Isajet 7.xx, IsaSUSY and my time working with Frank Paige

Howard Baer
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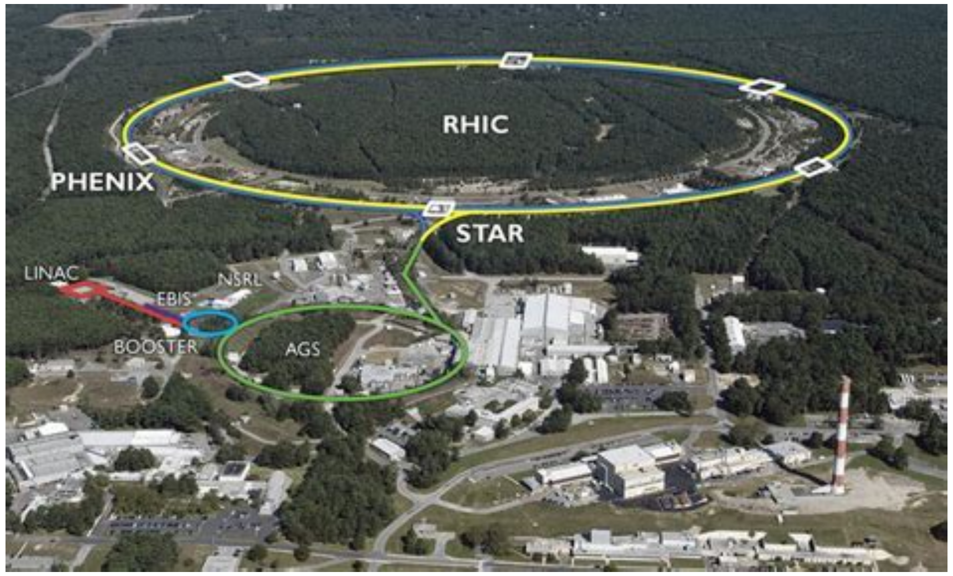

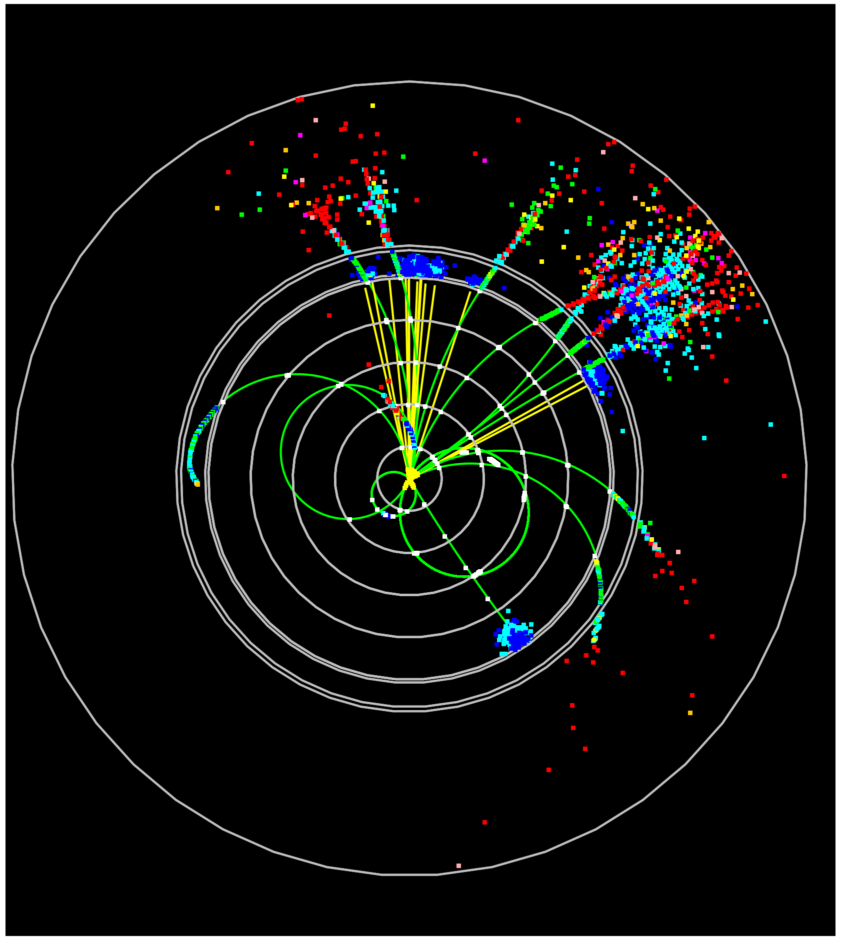

- Frank `grew up' working on forward scattering, Pomerons and phenomenology-
- Made transition to QCD/SM physics with famous Kubar-Andre/Paige NLO Drell-Yan
- As BNL prepared for IsaBelle pp collider, the questions arose:
- what does QCD predict for hadron-hadron collisions?

Frank and Serban rose to this challenge
by creating the Isajet computer code in late 1970s

- use perturbative QCD for hard scattering
- use new Fox-Wolfram algorithm for multi-parton emission
- use Field-Feynmann independent hadronization
- gain simulation of e.g. qqbar, gg scattering
- laid template for other generators: Pythia/Jetset and Herwig

Alas, ill-fated Isabelle collider `replaced' by SSC;
but Isajet could be used for CERN SppbarS, Tevatron, SSC, LHC

Early 1980s: added Sjostrand initial state backward shower algorithm

Isajet versions 1-6

Frank was involved in work on supersymmetry (SUSY) early on:
a SUSY phenomenology pioneer!

DETECTING SUPERSYMMETRIC HADRONS

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Supersymmetric grand unified models are of interest because they offer a possible explanation of the great disparity between the W mass and the grand unified scale (about 10^{15} GeV). In such models each of the familiar particles (gluons, quarks, etc.) has a partner differing by 1/2 unit of spin, presumably with a mass of order the W mass or less. Supersymmetry ensures that the couplings of the partners of the gluons and quarks to normal hadronic constituents are of about the usual QCD strength. Thus production cross-sections for these states need not be particularly small. In the present paper we investigate the possibility of detecting the sypersymmetric partners of gluons and quarks at a 400 × 400 GeV/c proton-proton collider.

The spin $\frac{1}{2}$ partner of the gluon, the gluino, should decay either into a photino plus a quark-antiquark pair or into a Goldstino plus a gluon. Both the photino and the Goldstino are essentially noninteracting, so the signature is unbalanced P_T plus missing momentum out of the plane. In addition, unlike the gluinos, the potential backgrounds, such as decays of heavy quarks involving neutrinos, tend to produce a lepton of at least moderate P_T.

The detector envisioned is a fine grained Uranium calorimeter covering the kinematic range $-2 < y < 2$, $0 < \phi < 2\pi$. A somewhat coarser grained end cap calorimeter serves to veto events which deposit > 10% of their transverse energy in the region $2 < |y| < 3$. The energy resolution assumed for the U calorimeter is $\sigma_E = .15E^{1/2}$ for electromagnetic and $.35E^{1/2}$ for hadronic particles. Muons are assumed to deposit a maximum of 1.1 GeV/c in the calorimeter.

A modified version of ISAJET[1] was used to produce gluinos in the reaction $pp \to \tilde{g}\tilde{g} + X$ at $\sqrt{s} = 800$ GeV/c according to cross sections provided by G. Kane and J.P. Leveille[2]. Events were generated for $\tilde{g}$ masses of 30 to 125 GeV/c^2. The response of the detector was simulated by smearing the energy of the final state particles with $|y| < 3$ according to the above mentioned resolutions. The sum of the transverse energy for particles with $2 < |y| < 3$ was separately calculated and events where this sum exceeded 10% of the total transverse energy were rejected. A sphericity tensor was calculated for the remaining events. The eigenvector with the largest eigenvalue was considered to be the reference axis. The detectable particles were divided into two groups depending on which hemisphere they lay in with respect to the reference axis. The sum of the transverse momenta of the particles in the hemisphere of the reference axis, $|\vec{P}_T|$, was required to be greater than 20 GeV/c, while the sum in the opposite hemisphere, $|\vec{P}'_T|$, was required to be greater than 5 GeV/c. As measures of the transverse momentum imbalance, the quantities X_E and P_{out} were defined as follows:

$$X_E = \frac{-\vec{P}_T \cdot \vec{P}'_T}{|\vec{P}_T|^2} \text{ and } P_{out} = \sqrt{|\vec{P}'_T|^2 - X_E |\vec{P}_T|^2}$$

Figures 1 and 2 show these distributions for gluino mass 30 GeV/c and 75 GeV/c, where it has been assumed that the gluino undergoes a three body decay ($\tilde{g} \to \tilde{\gamma} q\bar{q}$).[3] Also shown are the corresponding distributions for background events due to QCD production of high P_T light constituents (g, u, d, s). The differences between the distributions of the gluino signal and those of light constituent background are already quite striking at $M_{\tilde{g}} = 30$ and become even more dramatic as $M_{\tilde{g}}$ increases. Thus cuts on these quantitites can be made extremely effective. That such rejection

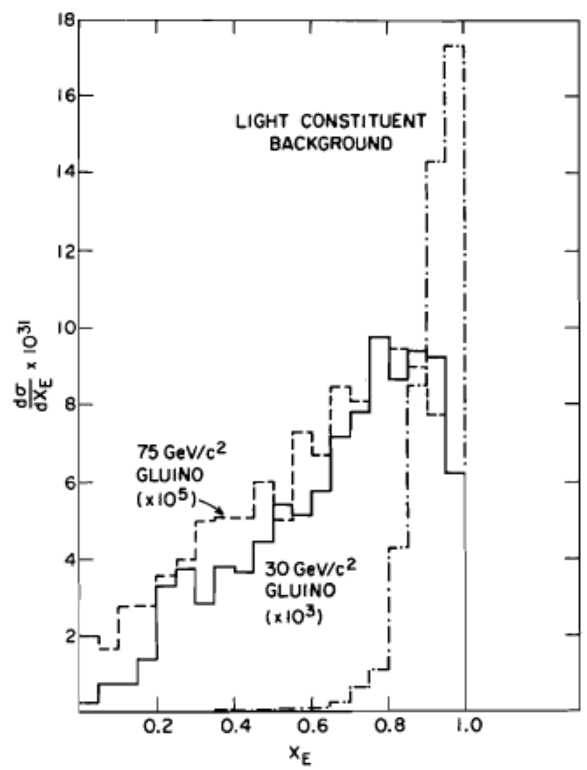

Figure 1. X_E distributions for gluinos of mass 30 and for light constituent background.

is necessary can be seen in Fig. 3, which shows the cross-section vs P_T of 30 GeV/c mass gluinos[4] compared to that of the light constituent background. It is clear that a relative rejection factor of order 500:1 is required.[5] In fact relative rejection rates of ∿ 2000:1 can readily be obtained with cuts which retain $\gtrsim$ 10% of the gluino signal. One such cut set is $X_E < .5$, $P_{out} > 5$ GeV/c. The resulting detected gluino event rate[3] vs mass is shown in Fig. 4. A total integrated luminosity of 10^{39}/cm^2 is assumed. Also shown is the event rate in the case that the P_{out} cut is increased to $P_{out} > 10$ GeV/c. If one regards ∿ 1000 events as the minimum detectable signal for such a process, masses of about 125 GeV/c^2 can be reached. However, in practice this limit may be severely reduced by the presence of background.

To study this question in detail, three types of background processes were simulated by ISAJET, submitted to the same detector emulation program and subjected to the same cuts as the gluino signal.[6] These were:

1) Light constituents (g, u, $\bar{u}$, d, $\bar{d}$, s, $\bar{s}$) scattered to large P_T in hard collisions.
2) $t\bar{t}$ pair production. M_t was assumed to be 20 GeV/c^2.
3) An appropriate mixture of $b\bar{b}$ and $c\bar{c}$ pairs.

The residual backgrounds are shown in Fig. 5. The light constituent background is still the largest, even

1982 Snowmass SUSY study using Kane-Leveille formulae into Isajet 3

- $pp \to \tilde{g}\tilde{g}, \tilde{q}\tilde{q}^{(*)}$
- $\tilde{g} \to q\tilde{q},\ q\bar{q}\tilde{\gamma}$
- $\tilde{q} \to q\tilde{\gamma},\ q\tilde{g}$

In conclusion, the prospects for detecting the supersymmetric partners of gluons and quarks at a high luminosity 400 × 400 GeV/c pp collider are quite good, if these particles lay in the theoretically interesting mass range ∿ M_W.

SUSY became a hot topic when UA1/UA2 identified some multi-jet+MET anomalous events at CERN SppbarS collider: were there gluinos/squarks ~40 GeV?

1984 Snowmass SUSY@SSC study adapting cross sections from Dawson, Eichten, Quigg into Isajet:

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Physics Division

To be published in the Proceedings of the 1984 DPF Summer Study on the Design and Utilization of the Superconducting Super Collider, Snowmass, CO, June 23 - July 13, 1984

SEARCHING FOR SUPERSYMMETRY AT THE SSC

S. Dawson, A. Savoy-Navarro, G. Alverson, R.M. Barnett, E. Fernandez, J. Freeman, L. Gladney, H. Haber, S. Lynn, F. Paige, and R. Wagner

October 1984

(I was leading 550 mile canoe trip across Canadian subarctic and preparing to defend Ph.D. thesis on top/4th generation quark signals at hadron colliders)

Table 2

Set of SUSY scenarios considered in our study

SUSY process	Decay mode for involved SUSY particle	Mass range
$pp \to \tilde g \tilde g$	$\tilde g \to q\bar q\tilde\gamma$	$m_{\tilde g} = 100$ GeV $m_{\tilde q} = 100$ GeV
$pp \to \tilde g \tilde g$	$\tilde g \to q\bar q\tilde\gamma$	$m_{\tilde g} = 1$ TeV $m_{\tilde q} = 1$ TeV
$pp \to \tilde g \tilde q$	$\tilde g \to q\bar q\tilde\gamma$ $\tilde q \to q\tilde g$	$m_{\tilde g} = 200$ GeV $m_{\tilde q} = 500$ GeV
$pp \to \tilde g \tilde q$	$\tilde g \to q\bar q\tilde\gamma$ $\tilde q \to q\tilde\gamma$	$m_{\tilde g} = 500$ GeV $m_{\tilde q} = 200$ GeV
$pp \to \tilde g \tilde\gamma$	$\tilde g \to q\bar q\tilde\gamma$ $\tilde\gamma$ stable	$m_{\tilde g} = 100$ GeV $m_{\tilde\gamma} = 0$
$pp \to \tilde g \tilde\gamma$	$\tilde g \to q\bar q\tilde\gamma$ $\tilde\gamma$ stable	$m_{\tilde g} = 500$ GeV $m_{\tilde\gamma} = 0$
$pp \to \tilde W \tilde g$	$\tilde W \to \ell\tilde\nu$, $\tilde\nu \to \nu\tilde\gamma$ $\tilde g \to q\bar q\tilde\gamma$	$m_{\tilde W} = 200$ GeV $m_{\tilde g} = 200$ GeV $m_{\tilde\gamma} = 0$ GeV
$pp \to \tilde W \tilde g$	$\tilde W \to \ell\tilde\nu$, $\tilde\nu \to \nu\tilde\gamma$ $\tilde g \to q\bar q\tilde\gamma$	$m_{\tilde W} = 1$ TeV $m_{\tilde g} = 1$ TeV $m_{\tilde\gamma} = 0$ GeV

My involvement with SUSY

- 1984: John Ellis thought SUSY being discovered at CERN SpparS; built simple event generator with Henrik Kowalski (experimentalist from DESY who had other obligations)

- I was hired as 1 year Scientific Associate at CERN starting October 1984: my strength was writing MC code

- Xerxes and I joined John and Dimitri to look at slepton pair production at SppbarS: November 1984

- As follow-up project, Xerxes suggested to investigate gluino/squark production but including as well decays to winos/zinos/photinos: Spring 1985

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

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CERN, CH 1211 Geneva 23, Switzerland

Received 26 June 1985

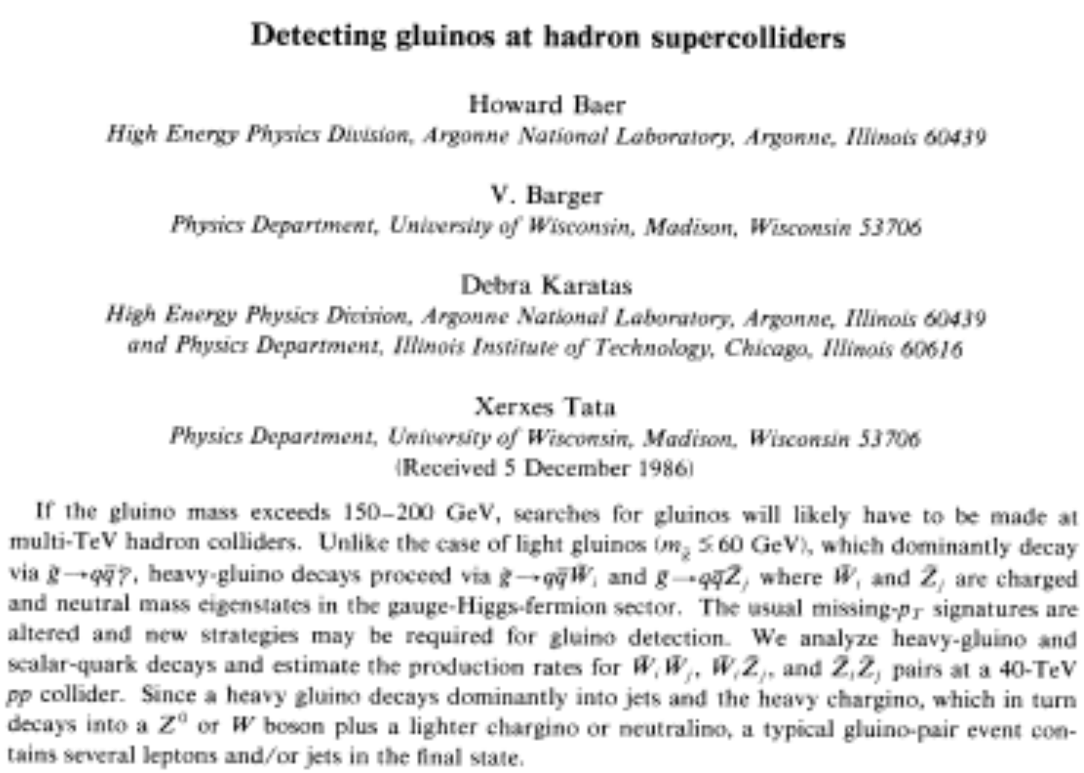
Conventional analyses of missing p_T events due to squark production at the CERN $p\bar{p}$ collider assume $\tilde{q} \to q\tilde{\gamma}$ decays dominate. In principle, the monojet and dijet cross sections could be reduced by competition from $\tilde{q} \to q\tilde{W}^{\pm}$ and $\tilde{q} \to q\tilde{Z}^{0}$ 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.

This included gluino cascades as well but those conflicted with John's SUSY interpretation so they were left out of title and abstract

Development of SUSY cascade decays

At Argonne NL in 1986, Xerxes, Barger and student Debra Karatas (Giudice) computed gluino/squark decays to all electroweakinos with general mixings computed numerically; include some EWino decays

This paper coined the term SUSY particle cascade decays



Detecting gluinos at hadron supercolliders

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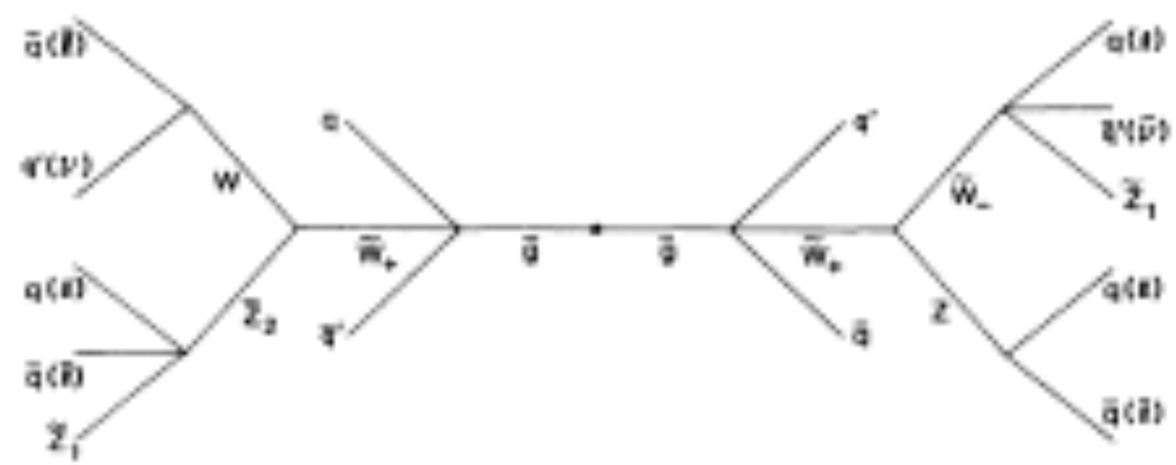
(Received 5 December 1986)

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.



We followed up by developing sparticle branching fraction subroutines and implementing them with parton level Monte Carlo production/decay- proper sparticle production required differentiating squark flavor and `handedness'

SUSYSM was used to calculate multi-lepton+jets+MET signatures for Tevatron/SSC; built SUSYSM interface with Pythia, but Sjostrand uninterested in this at the time

Jim Freeman was the entire 'BSM' group at CDF ~1990; he had worked earlier with Frank using Isajet with simple production/decay processes but wanted more realistic event generation.

We turned over our subroutines to Freeman who built a crude interface with Isajet- I in turn modifed/generalized Freeman code to make improved version called IsaSUSY

From 1990 Snowmass report FSU-HEP-901110

SUPERSYMMETRY: CURRENT STATUS AND FUTURE PROSPECTS*

H. Baer[a§], A. White[b§], N. Amos[c], R. M. Barnett[d],
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X. Tata[j], J. Woodside[k], P. Yamin[l]

V. EVENT GENERATORS - (H. Baer)

The event generator ISAJET[21] generates $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{G}$ and $\tilde{q}\tilde{G}$ events, where $\tilde{G} = \tilde{\gamma}, \tilde{W}$ or $\tilde{Z}$. The $\tilde{G}$ are assumed pure gauginos, with the mixings of their standard model counterparts. ISAJET has the virtue of containing both initial and final state QCD showers, Field-Feynman hadronization, and an n-cut Pomeron model for the underlying event. Decays of sparticles are input via a decay table. These can be input by hand, (a lengthy task for many cascade decays), or input via computer program. Jim Freeman[29] has produced an interface program which takes the sparticle masses and branching fractions from the above SUSYBF programs and enters them into the ISAJET decay table. H. Baer has upgraded and modified this interface program, which is currently obtainable from A. White. ISAJET run in conjuction with the cascade decays from SUSYBF is the most detailed simulation for gluino pairs. The case for squark pairs is less clear, since ISAJET does not discriminate between L- and R-type squarks. Currently, ISAJET produces squarks democratically, and some sort of averaging has to be done when implementing cascade decays.

A program SUSYSM has recently been developed by Baer and Tata which has the cascade decay mechanism built in from the start. The user must input a point in SUSY parameter space. The program calculates all the various cascades using the same SUSYBF routines. SUSYSM discriminates between different squark types, and has 136 different squark subprocess cross-sections included. SUSYSM can simultaneously generate $\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, and $\tilde{q}\tilde{q}$ events and keep track of squark type and flavor. The SUSYSM program uses the standard common block convention to keep track of event parameters and history as outlined in Ref. [31], and uses a standard particle labelling scheme. SUSYSM has been interfaced with the JETSET routines of Sjostrand[32] to incorporate final state string hadronization. The

In 1992, Frank suggested the IsaSUSY interface be hard wired in Isajet.
We worked closely together to make this happen.
End result was Isajet 7.0 with all 2->2 sparticle production mechanisms along with cascade decays, depending on pMSSM (weak scale) input parameters

FSU-HEP-930329
UH-511-764-93
April 1993

SIMULATING SUPERSYMMETRY WITH ISAJET 7.0 / ISASUSY 1.0

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ABSTRACT

We review the physics assumptions and input used in ISAJET 7.0 / ISASUSY 1.0 that are relevant for simulating fundamental processes within the framework of the Minimal Supersymmetric Standard Model (MSSM) at $p\bar{p}$ and pp colliders. After a brief discussion of the underlying MSSM framework, we discuss event simulation and list the sparticle production processes and decay modes that have been incorporated into our calculations. We then describe how to set up and run an ISAJET / ISASUSY job and the user input and output formats. The ISAJET program is sufficiently flexible that some non-minimal supersymmetry scenarios may be simulated as well. Finally, plans for future upgrades which include the extension to e^+e^- collisions, are listed.

The movement was from simplified models to detailed SUGRA model predictions

The collider events turned out to be far richer than expected from simplified models

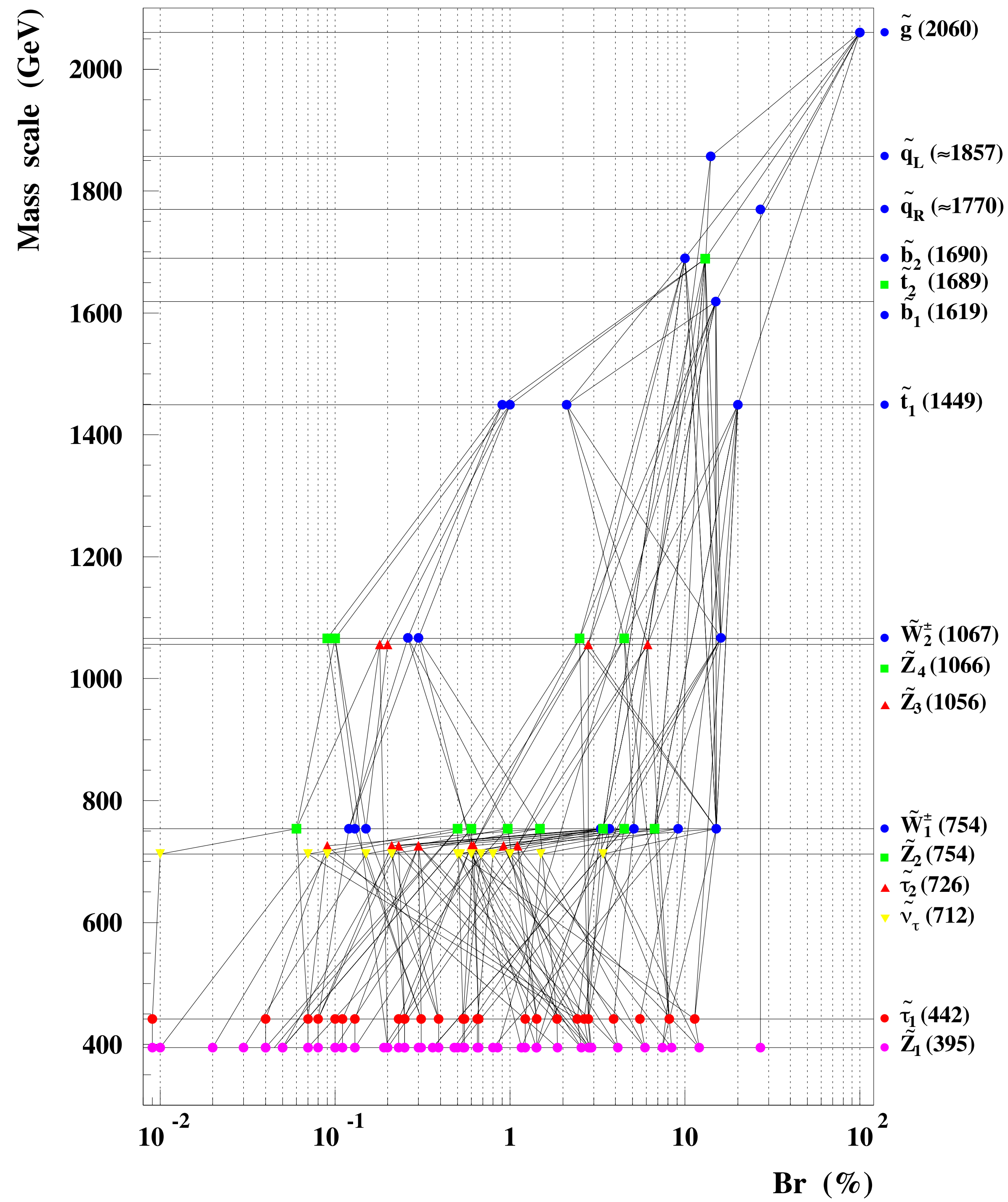
SUSY was well motivated in early 1990s due to measurement of gauge couplings at LEP which unified under MSSM evolution but not under SM evolution

For first time, had `realistic' simulation of how SUSY would appear at hadron colliders:

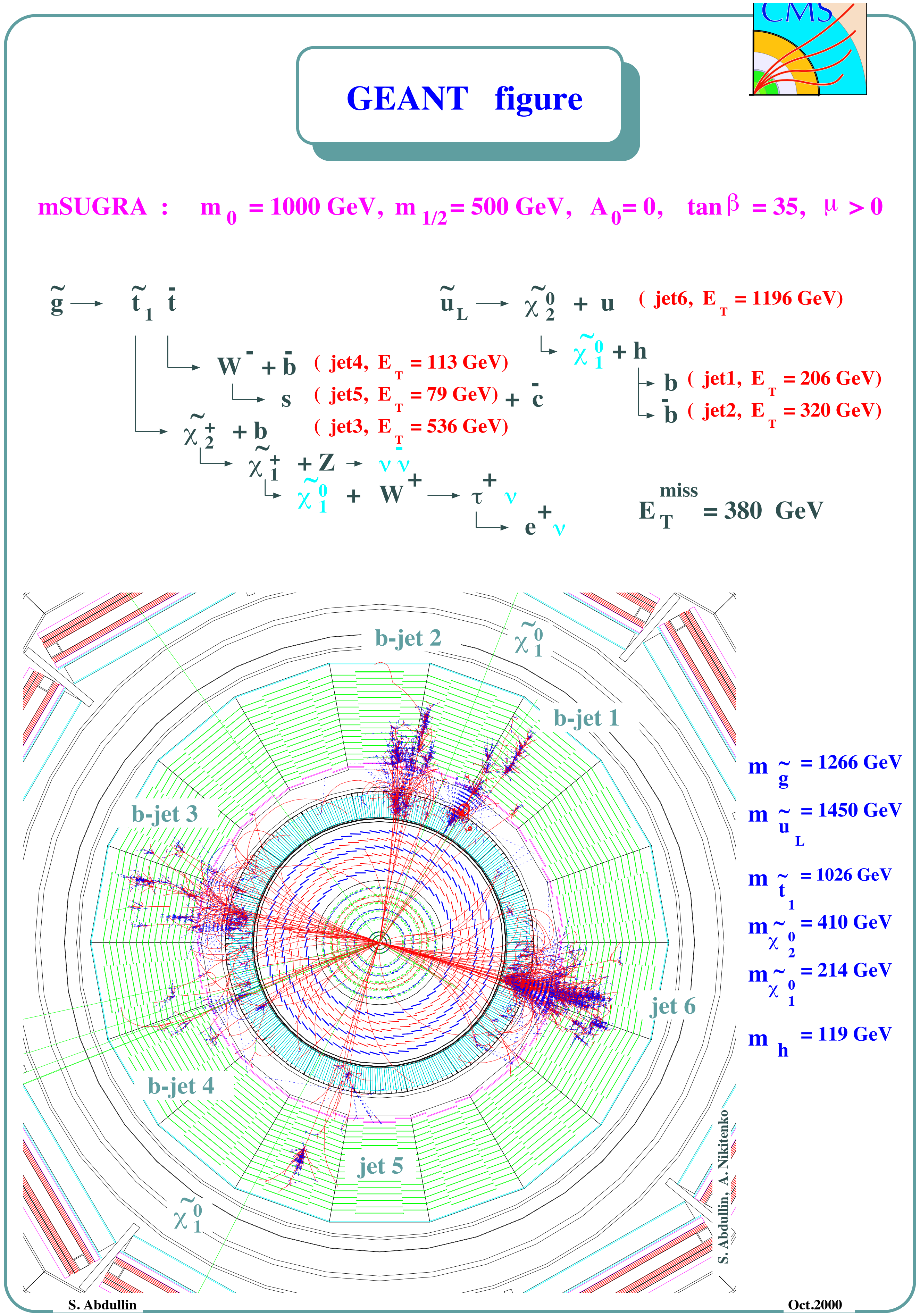
About 1000 distinct production subprocesses along with cascade decays
gave rise to an estimated 10^5 distinct production/decay chains

This was considered a big step up from previous use of simplified models and revealed the beautiful complexity of SUSY collider signals

Today, physicists have refrained from testing `models' to instead test `simplified models'- a step backwards IMO



$\tilde{Z}_1$ qq	(27.0 %)	$\tilde{Z}_1$ τνWWWbb	(4.1 %)
$\tilde{Z}_1$ τνWbb	(12.1 %)	$\tilde{Z}_1$ ττbb	(2.9 %)
$\tilde{Z}_1$ ττWWbb	(8.4 %)	$\tilde{Z}_1$ ττqq	(2.9 %)
$\tilde{Z}_1$ WWbb	(7.4 %)	$\tilde{Z}_1$ τνZWbb	(2.8 %)
$\tilde{Z}_1$ τνqq	(5.9 %)	$\tilde{Z}_1$ τνhWbb	(2.6 %)



What production of supersymmetric matter might look like at CMS detector using Isajet event generation

In 1994, we added IsaSUGRA to Isajet:
first publicly available SUSY spectrum generator
based on RGEs-
proposed SUSY searches in m0 vs. m(1/2) space

PHYSICAL REVIEW D VOLUME 51, NUMBER 3 1 FEBRUARY 1995

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

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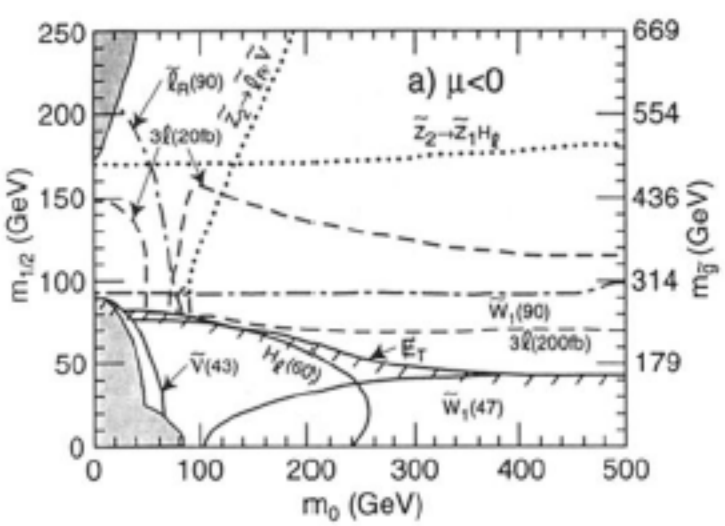
(Received 10 August 1994)

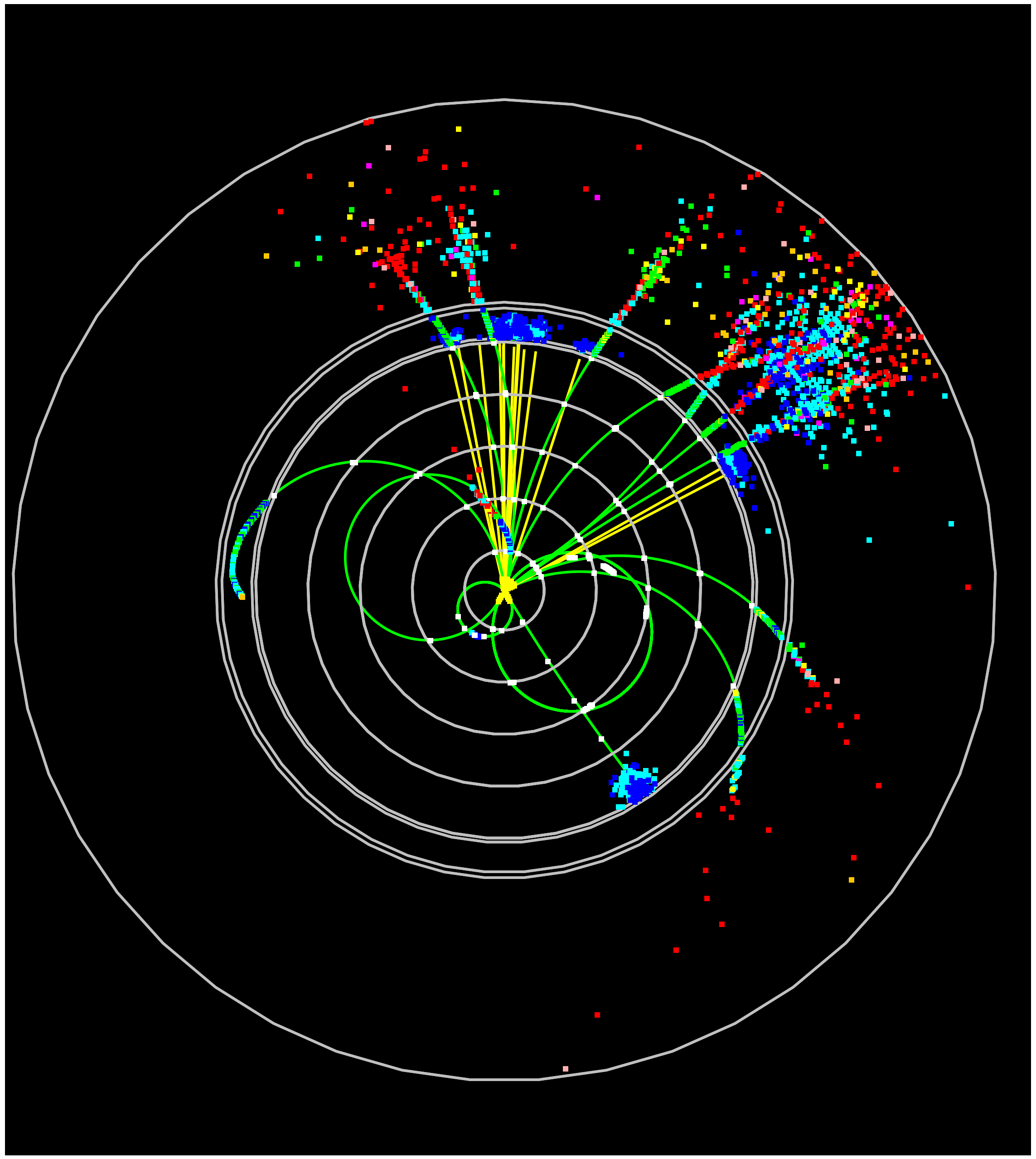
We examine the phenomenology of minimal supergravity models, assuming only that the low energy theory has the minimal particle content, that electroweak symmetry is radiatively broken, and that R parity is essentially conserved. After delineating regions of supergravity parameter space currently excluded 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.



In this context, limits from many different experiments could be plotted in same plane since they referred to same model: e.g. LEP e+e- bounds along with Tevatron bounds

Isasugra was later followed by European spectra calculators: SuSpect, SoftSUSY, Spheno

In 1994 (on honeymoon), we also added e+e- -> SUSY reactions: big effort from Uriel Nauenberg Colorado group using Isajet for NLC/ILC simulations



e+e- => W1+ W1-

- added bremssrahlung
- added beamstrahlung
- added beam polarization

Some further IsaDevelopments

- 1995: first LHC reach plots in m0 vs. mhf plane (see Xerxes)
- 1996-1998: upgrade to large tan(beta)- full Yukawa/mixing effects in decay BFs
- IsaWIG (Isajet/Herwig) interface
- upgrade to include actual decay matrix elements for 3-body decays rather than just phase space
- 2000: IsaReD, neutralino relic density Oh^2 (with A. Belyaev, C. Balazs)
- ISaTools: Oh2, g-2, b->s gamma, Bs-> mumu
- WIMP DM detection: sigma(SI, SD), <sigma.v>
- numerous other SUSY models: mGMSB, mAMSB, NUSUGRA, mirage: 13 total!
- SUSY Les Houches accord output (not input)
- SUSY Les Houches Events output- track color flow
- Delta(EW) as measure of EW fine-tuning in SUSY models
- kappa(Higgs)
- 2017: Most recently: Unpatchified Isajet 7.87: tarball
- 2018: Isajet 7.88 released including natural AMSB-
  first post-Frank release dedicated to Frank!

As Serban noted, so far no SUSY signal has emerged at LHC
in spite of `many' theorist expectations based on loose notions of naturalness

In 2012, we introduced the Delta(EW) fine-tuning measure into Isajet which we believe is the correct way to calculate naturalness: it accounts for correlated soft SUSY breaking parameters which leads to large cancellations in the fine-tuning calculation:
the measure is same for UV or IR parameter choices

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 + \Sigma_d^d - (m_{H_u}^2 + \Sigma_u^u)\tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \Sigma_u^u - \mu^2$$

non-negotiable naturalness

A crucial feature for low fine-tuning is that the mu parameter- which feeds mass to both SM (W,Z,h) and SUSY particles (higgsinos) be not too far from 100 GeV:
meanwhile, sparticle mass bounds re-evaluated:
SUSY quite natural for m(t1)<3 TeV and m(glno)<6 TeV

The Isajet models allow input of mu (low mu) so several NEW natural SUSY signatures found and evaluated using Isajet: same-sign diboson and soft OS dilepton+jet+MET from higgsino pair production

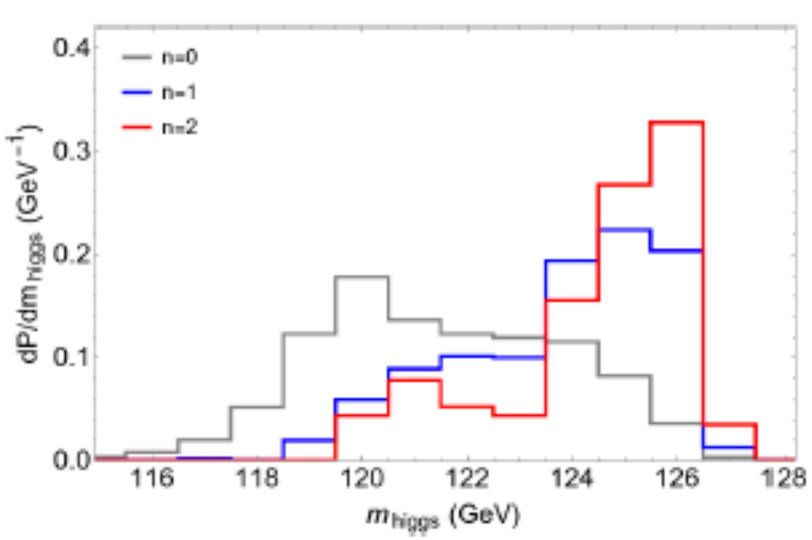
Since emergence of string theory with flux compactifications,
it becomes more clear from statistical studies of SUSY breaking scale
in the multiverse that string theory has a statistical bias
towards large soft terms arising from more complex SUSY breaking sector:
Denef and Douglas (from nearby SUNY Stony Brook)

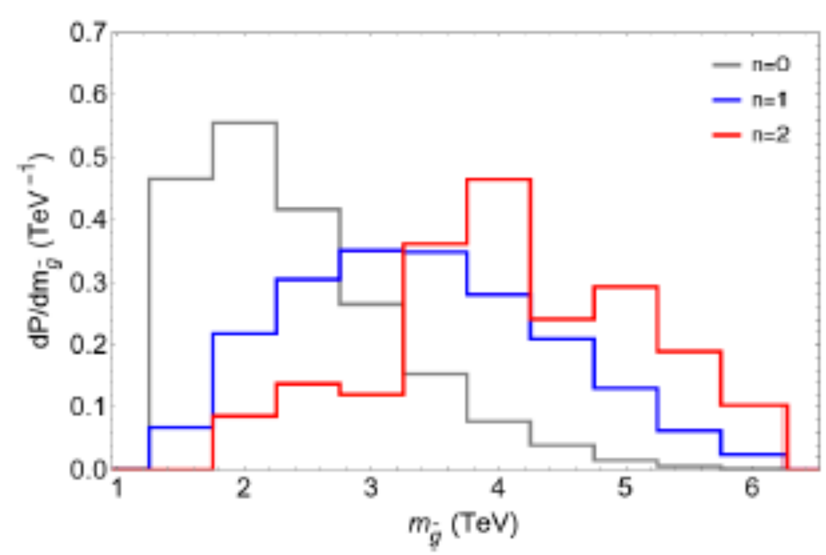
$$dN_{vac}[m^2_{hidden}, m_{weak}, \Lambda] = f_{SUSY}(m^2_{hidden}) \cdot f_{EWFT} \cdot f_{cc} \cdot dm^2_{hidden}$$

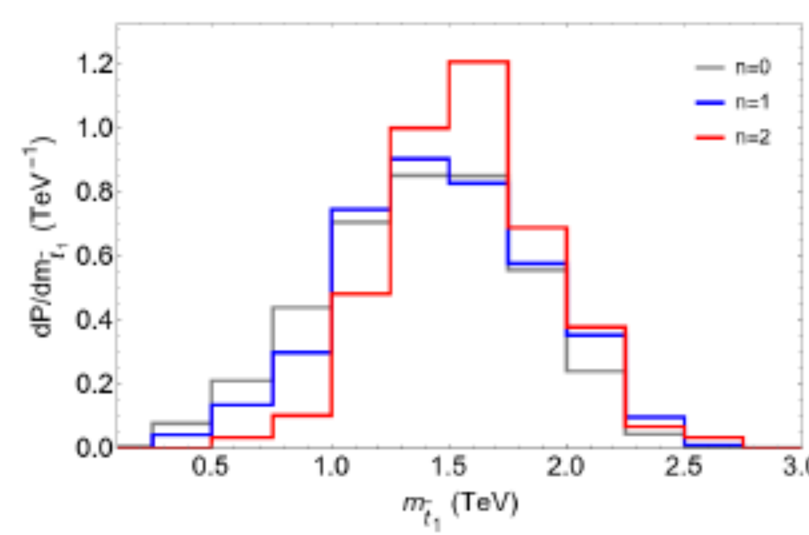
$$f_{SUSY}(m^2_{hidden}) \sim (m^2_{hidden})^{2n_F+n_D-1}$$

Draw to large soft terms balanced by anthropic requirement
of weak scale not too far from 100 GeV (Donoghue et al.)

for n=1,2, get m(h) just right: m(gl)~2-6 TeV and m(t1)~1-3 TeV







I am pretty certain Frank's efforts on SUSY will still bear fruit,
but signal should trickle in at LHC over next 2-20 years

The Isajet evaluation of <sigma.v>(T) for neutralino annihilation in early universe is input into unique code for mixed axion/WIMP dark matter production using eight coupled Boltzmann equations:

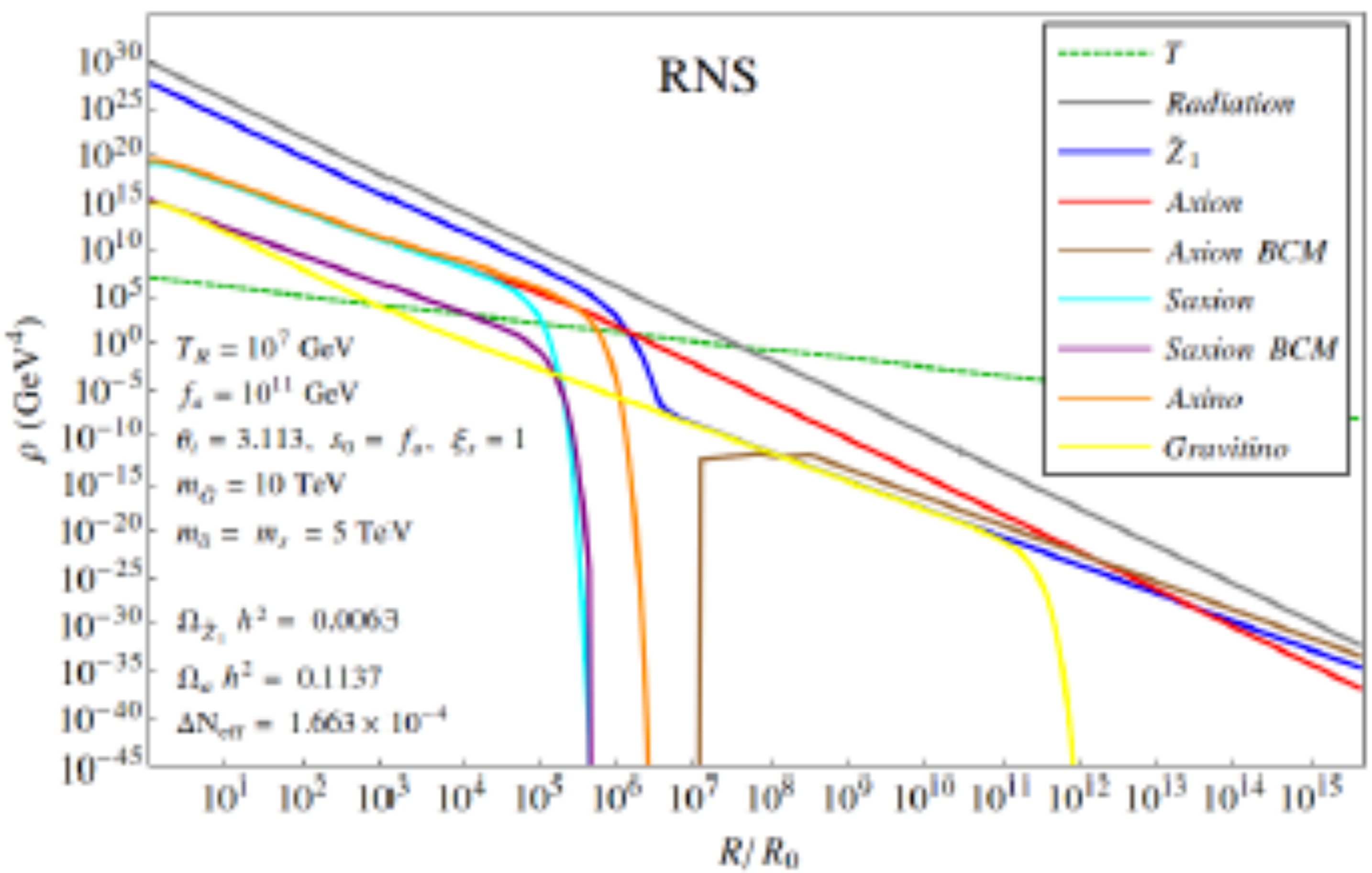


Figure 4. Evolution of various energy densities vs. scale factor R/R_0 for the RNS benchmark case with $\xi_s = 1$ and other parameters as indicated in the figure.

(Debating whether to include in Isajet)

Frank was a true physics pioneer

- forward/soft scattering
- Drell-Yan
- event generation- Isajet
- detailed SUSY simulation
- Snowmass contributions: huge influence
- Atlas jet calibration studies

We miss him dearly!