GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

TECHNISCHE UNIVERSITÄT DRESDEN

Constraining SUSY after two years of LHC data: a global view with Fittino

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Searching for SUSY at the TeV scale … and ?

2011: long LHC run, center-of-mass energy 7 TeV, luminosity ~5/fb.

- Direct step into Terascale
- No significant excess seen

https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/SUSY-2011-19/

- **CMSSM/NUHM1 parameter space still allowed ?**
- **Tension between LHC and pre-LHC ?**
- **Impact of light SUSY Higgs of 126 GeV ?**
- **Impact of direct & indirect search for dark matter ?**
- **Interpretation in (non-)minimal models?**

FITTINO

- C++ program for **SUSY model testing and SUSY parameter analysis**
- Currently supported SUSY models:
  CMSSM, GMSB, AMSB, MSSM24, NMSSM (E6SSM coming)
- Measurements from low/high energy experiments,
  LEP/SLC, Tevatron, cosmology, LHC and LC, $(g\text{-}2)_{\mu}$, B, K...
- Parameter analysis using full correlation information:
  Auto-adaptive Markov Chain Monte Carlo (MCMC)
- Proof of principle with SPS1a': **http://arxiv.org/abs/0907.2589v1**

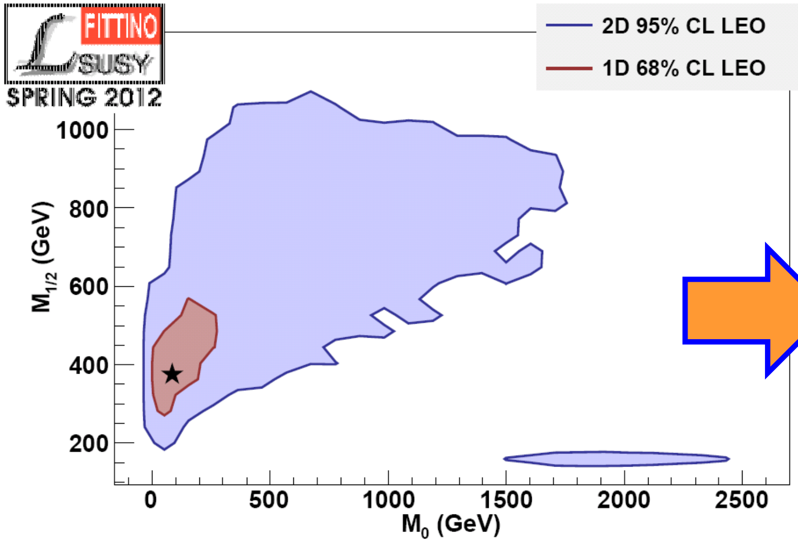
Study of a Constrained SUSY Model

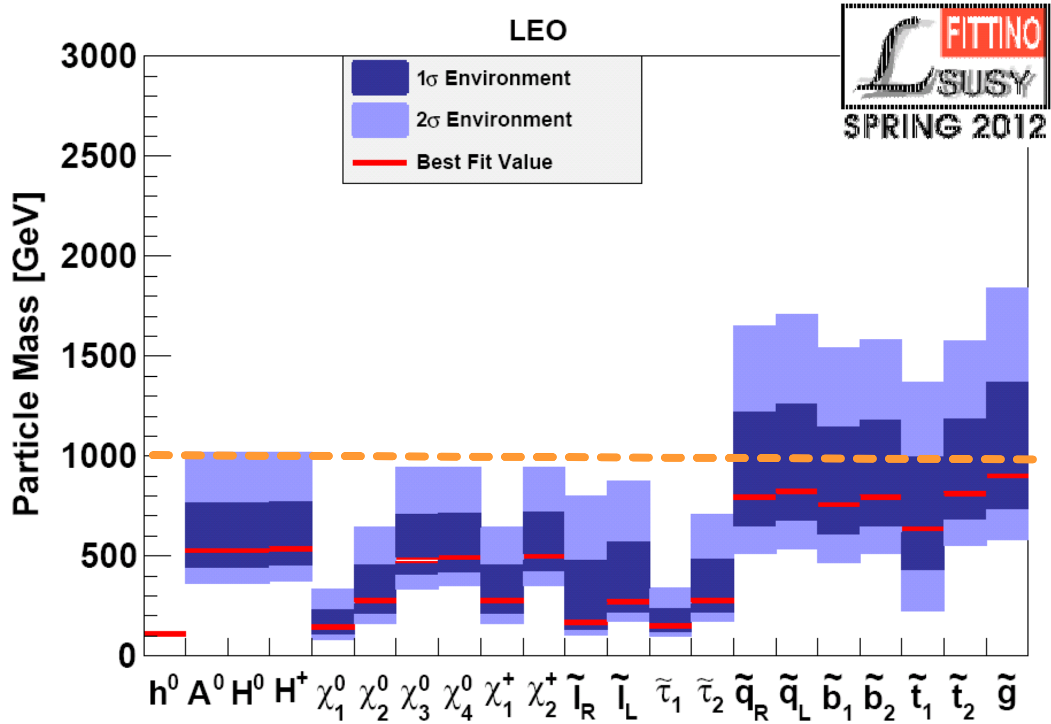
- General SUSY model > 120 parameters
  Current data insufficient
  Restrict to constrained model: **CMSSM**

-

$\tan\beta$	(ratio of Higgs VEVs)
A_0	(common trilinear coupling parameter)
$M_{1/2}$	(common gaugino mass parameter)
M_0	(common scalar mass parameter)
sign(μ)	(sign of Higgsino mass parameter)

Fit of CMSSM with Low Energy Observables





Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	$\tan\beta$	A_0	χ^2/ndf
LEO	$84.4^{+144.6}_{-28.1}$	$375.4^{+174.5}_{-87.5}$	$14.9^{+16.5}_{-7.2}$	$186.3^{+831.4}_{-843.7}$	$10.3/8$

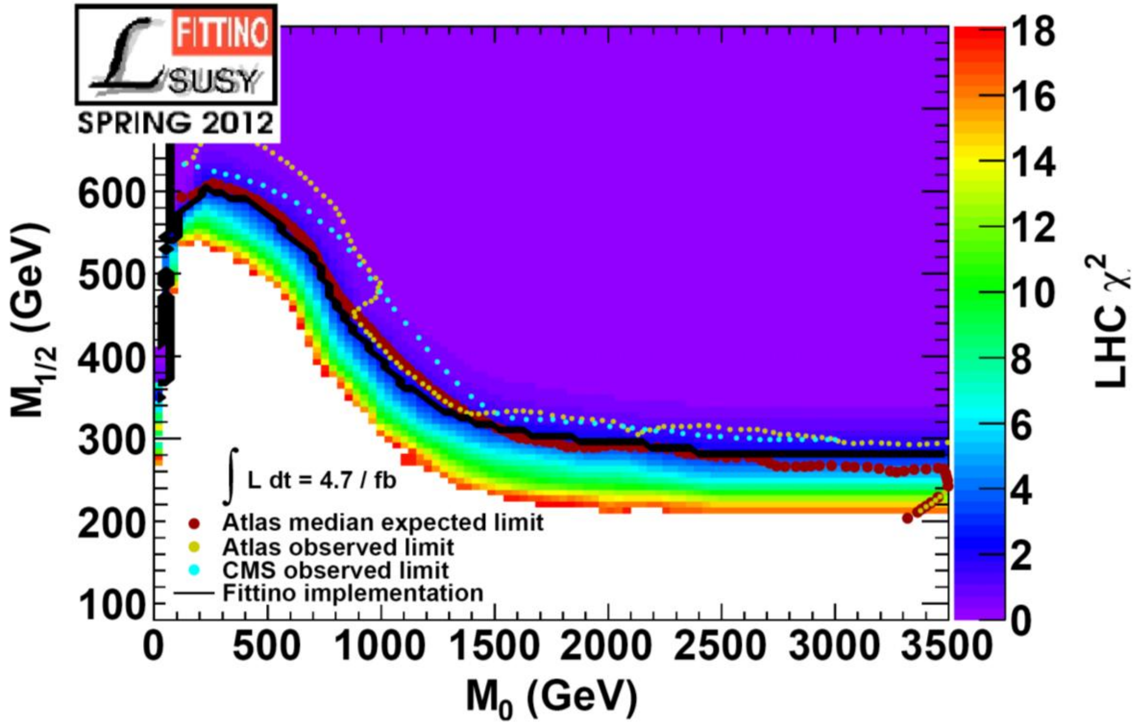
Light sparticles < 1 TeV, but large uncertainties

Including the LHC Constraints

- **Repeat 0 lepton ATLAS data analysis: grid in (M_0, $M_{1/2}$), A_0=0, Tanβ=10**

ATL-PHYS-PUB-2010-010

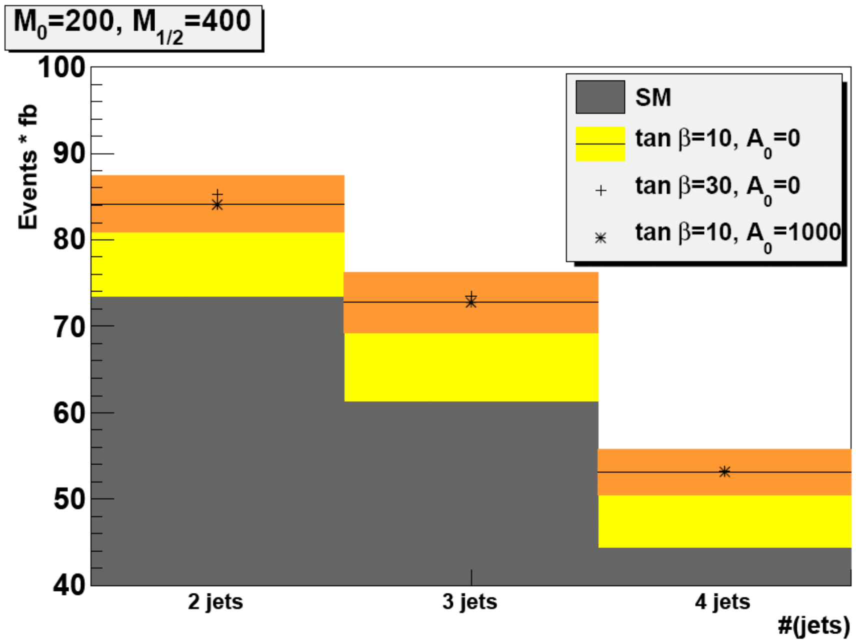
SPheno (spectrum)
↓
Herwig (MC generator)
↓
NLO+NLL k-factors
↓
Delphes (detector FastSim)
↓
Efficiencies correction
↓
ATLAS selections
↓
Background from ATLAS
↓
Statistical test → CL_{s+b}, $\chi 2$

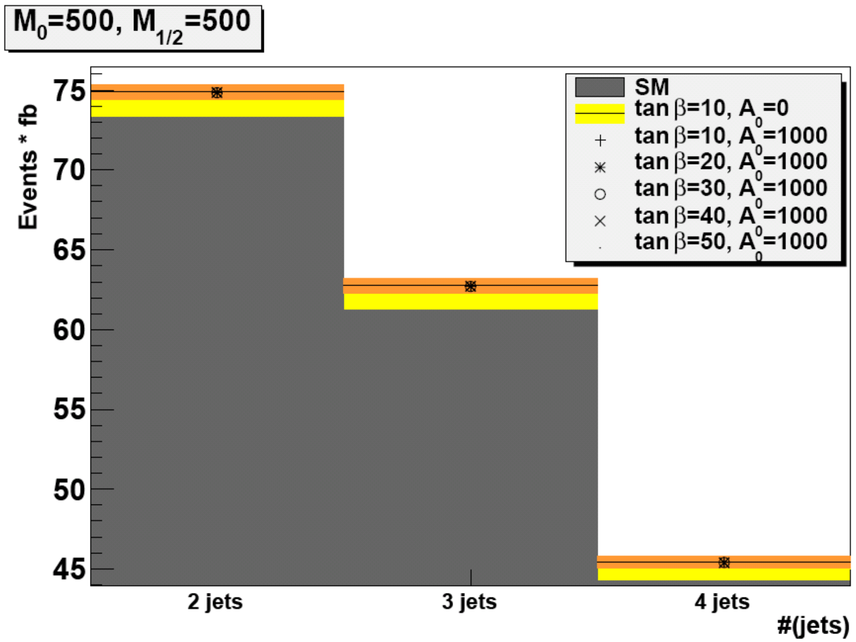


Very good agreement with ATLAS exclusion contour

Including the LHC Constraints

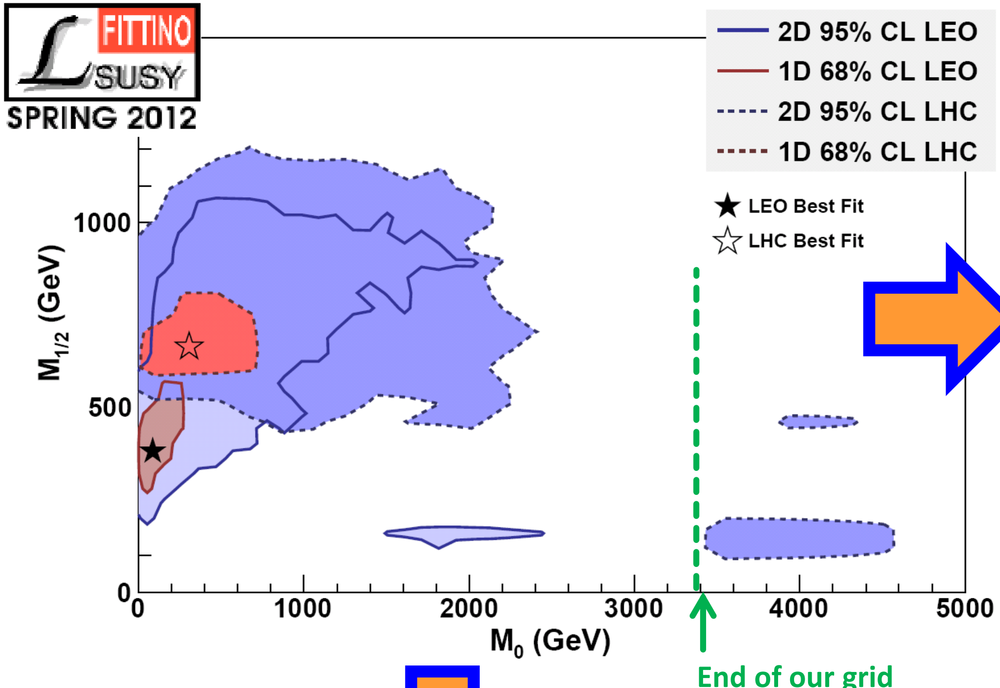
Testing the hypothesis of fixing A_0, $\tan\beta$...

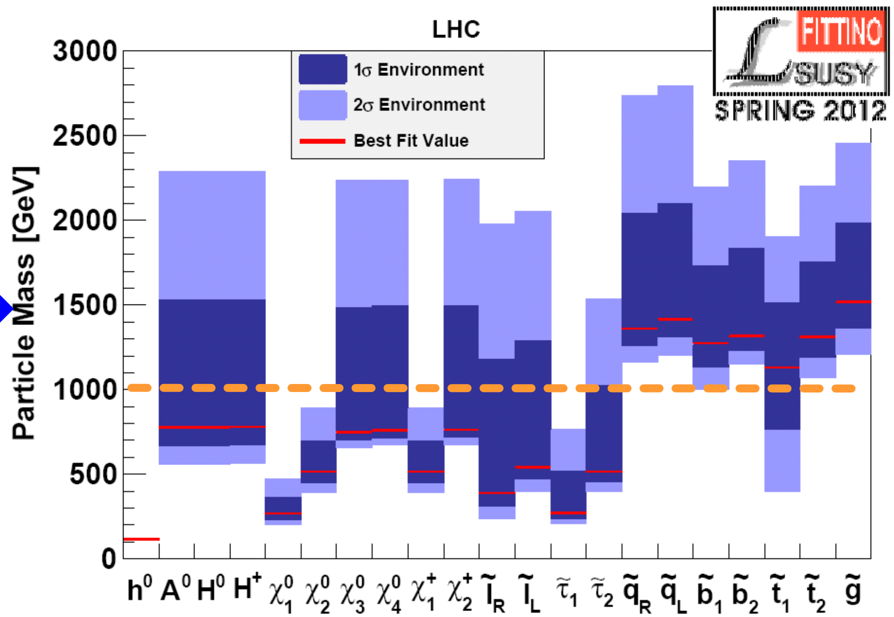




Sensitivity apparently negligible

Including the LHC Constraints





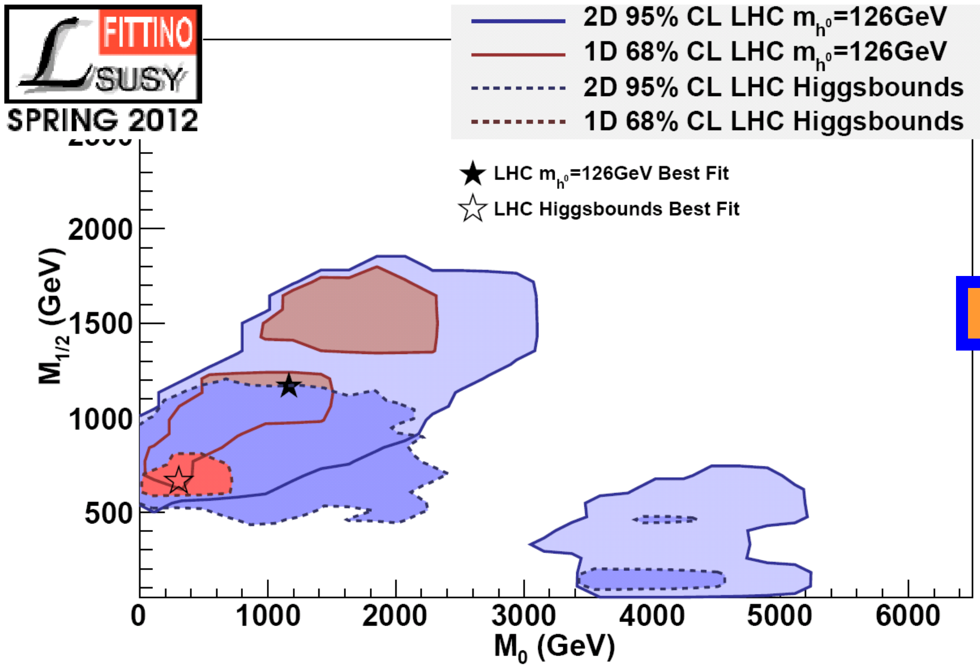
Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	$\tan\beta$	A_0	χ^2/ndf
LHC	$304.4^{+373.7}_{-185.2}$	$664.6^{+138.3}_{-70.9}$	$34.4^{+10.9}_{-21.3}$	$884.8^{+1178.0}_{-974.9}$	$13.1/9$

Goodness of fit decreases: colored/non-colored sectors coupled

Masses and tanβ shifted upwards: correlation with mass through $(g-2)_\mu$

$$a_\mu^{\rm SUSY} \sim {\rm sgn}(\mu) \tan\beta\, M_{\rm SUSY}^{-2}$$

Including a Higgs Mass of 126 GeV



Higher masses and tanβ

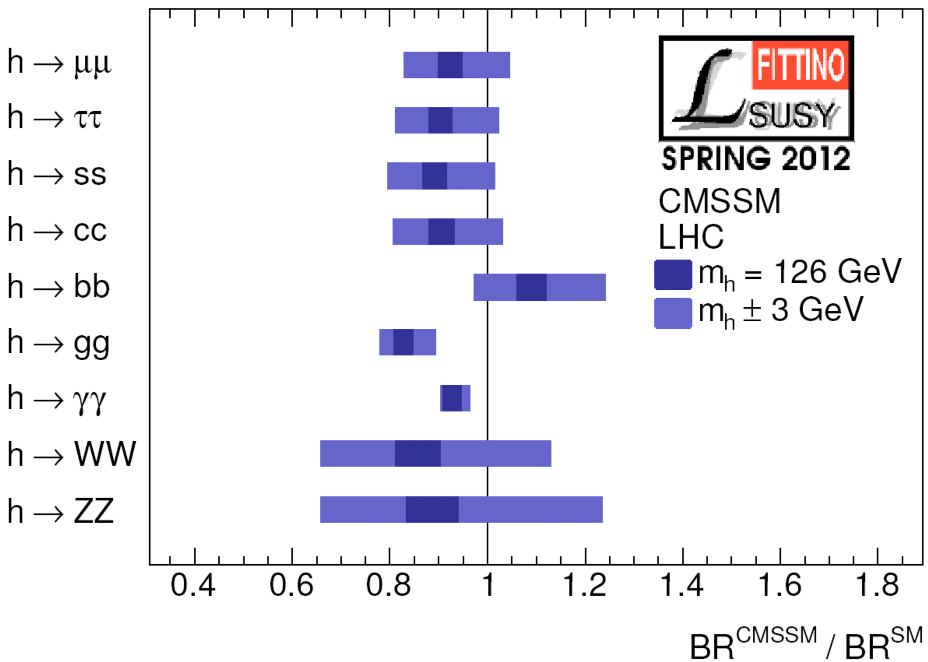
Increasing tension in CMSSM

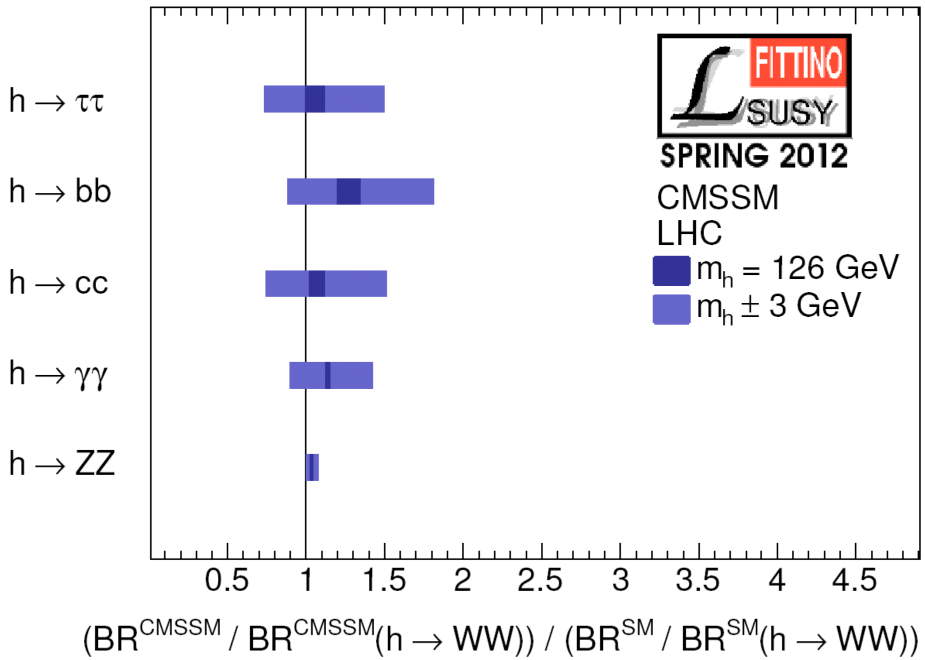
Little difference when fitting m(top)

Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	$\tan\beta$	A_0	χ^2/ndf
LHC+m_h = 126 GeV	$1163.2^{+1185.3}_{-985.7}$	$1167.4^{+594.0}_{-513.0}$	$39.3^{+16.7}_{-32.7}$	$-2969.1^{+6297.8}_{-1234.9}$	18.4/9
LHC	$304.4^{+373.7}_{-185.2}$	$664.6^{+138.3}_{-70.9}$	$34.4^{+10.9}_{-21.3}$	$884.8^{+1178.0}_{-974.9}$	13.1/9

Including a Higgs Mass of 126 GeV

Calculating Higgs BR ratios with *HDECAY* in 2σ region

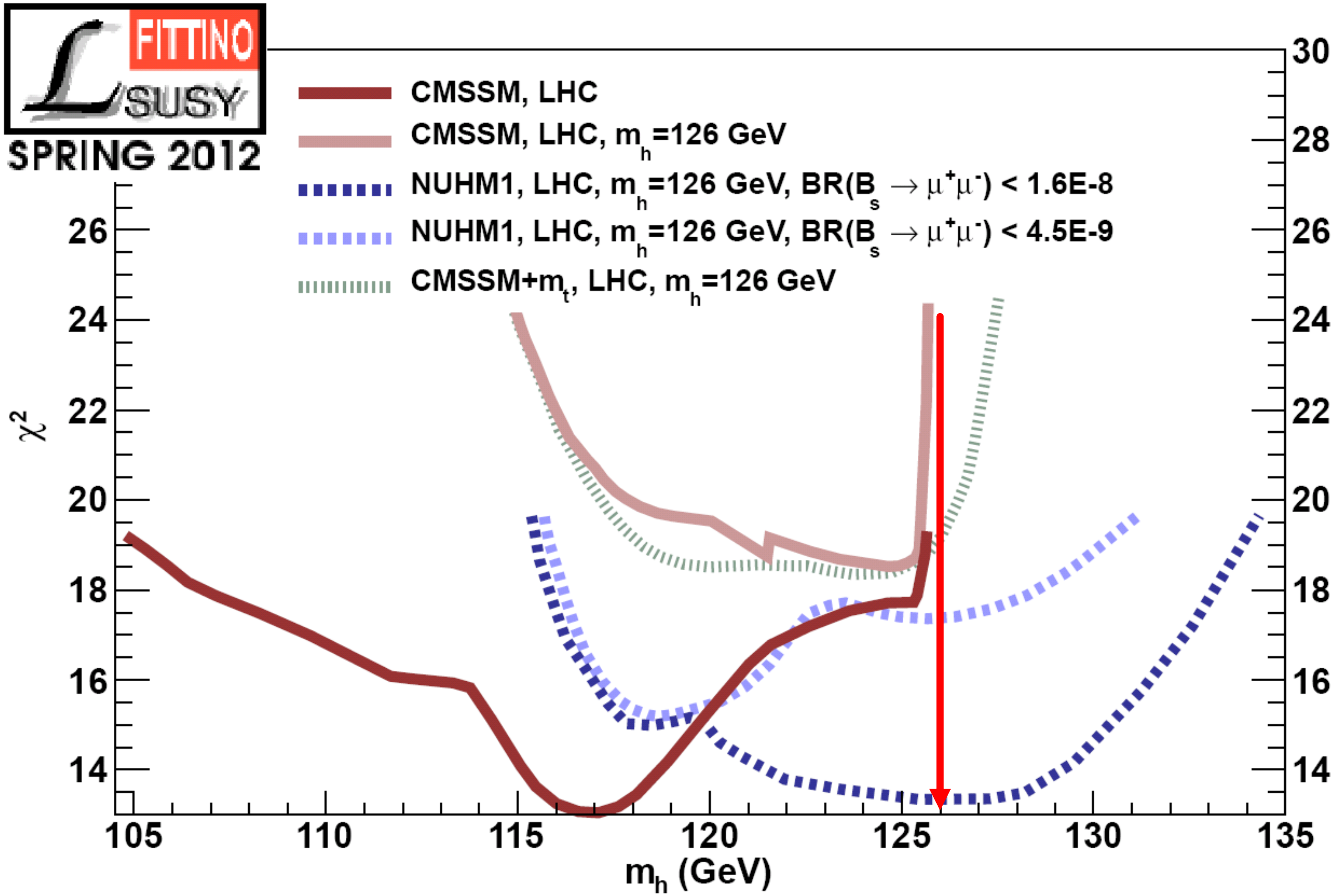




CMSSM: Enhancement of $b\bar{b}$, decrease of $\tau^+\tau^-$

Potential for discovering deviation from SM
even for mass scale beyond the reach at √s=7-8 TeV

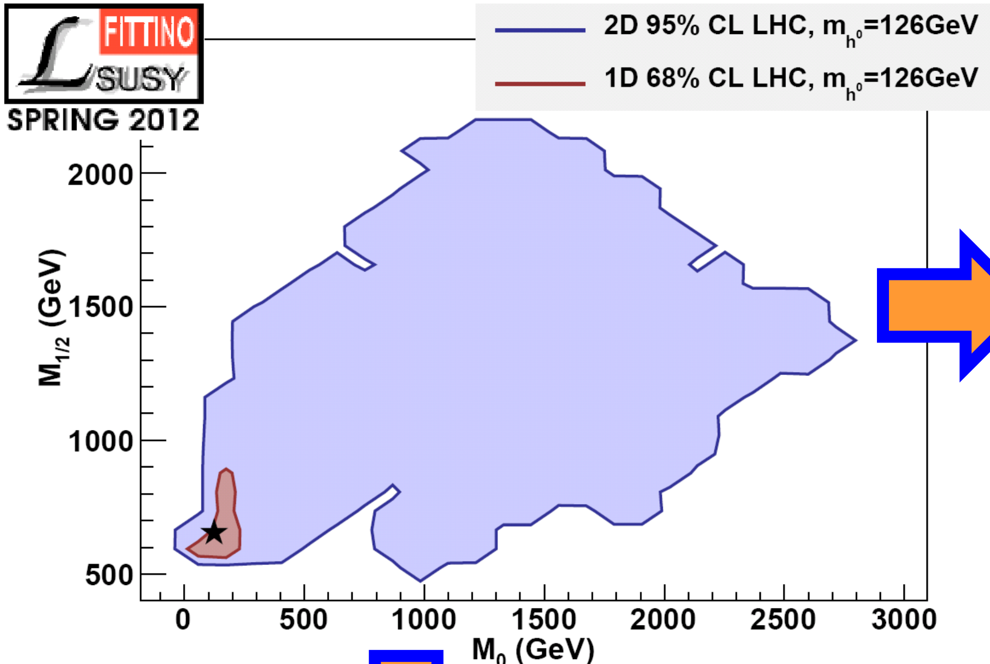
Including a Higgs Mass of 126 GeV

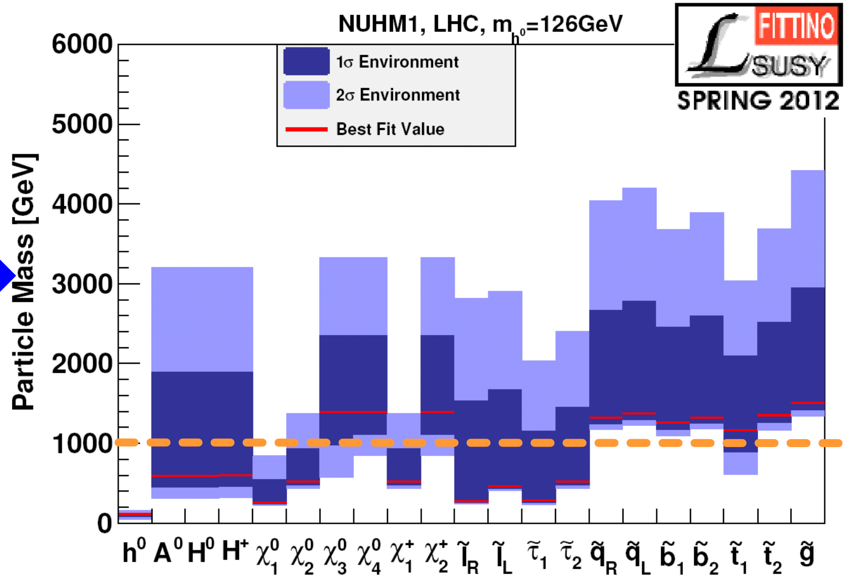


Heavy Higgs hard to accommodate in CMSSM
➔ Switch to non-minimal model ?

What about Non-Minimal Models ? NUHM1

NUHM1: Higgs GUT mass decouples from M_0





Fit	M_0 [GeV]	$M_{1/2}$ [GeV]	M_H^2 [GeV^2]	$\tan\beta$	A_0	χ^2/ndf
NUHM1+m_h	$124.3^{+95.2}_{-16.8}$	$655.5^{+218.0}_{-65.0}$	$(-1.7^{+0.5}_{-2.7}) \times 10^6$	$29.4^{+3.3}_{-7.8}$	$-511.2^{+574.7}_{-988.6}$	15.3/8

Large 2σ contour Lower mass, focus point excluded

Better fit but still tension: strong correlation between BF($B_s \rightarrow \mu\mu$), $(g-2)_\mu$, m(h^0)

Conclusion & Plans

- Current LHC exclusion leads to tension within CMSSM
  ➔ but not exclusion!

- Accommodate Higgs mass ≥ 125 GeV very hard in mSUGRA
  ➔ Improved description of $(g\text{-}2)_\mu$ would greatly help (source of tension)

- More results not presented here:
  - Higgs branching ratios
  - impact of various values for $BF(B_s \rightarrow \mu\mu)$
  - comparison of (in)direct detections
  - impact of individual observables
  - study of fine-tuning
  - impact of uncertainties

JHEP 06, 098 (2012) - arXiv:1204.4199v1

- Extension to more general SUSY models
- Improvement of code flexibility

Thank you

BACKUP

Scan of the SUSY parameter space with Markov chain

Each point, calculate χ2:

For measurements:

$$\chi^2_{\text{meas}} = \sum_{i=1}^{N_{\text{meas}}} \left(\frac{O^i_{\text{meas}} - O^i_{\text{pred}}(\vec{P})}{\sigma^i} \right)^2$$

For bounds:

$$\chi^2_{\text{meas+bound}} = \chi^2_{\text{meas}} + \sum_{i=1}^{N_{\text{bound}}} \begin{cases} \left(\frac{O^i_{\text{limit}} - O^i_{\text{pred}}(\vec{P})}{\sigma^i} \right)^2 & \text{for } O^i_{\text{pred}}(\vec{P}) > O^i_{\text{limit}} \\ 0 & \text{otherwise} \end{cases}$$

Require lightest neutralino to be LSP

Including "low energy" observables

$\mathcal{B}(b \to s\gamma)$	$(3.55 \pm 0.34) \times 10^{-4}$	SuperISO, FeynHiggs
$\mathcal{B}(B_s \to \mu\mu)$	$< 4.5 \times 10^{-9}$	SuperISO, FeynHiggs
$\mathcal{B}(B \to \tau\nu)$	$(1.67 \pm 0.39) \times 10^{-4}$	SuperISO, FeynHiggs
Δm_{B_s}	$17.78 \pm 5.2\,\mathrm{ps}^{-1}$	SuperISO, FeynHiggs
$a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}}$	$(28.7 \pm 8.2) \times 10^{-10}$	SuperISO, FeynHiggs
m_W	(80.385 ± 0.015) GeV	SuperISO, FeynHiggs
$\sin^2\theta_{\mathrm{eff}}$	0.23113 ± 0.00021	SuperISO, FeynHiggs
$\Omega_{\mathrm{CDM}} h^2$	0.1123 ± 0.0118	← micrOMEGAS, DarkSUSY
m_t	(173.2 ± 1.34) GeV	

(In)direct dark matter detection bounds ← **Astrofit**

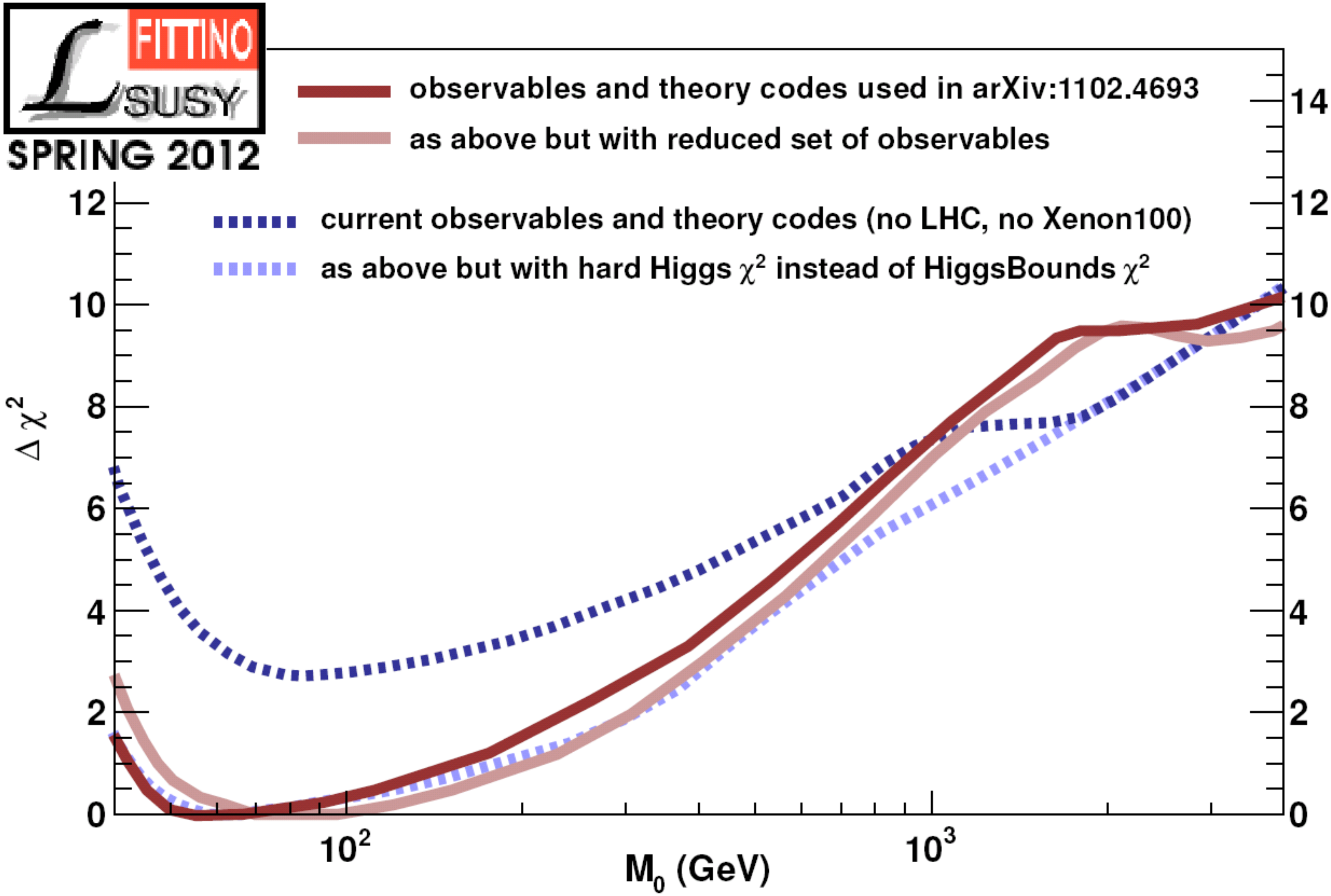
mass(h^0) ← **Higgsbound ± 3.0 GeV or direct cut for LHC result**

LEP bound in e+e-→$\chi_1^+\chi_1^-$ ← **SPheno, SoftSUSY**

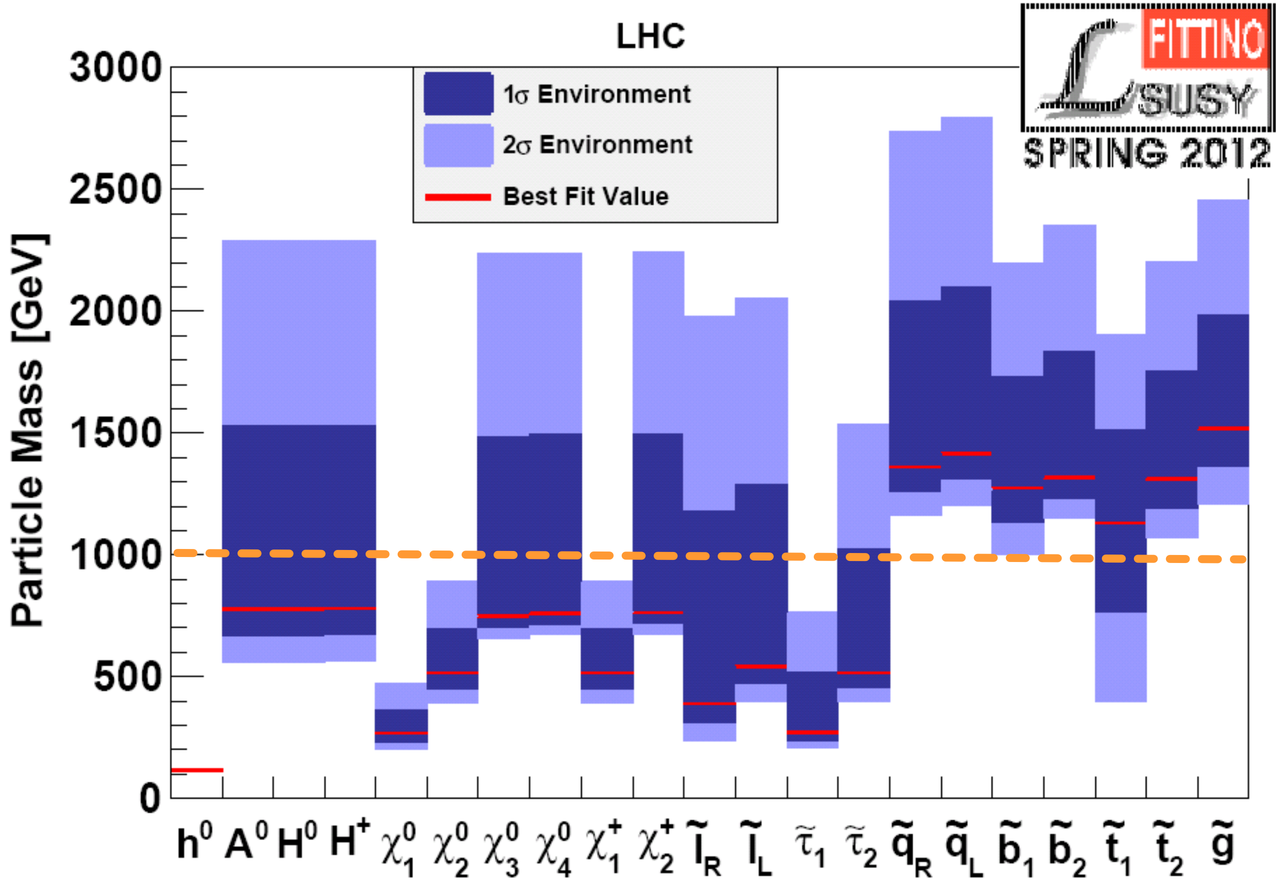
SM parameters fixed (PDG value)

Require lightest neutralino to be LSP

Comparison of the χ2 profile pour the two sets of observables used (long and reduced)



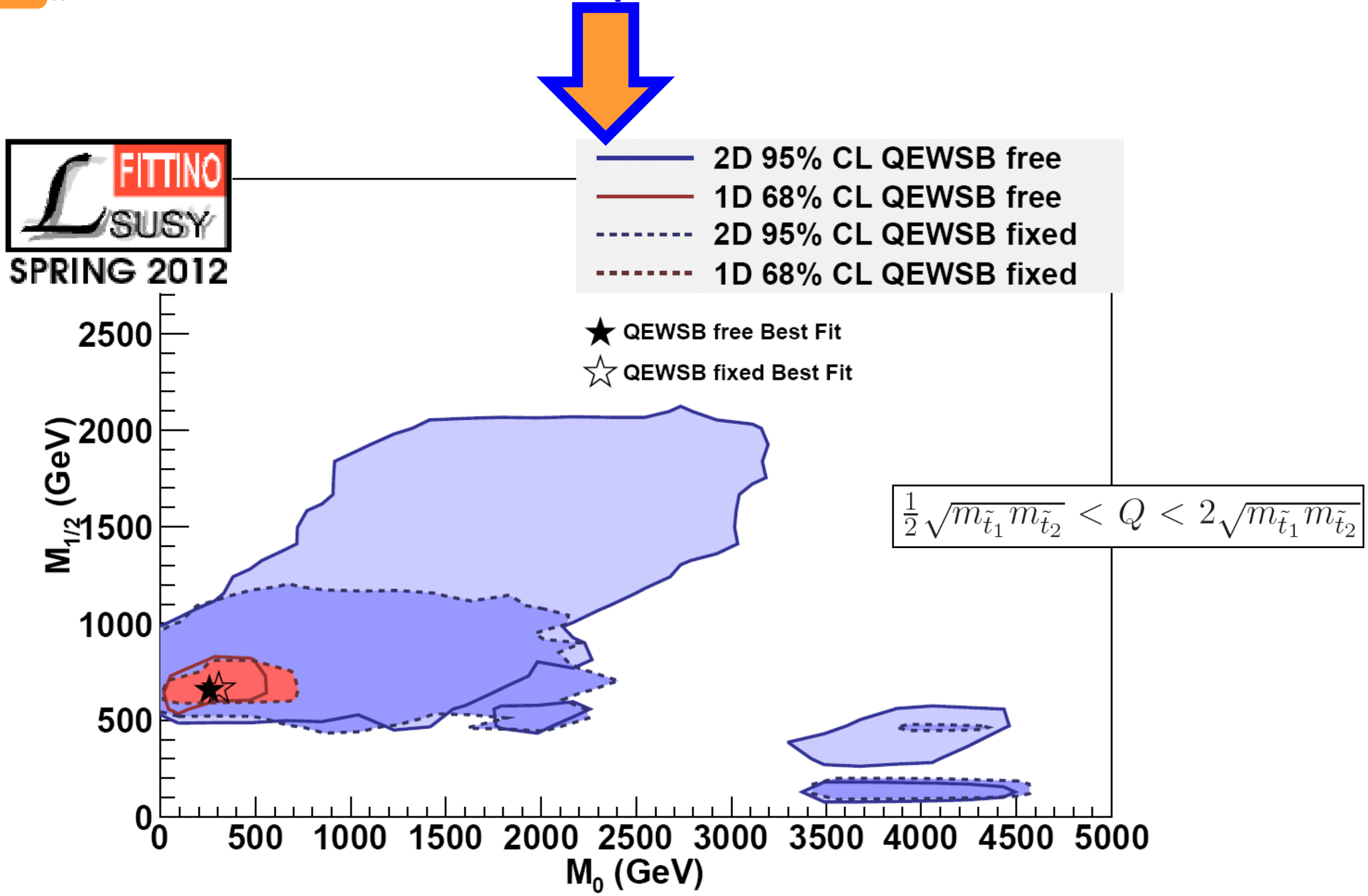
Including the LHC constraints



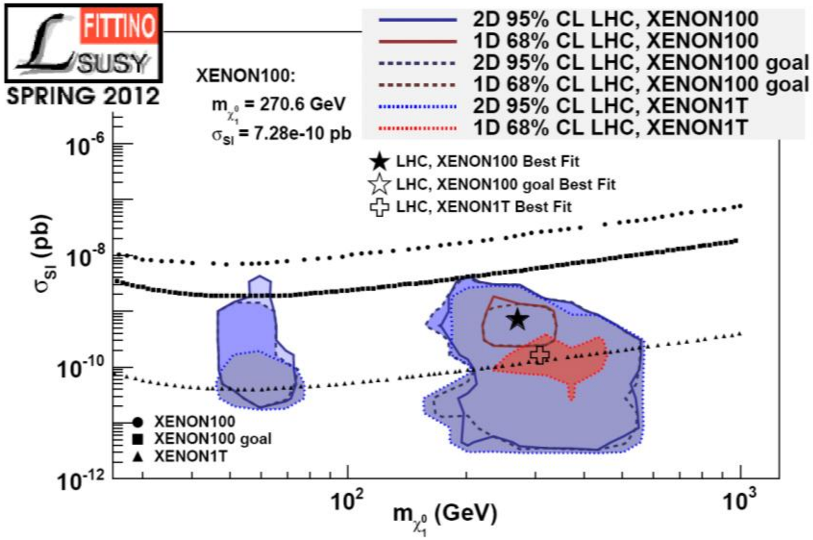
Masses pushed upwards by LHC , partly cancelled by LEO
Stronger bound for h^0 and $\chi^0{}_1$
Still room for masses < 500 GeV

Investigating uncertainties

- Comparing different calculators: DarkSUSY vs. Micromegas Spheno vs. SoftSUSY
- RGE scale „QEWSB“ included as nuisance parameter

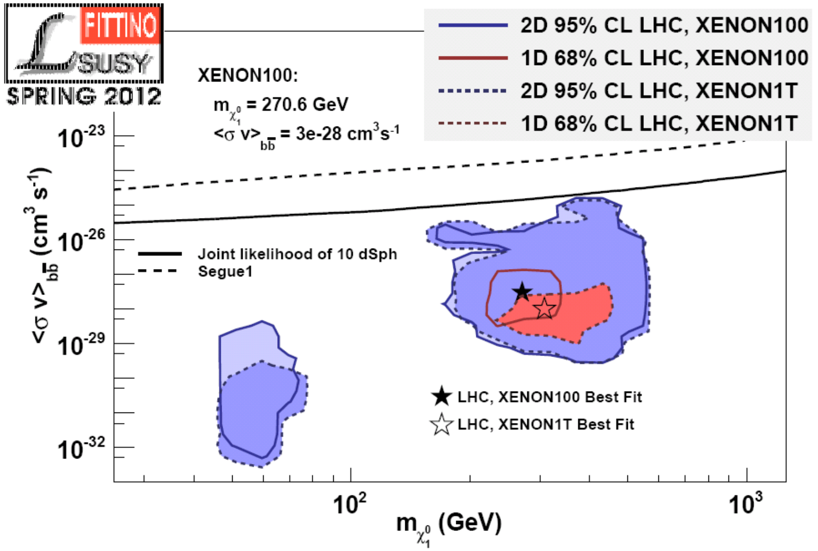


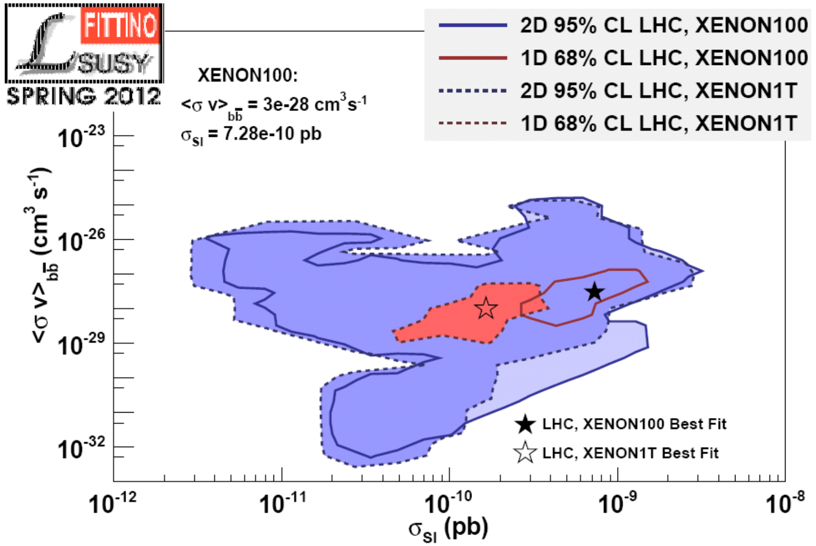
Including direct – indirect detection



CoGeNT, DAMA/LIBRA:
→signals not compatible with CMSSM

Constraint expected for future direct detection experiment only





Indirect detection constraints too weak (dwarf galaxies by Fermi)

Direct/indirect detections complementary

Investigating fine tuning

One of the arguments for SUSY: fine tuning in SM

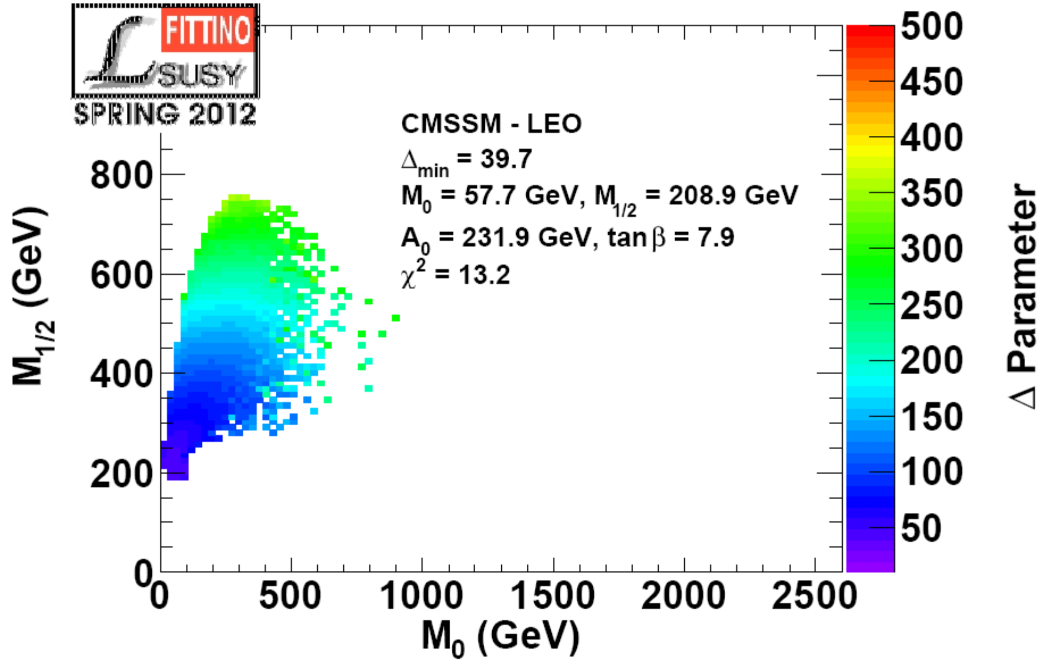
Is the best fit region less fine tuned ?

$$c_a = \left| \frac{\partial \ln M_Z^2}{\partial \ln a} \right|$$

$$\Delta = \max\left(c_a\right)$$

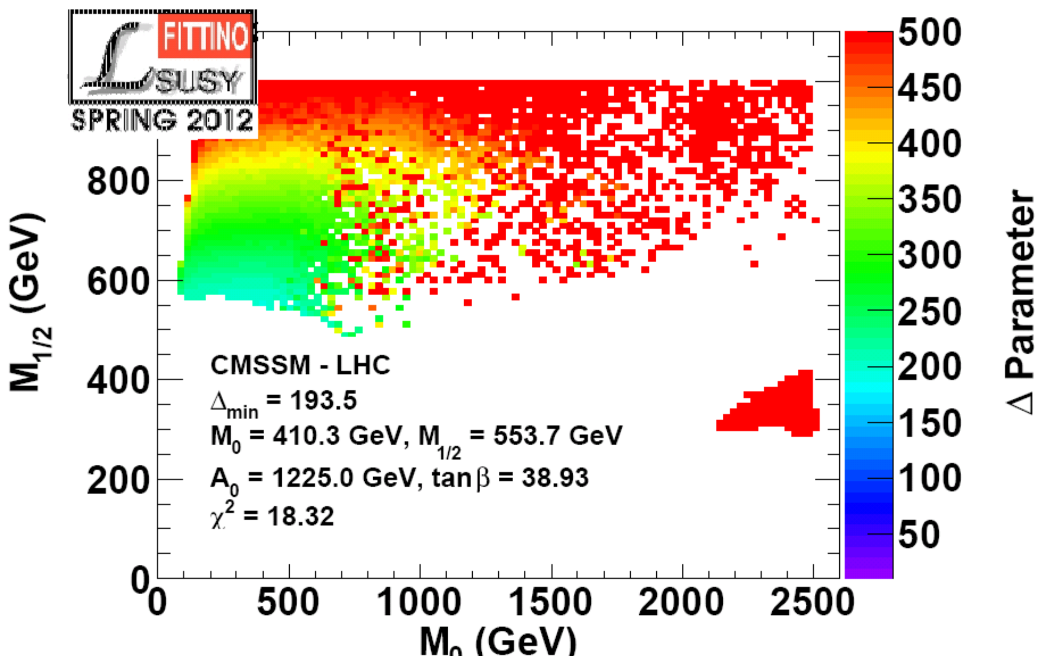
a = m_0, m_{12}, A_0…

Calculated for each CMSSM point using SOFTSUSY



Best fit point less fine tuned

Δ = 39.7



LHC: higher fine tuning (higher masses)

Δ = 193.5

Drawback of Δ definition:
- **nur EW scale**
- **change relative to uncertainty ?**
- **change of other observables than m_Z ?**

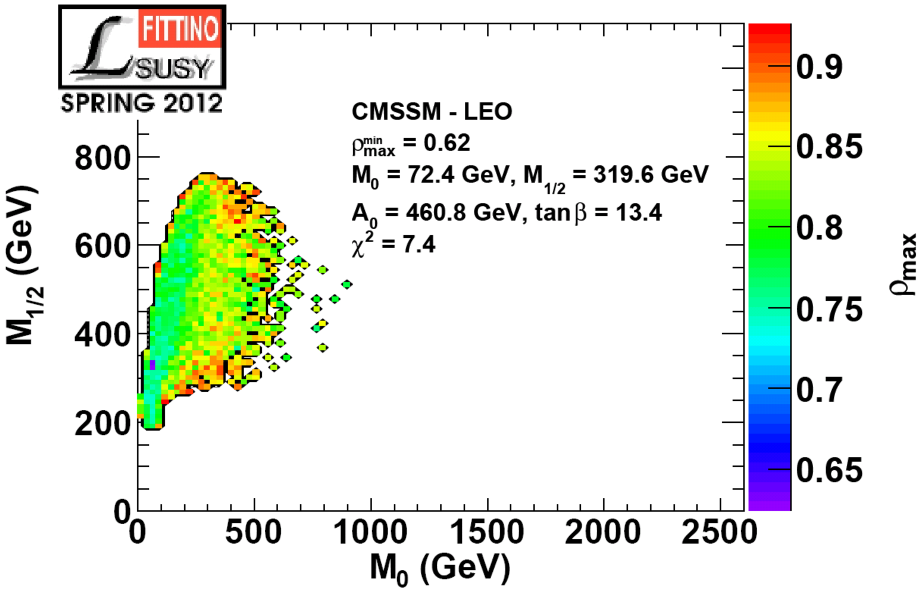
χ2-slices of ± 0.001
Calculate correlation between parameters:

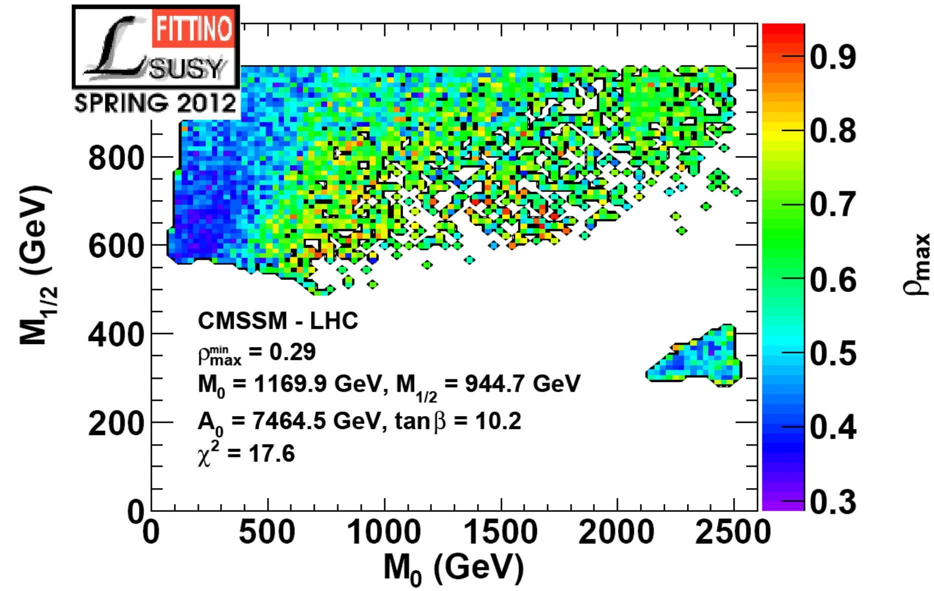
$$\varrho_{ij} \equiv \left\langle \frac{(P_i - \langle P_i \rangle) \cdot (P_j - \langle P_j \rangle)}{\sigma_{P_i} \sigma_{P_j}} \right\rangle$$

$$\varrho_{\max} = \max_{ij} \left(|\varrho_{ij}| \right)$$

$P_i = m_0, m_{12}, A_0, \tan\beta$

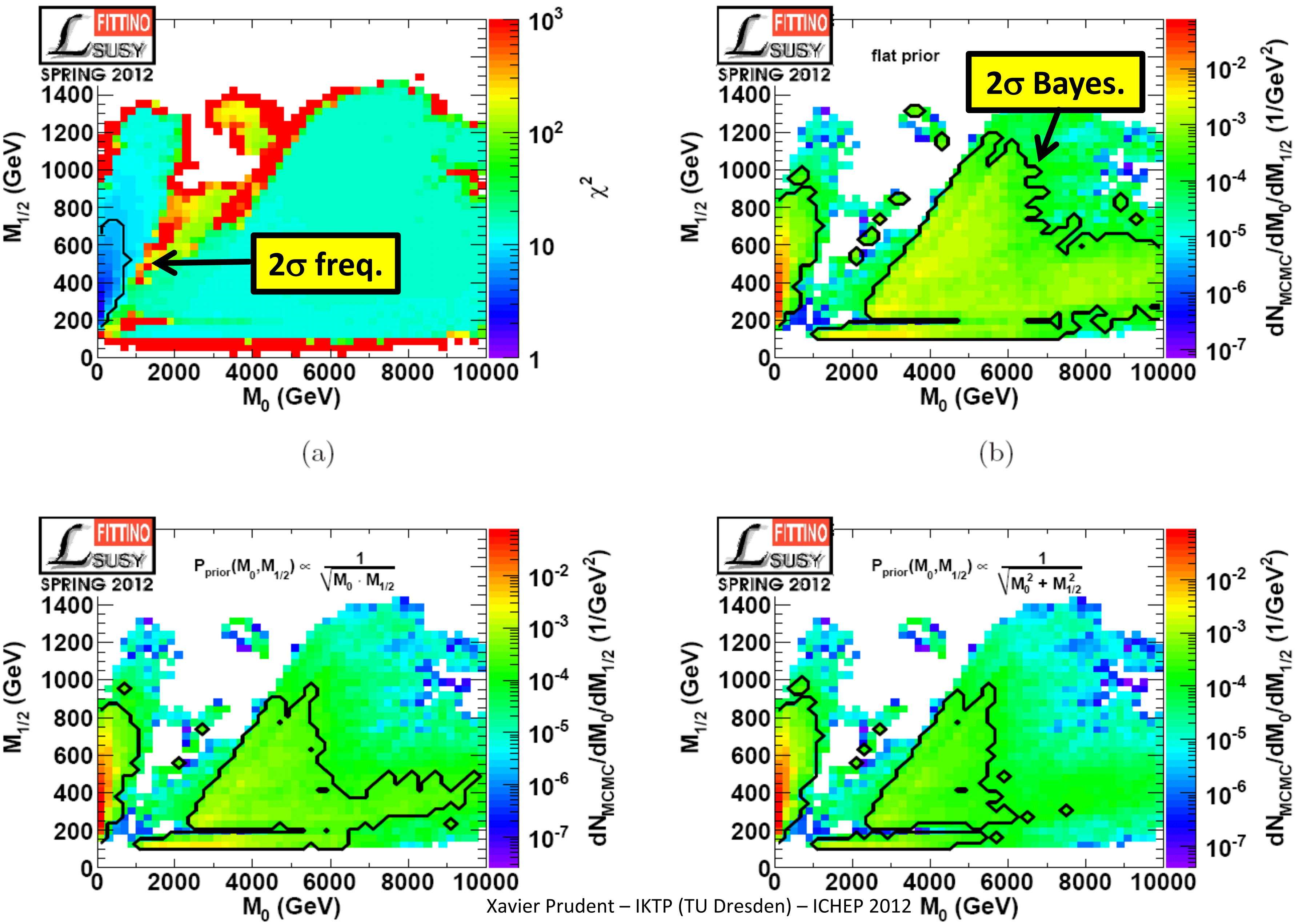
Express correlation & goodness of fit
- **Take the largest ρ over the 6 values → ρ_{max}**
- **For each point in (m_0, m_{12}) plane, take the smallest ρ_{max}**
- **A_0, tanβ profiled**





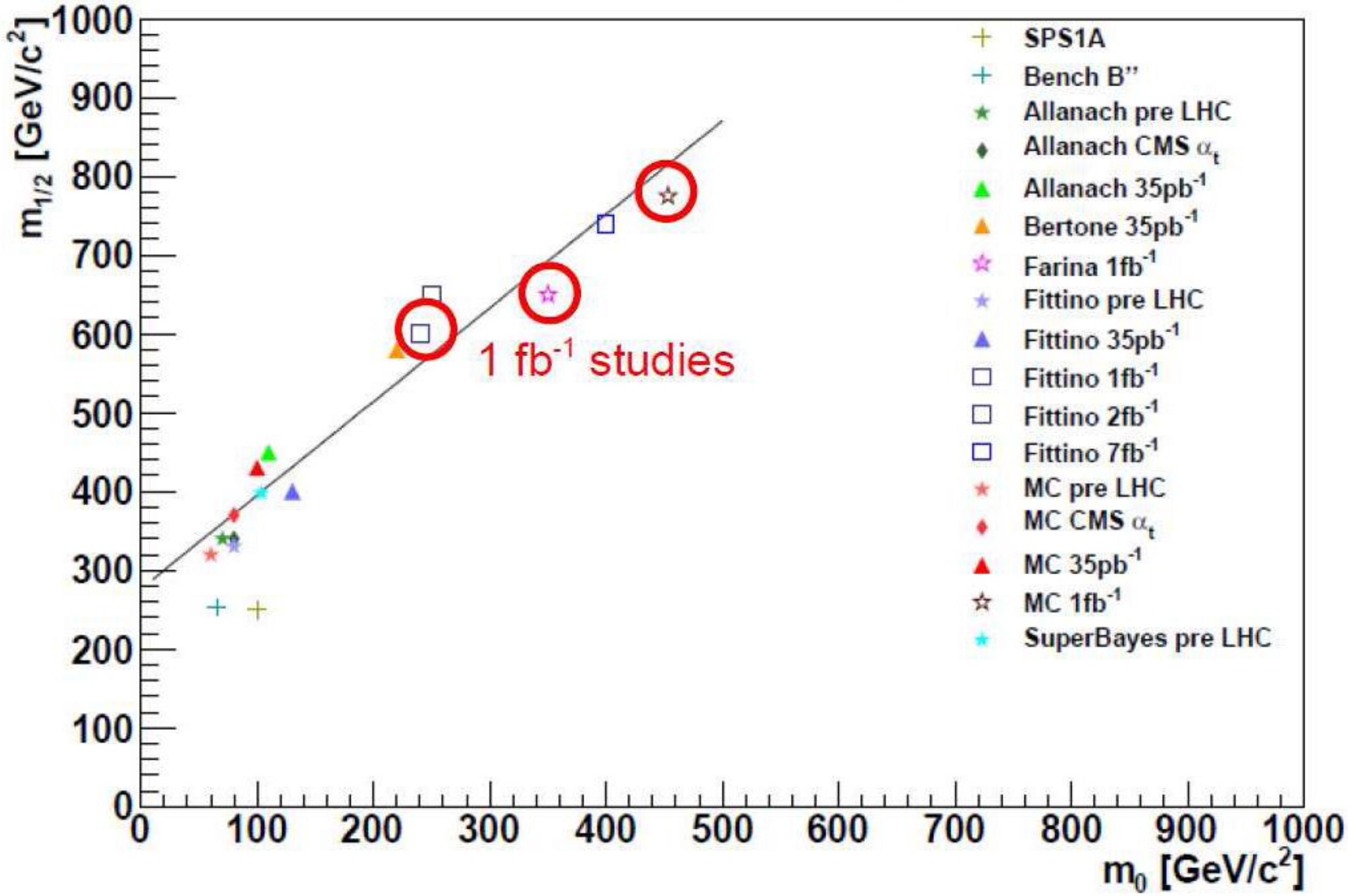
Lower correlation for best fit region
Lower correlation with LHC
Less constrained fit
➔wider region accessible for A_0, tanβ
➔Flatter χ2 profile
➔ smaller correlation

Don‘t underestimate the differences between statistical methods !
Attention to Bayesian priors !!



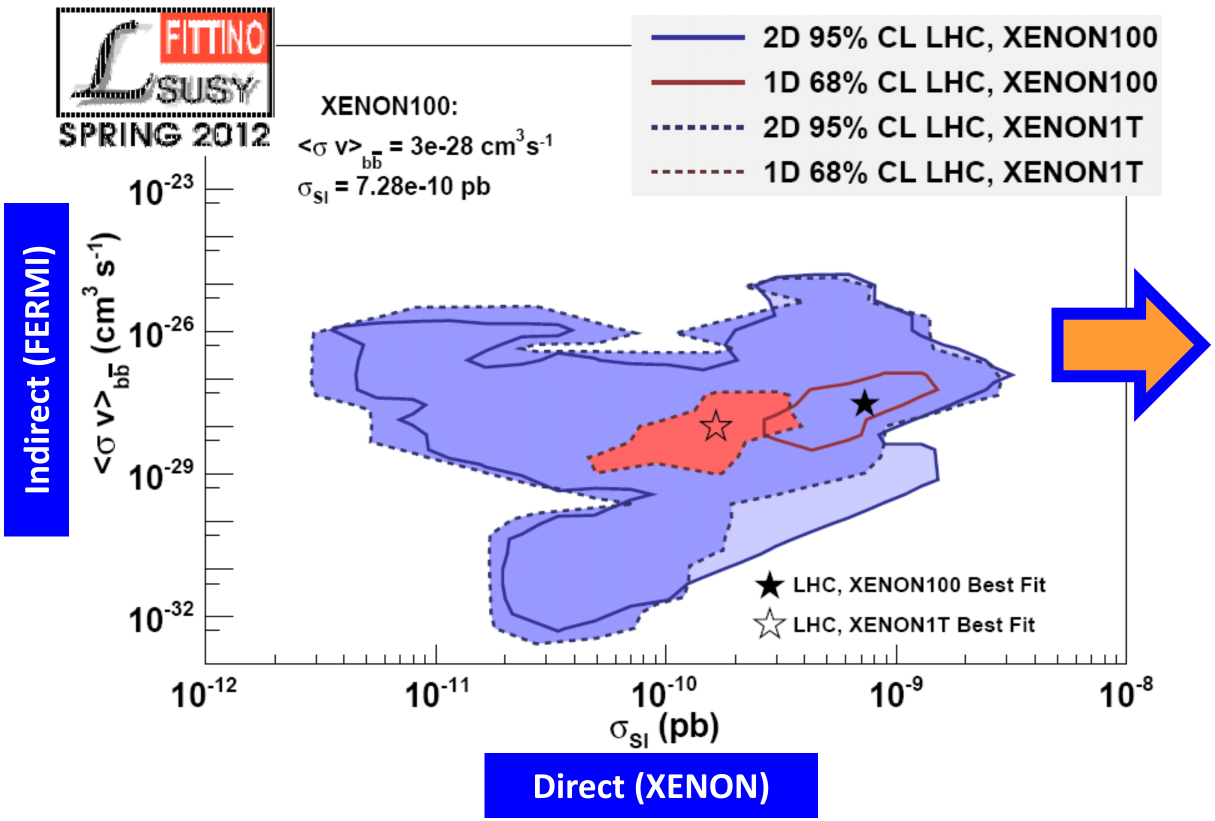
Different methods → different results !
(+different observable, calculators,…)

arXiv:1109.3859



Including Direct – Indirect Detection of Dark Matter

- **CoGeNT, DAMA/LIBRA** "signals": not compatible with CMSSM
- Constraint expected for **future direct detection** experiment only
- Indirect detection constraints too **weak** (Fermi)



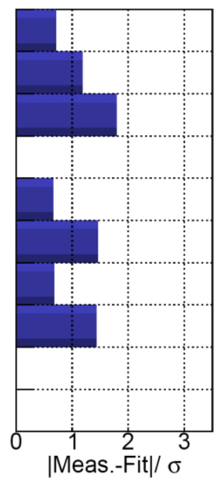
Direct/indirect detections **complementary**

Predicted values of the observables at the best fit points

FITTINO SUSY SPRING 2012

CMSSM, LEO

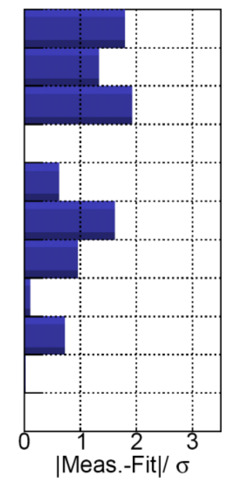
$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	2.3E-9
BR($b \to s\gamma$)	$(3.55 \pm 0.26 \pm 0.23)$E-4	3.14E-4
BR($B \to \tau\nu$)	(1.67 ± 0.39)E-4	0.97E-4
BR($B_s \to \mu^+\mu^-$)	<(4.50 ± 0.30)E-9	3.08E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	21.24
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23144
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.373
m_h (GeV)		113.6
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1123
σ^{SI} (pb)		2.04E-9



FITTINO SUSY SPRING 2012

CMSSM, LHC

$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	1.4E-9
BR($b \to s\gamma$)	$(3.55 \pm 0.26 \pm 0.23)$E-4	3.09E-4
BR($B \to \tau\nu$)	(1.67 ± 0.39)E-4	0.92E-4
BR($B_s \to \mu^+\mu^-$)	<(4.50 ± 0.30)E-9	3.76E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	20.97
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23147
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.368
m_h (GeV)		116.8
LHC		
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1125
σ^{SI} (pb)		7.28E-10



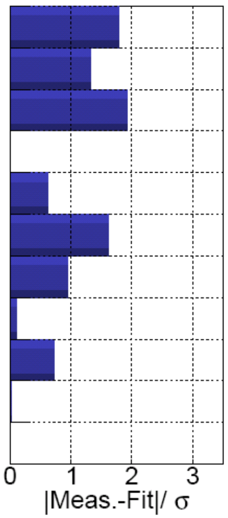
LEO prefers low masses (for non-colored sector)
LHC prefers high masses (for colored sector)

➔ Tension building-in, but not enough to exclude CMSSM

Predicted values of the observables at the best fit points

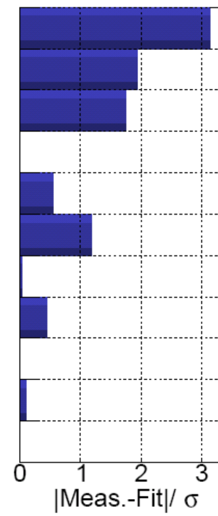
Fittino SUSY, Spring 2012 — CMSSM, LHC

Observable	Measurement	Fit
$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	1.4E-9
$BR(b \to s\gamma)$	$(3.55 \pm 0.26 \pm 0.23)$E-4	3.09E-4
$BR(B \to \tau\nu)$	(1.67 ± 0.39)E-4	0.92E-4
$BR(B_s \to \mu^+\mu^-)$	$<(4.50 \pm 0.30)$E-9	3.76E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	20.97
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23147
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.368
m_h (GeV)		116.8
LHC		
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1125
σ^{SI} (pb)		7.28E-10



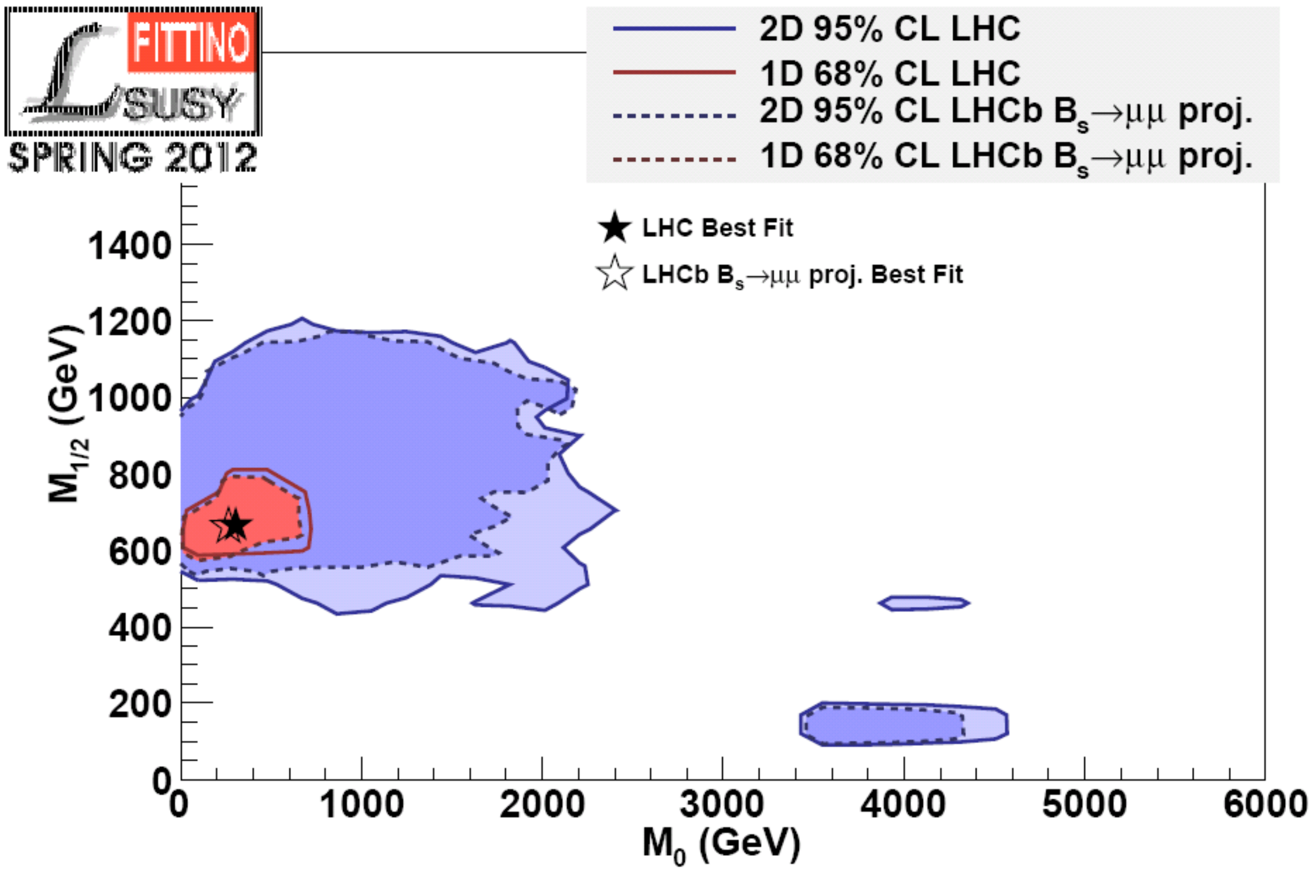
Fittino SUSY, Spring 2012 — CMSSM, LHC, m_h=126 GeV

Observable	Measurement	Fit
$a_\mu - a_\mu^{SM}$	$(2.9 \pm 0.8 \pm 0.2)$E-9	0.3E-9
$BR(b \to s\gamma)$	$(3.55 \pm 0.26 \pm 0.23)$E-4	2.88E-4
$BR(B \to \tau\nu)$	(1.67 ± 0.39)E-4	0.99E-4
$BR(B_s \to \mu^+\mu^-)$	$<(4.50 \pm 0.30)$E-9	3.61E-9
Δm_s (ps^{-1})	$17.78 \pm 0.12 \pm 5.20$	20.58
$\sin^2\theta^l_{eff}$	0.23113 ± 0.00021	0.23138
m_W (GeV)	$80.385 \pm 0.015 \pm 0.010$	80.386
m_h (GeV)	$126.0 \pm 2.0 \pm 3.0$	124.4
LHC		
$\Omega_{CDM}h^2$	$0.1123 \pm 0.0035 \pm 0.0112$	0.1112
σ^{SI} (pb)		2.44E-11



$$a_\mu^{\rm SUSY} \sim {\rm sgn}(\mu)\,\tan\beta\, M_{\rm SUSY}^{-2}$$

Impact of $B_s \rightarrow \mu\mu$

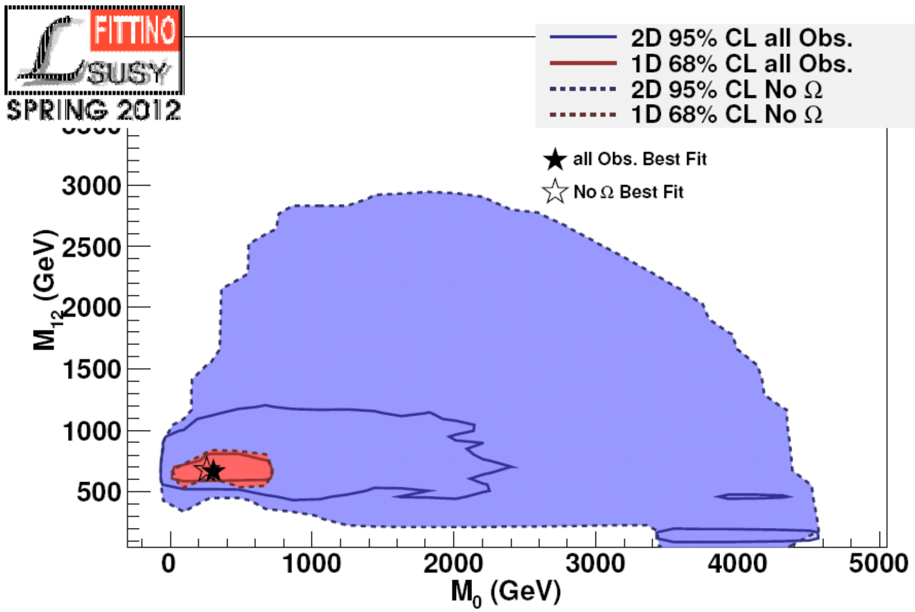


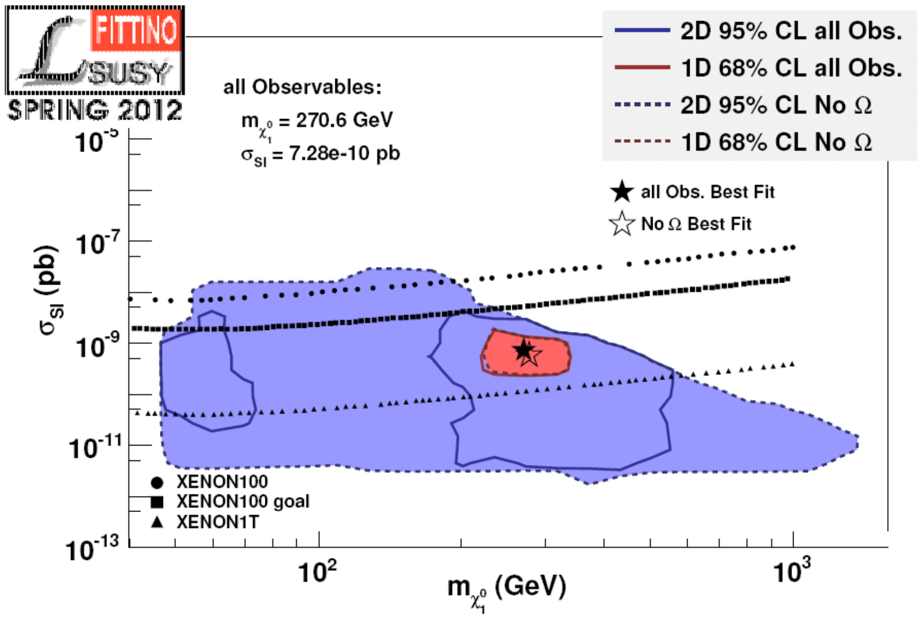
Small impact for SM value (~ LHC best fit value)

$$\mathcal{B}(B_s \rightarrow \mu\mu) = (3.2 \pm 0.3) \times 10^{-9}$$

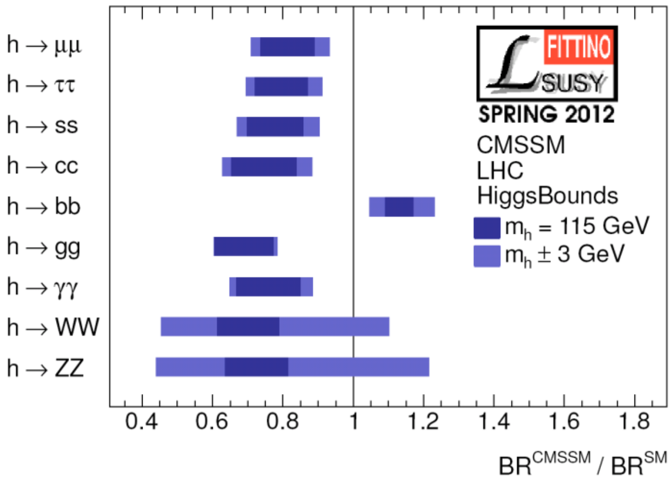
CDF „measurement“ would disfavor the focus point

Impact of the relic density

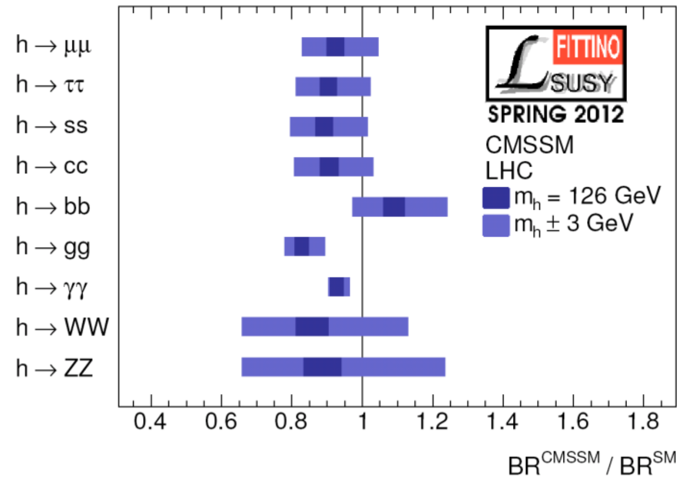




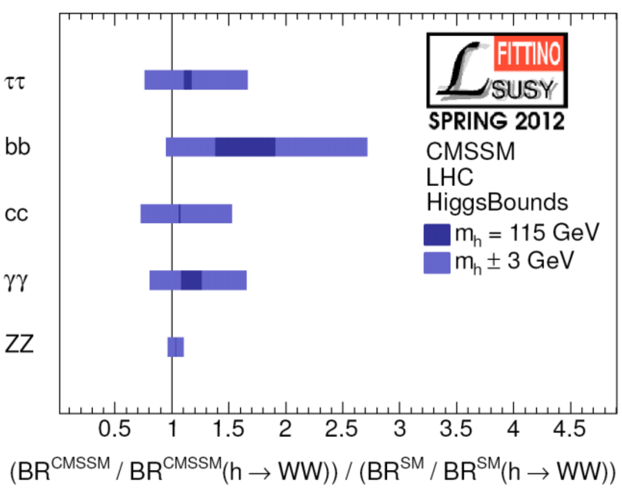
Predicted 2σ ranges of Higgs branching fractions

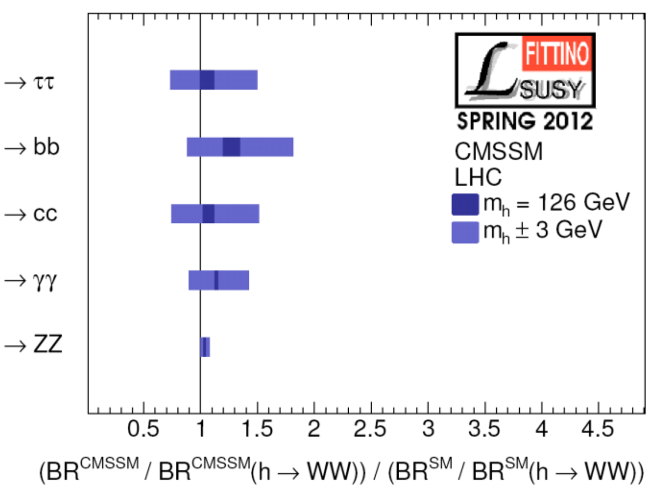


(a)



(b)





Looking beyond minimal model: NUHM1

Parameters:

$$M_0,\ M_H,\ M_{1/2},\ A_0,\ \tan\beta,\ \mathrm{sgn}(\mu)$$

Difference with CMSSM:

→ Universal Higgs mass differs from other scalars M_0

$$M_{H_u} = M_{H_d} = M_H$$

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Observable	Experimental Value	Uncertainty stat	syst	Exp. Reference
$\mathcal{B}(B \to s\gamma)/\mathcal{B}(B \to s\gamma)_{\rm SM}$	1.117	0.076	0.096	[47]
$\mathcal{B}(B_s \to \mu\mu)$	$< 4.7\times10^{-8}$			[47]
$\mathcal{B}(B_d \to \ell\ell)$	$< 2.3\times10^{-8}$			[47]
$\mathcal{B}(B \to \tau\nu)/\mathcal{B}(B \to \tau\nu)_{\rm SM}$	1.15	0.40		[48]
$\mathcal{B}(B_s \to X_s\ell\ell)/\mathcal{B}(B_s \to X_s\ell\ell)_{\rm SM}$	0.99	0.32		[47]
$\Delta m_{B_s}/\Delta m_{B_s}^{\rm SM}$	1.11	0.01	0.32	[49]
$\frac{\Delta m_{B_s}/\Delta m_{B_s}^{\rm SM}}{\Delta m_{B_d}/\Delta m_{B_d}^{\rm SM}}$	1.09	0.01	0.16	[47, 49]
$\Delta\epsilon_K/\Delta\epsilon_K^{\rm SM}$	0.92	0.14		[49]
$\mathcal{B}(K \to \mu\nu)/\mathcal{B}(K \to \mu\nu)_{\rm SM}$	1.008	0.014		[50]
$\mathcal{B}(K \to \pi\nu\bar{\nu})/\mathcal{B}(K \to \pi\nu\bar{\nu})_{\rm SM}$	< 4.5			[51]
$a_\mu^{\rm exp} - a_\mu^{\rm SM}$	30.2×10^{-10}	8.8×10^{-10}	2.0×10^{-10}	[52, 53]
$\sin^2\theta_{\rm eff}$	0.2324	0.0012		[46]
Γ_Z	2.4952 GeV	0.0023 GeV	0.001 GeV	[46]
R_l	20.767	0.025		[46]
R_b	0.21629	0.00066		[46]
R_c	0.1721	0.003		[46]
$A_{\rm fb}(b)$	0.0992	0.0016		[46]
$A_{\rm fb}(c)$	0.0707	0.0035		[46]
A_b	0.923	0.020		[46]
A_c	0.670	0.027		[46]
A_l	0.1513	0.0021		[46]
A_τ	0.1465	0.0032		[46]
$A_{\rm fb}(l)$	0.01714	0.00095		[46]
$\sigma_{\rm had}$	41.540 nb	0.037 nb		[46]
m_h	> 114.4 GeV		3.0 GeV	[54, 55, 56]
$\Omega_{\rm CDM}h^2$	0.1099	0.0062	0.012	[57]
$1/\alpha_{em}$	127.925	0.016		[58]
G_F	$1.16637\times10^{-5}\,{\rm GeV}^{-2}$	$0.00001\times10^{-5}\,{\rm GeV}^{-2}$		[58]
α_s	0.1176	0.0020		[58]
m_Z	91.1875 GeV	0.0021 GeV		[46]
m_W	80.399 GeV	0.025 GeV	0.010 GeV	[58]
m_b	4.20 GeV	0.17 GeV		[58]
m_t	172.4 GeV	1.2 GeV		[59]
m_τ	1.77684 GeV	0.00017 GeV		[58]
m_c	1.27 GeV	0.11 GeV		[46]

Previous set of observables

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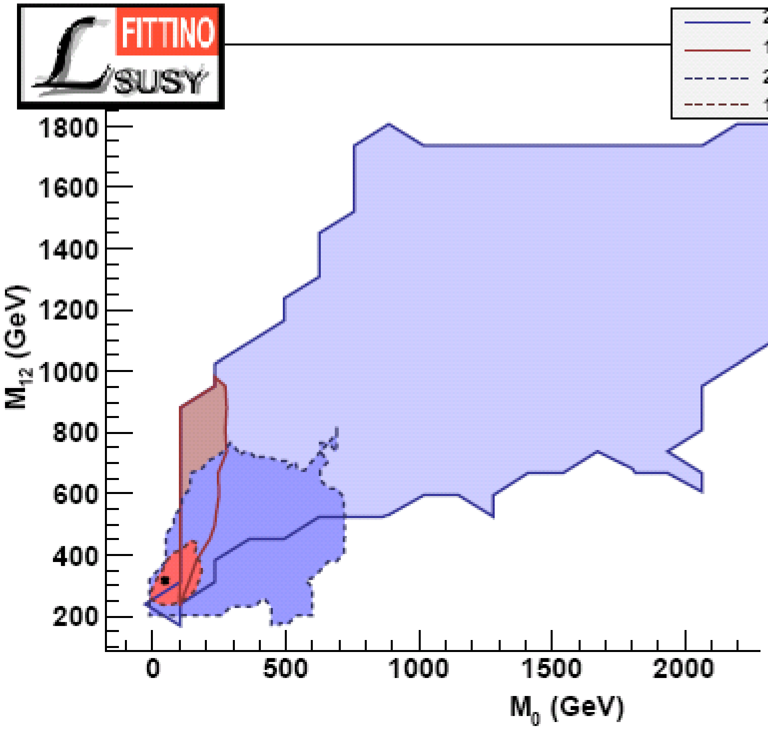
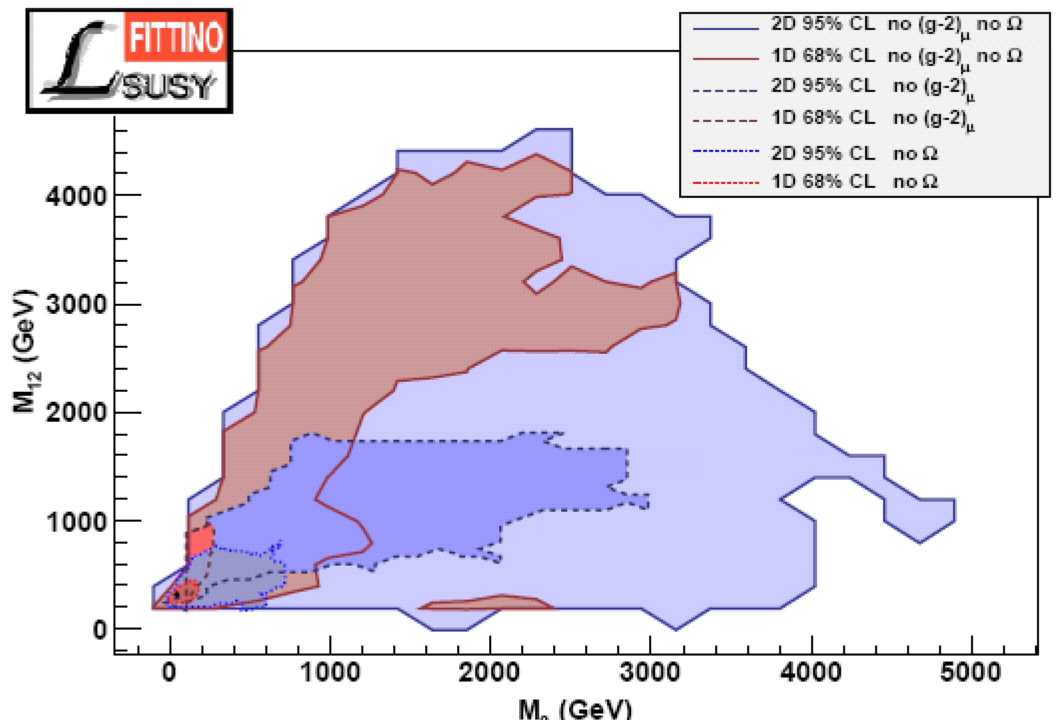


Impact of the muon magnetic moment and of the relic density



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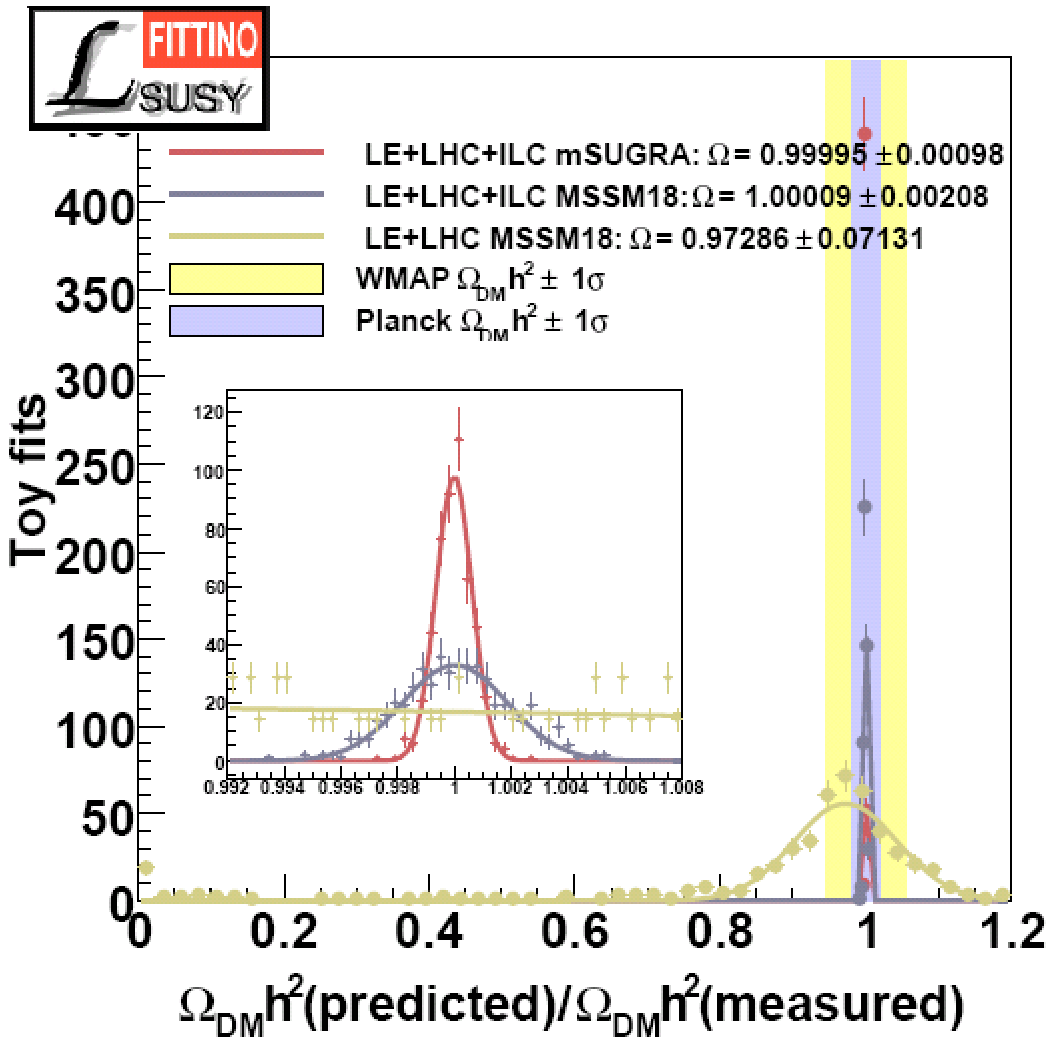

Fig. 40: Ratio of the predicted value of $\Omega_{\rm pred}h^2$ to the nominal value of $\Omega_{\rm SPS1a}h^2$ in the SPS1a scenario for a variety of Toy Fits without using $\Omega_{\rm CDM}h^2$ as an observable.

Fittino: Eur. Phys. J. C. 66, 215 (2010)

Table 25: Results of the Markov Chain MC analysis of the MSSM18 model using low energy observables, expected LHC results for $\mathcal{L}^{\mathrm{int}} = 300\,\mathrm{fb}^{-1}$ and ILC.

Parameter	Nominal value	ILC Fit		$\sigma_{\mathrm{LE+LHC300}}$	$\sigma_{\mathrm{LE+LHC300+ILC}}$
$M_{\tilde{\ell}_L}$ (GeV)	194.31	194.315	$\pm$	6.4	0.068
$M_{\tilde{\ell}_R}$ (GeV)	135.76	135.758	$\pm$	10.5	0.071
$M_{\tilde{\tau}_L}$ (GeV)	193.52	193.46	$\pm$	43.0	0.33
$M_{\tilde{\tau}_R}$ (GeV)	133.43	133.45	$\pm$	38.2	0.35
$M_{\tilde{q}_L}$ (GeV)	527.57	527.61	$\pm$	3.4	0.64
$M_{\tilde{q}_R}$ (GeV)	509.14	509.3	$\pm$	9.0	9.0
$M_{\tilde{b}_R}$ (GeV)	504.01	504.2	$\pm$	33.3	2.4
$M_{\tilde{t}_L}$ (GeV)	481.69	481.6	$\pm$	15.5	1.5
$M_{\tilde{t}_R}$ (GeV)	409.12	409.2	$\pm$	103.8	1.6
$\tan\beta$	10	10.01	$\pm$	3.3	0.29
μ (GeV)	355.05	355.02	$\pm$	6.2	0.88
X_τ (GeV)	−3799.88	−3795.1	$\pm$	3053.5	46.6
X_t (GeV)	−526.62	−526.8	$\pm$	299.2	4.7
X_b (GeV)	−4314.33	−4252.1	$\pm$	5393.6	728.7
M_1 (GeV)	103.15	103.154	$\pm$	3.5	0.046
M_2 (GeV)	192.95	192.95	$\pm$	5.5	0.11
M_3 (GeV)	568.87	568.66	$\pm$	6.9	1.65
m_A (GeV)	359.63	360.07	$\pm$	$^{+1181}_{-99.3}$	1.83

Table 24: Result of the fit of the mSUGRA model to the existing measurements and to the expected results from LHC with $\mathcal{L}^{\mathrm{int}} = 300\,\mathrm{fb}^{-1}$ and ILC.

Parameter	Nominal value	Fit		Uncertainty
$\tan\beta$	10	9.999	$\pm$	0.050
$M_{1/2}$ (GeV)	250	249.999	$\pm$	0.076
M_0 (GeV)	100	100.003	$\pm$	0.064
A_0 (GeV)	−100	−100.0	$\pm$	2.4