New Physics at LHC and Elsewhere

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Outline

TeV–scale supersymmetry

Supersymmetric signatures at LHC

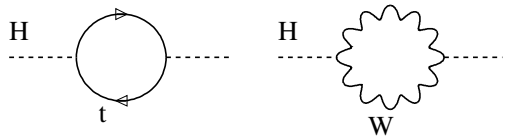
New physics mass measurements

New physics spin measurements

Supersymmetric parameter studies

If time — statistics and phenomenology

TeV–scale supersymmetry



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:
  $\delta m_H^2 \propto g^2 (2m_W^2 + m_Z^2 + m_H^2 - 4m_t^2)\, \Lambda^2$

$\Rightarrow$ 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]

$\Rightarrow$ LHC–relevant 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

SUSY breaking: (yet) unobserved partners heavy

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

  maximally blind mediation: mSUGRA [not an 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
  $\longrightarrow$ give mass to t and b?
  $\longrightarrow$ two Higgs doublets
- SUSY Higgs alone interesting

$\Rightarrow$ another talk... [Oliver Brein's talk]

$\Rightarrow$ SUSY partners at LHC

		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	$4 \cdot 2$	LSP?
gauge bosons	$W^\pm$	1	$2 \cdot 3$	
Higgs bosons	$H^\pm$	0	2	
$\longrightarrow$ charginos	$\tilde{\chi}_i^\pm$	1/2	$2 \cdot 4$	

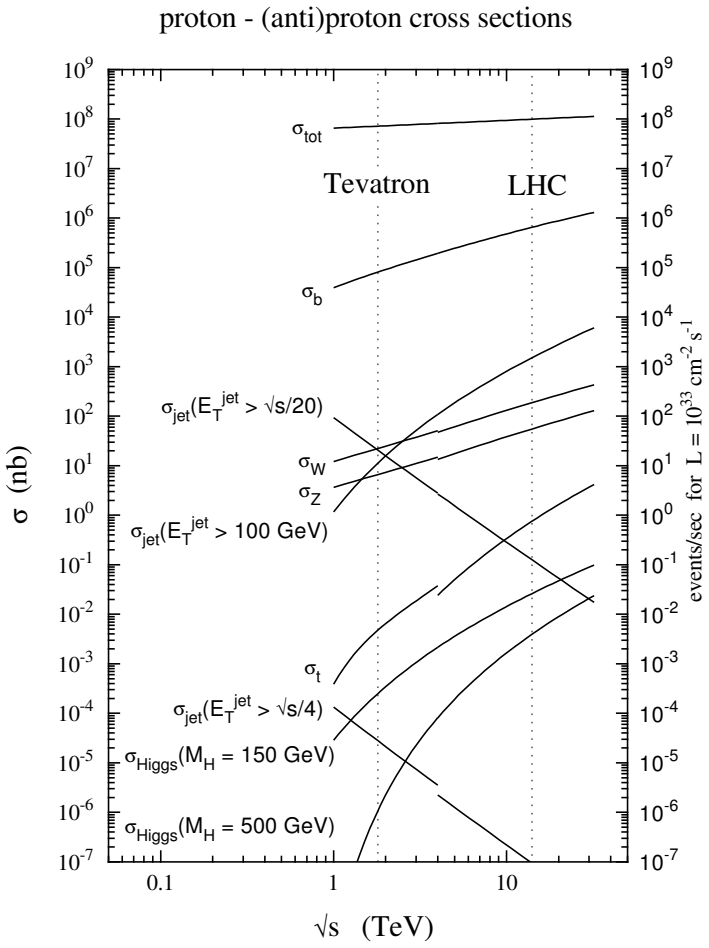
Hadron–collider searches

Conversion of beam energy into particle mass

- search for new particles easier if particle produced
  $\longrightarrow$ highest possible energies
- clean: e^+e^- colliders:
  LEP: Z pole
  LEP2: 206 GeV for e.g.chargino pairs
  ILC/CLIC/muon collider: 1...4 TeV in future
- brutal: hadron colliders:
  Tevatron: $p\bar{p}$ with 2 TeV [valence quarks]
  LHC: pp with 14 TeV [gluons]
- LHC partonic mass reach $\sim$ 3 TeV

New physics at hadron colliders

- what is a jet and what is inside? [b, τ tag]
- trigger: 'no leptons/photons — no data'
- backgrounds $pp \longrightarrow jj, t\bar{t}, WZ$+jets
- dark–matter motivated missing energy easy
- Gaussian statistics: $S/\sqrt{B} > 5$ discovery



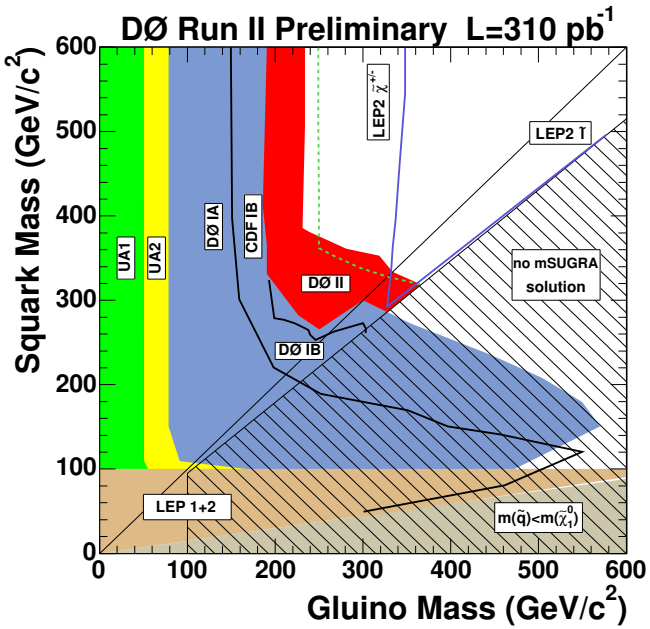
Supersymmetry at LHC

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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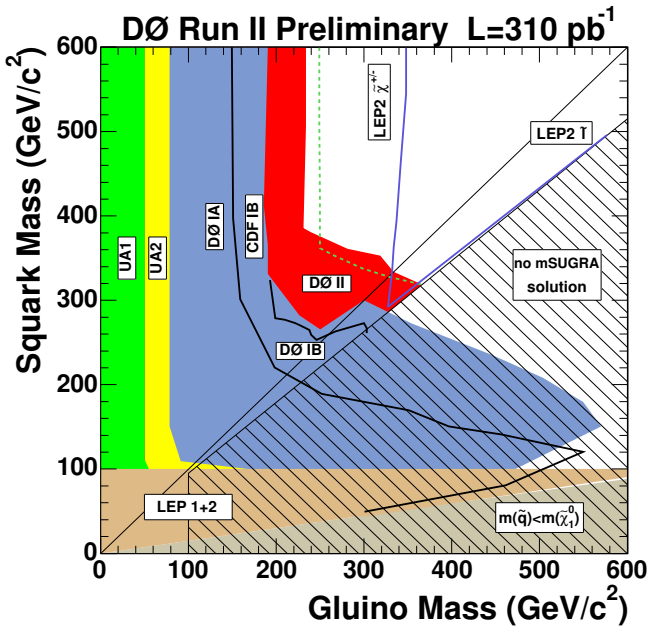
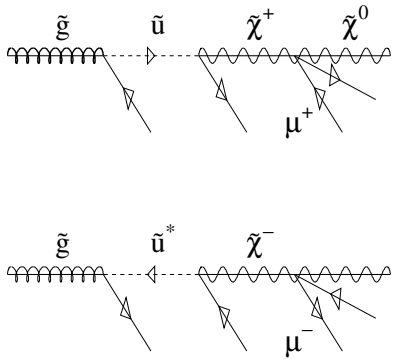


When do we see SUSY–QCD?

- 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 $\tilde{g}\tilde{g}$ [Barger,...; Barnett,...; Baer,...]



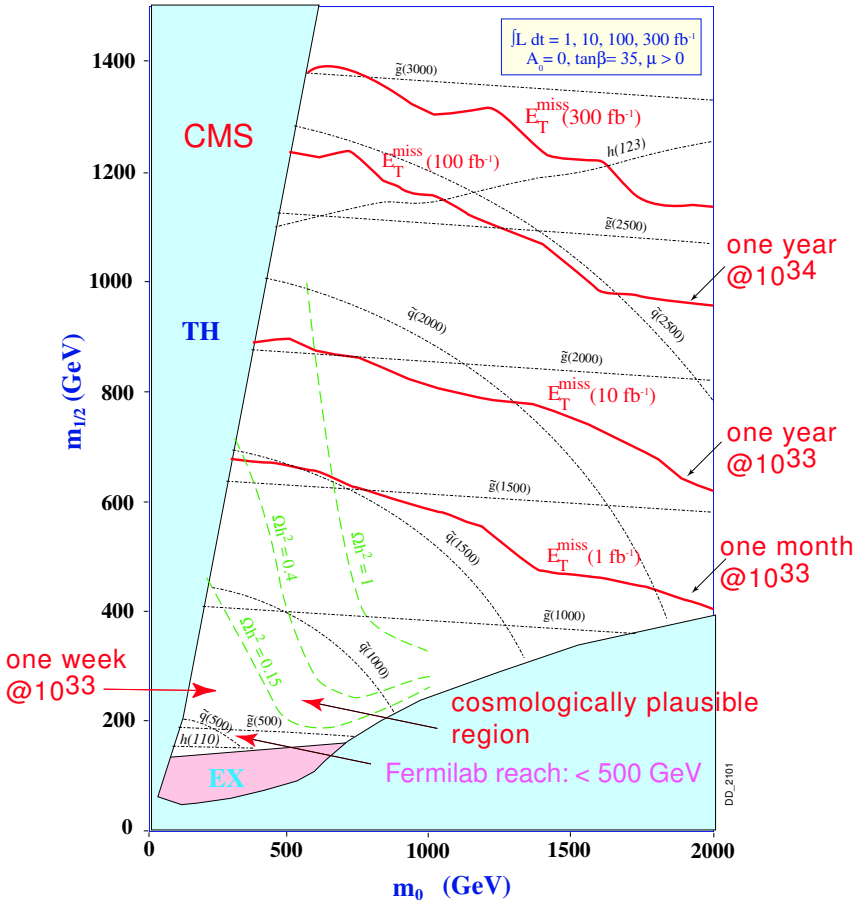
Supersymmetry at LHC

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 Lagrangean, SUSY breaking

$\Rightarrow$ approach independent of new physics model

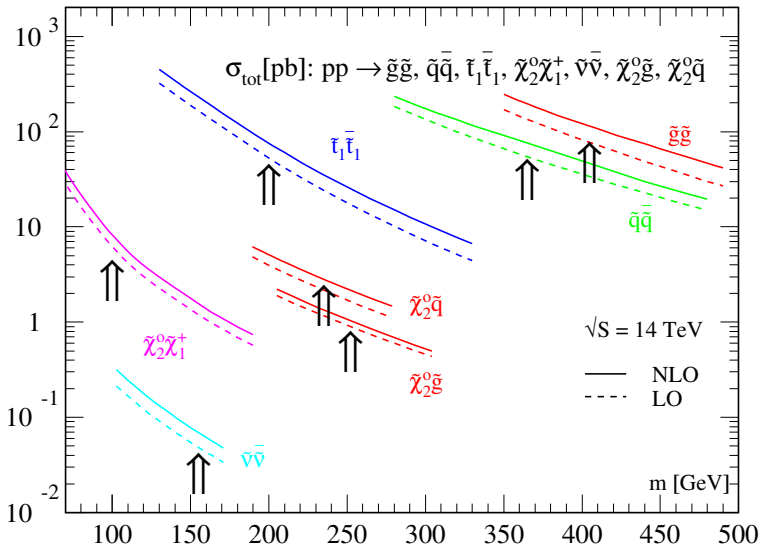
Some SUSY signals at LHC [NLO: Prospino2]

- 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: $pp \to \tilde{\chi}_2^0 \tilde{\chi}_1^-$

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

$\Rightarrow$ inclusive: similar to Tevatron

$\Rightarrow$ exclusive: enough events for studies



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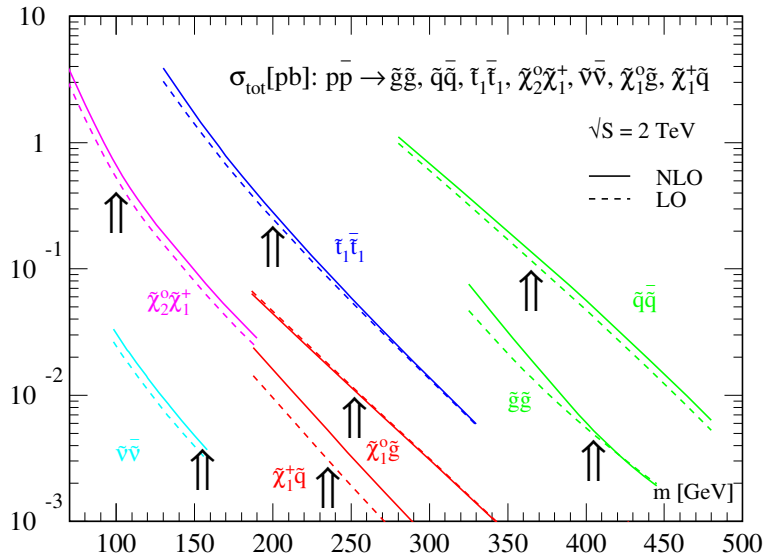
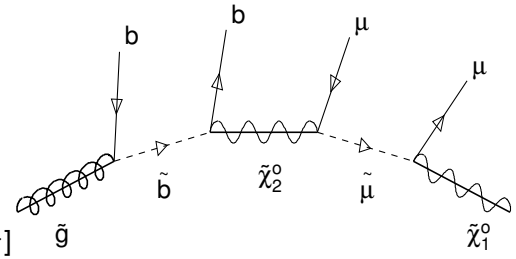


New physics mass measurements

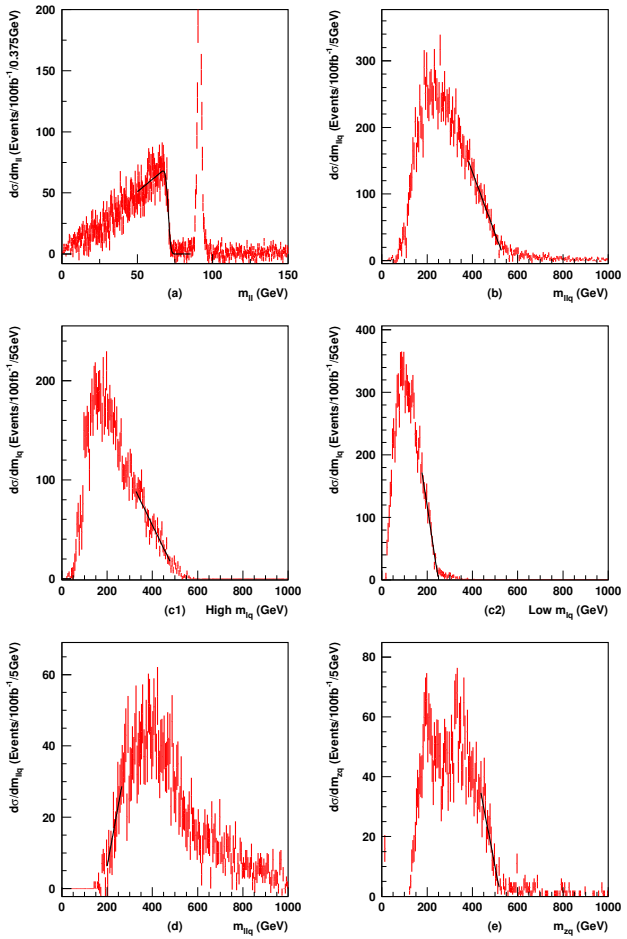


Spectra from cascade decays

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

$\Rightarrow$ spectrum information from decay kinematics

[Hinchliffe,...;Allanach,...; not only SUSY: Meade & Reece]



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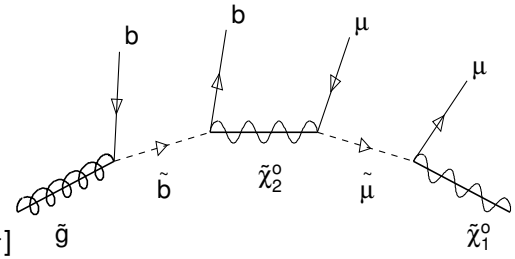

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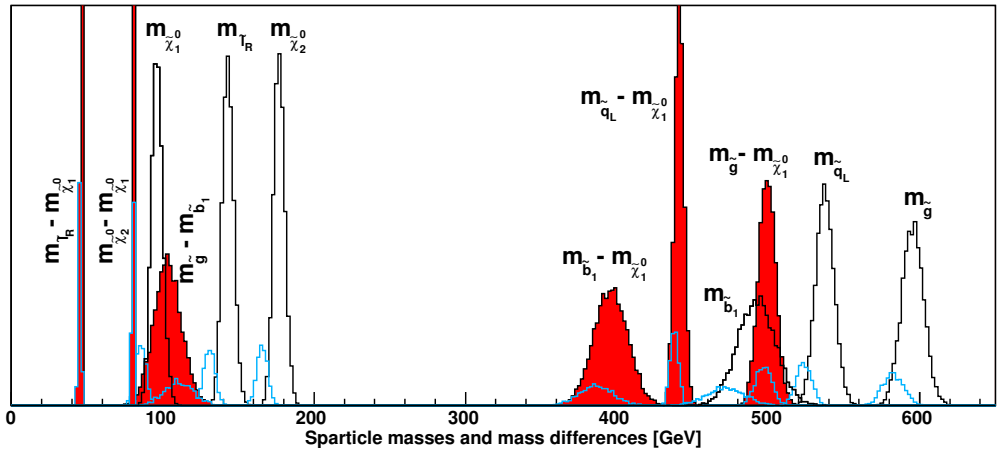
$\Rightarrow$ spectrum information from decay kinematics [mass differences with smaller errors]

Gluino mass from kinematic endpoints

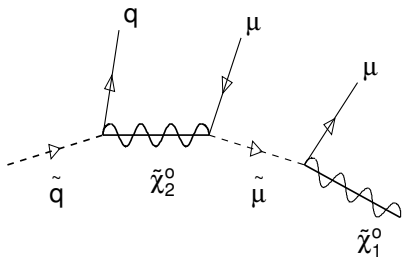
- all decay jets b-tagged [Gjelsten, Miller, Osland]
- most of time: cascade assumption correct

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

[theoretically defined?]



New physics spin measurements



New physics is hypothesis testing [nothing 'model independent at LHC']

- assume squark cascade observed

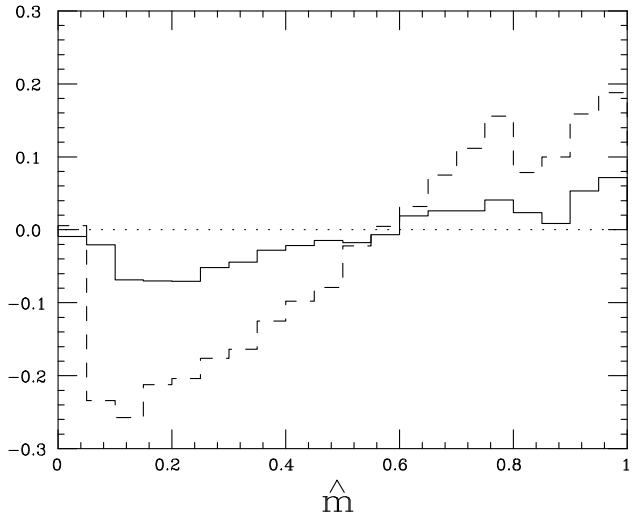
$\Rightarrow$ strongly interacting scalar?

$\Rightarrow$ straw-man model where squark is a fermion: universal extra dimensions

[Appelquist, Cheng, Dobrescu; Cheng, Matchev, Schmaltz; spectra degenerate — ignore; cross section larger — ignore]

Squark–slepton cascade [Barr; Smillie, Webber, Athanasiou, Lester]

- decay chain $\tilde{q} \to \tilde{\chi}_2^0 \to \tilde{\ell} \to \tilde{\chi}_1^0$
- trick 1: compare with KK q, Z, ℓ, γ
- trick 2: 'invariant angles'
  $\Rightarrow \widehat{m} = m_{j\ell}/m_{j\ell}^{\max}$ most promising
- typically largest $pp \to \tilde{q}\tilde{g}$
- trick 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? [Arkani-Hamed,...]

- masses from kinematic endpoints [use $m_{\ell j}, m_{\ell\ell}, m_{j\ell\ell} \ldots$]
- spins from distributions between endpoints [endpoints identical in SUSY and UED]

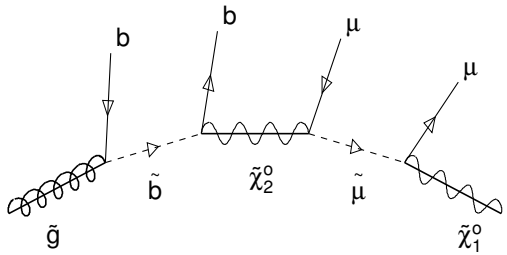
New physics spin measurements

Back to sign of SUSY–QCD

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

$\Rightarrow$ show gluino fermionic

$\Rightarrow$ compare with usual straw man [UED–Madgraph: Alves]



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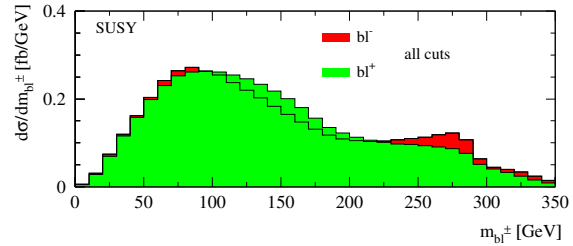
Gluino–bottom cascade [Alves, Eboli, TP]

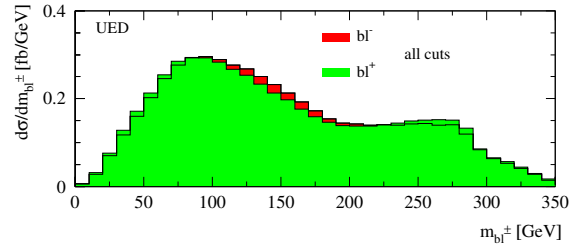
- decay chain like for gluino mass
- compare with first KK g, q, Z, ℓ, γ

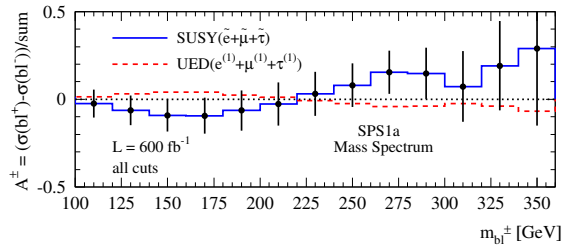
- replace initial–state asymmetry by b vs. $\bar{b}$
- independent of production channels
- asymmetry to write down:
  $\mathcal{A} = [\sigma(b\ell^+) - \sigma(b\ell^-)]/[\sigma(b\ell^+) + \sigma(b\ell^-)]$

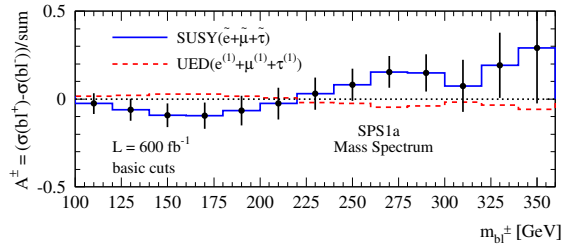
$\Rightarrow$ masses and spins accessible in decays at LHC

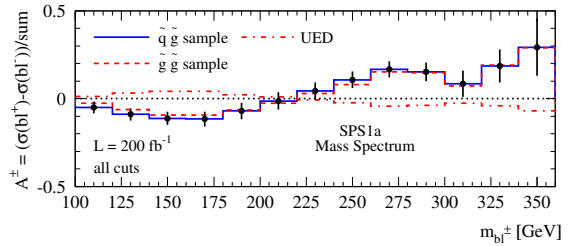
[slepton mixing, purely hadronic correlations, neutralino–sneutrino LSP,...]











Supersymmetric parameters

Theory output from LHC: SUSY parameters

- complex models, including dark matter, flavor physics, low-energy physics,...
- parameters: weak-scale Lagrangean [Sfitter: Lafaye, TP, Rauch, D Zerwas; Fittino; Harvard]
- 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 $m_0, m_{1/2}, A_0, \tan\beta, \text{sign}(\mu), y_t, \ldots$
- no problem, include indirect constraints

$\Rightarrow$ probability map as of today [Allanach, Lester, Weber]

$\Rightarrow$ best fit to LHC/ILC

$\Rightarrow$ ILC factor 10 more precise, but late...

	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 [TP, Lafaye, D Zerwas]

- technically painful:
  (1) grid for closed subset
  (2) fit of other parameters
  (3) complete fit
- LHC+ILC perfect [Weiglein etal]

$\Rightarrow$ 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

Probability maps of new physics [Allanach, Roszkowski]

- Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$ [$p(d)$ through normalization]
- likelihood: data given a model $p(d|m) \sim |\mathcal{M}|^2$
- theorist's prejudice: model $p(m)$

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

Weighted Markov chains [scanning algorithm for many dimensions: Rauch & TP]

- classical: produce representative set of states
  compute e.g. energy density of sample

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

- BSM physics: produce map $p(m|d)$ of parameter points
  evaluate same probability from (binned) density [Allanach,...; Baltz,...; Roszkowski,...]

$\Rightarrow$ weighted Markov chain [like MC with phase–space weights]

- MCMC resolution not sufficient

$\Rightarrow$ additional hill climber to rank maxima

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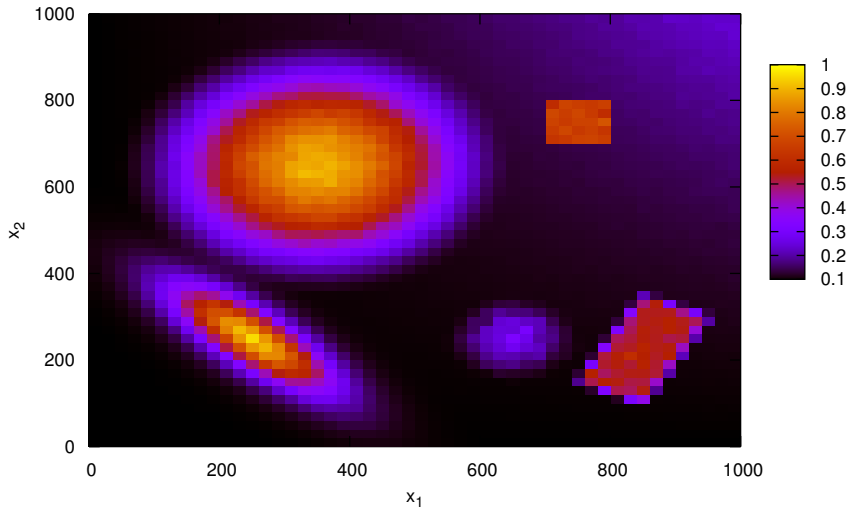
Toy model [Rauch & TP]

- 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=74.9	(655	253	347	348	349)
V=59.9	(850	224	650	649	654)
V=58.2	(849	225	587	650	650)
V=25.1	(750	749	450	450	450)
V=16.0	(245	253	552	542	544)
V=12.1	(350	650	650	650	650)
...					

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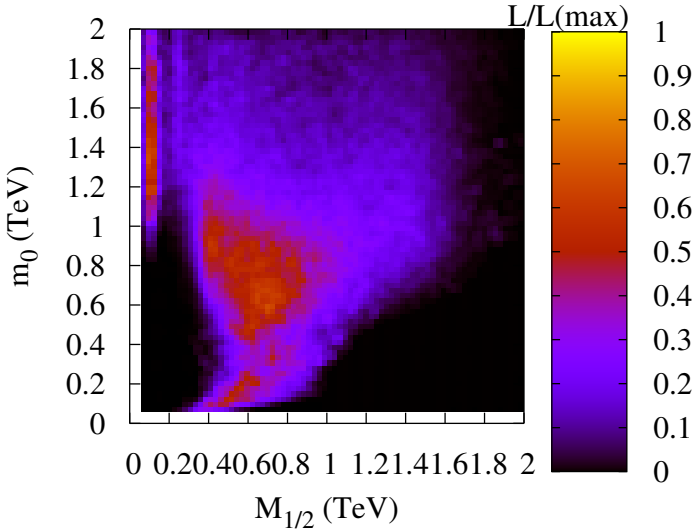
mSUGRA with today's measurements [Allanach, Lester, Weber]

- electroweak precision data, dark matter, $(g-2)_\mu$,...



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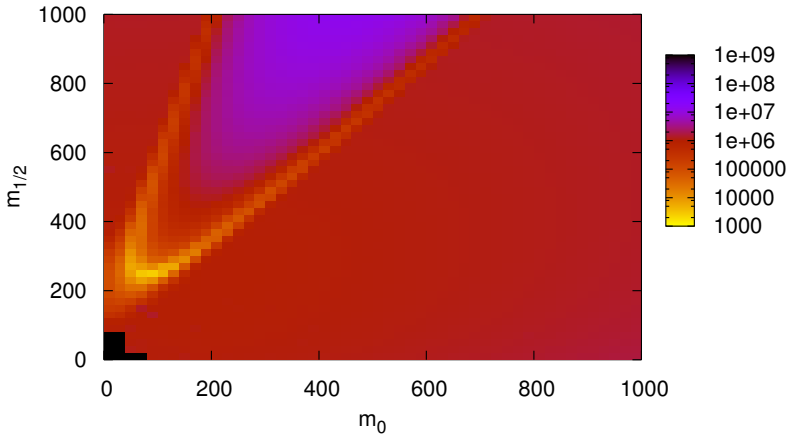
mSUGRA with LHC measurements [Lafaye, TP, Rauch, D.Zerwas]

- SPS1a kinematic edges with free m_b, m_t
- Sfitter output #1: probability map
  Sfitter output #2: list of local maxima [best fit]



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
...						

Supersymmetric parameters

Probability maps of new physics [Allanach, Roszkowski]

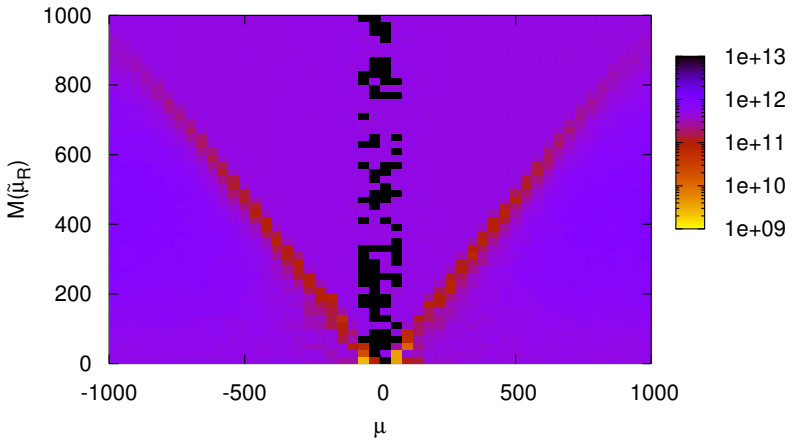
- Bayes' theorem: $p(m|d) = p(d|m)\ p(m)/p(d)$ [$p(d)$ through normalization]
- likelihood: data given a model $p(d|m) \sim |\mathcal{M}|^2$
- theorist's prejudice: model $p(m)$

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

MSSM with LHC measurements

- complete weak–scale MSSM
- Sfitter output #1: probability map
  Sfitter output #2: list of local maxima soon

$\Rightarrow$ ready to include bias [interpretation determined by quality of data]



Statistics and phenomenology

Problems in the spin extraction

- unclear if spin information available [top partners: Meade & Reece]

$\Rightarrow$ when can we distinguish two hypotheses?

Statistics: Neyman–Pearson lemma

- correct hypothsis m_1: SUSY cascade
  wrong hypothsis m_2: UED cascade

$\Rightarrow$ likelihood ratio $p(d|m_1)/p(d|m_2)$ best estimator

[lowest probability to mistake right for fluctuation of wrong (type-II error)]

- likelihood $p(d|m) \sim |\mathcal{M}|^2$

$\Rightarrow$ compute maximum statistical significance [Cranmer, TP]

Statistics and phenomenology

Problems in the spin extraction

– unclear if spin information available [top partners: Meade & Reece]

$\Rightarrow$ when can we distinguish two hypotheses?

Statistics: Neyman–Pearson lemma

– correct hypothsis m_1: Higgs signal in WBF $H \to \mu\mu$ [TP, Rainwater]
wrong hypothsis m_2: background

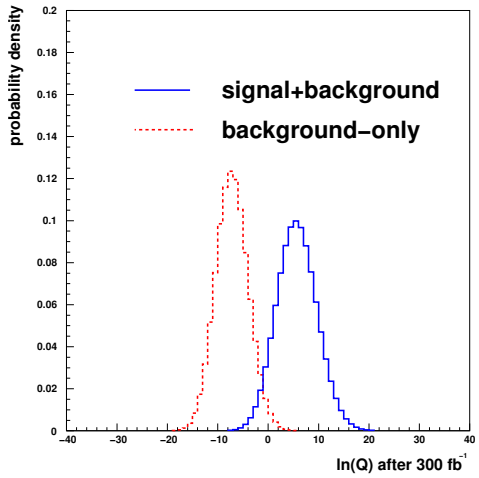
$\Rightarrow$ likelihood ratio $p(d|m_1)/p(d|m_2)$ best estimator

[lowest probability to mistake right for fluctuation of wrong (type-II error)]

– likelihood $p(d|m) \sim |\mathcal{M}|^2$

$\Rightarrow$ compute maximum statistical significance [Cranmer, TP]

$$CL_b(q) = \int_q^\infty dq' \rho_b(q')$$ [5σ is $CL_b = 2.85\,10^{-7}$]



'Matrix element method' [CDF, D0; McElrath]

– compute likelihood of top events estimating $|\mathcal{M}|^2$

– maximize likelihood $p(d|\text{SM}, m_t)$ as function of m_t...

Statistics and phenomenology

Maximum significance for LHC signals

- example: combined n-event Poisson $[p(n|s+b) = e^{-(s+b)}\,(s+b)^n/n!]$

$$q = \log \frac{p(n|s+b)}{p(n|b)} = -s + n\,\log\left(1+\frac{s}{b}\right) \longrightarrow -\sum_j s_j + \sum_j n_j\,\log\left(1+\frac{s_j}{b_j}\right)$$

- phase space integration over $p(d|s,b) \sim |\mathcal{M}_{s,b}|^2$ [LEP–Higgs inspired]

$$q(\vec{r}) = -\sigma_s \mathcal{L} + \log\left(1+\frac{|\mathcal{M}_s(\vec{r})|^2}{|\mathcal{M}_b(\vec{r})|^2}\right)$$

- probability distribution function via Fourier transform: $\rho_{s,b}(q)$

$\Rightarrow$ compute $CL_b(q)$

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Semi–realistic results [Cranmer & TP]

- irreducible & unsmeared

$$\sigma_{tot} = \int d\vec{r}\; M(\vec{r})\; d\sigma(\vec{r})$$

- smearing $\Delta m_{\mu\mu}^{\text{width}} \ll \Delta m_{\mu\mu}^{\text{meas}}$ [unobserved dimensions]

$$\sigma_{tot} = \int d\vec{r}_\perp\, dr_m^* \int_{-\infty}^{\infty} dr_m\; M(\vec{r})\; d\sigma(\vec{r})\; W(r_m, r_m^*)$$

- acceptance cuts to reduce phase space... [bad measurements]

$\Rightarrow$ WBF $H \to \mu\mu$: 3.5σ in 300 fb^{-1} [from 1.8 using cuts, now 4.4 with minijet veto]

Statistics and phenomenology

Maximum significance for LHC signals

- example: combined n-event Poisson $[p(n|s+b) = e^{-(s+b)}\,(s+b)^n/n!]$

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$\Rightarrow$ compute $CL_b(q)$

Estimate power of analyses [Cranmer, TP, Reuter]

- numerical evaluation instantaneous [sanity–check neural nets?]
- implementation into Whizard on the way
- cannot claim if search is possible
- but can tell if search is impossible

New physics at the LHC

LHC physics

- QCD will try to kill us
- all analyses will be hypothesis testing

$\Rightarrow$ phenomenologists and experimentalists have to work together

A lot has been done

- mass and spin measurements
- parameter extraction/probability maps...

A lot is still left to do

- QCD effects on new physics measurements
- scans of high–dimensional parameter spaces
- statistics tools for phenomenologists...

$\Rightarrow$ even exciting times require serious work