Status of the Electroweak Fit

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625. WE-Heraeus-Seminar
The High Energy LHC - Interplay between Precision Measurements and Searches for New Physics

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Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

Outline

The SM Electroweak Fit

Higgs Couplings

BSM Applications

- Two Higgs Doublet Models (2HDMs)
- Dimension-6 Operators

Some History

In 1990

- Germany celebrates the reunification
- Germany wins the World Cup

[Source: Wikipedia]

Some History

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- Germany celebrates the reunification
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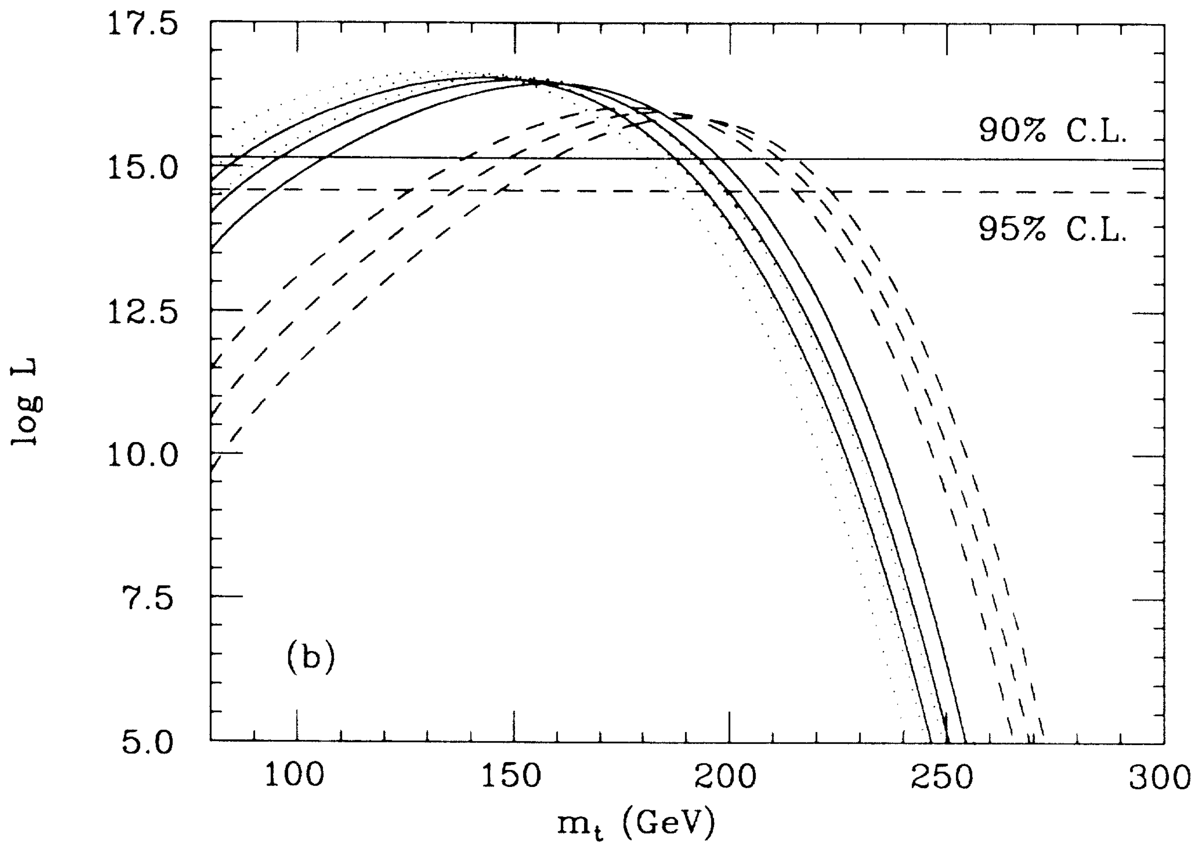
- The top mass is predicted to be

$$\boxed{m_t \sim 151^{+40}_{-50}\ \mathrm{GeV}}$$

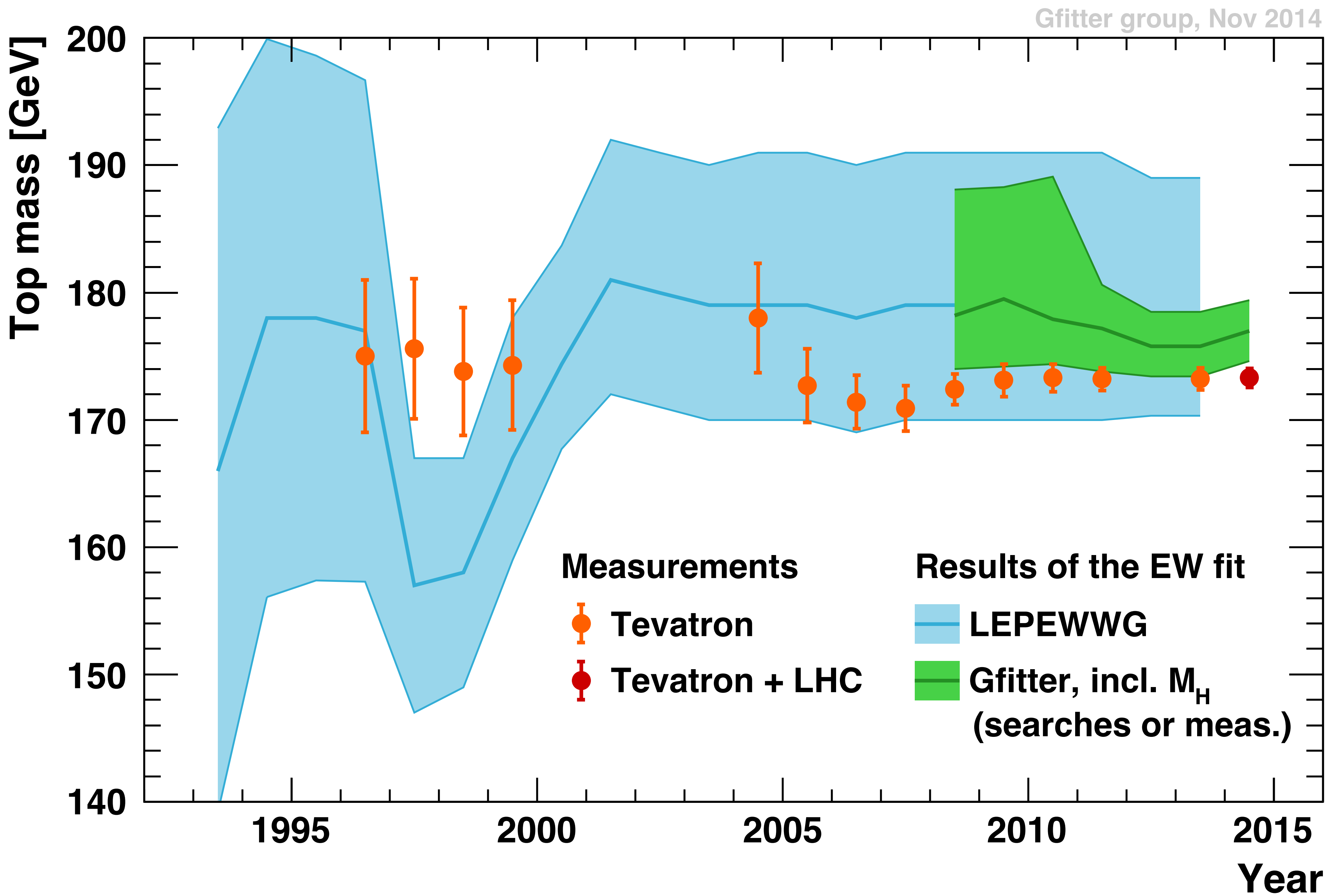
[V. Barger et al., PRL 65, 1313 (1990)]



[Source: Wikipedia]

History of the Top Quark

Discovery in 1995



How did we know the top quark mass before its discovery?

Some History

In 2011

- The Arab Spring shakes many countries of the Arabic League
- A huge earthquake and tsunami shocks Japan

[Source: Wikipedia]

Some History

In 2011

- The Arab Spring shakes many countries of the Arabic League
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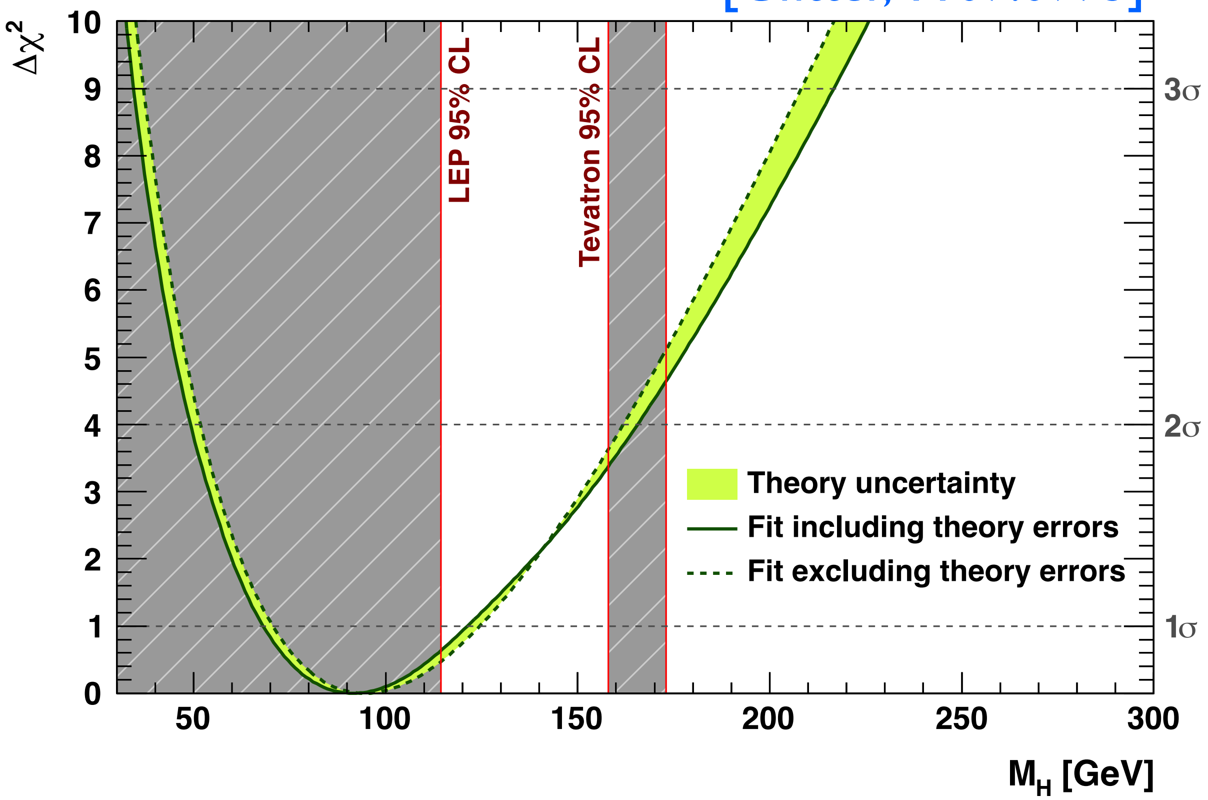
- The Higgs mass was predicted to be

$$\boxed{m_H \sim 91^{+30}_{-23}\ \text{GeV}}$$

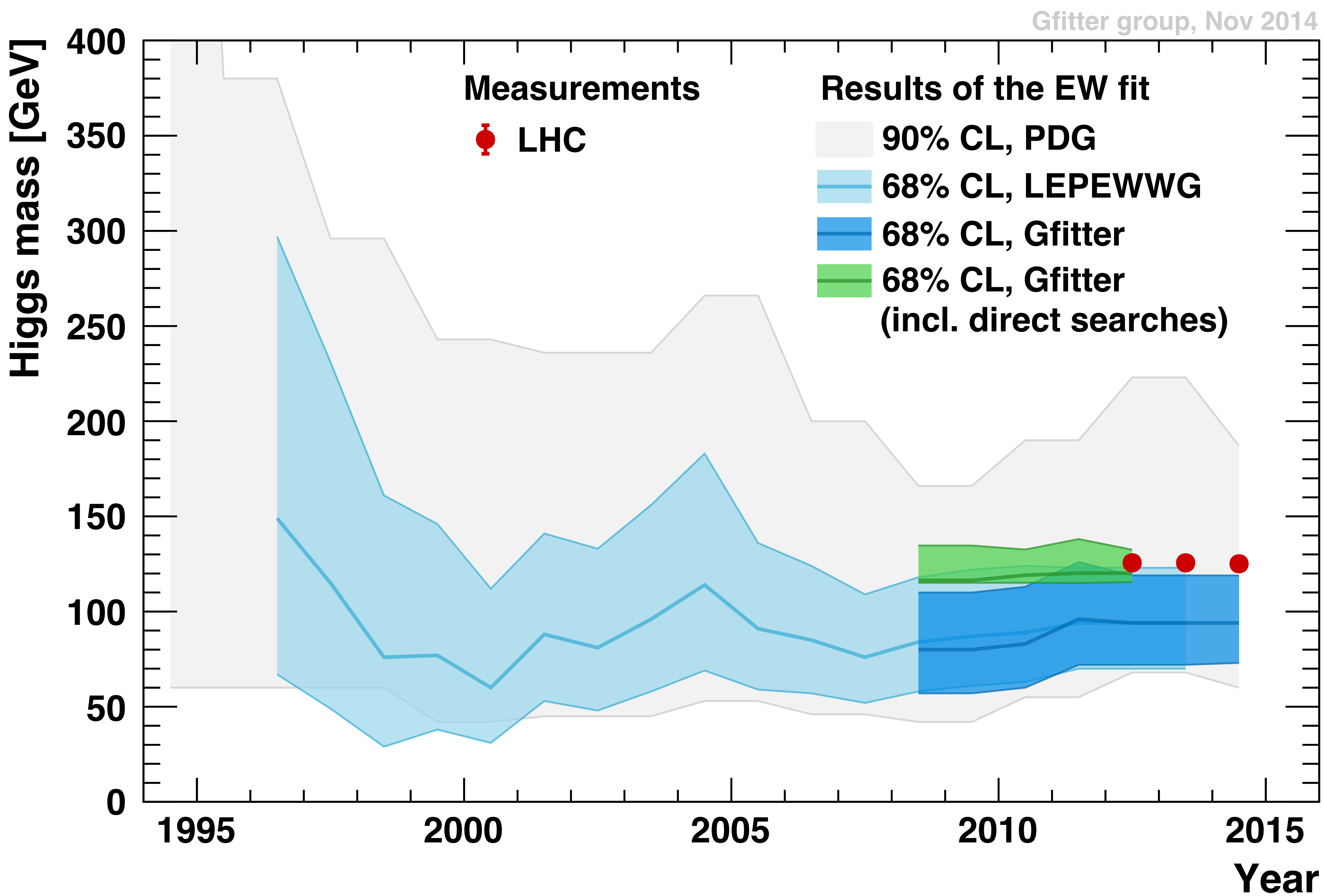
[Gfitter, 1107.0975]



[Source: Wikipedia]

History of the Higgs Boson

Discovery in 2012



How did we know the Higgs boson mass before its discovery?

How Did We Know?

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 : $\Delta M_Z/M_Z = 2\times10^{-5}$

Make predictions using α, G_F and M_Z

- measure more than the minimal set of parameters to test the theory

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

Let's Try It Out!

Prediction of M_W

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

- M_W (theo) = 79.794 ± 0.004 GeV
  - includes $\alpha(M_Z)^{-1}$ = 127.944 ± 0.017
  - uncertainty from input parameter uncertainties (parametric)

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Prediction of A_ℓ

$$A_\ell = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{\left(\frac{1}{2} - s^2\right)^2 - s^4}{\left(\frac{1}{2} - s^2\right)^2 + s^4}$$

$$s^2 = \sin^2\theta_W = 1 - \frac{M_W^2}{M_Z^2}$$

- A_ℓ (theo) = 0.1252 ± 0.0004
  - M_W obtained from tree-level formula (above)
  - parametric uncertainties small

Let's Try It Out!

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What went wrong?

How do m_t and M_H come into play?

Prediction

$$A_\ell = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R} = \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2} = \frac{\left(\frac{1}{2} - s^2\right)^2 - s^4}{\left(\frac{1}{2} - s^2\right)^2 + s^4}$$

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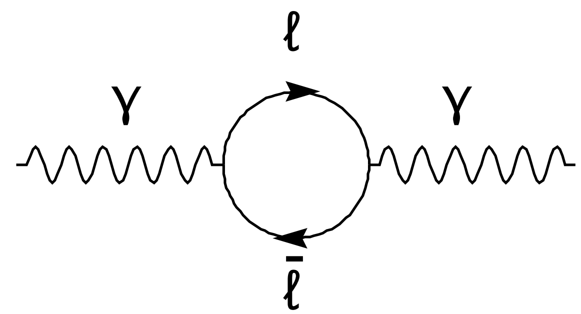
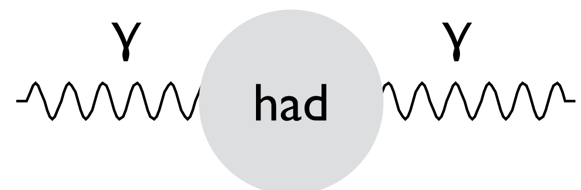
Radiative Corrections

Modifications of Propagators and Vertices

- QED corrections
  - leptonic loop insertions
    - calculable to high precision
  - quark loop insertions (hadronic)
    - partially not calculable in pure pQCD
- Weak corrections
  - Insertion of fermion loops
    - high sensitivity to m_f (if $m_f \gg m_\ell$)
  - Insertion of boson loops
    - logarithmic sensitivity to M_H
- QCD corrections
  - Sensitivity to strong coupling
    - numerically small contribution ($1 + \alpha_s/\pi$)

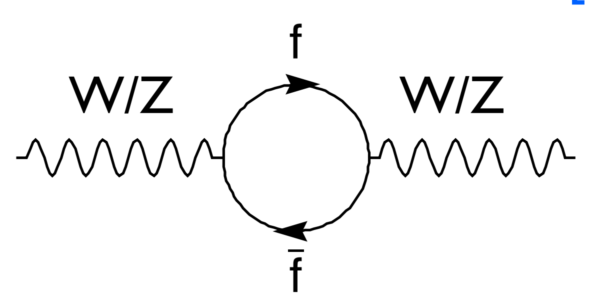


$$\propto \alpha \ln \frac{s}{m_\ell^2}$$

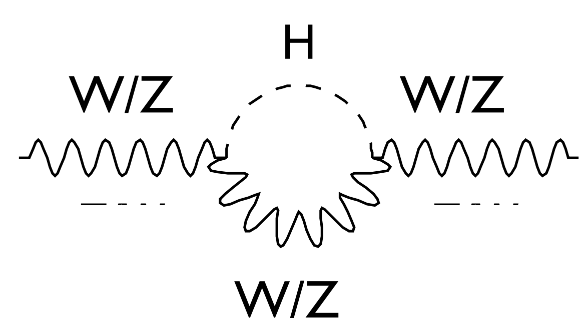


$$\propto \Delta\alpha_{\mathrm{had}}(s)$$

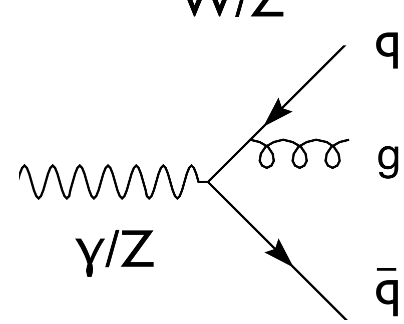
[not in Yvonne's talk]



$$\propto N_C m_f^2$$



$$\propto \ln \frac{M_H^2}{M_W^2}$$



$$\propto \alpha_s(s)$$

Electroweak Form Factors

Parametrisation of radiative corrections

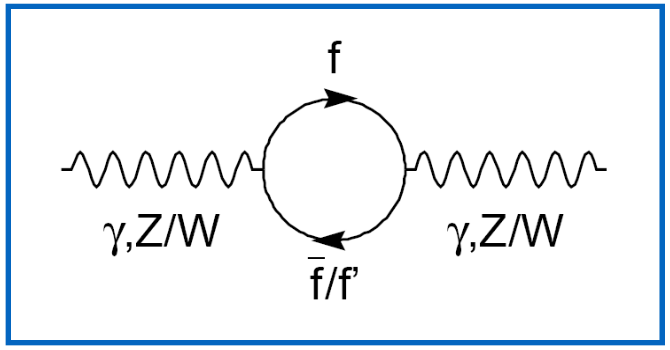
- Encode all corrections in form factors ρ, κ, Δr
- Effective couplings at the Z-pole:

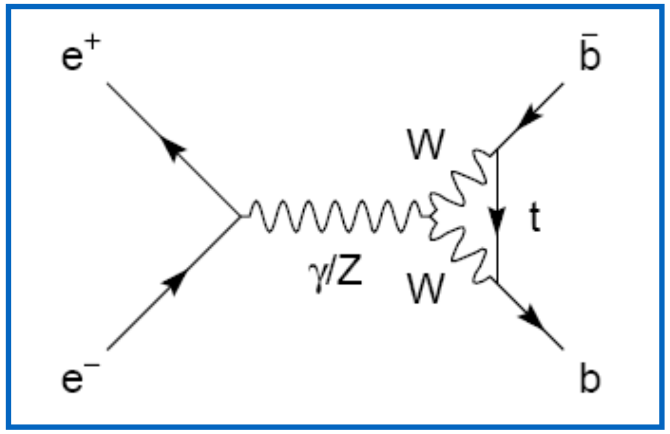
$$g_{V,f} = \sqrt{\rho_Z^f}\left(I_3^f - 2Q^f \sin^2\theta_{\rm eff}^f\right)$$

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

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

  - flavour dependence of κ for b-quarks (Wtb vertex)





- 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 take dependence of free parameters (m_t, M_H, α_s...)

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

(need to solve iteratively)

Free Parameters

EW sector

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

$$\begin{array}{rcccccc} \Delta\alpha(s) & = & \boxed{\Delta\alpha_{\mathrm{lep}}(s)} & + & \boxed{\Delta\alpha^{(5)}_{\mathrm{had}}(s)} & + & \boxed{\Delta\alpha_{\mathrm{top}}(s)} \\ \text{relative precision} & = & 1\times10^{-6} & & 2\times10^{-4} & & 1\times10^{-7} \end{array}$$

Fermion masses

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

Strong sector

- $\boxed{\alpha_s}$: can be constrained using Z-pole measurements

Higgs sector

- $\boxed{M_H}$: precision of LHC measurements is 0.3%

Measure more than minimal set to constrain the theory

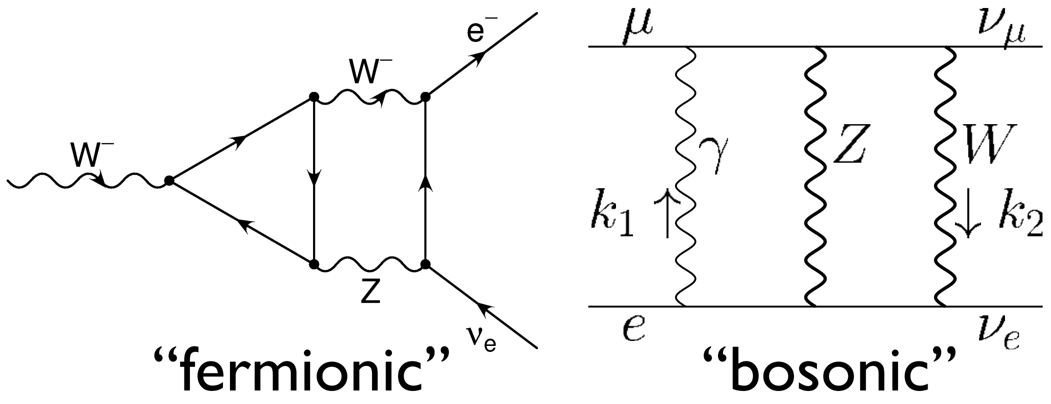
EW Fit: Experimental Input

Fit is overconstrained

- all $\boxed{\text{free parameters}}$ 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

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

Precision Calculations



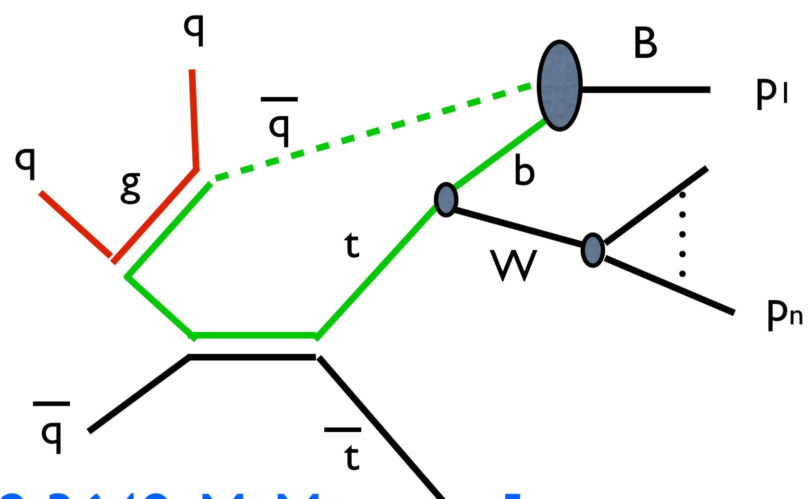
All observables calculated at 2-loop level

- **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)]
- **$\sin^2\theta^f_{eff}$** : 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)]
- **Radiator functions**: QCD corrections at N^{3}LO
  [Baikov et al., PRL 108, 222003 (2012)]
- **Γ_W** : 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, uncertainty of 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
$\sin^2\theta^l_{\rm eff}$	$1.6 \cdot 10^{-4}$	$0.5 \cdot 10^{-4}$
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\rm had}$	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

- 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)

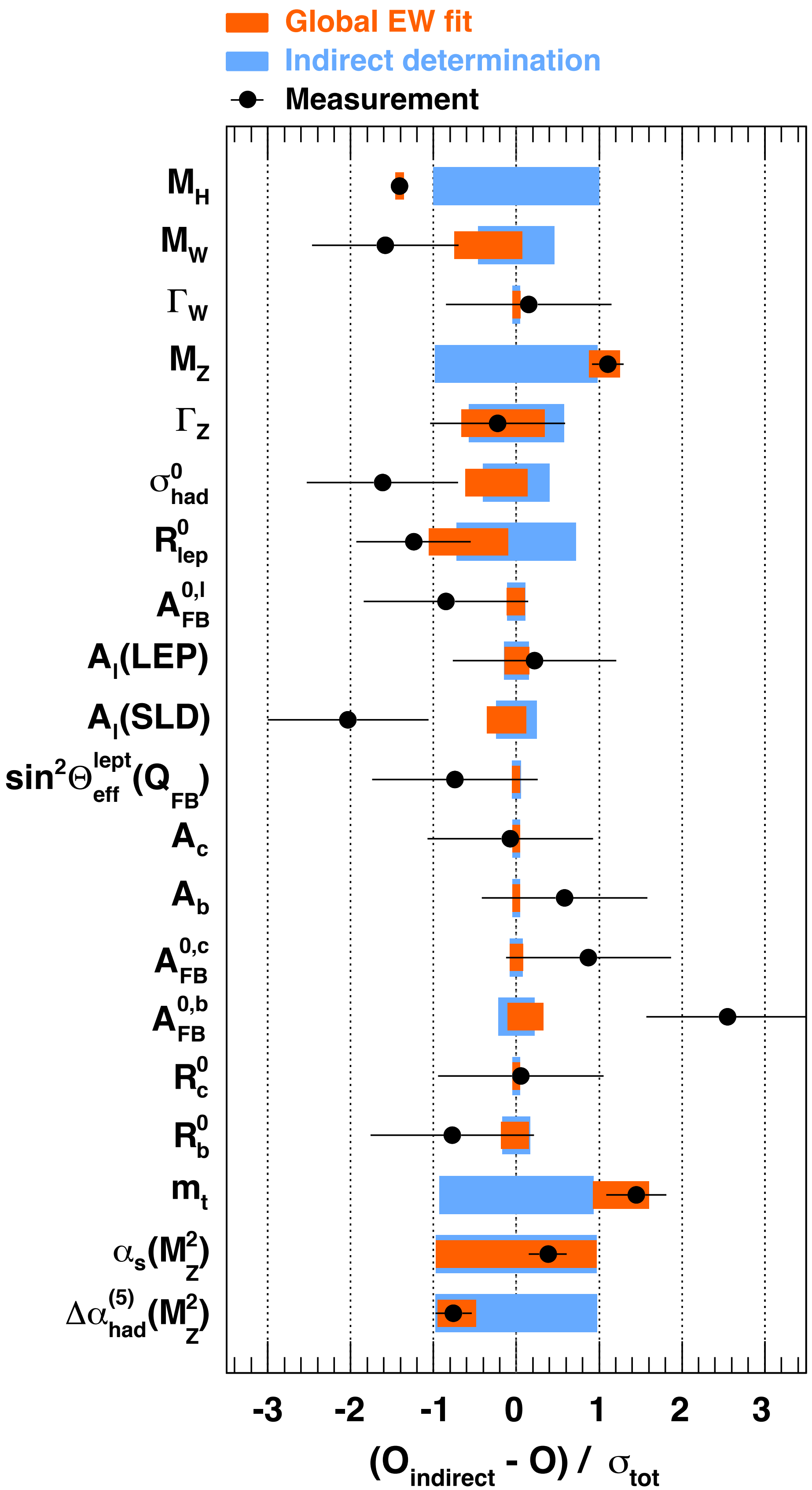
SM Fit Results

black: direct measurement (data)

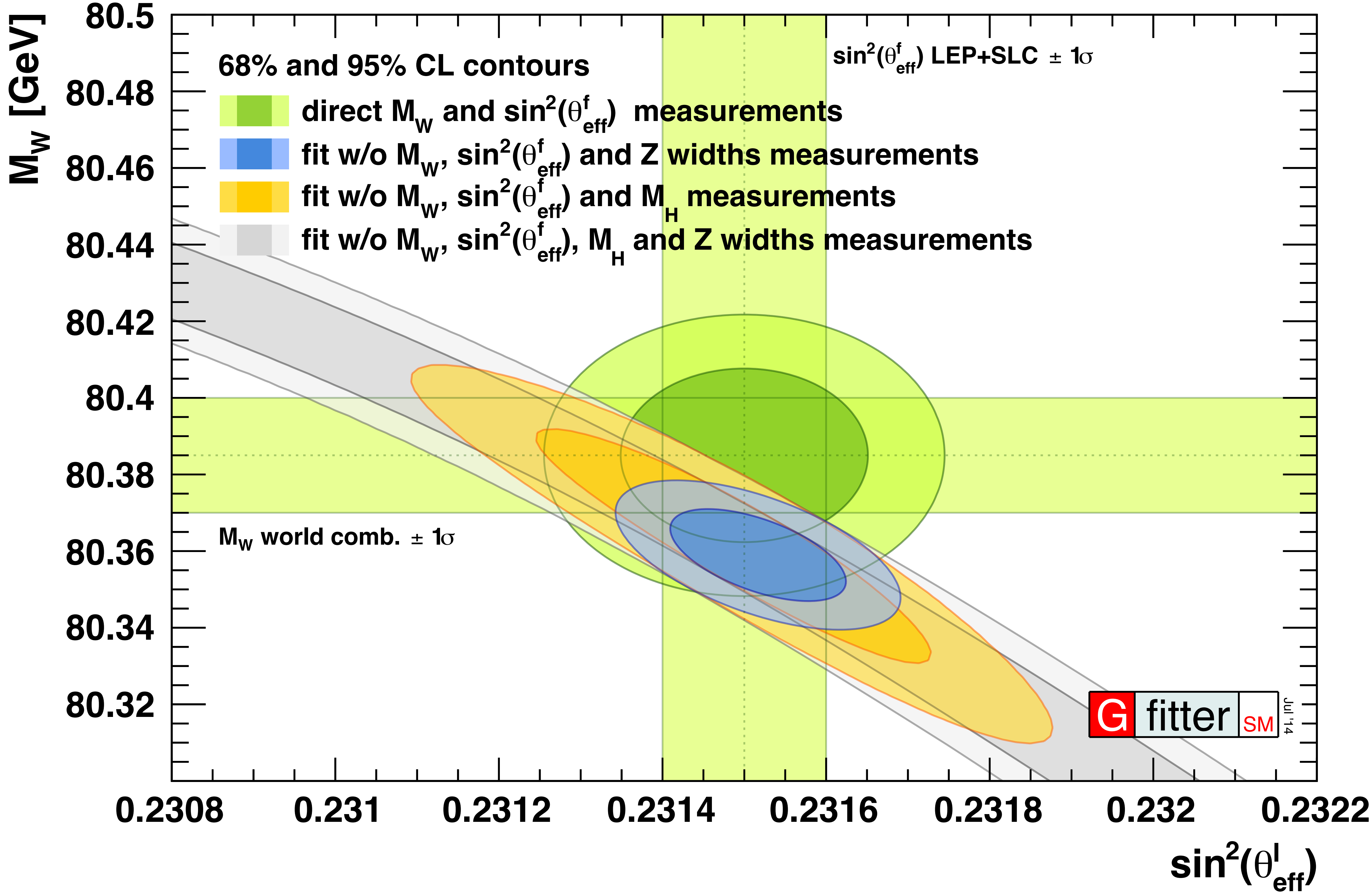
orange: full fit

light-blue: fit excluding input from row

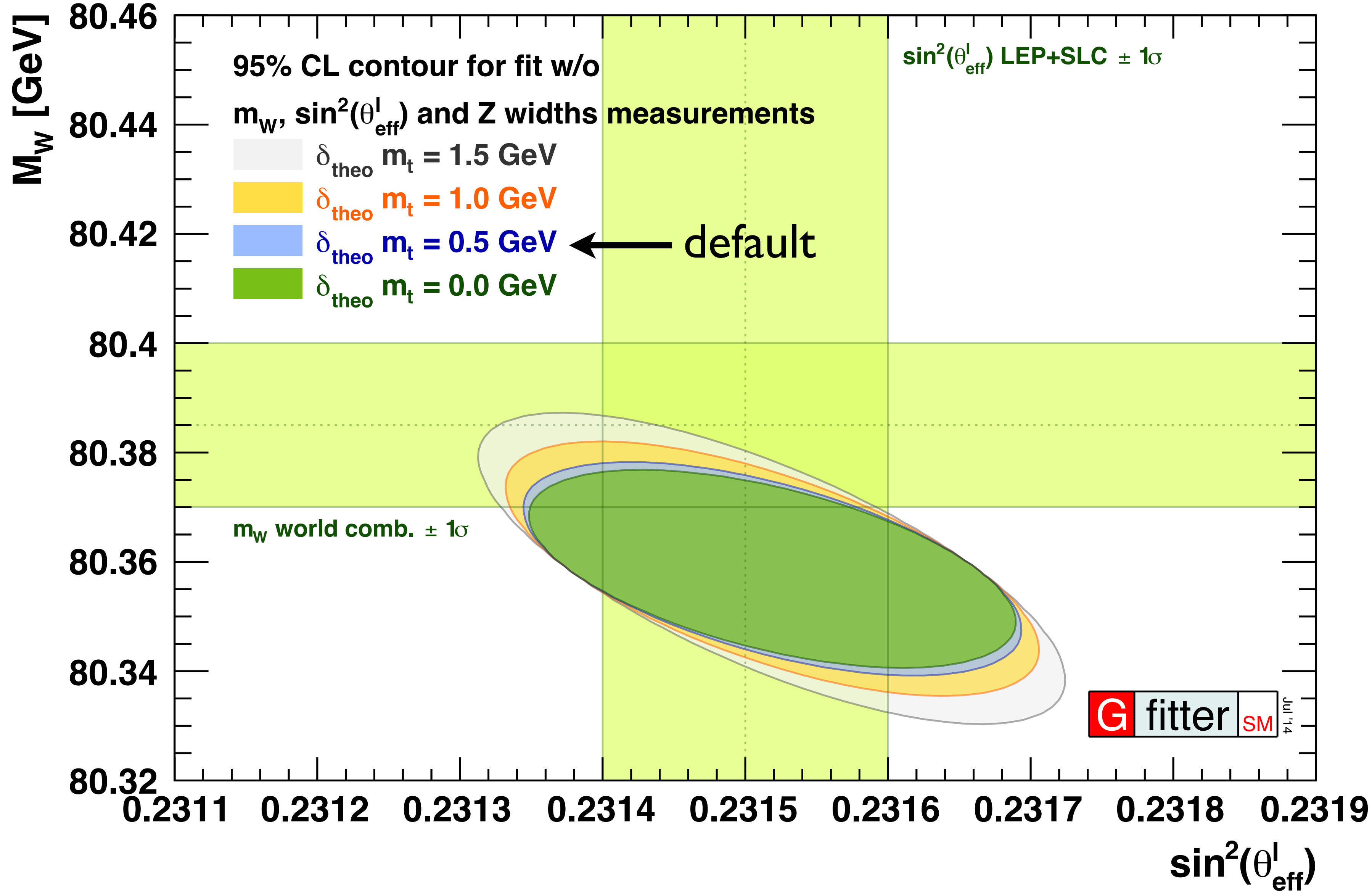
- goodness of fit, p-value:
  χ^2_{min}= 17.8 Prob(χ^2_{min}, 14) = 21%
  Pseudo experiments: 21 ± 2 (theo)%
  - χ^2_{min}(Γ_i in 1-loop) = 18.0
  - χ^2_{min}(no theory uncertainties) = 18.2
- no individual value exceeds 3σ
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ
    → largest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



State of the Standard Model



Theoretical uncertainty on m_t



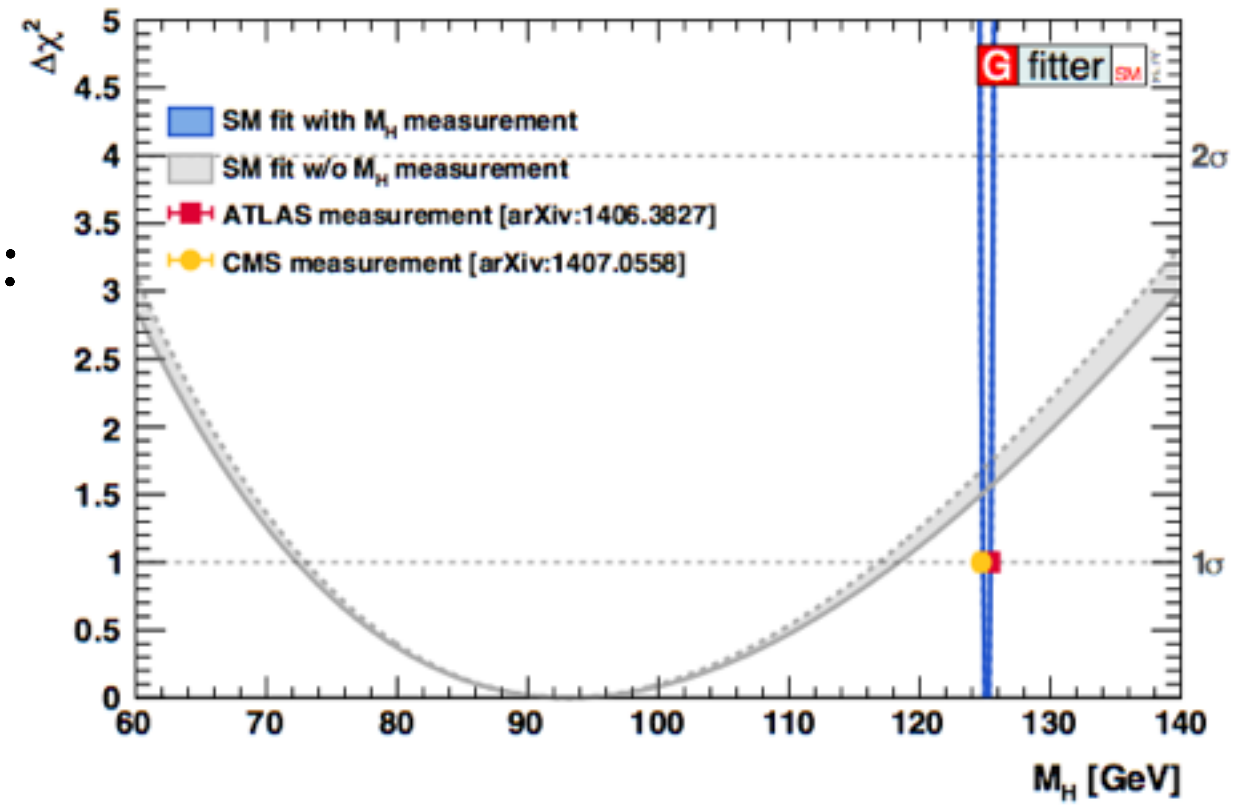
impact of variation in δ_{theo} m_t between 0 and 1.5 GeV

- better assessment of uncertainty on m_t important
- uncertainty of 0.5 GeV currently small impact on result

Higgs Mass from the EW Fit

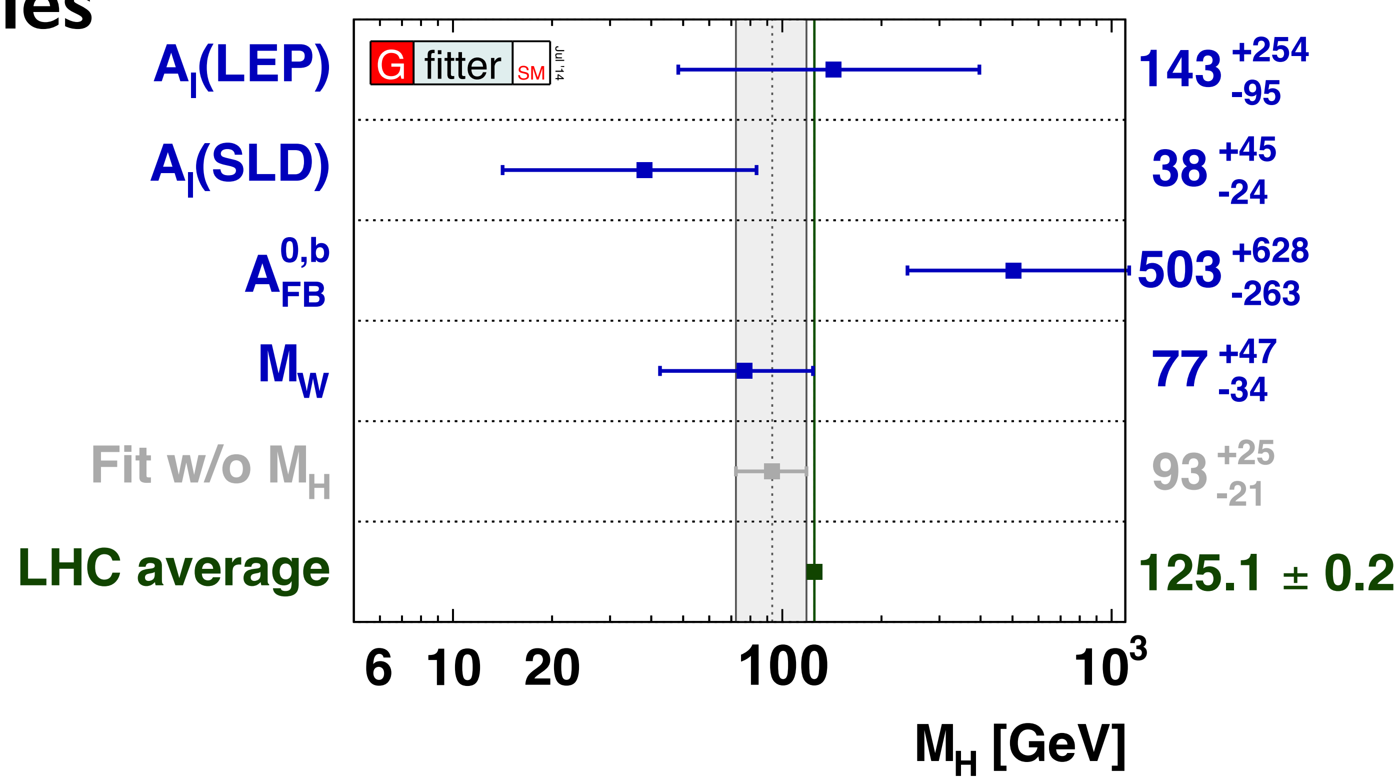
EW Constraints on M_H

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

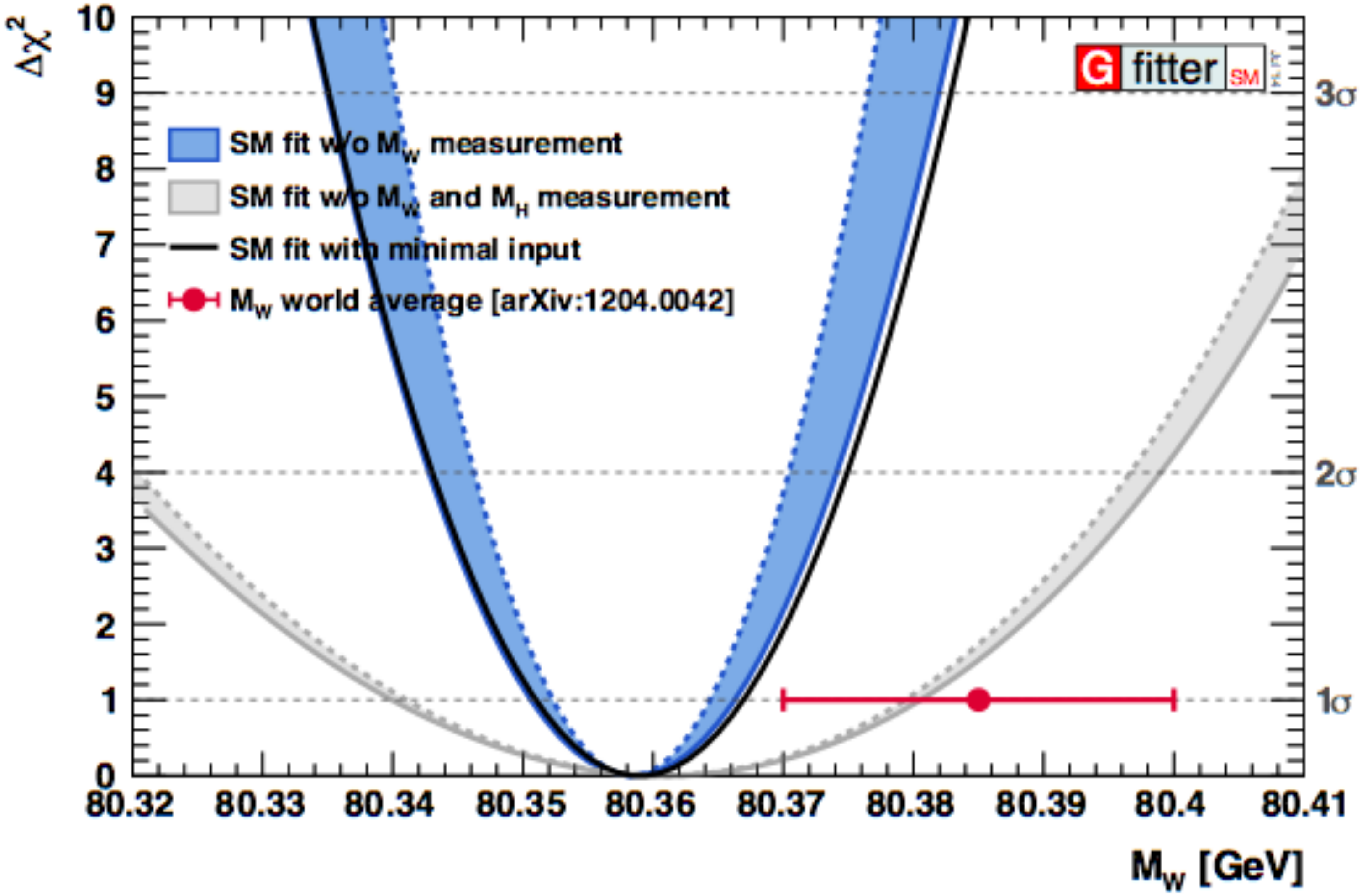


Impact of most sensitive observables

- 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



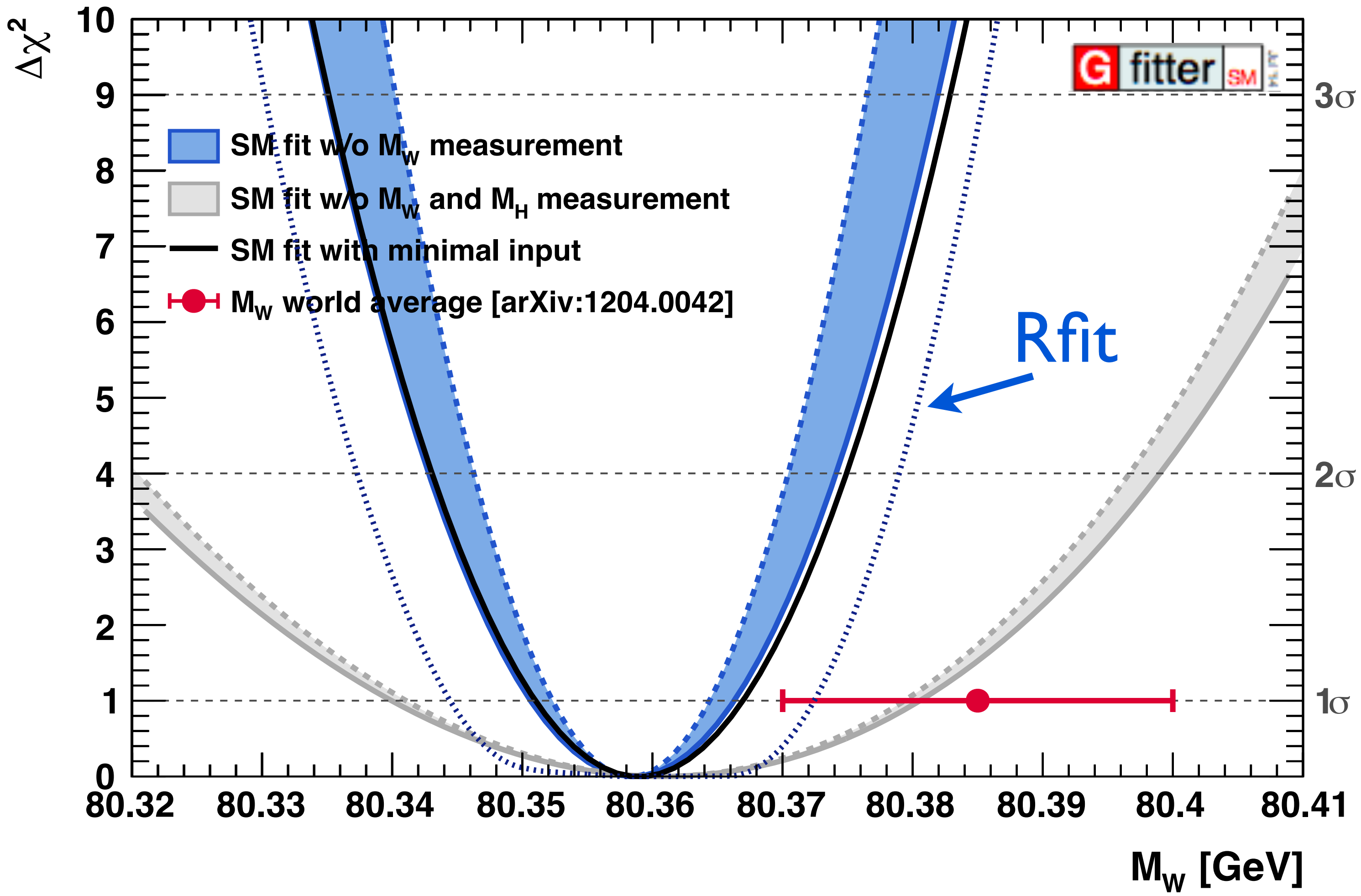
Indirect determination of M_W



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

more precise than direct measurement (15 MeV)

Indirect determination of M_W



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

(δm_t (1 GeV): ±9 MeV, Rfit: ±13 MeV)

more precise than direct measurement (15 MeV)

Precision Test of the SM Using M_W

warning:
personal guesses

Dominant uncertainties for indirect constraints

- **4.6 MeV: m_t exp**
  - large progress [Yvonne's talk] — LHC Run 2/3, O(5) years
- **4.0 MeV: Calculations, theo**
  - three-loop EW and mixed two-loop EW/QCD — O(10) years
- **3.0 MeV: m_t theo**
  - connection between m_t(MC) and m_t(pole) — O(5) years
- **2.6 MeV: M_Z exp**
  - improvement with ILC/GigaZ — O(30) years
- **2.0 MeV: α_s exp / theo**
  - understanding measurements / lattice calculations — O(5) years
- **1.8 MeV: $\Delta\alpha_{had}$ exp / theo**
  - measurements at low energy e^+e^- machines (charm)
    higher order pQCD calculations — O(10) years

Precision Test of the SM Using M_W

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- **4.0 MeV: Calculations, theo**
  - three- …) years
- **3.0 Me…**
  - conne…) years
- **2.6 Me…**
  - impro…) years

Expect significant improvements within next 5-10 years!
Note: about same time as experimental results for M_W measurements

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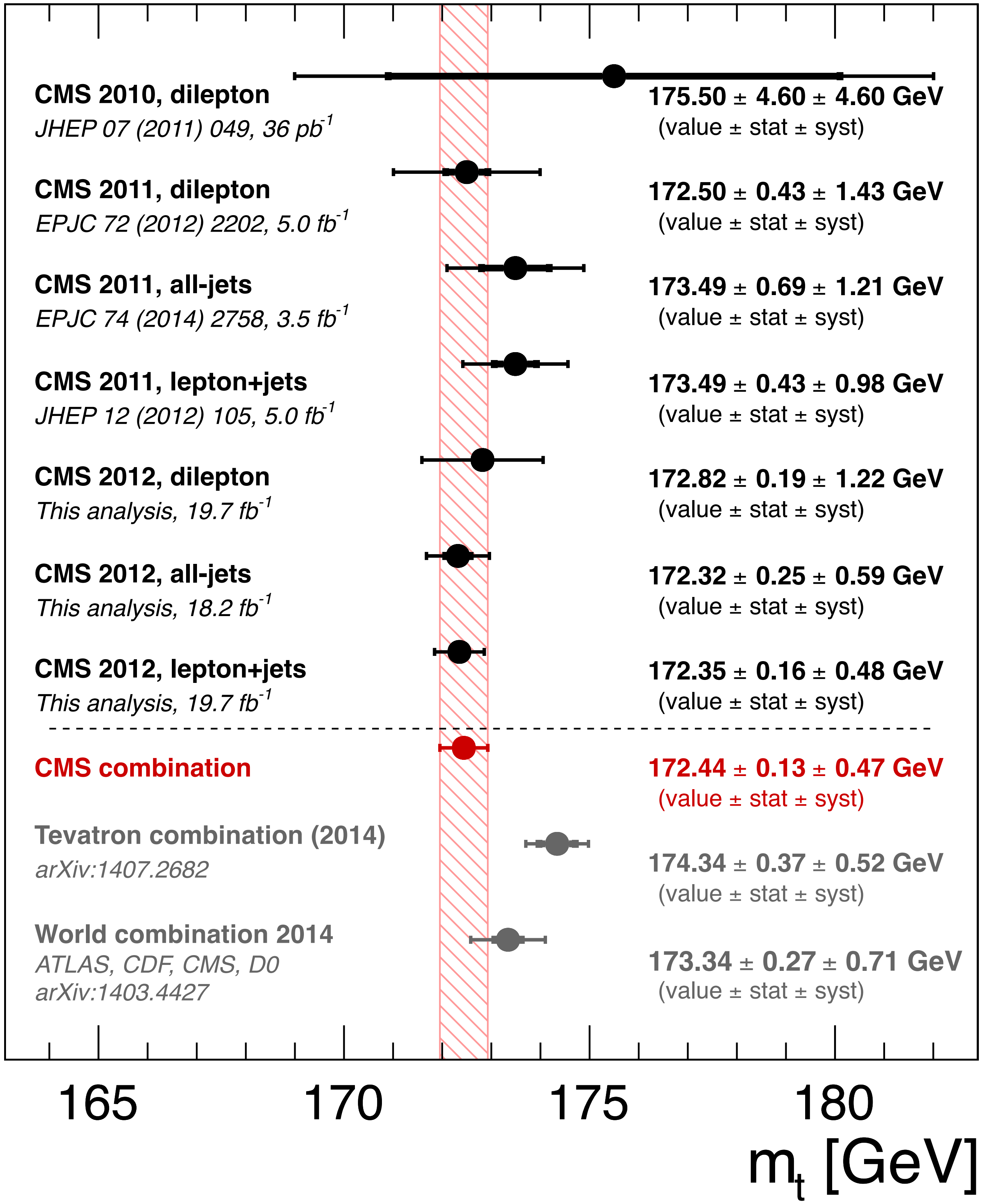
  - understanding measurements / lattice calculations — O(5) years
- **1.8 MeV: $\Delta\alpha_{had}$ exp / theo**
  - measurements at low energy e^+e^- machines (charm)
    higher order pQCD calculations — O(10) years

Top Mass: Experimental Status

CMS →

Tevatron →

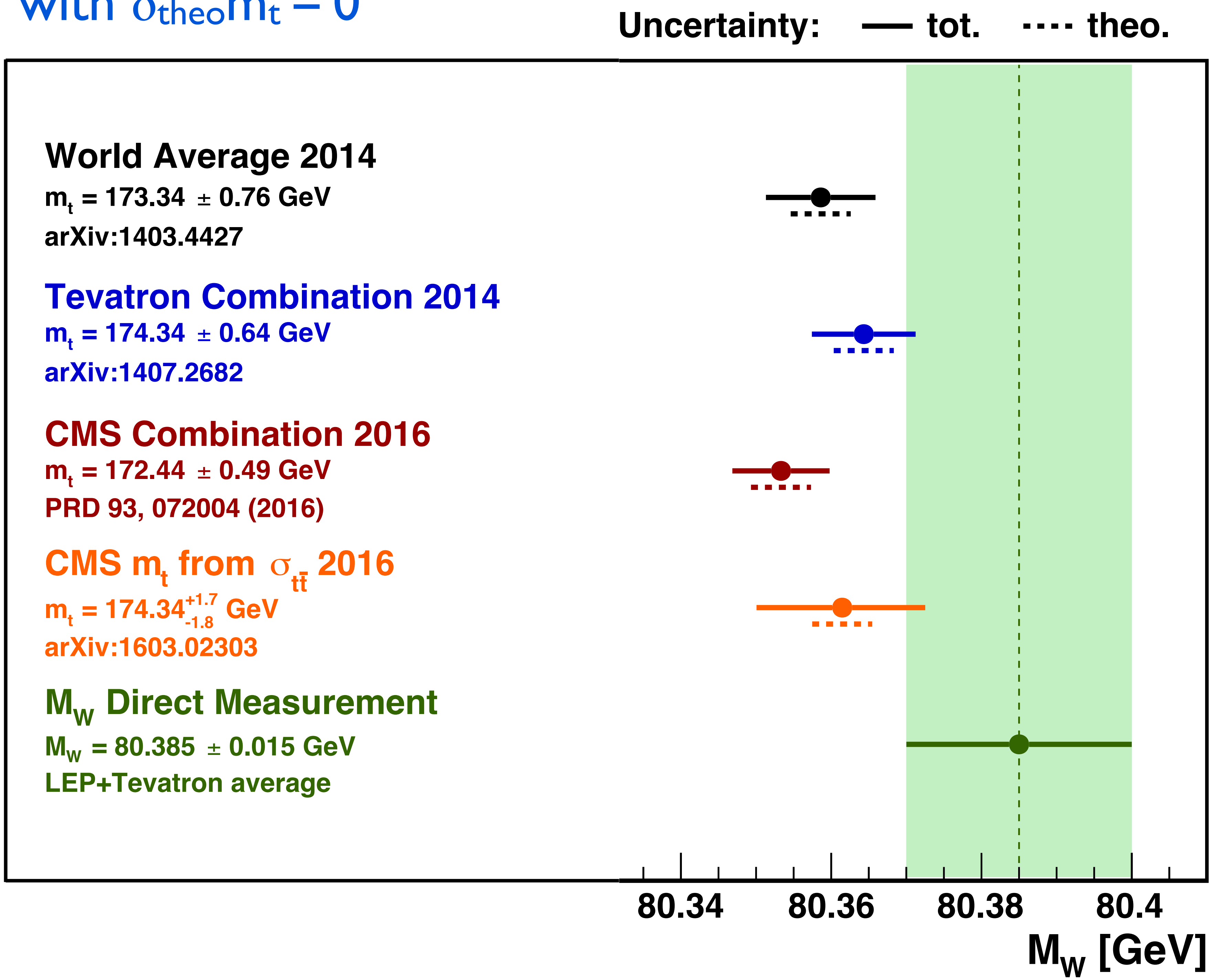
WA →



…we know m_t(MC) pretty precisely

Impact of m_t Measurements

Direct m_t measurements
with $\delta_{theo} m_t = 0$



- Difference of $M_W(m_t = \text{Tev})$ and $M_W(m_t = \text{CMS})$: **11 MeV!**
- Uncertainty from indirect constraint: 8 MeV
- Essential to understand the difference!

[A. Hoang, I. Stewart et al.]

Top Mass: Theoretical Status

Calibrating m_t(MC): Relationship between MSR mass and m_t(MC)

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{MSR}}(R = 1\ \mathrm{GeV}) + \Delta_{t,\mathrm{MC}}(R = 1\ \mathrm{GeV})$$

$$\Delta_{t,\mathrm{MC}}(1\ \mathrm{GeV}) = \bar{\Delta} + \delta\Delta_{\mathrm{MC}} + \delta\Delta_{\mathrm{pQCD}} + \delta\Delta_{\mathrm{param}}$$

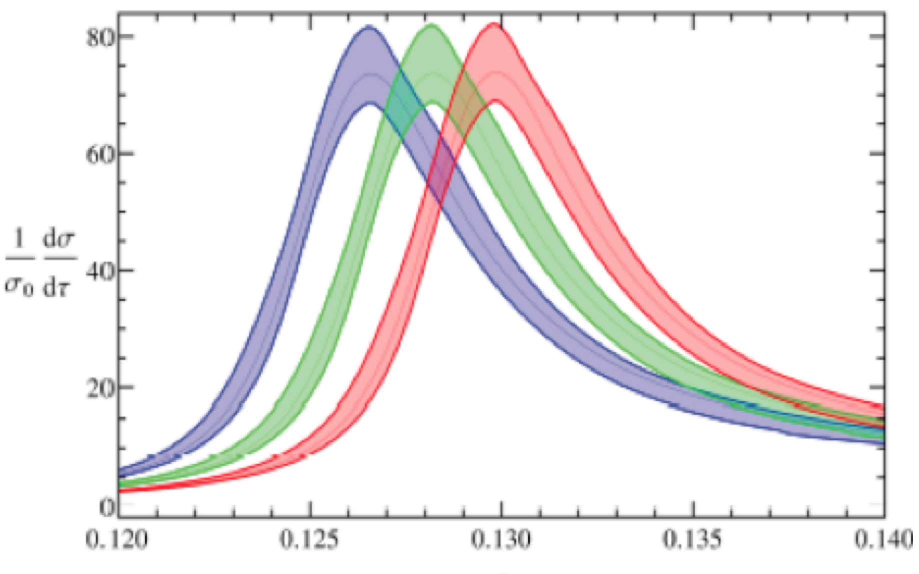
- strong coupling α_s
- Non-perturbative parameters

- different tunings
- parton showers
- color reconnection
- …

- perturbative error
- scale uncertainties
- electroweak effects

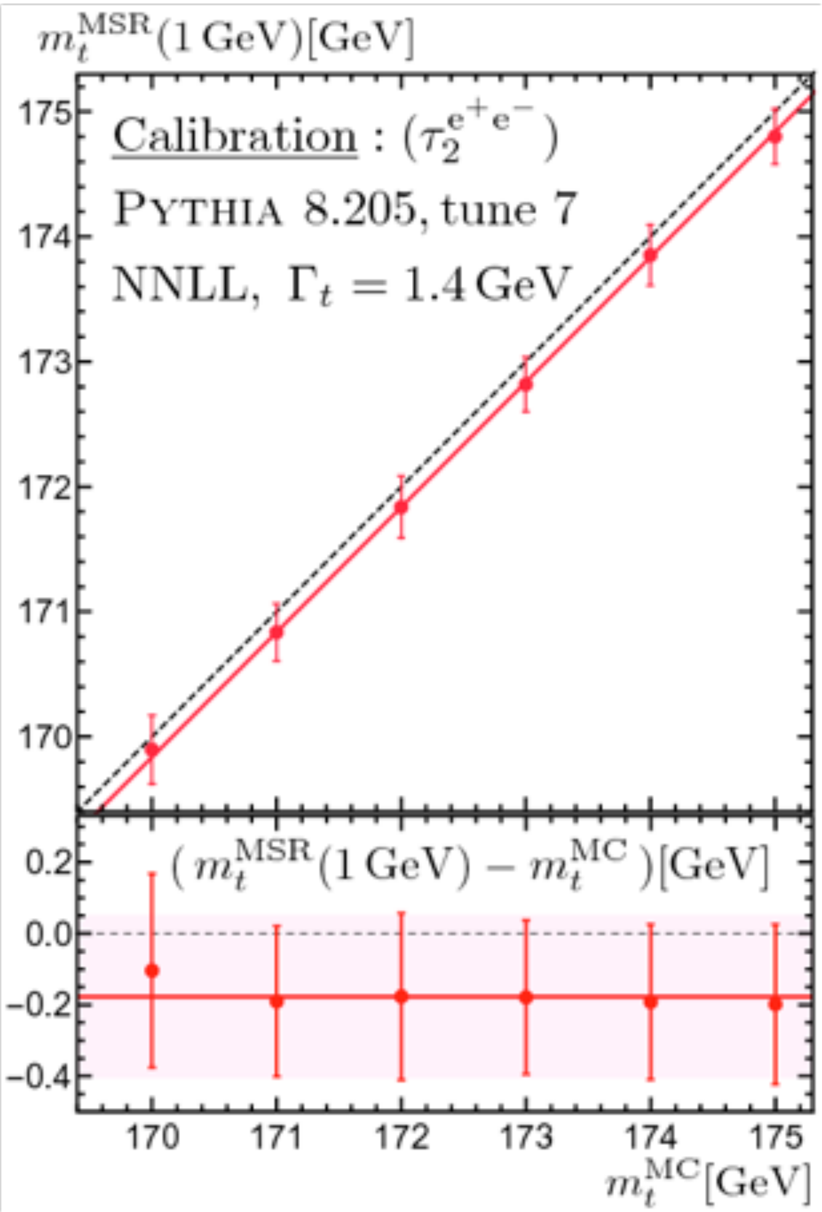
2-Jettiness for top production

Q=700 GeV



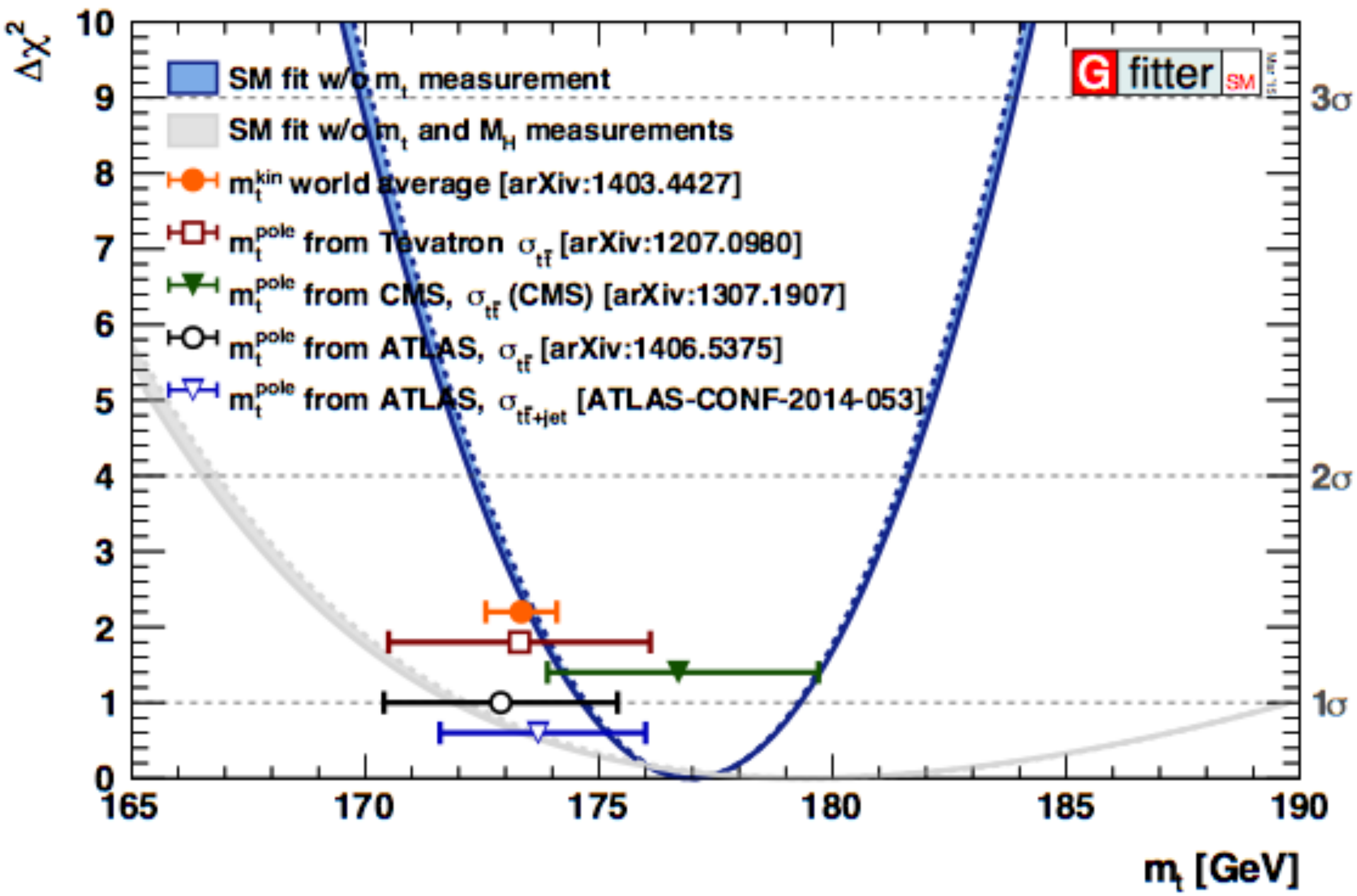
Fit Pythia ‘data’ with NNLL+NLO QCD calculations

[M. Butenscheon et al., arXiv:1608.01318]



Indirect determination of m_t

- m_t from Z-pole data (fully obtained from rad. corrections $\sim m_t^2$)

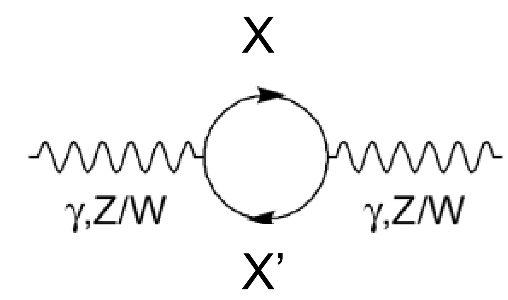


$$m_t = 177.0 \pm \boxed{2.3_{M_W,\, \sin^2\theta^f_{\mathrm{eff}}}} \pm 0.6_{\alpha_s} \pm 0.5_{\Delta\alpha_{\mathrm{had}}} \pm 0.4_{M_Z}\ \mathrm{GeV}$$

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

BSM: Oblique Corrections

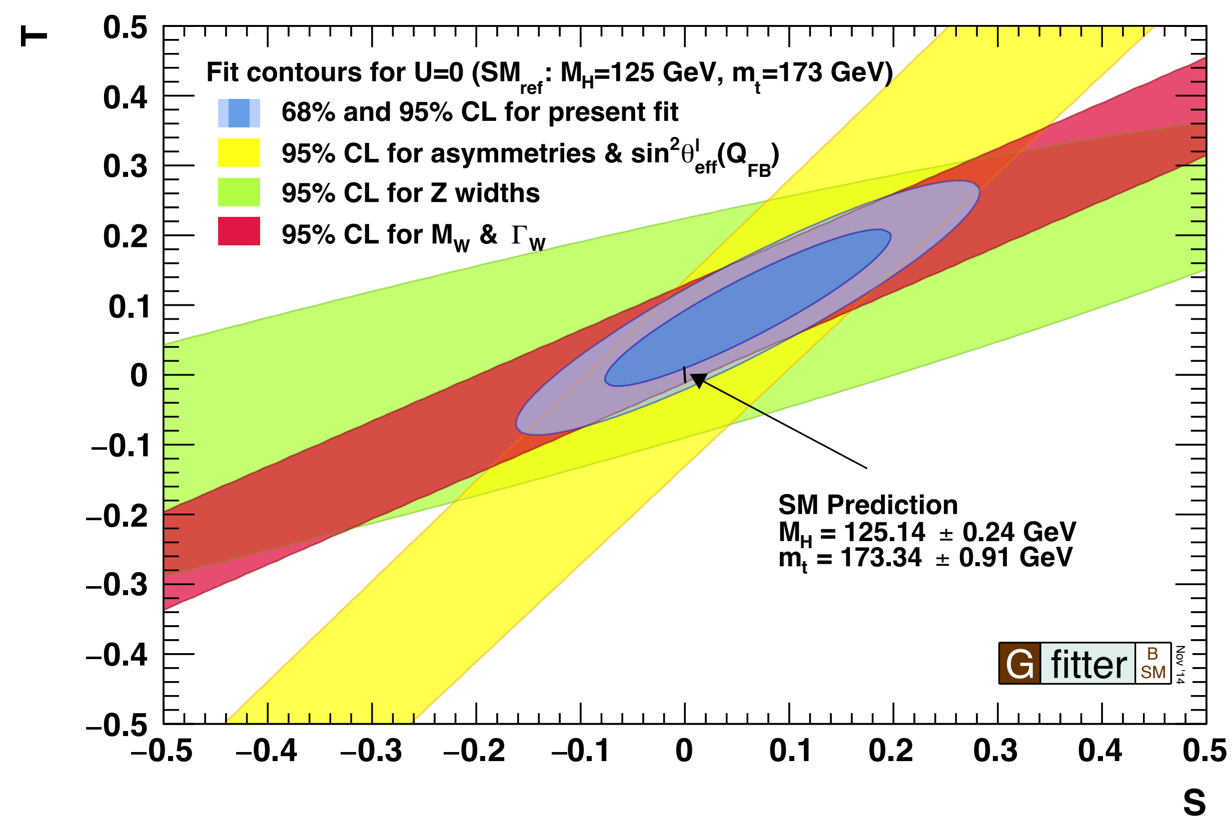
- If energy scale of NP is high, BSM physics could appear dominantly through vacuum polarisation corrections



- 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 M_H
- 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:

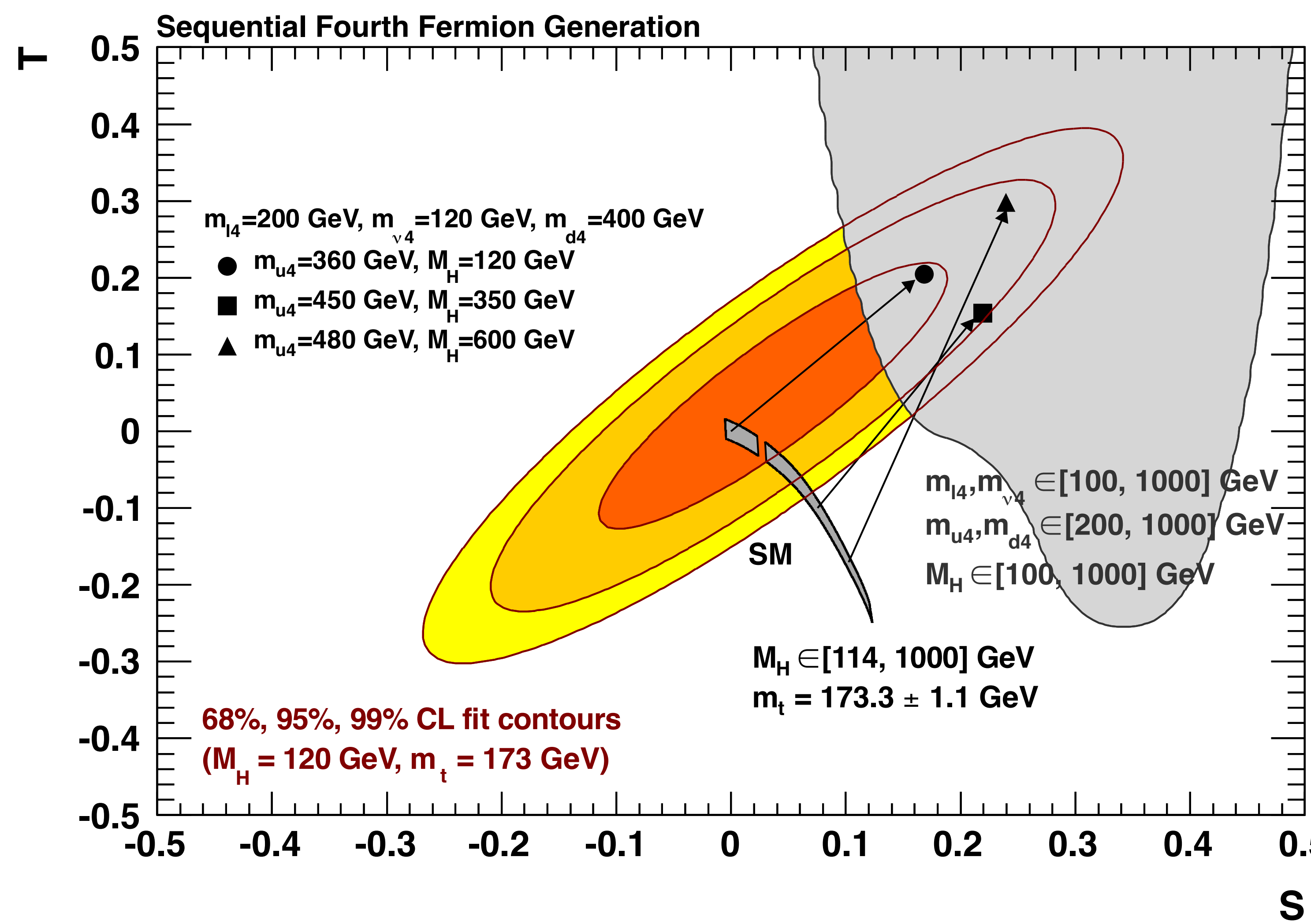


- No indication for new physics
- Use this to constrain parameter space in BSM models

Higgs Couplings

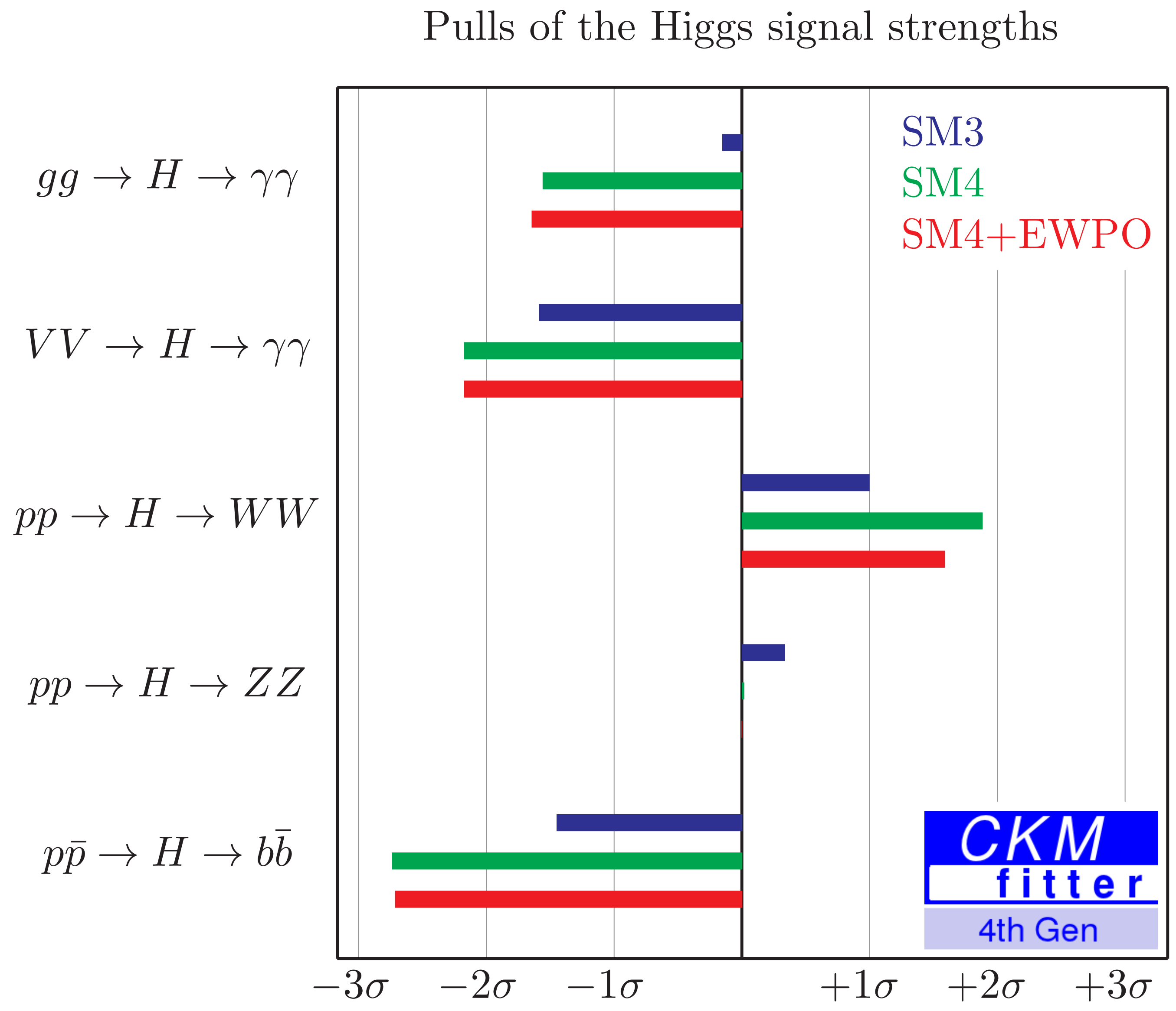
Constraints on Sequential 4th Generation

- 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



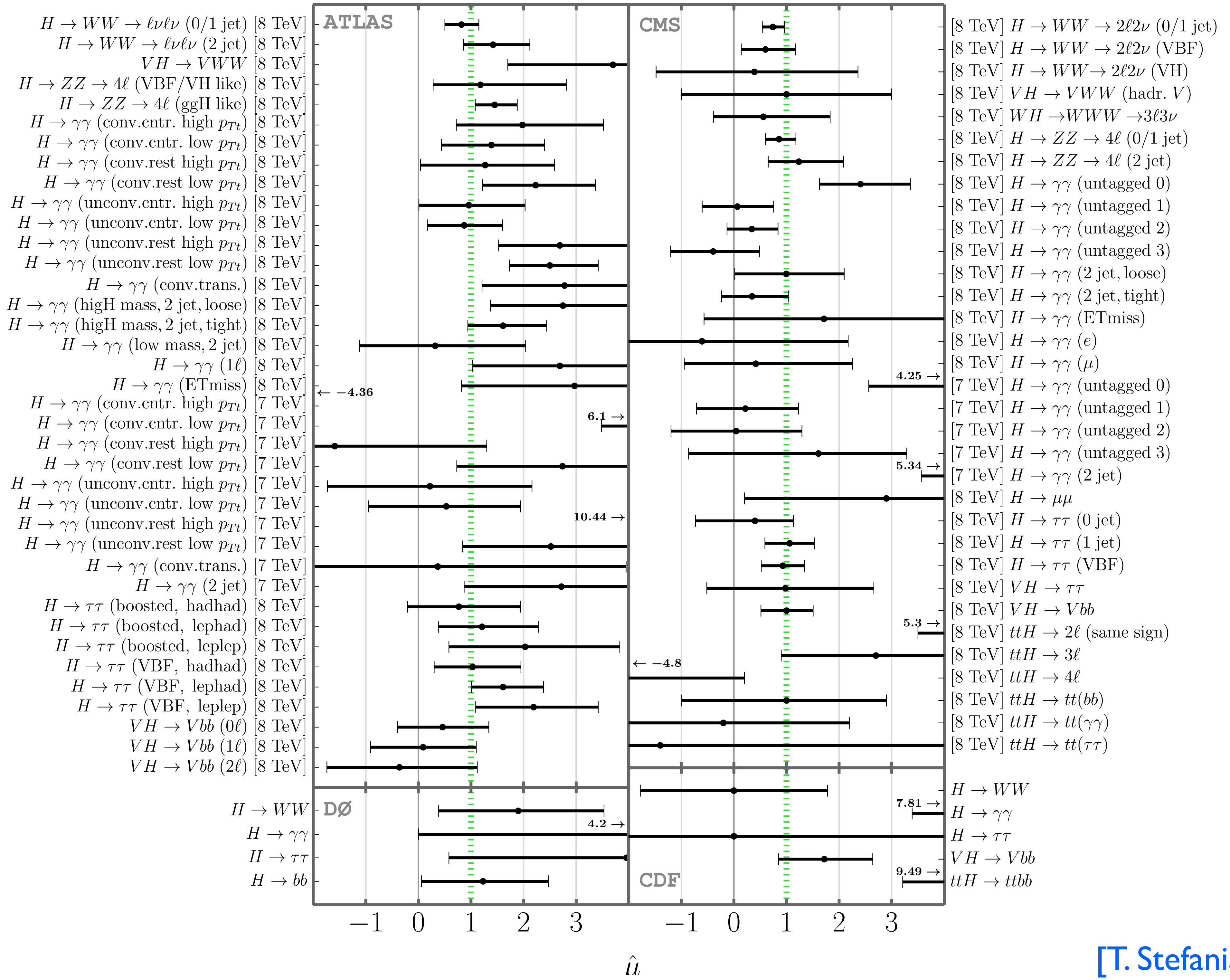
Constraints on Sequential 4^{th} Generation

- 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



Higgs Measurements Included

in total: 80 signal rate + 4 mass measurements

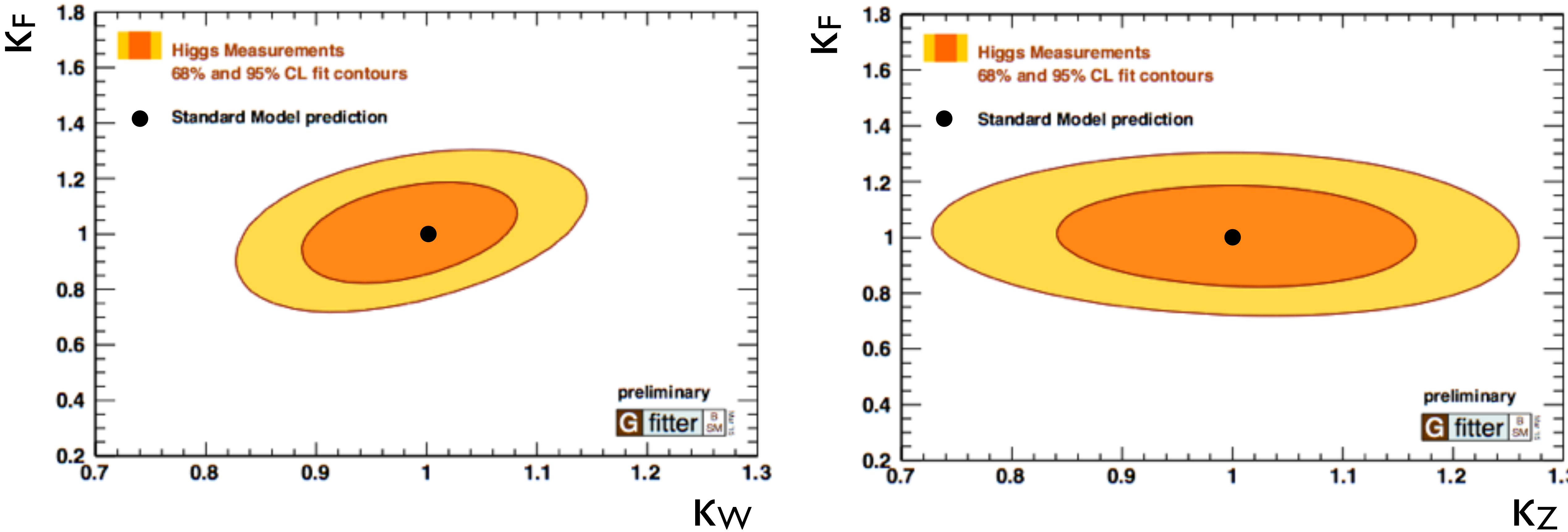


[T. Stefaniak, Nov 2014]

Tree Level Higgs Couplings

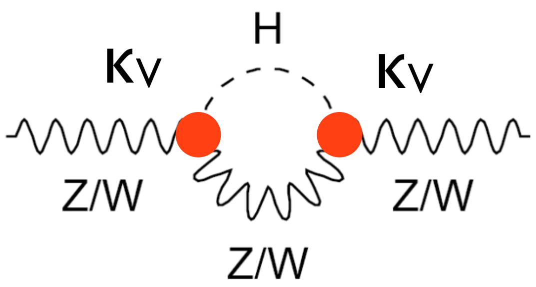
[see Adam and Chiara's talks]

- 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



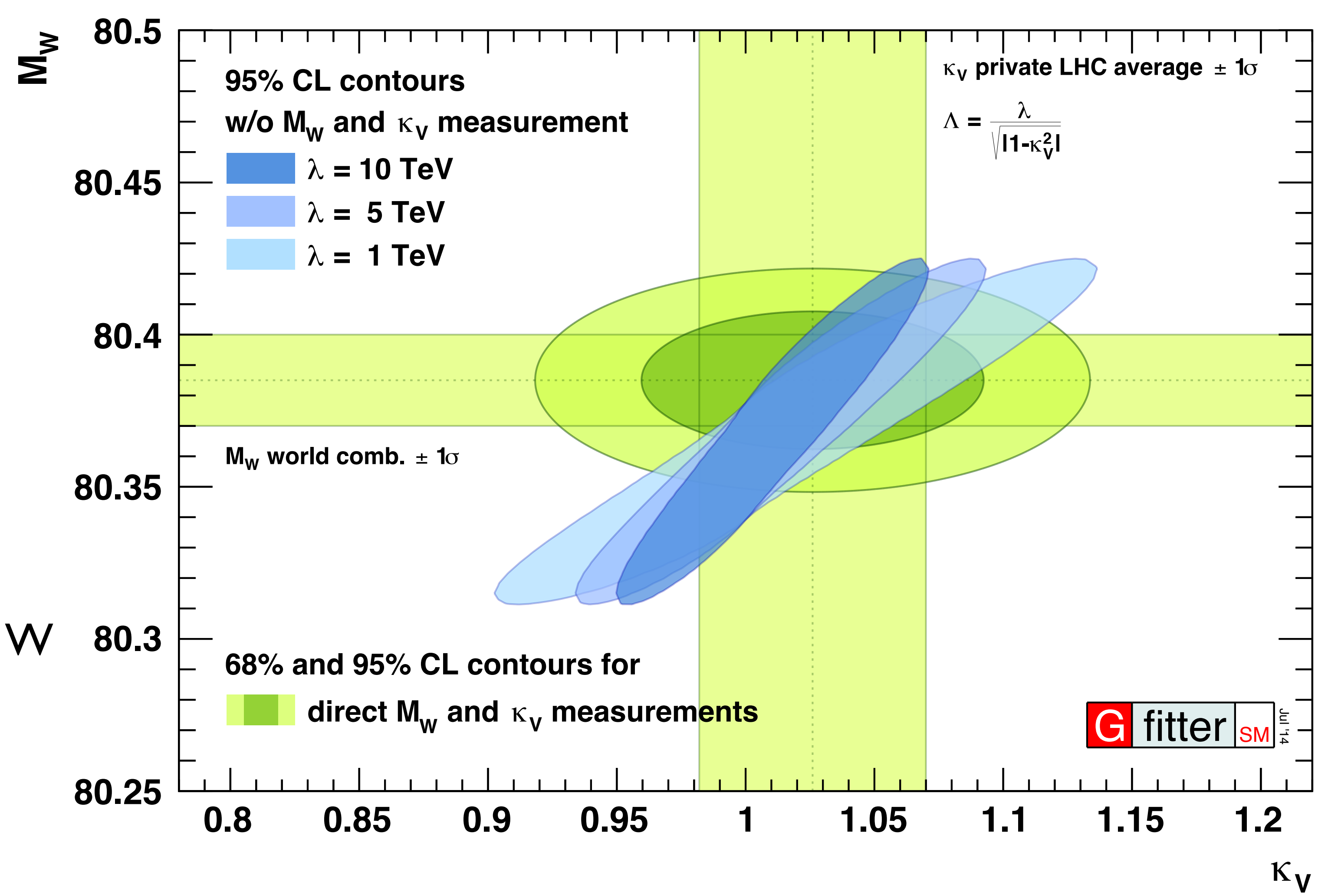
- Consider specific model in "κ parametrisation":
  - scaling of Higgs-vector boson (κ_V) and Higgs-fermion couplings (κ_F), with no invisible/undetectable widths
- Main effect on EWPD due to modified Higgs coupling to gauge bosons (κ_V)
  [Espinosa et al. arXiv:1202.3697, Falkowski et al. arXiv:1303.1812],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

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

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

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

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

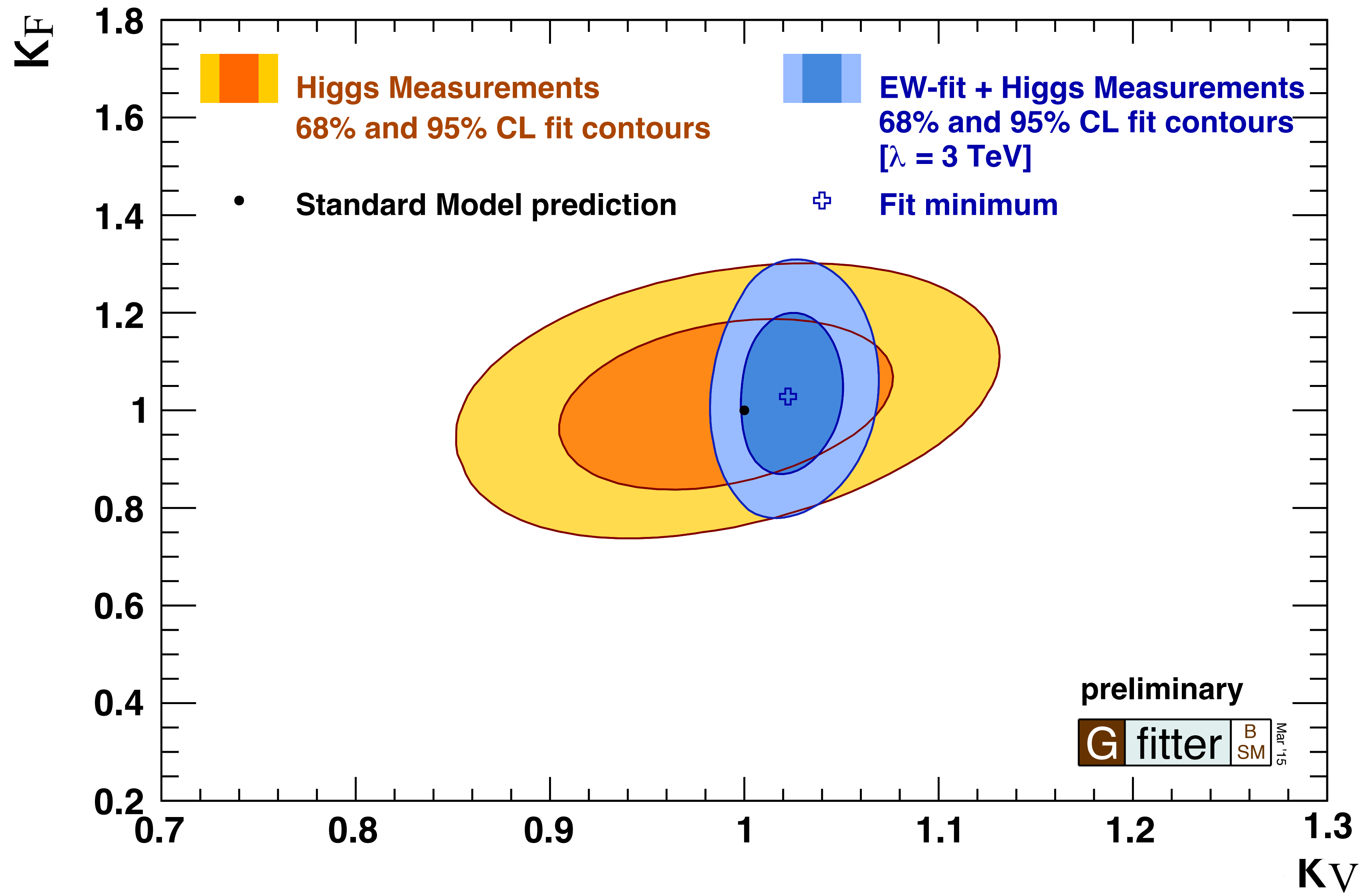


Higgs Coupling Results

Higgs coupling measurements:

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

- **Combined result:**
- $\kappa_V = 1.03 \pm 0.02$ (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]
  - note: precision of κ_V for very special assumptions
  - EW fit has positive deviation of κ_V from 1.0
    - many BSM models: $\kappa_V < 1$

Higgs coupling results

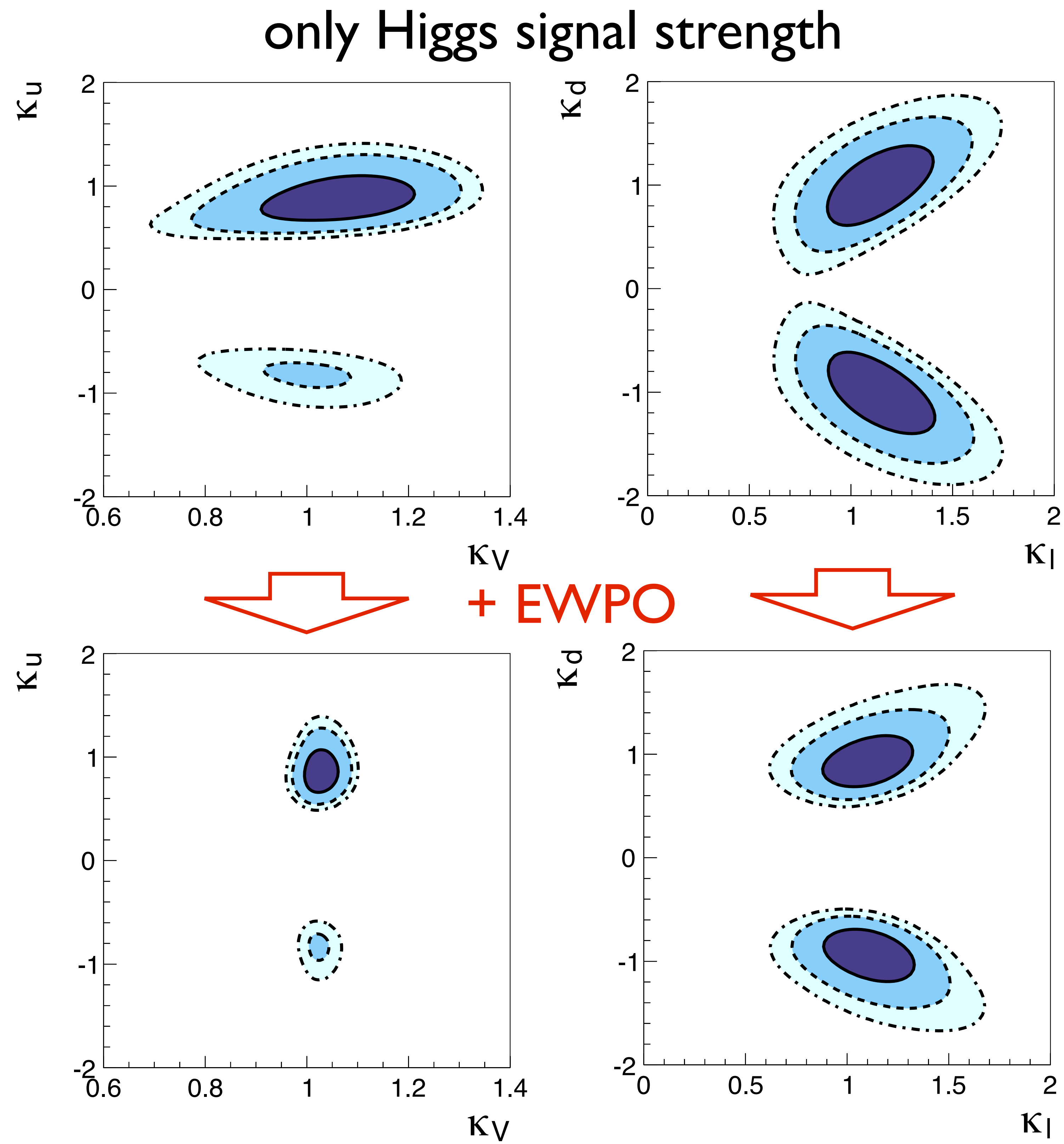
- Allowing for different couplings to up- and down-type quarks κ_u and κ_d

- 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

[see Adam and Chiara's talks]



[Marco Ciuchini et al, arXiv:1410.6940]

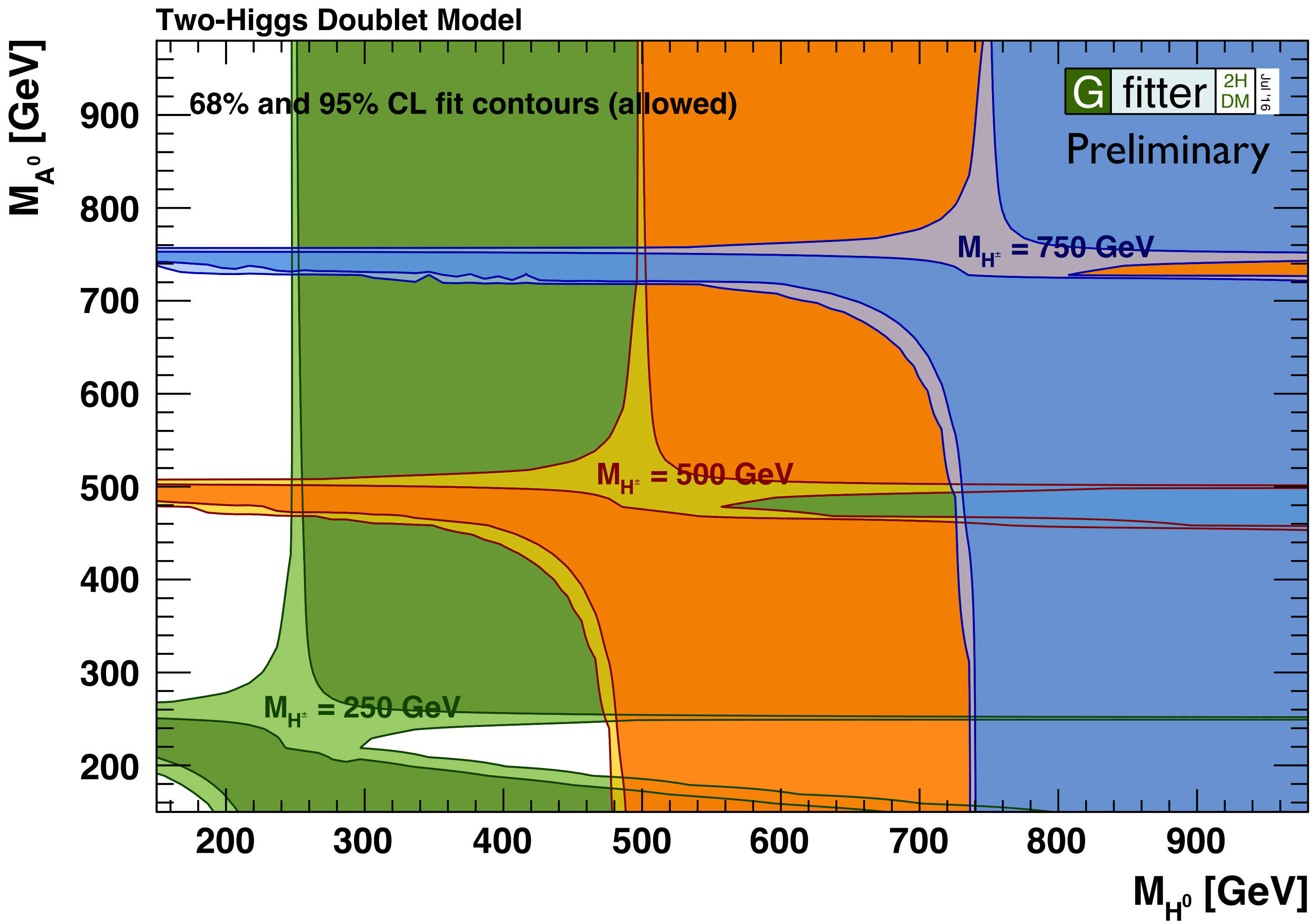
Two Higgs Doublet Models

Two Higgs Doublet Models

[see Rui's talk]

- 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

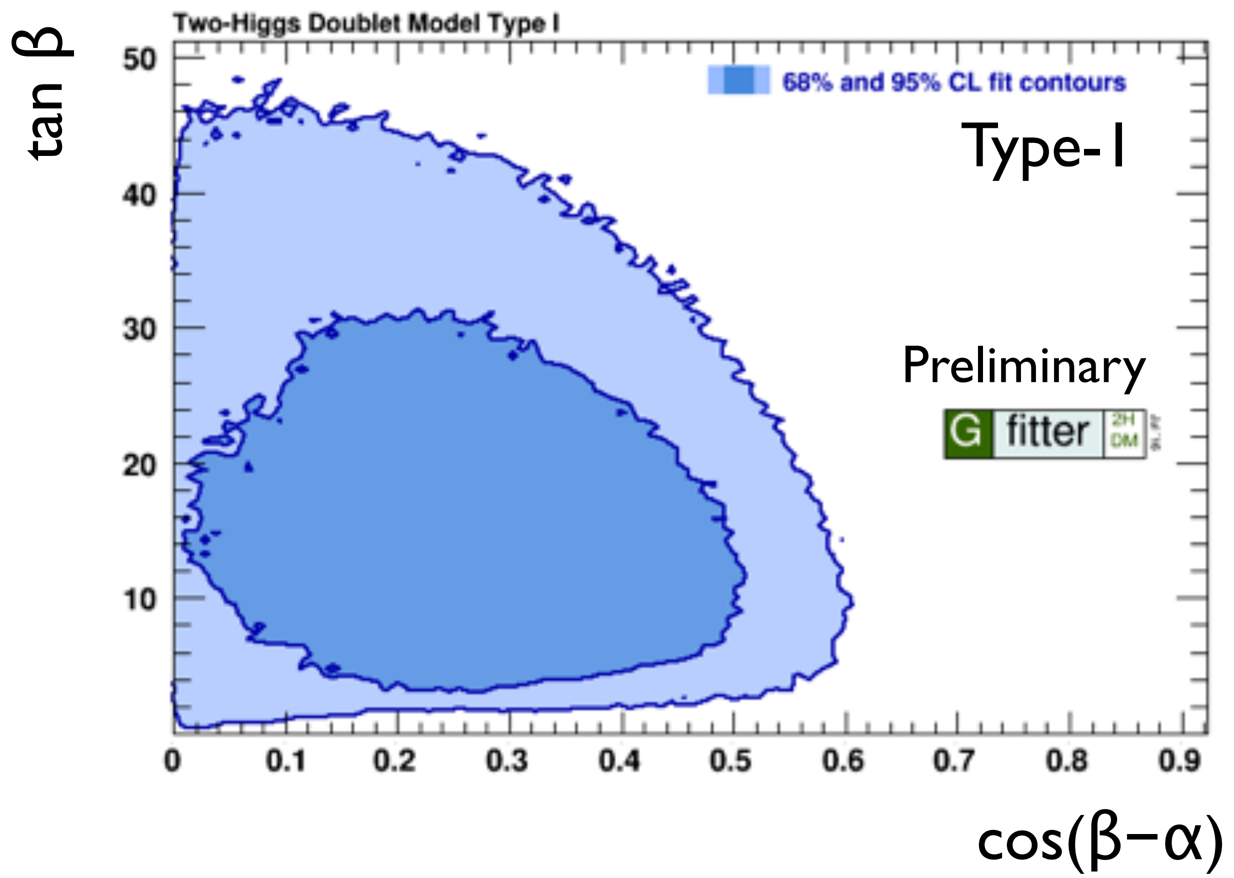


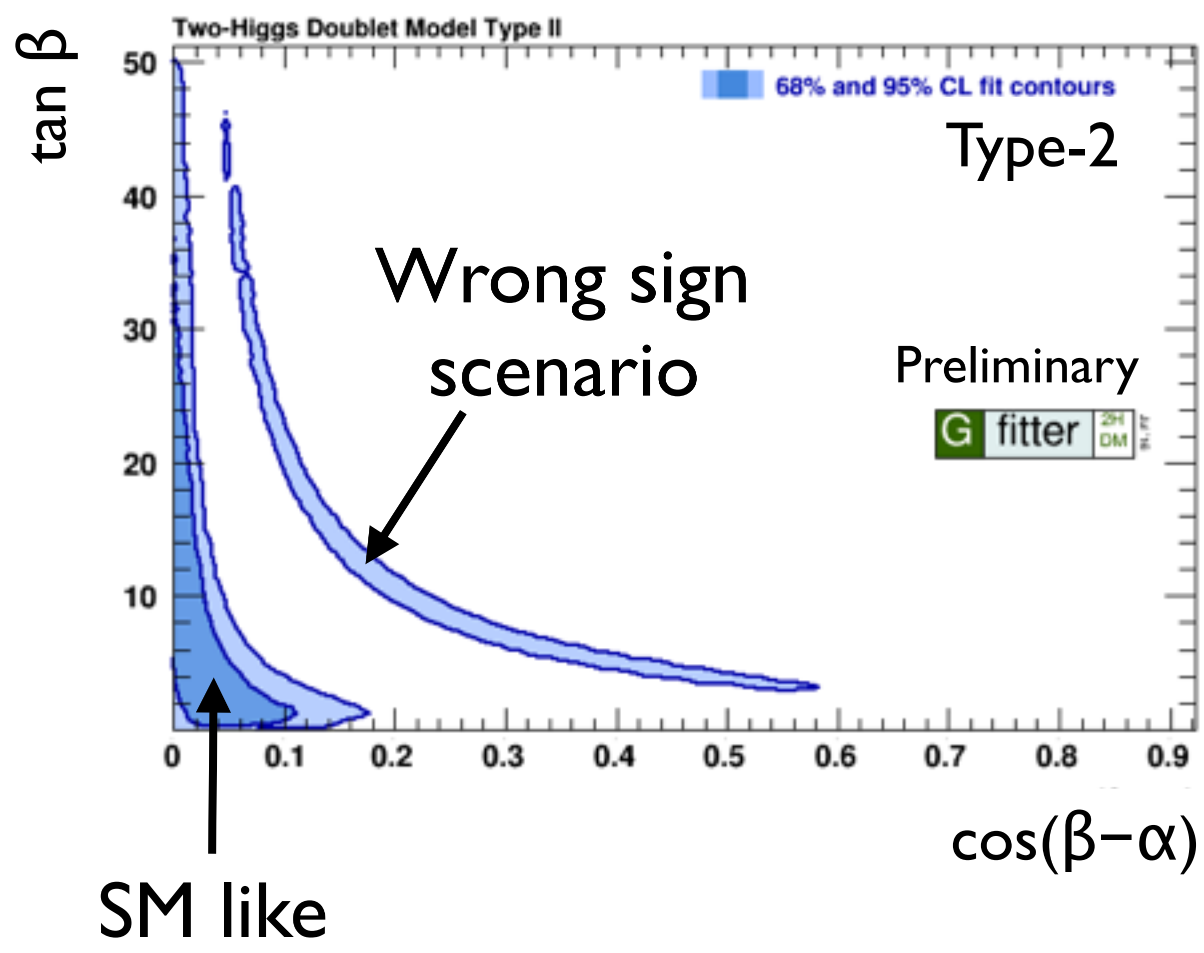
- Constraints derived from EWPD using S,T,U formalism
- Lightest scalar M_h = 125.1 GeV
- Weak constraints on masses, since $\tan\beta$ and $\cos(\beta-\alpha)$ are unconstrained

2HDM and H Coupling Measurements

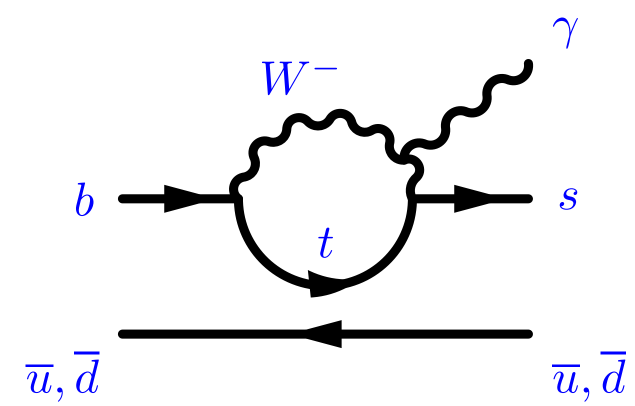
- Coupling measurements place important constraints on 2HDMs
- Predictions of BRs using 2HDMC [D. Eriksson et al., CPC 181, 189 (2010)]
- 7 additional, unconstraint parameters (4 masses, 2 angles, soft breaking scale): importance sampling with MultiNest [F. Feroz et al., arXiv:1306.2144]

[see Rui's talk]



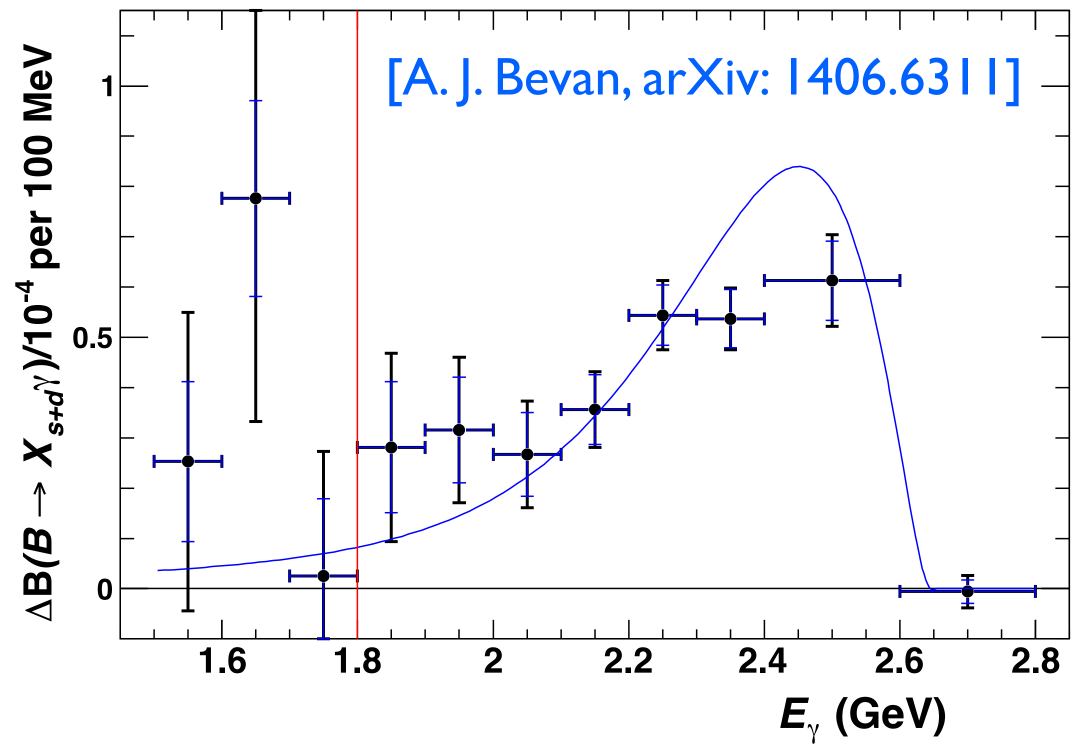


Flavour Measurements



$B \to X_s\,\gamma$

- loop-induced decays
  - sensitive probe to new physics
  - sensitivity to $|V_{tb}V_{ts}|^2$
- measurement relies on photon energy spectrum
  - need to correct for $B \to X_d$ contributions
- unfolded and background-subtracted after unblinding of signal region



- HFAG average from Belle and BARBAR measurements:

$$\mathcal{B}(B \to X_s\gamma) = (3.43 \pm 0.21 \pm 0.07) \times 10^{-4} \quad (E_\gamma > 1.6)$$

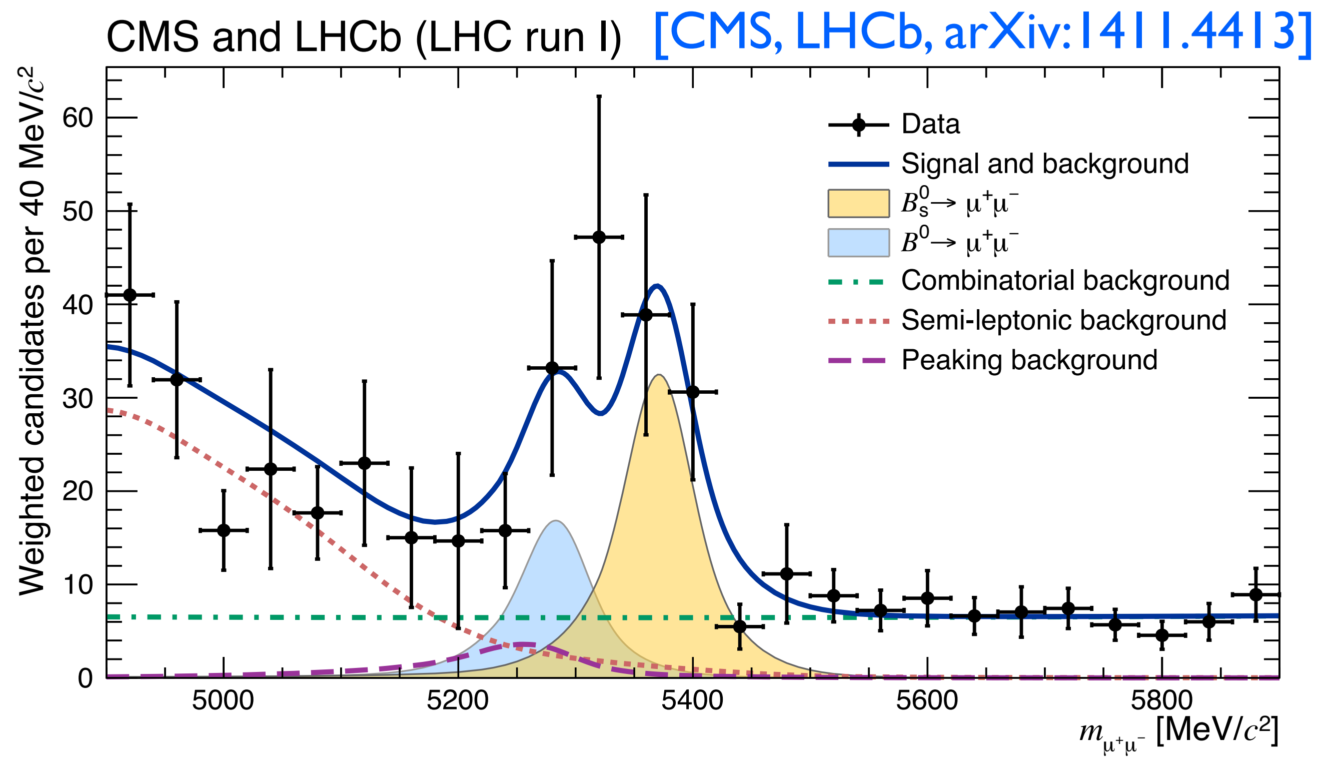
- SM prediction:

$$\mathcal{B}(B \to X_s\gamma)_{\mathrm{NNLL}} = (3.15 \pm 0.23) \times 10^{-4}$$

Flavour Measurements

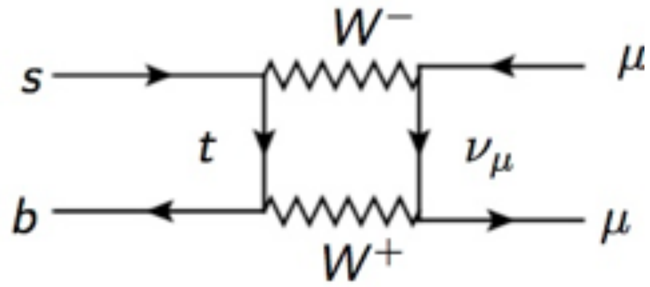
$B_s \to \mu\mu$

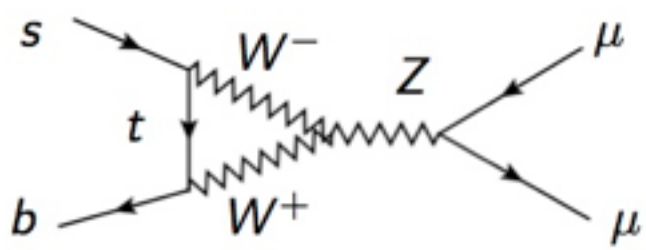
- Successful conclusion after 30 years of searches for this rare decay



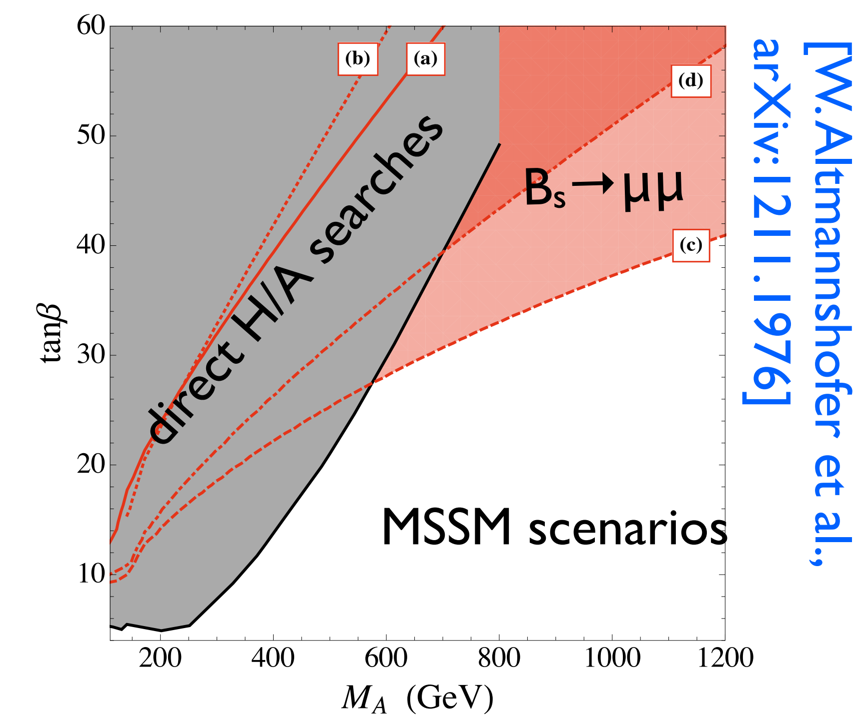
$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{exp}} = 2.8^{+0.7}_{-0.6} \times 10^{-9}$$

$$\mathrm{BR}(B_s \to \mu^+\mu^-)_{\mathrm{SM}} = (3.65 \pm 0.23) \times 10^{-9}$$





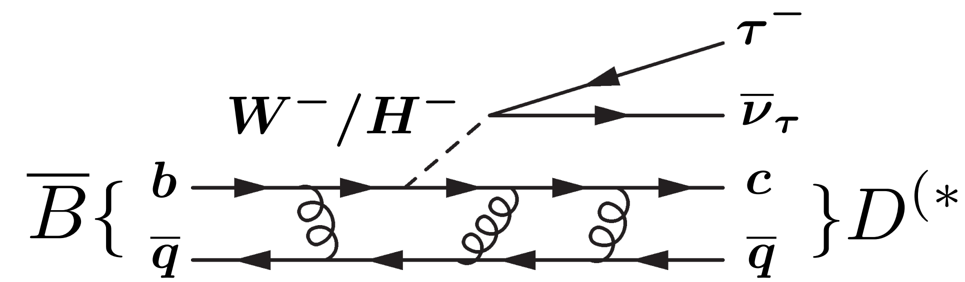
$$\propto |V_{tb}V_{ts}|^2$$

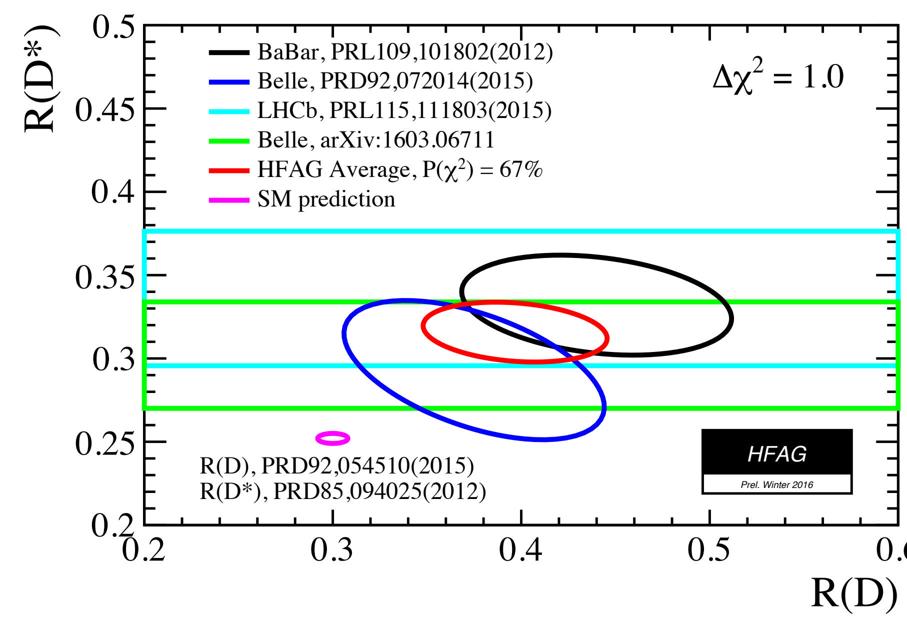


Flavour Measurements

$\bar{B} \to D\tau^-\bar{\nu}_\tau$

- measurement at e^+e^- colliders (Belle, BABAR)
- use $\Upsilon(4s) \to B\bar{B}$ for tag + probe
- Width $\Gamma \propto |V_{cb}|^2 \left(1 - \frac{\tan^2\beta}{m^2_{H^\pm}} \frac{q^2}{1 \mp m_c/m_b}\right)$

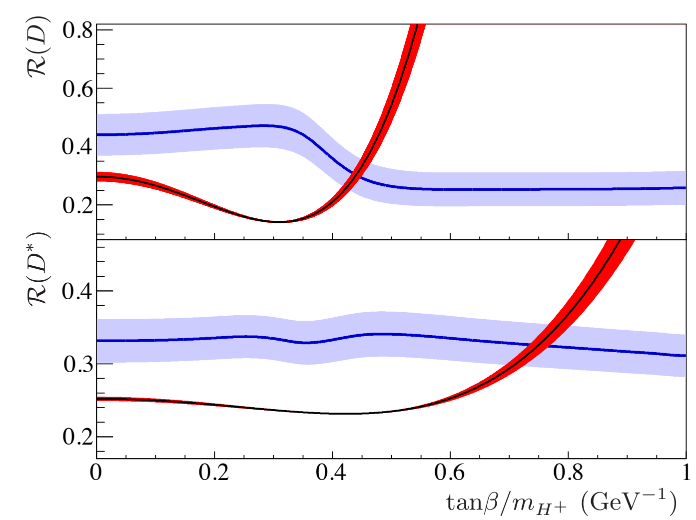




combined significance ~ 4σ (HFAG)

R(D) = BR(B → Dτν) / BR(B → Deν)

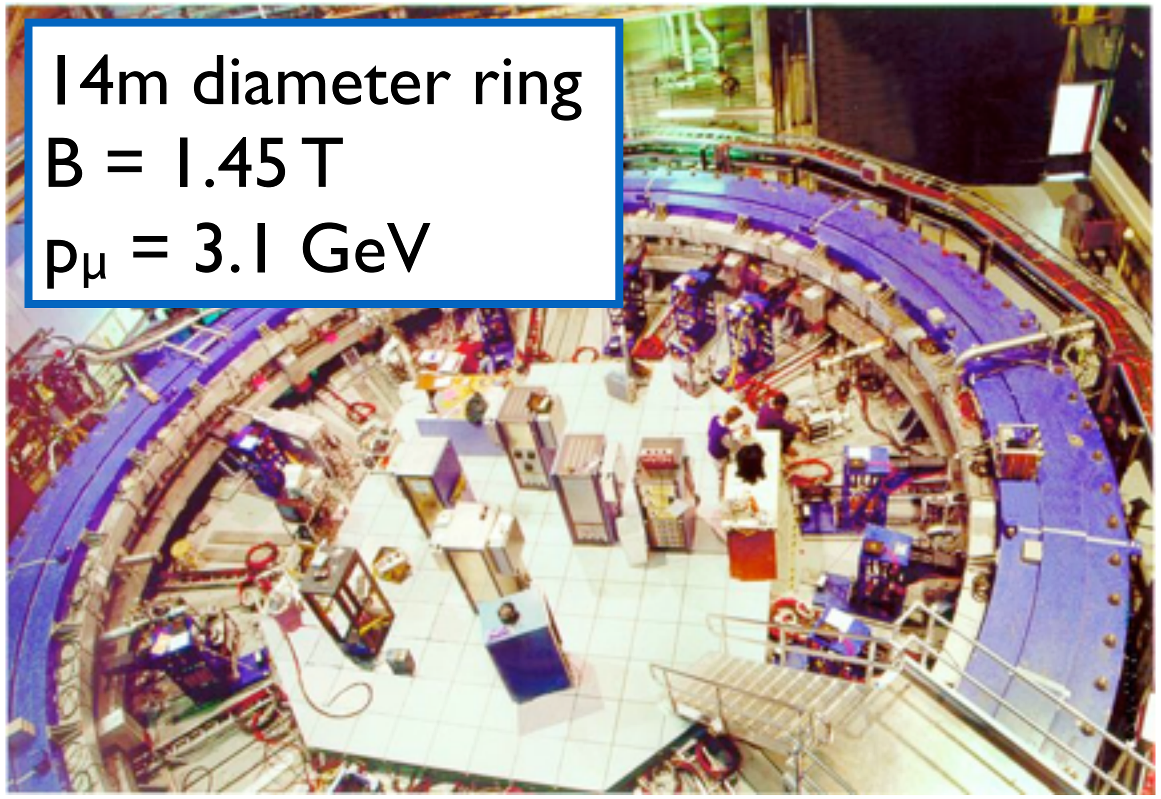
- cancellation of $|V_{cb}|^2$
- B → Deν not sensitive to $H^\pm$
- profit from cancellation of experimental uncertainties
- not compatible with 2HDM Type-2

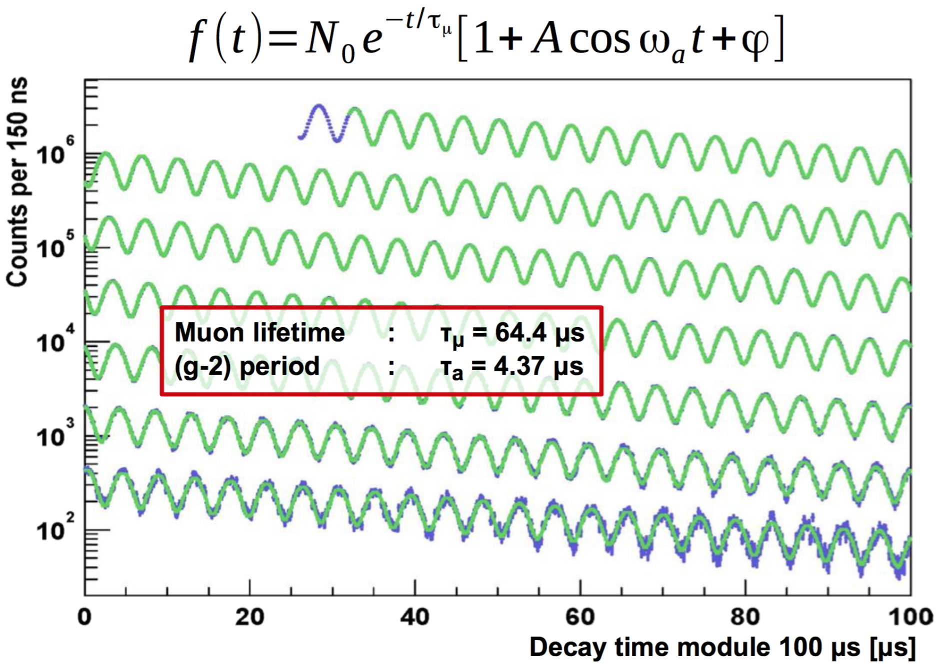


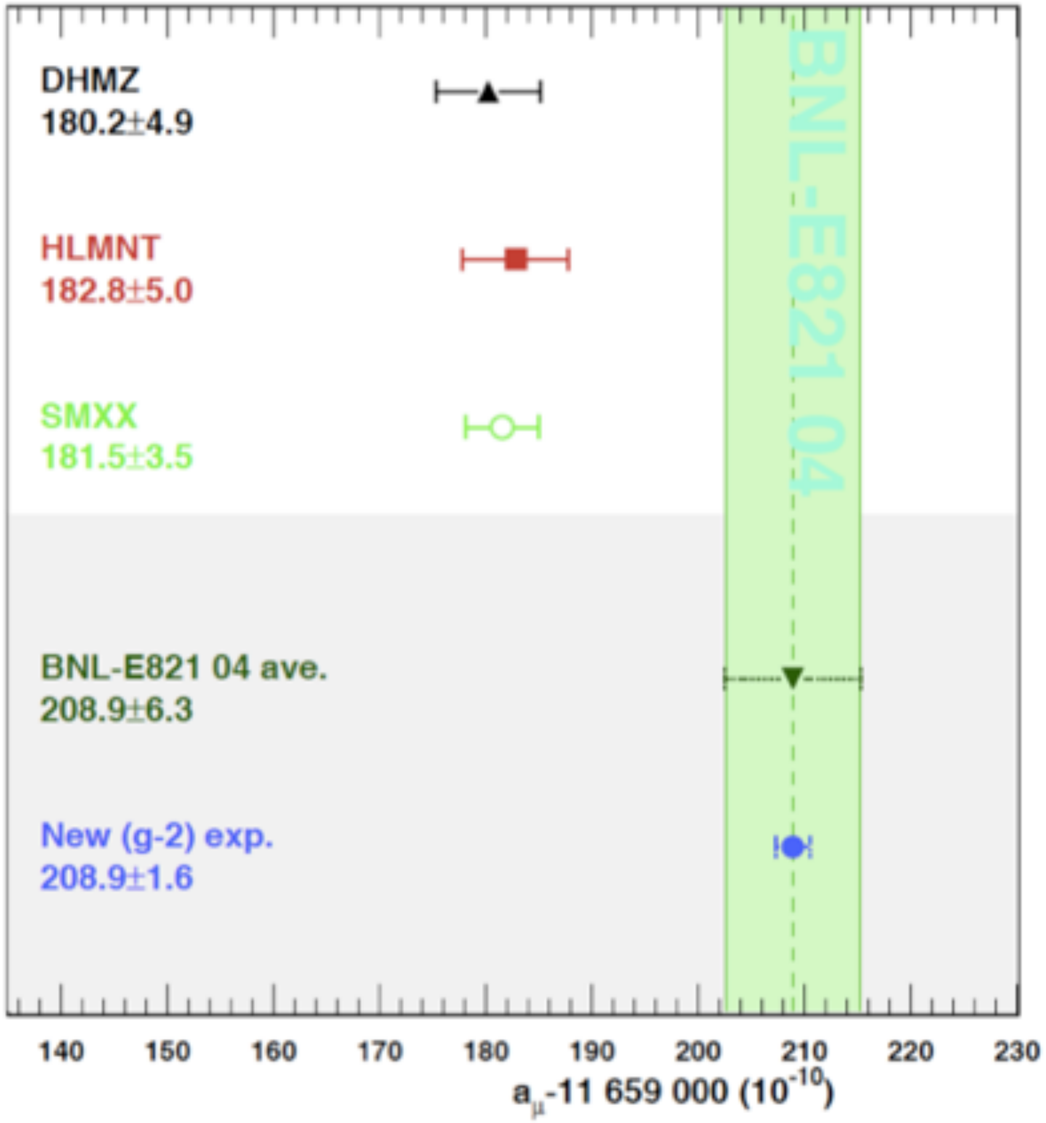
[BARBAR, arXiv: 1205.5442]

$(g-2)_\mu$

E821 Experiment at Brookhaven

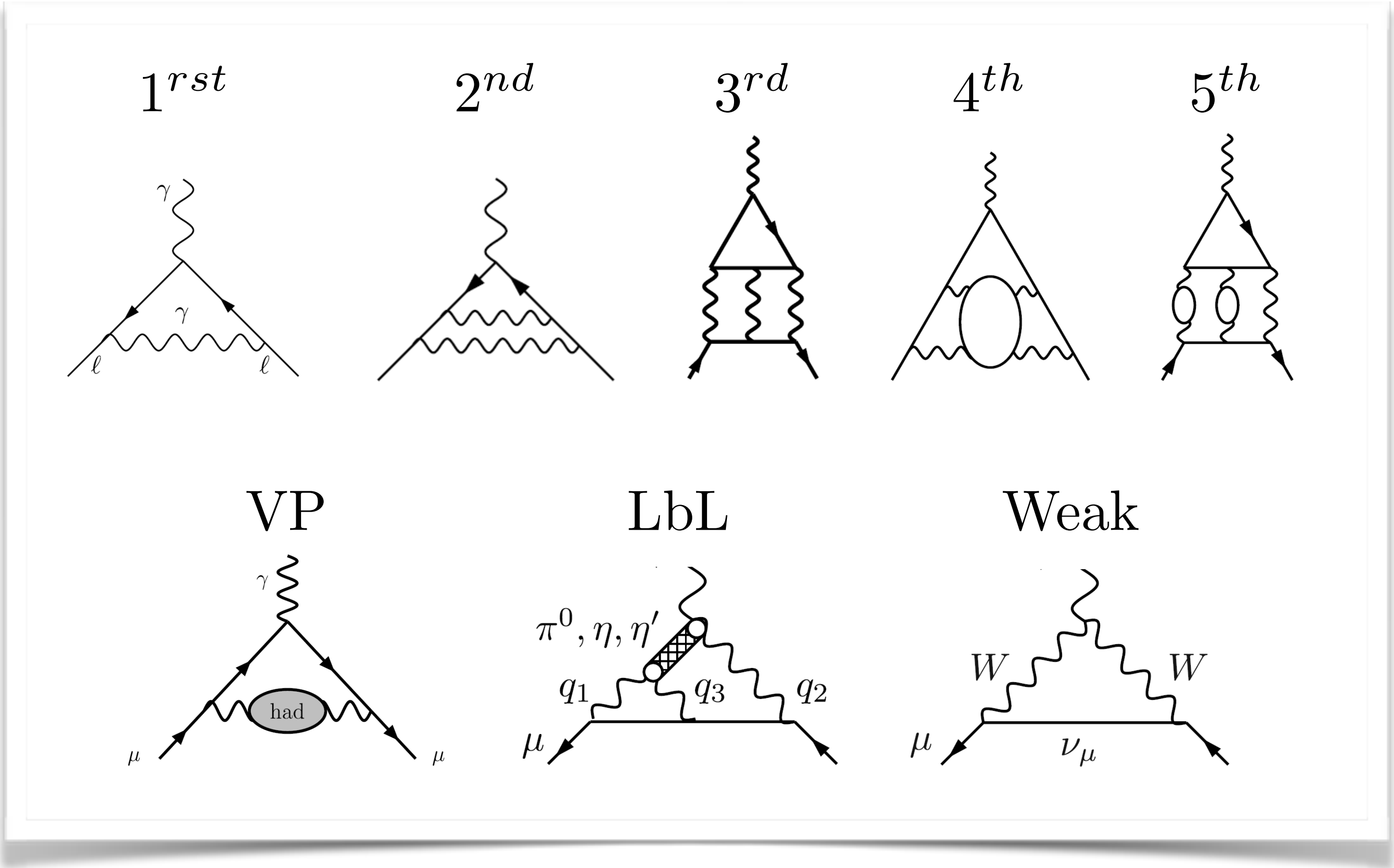






- Experimental precision: $\Delta a_\mu = 63 \times 10^{-11}$

$(g-2)_\mu$

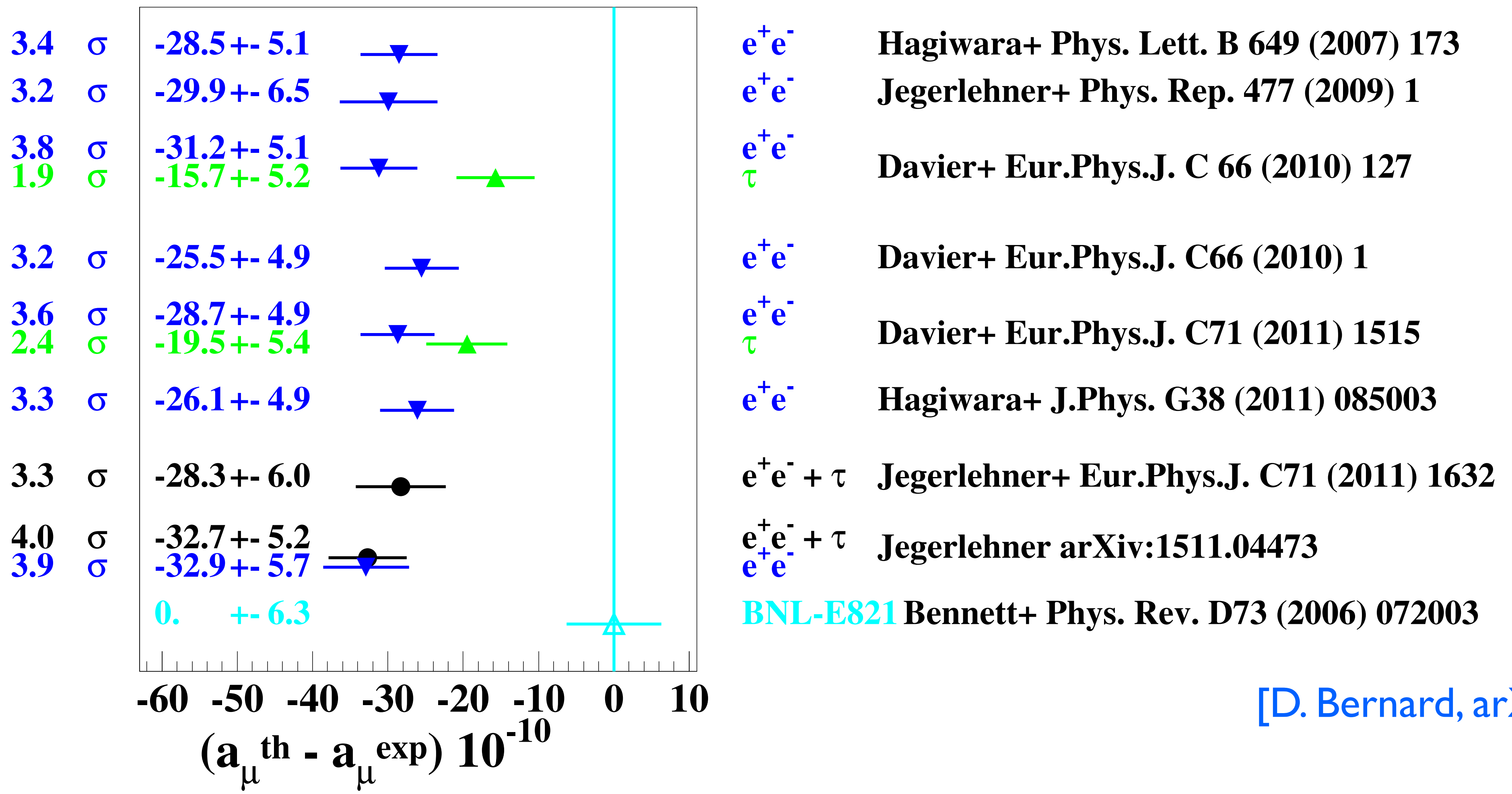


$$a_\mu = a_\mu^{\mathrm{QED}} + a_\mu^{\mathrm{QCD}} + a_\mu^{\mathrm{EW}}$$

	Value ($\times 10^{-11}$) units
QED ($\gamma + \ell$)	$116\,584\,718.853 \pm 0.022 \pm 0.029_\alpha$
HVP(lo)*	$6\,923 \pm 42$
HVP(ho)**	-98.4 ± 0.7
H-LBL†	105 ± 26
EW	153.6 ± 1.0
Total SM	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$

Significant work ongoing

Impact of $(g-2)_\mu$



[D. Bernard, arXiv: 1607.07181]

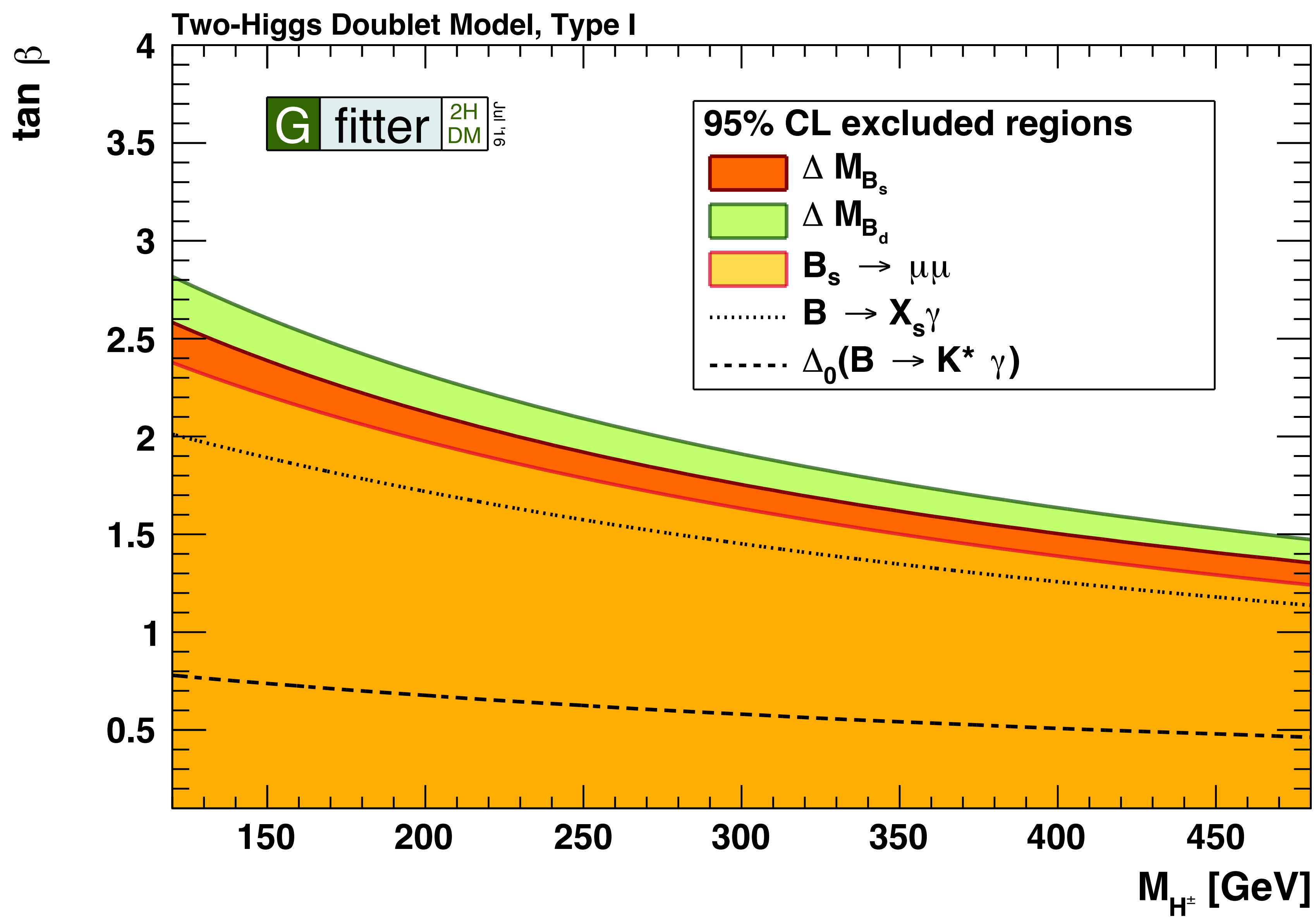
Include a_μ in EW Fit:

- p-values:
  - 5% ($\Delta\alpha_{had}$ from e^+e^- + τ decays)
  - 2% ($\Delta\alpha_{had}$ from e^+e^-)
  - 12% ($\Delta\alpha_{had}$ from τ decays)

Include a_μ in 2HDM Fit:

- exclude $\tan\beta < 0.2$

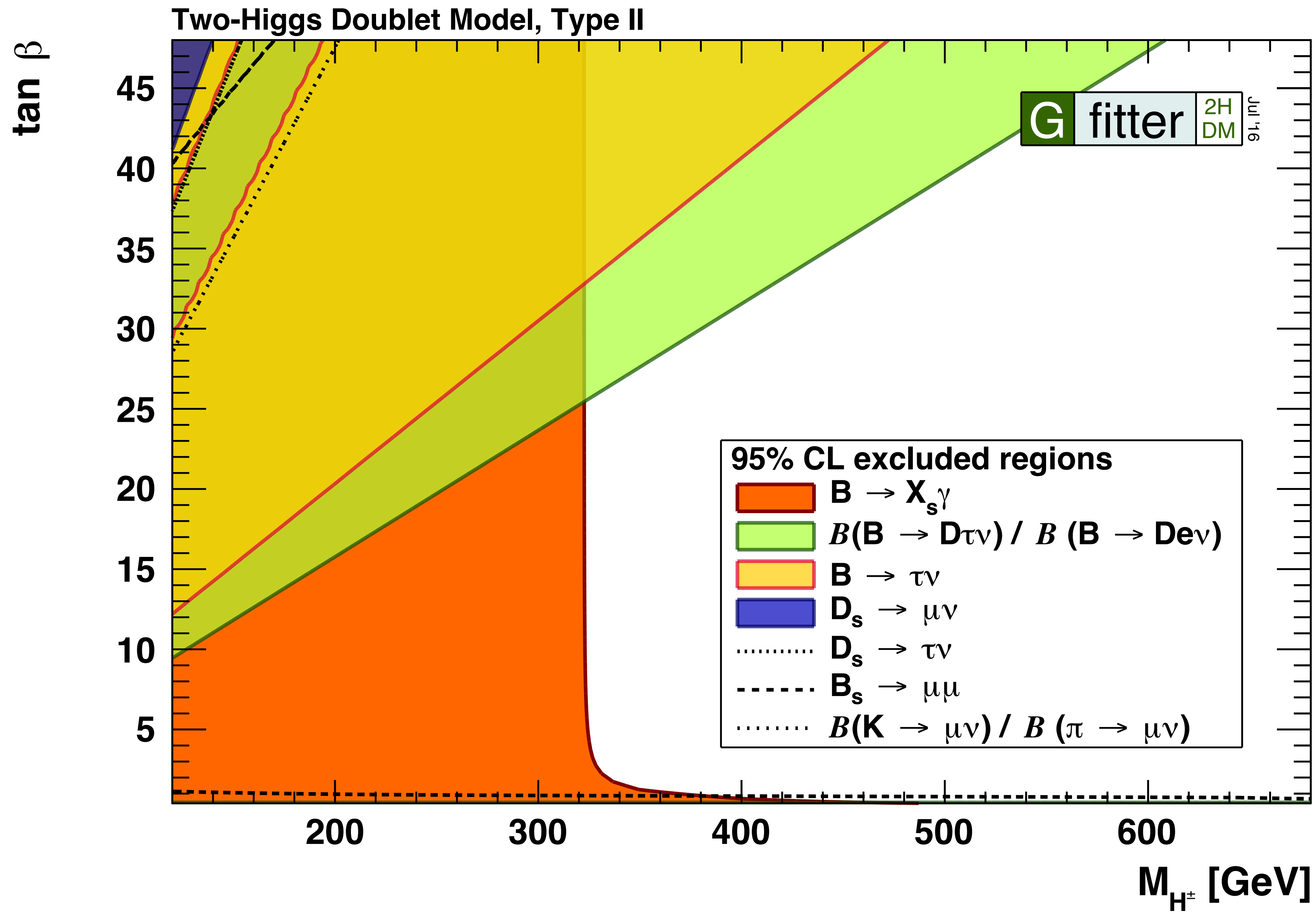
Flavour Constraints in Type-1 2HDM



tanβ > 1.5 for $M_{H\pm}$ < 500 GeV

- Strong constraints from $B_s \to \mu\mu$ and ΔM_{Bs}, ΔM_{Bd}
  - weak dependence on $M_{H\pm}$

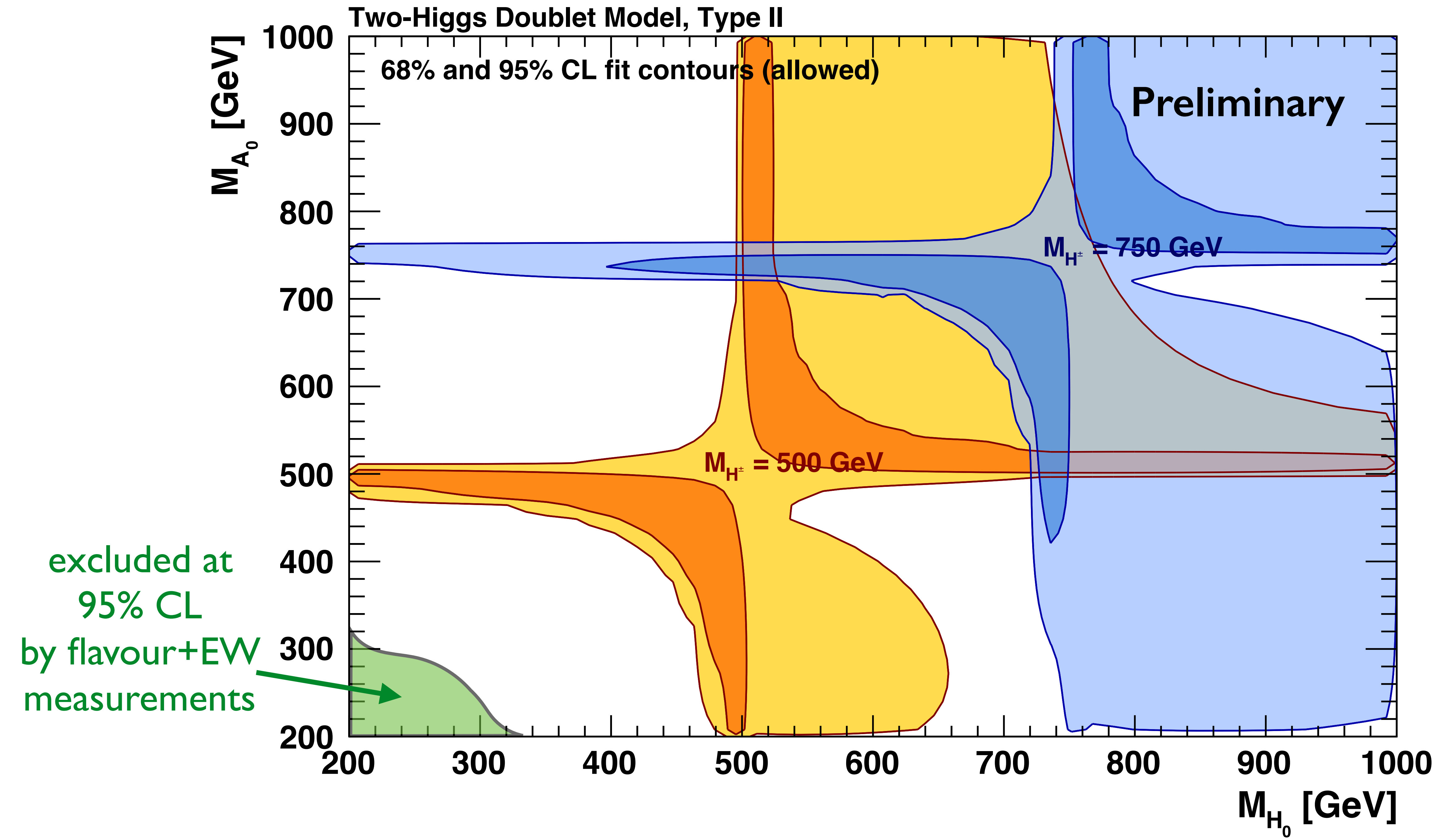
Flavour Constraints in Type-2 2HDM



$M_{H\pm}$ > 330 GeV, tighter constraints for high tanβ

- Strongest constraints from B → $X_s\gamma$
- BR(B → Dτν) / BR(B → Deν): deviation from SM prediction
  - can not be described within the Type-2 2HDM

Global Fit to 2HDM of Type-2



- For given $M_{H\pm}$ tight constraints from H coupling measurements and EWPD
- Expect improvements from direct searches

Dimension 6 Operators

[Engler, RK, Schulz, Spannowsky, arXiv:1511.05170]

What's Possible?

[see Adam's talk]

- All operators respecting gauge invariance, the SM gauge group and particle content
- Agnostic operator basis: **2499** non-redundant parameters at dim-6
- Flavour blind: **59** operators (still highly complex)

$$\mathcal{O}_H = \tfrac{1}{2}(\partial^\mu |H|^2)^2$$
$$\mathcal{O}_T = \tfrac{1}{2}\left(H^\dagger \overleftrightarrow{D}_\mu H\right)^2$$
$$\mathcal{O}_6 = \lambda |H|^6$$

$$\mathcal{O}_W = \tfrac{ig}{2}\left(H^\dagger \sigma^a \overleftrightarrow{D^\mu} H\right) D^\nu W^a_{\mu\nu}$$
$$\mathcal{O}_B = \tfrac{ig'}{2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right) \partial^\nu B_{\mu\nu}$$
$$\mathcal{O}_{2W} = -\tfrac{1}{2}(D^\mu W^a_{\mu\nu})^2$$
$$\mathcal{O}_{2B} = -\tfrac{1}{2}(\partial^\mu B_{\mu\nu})^2$$
$$\mathcal{O}_{2G} = -\tfrac{1}{2}(D^\mu G^A_{\mu\nu})^2$$

$$\mathcal{O}_{BB} = g'^2 |H|^2 B_{\mu\nu} B^{\mu\nu}$$
$$\mathcal{O}_{GG} = g_s^2 |H|^2 G^A_{\mu\nu} G^{A\mu\nu}$$
$$\mathcal{O}_{HW} = ig(D^\mu H)^\dagger \sigma^a (D^\nu H) W^a_{\mu\nu}$$
$$\mathcal{O}_{HB} = ig'(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu}$$
$$\mathcal{O}_{3W} = \tfrac{1}{3!} g \epsilon_{abc} W^{a\,\nu}_{\mu} W^b_{\nu\rho} W^{c\,\rho\mu}$$
$$\mathcal{O}_{3G} = \tfrac{1}{3!} g_s f_{ABC} G^{A\,\nu}_{\mu} G^B_{\nu\rho} G^{C\,\rho\mu}$$

$\mathcal{O}_{y_u} = y_u \|H\|^2 \bar{Q}_L \widetilde{H} u_R$	$\mathcal{O}_{y_d} = y_d \|H\|^2 \bar{Q}_L H d_R$	$\mathcal{O}_{y_e} = y_e \|H\|^2 \bar{L}_L H e_R$
$\mathcal{O}^u_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_R = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_L = (iH^\dagger \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(3)\,q}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{Q}_L \gamma^\mu \sigma^a Q_L)$		$\mathcal{O}^{(3)\,l}_L = (iH^\dagger \sigma^a \overleftrightarrow{D}_\mu H)(\bar{L}_L \gamma^\mu \sigma^a L_L)$
$\mathcal{O}^u_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^{(8)\,u}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{u}_R \gamma^\mu T^A u_R)$	$\mathcal{O}^{(8)\,d}_{LR} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{d}_R \gamma^\mu T^A d_R)$	
$\mathcal{O}^u_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^d_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{d}_R \gamma^\mu d_R)$	$\mathcal{O}^e_{RR} = (\bar{e}_R \gamma^\mu e_R)(\bar{e}_R \gamma^\mu e_R)$
$\mathcal{O}^q_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{Q}_L \gamma^\mu Q_L)$		$\mathcal{O}^l_{LL} = (\bar{L}_L \gamma^\mu L_L)(\bar{L}_L \gamma^\mu L_L)$
$\mathcal{O}^{(8)\,q}_{LL} = (\bar{Q}_L \gamma^\mu T^A Q_L)(\bar{Q}_L \gamma^\mu T^A Q_L)$		
$\mathcal{O}^{ql}_{LL} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{L}_L \gamma^\mu L_L)$		
$\mathcal{O}^{(3)\,ql}_{LL} = (\bar{Q}_L \gamma^\mu \sigma^a Q_L)(\bar{L}_L \gamma^\mu \sigma^a L_L)$		
$\mathcal{O}^{qe}_{LR} = (\bar{Q}_L \gamma^\mu Q_L)(\bar{e}_R \gamma^\mu e_R)$		
$\mathcal{O}^{lu}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{u}_R \gamma^\mu u_R)$	$\mathcal{O}^{ld}_{LR} = (\bar{L}_L \gamma^\mu L_L)(\bar{d}_R \gamma^\mu d_R)$	
$\mathcal{O}^{ud}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{d}_R \gamma^\mu d_R)$		
$\mathcal{O}^{(8)\,ud}_{RR} = (\bar{u}_R \gamma^\mu T^A u_R)(\bar{d}_R \gamma^\mu T^A d_R)$		
$\mathcal{O}^{ue}_{RR} = (\bar{u}_R \gamma^\mu u_R)(\bar{e}_R \gamma^\mu e_R)$	$\mathcal{O}^{de}_{RR} = (\bar{d}_R \gamma^\mu d_R)(\bar{e}_R \gamma^\mu e_R)$	
$\mathcal{O}^{ud}_R = y_u^\dagger y_d (i\widetilde{H}^\dagger \overleftrightarrow{D}_\mu H)(\bar{u}_R \gamma^\mu d_R)$		
$\mathcal{O}_{y_u y_d} = y_u y_d (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{Q}^s_L d_R)$		
$\mathcal{O}^{(8)}_{y_u y_d} = y_u y_d (\bar{Q}^r_L T^A u_R)\epsilon_{rs}(\bar{Q}^s_L T^A d_R)$		
$\mathcal{O}_{y_u y_e} = y_u y_e (\bar{Q}^r_L u_R)\epsilon_{rs}(\bar{L}^s_L e_R)$		
$\mathcal{O}'_{y_u y_e} = y_u y_e (\bar{Q}^{r\alpha}_L e_R)\epsilon_{rs}(\bar{L}^s_L u^\alpha_R)$		
$\mathcal{O}_{y_e y_d} = y_e y_d^\dagger (\bar{L}_L e_R)(\bar{d}_R Q_L)$		
$\mathcal{O}^u_{DB} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \widetilde{H} g' B_{\mu\nu}$	$\mathcal{O}^d_{DB} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R H g' B_{\mu\nu}$	$\mathcal{O}^e_{DB} = y_e \bar{L}_L \sigma^{\mu\nu} e_R H g' B_{\mu\nu}$
$\mathcal{O}^u_{DW} = y_u \bar{Q}_L \sigma^{\mu\nu} u_R \sigma^a \widetilde{H} g W^a_{\mu\nu}$	$\mathcal{O}^d_{DW} = y_d \bar{Q}_L \sigma^{\mu\nu} d_R \sigma^a H g W^a_{\mu\nu}$	$\mathcal{O}^e_{DW} = y_e \bar{L}_L \sigma^{\mu\nu} e_R \sigma^a H g W^a_{\mu\nu}$
$\mathcal{O}^u_{DG} = y_u \bar{Q}_L \sigma^{\mu\nu} T^A u_R \widetilde{H} g_s G^A_{\mu\nu}$	$\mathcal{O}^d_{DG} = y_d \bar{Q}_L \sigma^{\mu\nu} T^A d_R H g_s G^A_{\mu\nu}$	

What's Feasible?

- SIL H basis, focus on operators with Higgs involvement
- Do not consider operators constrained by electroweak precision measurements
- **8** operators of interest

$$
\begin{aligned}
\mathcal{L}_{\mathrm{SILH}} = & \frac{\bar{c}_H}{2v^2}\partial^\mu\left(H^\dagger H\right)\partial_\mu\left(H^\dagger H\right) + \frac{\bar{c}_T}{2v^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(H^\dagger \overleftrightarrow{D}_\mu H\right) - \frac{\bar{c}_6\lambda}{v^2}\left(H^\dagger H\right)^3 \\
& + \left(\frac{\bar{c}_{u,i} y_{u,i}}{v^2} H^\dagger H \bar{u}_L^{(i)} H^c u_R^{(i)} + \text{h.c.}\right) + \left(\frac{\bar{c}_{d,i} y_{d,i}}{v^2} H^\dagger H \bar{d}_L^{(i)} H d_R^{(i)} + \text{h.c.}\right) \\
& + \frac{i\bar{c}_W g}{2m_W^2}\left(H^\dagger \sigma^i \overleftrightarrow{D^\mu} H\right)\left(D^\nu W_{\mu\nu}\right)^i + \frac{i\bar{c}_B g'}{2m_W^2}\left(H^\dagger \overleftrightarrow{D^\mu} H\right)\left(\partial^\nu B_{\mu\nu}\right) \\
& + \frac{i\bar{c}_{HW} g}{m_W^2}(D^\mu H)^\dagger \sigma^i (D^\nu H) W^i_{\mu\nu} + \frac{i\bar{c}_{HB} g'}{m_W^2}(D^\mu H)^\dagger (D^\nu H) B_{\mu\nu} \\
& + \frac{\bar{c}_\gamma g'^2}{m_W^2} H^\dagger H B_{\mu\nu} B^{\mu\nu} + \frac{\bar{c}_g g_S^2}{m_W^2} H^\dagger H G^a_{\mu\nu} G^{a\mu\nu} .
\end{aligned}
$$

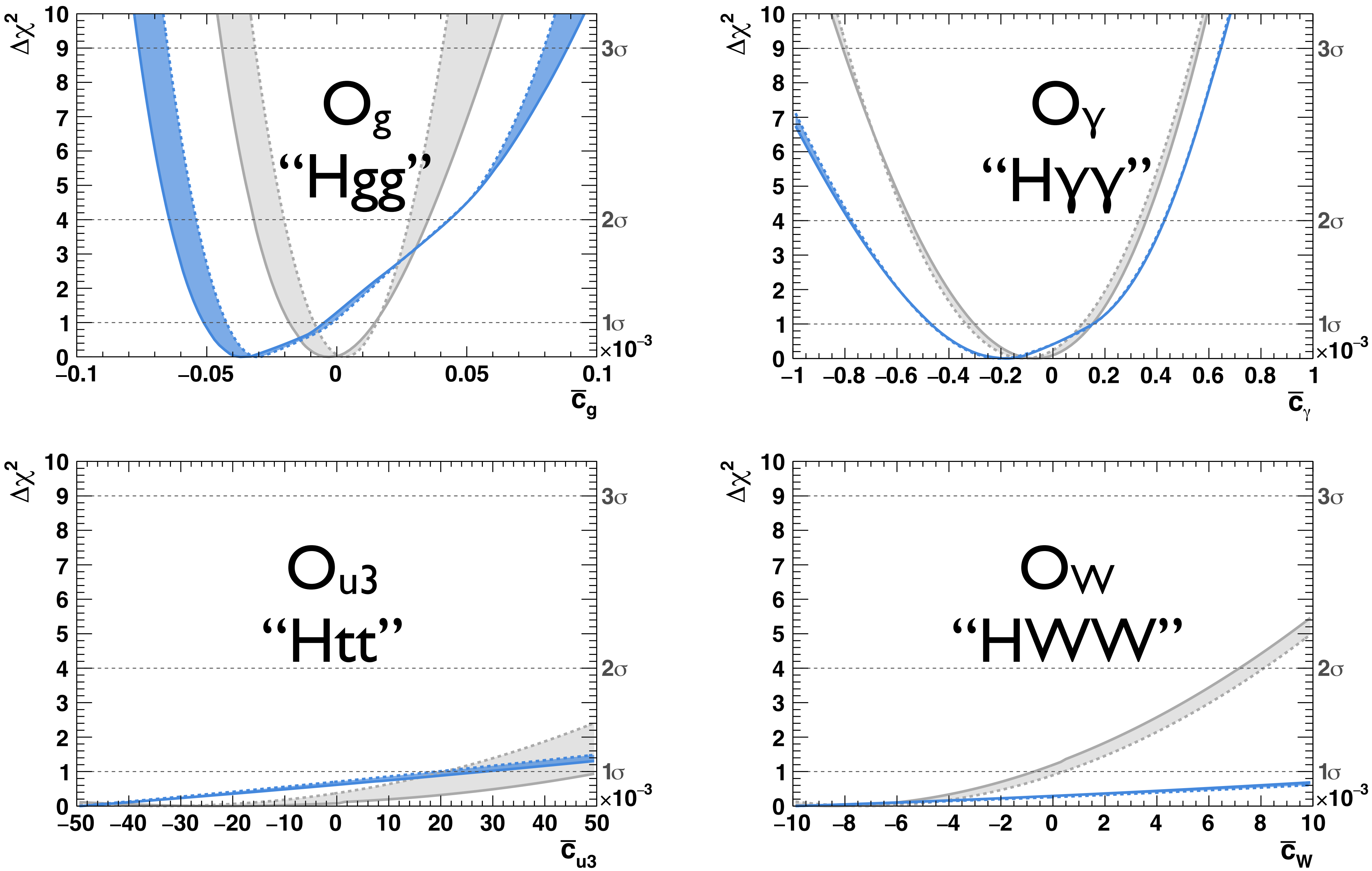
Focus on linear contribution: $\mathcal{M} = \mathcal{M}_{\mathrm{SM}} + \mathcal{M}_{d=6}$

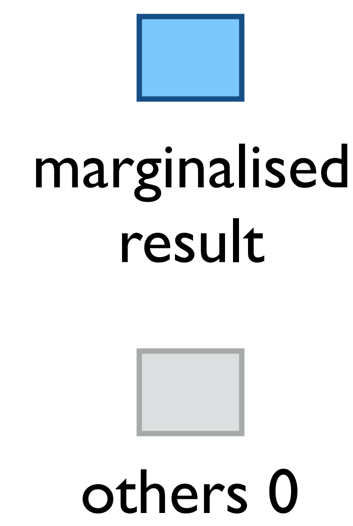
$$|\mathcal{M}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\,\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{d=6}\} + \mathcal{O}(1/\Lambda^4)$$

Sensitivity with the LHC

Results from Run 1

- Include all available Higgs measurements from ATLAS and CMS
- 77 signal strength measurements included





No noteworthy constraints on other 4 operators

Sensitivity with the LHC

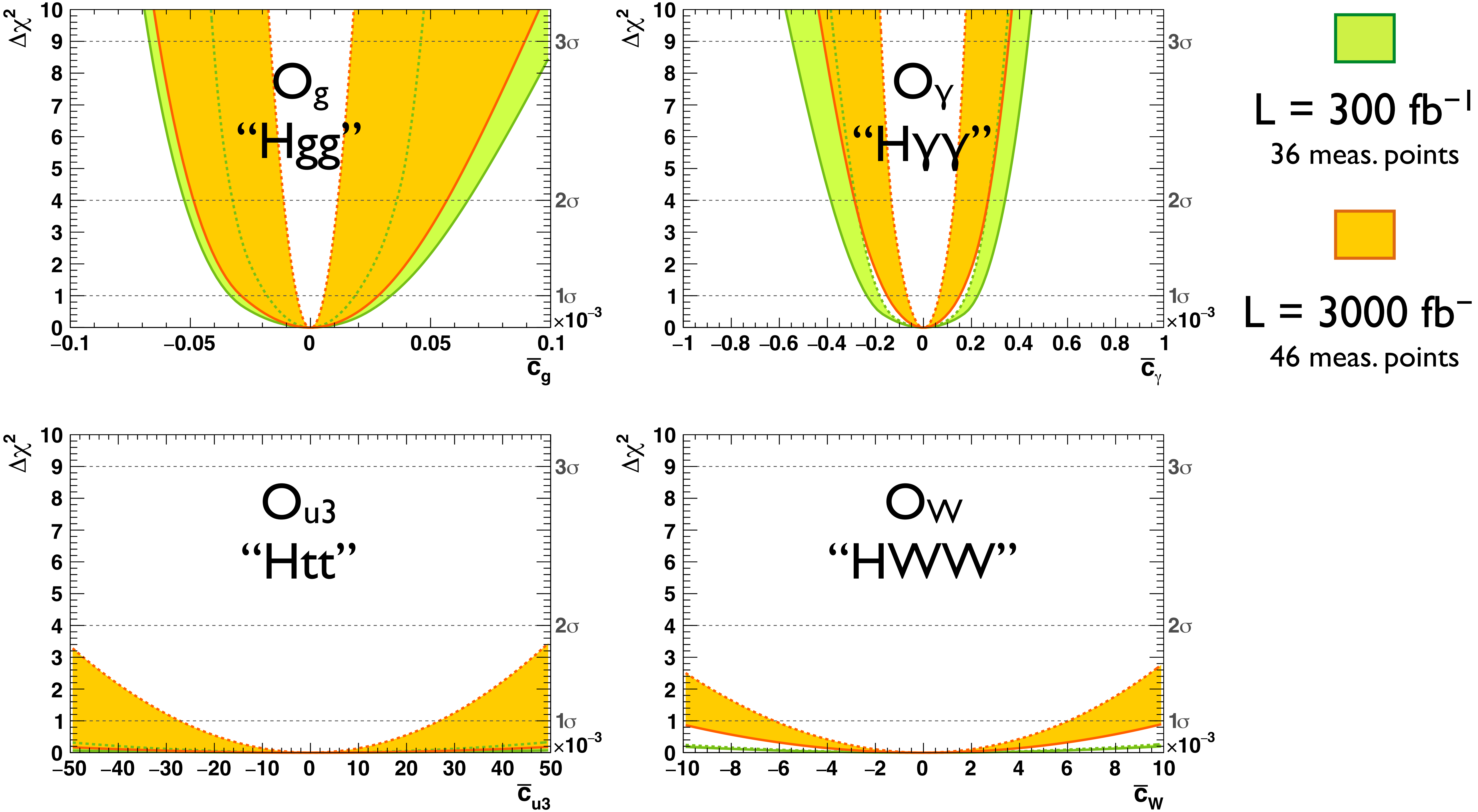
Prospects for Run 2

- Generate pseudo-data using realistic assumptions for efficiencies and systematic uncertainties
- Included production and decay modes: (with theory unc.)

production process		decay process	
$pp \to H$	14.7	$H \to b\bar{b}$	6.1
$pp \to H + \mathrm{j}$	15	$H \to \gamma\gamma$	5.4
$pp \to H + 2\mathrm{j}$	15	$H \to \tau^+\tau^-$	2.8
$pp \to HZ$	5.1	$H \to 4l$	4.8
$pp \to HW$	3.7	$H \to 2l2\nu$	4.8
$pp \to t\bar{t}H$	12	$H \to \mu^+\mu^-$	2.8

- Number of predicted events: $N_{\mathrm{th}} = \sigma(H + X) \times \mathrm{BR}(H \to YY) \times \mathcal{L} \times \mathrm{BR}(X, Y \to \text{final state})$
- Each channel has its own prod. and decay efficiencies: $N_{\mathrm{ev}} = \epsilon_p \epsilon_d N_{\mathrm{th}}$ (and uncertainties)

Constraints from (HL-)LHC



No constraints on O_{u3} and O_W with L = 3000 3000 fb^{-1} ??

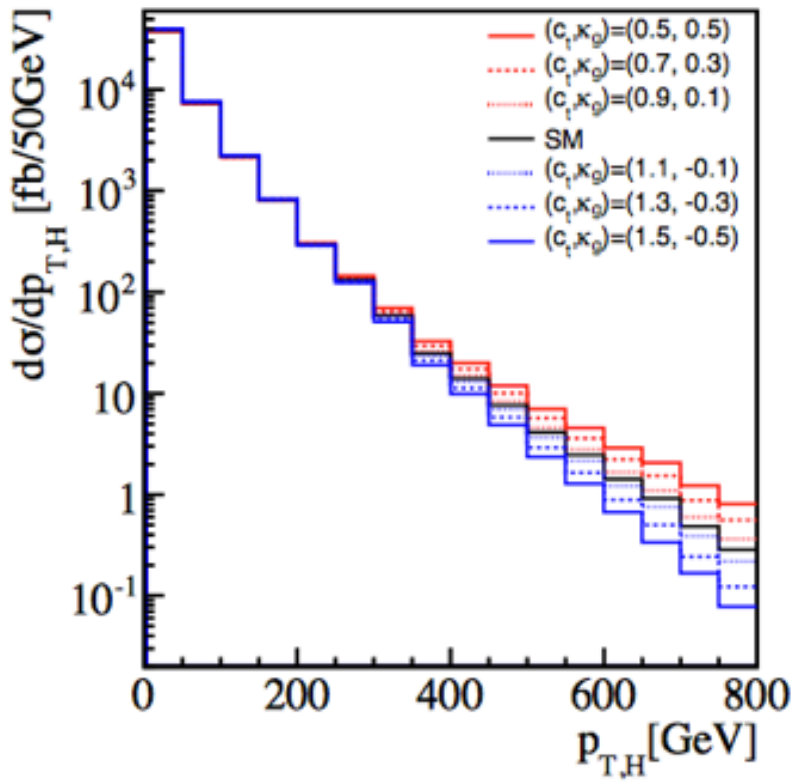
"Flat Directions"

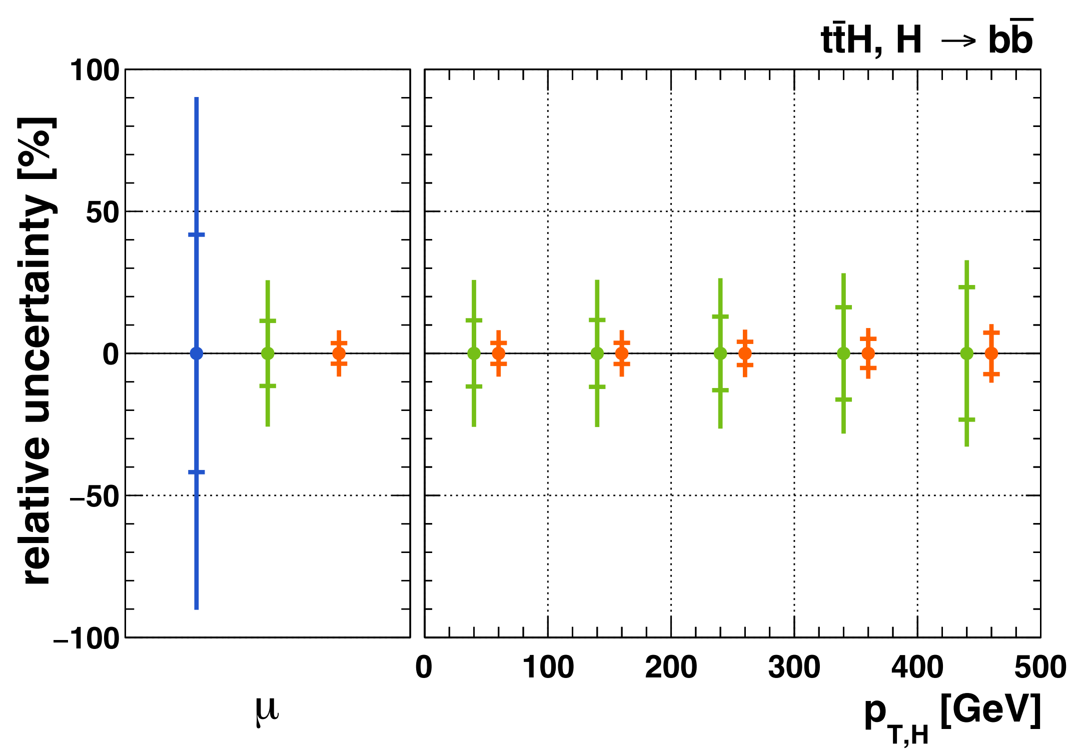
Multi-parameter fit

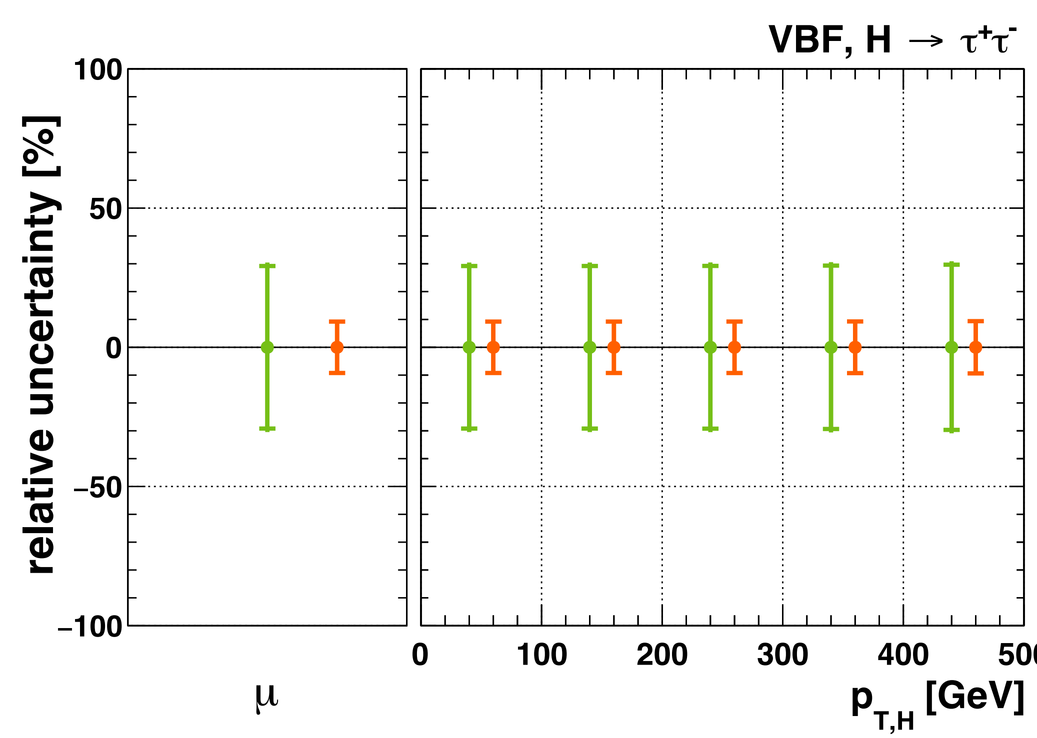
- Combinations of coefficients c_i can result in same signal strength
- No sensitivity without fixing some to 0 (but which ones?)

Solution

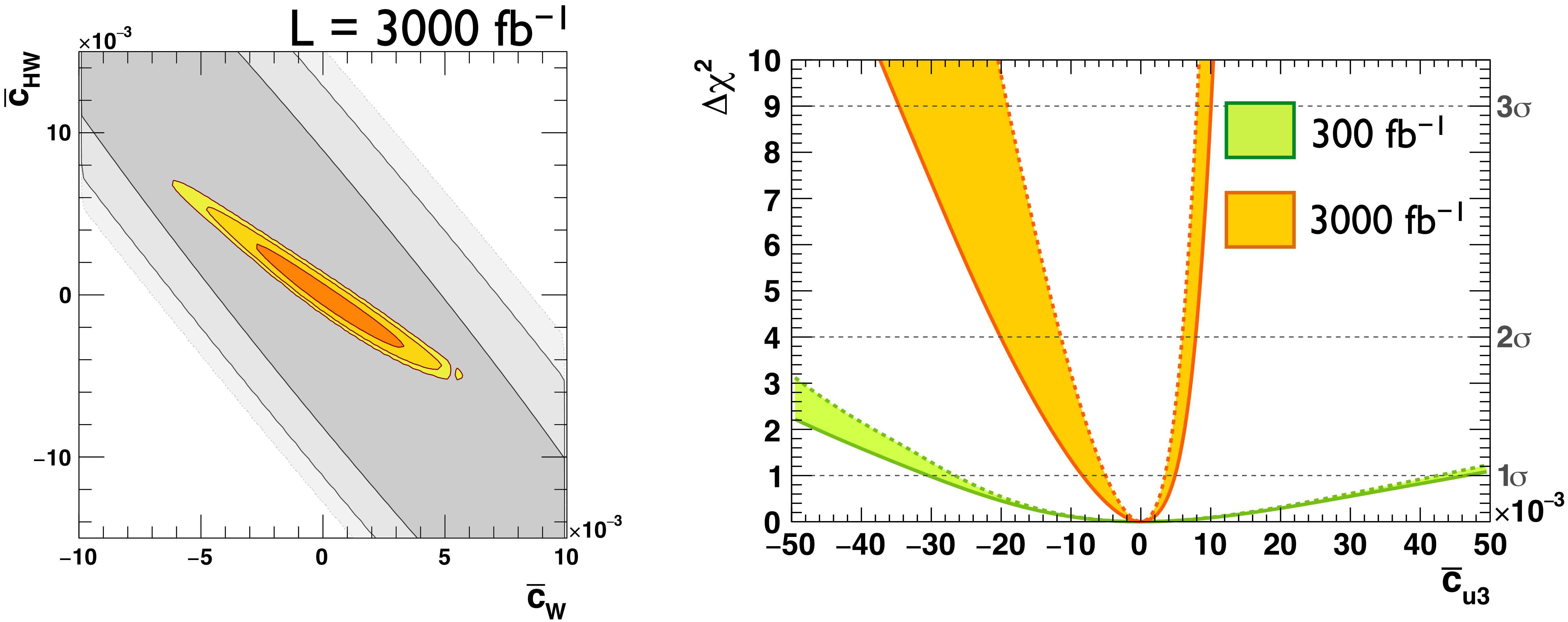
- Different behaviour at high energies
- Include differential measurements of $p_{T,H}$







Constraints from (HL-)LHC



only signal strength (46 meas. points)

including $p_{T,H}$ measurements (123 meas. points)

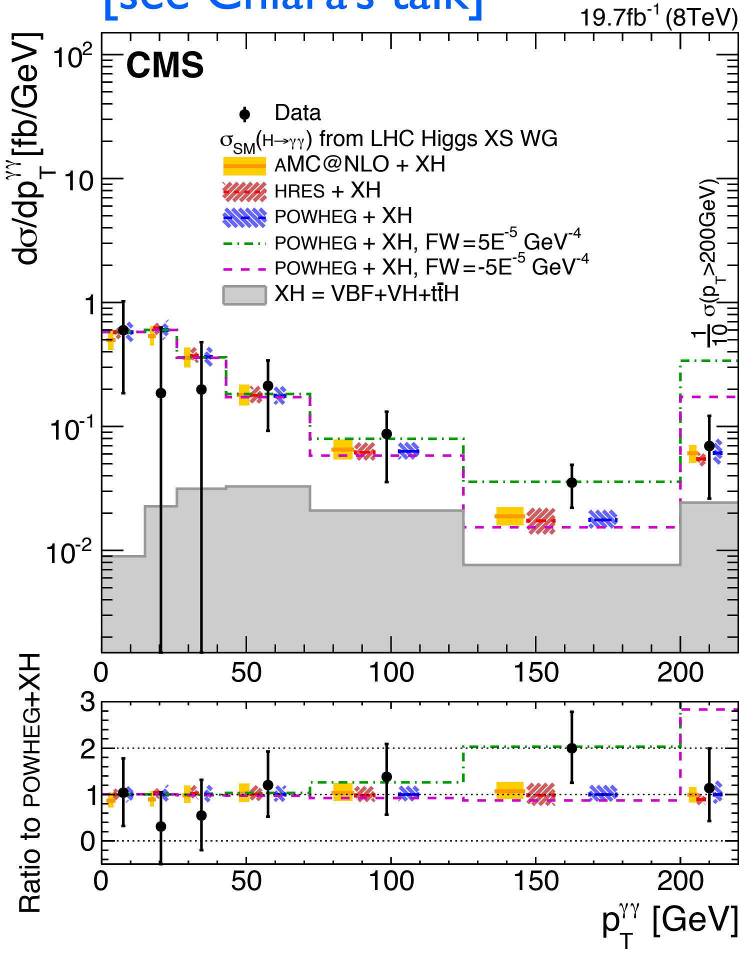
- Strong correlations between coefficients are lifted
- Simultaneous constraints on all parameters possible!

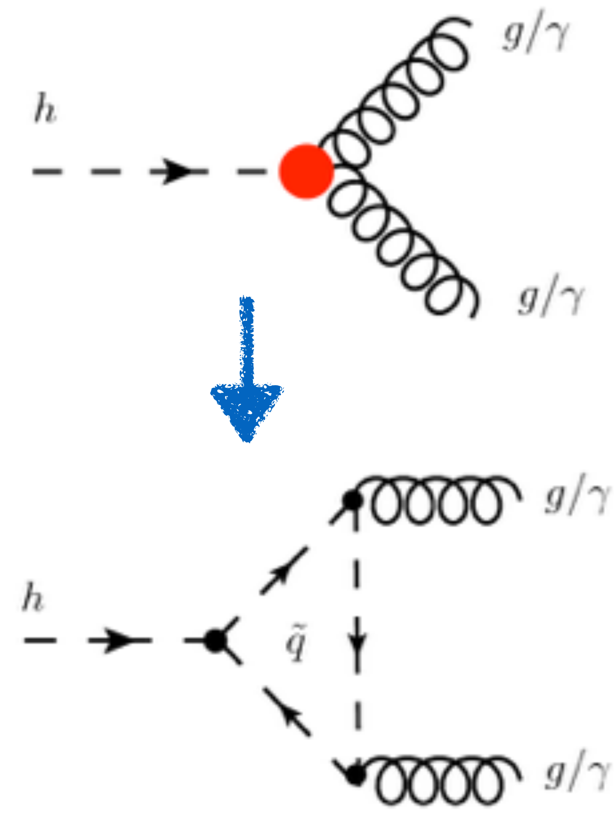
Present and Expected Constraints

Differential Cross Section Measurements

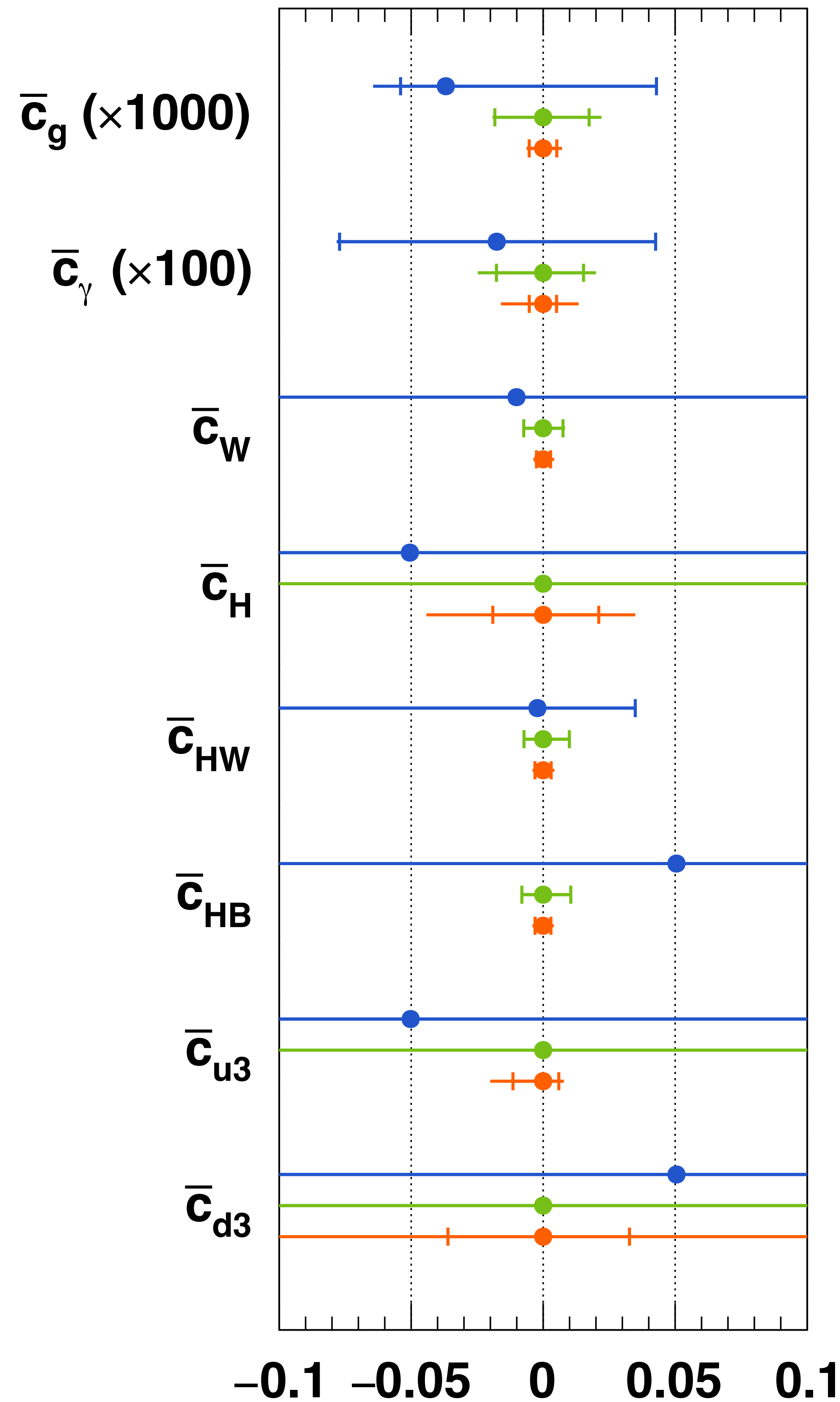
- Measure production and decay in all possible channels
- Only way to constrain full parameter space of dim-6 operator expansion

[see Chiara's talk]





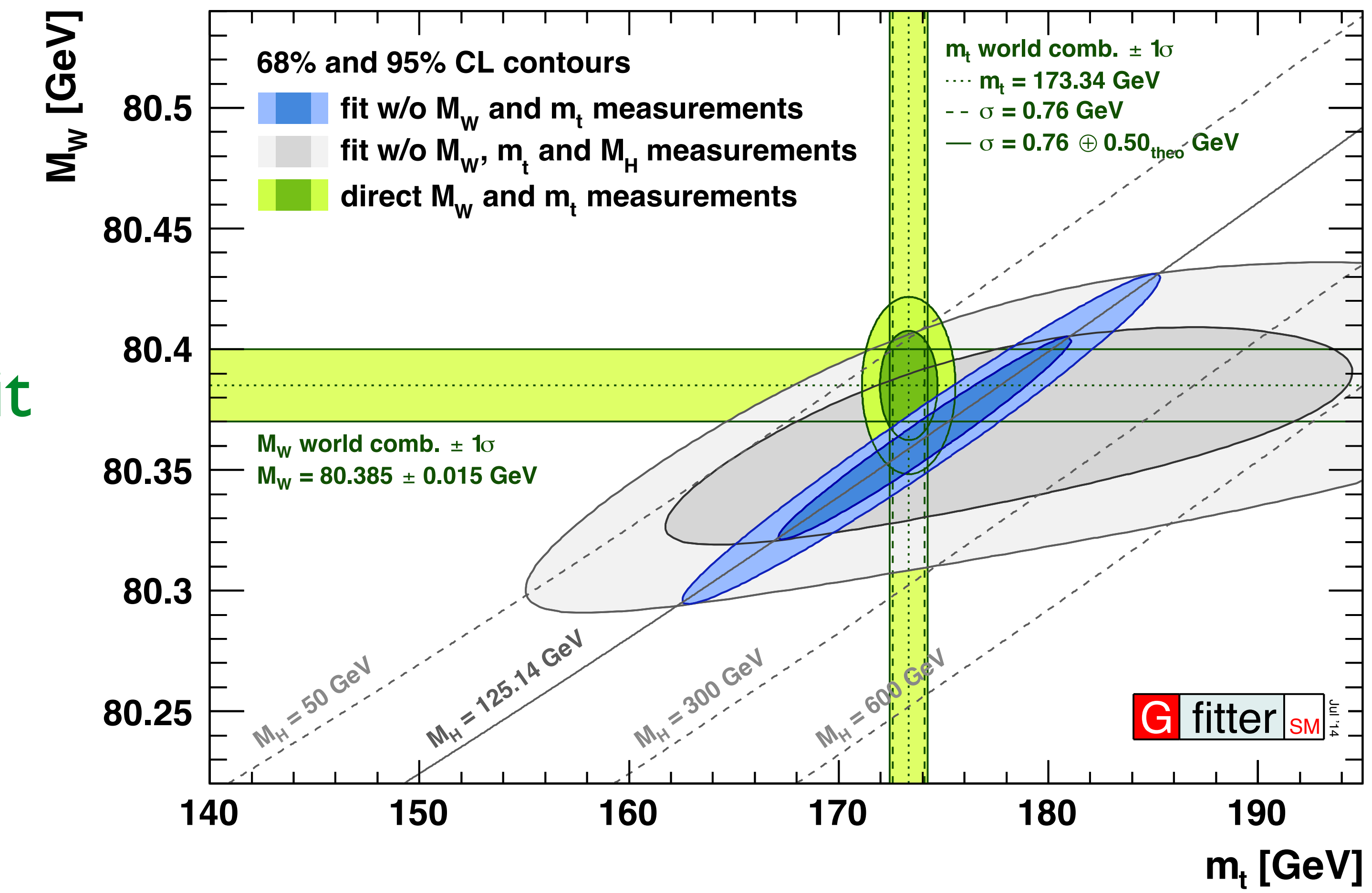
constrain full (UV complete) models



Summary

Paradigm change

- From the discovery of the Higgs boson to a probe of new physics
- M_H and two-loop calculations unprecedented precision of EW fit
- Cannot know M_W and $\sin^2\theta^l_{eff}$ precise enough
- BSM: 2HDM, dim-6 Ops, …
  - differential measurements



LHC 14 / 300 fb^{-1}

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

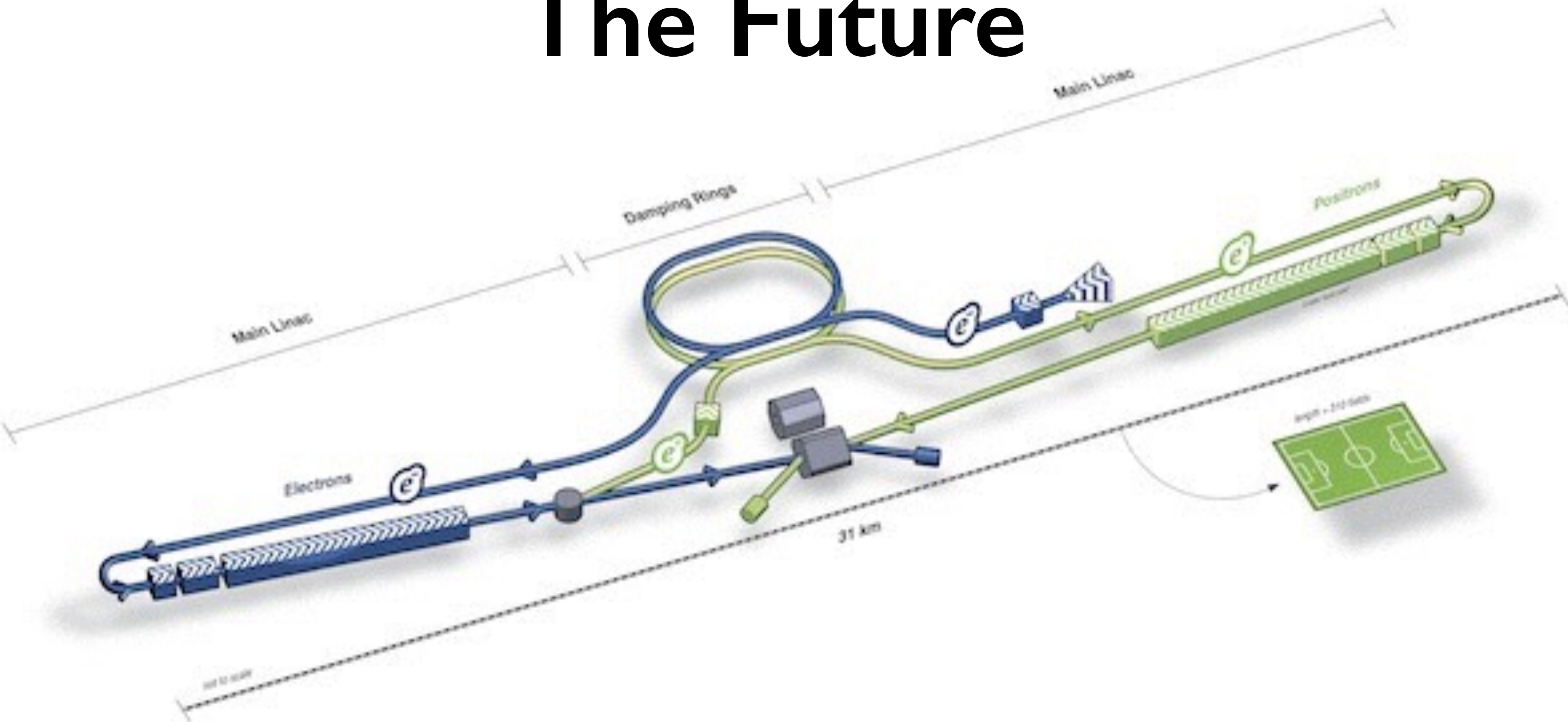
More information and latest results:
www.cern.ch/gfitter

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)

Additional Material

The Future



Main Linac
Damping Rings
Main Linac
Positrons
Electrons
31 km

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 →	4	4	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

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

- 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]

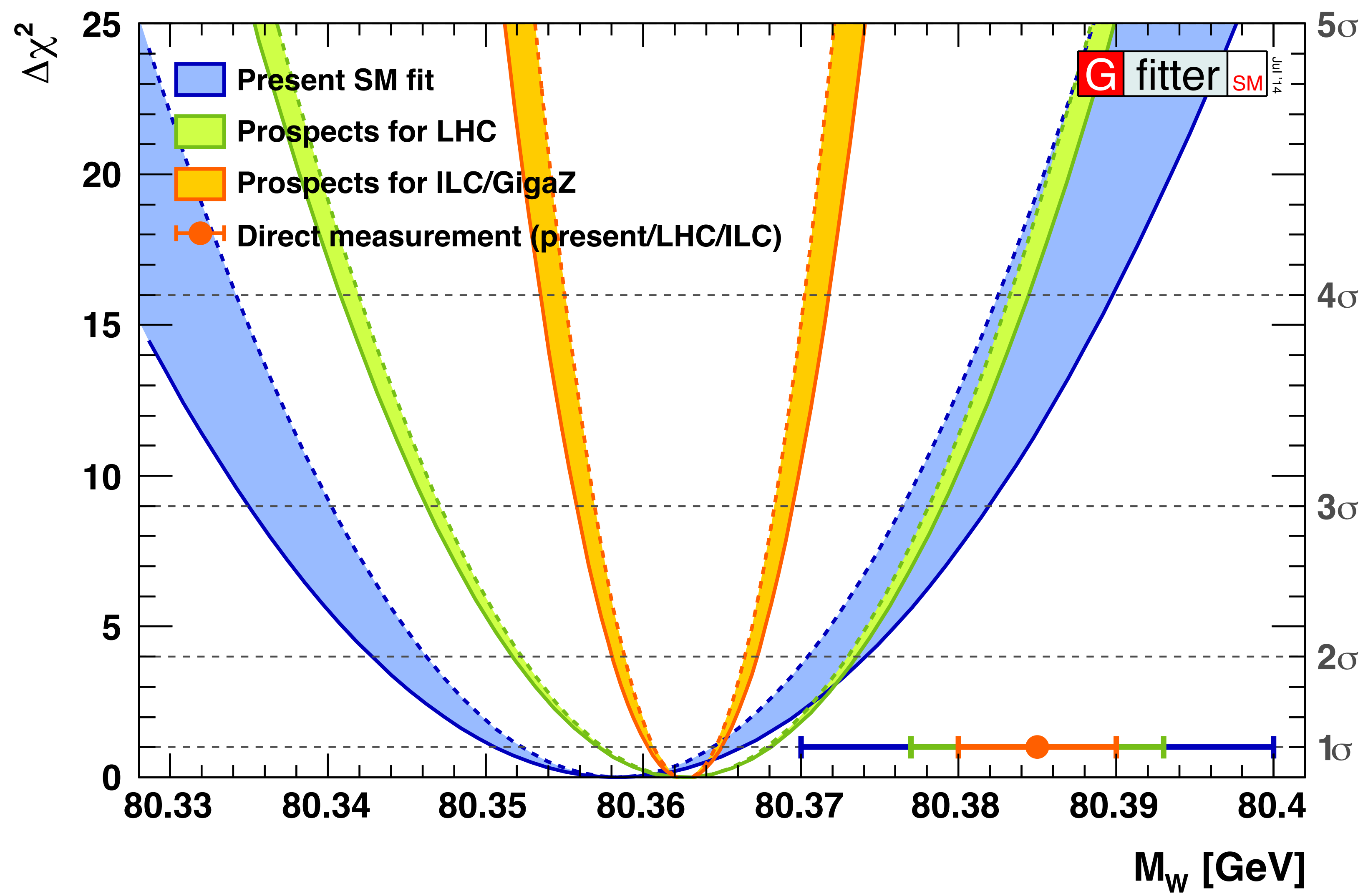
Future: M_W

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:

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

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

Measurement uncertainty for ILC: 5 MeV

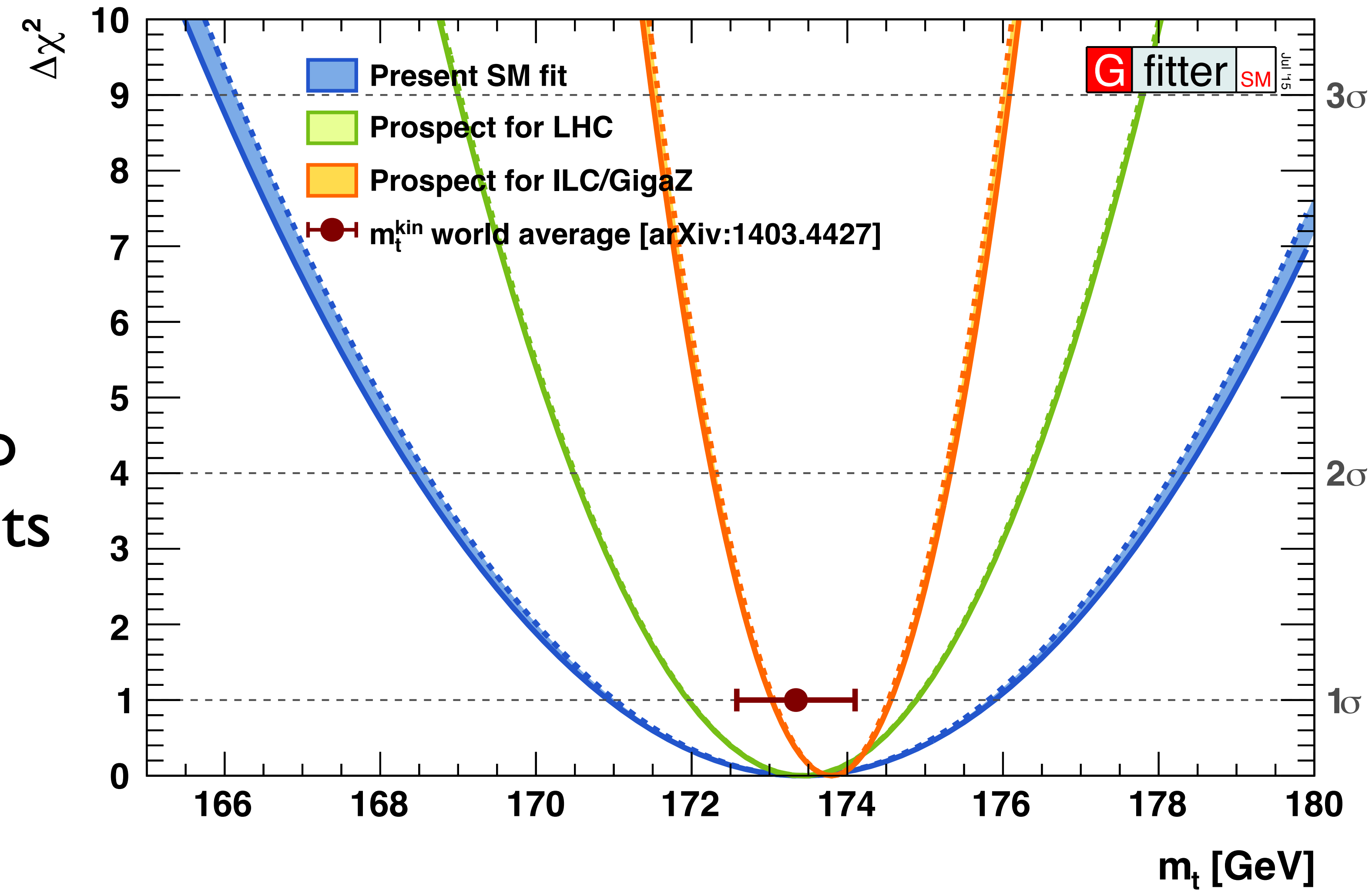
Future: Top Quark Mass

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:

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

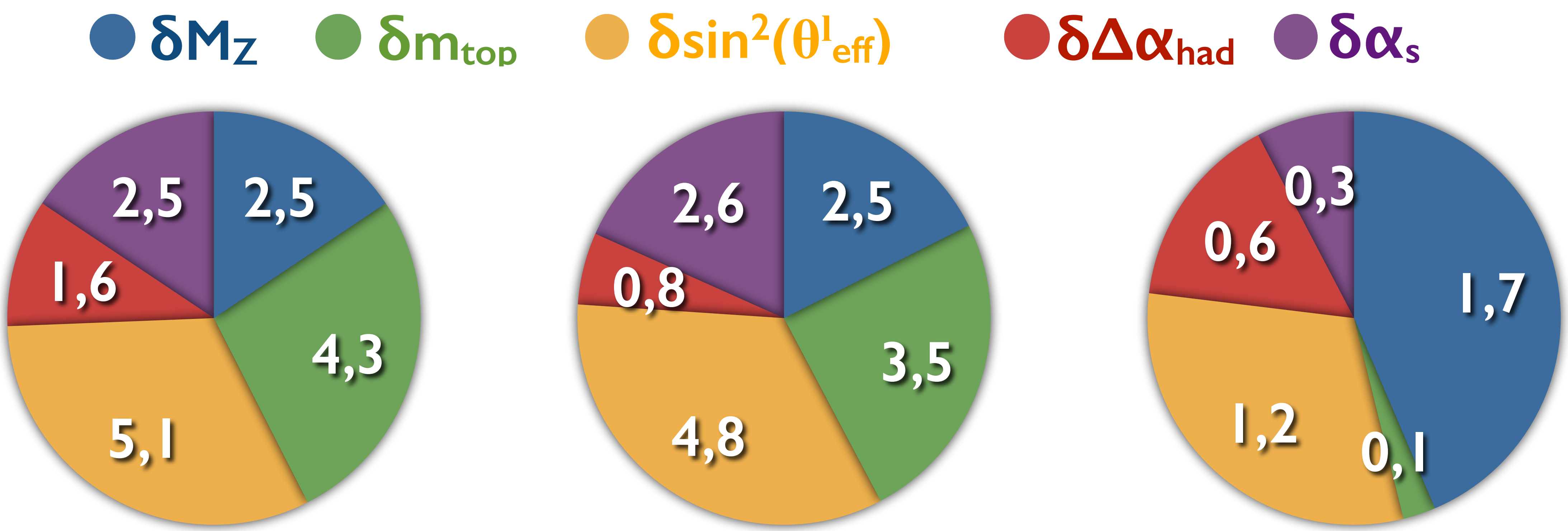
$$\delta m_t = \underline{0.2_{\rm theo}} \oplus \underline{0.7_{\rm exp}} \text{ GeV} = \underline{0.8_{\rm tot}} \text{ GeV}$$

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

Summary of Uncertainties

Uncertainties on M_W

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

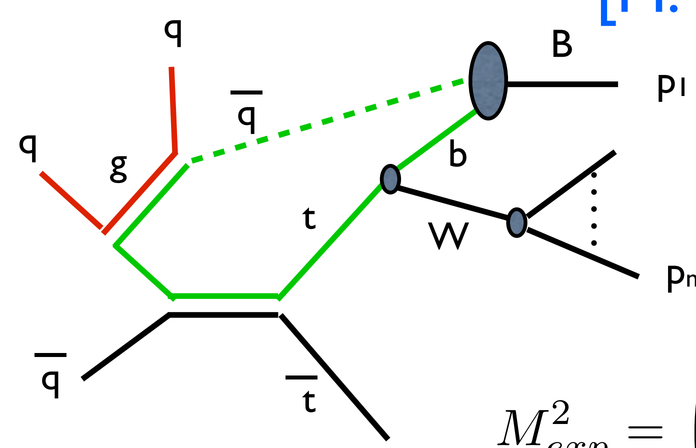
Interpreteation of m_t measurements

Accuracy of m_t ?

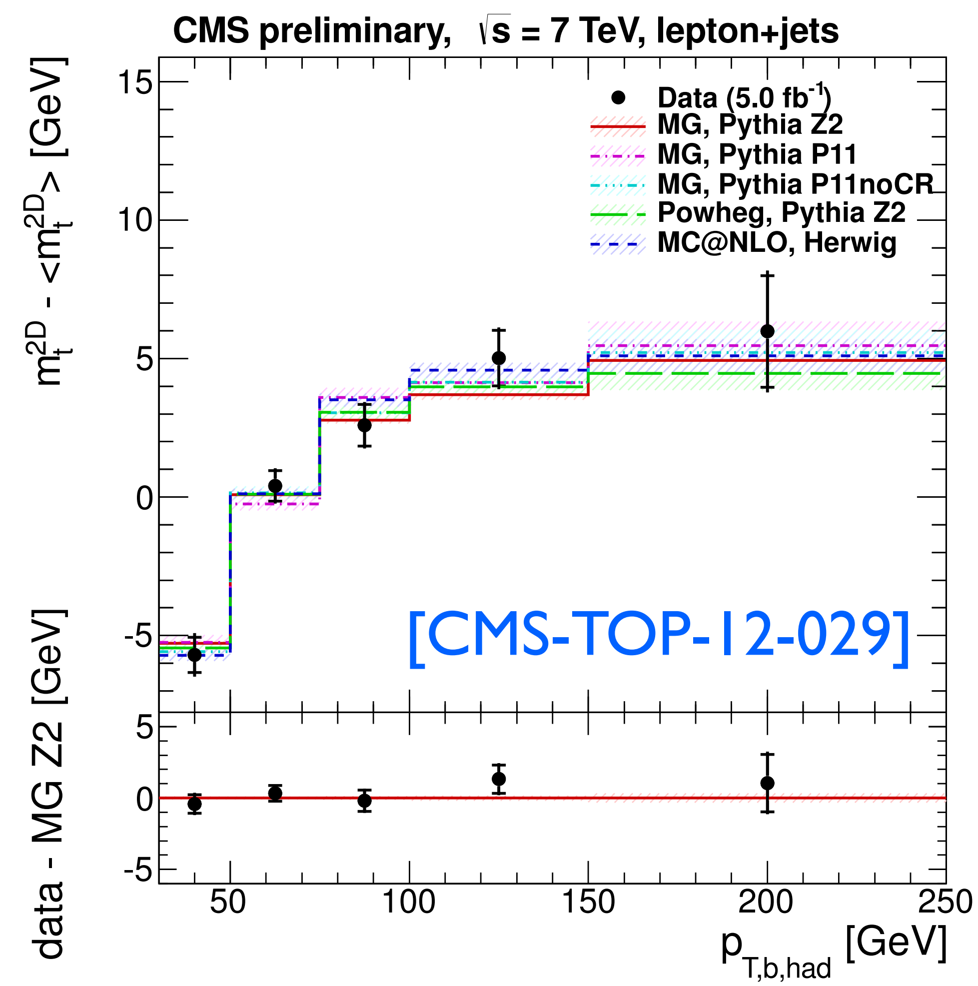
- kinematic top mass definition
  - factorization: hard function, universal jet-function, non-pert. soft function [Moch et al, arXiv:1405.4781]
  - MC mass is (may be) related to the low scale short-distance mass in the jet function
  - but: no quantitative statement available
  - relating m_t^{kin} 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]

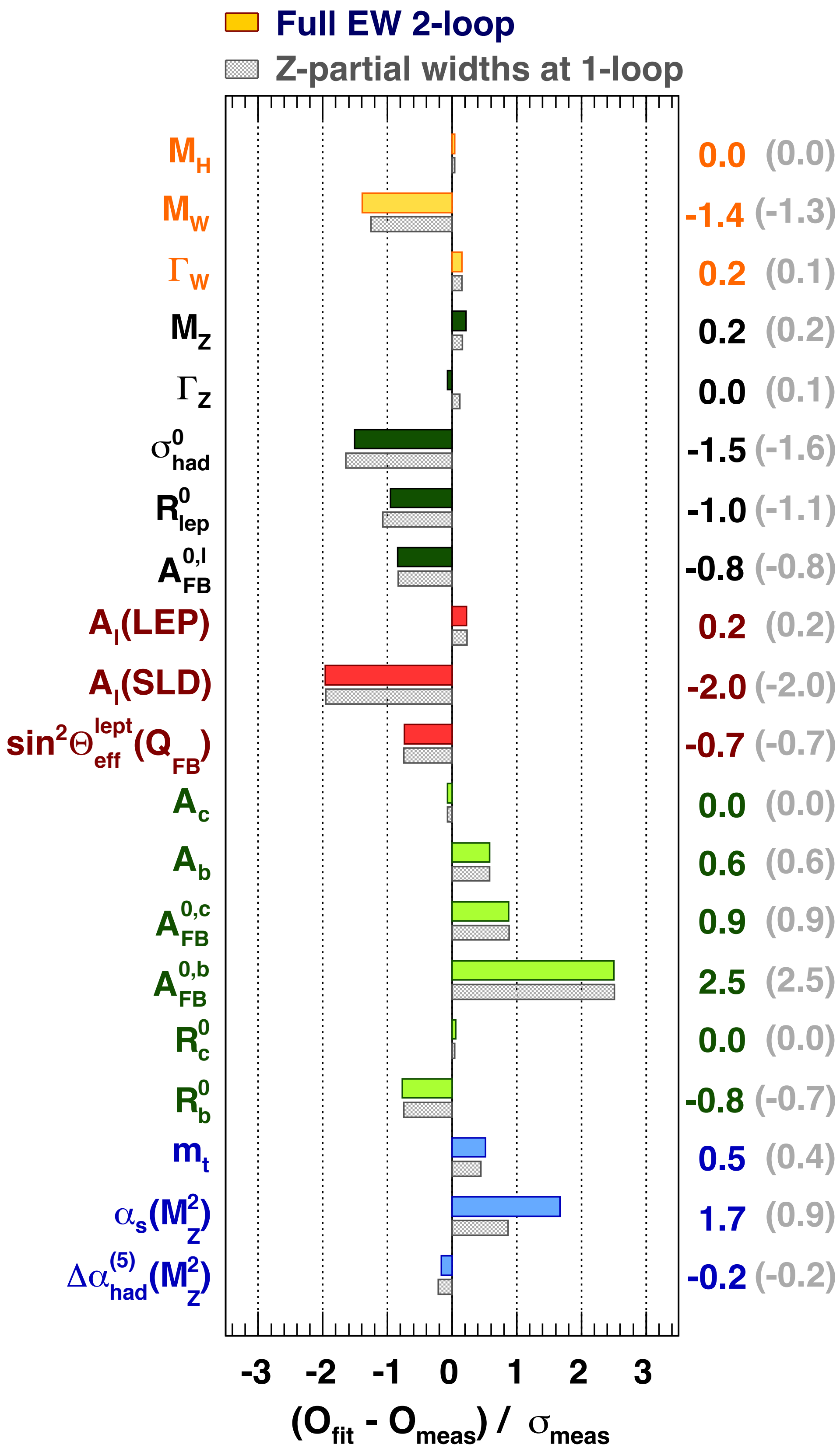
[M. Mangano]



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



SM Fit Results

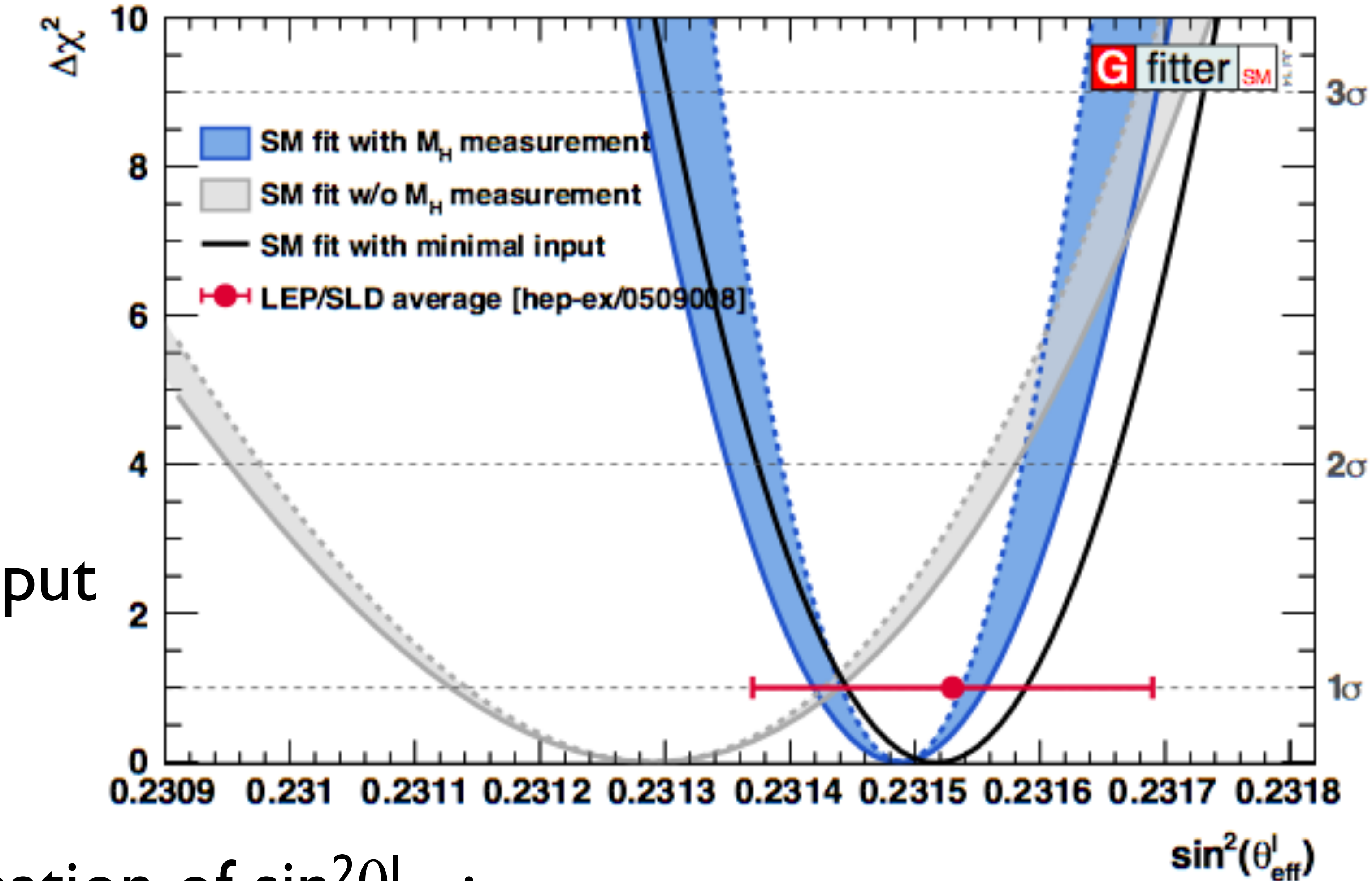


- no individual value exceeds 3σ
- largest deviations in b-sector:
  - $A^{0,b}_{FB}$ with 2.5σ
    → largest contribution to χ^2
- Small pulls for M_H, M_Z, m_c, m_b
  - input accuracies exceed fit requirements
- Goodness of fit, p-value:
  χ^2_{min}= 17.8 Prob(χ^2_{min}, 14) = 21%
  Pseudo experiments: 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

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 $\sin^2\theta^l_{eff}$:

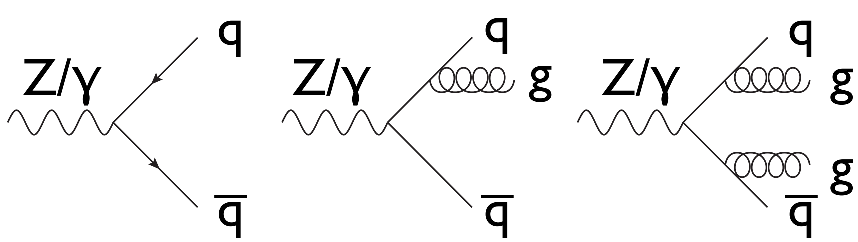
$$\begin{aligned}\sin^2\theta^\ell_{\rm eff} &= 0.231488 \pm \boxed{0.000024_{m_t}} \pm 0.000016_{\delta_{\rm theo} m_t} \pm 0.000015_{M_Z} \pm \boxed{0.000035_{\Delta\alpha_{\rm had}}} \\ &\qquad \pm 0.000010_{\alpha_S} \pm 0.000001_{M_H} \pm \boxed{0.000047_{\delta_{\rm theo}\sin^2\theta^f_{\rm eff}}}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

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

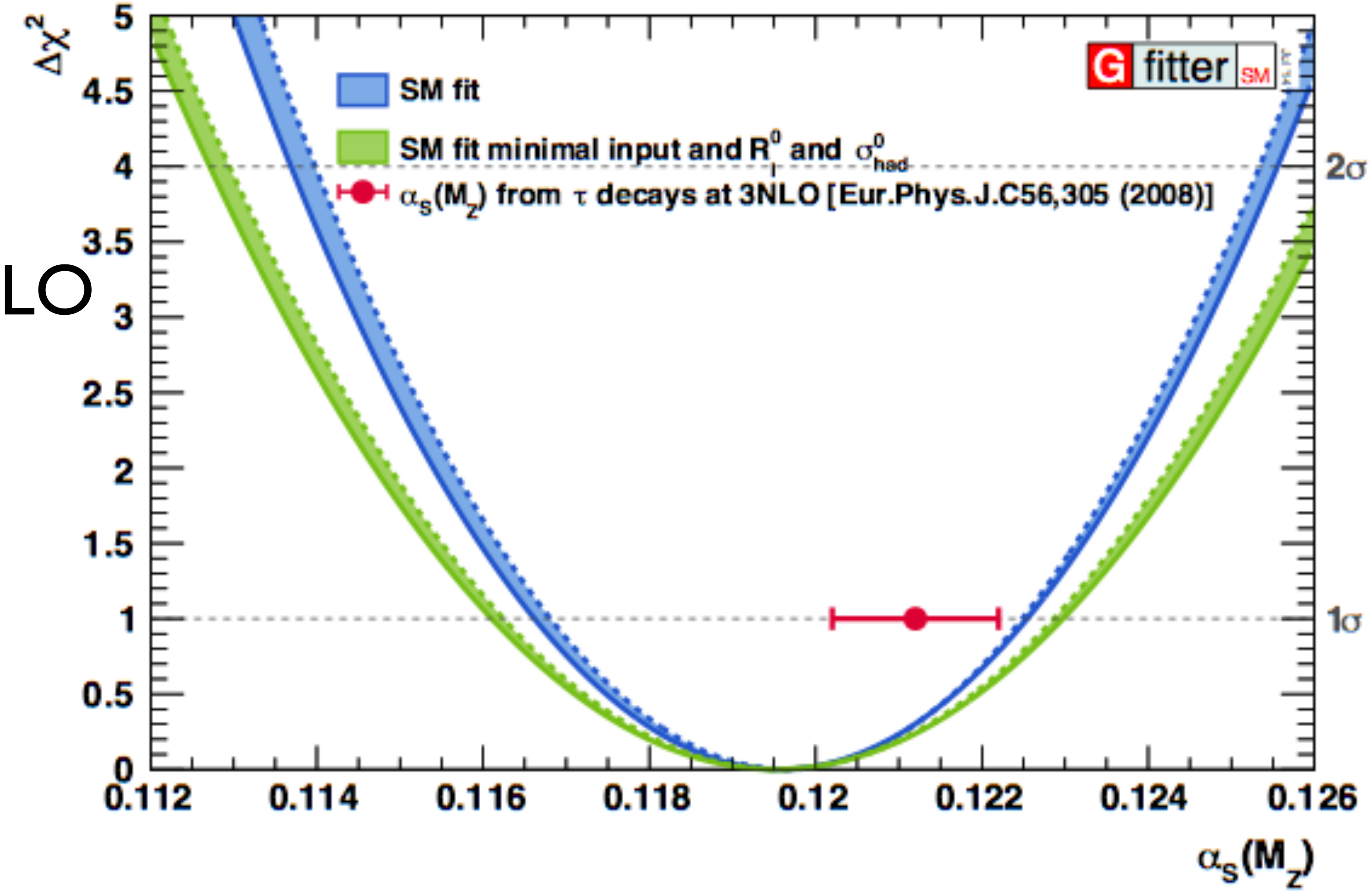
The strong coupling $\alpha_s(M_Z)$

$\Delta\chi^2$ 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



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

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

good agreement with WA, dominated by exp. uncertainty

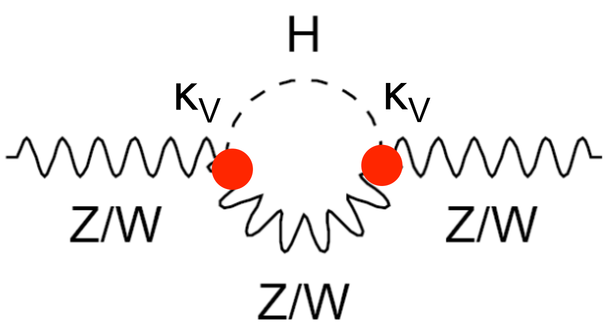
Modified Higgs Couplings

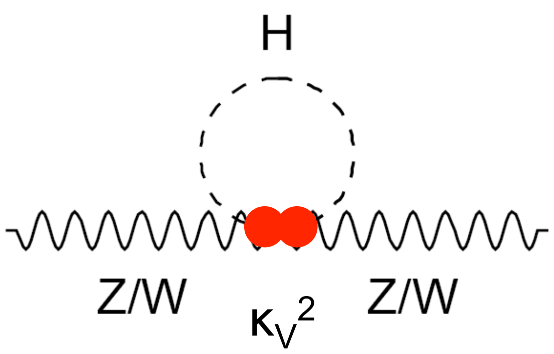
Study of potential deviations of Higgs couplings from SM

- BSM modelled as extension of SM through effective Lagrangian
  - Leading corrections only

$$L_V = \frac{h}{v}\left(2\kappa_V m_W^2 W_\mu W^\mu + \kappa_V m_Z^2 Z_\mu Z^\mu\right)$$
$$L_F = -\frac{h}{v}\left(\kappa_F m_t \bar{t}t + \kappa_F m_b \bar{b}b + \kappa_F m_\tau \bar{\tau}\tau\right)$$

- 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

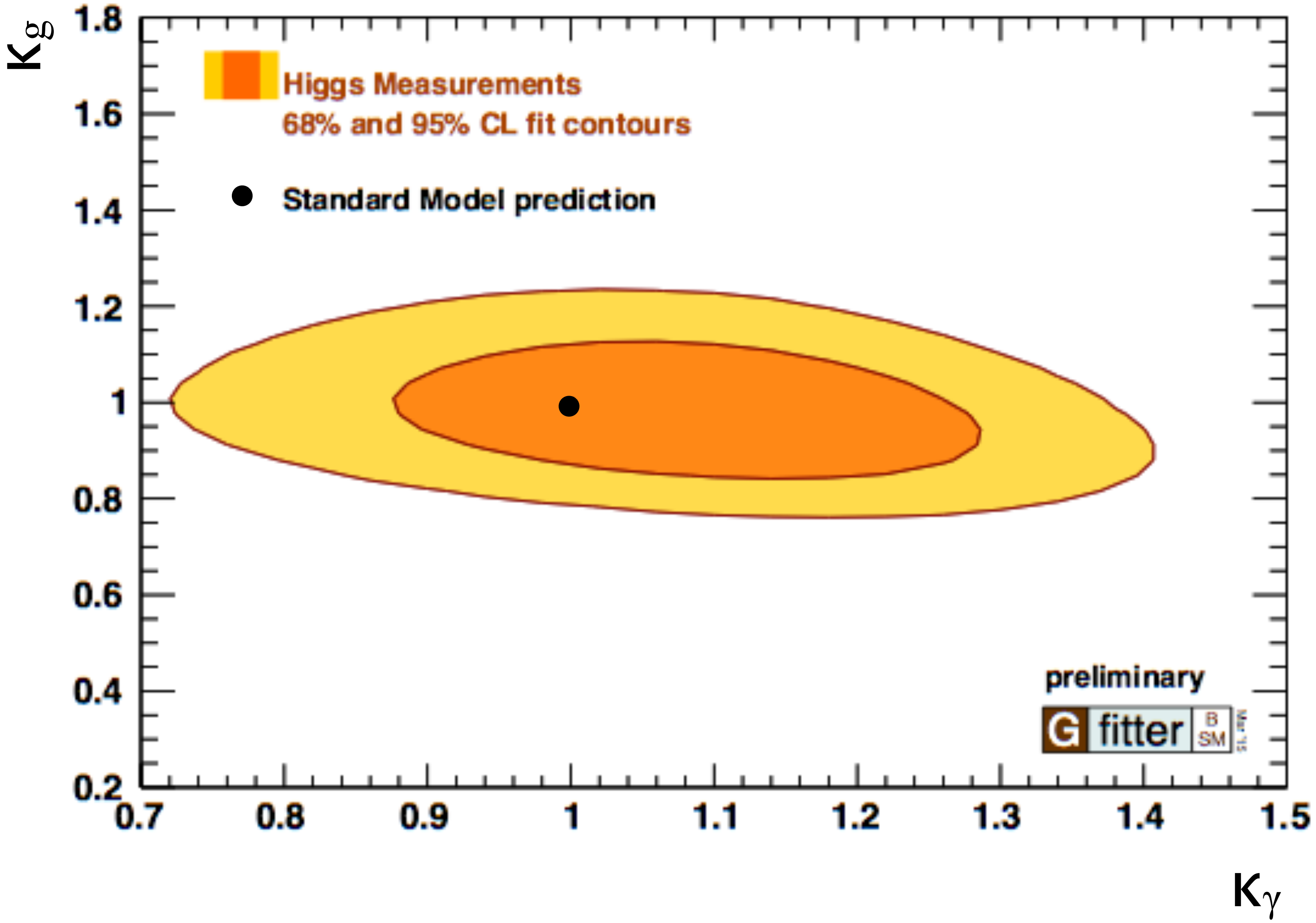




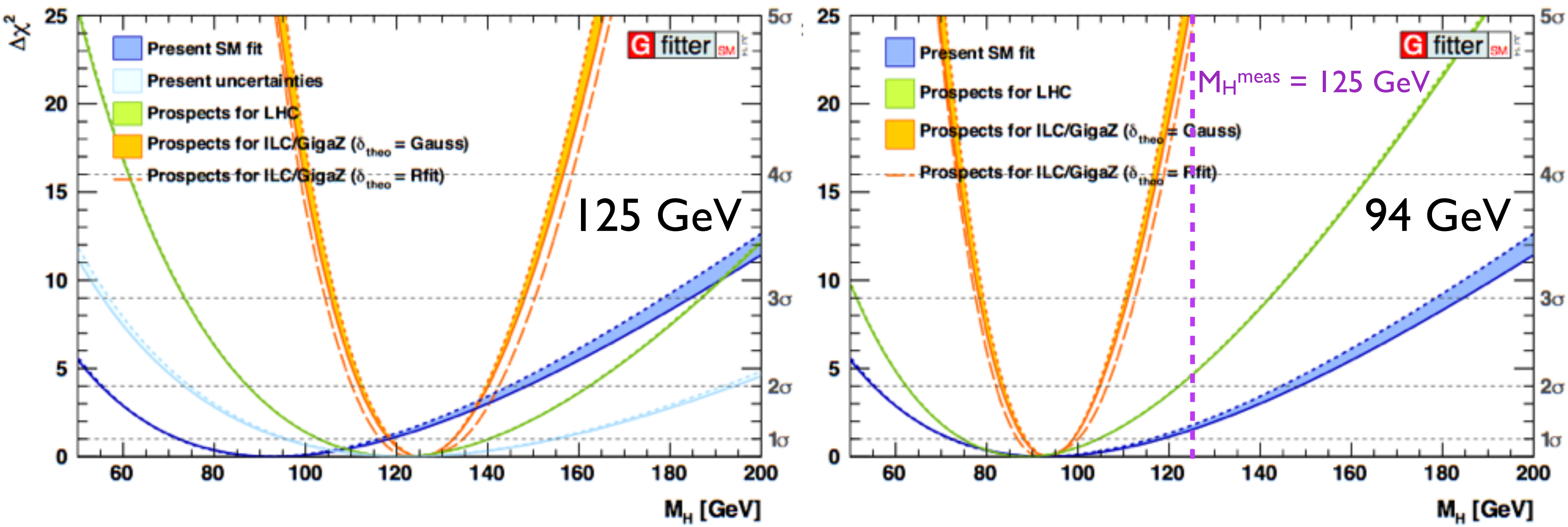
Higgs Couplings in Loops

- 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:
  - $\kappa_g = 0.99 \pm 0.15$
  - $\kappa_\gamma = 1.08 \pm 0.21$



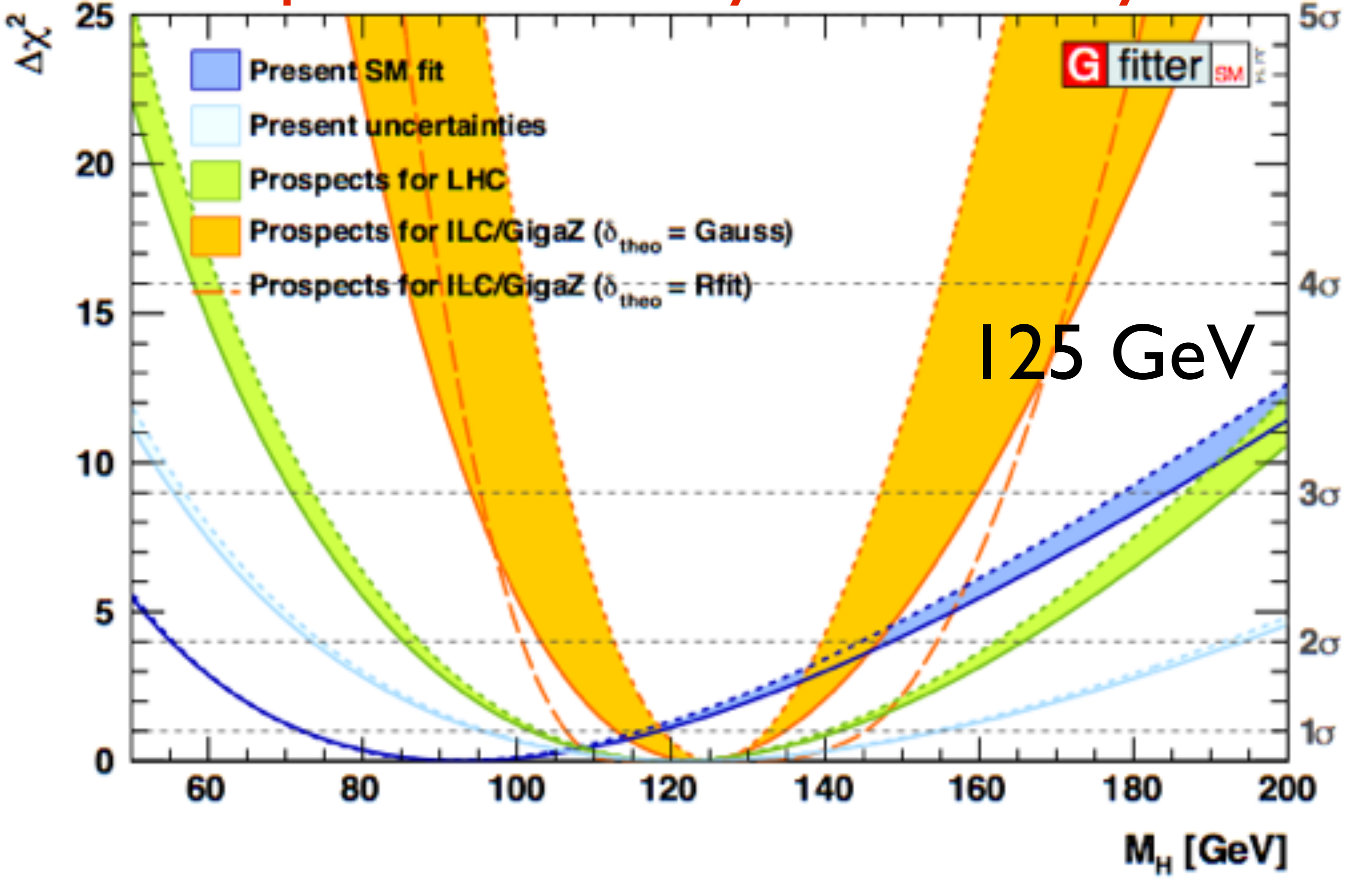
Future: Higgs Mass



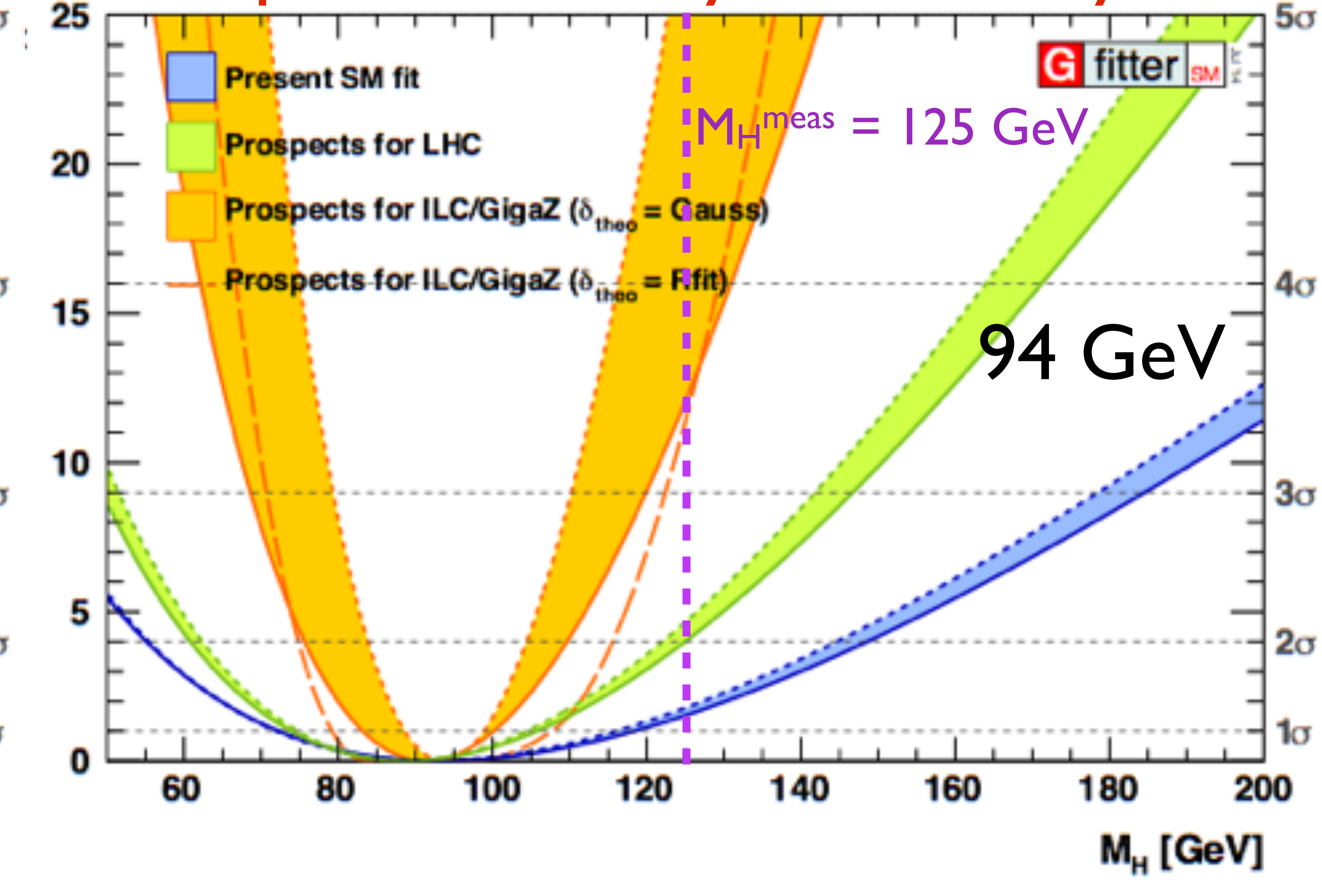
- Logarithmic dependency on M_H → cannot compete with direct M_H meas.
  - no theory uncertainty: $M_H = 125 \pm 7$ GeV
  - future theory uncertainty (Rfit): $M_H = 125\,^{+10}_{-9}$ GeV
  - present day theory uncertainty: $M_H = 125\,^{+20}_{-17}$ GeV
- If EWPO central values unchanged (94 GeV), ~5σ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

Future: Higgs Mass

present theory uncertainty



present theory uncertainty



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  - 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!

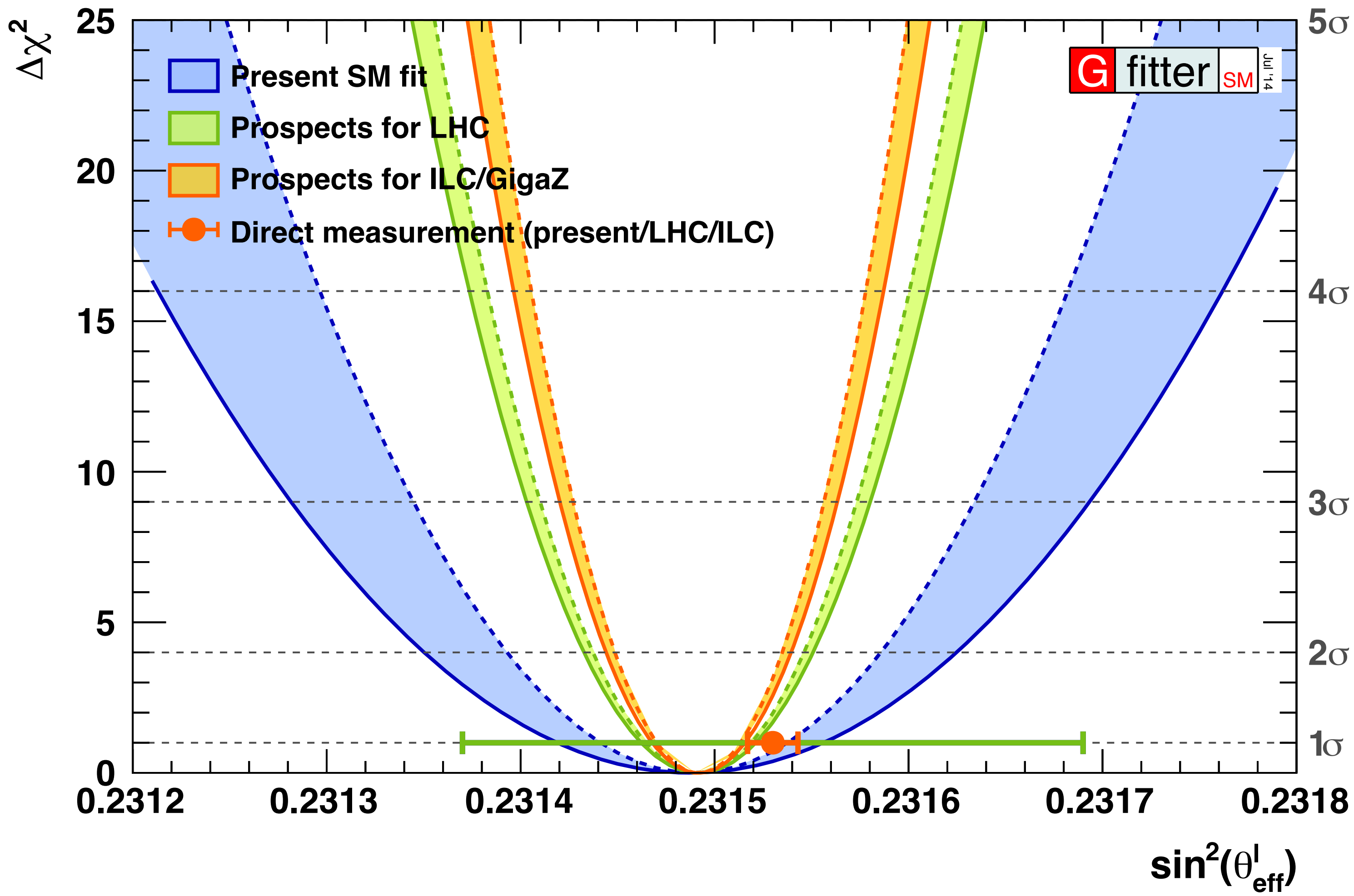
Future: Effective Weak Mixing Angle

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:

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

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

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

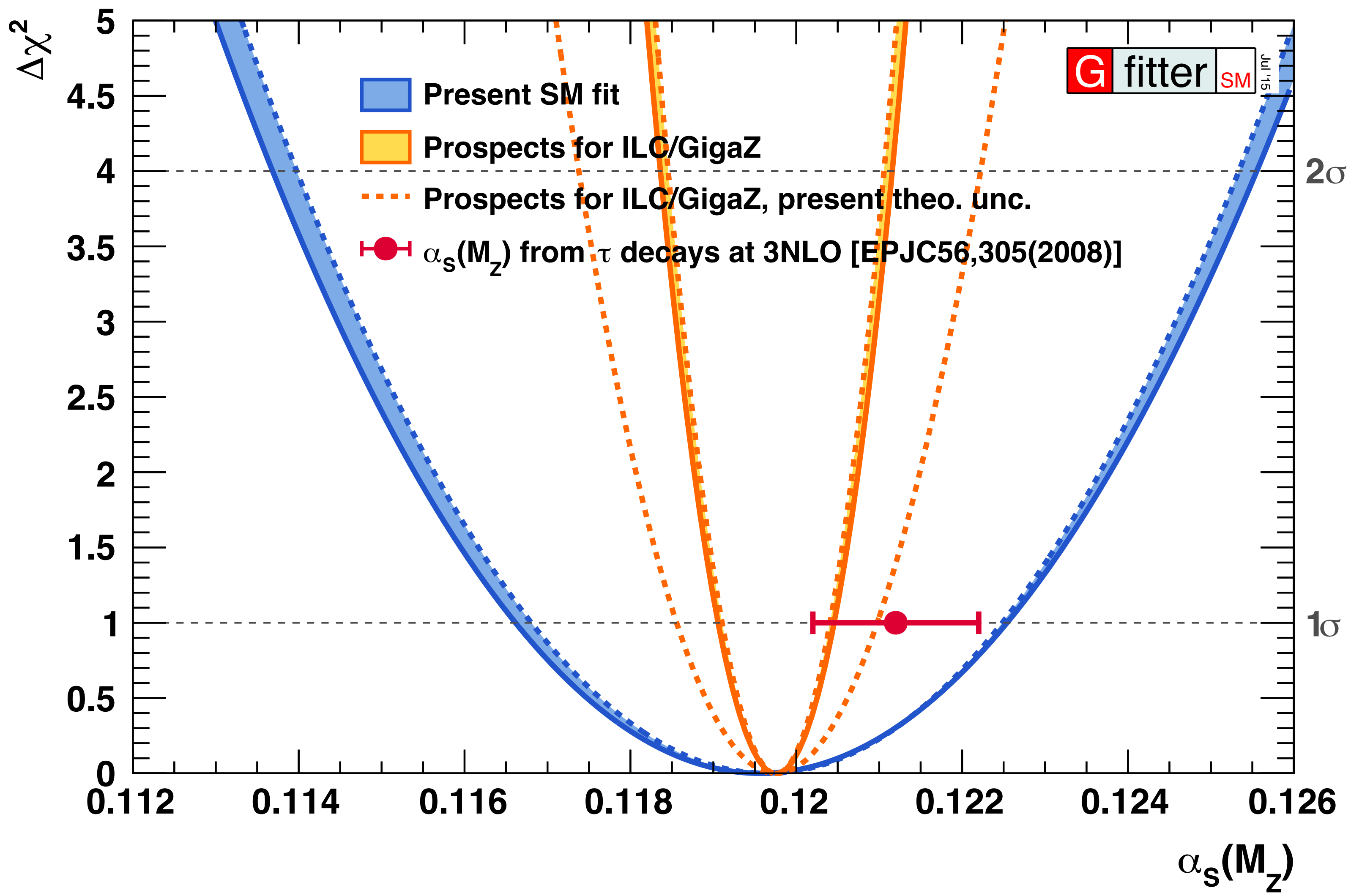
Future: the Strong Coupling $\alpha_s(M_Z)$

LHC-300 Scenario

- no improvement

ILC Scenario

- improvement of factor 4 or better possible
  - needs improvement from theory
  - present uncertainties: factor of 2.5 only



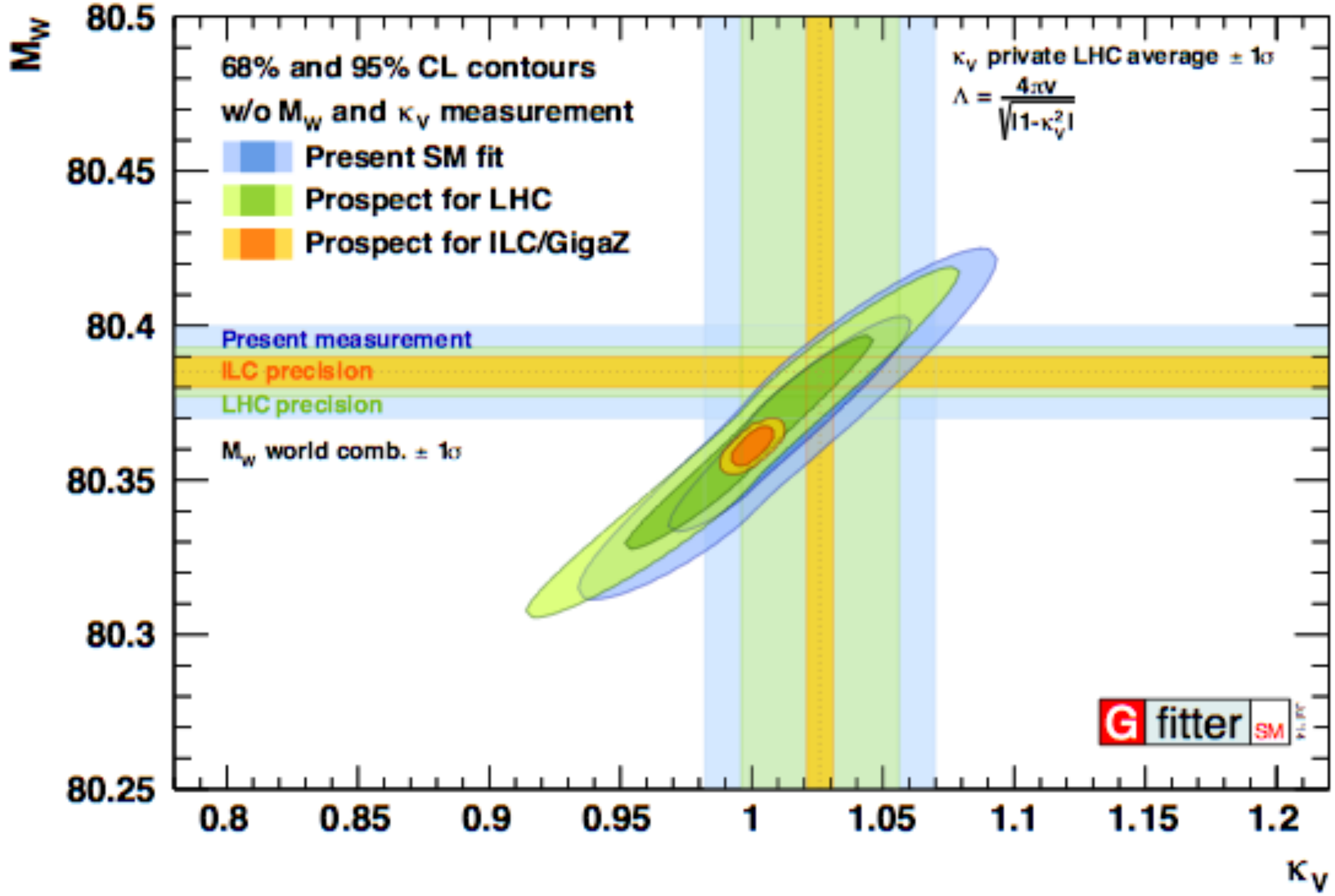
Fit Results:

$$\delta\alpha_s = (6.5_{\exp} \oplus 2.5_{\delta_{\text{theo}}\Gamma_i} \oplus 2.3_{\delta_{\text{theo}}\mathcal{R}_{V,A}}) \cdot 10^{-4}$$

$$\delta\alpha_s = (7.0_{\text{tot}}) \cdot 10^{-4}$$ (present theory uncertainty: $12.2 \cdot 10^{-4}$)

Promises most precise measurement of $\alpha_s(M_Z)$

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

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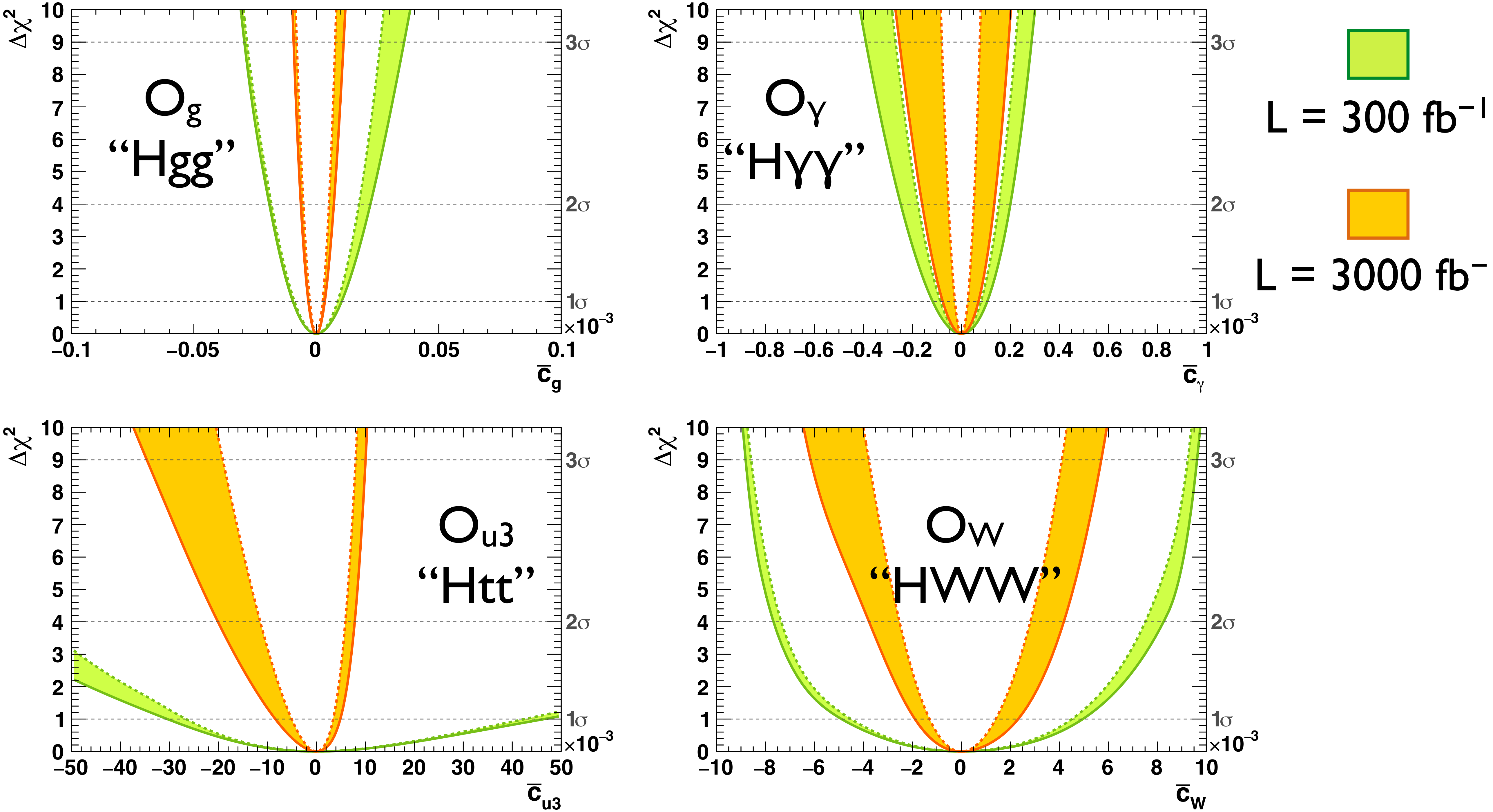
- Theory uncertainty needs to be reduced if we want to achieve the ultimate precision with the LHC!
- Future e^+e^- collider: fantastic possibilities for consistency tests of the SM on loop level and NP constraints

Constraints from HL-LHC

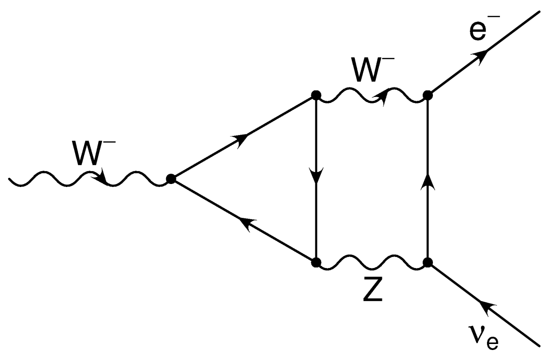


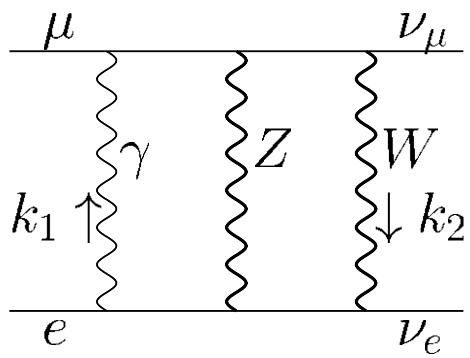
Much tighter constraints when using $p_{T,H}$ measurements!

Calculation of M_W

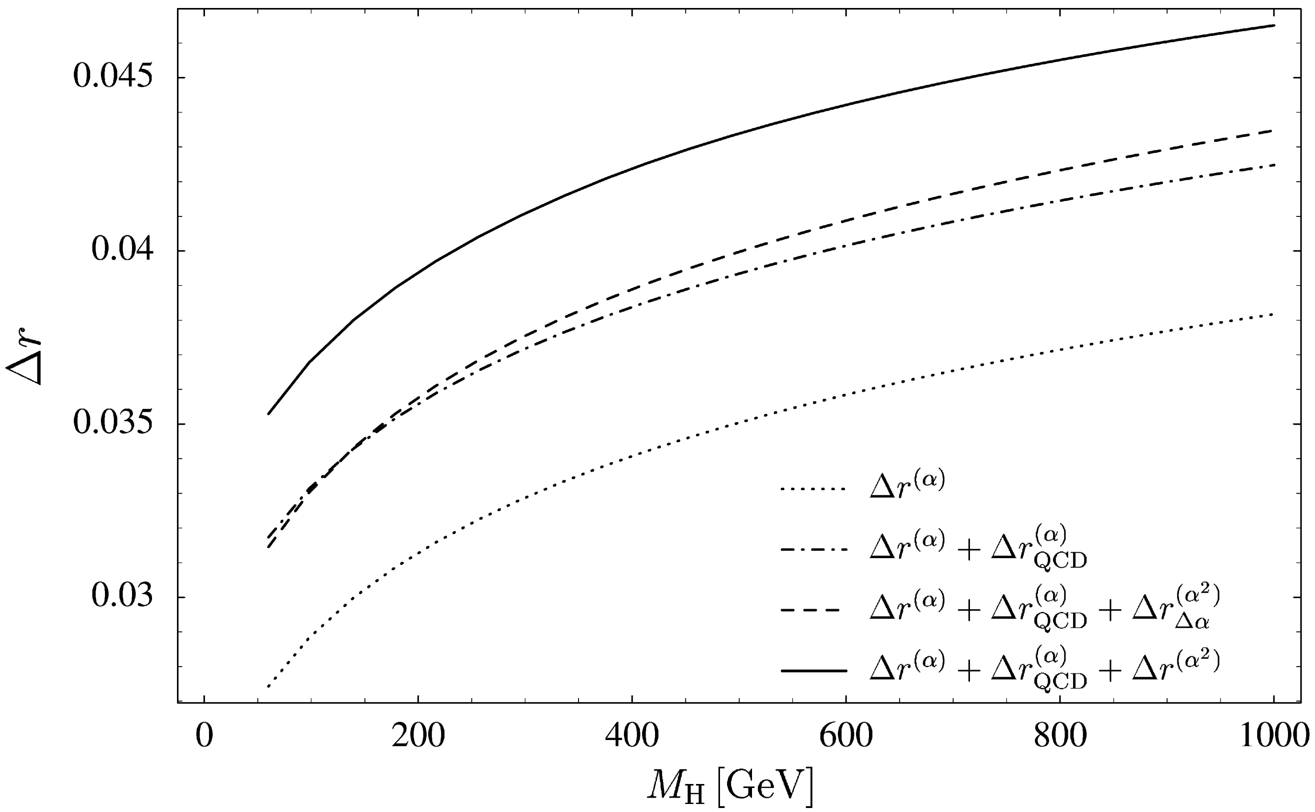
- Full EW one- and two-loop calculation of fermionic and bosonic contributions
- One- and two-loop QCD corrections and leading terms of higher order corrections
- Results for Δr include terms of order $O(\alpha)$, $O(\alpha\alpha_s)$, $O(\alpha\alpha_s^2)$, $O(\alpha^2{}_{\mathrm{ferm}})$, $O(\alpha^2{}_{\mathrm{bos}})$, $O(\alpha^2\alpha_s m_t^4)$, $O(\alpha^3 m_t^6)$
- 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 $\sin^2(\theta^l_{eff})$

- Effective mixing angle:

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

- 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:

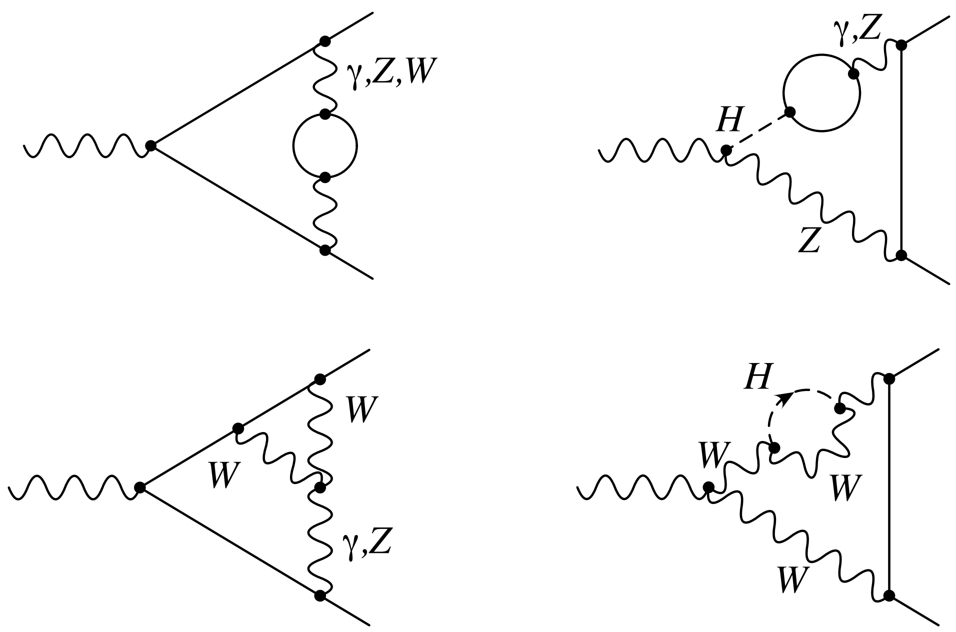
$$\mathcal{O}(\alpha^2\alpha_\text{s}) = \frac{\mathcal{O}(\alpha^2)}{\mathcal{O}(\alpha)}\,\mathcal{O}(\alpha\alpha_\text{s}).$$

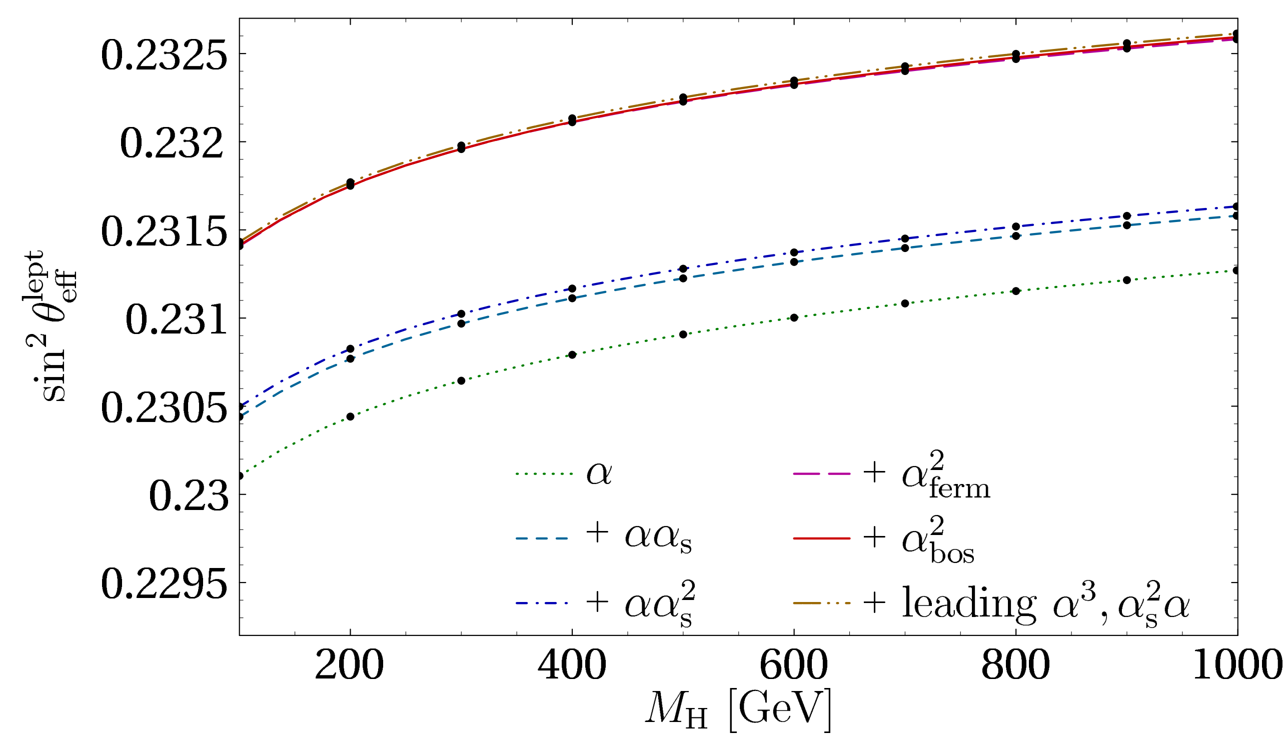
$\mathcal{O}(\alpha^2\alpha_\text{s})$ beyond leading m_t^4	$3.3\ldots2.8\times10^{-5}$
$\mathcal{O}(\alpha\alpha_\text{s}^3)$	$1.5\ldots1.4$
$\mathcal{O}(\alpha^3)$ beyond leading m_t^6	$2.5\ldots3.5$

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

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

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



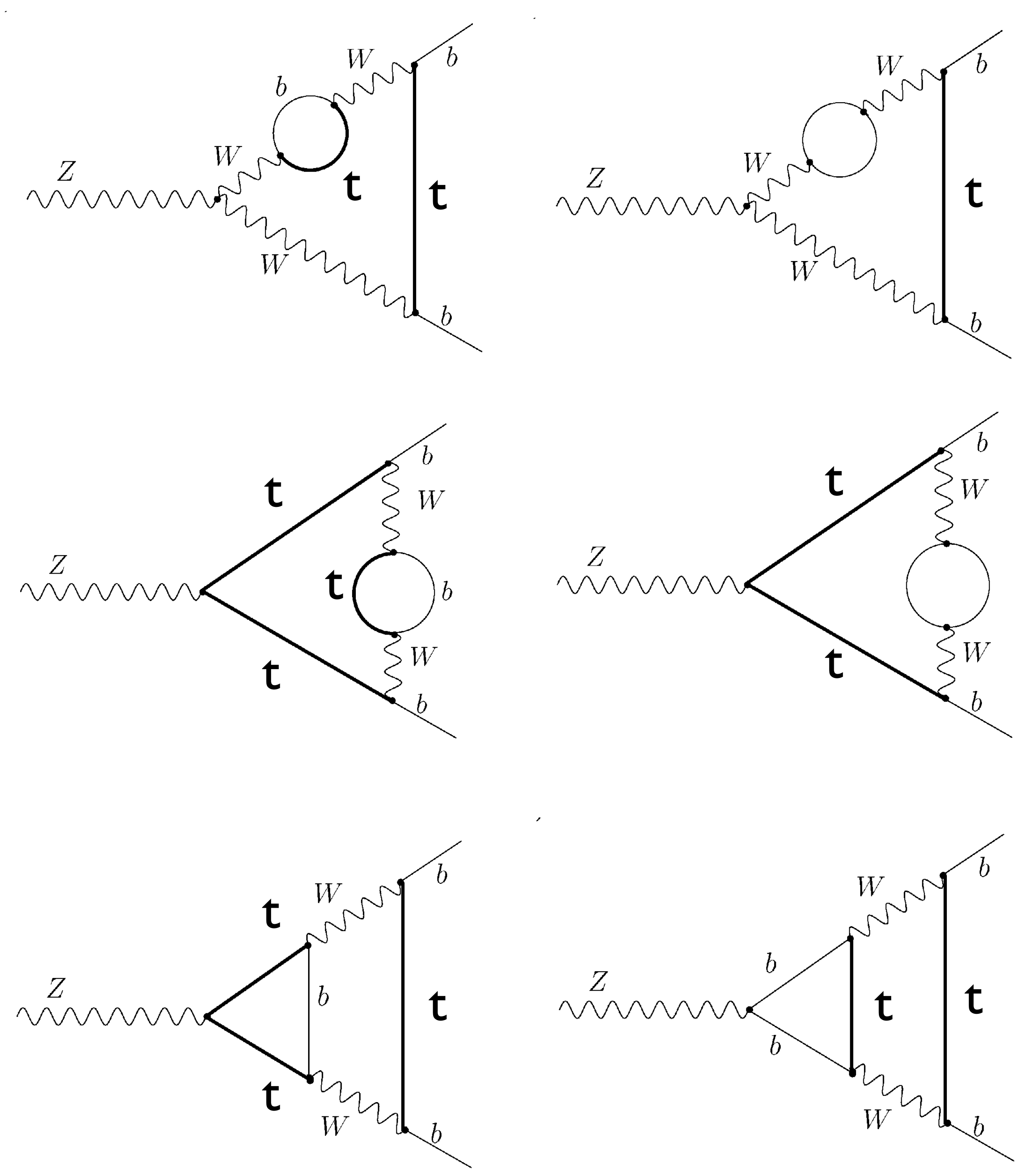


Calculation of $\sin^2(\theta^{bb}_{eff})$

[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 $Z \to b\bar{b}$ 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→b$\bar{\text{b}}$ [A. Freitas et al., JHEP 1208, 050 (2012) Erratum ibid. 1305 (2013) 074]

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

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

- 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]	$\mathcal{O}(\alpha) + \text{FSR}_{\alpha,\alpha_s,\alpha_s^2}$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\text{ferm}})$ $[10^{-4}]$	$\mathcal{O}(\alpha^2_{\text{ferm}}) + \text{FSR}_{\alpha_s^3,\alpha\alpha_s,m_b^2\alpha_s,m_b^4}$ $[10^{-4}]$	$\mathcal{O}(\alpha\alpha_s, \alpha\alpha_s^2)$ $[10^{-4}]$
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

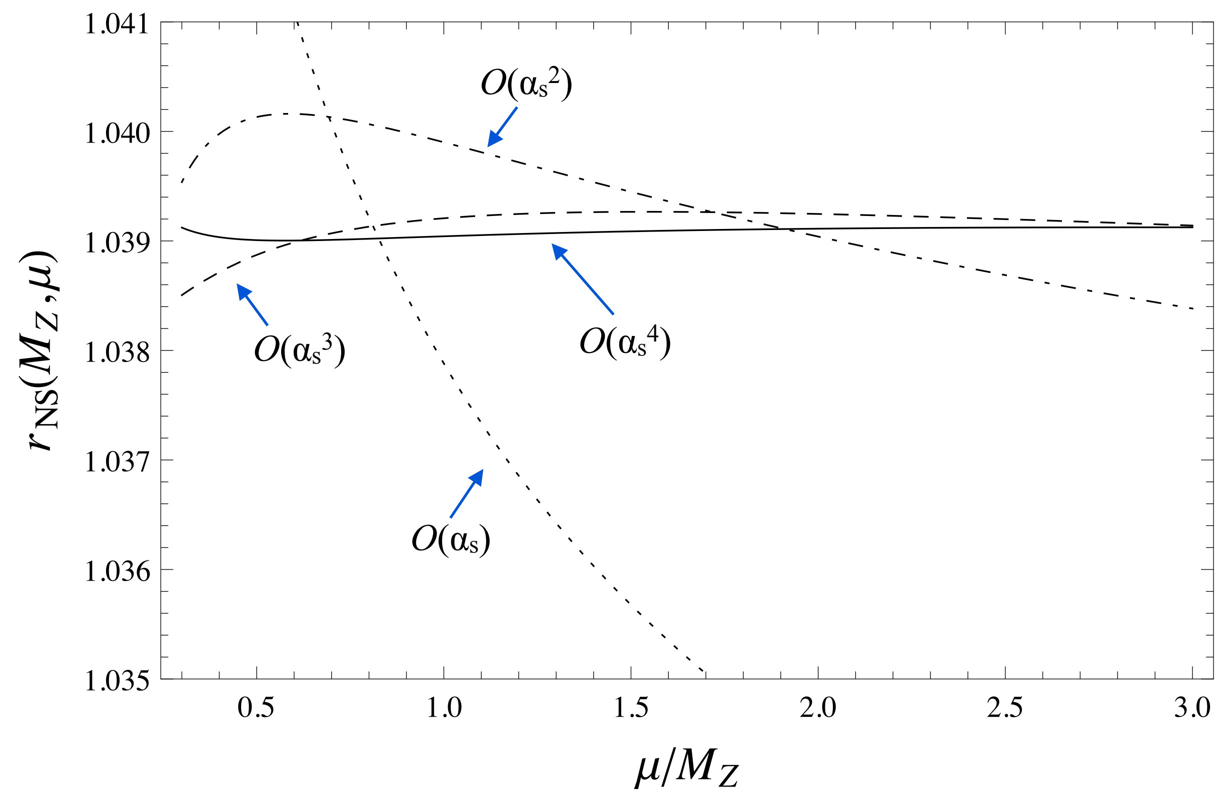
Radiator Functions

- 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)]