SUPERSYMMETRY AT THE LHC

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MPI & Edinburgh

– 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

$\Rightarrow$ (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

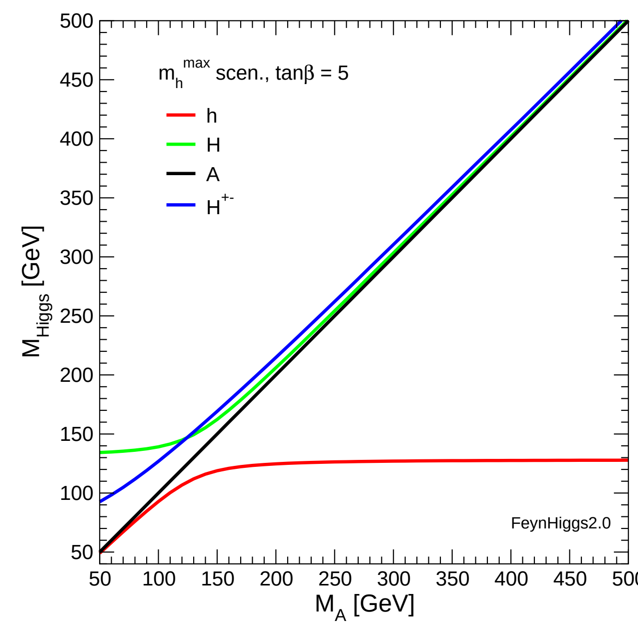
$\Rightarrow$ no MSSM know-how needed

		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	5	
$\longrightarrow$ gravitino	$\tilde{G}$	3/2	5	hard to catch

SUPERSYMMETRIC HIGGS SECTOR: 1

Required by supersymmetry: two Higgs doublet model

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

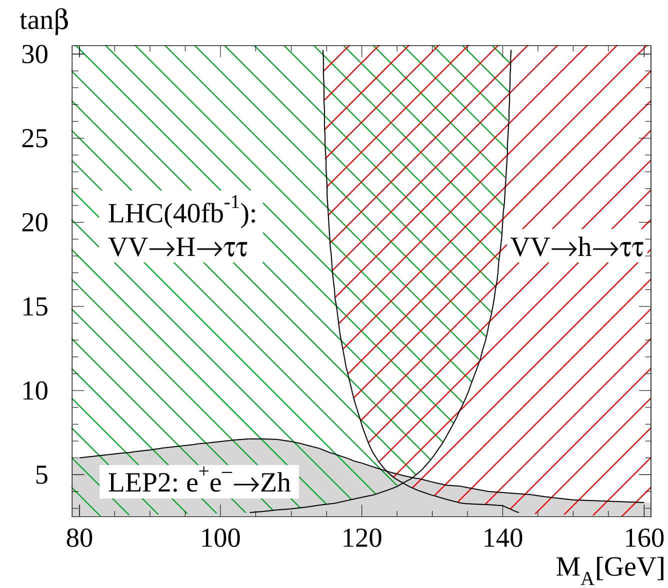
- ‘plateau Higgses’ coupling to W, Z
- heavy H^0, A^0 with $\tan\beta$-enhanced coupling to b, τ
- light h^0 mass limited from above $m_h \lesssim 135$ GeV

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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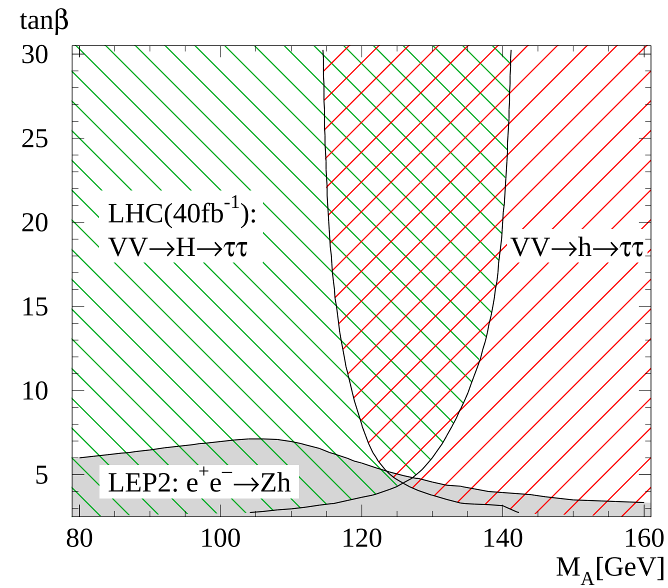
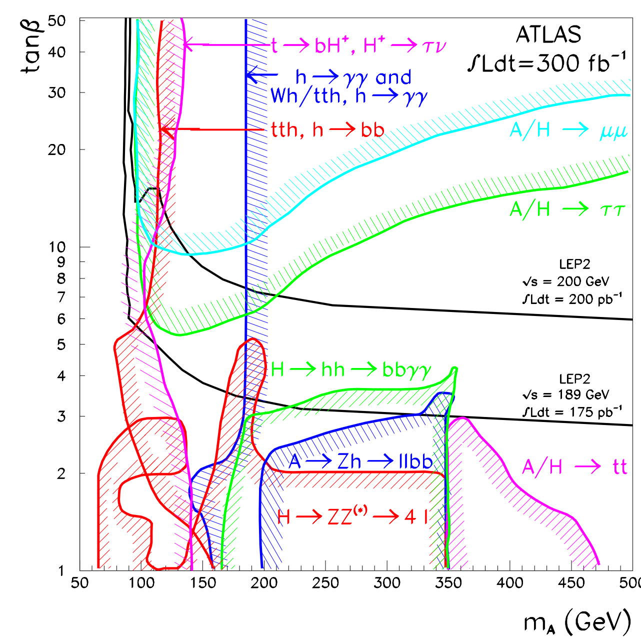


Nightmare: confirm SUSY Higgs sector

– decoupling regime $m_A \gtrsim 160$ GeV
  $\rightarrow$ Yukawa coupling for $H^0, A^0, H^\pm$: $m_b \tan\beta$
  $\rightarrow$ enhanced production e.g. $b\bar{b} \rightarrow H^0$ or $gb \rightarrow tH^-$
  $\rightarrow$ decays $H^0 \rightarrow \tau\tau, \mu\mu$ or $H^- \rightarrow \tau\bar{\nu}$

– intermediate $m_A \sim 120$ GeV:
  $\rightarrow$ many (light-ish) Higgses h^0, H^0, A^0 observable
  $\rightarrow$ top quark decays $t \rightarrow bH^+$? [Tevatron?]



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 $\tilde\chi_1^0, \tilde\nu \;\Rightarrow\;$ after dark matter data $\tilde\chi_1^0 \sim \tilde B, \tilde W$ [gravitinos?]

SUSY TOOLS

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. $m(q = \text{TeV}, v, m_t)$?]
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

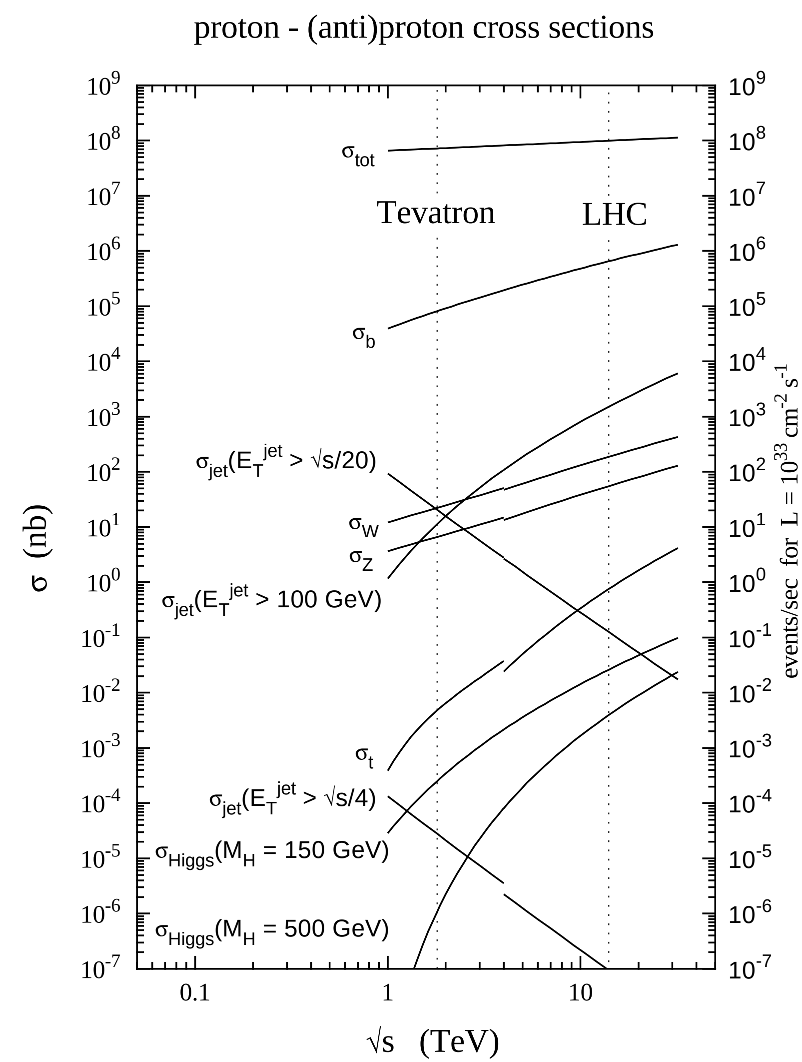
– dark matter: Micromegas

⇒ fixed parameter convention and read-write format [list still growing]

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

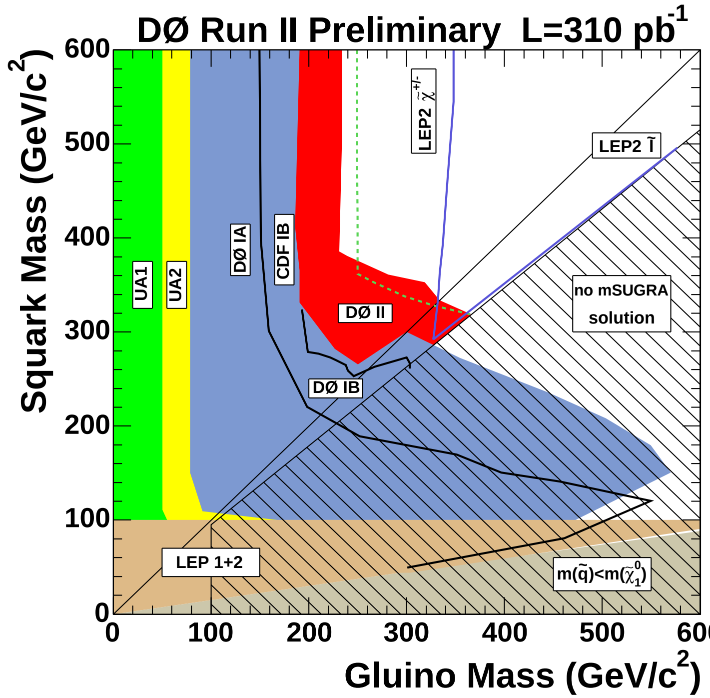
- what is a jet and what is inside? [b, τ tag]
- trigger: 'no leptons — no data'
- backgrounds $pp \rightarrow jj$ or $pp \rightarrow WZ$+jets
- statistics: $S/\sqrt{B} > 5$ we call discovery

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?

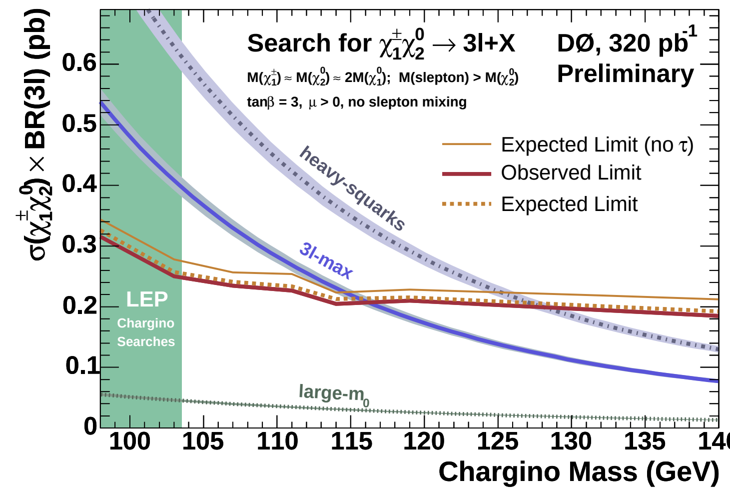
$\Rightarrow$ mSUGRA assumed, but effect moderate

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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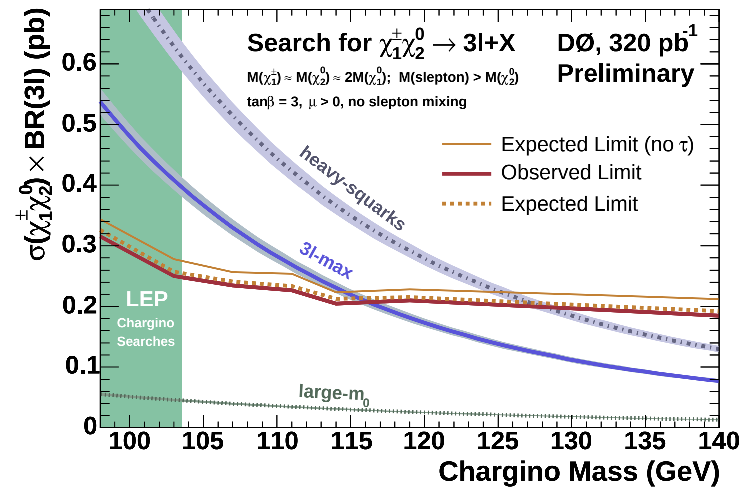
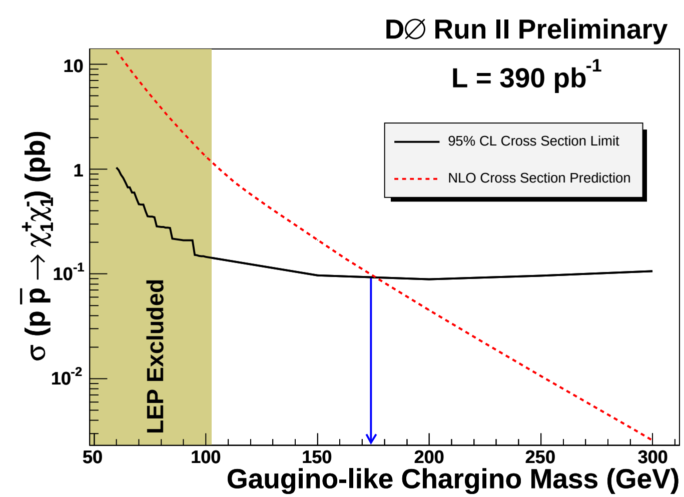


Even more specialized: long-lived gauginos

– 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 LHC: 1

Supersymmetry at the LHC

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

(2) measurements — masses, cross sections, decays

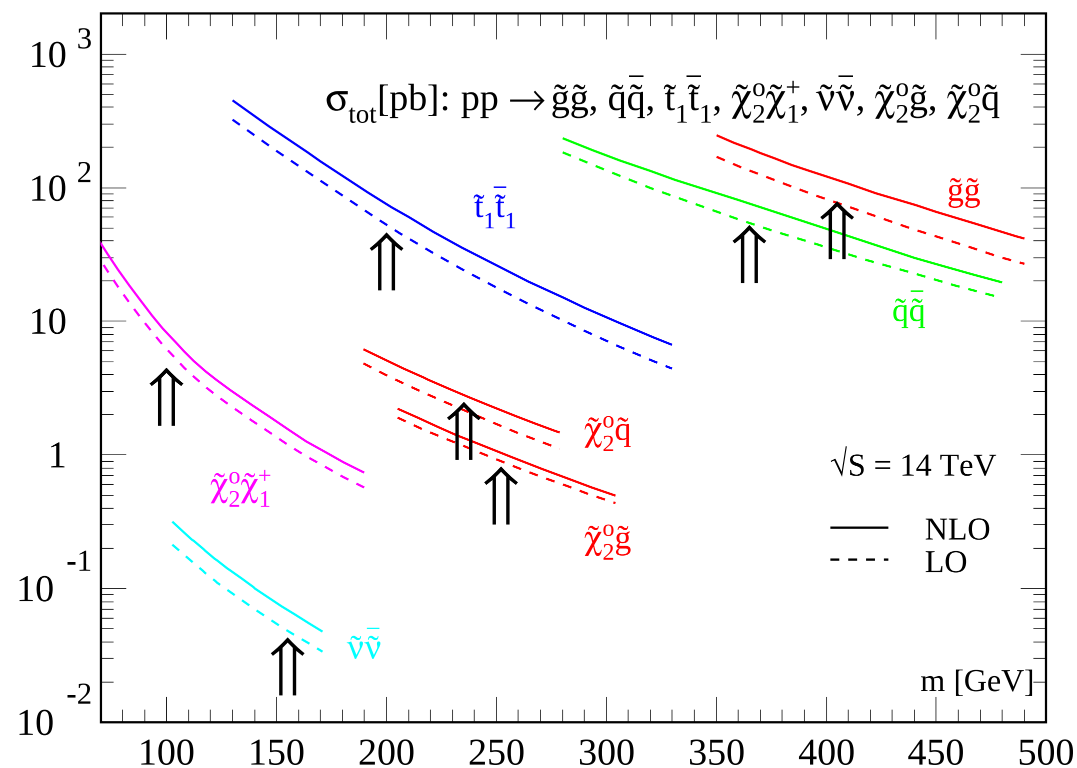
(3) parameter studies — MSSM Lagrangean, SUSY breaking

SUSY signals included

- QCD coupling $g\tilde{q}\tilde{q}, q\tilde{g}\tilde{q}, g\tilde{g}\tilde{g}$
- 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: $pp \to \tilde{\chi}_2^0\tilde{\chi}_1^-$

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



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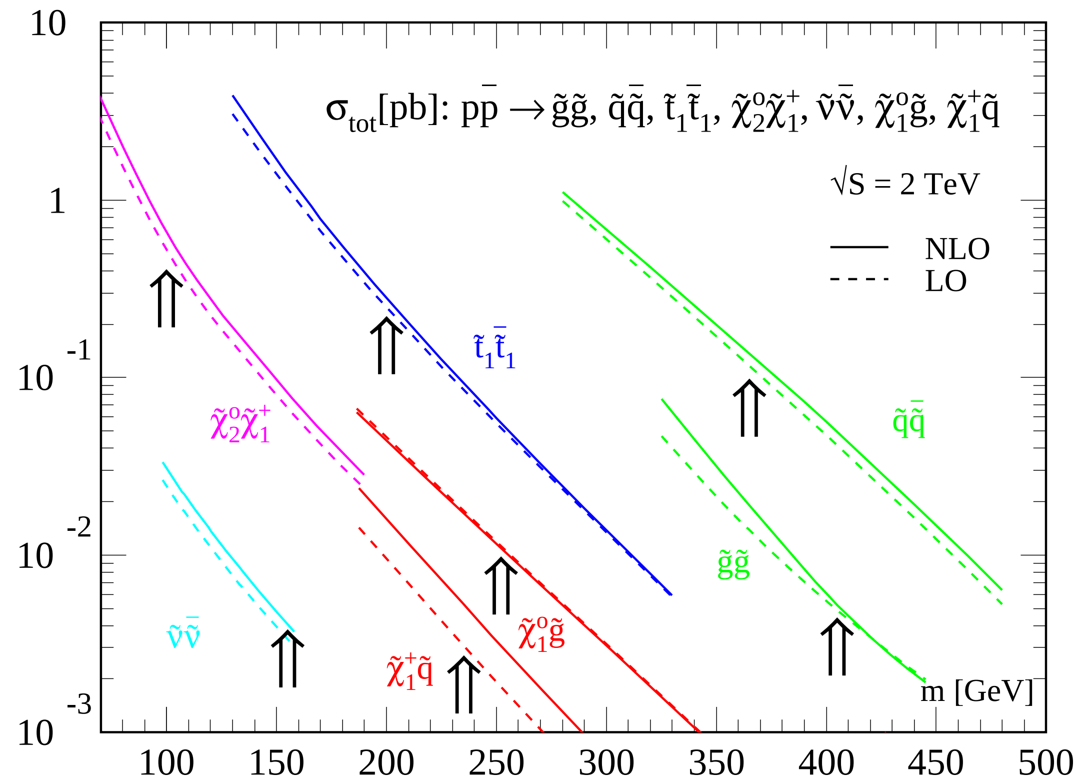
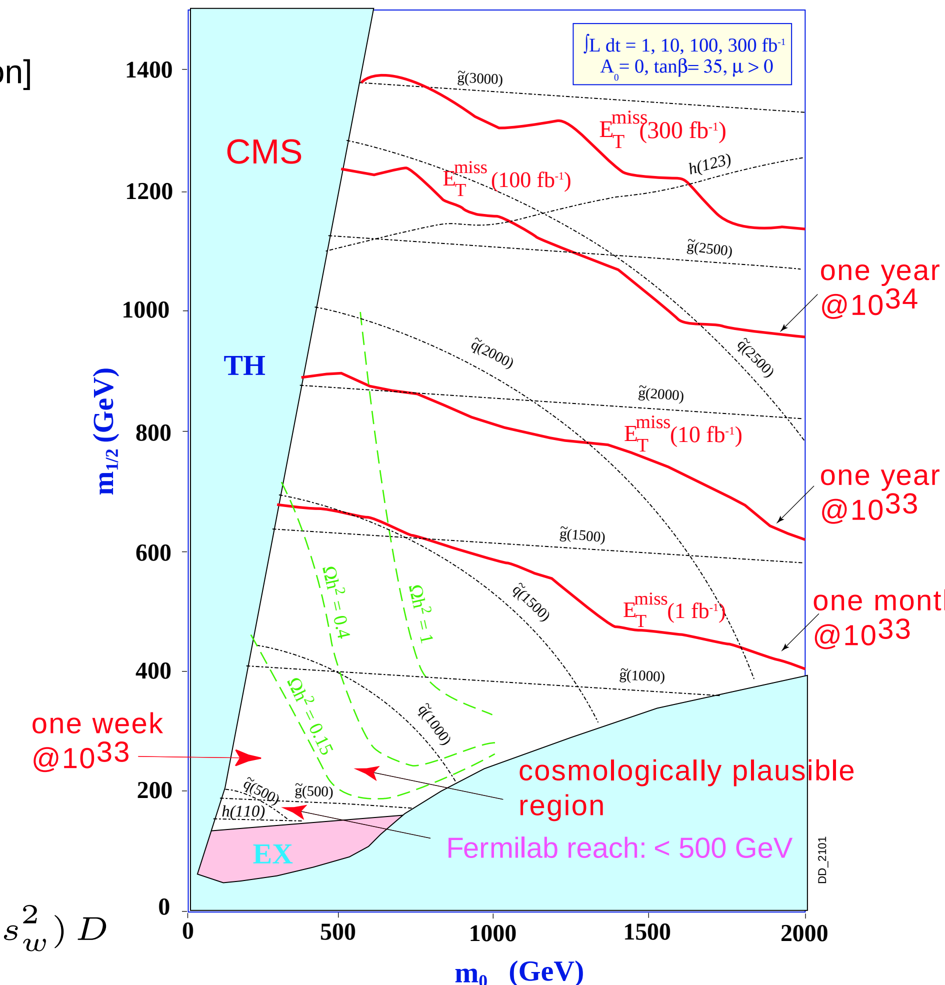


Tevatron-type LHC searches

- 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-partity conserving...



Approximate Sugra relations

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

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

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

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

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

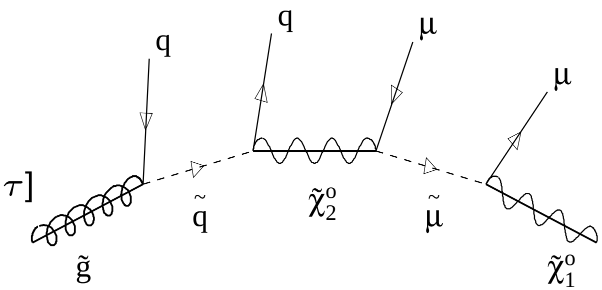
$$m^2(\tilde{u}_L) = m_0^2 + (0.47 + C)\, m_{1/2}^2 + (1/2 - 2/3 s_w^2)\, D$$

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

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

Catania 18

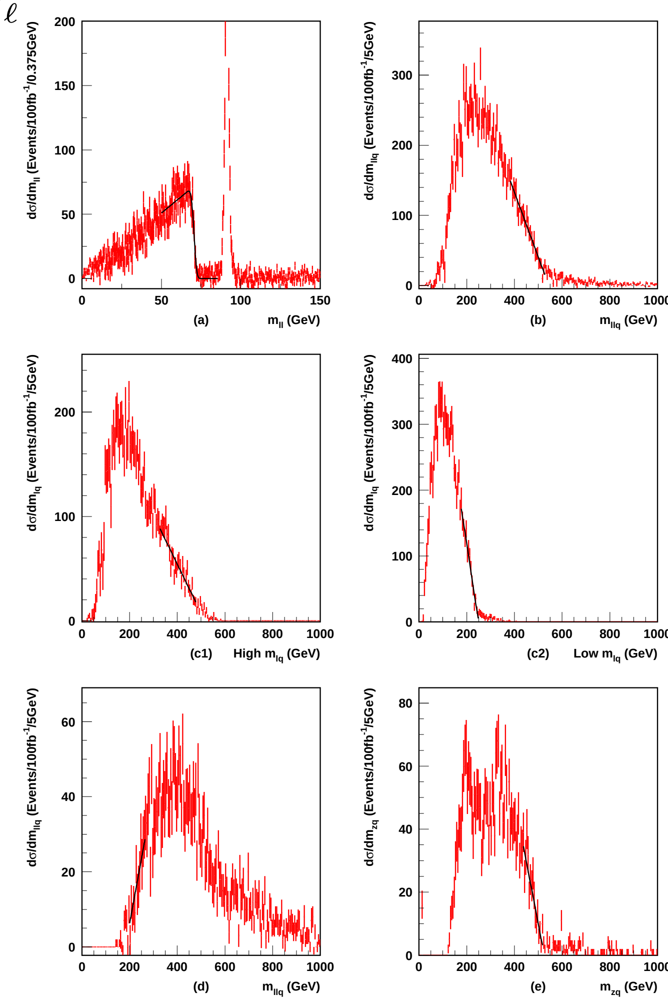
Spectra from cascade decays



- 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?

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

[known even from Atlas TDR]



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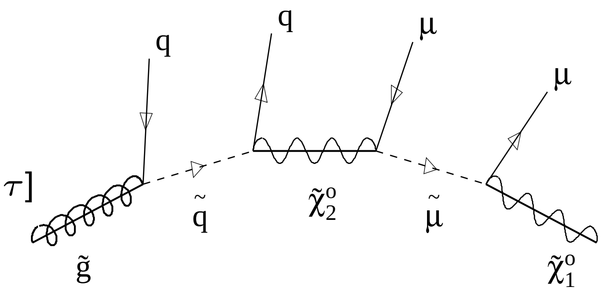

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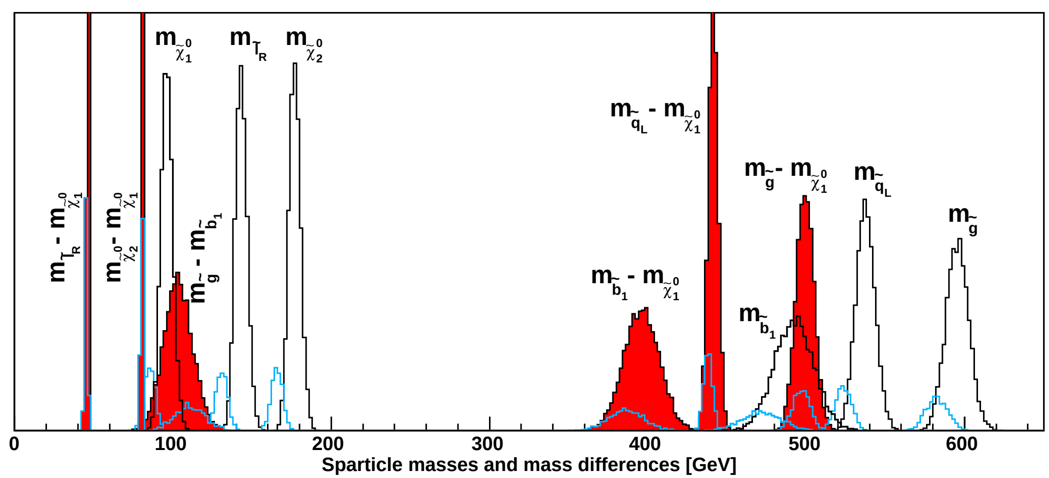
$\Rightarrow$ $\tilde{q}_L$ cascade reconstruction great [know now: mass differences even better]

Example: gluino mass

- now four jets instead of two
- $\tilde{b}_L$ instead, all jets b-tagged
- most of time: cascade identified

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

[statistical error dominant]



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

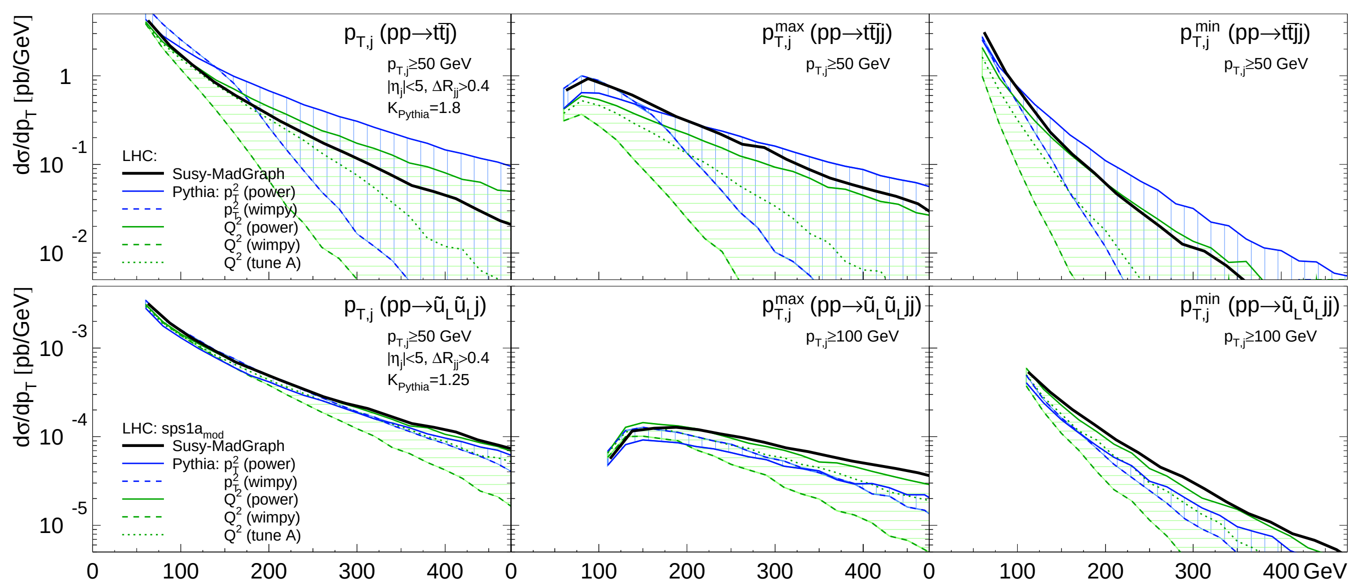
– cascade studies sensitive to jets?

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

– Pythia shower tuned at Tevatron

$\Rightarrow$ 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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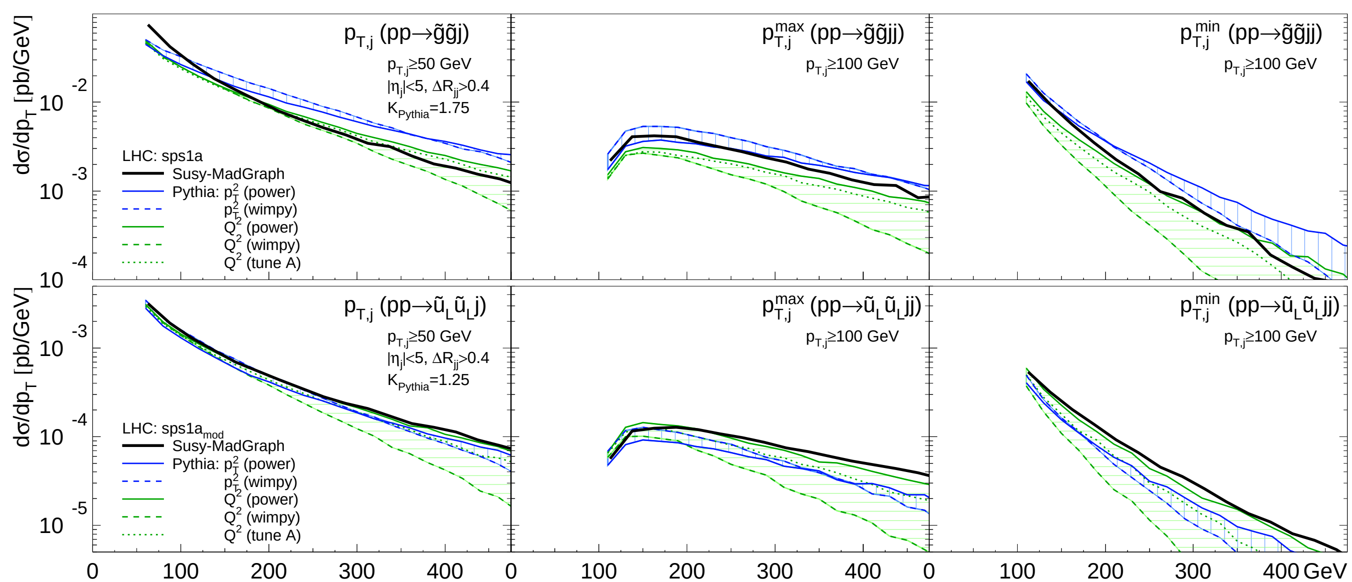


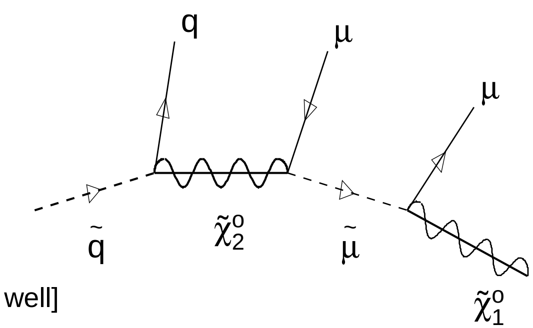
How to make sure it is SUSY

– assume neutralino is found in cascades

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

$\longrightarrow$ straw man: universal extra dimensions

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



Squark cascade

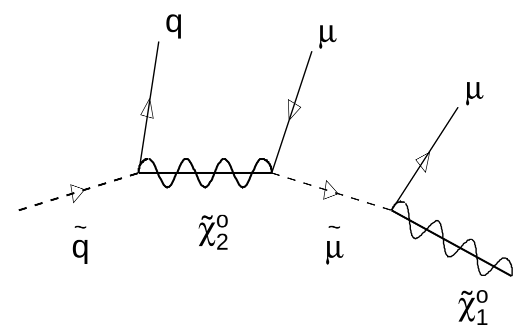
– decay chain $\tilde{q}_L \to q\tilde{\chi}_2^0 \to q\ell\tilde{\ell} \to q\ell\bar{\ell}\tilde{\chi}_1^0$
compared with first excited Z and ℓ [assume near/far lepton for now]

– polarization: 1: $(q_L, \ell_L^-, \ell_L^+)$
or 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: $dP_{1,2}^{\rm SUSY}/d\cos\theta \propto (1 \mp \cos\theta)$

$\Rightarrow$ rescaled invariant mass variable instead: $\hat{m} = m_{ql}/m_{ql}^{\rm max} = \sin\theta/2$

Squark cascade



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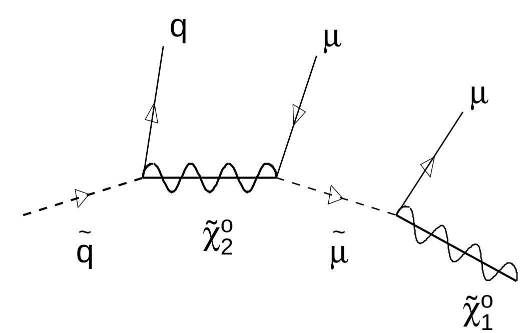
UED and SUSY distributions [Z_L^* for $m_{q^*} \gg m_{Z^*}$, Z_T^* for $m_{q^*} \ll m_{Z^*}$]

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

$$\frac{dP_1^{\rm UED,T}}{d\hat{m}} = \frac{12\hat{m}}{2+y}\left(y\hat{m}^2 + (1-y)\hat{m}^4\right) \qquad \frac{dP_2^{\rm UED,T}}{d\hat{m}} = \frac{12\hat{m}}{2+y}\left(1+(y-2)\hat{m}^2 + (1-y)\hat{m}^4\right)$$

$$\frac{dP_{1,2}^{\rm UED,L}}{d\hat{m}} = \frac{6\hat{m}}{2+y}\left(y + 4(1-y)(\hat{m}^2 - \hat{m}^4)\right) \qquad y = m_{\ell^*}^2/m_{Z^*}^2$$

Squark cascade



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

$\Rightarrow$ rescaled invariant mass variable instead: $\hat{m} = m_{ql}/m_{ql}^{\rm max} = \sin\theta/2$

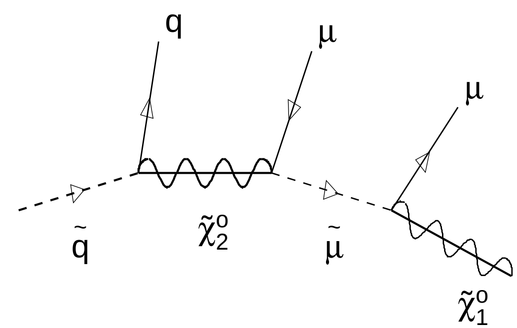
UED and SUSY distributions [SPS1a spectrum]

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

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

SUPERSYMMETRY AT LHC: 5

Squark cascade



– decay chain $\tilde{q}_L \to q\tilde{\chi}^0_2 \to q\ell\tilde{\ell} \to q\ell\bar{\ell}\tilde{\chi}^0_1$
  compared with first excited Z and ℓ

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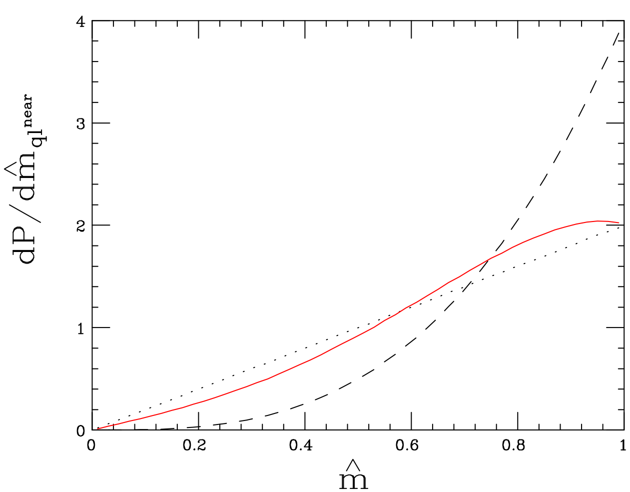

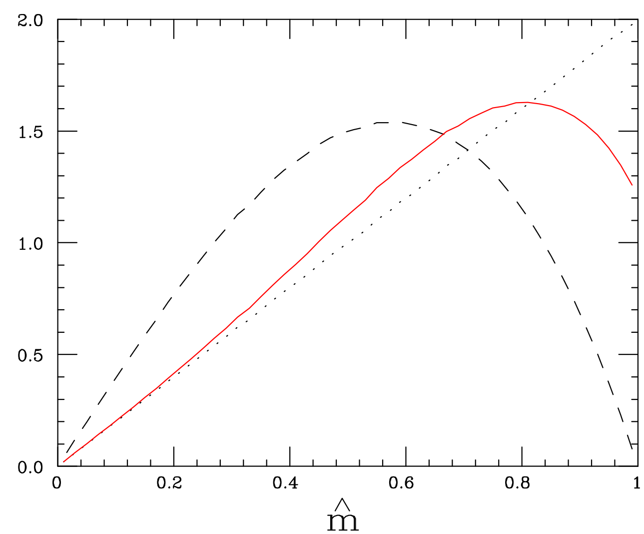

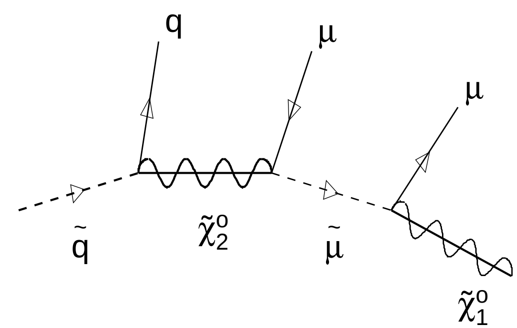

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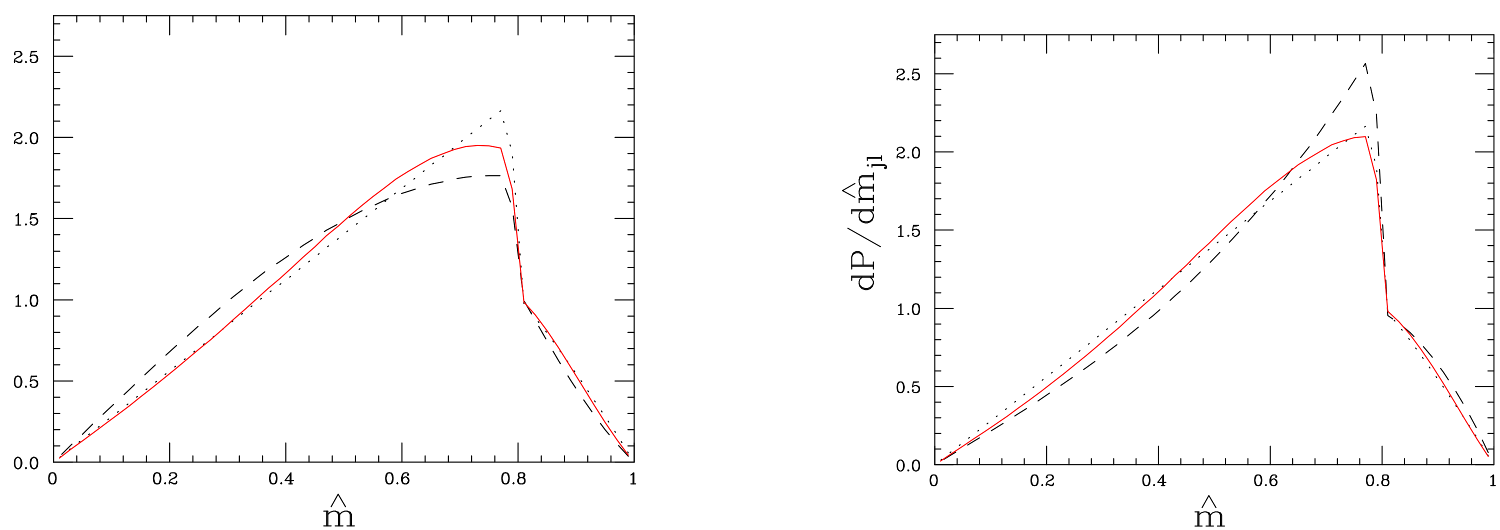
– initial-state asymmetry $pp \to \tilde{q}\tilde{g}$ $[\tilde{q}/\bar{\tilde{q}} \sim 2]$

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

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

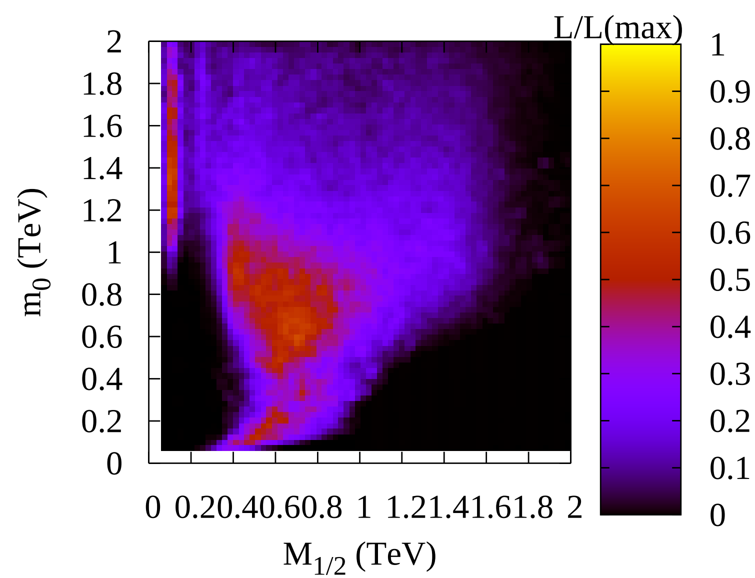
⇒ mSUGRA

– 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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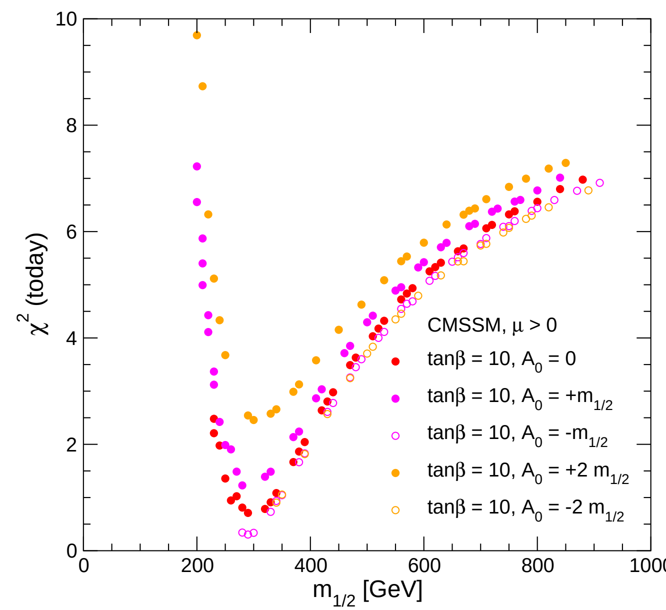

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Combination of methods [Sfitter, Fittino]

– (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

- Tevatron optimal training ground for SUSY at LHC
- many new tools/ideas on the market
- lots of more work to be done

$\Rightarrow$ LHC will be the coolest experiment ever!