SUPERSYMMETRY AT THE LHC

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– A few MSSM conventions
– SUSY-Higgs at the LHC
– SUSY at the Tevatron
– SUSY searches at the LHC
– SUSY measurements at the LHC (and ILC)

[sorry for skipping references altogether, many reviews around]

TeV Scale Supersymmetry: 1

Starting from data...

– ...which seem to indicate a light Higgs

– problem of light Higgs: mass driven to cutoff of theory [remember pain to get that up]

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

Veltman's condition $(\cdots) = 0$ would be fun

problem preferably solved to arbitrary loop order

$\Rightarrow$ solution: counter term for exact cancellation $\Rightarrow$ artificial, unmotivated, ugly

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

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

$\Rightarrow$ all really beautiful concepts and symmetries

$\Rightarrow$ in general problematic to realize at TeV scale [data seriously in the way]

Idea of supersymmetry: cancellation of divergences through statistics factor (-1)

[scalars vs. SM fermions; fermions vs. SM gauge bosons; fermions vs. SM scalars]

TeV Scale Supersymmetry: 2

SUSY idea: solve hierarchy problem by just doubling particle number?!

– stops (scalar) cancel top loop [couplings protected]

– gauginos (neutral or charged) cancel W, Z loop

– higgsinos cancel Higgs loop [mix with neutralinos]

– since we are at it, let's postulate gluino for 2-loop, plus sleptons and squarks

$\Rightarrow$ (1) hierarchy problem solved

$\Rightarrow$ (2) rich collider and non-collider phenomenology guaranteed

$\Rightarrow$ (3) Lorentz algebra properly extended

Serious change in Higgs sector

– adjoint Higgs field not allowed in $\mathcal{L}$
$\longrightarrow$ how to give mass to t and b?
$\longrightarrow$ two Higgs doublets

$\Rightarrow$ SUSY Higgs sector interesting in itself

$\Rightarrow$ no MSSM know-how needed

		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^o, H^o, A^o	0	3	
$\longrightarrow$ neutralinos	$\tilde{\chi}_i^o$	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
graviton	G	2	2	
$\longrightarrow$ gravitino	$\tilde{G}$	3/2	2	hard to catch

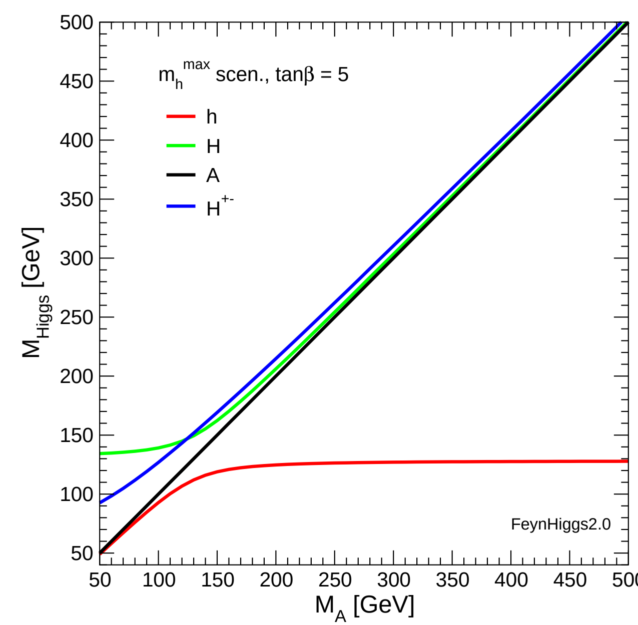
SUPERSYMMETRIC HIGGS SECTOR: 1

Required by supersymmetry: two Higgs doublet model

– one (complex) Higgs doublet: 4 degrees of freedom
  $\longrightarrow$ three for longitudinal W, Z, one for scalar Higgs

– two Higgs doublets: 8 degrees of freedom
  $\longrightarrow$ three for longitudinal W, Z, five for Higgs particles
  $\longrightarrow$ scalars h^0, H^0, pseudoscalar A^0, charged $H^\pm$

– free parameters
  (1) still only one free mass scale: m_A
  (2) two vacuum expectation values: $\tan\beta = v_t/v_b$



All you need to know: plateau structure [FeynHiggs]

– 'plateau Higgses' coupling to W, Z

– heavy H^0, A^0 with $\tan\beta$-enhanced coupling to b, τ

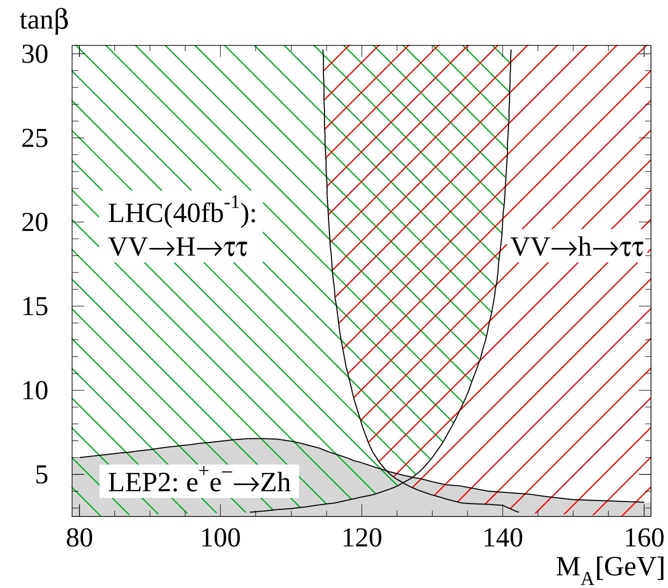
– light h^0 mass limited from above $m_h \lesssim 135$ GeV

SUPERSYMMETRIC HIGGS SECTOR: 2

Challenge: find one Higgs at the LHC

– decoupling regime $m_A \gtrsim 160$ GeV
  $\to h^0$ looks like SM Higgs [of corresponding mass]
  $\to qq \to qqh^0 \to qq\tau\tau$
– other end $m_A \lesssim 120$ GeV
  $\to qq \to qqH^0 \to qq\tau\tau$
– in between: maybe even two bumbs

$\Rightarrow$ No-lose theorem: $qq \to qq\{h^0, H^0\} \to qq\tau\tau$



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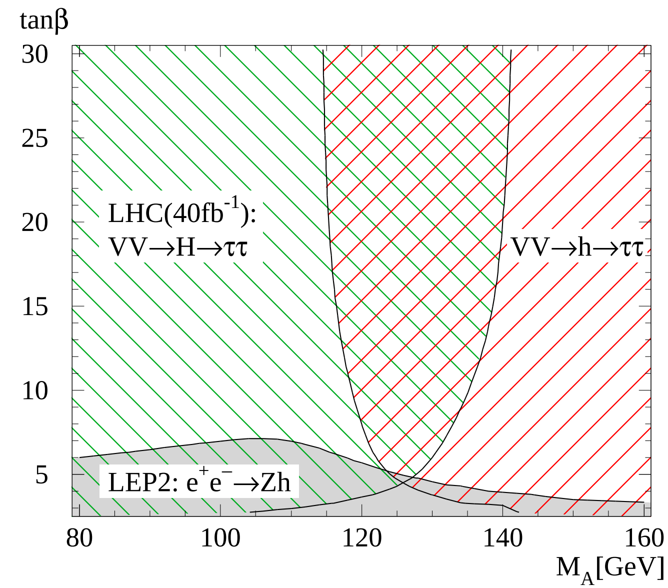
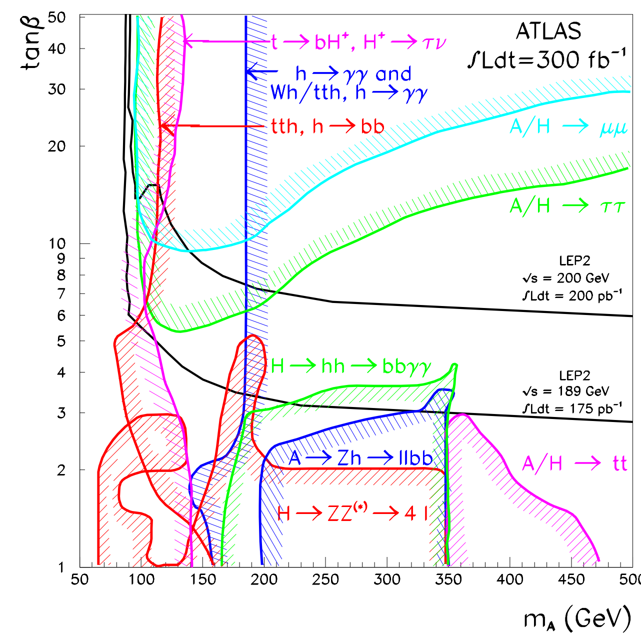


Nightmare: confirm SUSY Higgs sector

- decoupling regime $m_A \gtrsim 160$ GeV
  $\to$ Yukawa coupling for $H^0, A^0, H^\pm$: $m_b \tan\beta$
  $\to$ enhanced production e.g. $b\bar{b} \to H^0$ or $gb \to tH^-$
  $\to$ decays $H^0 \to \tau\tau, \mu\mu$ or $H^- \to \tau\bar{\nu}$
- intermediate $m_A \sim 120$ GeV:
  $\to$ many (light-ish) Higgses h^0, H^0, A^0 observable
  $\to$ top quark decays $t \to bH^+$? [Tevatron?]



Back to the MSSM: SUSY partner masses

– mechanism of mass generation unknown [soft breaking leaves quadratic divergences alone]

– link to flavor physics and baryogenesis/leptogenesis unknown

– SUSY breaking unknown [hidden sector, assume mediation to visible sector]

– maximally blind mediation at high scale: mSUGRA [really not the general LHC paradigm!!!]
scalars: m_0, fermions: $m_{1/2}$, tri-scalar term: A_0
plus $\text{sign}(\mu)$ and $\tan\beta$ in Higgs sector [Higgs masses let free: NUHM]

Alternatives to mSUGRA [SoftSusy,...]

– gauge mediation

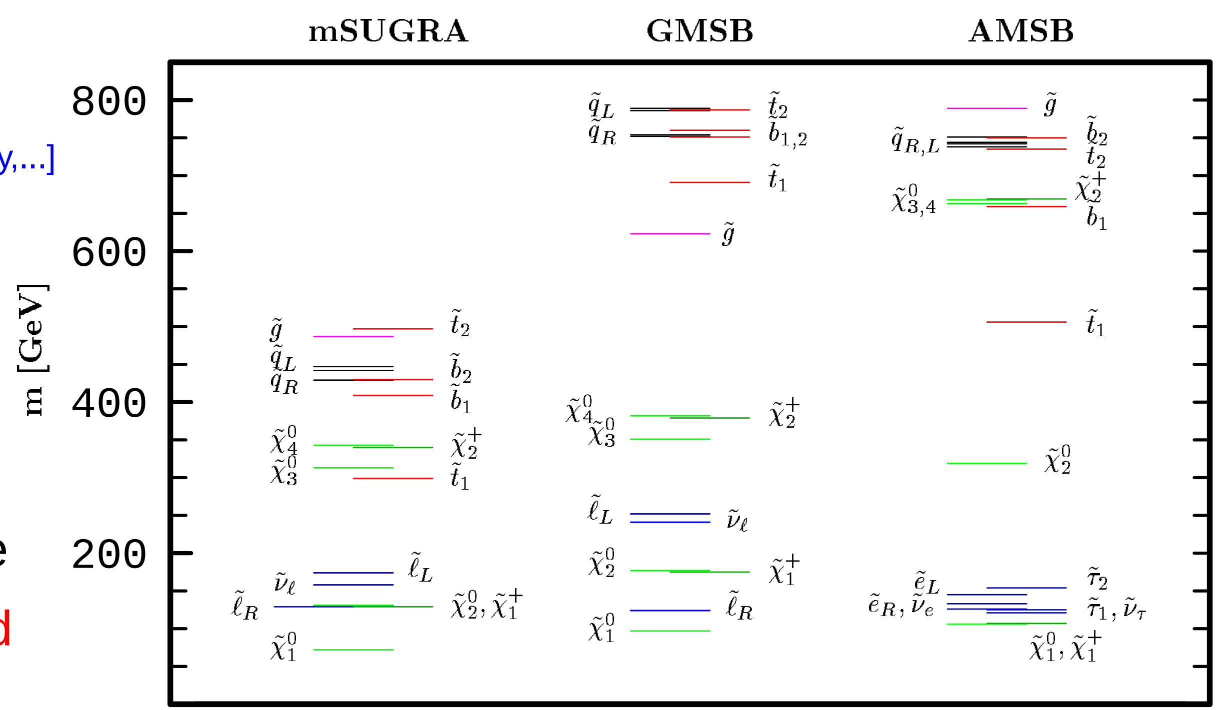
– anomaly mediation

– gaugino mediation

– ...

⇒ none of them convince me

⇒ measure spectrum instead



TeV Scale Supersymmetry: 4

Structures in the SUSY spectrum

– gauginos–higgsinos mixing: $m_{\tilde{\chi}_2^0} \sim m_{\tilde{\chi}_1^+}$ or $m_{\tilde{\chi}_1^0} \sim m_{\tilde{\chi}_1^+}$ in MSSM

$$\begin{pmatrix} m_{\tilde{B}} & 0 & -m_Z s_w c_\beta & m_Z s_w s_\beta \\ 0 & m_{\tilde{W}} & m_Z c_w c_\beta & -m_Z c_w s_\beta \\ -m_Z s_w c_\beta & m_Z c_w c_\beta & 0 & -\mu \\ m_Z s_w s_\beta & -m_Z c_w s_\beta & -\mu & 0 \end{pmatrix} \quad \begin{pmatrix} m_{\tilde{W}} & \sqrt{2} m_W s_\beta \\ \sqrt{2} m_W c_\beta & -\mu \end{pmatrix}$$

– stop and sbottom mixing in MSSM

$$\begin{pmatrix} m_Q^2 + m_t^2 + \left(\frac{1}{2} - \frac{2}{3} s_w^2 \right) m_Z^2 c_{2\beta} & -m_t \left(A_t + \mu \cot\beta \right) \\ -m_t \left(A_t + \mu \cot\beta \right) & m_U^2 + m_t^2 + \frac{2}{3} s_w^2 m_Z^2 c_{2\beta} \end{pmatrix}$$

– heavy gluinos, squarks through unification: $m_{\tilde{B},\tilde{W},\tilde{g}} / m_{1/2} \sim 0.4, 0.8, 2.6$

$m_{\tilde{\ell},\tilde{q}} / m_{1/2} \sim 0.7, 2.5$ $[m_0 \ll m_{1/2}]$

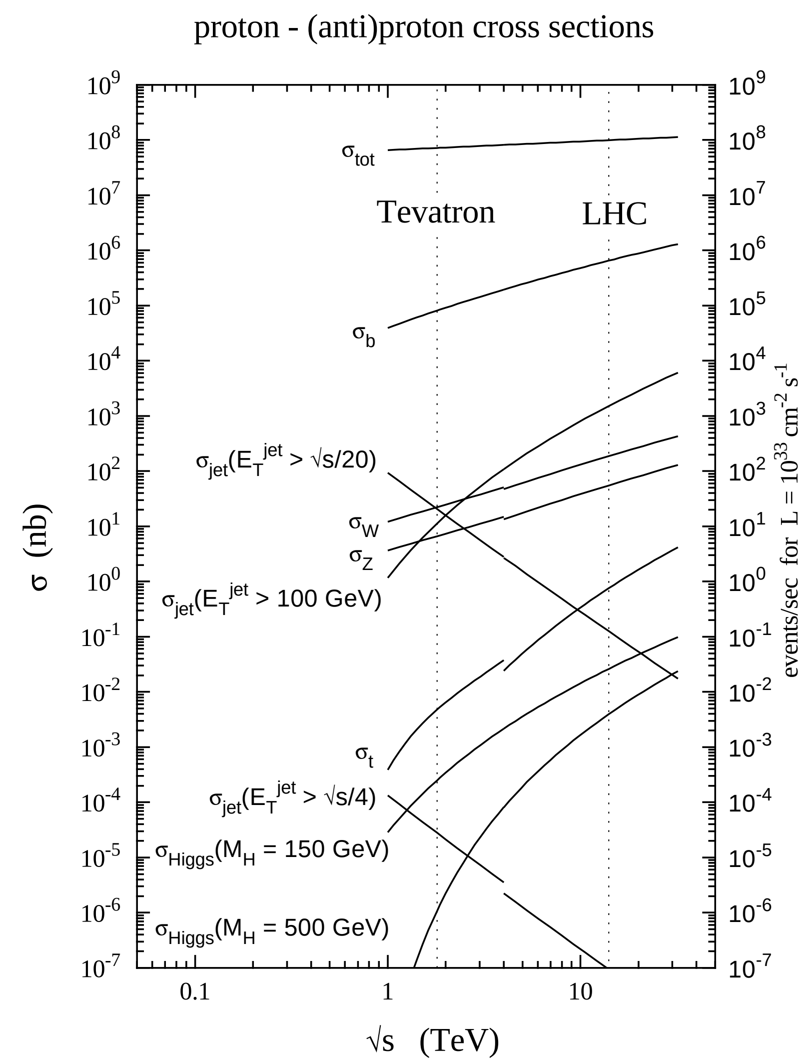
[mass and coupling unification independent]

– lightest SUSY partner $\tilde{\chi}_1^0, \tilde{\nu} \quad \Rightarrow \quad$ after dark matter data $\tilde{\chi}_1^0 \sim \tilde{B}, \tilde{W}$ [gravitinos?]

TEVATRON & LHC

Conversion of beam energy into particle mass

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



New physics at hadron colliders

- what is a jet and what is inside? [b, τ tag]
- trigger: ‘no leptons — no data’
- backgrounds pp $\rightarrow$ jj or pp $\rightarrow$ WZ+jets
- statistics: $S/\sqrt{B} > 5$ we call discovery

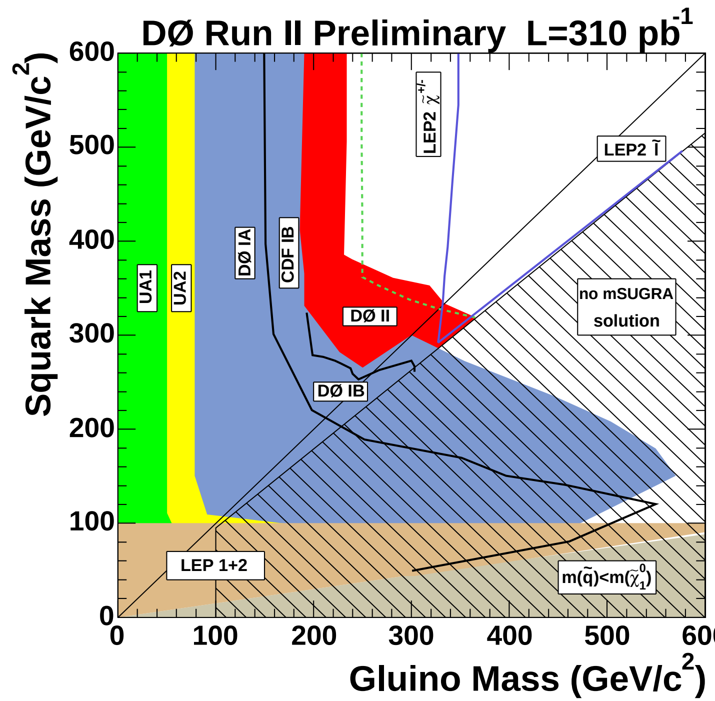
SUPERSYMMETRY AT THE TEVATRON: 1

Inclusive: squarks and gluinos at Tevatron

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

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

$\Rightarrow$ very promising search for jets plus LSP



Necessary model assumptions

– assume 100% branching into inclusive jets+LSP

– for detector efficiencies $m(\tilde{\chi}_2^0), \ldots$

– gluino decay into squark or vice versa?

$\Rightarrow$ mSUGRA assumed, but effect moderate

Supersymmetry at the Tevatron: 2

More specialized: trilepton channels

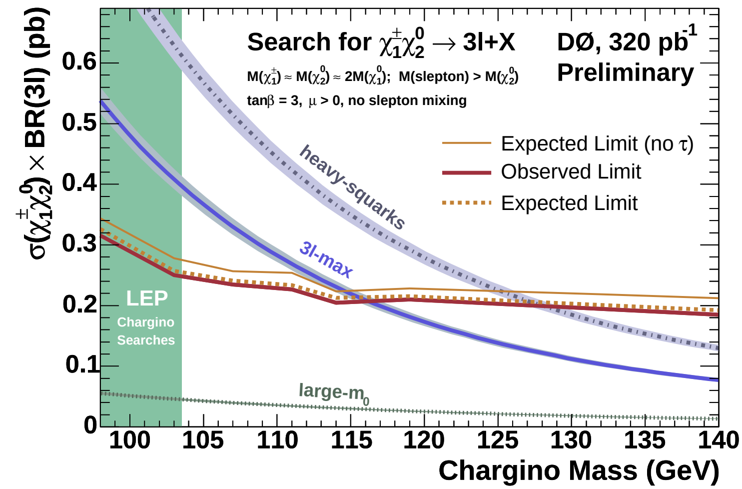
– generally assumed that charginos are light

– largest cross section $p\bar{p} \to \tilde{\chi}_1^+ \tilde{\chi}_2^0$
decays $\tilde{\chi}_1^+ \to \ell^+ \nu \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \to \ell^+ \ell^- \tilde{\chi}_1^0$

– gaugino rate determined by t channel squark

– signature plagued by W, Z background

$\Rightarrow$ about to pass LEP2 chargino limits



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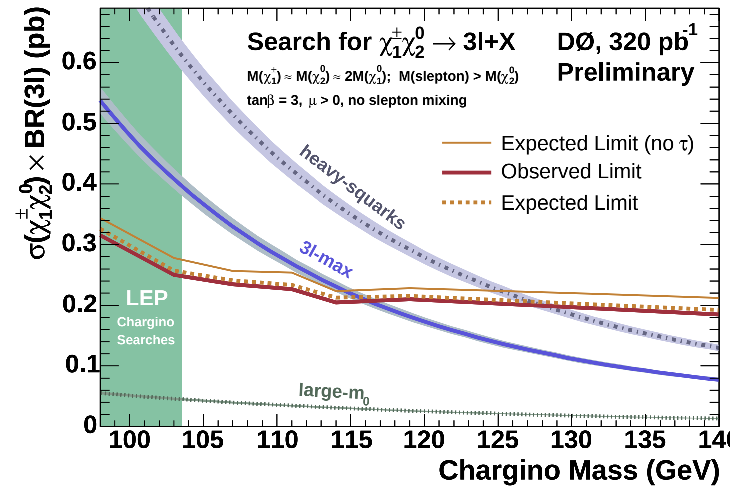
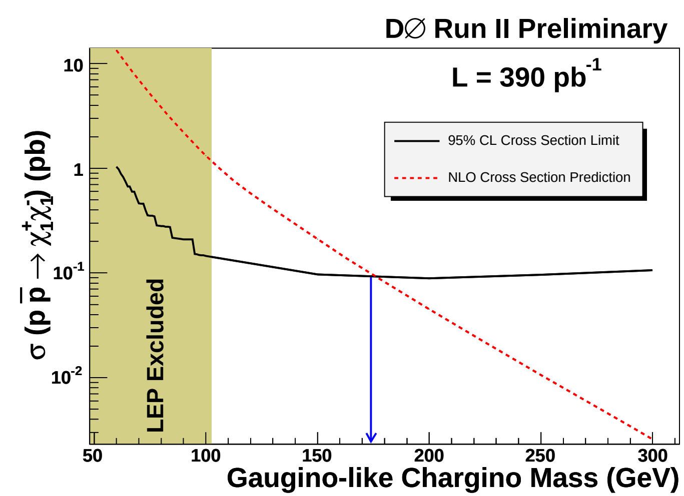


Even more specialized: long-lived gauginos

– stable on the detector time scale of ns

– like massive muons in tracker–muon chamber

– gauginos motivated by GMSB or AMSB



$\Rightarrow$ SUSY at the LHC does not come out of nowhere!

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

SUSY signals included [NLO: Prospino2]

– QCD coupling $g\tilde{q}\tilde{q}$, $q\tilde{g}\tilde{q}$, $g\tilde{g}\tilde{g}$

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

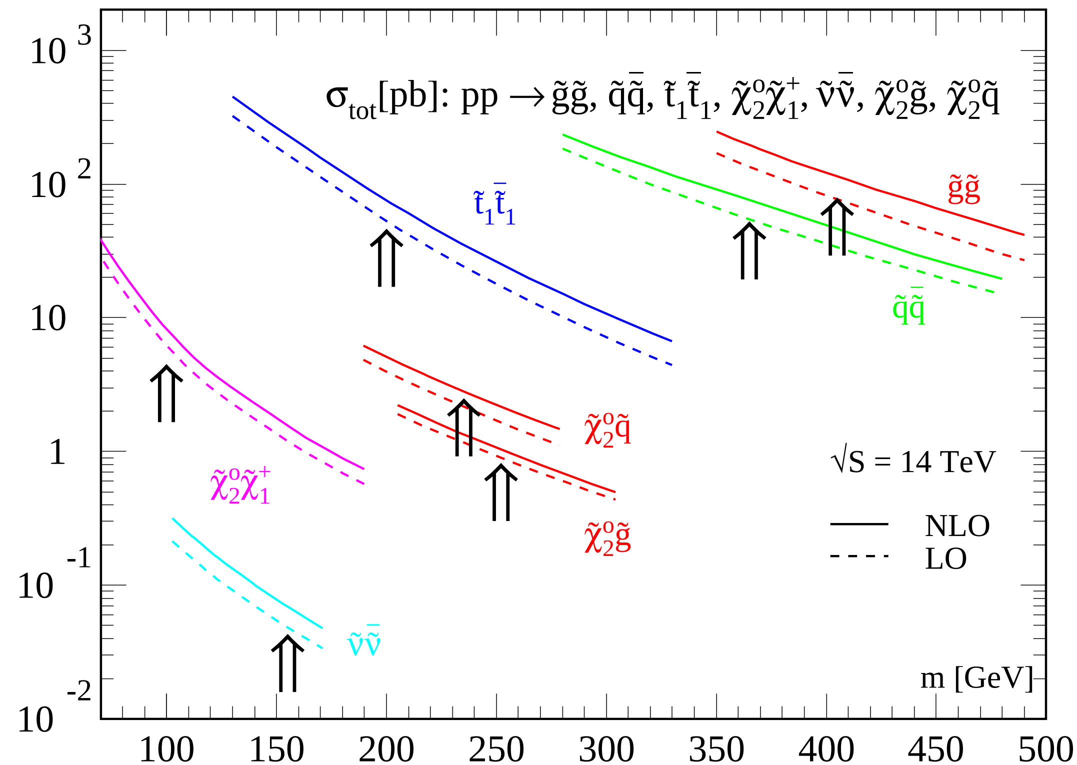
– funny tops: pp $\to \tilde{t}_1\tilde{t}_1^*$

– like sign dileptons: pp $\to \tilde{g}\tilde{g}$

$[\tilde{g} \to \tilde{u}\bar{u} \to \tilde{\chi}_1^+ d\bar{u}$ or $\tilde{g} \to \tilde{u}^* u \to \tilde{\chi}_1^- \bar{d}u]$

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

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



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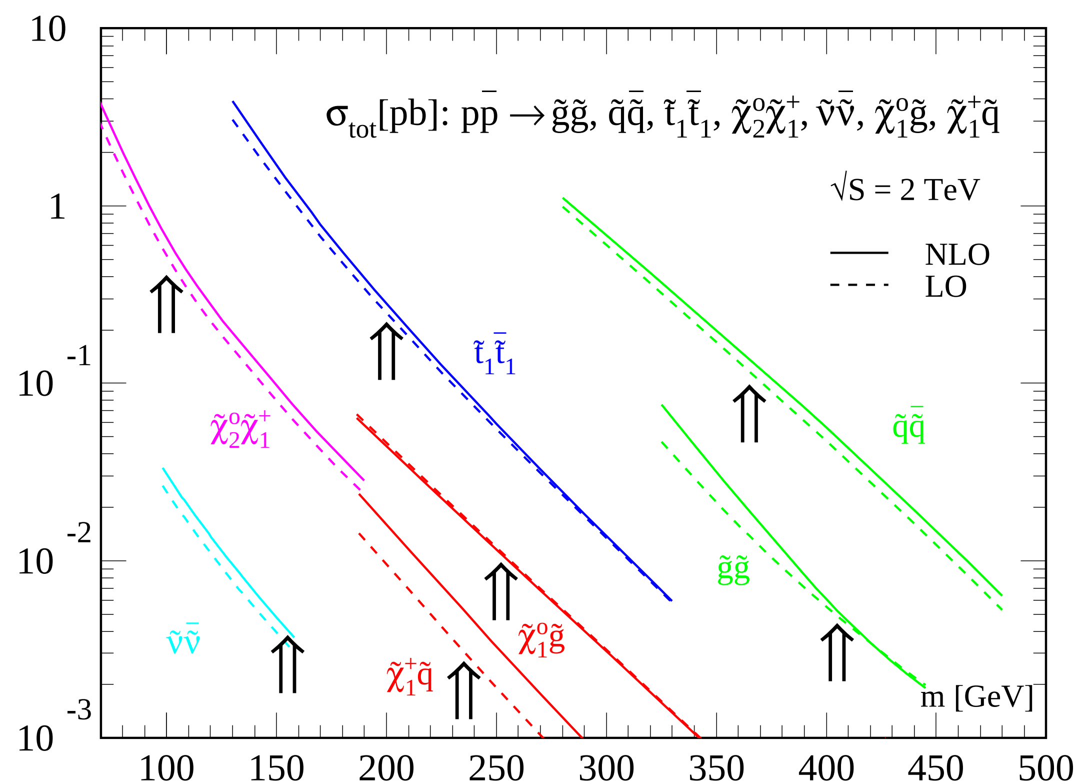
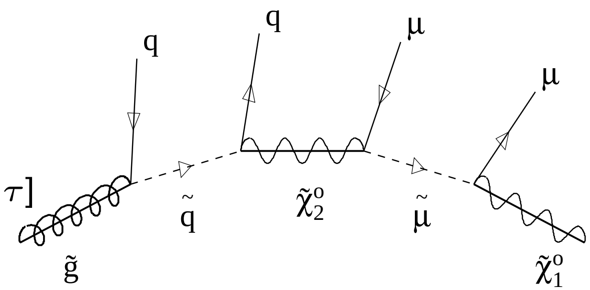


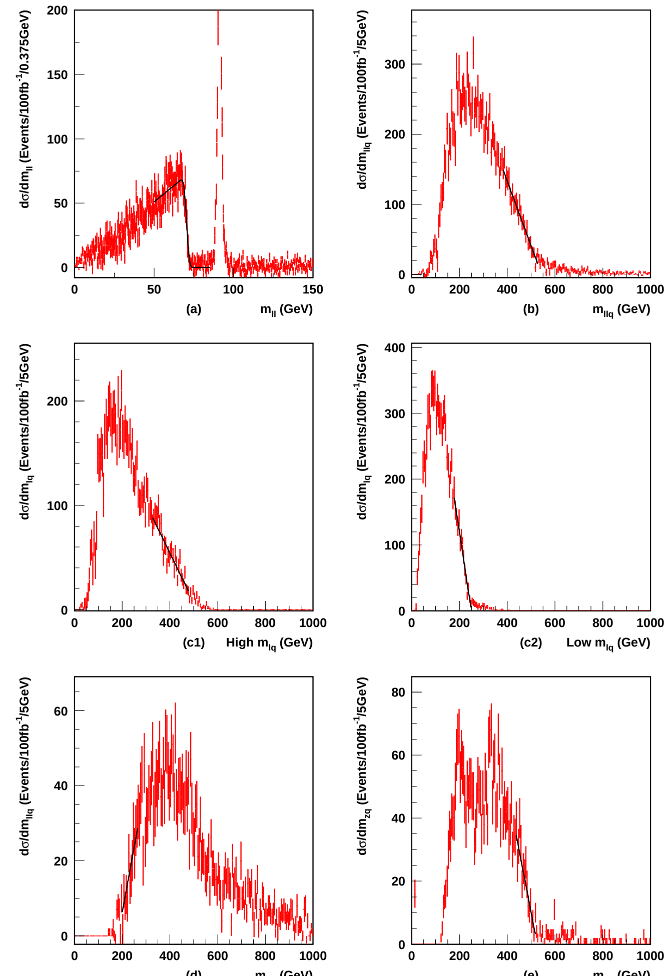
Spectra from cascade decays



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

⇒ $\tilde{q}_L$ cascade reconstruction great

[known even from Atlas TDR]



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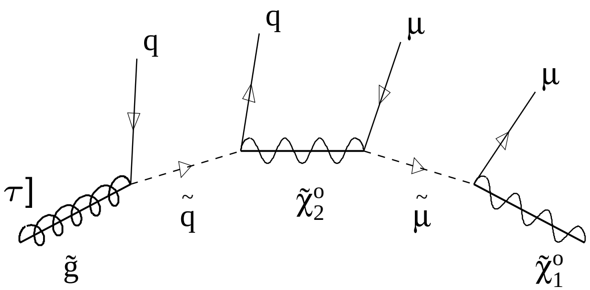

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$\Rightarrow$ $\tilde{q}_L$ cascade reconstruction great [know now: mass differences even better]

Example: gluino mass

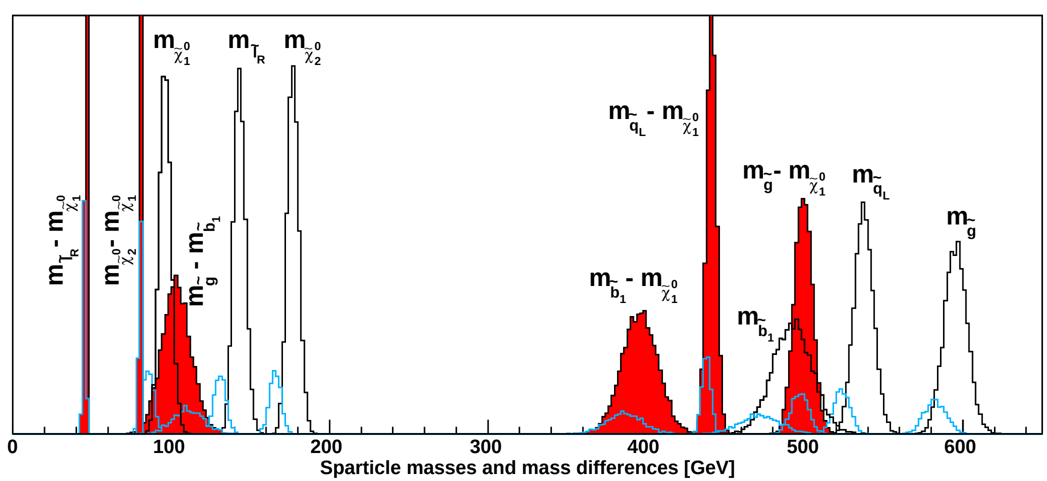
– now four jets instead of two

– $\tilde{b}_L$ instead, all jets b-tagged

– most of time: cascade identifiec

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

[statistical error dominant]



SUPERSYMMETRY AT LHC: 3

Complex final states [e.g. SUSY-Madevent]

– Majoranas and fermion number violation in tools like Madgraph

– complete set of Feynman rules [400+ processes compared with Whizard and Sherpa]

Squarks and gluinos always with many jets

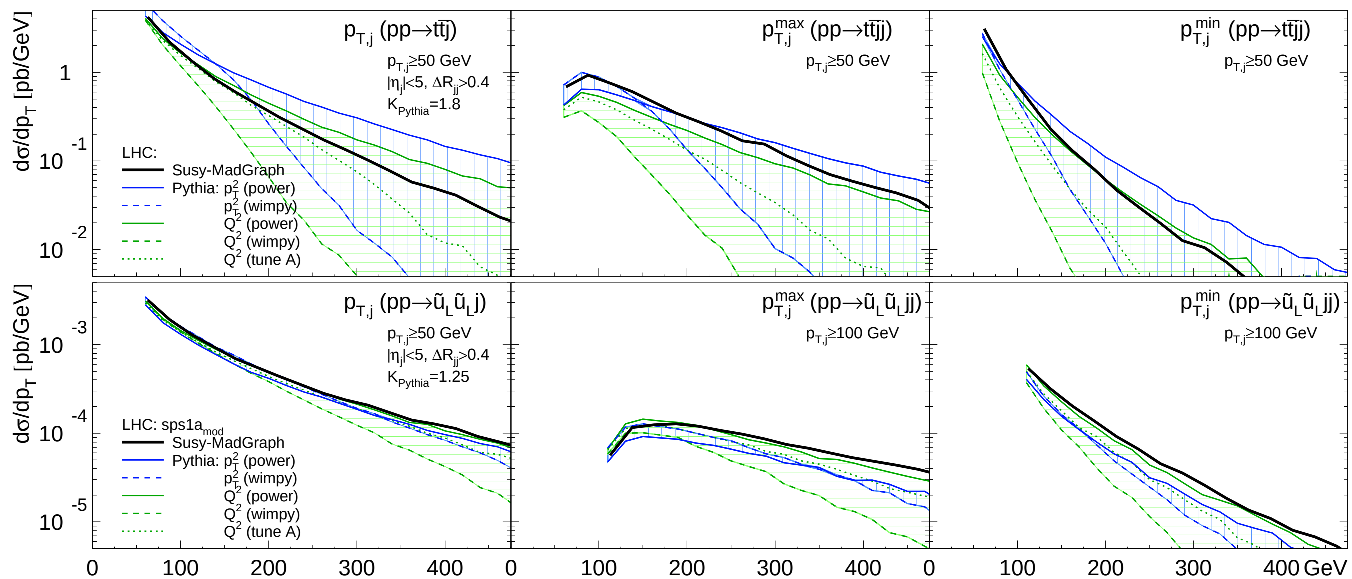
– cascade studies sensitive to jets?

– matrix element $\tilde{g}\tilde{g}$+2j and $\tilde{u}_L\tilde{g}$+2j [$p_{T,j} > 100$ GeV]

– Phythia shower tuned at Tevatron

$\Rightarrow$ SUSY easier than tops

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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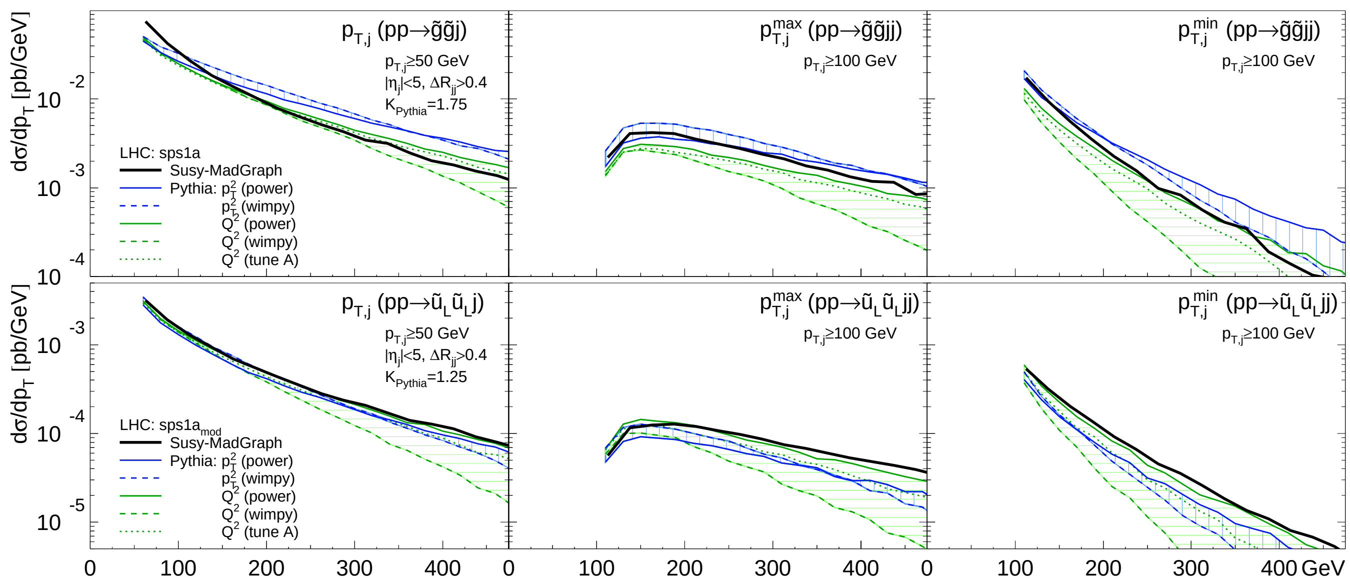


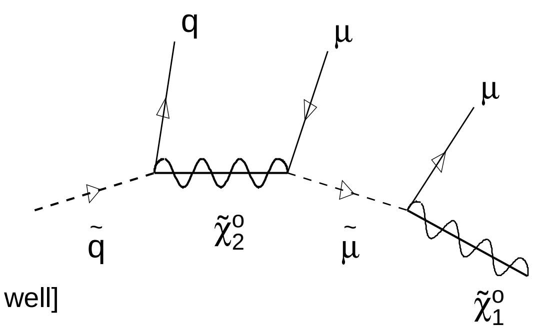
How to make sure it is SUSY

– assume neutralino is found in cascades

– compare with a model where gluino is a boson,...

→ straw man: universal extra dimensions

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



Slepton cascade

– decay chain $\tilde{\chi}_2^0 \to \ell \tilde{\ell}^* \to \ell \bar{\ell} \tilde{\chi}_1^0$

– compare with first excited Z and ℓ

– initial-state asymmetry pp $\to \tilde{q}\tilde{g}$ [$\tilde{q}/\bar{\tilde{q}} \sim 2$]

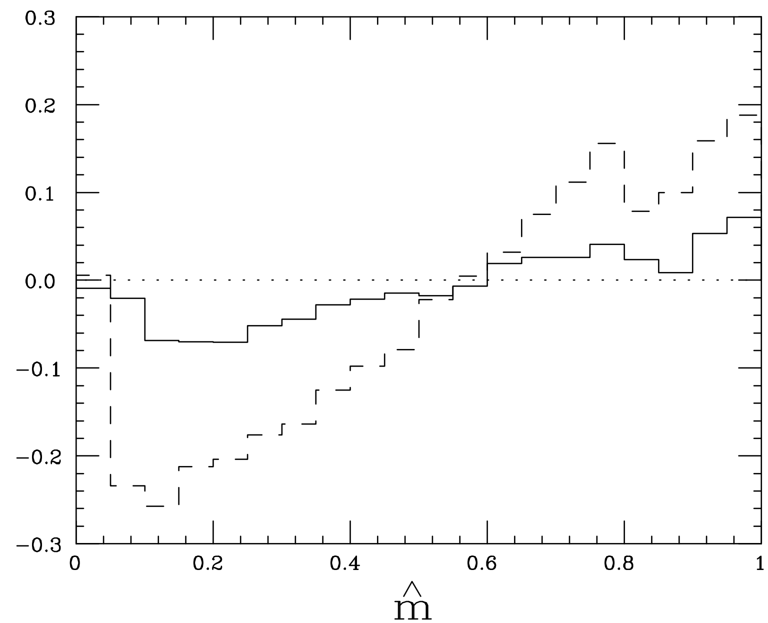
⇒ $\widehat{m} = m_{j\ell}/m_{j\ell}^{max}$ most promising

$\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$

– assume hierarchical SPS1a spectrum

[dashed SUSY, solid UED]

⇒ we can tell spin in cascade



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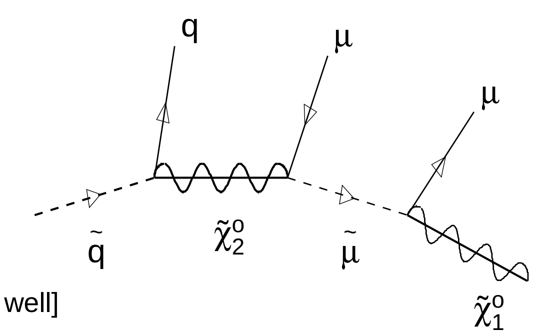

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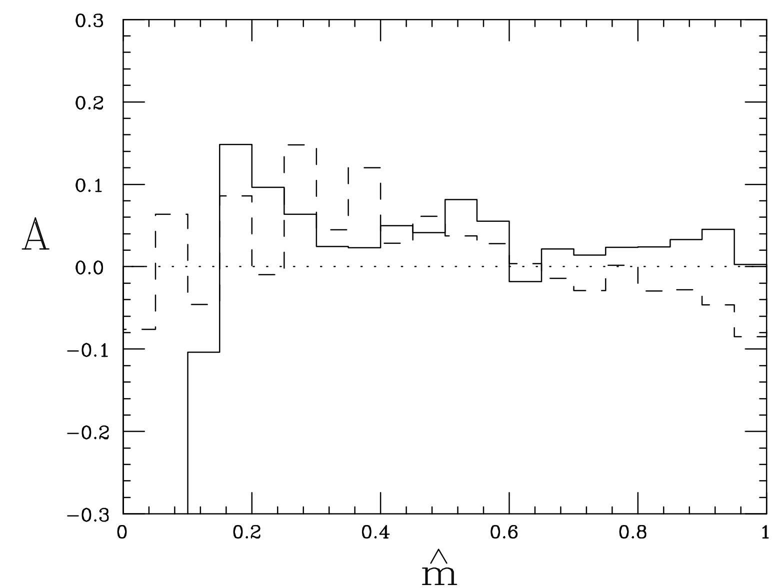
$$\mathcal{A} = [\sigma(j\ell^+) - \sigma(j\ell^-)]/[\sigma(j\ell^+) + \sigma(j\ell^-)]$$

– assume non-hierarchical UED spectrum

[dashed SUSY, solid UED]

$\Rightarrow$ we can tell spin in cascade



SUPERSYMMETRIC PARAMETERS

SUSY parameters from observables

– parameters: weak-scale MSSM 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, starting values, global minimum?

First go at problem

– ask a friend who knows how SUSY is broken

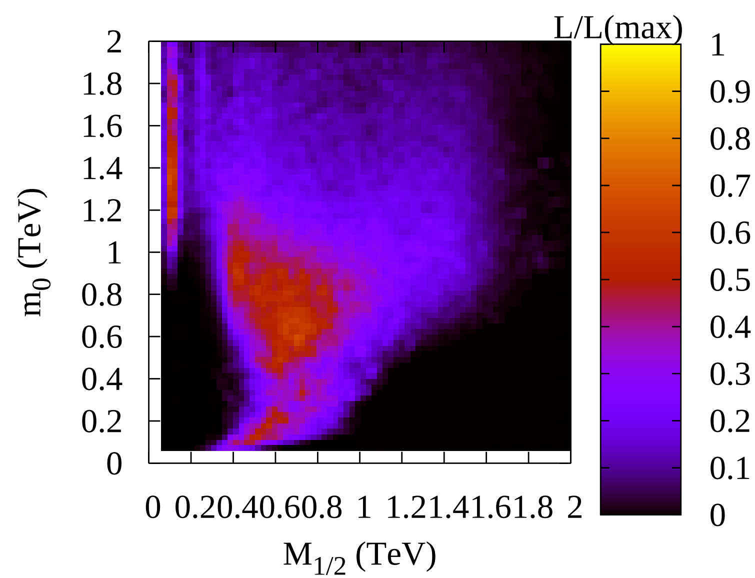
⇒ mSUGRA

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

– no problem, include indirect constraints

⇒ who the hell believes in mSUGRA?

– mSUGRA just testing ground for methods



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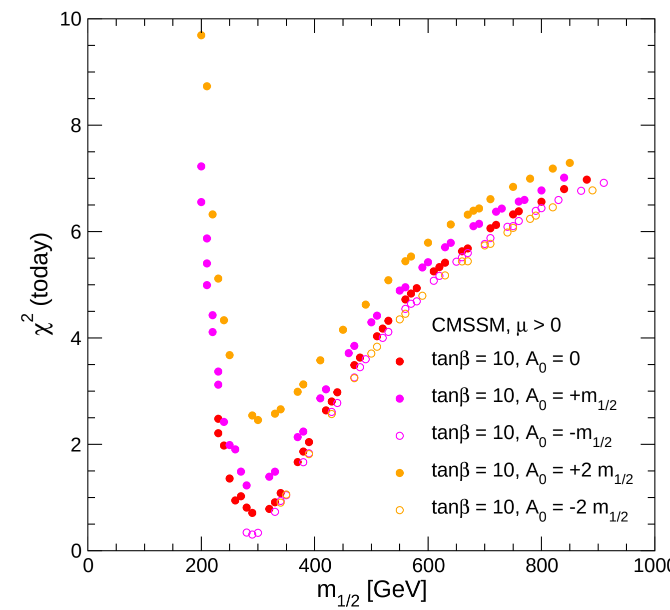
$\Rightarrow$ who the hell believes in mSUGRA?

– mSUGRA just testing ground for methods



SUPERSYMMETRIC PARAMETERS

SUSY parameters from observables

– parameters: weak-scale MSSM 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, starting values, global minimum

Combination of methods [Sfitter, Fittino]

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

– more modern alternaives:
simulated annealing
Markov Chains

⇒ LHC+ILC with no assumptions

	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

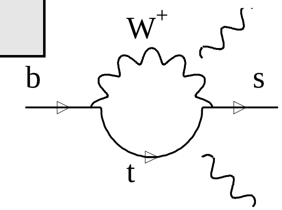
OUTLOOK

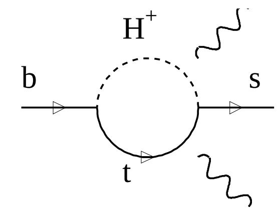
LHC phenomenology beyond the Standard Model

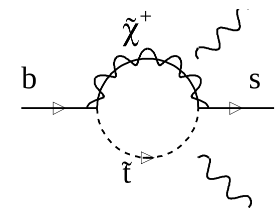
- world-wide pheno-experimental effort rolling
- many new tools/ideas on the market, waiting to be tested
- lots of more work to be done
- by now fast-growing and exciting field

We will be able to do amazing things at the LHC!

B Physics and Supersymmetry







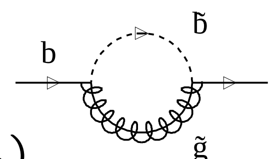
Search channel: $B_s \to \mu\mu$

– s-channel exchanges dominant: H, Z, γ
suppressed in Standard Model [$BR_{SM} \sim (2.4 \pm 0.5) \times 10^{-9}$]

– more Higgs bosons in 2HDM
$\tan\beta$ enhancement of s channel Higgses [$BR_{2HDM} \propto \tan^6\beta / m_A^4$]
additional Higgs loop

– charginos in MSSM
$\tan\beta$ enhancement for Higgsinos
gluino loop for non-minimal flavor physics...

Bottom Yukawa in the MSSM



– gluino-sbottom loops universal: $y_b \to y_b/(1 + \Delta_b)$

– large, leading in $\tan\beta$ & resummable $\Delta_b \sim \alpha_s \tan\beta \, m_{\tilde{g}} \mu / \max^2(m_{\tilde{b},\tilde{g}})$
$\Rightarrow$ decoupling in MSSM, but not in MSSM+μ
[similar terms for chargino/neutralino exchange]

– easy to implement in MC, numerically great for $\tan\beta > 10$

$\Rightarrow$ enhancement good for SUSY signals, but pain in analyses