

SUPERSYMMETRY AT THE LHC

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- Minimal set of MSSM conventions
- SUSY at the Tevatron
- SUSY searches at the LHC
- SUSY measurements at the LHC

TEV SCALE SUPERSYMMETRY: 1

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
- ⇒ (1) hierarchy problem solved
- ⇒ (2) rich collider and non-collider phenomenology guaranteed
- ⇒ (3) Lorentz algebra properly extended

Serious change in Higgs sector

- adjoint Higgs field not allowed in \mathcal{L}
 - how to give mass to t and b?
 - two Higgs doublets
- ⇒ SUSY Higgs sector interesting in itself
- ⇒ no MSSM know-how needed

		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^0, H^0, A^0	0	3	
→ neutralinos	$\tilde{\chi}_i^0$	1/2	4 · 2	Majorana
gauge bosons	W^\pm	1	2 · 3	
Higgs bosons	H^\pm	0	2	
→ charginos	$\tilde{\chi}_i^\pm$	1/2	2 · 4	Dirac
graviton	G	2	2	
→ gravitino	\tilde{G}	3/2	2	hard to catch

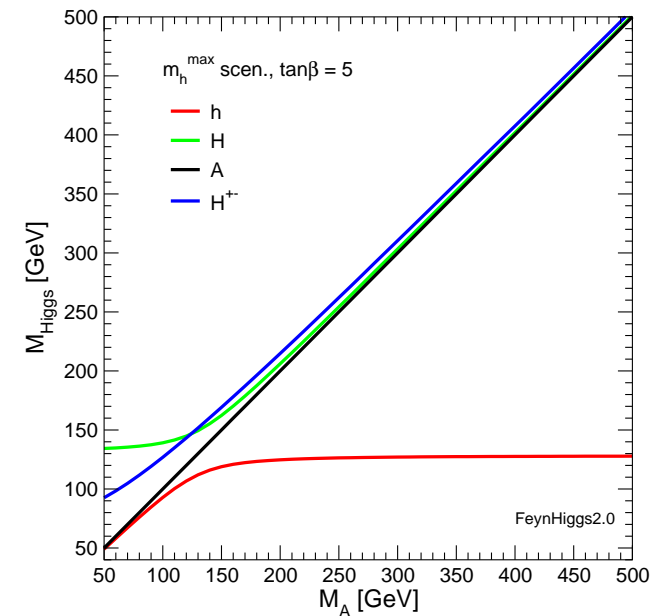
SUPERSYMMETRIC HIGGS SECTOR: 1

Required by supersymmetry: two Higgs doublet model

- one (complex) Higgs doublet: 4 degrees of freedom
→ three for longitudinal W, Z, one for scalar Higgs
- two Higgs doublets: 8 degrees of freedom
→ three for longitudinal W, Z, five for Higgs particles
→ 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]

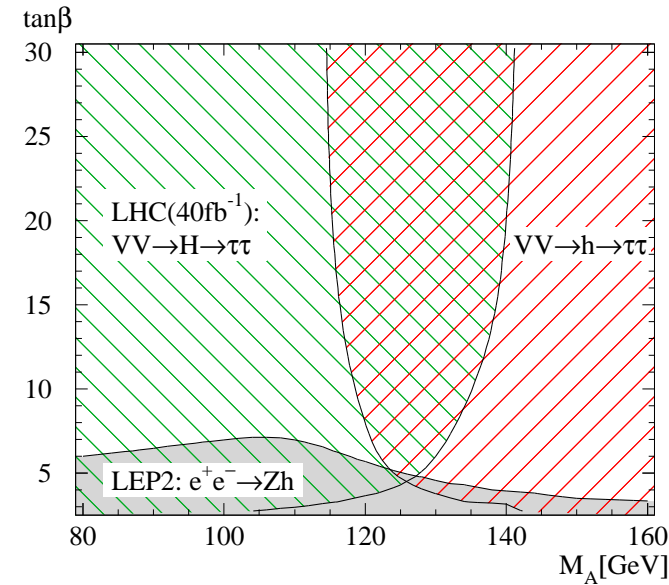
- ‘plateau Higgses’ coupling to W, Z
- heavy H^0, A^0 with $\tan \beta$ -enhanced coupling to b, τ
- light h^0 mass limited from above $m_h \lesssim 135$ GeV



SUPERSYMMETRIC HIGGS SECTOR: 2

Challenge: find one Higgs at the LHC

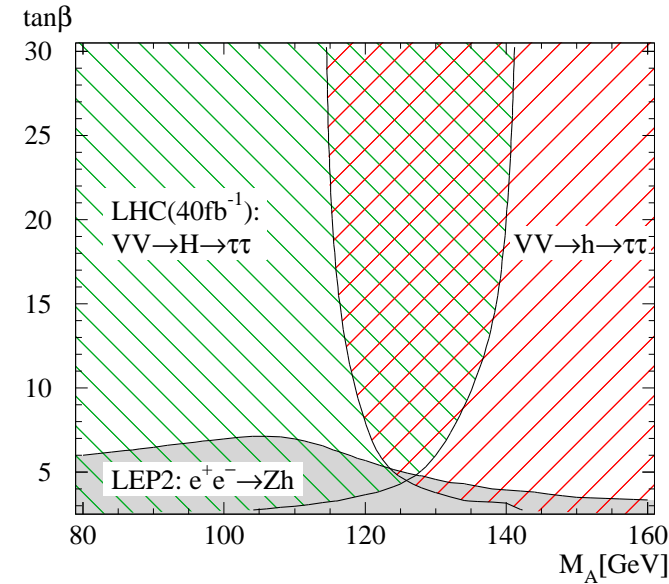
- decoupling regime $m_A \gtrsim 160$ GeV
 - h^0 looks like SM Higgs [of corresponding mass]
 - $qq \rightarrow qqh^0 \rightarrow qq\tau\tau$
 - other end $m_A \lesssim 120$ GeV
 - $qq \rightarrow qqH^0 \rightarrow qq\tau\tau$
 - in between: maybe even two bumps
- ⇒ **No-lose theorem: $qq \rightarrow qq\{h^0, H^0\} \rightarrow qq\tau\tau$**



SUPERSYMMETRIC HIGGS SECTOR: 2

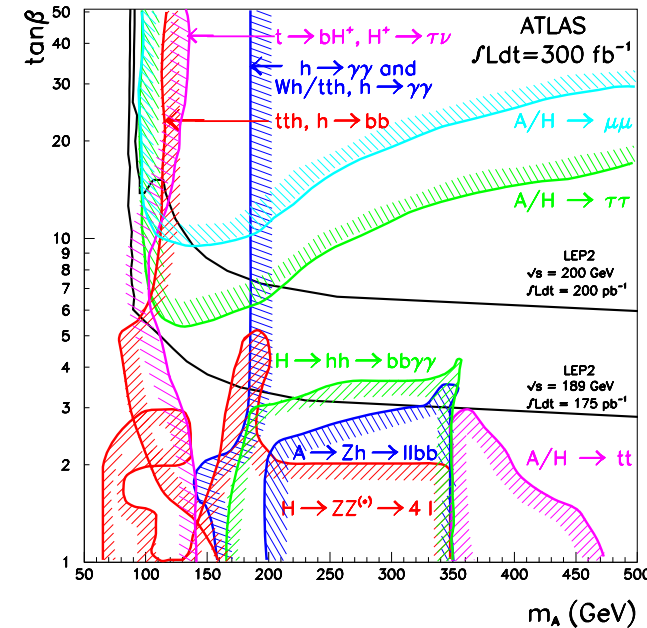
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Nightmare: confirm SUSY Higgs sector

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



TeV SCALE SUPERSYMMETRY: 2

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**

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

- stop and sbottom mixing in **MSSM**

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

- 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 $\tilde{\chi}_1^0, \tilde{\nu}$ \Rightarrow after dark matter data $\tilde{\chi}_1^0 \sim \tilde{B}, \tilde{W}$ [gravitinos?]

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. $m(q = \text{TeV}, \nu, m_t)$?]
 - definitions of mass matrixes, mixing angles [e.g. $\tilde{t}_{L,R}$ up or down?]

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

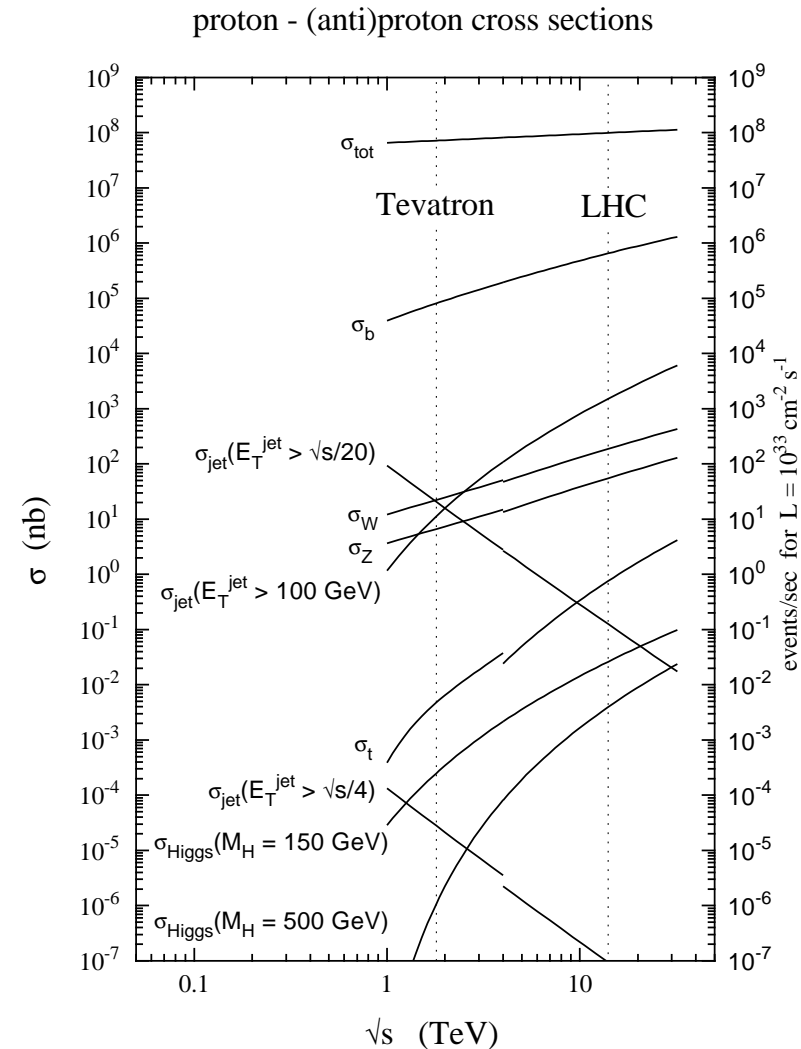
- spectrum generators: SoftSusy, SPheno, FeynHiggs,...
- multi-purpose Monte Carlos: Pythia, Herwig, Sherpa
- matrix element generators: Whizard, Smadgraph
- NLO cross sections: Prospino2
- NLO decay rates: Sdecay
- SUSY parameter extraction: Fittino, Sfitter
- dark matter: Micromegas
- ⇒ **fixed parameter convention and read-write format** [list still growing]

Conversion of beam energy into particle mass

- search for new particles easier if particle produced
→ 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 ~ 3 TeV** [win by luminosity]

New physics at hadron colliders

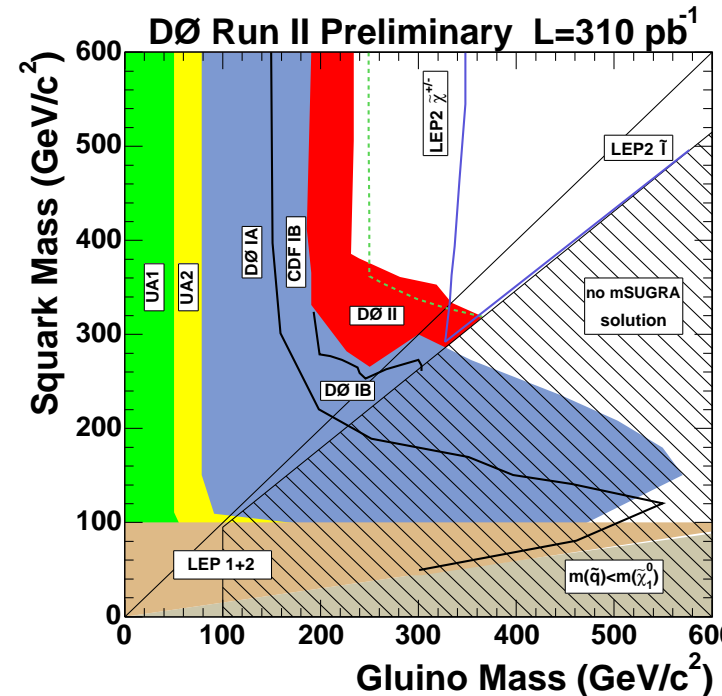
- what is a jet and what is inside? [b, τ tag]
- trigger: 'no leptons — no data'
- backgrounds $pp \rightarrow jj$ or $pp \rightarrow WZ+jets$
- **statistics: $S/\sqrt{B} > 5$ we call discovery**



SUPERSYMMETRY AT THE TEVATRON: 1

Inclusive: squarks and gluinos at Tevatron

- squarks, gluinos strongly interacting, $\sigma \sim \text{pb}$
 $p\bar{p} \rightarrow \tilde{q}\tilde{q}^*, \tilde{q}\tilde{g}, \tilde{g}\tilde{g}$ [best if $m(\tilde{q}) \sim m(\tilde{g})$]
 - decays to jets and LSP and
 $\tilde{g} \rightarrow \tilde{q}\bar{q}, \tilde{q}_L \rightarrow q\tilde{\chi}_2^0, \tilde{q}_R \rightarrow q\tilde{\chi}_1^0$
additional jets and leptons possible
- ⇒ **very promising search for jets plus LSP**



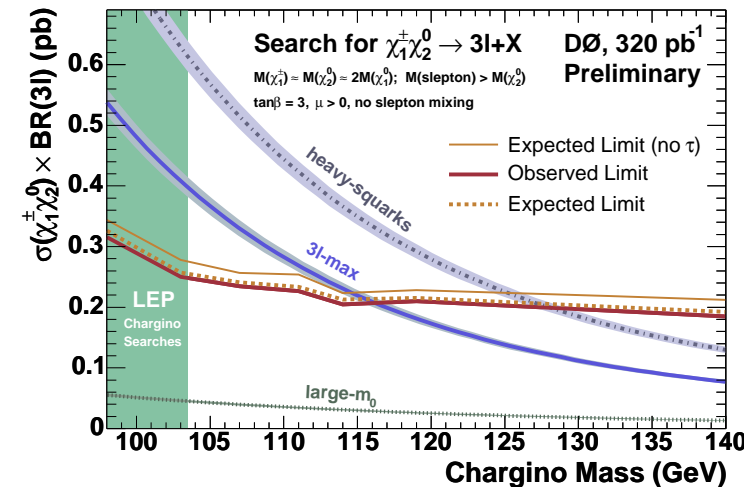
Necessary model assumptions

- assume 100% branching into inclusive jets+LSP
 - for detector efficiencies $m(\tilde{\chi}_2^0), \dots$
 - gluino decay into squark or vice versa?
- ⇒ mSUGRA assumed, but effect moderate

SUPERSYMMETRY AT THE TEVATRON: 2

More specialized: trilepton channels

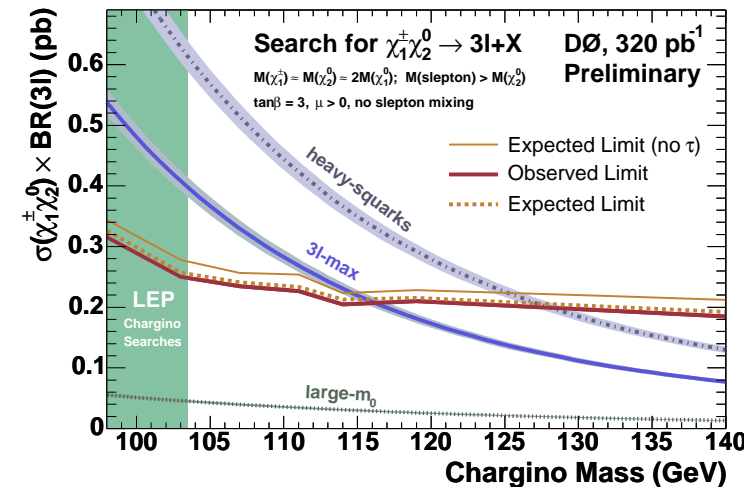
- generally assumed that charginos are light
- largest cross section $p\bar{p} \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^0$
decays $\tilde{\chi}_1^+ \rightarrow \ell^+ \nu \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$
- gaugino rate determined by t channel squark
- signature plagued by W, Z background
- ⇒ about to pass LEP2 chargino limits



SUPERSYMMETRY AT THE TEVATRON: 2

More specialized: trilepton channels

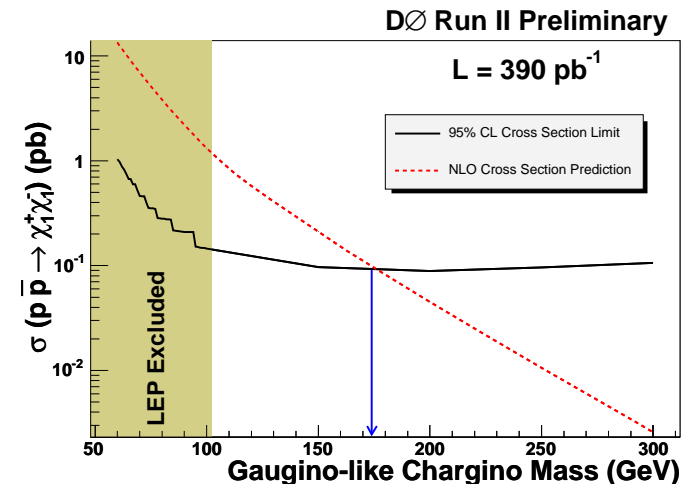
- generally assumed that charginos are light
- largest cross section $p\bar{p} \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_2^0$
- decays $\tilde{\chi}_1^+ \rightarrow l^+ \nu \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow l^+ l^- \tilde{\chi}_1^0$
- gaugino rate determined by t channel squark
- signature plagued by W, Z background
- ⇒ about to pass LEP2 chargino limits



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

⇒ SUSY at the LHC does not come out of nowhere!



SUPERSYMMETRY AT LHC: 1

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

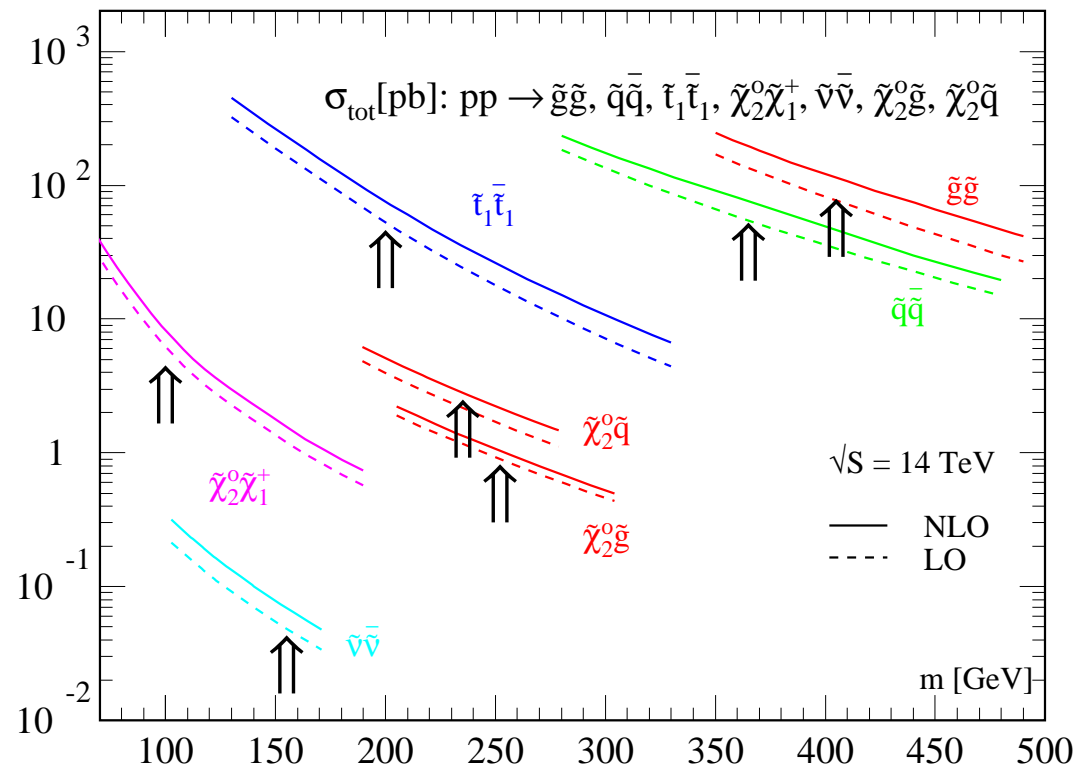
SUSY signals included

- QCD coupling $g\bar{q}q$, $q\bar{g}g$, $g\bar{g}g$
- jets and E_{T} : $pp \rightarrow \bar{q}q^*$, $\bar{g}g$, $\bar{q}g$
- funny tops: $pp \rightarrow \tilde{t}_1\tilde{t}_1^*$
- like sign dileptons: $pp \rightarrow \tilde{g}\tilde{g}$

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

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

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



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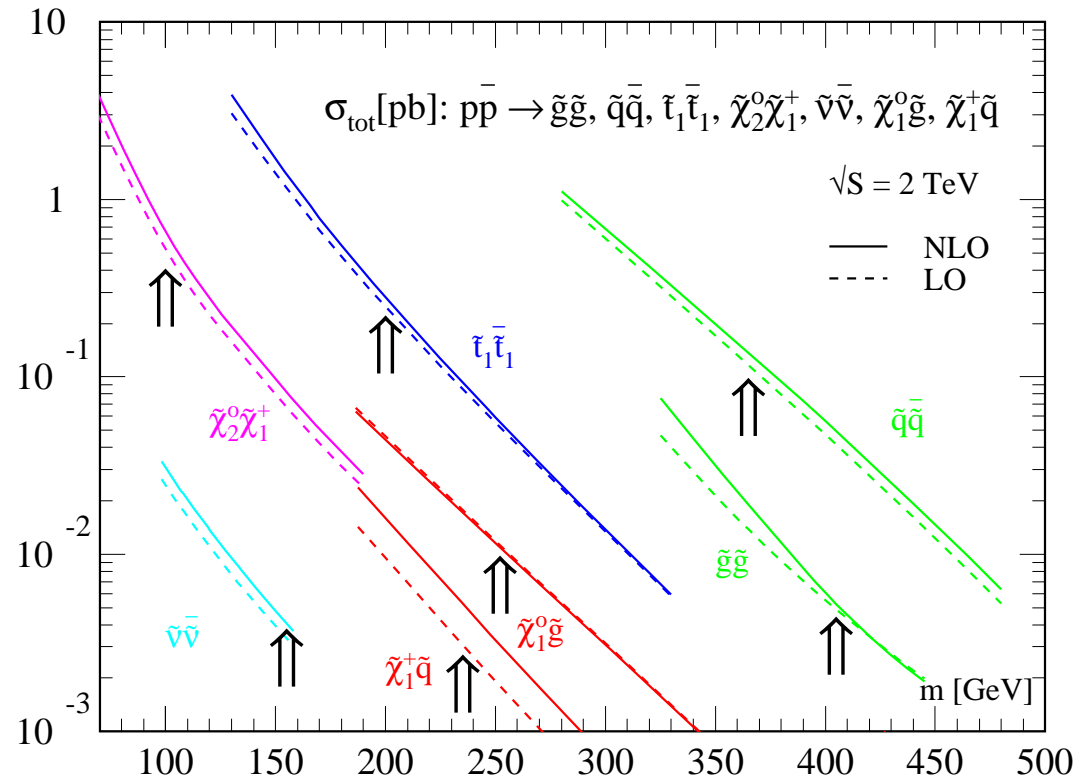
SUSY signals included

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SUPERSYMMETRY AT LHC: 2

Tevatron-type LHC searches

- inclusive jet + missing energy [squark-gluino dominant]
- stops to bottom-chargino [top-like]
- like-sign dileptons [gluino Majorana if fermion]
- trileptons [signal down, background up]
- all R-parity conserving...

Approximate SUGRA relations

$$m^2(\tilde{e}_R) = m_0^2 + 0.15 m_{1/2}^2 - s_W^2 D$$

$$m^2(\tilde{e}_L) = m_0^2 + 0.52 m_{1/2}^2 - (1/2 - s_W^2) D$$

$$m^2(\tilde{\nu}) = m_0^2 + 0.52 m_{1/2}^2 + 1/2 D$$

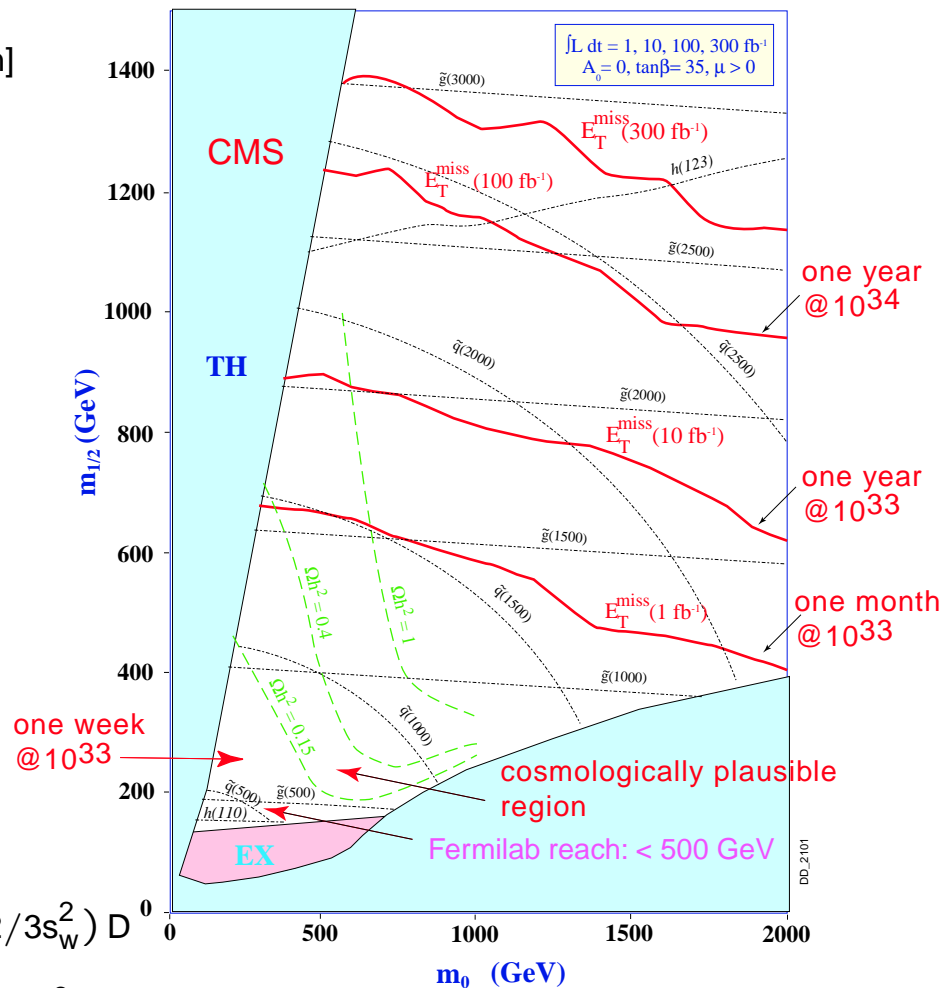
$$m^2(\tilde{u}_R) = m_0^2 + (0.07 + C) m_{1/2}^2 + 2/3 s_W^2 D$$

$$m^2(\tilde{d}_R) = m_0^2 + (0.02 + C) m_{1/2}^2 - 1/3 s_W^2 D$$

$$m^2(\tilde{u}_L) = m_0^2 + (0.47 + C) m_{1/2}^2 + (1/2 - 2/3 s_W^2) D$$

$$m^2(\tilde{d}_L) = m_0^2 + (0.47 + C) m_{1/2}^2 - (1/2 - 1/3 s_W^2) D$$

$$D = m_Z^2 c_{2\beta}$$



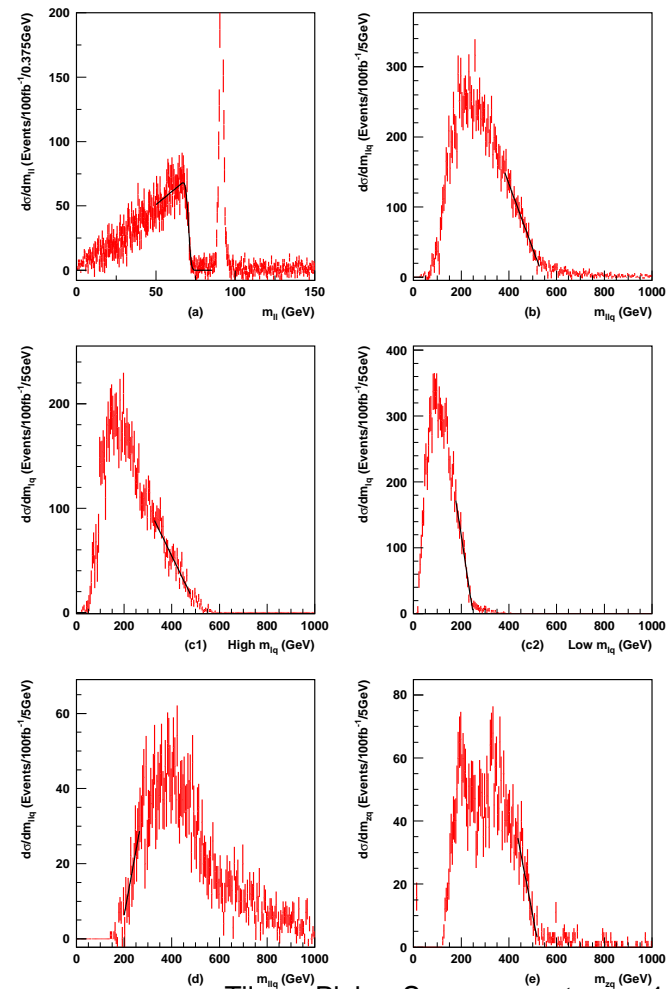
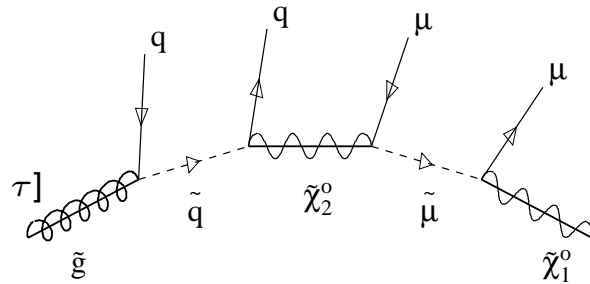
SUPERSYMMETRY AT LHC: 3

Spectra from cascade decays

- decay $\tilde{g} \rightarrow \tilde{q}\bar{q} \rightarrow \tilde{\chi}_2^0 q\bar{q} \rightarrow \mu^+ \mu^- q\bar{q} \tilde{\chi}_1^0$ [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?

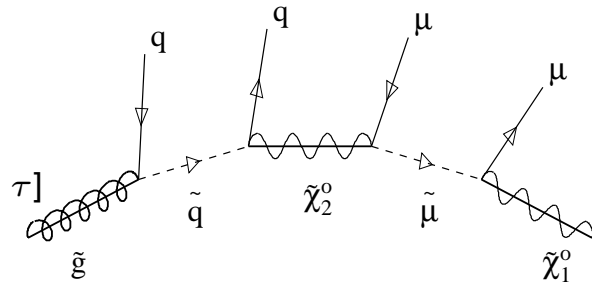
\Rightarrow \tilde{q}_L cascade reconstruction great

[known even from Atlas TDR]



SUPERSYMMETRY AT LHC: 3

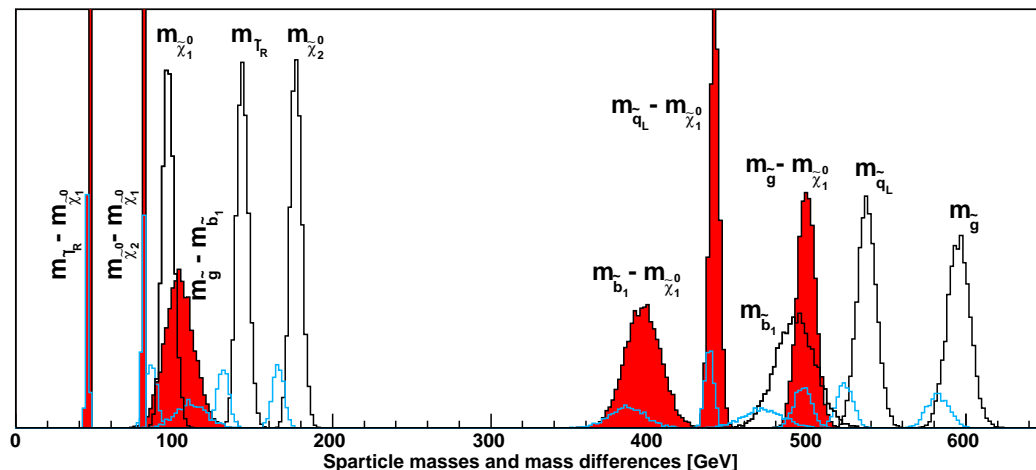
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 - detector resolution, calibration, systematic errors, shape analysis, cross sections as input?
- \Rightarrow \tilde{q}_L cascade reconstruction great [know now: mass differences even better]

Example: gluino mass

- now four jets instead of two
 - \tilde{b}_L instead, all jets b-tagged
 - most of time: cascade identific
- \Rightarrow gluino mass to $\sim 1\%$
[statistical error dominant]



SUPERSYMMETRY AT LHC: 4

Complex final states

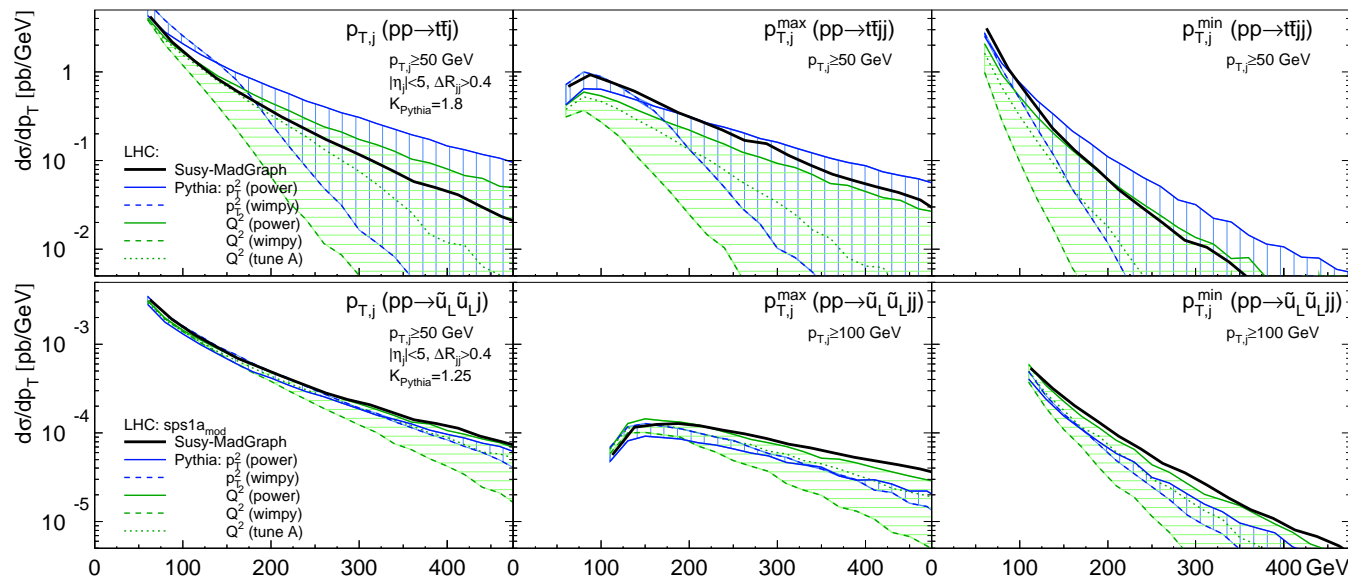
- Majoranas and fermion number violation in tools like Madgraph
- complete set of Feynman rules [400+ processes compared: Madgraph - Whizard - Sherpa]

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]
- Pythia shower tuned at Tevatron

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

\Rightarrow **SUSY easier than tops**



SUPERSYMMETRY AT LHC: 4

Complex final states

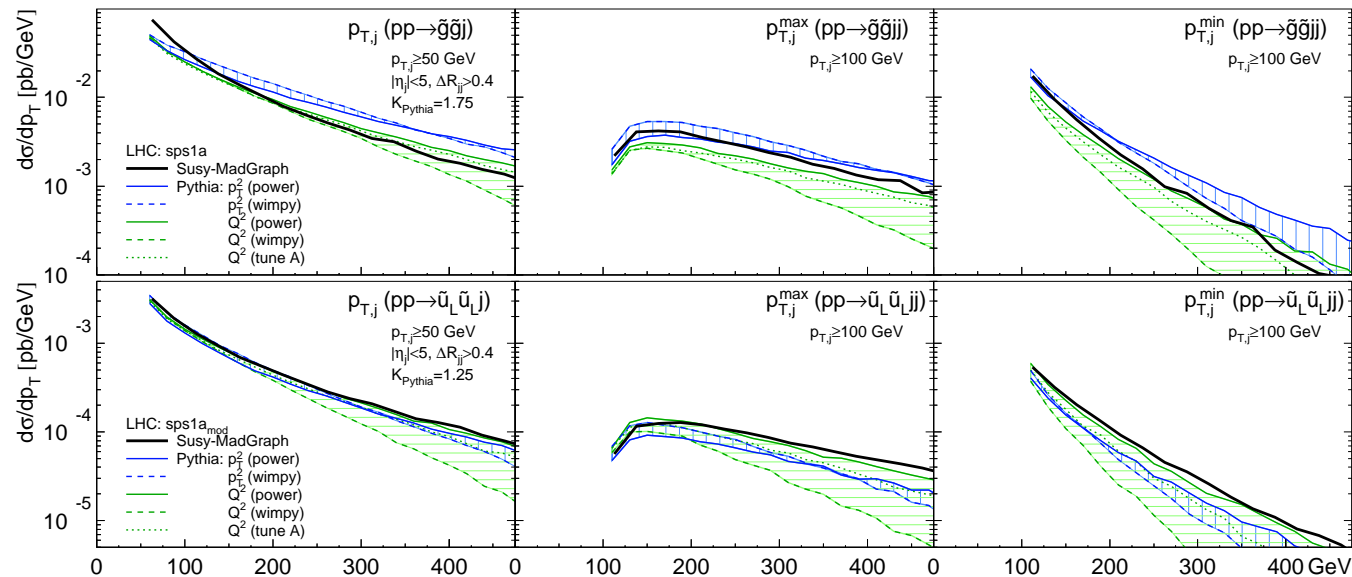
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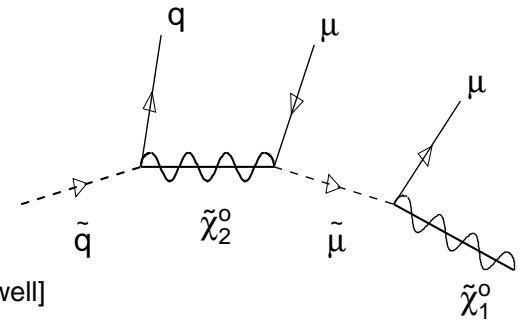
⇒ SUSY easier than tops



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]

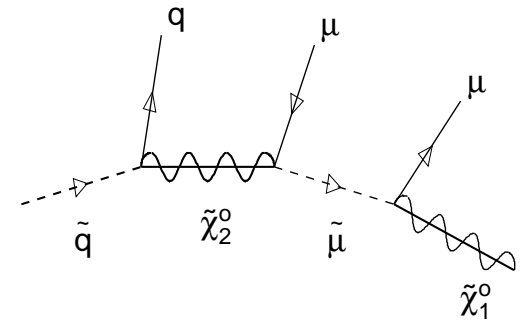


Squark cascade

- decay chain $\tilde{q}_L \rightarrow q \tilde{\chi}_2^0 \rightarrow q \ell \bar{\ell} \rightarrow q \ell \bar{\ell} \tilde{\chi}_1^0$
 compared with first excited Z and ℓ [assume near/far lepton for now]
- polarization: 1: (q_L, l_L^-, l_L^+)
 or 2: $(q_L, l_L^+, l_L^-) = (q_L, l_R^-, l_R^+) = (\bar{q}_L, l_L^-, l_L^+)$
- distribution of angle θ between q and ℓ : $dP_{1,2}^{\text{SUSY}} / d \cos \theta \propto (1 \mp \cos \theta)$
- ⇒ rescaled invariant mass variable instead: $\hat{m} = m_{q\ell} / m_{q\ell}^{\text{max}} = \sin \theta / 2$

Squark cascade

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UED and SUSY distributions [Z_L^* for $m_{q^*} \gg m_{Z^*}$, Z_T^* for $m_{q^*} \ll m_{Z^*}$]

$$\frac{dP_1^{\text{SUSY}}}{d\hat{m}} = 4\hat{m}^3$$

$$\frac{dP_1^{\text{UED,T}}}{d\hat{m}} = \frac{12\hat{m}}{2+y} (y\hat{m}^2 + (1-y)\hat{m}^4)$$

$$\frac{dP_{1,2}^{\text{UED,L}}}{d\hat{m}} = \frac{6\hat{m}}{2+y} (y + 4(1-y)(\hat{m}^2 - \hat{m}^4))$$

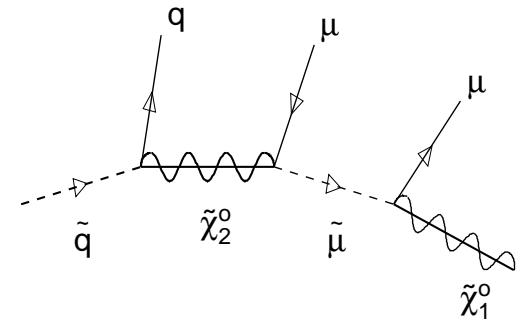
$$\frac{dP_2^{\text{SUSY}}}{d\hat{m}} = 4\hat{m} (1 - \hat{m}^2)$$

$$\frac{dP_2^{\text{UED,T}}}{d\hat{m}} = \frac{12\hat{m}}{2+y} (1 + (y-2)\hat{m}^2 + (1-y)\hat{m}^4)$$

$$y = m_{\ell^*}^2 / m_{Z^*}^2$$

Squark cascade

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compared with first excited Z and ℓ
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UED and SUSY distributions [SPS1a spectrum]

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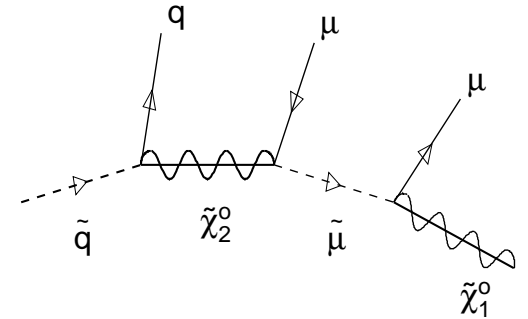
$$\frac{dP_1^{\text{UED}}}{d\hat{m}} = 1.213\hat{m} + 3.108\hat{m}^3 - 2.310\hat{m}^5$$

$$\frac{dP_2^{\text{SUSY}}}{d\hat{m}} = 4\hat{m}(1 - \hat{m}^2)$$

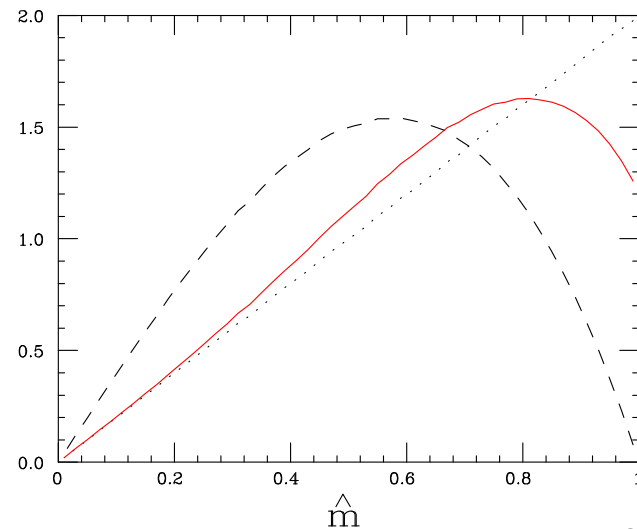
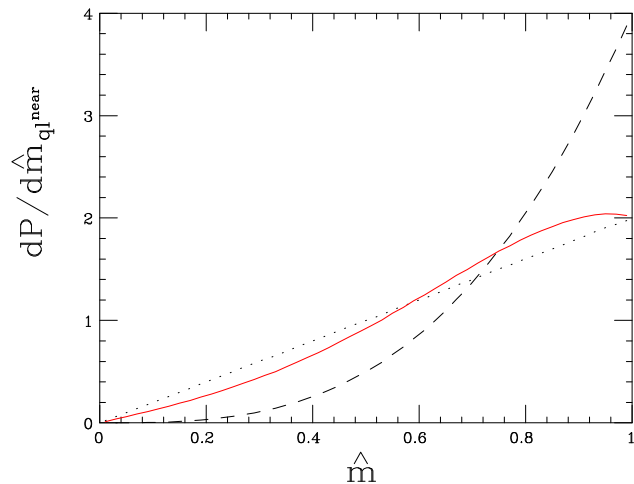
$$\frac{dP_2^{\text{UED}}}{d\hat{m}} = 2.020\hat{m} + 1.493\hat{m}^3 - 2.310\hat{m}^5$$

Squark cascade

- decay chain $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow ql\tilde{\ell} \rightarrow ql\bar{\ell}\tilde{\chi}_1^0$
compared with first excited Z and ℓ
- polarization: 1: (q_L, l_L^-, l_L^+)
or 2: $(q_L, l_L^+, l_L^-) = (q_L, l_R^-, l_R^+) = (\bar{q}_L, l_L^-, l_L^+)$
- distribution of angle θ between q and ℓ : $dP_{1,2}^{\text{SUSY}}/d\cos\theta \propto 1 \mp \cos\theta$
- \Rightarrow rescaled invariant mass variable instead: $\hat{m} = m_{q\ell}/m_{q\ell}^{\text{max}} = \sin\theta/2$



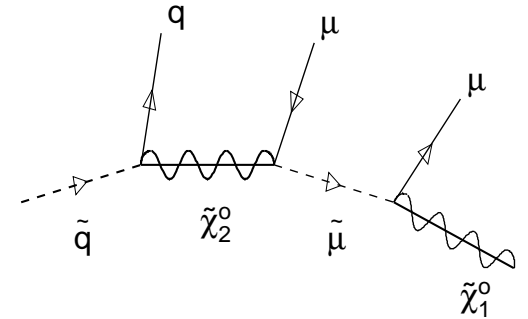
UED and SUSY distributions [SPS1a spectrum]



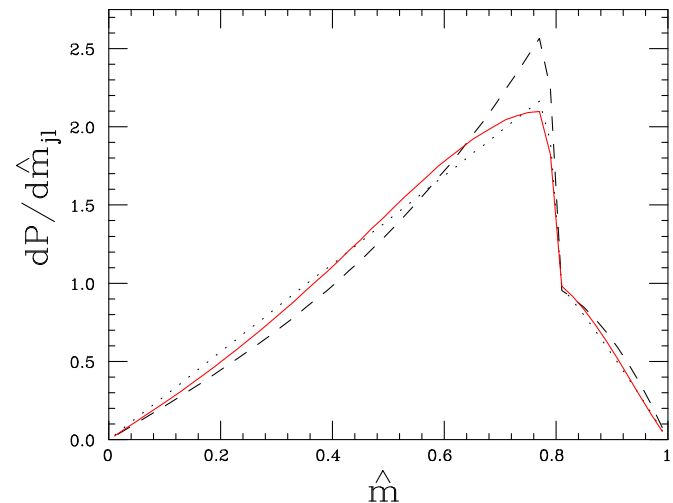
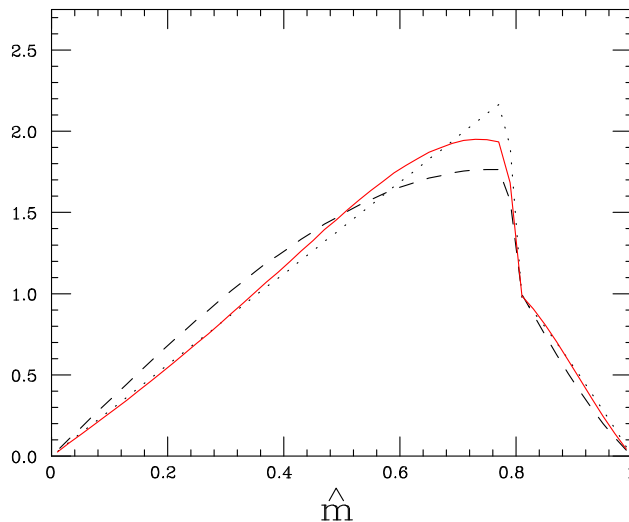
SUPERSYMMETRY AT LHC: 5

Squark cascade

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 - polarization: 1: (q_L, l_L^-, l_L^+)
or 2: $(q_L, l_L^+, l_L^-) = (q_L, l_R^-, l_R^+) = (\bar{q}_L, l_L^-, l_L^+)$
 - initial-state asymmetry $pp \rightarrow \tilde{q}\tilde{q} \quad [\bar{q}/q \sim 2]$
- \Rightarrow even better: $\mathcal{A} = [\sigma(jl^+) - \sigma(jl^-)] / [\sigma(jl^+) + \sigma(jl^-)]$



UED and SUSY distributions [SPS1a spectrum, now l^- vs l^+]



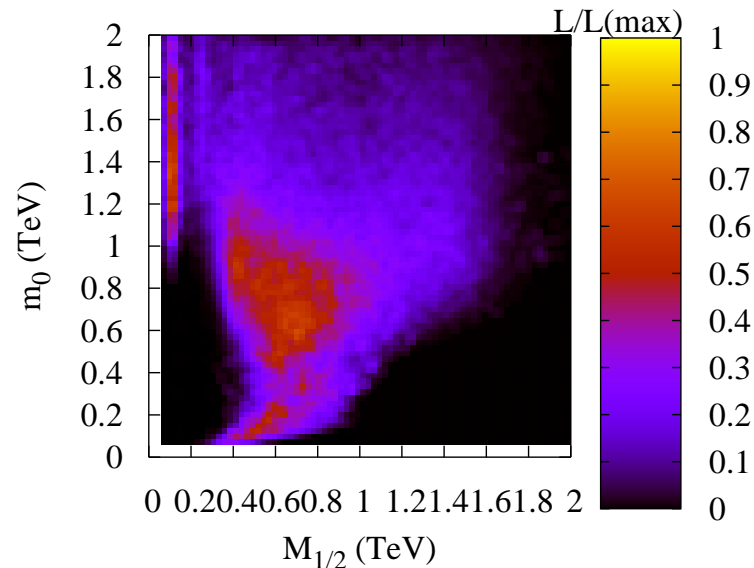
SUPERSYMMETRIC PARAMETERS

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**



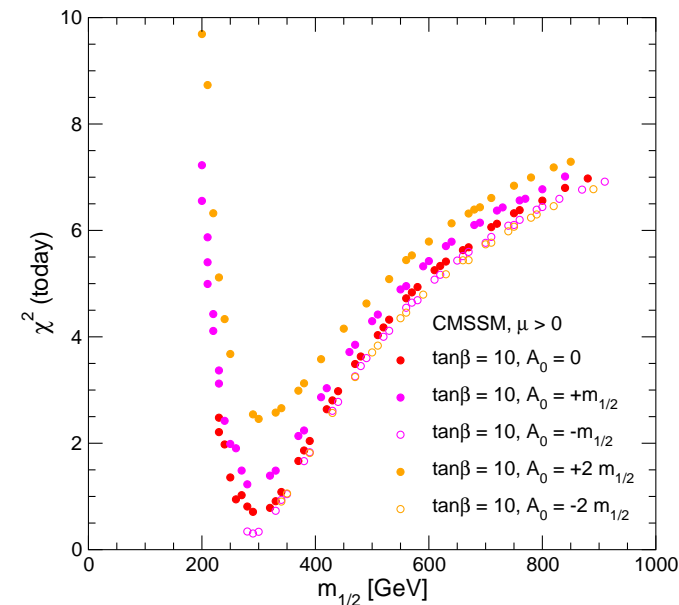
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Combination of methods [Sfitter, Fittino]

- (1) grid for closed subset
(2) fit of remaining parameters
(3) complete fit
 - more modern alternatives:
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	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
$M_{\tilde{q}_{3L}}$	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

LHC phenomenology beyond the Standard Model

- Tevatron optimal training ground for SUSY at LHC
 - many new tools/ideas on the market
 - lots of more work to be done
- ⇒ **LHC will be the coolest experiment ever!**