

Impact of LHC bounds on the W-boson mass prediction in the MSSM

based on work in collaboration
with Sven Heinemeyer and Georg Weiglein



Lisa Zeune

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W-boson mass

- Electroweak precision observables

$$M_W, \sin^2 \theta_{\text{eff}}, a_\mu \dots$$

- Highly sensitive to quantum effects of 'new physics'
- **Precise measurement & precise theoretical calculation needed**
 - Test models
 - Constrain model parameters

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Outline of this talk

- Theoretical prediction of the W-boson mass in the MSSM
- Effects of LHC results on the M_W prediction
- LHC and LC potential to discriminate between M_W in the SM and the MSSM

Experimental measurement of the W-boson mass

- Most accurate measurement from Tevatron
- Combination with LEP \rightarrow **World average:**

$$M_W^{\text{exp}} = 80.385 \pm 0.015 \text{ GeV}$$

Tevatron Electroweak
Working Group
April '12

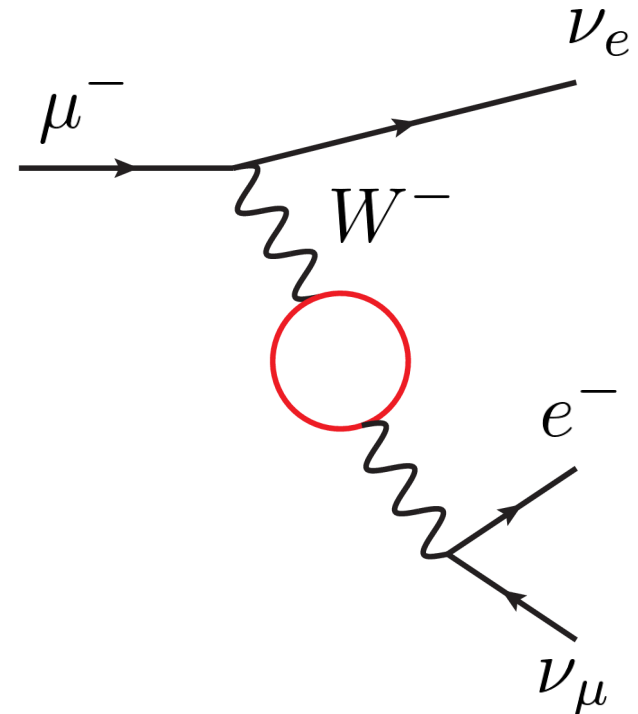
- Improvement at the LHC possible but very challenging
- Great improvement possible at a linear collider
 - \rightarrow **Measurement with ~ 7 MeV uncertainty plausible at LC**
- Improvement in the top mass measurement
 - \rightarrow LC goal: 100 MeV precision
 - \rightarrow Higher accuracy of theoretical M_W prediction

Determination of the W-boson mass

- Comparison of muon decay in SM and Fermi model gives:

$$\frac{G_F}{\sqrt{2}} = \frac{e^2}{8s_W^2 M_W^2} (1 + \Delta r(M_W, M_Z, m_t, \dots X))$$

- G_F , e , s_W known with high precision
- **X model dependent!**
- Precise calculation of Δr needed to test model and constrain model parameters!



Calculation of Δr

- 1-loop calculation of Δr in the MSSM
 - General MSSM, complex phases, CKM mixing (MFV)
- Incorporation of all known SM and SUSY higher order corrections
- To make use of advanced SM calculation:

$$\Delta r^{\text{MSSM}} = \Delta r^{\text{SM}} + \Delta r^{\text{SUSY}}$$

- **Most precise MSSM prediction for the W-boson mass**
- Easy to extend to other models: NMSSM, 2HDM ...

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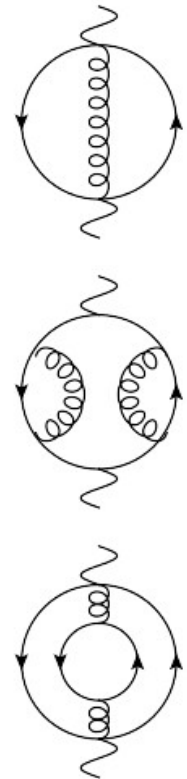
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SM contributions to W-boson mass

$$\Delta r^{SM} = \Delta r^{(\alpha)} + \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)} + \Delta r_{\text{ferm}}^{(\alpha^2)} + \Delta r_{\text{bos}}^{(\alpha^2)} \\ + \Delta r^{(G_\mu^2 \alpha_s m_t^4)} + \Delta r^{(G_\mu^3 m_t^6)} + \Delta r^{(G_\mu m_t^2 \alpha_s^3)}$$

- $\Delta r^{(\alpha)}$: 1-loop contribution
- $\Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)}$: 2- and 3-loop QCD correction
Chetyrkin, Kuhn, Steinhauser '95, Djouadi, Verzegnassi '88, ...
- $\Delta r_{\text{ferm}}^{(\alpha^2)} + \Delta r_{\text{bos}}^{(\alpha^2)}$: fermionic and bosonic electroweak 2-loop corrections (fitting formula)
Awramik, Czakon, Freitas '06, Awramik, Czakon, Freitas, Weiglein '03
- $\Delta r^{(G_\mu^2 \alpha_s m_t^4)} + \Delta r^{(G_\mu^3 m_t^6)}$: 3-loop top quark contributions
Faisst, Kuhn, Seidensticker, Veretin '03
- $\Delta r^{(G_\mu m_t^2 \alpha_s^3)}$: 4-loop QCD correction Boughezal '06
- QCD corrections enter at 2-loop level:

↪ Large corrections beyond 1-loop order



Calculation of Δr

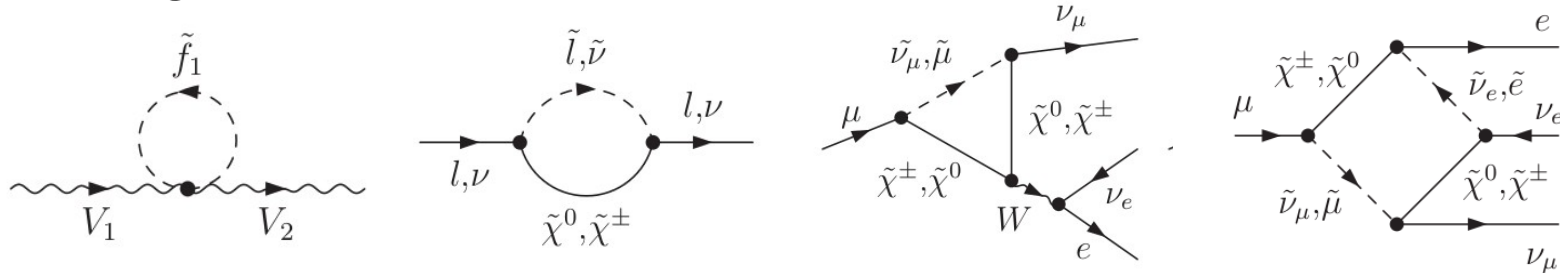
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SUSY contributions to W-boson mass

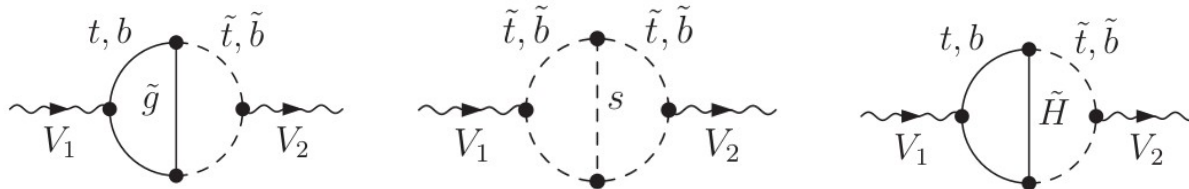
- 1-loop contributions from MSSM Higgs, sfermions, charginos and neutralinos



- Supersymmetric two-loop contributions:

- SUSY QCD corrections of $O(\alpha\alpha_s)$ Djouadi et. al '98
(S)quark loops with gluon and gluino exchange
- Yukawa contributions $O(\alpha_t^2)$, $O(\alpha_t\alpha_b)$, $O(\alpha_b^2)$ Haestier, Heinemeyer, Stoeckinger, Weiglein '05
(S)quark loops with Higgs and Higgsino exchange

- Leading reducible two-loop corrections Consoli, Hollik, Jegenlehner '89

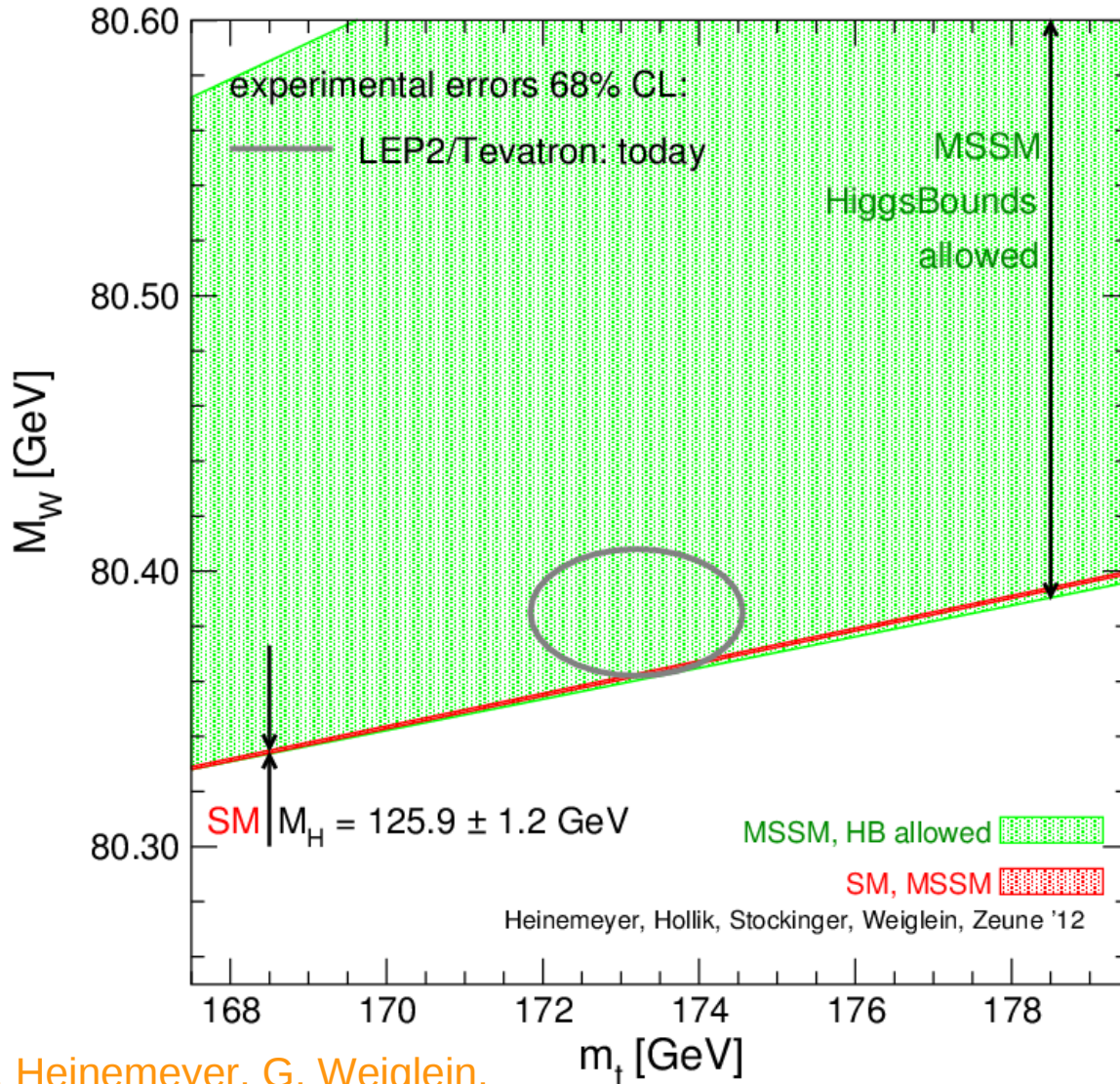


Detailed parameter scan

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	$-3 \max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$	$3 \max(M_{\tilde{Q}_3}, M_{\tilde{U}_3})$
$\tan \beta$	1	60
M_3	500	2000
M_A	90	1000
M_2	100	1000

$$M_1 \approx 1/2 M_2$$

W-boson mass prediction in the MSSM



MSSM region:
 allowed by
 HiggsBounds*
 and PDG limits on
 SUSY particles,
 neutralino LSP

Overlap region
 (SM and MSSM):
 After Higgs
 discovery SM band
 very narrow

* P. Bechtle, O. Brein,
 S. Heinemeyer, O. Stål,
 T. Stefaniak, G. Weiglein
 and K. Williams

S. Heinemeyer, G. Weiglein,
 L. Z. '13 - PRELIMINARY

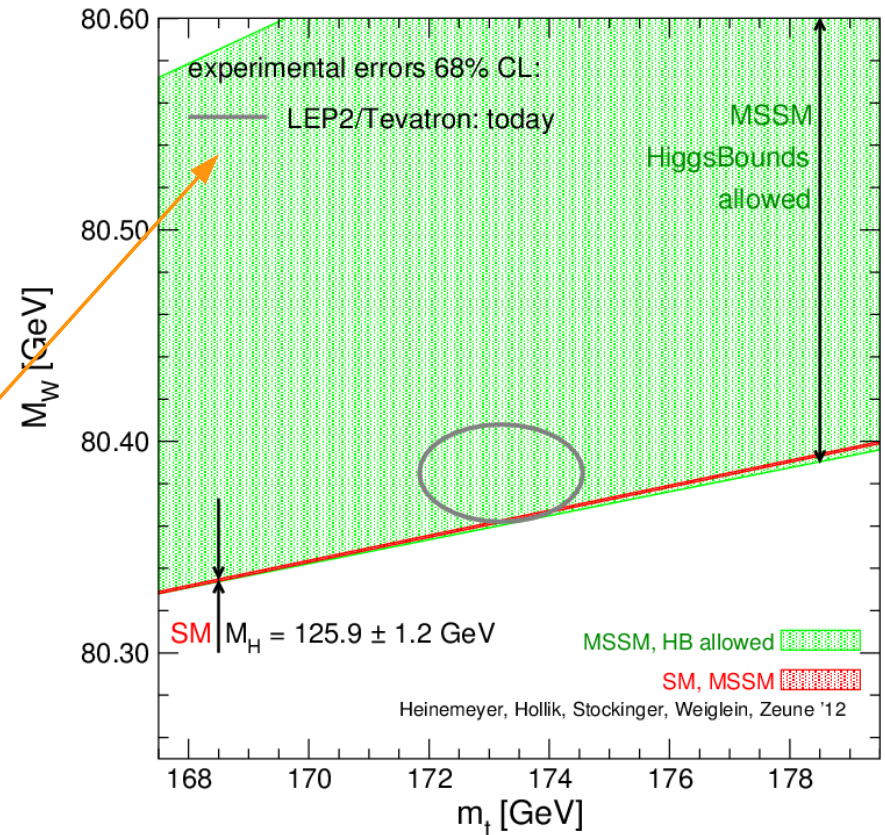
W-boson mass prediction in the MSSM

$$\Delta r^{1\text{-loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2} \Delta\rho + \Delta r_{\text{rem}}$$

- Largest SUSY contribution:
 \tilde{t}, \tilde{b} contribution to

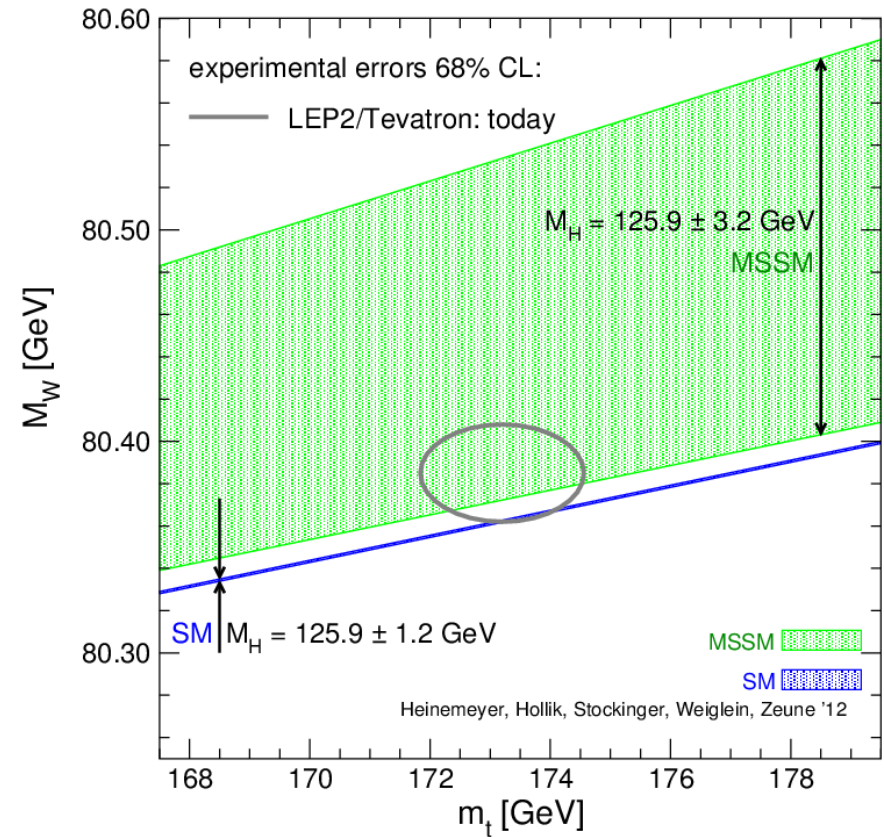
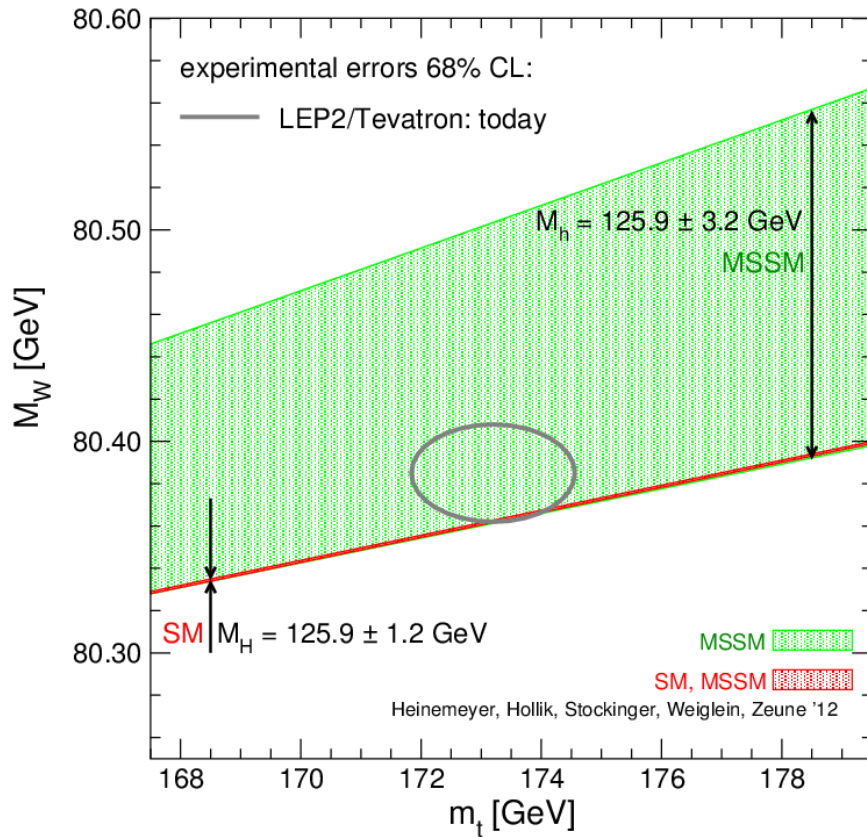
$$\Delta\rho = \frac{\Sigma_T^Z(0)}{M_Z^2} - \frac{\Sigma_T^W(0)}{M_W^2}$$

- Sensitive to mass splitting between stops and sbottoms
- Very large values for M_W possible for
 - Large mixing in \tilde{t}, \tilde{b} sector
 - \tilde{t}_1 or \tilde{b}_1 relatively light



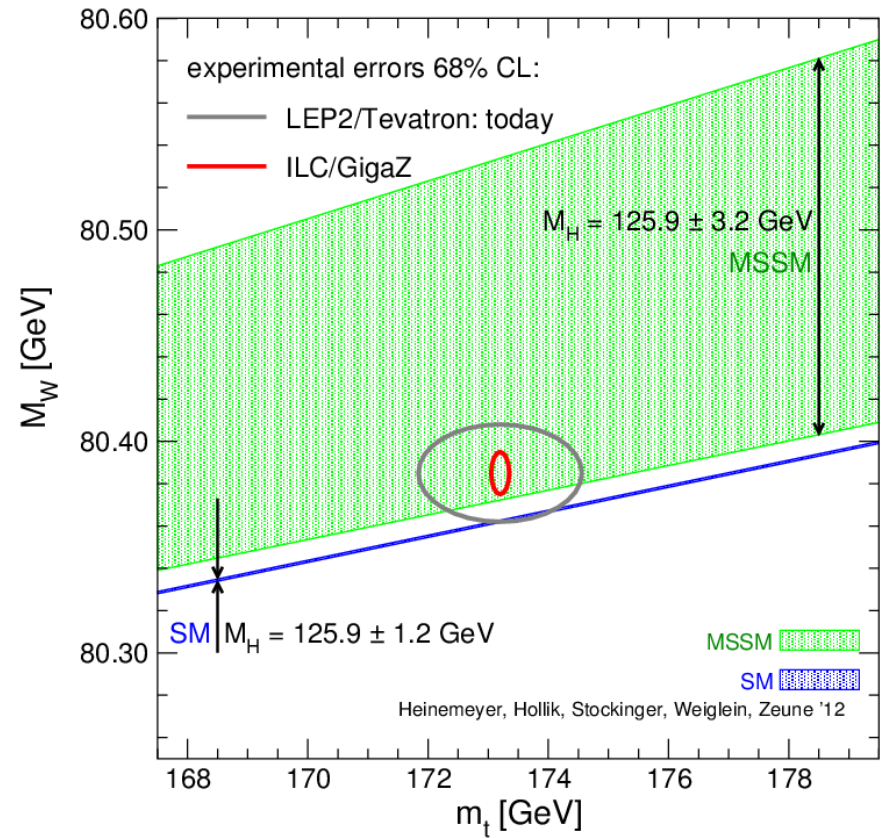
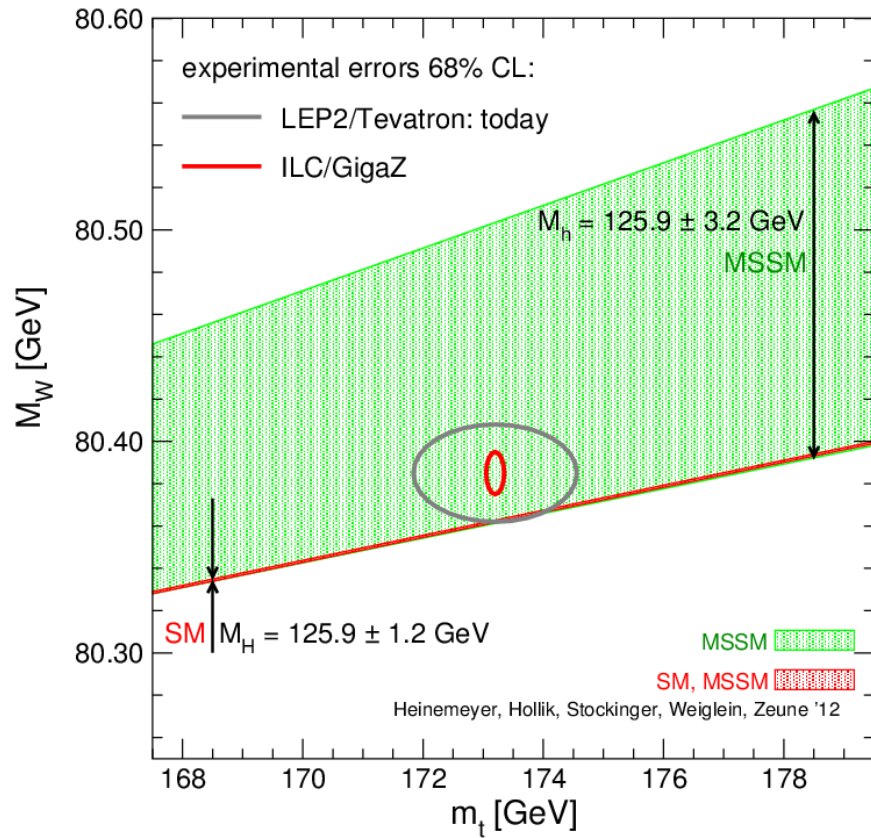
Impact of a Higgs at 125 GeV

S. Heinemeyer, G. Weiglein, L. Z. '13
- PRELIMINARY



- The discovered Higgs boson can in the MSSM be interpreted both as:
 - The light CP-even Higgs h
 - The heavy CP-even Higgs H (in region of low M_A and small $\tan \beta$)

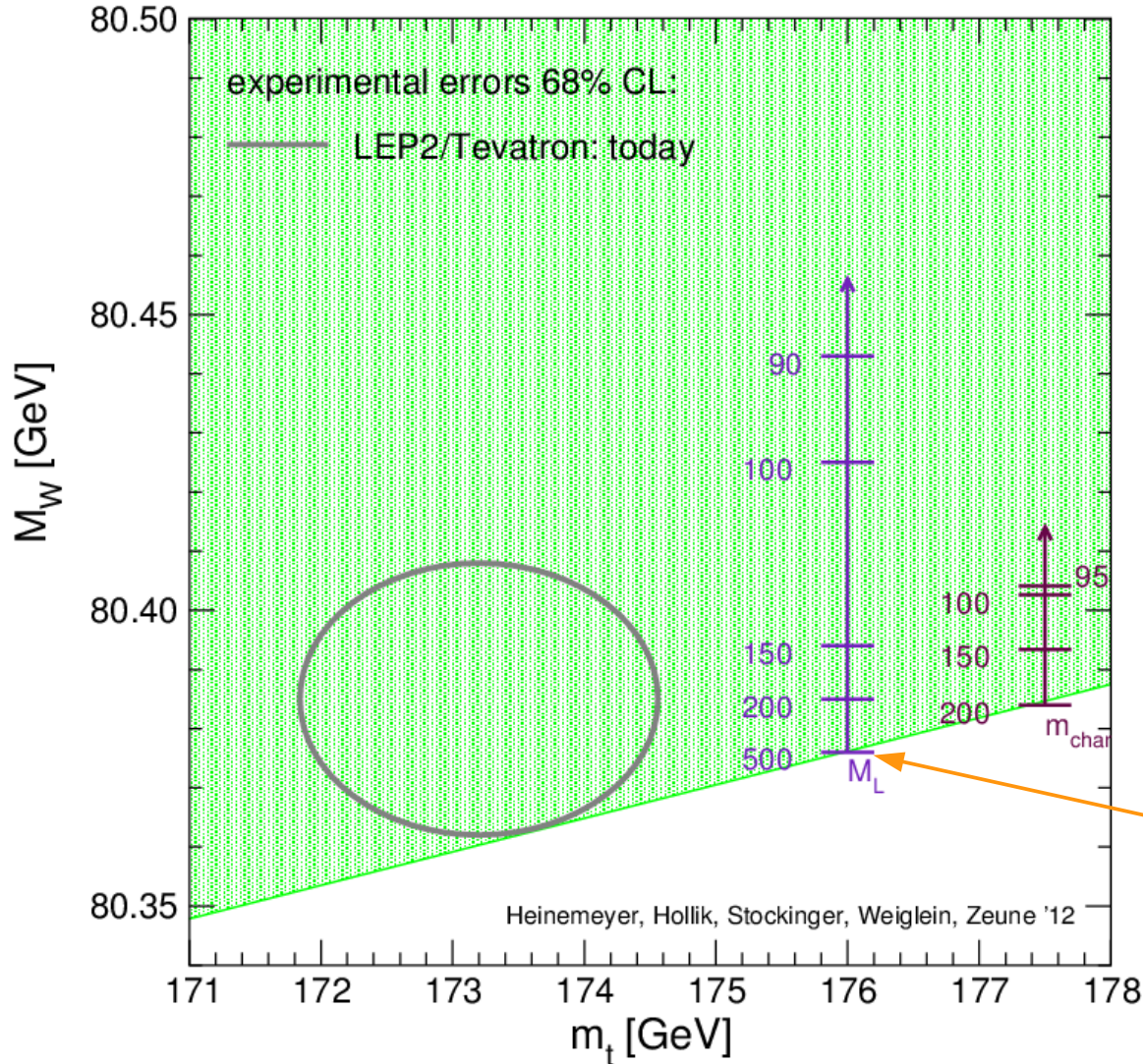
Impact of a Higgs at 125 GeV



- With current level of precision SUSY slightly favored
- Linear collider has potential to distinguish between the models

Contribution from SUSY particles

- Effects from charginos, neutralinos and sleptons:

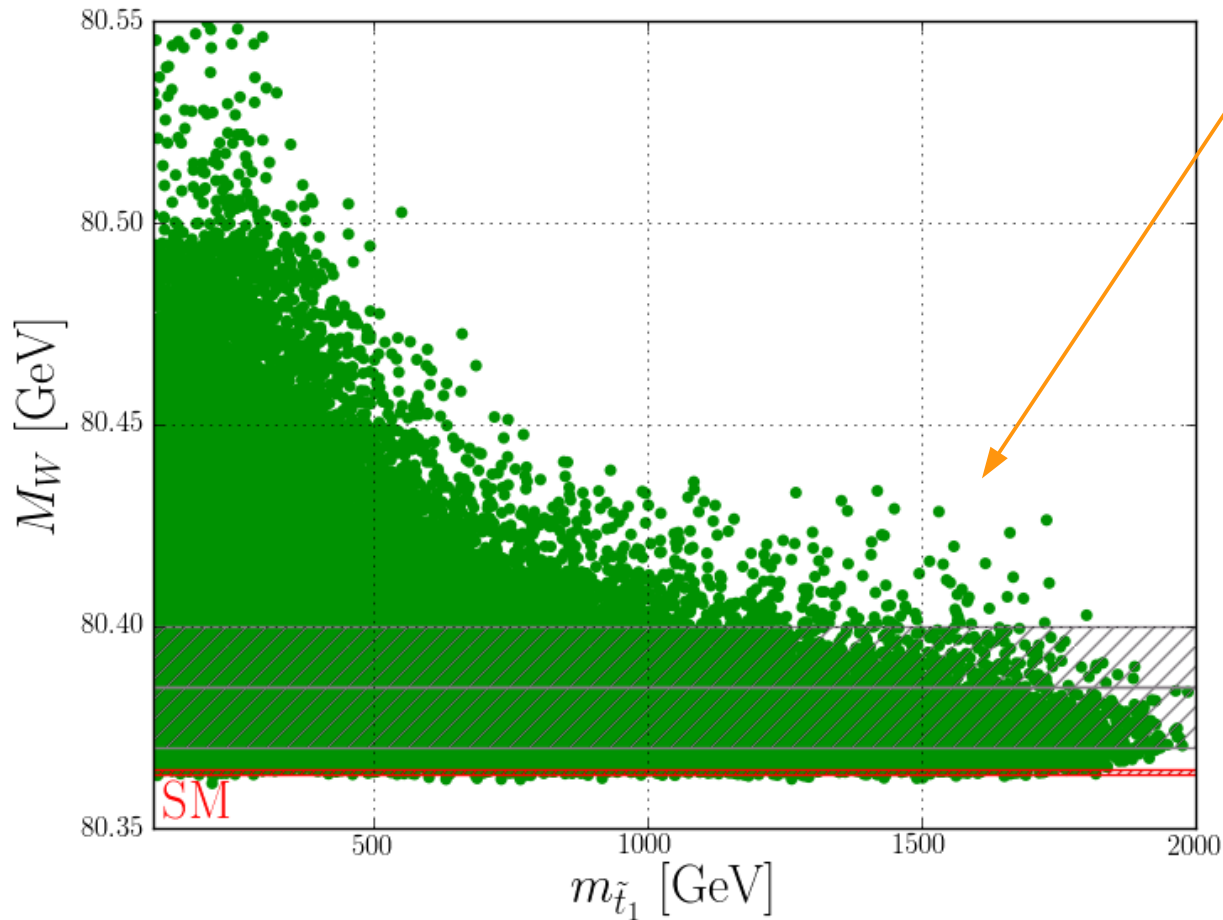


- Contribution from light sleptons $\gtrsim 60$ MeV (mainly from mass splitting between charged sleptons and sneutrinos)
- Contribution from charginos and neutralinos ≈ 20 MeV

All other SUSY particles heavy

Stop contribution

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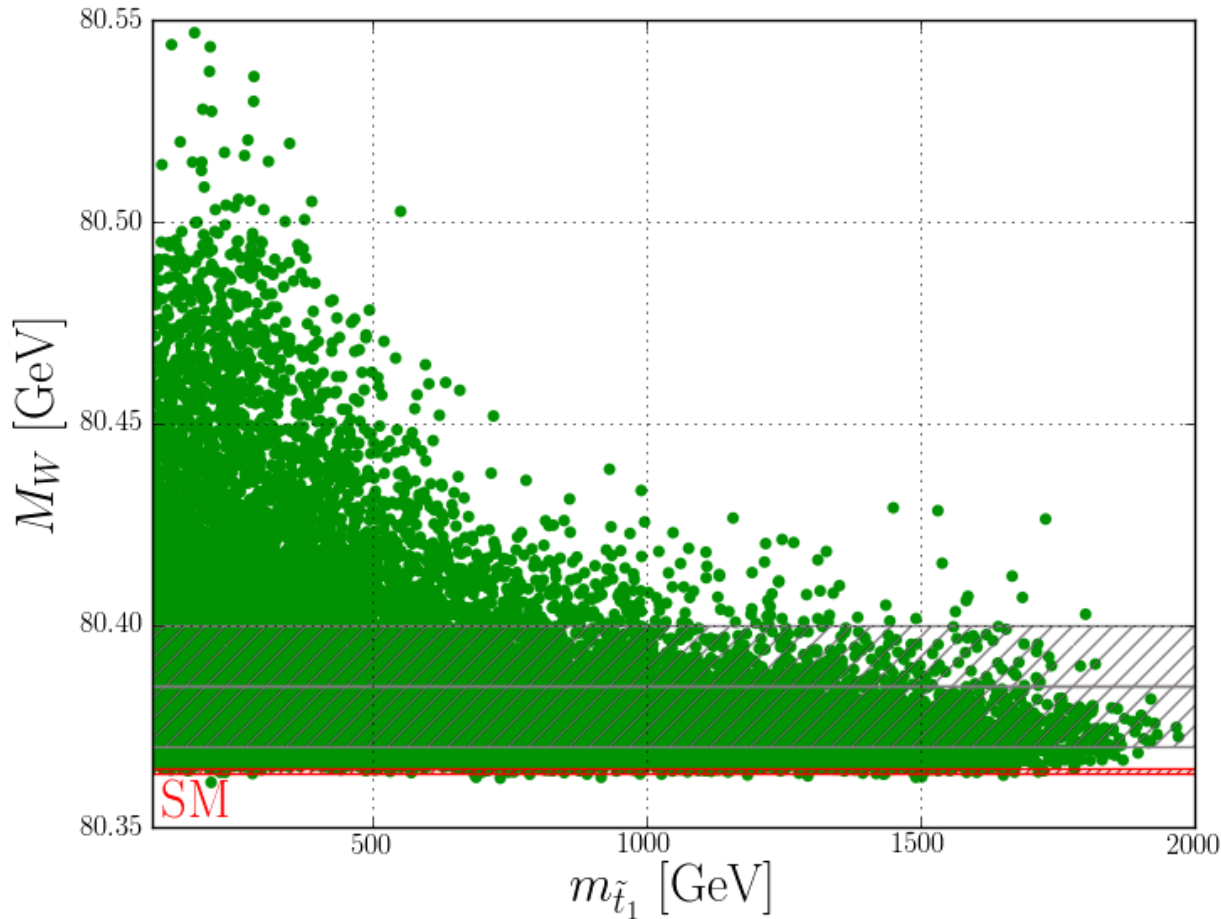
If stops are heavy:

- Still sizable SUSY contributions from:
 - sleptons
 - charginos,
 - neutralinos
- + remaining contributions from stop, sbottoms

Compatible with measurement

All HiggsBounds allowed points

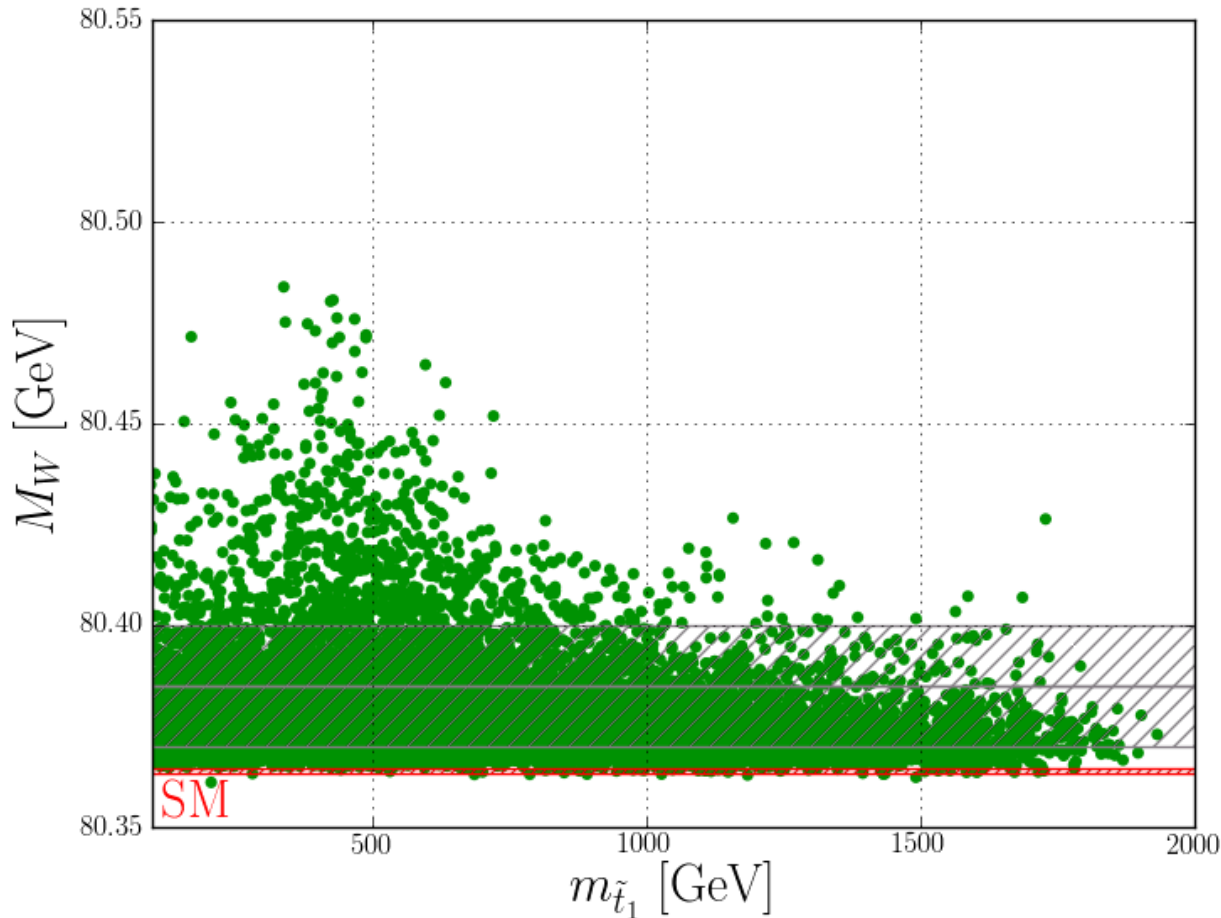
Stop contribution



LHC bounds on squarks and gluinos have very little impact on W-boson mass prediction

+ squarks and gluinos heavier than 1200 GeV

Stop contribution



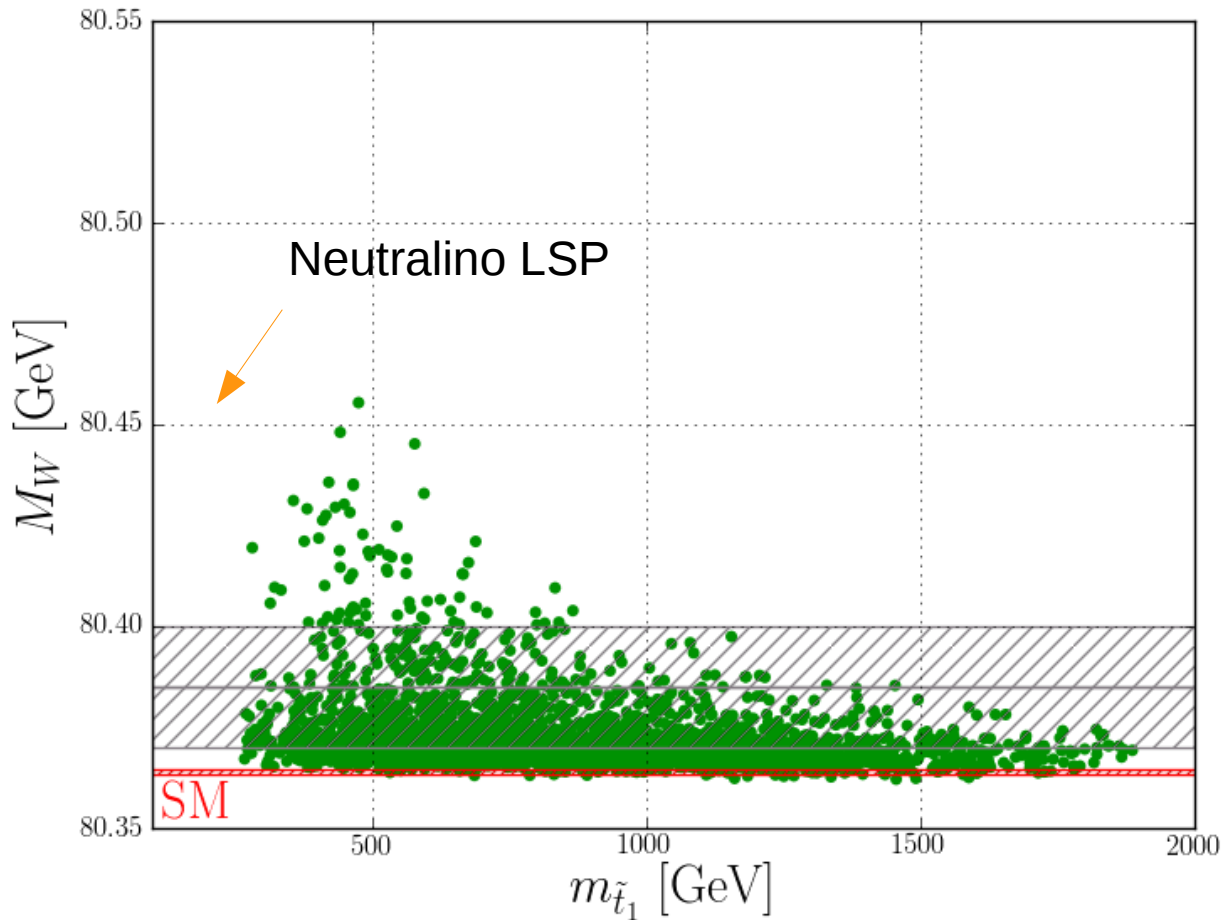
If sbottoms are heavier than 500 GeV:

Very large M_W values impossible

Good compatibility with experimental result

+ sbottoms heavier than 500 GeV

Stop contribution



With

$$m_{\tilde{t}_1} \sim 500 \text{ GeV}$$

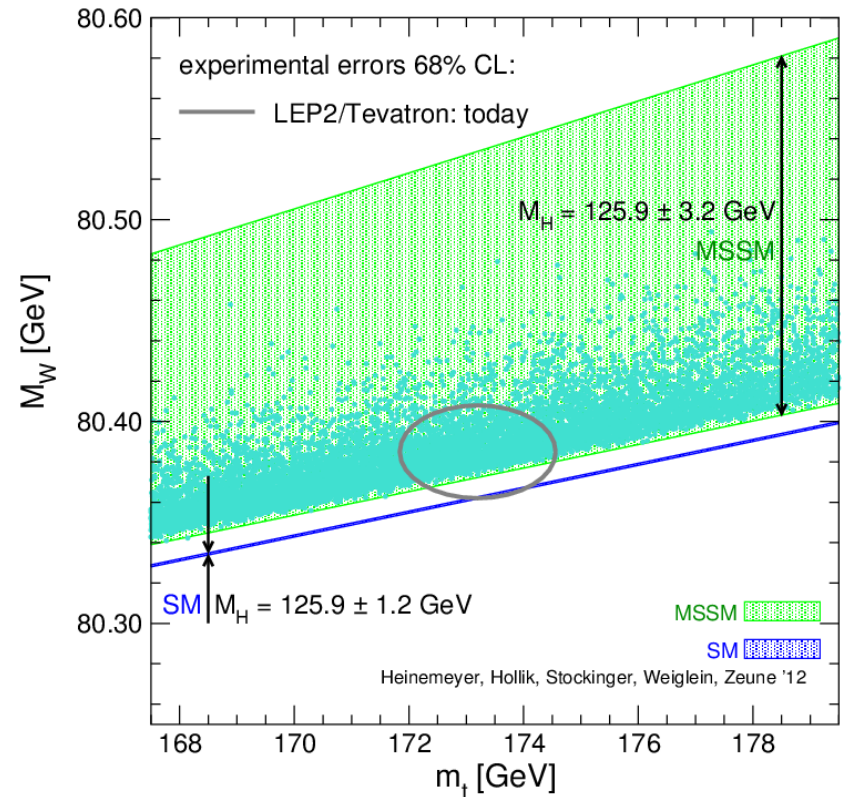
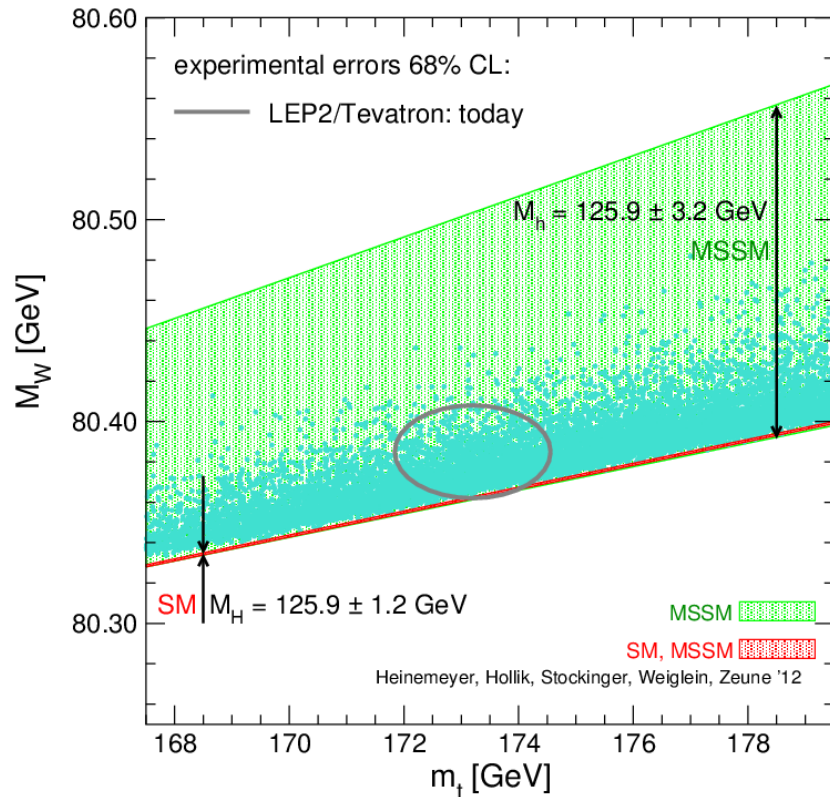
$$m_{\tilde{b}_1} > 500 \text{ GeV}$$

remaining M_W
contribution from
stop – sbottom
sector can still be
sizable

+ sleptons and charginos heavier than 500 GeV

Impact of stop and sbottom mass limit

Blue points:
Stop, sbottoms heavier than 500 GeV,
squarks and gluinos heavier than 1200 GeV



- Limits on stop and sbottom masses would decrease the possible size of the SUSY contributions
- M_W prediction in good agreement with exp. measurement
- Not possible to restrict stop masses

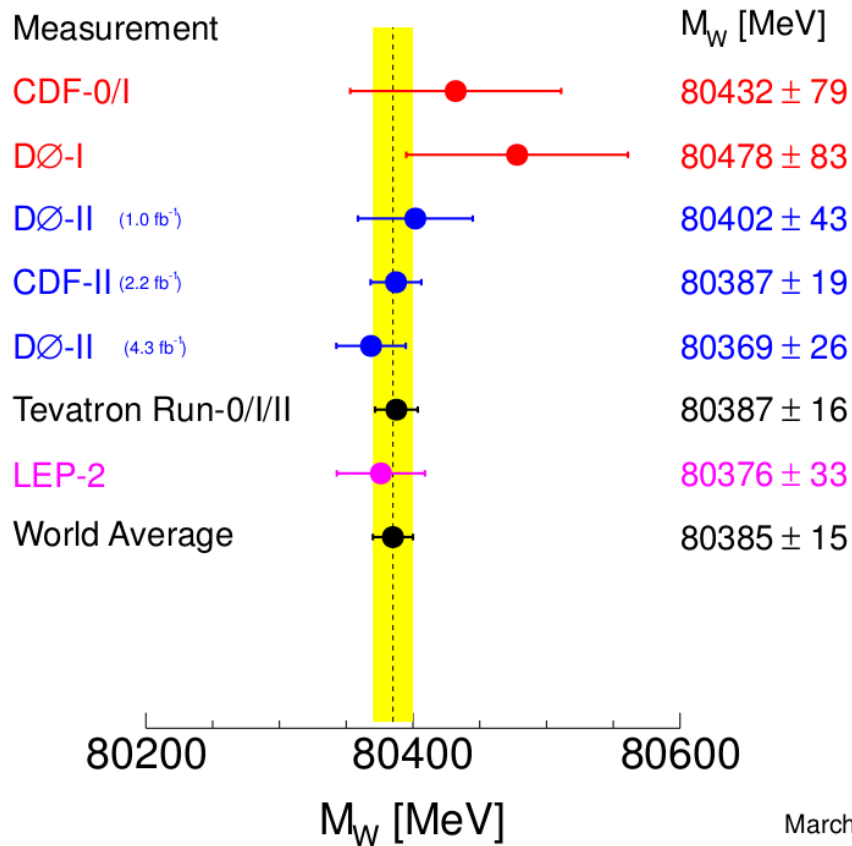
Conclusions

- Precise prediction of W-boson mass in the MSSM
- Size of SUSY contributions:
 - Largest contribution from stops and sbottoms
 - Limits on 3rd generation squarks have large impact on M_W
 - No restriction possible
 - Light sleptons and charginos, neutralinos give sizable contributions → sizable shift compared to SM even for very heavy squarks
- Both MSSM interpretations of a Higgs at 125 GeV give W-boson mass prediction in good agreement with measurement
- Current value favors non-zero SUSY contribution
- With LC precision it could be possible to distinguish between models

Back-up slides

New measurement of the W-boson mass

Mass of the W Boson

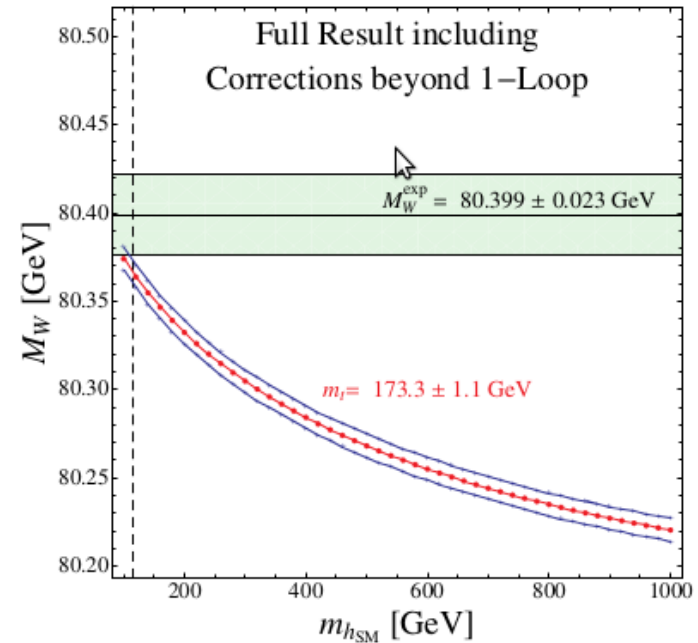
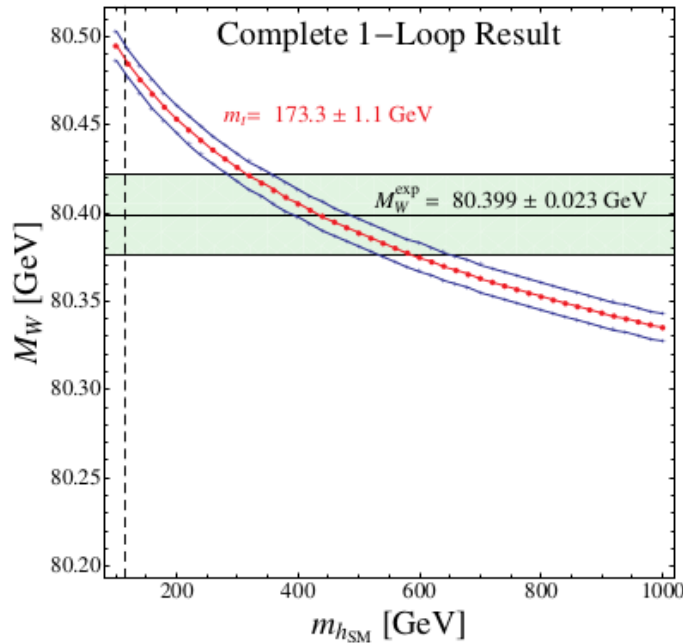


New CDF Result (2.2 fb⁻¹) Transverse Mass Fit Uncertainties (MeV)

	<i>electrons</i>	<i>muons</i>	<i>common</i>
W statistics	19	16	0
Lepton energy scale	10	7	5
Lepton resolution	4	1	0
Recoil energy scale	5	5	5
Recoil energy resolution	7	7	7
Selection bias	0	0	0
Lepton removal	3	2	2
Backgrounds	4	3	0
pT(W) model	3	3	3
Parton dist. Functions	10	10	10
QED rad. Corrections	4	4	4
Total systematic	18	16	15
Total	26	23	

March 2012

W boson mass prediction SM



- ▶ Corrections beyond one-loop cause downward shift of more than 100 MeV
- ▶ Dominant contributions: $\Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)}$ ($\approx 14\%$ of $\Delta r^{(\alpha)}$)
 $\Delta r^{(\alpha^2)}$ ($\approx 9\%$ of $\Delta r^{(\alpha)}$)
- ▶ Preference for small SM Higgs masses
- ▶ No overlap between 1σ band and theoretical prediction for $m_{h_{\text{SM}}} > 114 \text{ GeV}$
- ▶ Dominant theoretical uncertainty from m_t (higher order uncertainty 4 MeV)

Full Δr formula

$$\Delta r = \frac{\Sigma_T^{WW}(0) - \text{Re}(\Sigma_T^{WW}(M_W^2))}{M_W^2} + \Pi^{AA}(0) - \frac{c_W^2}{s_W^2} \text{Re} \left[\frac{\Sigma_T^{ZZ}(M_Z^2)}{M_Z^2} - \frac{\Sigma_T^{WW}(M_W^2)}{M_W^2} \right] \\ + 2 \frac{s_W}{c_W} \frac{\Sigma_T^{AZ}(0)}{M_Z^2} + \text{Vertex} + \text{Box} - \frac{1}{2} \text{Re} (\Sigma_L^e(0) + \Sigma_L^\mu(0) + \Sigma_L^{\nu_e}(0) + \Sigma_L^{\nu_\mu}(0))$$

Calculation of Δr

- 1-loop calculation of Δr in the MSSM
 - General MSSM, complex phases, CKM mixing
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$$\Delta r^{\text{MSSM}} = \Delta r^{\text{SM}} + \Delta r^{\text{SUSY}}$$

Most advanced result in the SM:

$$\begin{aligned}\Delta r^{\text{SM}} = & \Delta r^{(\alpha)} + \Delta r^{(\alpha\alpha_s)} + \Delta r^{(\alpha\alpha_s^2)} \\ & + \Delta r_{\text{ferm}}^{(\alpha^2)} + \Delta r_{\text{bos}}^{(\alpha^2)} + \Delta r^{(G_\mu^2 \alpha_s m_t^4)} \\ & + \Delta r^{(G_\mu^3 m_t^6)} + \Delta r^{(G_\mu m_t^2 \alpha_s^3)}\end{aligned}$$

Large QCD corrections enter at 2-loop level

All known SUSY corrections:

Higgs, sfermion, chargino, neutralino 1-loop corrections
+ leading 2-loop corrections

↪ Most precise MSSM prediction for the W-boson mass!