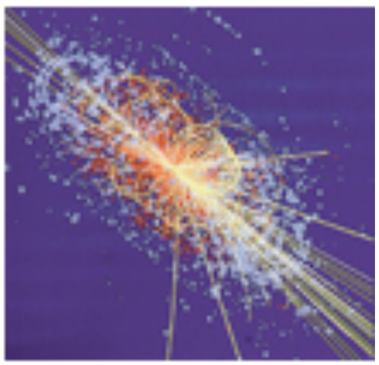
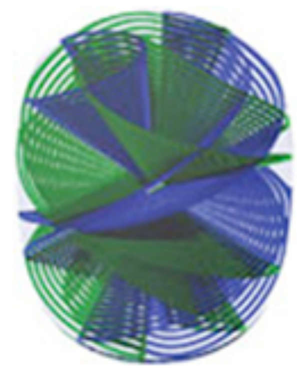
Indirect Constraints and SUSY



Albert De Roeck
CERN &
Antwerp University &
IPPP Durham, UK

Oliver Buchmuller
CERN



LHC New Physics Signatures Workshop

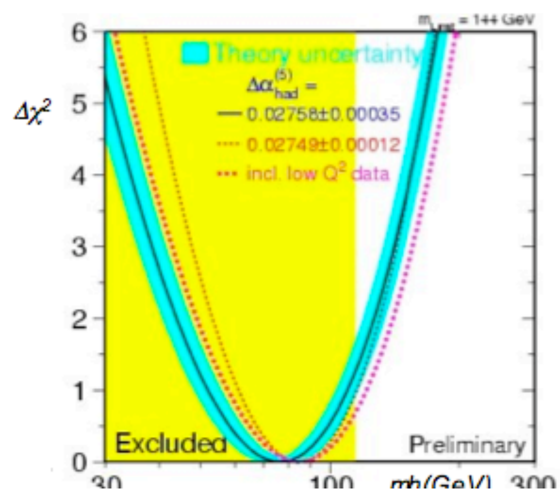
Use of indirect constraints: EW Fit

A prominent example for the comprehensive usage of indirect constraints!

Use high precision EW measurements to:

a) Test the consistency of the SM

*b) Predict the last unknown quantity in the SM: **the higgs mass***



Common framework

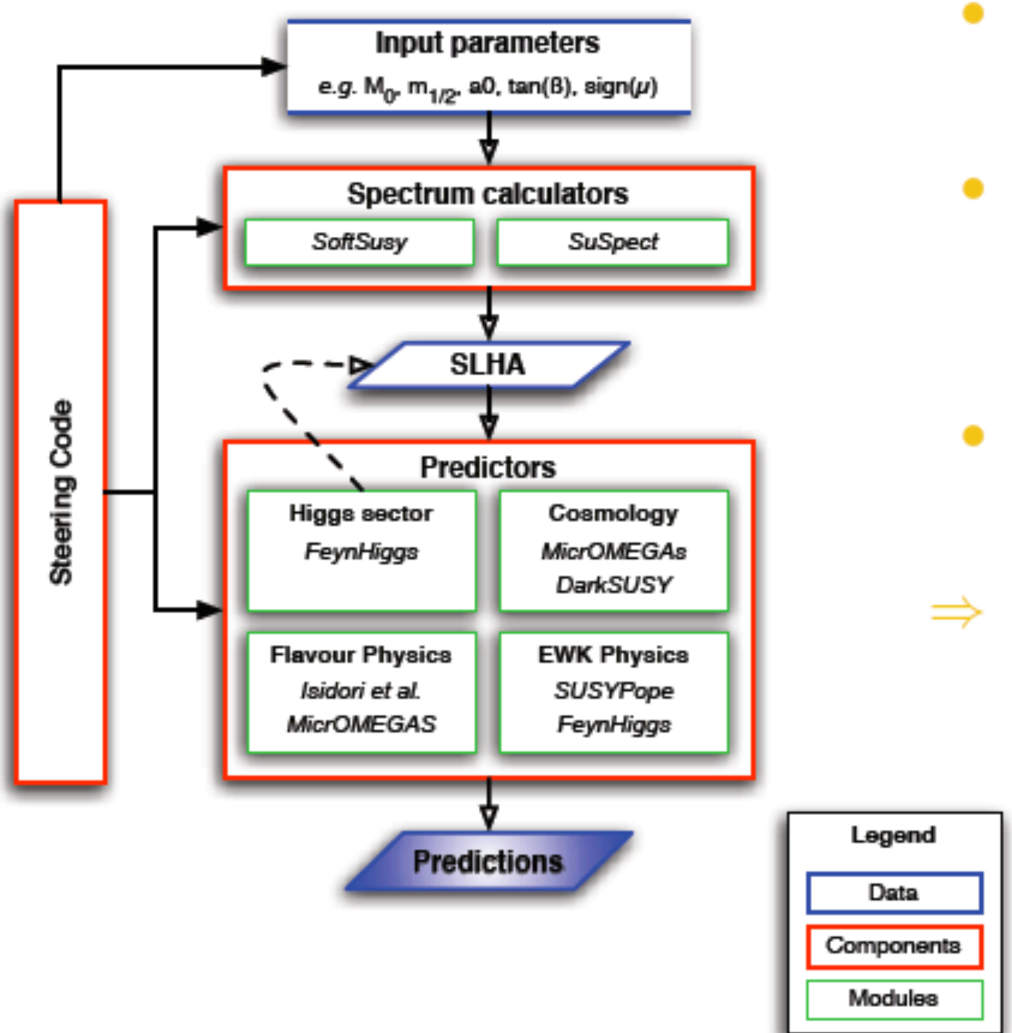
- Goal: a framework to provide consistent indirect constraints
- Collaboration of interested theorists and experimentalists

  Buchmüller, Oliver (CERN) – Exp.
  De Roeck, Albert (CERN & Uni. Antwerpen) – Exp.
  Heinemeyer, Sven (Santander) – Theo.
  Olive, Keith (Uni. of Minnesota) – Theo.
  Ronga, Frédéric (CERN) – Exp.
  Weiglein, Georg (Durham) – Theo.
  Cavanaugh, Richard (Uni. of Florida) – Exp.
  Ellis, John (CERN) – Theo.
  Isidori, Gino (INFN Frascati) – Theo.
  Paradisi, Paride (Uni. of Valencia) – Theo.
  Weber, Arne (Max Planck Inst. (Munich)) – Theo.

- Started at workshop on *Flavour Physics in the Era of the LHC*
  ⇒ See (draft) report, sec. 5.2
- Main focus of the work:
  - Development of a *common tool* for indirect constraints
  - Compilation (and integration) of state-of-the-art predictions
  - Application of the tool

Buchmuller et al., PLB 657/1-3 pp 87-94

Common framework



- Consistency
  Relies on SLHA interface
- Modularity
  Compare calculations
  Add/remove predictions
- State-of-the art calculations
  Direct use of code from experts

⇒ A unique "platform" for the integration of tools

First Exercise:
Look for regions in CMSSM Space using the constraints

"Preferred" Parameter Space

Pulls from mSUGRA fit:
χ^2/NDF = 17/14 ; P(χ^2)=20%

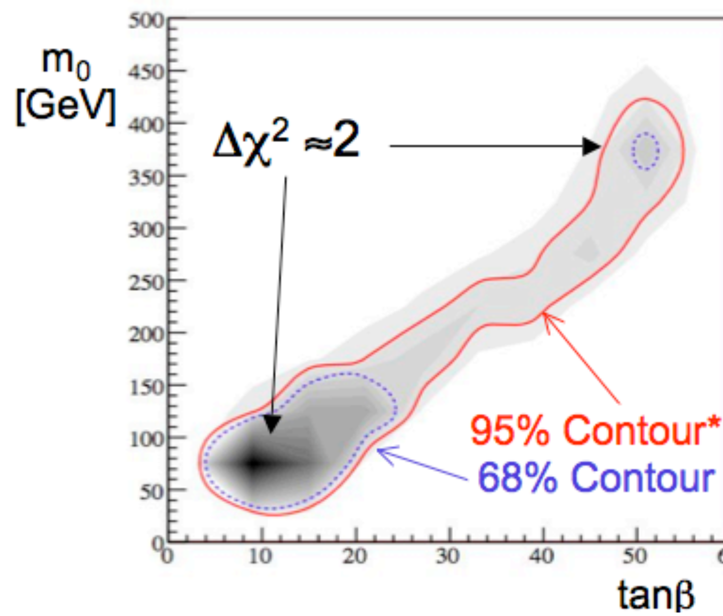
Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
σ_{had}^0 [nb]	41.540 ± 0.037	41.486	
R_l	20.767 ± 0.025	20.744	
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01641	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	
R_b	0.21629 ± 0.00066	0.21613	
R_c	0.1721 ± 0.0030	0.1722	
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1479	
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.382	
m_t [GeV]	170.9 ± 1.8	170.8	
$R(b\to s\gamma)$	1.13 ± 0.12	1.12	
$B_s\to\mu\mu$ [$\times10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

Collaboration of experimentalist and theorist:
arXiv:0707.3447

BUCHMULLER, CAVANAUGH, DE ROECK, HEINEMEYER, ISIDORI, PARADISI, RONGA, WEBER, WEIGLEIN.

$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f_{SM_i}^{obs} - f_{SM_i}^{fit})^2}{\sigma(f_{SM_i})^2}$$

Multi-parameter fit using all mSUGRA parameters. Relevant SM uncertainties like Δm_{top} are also considered

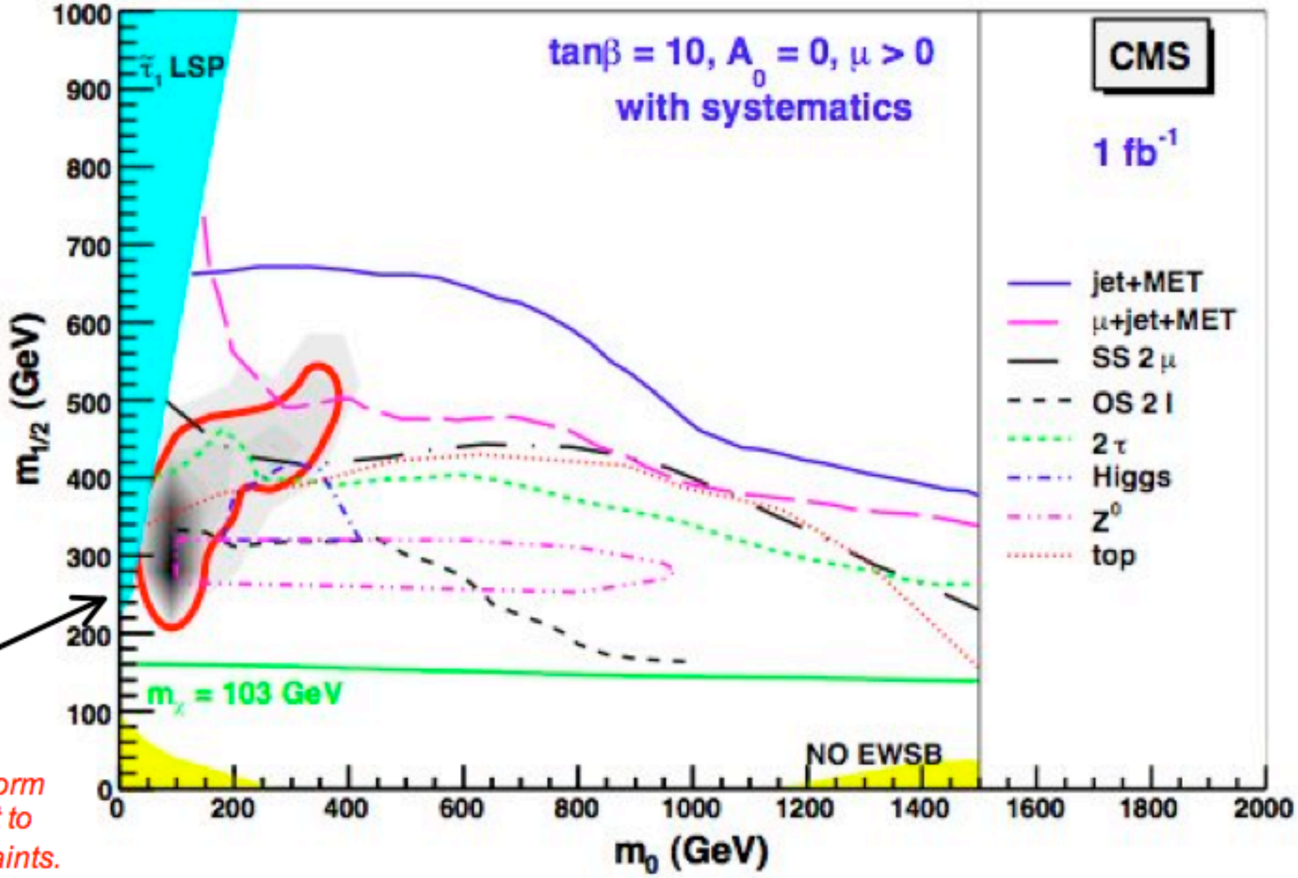


Preferred SUSY Parameter Space

CMS Discovery Reach for $1fb^{-1}$ (ATLAS similar)

Example of similar analyses:

- Ellis, Heinemeyer, Olive, Weber, Weiglein - ph/0706.0652
- Allanach, Lester, Weber - ph/0705.0487
- Trotta, Austri, Roszkowski - ph/0609126
- … there are more!



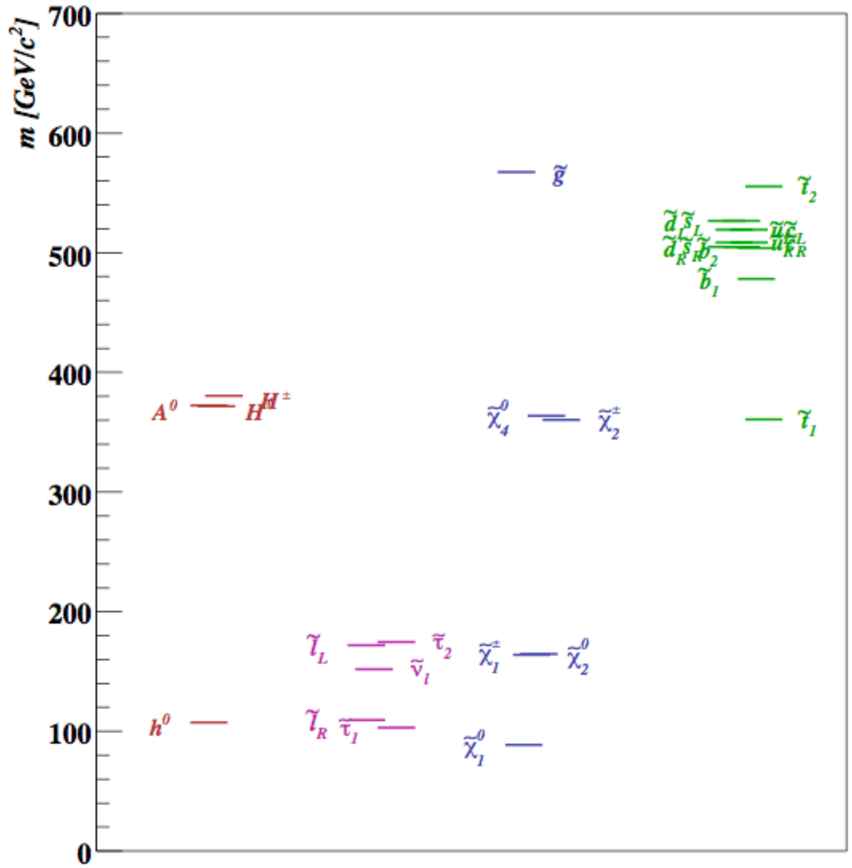
arXiv:0707.3447
95% contour obtained form a multi-parameter χ^2 fit to important indirect constraints.
χ^2/NDF = 17/15 - good fit
NOTE: All mSUGRA parameters are free in the fit!

"CMSSM fit clearly favors low-mass SUSY"

Sparticle Spectrum

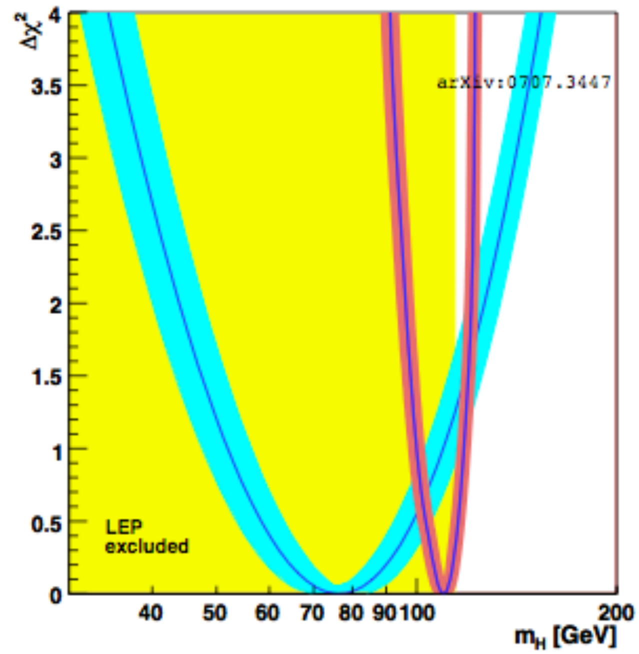
"best CMSSM Fit"

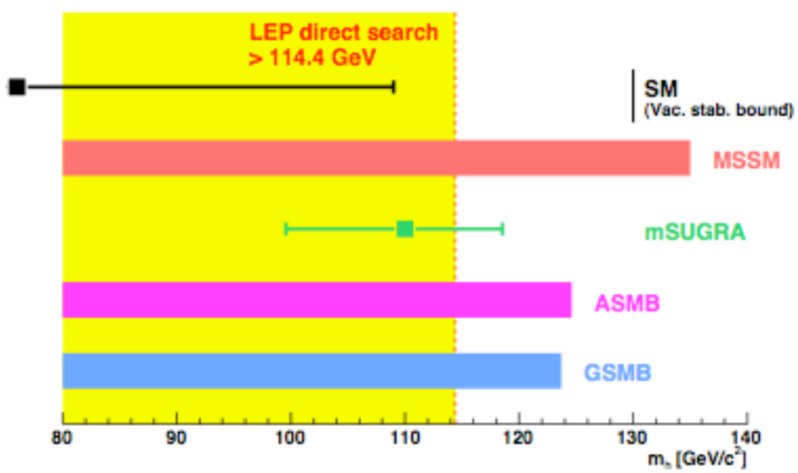
"LHC weather forecast"



M0 M12 A0 tb
49.2 232.3 -122.4 6.9
Ma=372 GeV; mu=336 GeV; mh=111 GeV

Higgs Mass "Prediction"





LEP m_H constrained not used in fit

- Constrain m_h to scan value;
- minimize all model parameters in each point;

⇒ determine error on m_h prediction

SM fit:

- $m_H = 78^{+33}_{-24}$ GeV$/c^2$
- 12% probability at exclusion limit
  Including theoretical uncertainty

CMSSM fit:

- $m_h = 110^{+8}_{-10} \pm 3$ GeV$/c^2$
- 20% probability at exclusion limit
  Including theoretical uncertainty

CMSSM vs. SM

CMSSM

Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02774	
m_Z [GeV]	91.1875 ± 0.0021	91.1873	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	
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Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

arXiv:0707.3447 [hep-ph]

$$\chi^2/\text{ndof} = 17.0/13 \text{ (20\% prob.)}$$

SM

Variable	Measurement	Fit	$\lvert O^{meas}-O^{fit}\rvert/\sigma^{meas}$
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768	
m_Z [GeV]	91.1875 ± 0.0021	91.1875	
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957	
σ^0_{had} [nb]	41.540 ± 0.037	41.477	
R_l	20.767 ± 0.025	20.744	
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645	
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	
R_b	0.21629 ± 0.00066	0.21586	
R_c	0.1721 ± 0.0030	0.1722	
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038	
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742	
A_b	0.923 ± 0.020	0.935	
A_c	0.670 ± 0.027	0.668	
A_l(SLD)	0.1513 ± 0.0021	0.1481	
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314	
m_W [GeV]	80.398 ± 0.025	80.374	
m_t [GeV]	170.9 ± 1.8	171.3	
Γ_W [GeV]	2.140 ± 0.060	2.091	

arXiv:hep-ex/0612034

$$\chi^2/\text{ndof} = 18.2/13 \text{ (15\% prob.)}$$

New Analyses

Markov Chain Monte Carlo (MCMC):

To ensure a comprehensive mapping of the parameter space we have performed several MCMC's with many different starting points. The shown contour is the combined result of all of them.

χ^2 Minima:

The overall χ^2 minima is determined using Minuit. The chosen starting values are determined from the results of the MCMC sampling of the parameter space.

Contours:

Contours are defined from all MCMC's. So far, we have not performed toys to validate and refine all the 68% (blue) and 95% (red) contours but cross checks show that the contours are reliable.

Extension of the Constraints

Low energy observables

$BR(b \to s\gamma)$	MicrOMEGAs	Isidori & Paradisi
$BR(b \to sll)$		Isidori & Paradisi
$BR(B_s \to \mu\mu)$	MicrOMEGAs	Isidori & Paradisi
$BR(B \to \tau\nu)$		Isidori & Paradisi
$BR(K \to \tau\nu)$		Isidori & Paradisi
$BR(K \to \pi\nu\nu)$		Isidori & Paradisi
$\Delta m_s / \Delta m_d$		Isidori & Paradisi
Δm_s		Isidori & Paradisi
Δm_K		Isidori & Paradisi
$g-2$	FeynHiggs	

Higgs sector observables

m_h^{light}	FeynHiggs

Cosmology observable

Ωh^2	MicrOMEGAs	DarkSUSY

High energy EW observables

R_l	A. Weber *et al.*
R_b	A. Weber *et al.*
R_c	A. Weber *et al.*
$A_{fb}(b)$	A. Weber *et al.*
$A_{fb}(c)$	A. Weber *et al.*
A_b	A. Weber *et al.*
A_c	A. Weber *et al.*
$A_l(SLD)$	A. Weber *et al.*
$\sin^2\theta_{eff}$	A. Weber *et al.*
m_W	A. Weber *et al.*
Γ_Z	A. Weber *et al.*

Improved Heavy flavour code (particularly for high $\tan\beta$)

Non-Universal Higgs Model (NUHM)

"NUHM = CMSSM but with decoupled Higgs sector at GUT scale"

➡ $m_0 := m_{SQ} = m_{SL} \neq m_H$

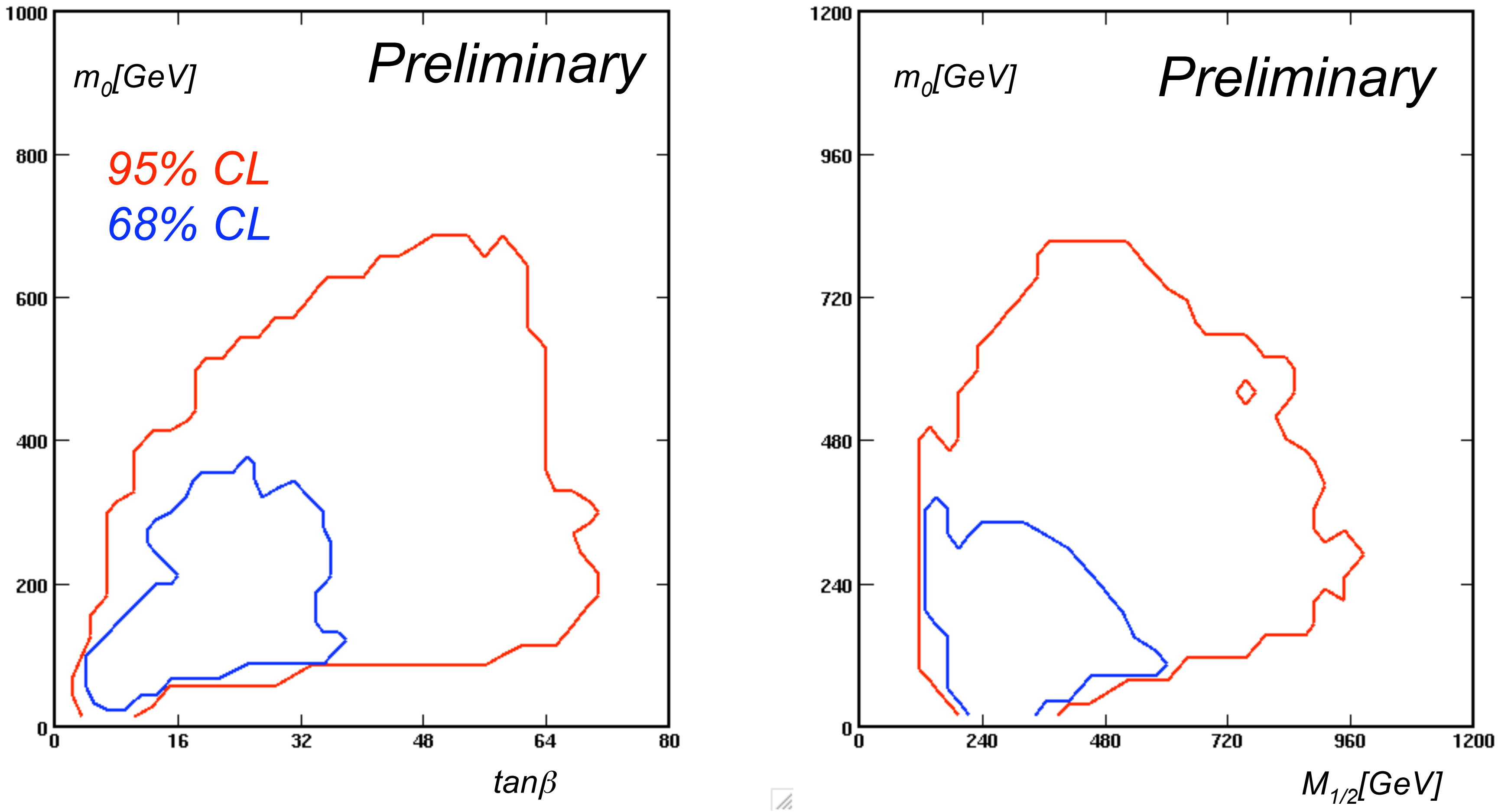
NUHM I Model (5 Parameter)

$m_0 , m_{1/2} , A_0 , \tan\beta , M_h \; [M_{hu} = M_{hd}]$

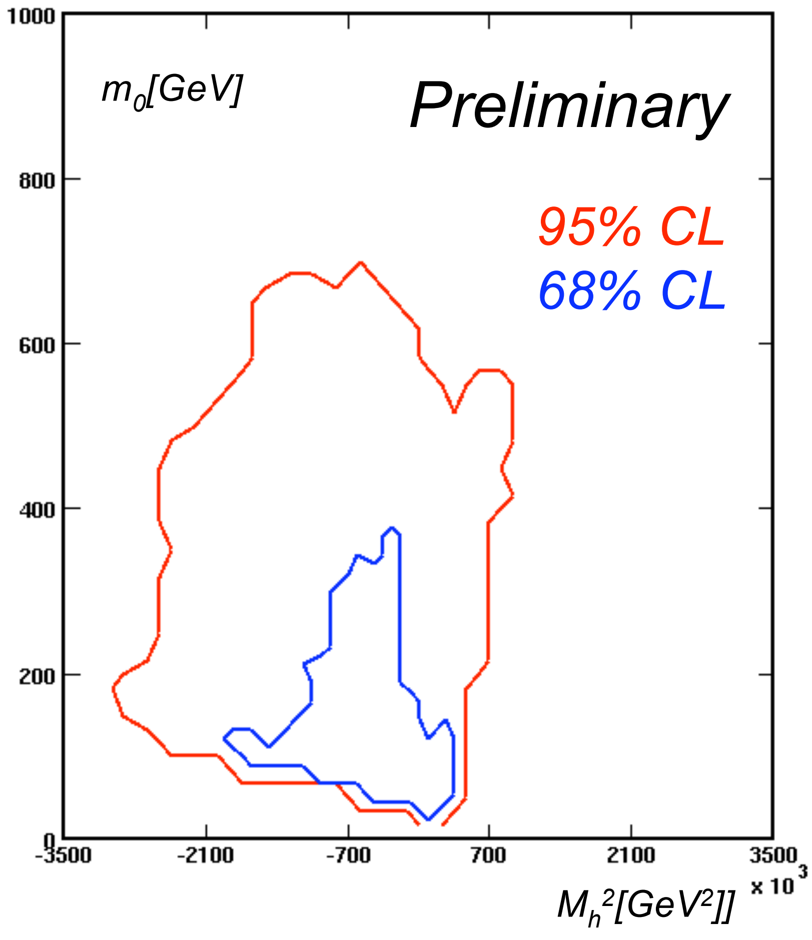
NUHM II Model (6 Parameter)

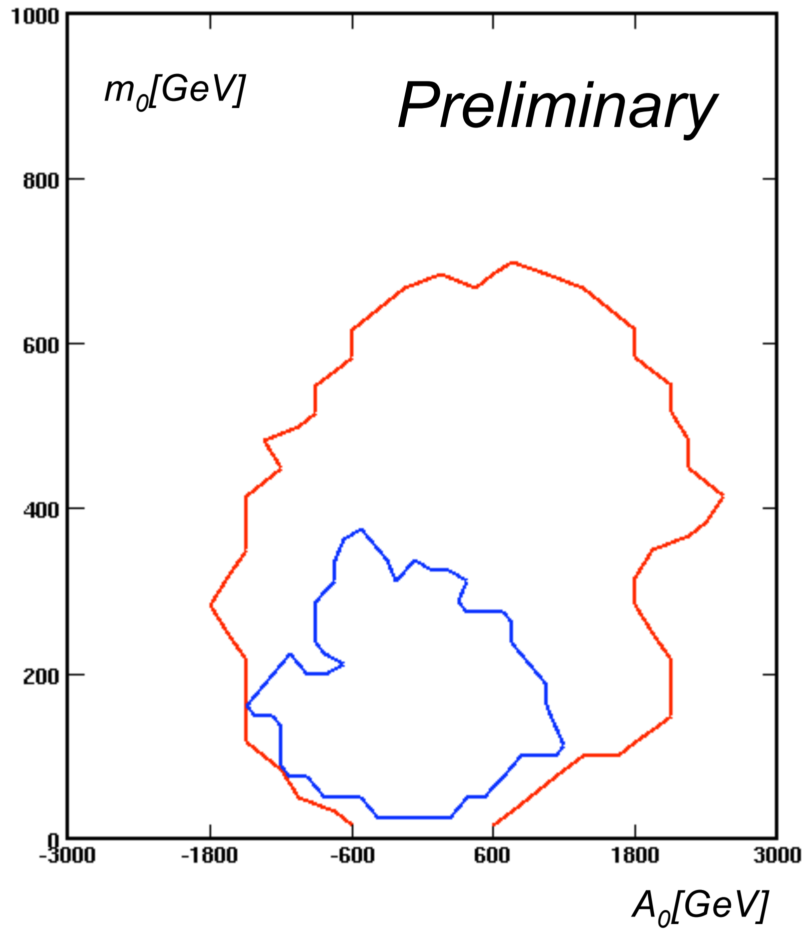
$m_0 , m_{1/2} , A_0 , \tan\beta , M_{hu} , M_{hd}$

NUHM I Contours - Part I

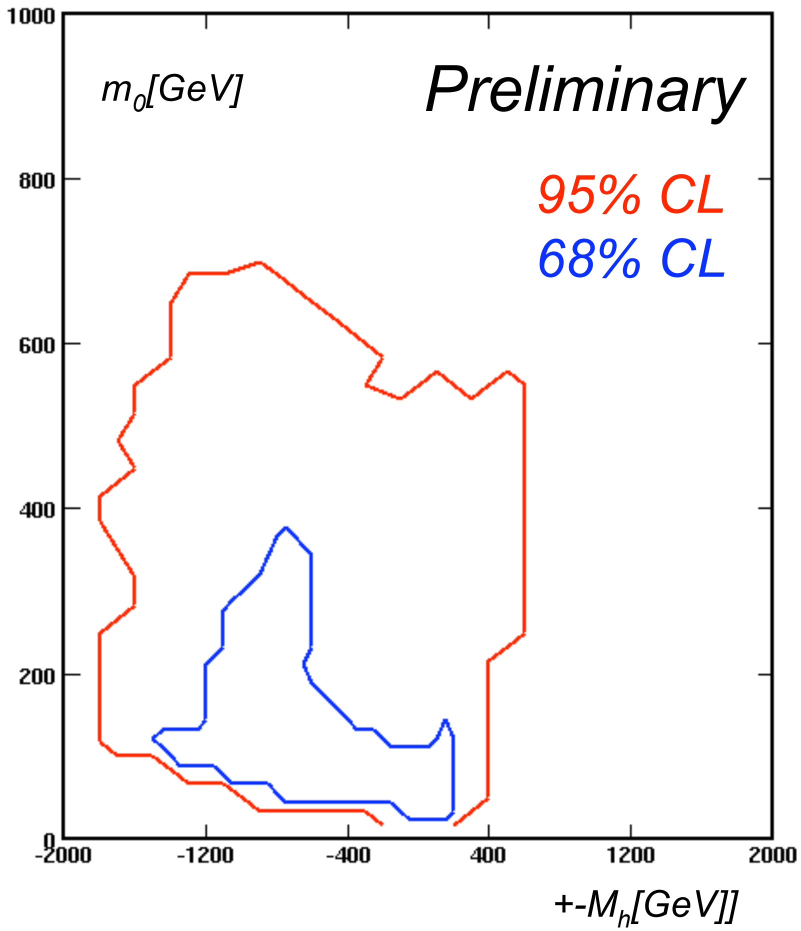


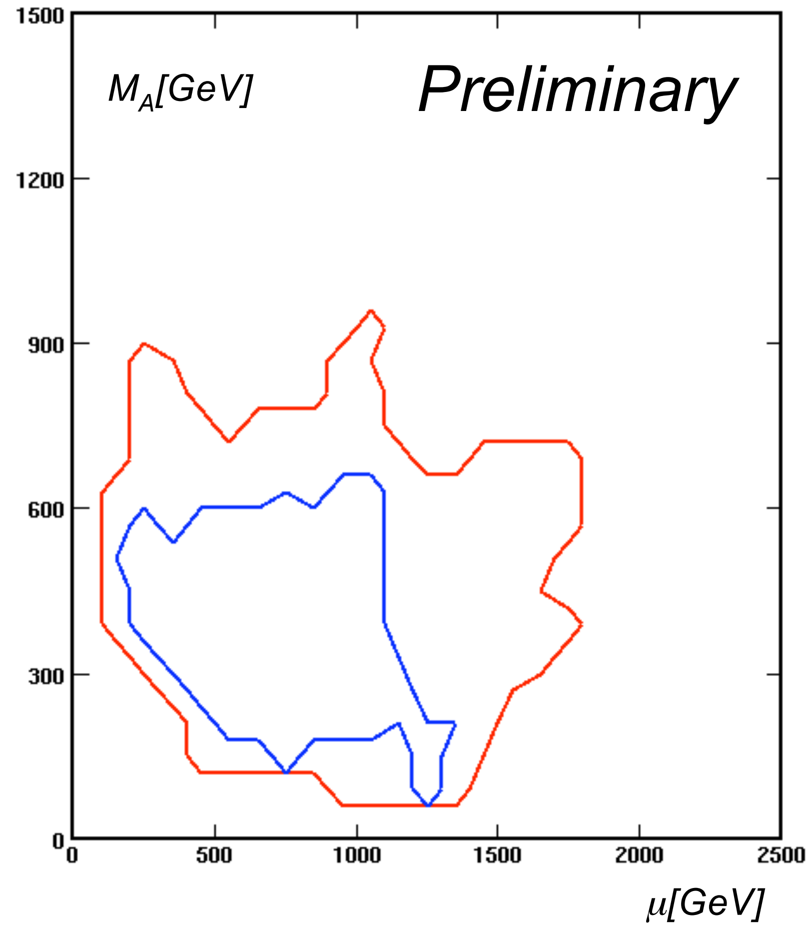
NUHM I Contours - Part II





NUHM I Contours - Part III





Considered Models

NUMH I TODAY: *Use of indirect constraints only*

CMSSM TODAY: *Use of indirect constraints only*

CMSSM 2009: *Use of indirect constraints &*
assumed kinematic edge measurements from LHC:

$$\left(m^2_{ll}\right)^{\text{edge}} = \frac{\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

Assume 5% measurement of the edge with leptons only

$$\left(m^2_{qll}\right)^{\text{edge}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{\chi}^0_2}}$$

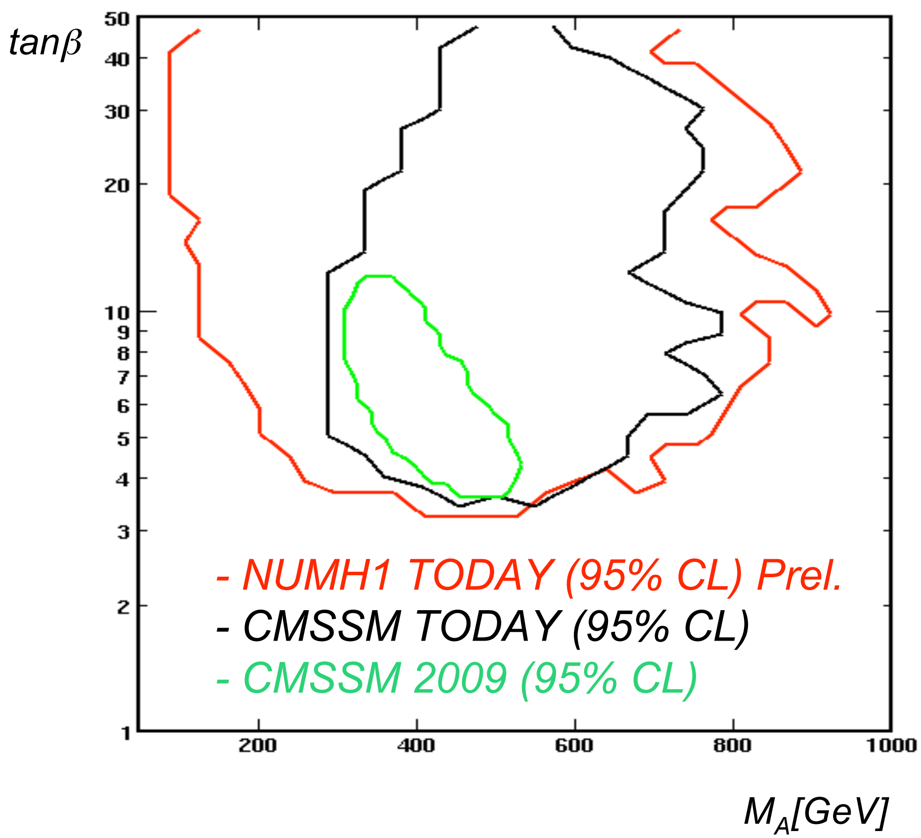
$$\left(m^2_{ql}\right)^{\text{edge}}_{\text{min}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{\chi}^0_2} - m^2_{\tilde{l}_R}\right)}{m^2_{\tilde{\chi}^0_2}}$$

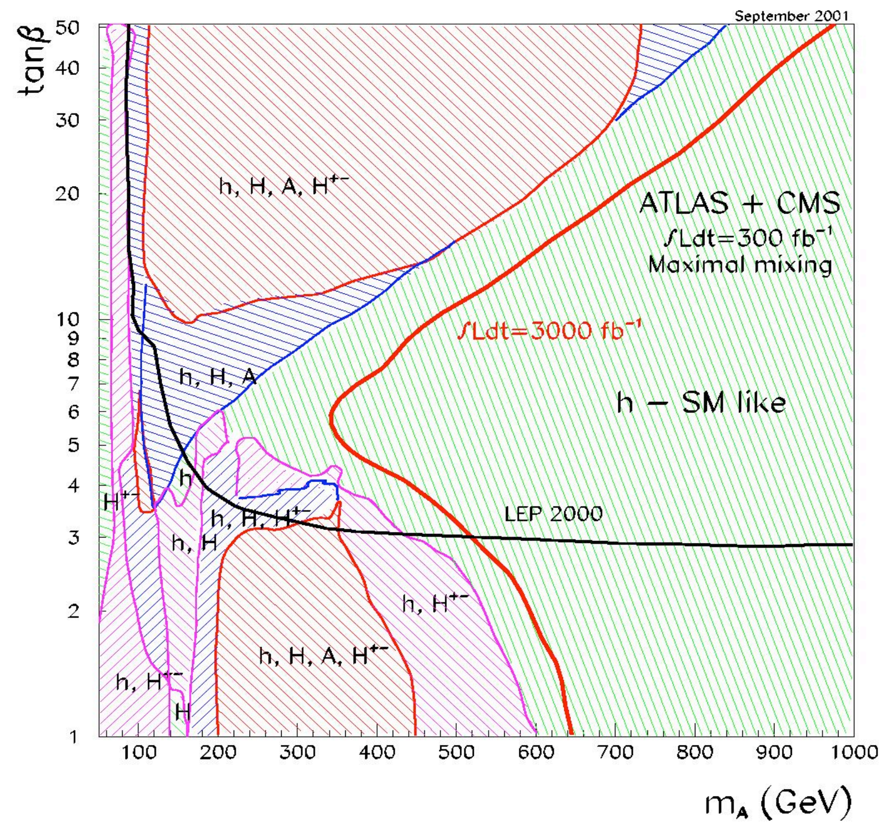
$$\left(m^2_{ql}\right)^{\text{edge}}_{\text{max}} = \frac{\left(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}^0_2}\right)\left(m^2_{\tilde{l}_R} - m^2_{\tilde{\chi}^0_1}\right)}{m^2_{\tilde{l}_R}}$$

Assume 10% measurements of the kinematic Quantities involving jets

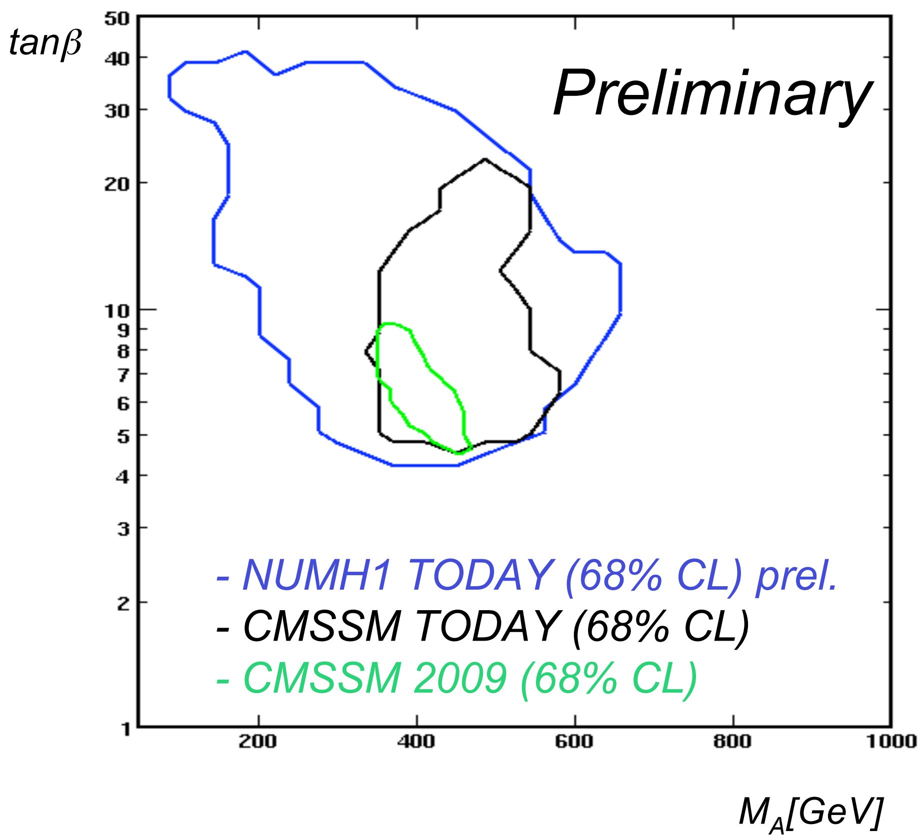
[Conservative uncertainty estimates]

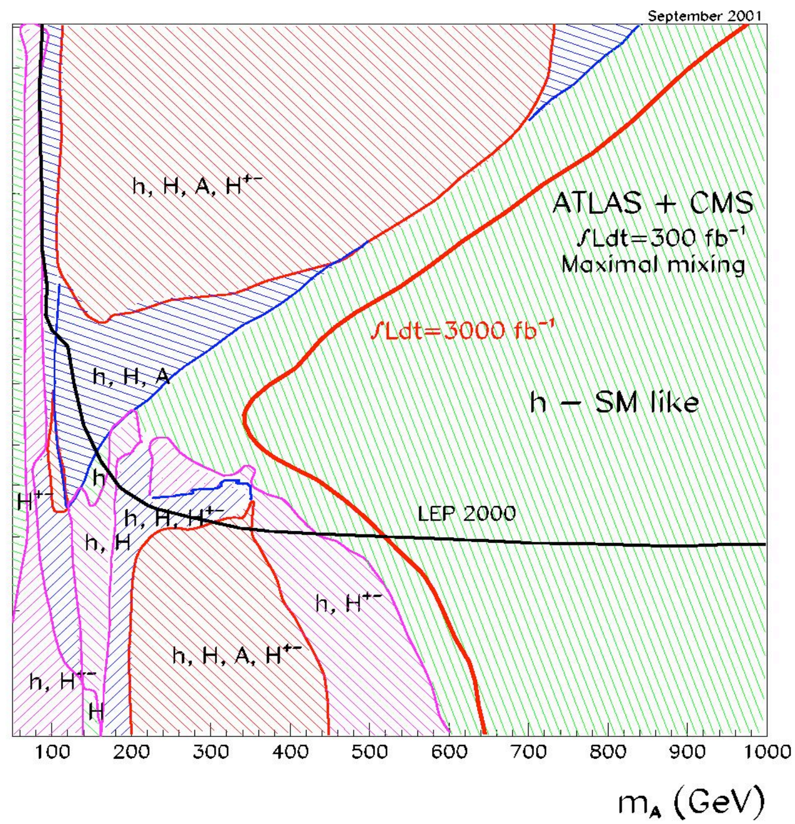
MSSM Higgs -95% CL





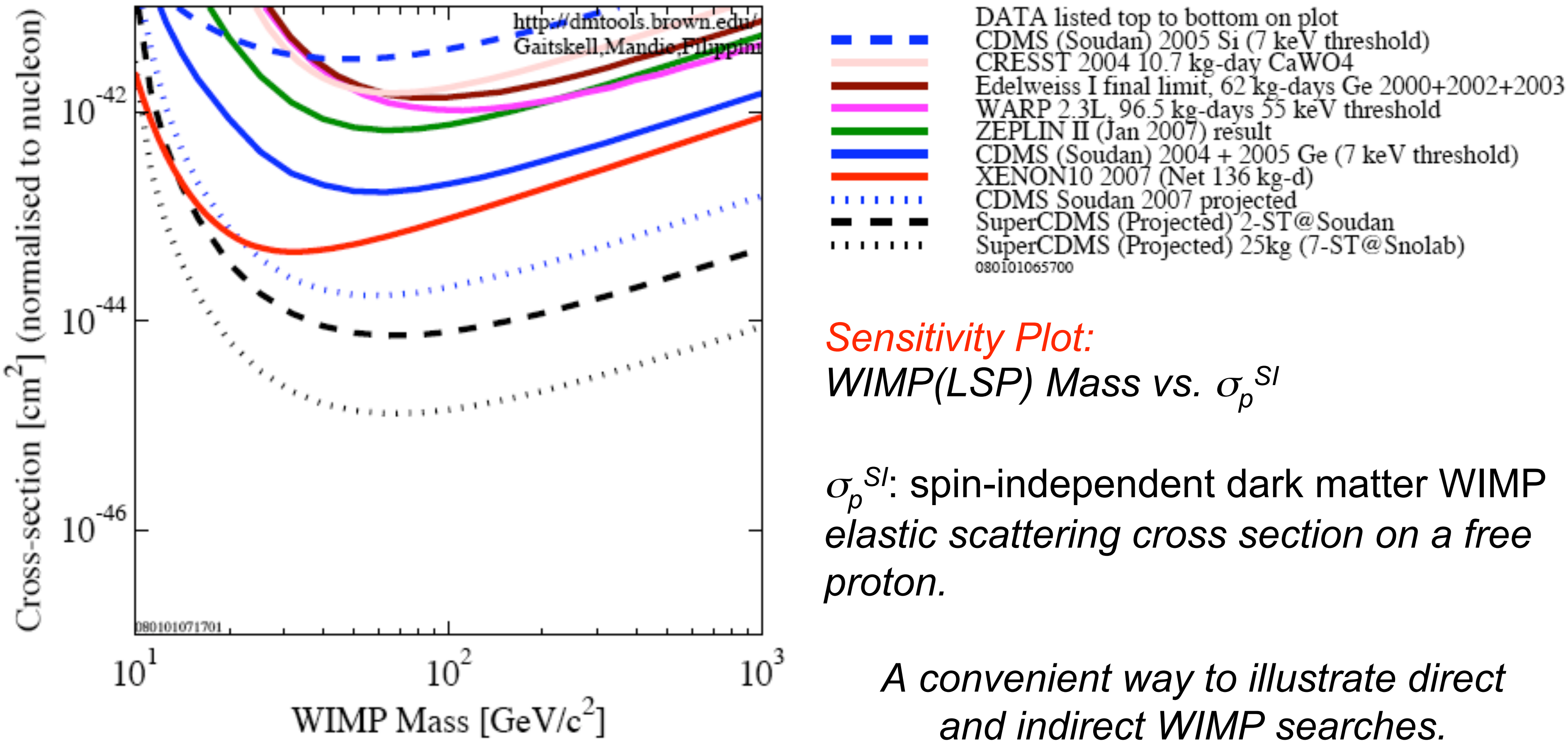
MSSM Higgs - 68% CL





Dark Matter

Direct detection of WIMP (LSP) Dark Matter

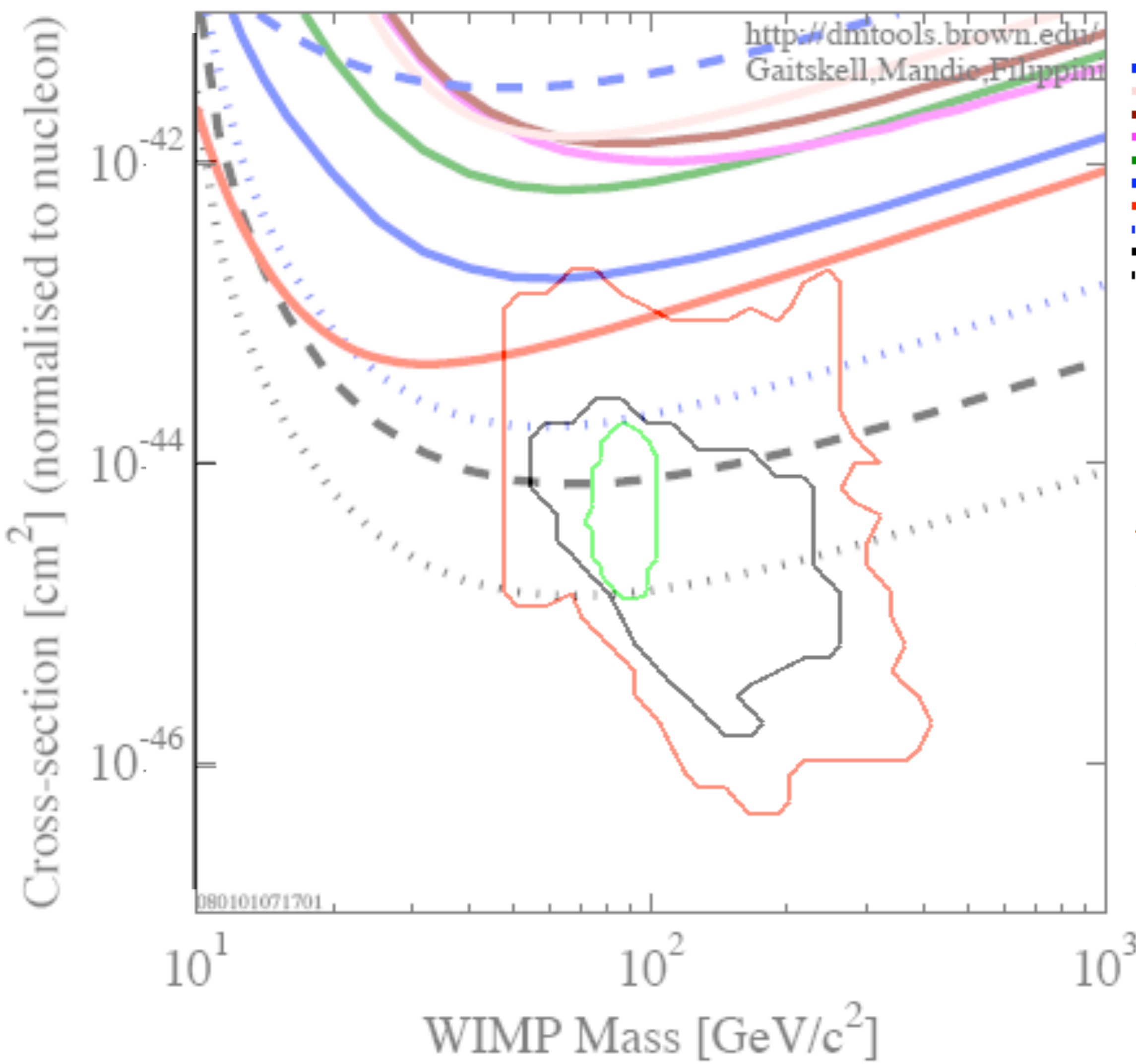


Sensitivity Plot:
WIMP(LSP) Mass vs. σ_p^{SI}

σ_p^{SI}: spin-independent dark matter WIMP *elastic scattering cross section on a free proton.*

A convenient way to illustrate direct and indirect WIMP searches.

WIMP Sensitivity Plot



Contours:

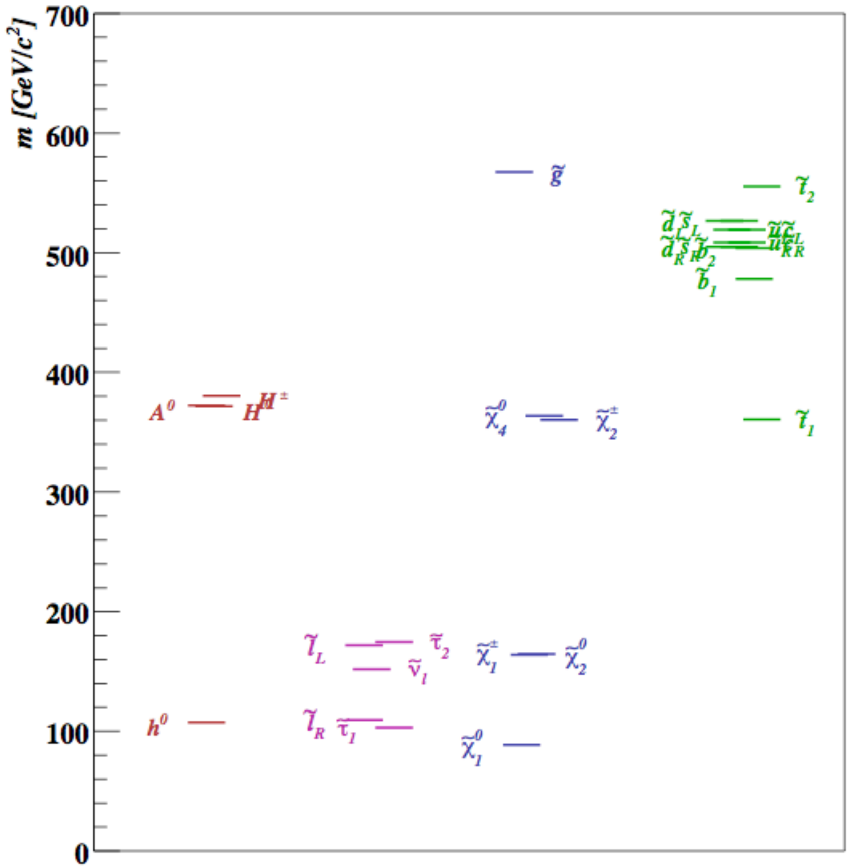
- NUMH1 TODAY (95% CL) prel.

- CMSSM TODAY (95% CL)

- CMSSM 2009 (95% CL)

Spectrum Comparison

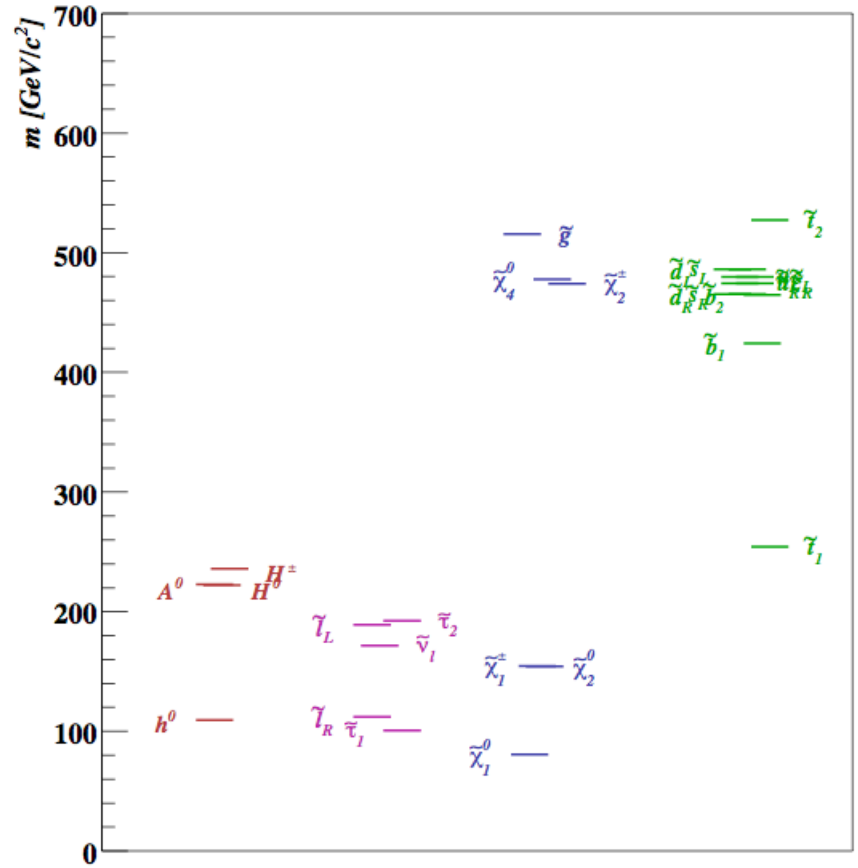
"best CMSSM Fit"



M0	M12	A0	tb
49.2	232.3	-122.4	6.9

MA=372 GeV; mu=336 GeV; mh=111 GeV

"best NUHM Fit"



M0	M12	A0	tb	Mhd^2	Mhu^2
101.9	208.1	-523.1	6.7	-183000	-72300

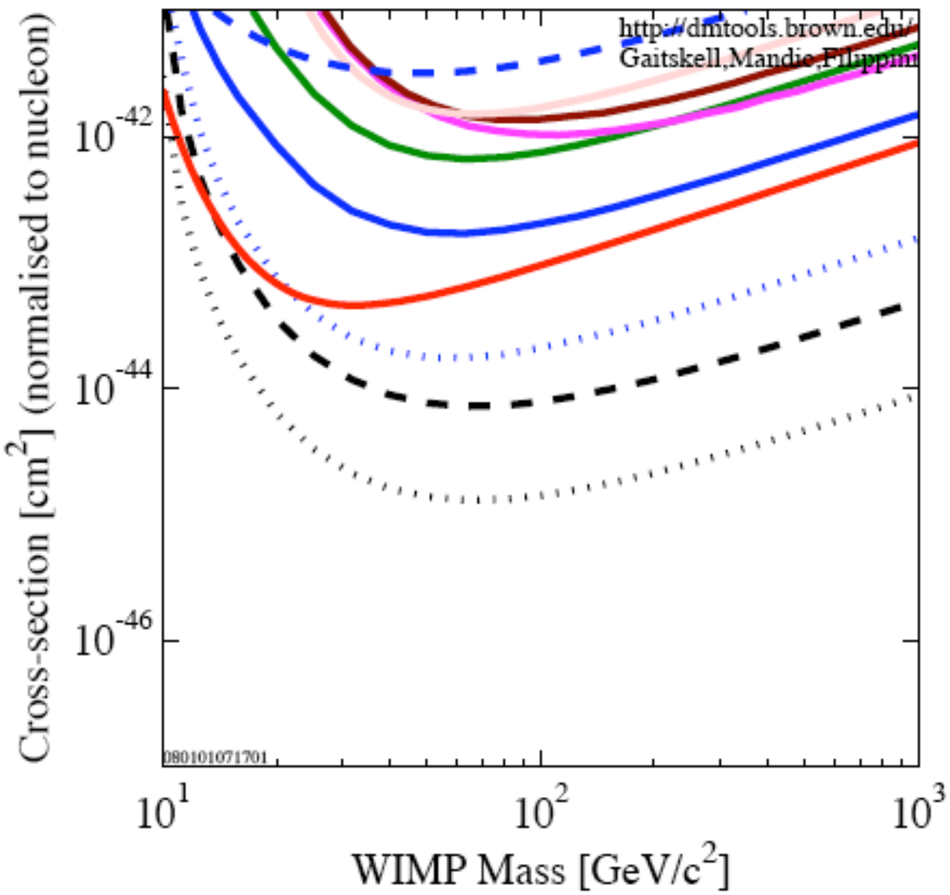
MA=220 GeV; mu=460 GeV; mh=113 GeV

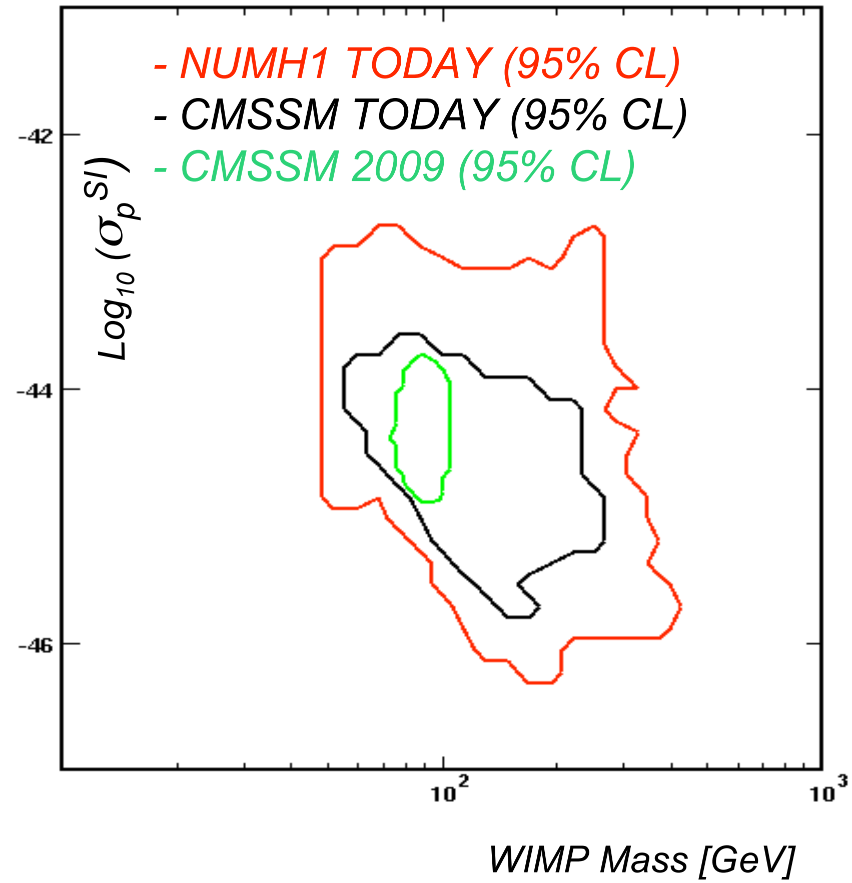
Conclusions

- Modular framework for comparison (~) in place
  - ✓ Allows to study "preference" of new physics phase space
  - ✓ Allows to study consistency between new signals and precision data
  - ✓ Expect to become important for the interpretation of potential discoveries, eg dark matter and heavy Higgs constraints
- Early SUSY discovery@LHC "preferred"
- Higgs perhaps already seen by LEP ☺
- This is an open project. Collaborators welcome
- Next steps could/will include
  - ✓ More systematic study of the individual effect of different variables
  - ✓ More systematic study on the uncertainties (eg. sparticle spectrum)
  - ✓ More general SUSY models
  - ✓ Other than SUSY BSM

Backup

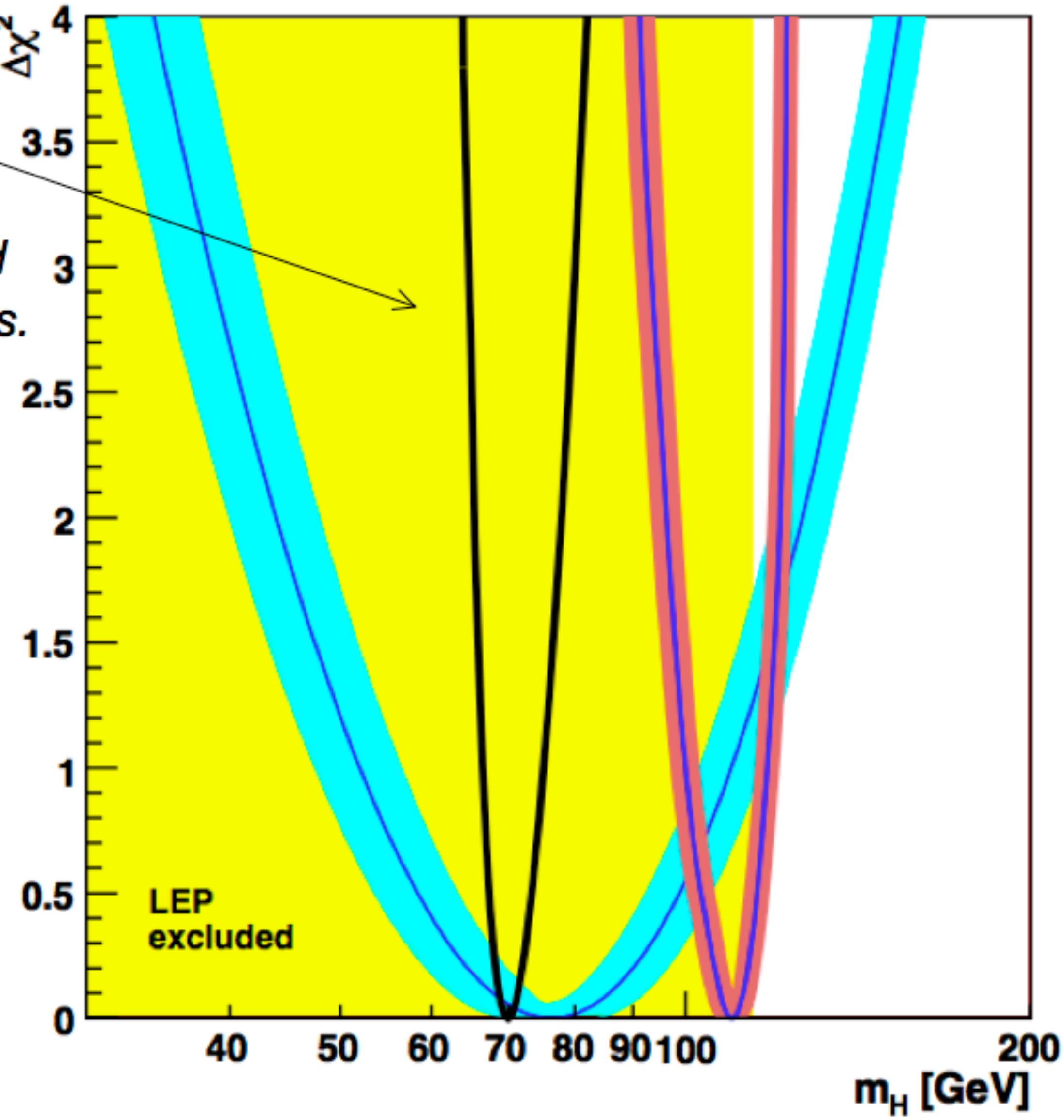
Dark Matter -WIMP(LSP) contours





SM-Like Higgs - Sensitivity

Define "hypothetical scenario" with m_h= 70 GeV (black line). Errors on indirect constraints are kept but constraints a varied to be compatible with hypothesis.



Conclusion:

"narrowness" of the ellipse is NOT a property of a particular scenario but rather determined by the errors of the indirect constraints and the general model properties of the Higgs sector in the CMSSM.

- Multi-parameter χ^2 fit:

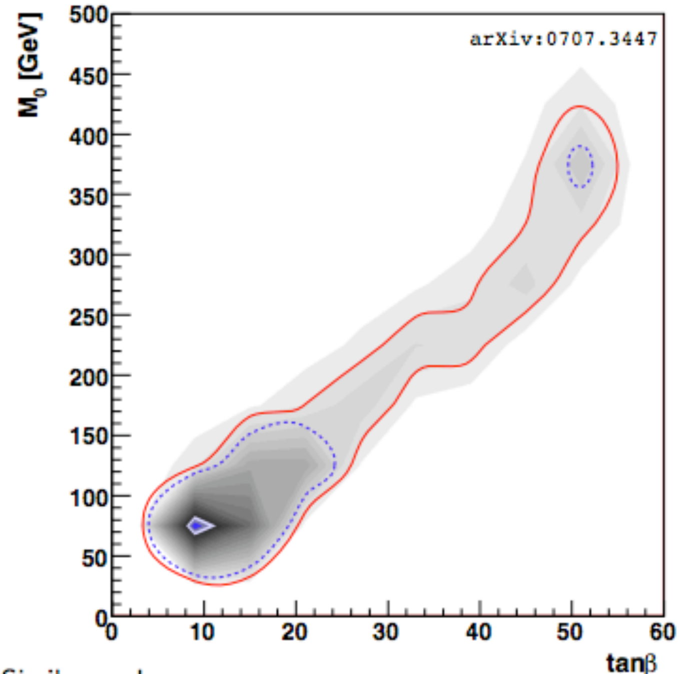
$$\chi^2 = \sum_i^N \frac{(C_i - P_i)^2}{\sigma(C_i)^2 + \sigma(P_i)^2} + \sum_i^M \frac{(f^{\rm obs}_{{\rm SM}_i} - f^{\rm fit}_{{\rm SM}_i})^2}{\sigma(f_{{\rm SM}_i})^2}$$

- fitting for all CMSSM parameters: M_0, $M_{1/2}$, A_0, $\tan\beta$;
- including relevant SM uncertainties (*e.g.* $m_{\rm top}$);

→ details in O. Buchmüller *et al.*, arXiv:0707.3447 [hep-ph]

Natural extension of J. Ellis *et al.*, arXiv:0706.0652 [hep-ph]

From fits on 2000 pseudo-experiments



Similar analyses:

- Ellis, Heinemeyer, Olive, Weber, Weiglein – hep-ph/0706.0652
- Allanach, Cranmer, Lester, Weber – hep-ph/0705.0487
- Trotta, Austri, Roszkowski – hep-ph/0609126

- overall preferred minimum at low $\tan\beta$, low squark mass;
- less preferred region at high $\tan\beta$, higher squark mass;
- consistent with previous studies.

Note: includes limit from LEP

⇒ Turn to fit *without* limit on m_h assessing preferred m_h value in CMSSM

CMSSM

Constrain soft-breaking parameters at the GUT scale

CMSSM - a very constraint model:

– Unification of the gaugino [bino, wino and gluino] masses:

$$M_1(M_{\rm GUT}) = M_2(M_{\rm GUT}) = M_3(M_{\rm GUT}) \equiv m_{1/2}$$

– Universal scalar [i.e. sfermion and Higgs boson] masses [i is the generation index]:

$$\begin{aligned} M_{\tilde{Q}_i}(M_{\rm GUT}) &= M_{\tilde{u}_{Ri}}(M_{\rm GUT}) = M_{\tilde{d}_{Ri}}(M_{\rm GUT}) = M_{\tilde{L}_i}(M_{\rm GUT}) = M_{\tilde{l}_{Ri}}(M_{\rm GUT}) \\ &= M_{H_u}(M_{\rm GUT}) = M_{H_d}(M_{\rm GUT}) \equiv m_0 \end{aligned}$$

– Universal trilinear couplings:

$$A^u_{ij}(M_{\rm GUT}) = A^d_{ij}(M_{\rm GUT}) = A^l_{ij}(M_{\rm GUT}) \equiv A_0\,\delta_{ij}$$

Free Parameters:

m_0 , $m_{1/2}$, A_0 , $\tan\beta$, sign(μ)

All the soft SUSY breaking parameters at the weak scale are obtained through

Renormalization Group Equations (RGE's)

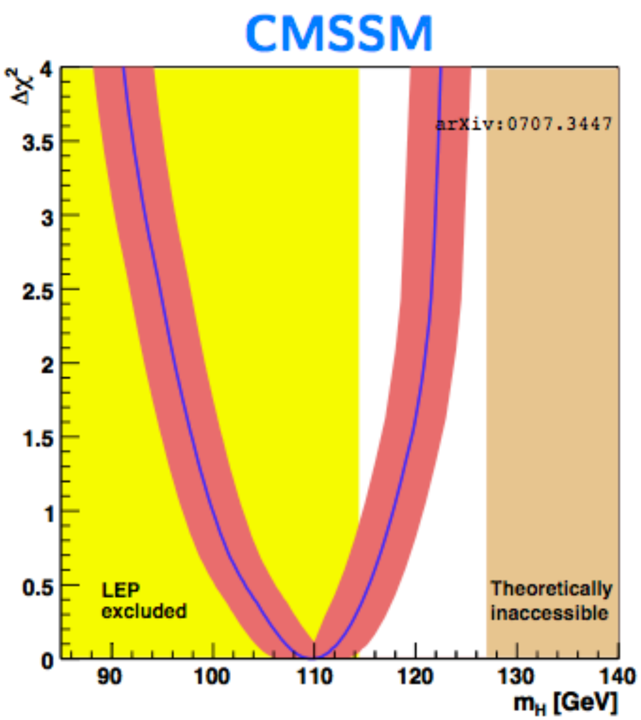
m_0: common scalar mass at GUT

$m_{1/2}$: the common gaugino mass at GUT

$\tan\beta$: $\langle H_U\rangle/\langle H_D\rangle$

A_0: common (scalar)^3 coupling

Sign(μ): Higgs mass term



- Constrain m_h to scan value;
- minimize all model parameters in each point;

$\Rightarrow$ determine error on m_h prediction

SM fit:

- $m_H = 78^{+33}_{-24}$ GeV$/c^2$
- 12% probability at exclusion limit

  Including theoretical uncertainty

CMSSM fit:

- $m_h = 110^{+8}_{-10} \pm 3$ GeV$/c^2$
- 20% probability at exclusion limit

  Including theoretical uncertainty

New list of constraints

Flavour code

$R(b\to s\gamma)$	1.13 ± 0.12
$R(\Delta m_s)$	1.040 ± 0.340
$B_s\to\mu\mu$ [$\times 10^{-8}$]	< 4.7000
$R(B\to\tau\nu)$	1.07 ± 0.42
$R(B_s\to X_s ll)$	0.99 ± 0.32
$R(K\to\tau\nu)$	0.992 ± 0.017
$R(\Delta m_K)$	0.880 ± 0.320
$R(K\to\pi\nu\nu)$	< 4.5
$B(B_d\to ll)$ [$\times 10^{-8}$]	< 2.30
$R(\Delta m_s/\Delta m_d)$	1.00 ± 0.08

FeynHiggs	Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87
MicrOMEGAs	Ωh^2	0.113 ± 0.009

SUSY-POPE

$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035
m_Z [GeV]	91.1875 ± 0.0021
Γ_Z [GeV]	2.4952 ± 0.0023
σ^0_{had} [nb]	41.540 ± 0.037
R_l	20.767 ± 0.025
$A^{0,l}_{fb}$	0.01714 ± 0.00095
$A_l(P_\tau)$	0.1465 ± 0.0032
R_b	0.21629 ± 0.00066
R_c	0.172 ± 0.003
$A^{0,b}_{fb}$	0.0992 ± 0.0016
$A^{0,c}_{fb}$	0.0707 ± 0.0035
A_b	0.923 ± 0.020
A_c	0.670 ± 0.027
$A_l(SLD)$	0.1513 ± 0.0021
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012
m_W [GeV]	80.398 ± 0.025
m_t [GeV]	170.9 ± 1.8

+ m_h >(115±1.1±3) GeV from FeynHiggs