The Status of Constrained SUSY, and implications from the Higgs

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FITTINO
SUSY

May 20th 2013

universitätbonn

1 Introduction and Inputs

2 HiggsSignals

3 Preliminary Results

We found something spectacular . . .

But it would be even more spectacular if it was part of something else!

- The MSSM is very hard to test against data – a lot of freedom
- Strategy: make SUSY as constrained as possible, and see if it still works. Only revert to more complex models if required.

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- The MSSM is very hard to test against data – a lot of freedom
- Strategy: make SUSY as constrained as possible, and see if it still works. Only revert to more complex models if required.
- Try to be as precise as possible in the implementation of each experimental constraint
- Does the non-observation of SUSY in the 2011 (and 2012?) LHC searches agree with the CMSSM and the NUHM1/2?
- Does the observabtion of a Higgs particle at $m_h \approx 125.5\,\text{GeV}$ agree with the CMSSM and the NUHM1/2?
- What are the implications for measuring the Higgs more precisely, discovering new particles and for future colliders?
- latest published results in `JHEP 06, 098 (2012) - arXiv:1204.4199`
- Many preliminary updates presented here

Fittino

C++ program for SUSY model testing and SUSY parameter analysis

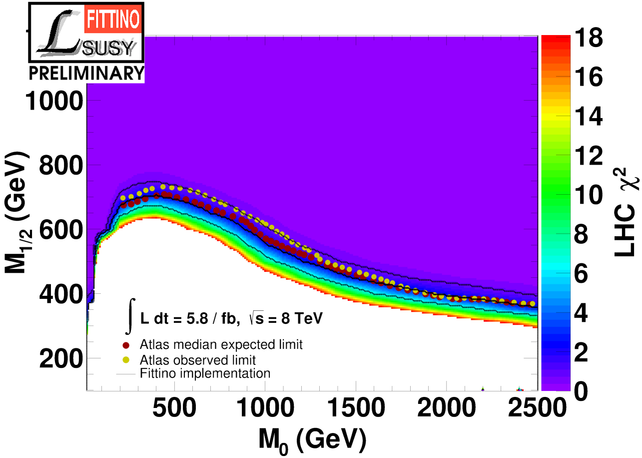
- Currently supported SUSY models:
  CMSSM, GMSB, AMSB, MSSM24, NMSSM, NUHM1, NUHM2
- Measurements from Higgs searches, low/high energy experiments, direct SUSY searches, LEP/SLC, Tevatron, cosmology, LHC and LC, $(g-2)_\mu$, B, K, ...
- Use public theory codes:
  SPheno, SuperIso, Micromegas, FeynHiggs, HDecay
- Parameter analysis using Auto-adaptive Markov Chain Monte Carlo (MCMC)
- Previous publications:
  arXiv:0412012[hep-ph], arXiv:0511006[hep-ph],
  arXiv:0907.2589[hep-ph] arXiv:0909.1820[hep-ph],
  arXiv:1105.5398[hep-ph], arXiv:1102.4693[hep-ph],
  arXiv:1204.4199[hep-ph]

Inputs

$\mathcal{B}(b \to s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$
$\mathcal{B}(B_s \to \mu\mu)$	$(3.2 \pm 1.5 \pm 0.76) \times 10^{-9}$
$\mathcal{B}(B \to \tau\nu)$	$(0.72 \pm 0.25 \pm 0.11 \pm 0.07) \times 10^{-4}$
Δm_{B_s}	$17.719 \pm 0.043 \pm 4.2\,\mathrm{ps}^{-1}$
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$(28.7 \pm 8.2) \times 10^{-10}$
m_W	$(80.385 \pm 0.015 \pm 0.010)$ GeV
$\sin^2\theta_{\mathrm{eff}}$	0.23113 ± 0.00021
$\Omega_{\mathrm{CDM}} h^2$	$0.1187 \pm 0.0017 \pm 0.0119$
m_t	(173.2 ± 1.34) GeV

- Higgs Signals via `HiggsSignals-1.0`
- Higgs Limits via `HiggsBounds 3.2`
- LEP chargino limit
- LHC exclusion from $\mathcal{L}^{int} = 5.8\,\mathrm{fb}^{-1}$
- Direct and Indirect Detection of DM via AstroFit (`Nguyen, Horns, Bringmann: ''AstroFit: An Interface Program for Exploring Complementarity in Dark Matter Research''`)

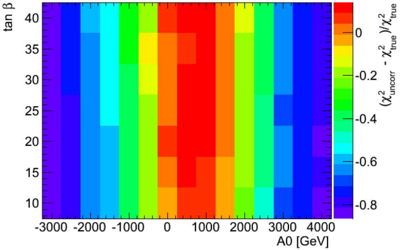
The LHC SUSY searches



- Full re-implementation of ATLAS-CONF-2012-109 $\mathcal{L} = 5.8\,\mathrm{fb}^{-1}$ @ 7 TeV
- Using `Herwig++`, `Prospino`, `Delphes` and profile likelihood limit
- Update to ATLAS-CONF-2013-047 $\mathcal{L} = 20\,\mathrm{fb}^{-1}$ @ 8 TeV to follow soon

The LHC SUSY searches – Details

- Parametrizing the LHC search results just in $M_0, M_{1/2}$ works perfectly for low M_0 in the CMSSM/NUHM
- At large M_0: Correction necessary for increased importance of $\tilde{t}$ production at different $\tan\beta, A_0$



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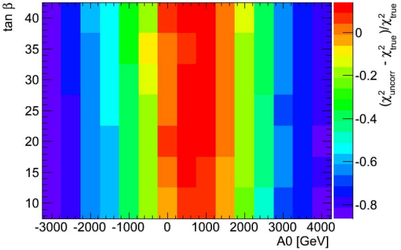
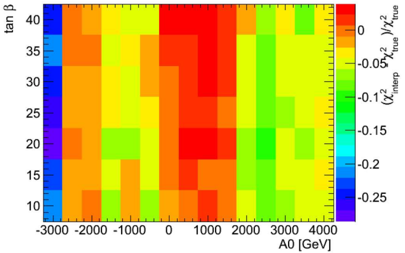
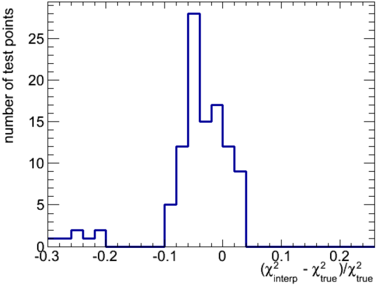


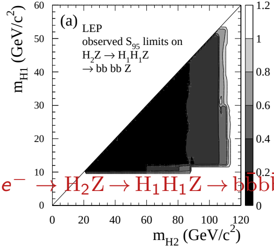




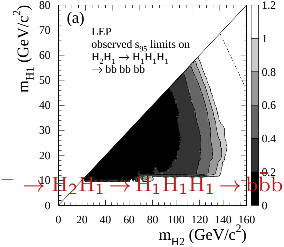
- In the entire interesting range: Deviations below 10 %

Limits from Higgs Searches in Arbitrary Models

- HiggsBounds project arXiv:0811.4169 [hep-ph], arXiv:1102.1898 [hep-ph]
- Use the model independent results from LEP/TeV/LHC statistically correctly interpreted in arbitrary models (but NOT combined)



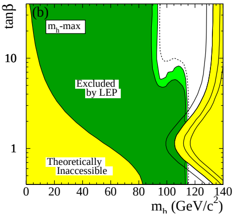
$e^+e^- \to H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}Z$

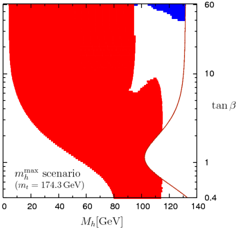


$e^+e^- \to H_2H_1 \to H_1H_1H_1 \to b\bar{b}b\bar{b}b\bar{b}$

Have to add a third dimension to these plots

Test using the MSSM:





HiggsSignals

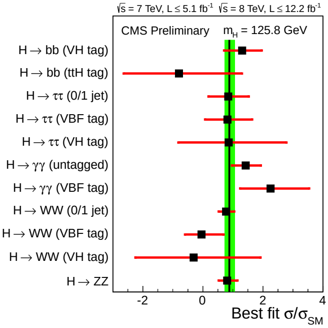
The program HiggsSignals
(PB,S. Heinemeyer,O. Stal,T. Stefaniak,G. Weiglein, arXiv:1305.1933)

- evaluates the total χ^2 for both the signal strengths and/or the mass measurements,
- featuring two distinct χ^2 methods (peak- and mass-centered),
- includes correlations among the major systematic uncertainties (cross sections, branching ratios, luminosity, theory mass uncertainty),
- includes many more features:
  - It finds best assignment of Higgs bosons to the signal and automatically combines signal rates of Higgses overlapping within mass resolution,
  - Framework to include signal efficiencies,
  - New (even hypothetical) signals can be implemented by the user,
  - Toy measurements can be given to existing observables for statistical studies,
  - Signal rate uncertainties can be scaled for future projections,
  - ...

HiggsSignals is a stand-alone program using the HiggsBounds libraries. Coding language is `Fortran90/2003`.

Peak-centered χ^2 method

- Tests agreement between model and data at the observed mass.
- Define observables by the best-fit signal strength, $\hat{\mu}_i$, at a hypothetical Higgs mass $\hat{m}_i$.
- The total χ^2 consists of a signal strength and a Higgs mass part,

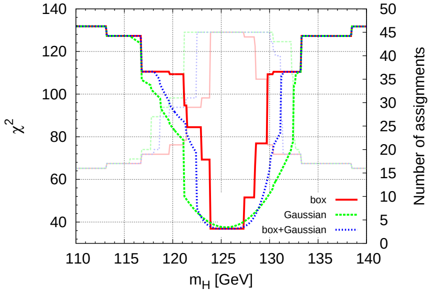


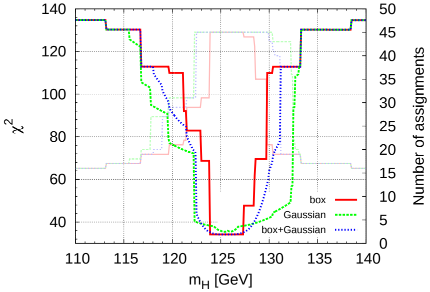
$$\chi^2_{total} = \chi^2_{\mu} + \sum_{assigned\ \ Higgses\ \ i} \chi^2_{m_i}$$

- Only analyses with a good mass measurement enter $\chi^2_{m_i}$ $(H \to \gamma\gamma, ZZ)$
- Can be evaluated at different $\hat{m}_i$ for each measurement
- Assign carefully chosen penalties if predicted Higgs m_i is too far off from $\hat{m}_i$

Good method to get a global picture on Higgs coupling properties.

Example: Simple SM scan in m_h

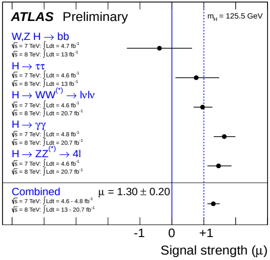


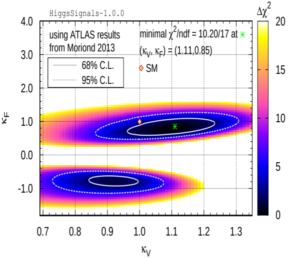


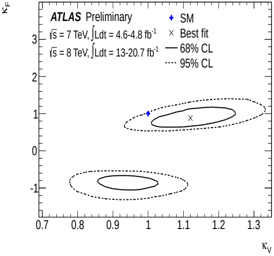
- Penalties cause flat lines for bad mass fit
- Assignment width can be chosen by the user dependent on model requirements

Test using ATLAS and κ_F, κ_V

- Test simple 2D effective coupling benchmark models, proposed in LHC Higgs Cross Section Working Group, Sep.12, [1209.0040]
- Scale fermion couplings by κ_F and vector boson couplings by κ_V
- non-trivial scaling of loop-induced $H\gamma\gamma$ coupling.
- loop-induced Hgg coupling scales with κ_F (effectively a fermion loop).
- No special treatment of negative μ_i



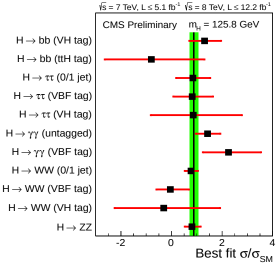


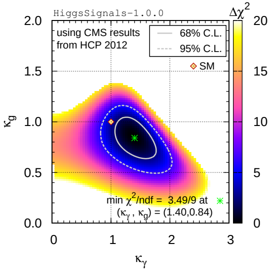


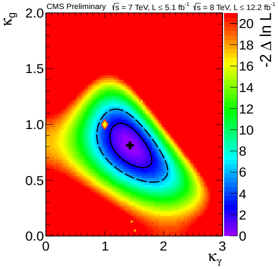
ATL-CONF-2013-034

Test using CMS and κ_g, κ_γ

- Test simple 2D effective coupling benchmark models, proposed in LHC Higgs Cross Section Working Group, Sep.12, [1209.0040]
- scale loop-induced gluon couplings by κ_g and photon couplings by κ_γ. (keep tree-level couplings at their SM value)
- probing new physics contributions to loop-induced couplings.
- No special treatment of negative μ_i

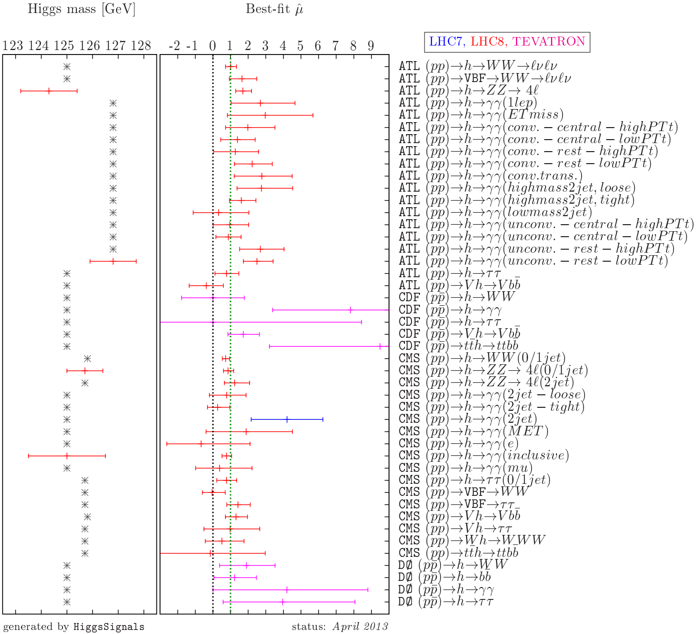




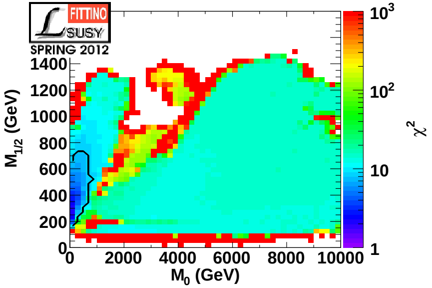


CMS-PAS-HIG-12-045

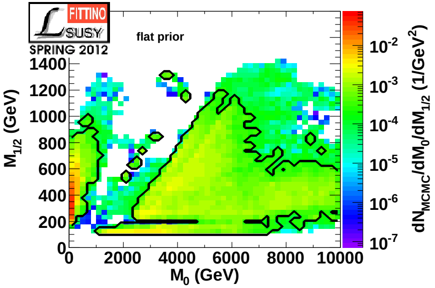
Full available dataset (Moriond 2013)



Statistics



Frequentist Profile Likelihood



Bayesian, Flat prior

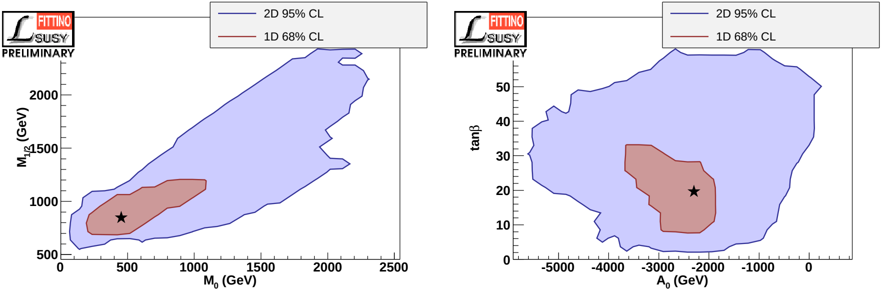
- Advanced MCMC scans with automatically adapting proposal density width
- Huge difference between different statistical philosophies
- Frequentist interpretation chosen for the rest of the plots

Statistics

	CMSSM	NUHM1 (additional points)	NUHM2 (additional points)
different points	572 540 703	413 799 435	329 626 234
$\chi^2 < 1000$	230 348 923	138 306 670	91 491 372

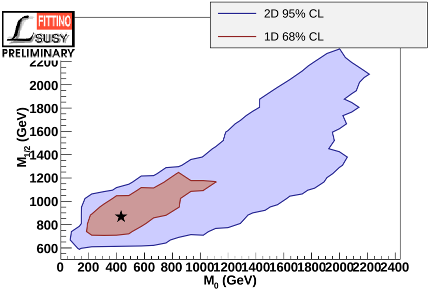
- Unprecedented sampling density
- Make the more constrained models trivial sub-samples of the more complex ones ($M_0^2 = M_{0,H}^2$)
- Sampling is still growing . . .

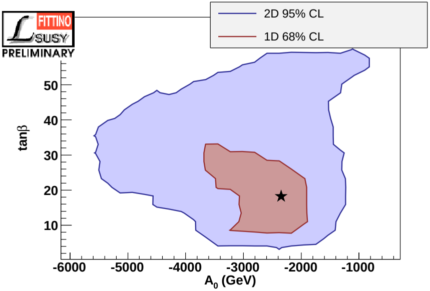
Allowed Parameter Range: CMSSM, $\Delta m_{h,theo} = 3\,\mathbf{GeV}$



- Focus point region excluded by detailed Higgs measurements
- Minimum just above present ATLAS/CMS SUSY exclusion from inclusive searches
- Region with significant $\tilde{t}$ production strongly disfavoured by the fit

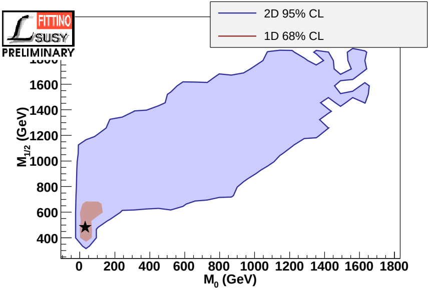
Allowed Parameter Range: CMSSM, $\Delta m_{h,theo} = 1.5\,\mathbf{GeV}$

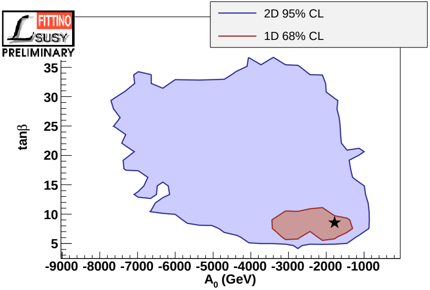




- Theoretical mass uncertainty on m_h is not (yet?) dominant

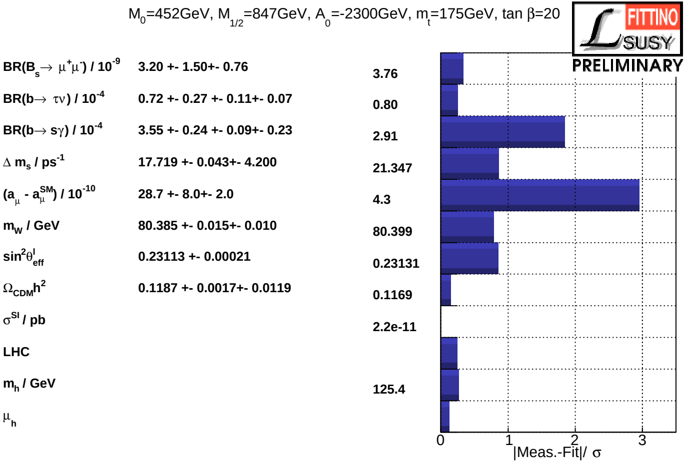
Allowed Parameter Range: NUHM1, $\Delta m_{h,theo} = 3\,\mathbf{GeV}$





- NUHM1 has significantly lower total χ^2, but similar behaviour at large $M_0, M_{1/2}$
- Hence lower upper bound on $M_0, M_{1/2}$
- Likes to squeeze in the unexcluded region at very low M_0 (typically not shown explicitely on ATLAS/CMS plots)

The pull of the individual observables



- Divided $\chi^2_{\mu_h}$ by 44, $\chi^2_{m_h}$ by 4 just for this plot
- Still $(g-2)_\mu$ biggest culprit.
- CMSSM is mostly really SM plus Dark Matter here!

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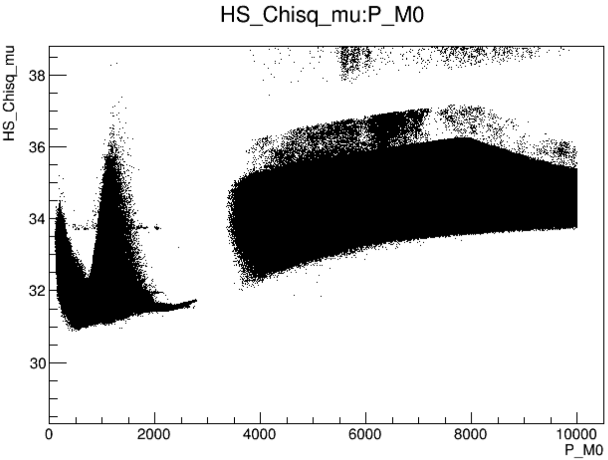

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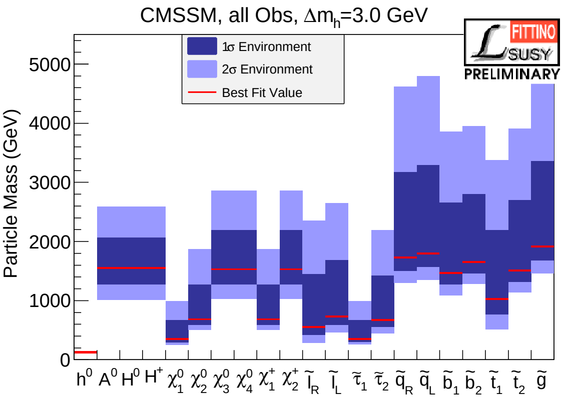
Predicted Mass Spectra



- Very interesting:
  Still a bit of room for light sleptons/gauginos for the ILC
- But also a lot of room for very heavy ones!

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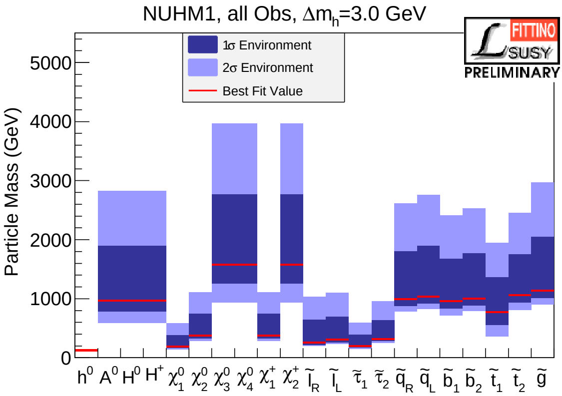

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Numerical Results on Parameters

main results for the CMSSM (first (second) row: $\Delta m_{h,theo} = 3(1.5)$ GeV):

$\tan\beta$	$M_{1/2}(GeV)$	$M_0(GeV)$	$A_0(GeV)$	$m_t(GeV)$	χ^2_{min}
$19.6^{+12.8}_{-12.1}$	$846.6^{+359.0}_{-139.4}$	$452.3^{+626.3}_{-227.3}$	$-2300.0^{+381.7}_{-1435.0}$	$175.2^{+1.6}_{-2.3}$	47.9
$18.2^{+14.0}_{-10.8}$	$867.4^{+338.2}_{-162.2}$	$431.8^{+646.8}_{-229.5}$	$-2346.1^{+371.3}_{-1378.7}$	$175.0^{+1.9}_{-2.0}$	48.0

which is a very good fit – there are 56 d.o.f., counting all 61 constraints and measurements, and 5 parameters.

And now for the NUHM1:

$\tan\beta$	$M_{1/2}(GeV)$	$M_0(GeV)$	$A_0(GeV)$	$m_t(GeV)$	$M^2_{0,H}(GeV)$	χ^2_{min}
$8.5^{+2.4}_{-2.6}$	$481.6^{+193.0}_{-100.2}$	$30.8^{+93.0}_{-10.0}$	$-1779.6^{+441.3}_{-1555.5}$	$176.8^{+1.4}_{-3.3}$	$-1604233.9^{+638171.9}_{-3353164.6}$	43.4
$8.8^{+2.7}_{-1.1}$	$616.2^{+118.9}_{-170.6}$	$77.6^{+88.8}_{-56.9}$	$-2806.5^{+932.1}_{-558.9}$	$175.9^{+1.9}_{-0.5}$	$-3926122.5^{+2805259.8}_{-894021.0}$	44.1

So what is the fit quality?

Putting a real number on fit probabilities

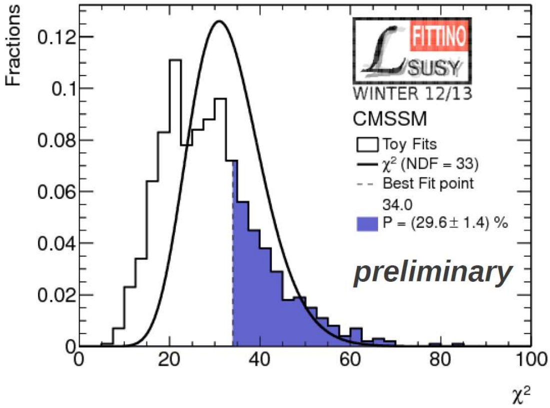
What is the p-value?

Assuming the best fit point found is the real one,
if measurements are repeated,
how often do you get agreement at least as bad as the one observed?

Computation of the p-value of the best fit point with toys:

- Take the observable values at the best fit point
- Smear the observables values
- Calculate the χ^2 for these new pseudo-measurements
- Spot the new best fit point
- Repeat that procedure many times
- Integrate the distribution for $\chi^2 \geq \chi^2$(best fit point)

First Glimpse of real Frequentist $\mathcal{P}$-values



- Preliminary HS version – thus less observables
- Tentative results: Naive $\mathcal{P}$-value

$$\mathcal{P}_{\chi 2-dist} = 41\,\%$$

overestimates goodness of fit!

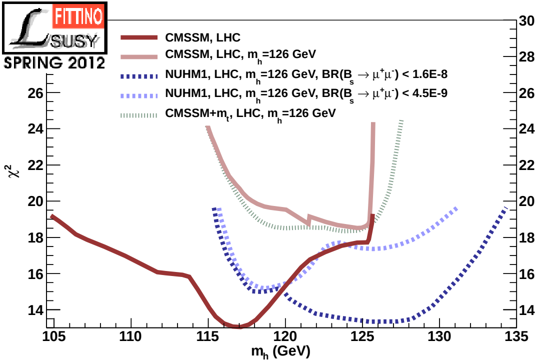
- This is not unexpected – the naive $\mathcal{P}$-value relies on the assumption that all $O_i(P_j)$ are linear around the minimum. Definitely not true here.
- Also, not all constraints are gaussian.
- Computationally extremely expensive!
- Very promising, should be further explored

Conclusions

- Extremely high statistics scan of the CMSSM and NUHM1 parameter space, including leading parametric uncertainty from m_t
- Special care taken to include Higgs measurements properly via HiggsSignals and on LHC SUSY limits.
- CMSSM and NUHM1 are both capable to describe given data
- Have to go to SM like region of parameter space. However still room for small but detectable deviations from SM $\rightarrow$
- Currently also testing combined sets of measurements from the Higgs sector (useful if careful about "$\mathcal{P}$-value dilution")
- Detailed predictions of Higgs rate measurements and couplings underway
- Fully Frequentist $\mathcal{P}$ values for the up-to-date data set to come soon

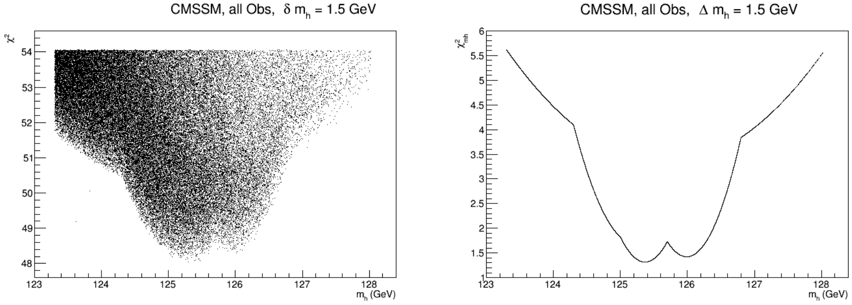
Backup Slides

Historical Comparison: How easy is it to accomodate $m_h = 125\,\text{GeV}$?



- $m_h \approx 125\,\text{GeV}$ is possible but not preferred in the CMSSM
- NUHM1 has much less pressure than CMSSM, but not much more convincing χ^2/ndf

Present m_h profiles



- Using actual measurements: clearer minimum around $m_h \approx 125.5$ GeV
- Preliminary χ^2 profils showing the point density at the highest achievable m_h
- Double-peak structure stems from effects of the systematic mass uncertainty
- Let's see fit probabilities in much more detail later