Theory Calculations of/for the W Boson Mass

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1. Introduction: Electroweak Precision Observables
2. Status and future of M_W in the SM
3. M_W in the MSSM
4. What precision do we want?
5. Conclusions

1. Introduction

Experimental situation:

LHC/ILC/FCC-ee/CEPC/. . . will provide (high!) accuracy measurements!

Theory situation:

– Measurements are performed using theory predictions

– measured observables have to be compared with theoretical predictions (in various models: SM, MSSM, . . .)

Full uncertainty is given by the (linear) sum of experimental and theoretical uncertainties!

My background: FCC-ee physics WG2 – Precision EW Calculations

Theoretical uncertainties for electroweak and Higgs-boson precision measurements at the FCC-ee

Conveners: A. Freitas[1], S. Heinemeyer[2],
Contributors: M. Beneke[3], A. Blondel[4], A. Hoang[5], P. Janot[6], J. Reuter[7], C. Schwinn[8], and S. Weinzierl[9]

⇒ Write-up as CDR contribution (only SM covered so far)

⇒ Many "theory numbers" are collider independent . . .

⇒ Here: SM numbers are based on this write-up
additional MSSM numbers as show-case

Where we need theory prediction:

1. Prediction of the measured quantity
   Example: M_W
   $\rightarrow$ at the same level or better as the experimental precision

2. Prediction of the measured process to extract the quantity
   Example: $pp \rightarrow W^+W^- \rightarrow$ 4f $\Rightarrow$ see Stefan's talk
   $\rightarrow$ better than then "pure" experimental precision

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Two types of theory uncertainties:

1. intrinsic: missing higher orders

2. parametric: uncertainty due to exp. uncertainty in SM input parameters
   Example: m_t, m_b, α_s, $\Delta\alpha_{\text{had}}$, ...

Combining uncertainties:

1. LHC/ILC/FCC-ee/CEPC/... (pure) experimental (anticipated) precision

2. Intrinsic uncertainties

3. Parametric uncertainties
   → taking into account the improved precision of SM paramters from LHC measurements

Total uncertainty:

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

Options for the evaluation of intrinsic uncertainties:

1. Determine all prefactors of a certain diagram class (couplings, group factors, multiplicities, mass ratios) and assume the loop is $\mathcal{O}(1)$

2. Take the known contribution at n-loop and $(n-1)$-loop and thus estimate the $n+1$-loop contribution:

$$\frac{(n+1)^{(\text{estimated})}}{n^{(\text{known})}} \approx \frac{n^{(\text{known})}}{(n-1)^{(\text{known})}}$$

   $\Rightarrow$ simplified example! Has to be done "coupling constant by coupling constant"

3. Variation of $\mu^{\overline{\text{MS}}}$ (QCD!, EW?)

4. Compare different renormalizations

$\Rightarrow$ Mostly used here: 1 & 2

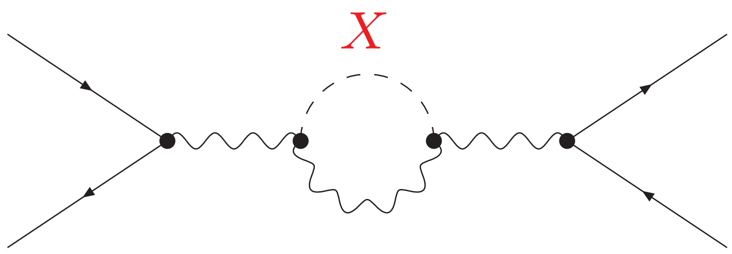
Electroweak Precision Observables

Comparison of observables with theory:

Precision data:		Theory:
$M_W, \sin^2\theta_{\rm eff}, a_\mu, M_h$	$\leftrightarrow$	SM, MSSM , . . .

$\Downarrow$

Test of theory at quantum level: Sensitivity to loop corrections, e.g. X



$\Downarrow$

SM: limits on M_H, BSM: limits on M_X

Very high accuracy of measurements and theoretical predictions needed

$\Rightarrow$ only models “ready” so far: SM, MSSM

The EWPO:

M_W (best from e^+e^- threshold scan)

$$\sigma^0_{\text{had}} = \sum_q \sigma_q(M_Z^2),$$

$$\Gamma_Z = \sum_f \Gamma[Z \to f\bar{f}],$$ (from a fit to $\sigma_f(s)$ at various values of s)

$$R_\ell = \left[\textstyle\sum_q \sigma_q(M_Z^2)\right]/\sigma_\ell(M_Z^2), \qquad (\ell = e, \mu, \tau)$$

$$R_q = \sigma_q(M_Z^2)/\left[\textstyle\sum_q \sigma_q(M_Z^2)\right], \qquad (q = b, c)$$

$$A^f_{\text{FB}} = \frac{\sigma_f(\theta < \frac{\pi}{2}) - \sigma_f(\theta > \frac{\pi}{2})}{\sigma_f(\theta < \frac{\pi}{2}) + \sigma_f(\theta > \frac{\pi}{2})} \equiv \frac{3}{4}\mathcal{A}_e\mathcal{A}_f,$$

$$A^f_{\text{LR}} = \frac{\sigma_f(P_e < 0) - \sigma_f(P_e > 0)}{\sigma_f(P_e < 0) + \sigma_f(P_e > 0)} \equiv \mathcal{A}_e|P_e|$$

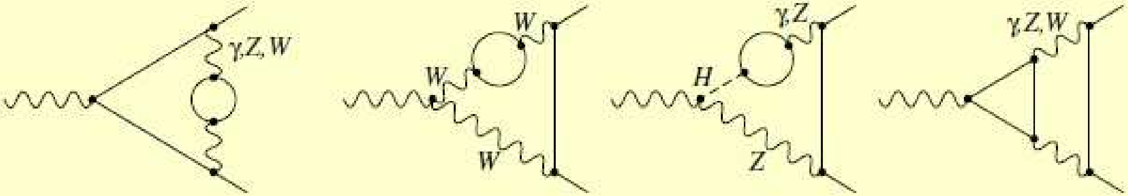
$$\mathcal{A}_f = 2\frac{g_{V_f}/g_{A_f}}{1 + (g_{V_f}/g_{A_f})^2} = \frac{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}}}{1 - 4|Q_f|\sin^2\theta^f_{\text{eff}} + 8(|Q_f|\sin^2\theta^f_{\text{eff}})^2} \quad (f = \ell, b, \ldots)$$

2. Status and future of M_W in the SM

Existing higher-order corrections to the EWPO

[taken from A. Freitas '16]

Known corrections to Δr, $\sin^2\theta^f_{\text{eff}}$, g_{Vf}, g_{Af}:



- Complete NNLO corrections (Δr, $\sin^2\theta^\ell_{\text{eff}}$) Freitas, Hollik, Walter, Weiglein '00
  Awramik, Czakon '02; Onishchenko, Veretin '02
  Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
  Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14
- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14
- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ Chetyrkin, Kühn, Steinhauser '95
  Faisst, Kühn, Seidensticker, Veretin '03
  Boughezal, Tausk, v. d. Bij '05
  Schröder, Steinhauser '05; Chetyrkin et al. '06
  ($\alpha_t \equiv \frac{y_t^2}{4\pi}$) Boughezal, Czakon '06

Current intrinsic uncertainties:

Quantity	current experimental unc.	current intrinsic unc.	
M_W [MeV]	15	4	$(\alpha^3, \alpha^2\alpha_s)$
$\sin^2\theta^{\ell}_{\text{eff}}$ $[10^{-5}]$	16	4.5	$(\alpha^3, \alpha^2\alpha_s)$
Γ_Z [MeV]	2.3	0.5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$
R_b $[10^{-5}]$	66	15	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$
R_l $[10^{-3}]$	25	5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$

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Current parametric uncertainties:

Quantity	$\delta m_t = 0.9$ GeV	$\delta(\Delta\alpha_{\rm had}) = 10^{-4}$	$\delta M_Z = 2.1$ MeV
$\delta M_W^{\rm para}$ [MeV]	5.5	2	2.5
$\delta \sin^2\theta^{\ell,{\rm para}}_{\rm eff}$ [10^{-5}]	3.0	3.6	1.4

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$\Rightarrow$ Current intrinsic/parametric uncertainties are substantially smaller than current experimental uncertainties :-)

Our future estimates:

- assume to go substantially beyond what is known now
- assume that many theorists will put many^2 hours of work into it in the next $\mathcal{O}(20)$ years (motivation?)
- do not assume that magically new calculational methods are invented
- are overall optimistic

$\Rightarrow$ they should be taken seriously!

Saying "Ah, theorists will have to work a bit harder and solve this" is not a realistic option!

Future intrinsic uncertainties:

Quantity	Current intrinsic unc.		Projected unc.
M_W [MeV]	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\rm eff}$ [10^{-5}]	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b [10^{-5}]	15	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	7
R_l [10^{-3}]	5	$(\alpha^2_{\rm bos}, \alpha^3, \alpha^2\alpha_s)$	1.5

These calculations are required for the projection:

– complete $\mathcal{O}\left(\alpha\alpha_s^2\right)$ corrections
– fermionic $\mathcal{O}\left(\alpha^2\alpha_s\right)$ corrections
– double-fermionic $\mathcal{O}\left(\alpha^3\right)$ corrections
– leading four-loop corrections enhanced by the top Yukawa coupling
– the $\mathcal{O}\left(\alpha^2_{\rm bos}\right)$ corrections are not the leading uncertainties now

For these calculations, qualitatively new developments of existing loop integration techniques will be required, but no conceptual paradigm shift.

Parametric uncertainties:

1. M_H: ~ 100 MeV $\Rightarrow$ negligible

2. M_Z: ~ 2.1 MeV $\Leftarrow e^+e^-$ improvement important?!

3. $\alpha_s(M_Z)$: better than ~ 0.001 $\Rightarrow$ negligible??
   $\Leftarrow e^+e^-$ improvement important?!

4. m_t: maybe down to ~ 0.5 GeV at the LHC
   $\Leftarrow e^+e^-$ improvement important?!

5. m_b: from lattice calculations $\Rightarrow$ negligible
   $\delta m_b \sim 10$ MeV (still under discussion, too optimistic?)

6. $\Delta\alpha_{\text{had}}$: BES III and Belle II: $\delta(\Delta\alpha_{\text{had}}) \sim 5 \times 10^{-5}$

Summary of future parametric uncertainties:

$$\delta m_t = 0.5\ \text{GeV},\ \delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5},\ \delta M_Z = 2.1\ \text{MeV}$$

Quantity	δm_t	$\delta(\Delta\alpha_{\text{had}})$	δM_Z	total parametric
δM_W^{para} [MeV]	3.0	1	2.5	4
$\delta \sin^2\theta_{\text{eff}}^{\ell,\text{para}}$ [10^{-5}]	1.7	1.8	1.4	2.8

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

⇒ parametric uncertainties of the same order as experimental accuracy

⇒ not negligible

One word of caution:

The above numbers have all been obtained assuming the SM as calculational framework.

The SM constitutes the model in which highest theoretical precision for the predictions of EWPO can be obtained.

We know that BSM physics must exist! (DM, gravity, . . .)

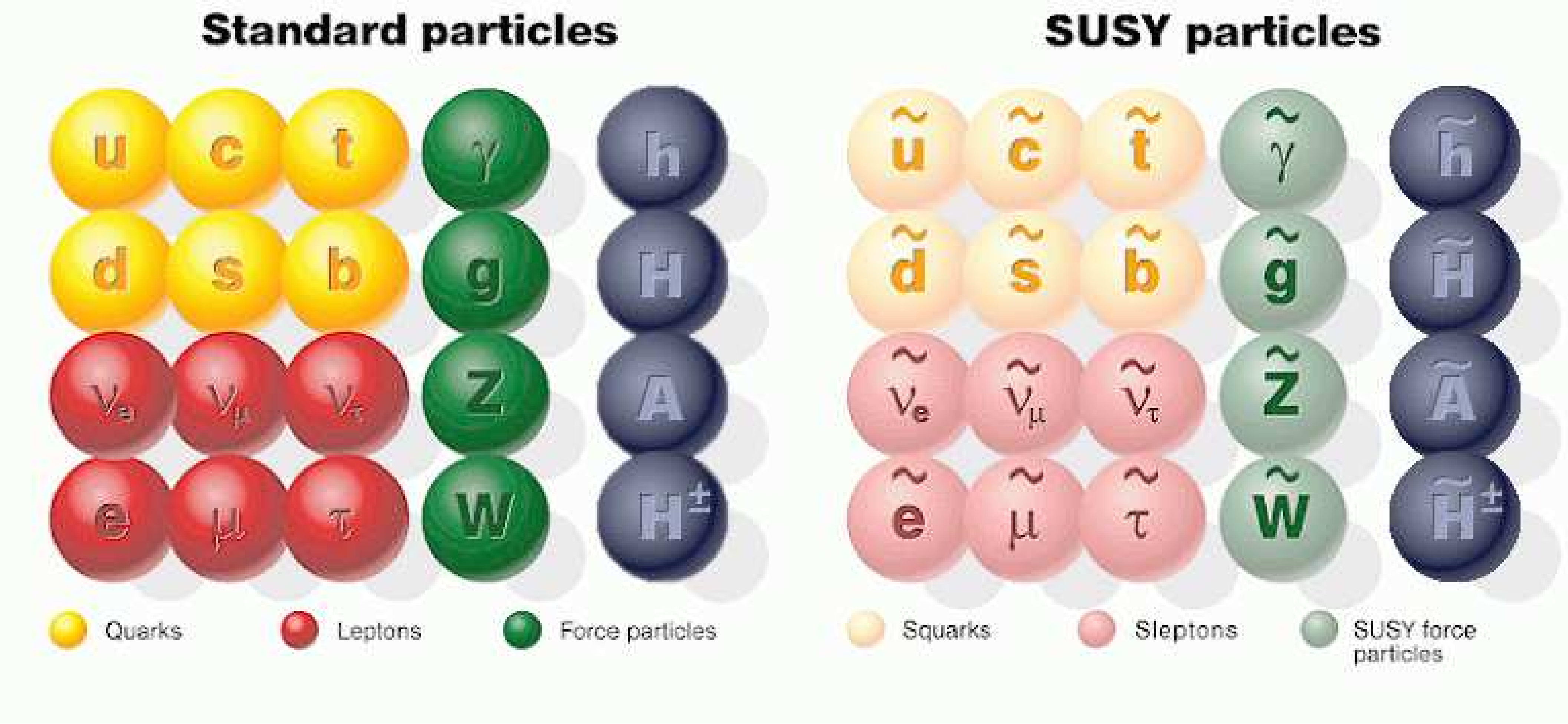
As soon as BSM physics will be discovered, an evaluation of the EWPO in any preferred BSM model will be necessary.

The corresponding theory uncertainties, both intrinsic and parametric, can then be larger (as known for the MSSM).

A dedicated theory effort (beyond the SM) would be needed in this case.

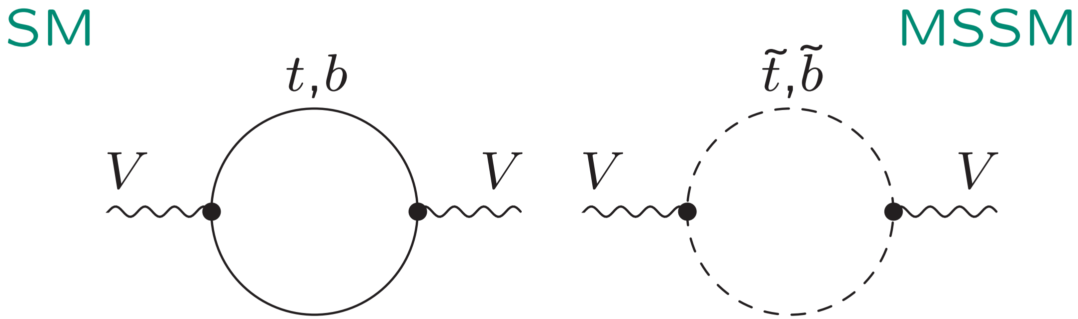
3. M_W in the MSSM

Superpartners for Standard Model particles



Differences between the MSSM and the SM:

1.) New contributions from SUSY particles:



2.) CPV effects via new complex phases

3.) large Yukawa corrections: $\sim m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

4.) large corrections from the $b/\tilde{b}$ sector for large $\tan\beta$

5.) non-decoupling SUSY effects: $\sim \log \frac{M_{\text{SUSY}}}{M_W}$

Corrections to M_W, $\sin^2\theta_{\rm eff}$ → approximation via the ρ-parameter:

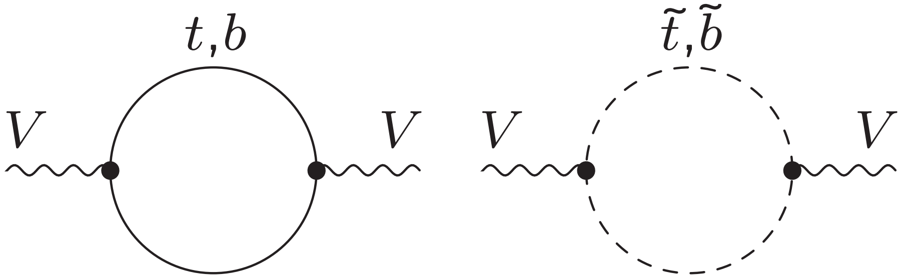
ρ measures the relative strength between
neutral current interaction and charged current interaction

$$\rho = \frac{1}{1 - \Delta\rho} \qquad \Delta\rho = \frac{\Sigma_Z(0)}{M_Z^2} - \frac{\Sigma_W(0)}{M_W^2}$$

(leading, process independent terms)

$\Delta\rho$ gives the main contribution to EW observables:

$$\Delta M_W \approx \frac{M_W}{2}\frac{c_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho, \qquad \Delta\sin^2\theta_W^{\rm eff} \approx -\frac{c_{\rm W}^2 s_{\rm W}^2}{c_{\rm W}^2 - s_{\rm W}^2}\Delta\rho$$



$\Delta\rho^{\rm SUSY}$ from $\tilde t/\tilde b$ loops > 0 $\Rightarrow M_W^{\rm SUSY} \gtrsim M_W^{\rm SM}$

$\Delta\rho^{\text{SUSY}}$ from $\tilde{t}/\tilde{b}$ loops > 0 $\Rightarrow M_W^{\text{SUSY}} \gtrsim M_W^{\text{SM}}$

SM result for M_W:

- full one-loop
- full two-loop
- leading 3-loop via $\Delta\rho$
- leading 4-loop via $\Delta\rho$

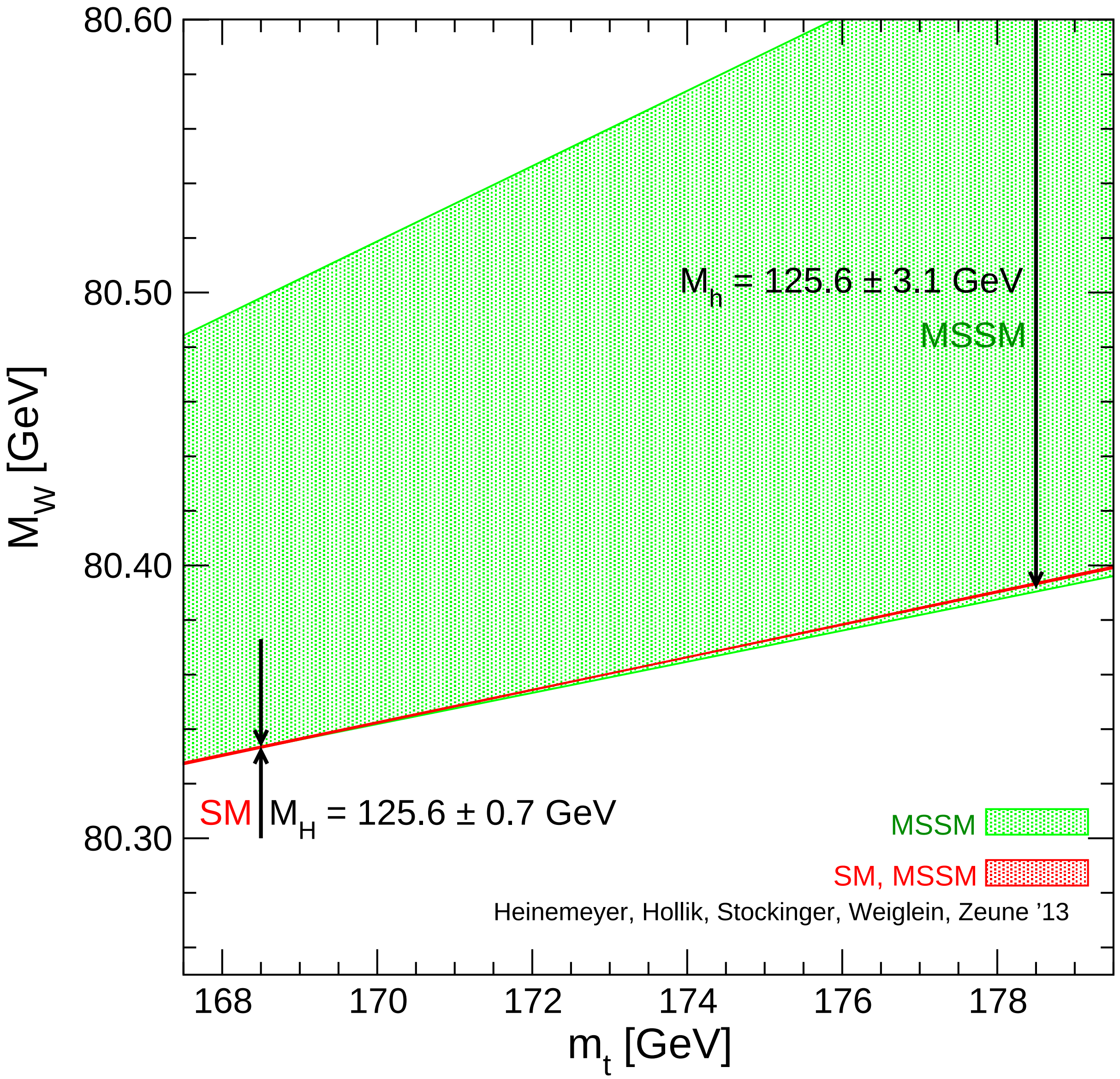
Best MSSM result for M_W: [S.H., W. Hollik, G. Weiglein, L. Zeune '13]

- full SM result (via fit formel)
- full MSSM one-loop (incl. complex phases)
- all existing two-loop $\Delta\rho$ contributions

$\Rightarrow$ non-$\Delta\rho$ one-loop and $\Delta\rho$ two-loop contributions sometimes non-negligible!

Example: Prediction for M_W in the SM and the MSSM :

[*S.H., W. Hollik, D. Stockinger, G. Weiglein, L. Zeune '13*]



MSSM band:
scan over
SUSY masses

overlap:
SM is MSSM-like
MSSM is SM-like

SM band:
variation of M_H^{SM}

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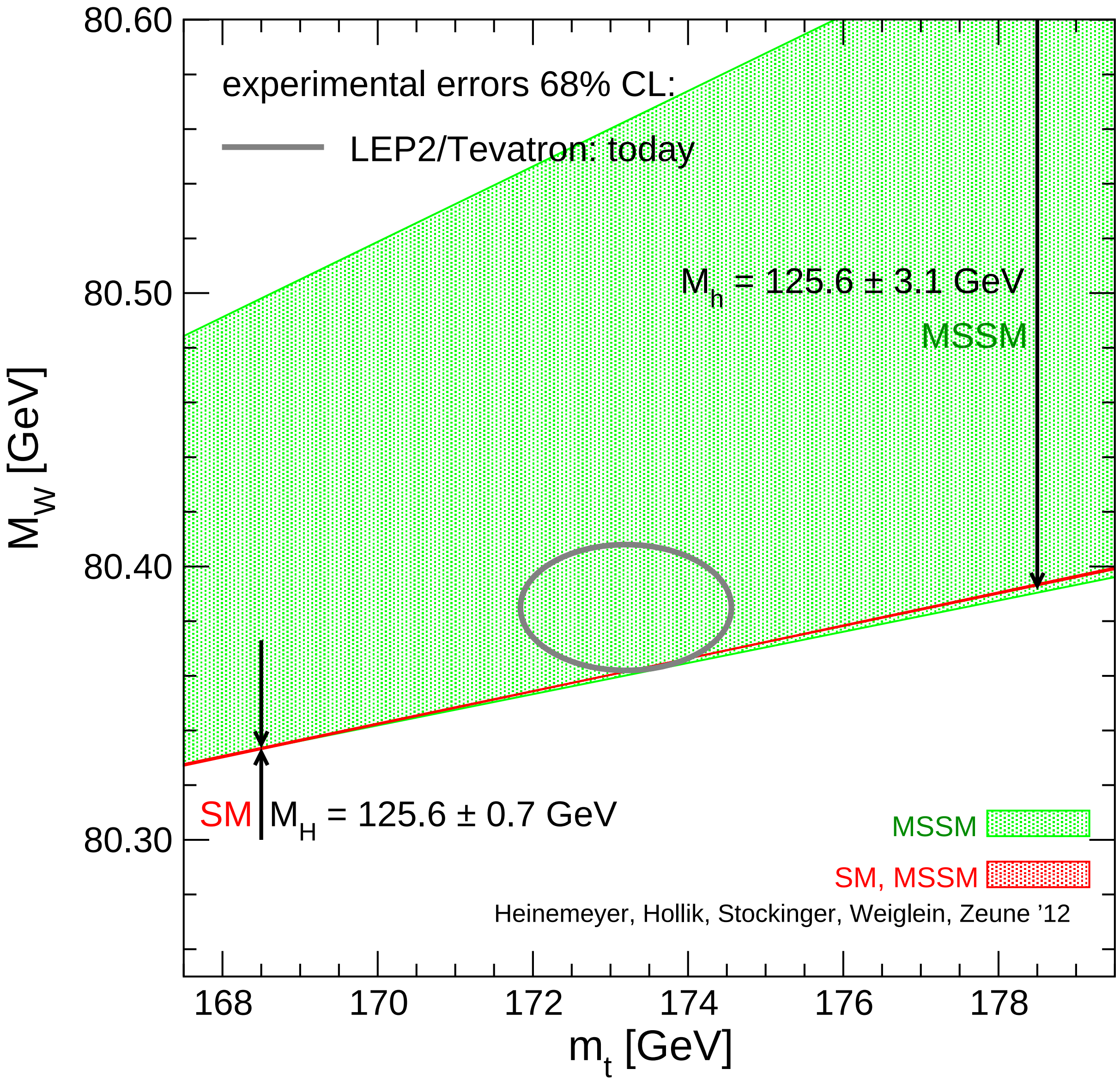

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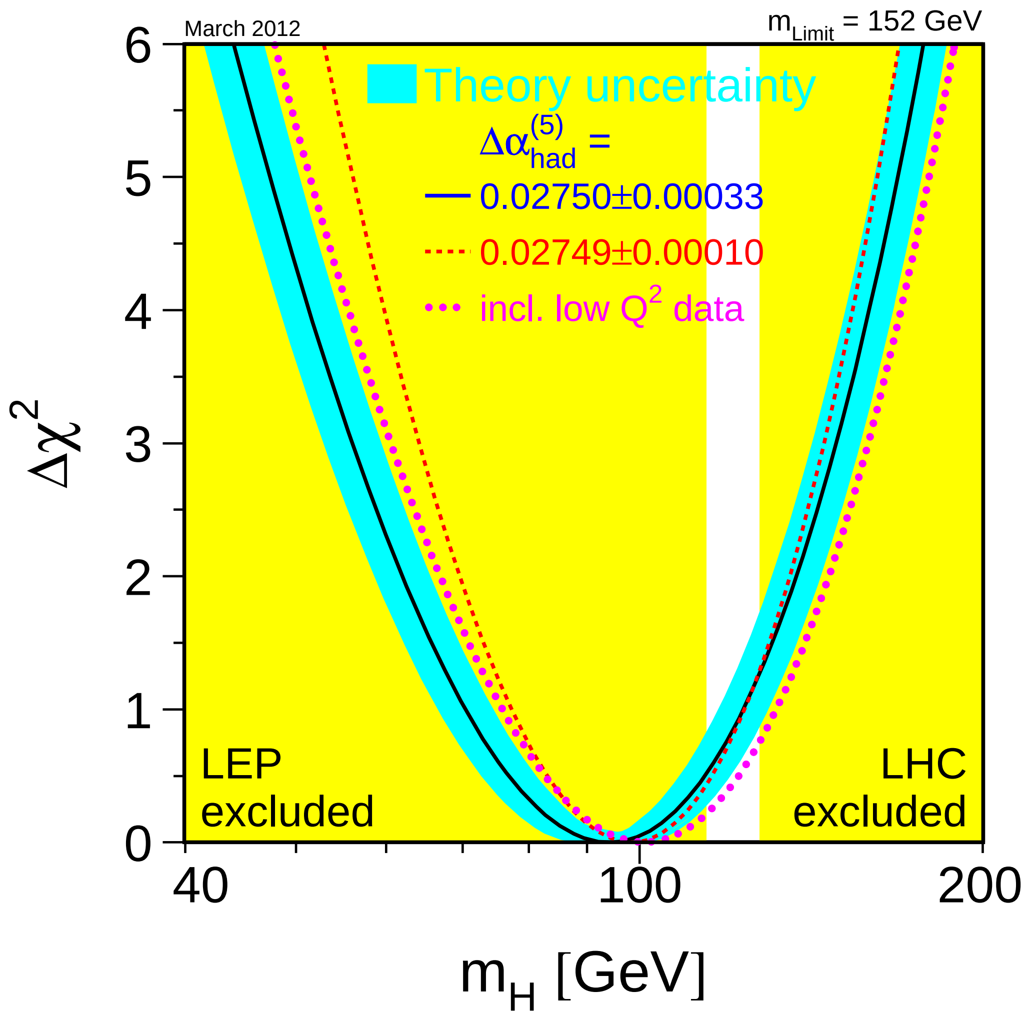
4. Which M_W precision do we want?

Test of the SM:

[*LEPEWWG '12*]



⇒ ILC precision becomes interesting . . .

⇒ more interesting: see effects of new physics!

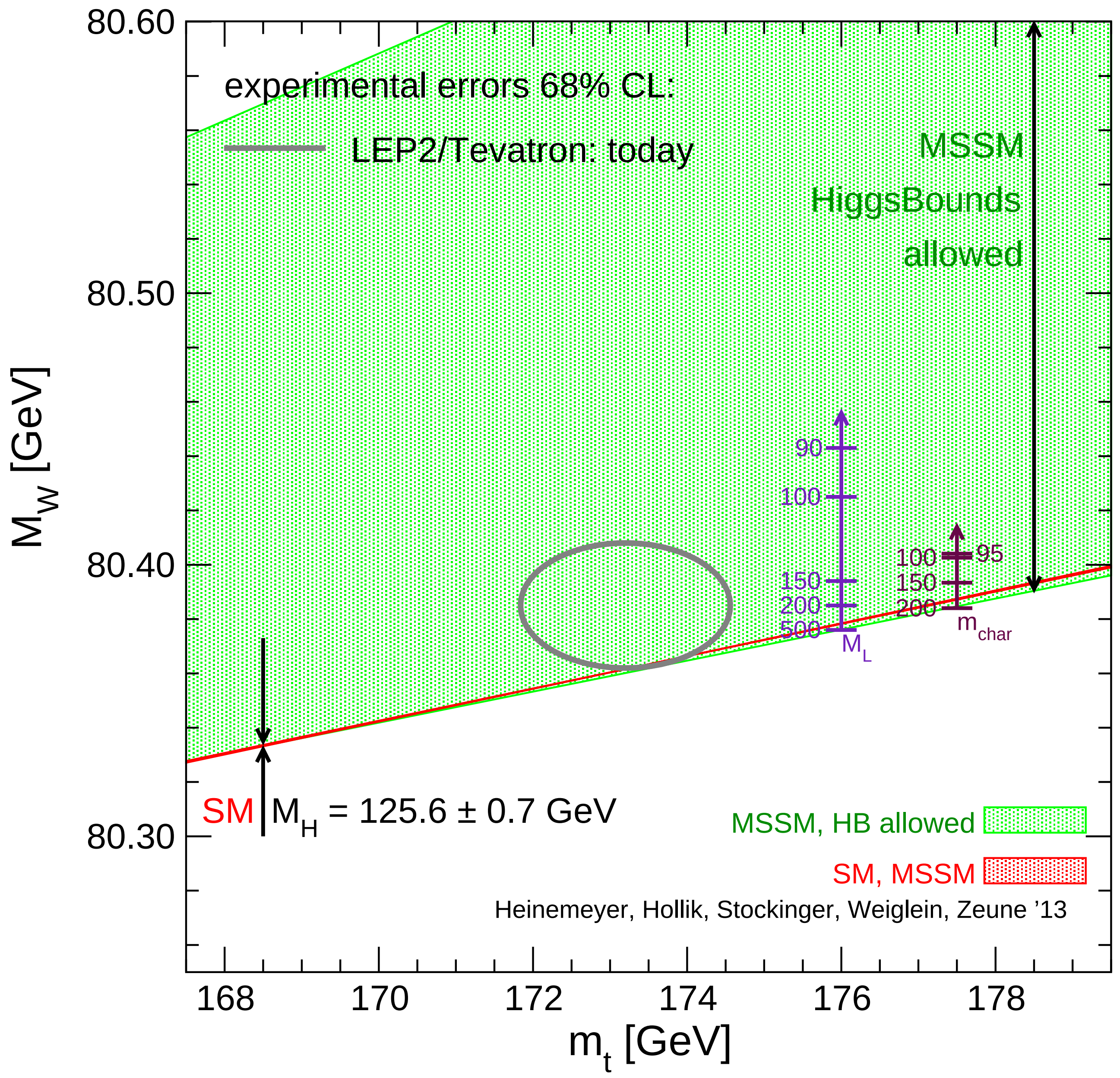
Example MSSM scenario (I):

[S.H., G. Weiglein, L. Zeune '13]

⇒ extensive parameter scan:

Parameter	Minimum	Maximum
μ	-2000	2000
$M_{\tilde{E}_{1,2,3}} = M_{\tilde{L}_{1,2,3}}$	100	2000
$M_{\tilde{Q}_{1,2}} = M_{\tilde{U}_{1,2}} = M_{\tilde{D}_{1,2}}$	500	2000
$M_{\tilde{Q}_3}$	100	2000
$M_{\tilde{U}_3}$	100	2000
$M_{\tilde{D}_3}$	100	2000
$A_e = A_\mu = A_\tau$	-3 $M_{\tilde{E}}$	3 $M_{\tilde{E}}$
$A_u = A_d = A_c = A_s$	-3 $M_{\tilde{Q}_{12}}$	3 $M_{\tilde{Q}_{12}}$
A_b	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{D}_3})$
A_t	-3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	3 max$(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
tan β	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

Example MSSM scenario (I): effects of EW particles



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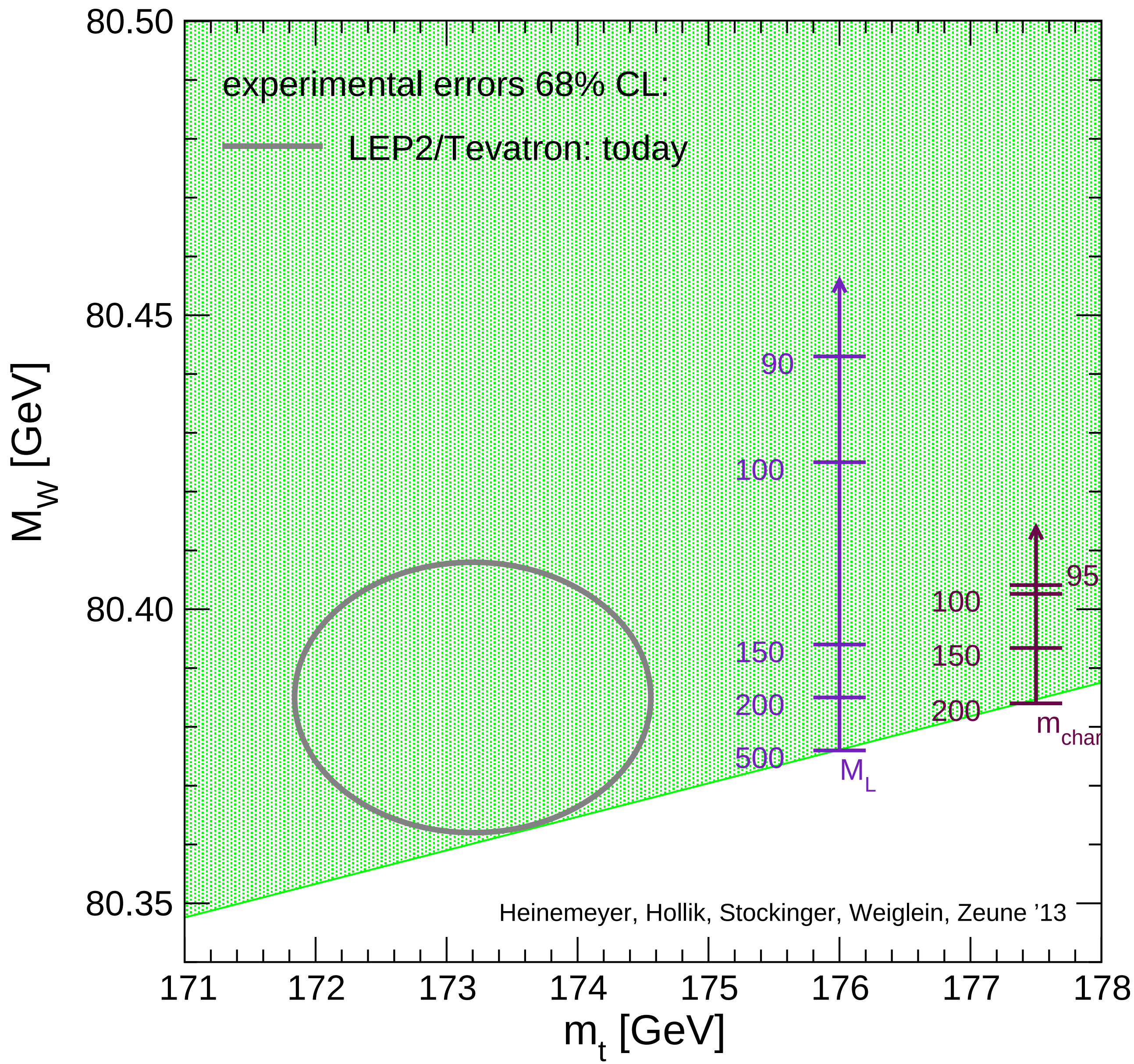
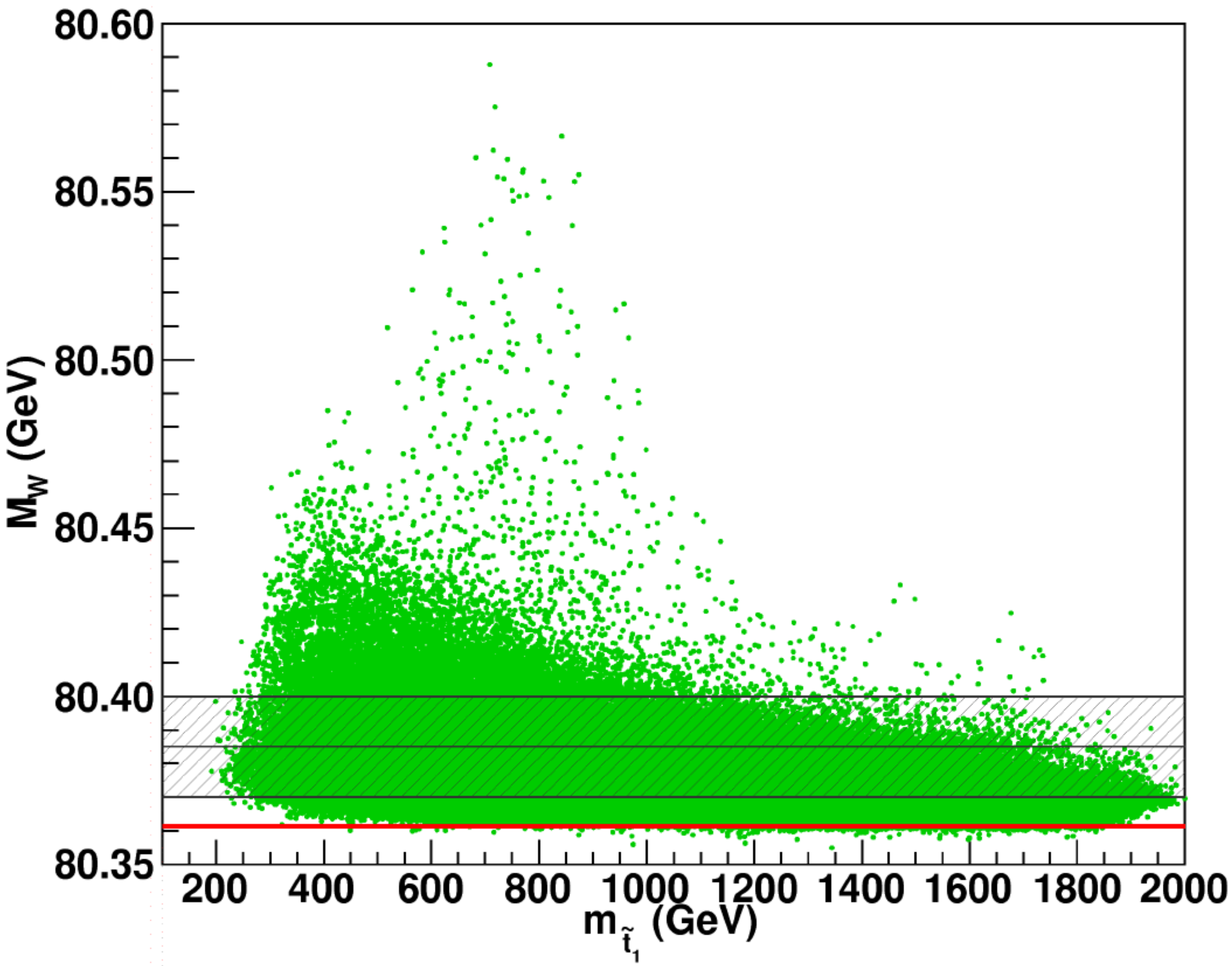


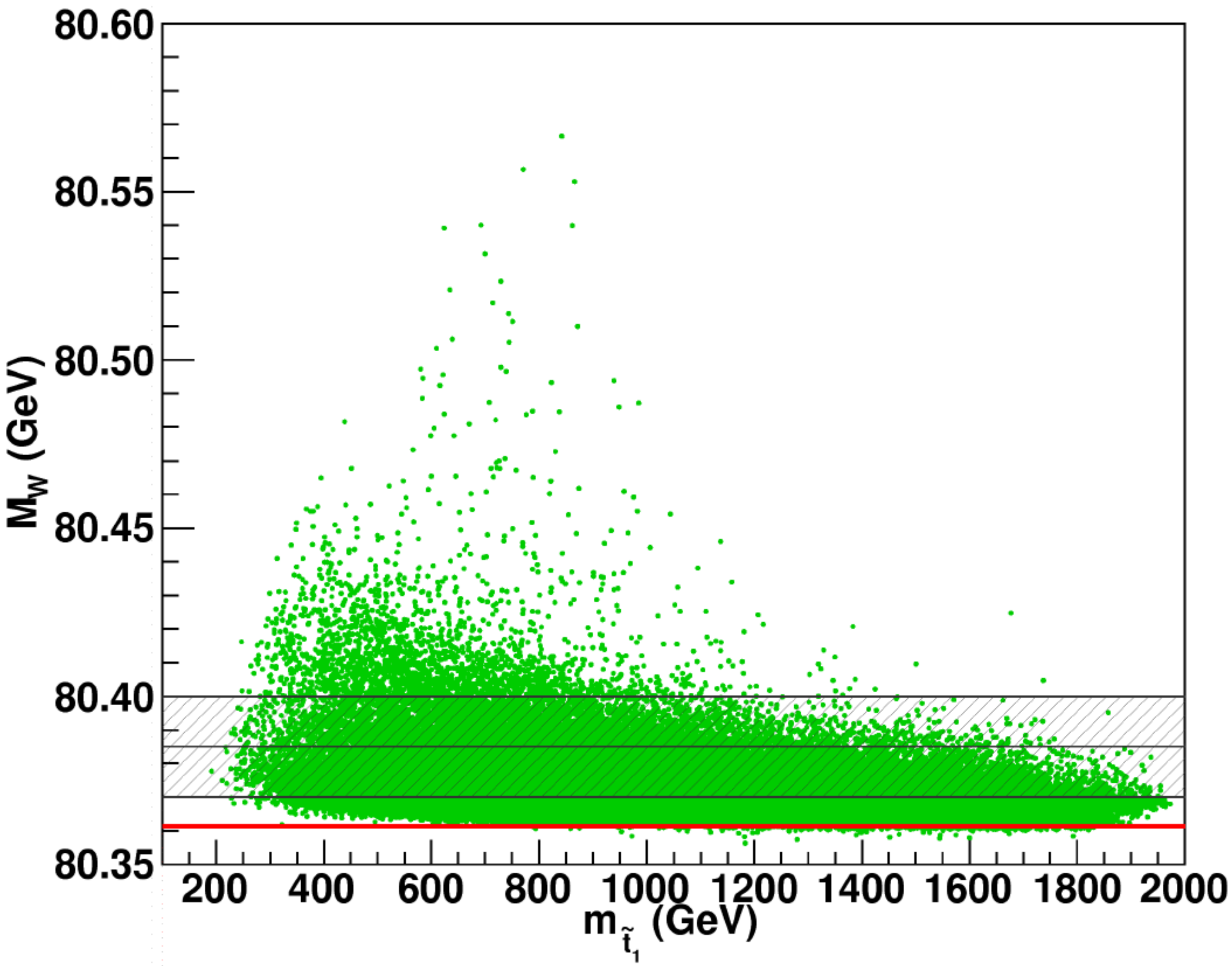
Effects of stops:

[S.H., G. Weiglein, L. Zeune '13]



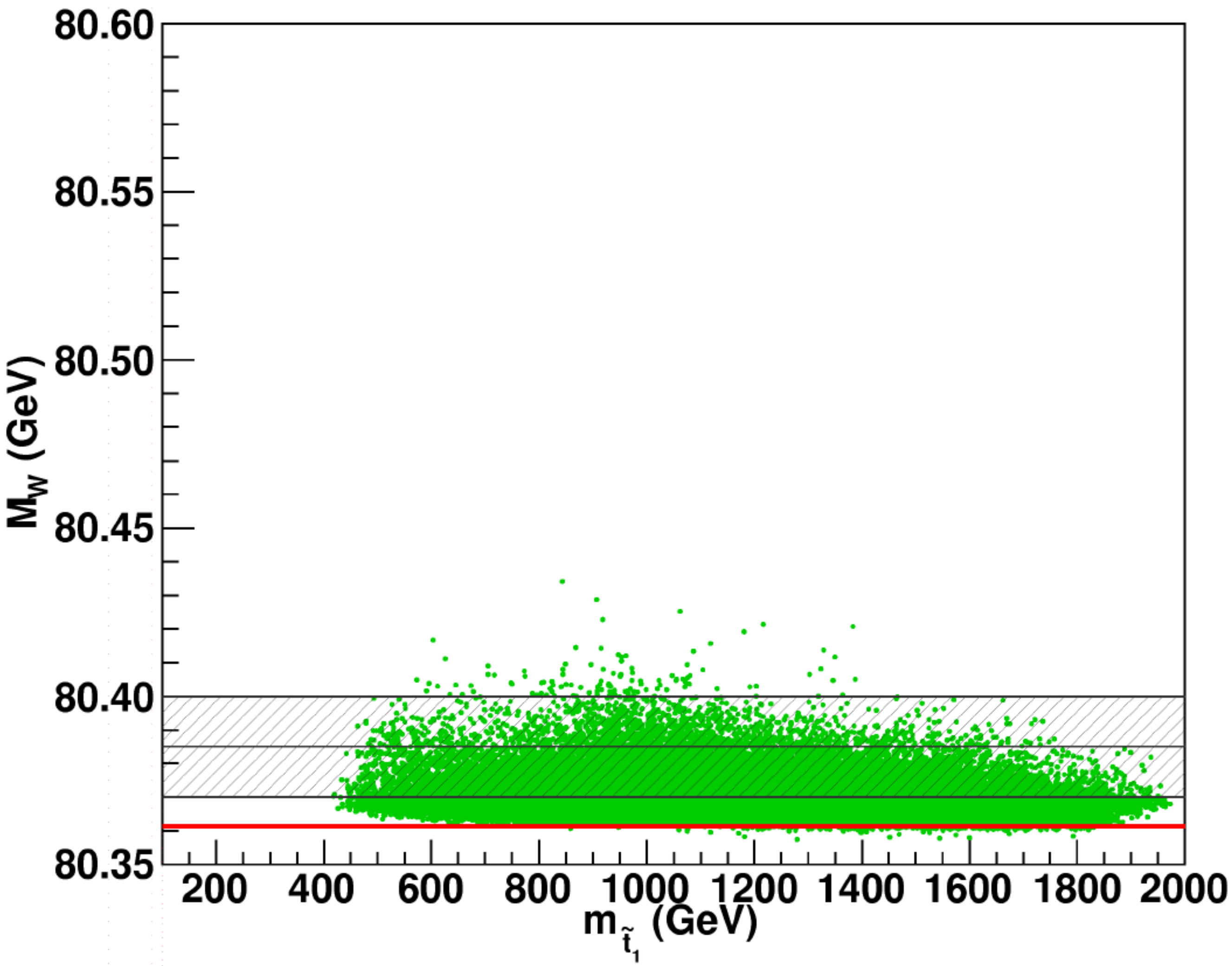
All points HiggsBounds allowed

Effects of stops: [S.H., G. Weiglein, L. Zeune '13]



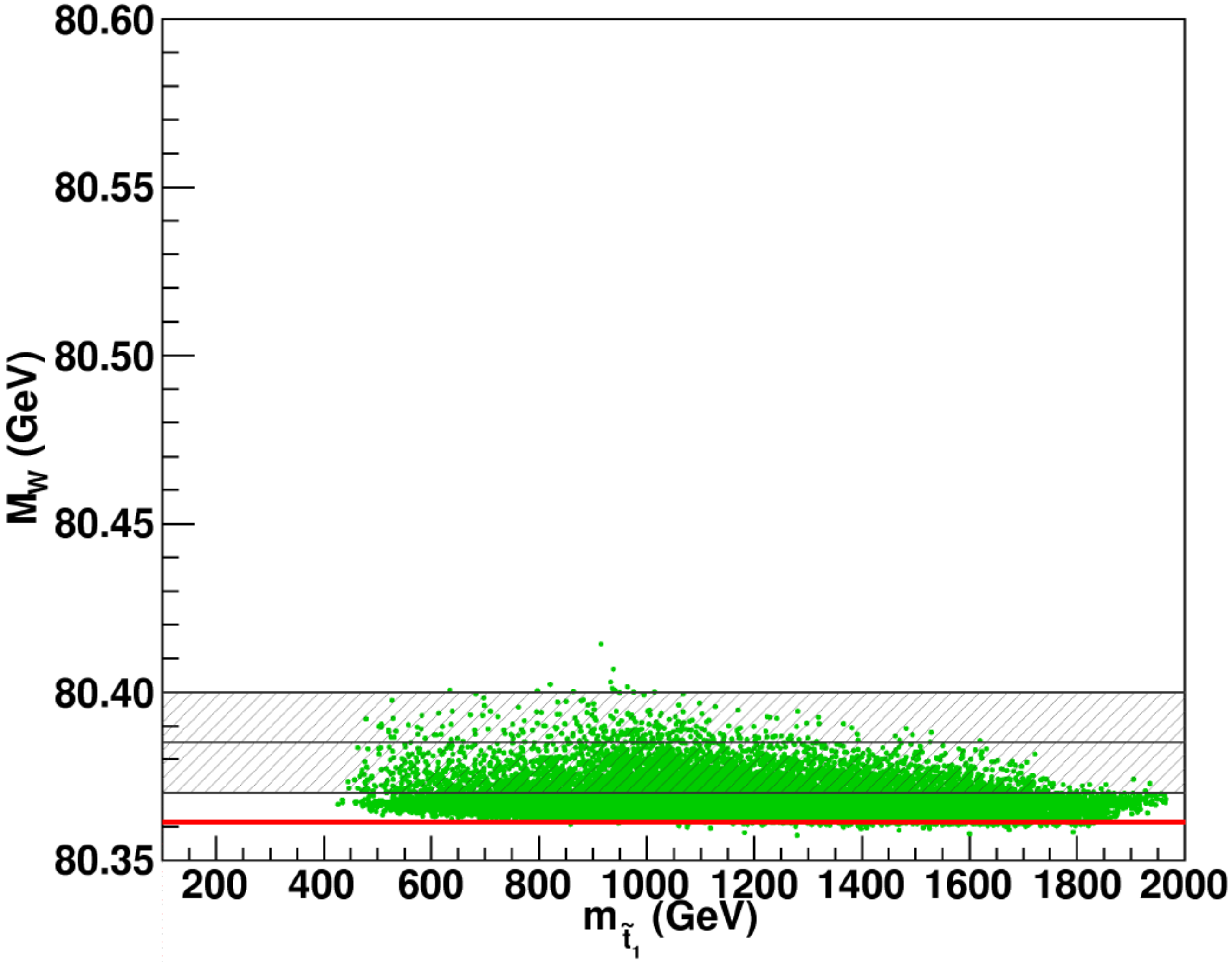
$\ldots \oplus\ m_{\tilde{q}_{1,2}}, m_{\tilde{g}} > 1200$ GeV

Effects of stops: [S.H., G. Weiglein, L. Zeune '13]



$\ldots \oplus m_{\tilde{b}_i} > 500$ GeV

Effects of stops: [S.H., G. Weiglein, L. Zeune '13]

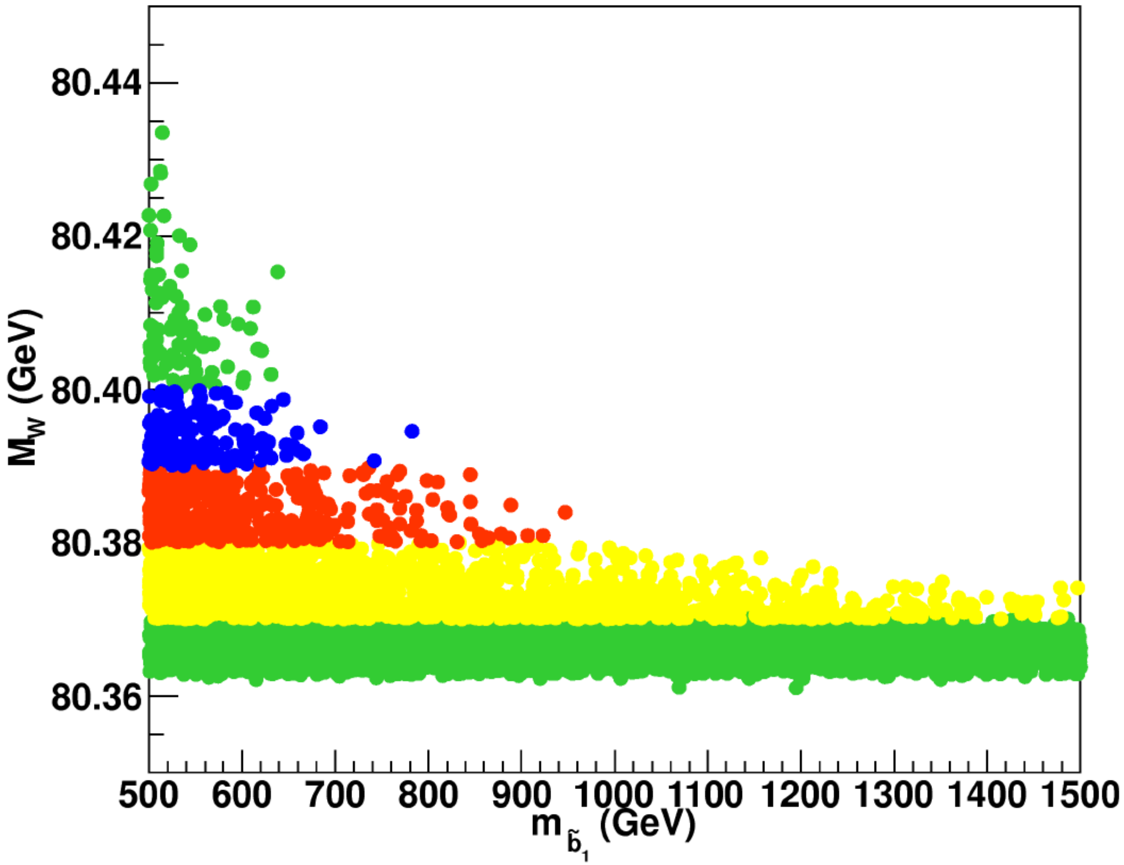


$\ldots \oplus\ m_{\tilde{l}}, m_{\tilde{\chi}_i^{\pm}}, m_{\tilde{\chi}_j^0} > 500$ GeV

Example MSSM scenario (II): [S.H., G. Weiglein, L. Zeune '15]

$m_{\tilde{t}_1} = 400 \pm 40$ GeV, Other masses $\gtrsim 500$ GeV

$M_W^{\rm exp} = 80.375 \pm 0.005$ GeV, 80.385 ± 0.005 GeV, 80.395 ± 0.005 GeV



⇒ precision below 5 MeV required, the better the better!

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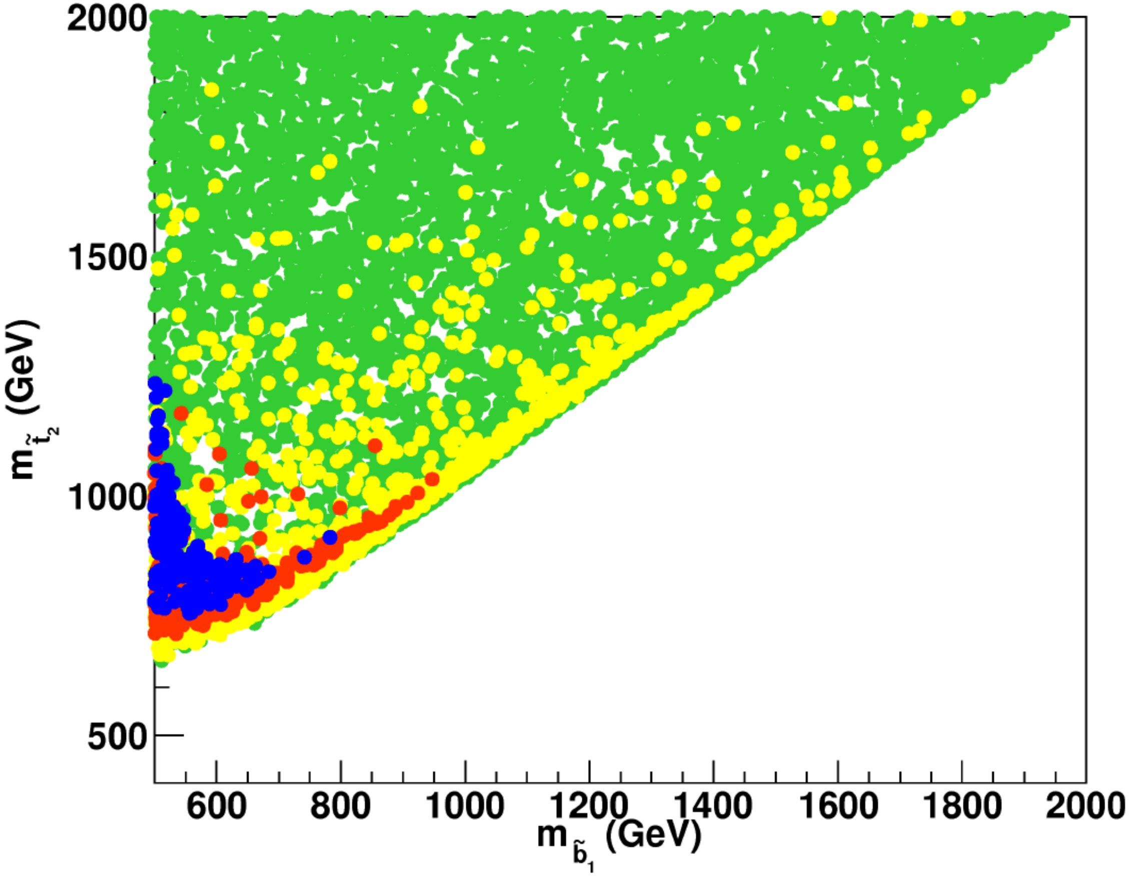


$\Rightarrow$ precision below 5 MeV required, the better the better!

5. Conclusions

- High anticipated experimental precision for M_W at the LHC

- Important: theory uncertainties: intrinsic and parametric

$$\text{total} = \sqrt{\text{experimental}^2 + \text{parametric}^2} + \text{intrinsic}$$

- Realistic/optimistic future estimates:
  - future intrinsic uncertainties: $\sim$ 1 MeV
  - future parametric uncertainties: $\sim$ 4 MeV

  $\Rightarrow$ improvement only with e^+e^- colliders?

- MSSM calculation: large effects possible
  also from EW particles!

- Desired precision? $\mathcal{O}$(5 MeV) total unc. interesting!


Further Questions?

Uncertainty budget for m_t at e^+e^- colliders:

[*talk by A. Hoang '15*]

$\delta\alpha_s(M_z) = 0.001$

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\text{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial

e^+e^- collider: precision measurement:

$$R_l := \frac{\Gamma(Z \to \text{ hadrons})}{\Gamma(Z \to l^+l^-)}$$

Improvement down to $\delta^{\text{exp}}\alpha_s \sim 0.001 - 0.0001$ possible?!

Note: TH uncertainty (assuming fermionic 3-loop corrections):

$\delta R_l^{\text{theo}} \sim 0.0015 \Rightarrow \delta\alpha_s^{\text{theo}} \sim 0.00015$ $\Rightarrow$ hard to beat . . .

SM input: $\Delta\alpha_{\rm had}$ $\Rightarrow$ could be limiting factor!

From $e^+e^- \to$ had. using dispersion relation

today: $\delta(\Delta\alpha_{\rm had}) \sim 10^{-4}$
possible improvement in the future: $\delta(\Delta\alpha_{\rm had}) \sim 5 \times 10^{-5}$

Direct determination at FCC-ee from $e^+e^- \to f\bar{f}$ off the Z peak

[*P. Janot '15*]
possible improvement in the future: $\delta(\Delta\alpha_{\rm had}) \sim 2 \times 10^{-5}$ $\Rightarrow$ TU neglected

Calculation of $e^+e^- \to f\bar{f}$ needed at 3-loop and beyond: [*A. Freitas '16*]
current techniques (2L/3L): corrections of $\sim 10^{-3}$
new calculation methods (2L/3L): corrections of $\sim 10^{-4}$
unknown methods 3L: $\lesssim 10^{-5}$
unknown methods 4L: $\sim 10^{-5}$
(+ higher-orders in real photon emission)
$\Rightarrow$ improvement unclear $\Rightarrow \delta(\Delta\alpha_{\rm had}) \sim 3 \times 10^{-5}$

Additional uncertainty for M_W from threshold scan:

Not only $e^+e^- \to W^{(*)}W^{(*)}$, but $e^+e^- \to WW \to$ 4f needed

Current status:

full one-loop for $2 \to 4$ process

[*A. Denner, S. Dittmaier, M. Roth, D. Wackeroth '99-'02*]

$\Rightarrow$ extraction of M_W at the level of $\sim$ 6 MeV

Most recent improvement:

leading 2L corrections from EFT

[*Actis, Beneke, Falgari, Schwinn '08*]

$\Rightarrow$ impact on M_W at the level of $\sim$ 3 MeV

$\Rightarrow$ full 2L for $2 \to 4$ process not foreseeable

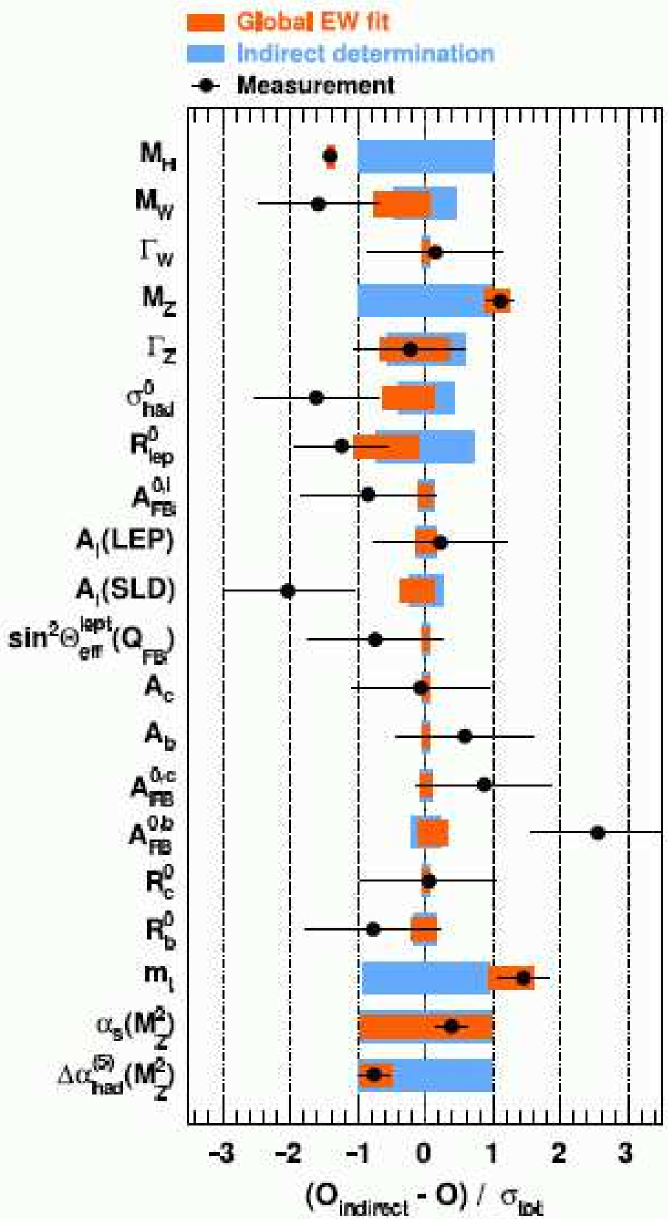
Potentially possible:

2L resummed higher-order terms for $e^+e^- \to WW$ and $W \to ff'$

$\Rightarrow$ extraction of M_W at $\sim$ 1 MeV?? $\oplus$ pure exp. uncertainty of $\sim$ 0.5 MeV

Overview about all EWPO:

[*taken from A. Freitas '16*]



Surprisingly good agreement:

χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

Most quantities measured with 1%–0.1% precision

GFitter coll. '14

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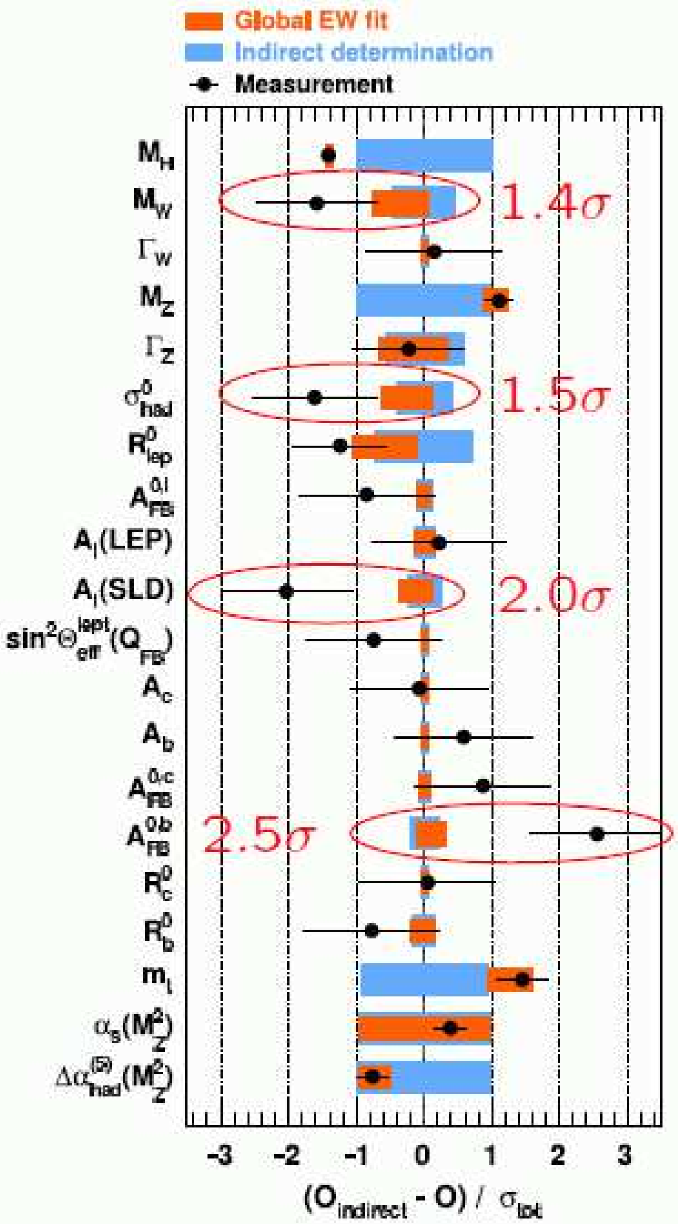


Surprisingly good agreement:

χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

Most quantities measured with

1%–0.1% precision

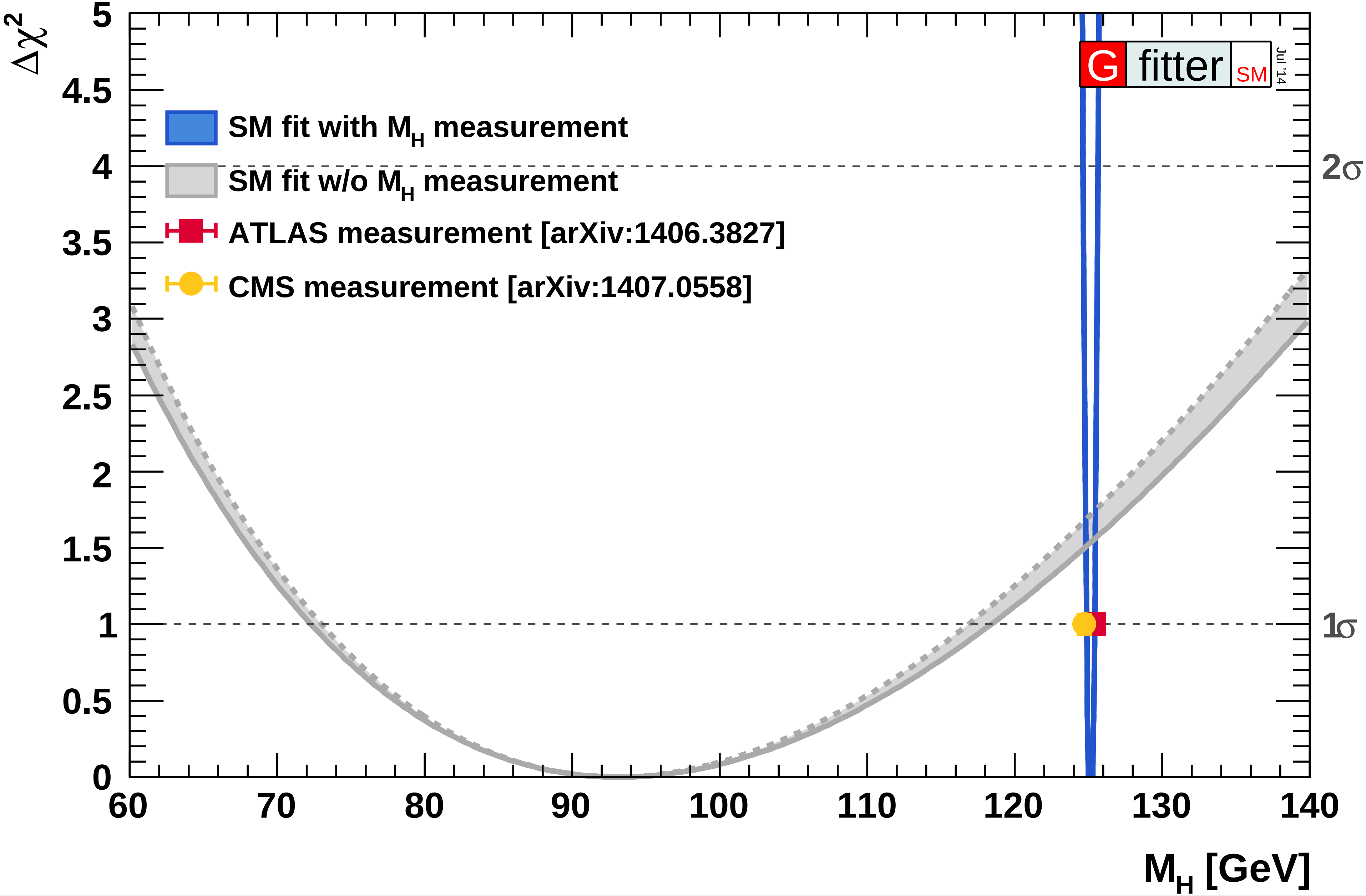
A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

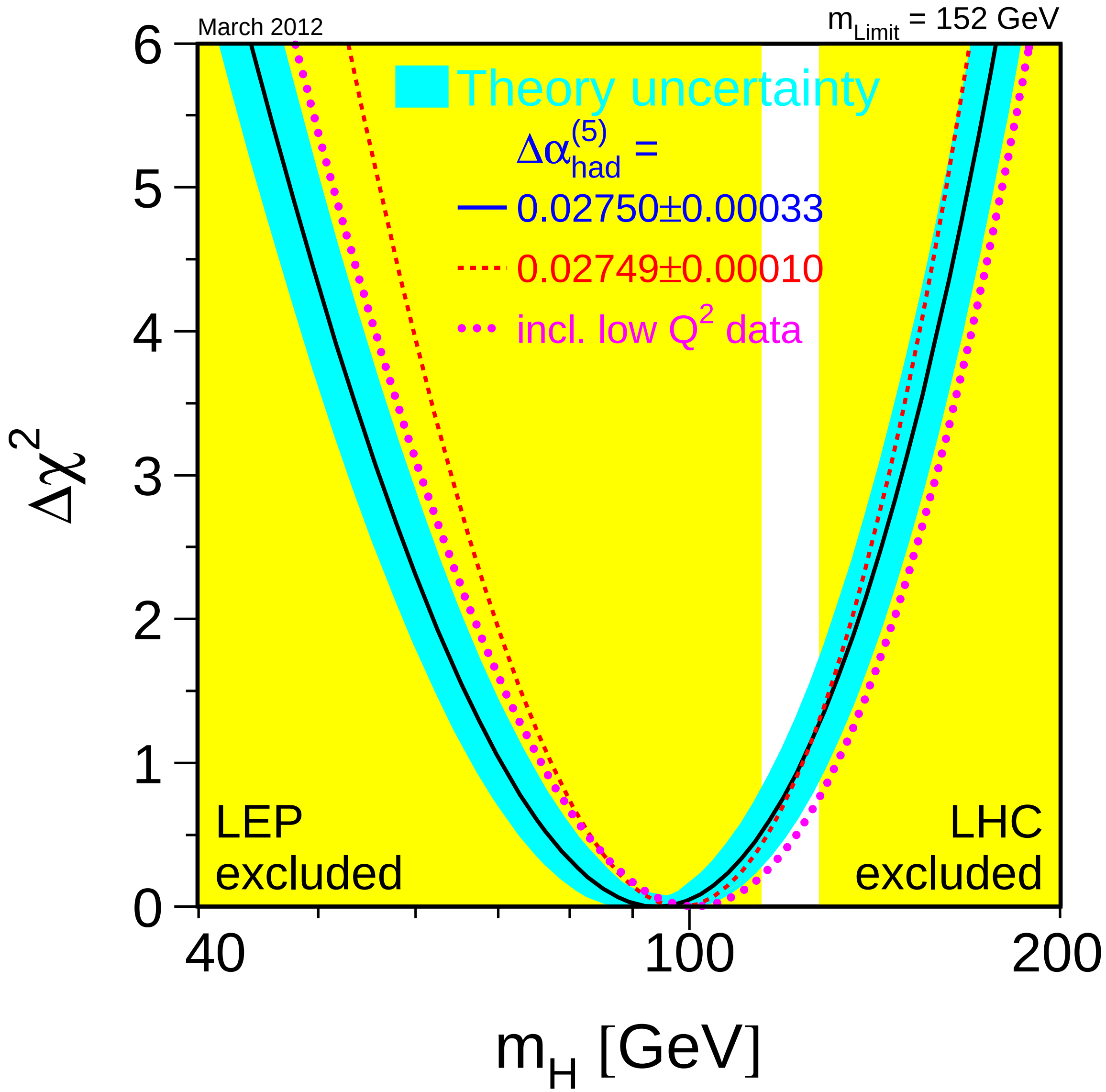
GFitter coll. '14

Current fit to M_H:

[GFitter '14]

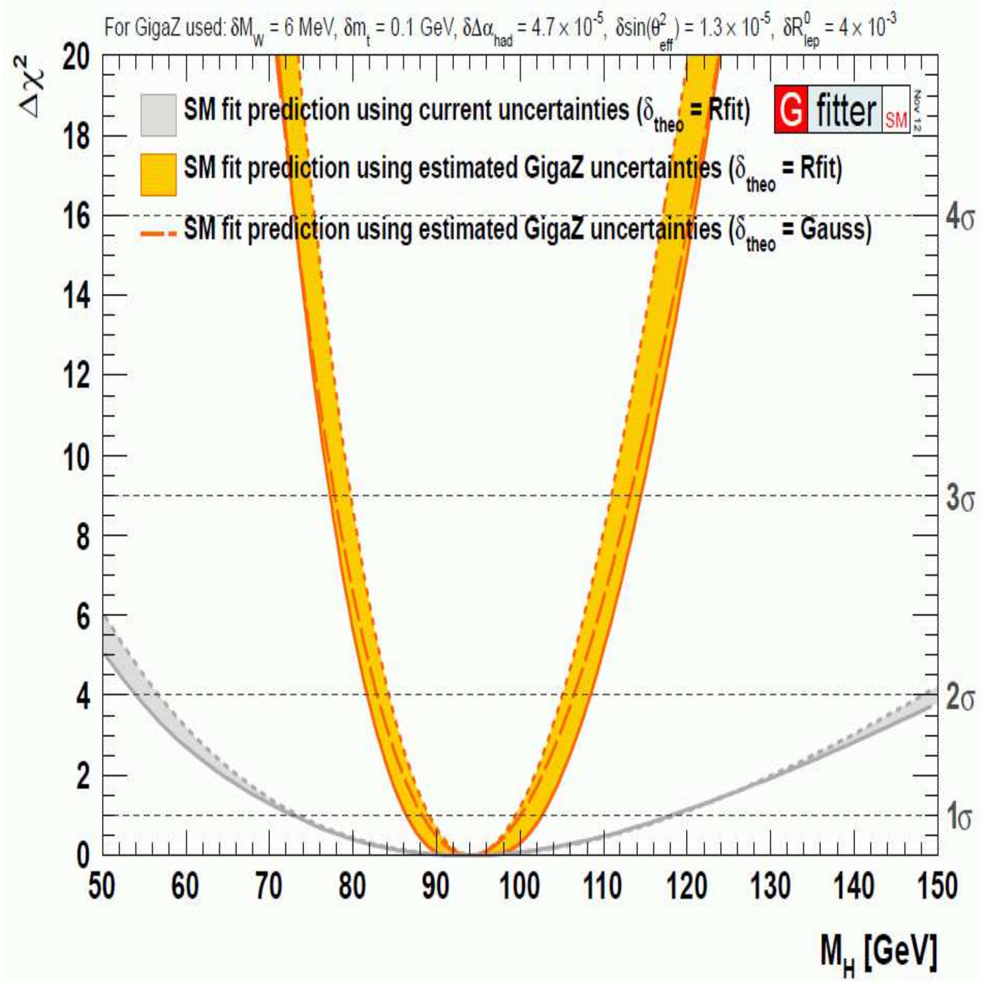


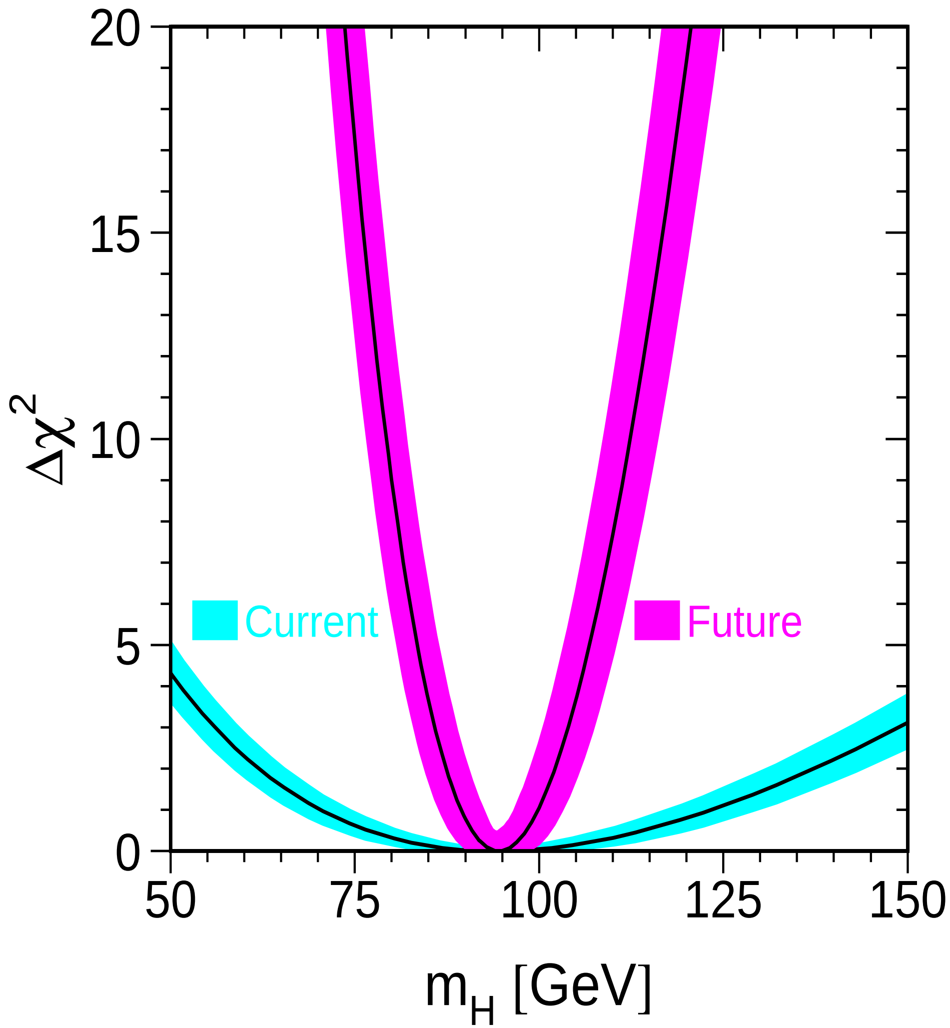
Current fit to M_H: [*LEPEWWG '12*]



Precise M_H test with the ILC precision:

[*GFitter '13*] [*LEPEWWG '13*]





$\Rightarrow \delta M_H^{\rm ind} \lesssim 6$ GeV $\Leftarrow$ only ILC analysis available so far

$\Rightarrow$ extremely sensitive test of SM (and BSM) possible