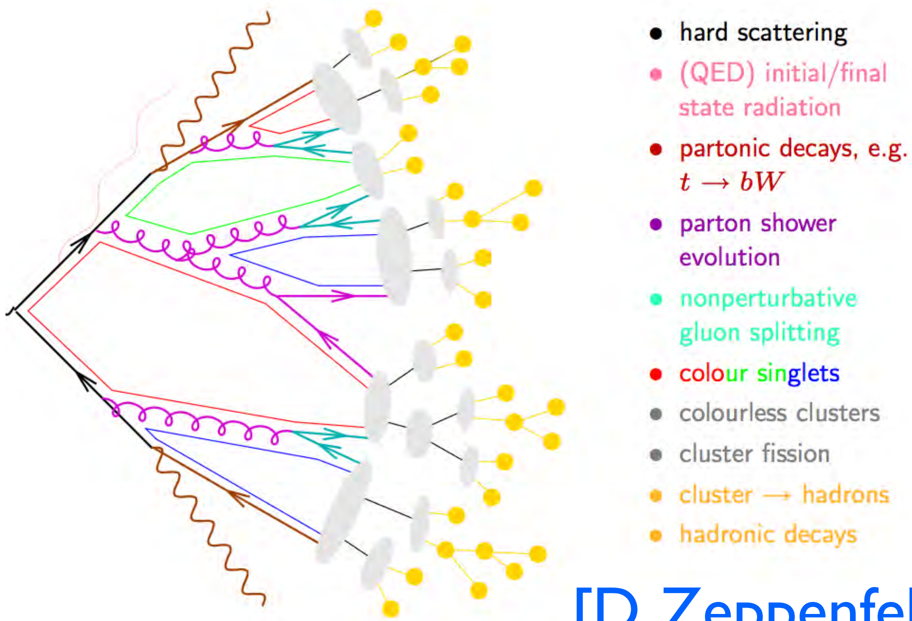


welcome to the community of precision measurements!

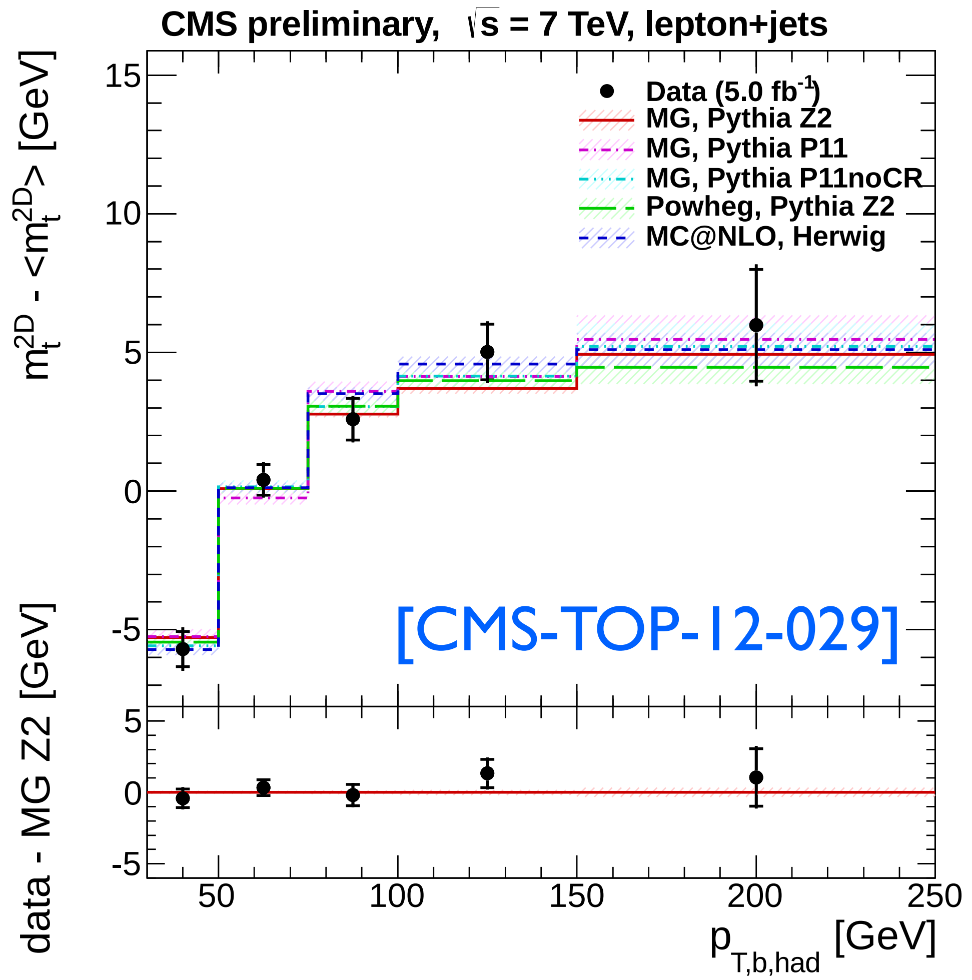
Interpreteation of m_t measurements

What about accuracy?

- top mass definition
  - EFT, 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 [Hoang, arXiv:1412.3649]
  - 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]

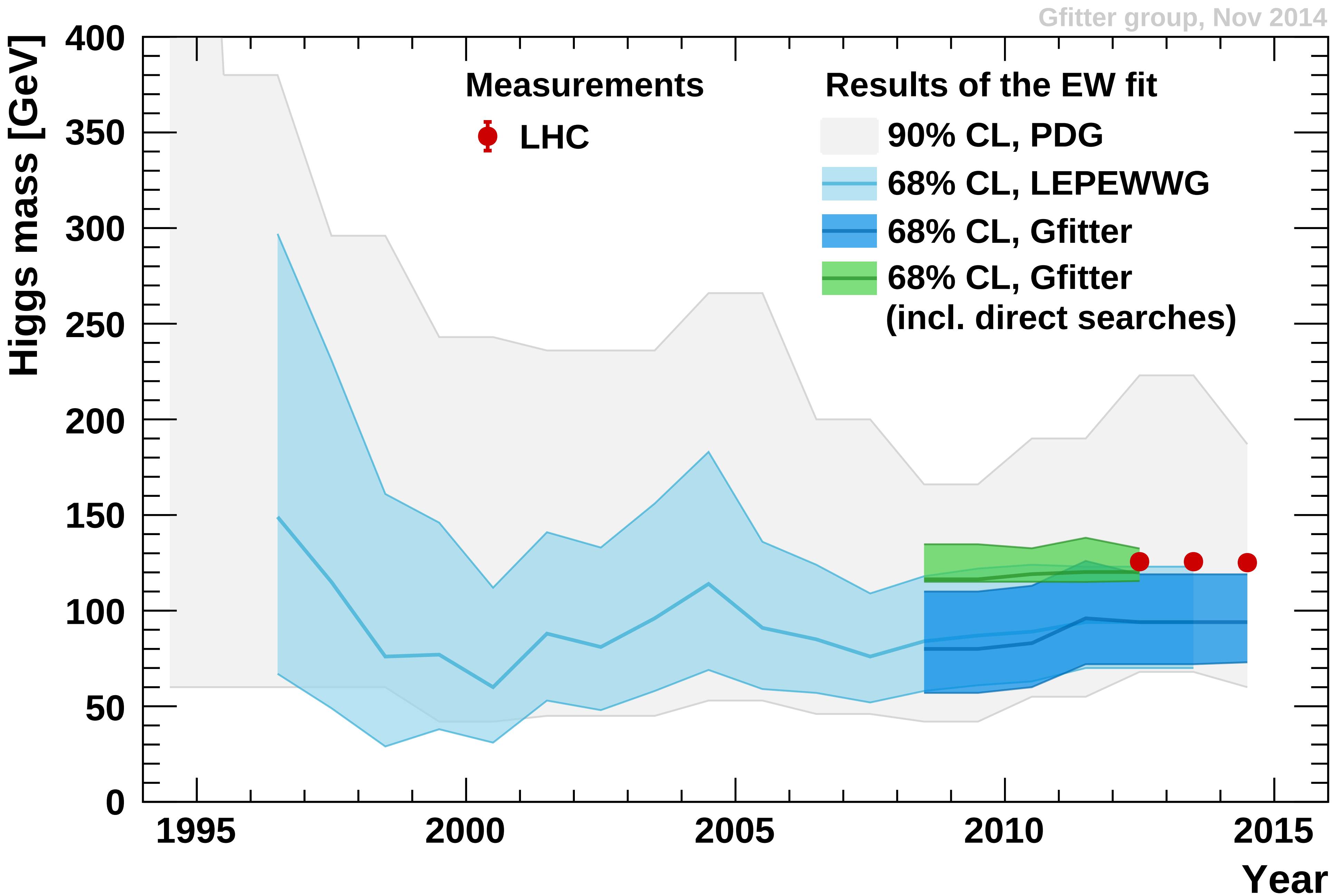


[D. Zeppenfeld]



[CMS-TOP-12-029]

Prediction of Higgs mass

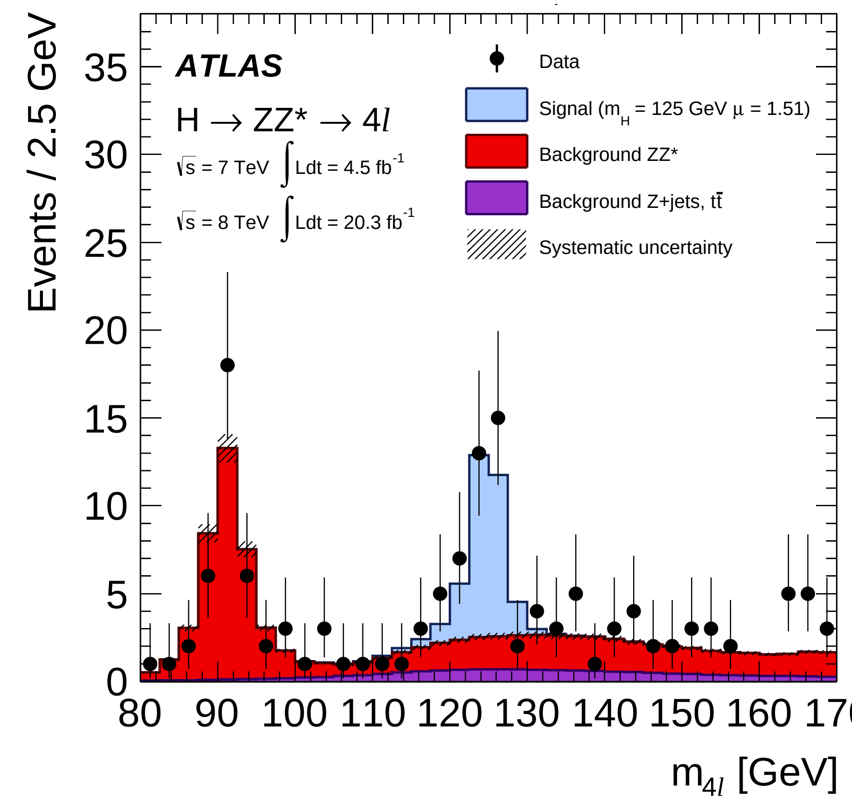


- M_H predictions from loop effects since the discovery of the top quark 1995
- weaker constraints than for m_t because of logarithmic dependence
- still, the fits have always predicted M_H correctly!

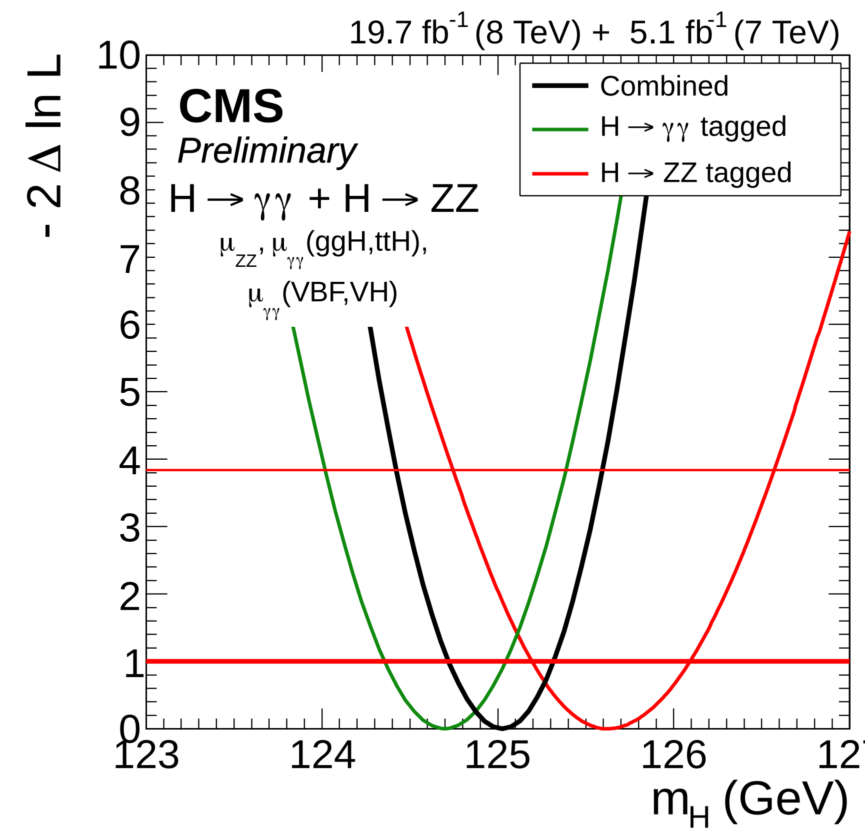
Measurements of M_H

Discovery of a Higgs boson

- cross section times branching ratios, spin, parity: compatible with SM Higgs boson
  - assume it's the SM Higgs boson
    - (or a BSM Higgs boson h in the decoupling region)
  - test the consistency of the SM including it
- best mass measurements: $H\to\gamma\gamma$, $H\to 4l$
  - ATLAS: 125.4 ± 0.4 GeV [ATLAS, 1406.3827]
  - CMS: 125.0 ± 0.3 GeV [CMS-PAS-HIG-14-009]
  - weighted average: 125.14 ± 0.24 GeV
    - change between fully uncorrelated and fully correlated systematic uncertainties is minor: δM_H : 0.24 → 0.32 GeV
  - accuracy: 0.2% !
    - sufficient for electroweak fit (more later)



[ATLAS, arXiv:1408.5191]



[CMS-PAS-HIG-14-009]

Measurements of M_W

M_W : key parameter in the SM

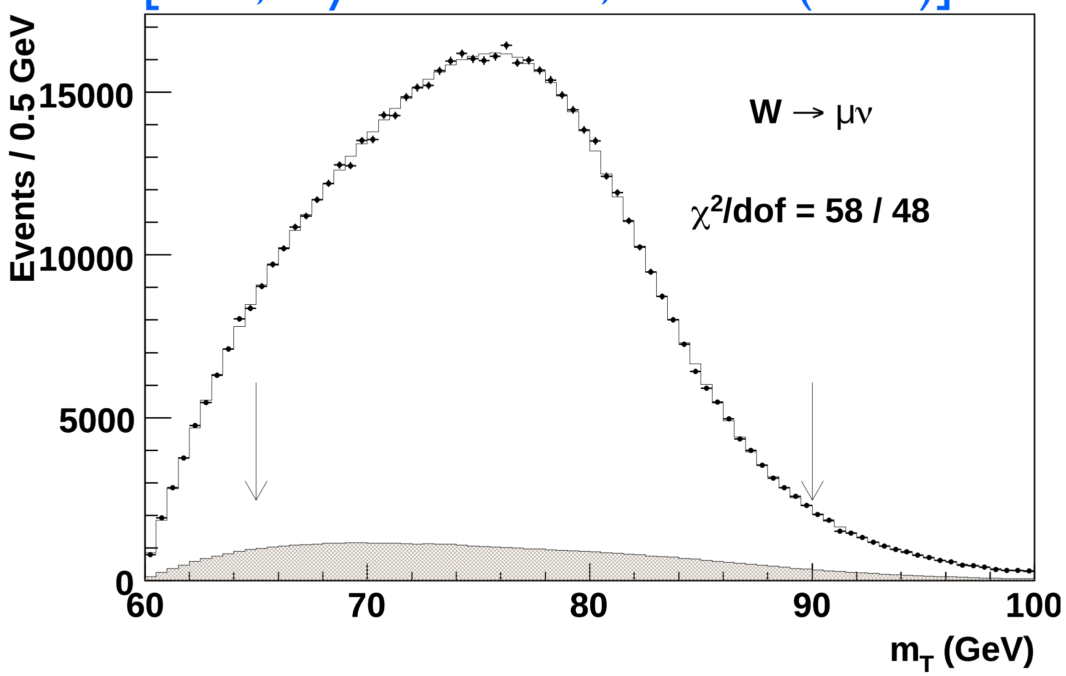
$$\Delta r = -\frac{3\alpha c_W^2}{16\pi s_W^4}\frac{m_t^2}{M_W^2} + \frac{11\alpha}{48\pi s_W^2}\ln\frac{M_H^2}{M_W^2} + \ldots$$

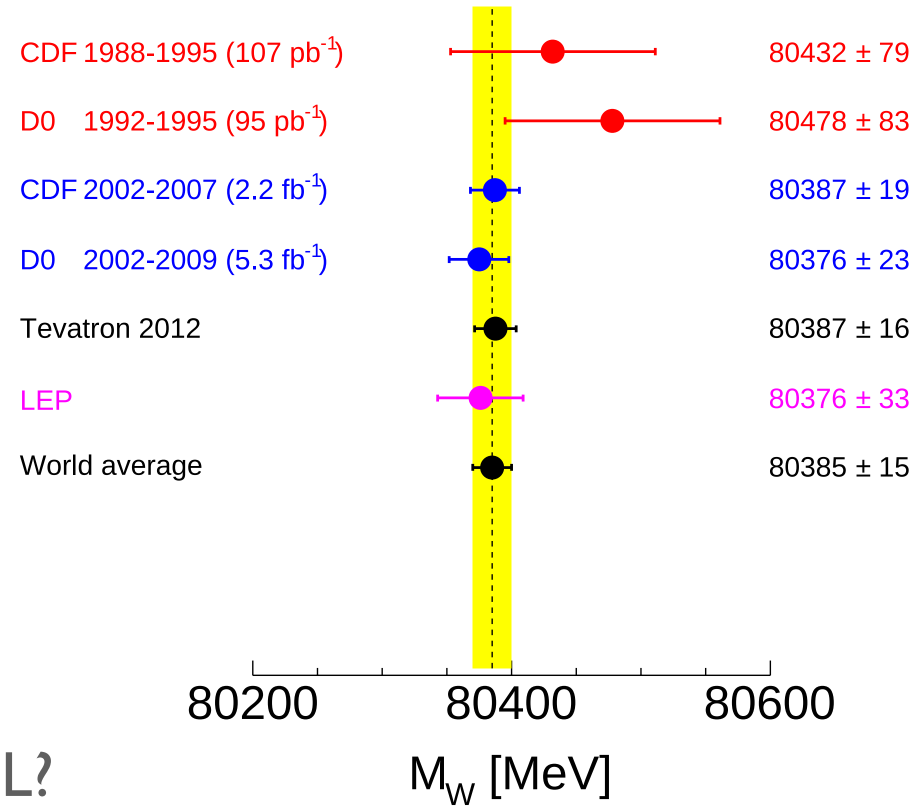
- final LEP-2 measurement (2013):
  - ΔM_W = 33 MeV [ADLO, Phys. Rept. 532:119,2013]
- Tevatron : most precise result so far
  - Jacobean peak in M_T and $p_{T,l}$ in $W \to l\nu$
  - ΔM = 16 MeV, accuracy: 0.02% !!
  - crucial: lepton energy and resolution, PDFs
- LHC : no result so far
  - (optimistic) scenarios: [arXiv:1310.6708]

ΔM_W [MeV]	LHC		
$\sqrt{s}$ [TeV]	8	14	14
$\mathcal{L}[\text{fb}^{-1}]$	20	300	3000
Total	15	8	5

  - very challenging
    - PDFs, momentum scale, hadronic recoil, pile-up at high L?

[CDF, Phys. Rev. D 89, 072003 (2014)]





[CDF, D0, Phys. Rev. D 88, 052018 (2013)]

Experimental Input

Fit is overconstrained

- all free parameters measured
  - most input from e^+e^- colliders
  - but crucial input from hadron colliders:
    - m_t : 0.4%
    - M_W : 0.02%
    - M_H : 0.2%
  - remarkable experimental precision (<1%)
- require precision calculations!

M_H [GeV]$^{(\circ)}$	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
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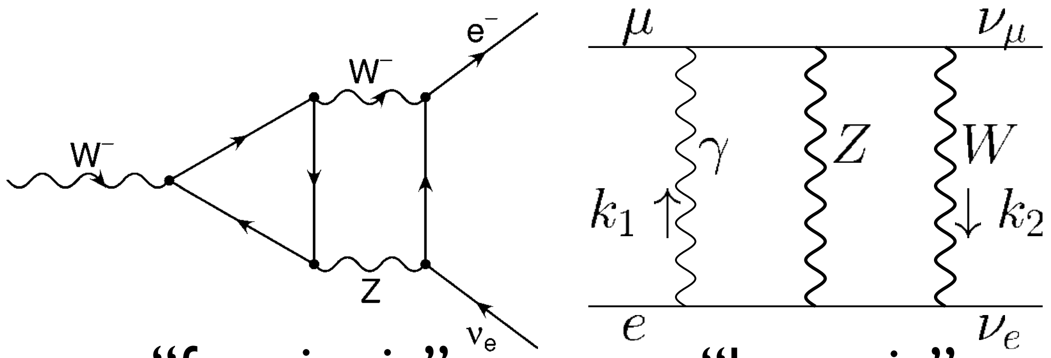
$A^{0,c}_{\rm FB}$	0.0707 ± 0.0035	LEP
$A^{0,b}_{\rm FB}$	0.0992 ± 0.0016	LEP
R^0_c	0.1721 ± 0.0030	LEP, SLD
R^0_b	0.21629 ± 0.00066	LEP, SLD
$\overline{m}_c$ [GeV]	$1.27^{+0.07}_{-0.11}$	
$\overline{m}_b$ [GeV]	$4.20^{+0.17}_{-0.07}$	
m_t [GeV]	173.34 ± 0.76	Tev.+LHC
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)$	2757 ± 10	

Calculations

All observables calculated at 2-loop level



- 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 known to two-loop level for all flavours (includes predictions for σ^0_{had}) [A. Freitas, JHEP04, 070 (2014)]
- 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 include one- and two-loop QCD corrections and leading terms of higher order corrections

All EWPOs calculated at two-loop level or better

Theoretical Uncertainties

Estimation

- assume that perturbative expansion follows a geometric series ($a_n = a\, r^n$) :

  for example: $\mathcal{O}(\alpha^2\alpha_s) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_s)$

- other methods (e.g. scale variation) not always feasible
  - but give similar results
- theoretical uncertainties smaller by a factor of 3-6 than measurements
  - for the first time, reasonable estimate for all observables

important

Observable	Exp. error	Theo. error
M_W	15 MeV	4 MeV
$\sin^2\theta^l_{\rm eff}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\rm had} = \sigma[e^+e^- \to Z \to \text{had.}]$	37 pb	6 pb
$R^0_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \text{had.}]$	$6.6 \cdot 10^{-4}$	$1.5 \cdot 10^{-4}$
m_t	0.76 GeV	0.5 GeV

new in fit

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

Fit method

Free parameters

- M_Z, $\Delta\alpha_{had}$, M_H, m_c, m_b, m_t, α_s
  - G_F is fixed to world average (PDG)
  - α_s is unconstrained → independent measurement

Treatment of theory uncertainties

- included as additional free parameters (10 parameters)
- different ways on how to treat their effect on the likelihood
  - Rfit : flat likelihood within uncertainties (box potential), corresponds to linear addition of uncertainties
  - Gaussian likelihood : corresponds to quadratic sum of uncertainties

Minimization

- pre-fitter : genetic algorithm (useful for many parameter fits)
- Minuit (standard, others are used as well)
- test of results using MC toy data

The global 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 (www.cern.ch/gfitter)

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 ± 0.85	$177.0^{+2.3}_{-2.4}{}^{(\triangledown)}$	$177.0 \pm 2.3^{(\triangledown)}$
$\Delta\alpha^{(5)}_{\rm had}(M_Z^2)^{(\dagger\triangle)}$	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

[Gfitter group, EPJC 74, 3046 (2014)]

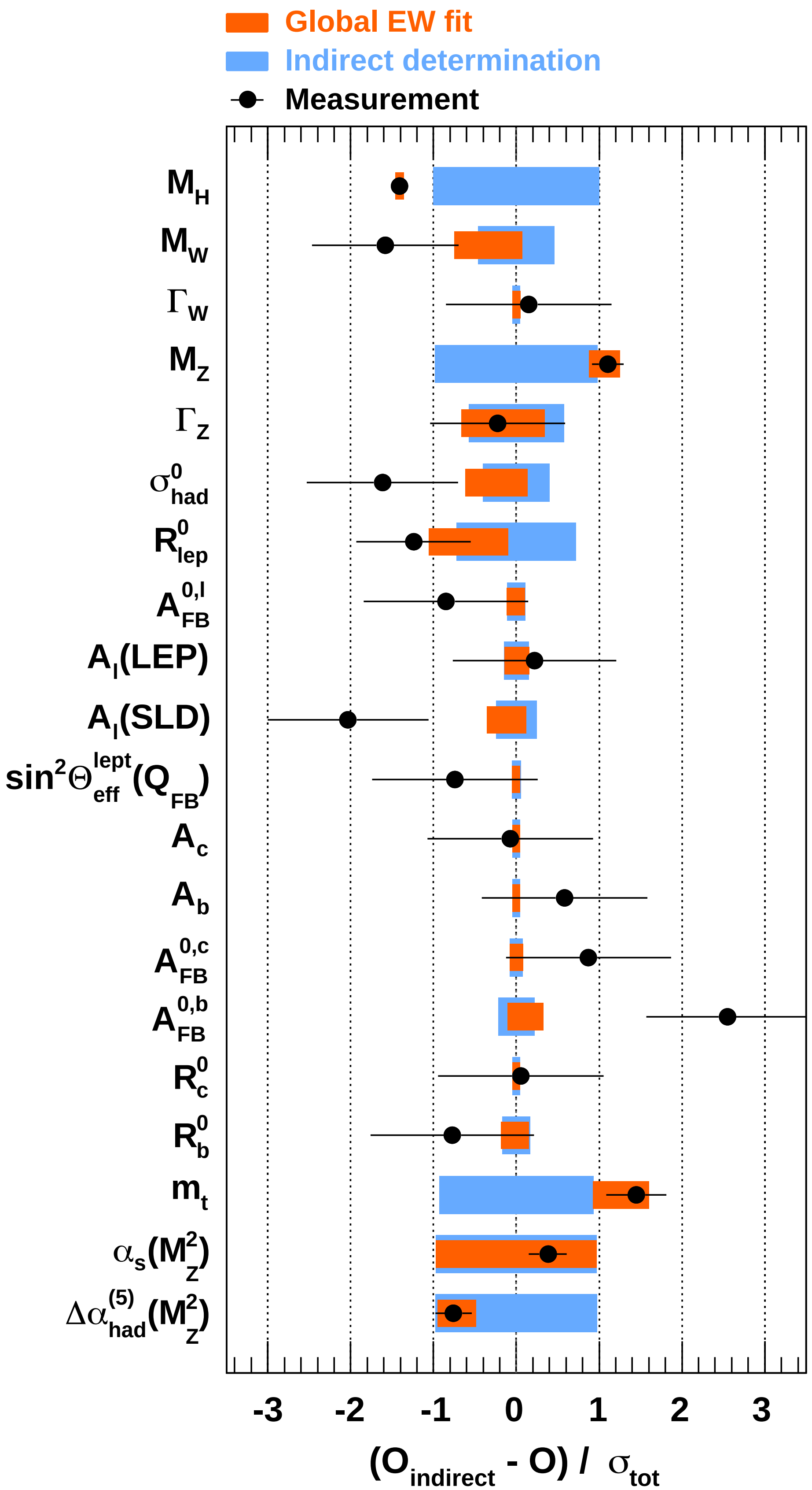
SM Fit Results

black: direct measurement (data)

orange: full fit

light-blue: fit excluding input from row

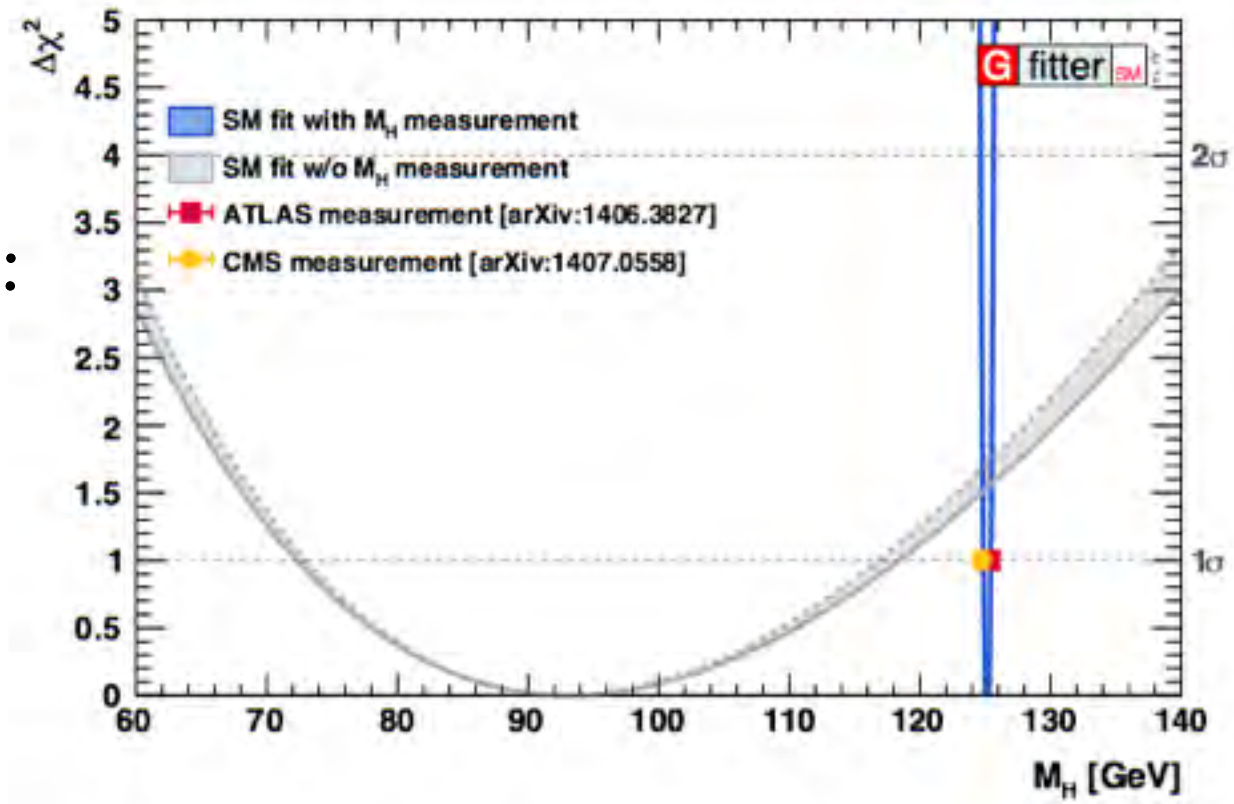
- goodness of fit, p-value:
  χ^2_{min}= 17.8 Prob(χ^2_{min}, 14) = 21%
  Pseudo experiments: 21 ± 2 (theo)%
  - χ^2_{min}(Z widths in 1-loop) = 18.0
  - χ^2_{min}(no theory uncertainties) = 18.2
- no individual value exceeds 3σ
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ
    → largest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



Higgs results

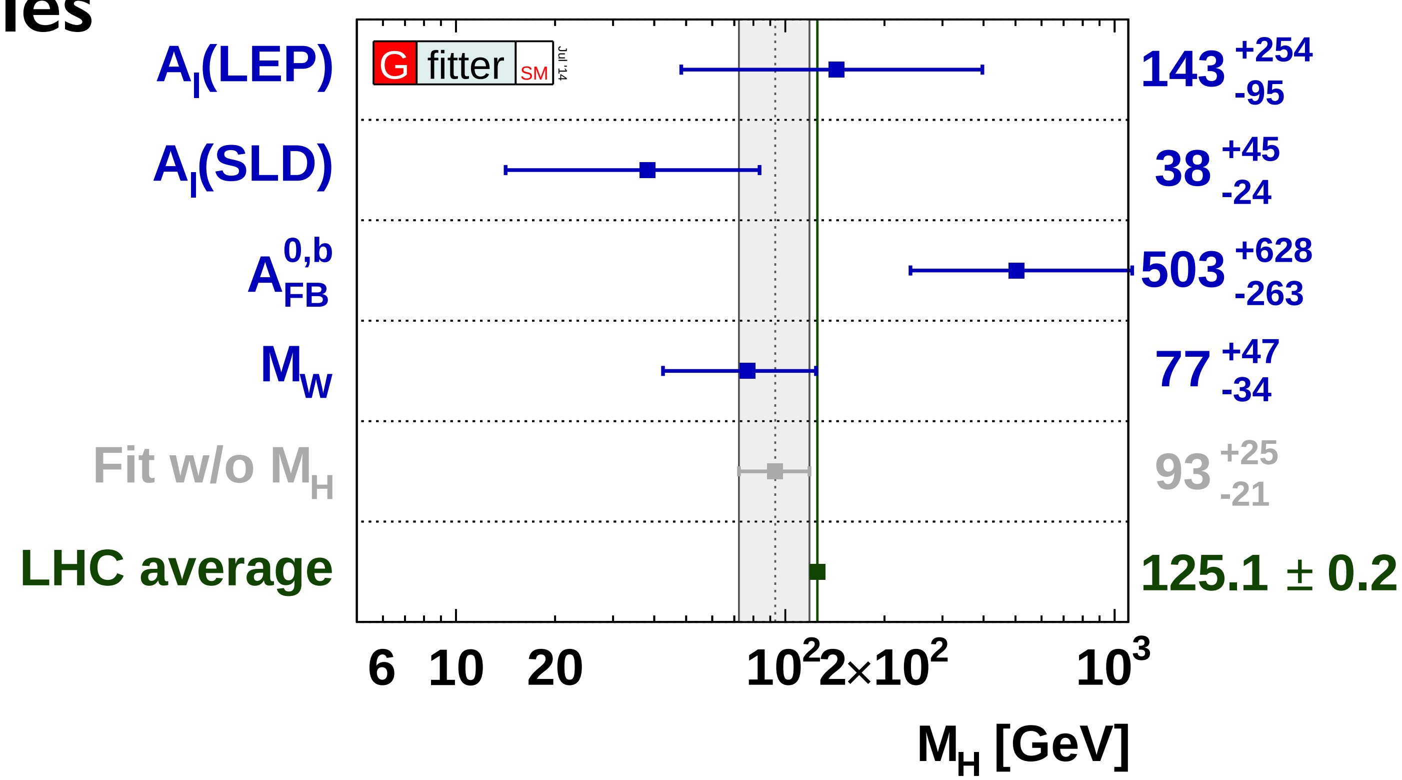
$\Delta\chi^2$ profile vs M_H

- 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

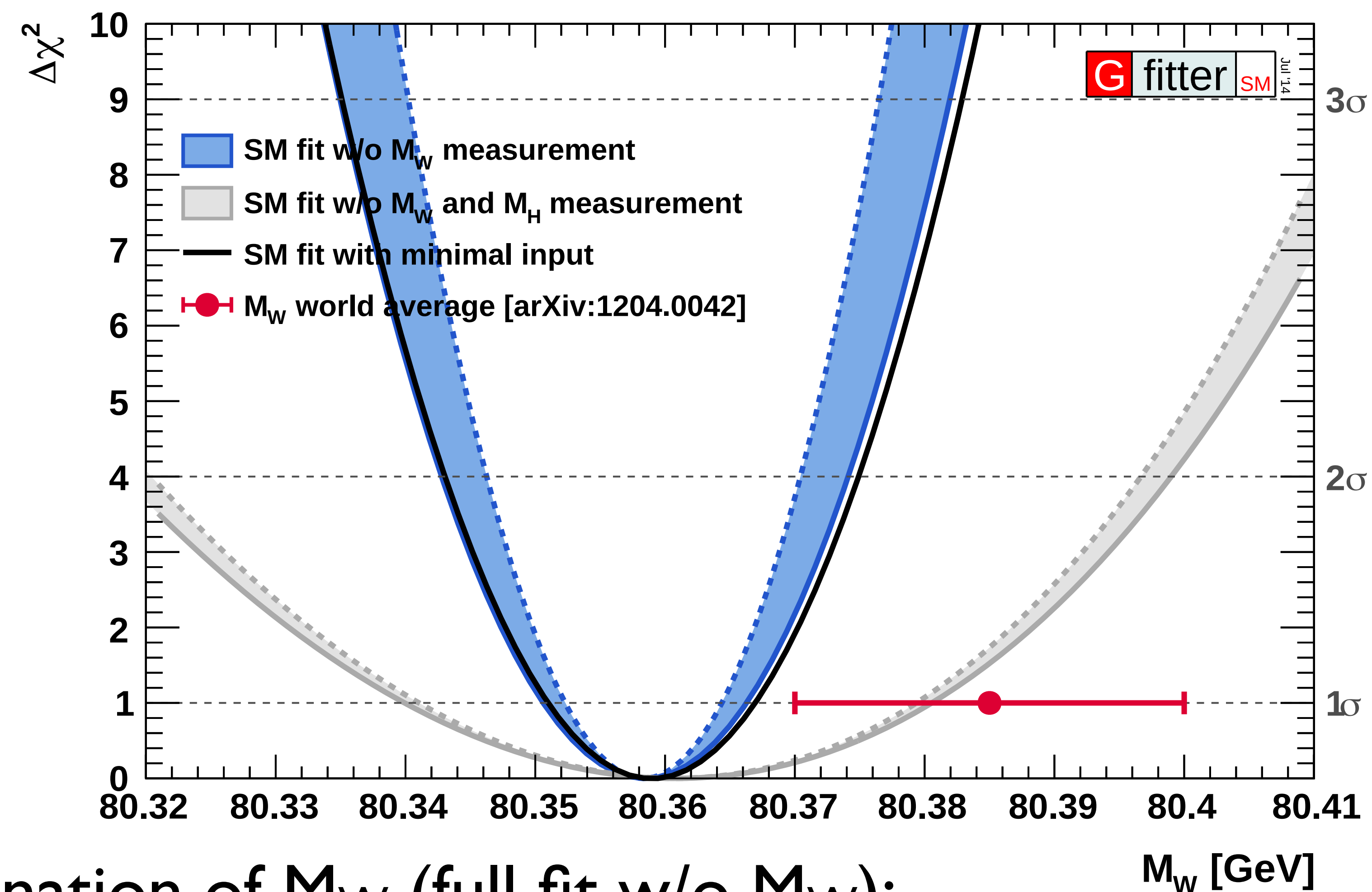
- determination of M_H, removing all sensitive observables except the given one
- known tension (3σ) between A_l(SLD), $A^{0,b}_{FB}$, and M_W clearly visible



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):

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

more precise than direct measurement (15 MeV)

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
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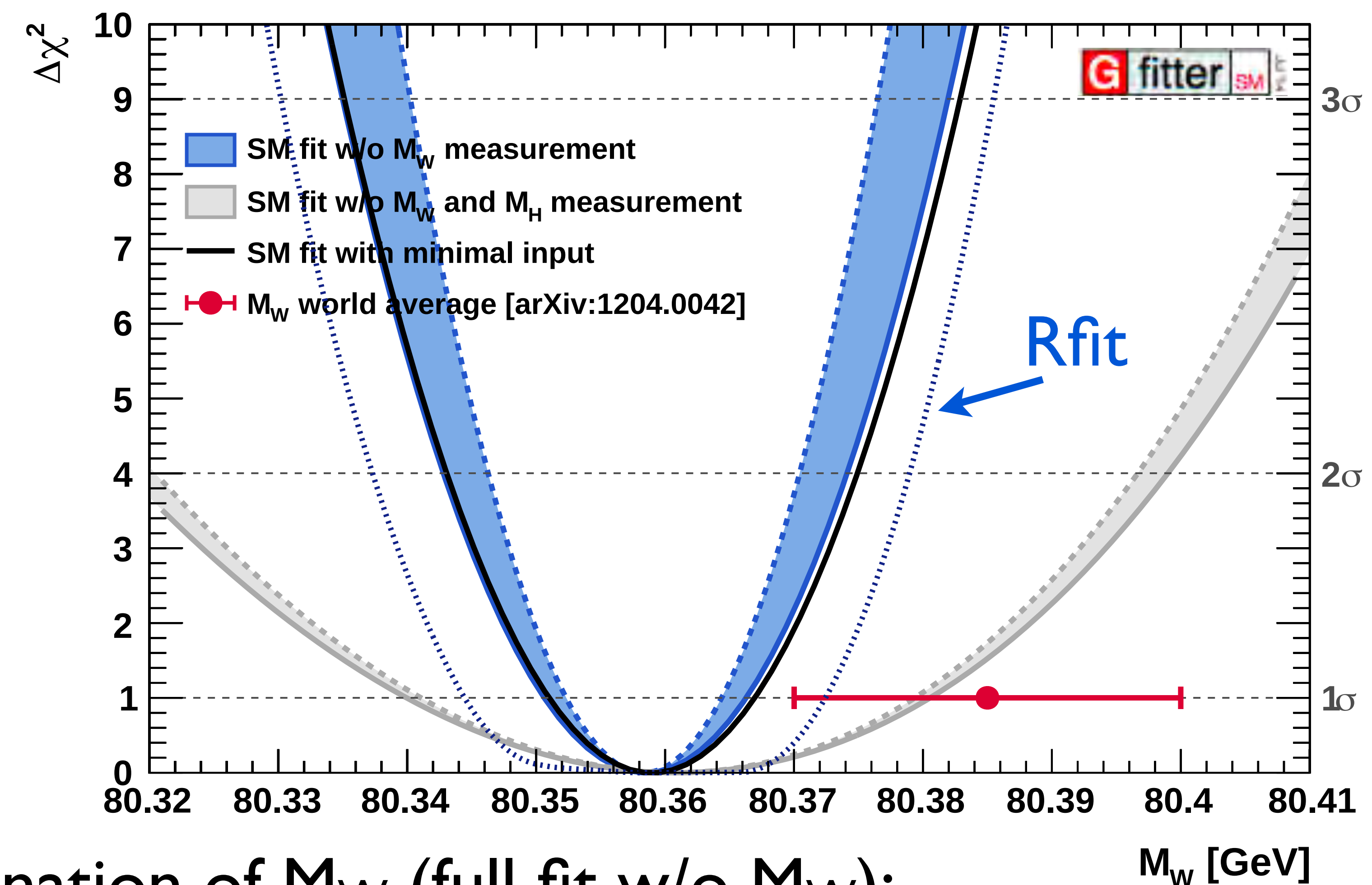


- fit result for indirect determination of M_W (full fit w/o M_W):

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

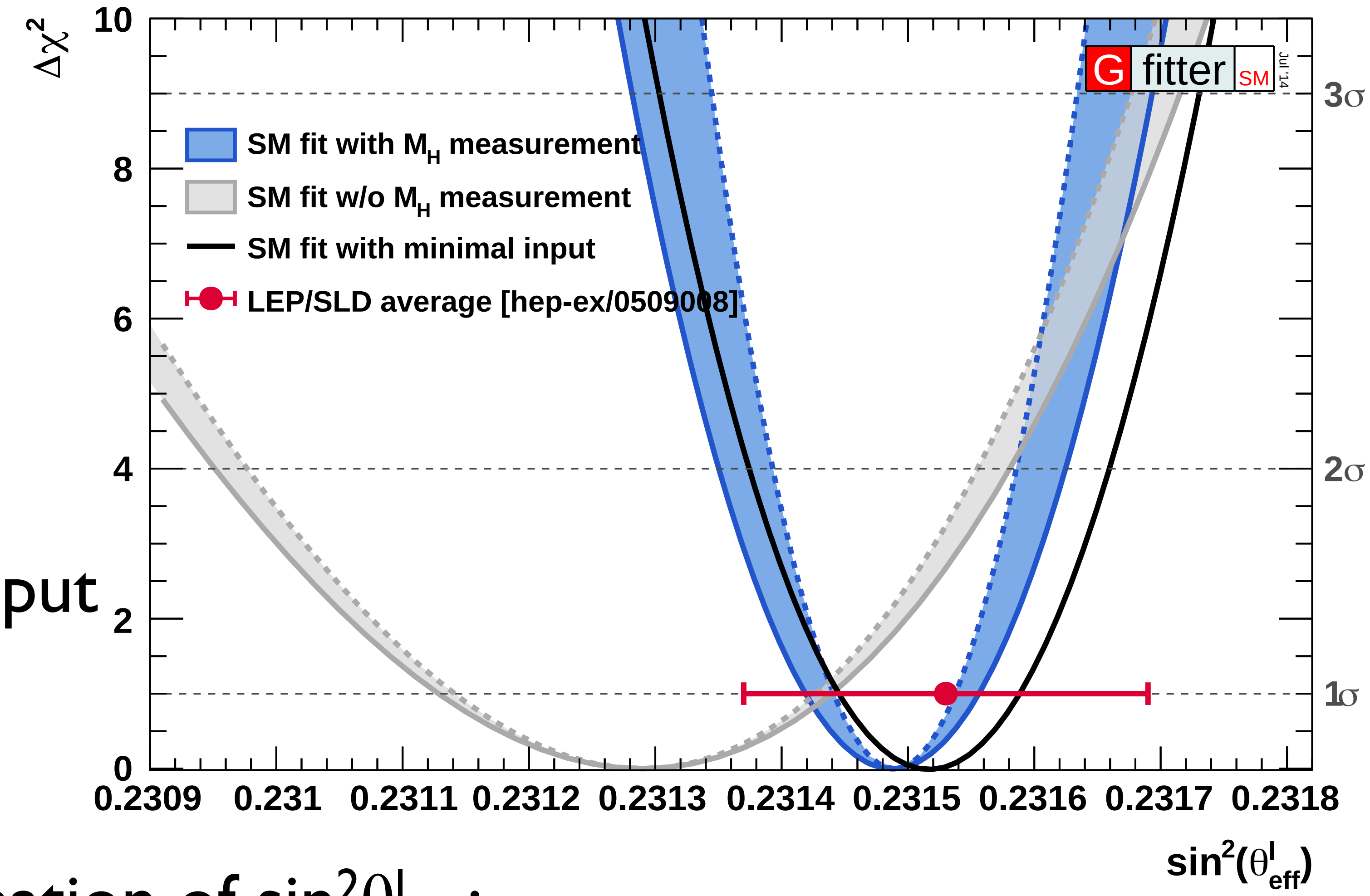
(Rfit: ±13 MeV)

more precise than direct measurement (15 MeV)

The effective weak mixing angle

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

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



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

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

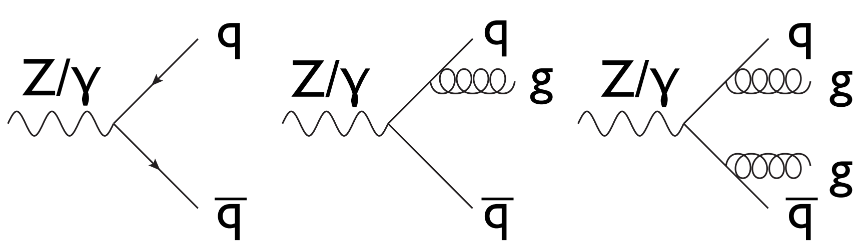
$$= 0.23149 \pm 0.00007_{\rm tot}$$

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

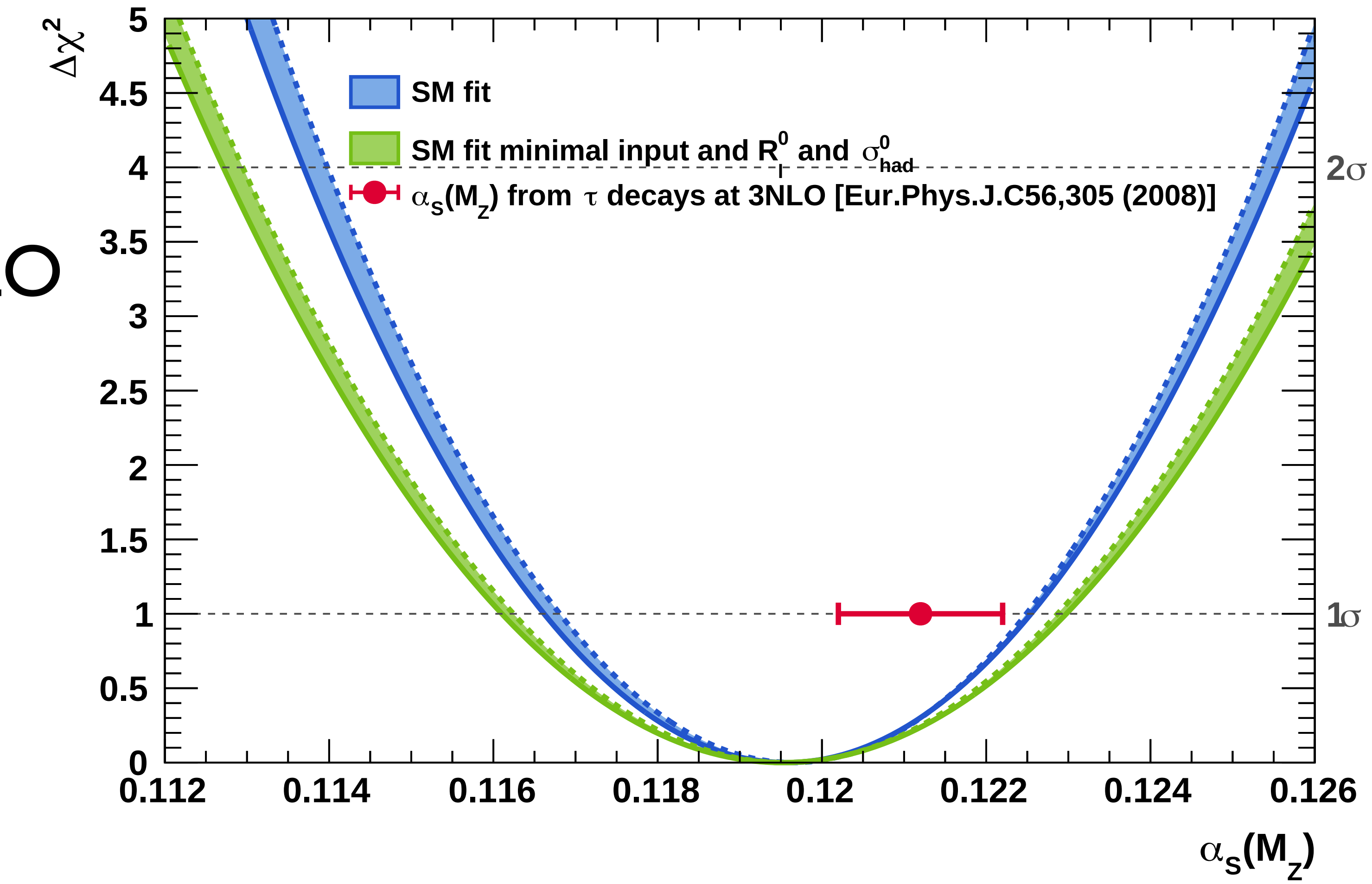
The strong coupling $\alpha_s(M_Z)$

$\Delta\chi^2$ 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



$$\alpha_s(M_Z^2) = 0.1196 \pm 0.0028_{\rm exp} \pm 0.0006_{\delta_{\rm theo}\mathcal{R}_{V,A}} \pm 0.0006_{\delta_{\rm theo}\Gamma_i} \pm 0.0002_{\delta_{\rm theo}\sigma^0_{\rm had}}$$

$$= 0.1196 \pm 0.0030_{\rm tot}$$

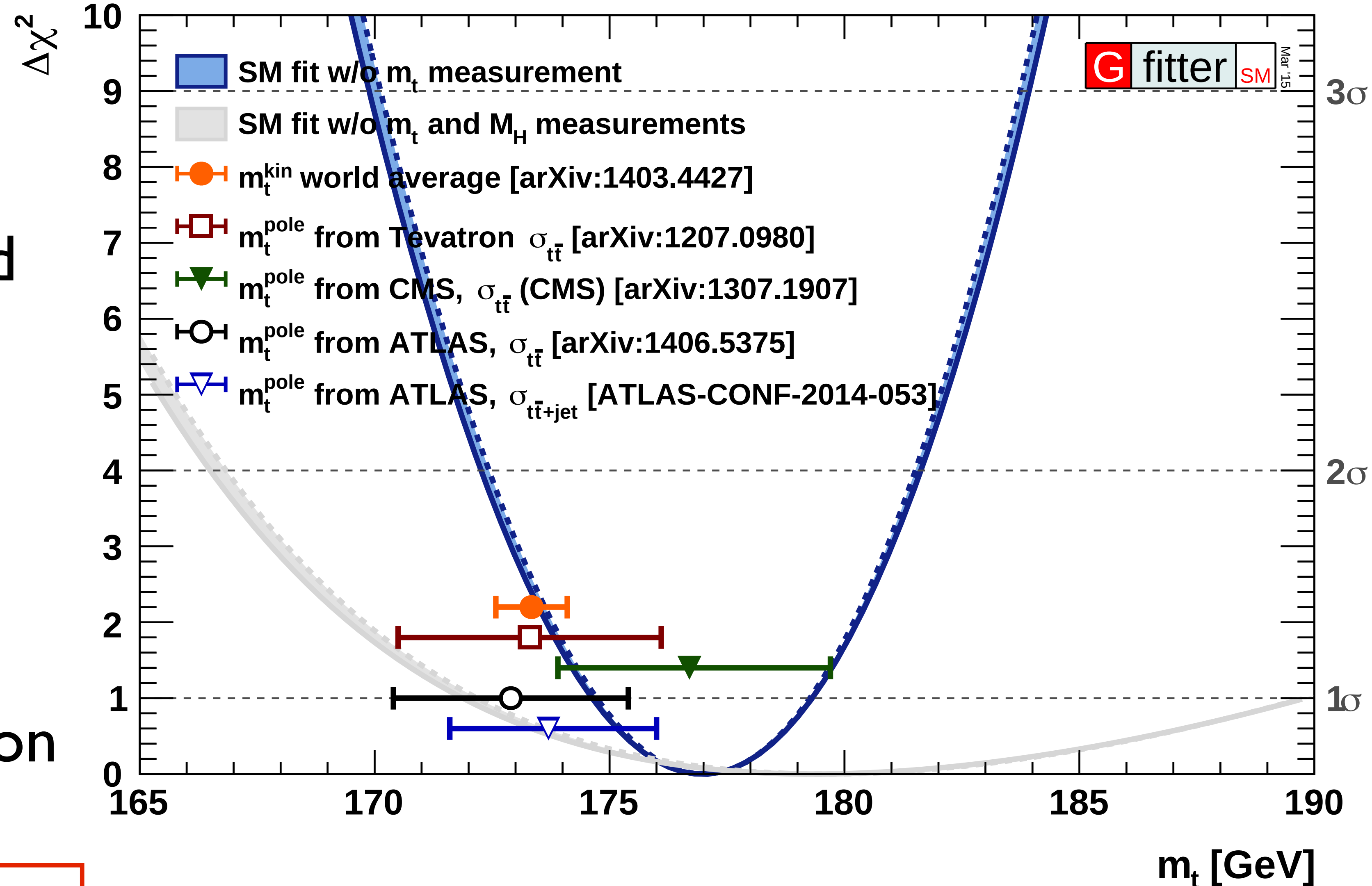
More accurate estimation of theo. uncertainties (previously: δ_{theo} = 0.0001 from scale variations)

good agreement with WA, dominated by exp. uncertainty

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

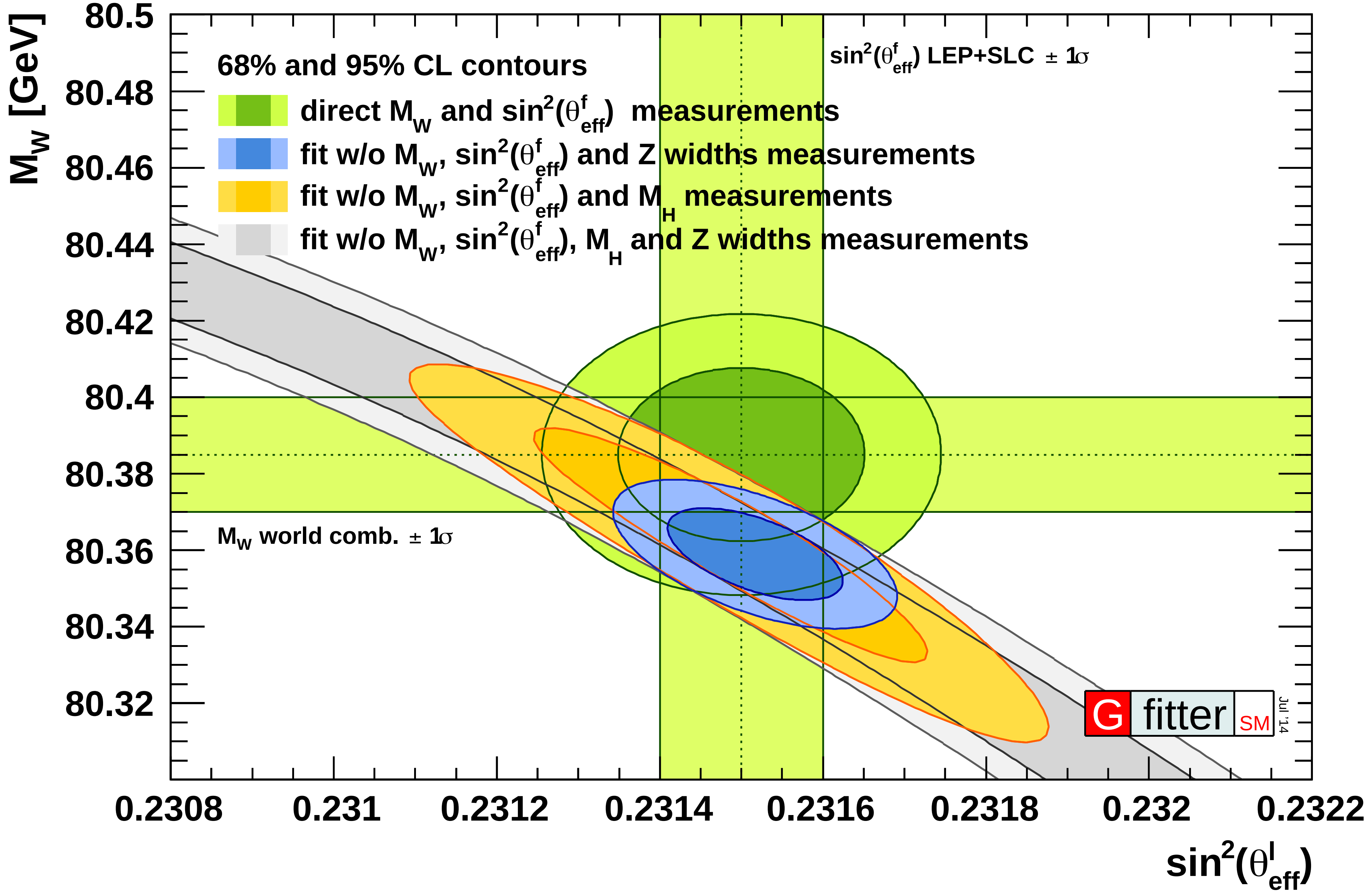


$$m_t = 177.0 \pm 2.3_{M_W,\, \sin^2\theta^f_{\rm eff}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\rm had}} \pm 0.4_{M_Z}\ \text{GeV}$$

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

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

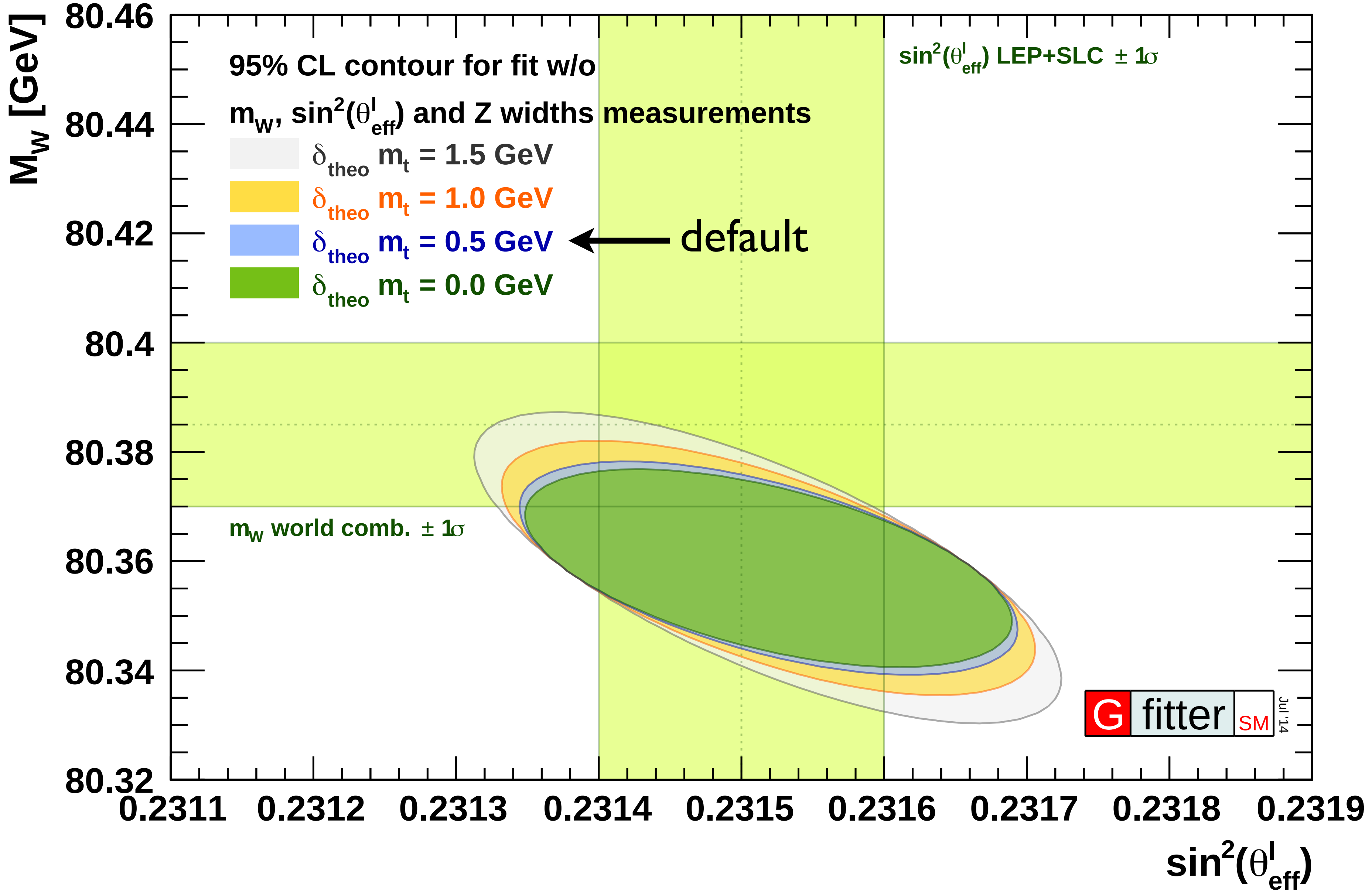
State of the SM: M_W vs $\sin^2\theta^l_{eff}$



sensitive probes of new physics

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

Theoretical uncertainty on m_t



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

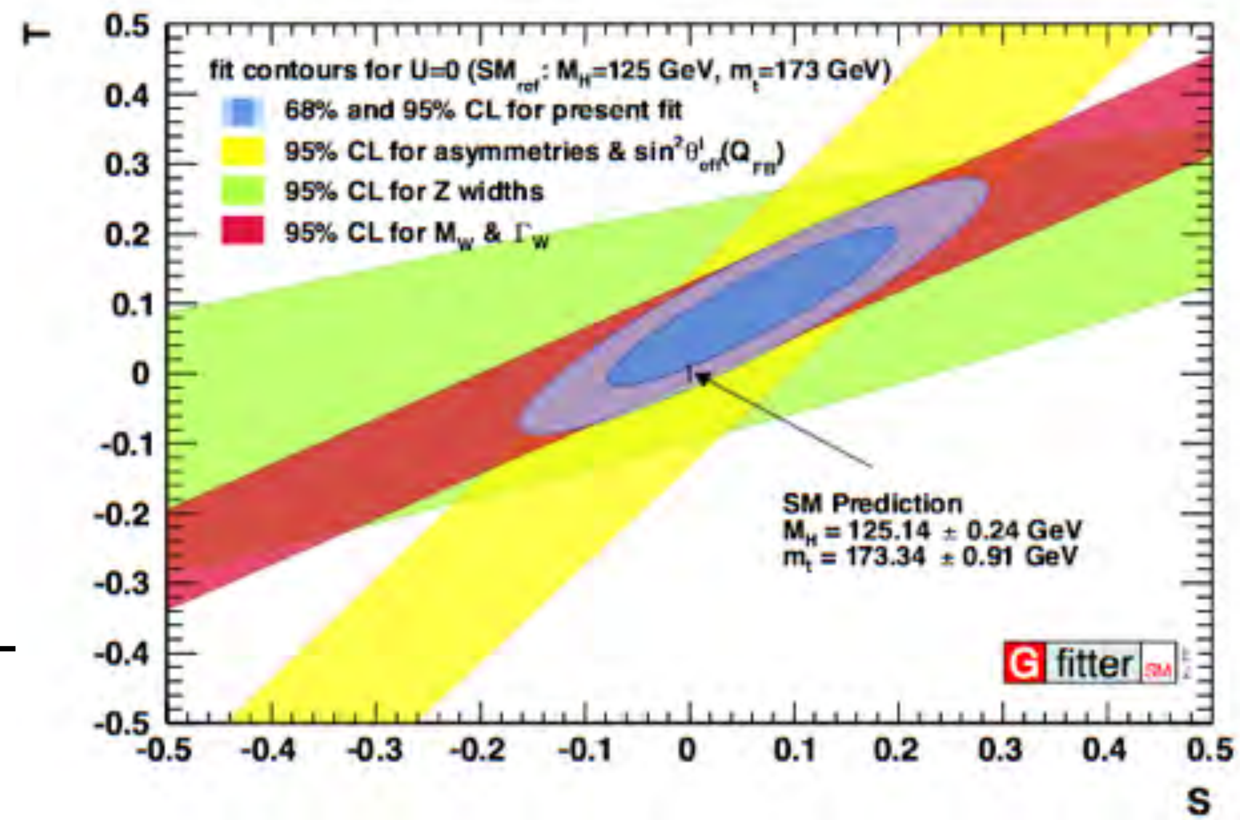
- better assessment of uncertainty on m_t important for the fit
- uncertainty of 0.5 GeV small impact on result

Constraints on BSM models

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

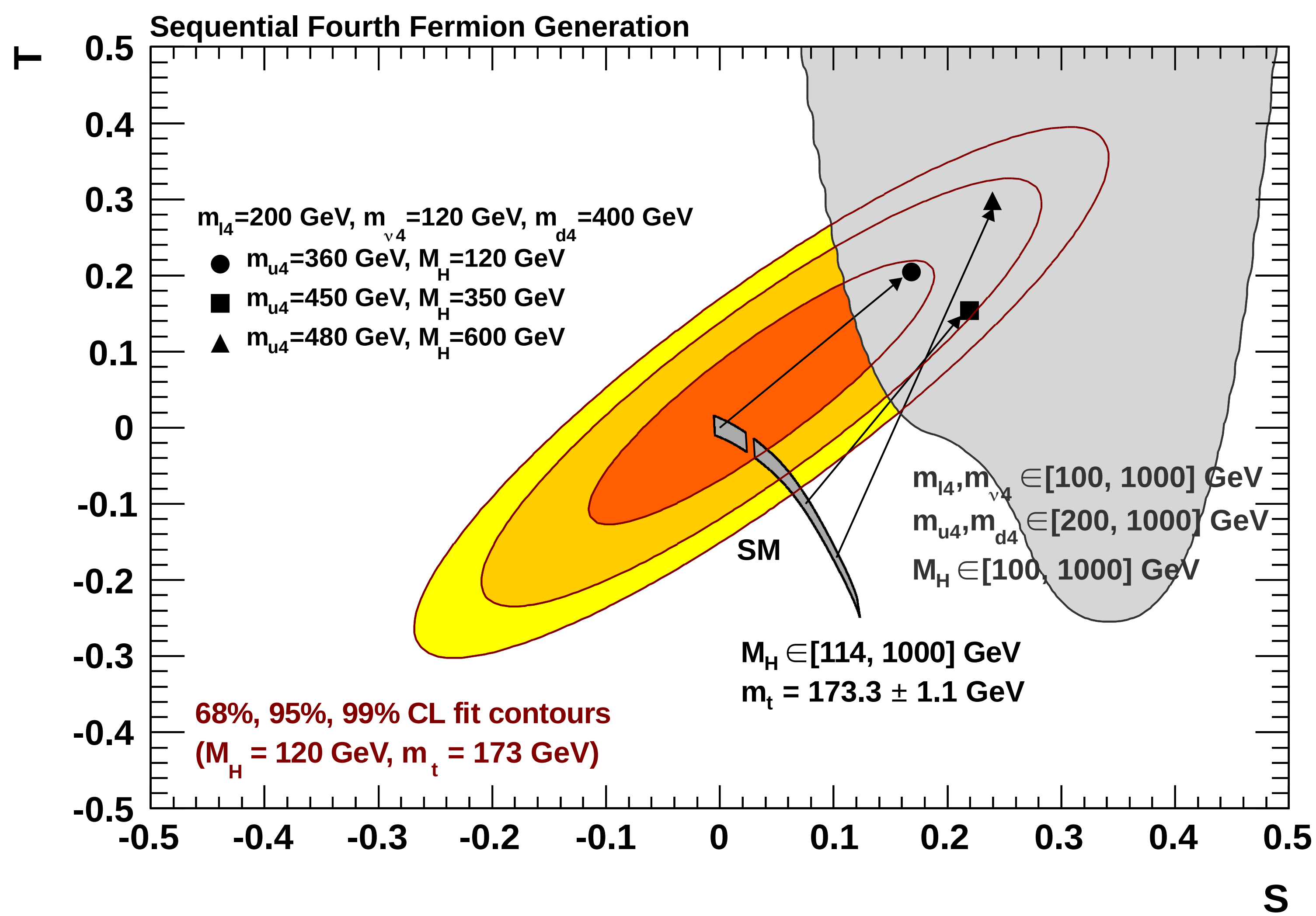
stronger constraints with U = 0:



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

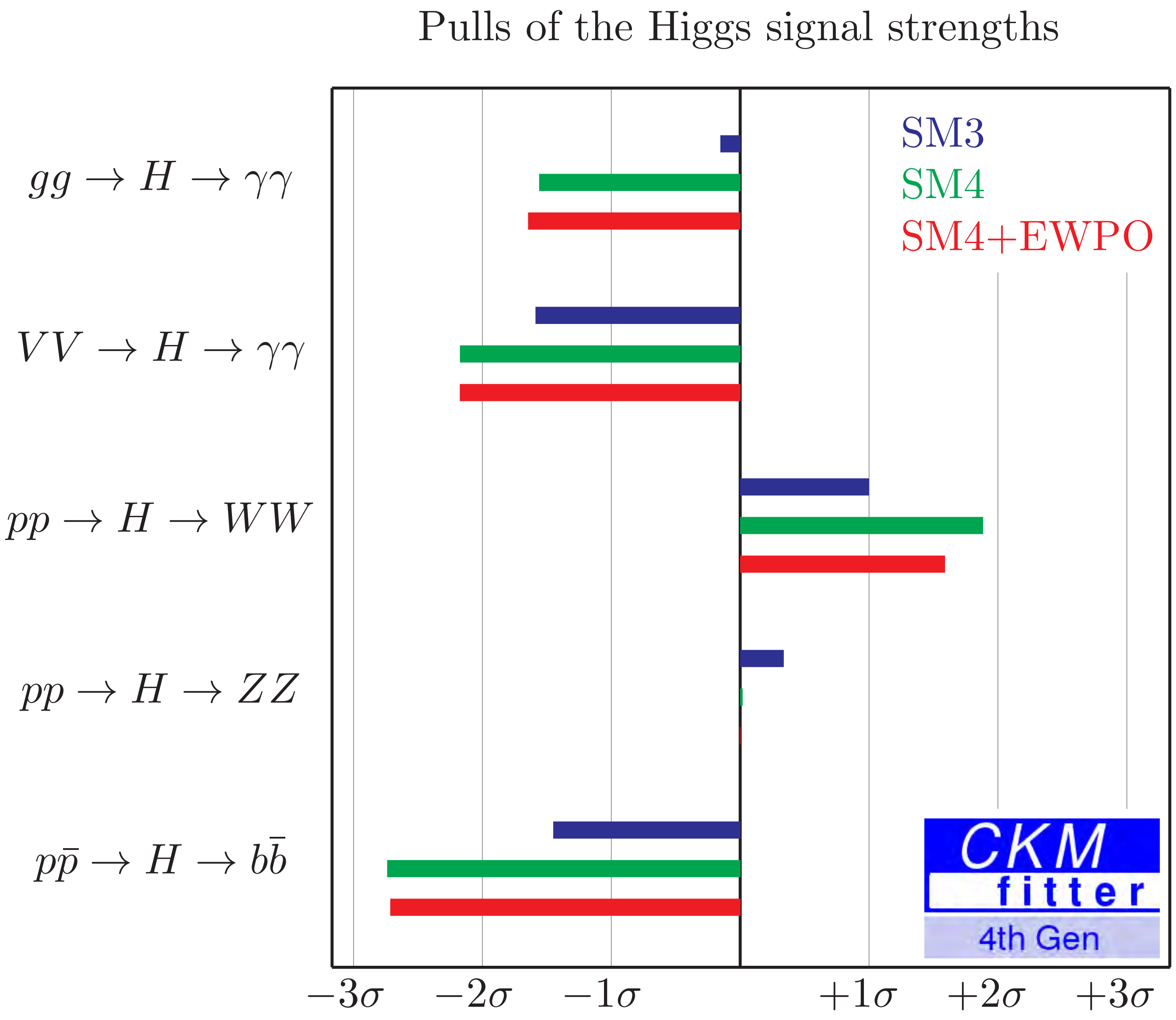
Constraints on BSM models

- with M_H unknown, changes in S, T and U could often be compensated by changes in M_H
- rather weak limits: e.g. large parameter space for sequential fourth generation open



Constraints on BSM models

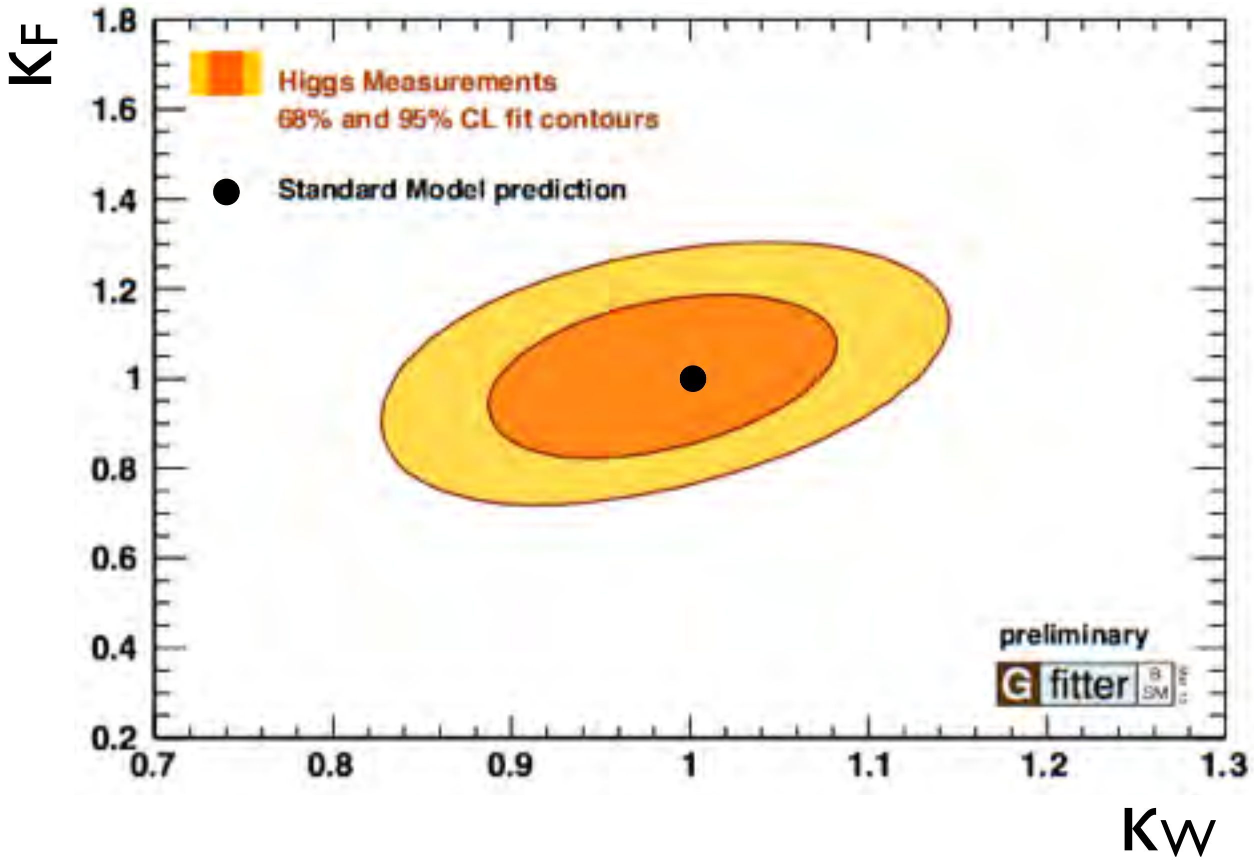
- with M_H unknown, changes in S, T and U could often be compensated by changes in M_H
- rather weak limits: e.g. large parameter space for sequential fourth generation open
- after discovery of a SM-like Higgs boson: chiral 4th generation ruled out
  [O. Eberhard et al., PRL 109, 241802 (2012)]
- note: mostly from Higgs signal strength, small impact of EWPO

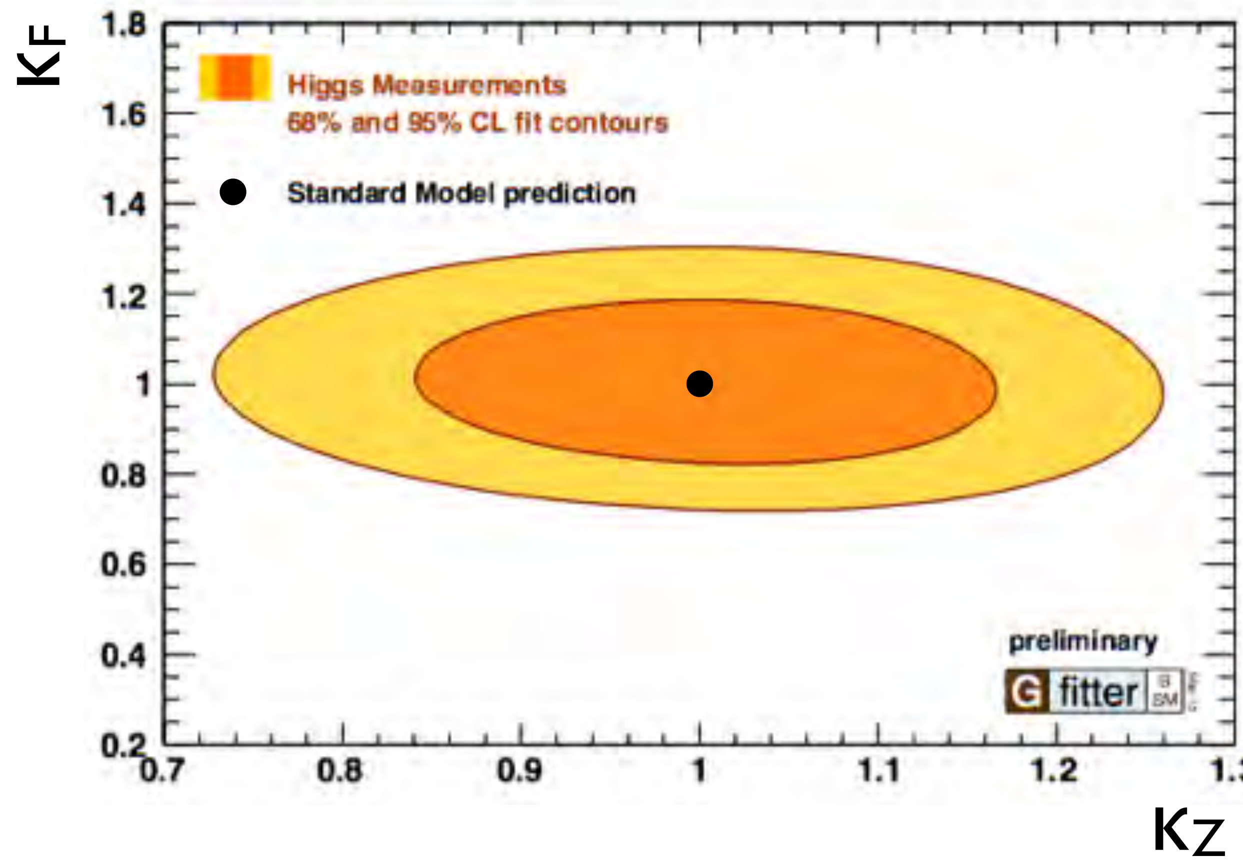


The Scalar Sector

Tree Level Higgs Couplings

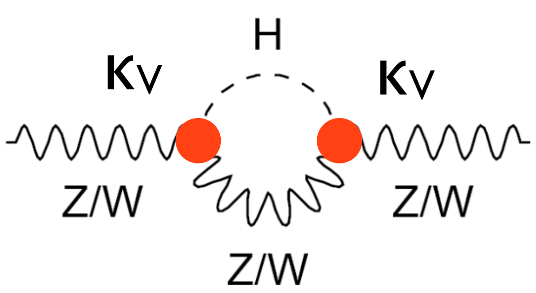
- study of potential deviations of Higgs couplings from SM
- leading corrections only, parametrize deviations with effective couplings
- LHC and Tevatron data included using HiggsSignals [P. Bechtle et al., JHEP11, 039 (2014)]





- 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



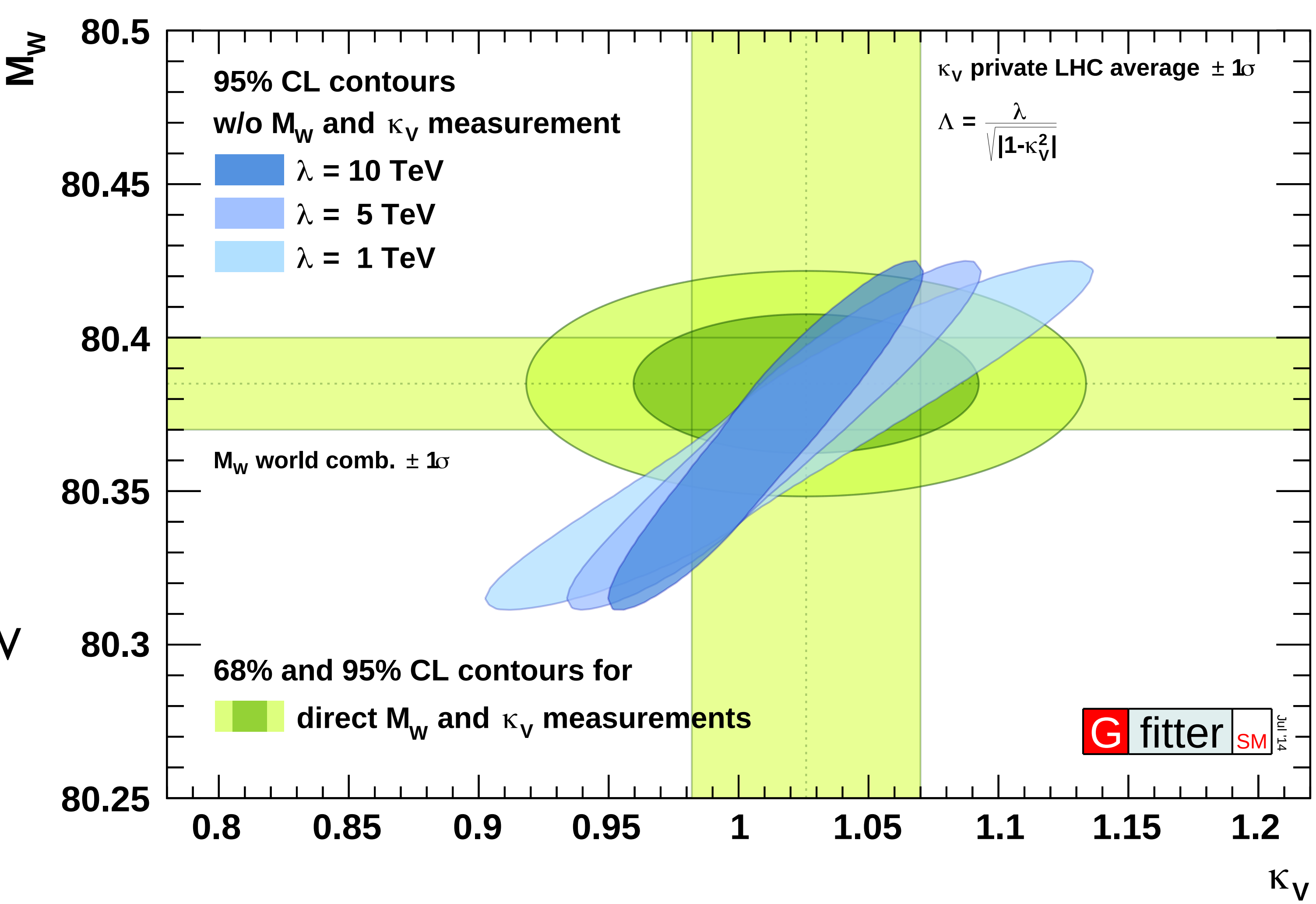
- consider specific model in "κ parametrisation":
  - scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F), with no invisible/undetectable widths
- main effect on EWPD due to modified Higgs coupling to gauge bosons (κ_V)
  [Espinosa et al. arXiv:1202.3697, Falkowski et al. arXiv:1303.1812],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

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

$$T = -\frac{3}{16\pi \cos^2\theta_{\text{eff}}^{\ell}}(1 - \kappa_V^2) \ln \frac{\Lambda^2}{M_H^2}$$

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

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

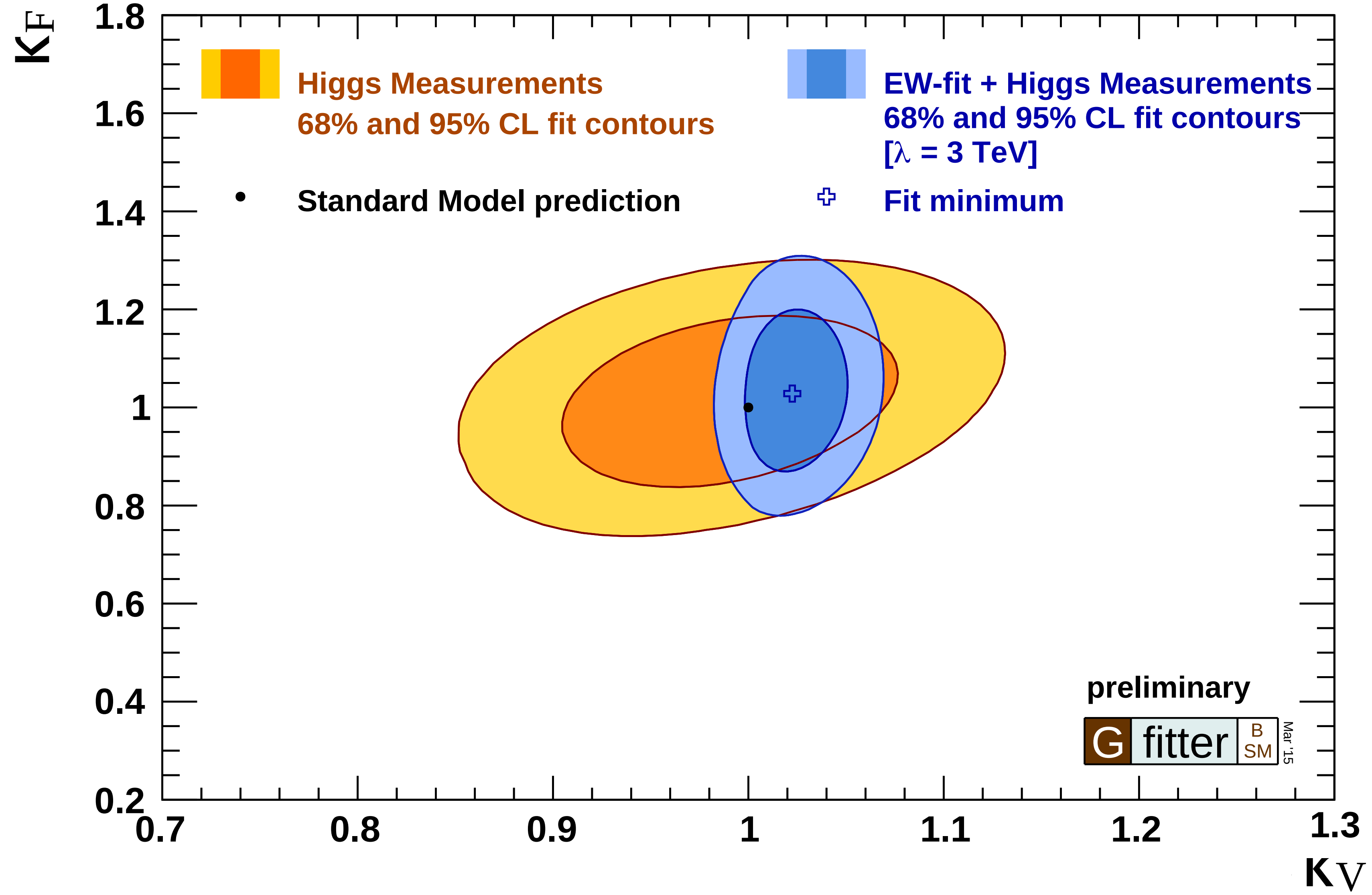


Higgs Coupling Results

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: $\kappa_V < 1$

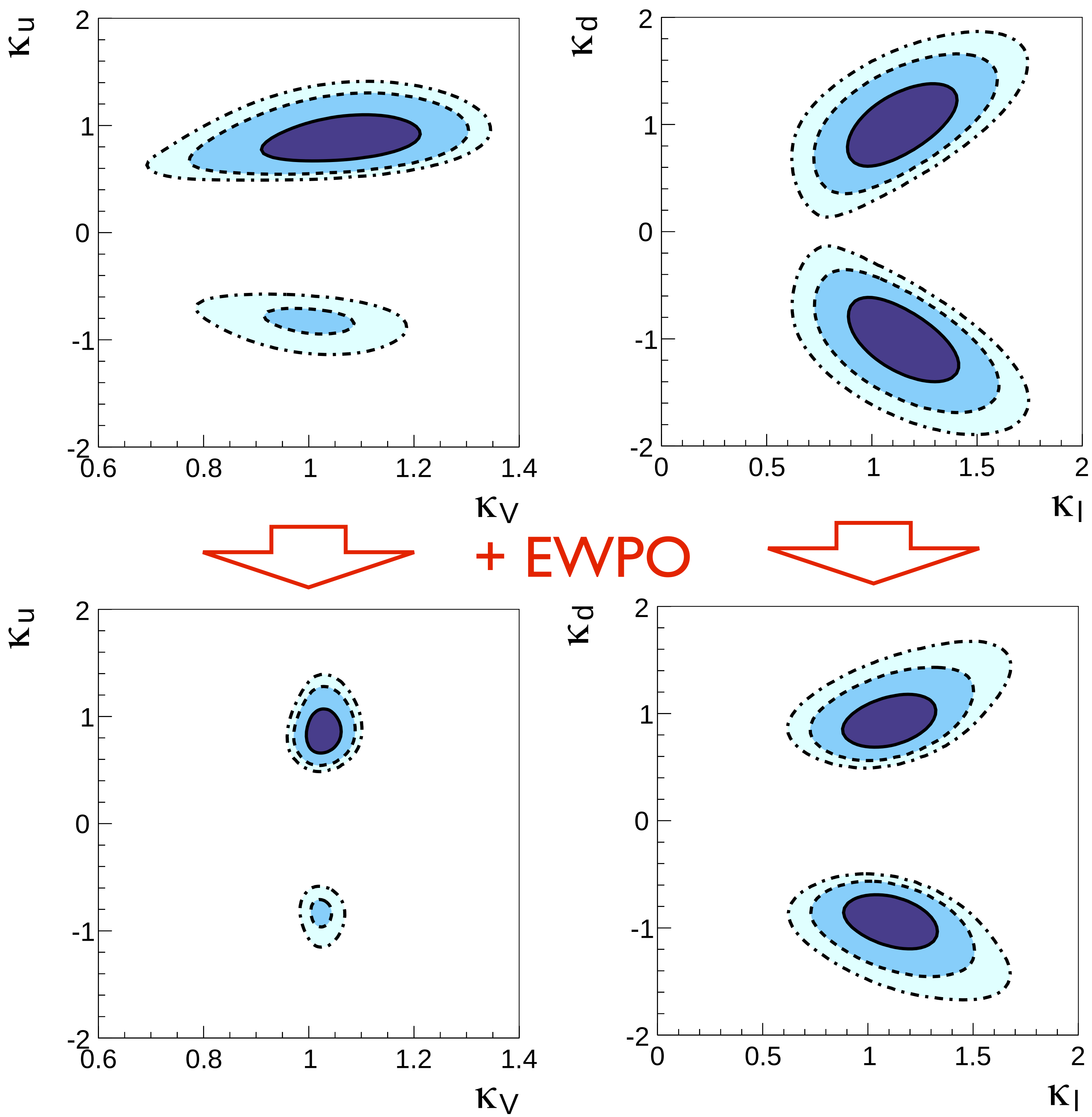
Higgs coupling results

- 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
  - contributions to EWPO have been worked out
  - theoretically sounder than constraints from S,T,U

only Higgs signal strength

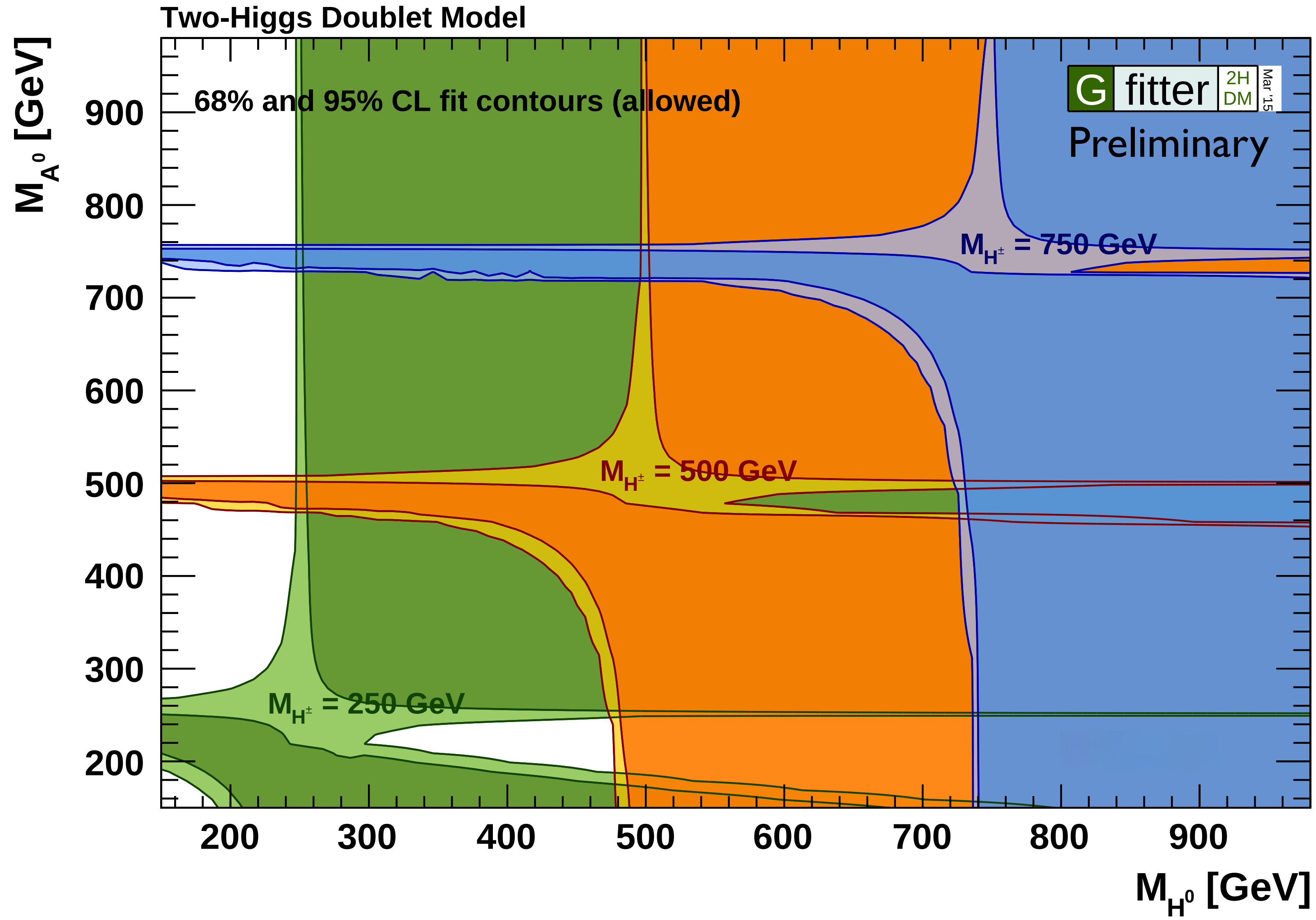


[Marco Ciuchini et al, arXiv:1410.6940]

Two Higgs Doublet Models

- 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

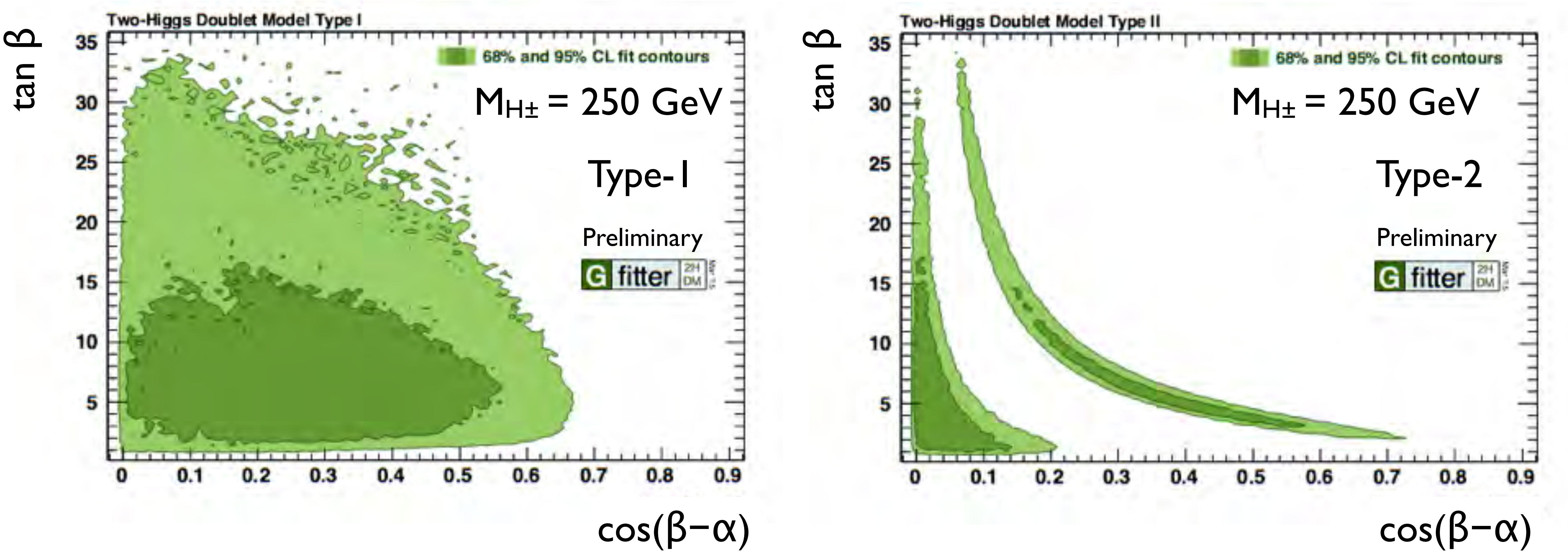
	Type I and Type II
Higgs	C_V
h	$\sin(\beta-\alpha)$
H	$\cos(\beta-\alpha)$
A	0



- 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

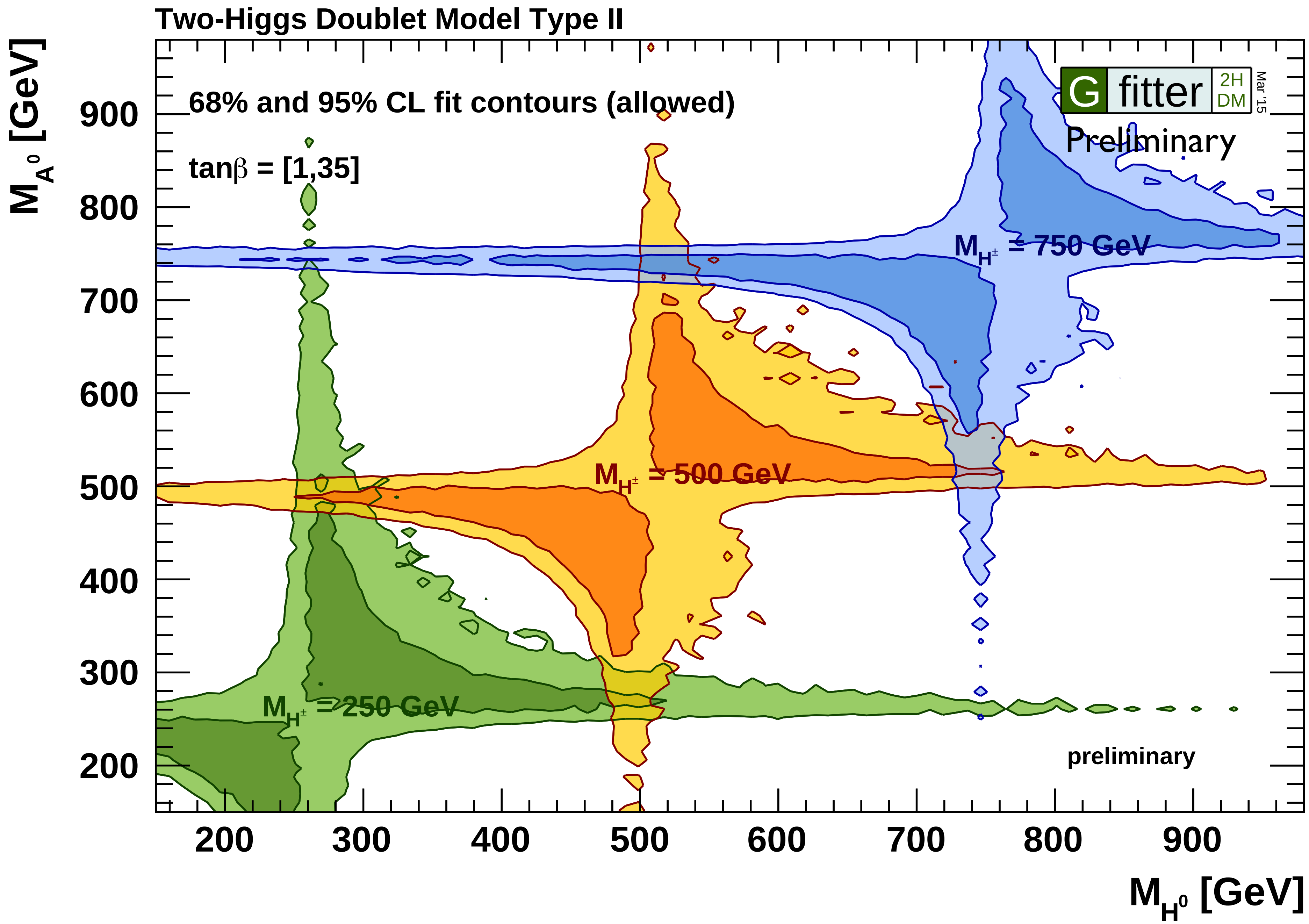
2HDM and H Coupling Measurements

- 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]



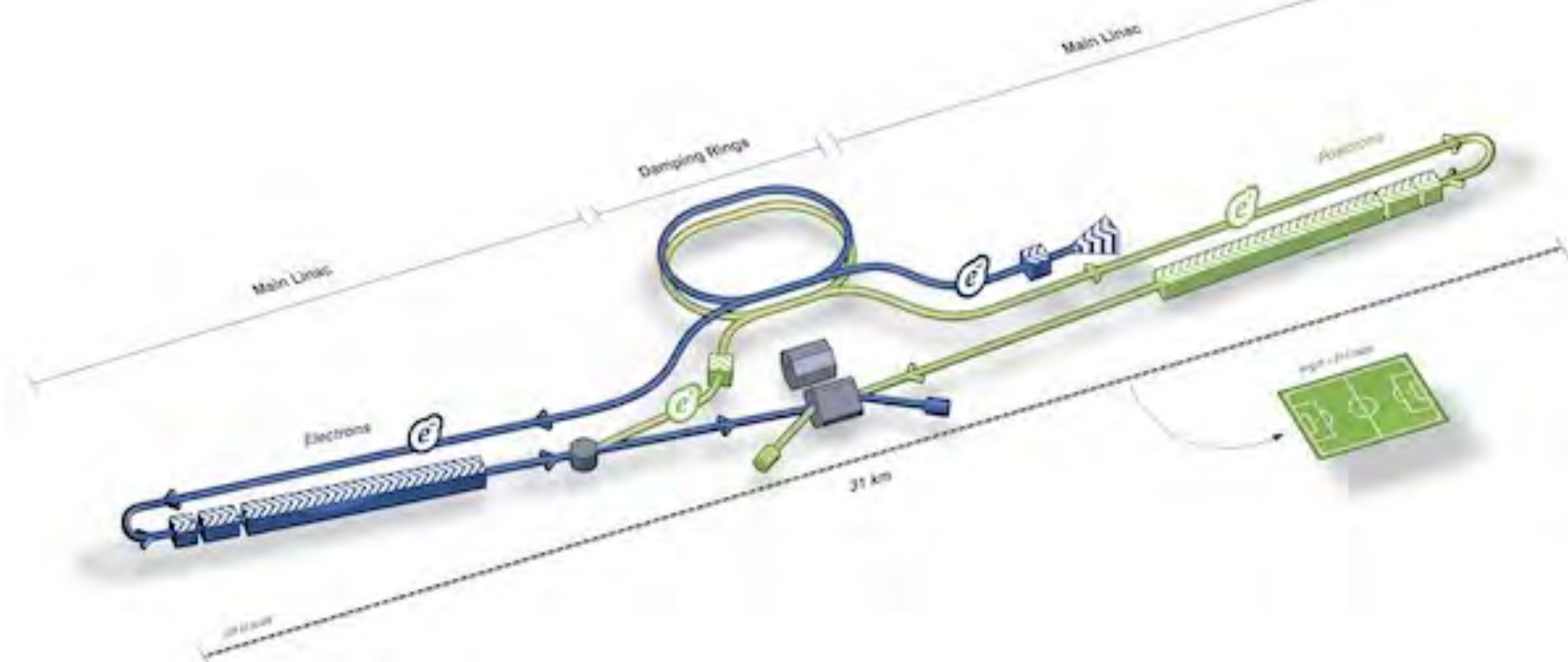
- additional constraints from flavour data
  - $B \rightarrow X_s \gamma$: $\tan\beta > 1$
  - $B_s \rightarrow \mu\mu$: constraints depending on M_H and $M_{H\pm}$

Global Fit to 2HDM of Type-2



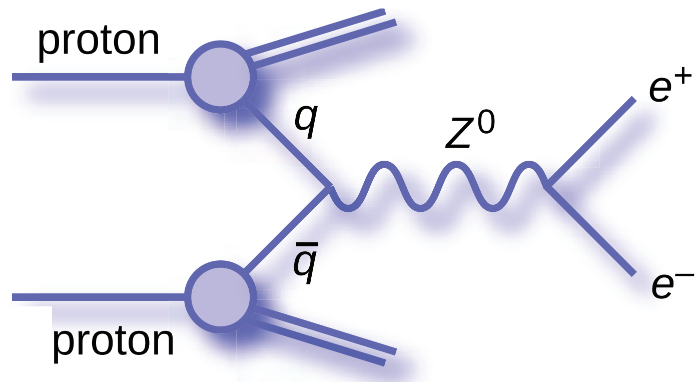
- for given $M_{H\pm}$ tight constraints from H coupling measurements and EWPD
- expect improvement from direct searches at the LHC

The Future

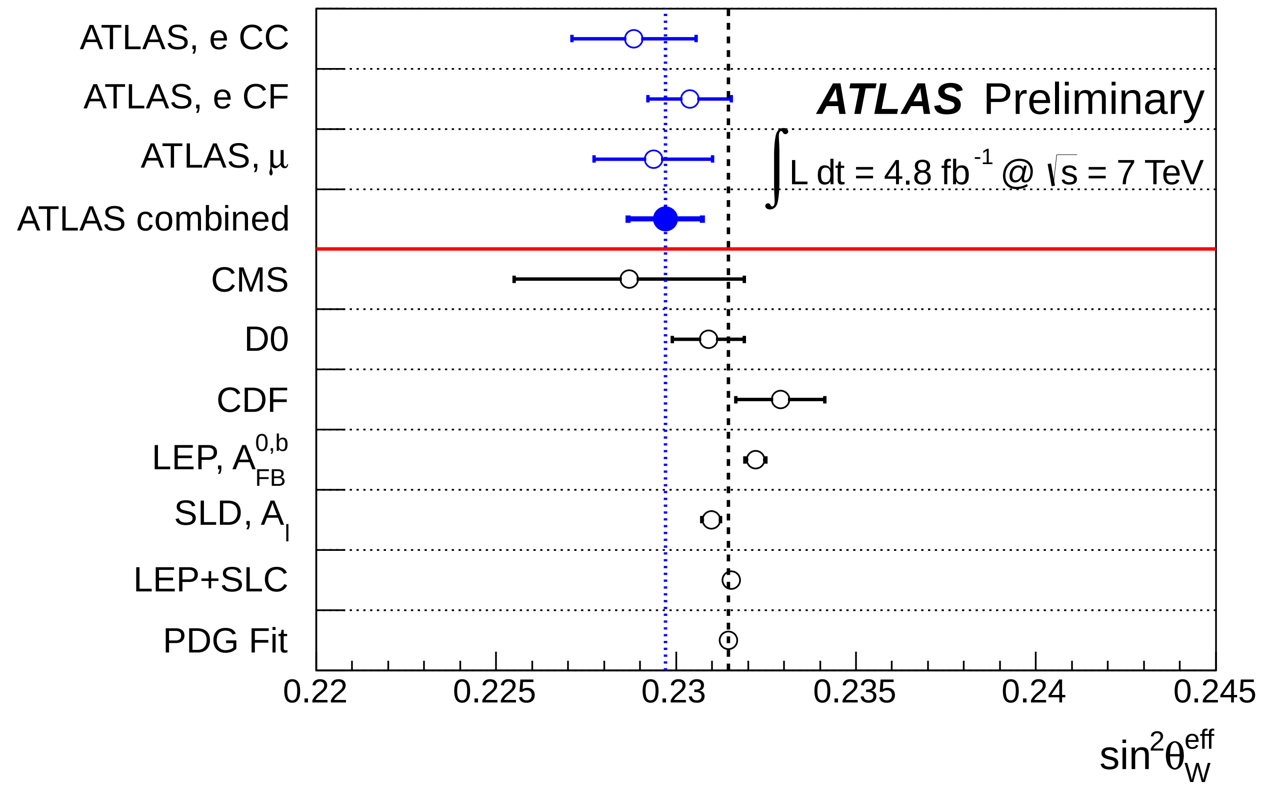

Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

$\sin^2\theta^l_{eff}$ measurements at the LHC

- Drell-Yan: A_{FB} sensitive to distribution of polar angle of lepton w.r.t. *quark* direction
  - LHC: quark direction unknown!
- assume: dilepton boost is quark direction
  - often: interaction of valence quark with sea antiquark
  - important: reach in $|y_{ll}|$, ie. $|\eta_l|$
- ambiguity due to PDFs dilution of A_{FB}
- $\sin^2\theta_{eff}$ from MC templates
  - accuracy of 9.8×10^{-4}
  - consistent with LEP/SLD result (accuracy 1.6×10^{-4})
- prediction for LHC 14/300
  - accuracy of 3.6×10^{-4} [arXiv:1310.6708]



[ATLAS-CONF-2013-043]



$$\sin^2\theta^\ell_{\rm eff}(\rm exp) = 0.23153 \pm 0.00016$$

$$\sin^2\theta^\ell_{\rm eff}(\rm fit) = 0.23149 \pm 0.00007$$

substantial contribution from LHC difficult

Future improvements

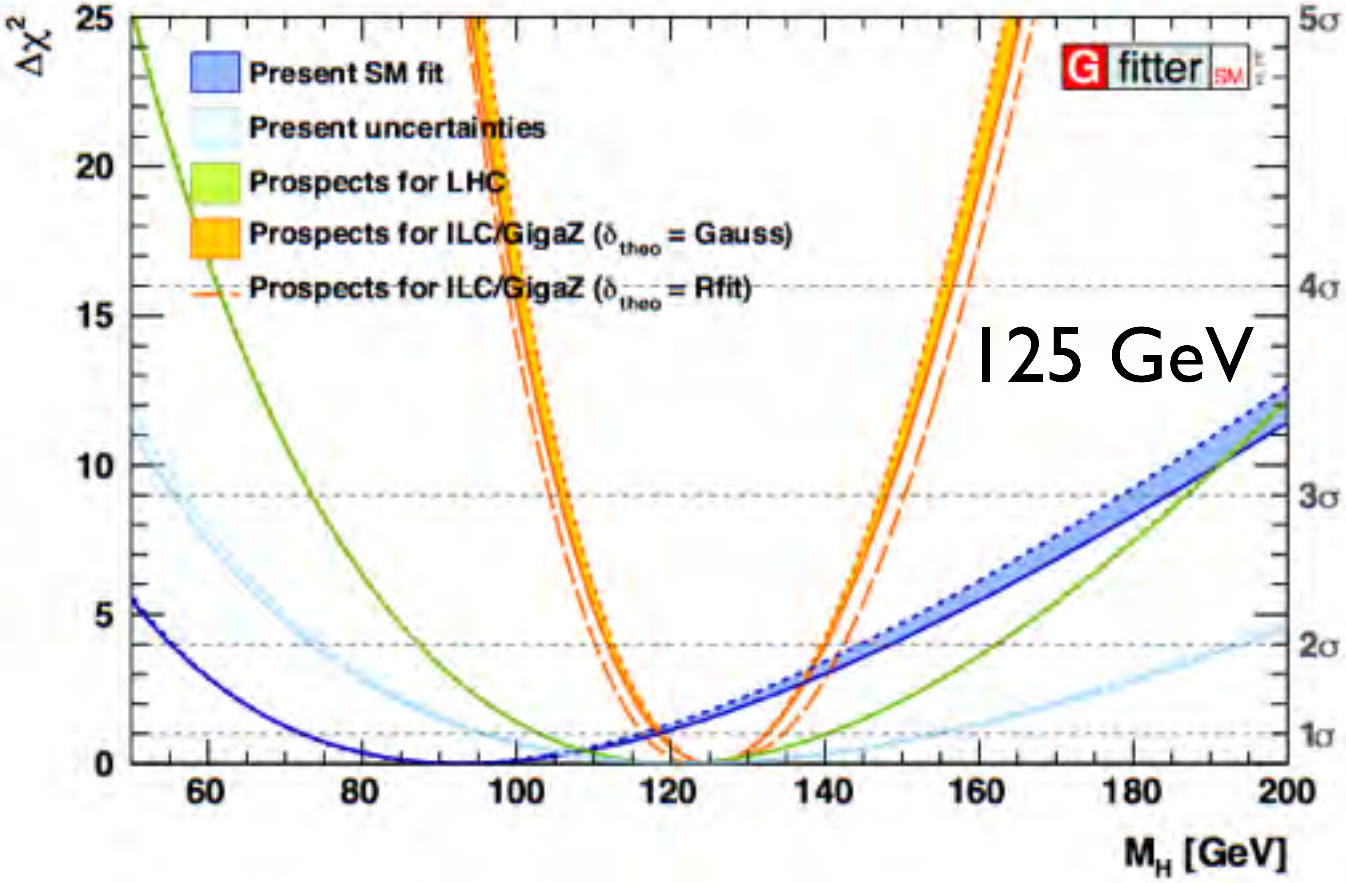
LHC = LHC with 300 fb^{-1}
ILC/GigaZ = future e$^+$e$^-$ collider, option to run on Z-pole (w polarized beams)

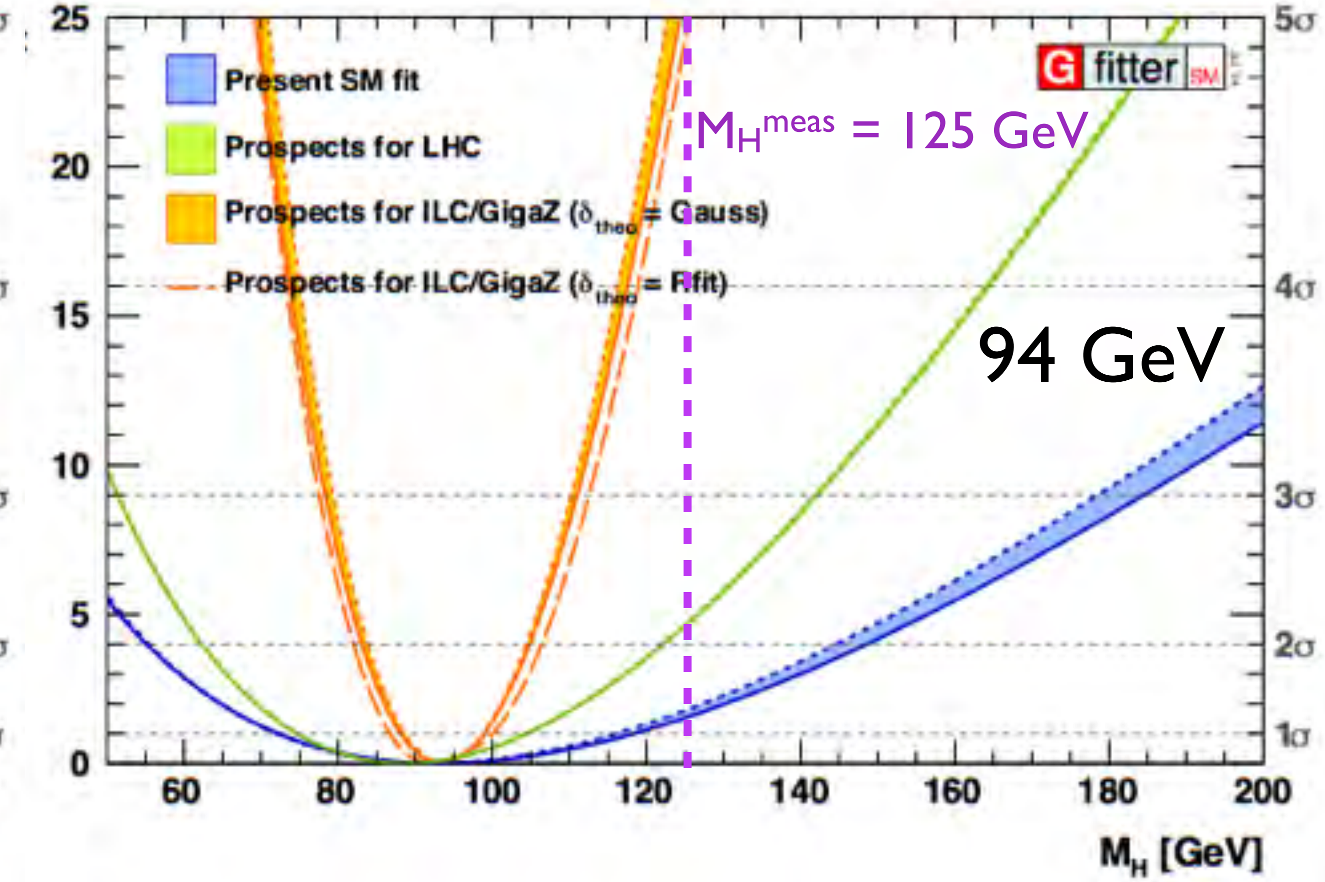
Parameter	Present		LHC		ILC/GigaZ	
M_H [GeV]	0.2	→	< 0.1		< 0.1	
M_W [MeV]	15	→	8	→	5	WW threshold
M_Z [MeV]	2.1		2.1		2.1	
m_t [GeV]	0.8	→	0.6	→	0.1	$t\bar{t}$ threshold scan
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	16		16	→	1.3	$\delta A^{0,f}_{LR}$: $10^{-3} \to 10^{-4}$
$\Delta\alpha^5_{\rm had}(M_Z^2)$ [10^{-5}]	10	→	4.7		4.7	low energy data, better α_s
R^0_l [10^{-3}]	25		25	→	4	high statistics on Z-pole
κ_V ($\lambda = 3\,$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]

Higgs mass

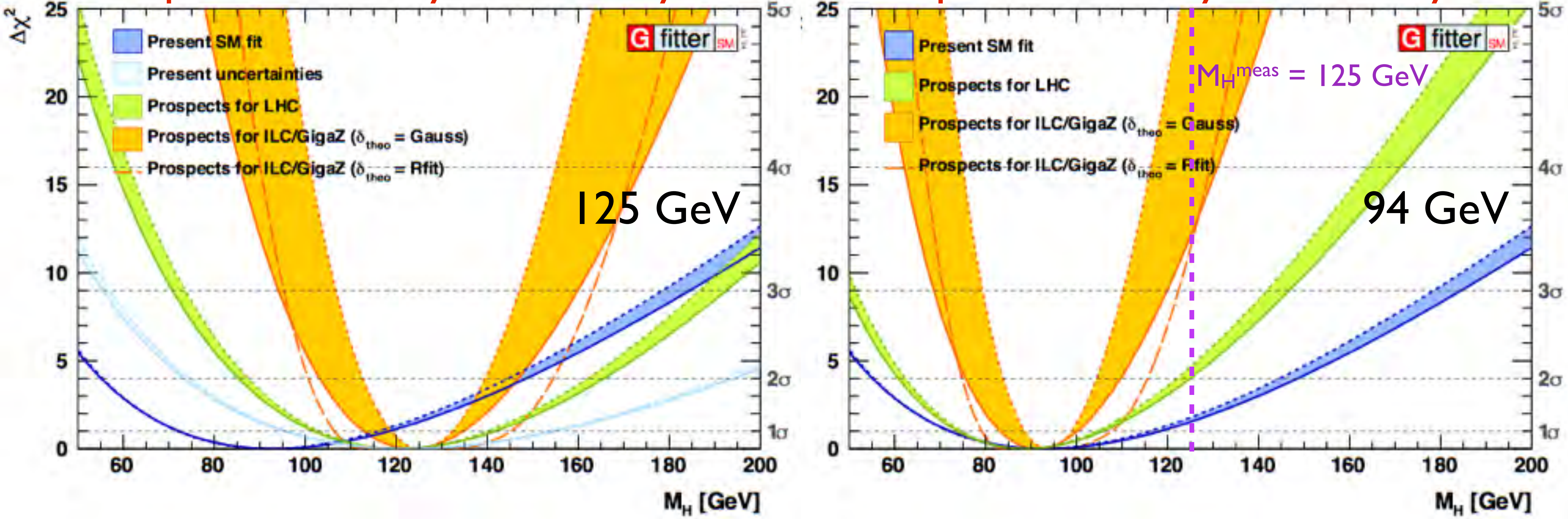




- Logarithmic dependency on MH → cannot compete with direct M_H meas.
  - no theory uncertainty: $M_H = 125 \pm 7$ GeV
  - future theory uncertainty (Rfit): $M_H = 125\,^{+10}_{-9}$ GeV
  - present day theory uncertainty: $M_H = 125\,^{+20}_{-17}$ GeV
- If EWPO central values unchanged (94 GeV), ~5σ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

Higgs mass

present theory uncertainty　　　　present theory uncertainty



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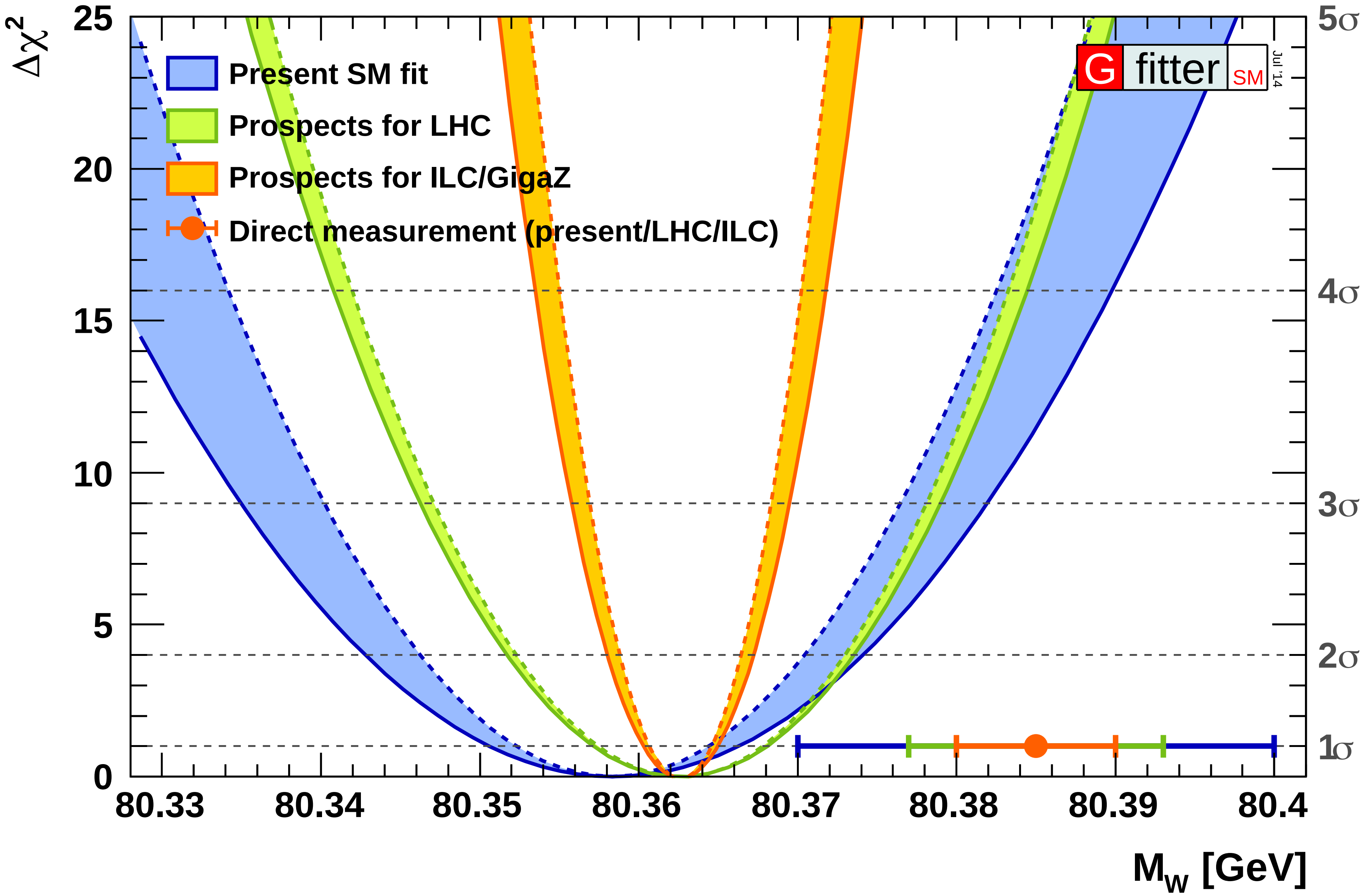
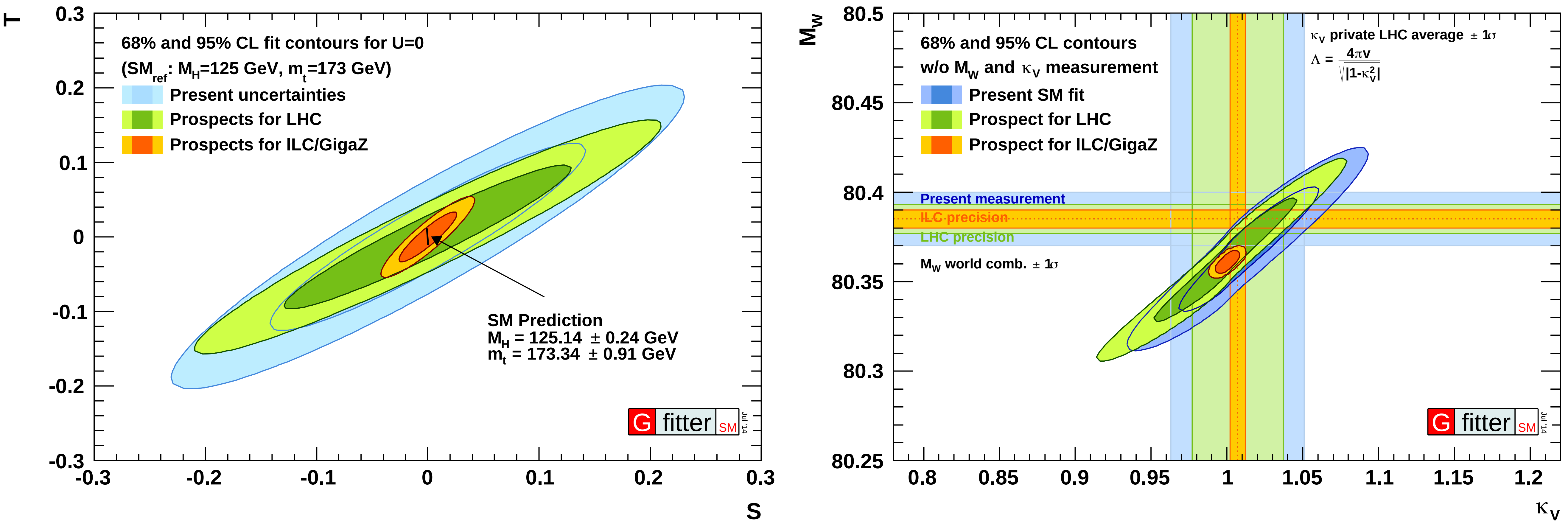
  - present day theory uncertainty: $M_H = 125^{+20}_{-17}$ GeV
- If EWPO central values unchanged (94 GeV), ~5σ discrepancy with measured Higgs mass compromised by present theory uncertainty!

Prospects for M_W



- improvement of a factor of 3 with the ILC (similar to measurement)
- stringent test of internal consistency of SM
- moderate improvement with LHC (~30%)
  - nevertheless, if at present values, theory uncertainties already important

BSM Prospects of EW fit



- for STU parameters, improvement of factor of >3 is possible at ILC
- again, at ILC a deviation between the SM predictions and direct measurements would be prominently visible.
- competitive results between EW fit and Higgs coupling measurements!
  - precision of about 1%

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
$S\|_{U=0}$	–	–	–	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

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
$S\|_{U=0}$	–	–	–	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!
- ILC/GigaZ offers fantastic possibilities to test the SM and constrain NP

M_W : Impact of Uncertainties

Today

δ_{meas} = 15 MeV

δ_{fit} = 8 MeV

LHC-300

δ_{meas} = 8 MeV

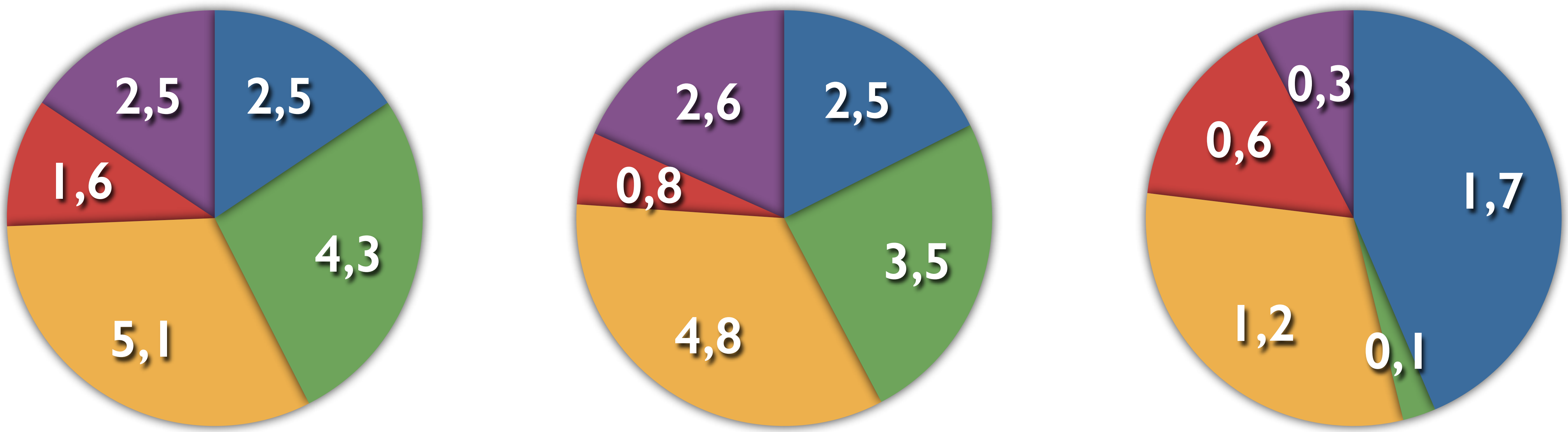
δ_{fit} = 6 MeV

ILC/GigaZ

δ_{meas} = 5 MeV

δ_{fit} = 2 MeV

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



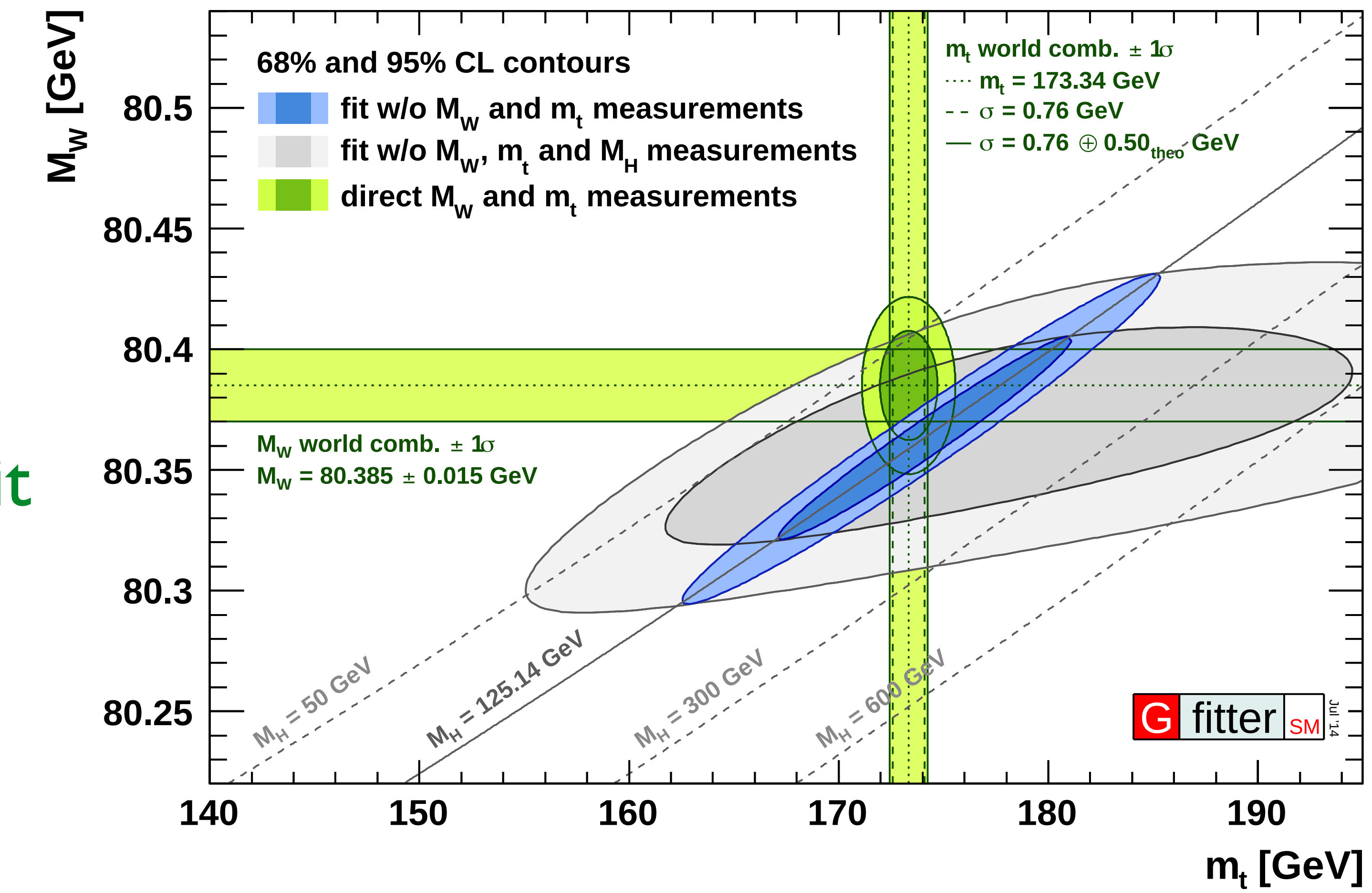
Impact of individual uncertainties on δM_W in fit (numbers in MeV)

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

Summary

Paradigm change

- from the discovery of the Higgs boson to a probe of new physics
- knowledge of M_H and two-loop calculations
  unprecedented precision of EW fit
- cannot know M_W and $\sin^2\theta^l_{eff}$ precise enough



LHC 14/300

- ΔM_W (indirect) = 5.5 MeV
  ΔM_W (exp) = 8 MeV

More information and latest results:
www.cern.ch/gfitter

ILC with GigaZ

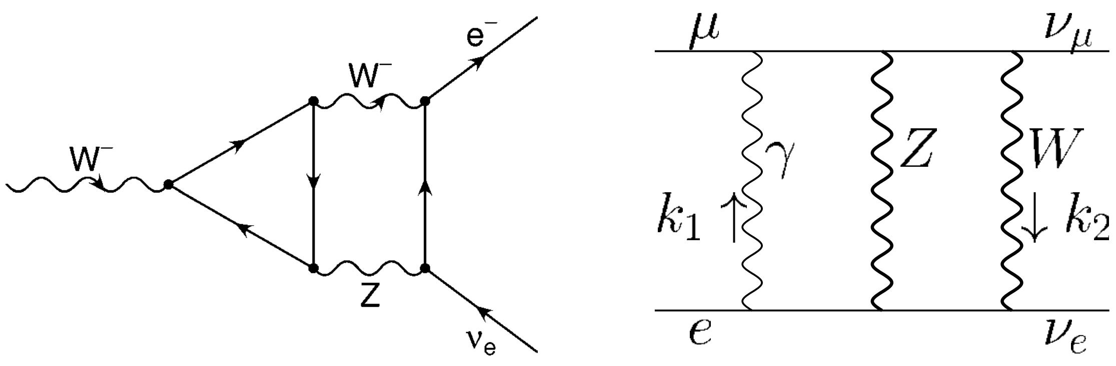
- Δm_t (exp) = 100 MeV → ΔM_W (indirect) = 2 MeV
  measurement of M_Z will become important again ($\Delta\alpha_{had}$ as well)
- indirect determinations of M_Z and $\Delta\alpha_{had}$ will match exp. precision

Additional Material

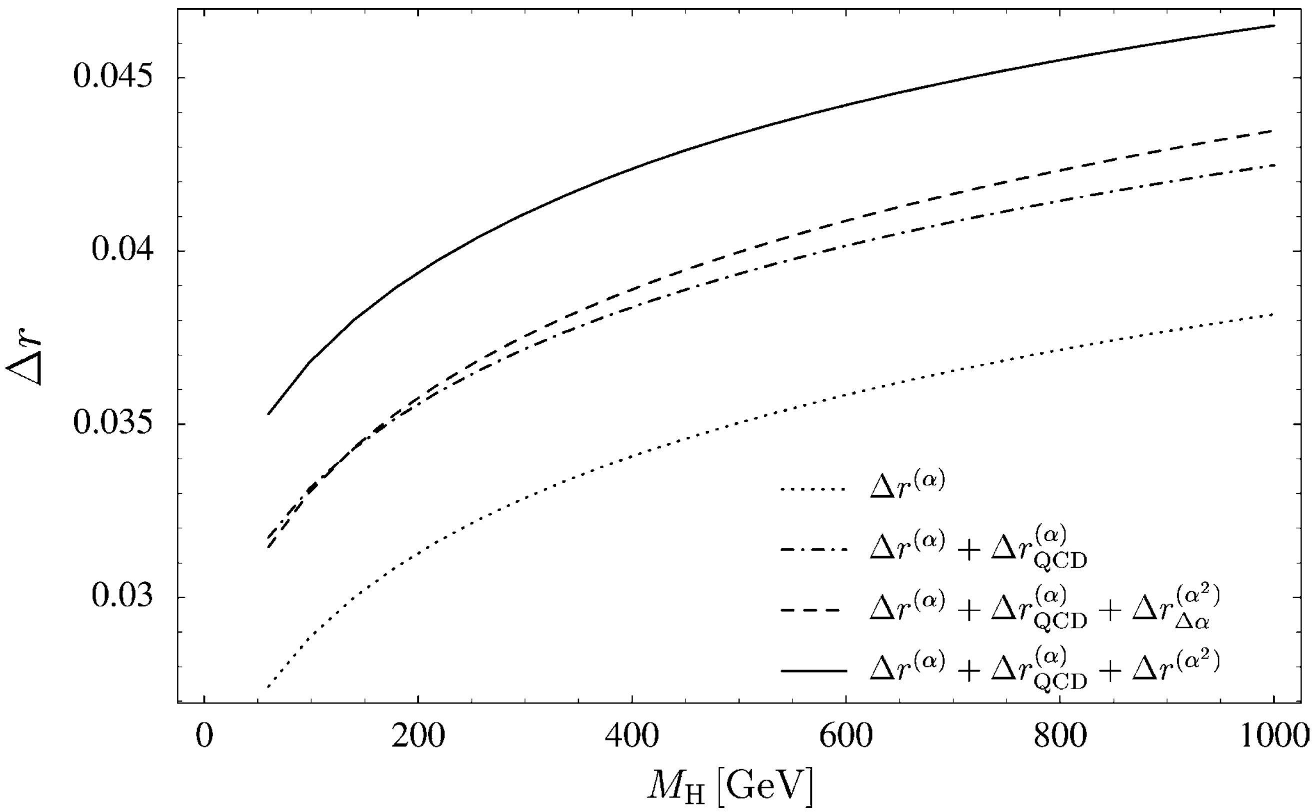
Calculation of M_W

- 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 $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2_{\text{ferm}})$, $O(\alpha^2_{\text{bos}})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- 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)]



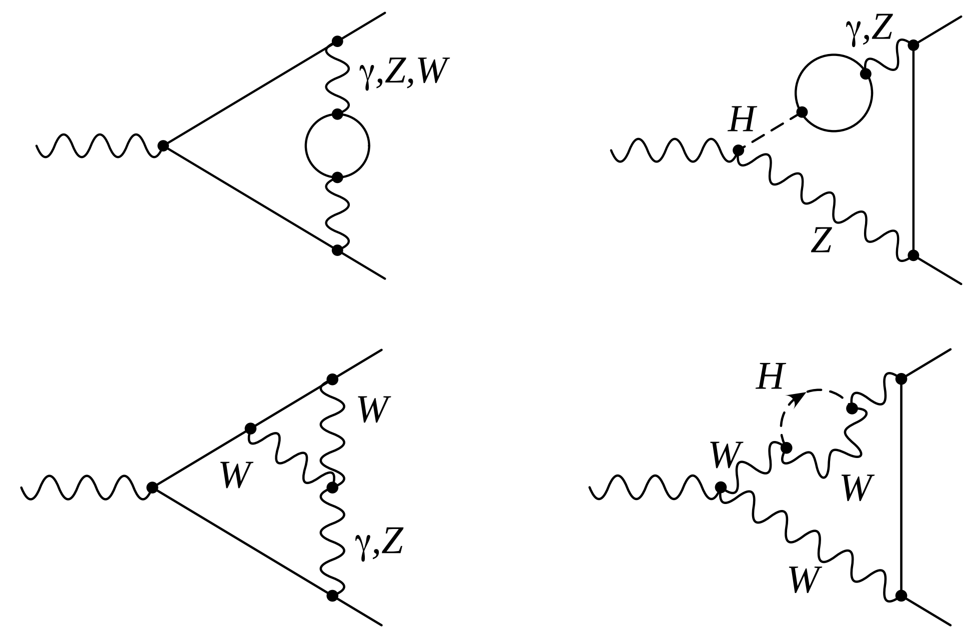
Calculation of $\sin^2(\theta^l_{eff})$

- Effective mixing angle:

$$\sin^2\theta^{\text{lept}}_{\text{eff}} = \left(1 - M_W^2/M_Z^2\right)(1+\Delta\kappa)$$

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

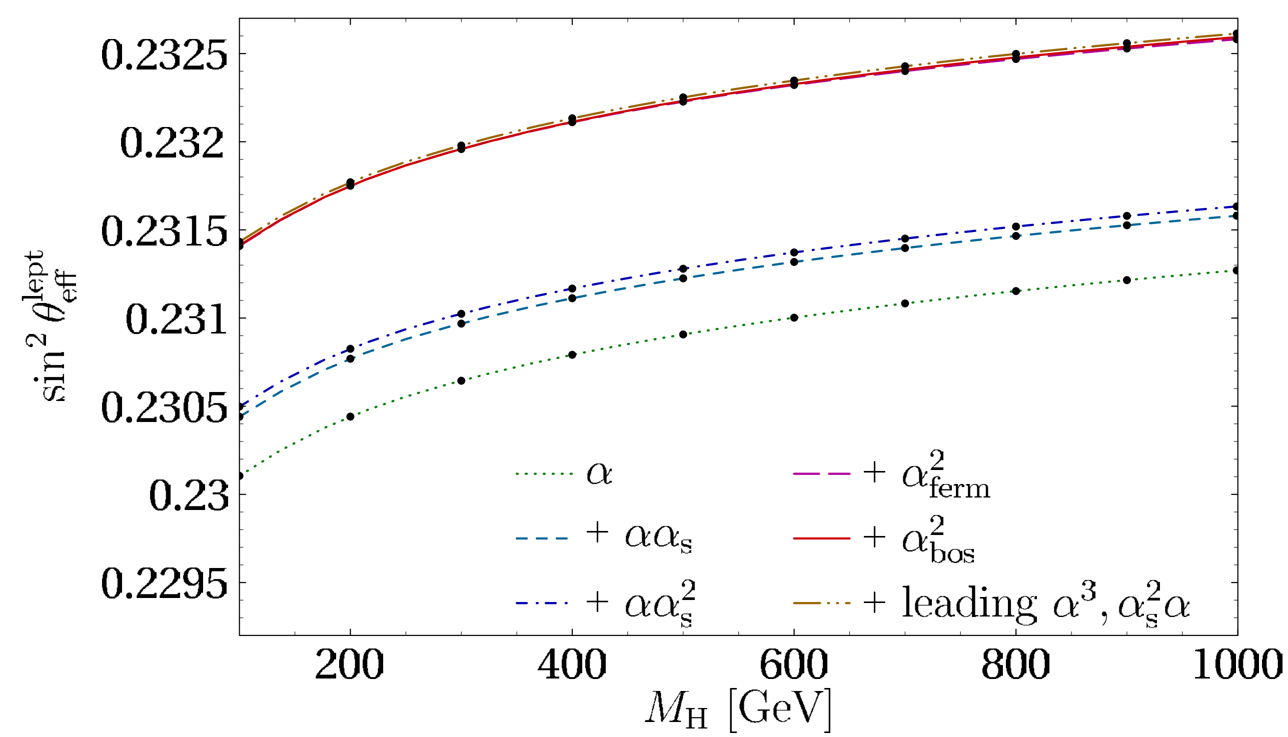
[M Awramik et al., JHEP 11, 048 (2006)]



- 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:

$$\mathcal{O}(\alpha^2\alpha_s) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_s).$$

$\mathcal{O}(\alpha^2\alpha_s)$ beyond leading m_t^4	$3.3\ldots2.8\times10^{-5}$
$\mathcal{O}(\alpha\alpha_s^3)$	$1.5\ldots1.4$
$\mathcal{O}(\alpha^3)$ beyond leading m_t^6	$2.5\ldots3.5$



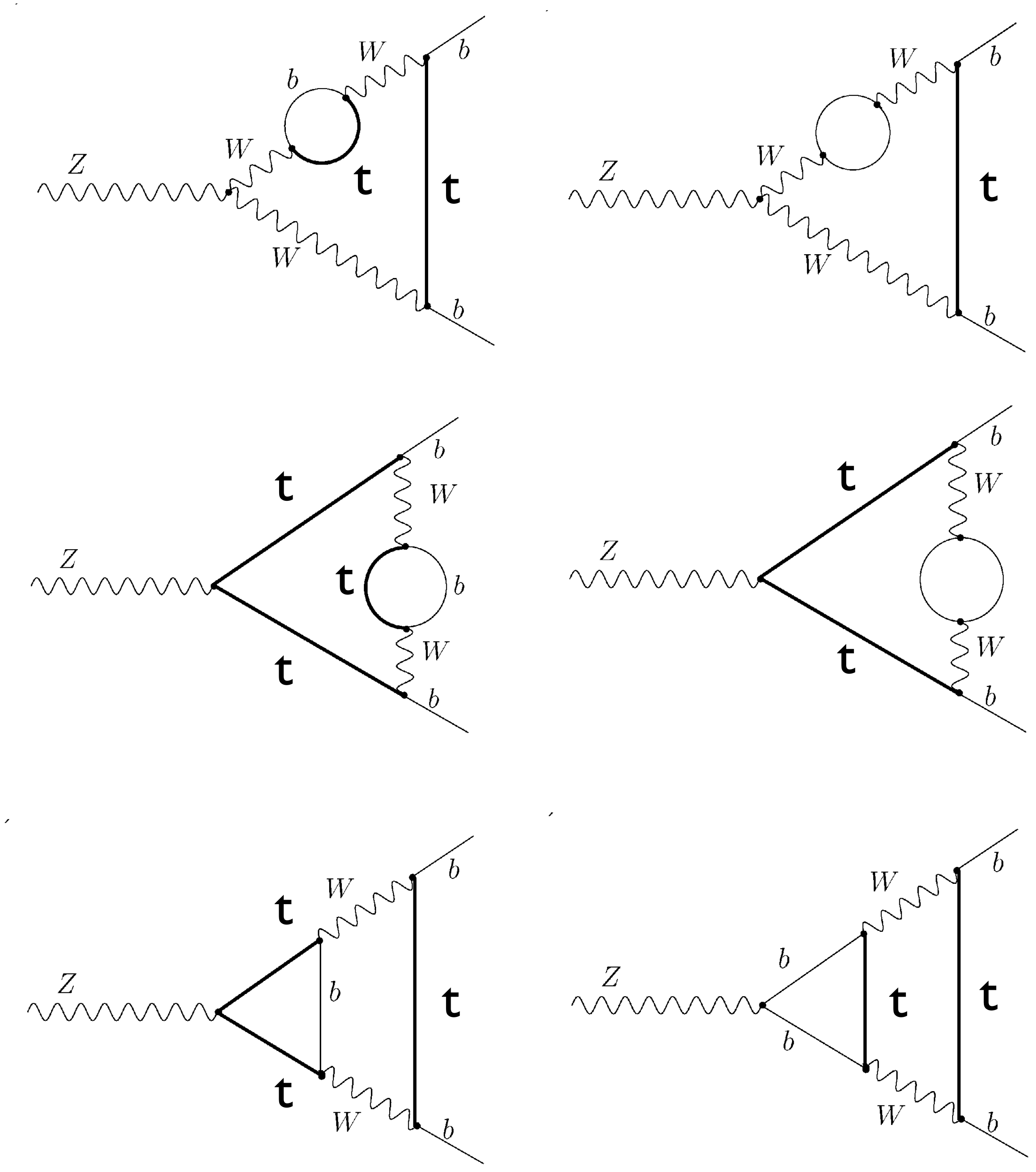
Total: $\delta\sin^2\theta^l_{eff} \approx 4.7\ 10^{-5}$

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

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

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

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



Calculation of R^0_b

Full two-loop calculation of $Z \rightarrow b\bar{b}$ [A. Freitas et al., JHEP 1208, 050 (2012) Erratum ibid. 1305 (2013) 074]

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

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

- Contribution of same terms as in the calculation of $\sin^2\theta^{bb}_{\rm eff}$
  → 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
$M_{\rm H}$ [GeV]	$\mathcal{O}(\alpha) + {\rm FSR}_{\alpha,\alpha_{\rm s},\alpha_{\rm s}^2}$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\rm ferm})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\rm ferm}) + {\rm FSR}_{\alpha_{\rm s}^3,\alpha\alpha_{\rm s},m_b^2\alpha_{\rm s},m_b^4}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_{\rm s}, \alpha\alpha_{\rm s}^2)$ $[10^{-4}]$
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

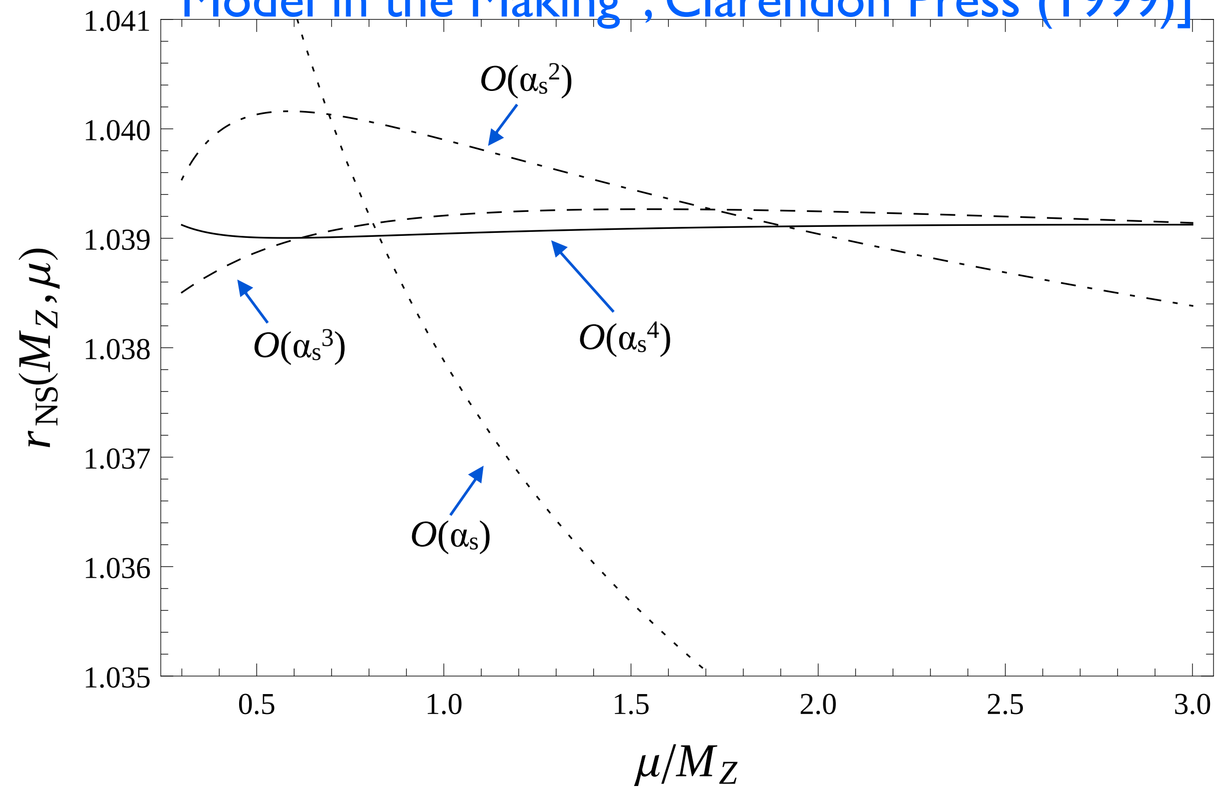
Radiator Functions

- 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