Framework for precision calculations in the NMSSM

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Tools, Stockholm

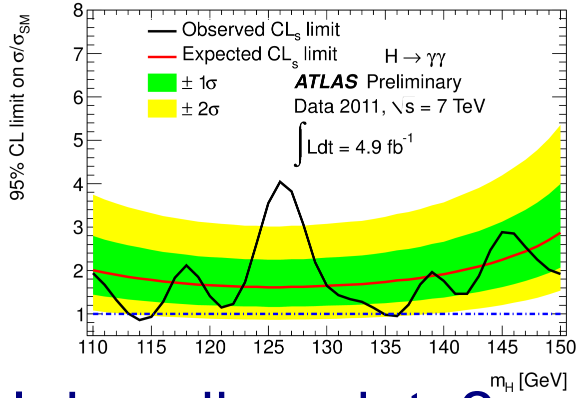
June 21, 2012

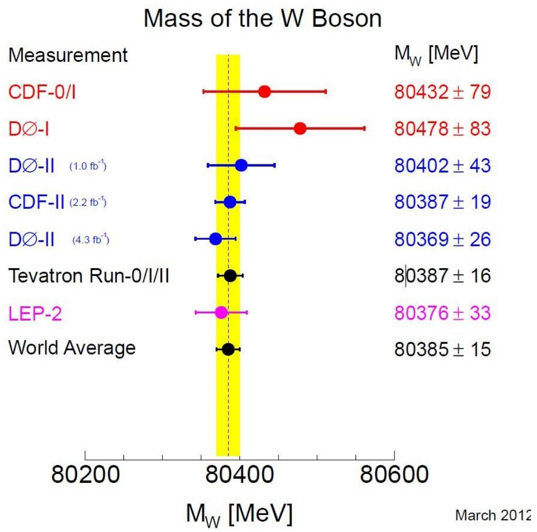
Based on work in collaboration with:

R. Benbrik, M. Gomez Bock, S. Heinemeyer, O. Stål, G. Weiglein

Motivation

- Many new experimental results





  - Which model describes data?
- Precise theory predictions in models beyond the SM needed
  - Test model predictions
  - Constrain model parameters
- Requires framework for loop-calculations and numerical studies
- First results using framework for the Next-to-Minimal Supersymmetric SM

Outline

- NMSSM
- Introduction to computational framework
- **Higgs decays**
  - Study of $h \to \gamma\gamma$
  - Comparison to experimental results
- **W-boson mass**
  - Theoretical prediction for M_W
  - Comparison to prediction for W-mass in the MSSM and SM
  - Impact of LHC results on M_W

The NMSSM

- Two complex Higgs doublets H_1, H_2 and one complex scalar singlet S
- NMSSM superpotential

$$W^{\mathrm{NMSSM}} = (\text{Yukawa terms}) + \lambda \hat{S} \hat{H}_2 \cdot \hat{H}_1 + \frac{1}{3} \kappa \hat{S}^3$$

- Soft breaking terms

$$V_{\mathrm{soft}}^{\mathrm{NMSSM}} = V_{\mathrm{soft}}^{\mathrm{MSSM}} + m_S^2 |S|^2 + \lambda A_\lambda S H_2 \cdot H_1 + \frac{1}{3} \kappa A_\kappa S^3$$

- Motivation for the NMSSM: Solves μ problem of the MSSM

$$W_{(2)} = \mu \hat{H}_2 \hat{H}_1 \rightarrow \lambda \hat{S} \hat{H}_2 \hat{H}_1$$

$\longrightarrow$ $\mu_{\mathrm{eff}} = \lambda v_s$ naturally of the EW scale

The NMSSM Higgs sector

- Spontaneous symmetry breaking

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}(\phi_1 - \mathrm{i}\chi_1) \\ -\phi_1^- \end{pmatrix}, \quad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}(\phi_2 + \mathrm{i}\chi_2) \end{pmatrix}$$

$$S = v_s + \frac{1}{\sqrt{2}}(\phi_s + \mathrm{i}\chi_s).$$

- Extended Higgs sector:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = U^H \begin{pmatrix} \phi_1 \\ \phi_2 \\ \phi_s \end{pmatrix}, \quad \begin{pmatrix} a_1 \\ a_2 \\ G \end{pmatrix} = U^A \begin{pmatrix} \chi_1 \\ \chi_2 \\ \chi_s \end{pmatrix}, \quad \begin{pmatrix} H^\pm \\ G^\pm \end{pmatrix} = U^A \begin{pmatrix} \phi_1^\pm \\ \phi_2^\pm \end{pmatrix}$$

3 CP-even Higgs   2 CP-odd Higgs   charged Higgs

- The Chargino sector and the Sfermion sector are unchanged with respect to the MSSM

The NMSSM

- Neutralino sector:

  Superpartner of Higgs singlet $\tilde{S} \rightarrow$ 5th neutralino

- Neutralino mass matrix in basis $(\tilde{B}, \tilde{W}^0, \tilde{H}_1^0, \tilde{H}_2^0, \tilde{S})$

$$\mathrm{M}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_Z s_W c\beta & M_Z s_W s\beta & 0 \\ 0 & M_2 & M_Z c_W c\beta & -M_Z c_W s\beta & 0 \\ -M_Z s_W c\beta & M_Z c_W c\beta & 0 & -\mu & -\lambda v_2 \\ M_Z s_W s\beta & -M_Z c_W s\beta & -\mu & 0 & -\lambda v_1 \\ 0 & 0 & -\lambda v_2 & -\lambda v_1 & 2K\mu \end{pmatrix}$$

- MSSM limit:

$$\lambda \rightarrow 0,\ \kappa \rightarrow 0, \quad K = \frac{\kappa}{\lambda} = \text{constant}$$

  - Doublet couplings become MSSM-like
  - Couplings of the singlet vanish

Framework for 'easy' loop calculations in NMSSM

- Framework we are using: **`FeynArts/FormCalc`** T. Hahn
  (Package involves model-files for SM, MSSM, 2HDM)
- We implemented NMSSM model file
- Generated with the use of **`SARAH`** F. Staub
- **`SARAH`** output optimized:
  - Using **`FormCalc`** standard notation
  - Applying unitarity relations

    → Improving the speed of calculations

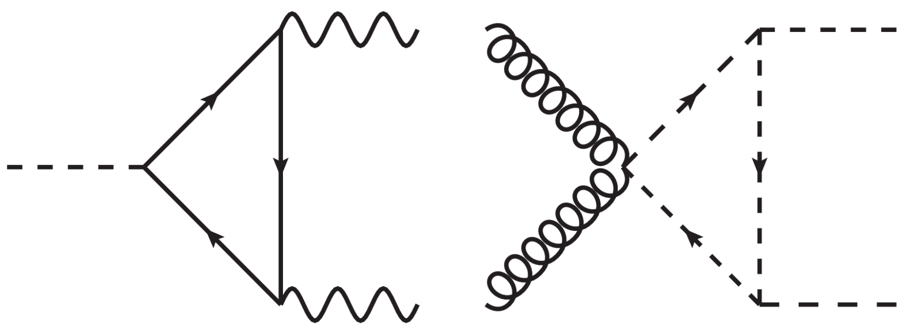
    → Achieving analytical cancellation of UV divergencies
- Supplemented with a code for numerical evaluation of calculated observables

Numercal evaluation

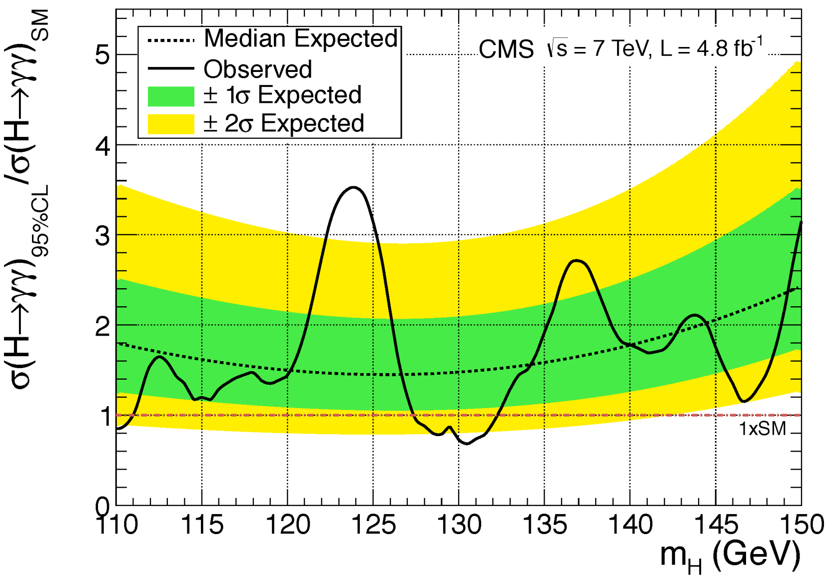
- Analytic **`FormCalc`** results can be exported to Fortran code
- Evaluation of loop-integrals with **`LoopTools`** T. Hahn, M. Perez-Victoria
- Calculation of Higgs and sparticle masses:
  - Choice at the moment between tree-level or masses from **`NMSSMTools`** U. Ellwanger, C. Hugonie
- Restrictions on the NMSSM parameter space can be imposed
  - Constraints implemented in **`NMSSMTools`** accessible (e.g. theoretical constraints, flavour constraints)
  - LEP, Tevatron and the LHC Higgs search limits can be checked with **`HiggsBounds`** P. Bechtle, O. Brein, S. Heinemeyer, O. Stål, T. Stefaniak, G. Weiglein and K. Williams

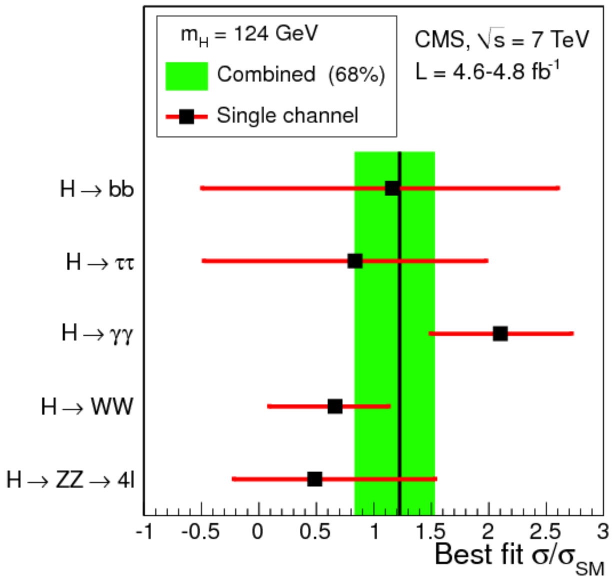
Verification of the new model file

- Consistency check
  - Model file checked against second independent implementation using **`FeynRules`** N. D. Christensen, C. Duhr, B. Fuks
- Calculations in MSSM limit checked
- Comparison of several tree-level processes with **`NMSSMTools`** results
- Extensive check of processes appearing at 1-loop level
  - Many $1 \to 2$ and $2 \to 2$ processes evaluated and checked for UV-finiteness



Excess in di-photon channel





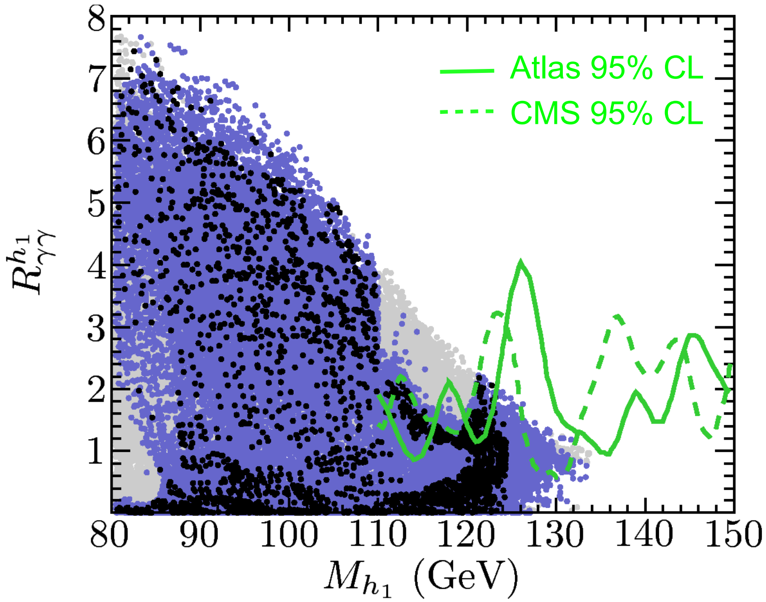
- Largest excess observed in the di-photon channel
  - by Atlas at 126.5 GeV with a local significance of 2.8σ
  - by CMS at 124 GeV with a local significance of 3.1σ
- γγ rate above and WW rate slightly below SM prediction
  - Statistical fluctuation?
  - Sign of physics beyond the SM?

Higgs decay into two photons

- Calculation of the one-loop induced process $h_{1,2} \to \gamma\gamma$
- Rate compared to SM:

$$R_{\gamma\gamma} = \frac{\sigma(gg \to h) \times BR(h \to \gamma\gamma)}{\sigma(gg \to h_{SM}) \times BR(h_{SM} \to \gamma\gamma)}$$

Light Higgs case



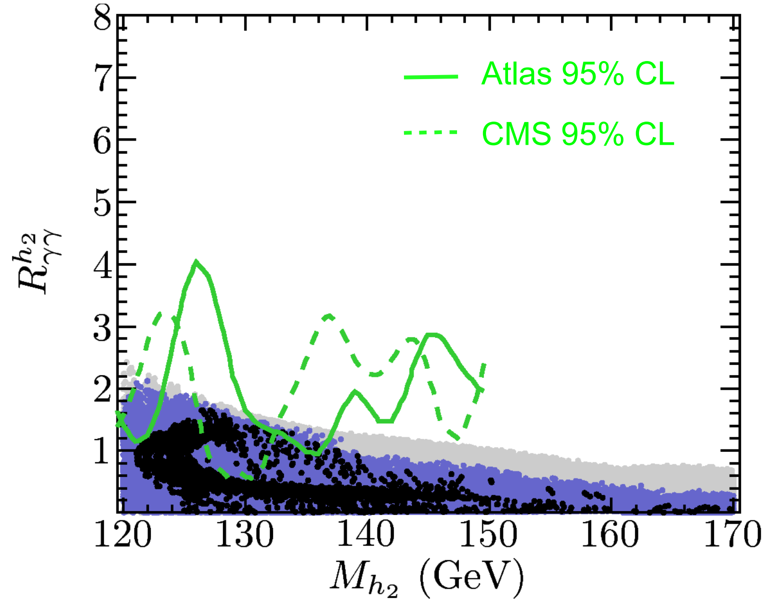
Blue: Allowed by Higgs constraints
Black: Allowed also by flavour constraints and (g-2)

- Sizable enhancement of $R_{\gamma\gamma}$ possible over the whole mass range

Higgs decay into two photons

Heavy Higgs case

- Additional light CP-even Higgs, could be below LEP limit

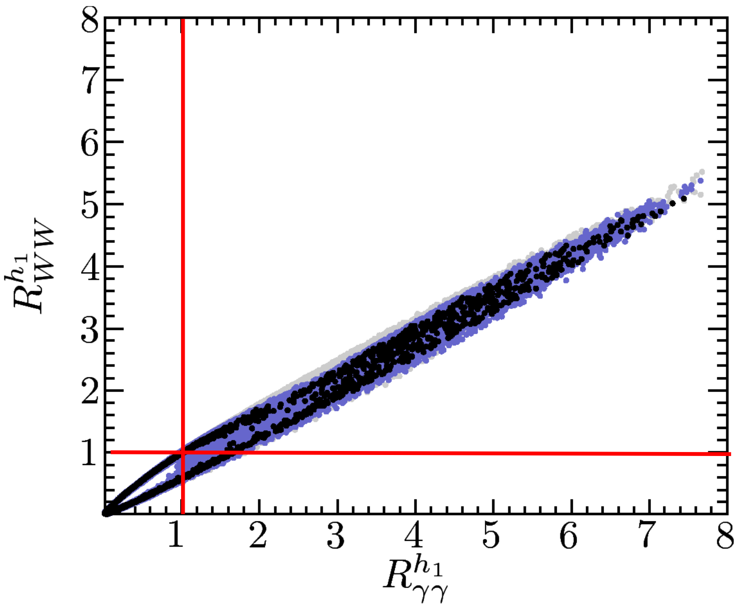


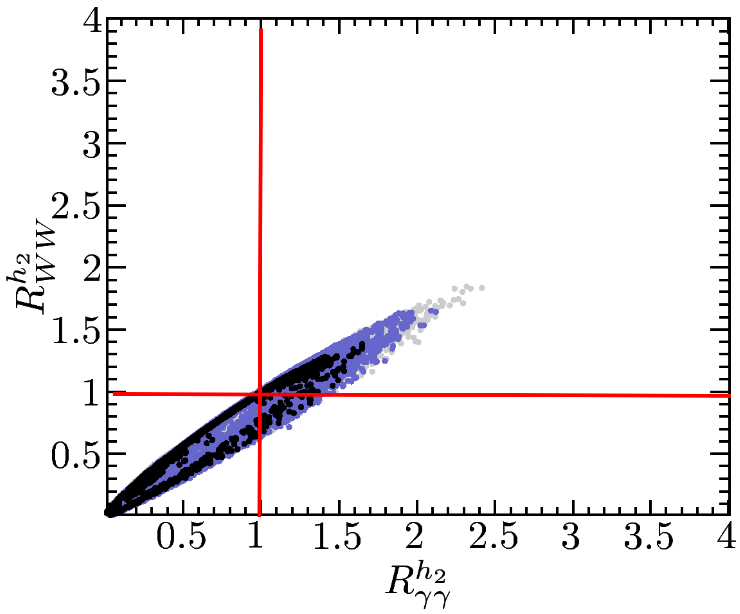
- Enhancement of $R_{\gamma\gamma}$ possible in the mass range 120-145 GeV

Both h_1 and h_2 at 125 GeV interpretations (with enhanced γγ rate) possible in the NMSSM

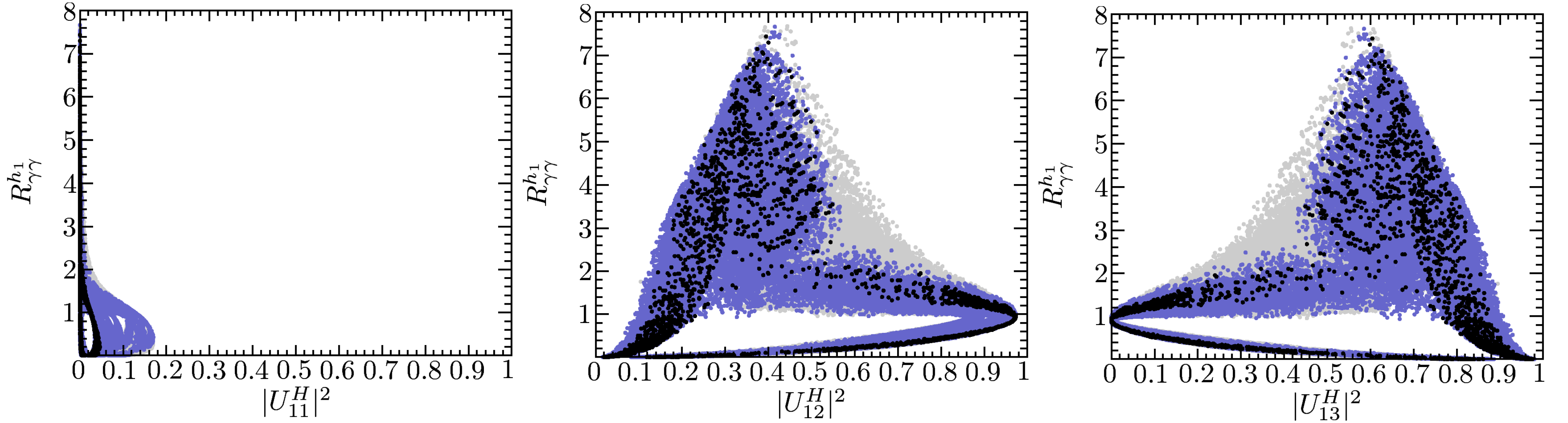
Higgs decay into WW

- Strong correlation between $R_{\gamma\gamma}$ and R_{WW}
  - $h_{1,2} \to \gamma\gamma$ dominated by W-boson loops
- But a slight simultaneous suppression of WW and enhancement of γγ is possible





Mechanism to enhance $R_{\gamma\gamma}$



H_1 component of h_1 | H_2 component of h_1 | S component of h_1

- Enhancement of $R_{\gamma\gamma}$ possible if H_1 component of h_1 vanishes
- Reduced h_1bb coupling in the NMSSM $\propto U_{11}^H$
- $R_{\gamma\gamma}$ enhanced by a strong suppression of $h \to bb$ via doublet – singlet mixing
- Genuine feature of the NMSSM

W-boson mass

- Electroweak precision observables

$$M_W, \Gamma_Z, \sin\Theta_W^{eff} \ldots$$

- Highly sensitive to quantum effects of 'New physics'
- New experimental values from Tevatron
    - World average:

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

Tevatron Electroweak Working Group, April '12

- Further improvement may be possible by LHC and LC
- To test and constrain a model:
  Precise theoretical calculation for the W-boson mass needed

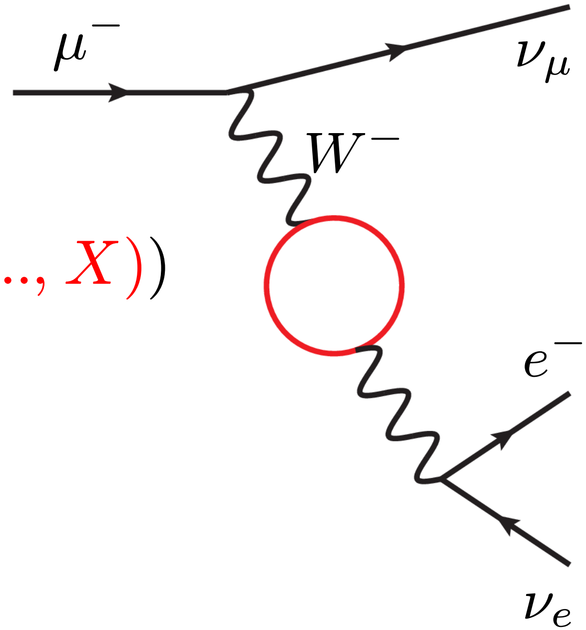
Our work:

W-boson calculation in the MSSM with complex parameters and in the NMSSM

Determination of the W-boson mass

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

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



- X model dependent!

Δr – Calculation:

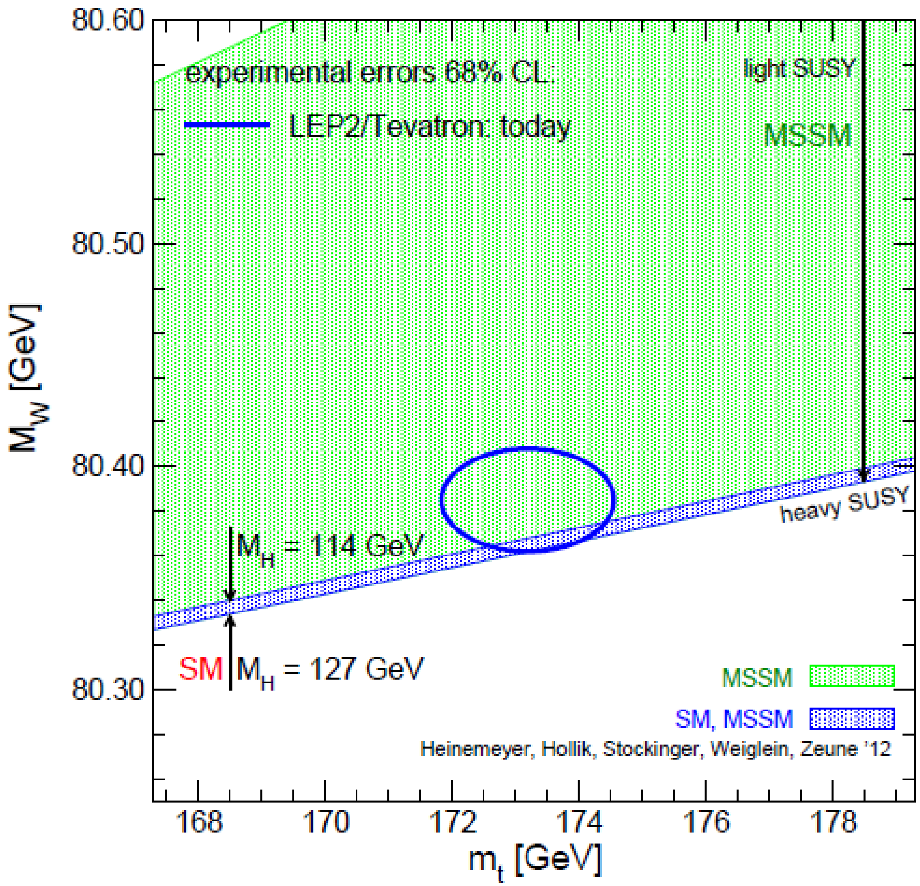
- Stand-alone one-loop calculation in SM, MSSM and NMSSM (general model, complex phases, CKM mixing)
- Incorporation of all known SM and SUSY higher order corrections

$$\Delta r^{\mathrm{(N)MSSM}} = \Delta r^{\mathrm{SM}} + \Delta r^{\mathrm{SUSY}} \longrightarrow$$

Easily extendable to new models

- Most exact MW prediction in MSSM and NMSSM

Mw in the MSSM



Green: MSSM region
Blue: Overlap region MSSM/SM

- LHC excludes SM Higgs with 127 < MH < 600 GeV

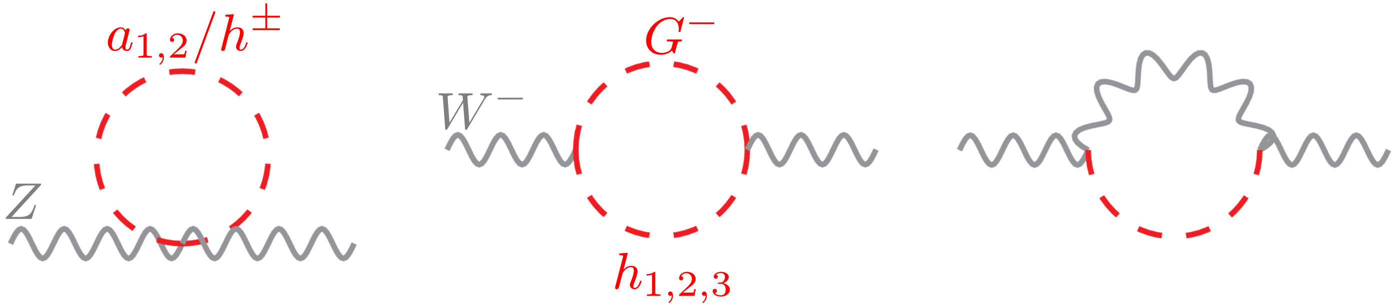
  → No SM-only region anymore

- Direct mass limits and **`HiggsBounds`** constraints applied

- Sizable SUSY contributions from Sfermions, Higgs, Charginos and Neutralinos
- Largest contributions from Stop/Sbottom sector

MW in the NMSSM

- Additional one-loop diagrams have been calculated
  - Containing NMSSM Higgs bosons



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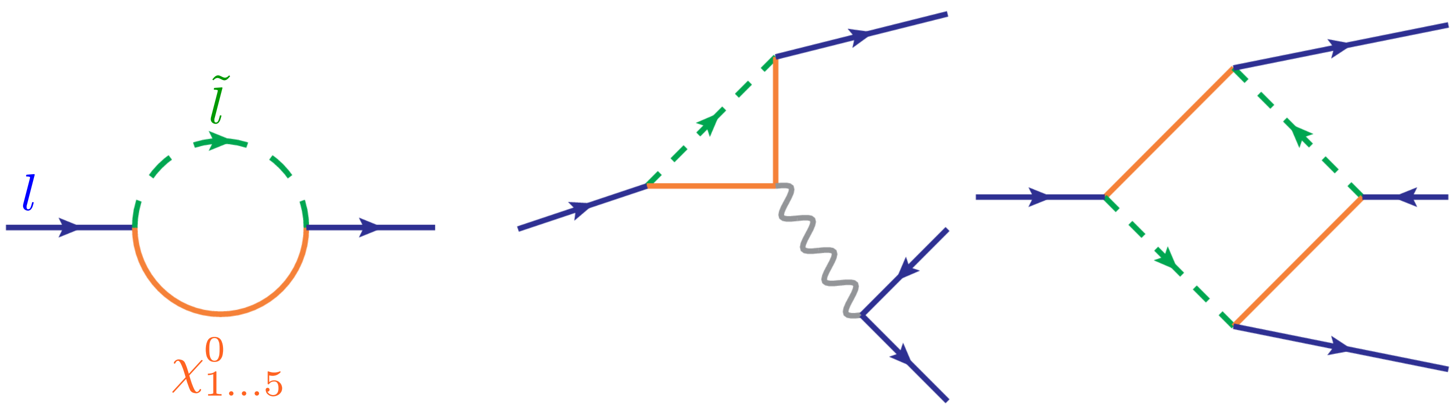
  - Containing the additional Neutralino



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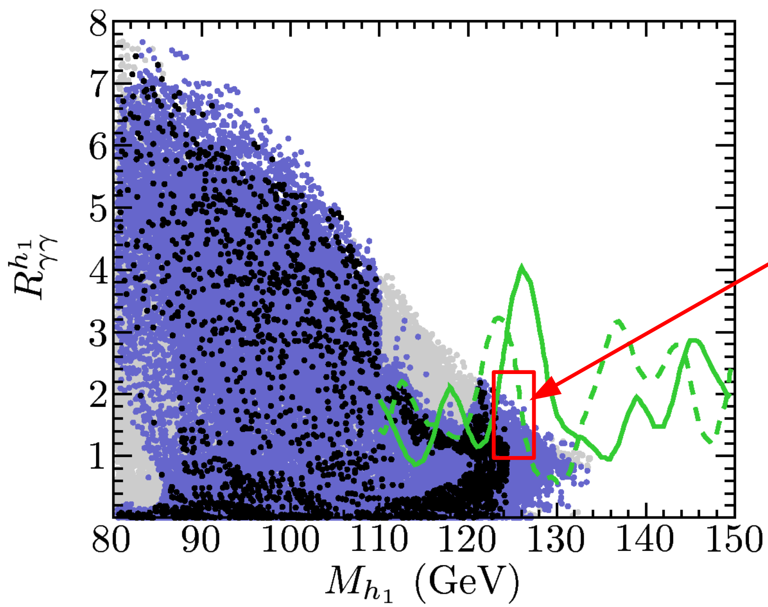
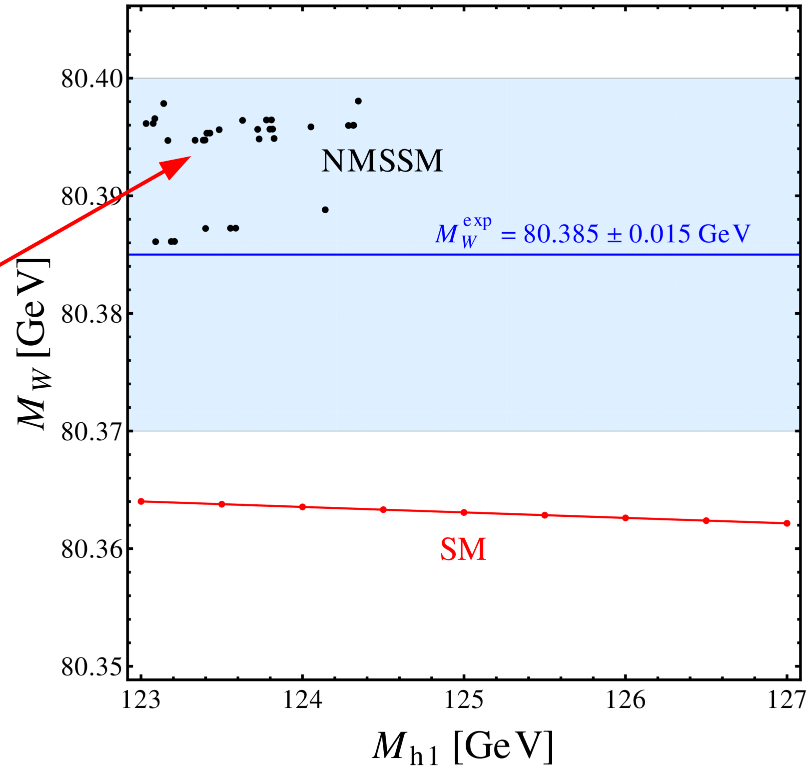
W-boson mass in the NMSSM

- Mw prediction for NMSSM points with:
  - Light CP-even Higgs around 125 GeV
  - Enhanced di-photon rate

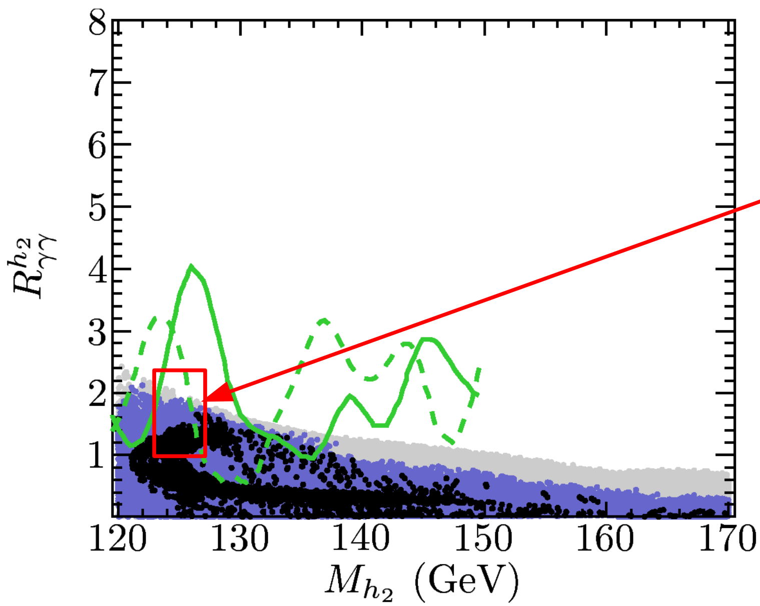


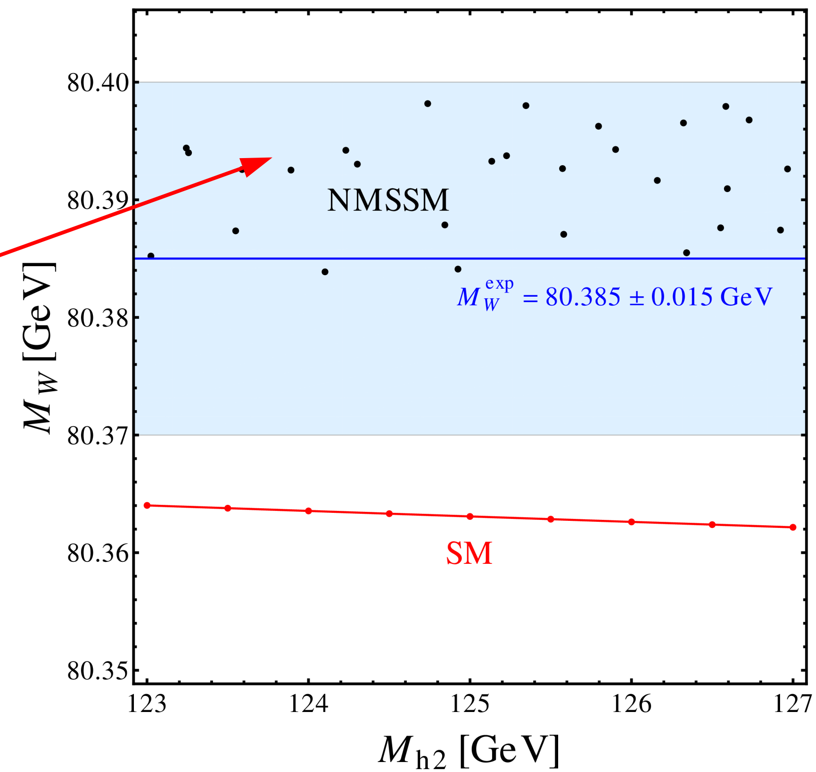


- SM prediction for W-boson mass too low
- MW prediction close to experimental value (within 1σ band)

W-boson mass in the NMSSM

- MW prediction for NMSSM points with:
  - Heavy CP-even Higgs around 125 GeV
  - Enhanced di-photon rate





- MW in good agreement with experimental measurement
- Improved exp. accuracy → Sensitivity to SUSY effects

SUSY contributions to Mw

Light Higgs case:

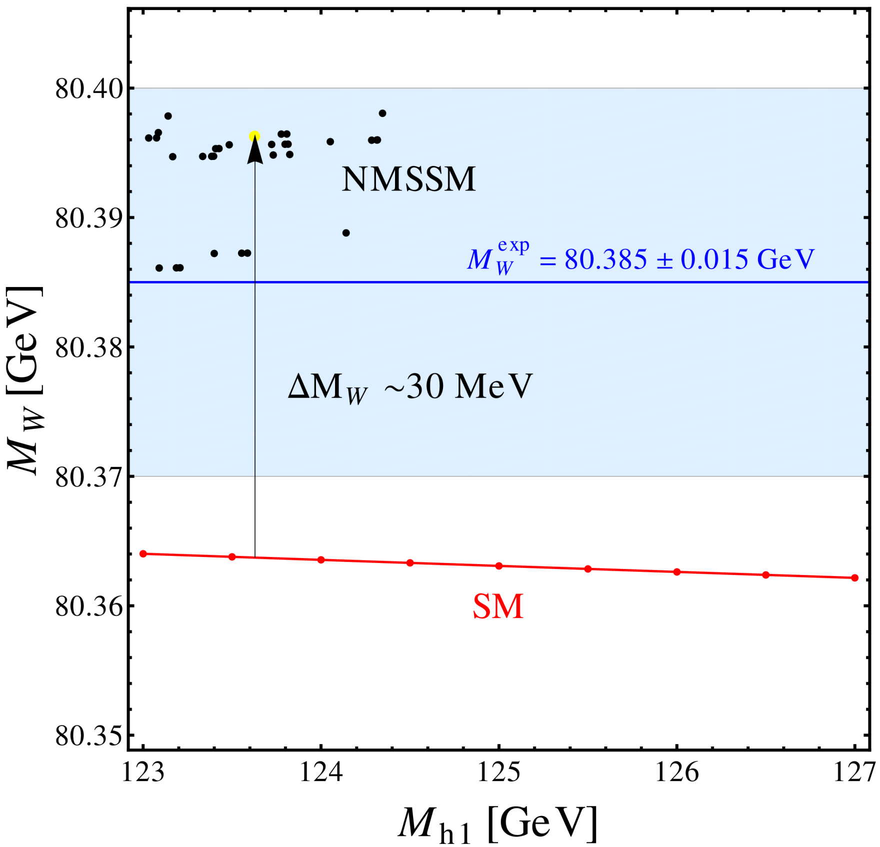
- SUSY contributions around 30 MeV
- Dominant contributions from

  → Charginos/Neutralinos: 11 MeV

  → Stops/Sbottoms: 8 MeV

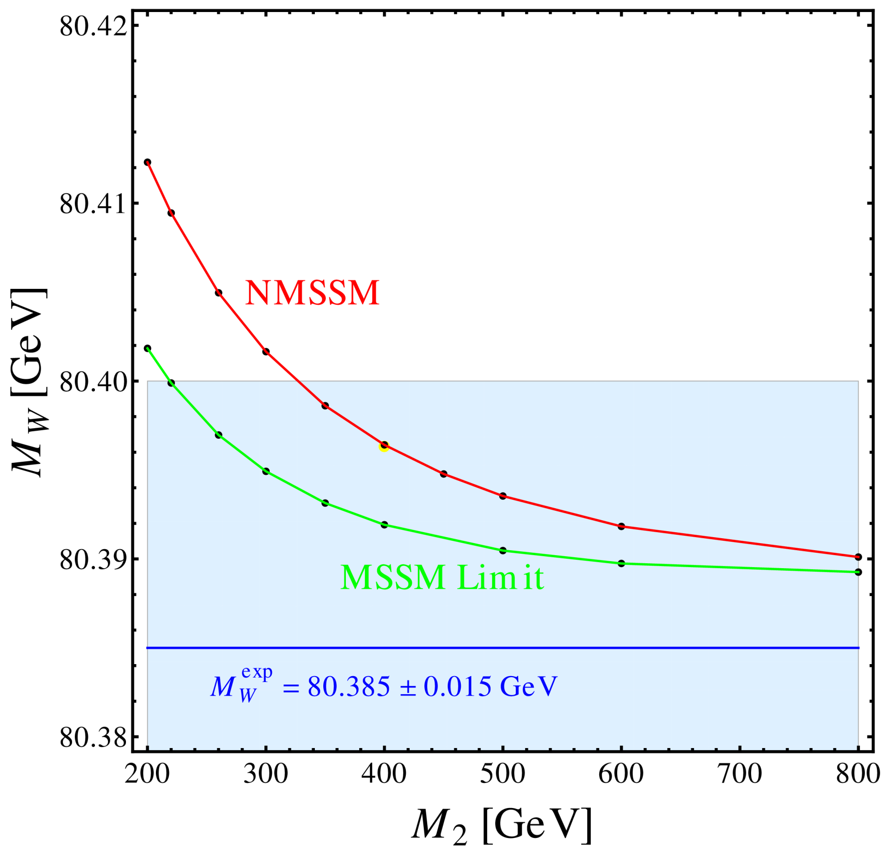
  → Sleptons: 6 MeV

- Mainly MSSM contributions
- How large are pure NMSSM-type effects?



NMSSM contribution

- Comparison to MSSM limit
- Higgs sector:
    - Light Higgs could give large contributions
    - But strongly constrained by Higgs searches
    - In allowed region Higgs contributions only few MeV
- Neutralino sector:
    - Contributions can be sizable



Conclusions and Outlook

- New framework facilitating loop calculations in the NMSSM
  - NMSSM model file and Fortran driver for FeynArts/FormCalc
- Two applications:

$H \rightarrow \gamma\gamma$ decay

- For both h_1 and h_2 we find a possible enhancement of the $H \rightarrow \gamma\gamma$ rate in the interesting mass region 120-130 GeV

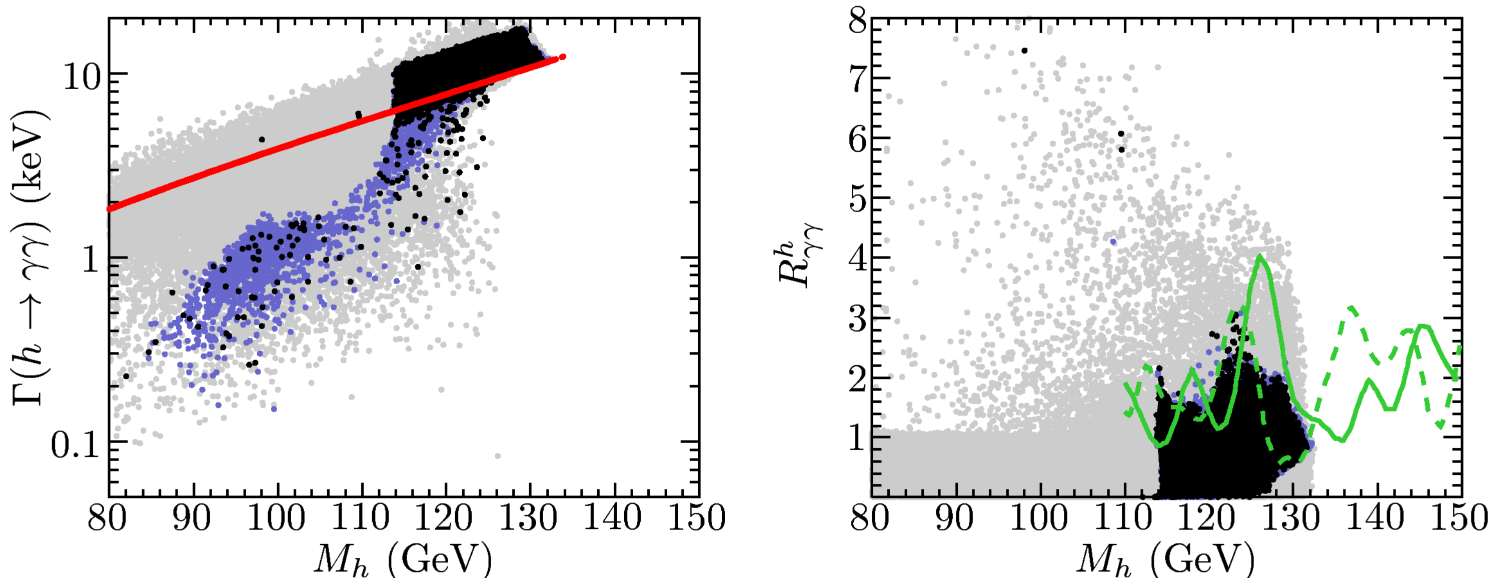
W - boson mass in the NMSSM

- Large SUSY contributions possible
- Genuine NMSSM effect rather small

Plan for the future

- Use this framework to include Higgs results into an NMSSM extension of FeynHiggs

Backup



- 40% enhancement of the width possible
  - Due to contributions from light staus Carena,Gori,Shah,Wagner
- Enhancement of Rγγ due to suppression of h → bb
  - hbb coupling suppressed if $\alpha_{\mathrm{eff}} \approx 0$ or Δ_b large
- Also heavy Higgs in the mass range 120 – 130 GeV with an enhanced Rγγ possible in the MSSM

Rγγ in the NMSSM

NMSSM Scan ranges

Parameter	Minimum	Maximum	
$A_t = A_b = A_\tau$	$-2\,400$	$2\,400$	GeV
μ	150	250	GeV
M_{H^+}	500	$1\,000$	GeV
$\tan\beta$	2.6	6	
λ	0.5	0.7	
K	0.3	0.5	
A_κ	-100	-5	GeV

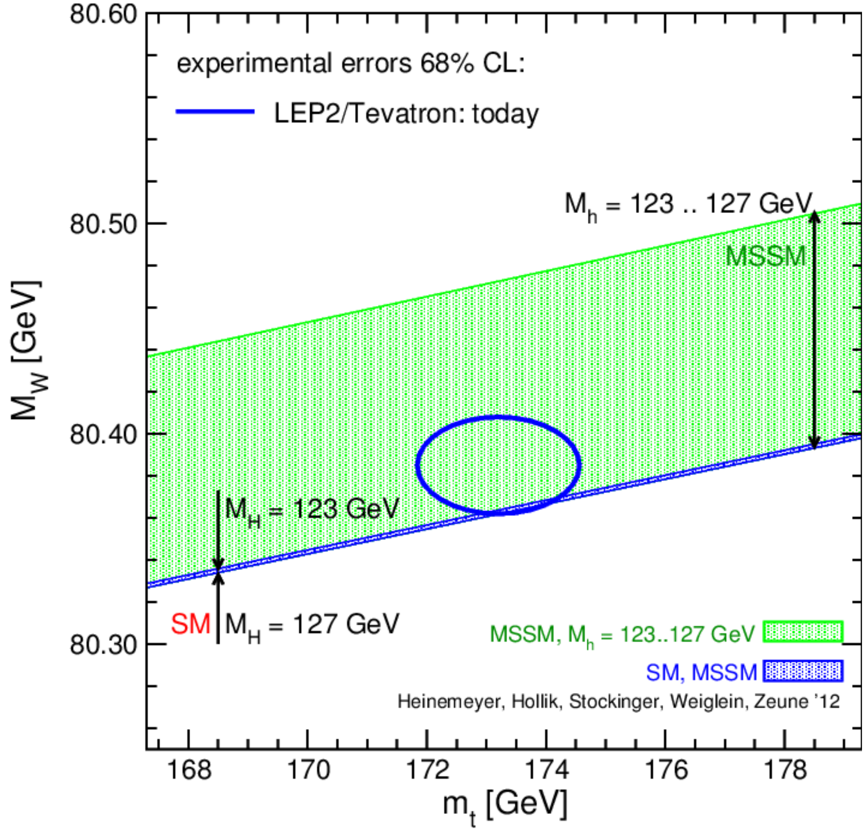
- Total width in the NMSSM calculated as

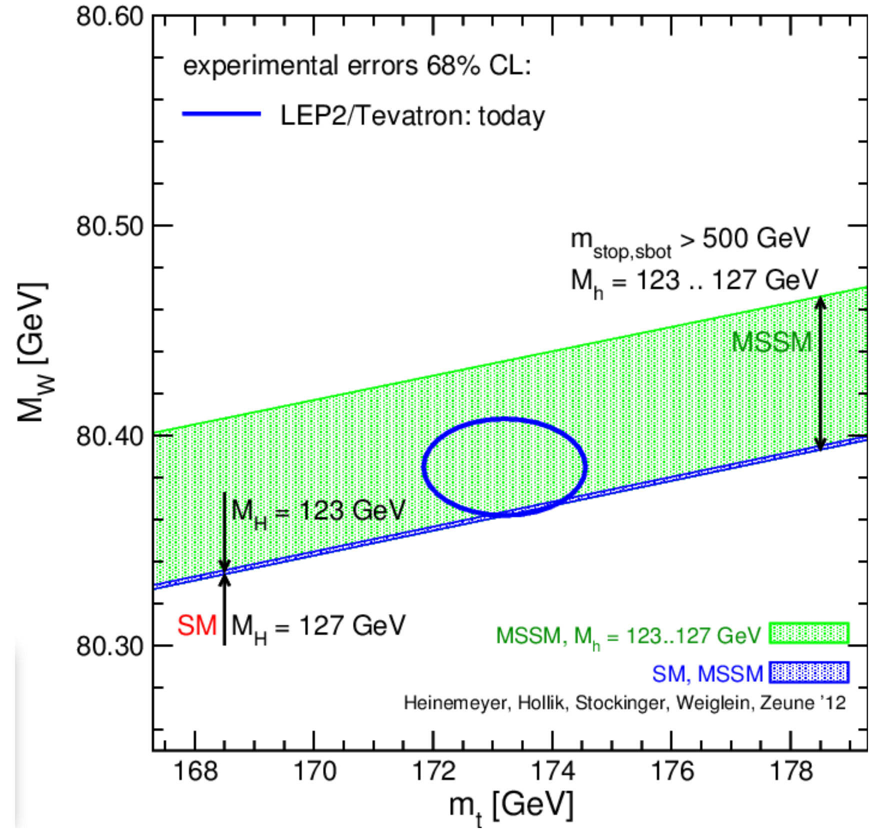
$$\Gamma_{tot}(h_i) = \frac{1}{m_{h_i}} \mathrm{Im}(\Sigma_{h_i}(m_{h_i}^2)) + \Gamma(h_i \to WW^{(*)}) + \Gamma(h_i \to \gamma\gamma) + \Gamma(h_i \to gg)$$

- $\sigma(gg \to h_i)$ approximated by $\Gamma(h_i \to gg) \to$

$$R_X^{h_i} \simeq = \frac{\Gamma(h_i \to gg) \times \Gamma(h_i \to X) \times \Gamma_{\mathrm{tot}}(H_S M)}{\Gamma(H_S M \to gg) \times \Gamma(H_S M \to X) \times \Gamma_{\mathrm{tot}}(h_i)}$$

MSSM Higgs at 125 and impact of stop/sbottom limits





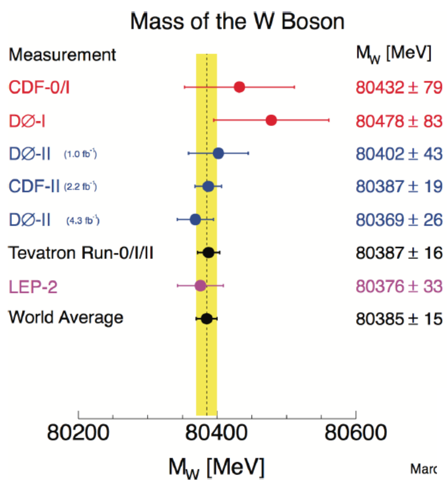
- Both MSSM interpretations of a Higgs at 125 GeV give MW prediction in good agreement with experimental value
- Even if stops are heavy:
  Sizable SUSY contributions possible

MW measurement at Tevatron and LHC challenge

W-boson mass measurements: Tevatron versus LEP2

World average computed by TeVEWWG
ArXiv:0908.1374
FERMILAB-TM-2439-E

Previous world average:
80399 ± 23 MeV



New Tevatron result is significantly more precise than LEP average

Slides from Daniel Froidevaux, Rencontres de Blois 2012

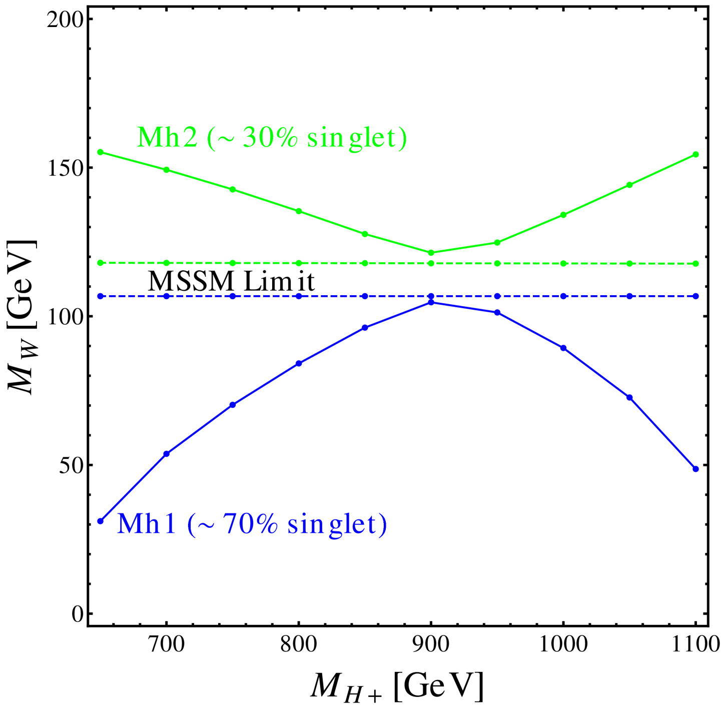
Measurement of m_W at the Tevatron: beyond the legacy of LEP!

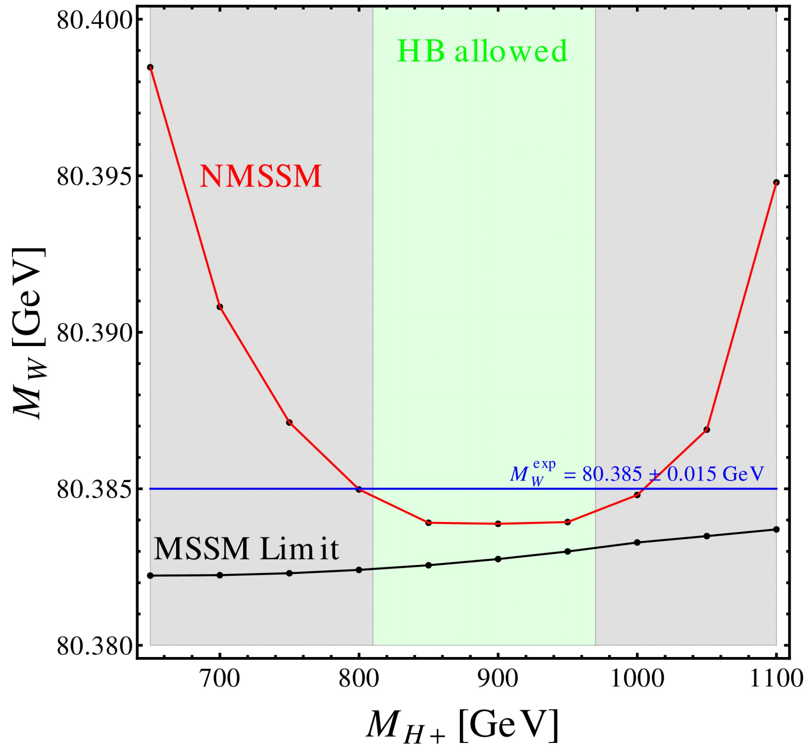
D0: W to eν (4+1 fb^{-1})	CDF: W to eν (2.2 fb^{-1})	CDF: W to μν (2.2 fb^{-1})
55k Z to ee	16k Z to ee (!!)	60k Z to μμ
1.7M W (|η| < 1.05!!)	0.5M W	0.6M W
δm_W(stat) = 13 MeV	δm_W(stat) = 13 MeV	δm_W(stat) = 13 MeV
δm_W(syst) = 22 MeV	δm_W(syst) = 18 MeV	δm_W(stat) = 16 MeV
Combine with 1 fb^{-1} result	Combine J/ψ&Υ to μμ with m_Z from LEP!!	
δm_W(tot) = 23 MeV	δm_W(tot) = 19 MeV	

- Can more than double statistics with full runII dataset
- Current incompressible systematic is 10 MeV from PDFs (not worked on yet to reduce this using Tevatron data)
- Hope to reach 10-15 MeV ultimately per experiment

→ challenge for LHC will be at the 5 MeV level

NMSSM Higgs sector contribution to MW

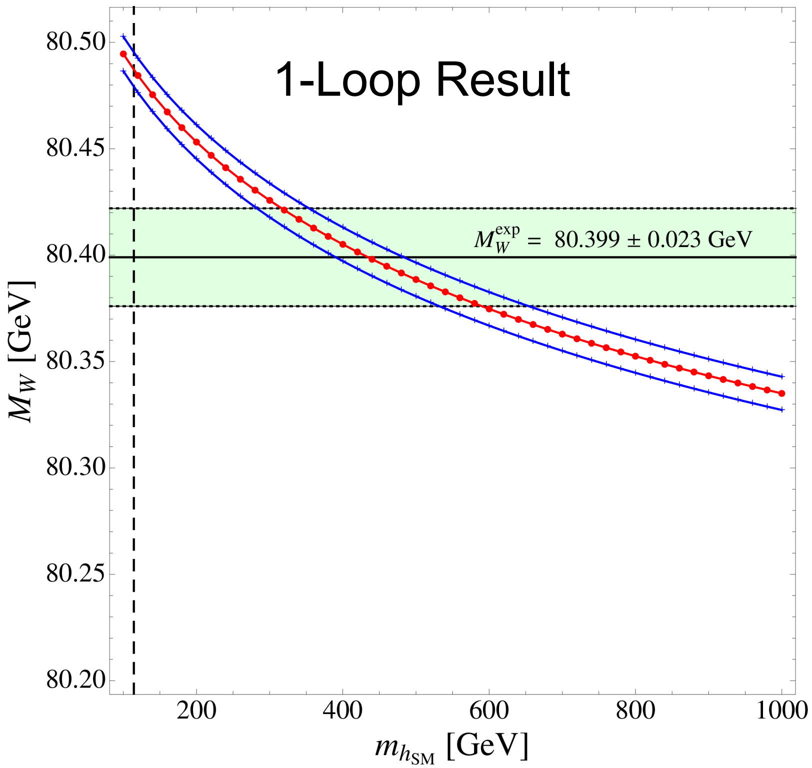


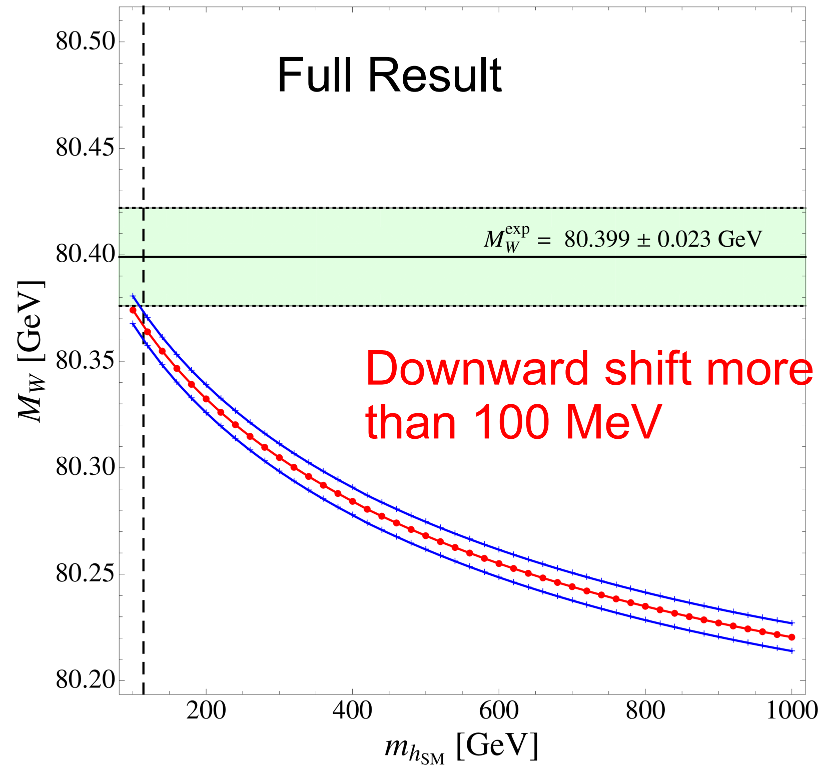


- A light NMSSM Higgs with a non vanishing doublet-component gives large contribution to MW
- But these scenarios are strongly constraint by Higgs search results → In allowed region NMSSM Higgs contributions only few MeV

MW in the SM

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

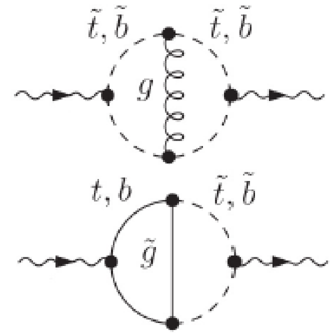




SUSY higher order corrections

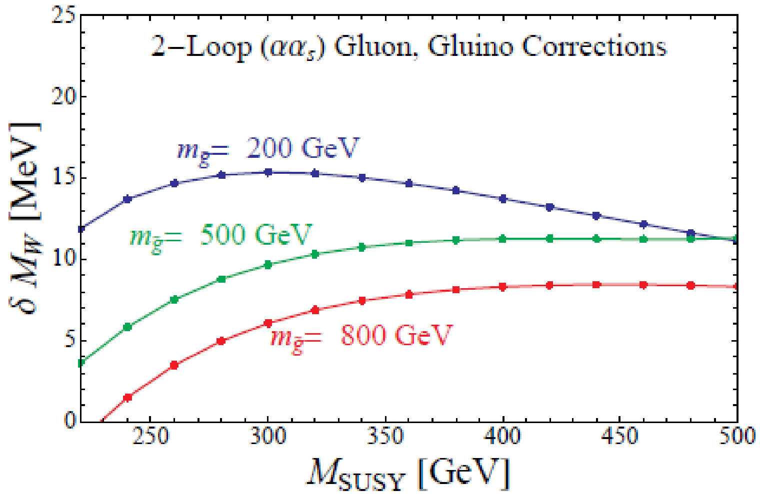
Supersymmetric two-loop contributions

- 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 LHC and ILC)
> Can enter with both signs
> Important for a precise M_W prediction!