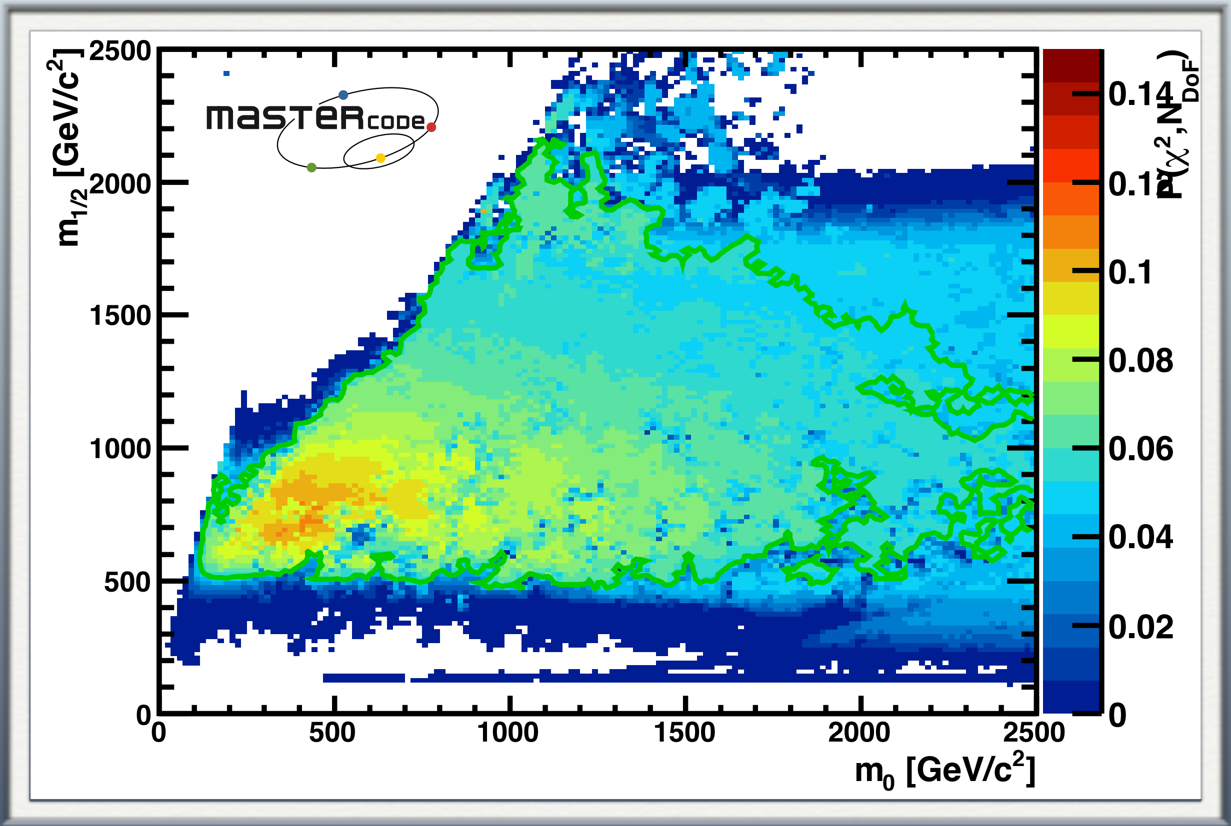
Confronting SUSY with LHC Data



O. Buchmueller, R. Cavanaugh, D. Colling, A. de Roeck, M.J. Dolan, J.R. Ellis, H. Flaecher, S. Heinemeyer, G. Isidori, D. Martinez Santos, K.A. Olive, S. Rogerson, F.J. Ronga, G. Weiglein

SUSY11
Fermilab, 28 August to 02 September, 2011

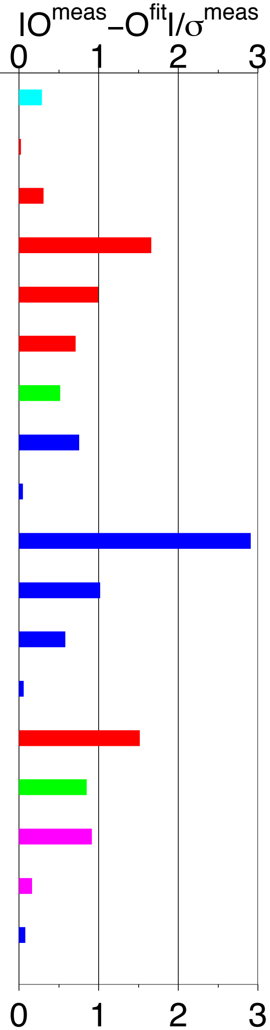
Overview

- Introduction
- Codes & Predictions
- Confronting Predictions with Data
- Conclusion

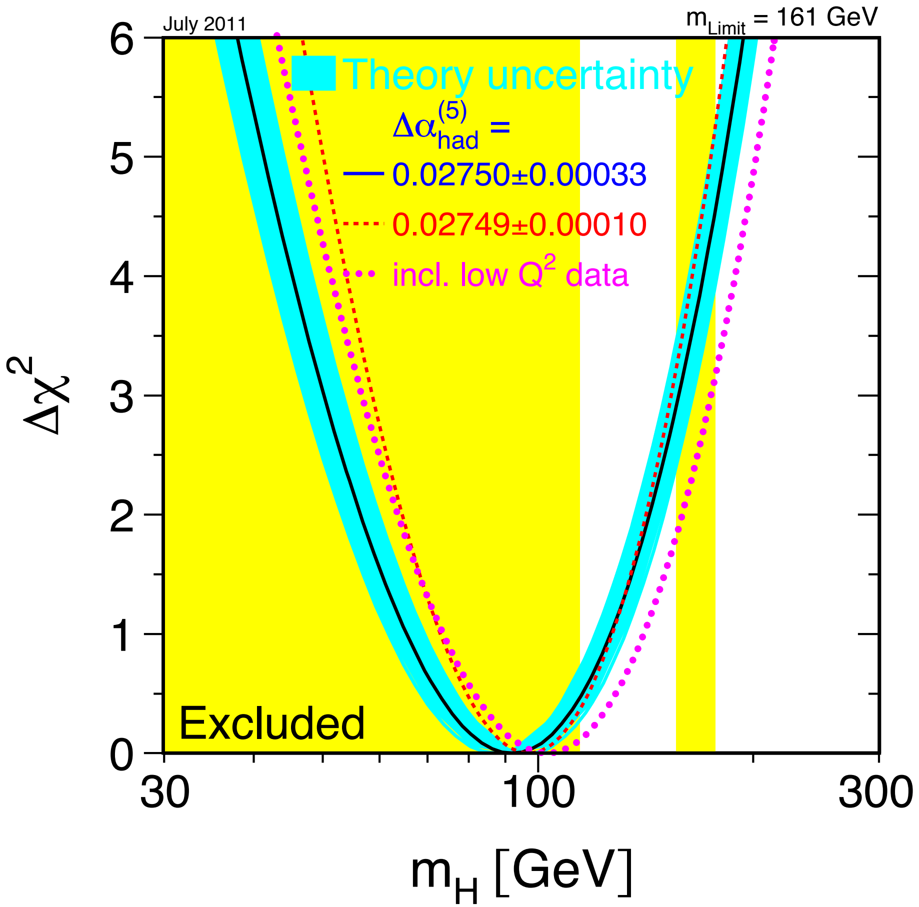
Introduction

- **Well known global fit to all SM data: "Blue Band Plot"**

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01646
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1482
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1039
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0743
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
$A_l(SLD)$	0.1513 ± 0.0021	0.1482
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.378
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.27



July 2011

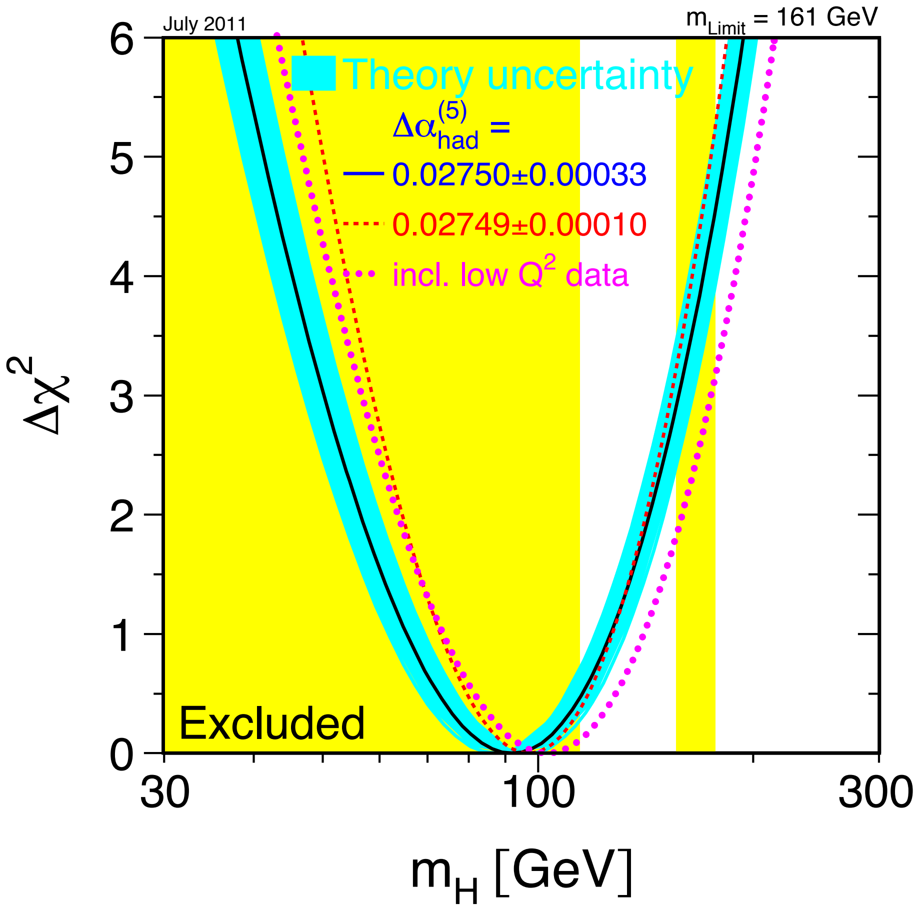


Introduction

- **Well known global fit to all SM data: “Blue Band Plot”**

$$m_H = 92^{+34}_{-26}\ \mathrm{GeV}$$

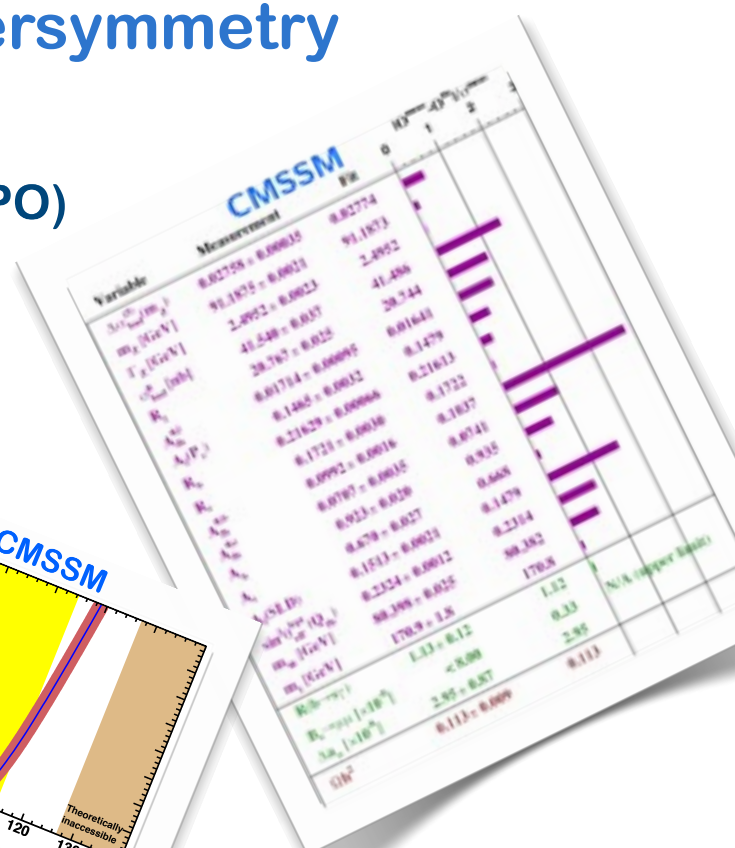
$$m_H < 161\ \mathrm{GeV}$$
$$\text{at } 95\%\ \mathrm{CL}$$

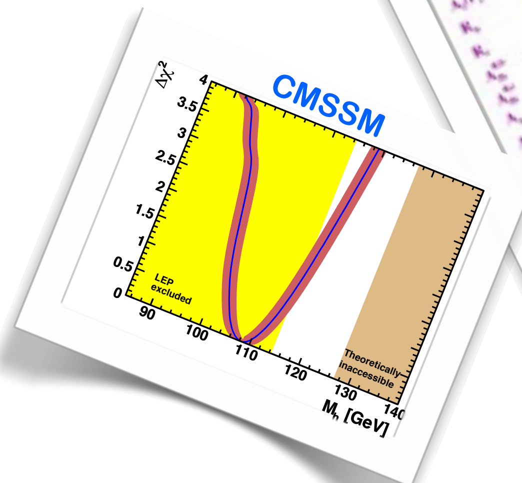


- **Assumption for the fit :**
  SM including Higgs boson

MasterCode

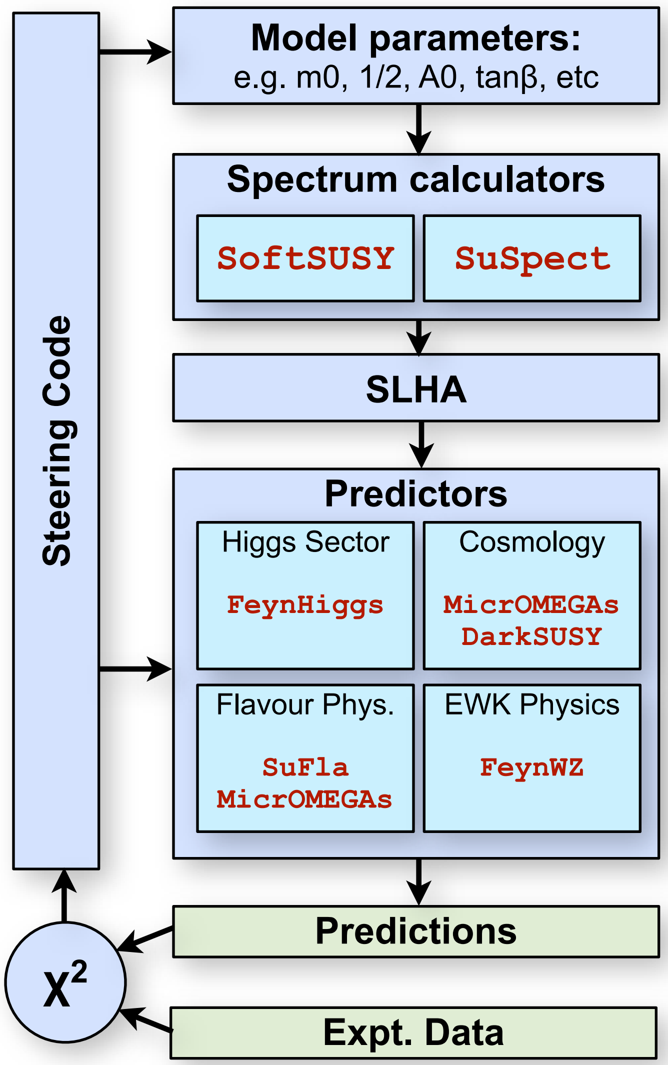
- Main idea: do the “same” in Supersymmetry
- Combine all existing data
  - Electroweak precision observables (EWPO)
  - Flavour physics observables (BPO)
  - Cold dark matter observables (CDM)
  - Low Energy observables (g-2)
  - Direct Searches!
    - LHC
    - XENON100
- Predict
  - best-fit model space points
  - ranges for Higgs masses
  - ranges for SM parameters
  - ranges for SUSY masses (exclusion, reach, interpretation)
- Important! “Red Band” instead of “Blue Band” ;-)





MasterCode

- Combines diverse set of tools
  - different codes : all state-of-the-art
    - Electroweak Precision (FeynWZ)
    - Flavour (SuFla, micrOMEGAs)
    - Cold Dark Matter (DarkSUSY, micrOMEGAs)
    - Other low energy (FeynHiggs)
    - Higgs (FeynHiggs)
  - different precisions (one-loop, two-loop, etc)
  - different languages (Fortran, C++, English, German, Italian, etc)
  - different people (theorists, experimentalists)
- Compatibility is crucial! Ensured by
  - close collaboration of tools authors
  - standard interfaces



consistent use of most-up-to-date tools crucial for precision studies

List of Observables

Flavour and Low Energy Observables

$\mathrm{BR}^{\mathrm{EXP}}_{b\to s\gamma}/\mathrm{BR}^{\mathrm{SM}}_{b\to s\gamma}$

$\mathrm{BR}(B_s \to \mu\mu)$

$\mathrm{BR}^{\mathrm{EXP}}_{\mathrm{B}\to\tau\nu}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{B}\to\tau\nu}$

$\mathrm{BR}(B_d \to \mu\mu)$

$\mathrm{BR}^{\mathrm{EXP}}_{\mathrm{B}\to X_s ll}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{B}\to X_s ll}$

$\mathrm{BR}^{\mathrm{EXP}}_{\mathrm{K}\to\mu\nu}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{K}\to\mu\nu}$

$\mathrm{BR}^{\mathrm{EXP}}_{\mathrm{K}\to\pi\nu\nu}/\mathrm{BR}^{\mathrm{SM}}_{\mathrm{K}\to\pi\nu\nu}$

$\Delta M^{\mathrm{EXP}}_{\mathrm{B}_s}/\Delta M^{\mathrm{SM}}_{\mathrm{B}_s}$

$\frac{\Delta M^{\mathrm{EXP}}_{\mathrm{B}_s}/\Delta M^{\mathrm{SM}}_{\mathrm{B}_s}}{\Delta M^{\mathrm{EXP}}_{\mathrm{B}_d}/\Delta M^{\mathrm{SM}}_{\mathrm{B}_d}}$

$\Delta\epsilon^{\mathrm{EXP}}_K/\Delta\epsilon^{\mathrm{SM}}_K$

$a^{\mathrm{EXP}}_\mu - a^{\mathrm{SM}}_\mu$

Dark Matter Observables

Ωh^2

σ^{SI}_p

LHC High Energy Observables

$\mathrm{jets} + \not{E}_{\mathrm{T}}$

$H/A,\ H^\pm$

Electroweak Observables

Γ_Z

σ^0_{had}

R_l

$A_{\mathrm{fb}}(l)$

$A_l(P_\tau)$

R_b

R_c

$A_{\mathrm{fb}}(b)$

$A_{\mathrm{fb}}(c)$

A_b

A_c

$A_l(SLD)$

$\sin^2\theta^l_{\mathrm{W}}(Q_{\mathrm{FB}})$

m_W

Standard Model Parameters

m_t

$\Delta\alpha^{(5)}_{\mathrm{had}}(m_Z^2)$

m_Z

Light Higgs Sector

m_h

More than 30 different observables used

Models Covered

Model	Parameters	Boundary Conditions
CMSSM	$m_0,\ m_{1/2},\ A_0,\ \tan(\beta),\ \mathrm{sign}(\mu)$	Unification +
VCMSSM	$m_0,\ m_{1/2},\ A_0,\ \mathrm{sign}(\mu)$	$B_0 = A_0 - m_0$
mSUGRA	$m_0,\ m_{1/2},\ A_0,\ \mathrm{sign}(\mu)$	$B_0 = A_0 - m_0$
NUHM1	$m_0,\ m_{1/2},\ A_0,\ m^2_{H_{1,2}},\ \mathrm{sign}(\mu)$	$m_{1,2} = m_0 + \Delta m_{H_{1,2}}$

Constructing the χ^2

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}}\right)^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

- N is number of observables studied
- M is number of SM parameters: $f_{\mathrm{SM}i} = \Delta\alpha_{\mathrm{had}}$, m_t, m_Z
- C_i are experimentally measured values (constraint)
- P_i are MSSM parameter-dependent predictions

Constructing the χ^2

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}}\right)^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

- **Fit Methods (globally over all model parameters!)**
  - **Markov Chain Monte Carlo (MCMC)**
    - Actually used as a mere sampling method (sampling density not used)
    - success and failure of the steps defined by the χ^2
  - χ^2 fit: `Minuit` minimisation
    - used for “scans” or in conjunction with MCMCs to get overall best minimum

Constructing the χ^2

MasterCode

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f_{\mathrm{SM}_i}^{\mathrm{obs}} - f_{\mathrm{SM}_i}^{\mathrm{fit}}\right)^2}{\sigma(f_{\mathrm{SM}_i})^2}$$

$$+ \chi^2(b \to s\gamma) + \chi^2(g_\mu - 2) + \chi^2(\Omega h^2) + \chi^2(m_h)$$

- **Fit Methods (globally over all model parameters!)**
  - **Markov Chain Monte Carlo (MCMC)**
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  - **χ^2 fit: `Minuit` minimisation**
    - used for "scans" or in conjunction with MCMCs to get overall best minimum
- **Afterburners**
  - **χ^2 terms additive $\longrightarrow$ effects therefore also additive**
  - **Study effect of "interesting" (g-2, b→sγ, Ωh^2, etc) observables!**
    - sample space without "interesting" terms → larger, more general sampling
    - a posteriori add "interesting" terms after general sampling
    - Only need to sample multi-d space once! Enormous cost savings to due RGEs

Constructing the χ^2

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f^{\mathrm{obs}}_{\mathrm{SM}_i} - f^{\mathrm{fit}}_{\mathrm{SM}_i}\right)^2}{\sigma(f_{\mathrm{SM}_i})^2}$$
$$+ \chi^2(b \to s\gamma) + \chi^2(g_\mu - 2) + \chi^2(\Omega h^2) + \chi^2(m_h)$$
$$+ \chi^2(\ \mathrm{BR}(B_s \to \mu\mu)\ ) + \chi^2(\mathrm{LHC}) + \chi^2(\mathrm{XENON100})$$

- **Fit Methods (globally over all model parameters!)**
  - **Markov Chain Monte Carlo (MCMC)**
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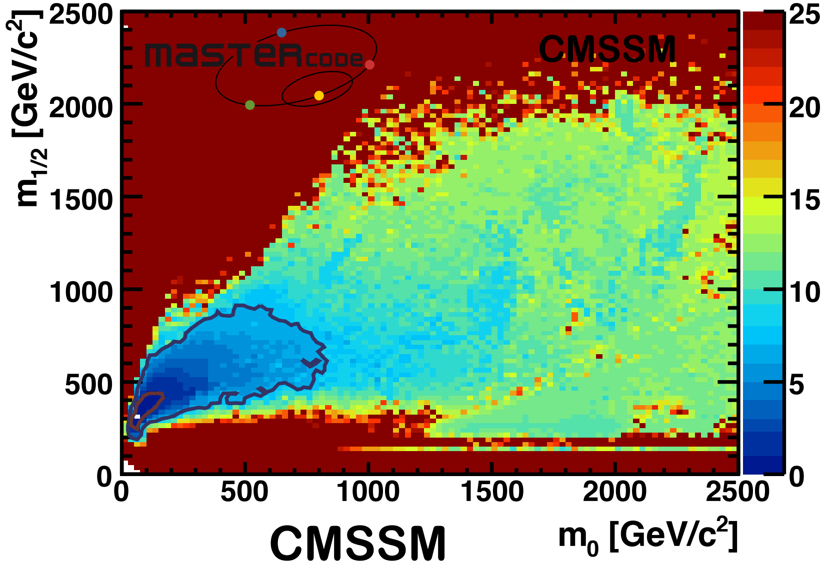
Constructing the χ^2

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{\left(f^{\rm obs}_{{\rm SM}_i} - f^{\rm fit}_{{\rm SM}_i}\right)^2}{\sigma(f_{{\rm SM}_i})^2}$$
$$+ \chi^2(b \to s\gamma) + \chi^2(g_\mu - 2) + \chi^2(\Omega h^2) + \chi^2(m_h)$$
$$+ \chi^2(\,{\rm BR}(B_s \to \mu\mu)\,) + \chi^2({\rm LHC}) + \chi^2({\rm XENON100})$$

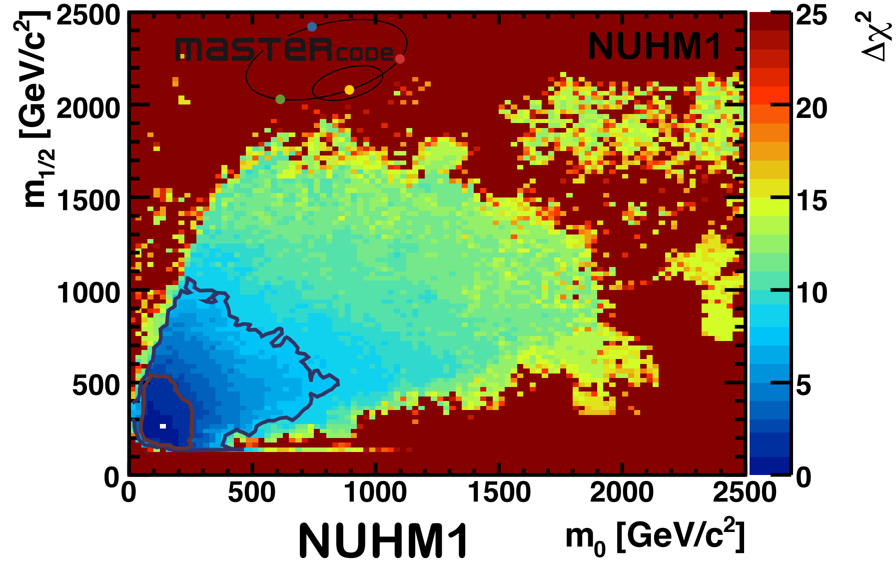
Recent Experimental Data!

- **Fit Methods (globally over all model parameters!)**
  - **Markov Chain Monte Carlo (MCMC)**
    - Actually used as a mere sampling method (sampling density not used)
    - success and failure of the steps defined by the χ^2
  - **χ^2 fit: `Minuit` minimisation**
    - used for "scans" or in conjunction with MCMCs to get overall best minimum
- **Afterburners**
  - **χ^2 terms additive $\longrightarrow$ effects therefore also additive**
  - **Study effect of "interesting" (g-2, b→sγ, Ωh^2, etc) observables!**
    - sample space without "interesting" terms $\rightarrow$ larger, more general sampling
    - a posteriori add "interesting" terms after general sampling
    - Only need to sample multi-d space once! Enormous cost savings to due RGEs

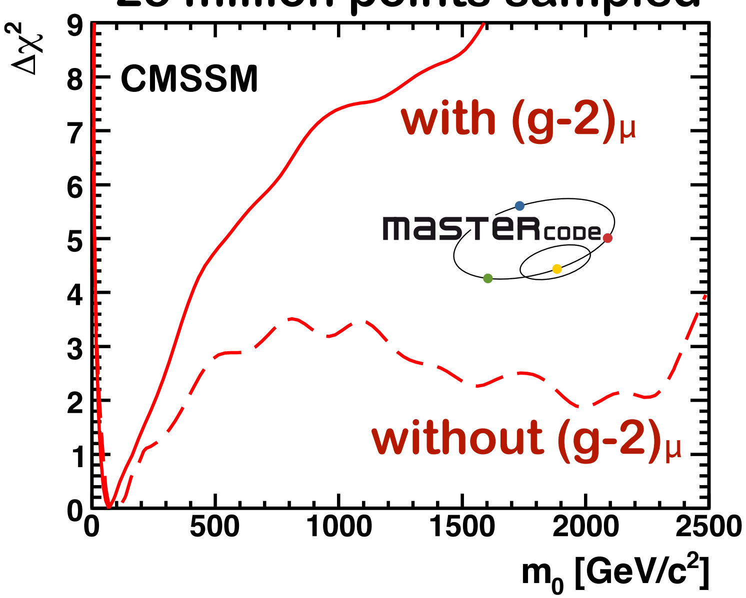
Pre-LHC, Pre-XENON100

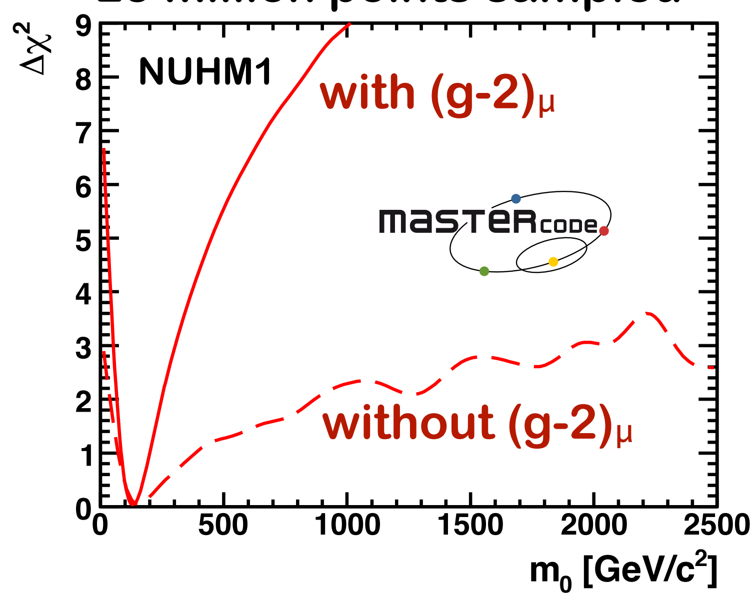


CMSSM
25 million points sampled

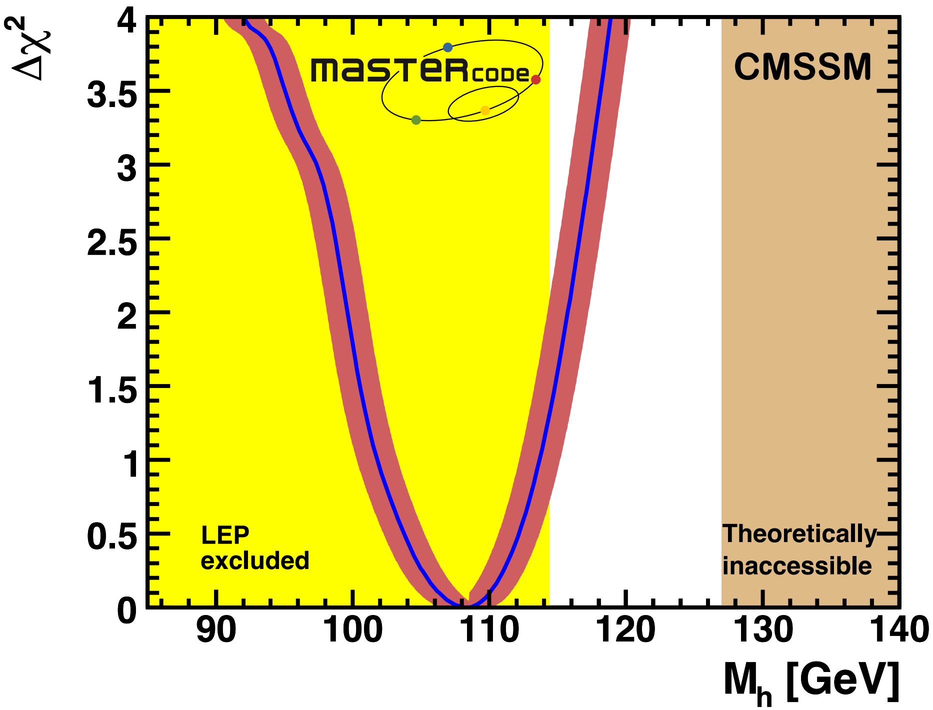


NUHM1
25 million points sampled

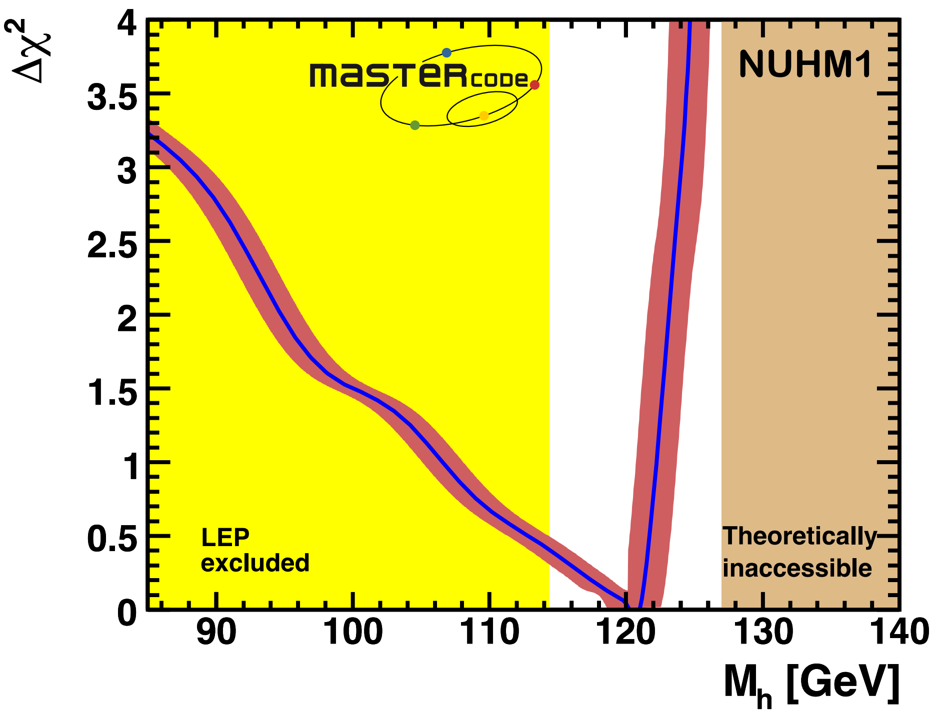




Pre-LHC, Pre-XENON100



CMSSM
25 million points sampled



NUHM1
25 million points sampled

SM Prediction: $m_H = 92^{+34}_{-26}$ GeV

Confronting SUSY with LHC

- **ATLAS + CMS Direct Searches**
- **Combination of**
  - **CMS 1.1 fb^{-1} (α_T)**
  - **ATLAS 1.0 fb^{-1} (0-lepton)**
- **Assume**

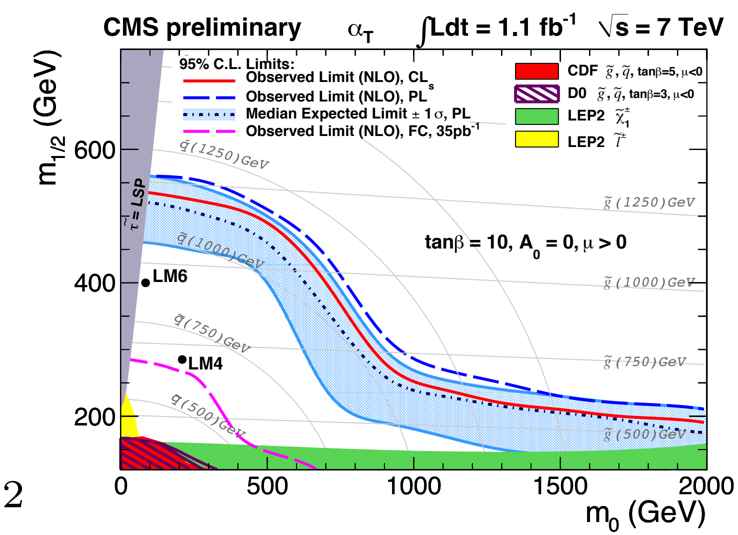
$$N_{\text{events}} \propto M^{-4} \quad \textbf{where} \quad M^2 = m_0^2 + m_{1/2}^2$$

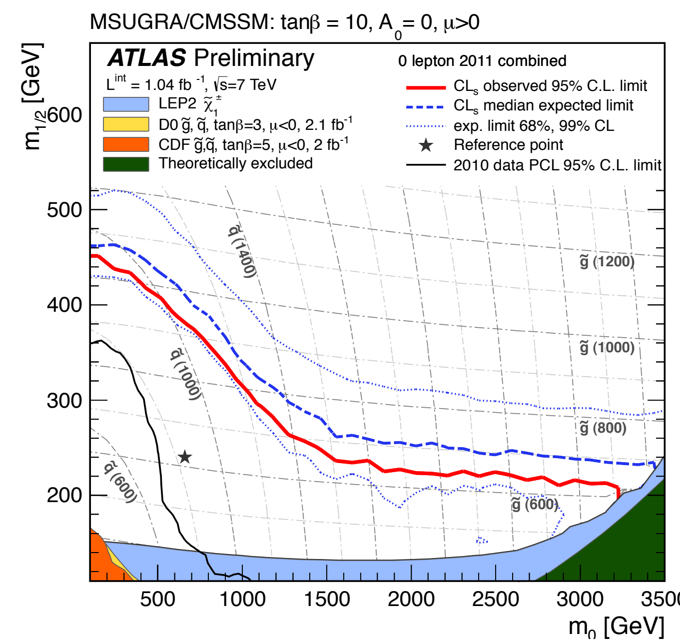
then

$$\chi_p^2 \sim \chi_{95\%}^2 \times \left[\frac{M_p}{M_{95\%}}\right]^4$$

- **For each point in $(m_0,\ m_{1/2})$ take**

$$\max\left[\chi^2(\text{CMS}), \chi^2(\text{ATLAS})\right]$$





Confronting SUSY with LHC

- **For fixed values of M_A Assume**
  - **Assume**

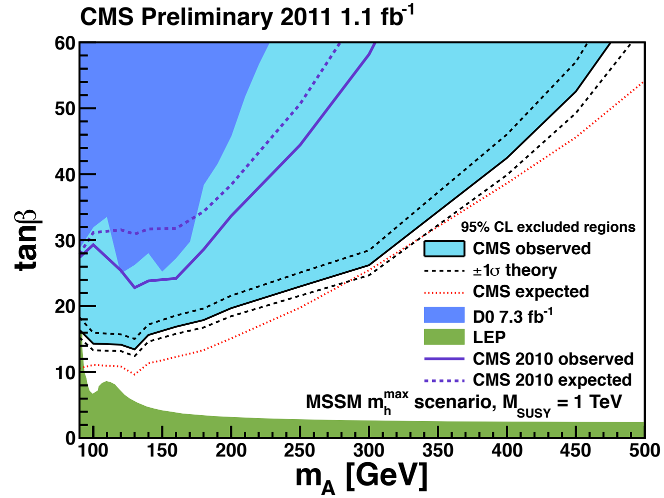
$$\chi^2 \propto (\sigma \times BR)^{p(M_A)}$$

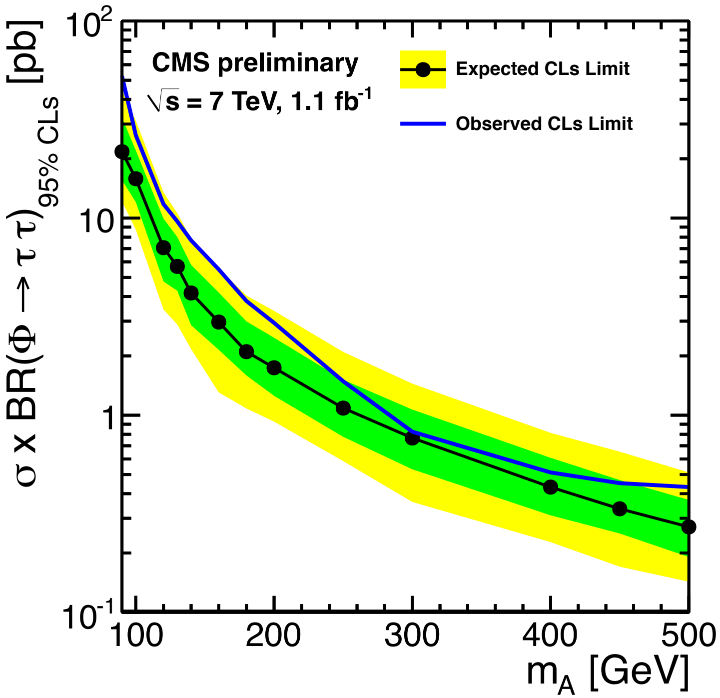
  - **Now, in the region of interest**

$$(\sigma \times BR) \propto \tan^2 \beta$$

  - **Hence,**

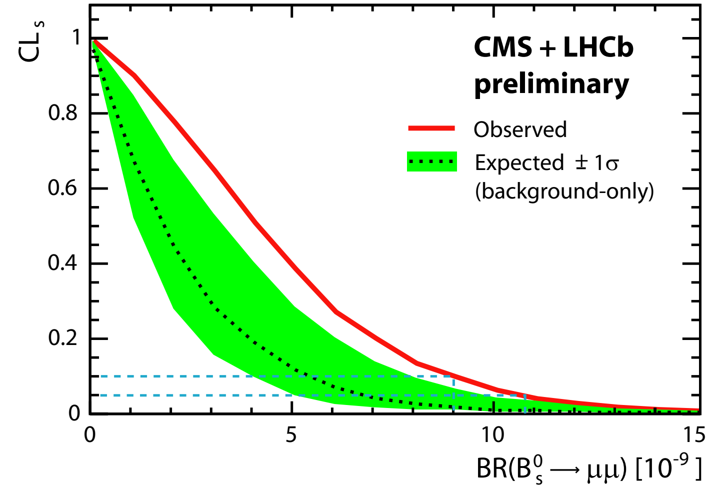
$$\chi^2 \sim \left[\frac{\tan^2(\beta)}{\tan^2(\beta)_{68\%}}\right]^{p(M_A)}$$

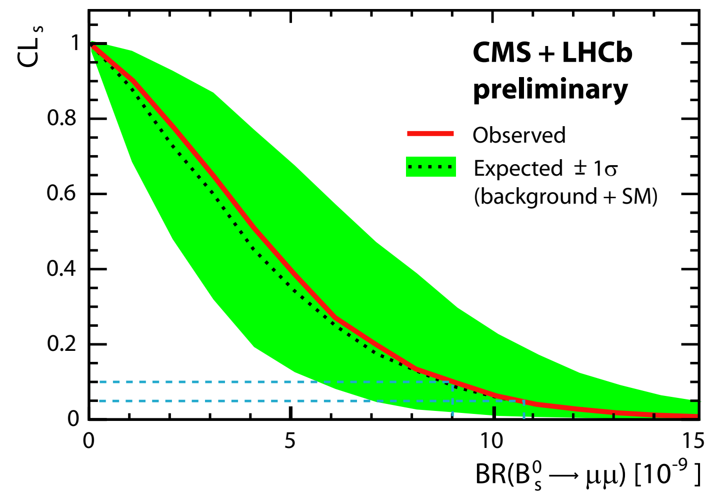




Confronting SUSY with LHC

- **LHCb**
  - BR($B_s \to \mu\mu$) < 1.5 x 10^{-8} at 95% CL
- **CMS**
  - BR($B_s \to \mu\mu$) < 1.9 x 10^{-8} at 95% CL
- **CDF**
  - BR($B_s \to \mu\mu$) = ($1.8^{+1.1}_{-0.9}$) x 10^{-8} at 95% CL
  - BR($B_s \to \mu\mu$) < 4.0 x 10^{-8} at 95% CL
  - **Some tension with CMS, LHCb**
    - **but still compatible**

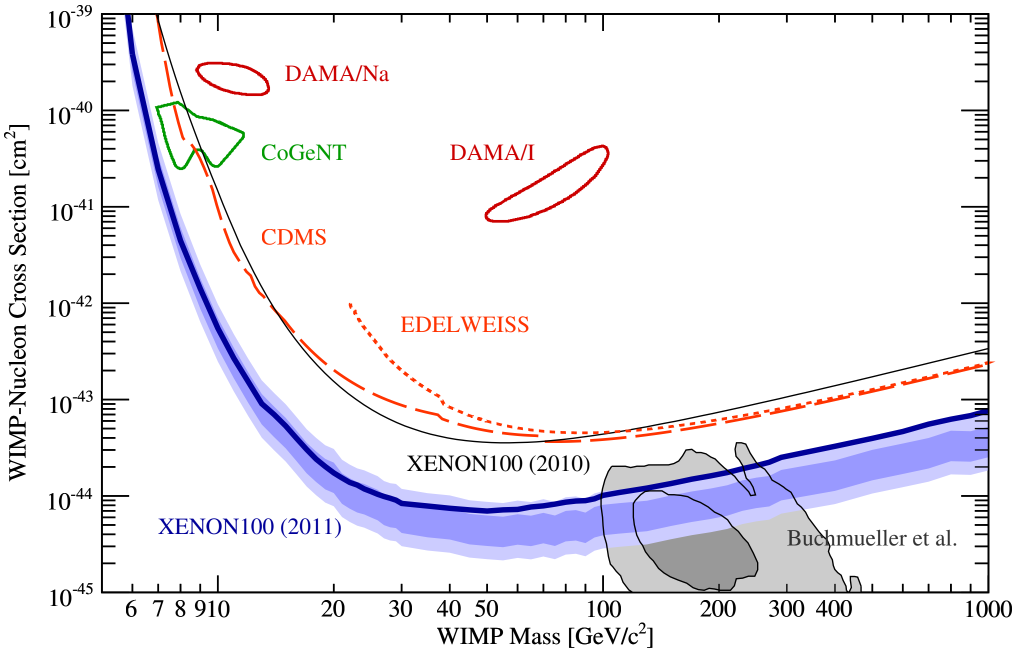




- **Use combined CMS + LHCb**
  - BR($B_s \to \mu\mu$) < 1.08 x 10^{-8} at 95% CL
- $\Delta\chi^2$ **corresponds to full likelihood**
  - **global minimum close to Standard Model value**

Confronting SUSY with XENON100

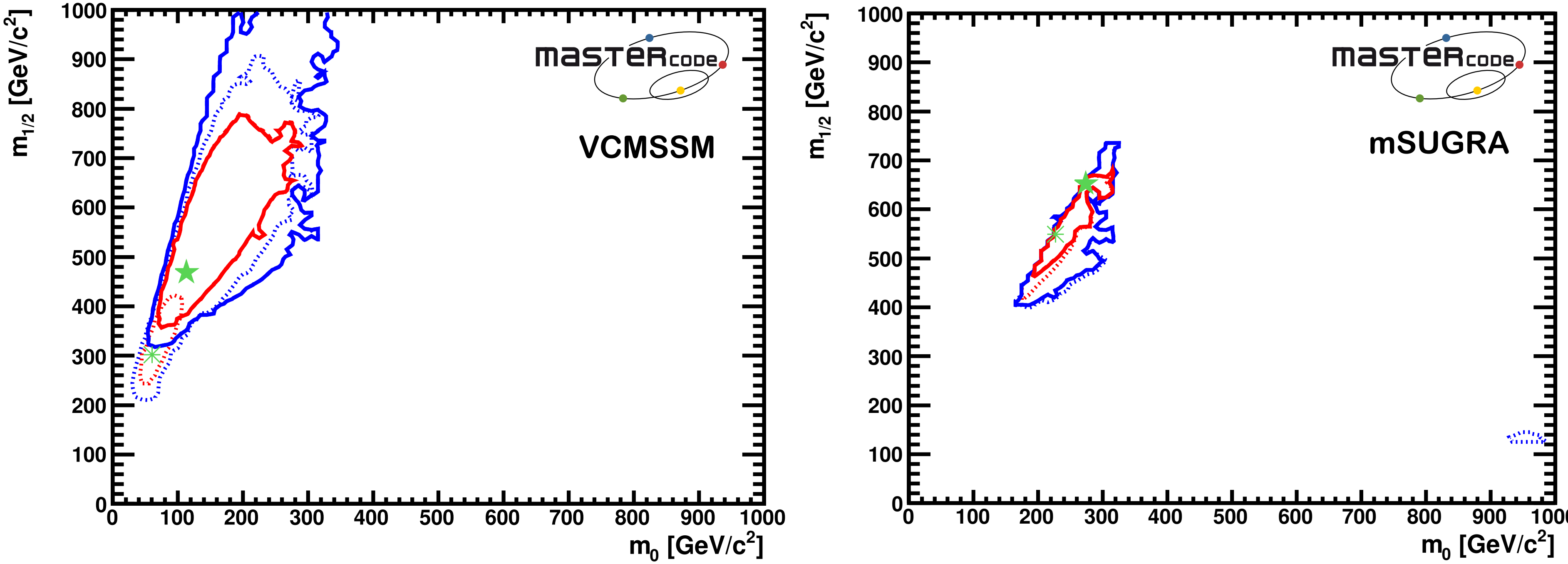
- Construct likelihood model for event numbers using $\mathrm{CL_s}$ method
  - Close to a Gaussian with $\mu = 1.2$, $\sigma = 3.2$
- 90% CL corresponds to 6.1 events, rescale from contour (right)



- The excess observed in XENON100 leads to a contribution of $\chi^2 = 0.3$ for small $\sigma^{SI}{}_p$
- The uncertainty on the π-nucleon σ term is also taken into account; we look at both
  - $\Sigma_{\pi N} = 50 \pm 14$
  - $\Sigma_{\pi N} = 64 \pm 8$

Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data



VCMSSM

60 million points sampled

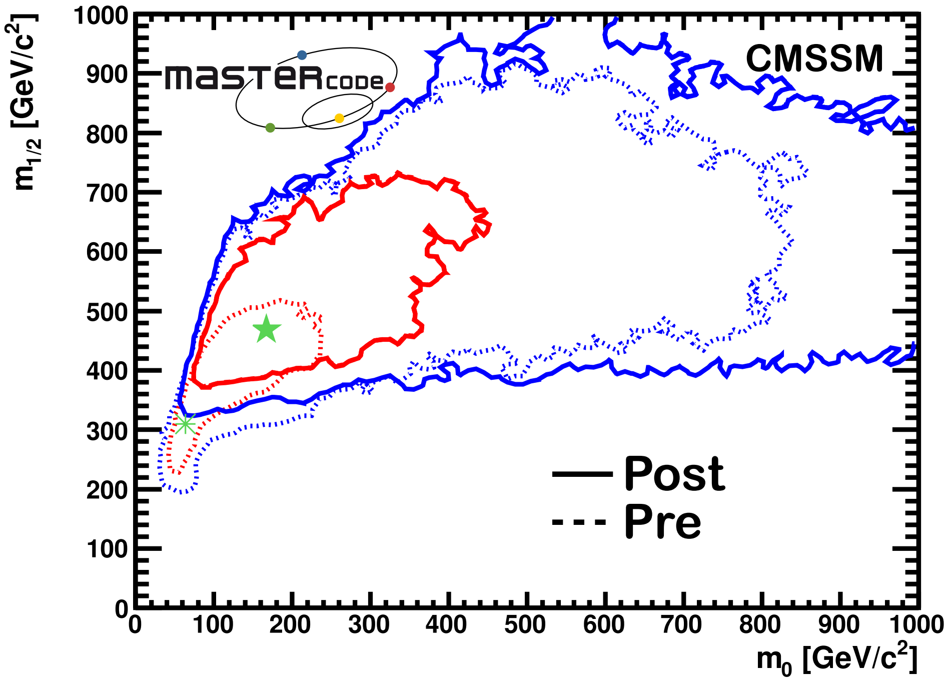
mSUGRA

60 million points sampled

Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
VCMSSM	22.5	31%	300	60	30	9
post-LHC/XENON100	27.1	13%	390	90	70	11
mSUGRA	29.4	6.1%	550	230	430	28
post-LHC/XENON100	30.9	5.7%	550	230	430	28

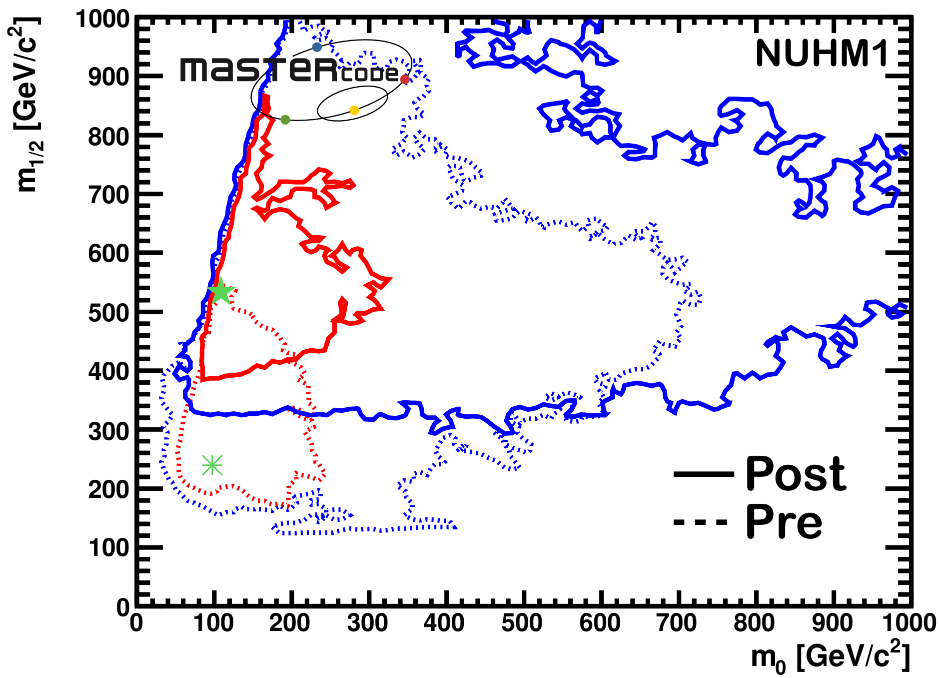
Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data



CMSSM

60 million points sampled

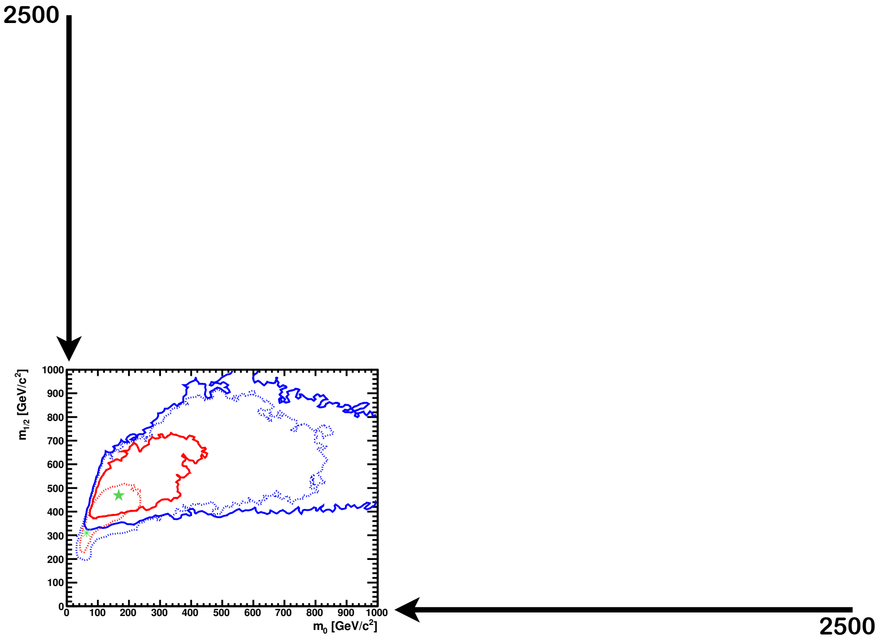


NUHM1

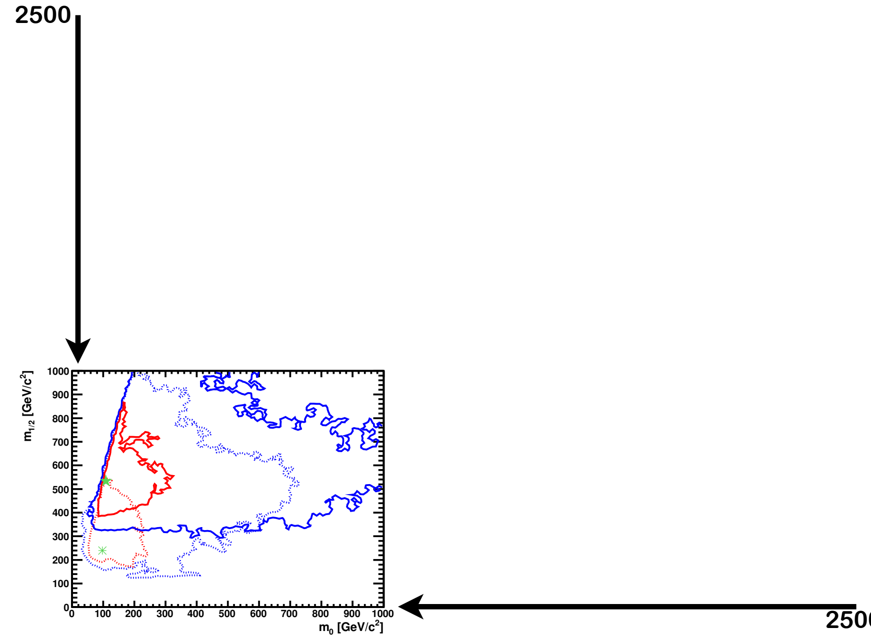
70 million points sampled

Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data



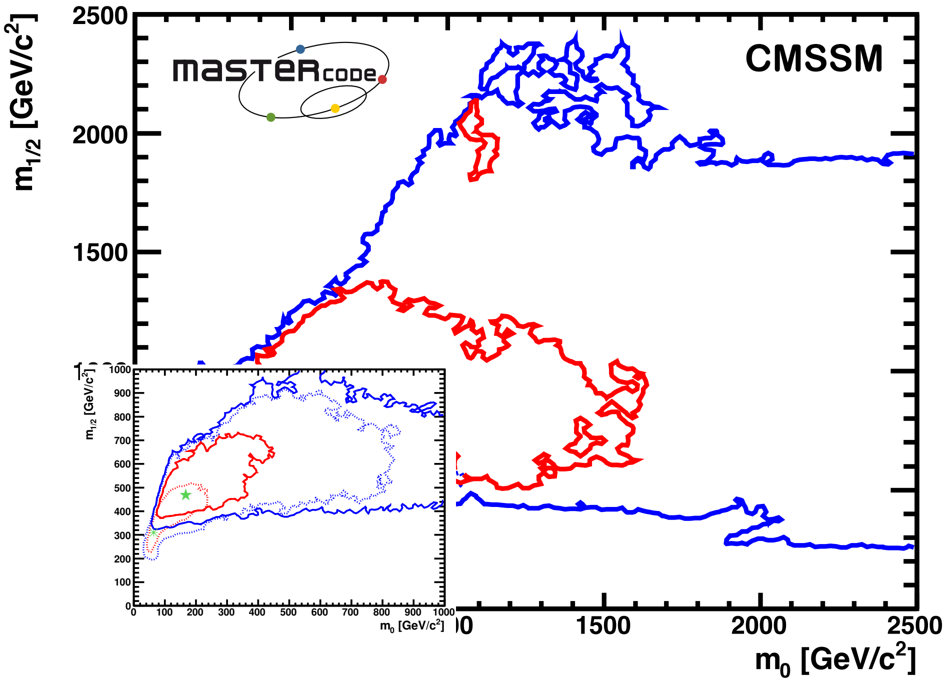
CMSSM
60 million points sampled

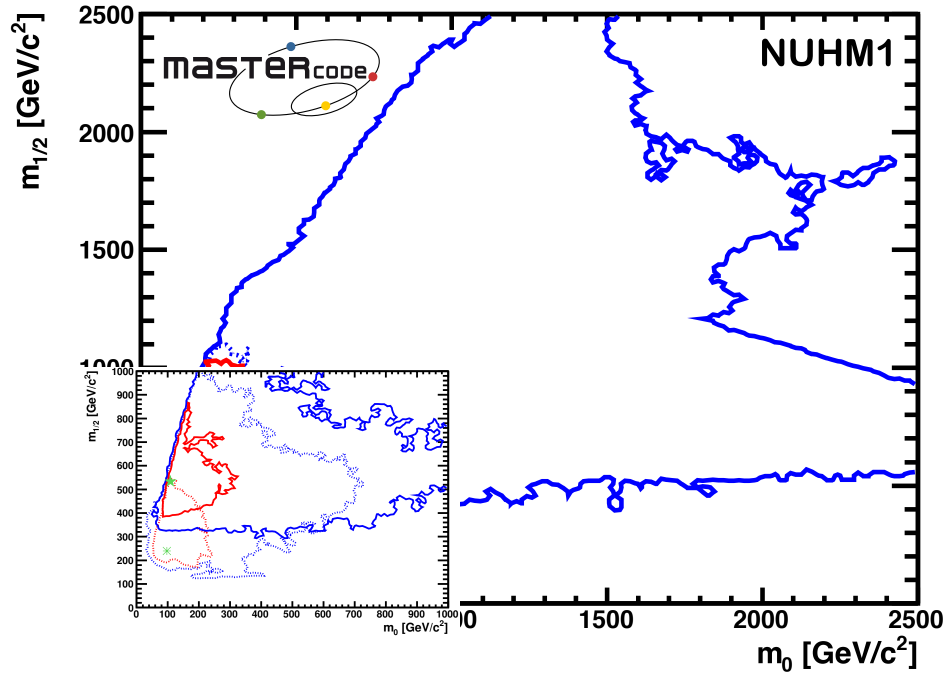


NUHM1
70 million points sampled

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



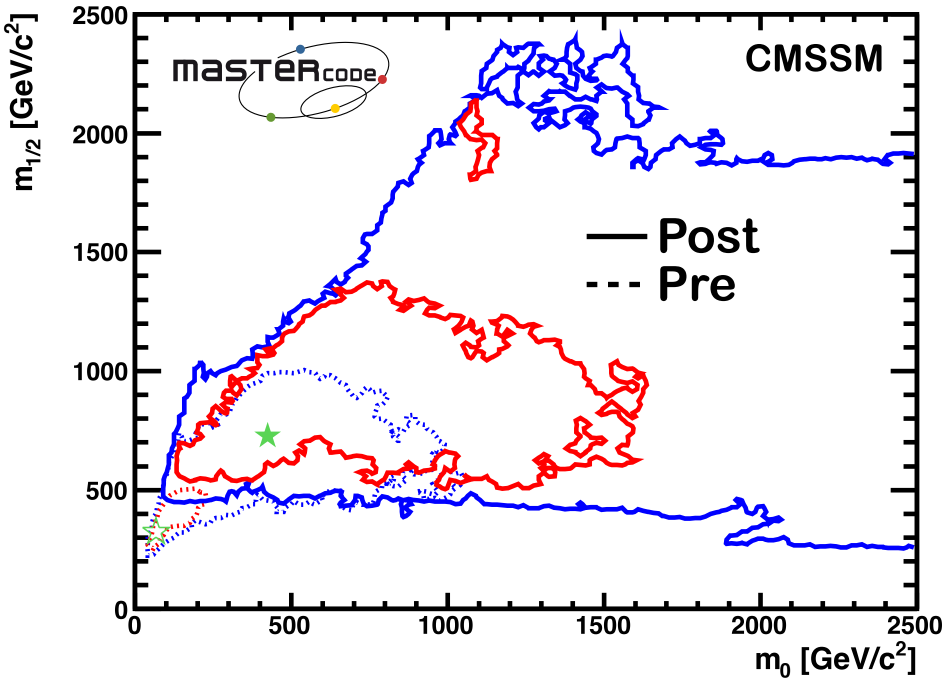


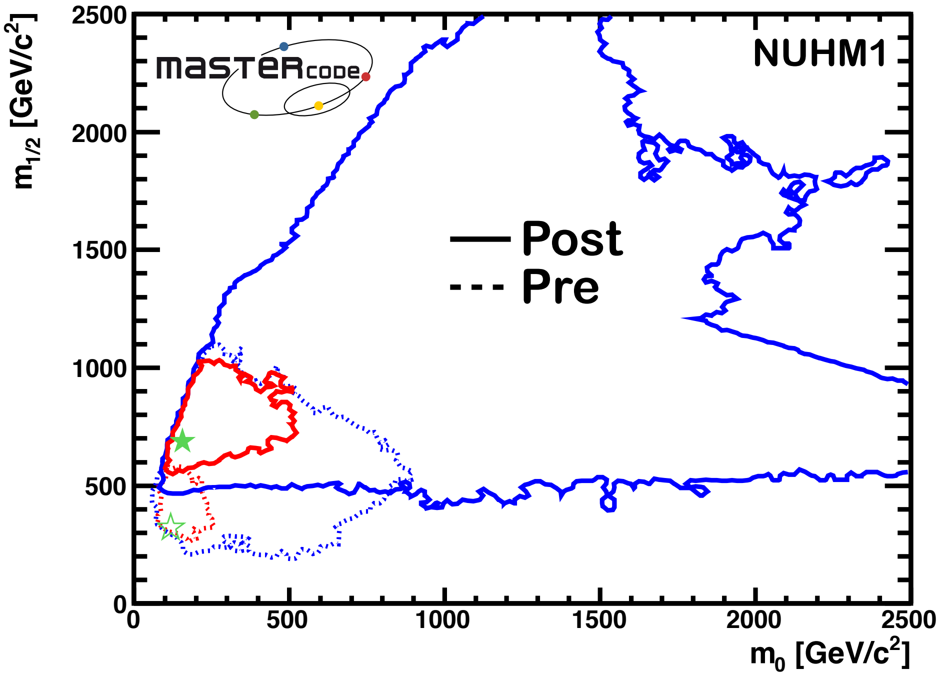
CMSSM
60 million points sampled

NUHM1
70 million points sampled

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data





CMSSM
60 million points sampled

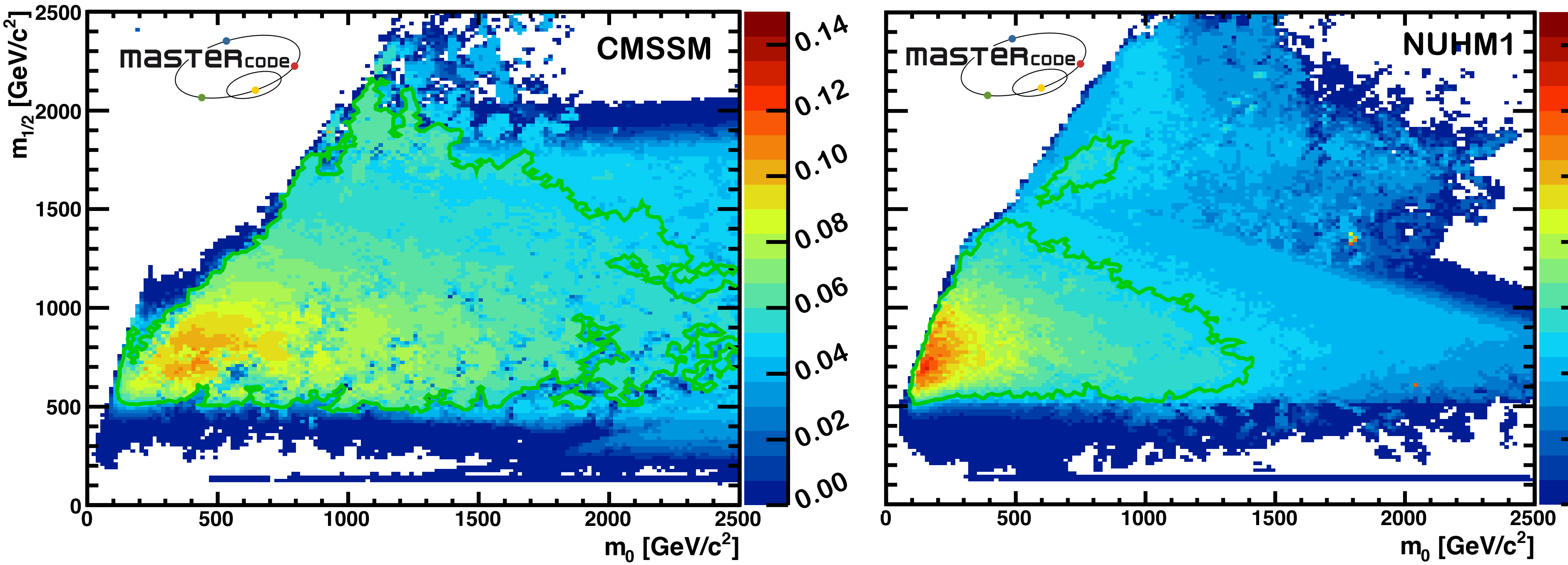
NUHM1
70 million points sampled

Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data



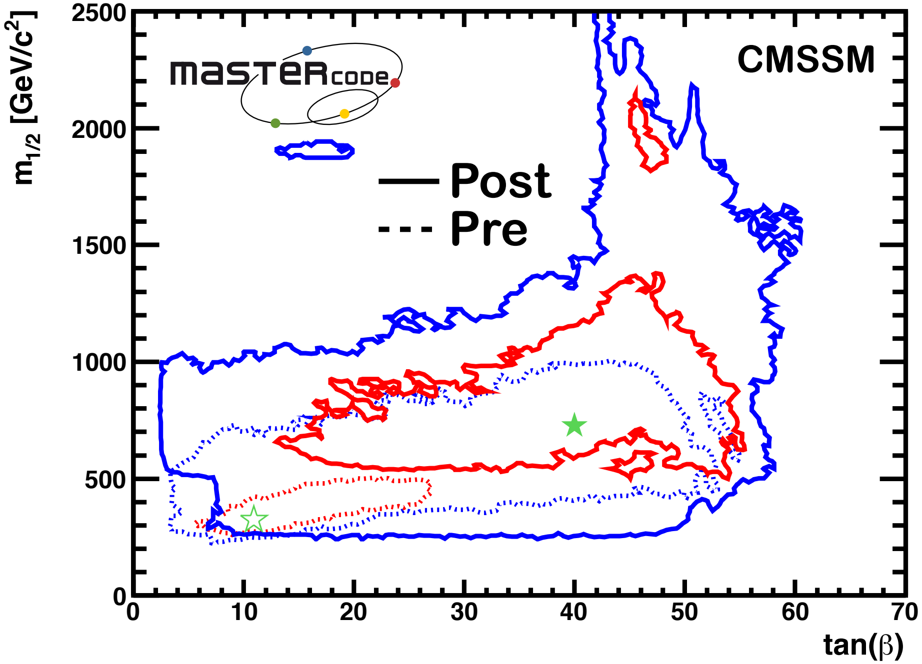
Model	Min χ^2	Prob	$m_{1/2}$	m_0	A_0	$\tan\beta$
CMSSM	22.5	26%	310	60	-60	10
post-LHC/XENON100	29.3	11%	730	420	-1100	40
NUHM1	20.5	25%	310	60	-60	10
post-LHC/XENON100	27.3	13%	690	160	-880	33

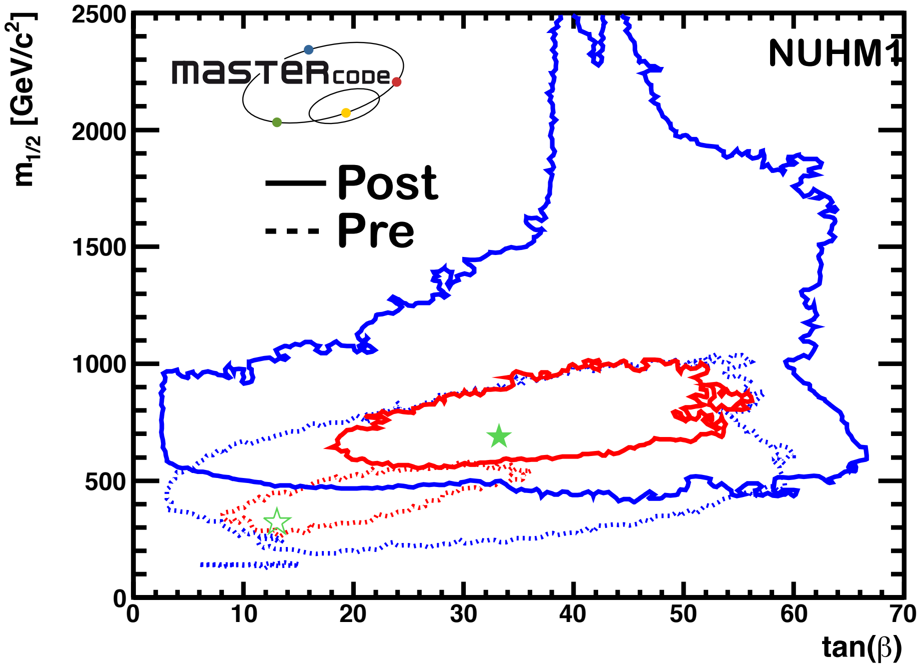
With 1 fb^{-1}: CMSSM and NUHM1 still above 10% CL

VCMSSM and mSUGRA now less than 5% CL

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data





CMSSM

60 million points sampled

NUHM1

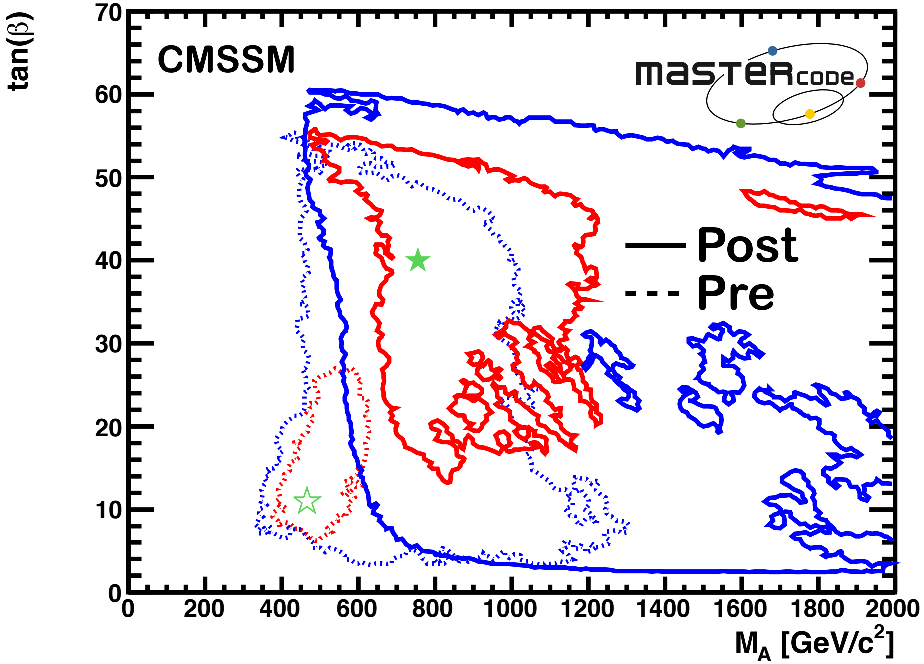
70 million points sampled

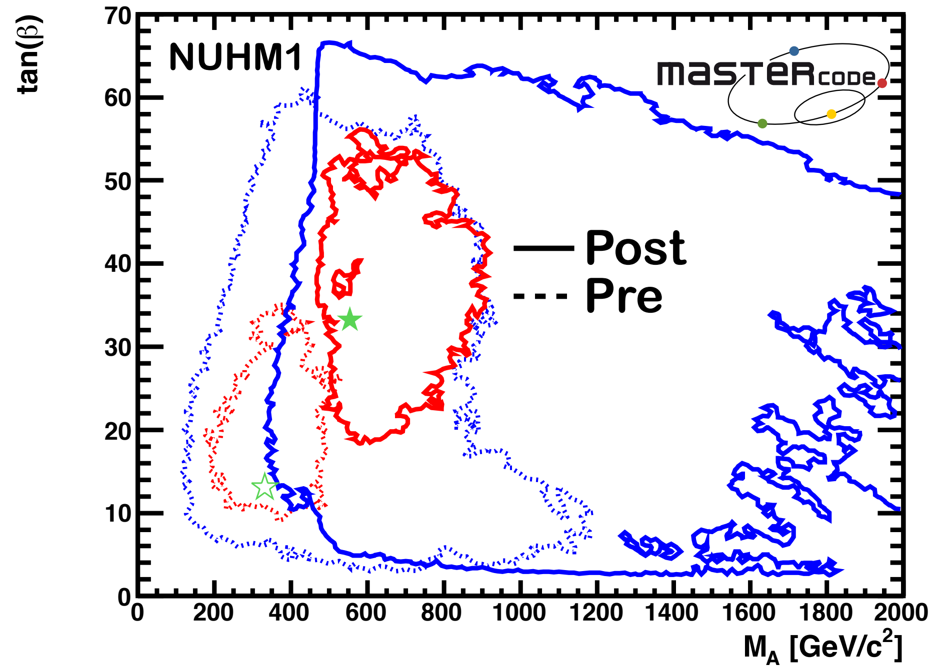
Red and blue curves represent $\Delta\chi^2$ from global minimum, located at ☆

Preferred region "opens up" at cost of worsening global χ^2 value!

Post-LHC, Post-XENON100

2011 ATLAS + CMS with 1 fb^{-1} of LHC Data





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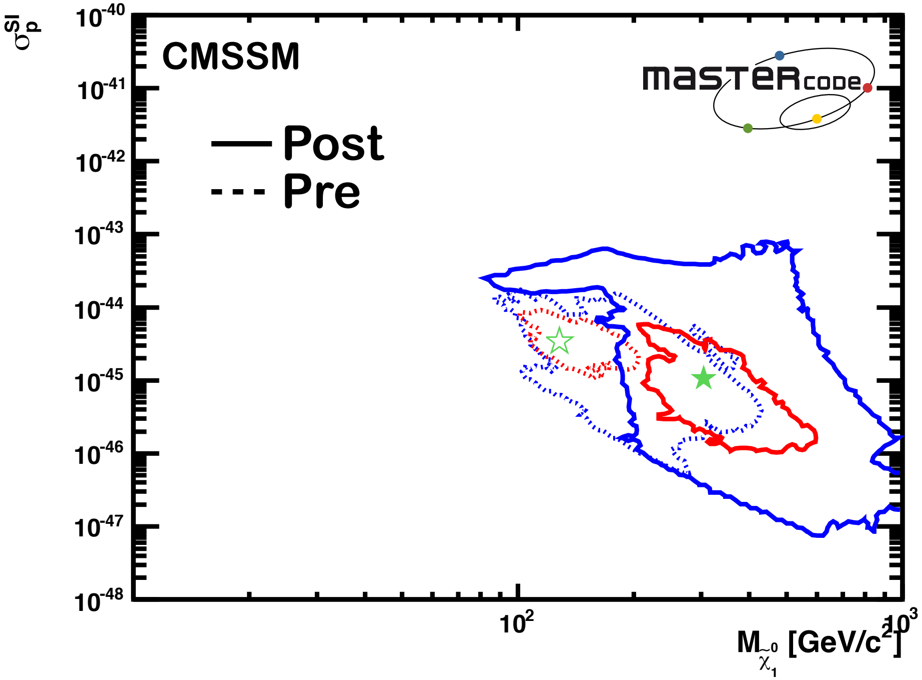

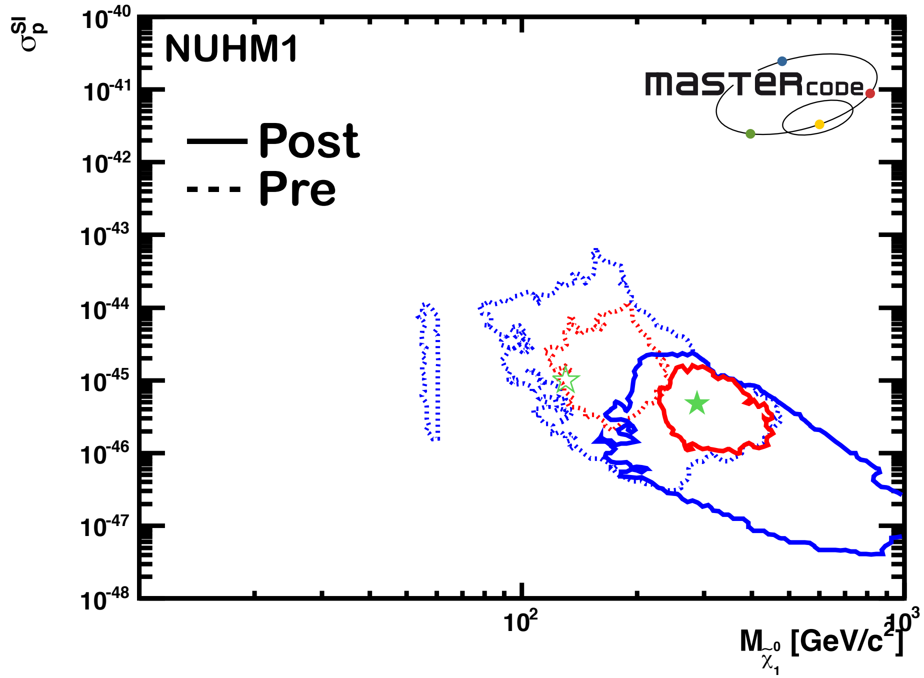

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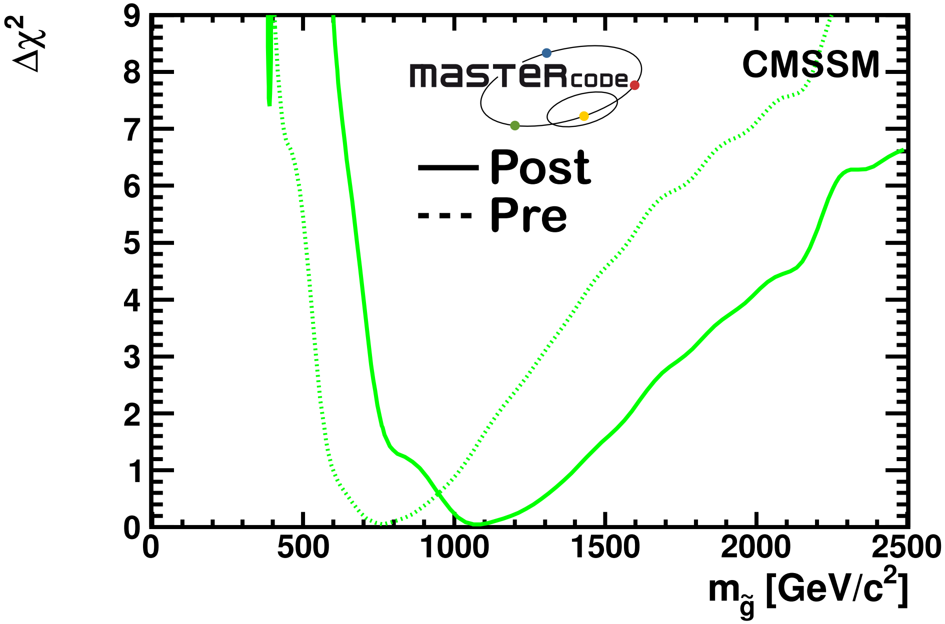
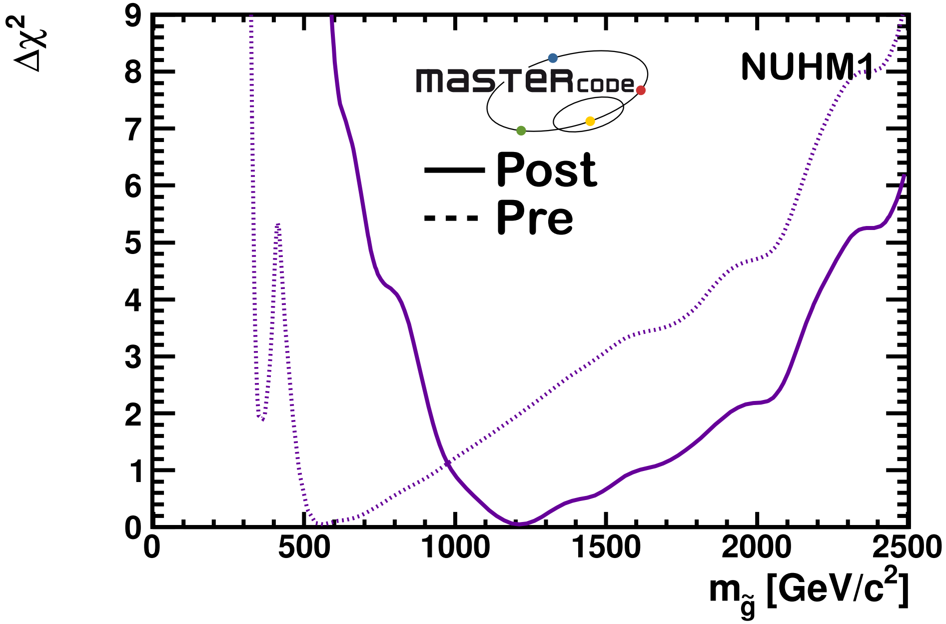
Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data





CMSSM Prediction:

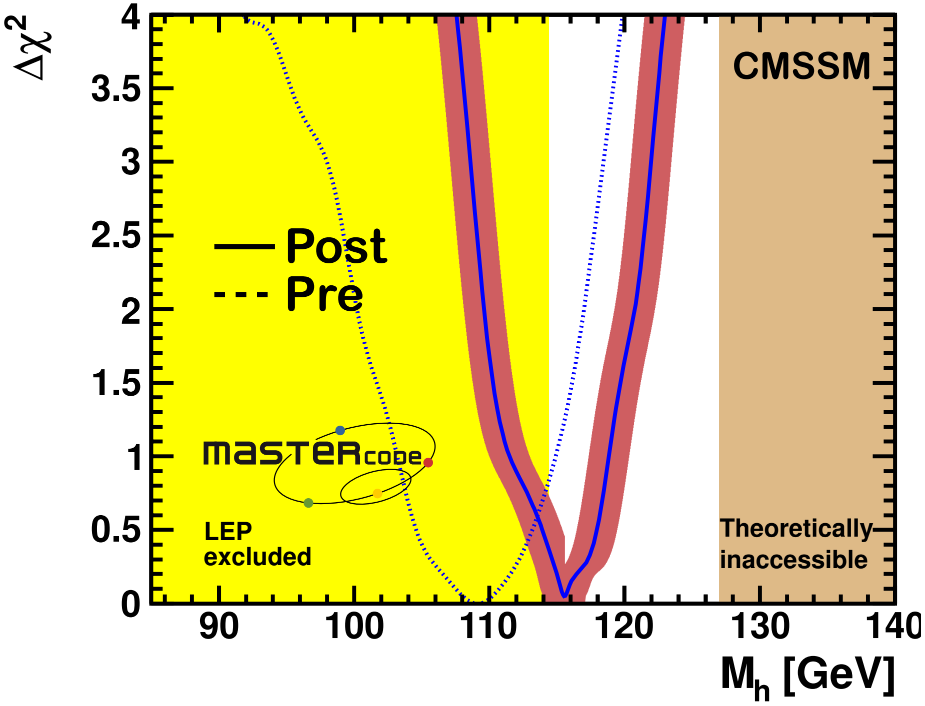
$$m_{\tilde{g}} = 1080^{+320}_{-100} \text{ GeV}$$

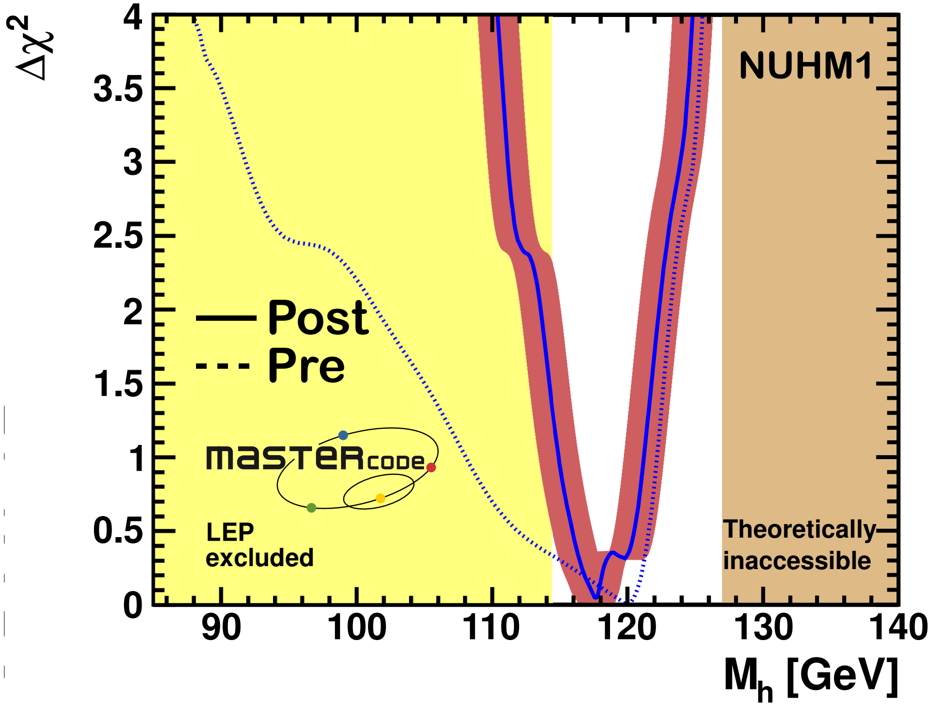
NUHM1 Prediction:

$$m_{\tilde{g}} = 1200^{+400}_{-200} \text{ GeV}$$

Post-LHC, Post-XENON100

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data





CMSSM Prediction:

$$m_H = 116^{+4}_{-6}\ \mathrm{GeV}$$

NUHM1 Prediction:

$$m_H = 118^{+4}_{-4}\ \mathrm{GeV}$$

SM Prediction: $m_H = 92^{+34}_{-26}\ \mathrm{GeV}$

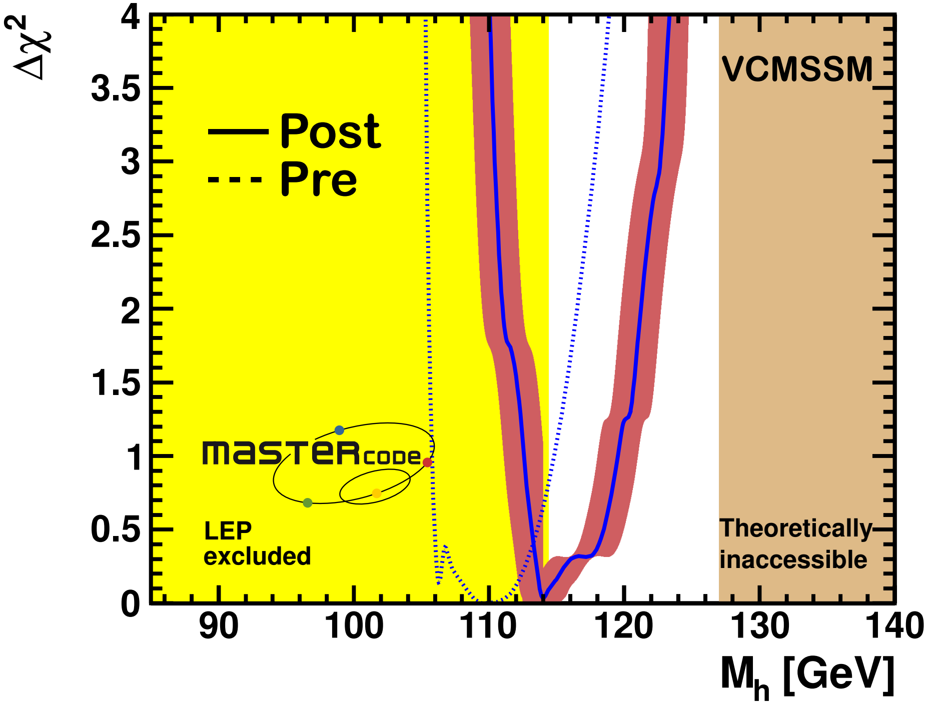
Summary and Conclusions

- mSUGRA, VCMSSM
  - With 1fb^{-1}, essentially excluded at 95% CL

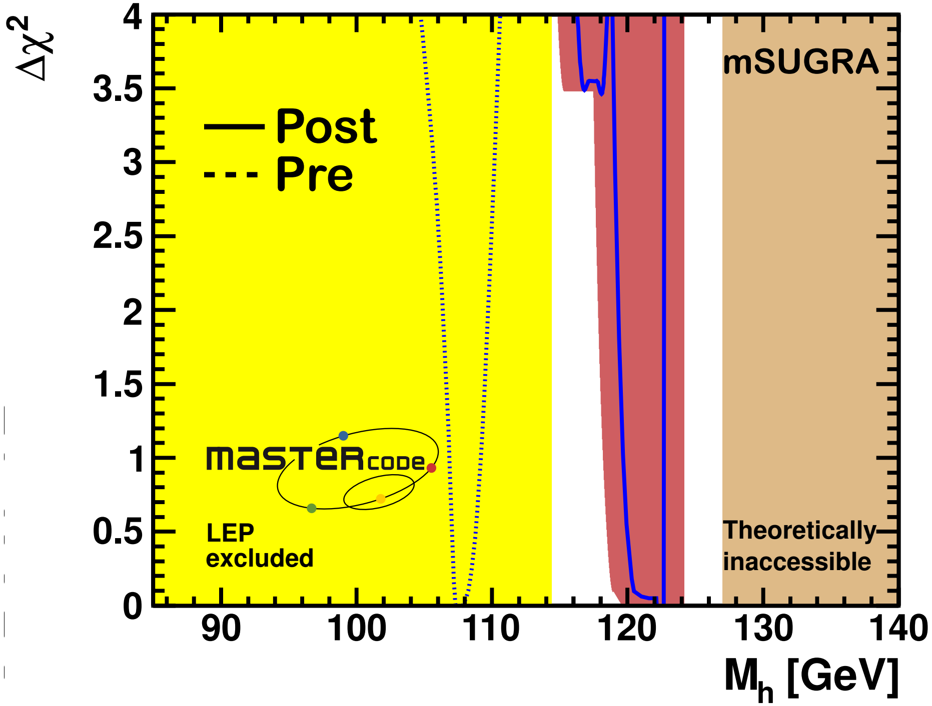
- CMSSM, NUHM1
  - With 36 pb^{-1},
    - gluino masses already preferred above TeV level
  - With 1 fb^{-1}, still alive at the 10% level:
    - Tension between post-LHC reality high $(m_0, m_{1/2})$ and pre-LHC preferred low $(m_0, m_{1/2})$
    - Tension partly compensated by higher $\tan\beta$
    - Lower preferred σ_p^{SI} and higher LSP mass
  - Lightest Higgs mass now preferred above LEP limit

BACKUP

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data



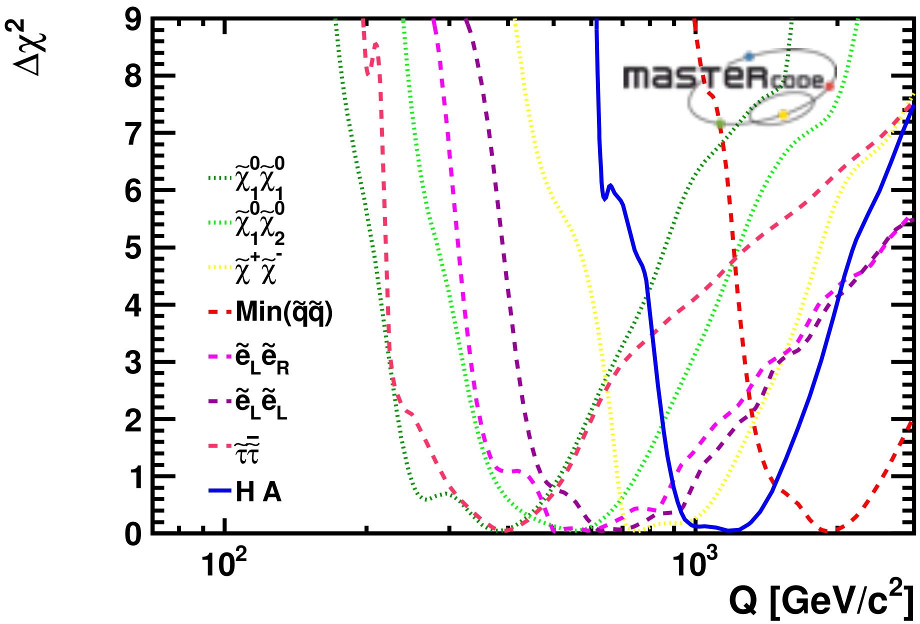
VCMSSM

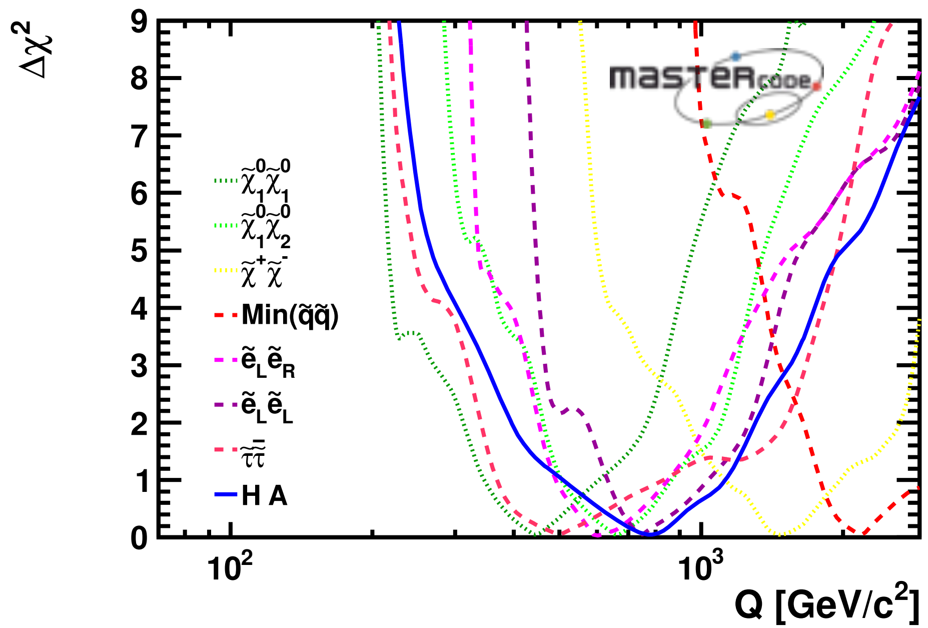


mSUGRA

SM Prediction: $m_H = 92^{+34}_{-26}$ GeV

2010 ATLAS + CMS with 36 pb^{-1} of LHC Data





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