Phenomenology 3: Supersymmetry

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Outline

Standard–Model effective theory

TeV–scale supersymmetry

Supersymmetric signatures

New physics mass measurements

New physics spin measurements

Supersymmetric parameter studies

Standard–Model effecive theory: 1

What is the Standard Model?

– a gauge theory with the group structure $SU(3) \otimes SU(2) \otimes U(1)$

– massless $SU(3)$ and $U(1)$ gauge bosons

– massive electroweak gauge bosons from spontaneous symmetry breaking

[Higgs mechanism with $v = 246$ GeV and m_H unknown]

– Dirac fermions in doublets and with masses equal to Yukawas

– generation mixing in quark and neutrino sector

$\Rightarrow$ defined by particle content and (gauge) interactions

Confronted with data

– renormalizable Lagrangian a la 't Hooft & Thomas Teubner [all operators to D4]

– neutrino masses? [see-saw at $10^1$1 GeV?]

– flavor physics? [new operators above 10^4 GeV?]

– dark matter? [only solid evidence for new physics]

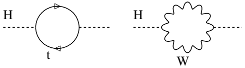
– gravity? [mostly negligible, and unrenormalizable in usual sense]

$\Rightarrow$ general effective–theory Lagrangian with those interactions and particles

$\Rightarrow$ cutoff scale built in, size of Λ negotiable

$\Rightarrow$ who the hell cares....???

Standard–Model effective theory: 2



...theorists care!

– compute loop corrections to scalar Higgs mass

– top loop in Higgs self energy Σ

$$\Sigma \sim -\left(\frac{g\,m_t}{v}\right)^2 \int \frac{d^4q}{(2\pi)^4} \frac{(\not{p}+m_t)\,(\not{p}+\not{q}+m_t)}{[q^2-m_t^2]\,[(q+p)^2-m_t^2]} \sim -\frac{1}{(4\pi)^2}\left(\frac{g\,m_t}{v}\right)^2 \Lambda^2 + \cdots$$

– sum to Higgs–mass correction

$$\begin{aligned} \frac{1}{p^2-m_H^2} &\longrightarrow \frac{1}{p^2-m_H^2} + \frac{1}{p^2-m_H^2}\Sigma\frac{1}{p^2-m_H^2} + \frac{1}{p^2-m_H^2}\Sigma\frac{1}{p^2-m_H^2}\Sigma\frac{1}{p^2-m_H^2} + \dots \\ &= \frac{1}{p^2-m_H^2}\sum_{j=0}^{\infty}\left(\frac{\Sigma}{p^2-m_H^2}\right)^j = \frac{1}{p^2-m_H^2}\frac{1}{1-\dfrac{\Sigma}{m^2-m_H^2}} \\ &= \frac{1}{p^2-m_H^2-\Sigma} \end{aligned}$$

– and see the desaster after collecting all loop functions

$$m_H^2 \longrightarrow m_H^2 - \frac{3g^2}{32\pi^2}\frac{\Lambda^2}{m_W^2}\left[m_H^2 + 2m_W^2 + m_Z^2 - 4m_t^2\right] + \cdots$$

$\Rightarrow$ Higgs mass including loops wants to be cutoff scale Λ

$\Rightarrow$ Standard–Model effective theory destabilized between v and Λ

[Higgs wants to be at Λ, but would not function as Higgs there]

$\Rightarrow$ hierarchy problem

Standard–Model effective theory: 3

Starting from data...

– ...which seems to indicate a light Higgs [e-w precision data]

– ...and seems to require higher–scale physics [neutrino masses, flavor,...]

– problem of light Higgs: mass driven to cutoff of effective Standard Model:
$\delta m_H^2/m_H^2 \propto g^2(2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\,\Lambda^2$

⇒ easy solution: counter term to cancel loops ⇒ artificial, unmotivated, ugly

⇒ or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs (Goldstone Higgs)
Higgsless, composite Higgs, TopColor,
YourFavoriteNewPhysics...

⇒ typically cancellation by new particles or discussing away high scale

⇒ beautiful concepts, but problematic at TeV scale [data seriously in the way]

⇒ new physics models in baroque state

Idea of supersymmetry:

cancellation of divergences through statistics factor (-1)

[SM fermions to scalar; SM gauge bosons to fermions; SM scalars to fermions]

(off to whiteboard to contract lots of indices...)

TeV–scale supersymmetry

SUSY breaking: (yet) unobserved partners heavy

- link to BSM dark matter
- link to BSM $(g-2)_\mu$?
- link to flavor physics and baryogenesis? [Standard Model fine??]
- mechanism for SUSY masses unknown [soft SUSY breaking mediated somehow?]

  maximally blind mediation: mSUGRA [not a LHC paradigm!]
  scalars: m_0, fermions: $m_{1/2}$, tri-scalar term: A_0
  plus sign(μ) and $\tan\beta$ in Higgs sector
- alternatives: gauge, anomaly, gaugino mediation $\cdots$?

⇒ measure spectrum at LHC instead

LHC phenomenology: MSSM

- conjugate Higgs field not allowed
  → give mass to t and b?
  → two Higgs doublets
- SUSY Higgs alone interesting

⇒ would be another talk...

⇒ SUSY partners at LHC

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

Supersymmetric signatures: 1

Inclusive: squarks and gluinos at Tevatron

– squarks, gluinos strongly interacting
$p\bar{p} \to \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [best if $m(\tilde{q}) \sim m(\tilde{g})$]

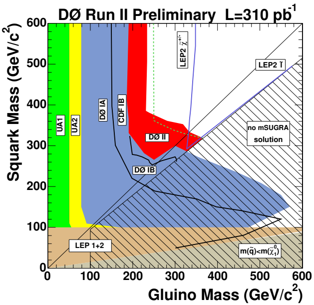
– large rates at hadron colliders

– decays to jets and LSP
$\tilde{g} \to \tilde{q}\bar{q}, \tilde{q}_L \to q\tilde{\chi}_2^0, \tilde{q}_R \to q\tilde{\chi}_1^0$

[additional jets and leptons possible]

– gaugino mass unification assumed for details

⇒ we know inclusive jets plus LSP



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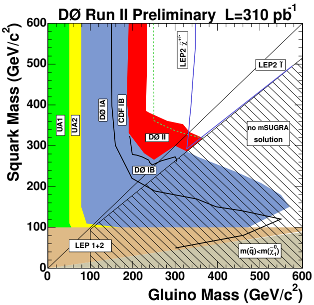


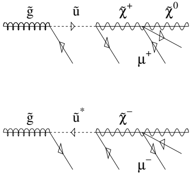
When do we see SUSY–QCD?

– gluinos: strongly interacting Majorana fermions

– first jet in gluino decay: q or $\bar{q}$

– final–state leptons with both charges

$\Rightarrow$ like–sign dileptons from $\tilde{g}\tilde{g}$



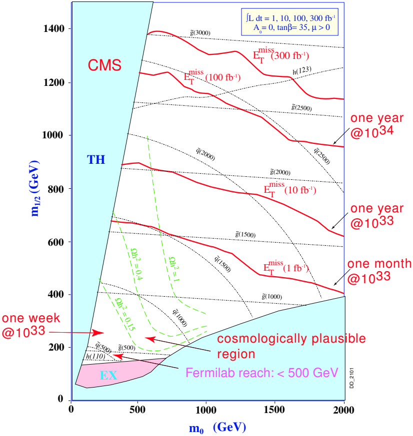
Supersymmetric signatures: 2

New physics at the LHC

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

(2) measurements

(3) parameter studies



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New physics at the LHC

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

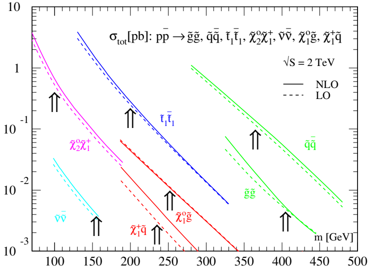
(2) measurements — masses, cross sections, decays

(3) parameter studies — MSSM Lagrangian, SUSY breaking

$\Rightarrow$ approach independent of new physics model

Some SUSY signals at Tevatron

- jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$
- like–sign dileptons: $pp \to \tilde{g}\tilde{g}$
- funny tops: $pp \to \tilde{t}_1 \tilde{t}_1^*$
- tri-leptons: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$
  $[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0 \ell\bar{\ell}; \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell\bar{\nu}]$



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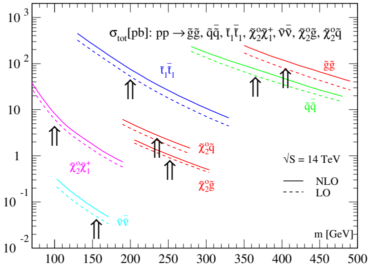
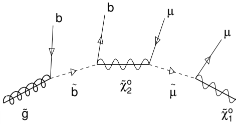
$[\tilde{\chi}_2^0 \to \tilde{\ell}\bar{\ell} \to \tilde{\chi}_1^0 \ell\bar{\ell};\ \tilde{\chi}_1^- \to \tilde{\chi}_1^0 \ell\bar{\nu}]$

$\Rightarrow$ inclusive: similar to Tevatron

$\Rightarrow$ exclusive: enough events for studies



New physics mass measurements: 1



Spectra from cascade decays

– decay $\tilde{g} \to \tilde{b}\bar{b} \to \tilde{\chi}_2^0 b\bar{b} \to \mu^+\mu^- b\bar{b}\tilde{\chi}_1^0$ [better not via Z or to τ]

– cross sections some 100 pb [more than 3×10^7 events]

– thresholds & edges

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

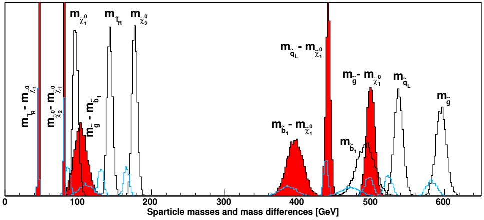
$\Rightarrow$ spectrum information from decay kinematics [mass differences with smaller errors]

Gluino mass from kinematic endpoints

– all decay jets b-tagged [otherwise dead by QCD]

– most of time: cascade assumption correct

$\Rightarrow$ gluino mass to $\sim 1\%$



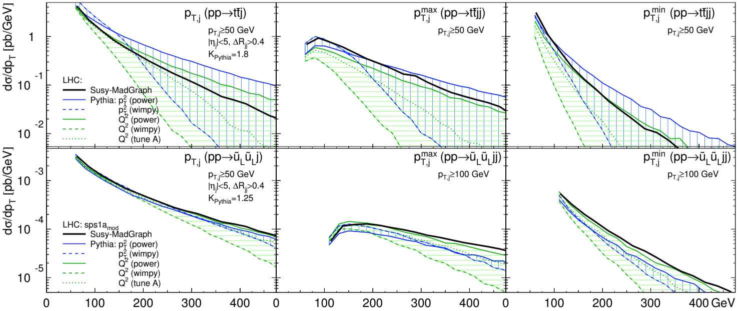
New physics mass measurements: 2

Squarks and gluinos always with many jets [QCD lecture]

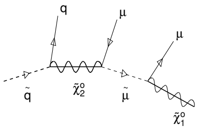
- cascade studies sensitive to jet simulation?
- matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]
- compared with Pythia shower
- hard scale μ_F huge for SUSY

$\Rightarrow$ Shower and matrix element identical for SUSY

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



New physics spin measurements: 1



All new physics is hypothesis testing

– assume squark cascade observed

⇒ strongly interacting scalar?

⇒ straw-man model where squark is a fermion: universal extra dimensions

[spectra degenerate — ignore; cross section larger — ignore]

Squark cascade $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\ell\tilde{\ell} \to q\ell\bar{\ell}\tilde{\chi}_1^0$

(1) compare with first excited Z and ℓ [assume near/far lepton for now]

– polarization: 1: $(q_L, \ell_L^-, \ell_L^+)$

2: $(q_L, \ell_L^+, \ell_L^-)$=$(q_L, \ell_R^-, \ell_R^+)$=$(\bar{q}_L, \ell_L^-, \ell_L^+)$

– distribution of angle θ between q and ℓ: $dP_{1,2}^{\text{SUSY}}/d\cos\theta \propto (1 \mp \cos\theta)$

(2) mass variable: $\hat{m} = m_{ql}/m_{ql}^{\max} = \sin\theta/2$

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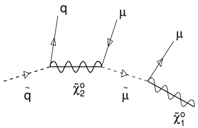

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Squark cascade $\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\ell\tilde{\ell} \to q\ell\bar{\ell}\tilde{\chi}^0_1$

(1) compare with first excited Z and ℓ [assume near/far lepton for now]

– polarization: 1: $(q_L, \ell^-_L, \ell^+_L)$

2: $(q_L, \ell^+_L, \ell^-_L)$=$(q_L, \ell^-_R, \ell^+_R)$=$(\bar{q}_L, \ell^-_L, \ell^+_L)$

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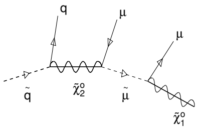
UED and SUSY distributions [SPS1a spectrum]

$$\frac{dP^{\text{SUSY}}_1}{d\hat{m}} = 4\hat{m}^3 \qquad \frac{dP^{\text{SUSY}}_2}{d\hat{m}} = 4\hat{m}\left(1 - \hat{m}^2\right)$$

$$\frac{dP^{\text{UED}}_1}{d\hat{m}} = 1.213\,\hat{m} + 3.108\,\hat{m}^3 - 2.310\,\hat{m}^5 \qquad \frac{dP^{\text{UED}}_2}{d\hat{m}} = 2.020\,\hat{m} + 1.493\,\hat{m}^3 - 2.310\,\hat{m}^5$$

New physics spin measurements: 2



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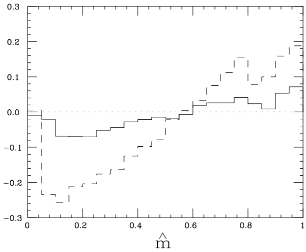
– distribution of angle θ between q and ℓ

(2) mass variable: $\hat{m} = m_{ql}/m_{ql}^{\max} = \sin\theta/2$

– typically largest $pp \to \tilde{q}\tilde{g}$

(3) production asymmetry $\tilde{q} : \tilde{q}^* \sim 2 : 1$
$\Rightarrow \mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$



Masses or spin or both?

– masses from kinematic endpoints [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell}\cdots$]

– spins from distributions between endpoints [endpoints identical in SUSY and UED]

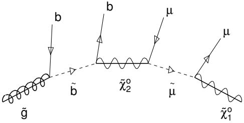
New physics spin measurements: 3

Back to sign of SUSY–QCD

- like–sign dileptons indicate Majorana fermion?
- always like–sign dileptons from bosonic gluon

⇒ show gluino fermionic

⇒ compare with usual UED straw man



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Gluino–bottom cascade

– decay chain like for gluino mass

– compare with first KK g, q, Z, ℓ, γ

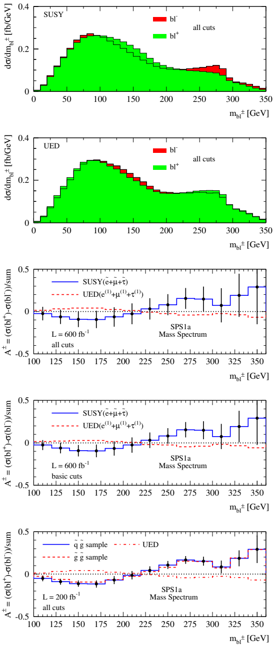
– replace initial–state asymmetry by b vs. $\bar{b}$

– independent of production channels

– asymmetry to write down:
$\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$

[still visible after cuts and smearing]

– Tim: yet another reason for detector upgrade



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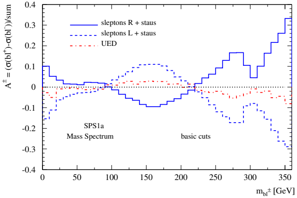


Gluino–bottom cascade

– interchange $\tilde{\ell}_{LR}$ in cascade

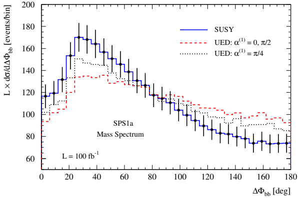
– test of lepton-ino couplings

– purely hadronic ϕ_{bb}

– independent of weak decays

– sensitive to gluino/KK-gluon boost

$\Rightarrow$ masses and spins from decays, but messy



Supersymmetric parameters: 1

Theory output from LHC: SUSY parameters

– parameters: weak-scale Lagrangian

– measurements: masses or edges
  branching fractions
  cross sections

– errors: general correlation, statistics & systematics & theory

– problem in grid: huge phase space, local minimum?
  problem in fit: domain walls, global minimum?

First go at problem

– ask a friend how SUSY is broken $\Rightarrow$ mSUGRA

– fit $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu), y_t, ...$

– no problem, include indirect constraints

$\Rightarrow$ probability map as of today

$\Rightarrow$ best fit from LHC/ILC measurements

	SPS1a	ΔLHC masses	ΔLHC edges	ΔILC	ΔLHC+ILC
m_0	100	3.9	1.2	0.09	0.08
$m_{1/2}$	250	1.7	1.0	0.13	0.11
$\tan\beta$	10	1.1	0.9	0.12	0.12
A_0	-100	33	20	4.8	4.3

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MSSM instead of mSUGRA

– (1) grid for closed subset
  (2) fit of other parameters
  (3) complete fit

$\Rightarrow$ too few measurements?
secondary minima? ...

	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	fix 500	588.05±11	589.4
$M_{\tilde{\tau}_L}$	fix 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
$M_{\tilde{t}_R}$	fix 500	420±2.1	411.73±12	420.2
$M_{\tilde{b}_R}$	522.26±113	fix 500	504.35±61	525.6
A_τ	fix 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	fix 0	-977±12467	-799.4

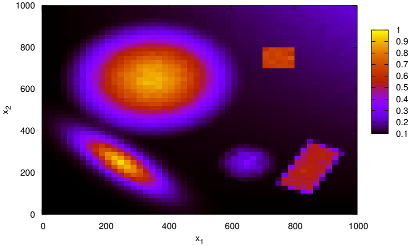
Supersymmetric parameters: 2

Probability maps of new physics

– Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$ [$p(d)$ through normalization]
– Pythia/Herwig/Sherpa: data given a model $p(d|m) \sim |\mathcal{M}|^2$
– theorist's prejudice: model $p(m)$
$\Rightarrow$ given measurements: (1) compute map $p(m|d)$ of parameter space
(2) rank local maxima

Bayesian or frequentist?

– test function $V(\vec{x})$ in 5 dimensions [general high–dimensional extraction tool]
– best–fitting point: small sphere
most likely scenatio: large sphere [water in spoon/cloud]



V=74.929 @(655.00,253.72,347.83,348.57,349.59)
V=59.972 @(850.04,224.99,650.00,649.99,654.56)
V=58.219 @(849.97,225.01,587.08,650.01,650.02)
V=25.110 @(750.00,749.99,450.00,450.01,450.01)
V=16.042 @(245.45,253.44,552.51,542.58,544.75)
V=12.116 @(350.70,650.40,650.36,650.40,650.38)
. . .

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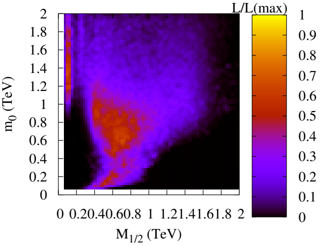
mSUGRA with today's measurements alone

- electroweak precision data



Supersymmetric parameters: 2

Probability maps of new physics

– Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$ [$p(d)$ through normalization]

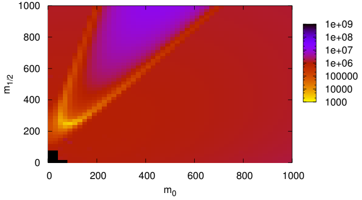
– Pythia/Herwig/Sherpa: data given a model $p(d|m) \sim |\mathcal{M}|^2$

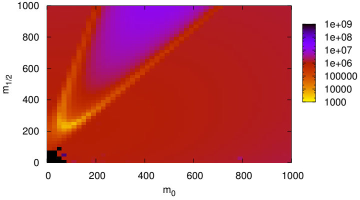
– theorist's prejudice: model $p(m)$

$\Rightarrow$ given measurements: (1) compute map $p(m|d)$ of parameter space
(2) rank local maxima

mSUGRA with LHC measurements alone

– SPS1a kinematic edges





New physics at the LHC

Supersymmetry as a well-studied example for BSM physics

- inclusive signatures from Tevatron
- exclusive analysis only at LHC
- mass and spin measurements
- parameter extraction/probability maps