TeV-scale Measurements or What to do with all that LHC Data

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Edinburgh & Heidelberg

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Outline

Effective Standard Model

Masses from cascades

Underlying parameters

Annoying Errors

TeV-scale MSSM: SFitter

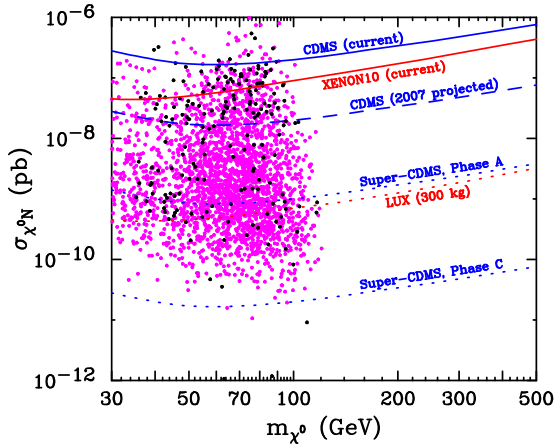
Effective Standard Model in the LHC era

Expectations from the LHC [Uli Baur's rule: 'there is always new physics at higher scales']

- find light Higgs?
- find new physics stabilizing Higgs mass?
- see dark–matter candidate?

Particle theory and new physics

- model–independent analyses likely not helpful
- testing testable hypotheses [theory: e.g. Higgs sector and underlying theory?]
  discrete hypotheses: spins,....
  continuous hypotheses: masses,...
- link to other observations [DM+Tevatron: Hooper, TP, Valinotto]
- reconstruction of Lagrangian [theory+experiment]



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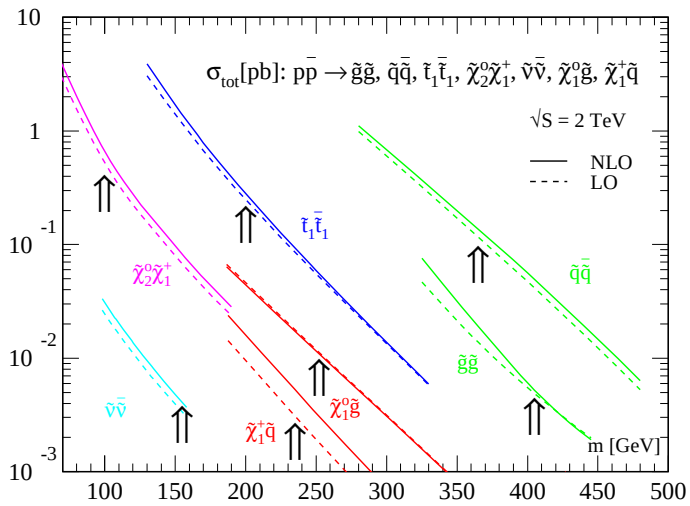
- beyond inclusive searches [that was Tevatron]
  lots of strongly interacting particles
  cascade decays to DM candidate
- general theme: try to survive QCD

$\Rightarrow$ aim at underlying theory — yes, we can!



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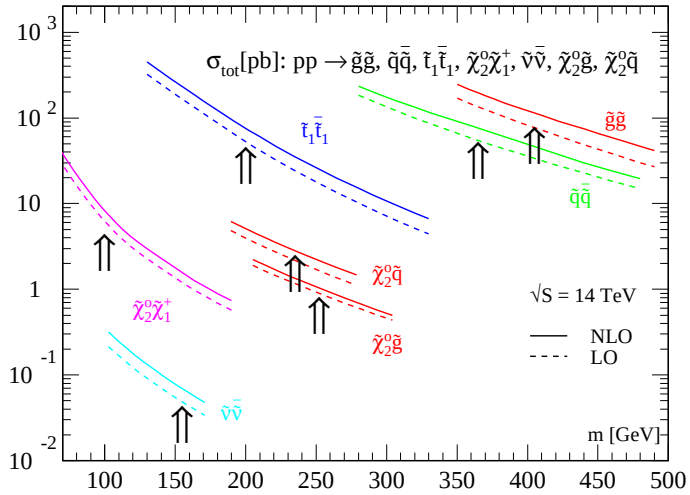

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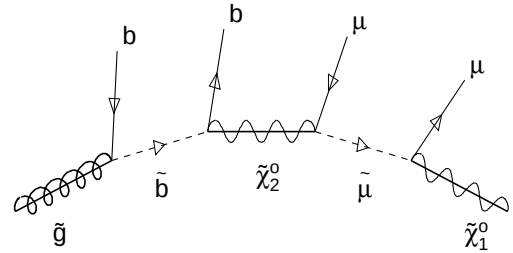

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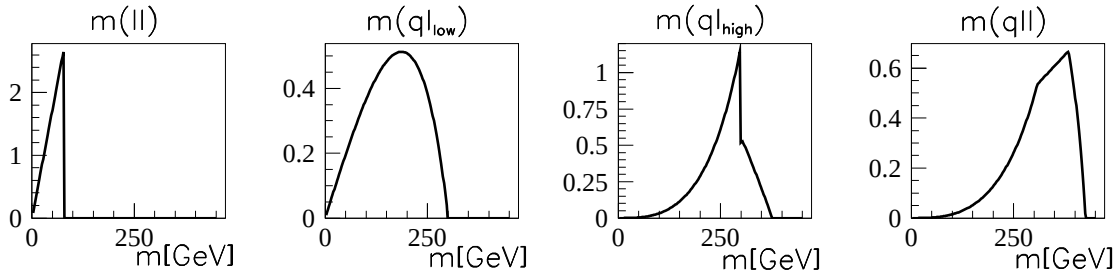
- long chain $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$
- thresholds & edges

$$0 < m^2_{\mu\mu} < \frac{m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}}}{m_{\tilde{\ell}}} \; \frac{m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}$$

$\Rightarrow$ new–physics mass spectrum from cascade kinematics



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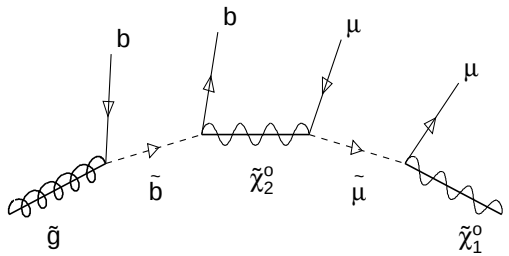

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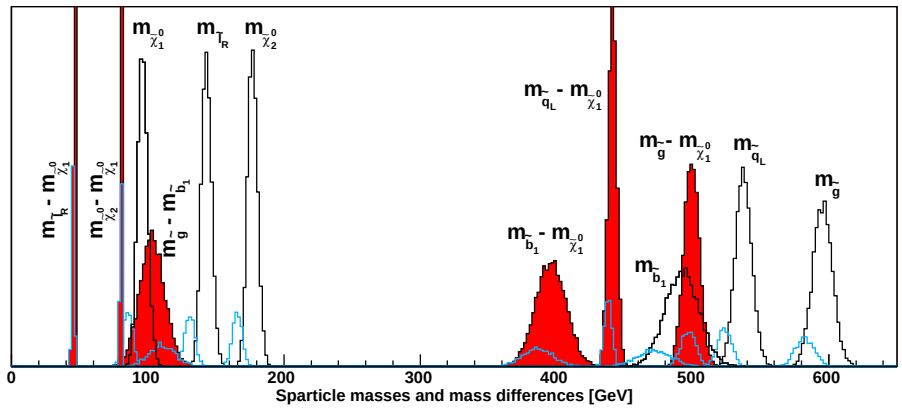
Gluino decay [Gjelsten, Miller, Osland]

- all decay jets b quarks [otherwise
- no problem: off-shell [Catpiss]
- no problem: jet radiation?
- gluino mass to $\sim 1\%$



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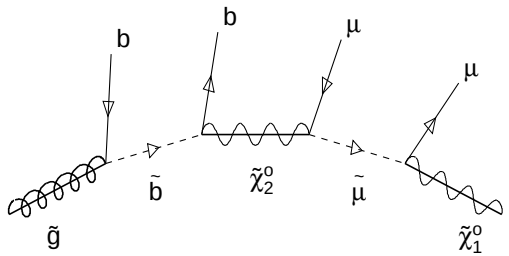

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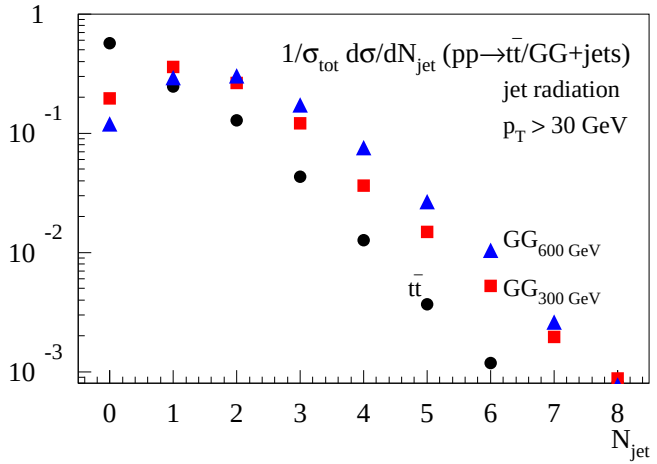
- decay jets vs QCD radiation
- collinear initial state radiation [$p_{T,j} < M_{\text{hard}}$]
- proper description: CKKW/MLM [in MadEvent]
- $\langle N_{\text{jet}} \rangle$ dependent on hard scale
- study: two heavy states

$\Rightarrow$ QCD basics useful at LHC...



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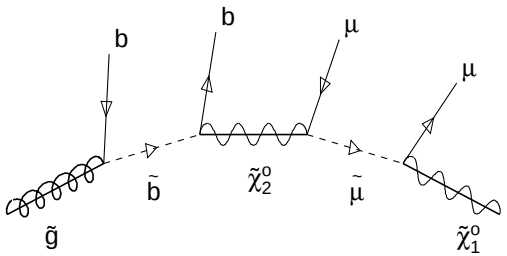

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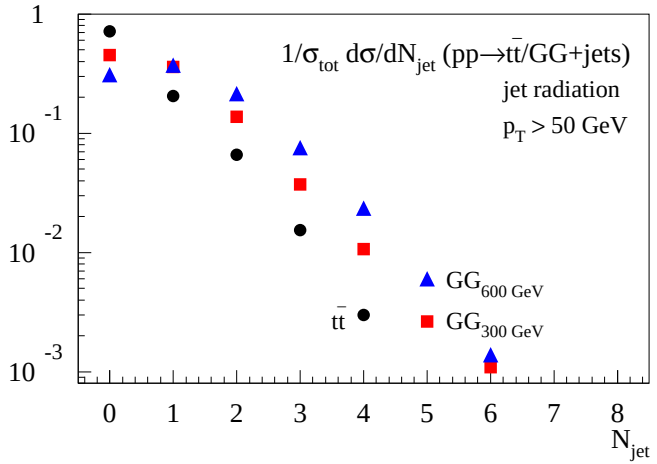

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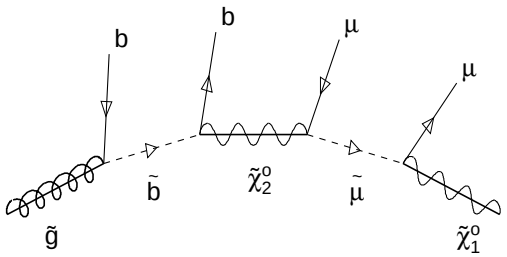

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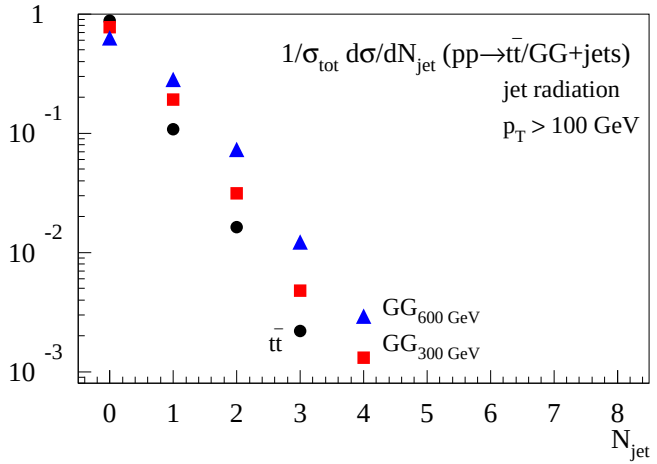

Underlying parameters

From kinematics to weak–scale parameters [Fittino; SFitter: Lafaye, TP, Rauch, Zerwas]

- parameters: weak-scale Lagrangian
- measurements: better edges than masses,
  branching fractions, rates,... [NLO, of course]
  flavor, dark matter, electroweak constraints,...
- errors: general correlation, statistics & systematics & theory [flat theory errors!]
- problem in grid: huge phase space, no local maximum?
  problem in fit: domain walls, no global maximum?
  problem in interpretation: bad observables, secondary maxima?

Probability maps of new physics [Baltz,...; Roszkowski,...; Allanach,...; SFitter]

- want to evaluate probability of model being true $p(m|d)$
- can compute fully exclusive likelihood map $p(d|m)$ over m [tough]
- additional LHC challenge: remove poor directions [e.g. endpoints vs rates]
- Bayesian: $p(m|d) \sim p(d|m)\ p(m)$ with theorists' bias $p(m)$ [cosmology, BSM]
  frequentist: best–fitting point $\max_m p(d|m)$ [flavor]
- LHC era: (1) compute high-dimensional map $p(d|m)$
  (2) find and rank local best-fitting points
  (3) predict additional observables

Markov chains

Define set of representative points in new–physics space

- measure of 'representative': likely to agree with data [Markov chain]
- evaluate any function over chain

(1) probability to agree with data
weighted Markov chains [Rauch & TP; Ferrenberg & Swendsen]

$$P_{\text{bin}}(p \neq 0) = \frac{N}{\sum_{i=1}^{N} 1/p}$$

(2) Higgs mass from LEP and DM relic density
LHC rates from LEP and DM relic density
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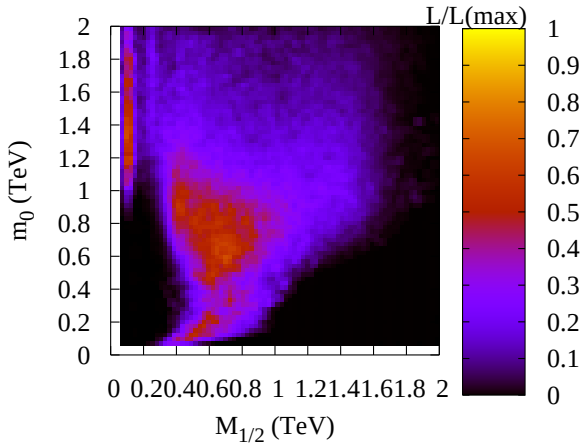
MSUGRA as of today [Allanach, Cranmer, Lester, Weber; Roszkowski]

- 'Which is the most likely parameter point?'
- 'How does dark matter annihilate/couple?'

$\Rightarrow$ really not hard to understand, aye?



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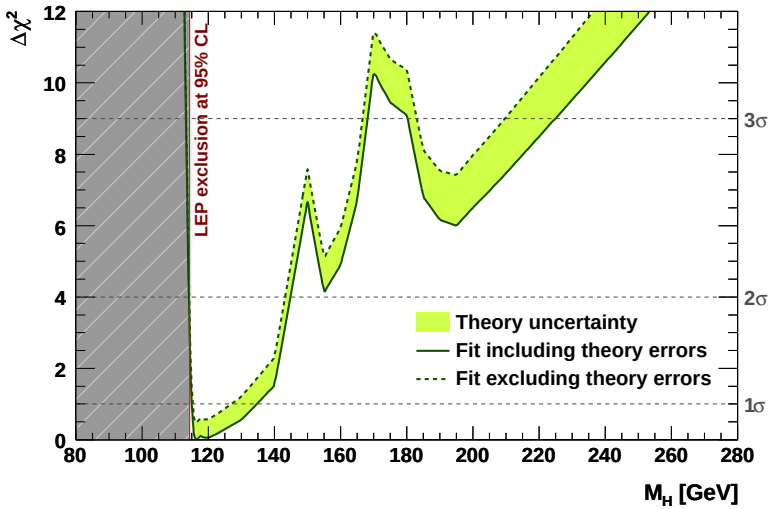
- see also Masterfitter talk: A de Roeck



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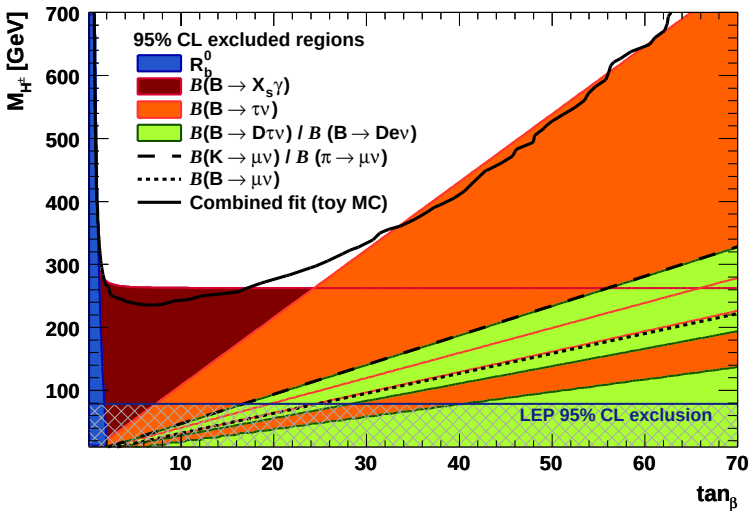

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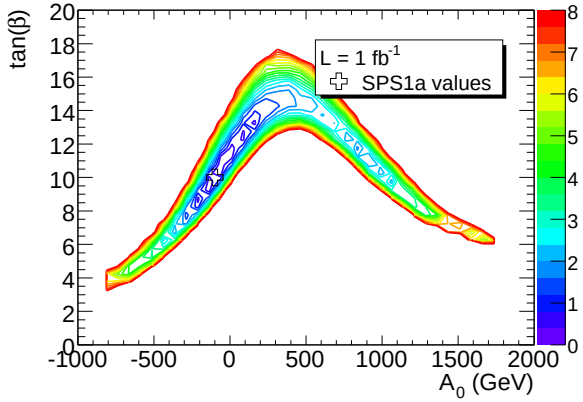

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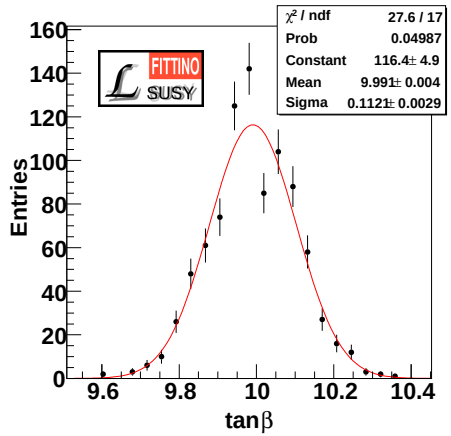

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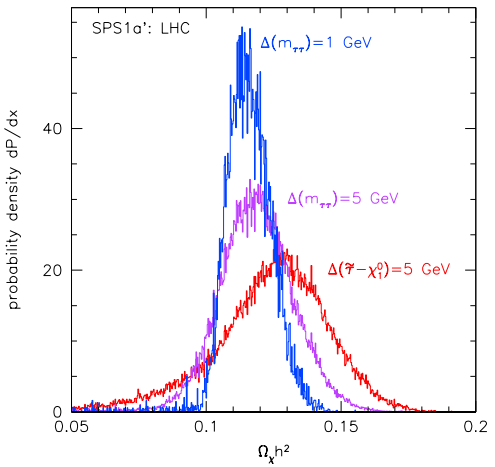

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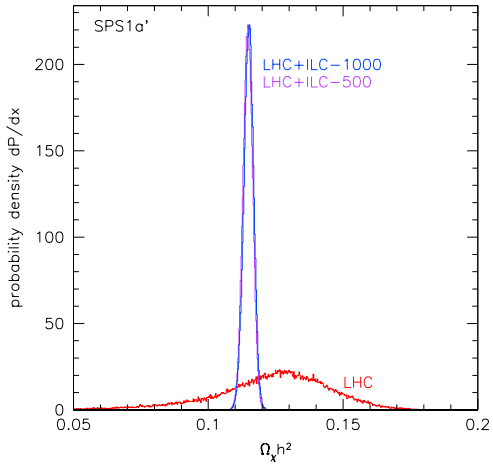
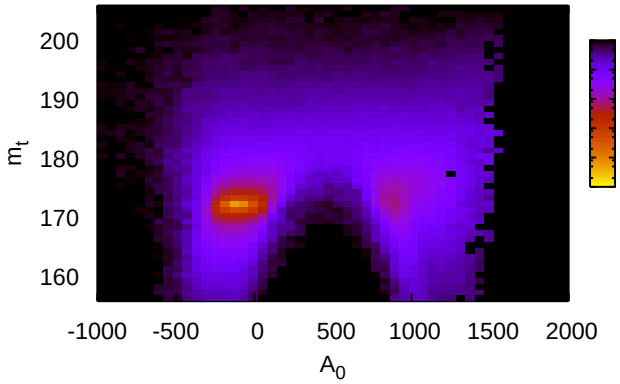


Correlations and errors

Toy model: MSUGRA map from LHC [LHC endpoints with free y_t]

- model unrealistic but useful testing ground [will do anything for citations]
- weighted Markov chains: several times faster
- SFitter output #1: fully exclusive likelihood map
  SFitter output #2: ranked list of local maxima
- strong correlation e.g. of A_0 and y_t [including all errors]

$\Rightarrow$ correlations and secondary maxima significant [0709.3985]



χ^2	m_0	$m_{1/2}$	$\tan\beta$	A_0	μ	m_t
0.3e-04	100.0	250.0	10.0	-99.9	+	171.4
27.42	99.7	251.6	11.7	848.9	+	181.6
54.12	107.2	243.4	13.3	-97.4	-	171.1
70.99	108.5	246.9	13.9	26.4	-	173.6
88.53	107.7	245.9	12.9	802.7	-	182.7
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A word on errors

- central values secondary locally
- statistical errors Gaussian
  systematic errors Gaussian, correlated
  theory errors flat
- RFit scheme [CKMFitter]

$$\chi^2 = -2 \log \mathcal{L} = \vec{\chi}_d^T \; C^{-1} \; \vec{\chi}_d$$

$$\chi_{d,i} = \begin{cases} 0 & |d_i - \bar{d}_i| < \sigma_i^{(\text{theo})} \\ \frac{\mathcal{D}|d_i - \bar{d}_i| - \sigma_i^{(\text{theo})}}{\mathcal{D}\sigma_i^{(\text{exp})}} & |d_i - \bar{d}_i| > \sigma_i^{(\text{theo})} \end{cases} ,$$

$$C_{i,i} = 1 \qquad C_{i,j} = C_{j,i} = \frac{0.99 \; \sigma_i^{(\ell)} \; \sigma_j^{(\ell)} + 0.99 \; \sigma_i^{(\text{j})} \; \sigma_j^{(\text{j})}}{\sigma_i^{(\text{exp})} \; \sigma_j^{(\text{exp})}}$$

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- theory error sizeable

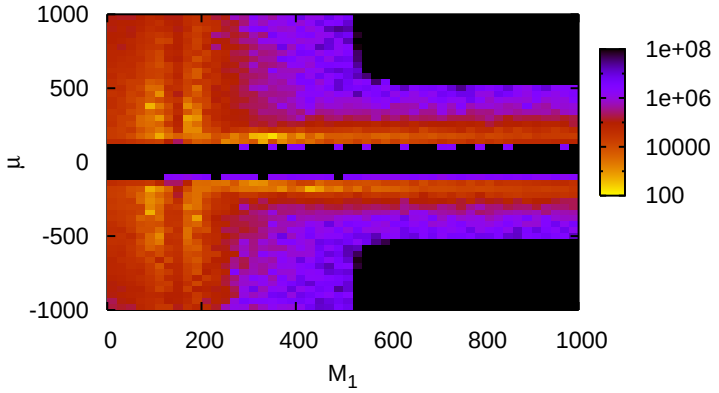
	SPS1a	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{expNoCorr}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{zero}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{gauss}}$	$\Delta^{\text{theo}-\text{exp}}_{\text{flat}}$
		masses	endpoints			
m_0	100	4.11	1.08	0.50	2.97	2.17
$m_{1/2}$	250	1.81	0.98	0.73	2.99	2.64
$\tan\beta$	10	1.69	0.87	0.65	3.36	2.45
A_0	-100	36.2	23.3	21.2	51.5	49.6
m_t	171.4	0.94	0.79	0.26	0.89	0.97

$\Rightarrow$ errors mean: endpoints instead of masses

TeV-scale MSSM: SFitter

MSSM map from LHC

- shifting from 6D to 19D parameter space [killing grids, Minuit, laptop–style fits...]
- Markov chain globally + hill climber locally
- SFitter outputs #1 and #2 still the same [weighted Markov chain plus hill climber]
- three neutralinos observed [left: Bayesian — right: likelihood]



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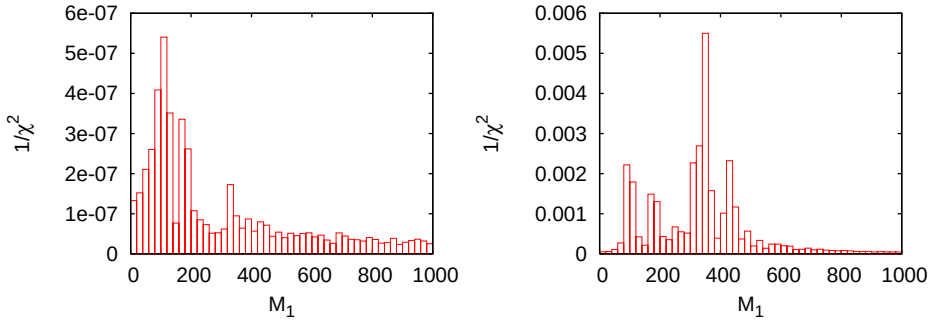

- quality of fit not always useful

	$\mu < 0$				$\mu > 0$			
M_1	96.6	175.1	103.5	365.8	98.3	176.4	105.9	365.3
M_2	181.2	98.4	350.0	130.9	187.5	103.9	348.4	137.8
μ	-354.1	-357.6	-177.7	-159.9	347.8	352.6	178.0	161.5
tan β	14.6	14.5	29.1	32.1	15.0	14.8	29.2	32.1
M_3	583.2	583.3	583.3	583.5	583.1	583.1	583.3	583.4
$M_{\tilde{\mu}_L}$	192.7	192.7	192.7	192.9	192.6	192.6	192.7	192.8
$M_{\tilde{\mu}_R}$	131.1	131.1	131.1	131.3	131.0	131.0	131.1	131.2
A_t $(-)$	-252.3	-348.4	-477.1	-259.0	-470.0	-484.3	-243.4	-465.7
A_t $(+)$	384.9	481.8	641.5	432.5	739.2	774.7	440.5	656.9
m_A	350.3	725.8	263.1	1020.0	171.6	156.5	897.6	256.1
m_t	171.4	171.4	171.4	171.4	171.4	171.4	171.4	171.4

$\Rightarrow$ means probably much more work to do...

Beyond the LHC

Why theorists involved?

- want to learn statistics [usually get that badly wrong]
- theory errors not negligible [rates for focus–point scenarios]
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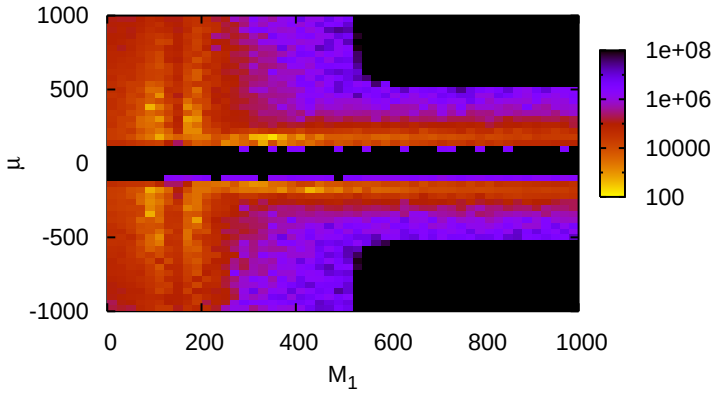

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	LHC		LHC $\otimes(g-2)$		SPS1a
tan β	**10.0**	**4.5**	**10.3**	**2.0**	**10.0**
M_1	102.1	7.8	102.7	5.9	103.1
M_2	193.3	7.8	193.2	5.8	192.9
M_3	577.2	14.5	578.2	12.1	577.9
$M_{\tilde{\mu}_L}$	193.2	8.8	194.0	6.8	194.4
$M_{\tilde{\mu}_R}$	135.0	8.3	135.6	6.3	135.8
$M_{\tilde{q}3_L}$	481.4	22.0	485.6	22.4	480.8
$M_{\tilde{b}_R}$	501.7	17.9	499.2	19.3	502.9
$M_{\tilde{q}_L}$	524.6	14.5	525.5	10.6	526.6
$M_{\tilde{q}_R}$	507.3	17.5	507.6	15.8	508.1
m_A	406.3	$\mathcal{O}(10^3)$	411.1	$\mathcal{O}(10^2)$	394.9
μ	350.5	14.5	352.5	10.8	353.7

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- 7% error on f_{B_s} by 2015 crucial [Della Morte, Del Debbio; SFitter + Jäger, Spannowsky]
- perturbative effects secondary

	no theory error			$\Delta\mathrm{BR}/\mathrm{BR} = 15\%$	
	true	best	error	best	error
tan β	**30**	**29.5**	**3.4**	**29.5**	**6.5**
M_A	344.3	344.4	33.8	344.3	31.2
M_1	101.7	100.9	16.3	100.9	16.4
M_2	192.0	200.3	18.9	200.3	18.8
M_3	586.4	575.8	28.8	575.8	28.7
μ	345.8	325.6	20.6	325.6	20.6
$M_{\tilde{t},R}$	430.0	400.4	79.5	399.8	79.5

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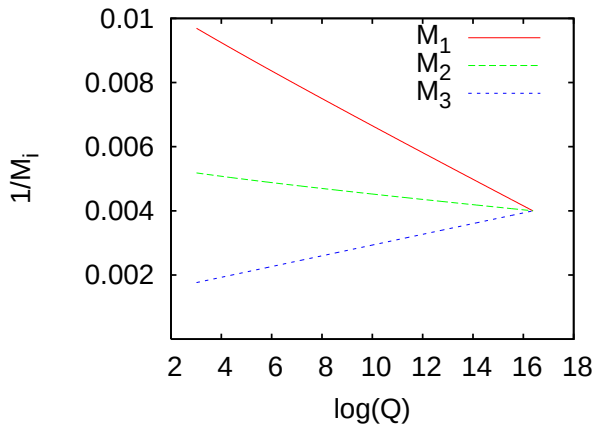
Renormalization group bottom–up [SFitter + Kneur]

- SUSY breaking, unification, GUT?
- scale-invariant sum rules? [Cohen, Schmalz]

$\Rightarrow$ solidly inference from weak scale



New physics at the LHC

Understanding the TeV scale

(1) look for solid new–physics signals

(2) measure weak–scale Lagrangian

(3) determine fundamental physics

- construct new–physics hypotheses
- avoid getting killed by QCD
- supersymmetry just one example

$\Rightarrow$ LHC more than a discovery machine!