Predicting and understanding supersymmetry

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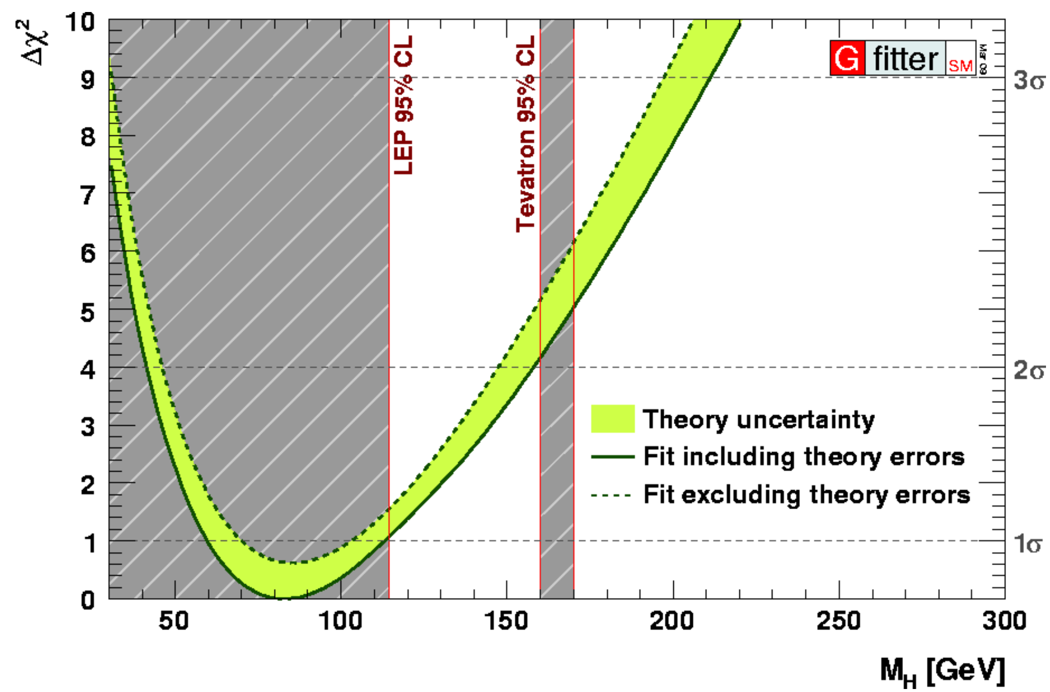
Understanding the Standard Model

Much work went into SM fits:

- very precise measurements
- equally precise theoretical calculations (→ radiative corrections)

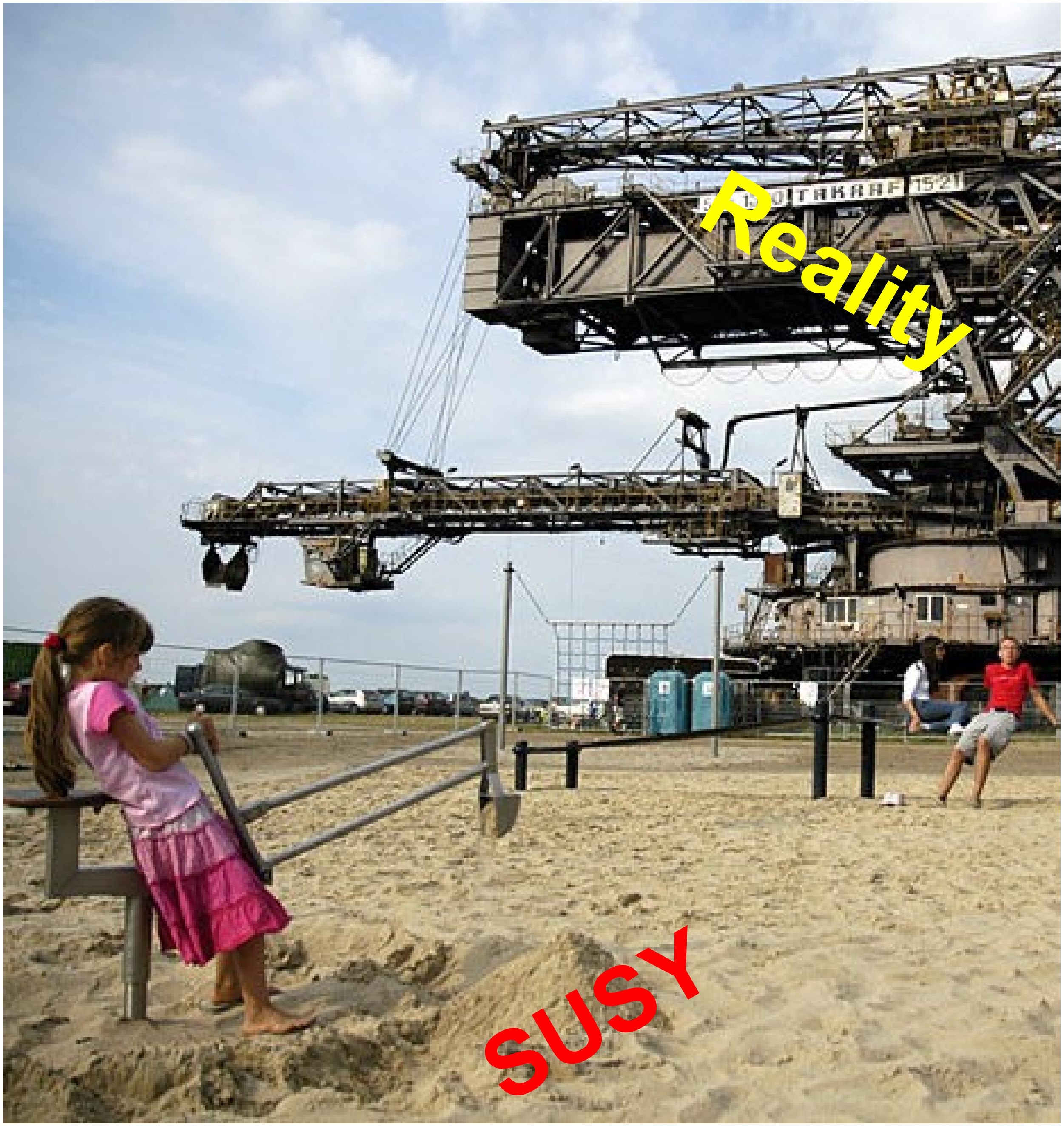
→ G_F, $\alpha_s(M_Z^{\,2})$, $\Delta\alpha_{em}^{(5)}(M_Z^{\,2})$, m_Z, m_t, m_H



Similarly, need to fit parameters of more complex extended theory if BSM physics is found

SUSY Playground

SUSY Playground



Supersymmetry

Despite of tremendous success, SM also exhibits shortcomings:

- Instability of the Higgs boson mass
- No dark matter candidate
- Unification of gauge couplings impossible
- …

Remedy could be provided by introduction of single additional symmetry:

Bosons ↔ Fermions (Δs=1/2)

Entails introduction of additional particles to SM. Since still undiscovered, SUSY must be broken.

To cure shortcomings of SM, SUSY particles must be light (~ O(1) TeV)

→ LHC and ILC will decide about fate of SUSY

SUSY parameters

Minimal supersymmetric SM (MSSM): 105 (!) new parameters

Most new parameters just parametrise our ignorance about SUSY breaking mechanism

Specific models of SUSY breaking have typically only 5 parameters

Example: mSUGRA:

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

Challenges for parameter fits

Stumbling block: observables ≠ parameters

Observables: masses, asymmetries, rates, …

Parameters: α_s, tan β, M_1, A_τ, ...

Establish mapping

parameters → observables

is straightforward (but achieving highest precision is challenging).

Unfortunately mapping cannot be inverted. Thus constructing mapping

observables → parameters

is cumbersome (→ lots of CO_2).

Tools for SUSY parameter analysis

SUSY/BSM fit programs

MASTERCODE

- Fittino (P. Bechtle, K. Desch, P. Wienemann, *et al.*)
  `http://www-flc.desy.de/fittino`
- SFitter (R. Lafaye, T. Plehn, D. Zerwas, *et al.*)
- Mastercode (O. Buchmüller, R. Cavanaugh, A. De Roeck, S. Heinemeyer, G. Isidori, F. Ronga, G. Weiglein, *et al.*)
- (Gfitter) (H. Flächer, M. Goebel, J. Haller, A. Höcker, K. Mönig, J. Stelzer, *et al.*)
  `http://gfitter.desy.de`
- Various other groups (e. g. B. Allanach *et al.*)

Fittino

- C++ program for SUSY model testing and SUSY parameter analysis
- Currently supported SUSY models:
  mSUGRA, GMSB, AMSB, MSSM24, NMSSM
- Can handle many measurements from low energy experiments, LEP/SLC, Tevatron, cosmology, LHC and LC
- Parameter analysis using full correlation information performed by either:
  - MINUIT
  - Simulated Annealing
  - Markov Chain Monte Carlo (MCMC)
- Theory predictions from `SPheno` (W. Porod), `Mastercode` (O. Buchmüller *et al.*)
- Limits from `HiggsBounds` (P. Bechtle *et al.*)

Iterative parameter analysis

Experiment:

- Measured observables O_i^m
- Errors ΔO_i^m

Output:

- SUSY parameters P_i
- Full error matrix V_{ij}

Obtain start values:

Rough estimates for:

- Parameters P_i
- Errors ΔP_i

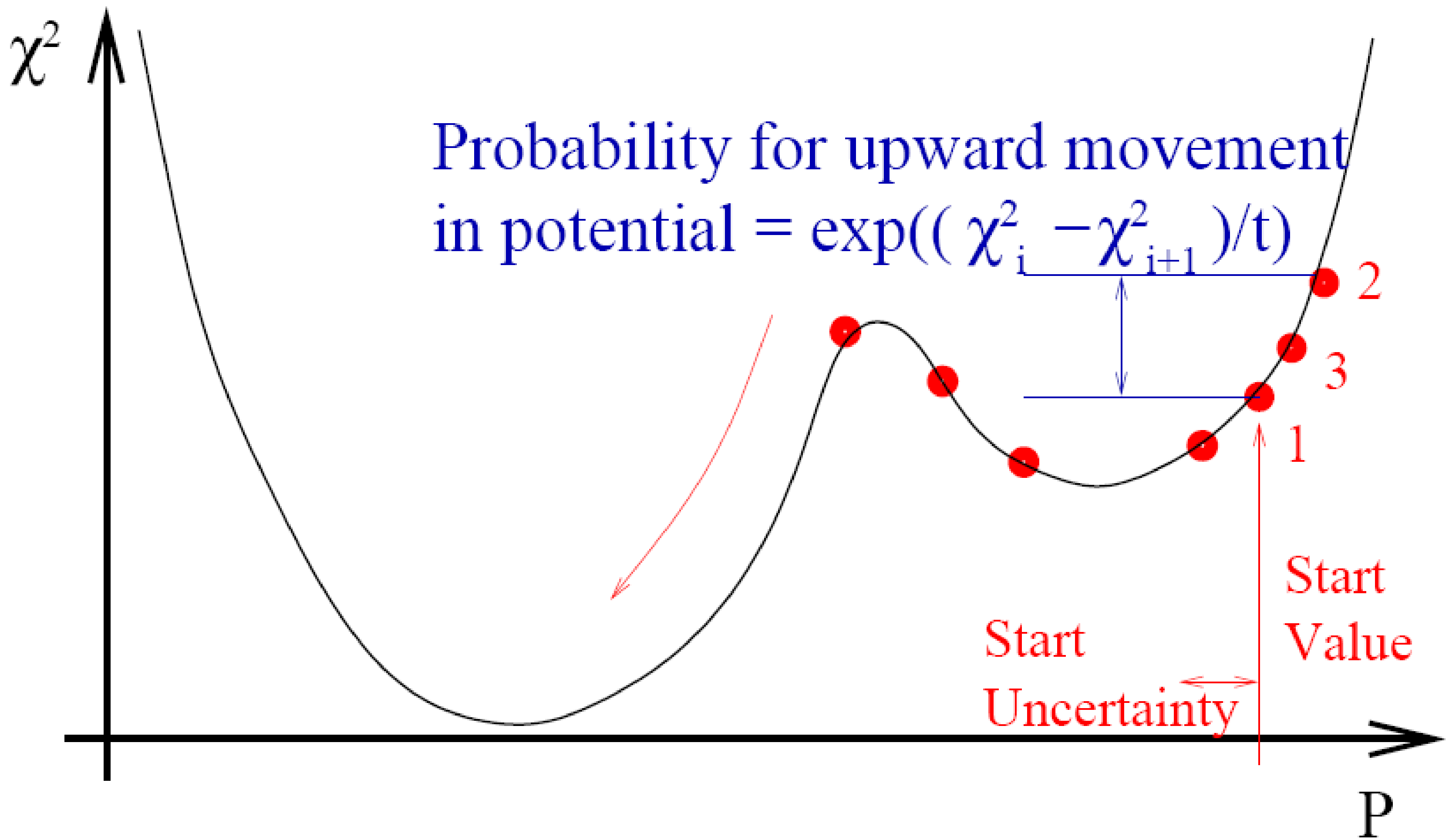
χ^2 fit:
vary P_i

Compare

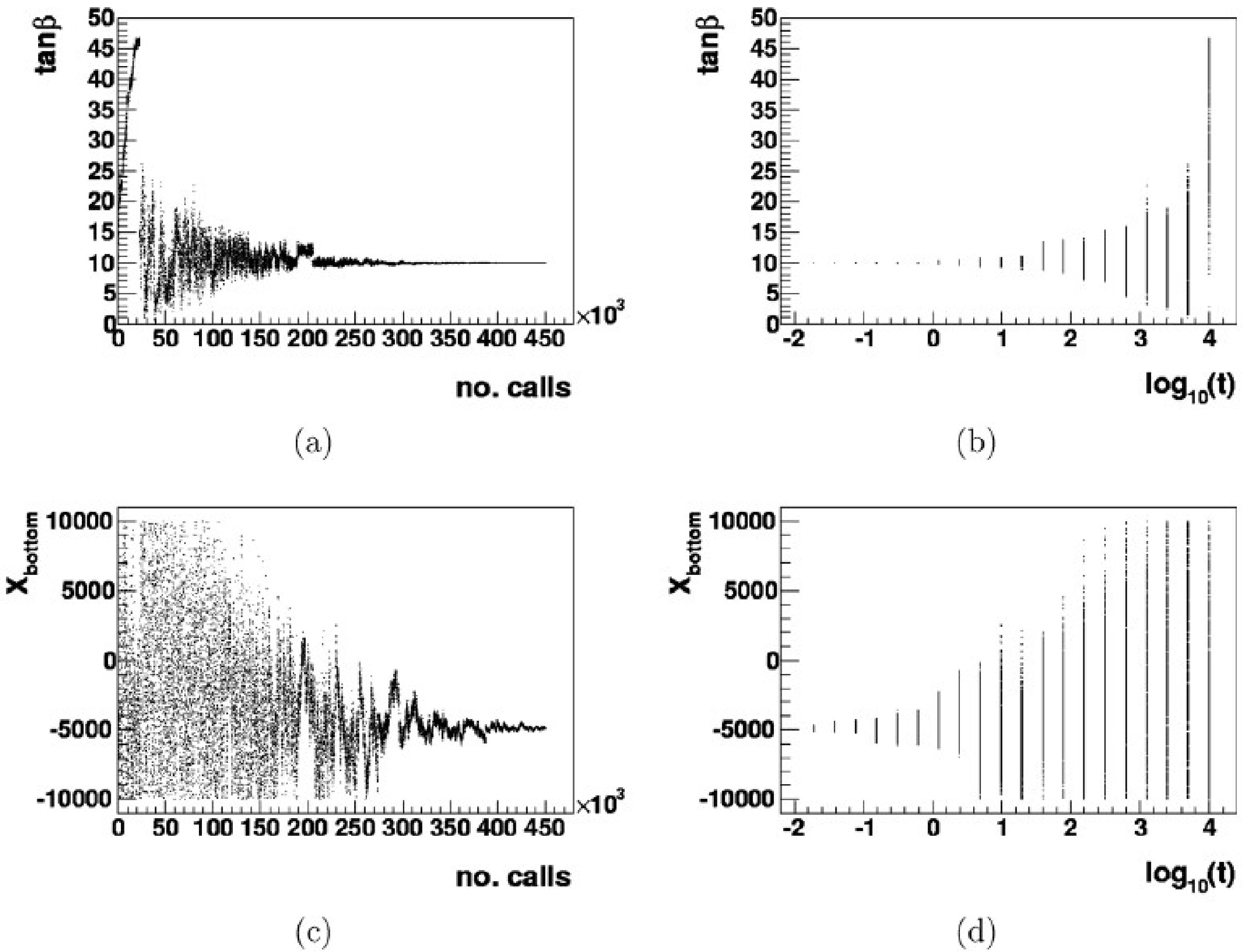
SUSY calculation package:

- Calculated observables O_i^c (including loop corrections)
- Full error matrix W_{ij}

Simulated annealing



Simulated annealing in action



Markov Chain Monte Carlo (MCMC)

Markov chain = sequence of points x_i (i=1,...n) in parameter space

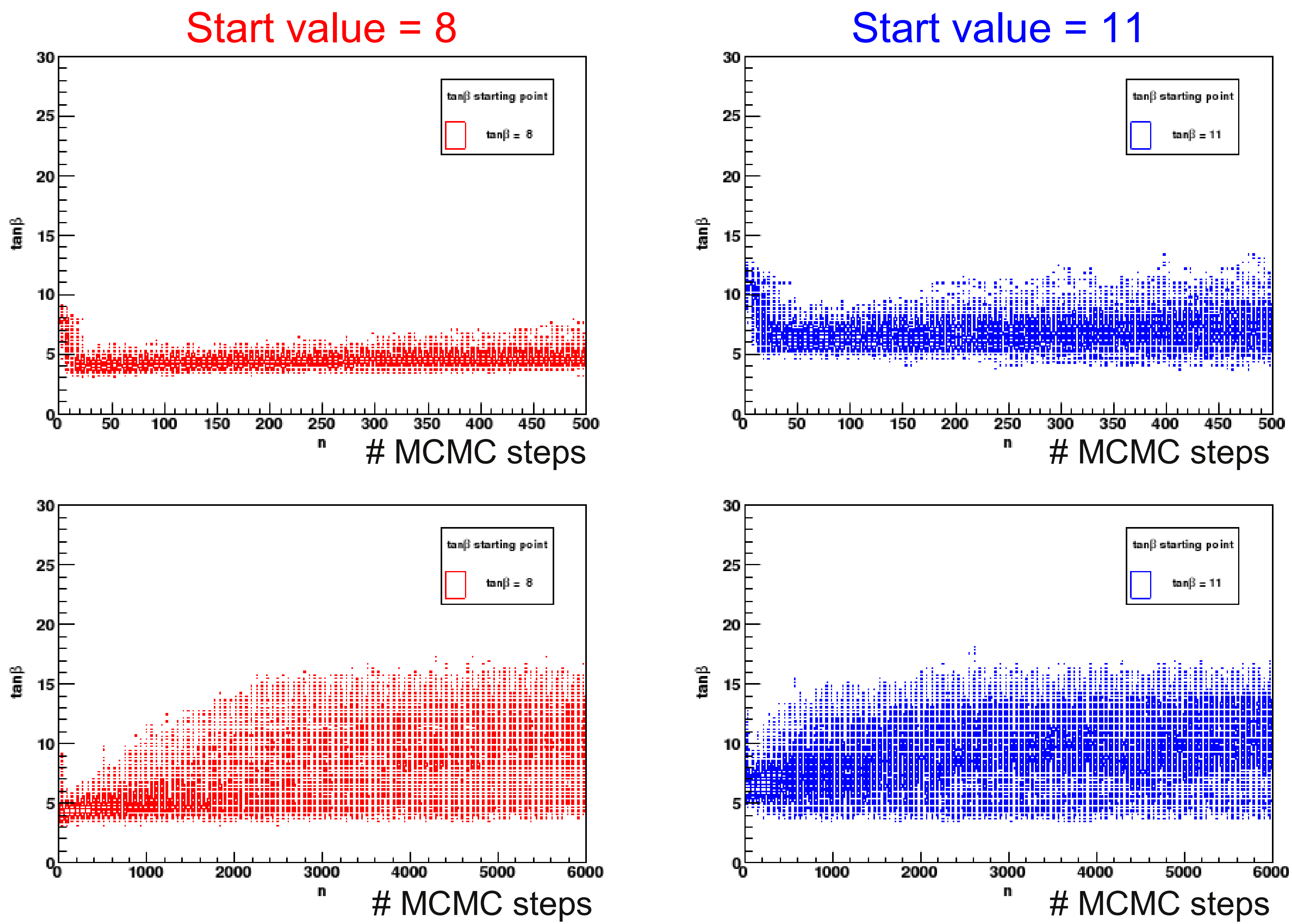
with associated likelihood $\mathcal{L} = \exp\left(-\frac{\chi^2}{2}\right)$

New point x_{n+1} randomly chosen according to proposal PDF is added to chain if $\mathcal{L}(x_{n+1}) > \mathcal{L}(x_n)$

Otherwise it is accepted with probability $\mathcal{L}(x_{n+1})/\mathcal{L}(x_n)$

If proposal PDF is chosen properly, sampling density of points x_i in Markov chain proportional to likelihood

Sampling behaviour of MCMCs

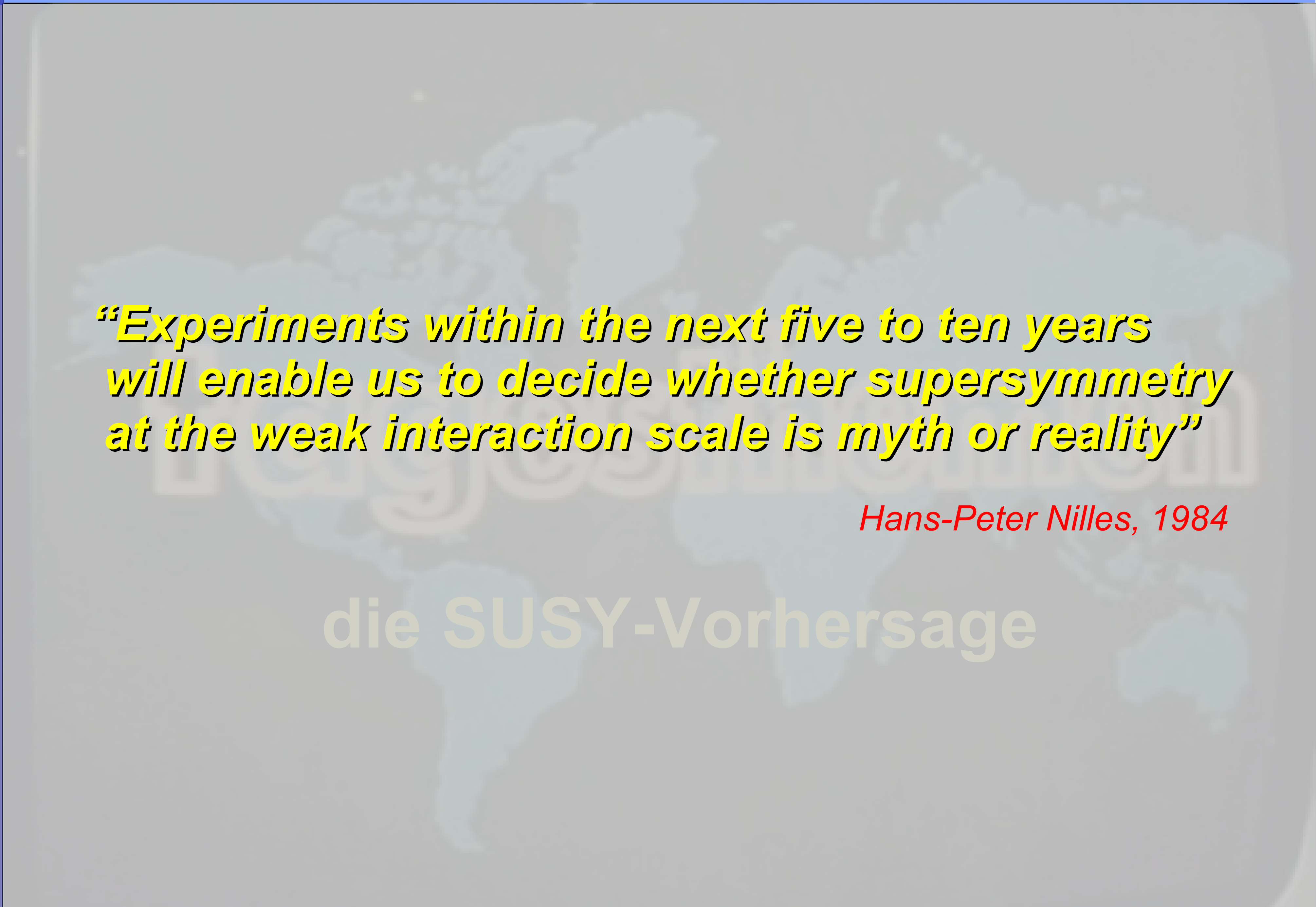


Sufficient chain length essential for unbiased results

SUSY forecast

SUSY forecast 25 years ago

SUSY forecast 25 years ago



"Experiments within the next five to ten years will enable us to decide whether supersymmetry at the weak interaction scale is myth or reality"

Hans-Peter Nilles, 1984

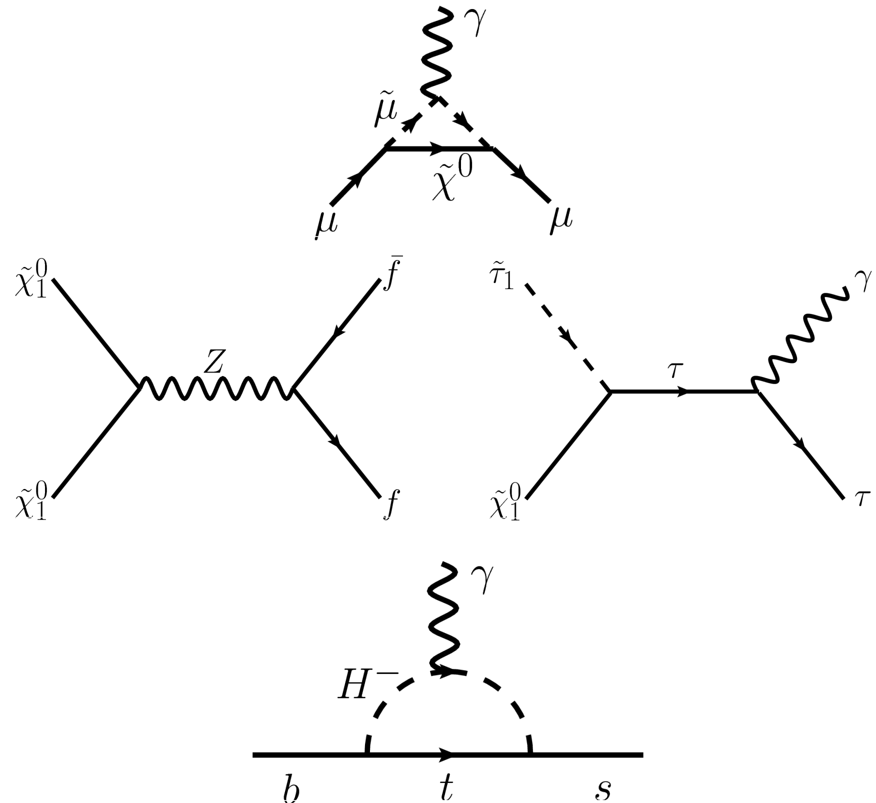
“Low energy” measurements

Can look for SUSY effects in already available data from LEP, Tevatron, SLC, B/K physics, $(g\text{-}2)_\mu$ and astrophysics.

“Low energy” precision observables exhibit sensitivity to SUSY parameters, in particular

Diagram examples:

- $(g\text{-}2)_\mu$
- $\Omega_{CDM}\ h^2$
- $BR(b \to s\ \gamma)$

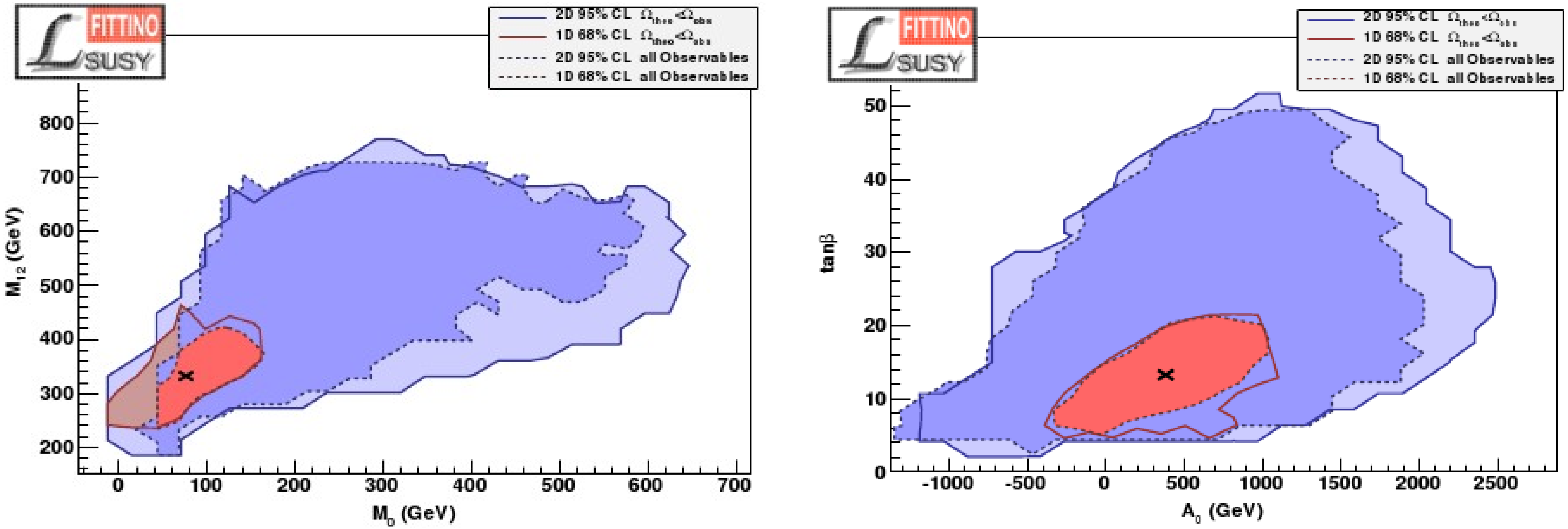


Complete LE observable list

Observable	Experimental Value	Uncertainty		Exp. Reference
		stat	syst	
$\mathcal{B}(B \to s\gamma)/\mathcal{B}(B \to s\gamma)_{\rm SM}$	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]

LE: mSUGRA parameters

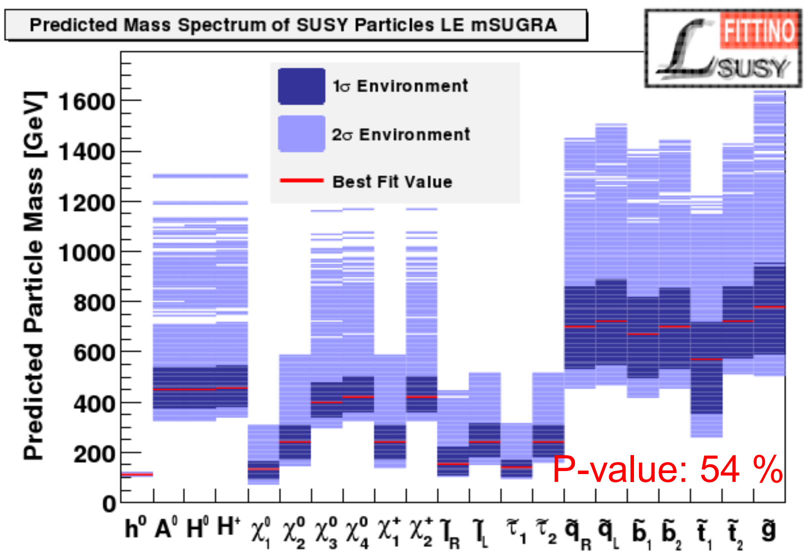
Fit of mSUGRA parameters to 35 LE measurements:



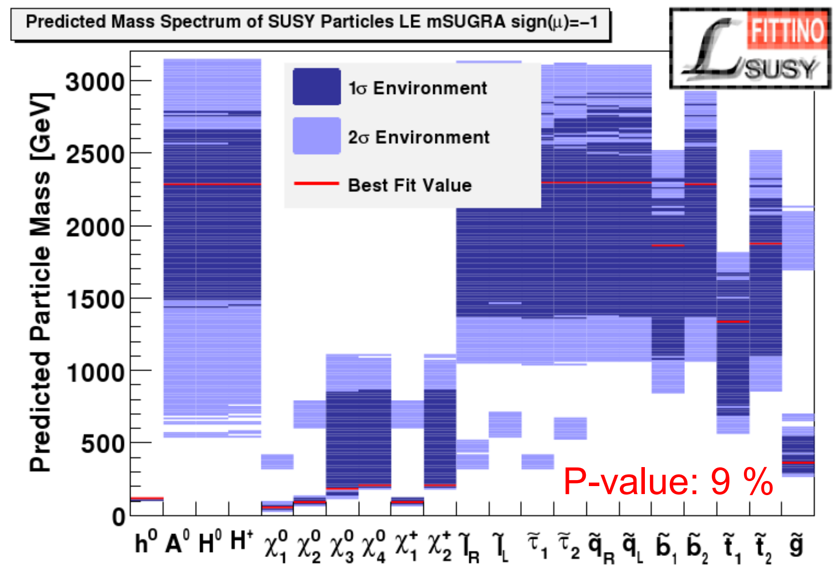
LE data favours light SUSY (consistent with findings by MASTERCODE group)

LE: Predicted mass spectra

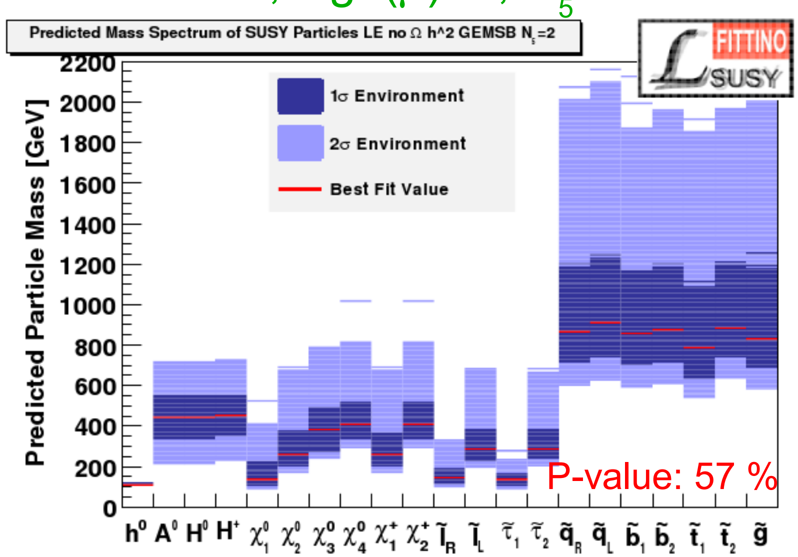
mSUGRA, sign(μ)>0:



mSUGRA, sign(μ)<0:



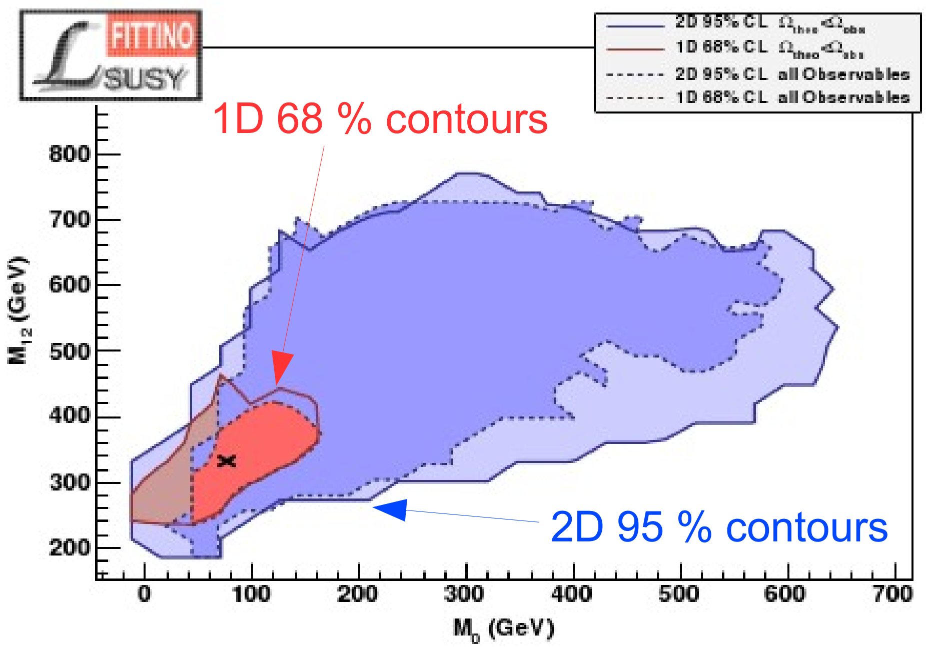
GMSB, sign(μ)>0, N_5 = 2:



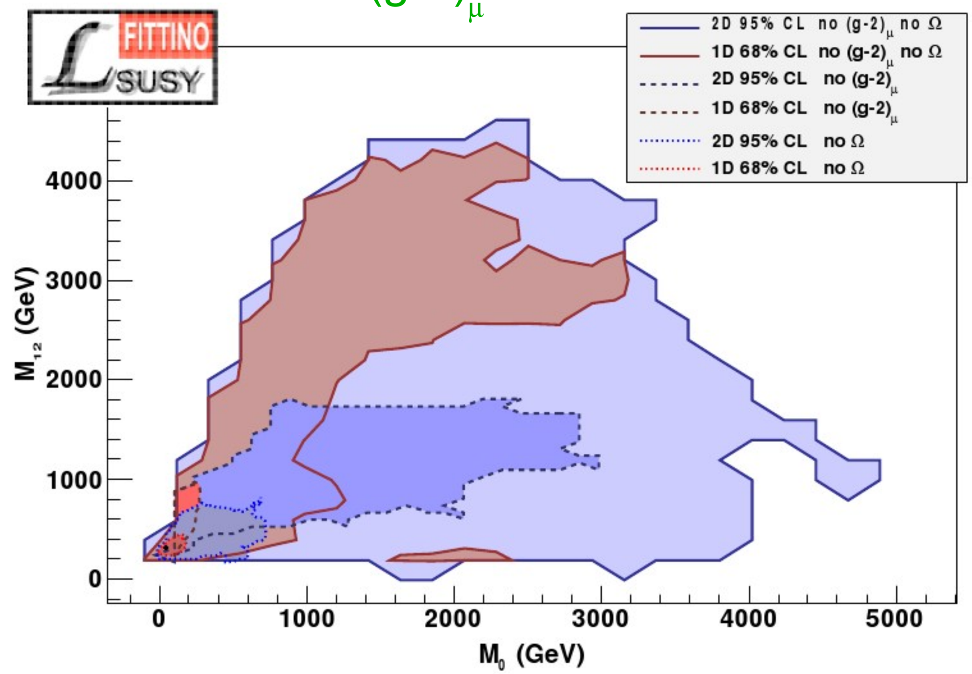
Light SUSY particles favoured

LE: Impact of individual observables

Fits with all observables:

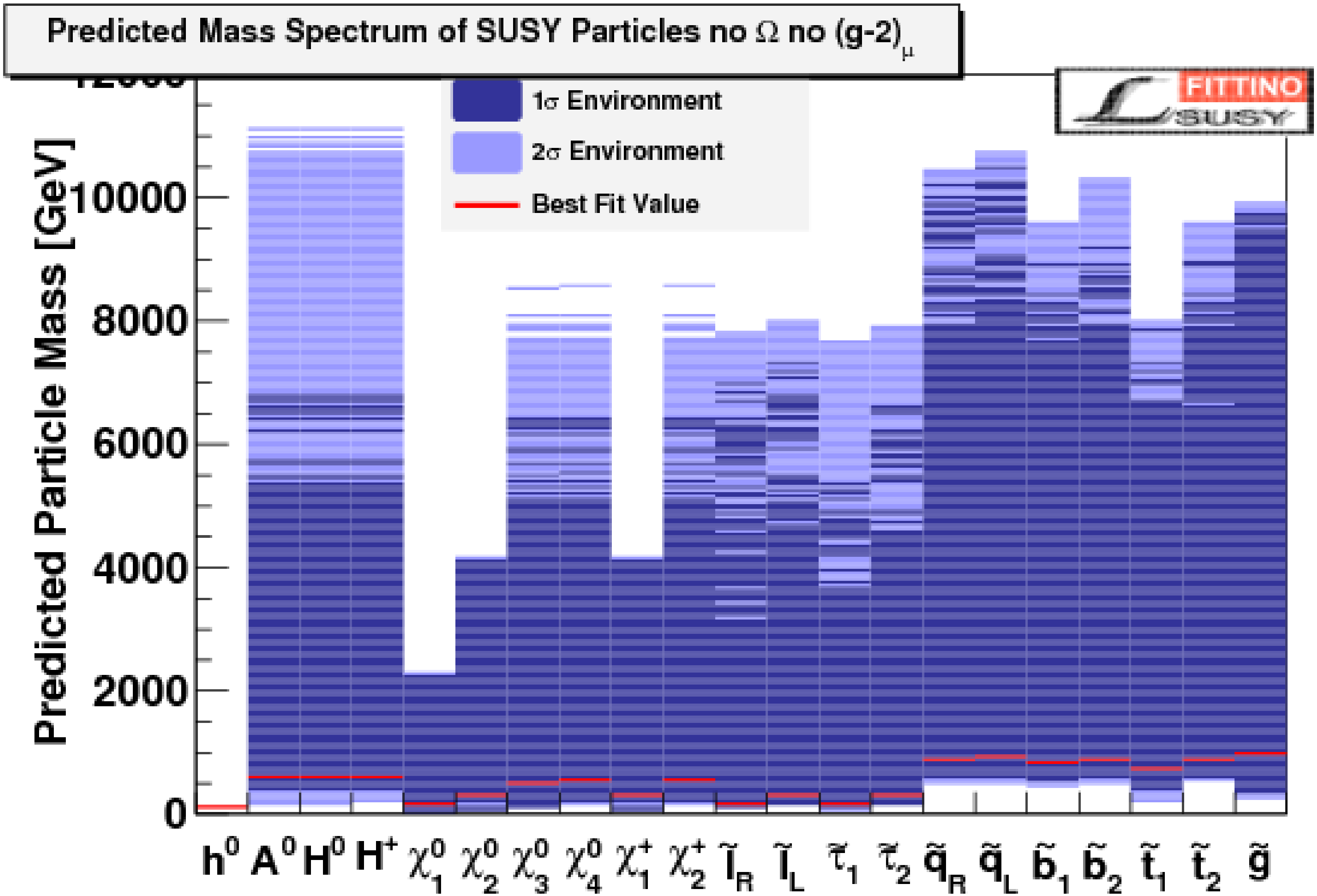


Fits without $(g\text{-}2)_\mu$ or/and Ωh^2:

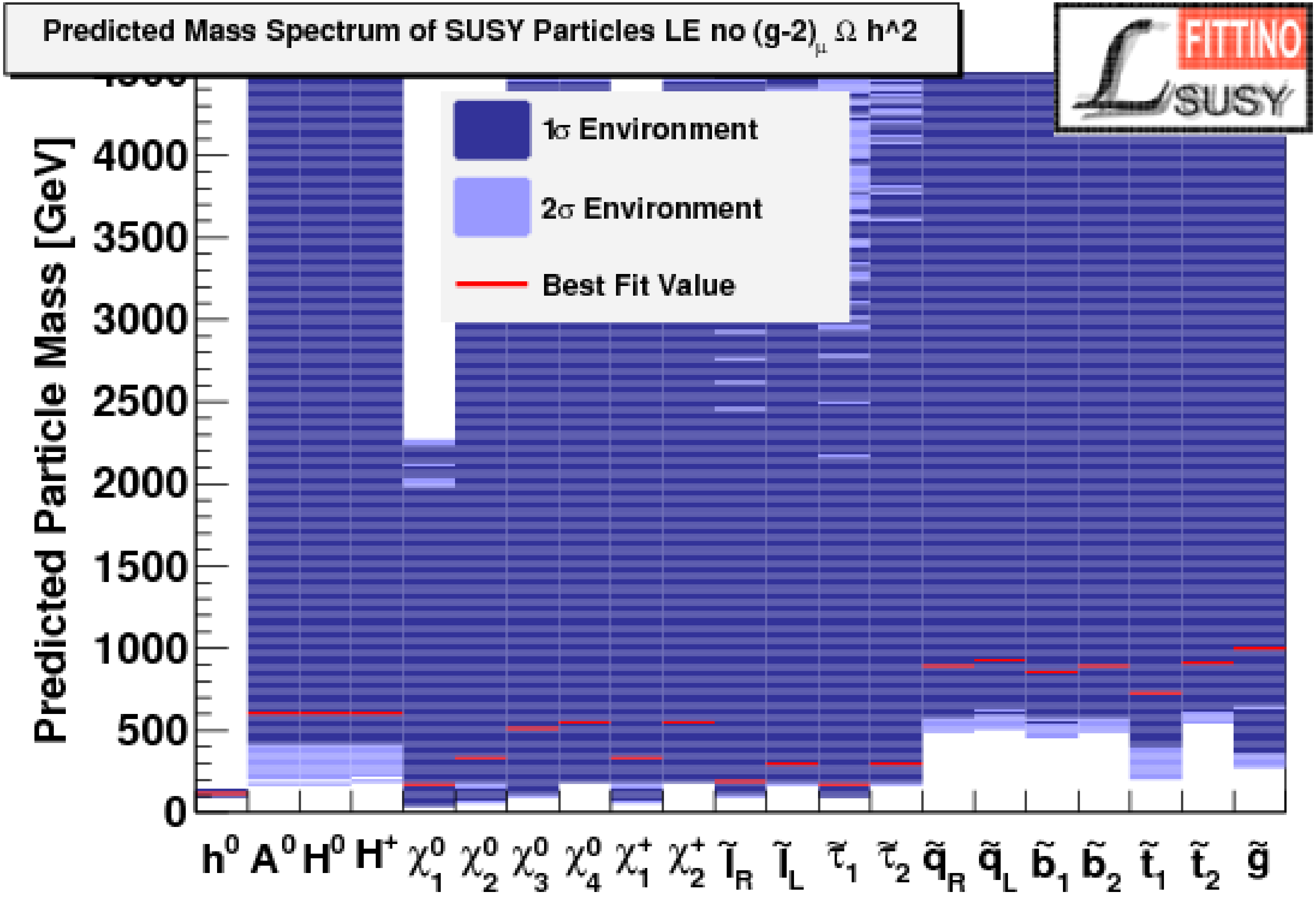


- Preferred region rather stable
- $(g\text{-}2)_\mu$ and to lesser extent Ωh^2 most constraining

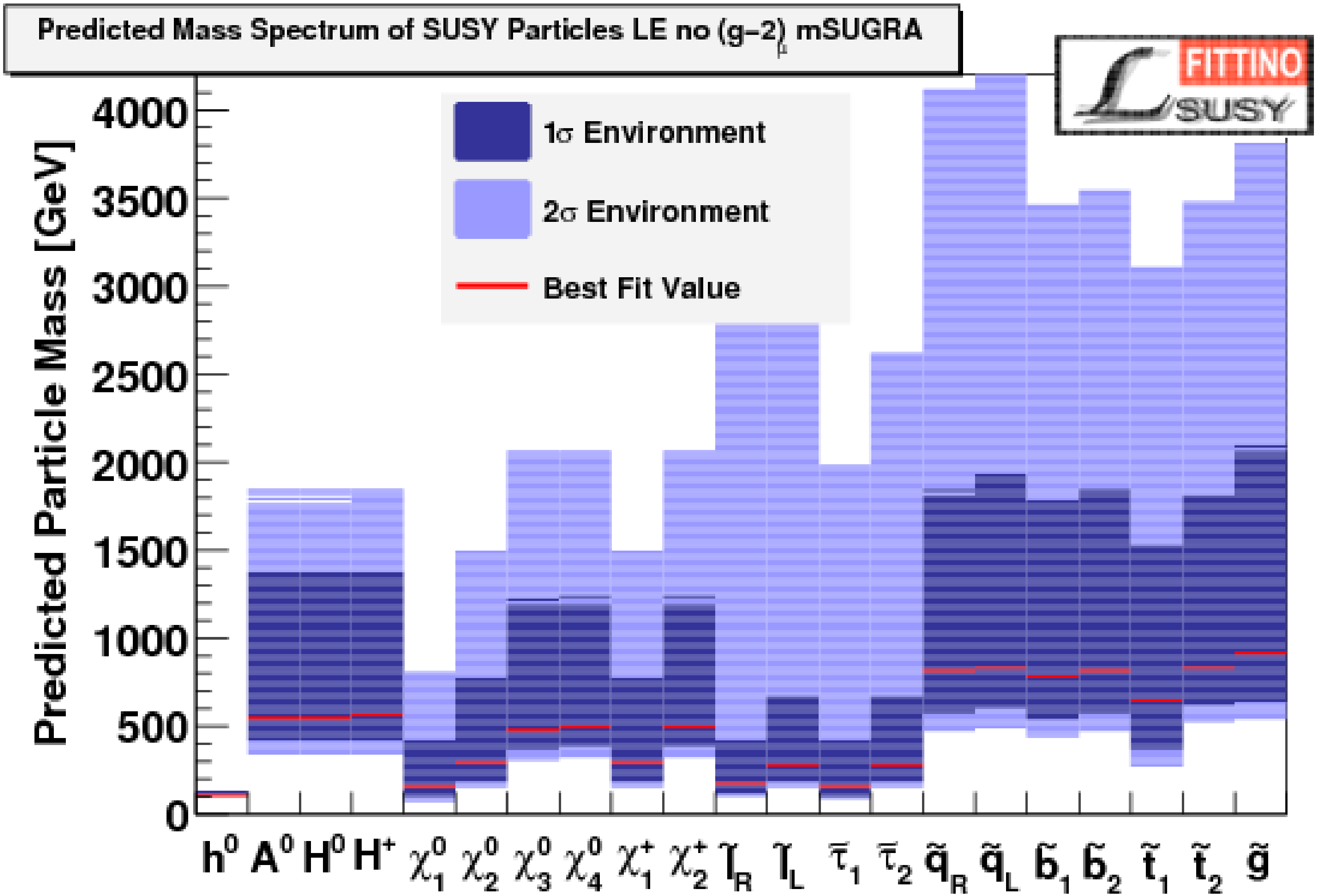
LE: Impact of individual observables



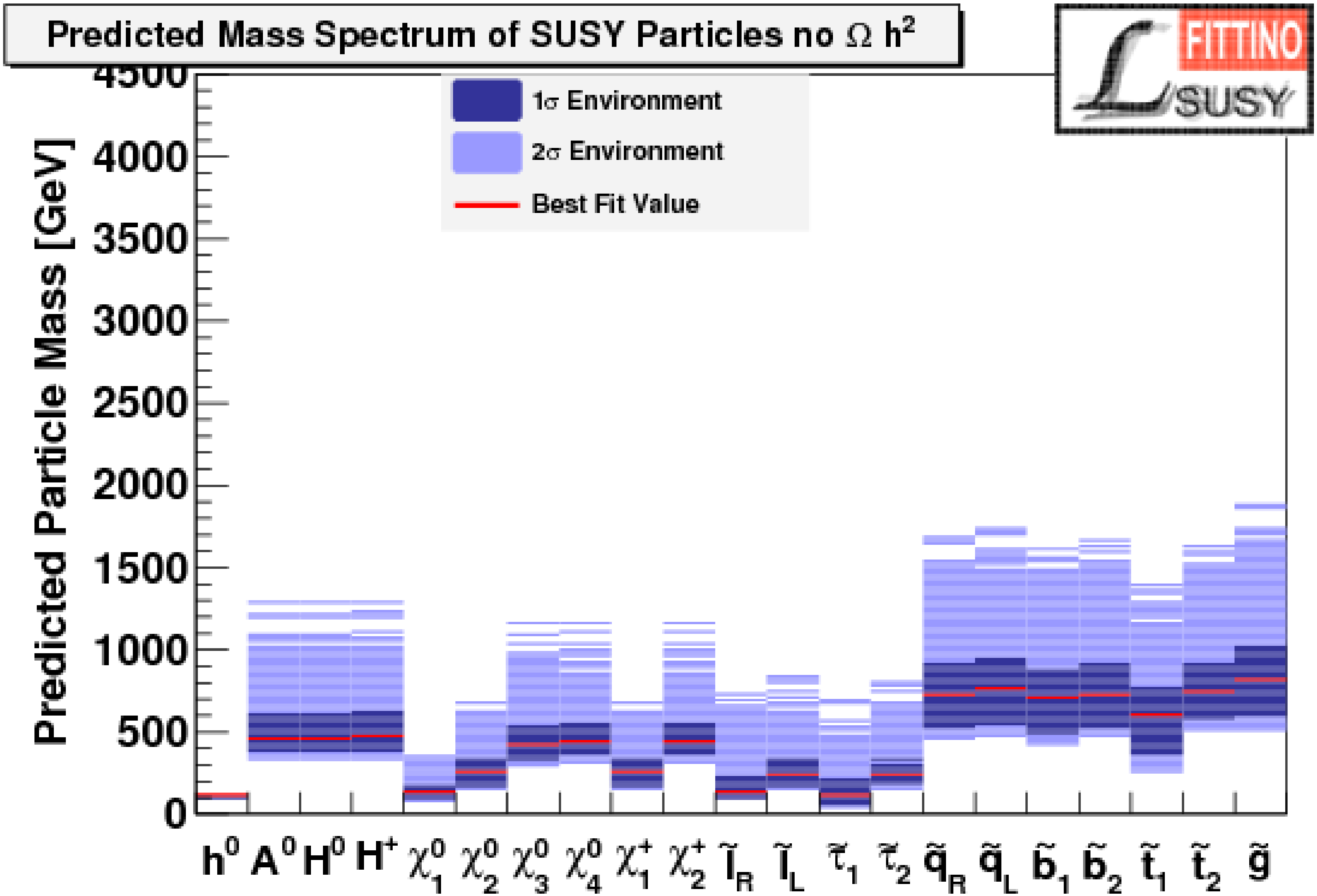
LE: Impact of individual observables



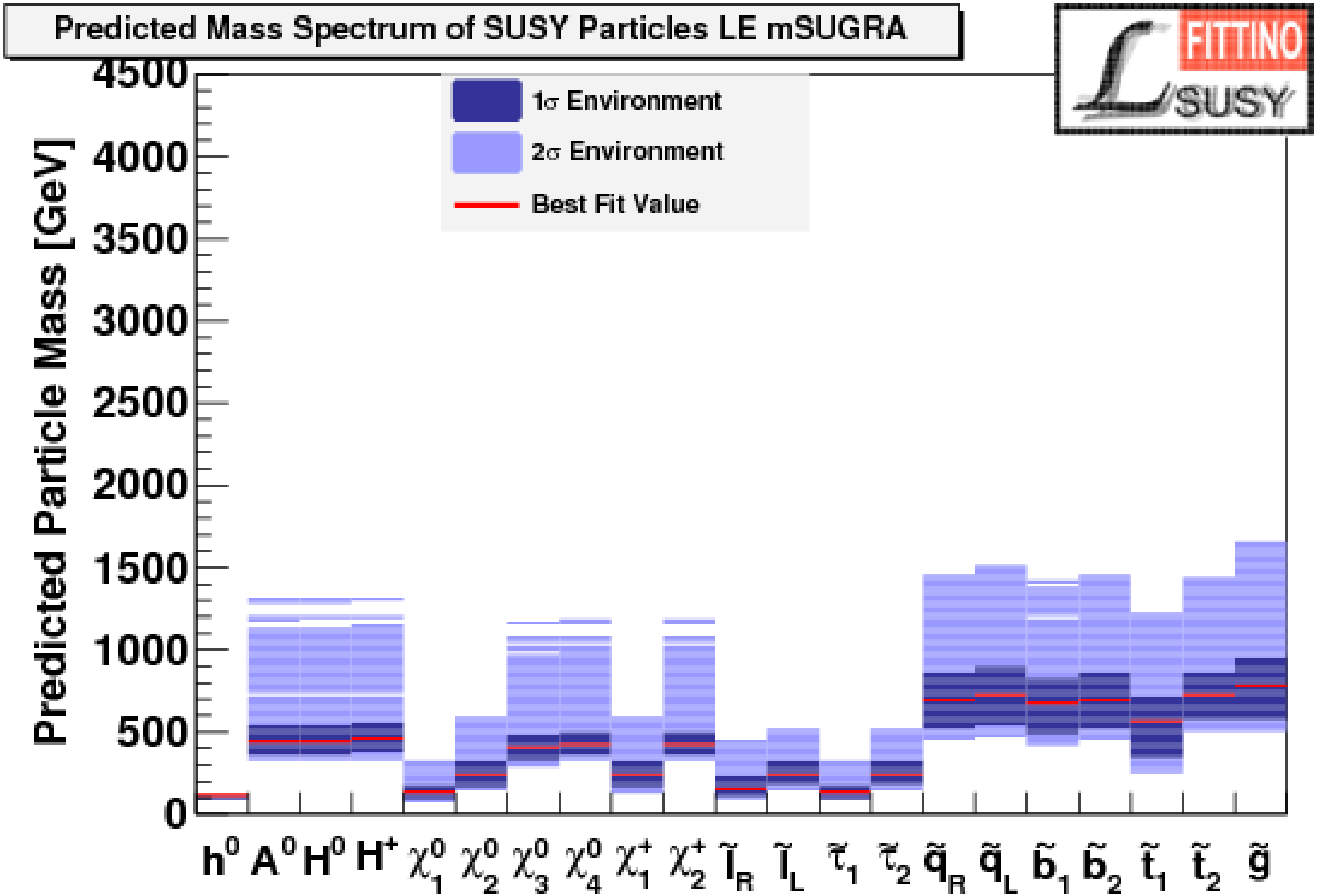
LE: Impact of individual observables



LE: Impact of individual observables



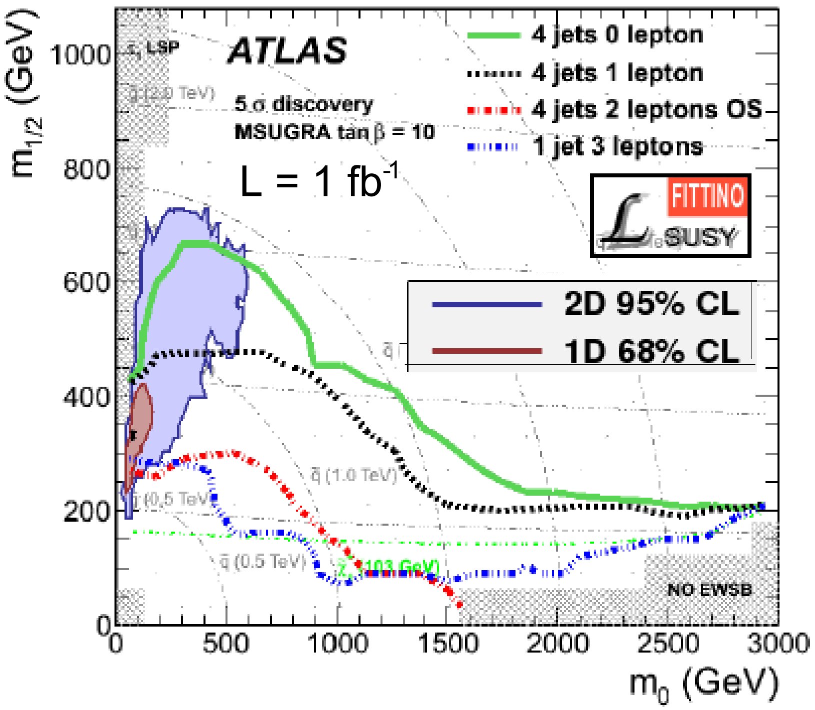
LE: Impact of individual observables

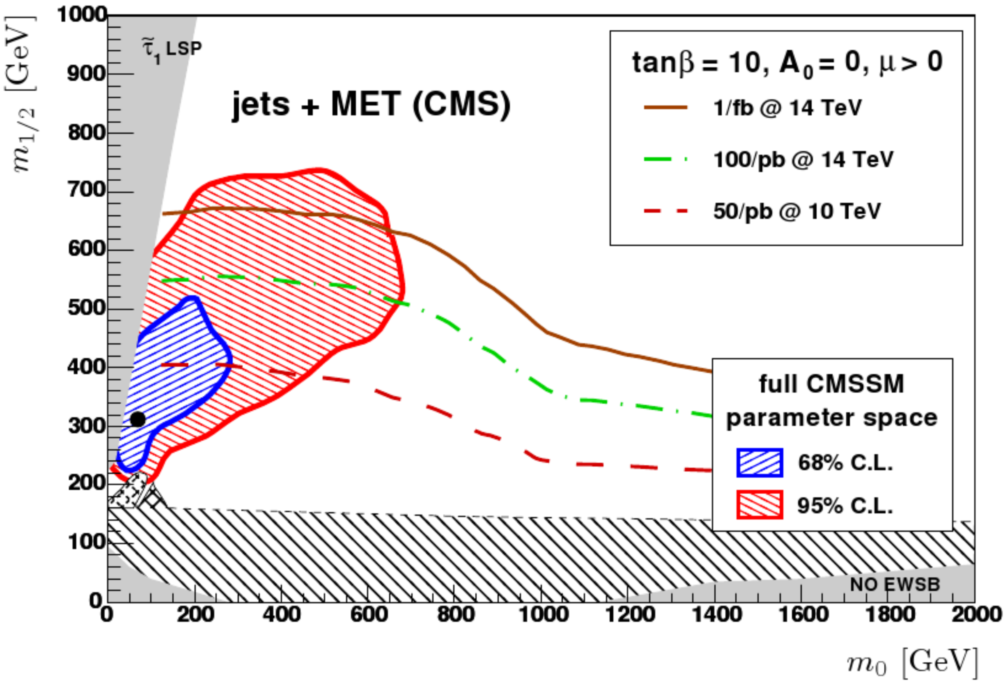


LE: Comparison with LHC potential

Bechtle, Desch, Uhlenbrock, Wienemann

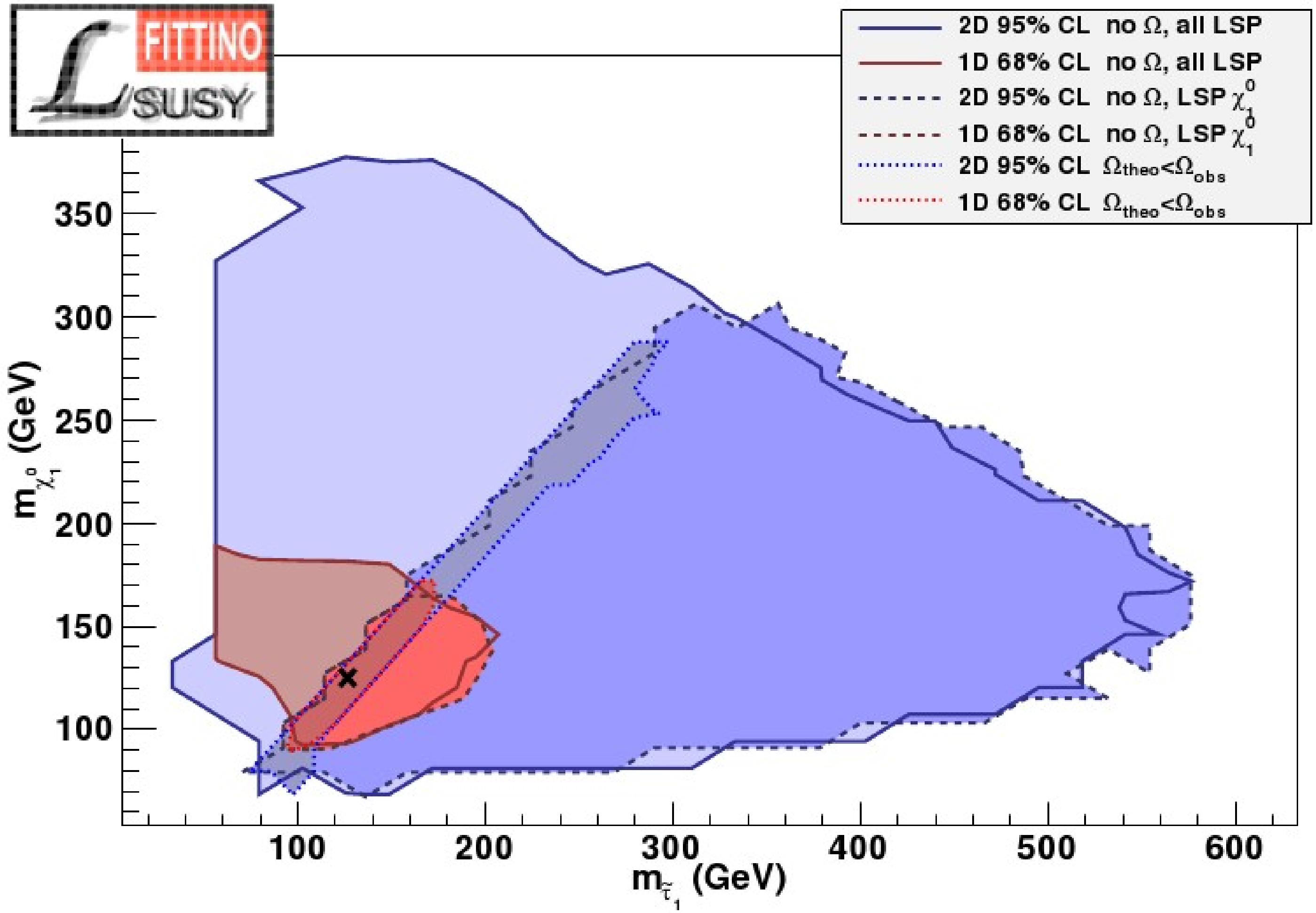
Buchmüller, et al.





Good prospects for early BSM hints at LHC

LE: Predicted LSP and NLSP masses



- DM relic density prefers co-annihilation region
- Seeing excess might be easy, measuring certain processes might be more difficult (soft taus!)

Projection to LHC

Fit result of mSUGRA fit to LE data accidentally close to experimentally well studied SUSY benchmark point:

				SPS1a values
$\tan\beta$	13.2	$\pm$	7.2	10
$M_{1/2}$ (GeV)	331.5	$\pm$	86.6	250
M_0 (GeV)	76.2		$^{+79.2}_{-29.1}$	100
A_0 (GeV)	383.8	$\pm$	647	-100

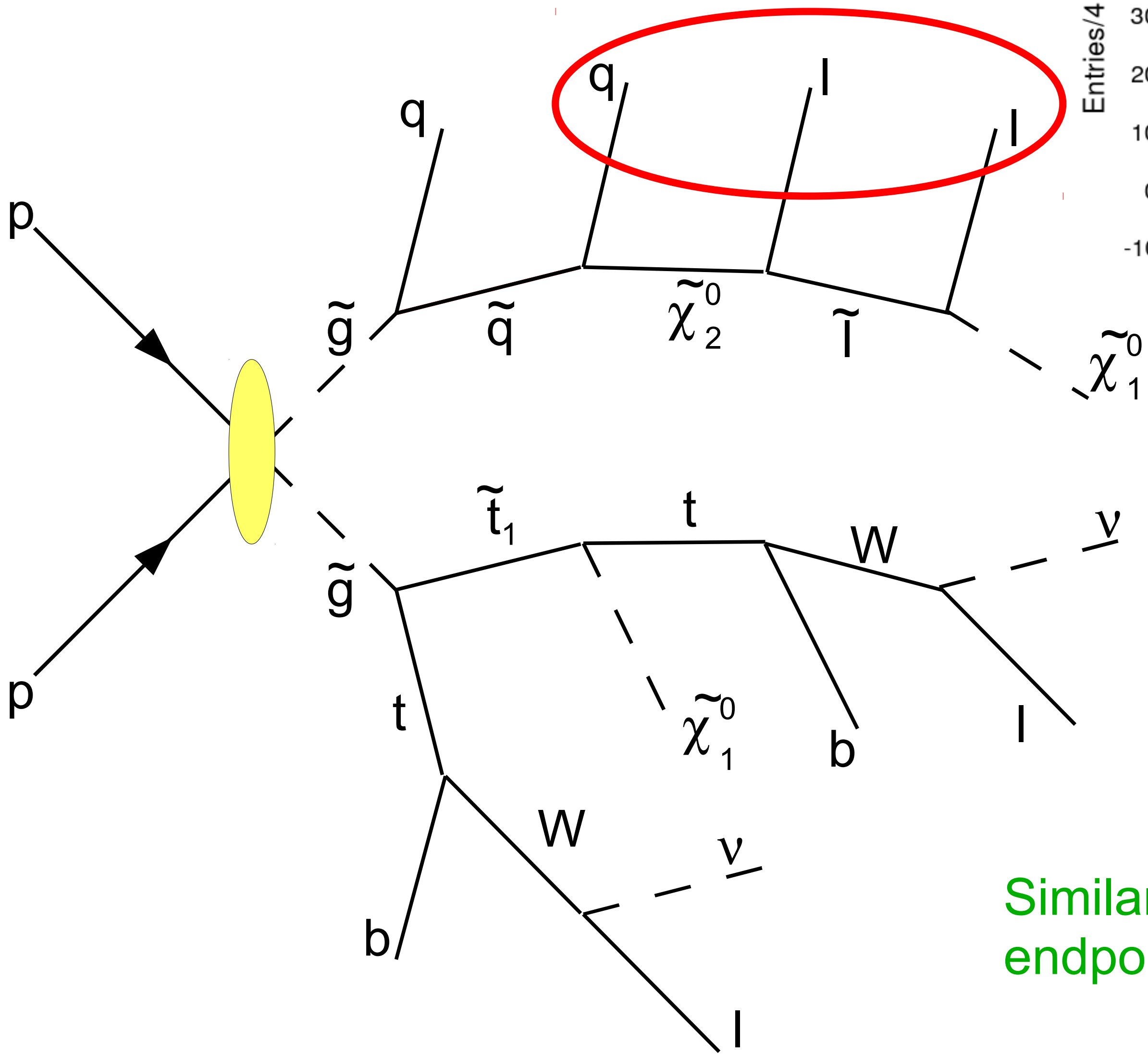
→ dare projection to LHC era based on SPS1a studies

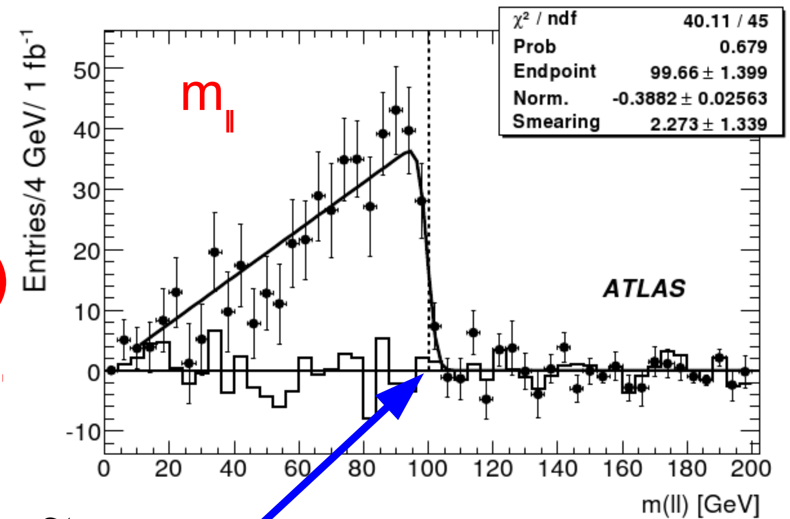
Understanding SUSY

SUSY mass reconstruction at LHC

No mass peaks due to 2 escaping LSPs
if R-parity conservation

Most important mass information source:





Endpoint sensitive to SUSY masses:

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

Similar formulae for other endpoints, e. g. m_{llq} , m_{lq}^{min} , m_{lq}^{max} , ...

LHC observable list

Observable	Nominal Value	Uncertainty 1 fb^{-1}	10 fb^{-1}	300 fb^{-1}	LES$_1$	LES$_{10,300}$	JES$_1$	JES$_{10,300}$	syst.
m_h	109.6		1.4	0.1		0.1			
m_t	172.4	1.1	0.05	0.01			1.5	1.0	
$m_{\tilde{\chi}_1^\pm}$	180.2			11.4				1.8	
$\sqrt{m_{\tilde{\ell}_L}^2 - 2m_{\tilde{\chi}_1^0}^2}$	148.8			1.7		0.1			6.0
$m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$	507.7		13.7	2.5				5.1	10.0
$\sqrt{m_{\tilde{q}_R}^2 - 2m_{\tilde{\chi}_1^0}^2}$	531.0	19.6	6.2	1.1			22.7	4.5	10.0
$m_{\tilde{g}} - m_{\tilde{b}_1}$	88.7			1.5				0.9	
$m_{\tilde{g}} - m_{\tilde{b}_2}$	56.8			2.5				0.6	
$m_{\ell\ell}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R})$	80.4	1.7	0.5	0.03	0.16	0.08			
$m_{\ell\ell}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_4^0}, m_{\tilde{\ell}_L})$	280.6		12.6	2.3		0.28			
$m_{\tau\tau}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\tau}_1})$	83.4	12.6	4.0	0.73			4.2	0.8	5.7
$m_{\ell\ell q}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{q}_L}, m_{\tilde{\chi}_2^0})$	452.1	13.9	4.2	1.4			22.7	4.5	
$m_{\ell q}^{\text{low}}(m_{\tilde{\ell}_R}, m_{\tilde{q}_L}, m_{\tilde{\chi}_2^0})$	318.6	7.6	3.5	0.9			16.2	3.2	
$m_{\ell q}^{\text{high}}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R}, m_{\tilde{q}_L})$	396.0	5.2	4.5	1.0			19.9	4.0	
$m_{\ell\ell q}^{\text{thres}}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R}, m_{\tilde{q}_L})$	215.6	26.5	4.8	1.6			10.8	2.2	
$m_{\ell\ell b}^{\text{thres}}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R}, m_{\tilde{b}_1})$	195.9		19.7	3.6				2.0	
$m_{tb}^{\text{w}}(m_t, m_{\tilde{t}_1}, m_{\tilde{\chi}_1^\pm}, m_{\tilde{g}}, m_{\tilde{b}_1})$	359.5	43.0	13.6	2.5			18.0	3.6	
$\frac{\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell) \times \mathcal{B}(\tilde{\ell}_R \to \tilde{\chi}_1^0 \ell)}{\mathcal{B}(\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau) \times \mathcal{B}(\tilde{\tau}_1 \to \tilde{\chi}_1^0 \tau)}$	0.076	0.009	0.003	0.001					0.008
$\frac{\mathcal{B}(\tilde{g} \to \tilde{b}_2 b) \times \mathcal{B}(\tilde{b}_2 \to \tilde{\chi}_2^0 b)}{\mathcal{B}(\tilde{g} \to \tilde{b}_1 b) \times \mathcal{B}(\tilde{b}_1 \to \tilde{\chi}_2^0 b)}$	0.168			0.078					

Caveat emptor:

- No decay chain ambiguities considered
- Uncertainties on theoretical calculations (mostly) not considered
- Mostly no information on LHC production rates

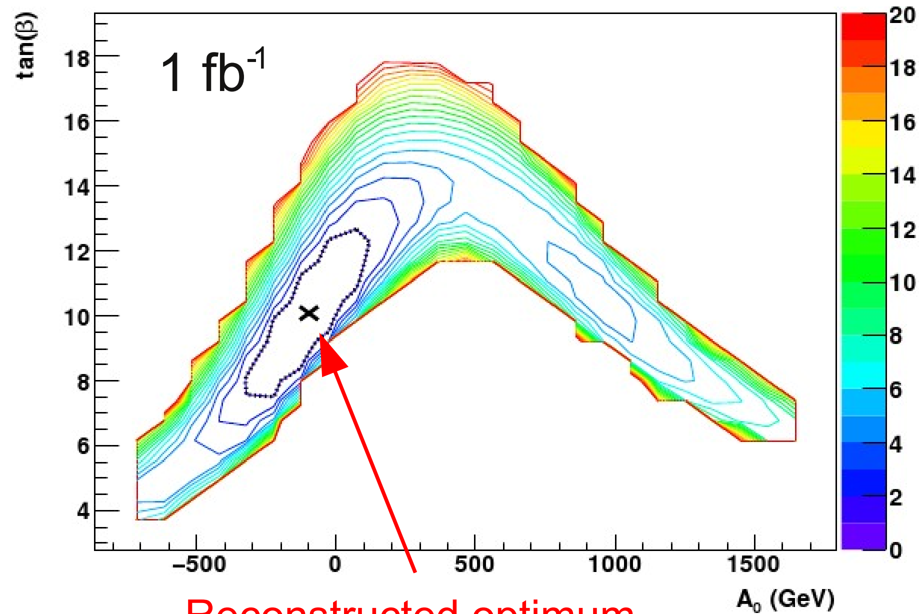
LHC: mSUGRA parameters

Likelihood maps for mSUGRA parameters, sign(μ) fixed to +

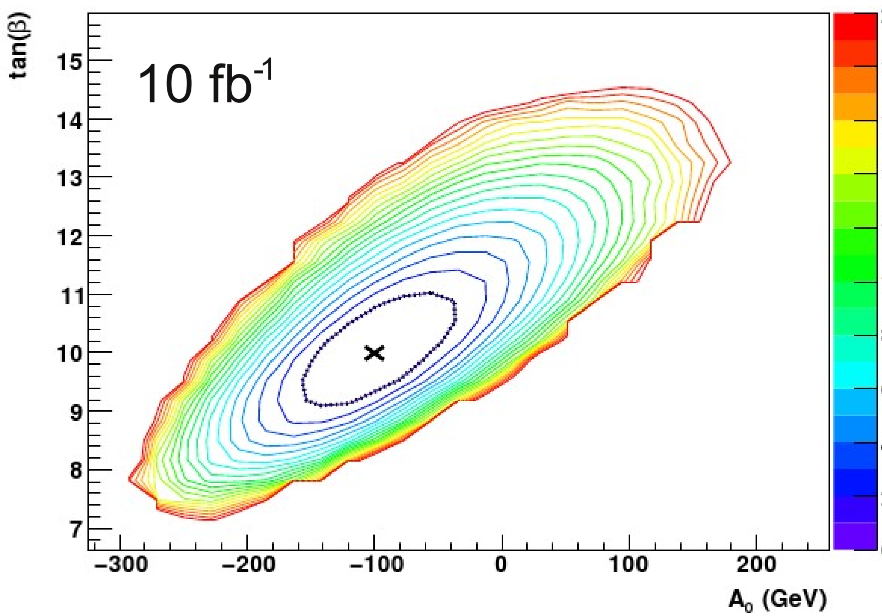
Plots show contours of
$$2\ln(\mathcal{L}_{\max}/\mathcal{L})$$

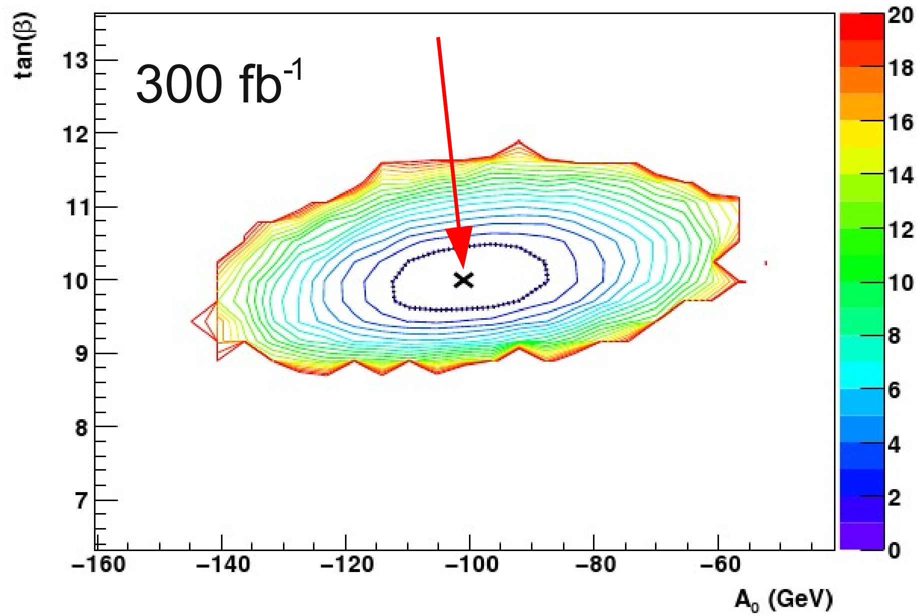
Note different scales!

SPS1a: tan β = 10, A_0 = -100 GeV



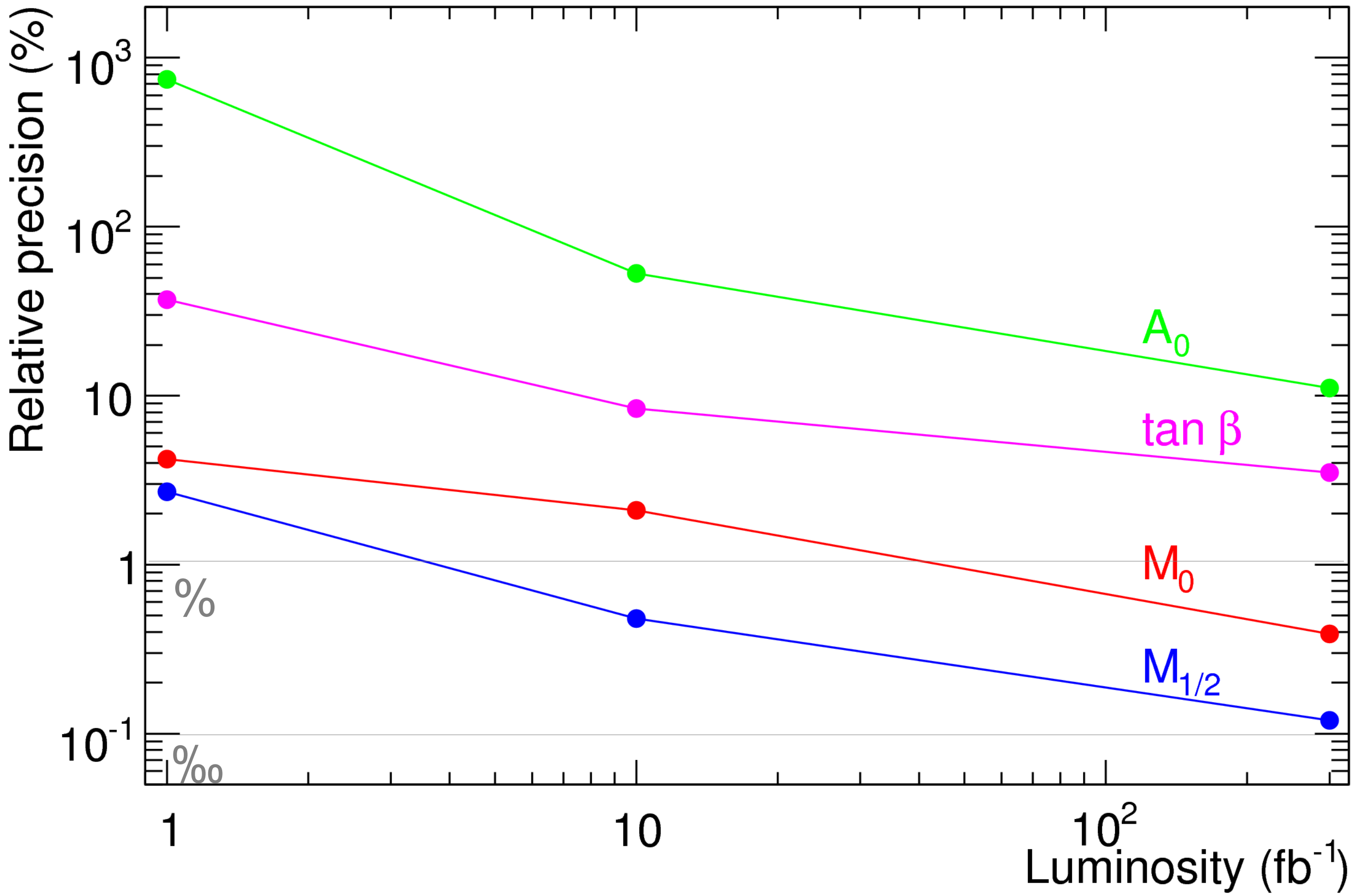
Reconstructed optimum





LHC: mSUGRA parameters vs. luminosity

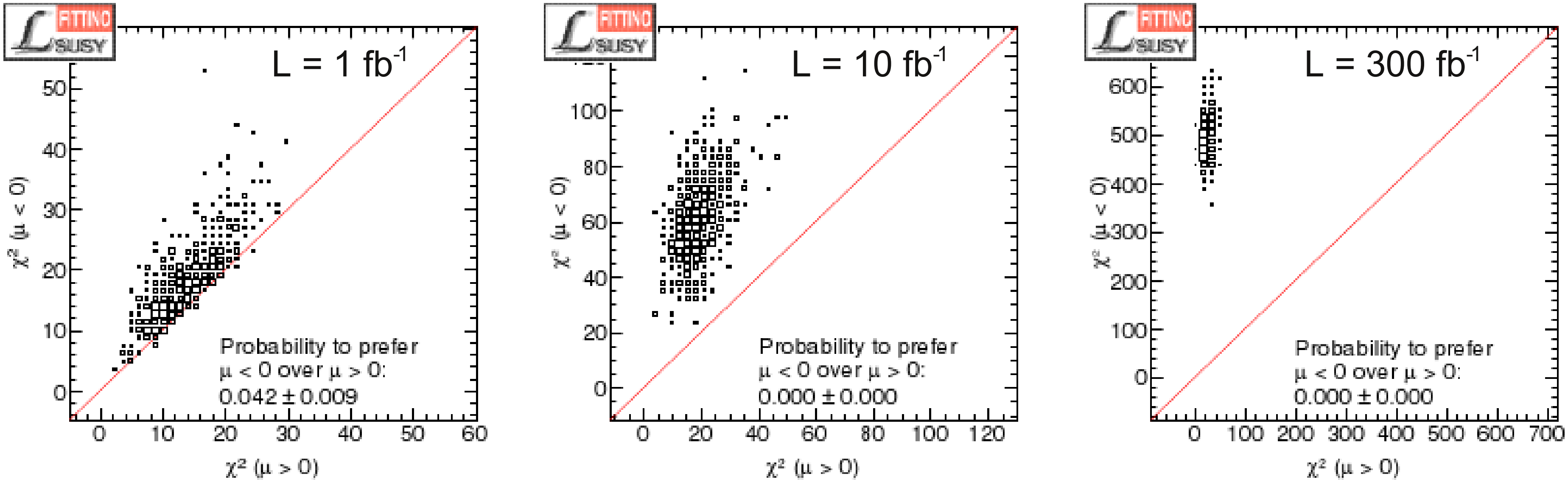
Precision on mSUGRA parameters for 1, 10 and 300 fb^{-1}:



LHC: sign(μ)

Perform fits to toy datasets generated by smearing observables within uncertainties

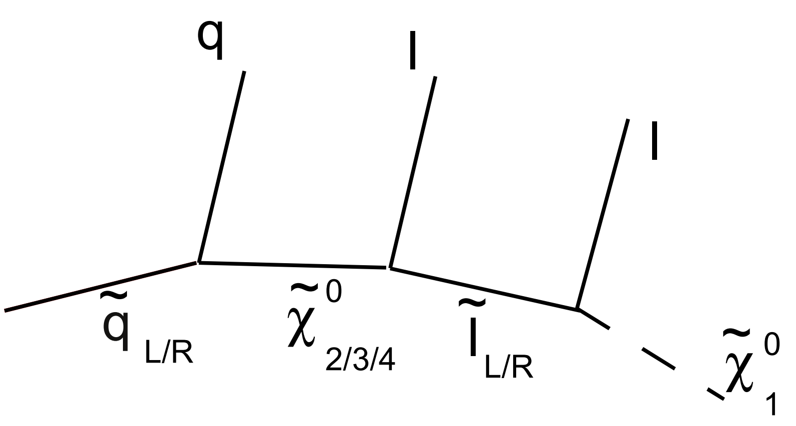
χ^2 correlations for fits with sign(μ)>0 and sign(μ)<0 to same toy dataset:



Any discrete “degree of freedom” (parameter, ambiguity, …) can be treated this way

LHC: Impact of decay chain ambiguities

Certain final states at LHC cannot be unambiguously assigned to single decay chain



Approach: Perform toy fits for all possibilities and choose best fit (smallest χ^2)

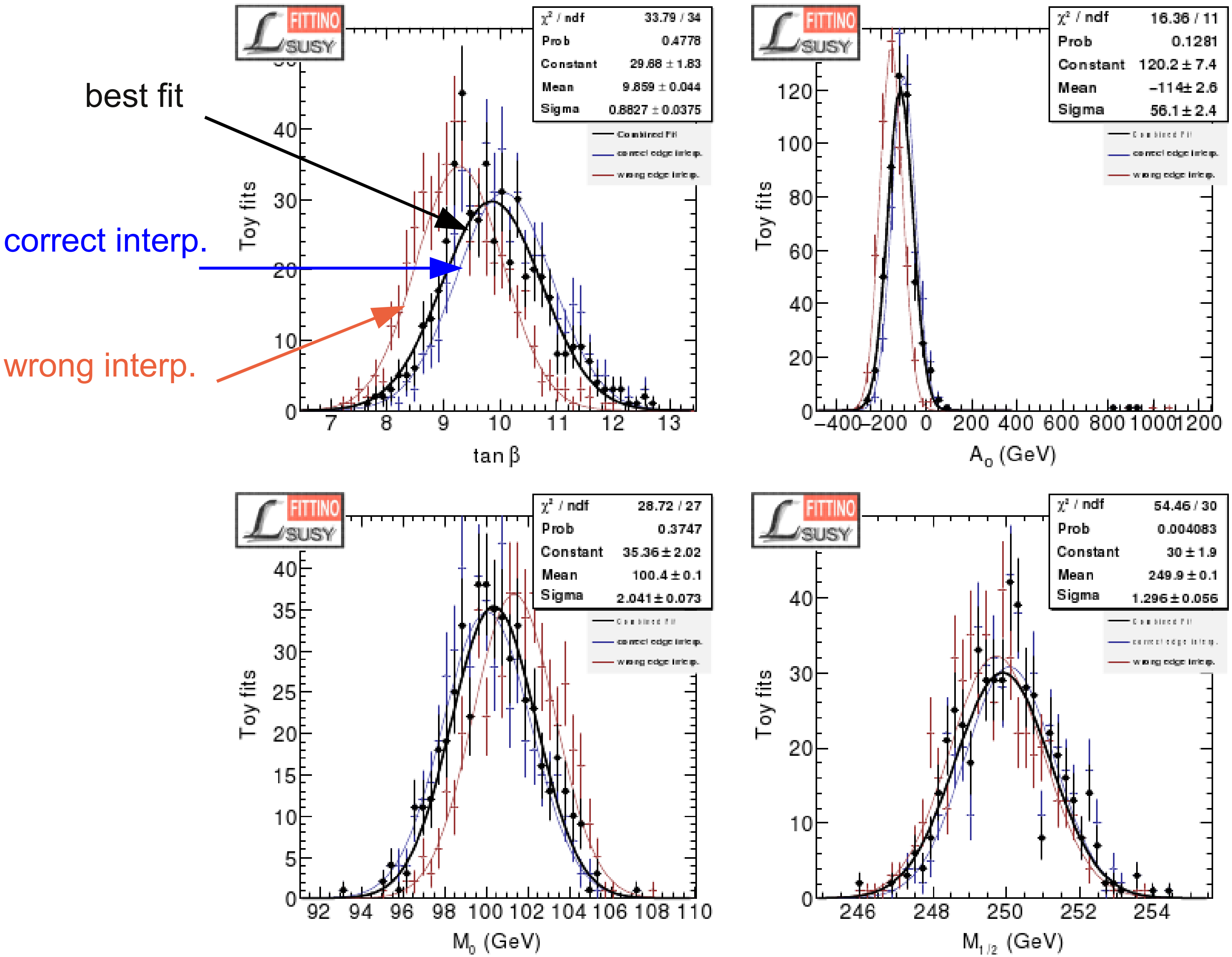
Proof-of-principle: Consider following two-fold ambiguity

correct interpretation: $m_{\ell\ell}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_4^0}, m_{\tilde{\ell}_L})$

wrong interpretation: $m_{\ell\ell}^{\max}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_4^0}, m_{\tilde{\ell}_R})$

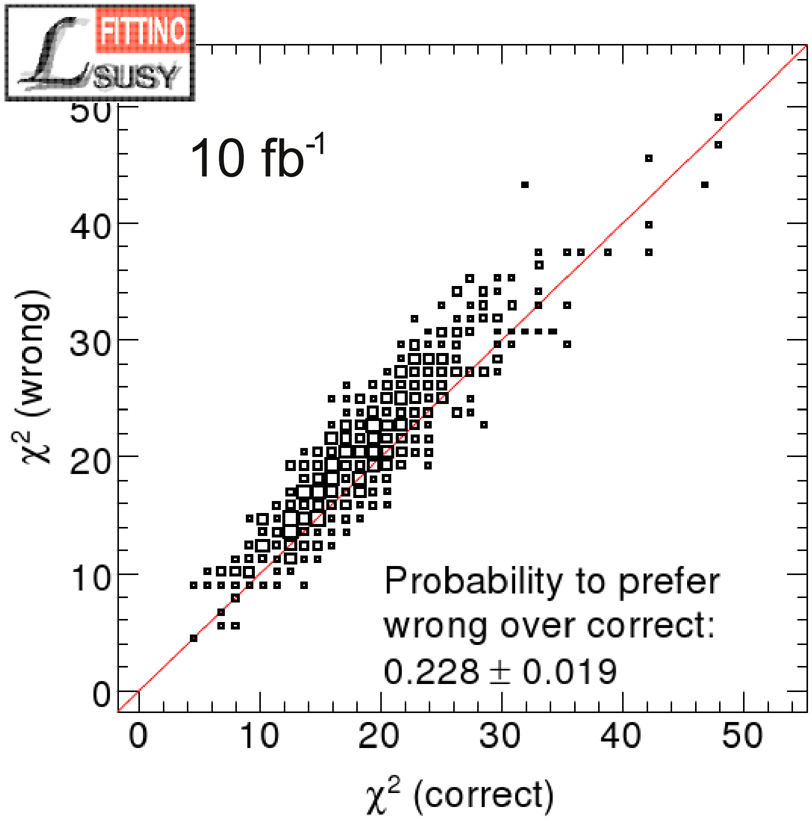
LHC: Impact of decay chain ambiguities

Distribution of fitted parameters from toy fits (10 fb^{-1}):



LHC: Impact of decay chain ambiguities

Probability to choose right or wrong interpretation can be obtained again from χ^2 correlation for fits with correct and wrong interpretation to same toy dataset:



Role of LE measurements in LHC era

LHC (1 fb^{-1}):

Parameter	Best Fit		Uncertainty
sign(μ)	+1		
$\tan\beta$	9.1	$\pm$	3.7
A_0 (GeV)	−131.8	$\pm$	742.1
M_0 (GeV)	100.2	$\pm$	4.2
$M_{1/2}$ (GeV)	249.7	$\pm$	6.7

LE+LHC (1 fb^{-1}):

Parameter	Best Fit		Uncertainty
sign(μ)	+1		
$\tan\beta$	10.2	$\pm$	2.3
A_0 (GeV)	−76.3	$\pm$	184
M_0 (GeV)	100.6	$\pm$	3.4
$M_{1/2}$ (GeV)	250.2	$\pm$	5.3

LHC (300 fb^{-1}):

Parameter	Best Fit		Uncertainty
sign(μ)	+1		
$\tan\beta$	9.98	$\pm$	0.35
A_0 (GeV)	−100.2	$\pm$	11.1
M_0 (GeV)	100.0	$\pm$	0.39
$M_{1/2}$ (GeV)	250.0	$\pm$	0.30

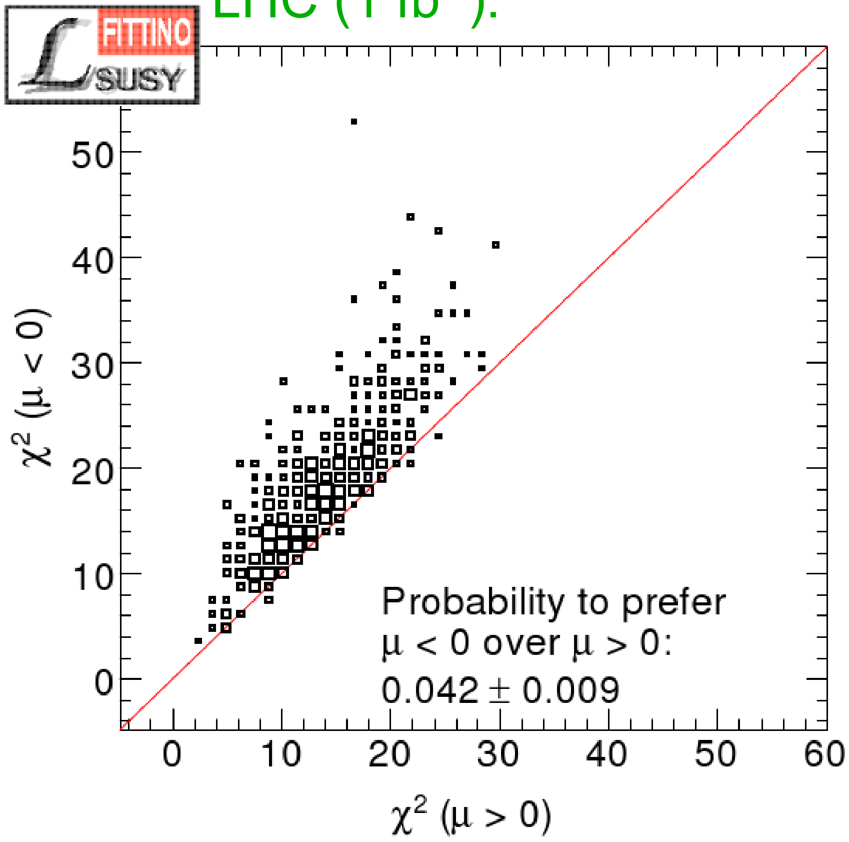
LE+LHC (300 fb^{-1}):

Parameter	Best Fit		Uncertainty
sign(μ)	+1		
$\tan\beta$	10.00	$\pm$	0.36
A_0 (GeV)	−99.1	$\pm$	12.0
M_0 (GeV)	100.00	$\pm$	0.39
$M_{1/2}$ (GeV)	250.01	$\pm$	0.33

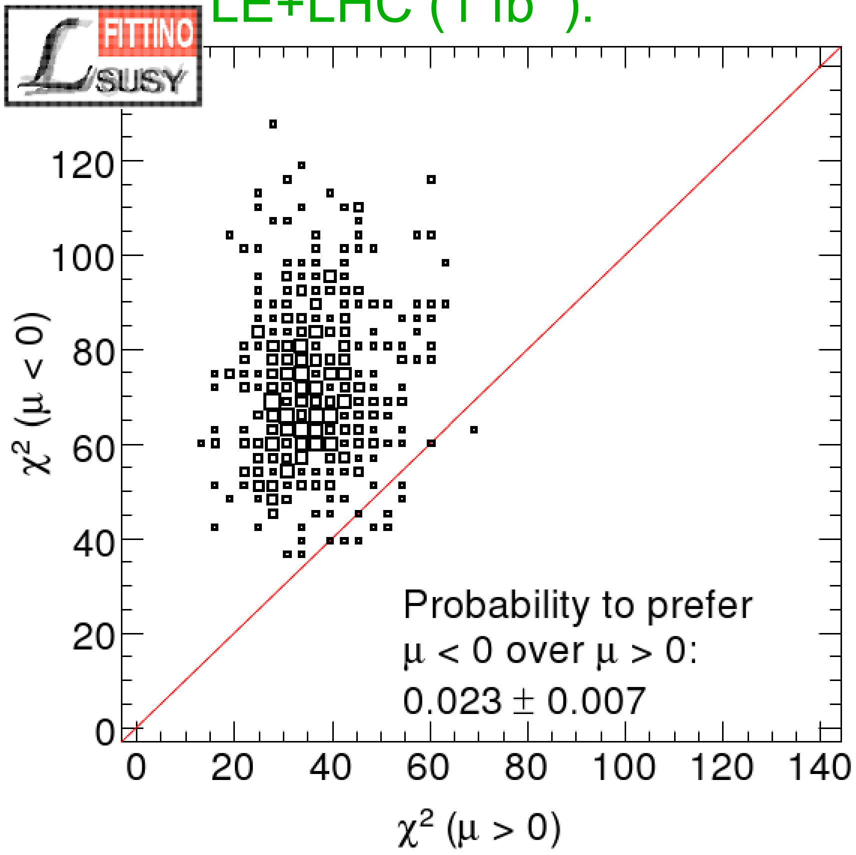
At the beginning of LHC running LE data may still be important (even in constrained mSUGRA model)

LE+LHC: sign(μ)

LHC (1 fb^{-1}):



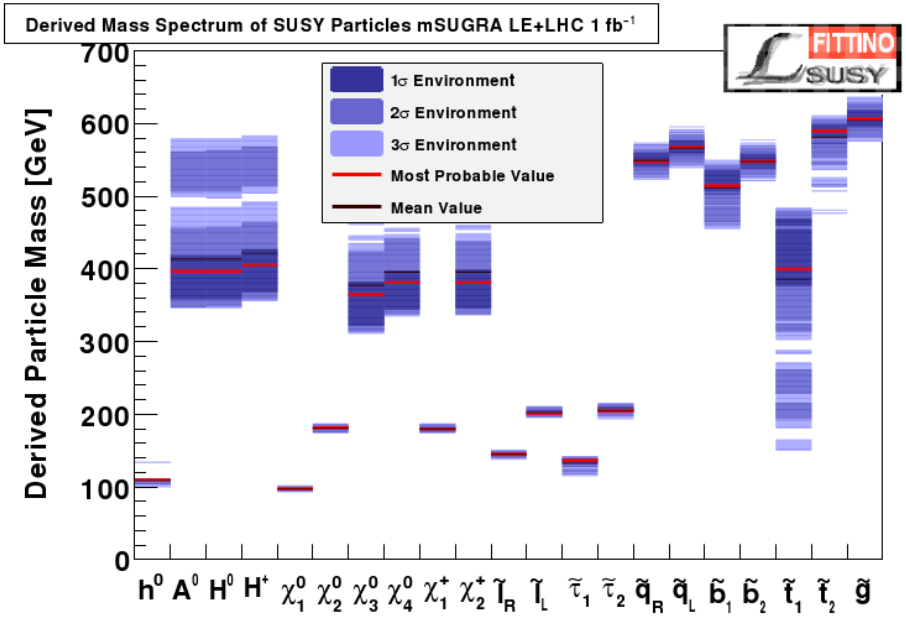
LE+LHC (1 fb^{-1}):



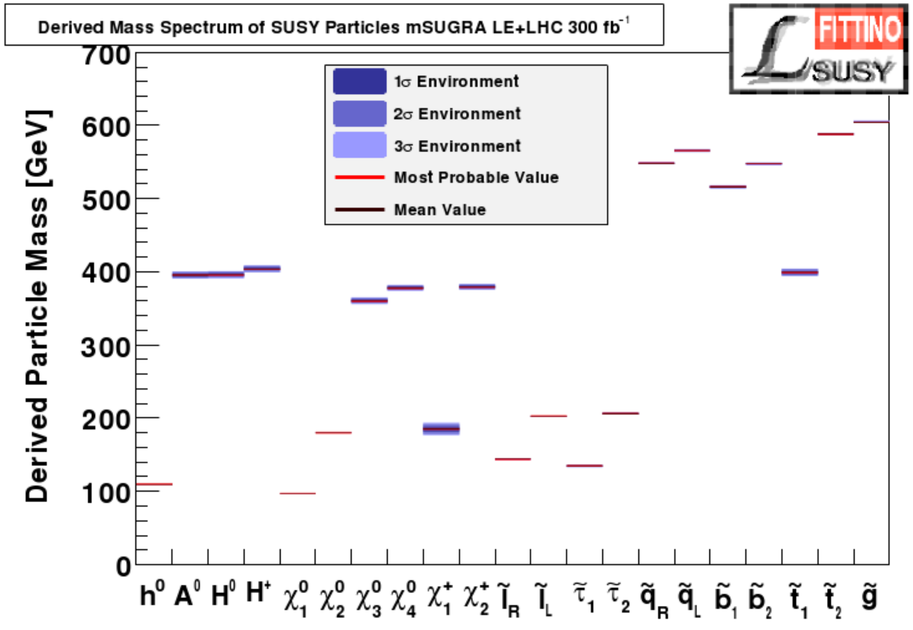
LE+LHC: Mass spectrum

SUSY mass spectra derived from LE and LHC (1 fb^{-1} and 300 fb^{-1}) observables assuming mSUGRA model:

mSUGRA, LE+LHC1:



mSUGRA, LE+LHC300:



MSSM18

So far, all analyses done within mSUGRA model (= strong assumption on SUSY breaking mechanism)

Can also perform analysis in more general SUSY model

Assumptions:

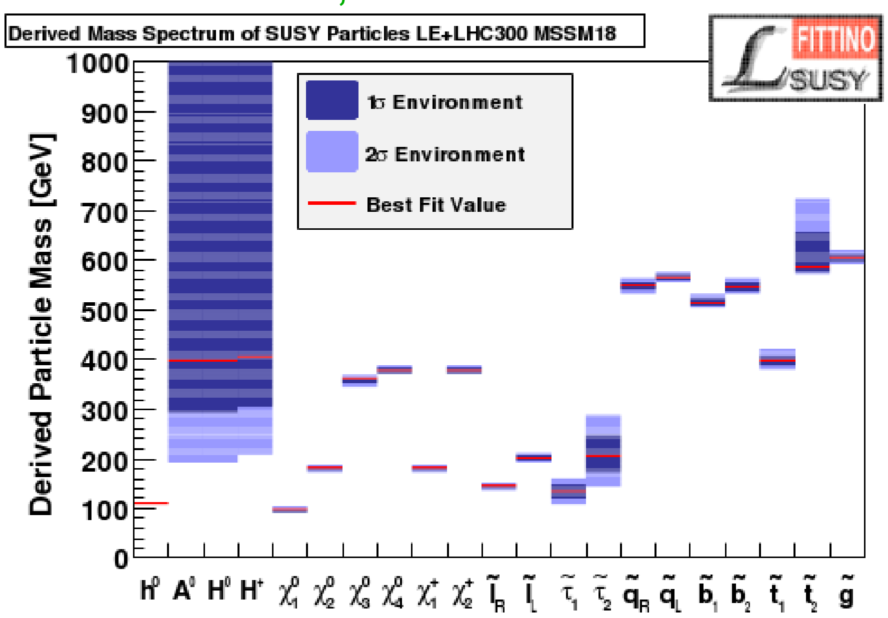
- no CP violation in SUSY sector (all phases = 0)
- no mixing between sfermion generations
- no mixing within first two sfermion generations
- universality of same-type sfermion mass parameters in first two generations

→ MSSM18

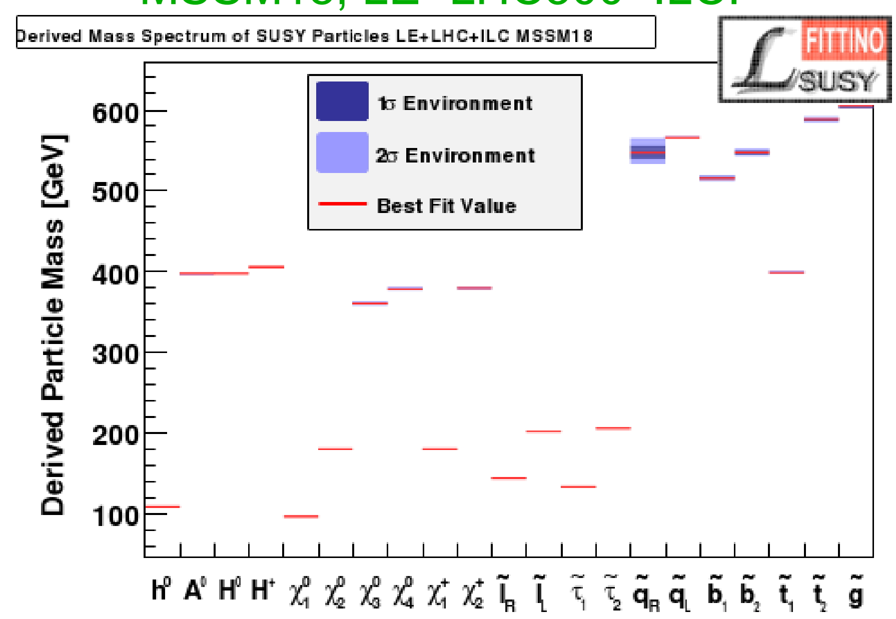
LE+LHC+ILC: Mass spectrum

SUSY mass spectra derived from LE and LHC (300 fb^{-1}) and optionally ILC observables assuming MSSM18 model:

MSSM18, LE+LHC300:



MSSM18, LE+LHC300+ILC:



LE+LHC(+ILC): MSSM18

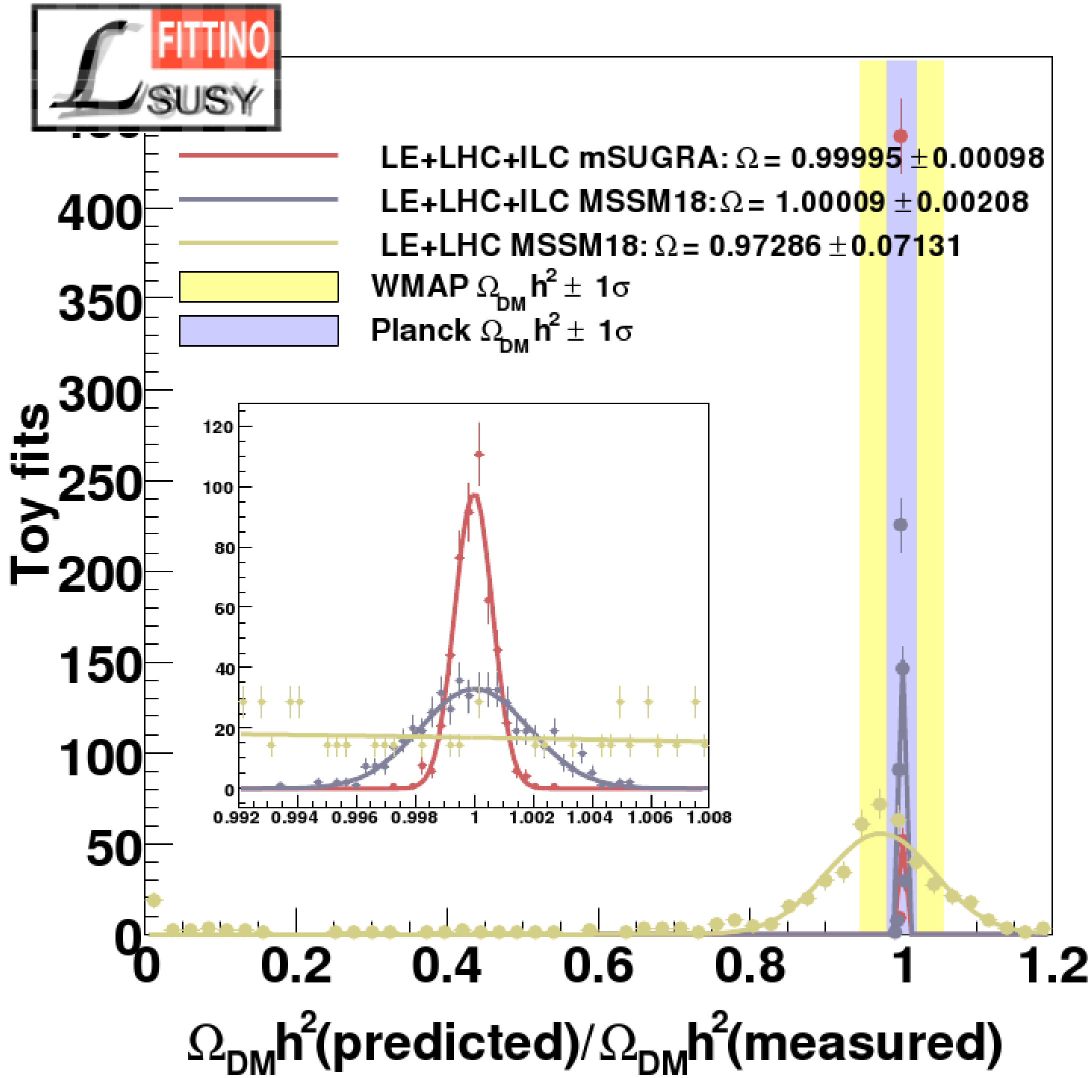
Parameter	Nominal value	ILC Fit		$\sigma_{\mathrm{LE+LHC\,300}}$	$\sigma_{\mathrm{LE+LHC300+ILC}}$
$M_{\tilde{\ell}_L}$ (GeV)	194.31	194.315	$\pm$	6.4	0.068
$M_{\tilde{\ell}_R}$ (GeV)	135.76	135.758	$\pm$	10.5	0.071
$M_{\tilde{\tau}_L}$ (GeV)	193.52	193.46	$\pm$	43.0	0.33
$M_{\tilde{\tau}_R}$ (GeV)	133.43	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

ILC reduces uncertainties by 1 to 2 orders of magnitude (except $\tilde{q}_R$ mass)

→ more direct measurements + strong decrease of correlations

Cold dark matter relic density

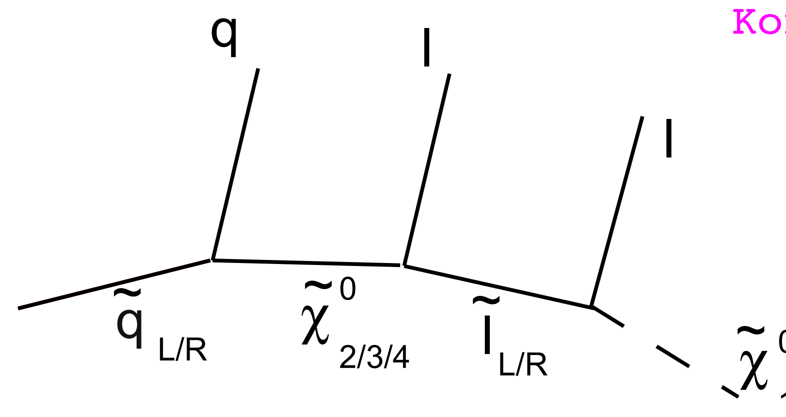
Cold dark matter relic density inferred from collider measurements:



Next steps: All decay chain ambiguities

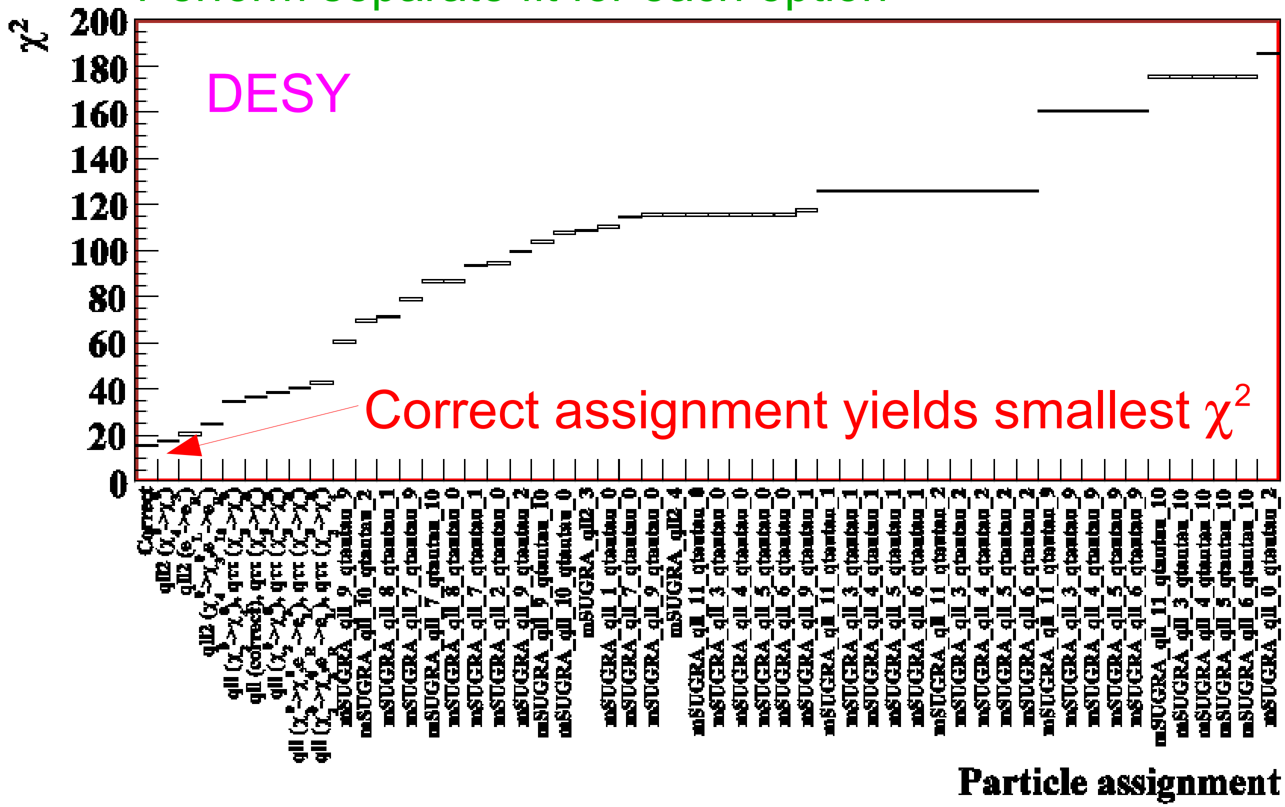
Kono

Consider all possible decay chain ambiguities in parameter analysis of LHC data



First steps started:

Perform separate fit for each option



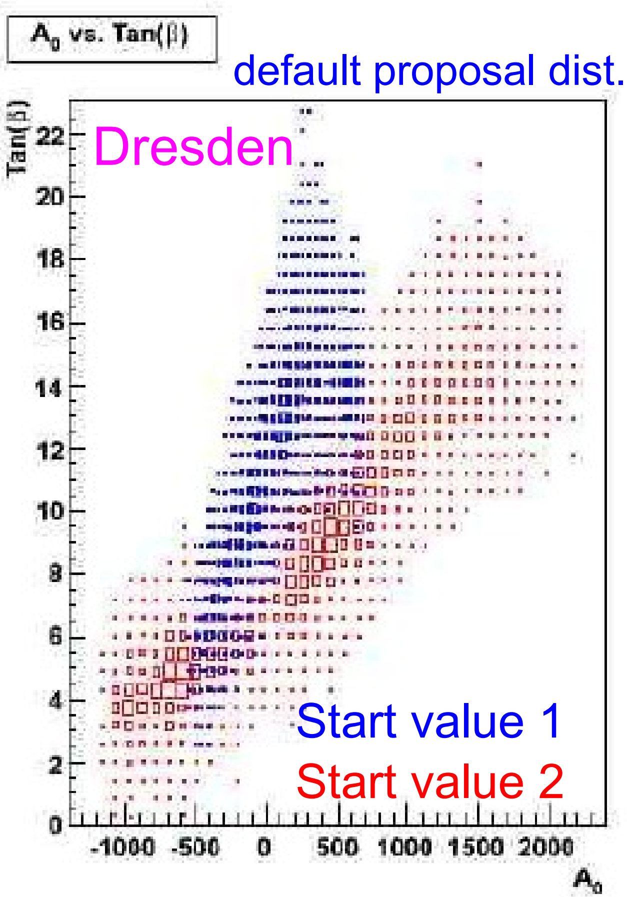
Next steps: Algorithm optimisation

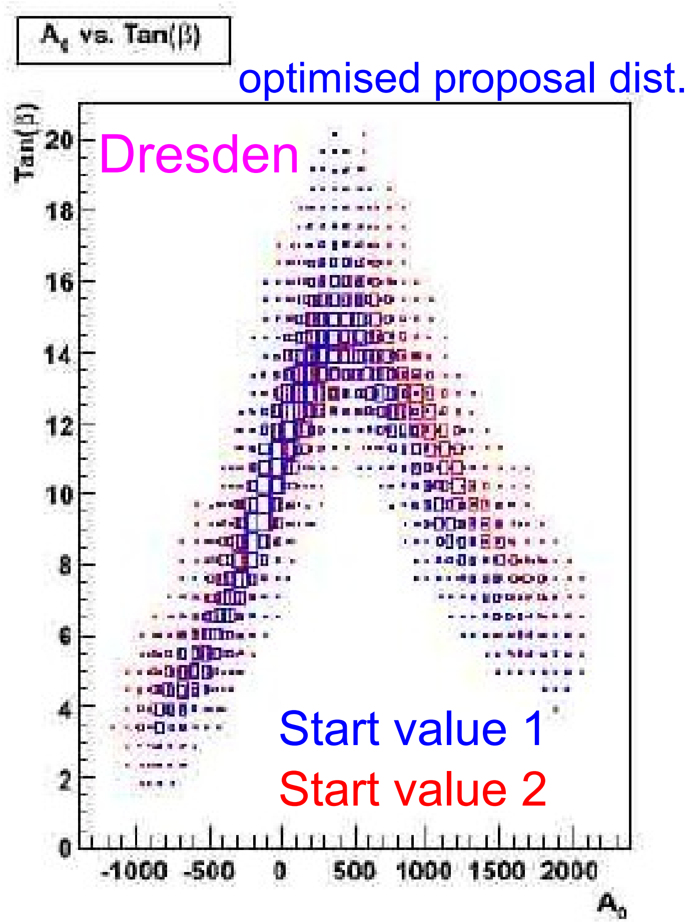
Prudent

Parameter analysis is CPU intensive

Optimised algorithm settings are crucial → green Fittino

Example: Optimised proposal density distribution for Markov chain





Short fixed chain length used for illustration

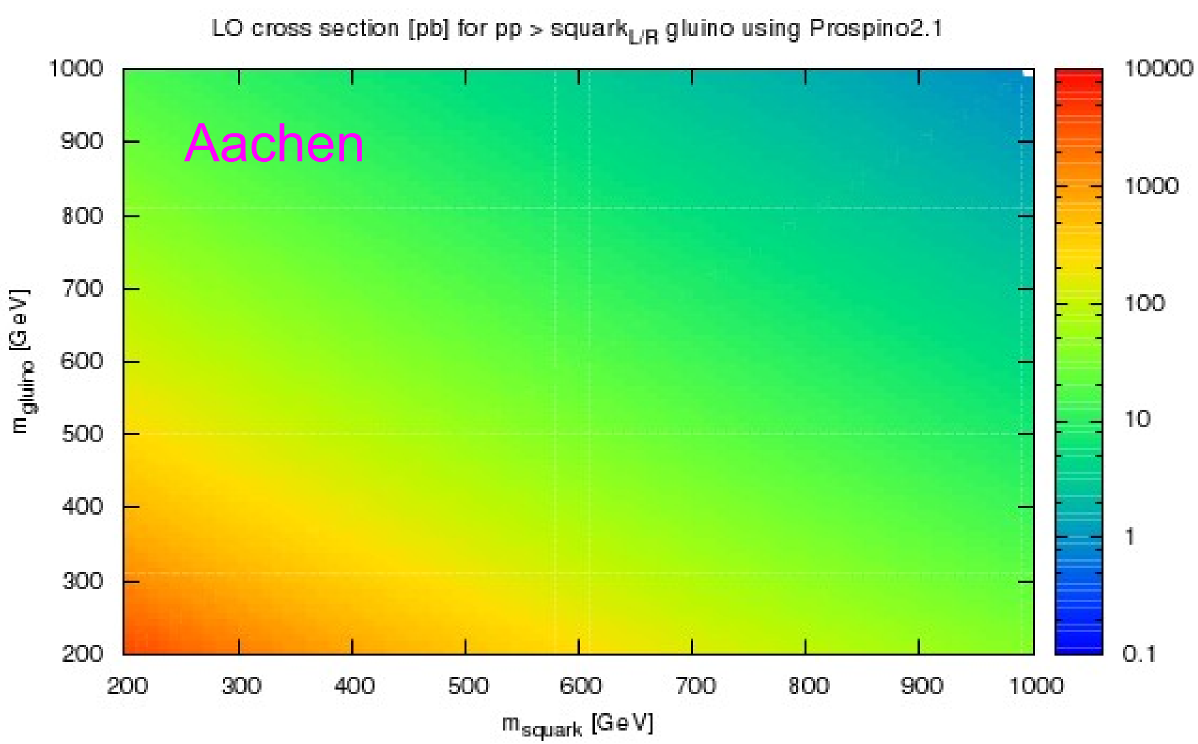
Next steps: LHC production rates

Krämer, Lindert, O'Leary

Conventional calculation of production rates at LHC too slow.

Investigated way out:

- Prospino look-up table (only 2 parameters: squark and gluino mass)
- Calculation of BRs by SPheno/SDecay
- Parametrised detector response



More plans

- Inclusion of SUSY direct search limits from LEP and Tevatron (Mainz, Bonn)
- Inclusion of indirect dark matter search results (Hamburg)
- Systematic comparison of different RGE codes (Göttingen)
- Inclusion of uncertainties/correlations of theory predictions (Würzburg, DESY, Heidelberg, …)
- Calculator speed-ups (Würzburg)
- ...

→ very lively activity

Summary

- Constraining SUSY parameter space will be essential task in upcoming years (both if $\exists$ SUSY and if $\nexists$ SUSY)
- Several powerful SUSY fitting frameworks developed during recent years
- Obtained fascinating results with them:
  - Light SUSY preferred by LE precision data
  - Demonstration of possible LHC and ILC potential
- Nevertheless some issues still need to be included in parameter analyses (decay chain ambiguities, LHC rates, uncertainties of calculations, ...)
- Joint effort by experimentalists (from different experiments) and theorists has started to address open issues
- Many interesting new results can be expected soon ...