Lecture 2

A Tough Question for Supersymmetry

Pick up where we left off last time:

Nice theory home for Split Supersymmetry

Unique signatures for cosmology and colliders

Back to naturalness: Further inquiries on the Higgs mass crisis

Tough Challenge to Supersymmetry

It should have been found by now!

Why?

Because…

… it's been around for so long!

Response: Nature does not care how long we wait to get experimental tools to find/confirm something.

Because …

… experts have said it will be showing up in the next experiment for a long time!

Response: Nature does not care what excitable/optimistic people say. We do not worry about SM Higgs boson because of that argument either. Nor are recently thought-of alternatives.

Normal naturalness criterion has been ‘new physics at or below about 1 TeV’ since birth of SUSY pheno, and many other beyond SM theories that stabilize the hierarchy.

1 TeV not so magical, but even that we are far from
sleptons/gauginos > 100 GeV
Squarks/gluinos > 300 GeV
Light Higgs mass bound concern, but precise nature of Higgs sector is subject to discussion without affect utility of SUSY.

Because …

… it’s speculation [said with derision].

Response: (First, see initial John Steinbeck quote.)

Speculation has led to all of our discoveries.

At this point, all ideas regarding EWSB issues are speculative, including the ‘Higgs boson’

No collider gets built without speculations.

Before-the-fact speculation may be required for discoveries to be made. (No Pink Elephants expected to stroll by.)

Because …

… the speculation is too grand, too ambitious!

Response: I find this the most interesting.

How to assess over-ambitiousness of theory?

Not too ambitious if …

It solves a pressing problem around the corner? Yes

Not too many implications or “gears” per problem solved? Maybe

High ambition correlates with lower probability …

Karl Popper rightly said:

"… if we aim, in science, at a high information content … then we have to admit that we also aim at a low probability."

"… only … an improbable theory is worth testing."

SUSY has high information content and may even be 'improbable', but it is certainly worth testing by all measures.

Picking up where we left off last time…

Ignoring Naturalness

Eliminating bad things:

1. FCNC
2. Proton decay strains
3. CP Violation
4. Too light Higgs mass

Accomplished by large scalar susy masses, but light fermion susy masses (gauginos, higgsinos)

Preserving good things:

- SUSY
- Light Higgs prediction
- Gauge Coupling Unification
- Dark Matter

Good theory for this? Yes.

The -ino masses charged under symmetries (R and PQ) whereas scalars are not. [Split SUSY literature.]

Non-singlet SUSY breaking

SUSY breaking accomplished by non-singlet.
Scalars don't care:

$$\int d^4\theta \frac{X^\dagger X}{M_{\rm Pl}^2} Q^\dagger Q \Longrightarrow \frac{F^\dagger F}{M_{Pl}^2} \tilde{Q}^\dagger \tilde{Q} \quad (m_{\tilde{Q}}^2 \simeq F^\dagger F / M_{\rm Pl}^2)$$

On the other hand, gauginos do care:

$$\int d^2\theta \frac{X}{M_{\rm Pl}^2} WW \quad \text{not gauge invariant } M_\lambda = 0$$

Assuming cosmological constant = 0 (I.e. tiny)
the gravitino mass is

$$m_{\tilde{G}}^2 = \frac{F^\dagger F}{M_{\rm Pl}^2}$$

Mass Spectrum

In this case, leading contribution to gaugino mass can be, e.g., the AMSB contribution:

$$M_\lambda = \frac{\beta(g_\lambda)}{g_\lambda} m_{\tilde{G}}$$

(Randall, Sundrum; Giudice, Luty, Murayama, Rattazzi)

The complete spectrum is

(light gauginos)

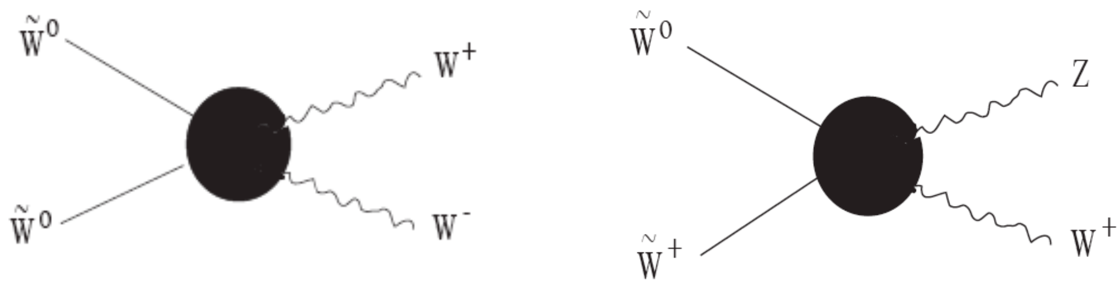
$$\begin{aligned} M_3 &\simeq M_{\tilde{G}}/40 \\ M_2 &\simeq M_{\tilde{G}}/320 \\ M_1 &\simeq M_{\tilde{G}}/120 \end{aligned}$$

LSP is Wino!

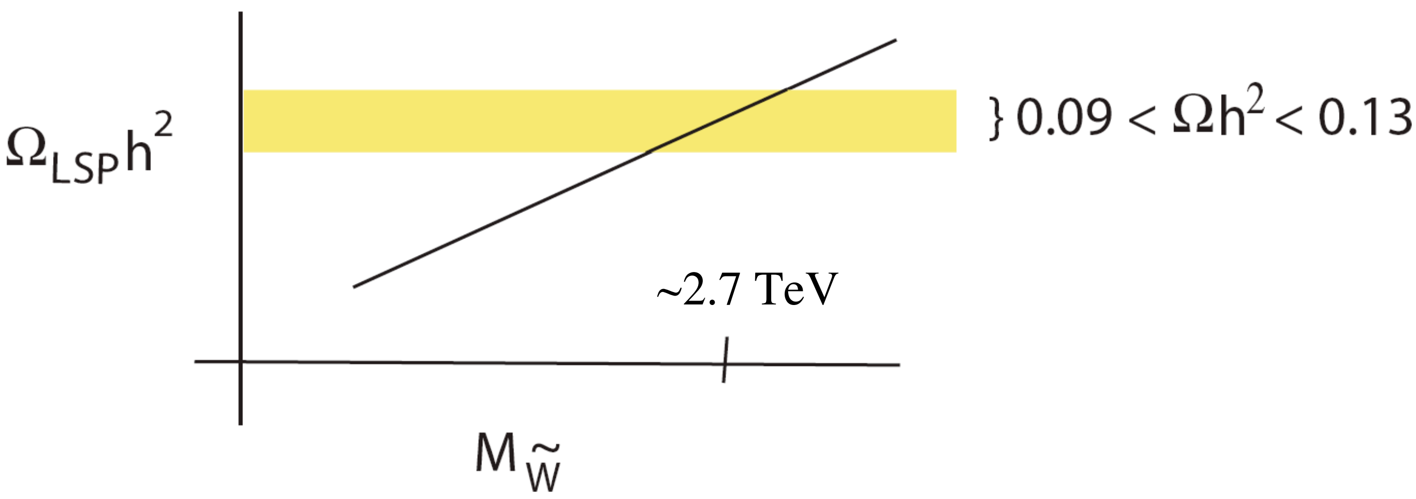
$$M_{\tilde{Q}} \sim M_{\tilde{e}} \sim M_{\tilde{G}}$$ **(Heavy scalars)**

Wino Dark Matter

Winos annihilate very efficiently



Mass must be quite high to be good CDM



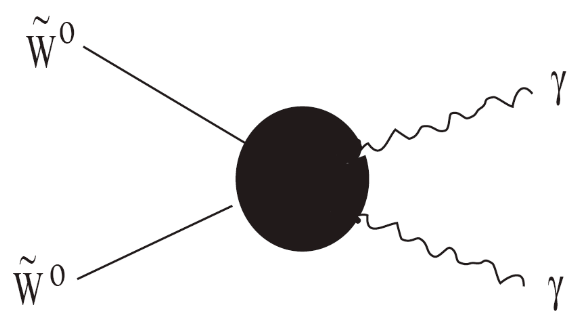
Thermal CDM and PeV Scale SUSY

If Wino is the CDM, the SUSY breaking mass is about a PeV

$$m_{\tilde{G}} \sim m_{scalars} \sim 1\,PeV$$
$$M_2 \sim 2\,TeV,\ M_1 \sim 6\,TeV,\ M_3 \sim 14\,TeV$$

This case: little hope for the LHC

Best hope: Wino annihilations in the galactic halo into detectable monochromatic photons.



(enters photon detector)

But …the gravitino is very heavy

It decays very rapidly … well before BBN

Non-thermal CDM source:
Inflation -> many gravitinos -> gravitino decays to Winos -> Good CDM (even if thermal prediction tiny)

$$\Omega_{LSP}^{\tilde{G}} \sim 30\left(\frac{M_2}{100\,GeV}\right) T_{13}(1-0.03\ln T_{13}),\ where\ T_{13} = \frac{T_R}{10^{13}\,GeV}$$

$T_R \sim 10^{11}\,GeV$ works well for $M_2 \sim 100\,GeV$

Thus any Wino mass less than 2.7 TeV limit can be good CDM.

Collider Implications

Example spectrum:

$$M_2 = 100\, GeV\ (wino)$$
$$M_1 = 300\, GeV\ (bino)$$
$$M_3 = 700\, GeV\ (gluino)$$
$$m_{\tilde{G}} \sim \mu \sim m_{scalars} \sim 36\, TeV$$

- Scalars are out of reach
- Binos are not produced
- Higgs mass predicted to be above current limit (but <140 still)
- Wino and gluino production give colliders hope

Wino Mass Splittings 1/2

Gherghetta, Giudice, JW, 98

Mass splitting of the charged and neutral Wino ($\tilde{W}^{\pm}$, $\tilde{W}^{0}$) occurs by operators

$$\mathcal{O} \sim M_{ab}\tilde{W}^{a}\tilde{W}^{b},$$

where M_{ab} must transform non-trivially under $SU(2)$. Lowest order operator is

$$\mathcal{O}_{\rm splitting} = \frac{1}{\Lambda^{3}}(H^{\dagger}\tau^{a}H)(H^{\dagger}\tau^{b}H)\tilde{W}^{a}\tilde{W}^{b}.$$

Wino Mass Splitting 2/2

Therefore, mass splitting at tree-level scales like $\sim m_W^4/\Lambda^3$, where Λ is heavy mass scale of integrated out particles. Expression for large μ and M_1 is

$$m_{\chi_1^\pm} - m_{\chi_1^0} = \frac{m_W^4 \sin^2 2\beta}{(M_1 - M_2)\mu^2} \tan^2\theta_W + \frac{2m_W^4 M_2 \sin 2\beta}{(M_1 - M_2)\mu^3} \tan^2\theta_W + \ldots$$

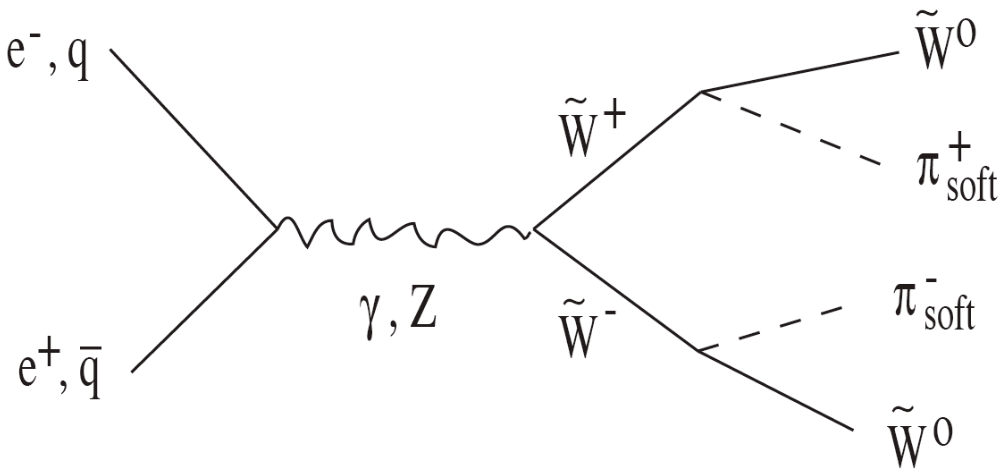
There are also important loop corrections. In the $\mu \to \infty$ limit,

$$(m_{\chi_1^\pm} - m_{\chi_1^0})_{\text{loop}} = \frac{\alpha M_2}{\pi \sin^2\theta_W}\left[f\left(\frac{m_W^2}{M_2^2}\right) - \cos^2\theta_W f\left(\frac{m_Z^2}{M_2^2}\right)\right]$$

$$\lim_{M_2\to\infty}(\cdots) \implies \frac{\alpha m_W}{2(1+\cos\theta_W)} \simeq 165\,\text{MeV}.$$

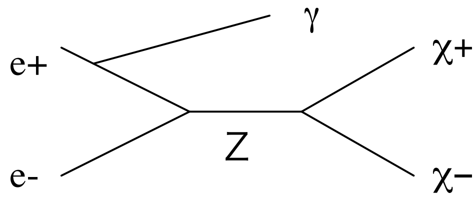
Wino Production and Decays

The mass splitting between charged and neutral is tiny.

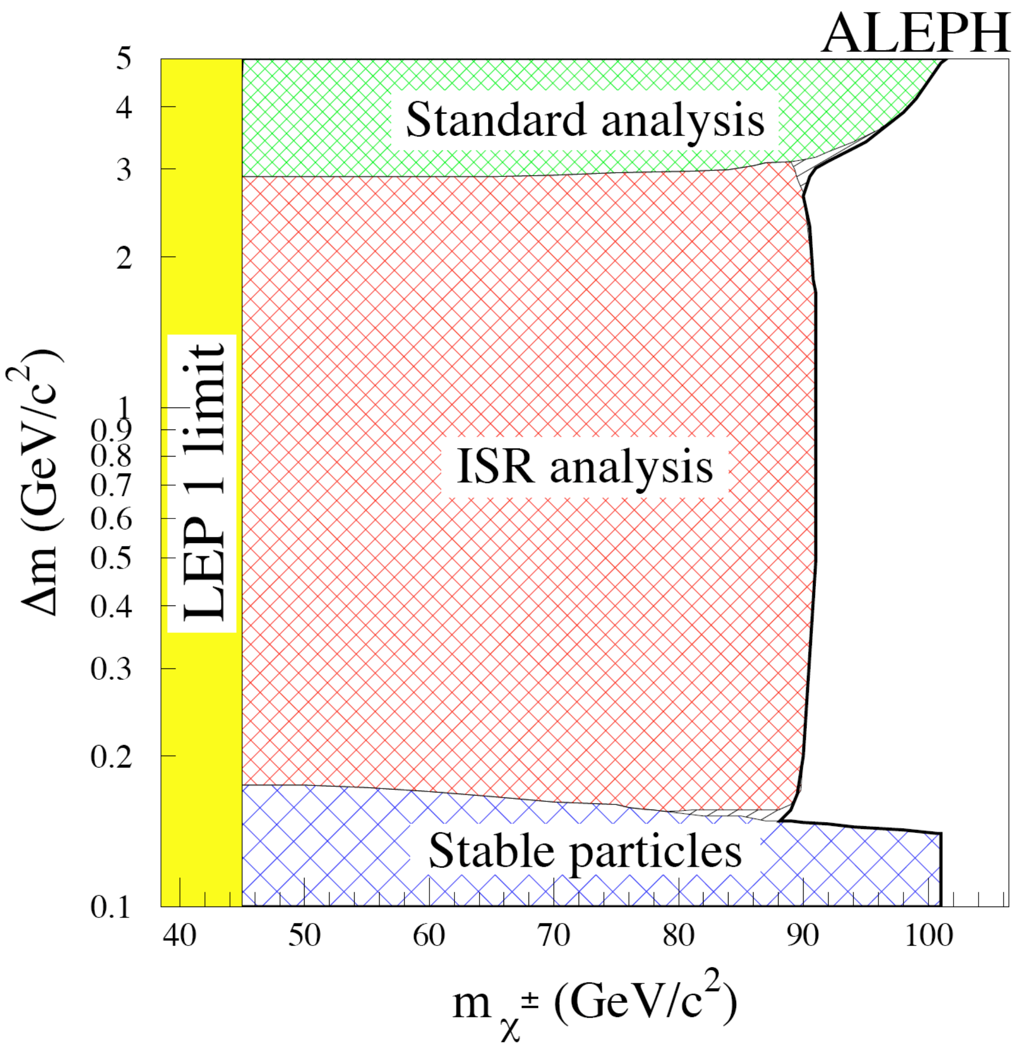


As it stands, difficult. LEP has limits (next slide).
Hadron colliders cannot trigger on soft pions.
Trigger on initial state gluon (Tevatron/LHC).
Can this be done?

ISR Analysis



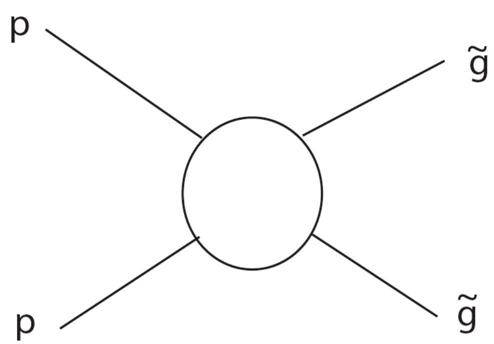
LEP Searches

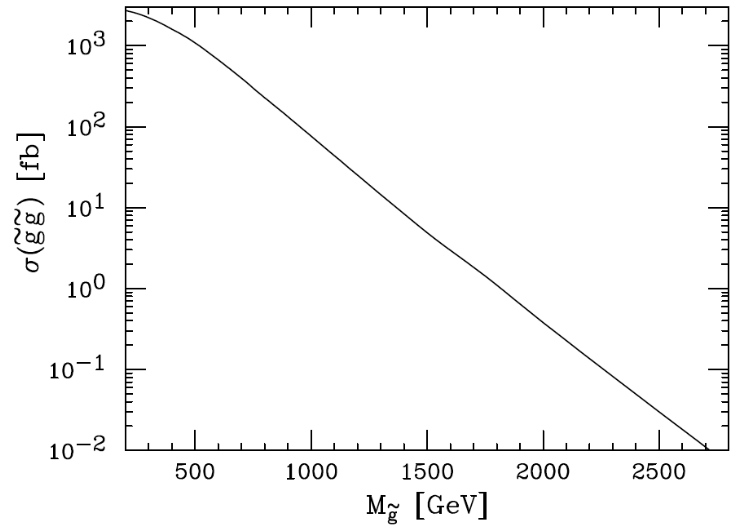


Wino mass limit
From LEP is
~ 90 GeV with
Small mass
Splitting.

ALEPH Collaboration,
hep-ex/0203020

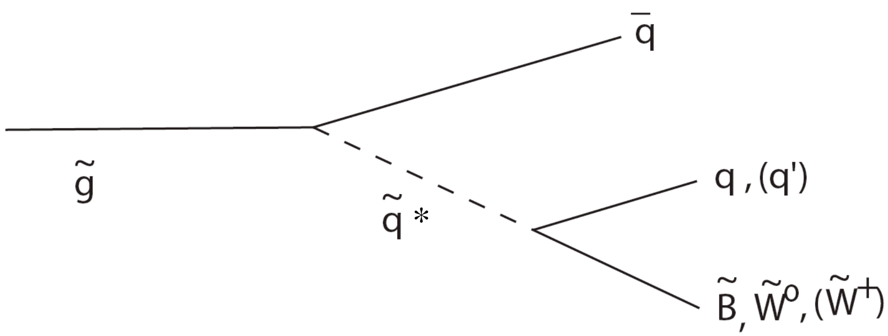
Gluino Production and Decays





Pythia output

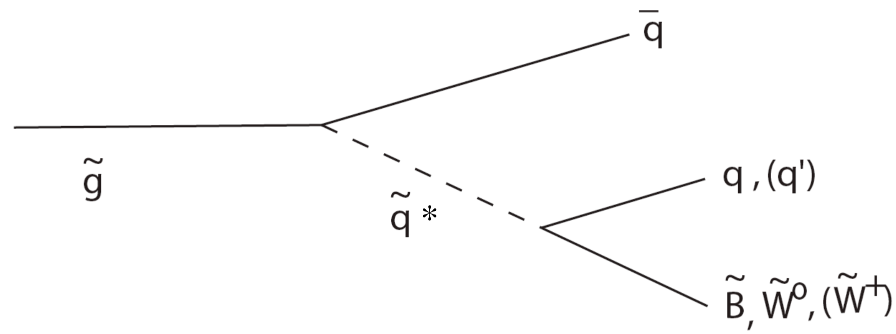
Main decay is three-body through off-shell squark



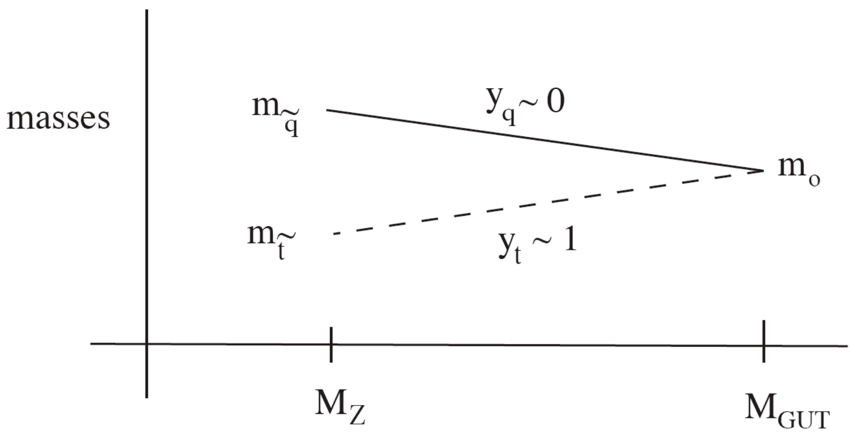
(Toharia, JW for more details on gluino decays within this scenario)

Preference for 3rd generation

The lighter the squark the higher the BR to its corresponding quark



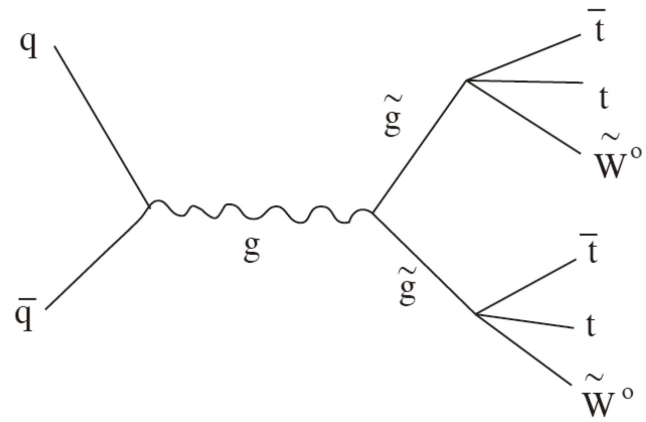
$$\frac{d\tilde{m}^2_{q_i}}{d\log Q} = -\frac{32}{3}M_3^2 + a_i y_{q_i}^2 \tilde{m}^2_{q_i} + \cdots \quad (a_i \text{ is positive})$$

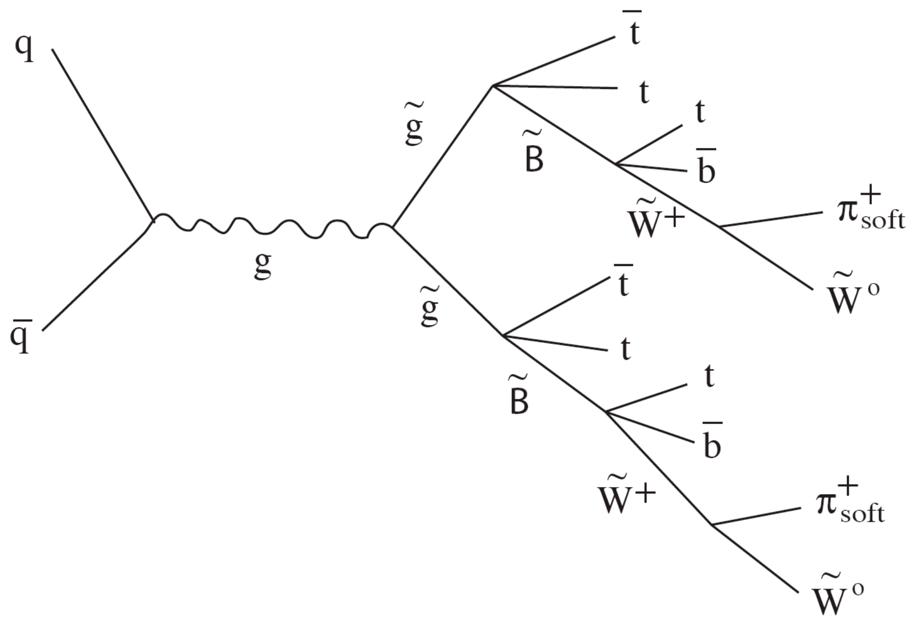


There is a generic preference for decays into 3rd generation quarks.

High multiplicity tops+MET events

Simplest event type: 4 top quarks plus missing energy. Can the missing energy be measured?





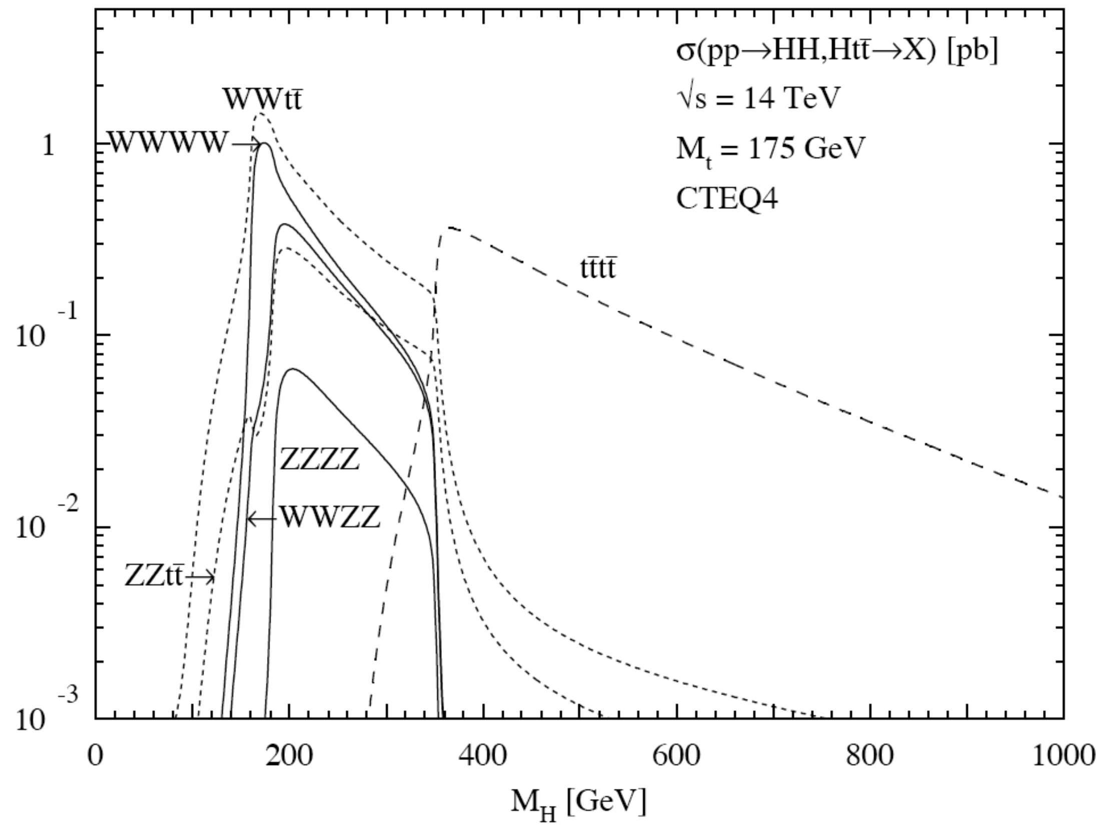
Combinatoric/experimental Challenge.

6 tops + 2 b's + 2 pions + MET

Non-SUSY Signature Equivalences

Higgs bosons
Strongly coupled
To the top quark
Can produce
4-top events
Copiously.

No missing E_T
Expected in this
Case.

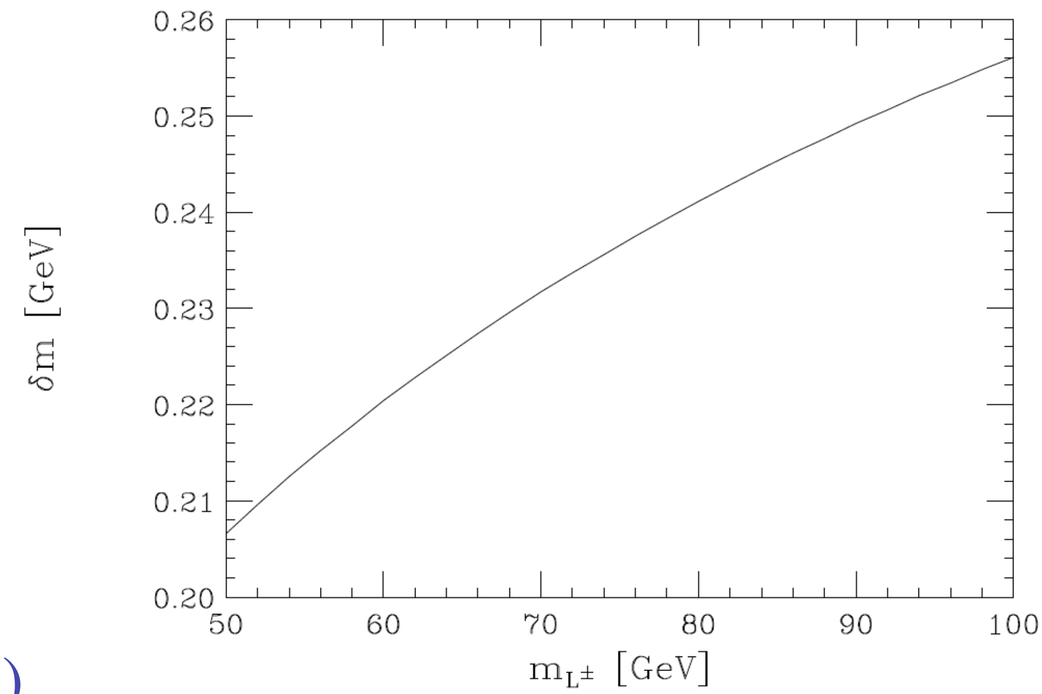


Spira, JW, 97

Lepton Vector-Like Doublets

$$\Delta\mathcal{L} = m_{L^\pm}\bar{L}L$$

Assume vector-like doublets. Mass generation not through Higgs.
Mass splitting issues similar to Wino. (Higgsino qualifies.)



Thomas, JW, 98

$$\delta m = \frac{\alpha}{2} m_Z f(m_L^2/m_Z^2)$$

where $f(r)$ is the loop function

$m_L^2 \gg m_Z^2$ is $\delta m = \frac{1}{2}\alpha m_Z \simeq 355$ MeV

$$f(r) = \frac{\sqrt{r}}{\pi} \int_0^1 dx\ \ (2-x)\ln\left[1 + \frac{x}{r(1-x)^2}\right].$$

Small mass Splitting. Challenge

For $r \ll 1,\ f(r) \to 0$ and for $r \gg 1,\ f(r) \to 1.$

Remarks on Extra Singlet Solution to Higgs Mass Problem

Introduce a SM singlet and a Z_3 symmetry to the superpotential:

$$W = \lambda S H_u H_d + \lambda' S^3 + \cdots$$

ϕ^4-like contributions to Higgs mass arise from $F_S^\dagger F_S$ contributions to the scalar potential.

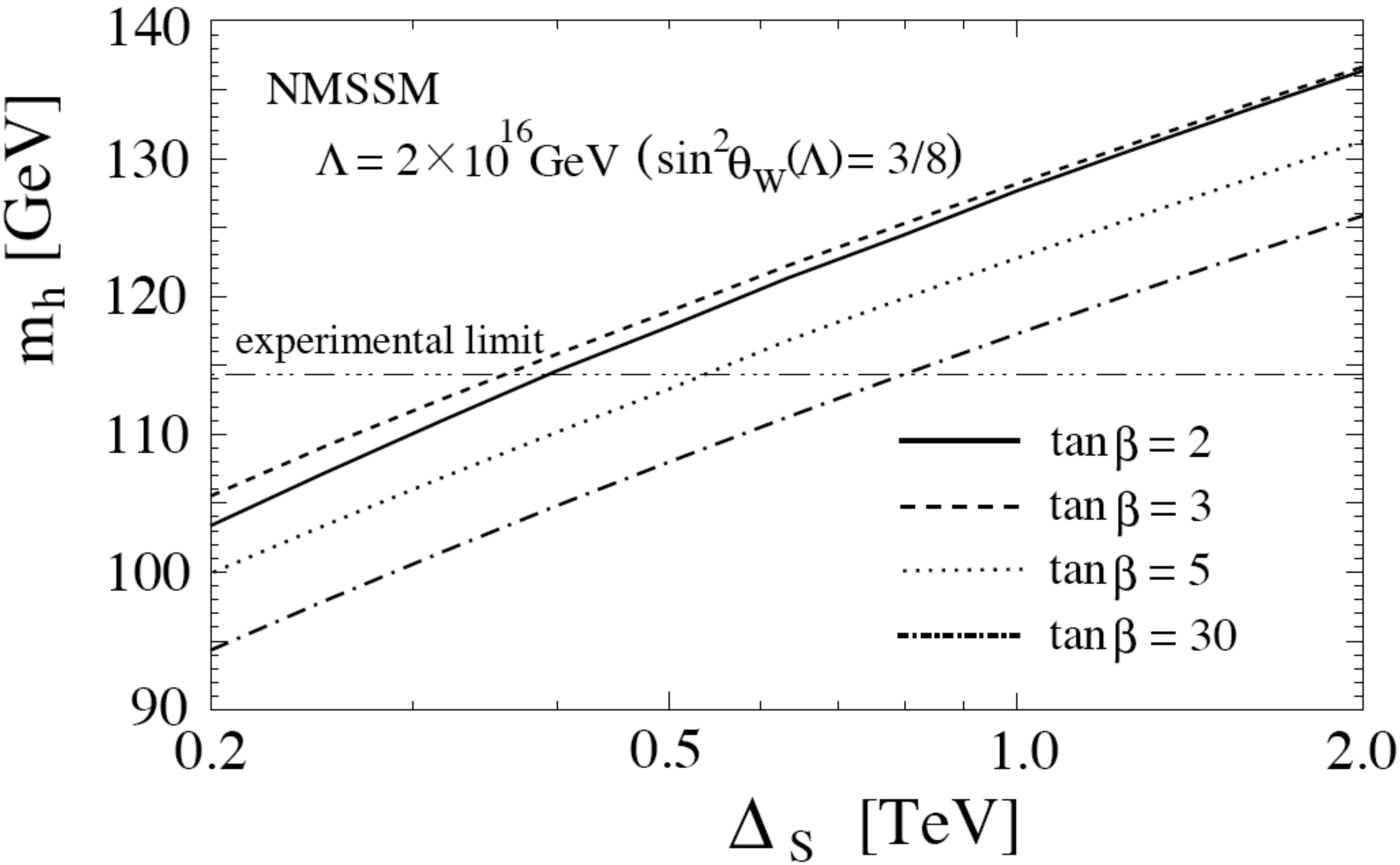
The Higgs mass bound then becomes

Normal radiative Corrections.

$$m_h^2 = m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta + \delta m_{h,rad}^2$$

Assuming λ perturbative up to unification scale ($M_U \simeq 2 \times 10^{16}$ GeV), gives predictions for the "reasonable upper limit" of lightest Higgs in NMSSM.

Easier to get m_h>114 GeV now



Not so fast …

Maybe NMSSM is end of this story....
However, there are well-known challenges.

Add a singlet S and impose a Z_3 to bypass new μ' problem:

$$W = \lambda S H_u H_d + \kappa S^3$$

However, domain wall problem in breaking the Z_3 during EWPT.

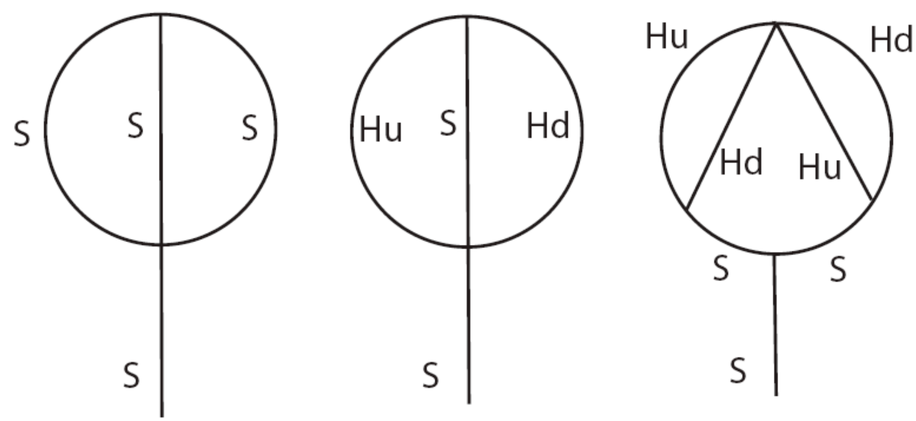
$\Rightarrow$ Must break Z_3 at higher order.

Destabilizes Hierarchy

Some terms that break the Z_3 symmetry:

$$W_{break} = \lambda_1 \frac{S^4}{M_{\rm Pl}} + \lambda_2 \frac{S^2(H_u H_d)}{M_{\rm Pl}} + \lambda_3 \frac{(H_u H_d)^2}{M_{\rm Pl}} + \cdots$$

This leads to tadpole divergences, and the return of the μ problem:



(Abel, Sarkar, White)

$$V_{\rm ind} \sim \frac{\lambda_1 \kappa}{(16\pi^2)^2} S M_{\rm Pl} m_{3/2}^2 + \frac{\lambda_2 \lambda}{(16\pi^2)^2} S M_{\rm Pl} m_{3/2}^2 + \frac{\lambda_3 \lambda^2 \kappa}{(16\pi^2)^3} S M_{\rm Pl} m_{3/2}^2 + h.c.$$

Give the singlet a charge!

Issues ameliorated by giving S a gauge charge.

$$W = \lambda S H_u H_d + \cdots$$

We investigate the case where all fields, including S, are charged under a $U(1)_X$ symmetry, that is spontanously broken by $\langle S \rangle \neq 0$.

Of course, if $s = 0$, then $h_u \neq -h_d$ (charges are denoted by lower-case letters).

H_u and H_d no longer form a vector-like pair, and explicit μ term is forbidden.

$$\lambda \langle S \rangle \to \mu_{\text{eff}}$$

Even better than pure singlet NMSSM?

Higgs mass is similar to NMSSM except there is an additional term from

$$V = \frac{1}{2} D_X^2 + \cdots$$

where,

$$D_X = g_X \sum_i q_i Q_i^* Q_i = g_X h_u |H_u|^2 + g_X h_d |H_d|^2 + \cdots$$

Thus,

$$\begin{aligned} m_h^2 &= m_Z^2 \cos^2 2\beta + \lambda^2 v^2 \sin^2 2\beta \\ &\quad + 2 g_X^2 v^2 (h_u \cos^2 \beta + h_d \sin^2 \beta)^2 + \delta m_{h,rad}^2 \end{aligned}$$

Higgs boson is even heavier than the NMSSM case.

But wait …

Gauge Coupling Unification is now suspect.

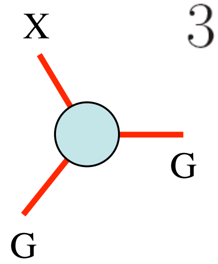
Morrissey, JW, ‘06

If we assume that …

$$W = y_t Q H_u t^c + y_b Q H_d b^c + y_\tau Q H_d \tau^c + \cdots$$

1. All the terms present in the MSSM superpotential appear in the superpotential of the extended model. *(Ensures the model reproduces correct low-energy physics)*

2. The $U(1)_X$ charges of the MSSM matter fields are family-universal. *(Prevents FCNC problems)* $Q_X(e) = Q_X(\mu) = Q_X(\tau),\ etc.$



3. The exotic matter needed to cancel the $U(1)_X$ anomalies consists either of G_{SM} singlets, or of complete $SU(5)$ multiplets (with the usual $G_{SM} \subset SU(5)$ embedding). *(Preserves "automatic gauge coupling unification")*

4. The full set of exotic matter is vector-like in its G_{SM} representation. *(Ensures SM anomalies are ok, and precision electroweak corrections controlled)*

We get …

Claim: It is impossible to arrange the collection of G_{SM} exotics into $SU(5)$ multiplets, given the above requirements and assumptions, such that each field within the $SU(5)$ multiplet has the same $U(1)_X$ charge. Thus, the charges within each "GUT multiplet" are split.

$$\begin{pmatrix} e'_L \\ \nu' \\ d'_1 \\ d'_2 \\ d'_3 \end{pmatrix}$$

Implication: It is not possible to interpret our theory easily as an $SU(5) \times U(1)_X$ (or $G \times U(1)_X$ where $SU(5) \subset G$).

Epicyclic response: For example, take many 5 and $\bar{5}$ reps with various $U(1)_X$ charges, split them apart, project out/give mass to unwanted components, and piece the remaining parts back together again in complete $5 + \bar{5}$ multiplets, from G_{SM} point of view, with split X charges.

Conclusions to Lecture 2

•High mass scalars, but low mass -inos in Supersymmetry are motivated by data pressures, including the Higgs boson mass bound.
•FCNC, Higgs mass, CP violation, gauge coupling unification, and CDM stories are good.
•Not sure what to think about "naturalness"

•Collider phenomenology is perhaps most challenging, motivated weak-scale susy scenario?
•Search for electroweak winos with small mass splittings.
•Search for strongly coupled gluinos decaying into jets or top quarks.

Next Lecture: The Opposite End of Supersymmetry