SUPERSYMMETRY AT THE LHC

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Edinburgh/Munich

- TeV–scale supersymmetry
- Inclusive signals
- Exclusive measurements
- SUSY parameters

TeV–Scale Supersymmetry

Bright side

- 3 running gauge couplings meet — GUT gauge group
- 2 Higgs doublets — radiative symmetry breaking
- R parity — stable proton yields dark matter
- local supersymmetry – including gravity?
- rich LHC phenomenology — no nasty surprises [if you can do SUSY you can do everything]

Dark side

- unknown SUSY breaking
  $\longrightarrow$ masses, couplings, phases...
  $\longrightarrow$ e.g. hierarchical spectrum?
- flavor physics and SUSY breaking
  $\longrightarrow$ CKM and lepton flavor?
- 2 Higgs doublet model
  $\longrightarrow$ μ parameter and SUSY breaking?

$\Rightarrow$ as many as exclusive analyses as possible

		spin	d.o.f.	
fermion	f_L , f_R	1/2	1+1	
$\longrightarrow$ sfermion	$\tilde{f}_L$, $\tilde{f}_R$	0	1+1	
gluon	G_μ	1	n-2	
$\longrightarrow$ gluino	$\tilde{g}$	1/2	2	Majorana
gauge bosons	γ , Z	1	2+3	
Higgs bosons	h^0 , H^0 , A^0	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^0$	1/2	$4 \cdot 2$	Majorana
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	Dirac

SUSY TOOLS

Supersymmetric parameter conventions

– comparison of specialized codes crucial [remember: e.g. Comphep–Pythia–Isajet]

⇒ fix SUSY conventions once for all

soft breaking parameters [e.g. $\pm A_t$]
scale dependence of couplings, masses [e.g. $m(q = \text{TeV}, v, m_t)$?]
definitions of mass matrixes, mixing angles [e.g. $\tilde{t}_{L,R}$ up or down?]

SUSY Les Houches Accord [Allanach, Skands et al.]

– spectrum generators: SoftSusy, SPheno, FeynHiggs,...

– multi-purpose Monte Carlos: Pythia, Herwig, Sherpa

– matrix element generators: Whizard, Smadgraph

– NLO cross sections: Prospino2

– NLO decay rates: Sdecay

– SUSY parameter extraction: Fittino, Sfitter

– dark matter: Micromegas

⇒ fixed parameter convention and read-write format [list still growing]

INCLUSIVE SUSY SIGNALS

Supersymmetry at the LHC

(1) possible discovery — signals for new physics, exclusion of parameter space

(2) measurements — masses, cross sections, decays

(3) parameter studies — MSSM Lagrangean, SUSY breaking

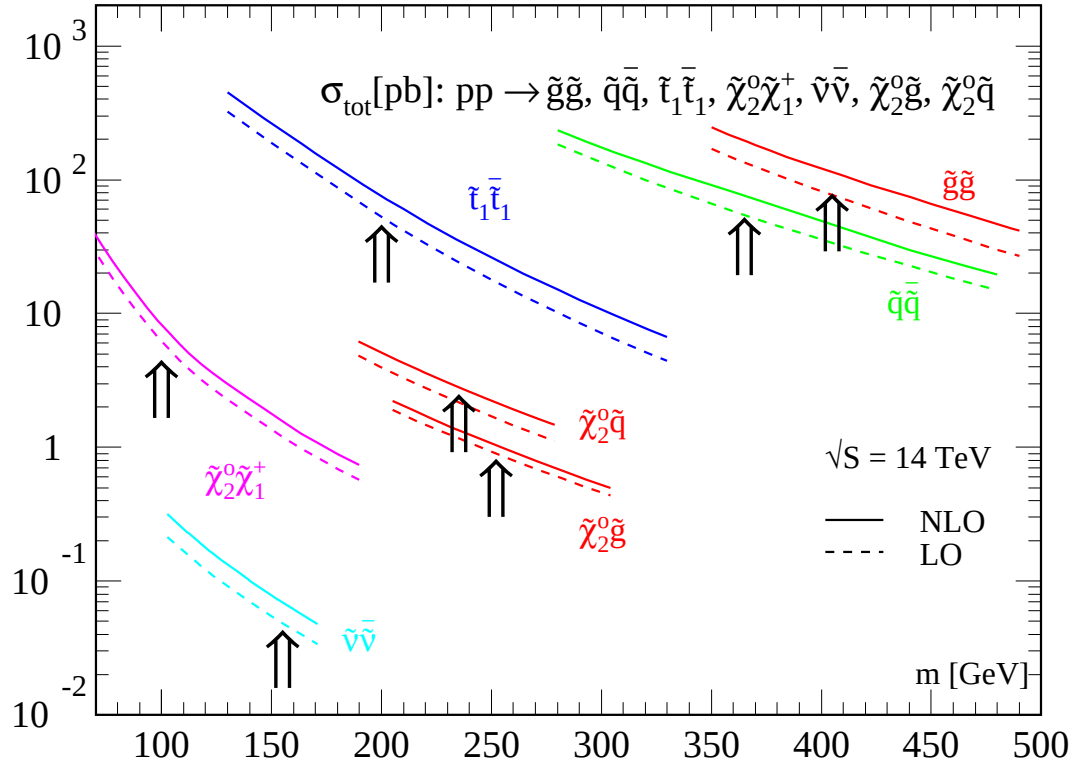
$\Rightarrow$ at least 10% precision to be matched at LHC [theorist's nightmare, yet unsolved]

SUSY signals in Prospino2

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons: $pp \to \tilde{g}\tilde{g}$

  $[\tilde{g} \to \bar{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ or c. c.$]$
- tri-leptons: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$

  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0\ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0\ell\bar{\nu}]$
- bottoms and $\not{E}_T$: $pp \to \tilde{b}_1\tilde{b}_1^*$



Inclusive Susy Signals

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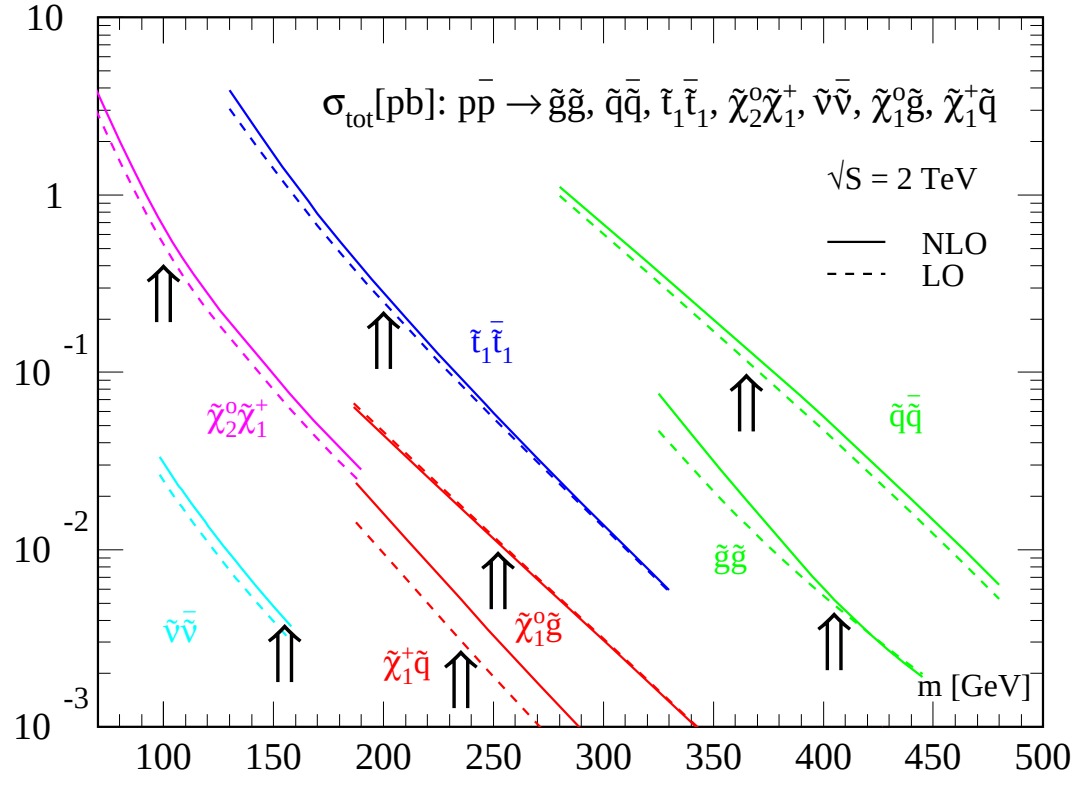
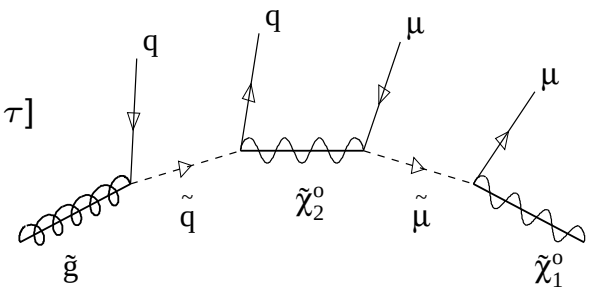


SUSY MASS MEASUREMENTS

Spectra from cascade decays



- decay $\tilde{g} \to \tilde{q}\bar{q} \to \tilde{\chi}_2^0 q\bar{q} \to \mu^+\mu^- q\bar{q}\tilde{\chi}_1^0$ [better not via Z or to τ]
- cross sections some 100 pb [more than 3×10^5 events]
- thresholds & edges [Hinchliffe, Paige...; Cambridge ex-ph]

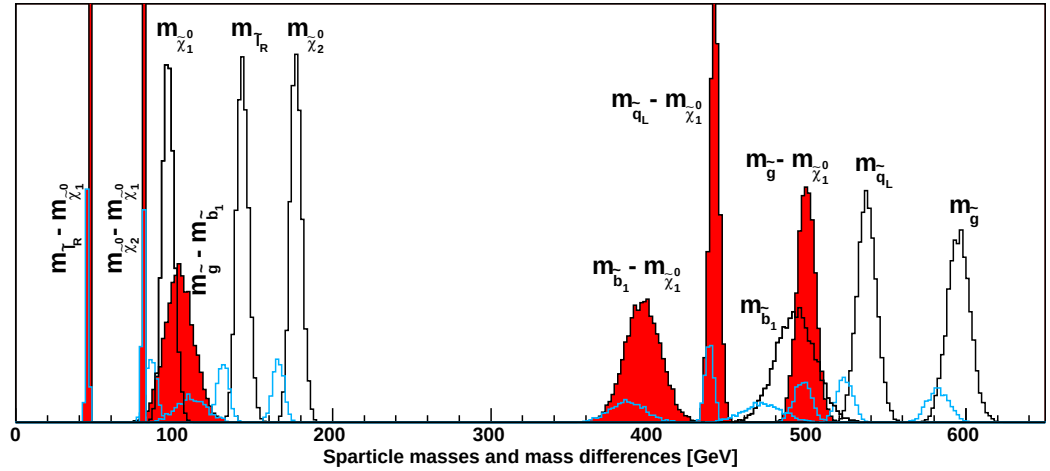
  classical $m^2_{\ell\ell} < (m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}})(m^2_{\tilde{\ell}} - m^2_{\tilde{\chi}_1^0})/m^2_{\tilde{\ell}}$
- detector resolution, calibration, systematic errors, shape analysis?
- cross sections as additional input? [Lester...]

$\Rightarrow$ $\tilde{q}_L$ cascade reconstruction great for SPS1a [mass differences better]

Gluino mass [Gjelsten, Miller, Osland]

- now four jets instead of two
- jet identification crucial
- $\tilde{b}_L$ instead, all jets b-tagged

$\Rightarrow$ gluino mass to $\sim 1\%$
statistical error dominant



SUSY SPIN DETERMINATION

How to make sure it is SUSY

- assume neutralino is found in cascades

$\Rightarrow$ if fermion, then weakly interacting Majorana [that's what we call a neutralino]

$\Rightarrow$ compare with a model where gluino is a boson: universal extra dimensions

[Cheng, Dobrescu,...; mass spectra degenerate —ignore this information; cross section factor 10 larger —ignore this as well]

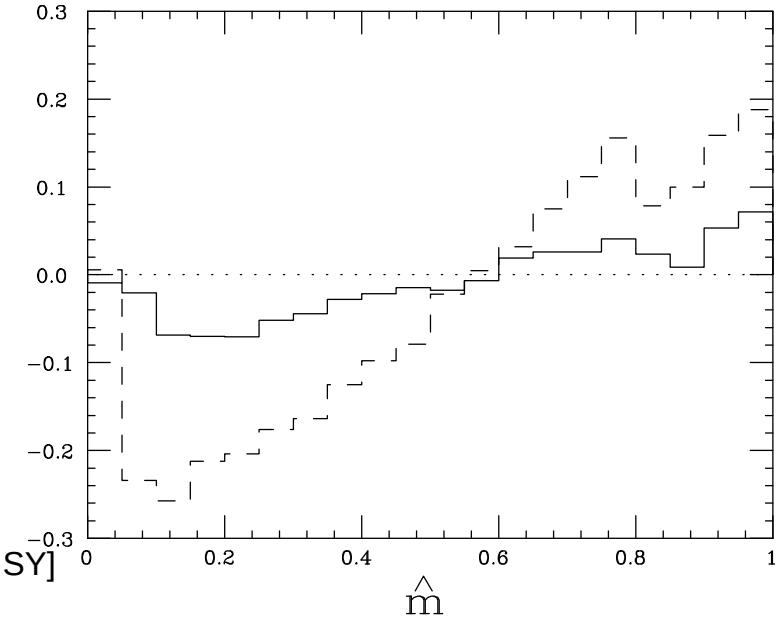
Slepton cascade [Smillie, Webber]

- decay chain $\tilde{\chi}_2^0 \to \ell\tilde{\ell}^* \to \ell\bar{\ell}\tilde{\chi}_1^0$
- compare with first KK Z and ℓ
- initial-state asymmetry pp $\to \tilde{q}\tilde{g}$ [$\tilde{q}/\bar{\tilde{q}} \sim 2$]
- trick: mass variables, 'normalized angles' [Barr]

  $\hat{m} = m_{j\ell}/m_{j\ell}^{max}$ most promising

  $\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$
- assume hierarchical SPS1a spectrum [dashed SUSY]

$\Rightarrow$ SUSY spins accessible



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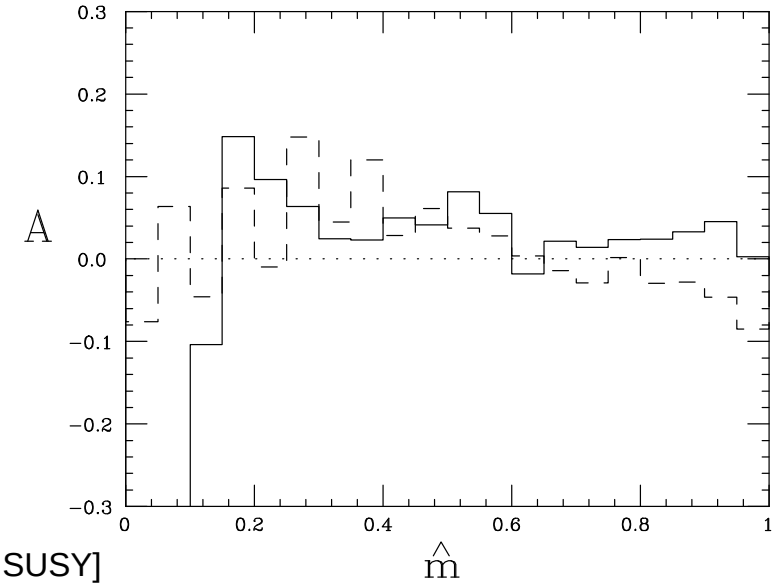


SUSY MATRIX ELEMENTS

Complex final states: SUSY-Madgraph [Hagiwara, Kanzaki, TP, Rainwater, Stelzer]

- Majoranas and fermion number violation in Madgraph [Denner, Eck, Hahn, Küblbeck]
- complete set of Feynman rules [400+ processes compared with Whizard and Sherpa]

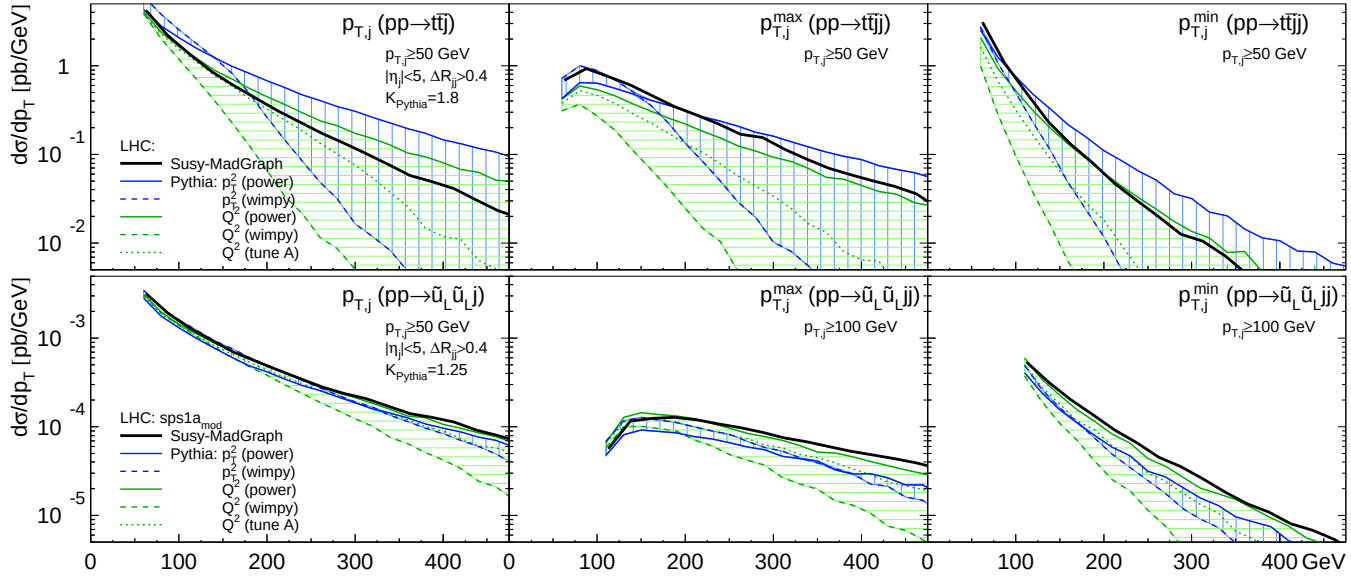
Squarks and gluinos plus jets [TP, Rainwater, Skands]

- cascade studies sensitive to jets?
- SUSY-Madevent: $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]

$\Rightarrow$ Phythia shower tuned at Tevatron?

$\Rightarrow$ SUSY will be fine, top harder

σ [pb]	$t\bar{t}_{600}$	$\tilde{g}\tilde{g}$	$\tilde{u}_L\tilde{g}$
σ_{0j}	1.30	4.83	5.65
σ_{1j}	0.73	2.89	2.74
σ_{2j}	0.26	1.09	0.85



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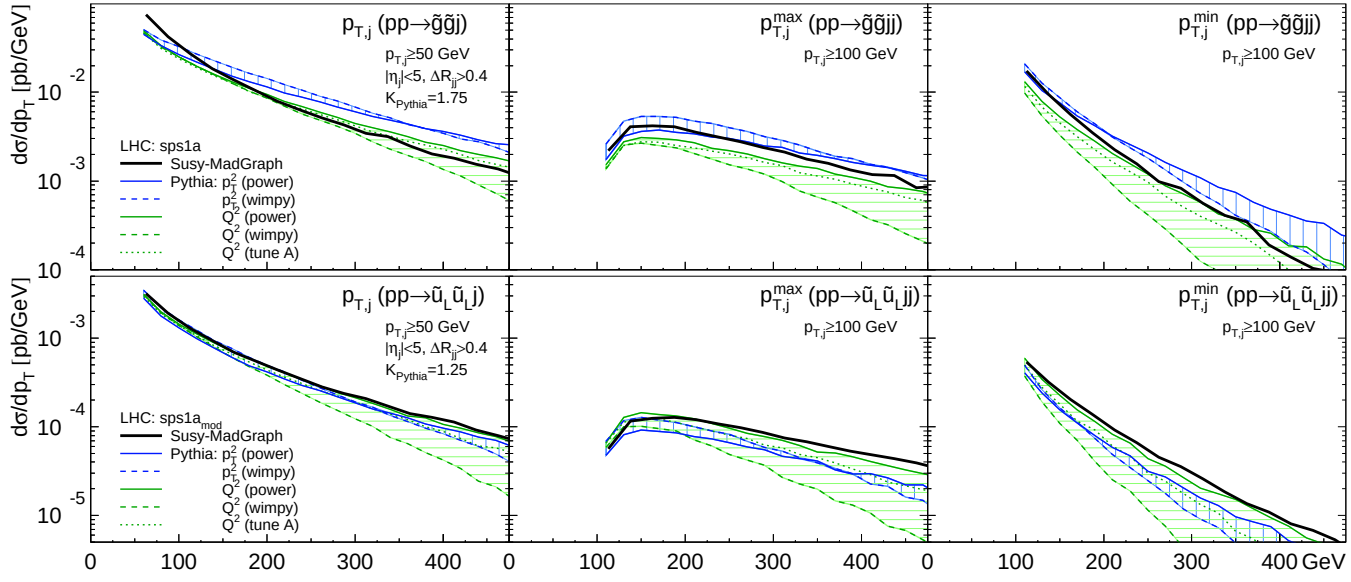


SUSY PARAMETERS

SUSY parameters from observables

- parameters: weak-scale MSSM Lagrangean
- measurements: masses or edges
  branching fractions [MSMlib, Sdecay]
  cross sections [Prospino2, MSMlib],...
- errors: general correlation, statistics & systematics & theory
- problem in grid: huge phase space, local minimum?
  problem in fit: domain walls, starting values, global minimum?

First go at problem

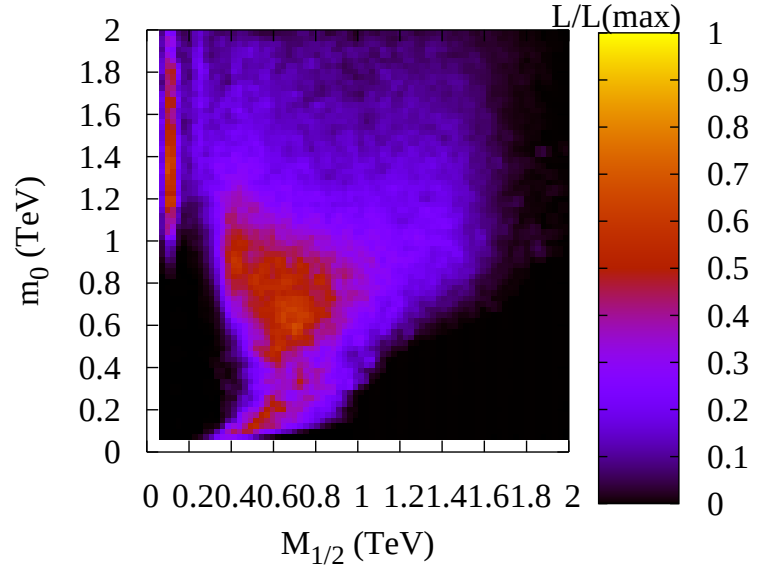
- assume we know how SUSY is broken

$\Rightarrow$ mSUGRA

- include some indirect constraints
- fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$ [Allanach]

$\Rightarrow$ who believes in mSUGRA?

mSUGRA useful testing ground for methods



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First go at problem

- assume we know how SUSY is broken

$\Rightarrow$ mSUGRA

- include more indirect constraints [Weiglein, Stöckinger,...]
- fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu)$

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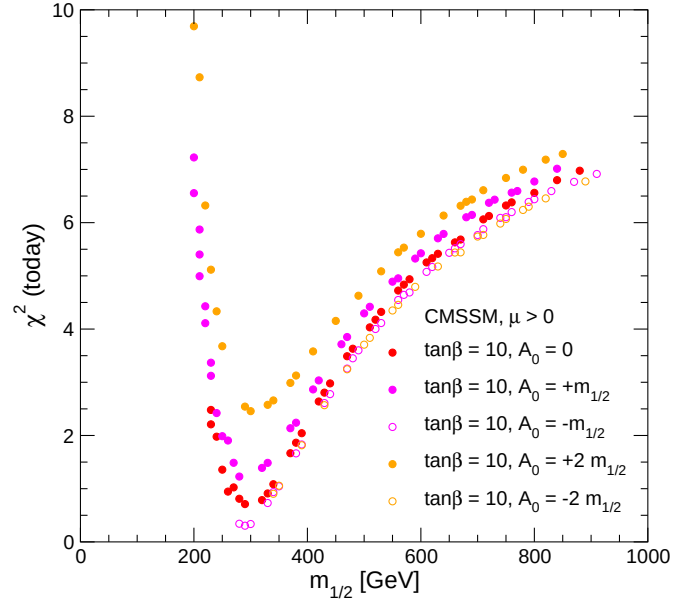
mSUGRA useful testing ground for methods



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Sfitter/Fittino [Lafaye, TP, Zerwas; Bechtle, Desch, Wienemann]

- (1) grid for closed subset
  (2) fit of remaining parameters
  (3) complete fit

- LHC better than expected
- LHC+ILC without assumptions
- SUSY breaking bottom–up

	LHC	ILC	LHC+ILC	SPS1a
$\tan\beta$	10.22±9.1	10.26±0.3	10.06±0.2	10
M_1	102.45±5.3	102.32±0.1	102.23±0.1	102.2
M_3	578.67±15	fi x 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fi x 500	197.68±1.2	199.25±1.1	197.8
$M_{\tilde{\tau}_R}$	129.03±6.9	135.66±0.3	133.35±0.6	135.5
$M_{\tilde{\mu}_L}$	198.7±5.1	198.7±0.5	198.7±0.5	198.7
$M_{\tilde{q}3_L}$	498.3±110	497.6±4.4	521.9±39	501.3
$M_{\tilde{t}_R}$	fi x 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fi x 500	504.35±61	525.6
A_τ	fi x 0	-202.4±89.5	352.1±171	-253.5
A_t	-507.8±91	-501.95±2.7	-505.24±3.3	-504.9
A_b	-784.7±35603	fi x 0	-977±12467	-799.4

OUTLOOK

LHC phenomenology

- pheno-experimental efforts very strong in Scotland and northern England
- lots of new tools on the market, waiting to be tested
- We will be able to do amazing things at the LHC

$\Rightarrow$ come to Georg's talk for what we still need for the future of HEP...