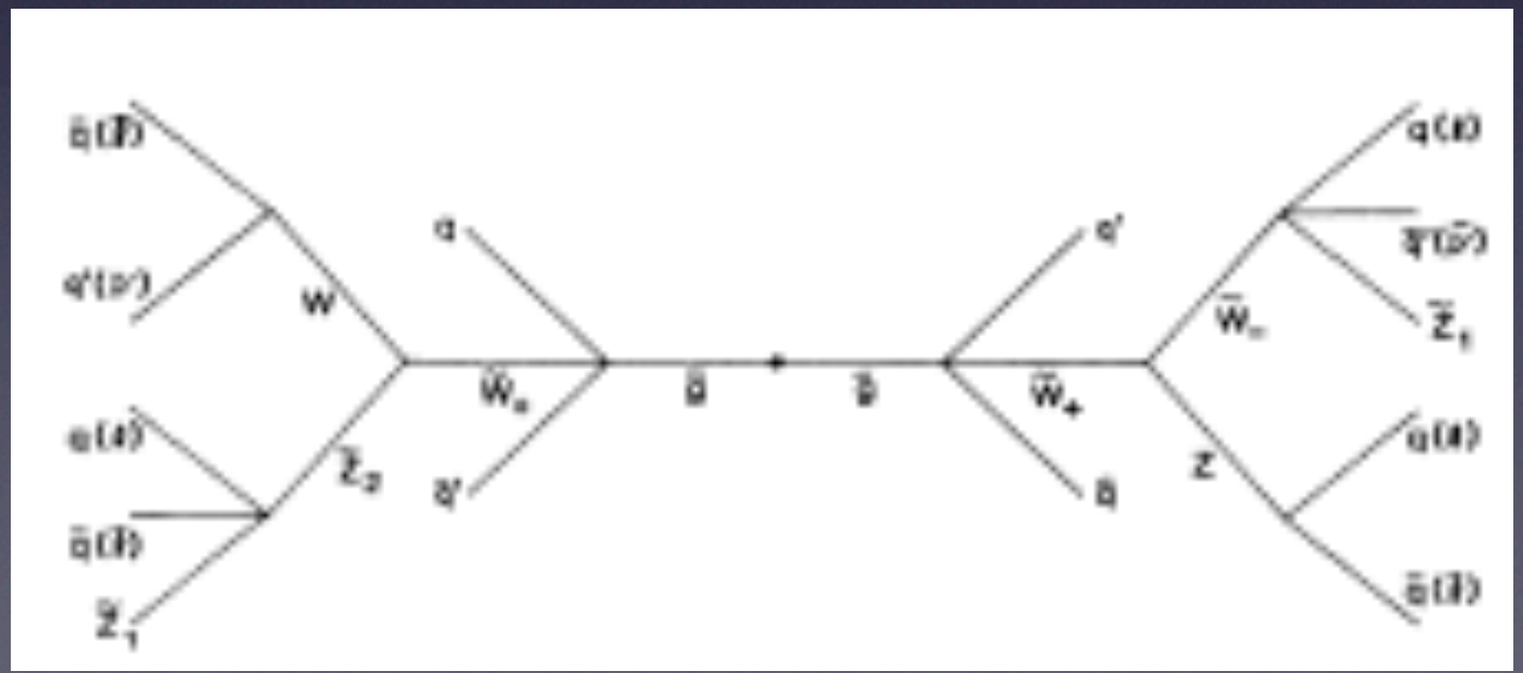
From simplified models to cascade decays (and back again?)

Howard Baer
University of Oklahoma



A long time ago: the dawn of SUSY theory....

- Beginnings of theory: SUSY field theory (1974)
- Supergravity: local SUSY (1975)
- MSSM, global SUSY: (1978)
- SUSYGUTs (1981-82)
- SUGRAGUTS, radiative EWSB, hidden sector SUSY breaking (1982)
- Theory in place; review articles (1984)

And phenomenology...
(some early influential papers)

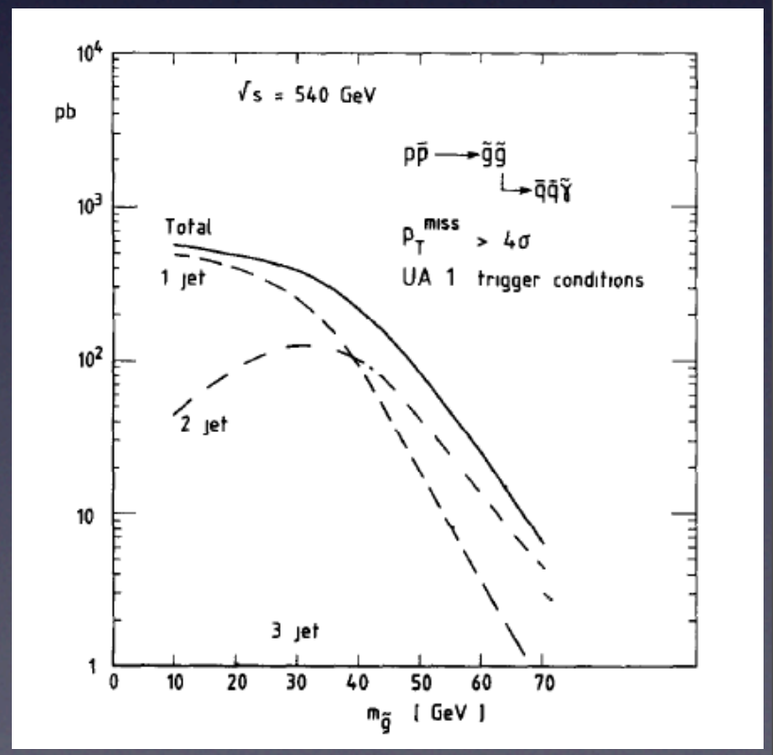
- Fayet and Farrar (1978)
- Harrison & Llewellyn-Smith (1982)
- SUSY confronting exp't, CERN (1982)
- Ellis et al.: Zen events (one hand clapping, 1983)
- Dawson, Eichten, Quigg (1984)
- Haber & Kane/ Nilles reviews (1984)

Excitement at CERN SppbarS: UA1/UA2 monojets (1984)

- Anomalous jets + missing ET events
- Interpretation by many groups: gluino and/or squark pair production followed by simple decays to massless photino:

$$\tilde{g} \to q\bar{q}\tilde{\gamma} \quad \tilde{q} \to q\tilde{\gamma}$$

- e.g. Ellis-Kowalski, 1984
- in spite of excitement, excess ultimately interpreted in terms of known background processes



Analysis in terms of simplified models was the norm (but we didn't know they were simplified, and compared to what?)

* Squark vs gluino plane: already by CHARM collaboration beam dump search 1983

* ASP collaboration: selectron vs photino plane,

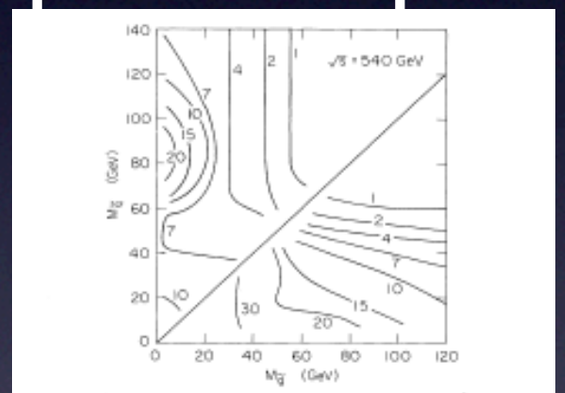


FIG. 1. The number of monojets per 100 nb^{-1} passing the UA1 cuts plus the $E\!\!\!/_T^{min} > 32$ GeV cut shown as a contour plot as a function of $M_{\tilde{g}}$ and $M_{\tilde{q}}$.

* Barnett, Haber, Kane: squark/gluino plane circa1985

* HB, Karatas, Tata, 1986: diminution of limits for massive photino/ compressed spectra; same SiMo as Alves#1

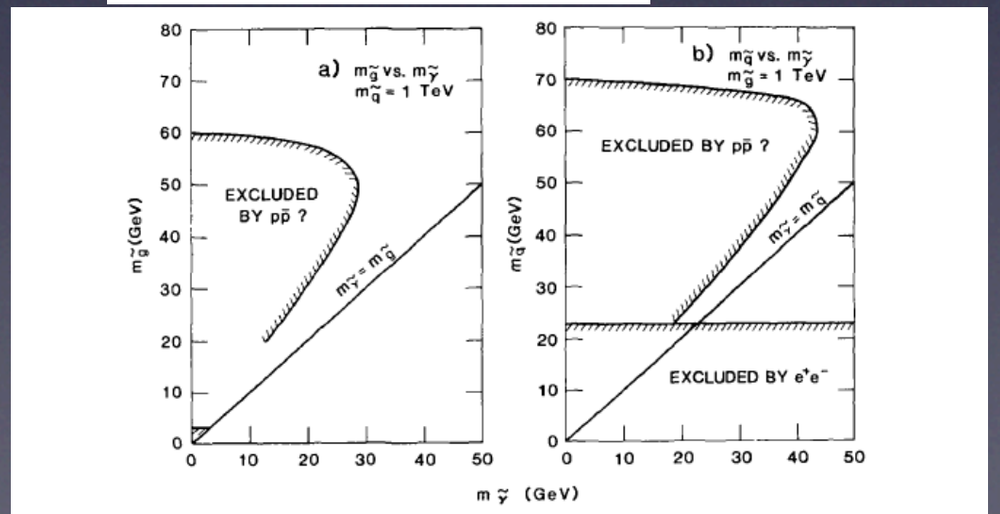


Fig. 2. Mass limits of (a) the gluino plotted in the plane $m_{\tilde{g}}$ versus $m_{\tilde{\gamma}}$ and (b) the squark plotted in the plane $m_{\tilde{q}}$ versus $m_{\tilde{\gamma}}$. The contours show where the total n-jet + $\not{p}_T$ cross section equals σ_0 when the squark or gluino mass is at the UA1 limit in eq. (3).

First foray into cascade decays

SQUARK DECAYS INTO GAUGINOS AT THE $p\bar{p}$ COLLIDER

H. BAER, John ELLIS, G.B. GELMINI [1,2], D.V. NANOPOULOS and Xerxes TATA
CERN, CH 1211 Geneva 23, Switzerland

Received 26 June 1985

Conventional analyses of missing p_T events due to squark production at the CERN $p\bar{p}$ collider assume $\tilde{q} \to q\tilde{\gamma}$ decays dominate. In principle, the monojet and dijet cross sections could be reduced by competition from $\tilde{q} \to q\tilde{W}^{\pm}$ and $\tilde{q} \to q\tilde{Z}^0$ decays. We compute this reduction factor for two mass scenarios: $m_{\tilde{q}} > m_{\tilde{W}} > m_{\tilde{\gamma}}$ and $m_{\tilde{\gamma}} \approx m_{\tilde{q}} > m_{\tilde{W}}$. The monojet and dijet cross sections for squarks light enough to be observed in present collider experiments are reduced by no more than 55%, while there may exist an observable cross section for jet(s) + charged lepton(s) + missing p_T events. Thus the lower bounds on $m_{\tilde{q}}$ usually derived from $\tilde{q} \to q\tilde{\gamma}$ decays remain valid.

While title emphasized squarks, gluinos were included as well, although they didn't mesh with EK monojet scenario

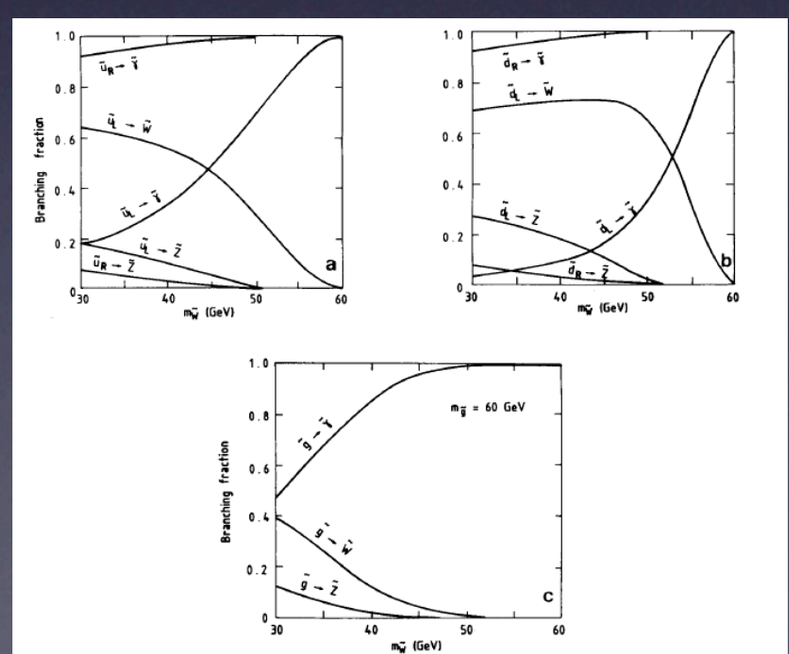
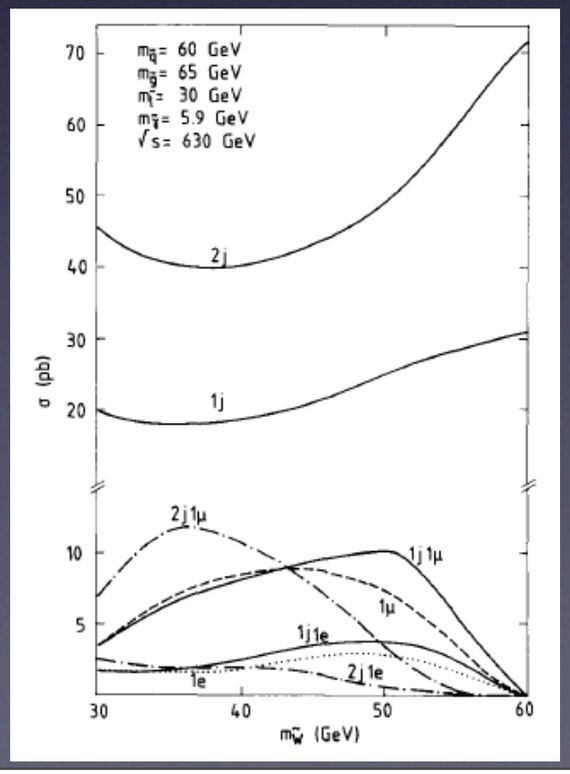


Fig. 2. Branching fractions for decays into zinos, winos and photinos versus wino mass for left- and right-hand up- (a) and down-type (b) squarks, and (c) gluinos. In (a, b) and in (c), the squark and gluino mass is taken to be 60 GeV, while the photino mass is 5.9 GeV.

Built parton level event generator with simple q~, g~ decays to gauginos: jets+leptons+MET signatures



Gamberini in Italy also embarked on gluino/squark decay to gauginos half year later, unaware of our work

Z. Phys. C – Particles and Fields 30, 605–613 (1986)

Zeitschrift für Physik C Particles and Fields

Heavy Gluino and Squark Decays at $p\bar{p}$ Collider

G. Gamberini

Scuola Normale Superiore di Pisa and I.N.F.N. I-56100 Pisa, Italy

Received 5 December 1985

Abstract. The recent limits $m_{\tilde{g}}$, $m_{\tilde{q}} \gtrsim 40$ GeV for gluino and squark masses obtained from experiments at the collider are based on jet$+\not{p}_T$ analysis, in the hypothesis that the gluino or the squark decays into photino+quarks with a branching ratio near to one. We show that this hypothesis is generally not justified for higher masses of the gluino and the squarks, $50\,\text{GeV} \lesssim m_{\tilde{g},\tilde{q}} \lesssim 150\,\text{GeV}$, relevant to present and future $p\bar{p}$ colliders. In an interesting range of the parameters we study the different decay modes and the related signatures, among which isolated leptons or photons in the final states.

The purpose of this paper is to look carefully into the above situation, with an eye to:

i) the actual composition of the lightest neutralino, which can be mainly a higgsino, rather than a photino;

ii) the possibility of having many open channels for the decay of a gluino (or a squark), other than the direct one into the neutralino plus quarks.

As we shall see all these possibilities exist in a non-negligible range of the relevant mass parameters with important implications: i) on the actual amount of sizeable $\not{p}_T$ events ($\not{p}_T$ dilution); ii) the possible presence of photons in the final state; iii) the occur-

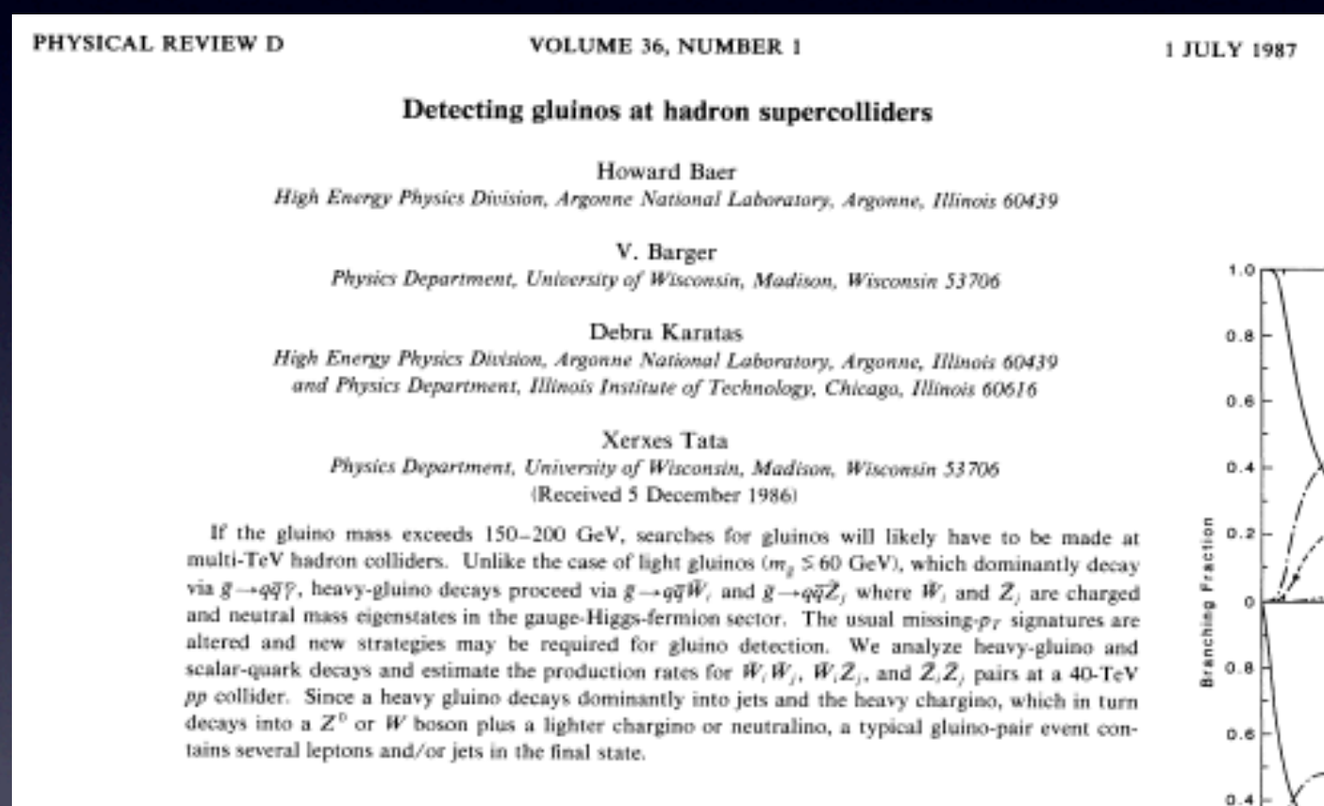
$m_{\tilde{g}}$ = 140 GeV, $m_{\tilde{\gamma}}$ = 29 GeV		m = 30, $m_{\tilde{W}}$ = 42, $m_{\tilde{Z}}$ = 55	m = 40, $m_{\tilde{W}}$ = 37, $m_{\tilde{Z}}$ = 50	m = 50, $m_{\tilde{W}}$ = 32, $m_{\tilde{Z}}$ = 45
$\tilde{g} \to q\bar{q}\tilde{g}$	BR	28%	26%	24%
$\tilde{g} \to q\bar{q}\tilde{W}$				
$q\bar{q}\tilde{\gamma}$	BR	19%	39%	40%
$\nu\ell\tilde{\gamma}$	BR	9%	20%	21%
$q\bar{q}\chi_2$	BR	20%	--	--
$\nu\ell\chi_2$	BR	10%	--	--
$\tilde{g} \to q\bar{q}\tilde{Z}$				
$q\bar{q}\tilde{\gamma}$	BR	--	4%	11%
$\ell\bar{\ell}\tilde{\gamma}$	BR	--	2%	6%
$q\bar{q}\chi_2$	BR	9%	6%	--
$\ell\bar{\ell}\chi_2$	BR	4%	3%	--
$\chi_2 \to q\bar{q}\tilde{\gamma}$	BR	--	29%	
$\chi_2 \to \ell\bar{\ell}\tilde{\gamma}$	BR	--	13%	
$\chi_2 \to \gamma\tilde{\gamma}$	BR	100%	58%	

Status of event generators circa 1984

- Isajet (Jet production for BNL Isabelle pp collider) 1979
- FrankPaige added gluino/squark production 1984 with 100% 2 and 3 body decays to photino
- Used by UA1/UA2 for SUSY analyses
- Pythia to appear 1986 (no SUSY 'til Spythia 1996)
- Herwig to appear 1987 (SUSY/IsaWIG 2000)
- In 1984, most theorists wrote their own parton level Monte Carlo programs; it was considered bad form to run other people's codes; Isajet was circulated to the experimental groups only

Cascade decays: this time for real

In 1986, Tata and I began work on gluino and squark decay to arbitrarily mixed charginos and neutralinos; we were joined by Debra Karatas (Giudice), a grad student from IIT/ANL and Vernon Barger



PHYSICAL REVIEW D VOLUME 36, NUMBER 1 1 JULY 1987

Detecting gluinos at hadron supercolliders

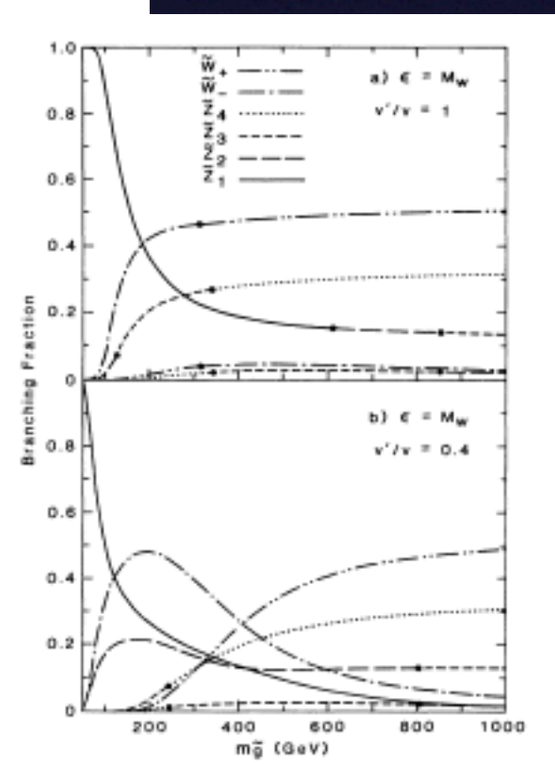
Howard Baer
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

V. Barger
Physics Department, University of Wisconsin, Madison, Wisconsin 53706

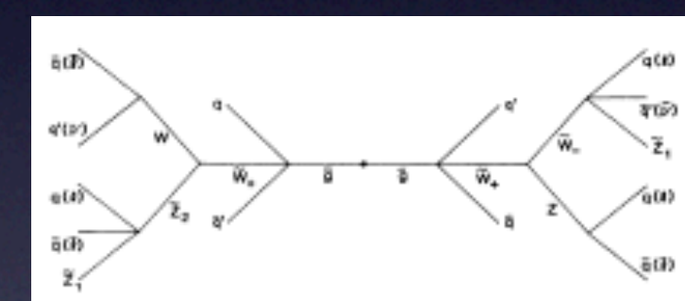
Debra Karatas
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439 and Physics Department, Illinois Institute of Technology, Chicago, Illinois 60616

Xerxes Tata
Physics Department, University of Wisconsin, Madison, Wisconsin 53706
(Received 5 December 1986)

If the gluino mass exceeds 150–200 GeV, searches for gluinos will likely have to be made at multi-TeV hadron colliders. Unlike the case of light gluinos ($m_{\tilde g} \lesssim 60$ GeV), which dominantly decay via $\tilde g \to q\bar q\tilde\gamma$, heavy-gluino decays proceed via $\tilde g \to q\bar q\tilde W_i$ and $\tilde g \to q\bar q\tilde Z_j$ where $\tilde W_i$ and $\tilde Z_j$ are charged and neutral mass eigenstates in the gauge-Higgs-fermion sector. The usual missing-p_T signatures are altered and new strategies may be required for gluino detection. We analyze heavy-gluino and scalar-quark decays and estimate the production rates for $\tilde W_i\tilde W_j$, $\tilde W_i\tilde Z_j$, and $\tilde Z_i\tilde Z_j$ pairs at a 40-TeV pp collider. Since a heavy gluino decays dominantly into jets and the heavy chargino, which in turn decays into a Z^0 or W boson plus a lighter chargino or neutralino, a typical gluino-pair event contains several leptons and/or jets in the final state.



Here, we coined the term gluino and squark cascade decays



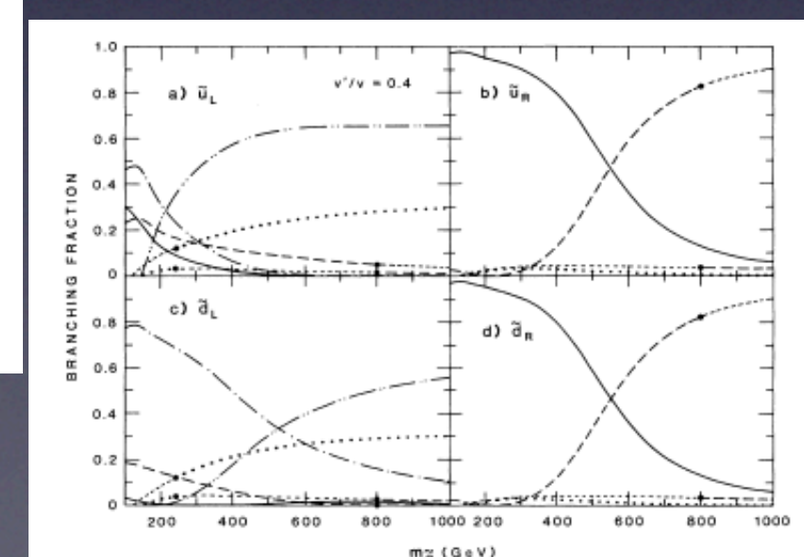


FIG. 4. Branching fractions for scalar quarks into gauginos as in Fig. 3, except $v'/v = 0.4$.

Also calculated many heavy chargino/neutralino decay modes:

Shortly thereafter, when Alfred Bartl visited ANL, we began similar calculations (with Majerotto) for general slepton, chargino and neutralino production followed by cascade decays for a TeV scale e+e- collider

SEARCHING FOR SUPERSYMMETRY AT e^+e^- SUPERCOLLIDERS

HOWARD BAER
Department of Physics, Florida State University, Tallahassee, Florida 32306,USA

A. BARTL
Institut für Theoretische Physik, Universität Wien, Austria

DEBRA KARATAS
High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA

and

Physics Department, Illinois Institute of Technology, Chicago, Illinois 60610, USA

W. MAJEROTTO
Institut für Hochenergiephysik, der Österreichischen Akademie der Wissenschaften, Wien, Austria

and

XERXES TATA*
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706, USA

Received 15 June 1988
Revised 2 December 1988

We study the signals resulting from the production and subsequent decays of heavy sleptons, sneutrinos and all the charginos ($\tilde{W}_i$) and neutralinos ($\tilde{Z}_i$) at ultrahigh energy e^+e^- colliders. In contrast to existing studies that assume that supersymmetric particles directly decay to the lightest supersymmetric particle (taken here to be the lightest neutralino, $\tilde{Z}_1$) which then escapes detection, we incorporate realistic decay patterns using the minimal supersymmetry model as a guide for the masses and mixing angles in the gaugino-Higgsino sector. We show that very heavy sleptons and sneutrinos often decay into heavier charginos and neutralinos which themselves often decay into real W and Z^0 bosons and lighter $\tilde{W}$'s and $\tilde{Z}$'s. This results in a considerably softer missing transverse momentum ($\not{p}_T$) spectrum than would be expected if sparticles decayed directly to the $\tilde{Z}_1$ so that $\not{p}_T$ is not necessarily a viable signature for very heavy sparticles. We show that the optimal signature for supersymmetry in very high energy e^+e^- collisions depends on the model parameters. Whereas $\not{p}_T$ is a viable signature for lighter sleptons and sneutrinos ($m \sim 0.3$ TeV), the production of very heavy sparticles is signalled by events with two or more large angle W and Z^0 bosons and often a very hard electron. We discuss strategies for extracting the SUSY signal and argue that it can be separated from standard model backgrounds over the whole of parameter space.

- During 1987-1989, CERN monojet signal collapsed, and all the excitement was on string theory

- However, Fermilab Tevatron turned on and established bounds of m(gl)~m(sq)>73 GeV based on simple Isajet one-step decays to photino

- I constructed a parton level generator later called SUSYSM which implemented general sparticle production and cascade decays.

- Using cascade decays, the Tevatron bounds diminished by 3-30 GeV due to softer MET

- Could now track multilepton (n(l)~1-6) production from cascade decays

This paper established a number of results:

PHYSICAL REVIEW D VOLUME 41, NUMBER 3 1 FEBRUARY 1990

Gluino-cascade-decay signatures at the Fermilab Tevatron collider

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078
(Received 18 May 1989)

As the search for gluinos is extended to higher masses, the gluino cascade decays through lighter gaugino species can no longer be neglected. We compare gluino-cascade-decay signatures with signatures from direct gluino decay to the lightest supersymmetric particle assumed to be massless at the Fermilab Tevatron collider, assuming $m_{\tilde{g}} < m_{\tilde{q}}$. Cascade decays yield a softer missing-p_T ($\not{p}_T$) spectrum which reduces the $\not{p}_T$ cross section by a factor of 2–3 for $m_{\tilde{g}} = 100$–150 GeV. However, new signatures characteristic of the cascade appear in the 0, 1, and 2 lepton plus jets plus $\not{p}_T$ channels. We examine these signatures and compare with dominant standard-model backgrounds.

- Multilepton n(l)~1,2,3 +jets+MET production from cascades
- SS/OS dilepton signals
- OS dileptons from $\tilde{Z}_2 \to \tilde{Z}_1 \ell^+ \ell^-$
  and presence of dilepton mass edge to measure mz2-mz1
- Use of H_T (introduced slightly earlier by HB, Barger, Phillips for ttbar extraction at Tevatron over W+jets BG) for SUSY searches
- reconstructing m(gluino) via multijet invariant masses/hemispheric separation

At this point, SUSY collider phenomenology was our personal playground:

Z^0+jets+$\not{p}_T$ events as a signal for supersymmetry at the Fermilab Tevatron collider

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078
(Received 20 February 1990)

We examine the processes $p\bar{p} \to \tilde{g}\tilde{g}$, $\tilde{q}\tilde{g}$, and $\tilde{q}\tilde{q}$ at Fermilab Tevatron collider energies and find an observable signal for $Z^0 + \geq 2$ jets + missing p_T events due to cascade and loop decays of squarks and gluinos. This signal occurs in a substantial region of the supersymmetric parameter space provided only that the Higgsino-mixing mass parameter is small. We evaluate several different standard-model backgrounds, and show that the signal (which can yield up to 25 events in the next Tevatron run) exceeds background for $m_{\tilde{q}}$ or $m_{\tilde{g}}$ as large as 200 GeV. Distributions which discriminate the supersymmetric signal from background are also shown.

PHYSICAL REVIEW D VOLUME 42, NUMBER 5 1 SEPTEMBER 1990

Phenomenology of gluino decays via loops and top-quark Yukawa coupling

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside*
Physics Department, Oklahoma State University, Stillwater, Oklahoma 74078
(Received 14 May 1990)

We have reanalyzed the decay patterns of the gluino ($\tilde{g}$) incorporating all its decays to charginos ($\tilde{W}_i$) and neutralinos ($\tilde{Z}_i$) as given by the minimal model. We have made an independent computation of the decay width for $\tilde{g} \to g\tilde{Z}_i$ which occurs at one loop and shown that the branching fraction for this can be up to 0.5. We have also computed the width for $\tilde{g} \to t\bar{t}\tilde{Z}_i$ including the effect of the top-quark Yukawa coupling, which significantly increases this width. We have studied the gluino decay modes as a function of parameter space, and clearly delineated the regions where the loop decays or $\tilde{g} \to t\bar{t}\tilde{Z}_i$ is large. The significance of these decays for gluino signatures in collider experiments is briefly commented on.

PHYSICAL REVIEW D VOLUME 44, NUMBER 3 1 AUGUST 1991

Phenomenology of light top squarks at the Fermilab Tevatron

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Manuel Drees
Theory Group, DESY, Notkestrasse 85, D2000 Hamburg 52, Germany

Rohini Godbole
Department of Physics, University of Bombay, Vidyanagari, Santacruz(E) Bombay, 400 098 India

John F. Gunion
Department of Physics, University of California, Davis, California 95616

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822
(Received 20 March 1991; revised manuscript received 25 April 1991)

We consider the possibility that one of the supersymmetric partners of the t quark (the $\tilde{t}_1$) is considerably lighter than all the other squarks as well as lighter than the top. We show that $\tilde{t}_1$ will decay into a chargino and a bottom quark if this decay is kinematically accessible; otherwise, it decays via $\tilde{t}_1 \to c + \tilde{Z}_1$, where $\tilde{Z}_1$, the lightest neutralino, is also the lightest supersymmetric particle (LSP). We then show that a $\tilde{t}_1$ with a mass just larger than $M_Z/2$ could easily have escaped detection at the Fermilab Tevatron. Such a $\tilde{t}_1$ can completely alter the decay patterns of the top quark; if $m_t < M_W + m_b$, the t dominantly decays via $t \to \tilde{t}_1 + \tilde{Z}_1$ when this decay is kinematically accessible. This then invalidates any bounds on m_t obtained from searches for isolated leptons. We show that if the LSP mass is around 10 GeV, it is possible that a top as light as 60 GeV could have escaped detection even via the missing-$\not{E}_T$ analysis of the Collider Detector at Fermilab Collaboration. Finally, we evaluate the prospects for $\tilde{t}_1$ detection in future Tevatron runs and also examine how signals for a heavy t may be modified if there is a light $\tilde{t}_1$.

PHYSICAL REVIEW D VOLUME 46, NUMBER 1 1 JULY 1992

Supercollider signals from gluino and squark decays to Higgs bosons

Howard Baer
Department of Physics, Florida State University, Tallahassee, Florida 32306

Mike Bisset and Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Department of Physics, Iowa State University and Ames Laboratory, Ames, Iowa 50011
(Received 5 March 1992)

If the mass of the charged Higgs boson of the minimal supersymmetric model (MSSM) is smaller than about 150 GeV, the branching fraction for heavy gluinos and left-handed squarks to cascade decay to the heavier Higgs bosons H_h, H_p, and $H^\pm$ of the MSSM may be as large as 50–60 % for values of supersymmetric parameters consistent with experimental data. These decays, which have been assumed to be kinematically inaccessible in earlier analyses, can potentially lead to significant modification of the cross section for missing E_T ($\not{E}_T$), same-sign dilepton, and multilepton events from squarks and gluinos. We find that the $\not{E}_T$, same-sign dilepton, and trilepton production rates are relatively insensitive to low values of m_{H^+}, so that these remain viable signals for the identification of gluinos and squarks at the Superconducting Super Collider or the CERN Large Hadron Collider. Finally, our exploratory study shows that substantial production of H_h and H_p ($H^\pm$) in gluino and squark pair events can lead to $\not{E}_T$ events with anomalously large numbers of b quarks (τ leptons). There also exist small regions of parameter space where the H_l and H_h may be identifiable via the presence of $\gamma\gamma$ in $\not{E}_T$ events.

Moving beyond parton level

At this point, we wanted a more detailed event generation including IS/FS radiation, hadronization, unerlying event

SUSYSM/Pythia interface

*Calculates ++/-- SS asym.;
*H_T at SSC/LHC;
*b-jet multiplicity
*cascade to mixed t_1, t_2

PHYSICAL REVIEW D VOLUME 45, NUMBER 1 1 JANUARY 1992

Multilepton signals from supersymmetry at hadron supercolliders

Howard Baer
Physics Department, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822

Jeffrey Woodside
Department of Physics and Ames Laboratory, Iowa State University, Ames, Iowa 50011
(Received 7 August 1991)

We have developed a new event generator SUSYSM to simulate the production of squarks and gluinos at hadron supercolliders including all the cascade decays as given by the minimal supersymmetric model. The simulation incorporates final-state hadronization and fragmentation effects for the decays of heavy flavors. We have used this to compute the rates for $\not{E}_T$ events, same-sign dilepton events, $n_l = 3$, 4, and 5 isolated-lepton events, and single or double $Z^0 + \not{E}_T$ events from squark and gluino production at the CERN Large Hadron Collider (LHC) and the Superconducting Super Collider (SSC) for cuts inspired by the Solenoidal Detector Collaboration. We have identified and estimated several backgrounds to the various event topologies and shown that it should be possible to extract signals in several channels both at the LHC and SSC. We have shown that after accumulating one year's worth of design luminosity, it should be possible to identify a gluino with mass up to 2 TeV at the SSC, while the corresponding reach of the LHC is 1.2–1.7 TeV, depending on the luminosity.

In order to compute various signals from the production of squark and gluinos, we have developed a new program SUSYSM which, for any set of input values of the six MSSM parameters, generates $\tilde{g}\,\tilde{g}$, $\tilde{q}\,\tilde{g}$, and $\tilde{q}\tilde{q}$ events keeping track of squark type and flavor (this is important as the decay patterns of $\tilde{q}$ depend on the type of squark while the decays and fragmentation of the daughter quarks depend on their flavor, which is the same as that of the decaying squark) and interfaces with SUSYBF to generate various final states as given by the MSSM. The fact that SUSYSM, has the cascade decays built in is an advantage over a program like ISAJET [31] which does not discriminate between L and R squark type so that the cascades can only approximately be incorporated via decay tables generated using, e.g., SUSYBF. SUSYSM also uses the standard common block convention to keep track of event histories and a standard particle labeling scheme [32]. SUSYSM has been interfaced with the JETSET routines of Sjostrand [33] to incorporate final-state string hadronization of quarks and gluons, and also the fragmentation and decay of heavy flavors. Finally, a soft scattering event as generated by PYTHIA [26] has been superimposed to simulate the underlying event.

Our main rationale for incorporating an underlying event and hadronization into the event generator is to better simulate lepton isolation in multilepton events from supersymmetric sources. This is rather important

Onto Isajet/IsaSUSY

- circa 1992, there was *only one* person on CDF working on BSM/SUSY physics (Jim Freeman)
- D0 not yet viable with analysis groups
- Freeman had used Isajet for previous CDF SUSY searches using old code with 2-3 body decays to massless photino
- He borrowed our cascade decay subroutines, building a rough Isajet hack that didn't differentiate qL and qR decays (all squarks bunched in same production reactions)

Isajet 7.0: May, 1993

- Frank Paige offered to work with Tata and I to correctly incorporate cascade decays into Isajet
- The pMSSM spectra calculation and decay table called IsaSUSY

SIMULATING SUPERSYMMETRY WITH
ISAJET 7.0 / ISASUSY 1.0

HOWARD BAER
Department of Physics, Florida State University
Tallahassee, FL 32306 USA

FRANK E. PAIGE
Superconducting Supercollider Laboratory
Dallas, TX 75237 USA

SERBAN D. PROTOPOPESCU
Brookhaven National Laboratory
Upton, NY 11973 USA
and

XERXES TATA
Department of Physics and Astronomy, University of Hawaii
Honolulu, HI, 96822 USA

PHYSICAL REVIEW D VOLUME 48, NUMBER 7 1 OCTOBER 1993

New signals for gluinos and squarks of supergravity at the Fermilab Tevatron collider

Howard Baer and Chung Kao
Department of Physics, Florida State University, Tallahassee, Florida 32306

Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822
(Received 9 June 1993)

Within the supergravity framework, sleptons are expected to be considerably lighter than squarks if gluinos and squarks are approximately degenerate. This can lead to a significant enhancement in leptonic branching ratio for neutralinos, and, sometimes, charginos. Using ISAJET 7.0 and/or ISASUSY 1.0, we evaluate the multilepton signals from cascade decays of gluinos and squarks produced at the Fermilab Tevatron $p\bar{p}$ collider assuming squark and slepton masses are related as in supergravity models. We find observable cross sections for spectacular event topologies: m lepton + n jet + $\not{E}_T$ events ($m \leq 4$, $n \geq 2$) and same-sign dilepton + $\not{E}_T$ events and show that the SM backgrounds to the isolated trilepton, four-lepton, and same-sign dilepton signals are very small. These signals can extend the mass reach of the Tevatron experiments to $m_{\tilde{g}} \sim 300$ GeV if $m_{\tilde{g}} \sim m_{\tilde{q}}$ and $\sim (1000)$ pb^{-1} of data are collected.

PACS number(s): 14.80.Ly, 12.10.Gq, 13.85.Qk

Isasugra, 1994

- Next step: build program to solve SUSY RGEs with radiative EWSB
- Isasugra, first public spectra code, in 1994
- Followed later by SuSpect, SoftSUSY, SPheno
- In this paper, we recommended all collider search limits be plotted in m0 vs. mhf plane of mSUGRA and provided the code to do so

PHYSICAL REVIEW D VOLUME 51, NUMBER 3 1 FEBRUARY 1995

Multichannel search for minimal supergravity at $p\bar{p}$ and e^+e^- colliders

Howard Baer,[1] Chih-hao Chen,[1] Ray Munroe,[1] Frank E. Paige,[2] and Xerxes Tata[3]
[1] *Department of Physics, Florida State University, Tallahassee, Florida 32306*
[2] *Brookhaven National Laboratory, Upton, New York, 11973*
[3] *Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822*
(Received 10 August 1994)

We examine the phenomenology of minimal supergravity models, assuming only that the low energy theory has the minimal particle content, that electroweak symmetry is radiatively broken, and that R parity is essentially conserved. After delineating regions of supergravity parameter space currently excluded by direct particle searches at CERN LEP and the Fermilab Tevatron we quantify how this search region will be expanded when LEP II and the Tevatron main injector upgrades become operational. We describe how various experimental analyses can be consistently combined within a single framework, resulting in a multichannel search for supersymmetry, but note that this analysis is sensitive to specific assumptions about physics at the unification scale.

On honeymoon in 1994, Nauenberg at Colorado put us up in hotel at Boulder if I added e+e- capabilities

- e+e- -> sparticles, cascade decays
- include beam polarization effects
- later, include bremsstrahlung, Drees' beamstrahlung routines

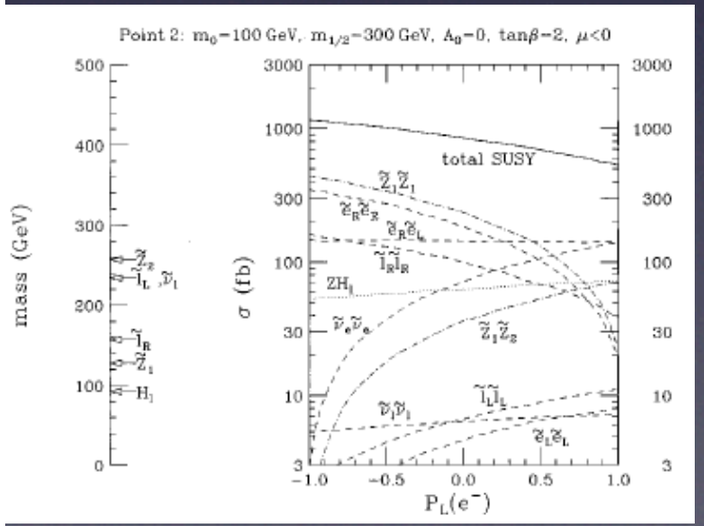
PHYSICAL REVIEW D VOLUME 54, NUMBER 11 1 DECE

Supersymmetry studies at future linear e^+e^- colliders

Howard Baer and Ray Munroe
Department of Physics, Florida State University, Tallahassee, Florida 32306

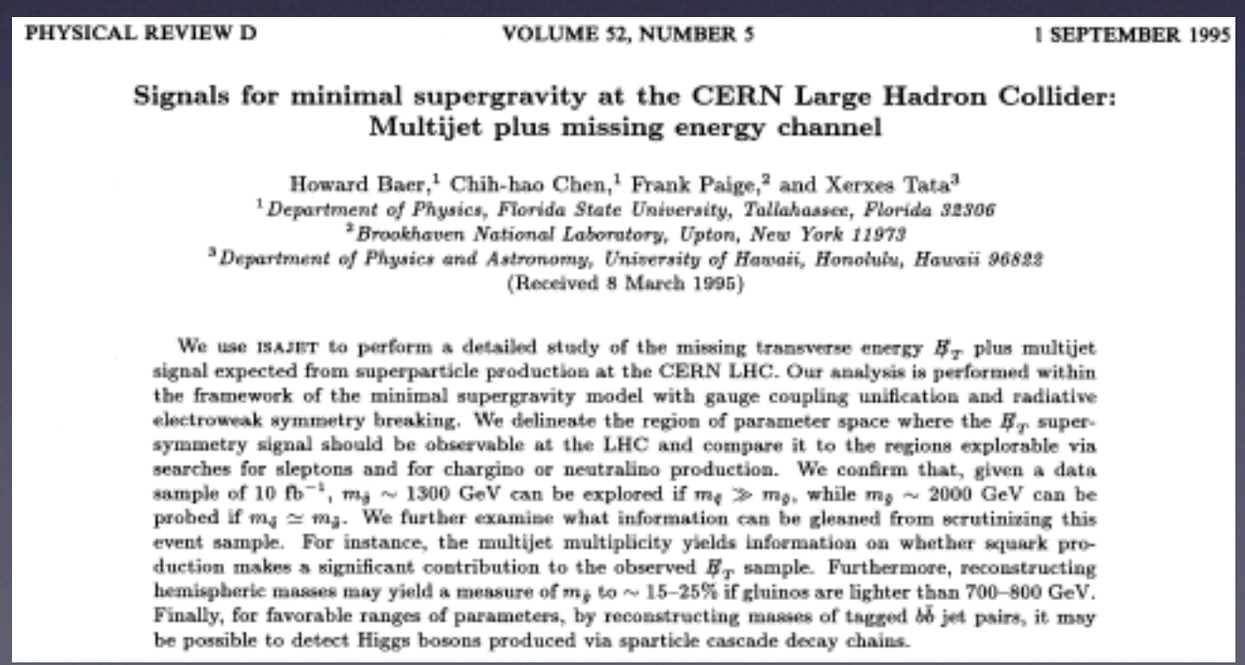
Xerxes Tata
Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822
(Received 13 June 1996)

We examine various aspects of supersymmetric particle production at linear e^+e^- colliders operating at a center-of-mass energy of $\sqrt{s}=500$ GeV, and integrated luminosity of $\int \mathcal{L}dt=20-50$ fb^{-1}. Working within the framework of the minimal supergravity model with gauge-coupling unification and radiative electroweak symmetry breaking (SUGRA), we study various signatures for detection of sparticles, taking into account their cascade decays, and map out the regions of parameter space where these are observable. We also examine strategies to isolate different SUSY processes from each other. In addition, we perform four detailed SUGRA case studies and examine the detectability of sparticles when several SUSY processes are occuring simultaneously. We show that precision mass measurements of neutralinos, sneutrinos, and top squarks are possible, in addition to previously studied precision mass measurements of sleptons and charginos.



For a year or two, we had the field to ourselves: could calculate lots of things

- LHC reach for slepton pair production, 1994
- LHC reach for clean trileptons from gauginos
- LHC reach for multijet+MET events, 1995
- LHC reach for multilepton+multijets+MET, 1995
- h->bb in cascades; gluino mass measurement



PHYSICAL REVIEW D VOLUME 52, NUMBER 5 1 SEPTEMBER 1995

Signals for minimal supergravity at the CERN Large Hadron Collider: Multijet plus missing energy channel

Howard Baer,[1] Chih-hao Chen,[1] Frank Paige,[2] and Xerxes Tata[3]
[1] *Department of Physics, Florida State University, Tallahassee, Florida 32306*
[2] *Brookhaven National Laboratory, Upton, New York 11973*
[3] *Department of Physics and Astronomy, University of Hawaii, Honolulu, Hawaii 96822*
(Received 8 March 1995)

We use ISAJET to perform a detailed study of the missing transverse energy $\not{E}_T$ plus multijet signal expected from superparticle production at the CERN LHC. Our analysis is performed within the framework of the minimal supergravity model with gauge coupling unification and radiative electroweak symmetry breaking. We delineate the region of parameter space where the $\not{E}_T$ supersymmetry signal should be observable at the LHC and compare it to the regions explorable via searches for sleptons and for chargino or neutralino production. We confirm that, given a data sample of 10 fb^{-1}, $m_{\tilde{g}} \sim 1300$ GeV can be explored if $m_{\tilde{q}} \gg m_{\tilde{g}}$, while $m_{\tilde{g}} \sim 2000$ GeV can be probed if $m_{\tilde{q}} \simeq m_{\tilde{g}}$. We further examine what information can be gleaned from scrutinizing this event sample. For instance, the multijet multiplicity yields information on whether squark production makes a significant contribution to the observed $\not{E}_T$ sample. Furthermore, reconstructing hemispheric masses may yield a measure of $m_{\tilde{g}}$ to $\sim$ 15–25% if gluinos are lighter than 700–800 GeV. Finally, for favorable ranges of parameters, by reconstructing masses of tagged $b\bar{b}$ jet pairs, it may be possible to detect Higgs bosons produced via sparticle cascade decay chains.

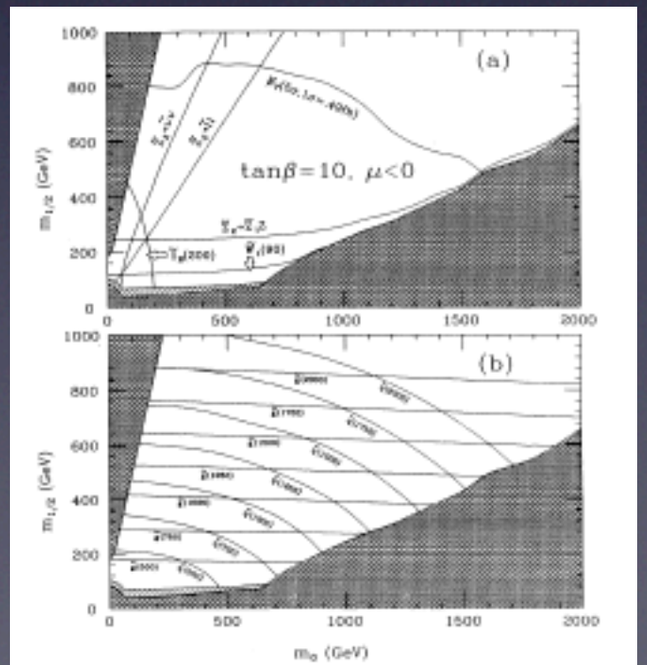


FIG. 8. Same as Fig. 5, except for $\tan\beta = 10$.

Subsequent events

- Snowmass 1996, Paige, Hinchliffe et al. Isajet benchmark studies hugely influential, initiating a SUSY@LHC industry
- 1996: add non-universal soft terms to Isasugra
- 1997: upgrade to include b- and tau- Yukawa couplings; valid ev. gen. at large tan(beta)
- 1998: add GMSB to Isasugra
- 2000: add AMSB to Isasugra
- 2002: add Isatools, IsaReD
- 2006: add Mirage-mediation
- 2011: IsaFLVR

Simplified models: some discussion

First a disclaimer:
I have promoted several simplified models:

1. gluino and squark pair production with simple decays to massive lightest neutralino (1985)
2. top squark pair production with decays c+Z1 or b+W1 (1994)
3. bottom squark pair production with decays to b+Z1 (1999)

In the case of SUSY, when signal is dominated by a single production mechanism and one or two decay modes, situation may be well-described by a simplified model.
If one can reduce parameter space to 1-2 components, then can conveniently display results on paper or computer screen. In fact, this is the way analyses are traditionally done.

For signature-based analyses, the reader has come to expect a limit plot in a 2-d plane; simplified models can fulfill this role

Simplified models are, well, *simplified*. Again, in the case of SUSY, theory predicts numerous production processes, e.g of order 10^3 if one tracks initial and final flavors and handedness, and of order 5-20 decay modes. This may yield, naively, of order 10^5 distinct 2->n subprocesses, a situation of exquisite complexity. It is the reason we had to move from simplified models to complete calculations, generating sparticles according to calculated cross section rates, and cascade decays according to calculated BFs.

The manifold SUSY production processes followed by cascade decays is the complete expression of the SUSY Lagrangian at high energy collider experiments

The production/cascade decay events evolve and change as one moves through the parameter space of any given SUSY model

Simplified models may hold as an approximation in some regions of p-space, but of necessity almost always lose some essential features

In general, in SUSY models the strongly interacting particles tend to be among the heaviest, followed by those with SU(2) quantum numbers, followed by those with U(1)_Y quantum numbers. This is simply a reflection of the fact that g_3>g_2>g_1. In this rather general case, lengthy cascade decays tend to be the rule rather than the exception.

Further, cascade decays are sufficiently complex that new and surprising signatures almost certainly exist.

Some largely unexamined cases by exp't: (NUHM2)

1. Low mu scnarios where gl,sq cascade to W2 and Z4,Z3
2. Low mA scenarios where gl/sq cascade to h,A,H,H^\pm

An alternative path is analyses within specific top-down models: benchmarks, slopes, planes,....

This allows for full expression of cascade decays in various models

However, in looking for theoretical guidance, recent papers on this topic tend to favor the author's favorite scenarios, or else rather arbitrary parameters are selected, giving the impression that these cases are somehow favored or legitimate.

Some compelling models also deserving of attention

- t-b-tau Yukawa-unified SUSY
- effective SUSY
- Kane G2 string model
- split SUSY
- normal scalar mass hierarchy (NMH)
- bilinear RPV
- gaugino MSB, above GUT running
- hypercharged AMSB
- gaugino AMSB
- deflected mirage mediation
- well-tempered neutralino models
- NUGM with SU(5)/SO(10) BCs
- compressed SUSY
- many others....

Some recommendations

- Spend time on SPIRES searching and reading the literature; many exciting models out there deserve attention; find out their motivations and consequences for experiment
- p-off the upper level Atlas/CMS managers: instigate new and exiting analyses of non-standard models
- p-off the theorists: take tan(beta)=\pi^2 or 11; analyze models not included in List Papers