Phenomenology 3: Beyond the Standard Model

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Campos do Jordao, 2/2007

Outline

TeV–scale supersymmetry

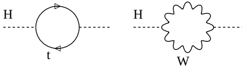
Supersymmetric signatures

New physics mass measurements

New physics spin measurements

Supersymmetric parameter studies

TeV–scale supersymmetry: 1



Starting from data...

- ...which seems to indicate a light Higgs [e-w precision data]
- problem of light Higgs: mass driven to cutoff of effective Standard Model:
  $\delta m_H^2 \propto g^2 (2 m_W^2 + m_Z^2 + m_H^2 - 4 m_t^2)\ \Lambda^2$

$\Rightarrow$ easy solution: counter term to cancel loops $\Rightarrow$ artificial, unmotivated, ugly

$\Rightarrow$ or new physics at TeV scale: supersymmetry
extra dimensions
little Higgs (pseudo–Goldstone Higgs)
Higgsless, composite Higgs, TopColor,
YourFavoriteNewPhysics...

$\Rightarrow$ typically cancellation by new particles or discussing away high scale

$\Rightarrow$ beautiful concepts, but problematic at TeV scale [data seriously in the way]

$\Rightarrow$ 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]

TeV–scale supersymmetry: 2

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 β in Higgs sector

– alternatives: gauge, anomaly, gaugino mediation $\cdots$?

$\Rightarrow$ measure spectrum at LHC instead

LHC phenomenology: MSSM

– conjugate Higgs field not allowed
$\to$ give mass to t and b?
$\to$ two Higgs doublets

– SUSY Higgs alone interesting

$\Rightarrow$ would be another talk...

$\Rightarrow$ SUSY partners at LHC

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

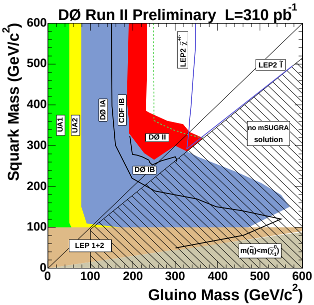
Supersymmetric signatures: 1

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

$\Rightarrow$ we know inclusive jets plus LSP



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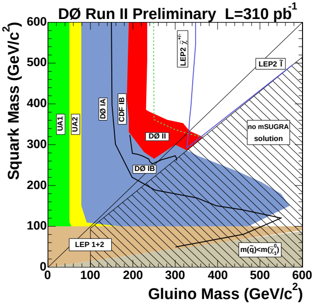


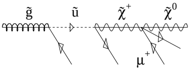
When do we see SUSY–QCD?

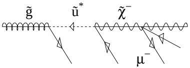
– gluinos: strongly interacting Majorana fermions

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

– final–state leptons with both charges

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





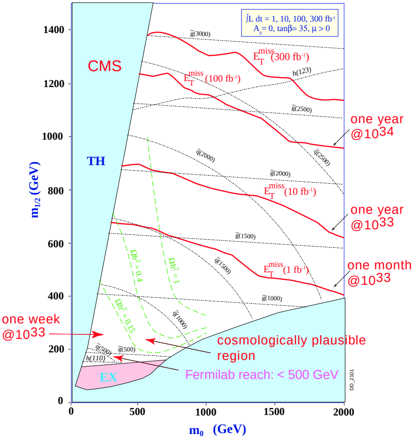
Supersymmetric signatures: 2

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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$\Rightarrow$ approach independent of new physics model

Some SUSY signals at Tevatron

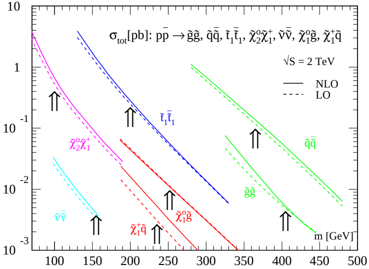
– jets and $\not{E}_T$: $pp \to \tilde{q}\tilde{q}^*, \tilde{g}\tilde{g}, \tilde{q}\tilde{g}$

– 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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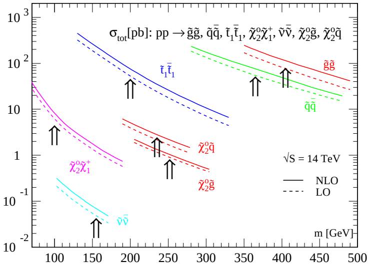
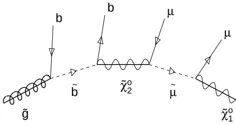
$\Rightarrow$ inclusive: similar to Tevatron

$\Rightarrow$ 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

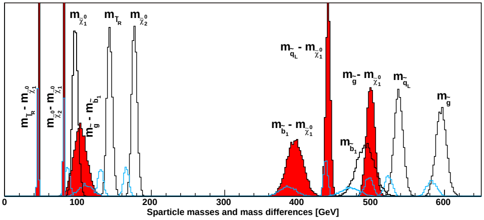
$$m_{\ell\ell}^2 < \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\ell}}^2}{m_{\tilde{\ell}}} \; \frac{m_{\tilde{\ell}}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\ell}}}$$

$\Rightarrow$ 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 $\sim 1\%$



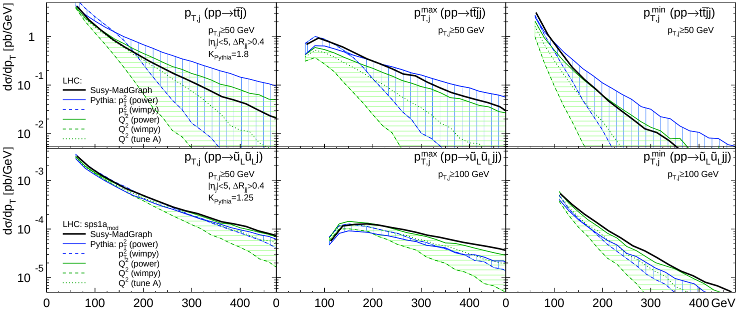
New physics mass measurements: 2

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



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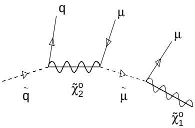

All new physics is hypothesis testing

– 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: $\hat{m} = m_{ql}/m_{ql}^{\text{max}} = \sin\theta/2$

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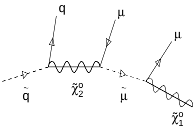

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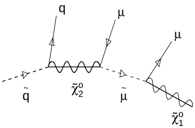
UED and SUSY distributions [SPS1a spectrum]

$$\frac{dP_1^{\rm SUSY}}{d\hat{m}} = 4\hat{m}^3 \qquad \frac{dP_2^{\rm SUSY}}{d\hat{m}} = 4\hat{m}\left(1-\hat{m}^2\right)$$

$$\frac{dP_1^{\rm UED}}{d\hat{m}} = 1.213\,\hat{m} + 3.108\,\hat{m}^3 - 2.310\,\hat{m}^5 \qquad \frac{dP_2^{\rm UED}}{d\hat{m}} = 2.020\,\hat{m} + 1.493\,\hat{m}^3 - 2.310\,\hat{m}^5$$

New physics spin measurements: 2



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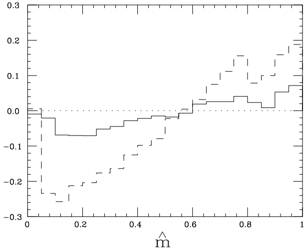
– distribution of angle θ between q and ℓ

(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?

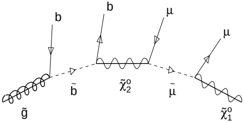
– masses from kinematic endpoints [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell}\cdots$]

– 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

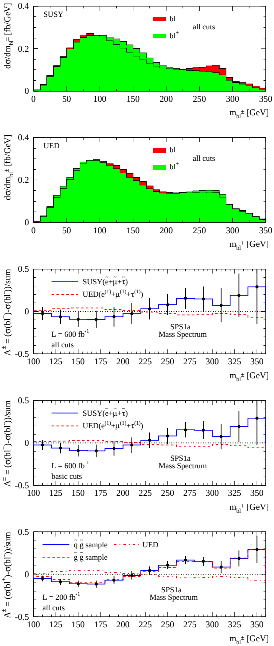
– compare with first KK g, q, Z, ℓ, γ

– 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]



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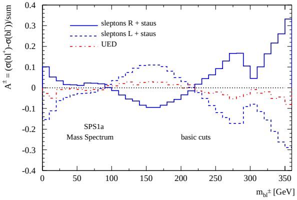


Gluino–bottom cascade

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

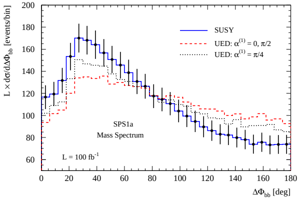
– test of lepton-ino couplings

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

– LHC+ILC perfect

$\Rightarrow$ 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

Weighted Markov chains

– classical: produce representative set of spin states
compute average energy based on this reduced sample

$\Rightarrow$ map (chain) based on probability of a state
expensive energy function on sample

– BSM physics: produce map $p(m|d)$ of parameter points
evaluate same probability from (binned) density

– already for mSUGRA: MCMC resolution not sufficient

$\Rightarrow$ use additional probability maximization to rank maxima

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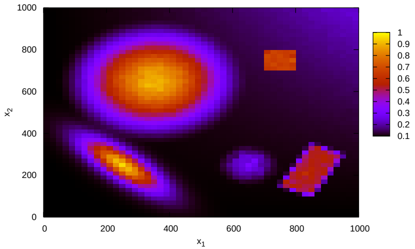
Toy model

– test function $V(\vec{x})$ in 5 dimensions [general high–dimensional extraction tool]

– Sfitter output #1: probability map
Sfitter output #2: list of local maxima [best fit]



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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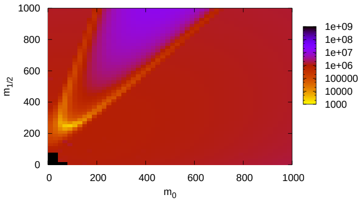
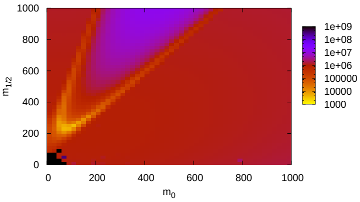
mSUGRA with LHC measurements alone

- SPS1a kinematic edges with free m_t





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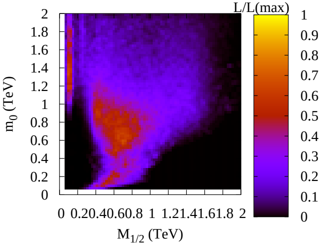
mSUGRA with today's measurements alone

– electroweak precision data with free m_t



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