So the LSP must be neutral and colorless, as weakly interacting as a neutrino, or weaker.

- In some cases this object is a good dark matter candidate!
- This is a consequence of R-parity — a new global symmetry — and not SUSY!!!!!
- Any new global symmetry (continuous or discrete) will give a new stable particle

Is SUSY is better than other theories because it gives you a dark matter candidate?! Hmmm...

Spectrum of superpartners??

The spectrum is not a simple list of the sparticles.

- The gluino and the first two generations of squarks/sleptons are pretty simple.
- The top squark and anti-top squark mix, giving two different scalar mass eigenstates t_1, t_2.
- Same for bottom squarks.
- The $\tilde{W}^+$, $\tilde{H}^+$ mix to form two "charginos" $\tilde{\chi}_i^{\pm}$.
- The $\tilde{W}^0$, $\tilde{X}^0$ [or $\tilde{B}^0$], and $\tilde{H}_u^0, H_d^0$ mix to form four "neutralinos" $\tilde{\chi}_i^0$.
- Higgses: $h^0, H^0, A^0, H^{\pm}$ mixtures of components of H_u, H_d.

NOTE:

- to figure out the parameters in the Lagrangian, we need to invert all this mixing!
- Thus need masses *and* mixing angles of **all** the charginos and neutralinos, stops, sbottoms, Higgses.
- This is VERY difficult at the LHC alone!!!
- We will be working with partial information for a very long time.

Must avoid causing flavor problem! Squarks/sleptons

- Degenerate (by charge)? Only 1st two generations??
- Aligned with quarks/leptons?
- Only 3rd generation light?
- $U(1)_R$-symmetric models with only dimension-6 flavor violation?

Lots of unfixed parameters. But in many models

- SUSY masses of sparticles are rather similar at high scales
- Running of masses due to interactions with gauge bosons are largest for colored particles.
- The colored particles end up heavier than the uncolored ones (factor of 5 – 10)
- But often not so heavy that they are more rarely produced than the uncolored ones!
- And also more spectacular and easier to separate from backgrounds than uncolored production.

So — typically (fine print fine print fine print)

- Gluinos and squarks are produced in pairs
- Each decays to high p_T jets plus a neutralino or chargino
- The neutralinos/charginos decay to LSMSP plus lower p_T leptons/neutrinos or jets

Thus every event gives two cascade decays, giving jets, maybe leptons/neutrinos, and two LSMSPs.

This structure is true of many classes of models, for similar reasons.

- Therefore, the same search strategies are also sensitive to many non-SUSY models also.
- Conversely, discovery of such a signal does not necessarily imply SUSY.

Now how do Gravity Mediation and Gauge Mediation typically differ? In the behavior and nature of the LSMSP.

In Gravity Mediation the LSMSP is the LSP, so it must be

- neutral
- colorless
- and thus invisible to the detector

which means the only options in the MSSM are

- Sneutrino (rarely in models)
- Neutralino (mix of $\tilde{W}^3$, $\tilde{X}$ [“Bino”] and $\tilde{H}$)

Therefore Gravity Mediation in **M**SSM gives large MET signals, no reconstructible resonances.

Now what about gauge mediation? Run the logic again:

- The LSMSP is NOT the LSP.
- Therefore it is NOT stable.
- Therefore it does NOT need to be neutral and colorless.

In minimal gauge mediation the colored sparticles are heavy.
So here we expect either the Bino or the $SU(2)$-singlet stau as LSMSP.

However in non-minimal gauge mediation there are other possibilities, including Wino and Higgsino.
(In more general models the stop and gluino have shown up as LSMSPs!)

Start with the neutralino $\tilde{\chi}^0$ case:

- Typically $\tilde{\chi}^0 \to \tilde{G}$ plus γ or Z or h^0.

What is its lifetime? Variable!

$$c\tau_{\tilde{\chi}^0} = 10^{-2}\ \text{cm} \left(\frac{\sqrt{F}}{100\ \text{TeV}}\right)^4 \left(\frac{100\ \text{GeV}}{m_{\tilde{G}}}\right)^5 \times \text{function of mixing angles}$$

- If the lifetime is very long, back to gravity-mediation signal (not too hard)
- If the decays are prompt, each event has two of these particles, plus somewhat reduced MET.
  - if two photons in each event, very easy.
  - if two Z/h in every event, challenging.
- If the decays are highly displaced, event can have
  - non-pointing photons
  - pairs of leptons appearing from nowhere
  - pairs of jets appearing from nowhere

  all of which can be challenging to very challenging experimentally.

If instead the $\tilde{\tau}$ is the LSP, then typically one has a chain like

$$\tilde{g} \to q\bar{q}\tilde{\chi}^0 \to q\bar{q}\tau\tilde{\tau} \to q\bar{q}\tau\tau\tilde{G}$$

so there are four τs in the event! Striking!

And if the $\tilde{\tau}$ is long-lived, it gives a CHAMP signal: a heavy muon-like particle, sometimes slow. (Discover using dE/dx and slow time-of-flight.)

The full richness of the possible phenomenology could take us a week. See two recent long (and not exhaustive!) papers by Meade, Reece and Shih.

LESSON: Even within the MSSM, the predictions for what we might observe vary enormously.

The map between models and signatures is extremely nonlinear!! Not just in SUSY!

Once we discover some process with these characteristics, we've just begun the battle.

- Figure out what we are looking at!
  - What might be the basic process we're seeing?
  - What might be the masses and quantum numbers of the particles involved?
- Show that this is actually consistent with one or more SUSY models.
  - Test whether SUSY is really true
  - Determine the parameters in the SUSY Lagrangian

This process might take a LONG time (extending beyond LHC) and could be very ambiguous and tortured.

- Many non-SUSY models predict jets, leptons and MET.
- Many non-minimal SUSY models differ from the minimal one by a LOT.

But hopefully there will be a simplest possible guess, and hopefully it will be true.

Composite Higgs models and their Gauge/String duals

All such models have trouble: how to generate FHf in a reasonable way? and without FCNCs?

Technicolor

This is a very general idea. It's simplest realizations don't work at all, but it is so simple that perhaps a variant of it is right.

Just as QCD breaks global $SU(2)_L \times SU(2)_R \to SU(2)_V$ at 300 MeV through strong dynamics, perhaps TQCD breaks gauged $SU(2)_W \times U(1)_Y \to U(1)_{EM}$ at 246 GeV through strong dynamics.

- $\pi^{\pm}, \pi^0$ of QCD $\Rightarrow$ $\mathcal{G}^{\pm}, \mathcal{G}^0$ of W, Z bosons
- wide, heavy, almost undetectable σ resonance of QCD $\Rightarrow$ wide, heavy h^0
- dramatic $\rho^{\pm}$, ρ^0, ω resonances at 800 GeV $\Rightarrow$ dramatic $\rho_T^{\pm}$, ρ_T^0, ω_T resonances at TeV scale

Thus technicolor predicts possibly unobservable heavy Higgs and new TeV-mass resonances.

Technically: Use the equations for the pions of QCD, but replace quarks u, d with techniquarks U, D, and replace $SU(3)_C \times SU(2)_L \times SU(2)_R$ with $SU(N)_{TC} \times SU(2)_W \times SU(2)_R \supset U(1)_Y$

In QCD these σ, ρ, ω resonances couple strongly to $\pi\pi$, so in TQCD the corresponding resonances couple strongly to $\mathcal{G}\mathcal{G}$ — the longitudinal W and Z bosons.

- They do not couple strongly to light quarks or gluons — difficult to produce!
- Must study scattering of longitudinal W, Z bosons using Vector Boson Fusion.
- Or rare $gg \to \omega_T \to WWZ$. (Luty)

Problem: very large background at LHC from scattering of *transverse* W, Z bosons!!! (SSC would have been a lot better.)

In some variants of technicolor $\bar{t}$ and perhaps $Q_3 = (t\ b)$ are also composite.

Then $\rho_T \to t\bar{t}$ decays, etc.

But the essential problems with Technicolor are:

- How to do all of this without messing up precision electroweak measurements.
  - Expect effects of order $(100\ \text{GeV}/M_{\rho_T})^2$, pushes M_{ρ_T} up to 3 TeV (?)
- How to generate FHf terms without new interactions that also generate flavor-violating $FFFF$ or $FFff$ or $ffff$ terms that lead to large FCNC's.
  - Coefficients of 1/ (few TeV)^2 expected; but 1/(100 TeV)^2 by small $K\bar{K}$ mixing.

Theorists have trouble solving these problems but technicolor is not rigorously excluded.

Warped Extra Dimensions a la Randall-Sundrum: 4 + 1 (+ 5?) additional dimensions where the 4+1 form an approximately AdS space with coords x^μ, r.

We'll consider the case with a cutoff at both large and small r

- Think of small r cutoff as dual to an IR cutoff from a confining scale (doesn't have to be but we could create such models)
- Think of large r cutoff as dual to new physics, such as a scale where gravity and a string compactification become important.

In AdS/CFT,

- global current in the CFT ⇒ bulk gauge field in *AdS*
- hadrons created by global current in an confining CFT ⇒ tower of KK-modes of bulk gauge field in *AdS* with small-r cutoff.
- gauged current in the CFT ⇒ bulk gauge field in *AdS* plus a 4-d mode at boundary that couples to it
- hadrons and gauge field in a UV-cutoff/IR-cutoff CFT ⇒ tower of KK-modes bulk gauge field in *AdS* plus a 4-d mode at boundary;
  this extra mode can also be treated as a zero mode in the bulk.

We have W boson and (as in QCD) a ρ_T, above which is a ρ', a ρ'', etc.

So we put $SU(2) \times U(1)$ (at least) in the bulk and this gives us W^a_μ and X_μ at the bottom of a tower of composite spin-one bosons.

Then we need the IR cutoff at small r to encode the breaking of $SU(2) \times U(1)$.

This can be done with a bulk Higgs-like boson which gets an r-dependent vev and breaks $SU(2) \times U(1) \to U(1)$ at small r.

Thus qualitatively Technicolor and this type of Warped Extra Dimension are dual

- traditional Technicolor is QCD-like, and is excluded.
- AdS/CFT is calculable at large N, g^2N — not very QCD-like. Is this variant any better?

Not really; it shares the same problems as technicolor.

The attempts at solutions for these problems have duals, but they are not really any better.

There still really isn't a satisfying model of technicolor, but... are we just lacking in imagination? or lacking a technical idea?

Additional possible predictions of warped extra dimensions:

Kaluza-Klein Graviton: Spin-two resonance

- This is like a spin-two glueball of a technicolor theory.
- In QCD glueballs fall apart very rapidly to $\pi\pi$ and are too wide to observe. We might expect this in TQCD.
- In some variants of RS models (realistic?) there are narrower spin-two particles that can be produced in gg and decay often to $\gamma\gamma$.
- Couplings to light fermions such as e^+e^- are often mentioned, but this requires a definite model of flavor that avoids flavor-changing neutral currents (issue often ignored in the literature.)

Kaluza-Klein Gluon:

If there is also a tower of states above the gluon (as may well occur if the $\bar{t}$ or $(t\ b)$) then there may be a resonance easily produced in gg and decaying to $t\bar{t}$.

How to reconstruct? t will be highly boosted and looks like an unusual fat jet with three subjets.

Techniques for reducing QCD background have been developed successfully by experimentalists (Brooijmans) and by theorists (JHU group) in the last two years.

"Higgsless Models"

Take AdS seriously: solve the unitarity problem through a tower of KK W, Z bosons and NO Higgs boson.

Essentially dual to a limit where H is a very high dimension operator and the Higgs is never produced.

Realistic flavor??!

Predicts tower of KK W bosons. (But these look like techni-rho tower.)

Formally interesting because of solution to unitarity problem, but probably not realistic.

Experimentally all of these models with towers of states unfortunately will probably only put one (or possibly two) of them in the LHC reach.

Little Higgs

In Technicolor, the Higgs is like the σ of QCD: heavy, wide, and decaying to WW, ZZ.

In Little Higgs, the Higgs is like a Kaon of QCD — so it is light — but with a potential to make it develop a vev.

For instance: if we take $SU(3)_L \times SU(3)_R$ and embed $SU(2) \times U(1)$ so that $SU(2)_L$ rotates $u \leftrightarrow d$, then (K^+, K^0) is a doublet under $SU(2) \times U(1)$, just like H is supposed to be.

$$\begin{bmatrix} \pi^0 & \pi^+ & K^+ \\ \pi^- & -\pi^0 & K^0 \\ K^- & \bar{K}^0 & \eta \end{bmatrix}$$

caution: the diagonal entries are simplified here to keep the matrix from being unnecessarily cluttered

Inside of $SU(3) \times SU(3)$ is $SU(2) \times U(1)$.

Now arrange some dynamics so that $\langle K^0 \rangle$ is nonzero and you break $SU(2) \times U(1) \to U(1)$.

Gauging $SU(2) \times U(1)$ explicitly breaks the $SU(3) \times SU(3)$, so the "h^0" in the "Kaon" becomes a PNGB — but still light!

Not quite light enough:

$$m_h^2 \sim \frac{g_2^2}{4\pi} \Lambda^2$$

at one loop.

But there's a trick: Collective Symmetry Breaking. Quick toy example (ignore hypercharge for now):

- Imagine a larger global symmetry structure G with $SU(2) \times SU(2)$ embedded in G.
- Break G spontaneously so that
  - $SU(2) \times SU(2) \to SU(2)_D$ which we will identify as $SU(2)_W$.
  - There is a complex scalar doublet of the diagonal $SU(2)$.
- Break G explicitly by turning on gauge couplings g_2, g_2' for $SU(2) \times SU(2)$
- Break the gauge group to diagonal $SU(2)_W$.
- If G is such that if *either* $g_2 = 0$ or $g_2' = 0$, "h^0" is still exact NGB, then $m_h^2 \propto g_2 g_2'$ or $(g_2 g_2')^2$.
- *But there is on one loop graph that goes like* $g_2 g_2'$.
- *So the* h^0 *mass is generated at higher order:*

$$m_h^2 \sim \frac{g_2^2 g'^2}{(4\pi)^2} \Lambda^2$$

This only suppresses the Higgs mass by one order in perturbation theory, unlike SUSY.

But means the UV cutoff (the strong coupling scale) could be 10 TeV, not 1 TeV as in technicolor.

But how does this work? What suppresses the usual corrections to Higgs mass from W, Z, t?

Requires W', Z', t', H' with **same spin** as W, Z, t, H but naturally **opposite-sign couplings** to Higgs so that loop graphs cancel, as they do in SUSY.

Suppressing m_h requires their masses be less than or of order 1 TeV.

So LHC will observe W', Z', t' (b'?), H's: partners with the SAME spin.

However there are various types of models with various signatures; too long a subject.

Breakdown of Quantum Field Theory?!

This doesn't seem especially likely (wouldn't we have seen signs by now?)

One example: if there are rather flat Large Extra Dimensions, then full-fledged higher-dimensional quantum gravity (NOT dual to gauge theory) could await us.

$$M_{Planck}^2 = Volume \times (M_{Planck}^{(true)})^D$$

Really?!

Well, at least we know what to expect:

- Stringy resonances (if string coupling not too large)
- Black holes (at the highest energies)
  - Decays via Hawking Radiation
  - Quasi-spherical-thermal distribution of SM particles
  - BUT usual assumptions of universality of Hawking radiation probably false so close to Planck scale

However, some other, more subtle, breakdown in QFT seems much less radical to me.

String theory has revealed some difficult-to-understand dynamics.

- Non-commutative field theory
- Non-geometric compactifications
- Little String Theory (M5 brane)

Perhaps one of these, or one yet undiscovered, awaits us? and resolves the hierarchy and flavor problems in a fashion that we have not yet imagined?

Going beyond — well beyond — the minimal versions of models.

- As theorists, we don't care much about non-minimal models.
  - The minimal model solves the hierarchy problem.
  - A non-minimal model is simply more complicated and makes fewer predictions.
- But the effect on experimentalists is totally different.
  - A small change in a Lagrangian or mass spectrum can completely change the signatures.
  - If experimentalists only prepare for minimal versions of a minimal model, they are not truly prepared.
  - Theory bias could delay discoveries by years, or even decades.

A little investigation reveals that many non-minimal models, though they fail Occham's razor, pass Strassler's machete.

And a little history reveals that the SM itself is/was not minimal

- 3 generations, not 1 ("who ordered that?!")
- Neutral currents ($SU(2) \times U(1)$ instead of just $SU(2)$.)
- Neutrino masses (or at least neutrino masses bigger than 1 meV.)

So we'd better think about this.

We have already seen that adding just one particle can completely change Higgs physics.

What about adding a sector as rich as the SM itself?

An enormous class (by no means exhaustive) of experimentally allowed and theoretically reasonable models involve adding a hidden sector to your favorite minimal model.

For example: Gravity-Mediated SUSY plus a sector of 3-2-1 neutral particles, but with their own interactions, coupled to the SM somewhere in the 1 GeV to 100 TeV scale.

Call the lightest superpartner in the hidden sector the LHSP (lightest hidden sparticle.)

If the LSMSP is heavier than the LHSP, then the LHSP is the LSP and the LSMSP decays into the hidden sector!

Note

- This can make a gravity-mediated model look like a gauge-mediated model, with $\tilde{\chi}^0 \to \gamma/Z/h$ plus invisible.
- Just as in gauge mediation, the LSMSP no longer need be neutral; it could be a stau, stop or gluino.
- Just as in gauge mediation, the LSMSP lifetime can be short, medium or long.

- In a class of models called “hidden valleys”, some of the hidden sector particles produced in the LSMSP decay themselves decay back to the SM
  - This makes the final state potentially much more complicated.
  - The MET can be reduced significantly.
  - Interpreting the model as a SUSY model will be tied up with understanding the hidden sector — will be confusing.
  - The range of possible hidden sectors – and thus final states of SUSY events – is mind-boggling.

Possible Hidden Valley signatures include but are not limited to

- several low-p_T $b\bar{b}$ pairs
- new light or ultra-light (“dark photon” or “dark vector boson”) e^+e^- or $\mu^+\mu^-$ resonances
  - possibly clustered
  - possibly widely distributed
- many long-lived particles
- or perhaps short-lived, but all emerging from a long-lived LSMSP

Are we prepared?

Could we have missed SUSY at the Tevatron? Have we asked the wrong questions?

Is new physics slipping by the trigger? the reconstruction software? the analysis techniques?

Final Remarks

- This is a difficult experimental endeavor, with many unknowns and many challenges.
- It is the only near-term hope for breaking through the bottleneck that has paralyzed our field for over 30 years.
- If it is a failure... [...]
- Enormous efforts are necessary to ensure its success
- Theorists’ role is to help with understanding backgrounds and assisting with search strategies
- Theoretical bias is a concern and we need to be on the lookout for blind spots in our thinking

Wish us luck! Hopefully at the next TASI, or the next, we’ll be talking about interpretation of LHC discoveries.