Dimitri and the advent of SUSY phenomenology

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I will focus on just three out of many topics of which Dimitri was a pioneer- along with some present day status

- Collider physics
- Relic SUSY WIMPs
- Naturalness

Dimitri became heavily involved in SUSY already in 1981-1982, making transition from GUTs to SUSYGUTs, SUGRA model building, inflationary cosmology and then collider phenomenology as perhaps dominant themes in that time period.

Dimitri and Aurora Savoy-Navarro organized conference on experimental detection of SUSY at CERN ppbar collider, April 1982

SUPERSYMMETRY CONFRONTING EXPERIMENT

edited by:

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Received August 1983

Contents:

Abstract:

This review puts together texts written after talks presented at the CERN Workshop "Supersymmetry versus Experiment" which took place in April 1982, but updated in order to include all latest developments. This altogether represent a self contained survey which puts together theoretical expectations and experimental possibilities. A general introduction to supersymmetry is followed by a thorough discussion of expectations at present machine energy – this including LEP – Next comes a discussion of supersymmetry in the framework of Grand Unified Theory – Experimental prospects, both for present and future machines are then considered in some detail. The conclusion provides a global review of the field.

EHNS propose monojet signature from W boson decay:

$$p\bar{p} \to W \to \chi_1^{\pm}\chi_1^0 \to q\bar{q}'\chi_1^0\chi_1^0$$

SEARCH FOR SUPERSYMMETRY AT THE $\bar{p}$p COLLIDER ☆

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Received 25 April 1983

Many models of broken supersymmetry predict the existence of supersymmetric fermions $\chi^{\pm,0}$ with masses less than the $W^{\pm}$ and Z^0. Often there are two light neutral fermions χ^0, even in models with large gaugino masses. The $W^{\pm}$ have large branching ratios for decays into $\chi^{\pm} + \chi^0$, with the $\chi^{\pm}$ subsequently decaying into χ^0 plus hadrons or leptons. We propose looking at the CERN $\bar{p}$p collider for $W^{\pm}$ production and decay into supersymmetric fermions, a likely signature being "zen" events with one broadened hadronic jet system recoiling against invisible missing transverse energy.

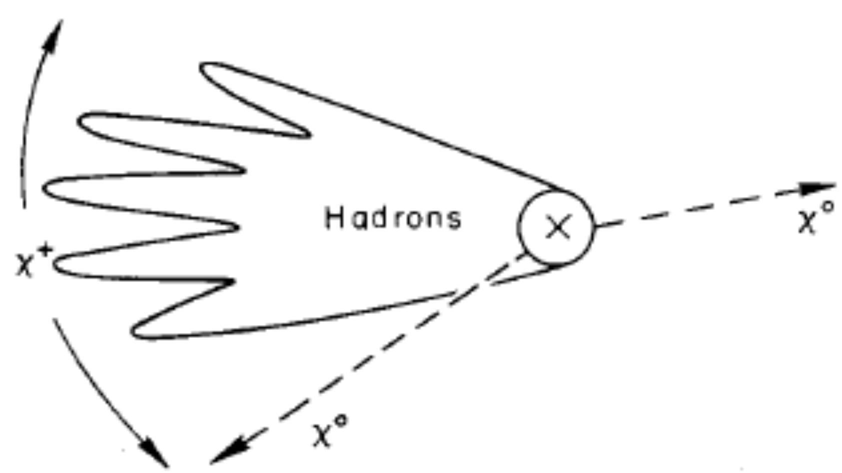

Fig. 1. Zen event signature, with a charged susy fermion $\chi^{\pm}$ decaying into a spray of hadrons on one side of the beam axis denoted by ⊗, and transverse energy-momentum balanced by two light neutral supersymmetric fermions χ^0.

I became involved with Dimitri in 1984

For some reason, CERN hired me fresh out of grad school
at UW-Madison as a 1-year Paid Scientific Associate:
in those days, non-member states got 1-year term

After a 550 mile canoe trip down Kazan river in east Arctic
barren grounds in summer 1984, I joined CERN TH group in October, 1984

I had to apply for next PD one month later,
Nov. 1984, so had to show something fast

With the turn-on of the SppbarS collider at 540 GeV,
anomalous events were seen: monojets+MET, eegamma, mumugamma etc.

John Ellis and Henrik Kowalski interpreted the monojet events
as squark pair production followed by
squark-> quark+photino, with m(squark)~40 GeV

Although I was a dummy, the one thing I could do well
was to compute tree level production/decay processes and
write Monte Carlo code
to generate cross sections and distributions.

When I arrived at CERN, I was bewildered by the 120 members of the TH group-

I knocked on door of a Swiss PD, Benedict Humpert (QCD),
with whom I had shared a boarding house in Madison in 1977-1978

He told me to go see Prof. Nanopoulos, as he would be excited to see me

Sure enough, Dimitri invited me into his office, slapped me on the back,
and told me that he and John had some projects to work on
with me and that other young fella Xerxes Tata who had also just arrived
for a 1-year stint

We got together, and John and Dimitri proposed that if
m(squark)~40 GeV, then m(slepton) likely close by:
should check to see what signatures would arise from
slepton pair production with decays to 1 or 2 lepton+MET final states

I thought, wow!, these guys are great- looks like maybe
I will survive here!

SUPERSYMMETRY AT BAY?

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Received 10 December 1984

Happily, we were able to get a major piece of work out within a month so I was able to get next job at Argonne Nat'l Lab starting Sept., 1985

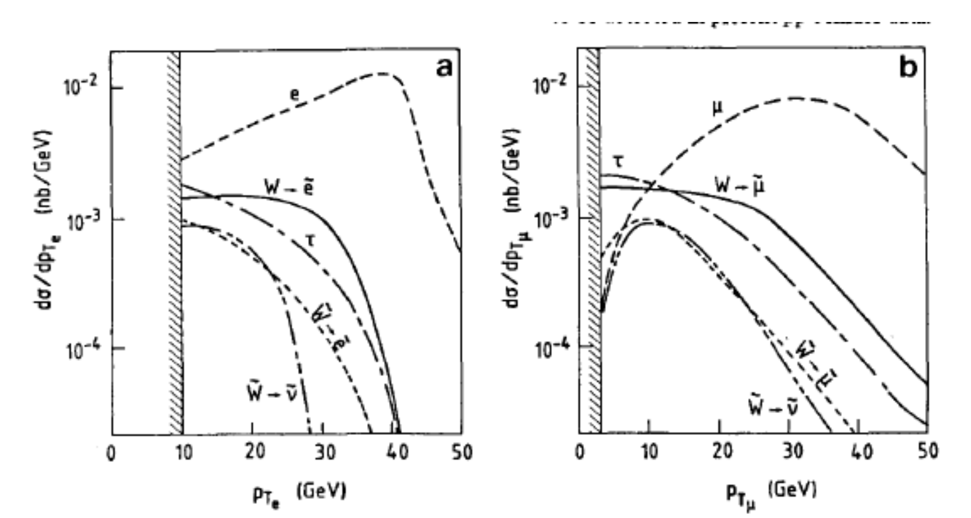
If the squark mass $m_{\tilde{q}}$ is O(40) GeV, as suggested by one interpretation of the CERN p$\bar{\text{p}}$ collider data, then one expects slepton masses $m_{\tilde{\ell}} \sim$ O(20–30) GeV in a wide class of models. Sleptons with such masses would be produced copiously in $W \to \tilde{\ell}\bar{\tilde{\nu}}$ and $Z^0 \to \tilde{\ell}^+\tilde{\ell}^-$ decays. We present rates and distributions for these processes, incorporating detector resolutions and experimental cuts. We show how the supersymmetric signals (especially for $Z^0 \to \tilde{\ell}^+\tilde{\ell}^-$) can easily be distinguished from the standard model backgrounds.

Table 1
Total cross sections for single lepton plus missing energy events due to the decays of W bosons produced in p$\bar{\text{p}}$ collisions at $\sqrt{s}$ = 630 GeV. The figures in parentheses are the resultant cross sections after applying the cuts $p_{T_\ell} < 30$ GeV and $\cos\theta_\ell < 0.0$, introduced in the text to maximize the supersymmetry signal to background ratio. In all calculations, we convolute subprocess cross sections with the parton densities of Duke and Owens [23] (set 1) assuming an SU(4) sea. We multiply the cross sections for all processes by a QCD motivated factor $K = 1.4$. We account for initial state soft gluon bremsstrahlung by giving the W and Z a Q_T distribution which approximates the results of ref. [24]. Throughout, we assume $m_{\tilde{\nu}} = m_{\tilde{\ell}}$, M_W = 83 GeV, M_Z = 94 GeV and $\sin^2\theta_W = 0.22$. In the case of a light sneutrino, the $W \to \tilde{\ell}\tilde{\nu}$ signal remains large for even higher slepton masses than those given here.

Process	$m_{\tilde{\ell}}$	σ_e (nb)	σ_μ (nb)
$p\bar{p} \to W^- \to \ell^- + \not{p}_T$	–	0.254 (0.010)	0.245 (0.021)
$p\bar{p} \to W^- \to \tau^-\bar{\nu}_\tau \to \ell^- + \not{p}_T$	–	0.024 (0.006)	0.036 (0.011)
$p\bar{p} \to W^- \to \tilde{\ell}^-\bar{\tilde{\nu}} \to \ell^- + \not{p}_T$	20	0.039 (0.019)	0.052 (0.024)
	25	0.031 (0.014)	0.041 (0.020)
	30	0.021 (0.010)	0.027 (0.011)
$p\bar{p} \to W^- \to \tilde{W}^-\tilde{\gamma} \to \tilde{\ell}^-\bar{\nu}\tilde{\gamma} \to \ell^- + \not{p}_T$	20	0.008 (0.005)	0.015 (0.007)
	25	0.010 (0.005)	0.015 (0.007)
	30	0.012 (0.005)	0.014 (0.007)
$p\bar{p} \to W^- \to \tilde{W}^-\tilde{\gamma} \to \ell^-\bar{\tilde{\nu}}\tilde{\gamma} \to \ell^- + \not{p}_T$	20	0.013 (0.006)	0.015 (0.007)
	25	0.010 (0.004)	0.014 (0.006)
	30	0.006 (0.003)	0.013 (0.006)

Table 2
Total cross sections for Z^0 production and decays into dileptons plus missing energy in p$\bar{\text{p}}$ collisions at $\sqrt{s}$ = 630 GeV. We ha included both ℓ_L and ℓ_R in the calculations, and have assumed they have equal masses: this is not expected [14,9] to be exac true [cf. eqs. (1b) and (1c)], but the induced error is negligible. The parameters used in these calculations are the same as in t 1, leading to $B(Z^0 \to \tilde{e}_R^+\tilde{e}_R^-)/B(Z^0 \to \tilde{e}_L^+\tilde{e}_L^-) = 0.64$. The non-observation of events corresponding to the above cross sections be used to put a new lower bound on slepton masses from p$\bar{\text{p}}$ collider data.

Process	$m_{\tilde{\ell}}$ (GeV)	σ_e (nb)	σ_μ (nb)
$p\bar{p} \to \gamma^*, Z \to \ell^+\ell^- + \not{p}_T$	–	0.083	0.393
$p\bar{p} \to Z \to \tau^+\tau^- \to \ell^+\ell^- + \not{p}_T$	–	<0.001	0.001
$p\bar{p} \to \gamma^*, Z \to \tilde{\ell}^+\tilde{\ell}^- \to \ell^+\ell^- + \not{p}_T$	20	0.011	0.017
	25	0.009	0.014
	30	0.007	0.011
	35	0.005	0.007
	40	0.003	0.004



Thus, I was set upon the happy path of SUSY phenomenology by Dimitri, John and Xerxes

Since string anomaly cancellation was also found near this time, Dimitri and John quickly transitioned to aspects of string theory.

Also, it was realized that various QCD backgrounds could account for the CERN anomalous events, so SUSY was not being discovered after all.

But we did do one more paper:
the advent of superparticle cascade decays

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

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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: $m_{\tilde{q}} > m_{\tilde{W}} > m_{\tilde{Z}}$ and $m_{\tilde{Z}} \approx m_{\tilde{q}} > m_{\tilde{W}}$. 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.

We calculated gluino and squark cascade decays to winos, zinos, photinos, although squarks were emphasized in title in support of John/Dimitri interpretation of CERN monojet events from squark production/decay

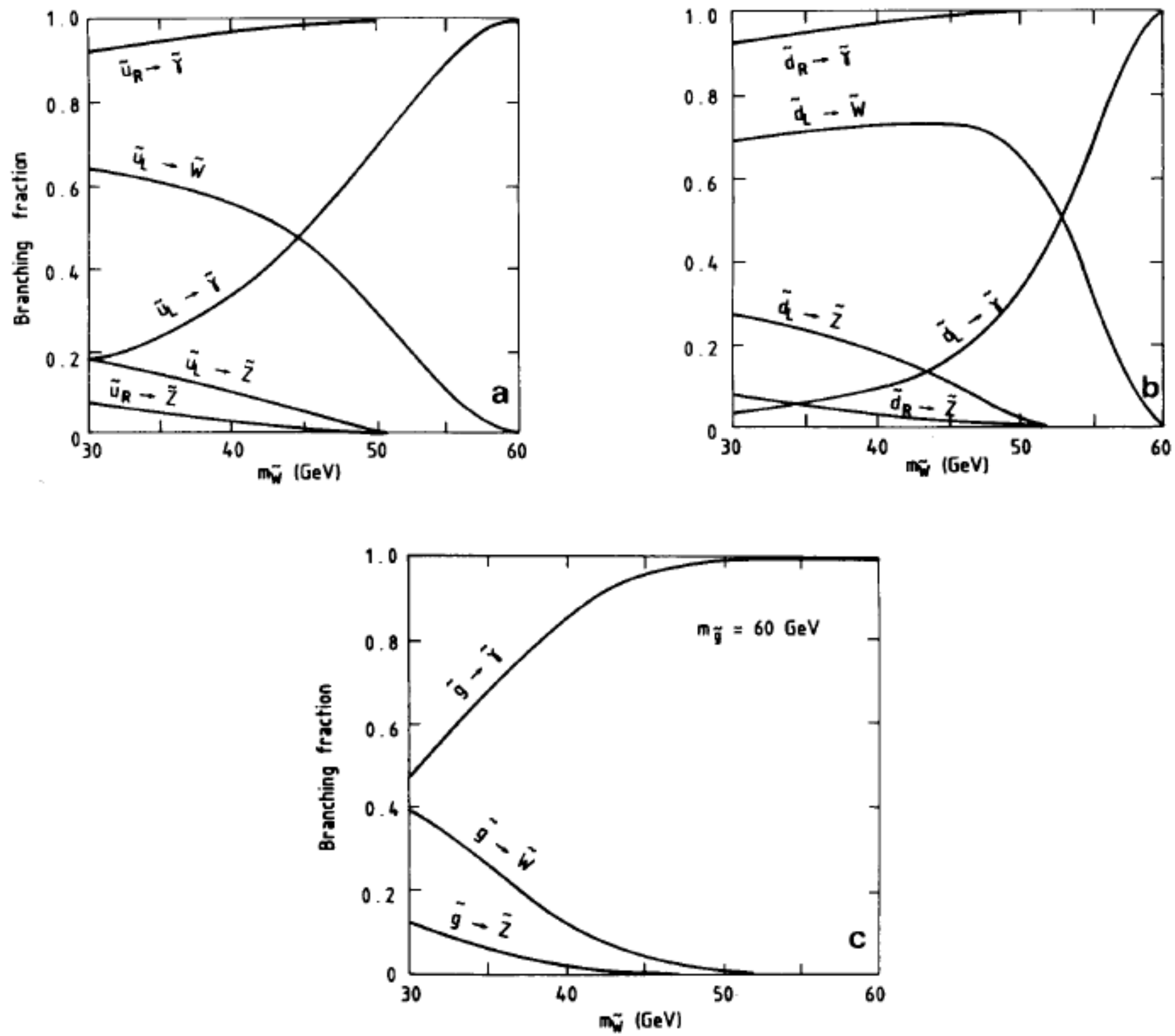


Fig. 2. Branching fractions for decays into zinos, winos and photinos versus wino mass for left- and right-hand up- (a) and down-type (b) squarks, and (c) gluinos. In (a, b) and in (c), the squark and gluino mass is taken to be 60 GeV, while the photino mass is 5.9 GeV.

We emphasized that in squark and gluino production events, a variety of multi-lepton+multijet+MET events should appear at hadron colliders

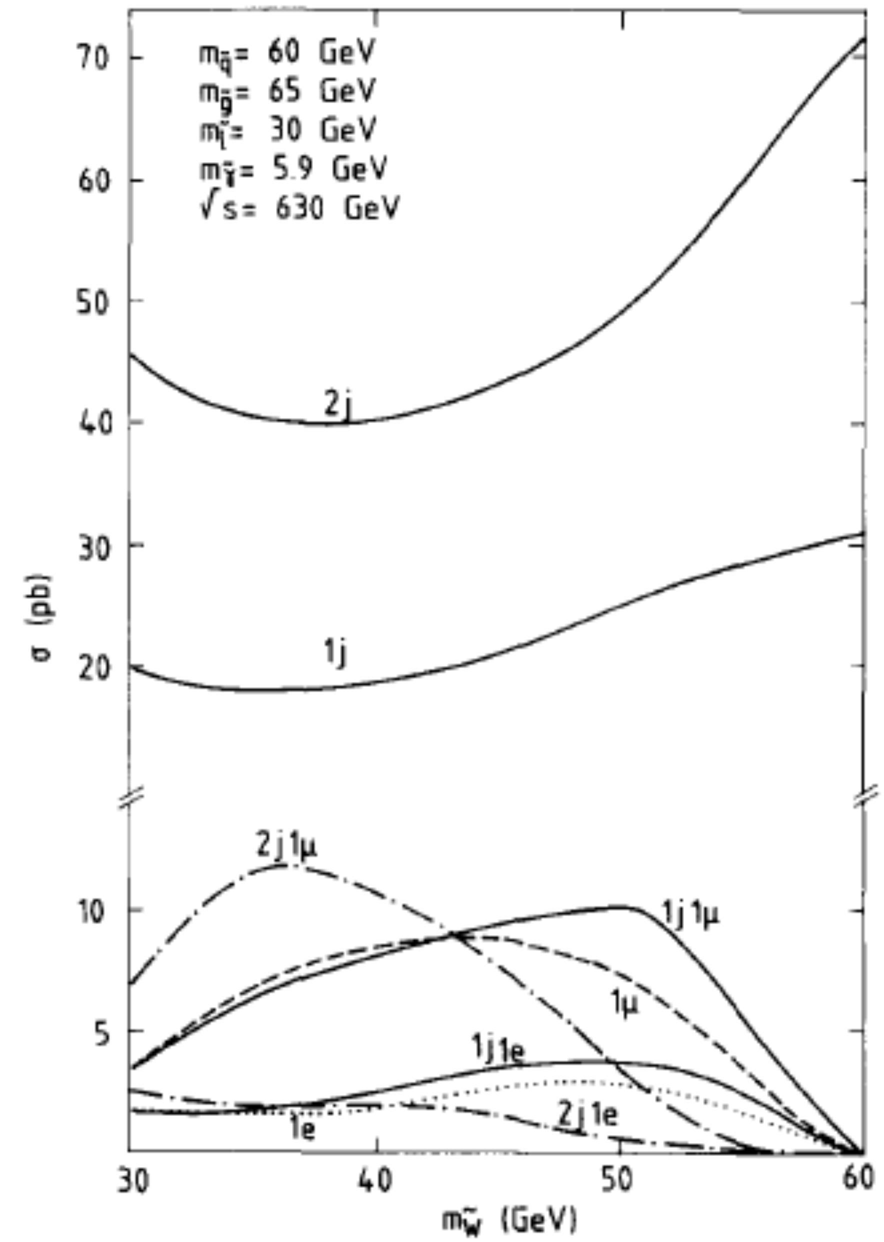


Fig. 4. Relative rates for different topological signatures of $p\bar{p} \to \tilde{q}\bar{\tilde{q}}, \tilde{q}\tilde{q}$ versus $m_{\tilde{W}}$. The scale 0–13 GeV is enhanced to exhibit better the leptonic cross sections. Other signatures of the form n jet + m lepton + $\not{p}_T$ will be present, but at much smaller rates than the plotted signals. Scenario parameters are given in the figure; we require $\not{p}_T > \max(15, 4\sigma)$ for all events, along with other cuts described in the text.

After I left CERN, we generalized the squark and gluino decays to include decays to general mixed -ino states and included all sparticle production/decay processes

Thus, I built up a 'by hand' Monte Carlo program called SUSYSIM that would predict how SUSY would be revealed by collider experiments- I made a rough interface of SUSYSIM with Pythia, but this was considered pretty radical by Sjostrand

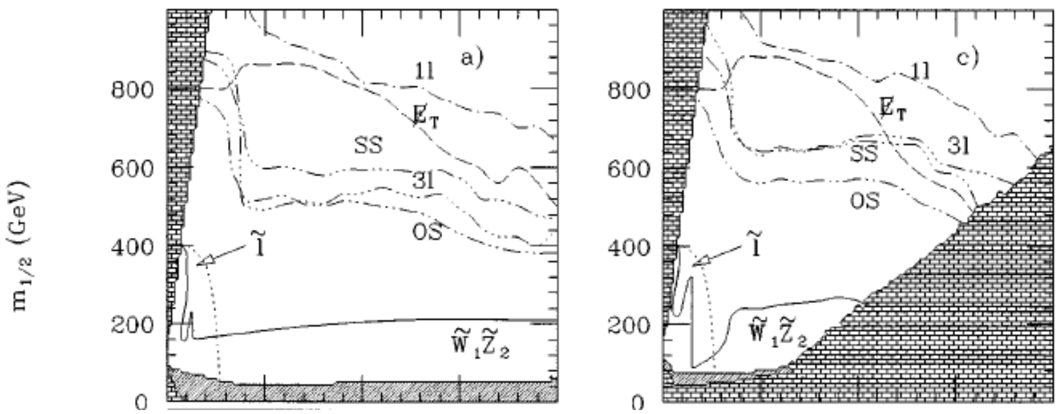
Our code was incorporated as a patch by Jim Freeman (CDF) into Isajet to gain experimental simulation of what SUSY actually predicted

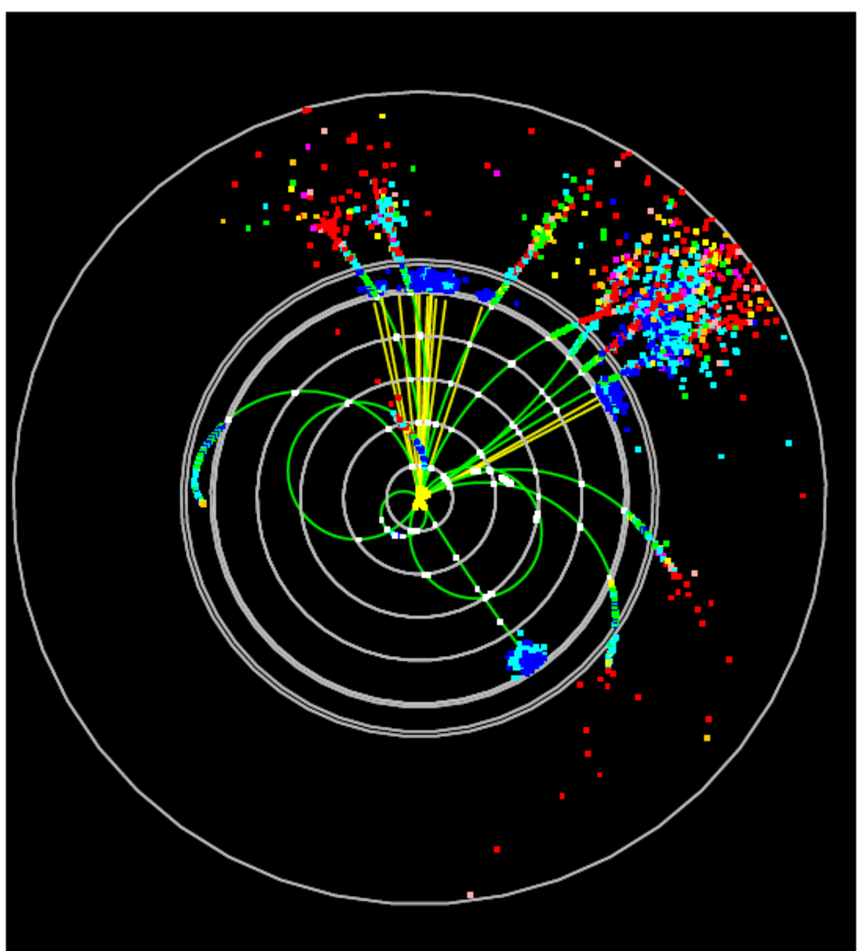
Frank Paige then invited Tata and I to join him in hard-wiring all our code into Isajet- he called it IsaSUSY which appeared in 1993

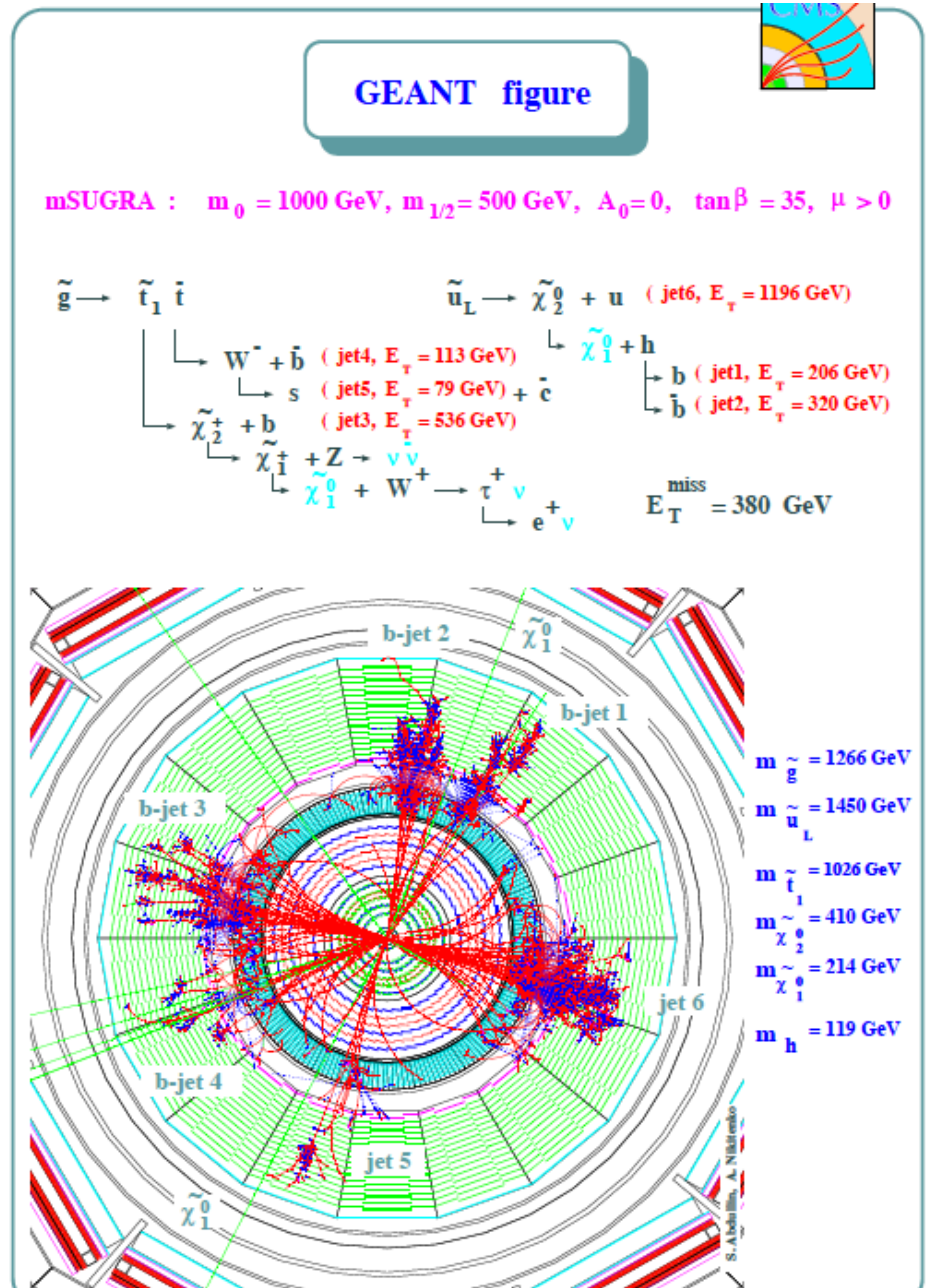
Then 1994 we released first publicly available RG-running code IsaSUGRA for sparticle masses

(Followed years later by SuSpect, SoftSUSY, Spheno)

Could finally plot SUSY signal expectations in iconic m0 vs. mhf plane







A second way Dimitri has inspired me is via his pioneering work on SUSY WIMP dark matter:

SUPERSYMMETRIC RELICS FROM THE BIG BANG*

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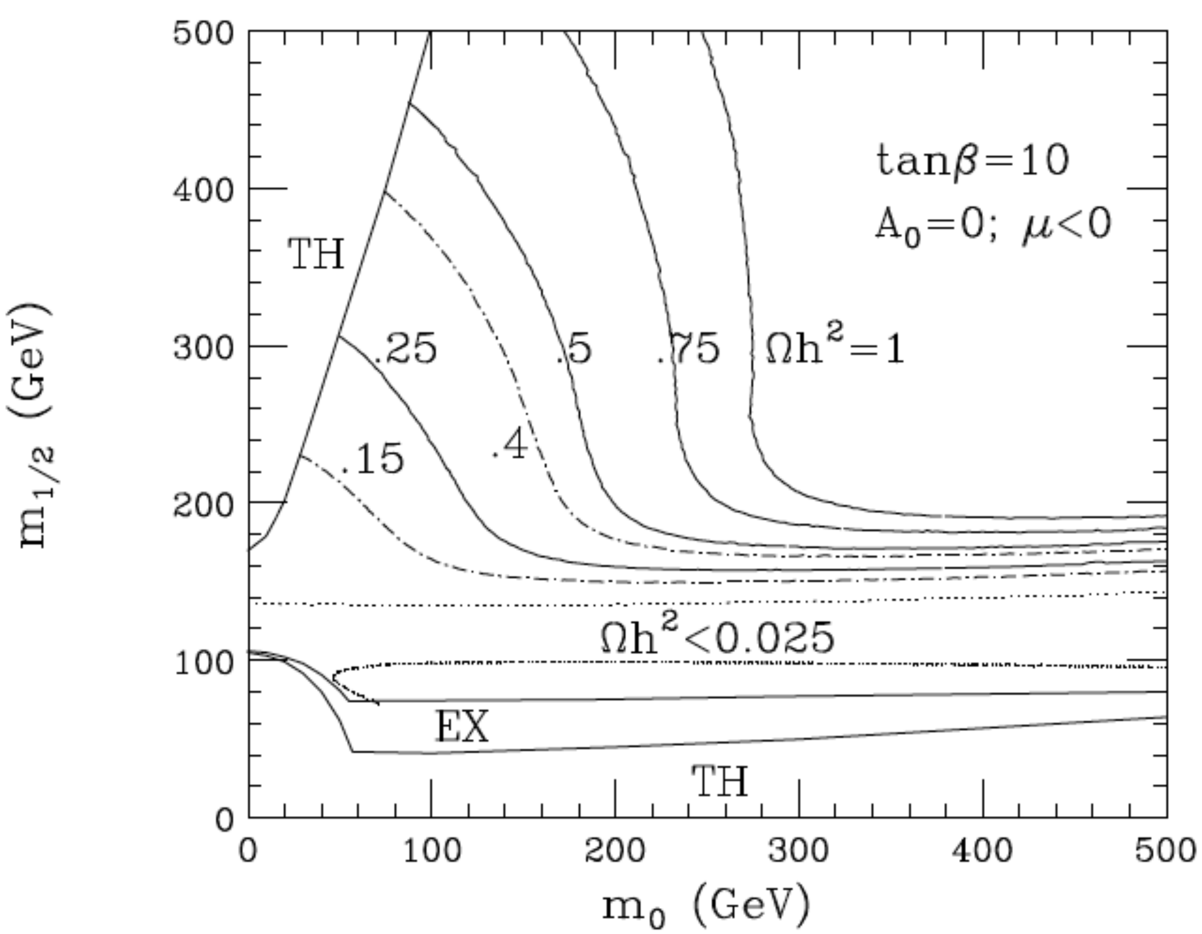
Received 16 September 1983
(Revised 15 December 1983)

We consider the cosmological constraints on supersymmetric theories with a new, stable particle. Circumstantial evidence points to a neutral gauge/Higgs fermion as the best candidate for this particle, and we derive bounds on the parameters in the lagrangian which govern its mass and couplings. One favored possibility is that the lightest neutral supersymmetric particle is predominantly a photino $\tilde{\gamma}$ with mass above $\frac{1}{2}$ GeV, while another is that the lightest neutral supersymmetric particle is a Higgs fermion with mass above 5 GeV or less than O(100) eV. We also point out that a gravitino mass of 10 to 100 GeV implies that the temperature after completion of an inflationary phase cannot be above 10^{14} GeV, and probably not above 3×10^{12} GeV. This imposes constraints on mechanisms for generating the baryon number of the universe.

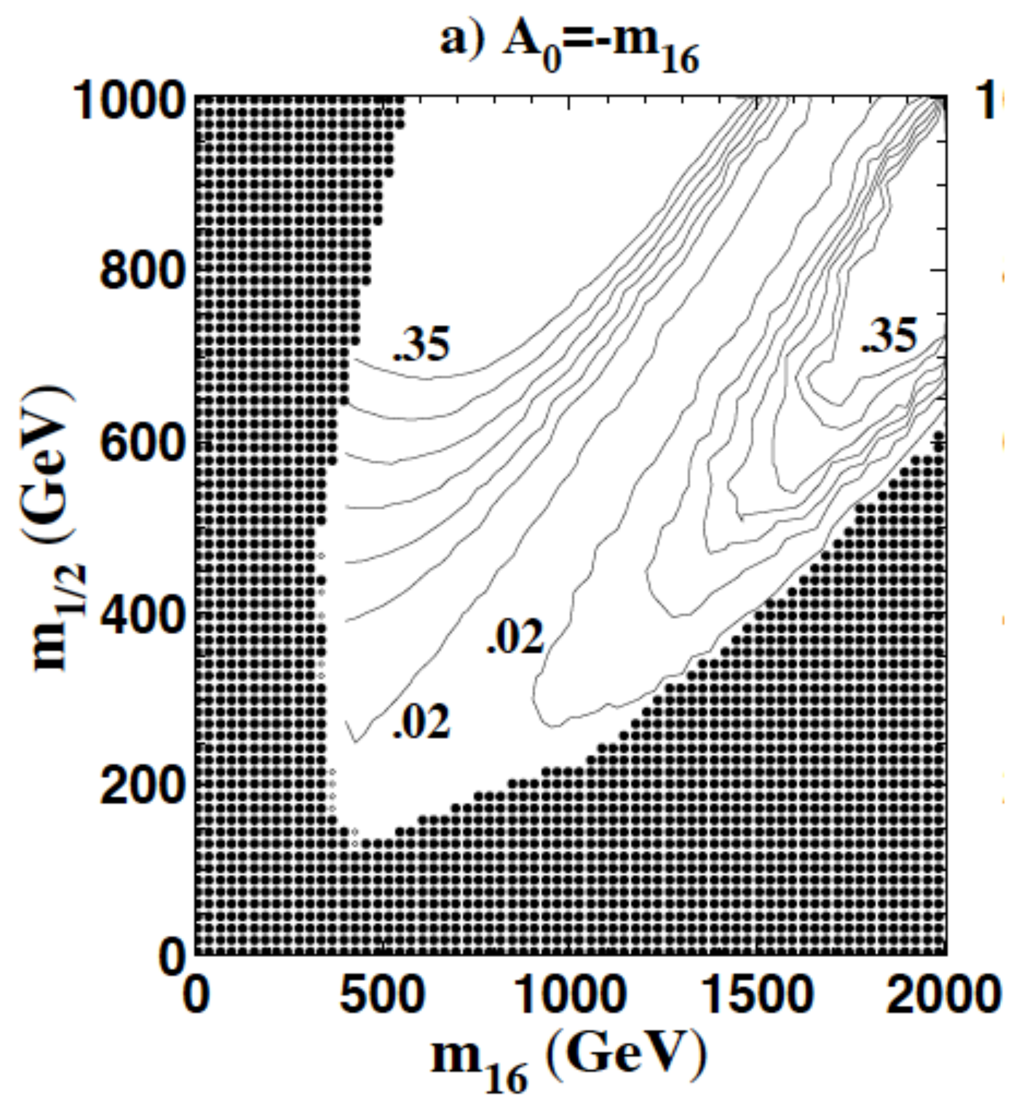
I only entered this fray in 1996 after Isajet was `finished'

My student Michael Brhlik and I put together code including proper relativistic integral over neutralino annihilation via Z or h resonances



We left off co-annihilation processes which Ellis& Olive accounted for

Later, we discovered that annihilation thru the A resonance was also important, which Ellis& Olive later dubbed the A-funnel



YUKAWA UNIFIED SUPERSYMMETRIC SO(10) MODEL: COSMOLOGY, RARE DECAYS AND COLLIDER SEARCHES

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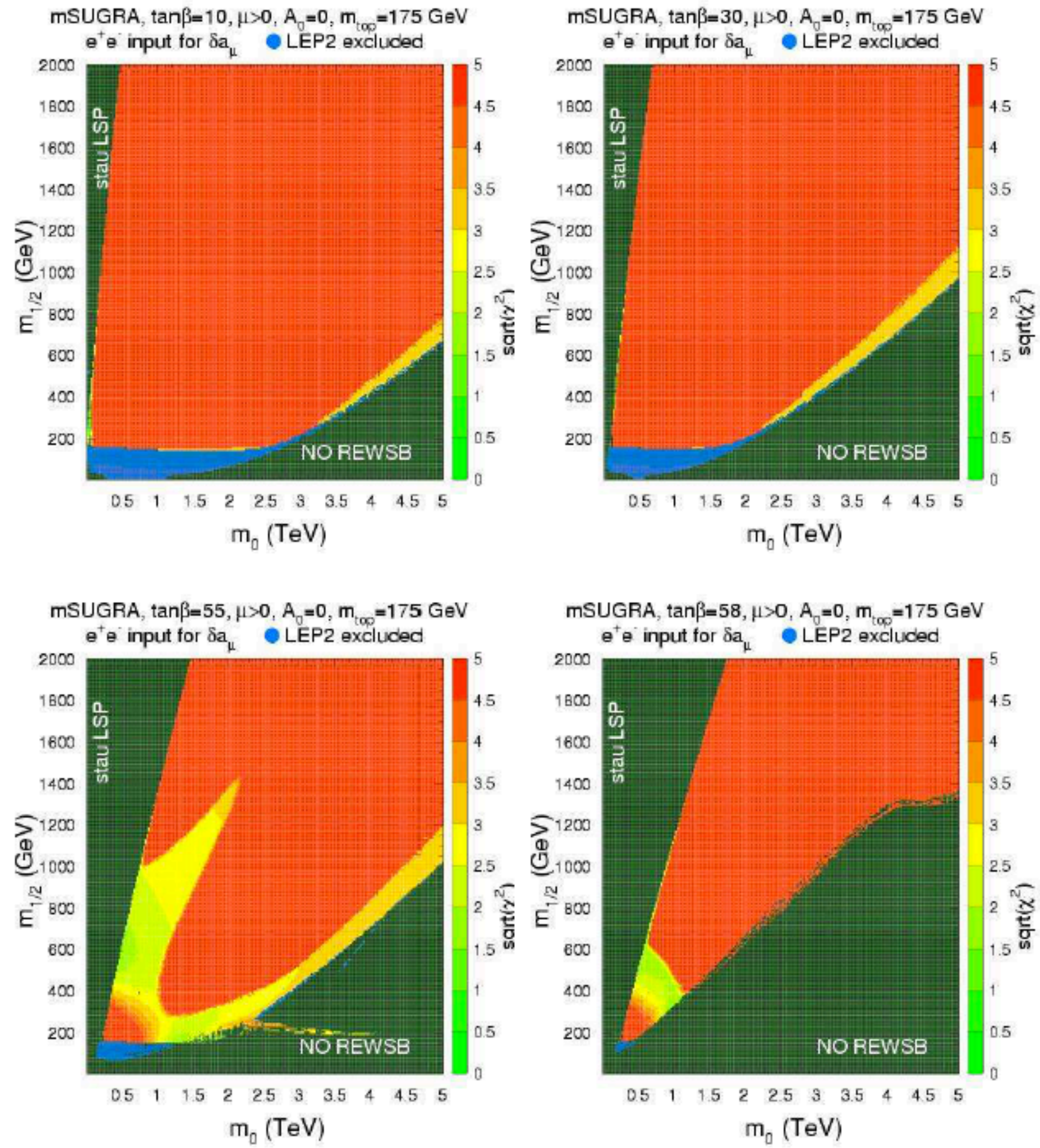
2 2 Aug 2000

Coannihilations included in IsaReD
(HB, Balazs, Belyaev)

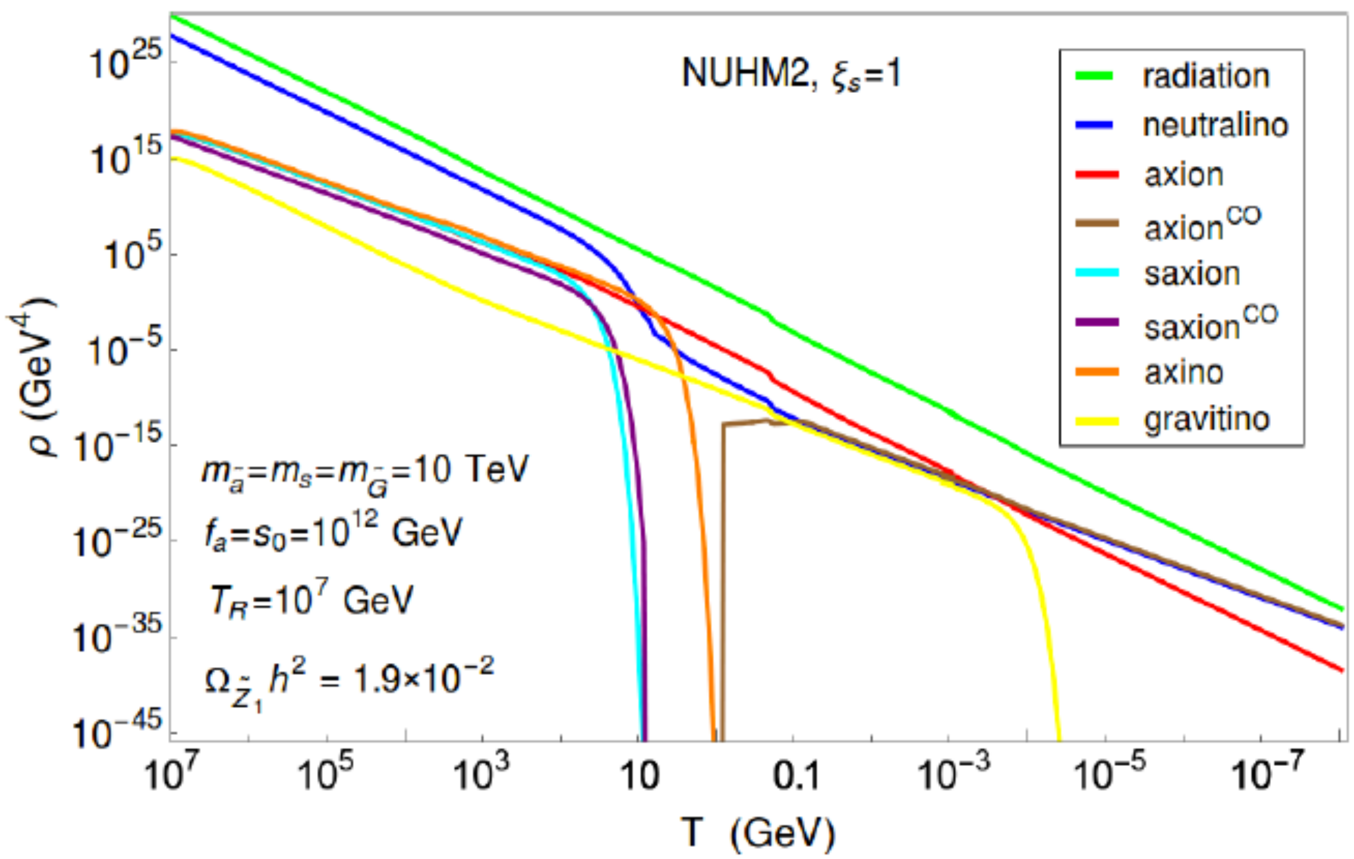


Nowadays, it seems essential to us to include the axion in the mix since if one doesn't contain a solution to the strong CP problem, then one's theory may be lacking a key ingredient.

Also, the SUSY DFSZ axion model contains the Kim-Nilles solution to the SUSY mu problem

$$\mathcal{L}_{\rm QCD} \ni \frac{\alpha_s \bar{\theta}}{8\pi} G_{\mu\nu A} \tilde{G}^{\mu\nu}_A$$

$$W \ni \frac{\lambda_\mu}{m_P} S^2 H_u H_d \Rightarrow \mu H_u H_d$$



Need 8-coupled Boltzmann equation treatment of mixed axion-SUSY WIMP dark matter

Figure 1: A plot of various energy densities ρ vs. temperature T starting from $T_R = 10^7$ GeV until the era of entropy conservation from our eight-coupled Boltzmann equation solution to the mixed axion-neutralino relic density in the SUSY DFSZ model for a natural SUSY benchmark point. We take $\xi_s = 1$.

Bae, HB,Lessa,Serce; Bae, HB,Serce

A third way Dimitri has inspired me is via his pioneering work on naturalness issue

CERN-TH.4350/86

OBSERVABLES IN LOW-ENERGY SUPERSTRING MODELS

John Ellis, K. Enqvist*), D.V. Nanopoulos and F. Zwirner**)
CERN -- Geneva

ABSTRACT

We compile phenomenological constraints on the minimal low-energy effective theory which can be obtained from the superstring by Calabi-Yau compactification. Mixing with the single additional neutral gauge boson in this model reduces the mass of the conventional Z^0. Field vacuum expectation values are constrained by the experimental upper bound on this shift. Then, requiring the sneutrino mass squared to be positive constrains the scale of supersymmetry breaking more than do lower bounds on the masses of new charged particles and of sparticles. More model-dependent constraints follow from the "naturalness" requirement that observables do not depend sensitively on input parameters. We find a preference for the second neutral gauge boson to weigh $\lesssim 320$ GeV, $m_{\tilde{g}} \lesssim 250$ GeV and $m_{\tilde{q}} \lesssim 500$ GeV. Dynamical generation of the gauge hierarchy is possible if $m_t \lesssim 70$ GeV, with lower values of m_t being favoured.

$$\Delta_{EENZ/BG} \equiv max_i \left| \frac{\partial \log m_Z^2}{\partial \log p_i} \right|$$

Particle	Lower Limit	Upper limit
t	—	70
Z_2	185	320
$\tilde{g}$	100	250
$\tilde{\gamma}$	15	35
$\tilde{e}_L$	55	150
$\tilde{e}_R$	90	170
$\tilde{\nu}$	0	150
$\tilde{q}_{1,2}$	180	500

EENZ upper limits on m(t) and sparticle masses from naturalness

Answer strongly depends on what one takes as input parameters

Expand m(Z)^2 using semi-analytic RGE solutions for tan(beta)=10:

$$\frac{m_Z^2}{2} = \frac{m_{H_d}^2 - m_{H_u}^2 \tan^2\beta}{\tan^2\beta - 1} - \mu^2 \simeq -m_{H_u}^2 - \mu^2$$

$$\begin{aligned}
-2\mu^2(m_{SUSY}) &= -2.18\mu^2 \\
-2m_{H_u}^2(m_{SUSY}) &= 3.84M_3^2 + 0.32M_3M_2 + 0.047M_1M_3 - 0.42M_2^2 \\
&+0.011M_2M_1 - 0.012M_1^2 - 0.65M_3A_t - 0.15M_2A_t \\
&-0.025M_1A_t + 0.22A_t^2 + 0.004M_3A_b \\
&-1.27m_{H_u}^2 - 0.053m_{H_d}^2 \\
&+0.73m_{Q_3}^2 + 0.57m_{U_3}^2 + 0.049m_{D_3}^2 - 0.052m_{L_3}^2 + 0.053m_{E_3}^2 \\
&+0.051m_{Q_2}^2 - 0.11m_{U_2}^2 + 0.051m_{D_2}^2 - 0.052m_{L_2}^2 + 0.053m_{E_2}^2 \\
&+0.051m_{Q_1}^2 - 0.11m_{U_1}^2 + 0.051m_{D_1}^2 - 0.052m_{L_1}^2 + 0.053m_{E_1}^2
\end{aligned}$$

model	c_{m_0}	$c_{m_{1/2}}$	c_{A_0}	c_μ	c_{H_u}	c_{H_d}	Δ_{BG}
mSUGRA	156	762	1540	-25.1	−−	−−	1540
NUHM2	16041	762	1540	-25.1	-15208	-643.6	16041

Table 1: Sensitivity coefficients and Δ_{BG} for mSUGRA and NUHM2 model with $m_0 = 9993.4$ GeV, $m_{1/2} = 691.7$ GeV, $A_0 = -4788.6$ GeV and $\tan\beta = 10$. The mSUGRA output values of $\mu = 309.7$ GeV and $m_A = 9859.9$ GeV serve as NUHM2 inputs so that the two models have exactly the same weak scale spectra.

This may tell you how much your computer code is fine-tuned, but what we really want to know is: Is nature fine-tuned?

Introduce Δ_{EW}

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

$$\Delta_{EW} \equiv max_i \left|C_i\right| / (m_Z^2/2)$$

CETUP*-12/002, FTPI-MINN-12/22, UMN-TH-3109/12, UH-511-1195-12

Radiative natural SUSY with a 125 GeV Higgs boson

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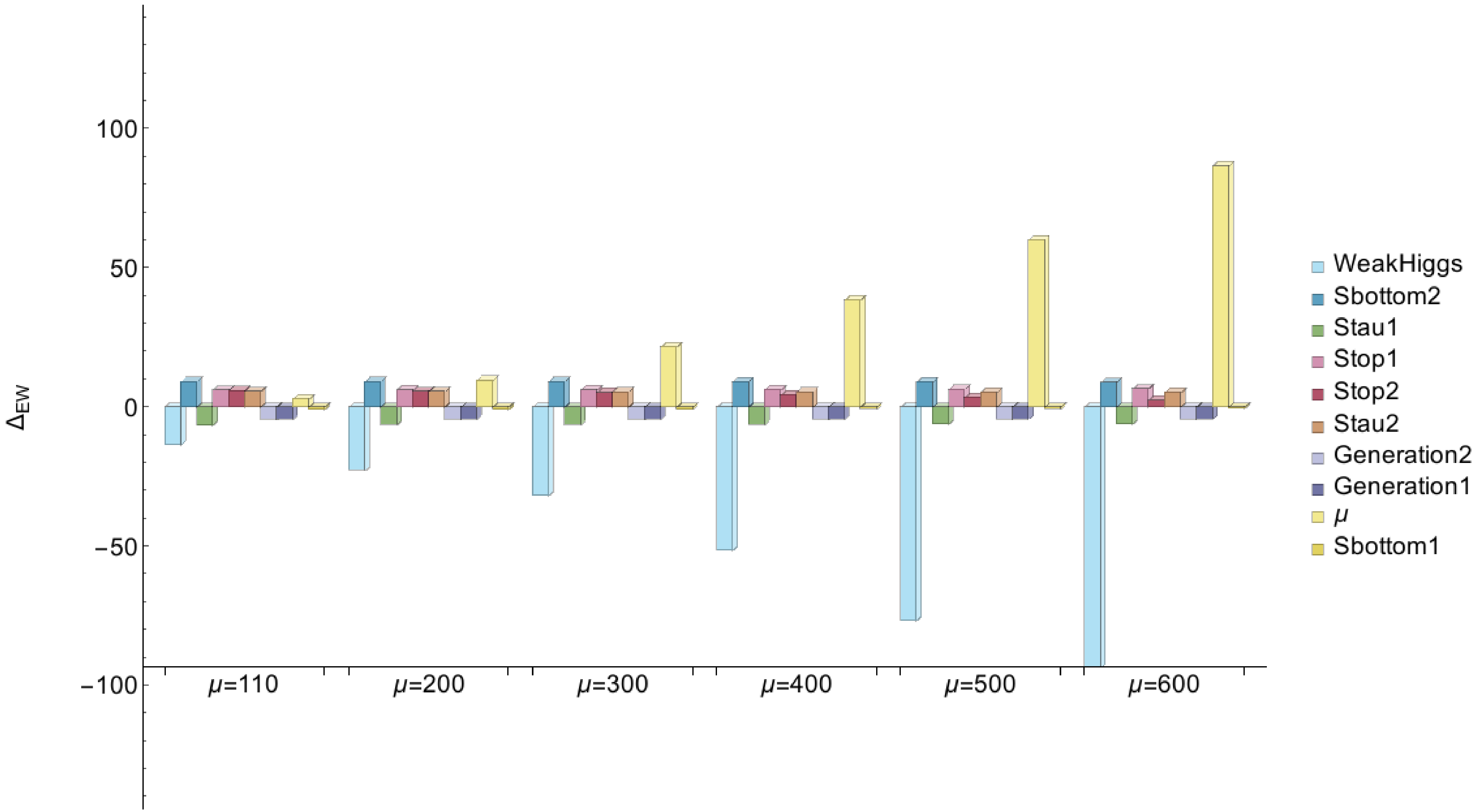
Why is weak scale m(W,Z,h)~100 GeV?

Because all weak scale contributions to m(weak)—
some positive, some negative—
are comparable to m(weak)

If one contribution to m(weak) is >> m(weak),
then some other would have to be tuned to large opposite sign value
to regain m(weak)~100 GeV



tuning already required by mu~300-400 GeV

or

$$\Delta_{EW} <\sim 30$$

HB, Barger, Savoy

Aside on high scale (HS, stop mass) measure

$$m_h^2 \simeq \mu^2 + m_{H_u}^2(\Lambda) + \delta m_{H_u}^2$$

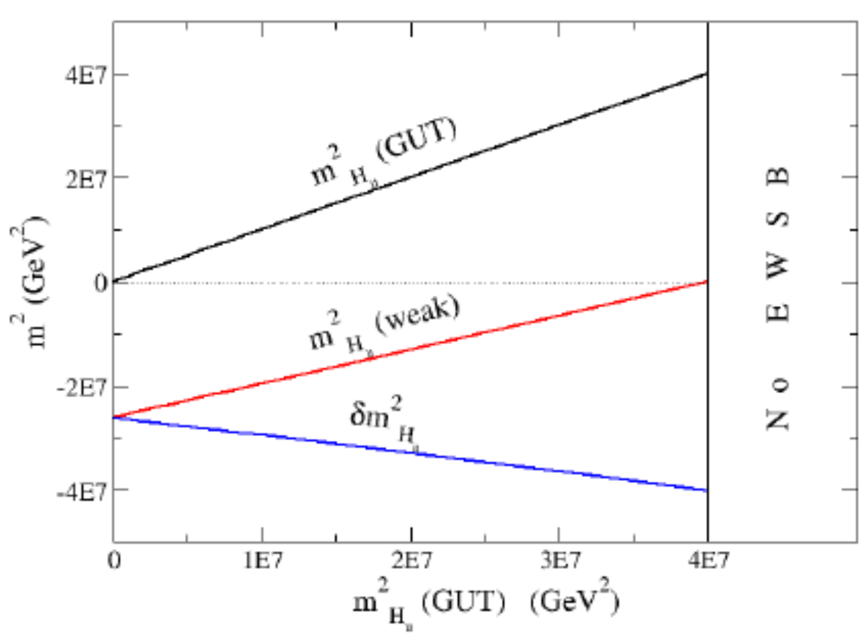
$$\delta m_{H_u}^2 \sim -\frac{3f_t^2}{8\pi^2}(m_{Q_3}^2 + m_{U_3}^2 + A_t^2)\ln\left(\Lambda^2/m_{SUSY}^2\right)$$

Implies 3 3rd generation squarks <500 GeV:
SUSY ruled out under Δ_{HS}

BUT! too many terms ignored! NOT VALID!

$$\frac{dm_{H_u}^2}{dt} = \frac{1}{8\pi^2}\left(-\frac{3}{5}g_1^2M_1^2 - 3g_2^2M_2^2 + \frac{3}{10}g_1^2 S + 3f_t^2 X_t\right)$$

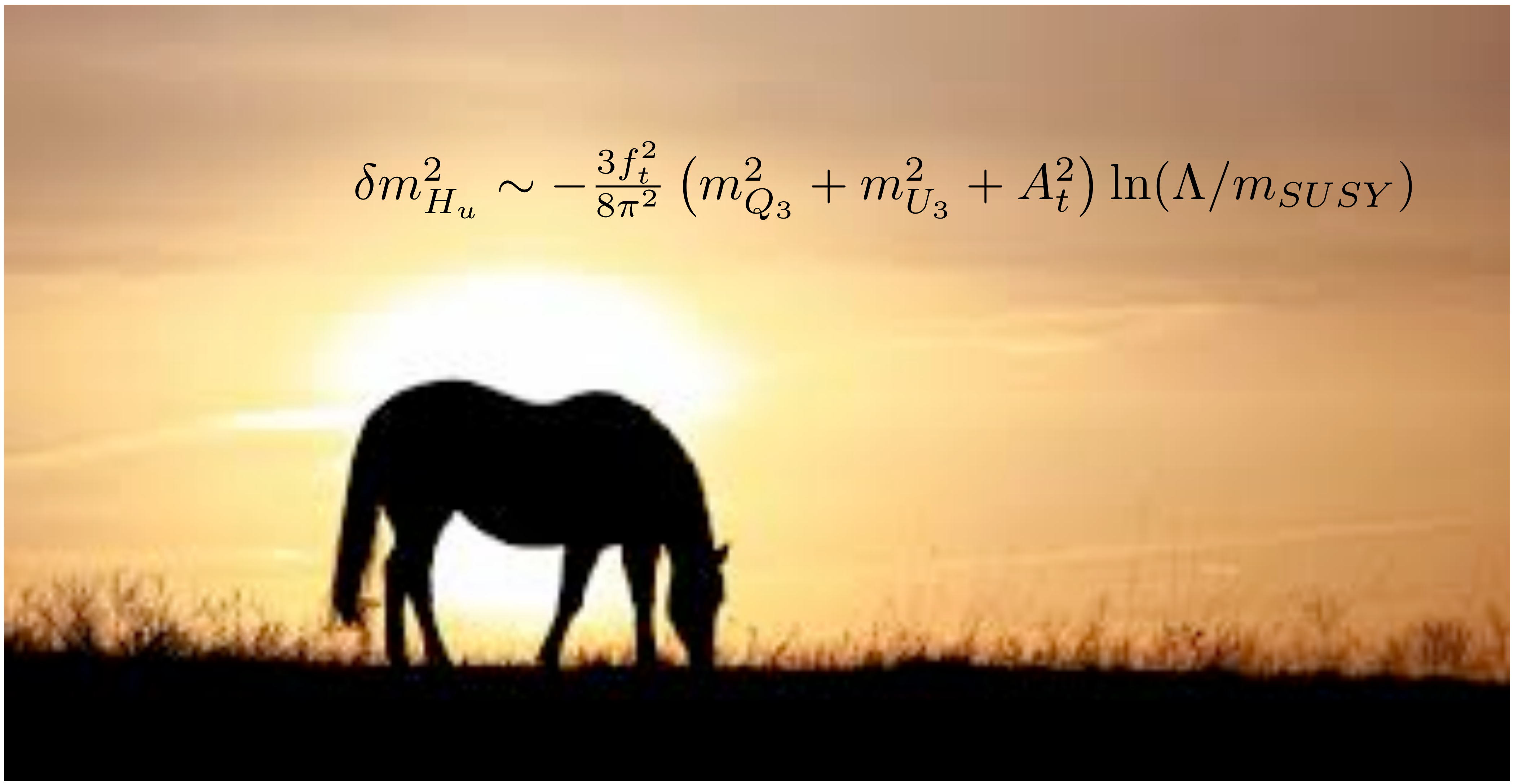
where $t = \ln(Q^2/Q_0^2)$, $S = m_{H_u}^2 - m_{H_d}^2 + Tr\left[\mathbf{m}_Q^2 - \mathbf{m}_L^2 - 2\mathbf{m}_U^2 + \mathbf{m}_D^2 + \mathbf{m}_E^2\right]$ and $X_t = m_{Q_3}^2 + m_{U_3}^2 + m_{H_u}^2 + A_t^2$. By neglecting gauge terms and S ($S = 0$



The bigger $m_{H_u}^2(\Lambda)$ is, the bigger is the cancelling correction- these terms are *not independent*.

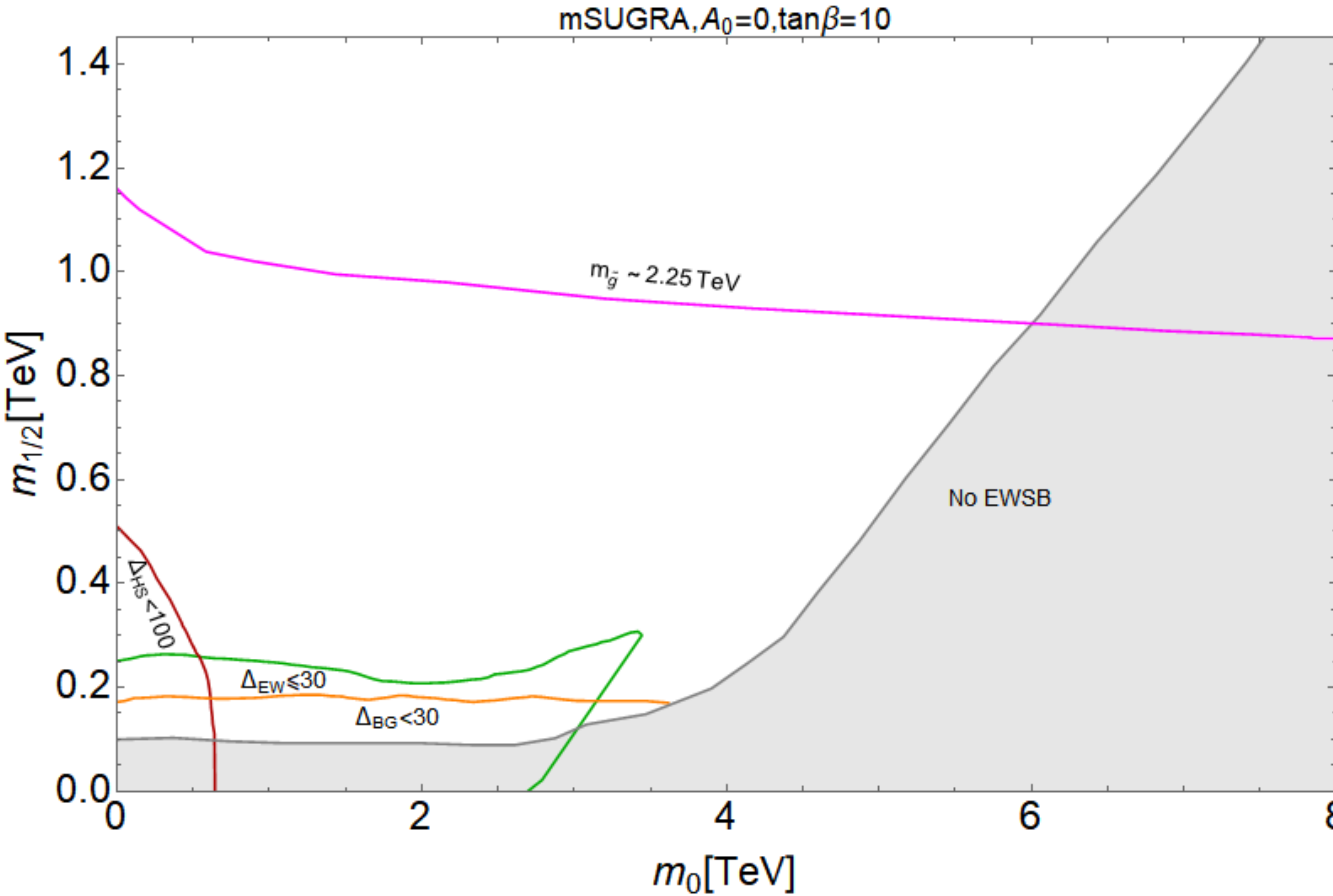
For big enough $m_{H_u}^2(\Lambda)$, then $m_{H_u}^2$ driven to natural value at weak scale: *radiatively driven naturalness (RNS)*

Recommendation: put this horse out to pasture



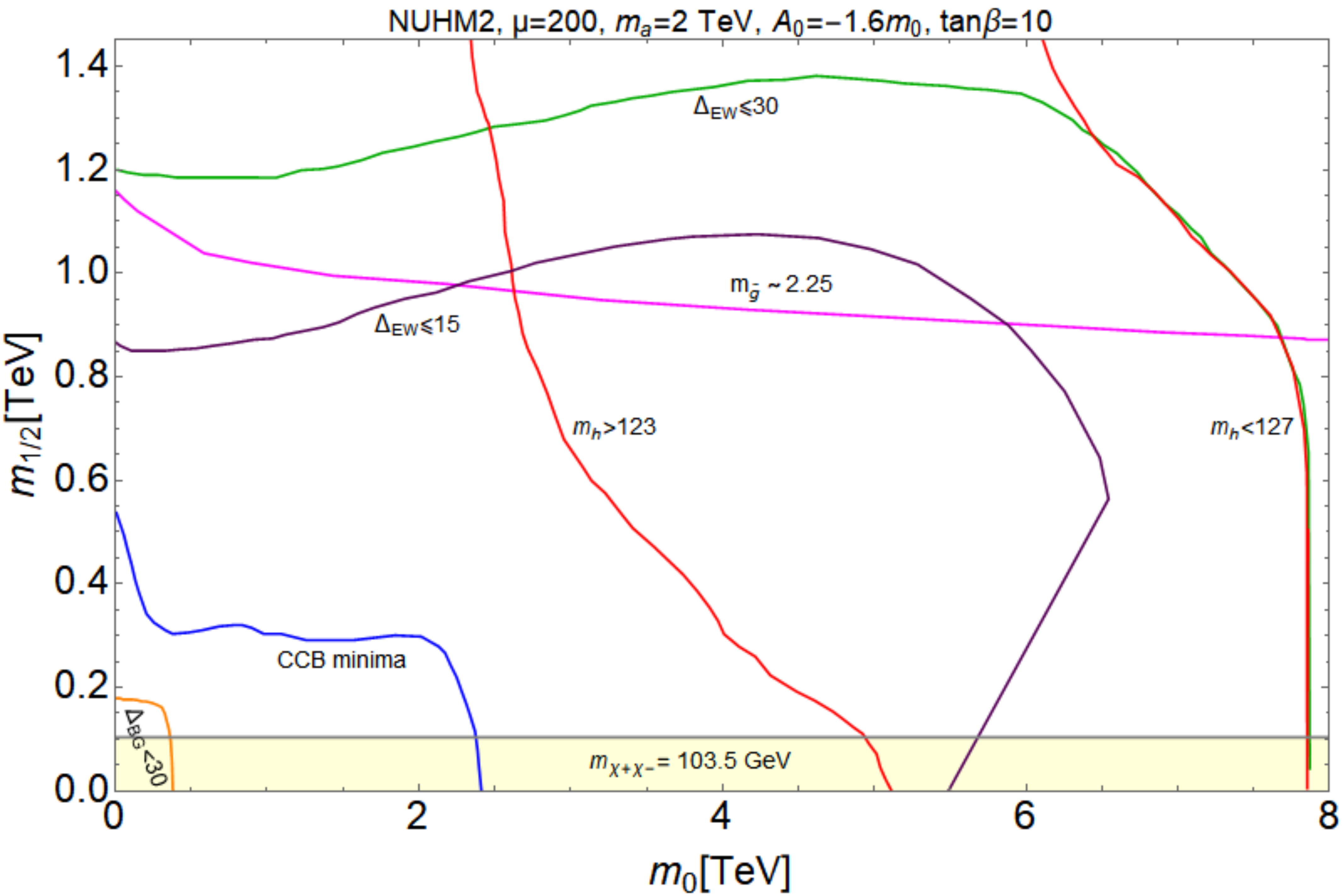
R.I.P.

sub-TeV 3rd generation squarks not required for naturalness



CMSSM is fine-tuned

HB, Barger, Salam



NUHM2,3 still natural even with mh(125) and
LHC limits on m(gluino)>~2250 GeV and m(t1)>1 TeV

Conventional naturalness: lower m0, mhf are more natural;
stringy naturalness: higher m0, mhf more natural: see Thursday talk

HB, Barger, Salam

Dimitri is a pioneer in many
of the most exciting avenues of
particle physics and cosmology:
for me personally, he has made a profound impact
Thanks Dimitri!

- SUSY collider phenomenology
- dark matter from SUSY
- the naturalness issue
- other speakers will no doubt address many other important topics to which Dimitri contributed