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

based on work in collaboration with Sven Heinemeyer and Georg Weiglein

Lisa Zeune
EPS HEP 2013, Stockholm
19 July 2013
W-boson mass

- Electroweak precision observables
  \[ M_W, \quad \sin^2 \theta_{\text{eff}}, \quad a_\mu \ldots \]
- Highly sensitive to quantum effects of 'new physics'
- Precise measurement & precise theoretical calculation needed

→ Test models

→ Constrain model parameters
W-boson mass

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Outline of this talk

- Theoretical prediction of the W-boson mass in the MSSM
- Analyze effect of SUSY particles on the \( M_W \) prediction
- Effects of LHC results on the \( M_W \) prediction
Experimental measurement of the W-boson mass

- Most accurate measurement from Tevatron
- Combination with LEP \( \rightarrow \) World average:
  \[
  M_W^{\text{exp}} = 80.385 \pm 0.015 \text{GeV}
  \]

- Improvement at the LHC possible but very challenging
- Great improvement possible at a linear collider
  \( \rightarrow \) Measurement with \( \sim7 \) 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

Further improvement possible
→ See talk by T. Kurca

Tevatron Electroweak Working Group
April '12

→ See talk by A. Vicini
Determination of the W-boson mass

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

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

- \( G_F, e, s_W \) known with high precision

- X model dependent!

- Precise calculation of \( \Delta r \) needed to test model and constrain model parameters!
Calculation of $\Delta r$

- 1-loop calculation of $\Delta r$ in the MSSM and the NMSSM
  - General (N)MSSM, complex phases, CKM mixing (MFV)
- Incorporation of all known SM and SUSY higher order corrections
- To make use of advanced SM calculation:
  \[
  \Delta r^{(N)\text{MSSM}} = \Delta r^{\text{SM}} + \Delta r^{\text{SUSY}}
  \]
- Most precise MSSM prediction for the W-boson mass
- Easy to extend to other models
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SM contributions to W-boson mass

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

- \( \Delta r^{(\alpha)} \): 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, ...
- \( \Delta r^{(\alpha^2)}_{\text{ferm}} + \Delta r^{(\alpha^2)}_{\text{bos}} \): 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 $\Delta r$

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  \[ \Delta r^{(N)}_{\text{MSSM}} = \Delta r^{\text{SM}} + \Delta r^{\text{SUSY}} \]
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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
    (S)quark loops with Higgs and Higgsino exchange
  - Leading reducible two-loop corrections Consoli, Hollik, Jegenlehner '89

Haestier, Heinemeyer, Stoeckinger, Weiglein '05
## Detailed parameter scan

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Minimum</th>
<th>Maximum</th>
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<tr>
<td>$\mu$</td>
<td>-2000</td>
<td>2000</td>
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<tr>
<td>$M_{\tilde{E}<em>{1,2,3}} = M</em>{\tilde{L}_{1,2,3}}$</td>
<td>100</td>
<td>2000</td>
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<td>2000</td>
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<td>$M_{\tilde{Q}_3}$</td>
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<td>2000</td>
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<tr>
<td>$M_{\tilde{U}_3}$</td>
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<td>$M_{\tilde{D}_3}$</td>
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<td>2000</td>
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<td>$3 M_{\tilde{E}}$</td>
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<td>$A_u = A_d = A_c = A_s$</td>
<td>$-3 M_{\tilde{Q}_{12}}$</td>
<td>$3 M_{\tilde{Q}_{12}}$</td>
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<tr>
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<td>$-3 \max (M_{\tilde{Q}<em>3}, M</em>{\tilde{D}_3})$</td>
<td>$3 \max (M_{\tilde{Q}<em>3}, M</em>{\tilde{D}_3})$</td>
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<tr>
<td>$A_t$</td>
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<td>$3 \max (M_{\tilde{Q}<em>3}, M</em>{\tilde{U}_3})$</td>
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<td>$\tan \beta$</td>
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<tr>
<td>$M_3$</td>
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<td>$M_A$</td>
<td>90</td>
<td>1000</td>
</tr>
<tr>
<td>$M_2$</td>
<td>100</td>
<td>1000</td>
</tr>
</tbody>
</table>

$M_1 \approx 1/2 M_2$
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

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

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

\[ \Delta \rho = \frac{\Sigma^Z_T(0)}{M_Z^2} - \frac{\Sigma^W_T(0)}{M_W^2} \]

- 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
  - Restriction: \( m_{\tilde{t}_2}/m_{\tilde{t}_1} < 2.5, \ m_{\tilde{b}_2}/m_{\tilde{b}_1} < 2.5 \)
Impact of a Higgs at 125 GeV

- The discovered Higgs boson can in the MSSM be interpreted both as the light or heavy CP-even Higgs

- In both cases $M_W$ prediction in good agreement with current measurement
Contribution from SUSY particles

- Effects from charginos, neutralinos and sleptons:

![Graph showing contributions from SUSY particles]
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 $\approx 20$ MeV

All other SUSY particles heavy
Impact of stop and sbottom mass limit

- Limits on stop and sbottom masses would decrease the possible size of the SUSY contributions
- $M_W$ prediction in good agreement with exp. measurement

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

● Higher precision needed to distinguish between models
Back-up slides
If stops are heavy:

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

Compatible with measurement

All HiggsBounds allowed points
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
New measurement of the W-boson mass

Mass of the W Boson

<table>
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<tr>
<th>Measurement</th>
<th>$M_W$ [MeV]</th>
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<tbody>
<tr>
<td>CDF-0/I</td>
<td>80432 ± 79</td>
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<tr>
<td>DØ-I</td>
<td>80478 ± 83</td>
</tr>
<tr>
<td>DØ-II (1.0 fb$^{-1}$)</td>
<td>80402 ± 43</td>
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<tr>
<td>CDF-II (2.2 fb$^{-1}$)</td>
<td>80387 ± 19</td>
</tr>
<tr>
<td>DØ-II (4.3 fb$^{-1}$)</td>
<td>80369 ± 26</td>
</tr>
<tr>
<td>Tevatron Run-0/I/II</td>
<td>80387 ± 16</td>
</tr>
<tr>
<td>LEP-2</td>
<td>80376 ± 33</td>
</tr>
<tr>
<td>World Average</td>
<td>80385 ± 15</td>
</tr>
</tbody>
</table>

New CDF Result (2.2 fb$^{-1}$) Transverse Mass Fit Uncertainties (MeV)

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<tr>
<td>Total</td>
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</table>

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 $\Delta r(\alpha)$
  \[ \Delta r(\alpha^2) \approx 9\% \text{ of } \Delta r(\alpha) \]
- Preference for small SM Higgs masses
- No overlap between $1\sigma$ band and theoretical prediction for $m_{h_{SM}} > 114$ GeV
- Dominant theoretical uncertainty from $m_t$ (higher order uncertainty 4 MeV)
Full $\Delta r$ formula

$$
\Delta r = \frac{\Sigma_{T}^{WW}(0) - \text{Re} \left( \Sigma_{T}^{WW}(M_{W}^{2}) \right)}{M_{W}^{2}} + \Pi^{AA}(0) - \frac{c_{W}^{2}}{s_{W}^{2}} \text{Re} \left[ \frac{\Sigma_{T}^{ZZ}(M_{Z}^{2})}{M_{Z}^{2}} - \frac{\Sigma_{T}^{WW}(M_{W}^{2})}{M_{W}^{2}} \right] \\
+ 2 \frac{s_{W}}{c_{W}} \frac{\Sigma_{T}^{AZ}(0)}{M_{Z}^{2}} + \text{Vertex + Box} - \frac{1}{2} \text{Re} \left( \Sigma_{L}^{e}(0) + \Sigma_{L}^{\mu}(0) + \Sigma_{L}^{e}(0) + \Sigma_{L}^{\mu}(0) \right)
$$