Precise predictions for the W boson mass in BSM

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Based on work together with Georg Weiglein

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Introduction

How to find new physics?

- Direct search for new particles
- Search for virtual effects of new particles

Electroweak precision observables

- EWPO: M_W, Γ_Z, $\sin\Theta_W^{eff}$, $g_\mu - 2$, BR($b \to s\gamma$) ...
- Highly sensitive to quantum effects involving the whole structure of a BSM model
- Precision measurement and precise theoretical prediction needed

  $\Longrightarrow$ Test Models

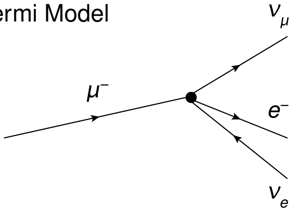
  $\Longrightarrow$ Constrain model parameters
- Current exp. value: $M_W^{exp} = 80.399 \pm 0.023$GeV (accuracy 0.03%)

  Combined Tevatron measurements: Expected $\delta M_W^{exp} \approx 12$MeV

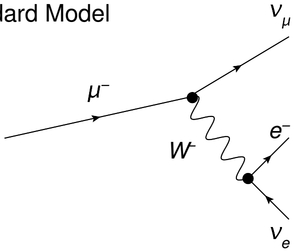
  [Jan Stark, Lepton and Photon 2011]

Determination of M_W

Fermi Model



Standard Model



- Compare Born amplitudes:

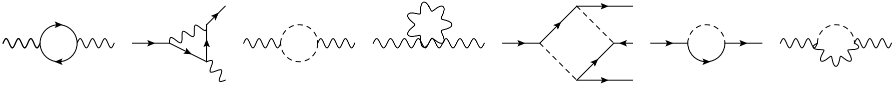
$$\frac{G_F}{\sqrt{2}} = \frac{M_Z^2 e^2}{8(M_Z^2 - M_W^2) M_W^2}$$

G_F contains the QED corrections in the Fermi model

- All other loop corrections can be written as $\mathcal{M}_{\text{Loops}} = \Delta r\ \mathcal{M}_{\text{Born}}$

$$\frac{G_F}{\sqrt{2}} = \frac{M_Z^2 e^2}{8(M_Z^2 - M_W^2) M_W^2} \left(1 + \Delta r(M_W, M_Z, m_t, ..., X)\right) \qquad X = m_H, m_{\tilde{t}}, ...$$

- Model dependent prediction of the W boson mass!



Δr Calculation

Current status of Δr

- SM: Full two-loop result and leading higher order corrections
- MSSM: One-loop result and dominant two-loop corrections

Our work

- New stand-alone one-loop calculation in SM and MSSM (general model,complex phases)
- Incorporation of all known SM and SUSY higher order corrections

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

Δr^{SM} : Most advanced result in SM

Δr^{SUSY} : All known SUSY corrections

- Most exact MSSM prediction for M_W
- Cross-check with earlier calculations
- Easily extendable to new models

  NMSSM, Models with 4th fermion generation, 2HDM, InertDM

$\Longrightarrow$ Different models comparable in one framework

One-loop Δr formula

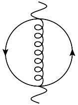
- Δr can be split into three parts: $\Delta r = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{rem}$
- $\Delta\alpha \propto \log(m_f/M_Z)$: Contribution from light fermions
- $\Delta\rho = \frac{\Sigma_T^Z(0)}{M_Z^2} - \frac{\Sigma_T^W(0)}{M_W^2}$: Sensitive to mass splitting!

SM higher order corrections

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

- $\Delta r^{\alpha\alpha_s}$ and $\Delta r^{\alpha\alpha_s^2}$: Two- and three-loop QCD corrections

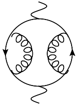
  [Chetyrkin, Kuhn, Steinhauser '95, Djouadi, Verzegnassi '88, ...]



- $\Delta r^{\alpha^2}_{ferm}$ and $\Delta r^{\alpha^2}_{bos}$: Fermionic and bosonic electroweak two-loop corrections

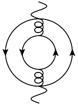
  Fitting formula: Exact result within maximal deviations of 2.7×10^{-5}

  [Awramik, Czakon, Freitas '06, Awramik, Czakon, Freitas, Weiglein '03]



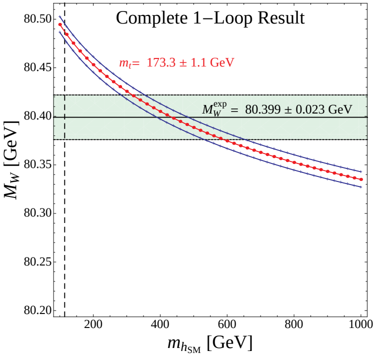
- $\Delta r^{G_\mu^2 \alpha_s m_t^4}$ and $\Delta r^{G_\mu^3 m_t^6}$: Three-loop Top Quark contributions

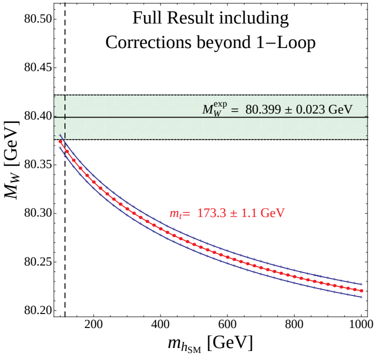
  [Faisst, Kuhn, Seidensticker, Veretin '03]



- $\Delta r^{(G_\mu m_t^2 \alpha_s^3)}$: Four-loop QCD Correction [Boughezal '06]

W boson mass prediction in the 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%), $\Delta r^{(\alpha^2)}$ ($\approx$ 9% of $\Delta r^{(\alpha)}$)
- Preference for small SM Higgs masses
- No overlap between 1σ band and theoretical prediction for $m_{h_{SM}} > 114$ GeV
- Dominant theoretical uncertainty from m_t (higher order uncertainty 4 MeV)

Particle content of the MSSM

Higgs sector

- Two Higgs doublets needed to give mass to up- and down-type fermions
- Five Higgs bosons h, H, A, $H^{\pm}$, three unphysical Goldstone bosons
- At tree-level: Higgs sector fully described by m_A, $\tan\beta = \frac{v_2}{v_1}$ = ratio of vevs

Sfermion sector

- Sfermion mass matrix:

$$M_{\tilde{f}} = \begin{pmatrix} M_{\tilde{f}_L}{}^2 + M_Z^2 \cos 2\beta (I_3^f - Q_f s_W^2) + m_f^2 & m_f X_f{}^* \\ m_f X_f & M_{\tilde{f}_R}{}^2 + M_Z^2 \cos 2\beta \, Q_f s_W^2 + m_f^2 \end{pmatrix}$$

- $M_{\tilde{f}_L}, M_{\tilde{f}_R}$: soft SUSY breaking parameters
- In numerical analysis: $M_{\tilde{f}_L} = M_{\tilde{f}_R} = \{ML, MQ_{12}, MQ_3\}$
- $X_f = A_f - \mu^* \{\cot\beta, \tan\beta\}$ defines sfermion mixing

Chargino and neutralino sector

- Gauginos and Higgsinos mix to mass eigenstates: Charginos and neutralinos
- Chargino and neutralino sector governed by M_1, M_2 and μ

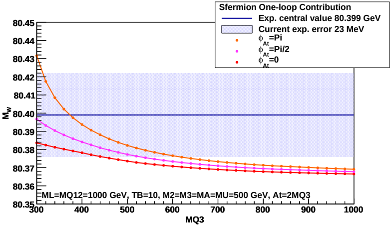
SUSY contributions to M_W

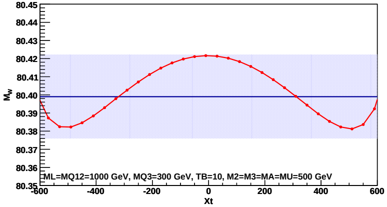
One-loop contributions

- Additional contributions: Sfermion, MSSM Higgs, chargino/neutralino sector

Sfermion sector

- Leading one-loop SUSY contributions ($\tilde{t}$, $\tilde{b}$ loops)
- Contribution sizable for small MQ_3, Significant phase dependence
- $\Delta\rho$: Sensitive to mass splitting between stops and sbottoms





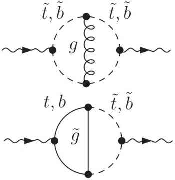
Supersymmetric two-loop contributions

- Irreducible supersymmetric two-loop contributions
  - SUSY QCD corrections of $\mathcal{O}(\alpha\alpha_s)$:

    (S)quark loops with gluon and gluino exchange [Djouadi et. al '98]
  - Two-loop Yukawa contributions $\mathcal{O}(\alpha_t^2)$,$\mathcal{O}(\alpha_t\alpha_b)$,$\mathcal{O}(\alpha_b^2)$:

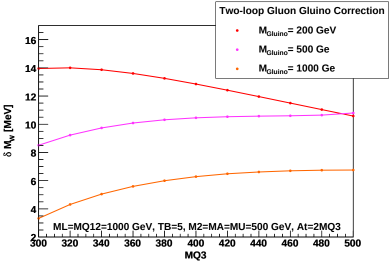
    (S)quark loops with Higgs and Higgsino exchange

    [Haestier, Heinemeyer, Stoeckinger, Weiglein '05]



- Leading reducible two-loop corrections [Consoli, Hollik, Jegenlehner '89]
- Complete Δr^{MSSM} agrees with previous result [Heinemeyer, Hollik, Stöckiger, Weber, Weiglein '06]

Sfermion sector

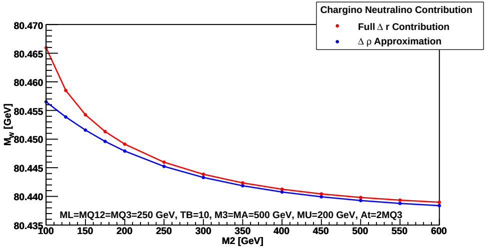


- $\mathcal{O}(\alpha\alpha_s)$ contributions up to 15 MeV

  ($\gtrsim$ exp. accuracy at Tevatron)
- Can enter with both signs
- Important for a precise M_W prediction!

Chargino and neutralino sector

- Contribution to M_W from one-loop diagrams
- For small scale input values:
  - Chargino and neutralino sector contribution up to 28 MeV
  - Contribution larger than current experimental error



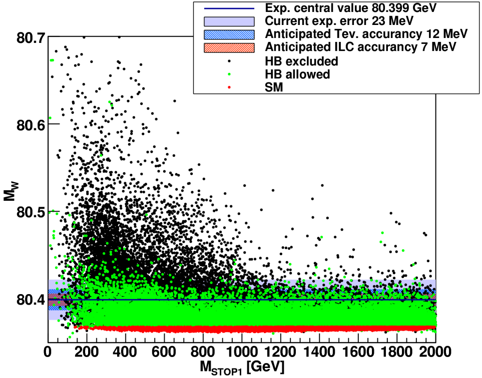
$\Delta\rho$ Approximation

- Corresponds to T parameter of the S,T,U parameters
- Difference up to 10 MeV
- Not sufficient for small SUSY mass range

Higgs Sector

- Higgs sector contribution up to about 20 MeV

M_W in the MSSM



Parameter Scan

$$ML = 100...2000 \text{ GeV}$$

$$MQ_{12} = 100...2000 \text{ GeV}$$

$$MQ_3 = 100...2000 \text{ GeV}$$

$$A_t = -2\ MQ_3...2MQ_3$$

$$\mu = -2000...2000 \text{ GeV}$$

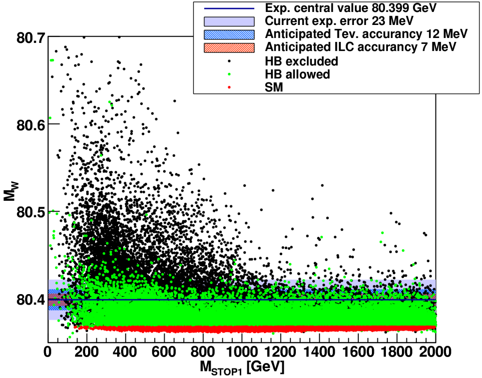
$$\tan\beta = 1.1...60$$

$$m_{\tilde{g}} = 200...1500 \text{ GeV}$$

$$m_A = 90...1000 \text{ GeV}$$

$$M_2 = 100...2000 \text{ GeV}$$

M_W in the MSSM



Imposed Limits

- Chargino mass limit:
  $m_{\chi^\pm} > 94$ GeV
  [The DELPHI Collaboration: J. Abdallah, et al, 2003]
- MSSM Higgs mass limits from `HiggsBounds 3.4.0.beta`:
  Exclusion from Higgs searches at LEP, Tevatron and the LHC
- SM Higgs mass limit:
  $m_{h_{SM}} > 114.4$ GeV
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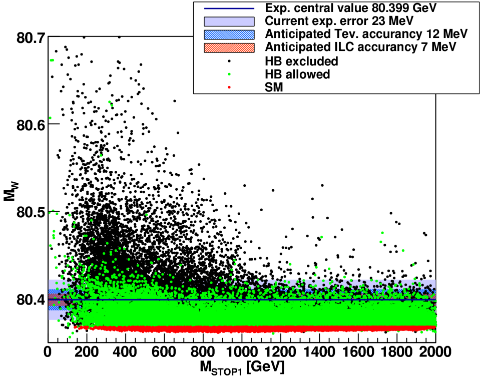
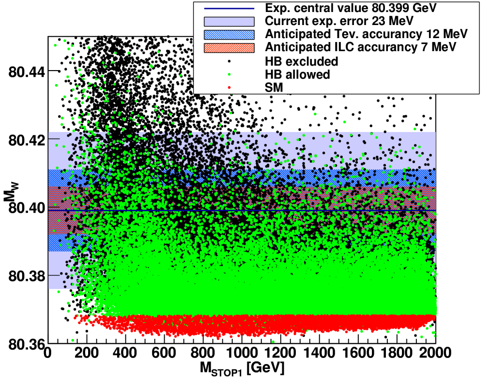


- W boson in the MSSM generally heavier than in the SM
- M_W is highly sensitive to quantum effects of SUSY particles
- Large SUSY contributions: $M_W > 80.5$ GeV possible

  BUT: Very large splitting in $\tilde{t},\tilde{b}$ sector. Close to experimental boundaries!

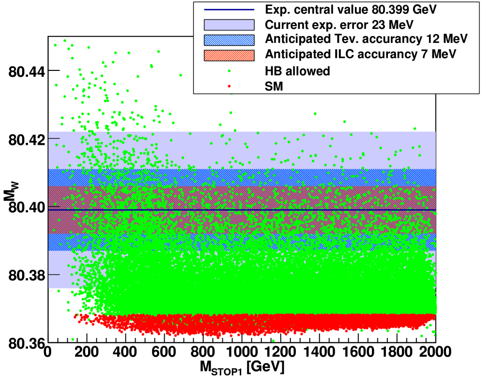
M_W in the MSSM



Impact of Higgs bounds

- Most points with very large M_W ruled out by `HiggsBounds`
- Many points with M_W up to M_W^{exp} and higher are allowed by Higgs searches
- Large SUSY contributions possible
- Improved experimental accuracy $\Longrightarrow$ Sensitivity to SUSY effects increases
- SUSY favoured over the SM by the current experimental data

M_W in the MSSM



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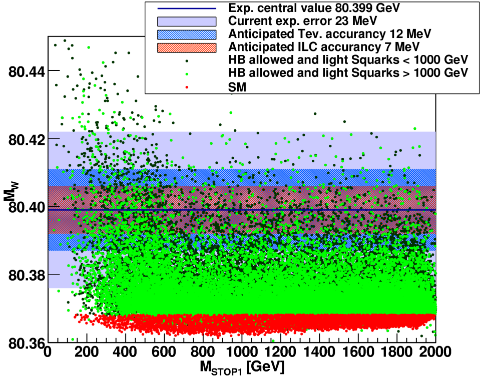
M_W in the MSSM: Potential impact of LHC searches



Effect of LHC searches on M_W

- Sizable SUSY contribution to M_W are still possible if squarks up to 1000 GeV (or higher) are ruled out by LHC
- Impact of additional limits on stops and sbottoms would be small
- If Squarks are heavy:
  Sizeable SUSY contributions from Slepton, Higgs and Chargino, Neutralino sector

Conclusion and Outlook

Δr Calculation

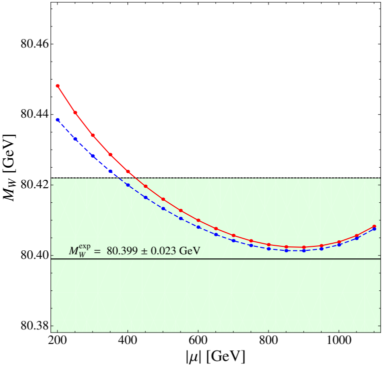
- Complete one-loop calculation of M_W in the MSSM
  + Incorporation of higher order corrections
- Most precise and general M_W prediction
- Framework that allows easy extensions to other models

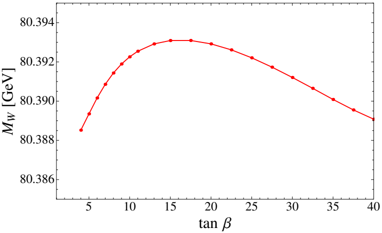
M_W in the MSSM

- Contributions from all SUSY sectors can be sizable
- M_W prediction in MSSM in general higher than in SM
- M_W values around M_W^{exp} possible in the MSSM and allowed by Higgs searches
  $\Longrightarrow$ Experimental value favours non-zero SUSY contribution
- The LHC limits from squark searches hardly constrain the possible range of M_W further

Back up

Dependence on other SUSY parameters





Sfermion mixing parameter

$$X_t = A_t - \mu \frac{1}{\tan\beta}$$
$$X_b = A_b - \mu \tan\beta$$

Resummation formula

One-loop formula

- One-loop result dominated by fermionic contributions

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

- $\Delta\alpha$: Shift of the fine structure constant
- $\Delta\rho = \frac{\Sigma_T^Z(0)}{M_Z^2} - \frac{\Sigma_T^W(0)}{M_W^2}$
  - Correction to ρ parameter, which describes the ratio between neutral and charged weak current
  - Sensitive to mass splitting!

Leading reducible two-loop corrections

- Resummation formula:

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

- Includes $(\Delta\alpha)^2$, $(\Delta\rho)^2$, $\Delta\alpha\Delta\rho$ correctly

$\Delta\rho$ Contribution

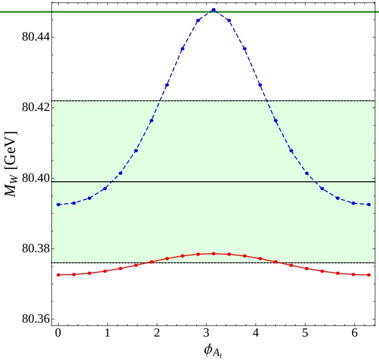
$$\Delta\rho^{\mathrm{SM}} = \frac{3}{16\pi s_W^2 c_W^2}\left(\frac{2G_\mu s_W^2 M_W^2}{\sqrt{2}\pi}\right)\frac{1}{M_Z^2}F_0(m_t^2, m_b^2) = \frac{3G_\mu}{8\sqrt{2}\pi^2}F_0(m_t^2, m_b^2)$$

$$\begin{aligned}\Delta\rho^{\mathrm{SUSY}} = \frac{3G_\mu}{8\sqrt{2}\pi^2}\Big(& -\sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{t}}F_0(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2) - \sin^2\theta_{\tilde{b}}\cos^2\theta_{\tilde{b}}F_0(m_{\tilde{b}_1}^2, m_{\tilde{b}_2}^2) \\ & + \cos^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}}F_0(m_{\tilde{t}_1}^2, m_{\tilde{b}_1}^2) + \cos^2\theta_{\tilde{t}}\sin^2\theta_{\tilde{b}}F_0(m_{\tilde{t}_1}^2, m_{\tilde{b}_2}^2) \\ & + \sin^2\theta_{\tilde{t}}\cos^2\theta_{\tilde{b}}F_0(m_{\tilde{t}_2}^2, m_{\tilde{b}_1}^2) + \sin^2\theta_{\tilde{t}}\sin^2\theta_{\tilde{b}}F_0(m_{\tilde{t}_2}^2, m_{\tilde{b}_2}^2)\Big)\end{aligned}$$

with

$$F_0(x,x) = 0 \quad \text{and} \quad F_0(x,0) = x$$

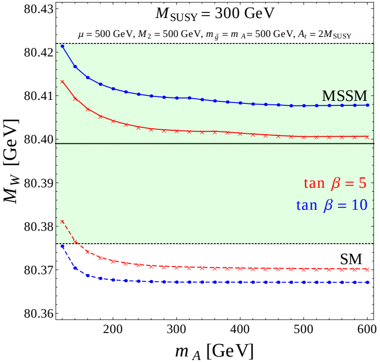
Full Phase dependence



Phase dependence

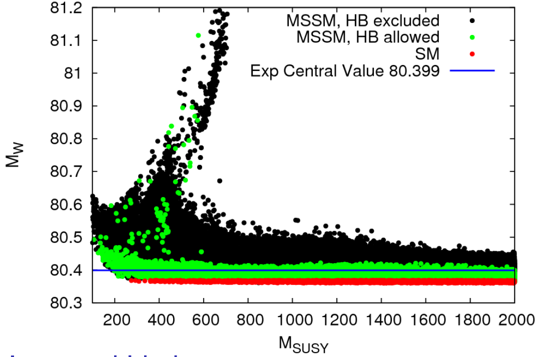
- M_W as a function ϕ_{A_t} for two values, $M_{\text{SUSY}} = 300$ GeV (blue, dashed line) and $M_{\text{SUSY}} = 600$ GeV (red, solid line)
- The other SUSY parameters are: $A_t = 2M_{\text{SUSY}}$, $M_2 = 500$ GeV, $m_{\tilde{g}} = 500$ GeV, $\mu = 500$ GeV, $m_A = 500$ GeV, $\tan\beta = 10$

Higgs Sector, Comparison SM and MSSM



- Higgs masses include one- and two-loop corrections (FeynHiggs)
- $m_{h_{SM}}$ set to mass of the MSSM Higgs that couples SM-like
  - > SM prediction depends on SUSY parameters
- MSSM prediction is higher than the SM prediction
- Higgs sector contribution up to about 20 MeV (mainly effect of SM corrections)

M_W in the MSSM



Parameter Scan

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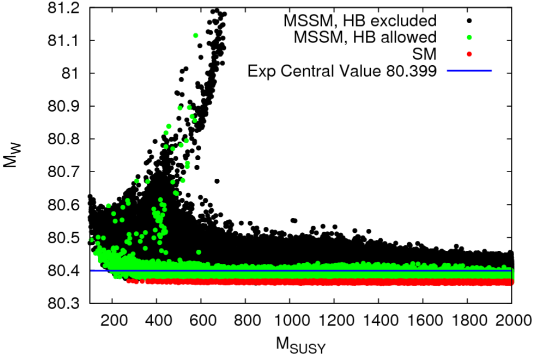

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- Large SUSY contributions: $M_W > 81$ GeV possible

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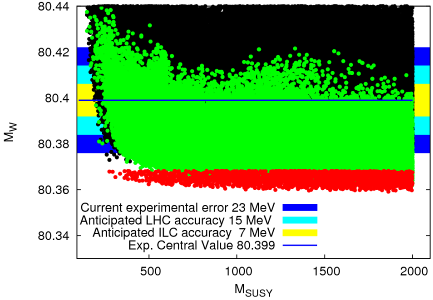
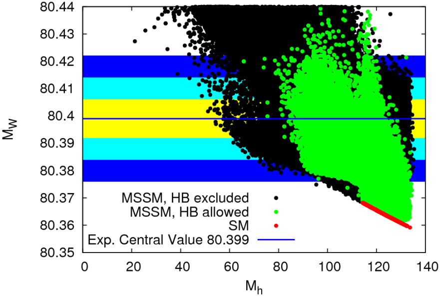
M_W in the MSSM: Impact of Higgs bounds





Effect of Higgs bounds on M_W

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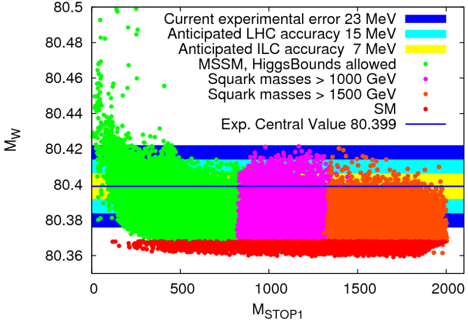
M_W in the MSSM: Potential impact of LHC searches



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