Ann Nelson, Pathfinder

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Summiting the Unknown
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unfinished business of the Standard Model:

Strong CP problem
    can θ naturally be close to 0 ?

Fermion mass spectrum
    Is the top quark a heavy quark or an ordinary quark ?

Electroweak symmetry breaking
    Is there a dynamical mechanism ?

    bringing up also the issues:

What is supersymmetry good for ?
Can quarks and leptons be composite ?

"Naturally Weak CP Violation",
Phys. Lett. 136B, 387 (1983)
"Calculation of θ Barr"
Phys. Lett. 143B, 165 (1984)

Start from an SU(5) x SO(3) GUT model desiged to suppress $p \to \pi^0 e^+$. Impose CP conservation.

Engineer, with a U(1) global symmetry, the mass matrix for the SM quarks plus a vectorlike massive quark:

$$\mathcal{M} = \begin{pmatrix} R & 0 & \xi \\ 0 & 0 & M \\ \eta & M & 0 \end{pmatrix}$$

The complex mass matrix has real determinant.

But, integrating out the massive quark, we find a complex mass matrix for the SM quarks !

Barr formalized the rules for this construction (in a U of Washington preprint).

Ann showed that θ is zero not only at the tree level but also at 1-loop.   And, she showed that the 2-loop corrections are sufficiently small.
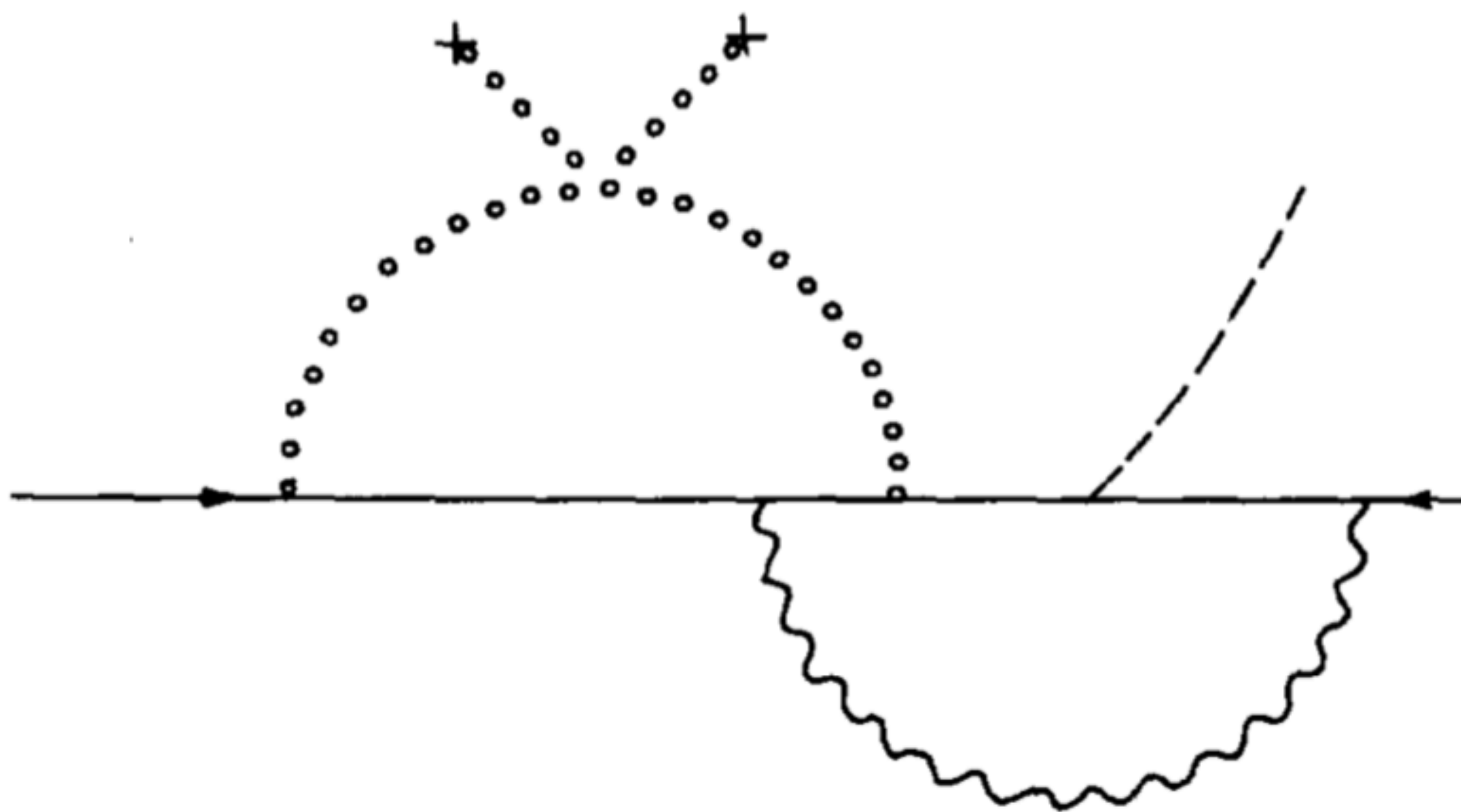
Fig. 3. This is an example of a complex two-loop contribution to λ_{ij} which is suppressed by small Yukawa couplings instead of fermion masses, fondly known as the dead duck graph.

supersymmetry c. 1990:

Write the most general renormalizable model with SUSY

Add the most general soft SUSY breaking terms, generated by supergravity with zero cosmological constant

This is a weak-coupling model. Explore its phase space in detail.
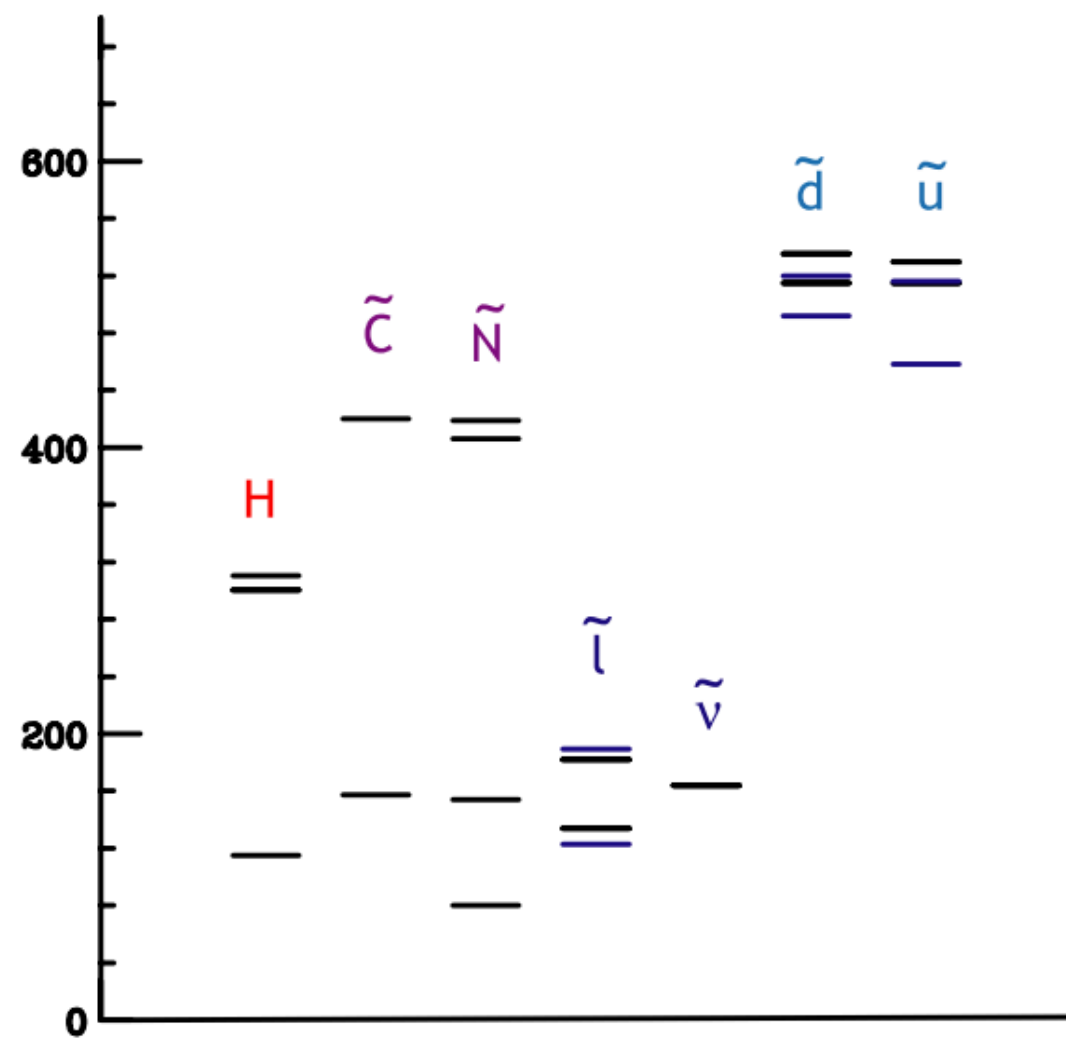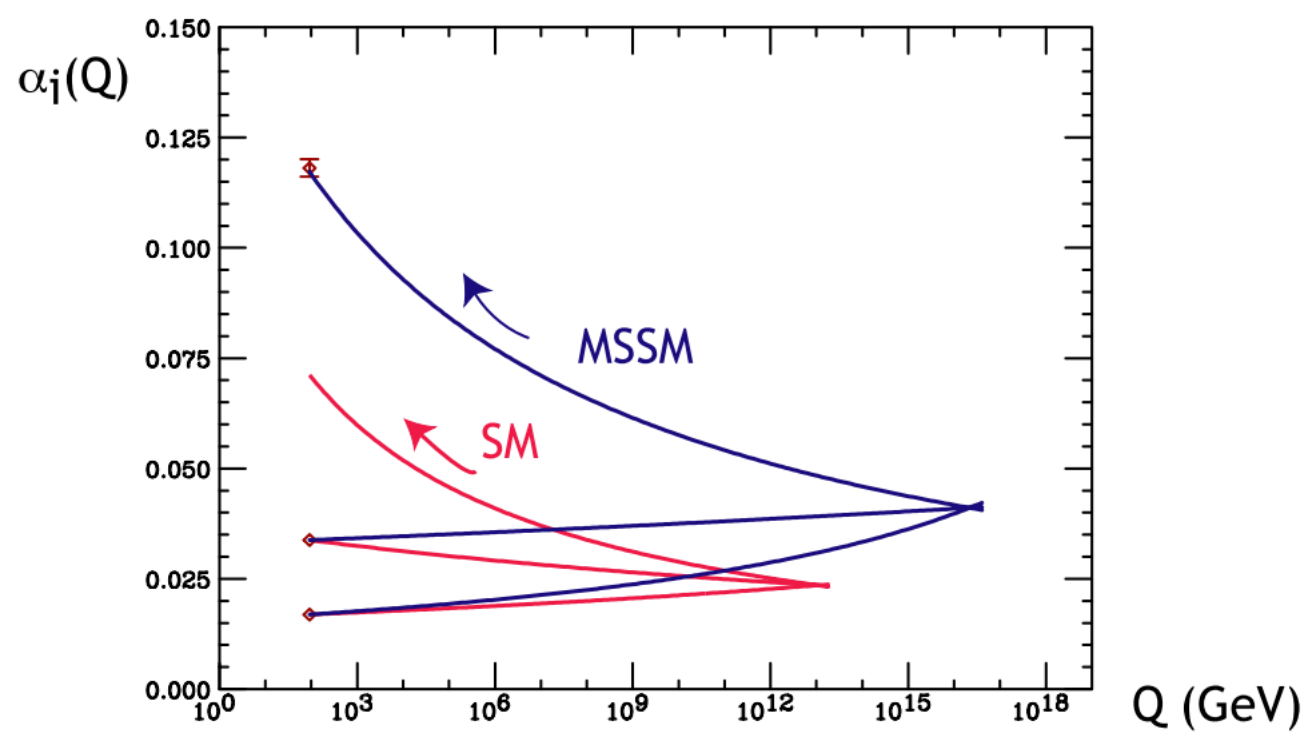
"The more minimal supersymmetric standard model"
Phys. Lett B388, 588 (1996), with Kaplan and Cohen

"It is important for our subsequent discussion to address the question of how much supersymmetry is enough to maintain naturalness. As was pointed out when the MSSM was introduced in [6], exact supersymmetry is not absolutely necessary."

"Dynamical supersymmetry breaking at low energies"
   Phys. Rev. D48, 1277 (1993)   w. Michael Dine
"Low Energy Dynamical Symmetry Breaking Simplified"
   Phys. Rev. D51, 1362 (1995) w. Dine and Yuri Shirman
"New Tools for Low Energy Dynamical Supersymmetry"
   Phys. Rev. D53, 2658 (1996) w. Dine, Shirman, Yossi Nir

In the early 90's, Nati Seiberg opened up the subject of the behavior of strongly coupled supersymmetric gauge theories. Ann asked, can supersymmetry be more than a device for a weakly-coupled model ?

Dine-Nelson 1993:

many new examples of dynamical SUSY breaking
an explicit model: $SU(7) \times SU(2) \times SU(3)_L \times SU(3)_R$
radiative feed-down of SUSY breaking to SM fields

Dine-Nelson-Shirman 1995:

simpler models with a U(1) "hypercharge" mediator

Dine-Nelson-Nir-Shirman 1996

Section II: Yet more models with dynamical SUSY
breaking
e.g. $SU(N) \times U(1)$ with
$$A_2 + F + (N-3)\overline{F} + (N-3)S$$

then, in Section III, we step back:

$$m_{\lambda_i} = c_i \frac{\alpha_i}{4\pi} \Lambda, \qquad (3.4)$$

where $c_1 = 5/3$, $c_2 = c_3 = 1$, and the parameter Λ,

$$\Lambda = \frac{F_X}{X}, \qquad (3.5)$$

sets the scale for *all* of the soft breakings in the low-energy theory. Masses for the squarks and sleptons appear due to gauge interactions at two loops. They are given by

$$\tilde{m}^2 = 2\Lambda^2 \left[C_3 \left(\frac{\alpha_3}{4\pi} \right)^2 + C_2 \left(\frac{\alpha_2}{4\pi} \right)^2 + \frac{5}{3} \left(\frac{Y}{2} \right)^2 \left(\frac{\alpha_1}{4\pi} \right)^2 \right].$$
$$(3.6)$$

"Dirac gaugino masses and supersoft supersymmetry breaking",

JHEP 08, 035 (2002) with Paddy Fox and Neal Weiner

"In this paper we propose extending the standard model to include the maximal amount of supersymmetry which is allowed by experimental and theoretical consistency."

gauginos in N=2 multiplets, coupling to matter in N=1 multiplets

"There are the 3-2-1 adjoint fermions Ai, which marry the gauginos to become massive. There are also fields Bi which ae the GUT partners of the Ai. These have no partner fermions to marry and hence remain massless. Discovery of such particles would give direct information about Grand Unification! These "bachelor fields" are naturally the source much of the new phenomenology of these models."

The feed-down of SUSY breaking through "supersoft" operators generated by Dirac gauginos has recently been taken up by Chakraborty, Martin, and Roy, Linda Carpenter, and Baer, Tata, and collaborators.

It is a physically motivated mechanism to explain why the gluino is far beyond the direct reach of the LHC.

The work takes inspiration from Seiberg's results on strongly coupled N=1 SUSY gauge theories with large flavor groups. Massless composite fermions are found in an antisymmetric tensor representation of the chiral symmetry.

Ann and Matt created a model that combines this with dynamical SUSY breaking to produce low-energy SUSY phenomenology. The gauge group is

$$SU(2)_1 \times SU(2)_2 \times SU(2)_3 \times SU(3)_c \times SU(2) \times U(1)$$

The analysis of this model is somewhat baroque.

"Step IV: $SU(2)_2$ confines at $\Lambda_2 = 300 \text{ TeV}$ ..."

"Step VI: For reasons that will be discussed in Sec. III, we expect soft supersymmetry breaking masses for scalars and gauginos, which are of order 100-1000 GeV, to be generated at a scale of about 30 TeV."

"The littlest Higgs", JHEP 07, 034 (2002)
with Ami Katz, Nima Arkani-Hamed, and Andy Cohen

The idea that the Higgs doublet field is a Goldstone boson of a high-scale symmetry breaking is a very attractive idea for explaining the naturalness of the Higgs vev.   The idea was originally put forward by Georgi and Pais and was worked out in detail in David Kaplan's thesis.

The early models turned out to be unnatural due to the requirement of generating a large Higgs quartic coupling.

In 2001-2002, Arkani-Hamed, Cohen, and Georgi took up this problem again. The pursued the idea that the theory could contain multiple chiral symmetries that individually forbid the masses of the Goldstone bosons. The Goldstones get mass only when a single diagram can include breaking terms for all of these symmetries ("collective symmetry breaking").

Ann jumped this program forward with a very simple and specific example — a nonlinear sigma model on the coset space SU(5)/SO(5) .

This model has two different global SU(2) subgroups that protect the Goldstone bosons, and these can be broken individually by coupling subgroups of SU(5) with the Standard Model gauge fields. This leads to a symmetry-breaking potential

$$cg_j^2 f^4 \sum_a \mathrm{tr}\left[(Q_j^a \Sigma)(Q_j^a \Sigma)^*\right] + cg_j'^2 f^4 \, \mathrm{tr}\left[(Y_j \Sigma)(Y_j \Sigma)^*\right]$$

Again, it was important to work through all of the details.

The top quark could be included in the model, but only together with a vectorlike top singlet partner. Integrating out the top and the partner, one finds a dynamically generated SU(2)xU(1) breaking potential. This competes with the gauge boson effects, but it is likely to be the largest (and negative) contribution to the Higgs field mass term.

In a UV model, SU(5)/SO(5) can result from strong interaction chiral symmetry breaking. In such a model, the vectorlike partner would need to be a massless composite fermion.

Conclusions ?

Wordworth's image of a theorist:

The antechapel where the statue stood
Of Newton with his prism and silent face,
The marble index of a mind for ever
Voyaging through strange seas of Thought, alone.

A cold, masculine ideal ?

Ann shattered this, but ...

Ann's lesson, Ann's ideals:

Everything in Nature happens for a reason.   If you don't know the reason, you haven't thought about it hard enough.

No model is too baroque to offer lessons. You need to follow the implications of each model to the end.

Whatever the outcome, there is joy in finding the path. And, in bringing your friends along on the climb.