Supersymmetry Phenomenology

Lecture 1:
Supersymmetry and the LHC
(with emphasis on Higgs boson implications)

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Some motivations to study Supersymmetry

1. Gauge Coupling Unification
2. “Obvious” space-time symmetry extension to explore
3. String theory seems to like it
4. Source of dark matter (R-parity)
5. Radiative electroweak symmetry breaking
6. Can solve gauge hierarchy problem
7. Rich, calculable, self-consistent beyond-the-SM theory

Other reasons: QFT laboratory, etc.

The Particle Spectrum of Minimal Supersymmetry

Names		spin 0	spin 1/2	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L\ \ \widetilde{d}_L)$	$(u_L\ \ d_L)$	$(\,\mathbf{3},\ \mathbf{2}\,,\ \frac{1}{6})$
($\times$3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu}\ \ \widetilde{e}_L)$	$(\nu\ \ e_L)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$
($\times$3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(\,\mathbf{1},\ \mathbf{1},\ 1)$
Higgs, higgsinos	H_u	$(H^+_u\ \ H^0_u)$	$(\widetilde{H}^+_u\ \ \widetilde{H}^0_u)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ +\frac{1}{2})$
	H_d	$(H^0_d\ \ H^-_d)$	$(\widetilde{H}^0_d\ \ \widetilde{H}^-_d)$	$(\,\mathbf{1},\ \mathbf{2}\,,\ -\frac{1}{2})$

Names	spin 1/2	spin 1	$SU(3)_C,\ SU(2)_L,\ U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(\,\mathbf{8},\ \mathbf{1}\,,\ 0)$
winos, W bosons	$\widetilde{W}^\pm\ \ \widetilde{W}^0$	$W^\pm\ \ W^0$	$(\,\mathbf{1},\ \mathbf{3}\,,\ 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(\,\mathbf{1},\ \mathbf{1}\,,\ 0)$

Superpartners highlighted in red.

SUSY Primer: Martin, hep-ph/9709356

Mixed States: Charginos of the MSSM

Charginos in the $\chi_i^{\pm} = \left\{ \widetilde{W}^{\pm}, \widetilde{H}^{\pm} \right\}$ basis,

$$U^{\dagger} X V^{-1} = \mathrm{diag}(m_{\chi_1^{\pm}}, m_{\chi_2^{\pm}}), \quad \text{where}$$

$$X = \begin{pmatrix} M_2 & \sqrt{2} s_{\beta} m_W \\ \sqrt{2} c_{\beta} m_W & \mu \end{pmatrix}$$

Mixed States: Neutralinos of the MSSM

Neutralinos in the $\chi_i^0 = \{\widetilde{B}, \widetilde{W}^0, \widetilde{H}_d^0, \widetilde{H}_u^0\}$ basis,

$$N^* Y N^{-1} = \mathrm{diag}(m_{\chi_1^0}, m_{\chi_2^0}, m_{\chi_3^0}, m_{\chi_4^0}), \quad \text{where}$$

$$Y = \begin{pmatrix} M_1 & 0 & -c_\beta s_W m_Z & s_\beta s_W m_Z \\ 0 & M_2 & c_\beta c_W m_Z & -s_\beta c_W m_Z \\ -c_\beta s_W m_Z & c_\beta c_W m_Z & 0 & -\mu \\ s_\beta s_W m_Z & -s_\beta c_W m_Z & -\mu & 0 \end{pmatrix}$$

Description of SUSY Breaking

SUSY breaking resides in <F> of chiral multiplet

$$X = x + \sqrt{2}\psi\theta + F\theta^2$$

This leads to gravitino mass: $m_{3/2}^2 \sim \frac{F^\dagger F}{M_{\mathrm{Pl}}^2}$

Gravitino is spin 3/2 particle. ψ is the absorbed ±1/2 spin component (goldstino).

Gaugino masses: $\int d^2\theta \frac{X}{M_{\mathrm{Pl}}} \mathcal{W}\mathcal{W} \sim m_{3/2}\lambda\lambda$

Scalar masses: $\int d^2\theta d^2\bar{\theta} \frac{X^\dagger X}{M_{\mathrm{Pl}}^2} \Phi_i^\dagger \Phi_i \rightarrow m_{3/2}^2 \phi_i^* \phi_i$

Everybody $\sim m_{3/2}$, and $m_{3/2} \sim m_W$ for naturalness.

Challenges for Low-Energy SUSY

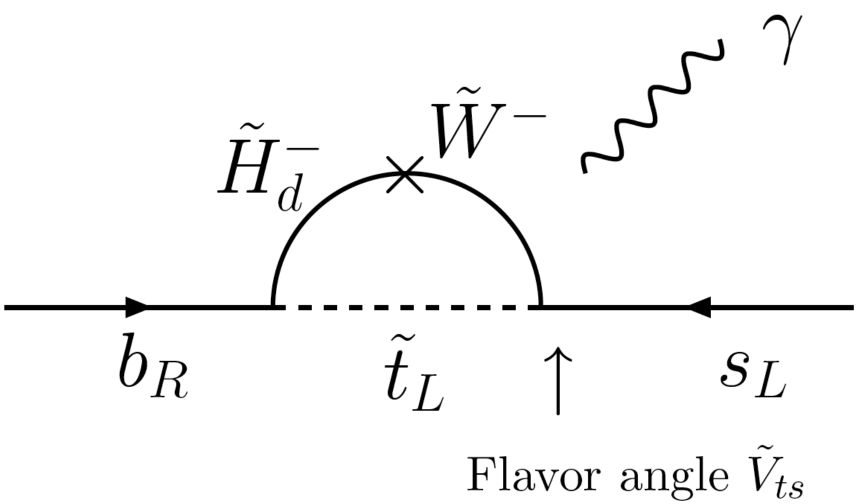
Throw a dart into Minimal SUSY parameter space,
And what do you get?

Observable predictions would be wildly
Incompatible with experiment.

Briefly review these challenges ….

Flavor Changing Neutral Currents

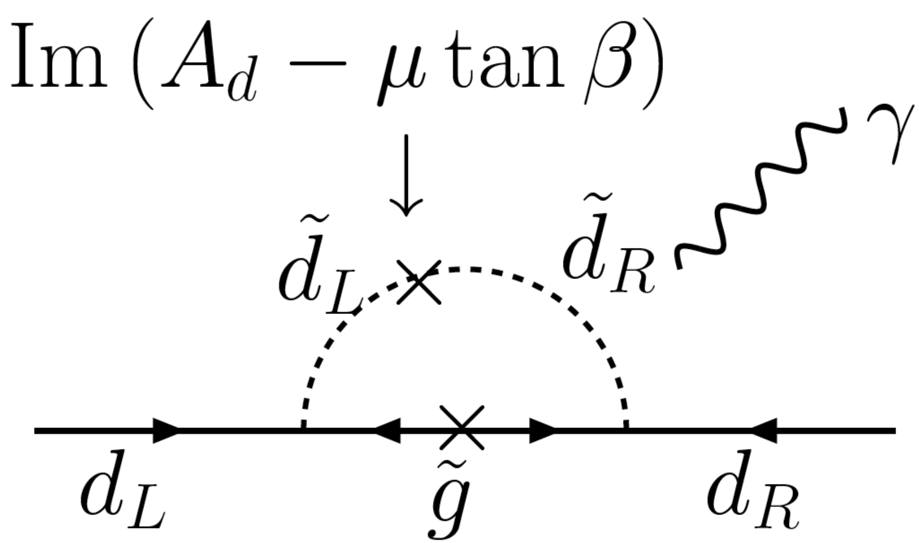
Random superpartner masses and mixing angles would generate FCNC far beyond what is measured:



However: heavy scalars would squash these FCNCs

CP Violation

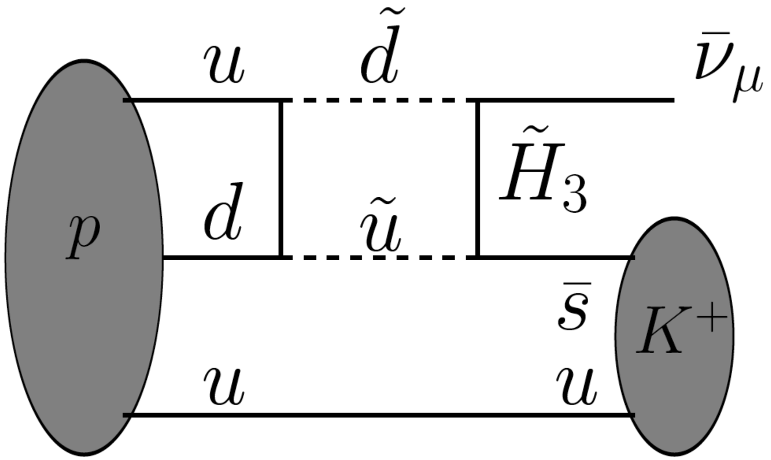
Supersymmetry has many new sources of CP violation:



Large unless CP angle small or scalar masses heavy.

Proton Decay

Perhaps less troublesome…. Proton decay can be problematic, even in R-parity conserving supersymmetry.



Dim-5 operator suppressed by heavy triplet or
Much heavier scalar mass superpartners

Model Building

Many clever solutions exist to overcome these challenges.

To me, the most challenging one is the flavor problem.

Very simple mSUGRA idea is minimal solution (see next slide)

mSUGRA / CMSSM

$M_{1/2}$ = Common Gaugino mass at GUT scale

M_0 = Common scalar masses at GUT scale

A_0 = Common tri-scalar interaction mass at GUT scale

$\tan\beta$ = Ratio of H_u to H_d vacuum expectation values

$\mathrm{Sgn}(\mu)$ = Sign of the H_uH_d μ–term in the superpotential

$$16\pi^2 \frac{d}{dt} g_i = -b_i g_i^3 \qquad 16\pi^2 \frac{d}{dt} M_i = -2 b_i M_i g_i^2 \qquad i = 1,2,3; \qquad b_i = \begin{cases} -\frac{3}{5} - 2n_f & i=1 \\ 5 - 2n_f & i=2 \\ 9 - 2n_f & i=3 \end{cases}$$

The light squark and slepton masses obey the RG equations

$$\begin{aligned}
16\pi^2 \frac{d}{dt} m^2_{\tilde{Q}_L} &= -\frac{2}{15} g_1^2 M_1^2 - 6 g_2^2 M_2^2 - \frac{32}{3} g_3^2 M_3^2 + \frac{1}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{u}_R} &= -\frac{32}{15} g_1^2 M_1^2 - \frac{32}{3} g_3^2 M_3^2 - \frac{4}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{d}_R} &= -\frac{8}{15} g_1^2 M_1^2 - \frac{32}{3} g_3^2 M_3^2 + \frac{2}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{L}_L} &= -\frac{6}{5} g_1^2 M_1^2 - 6 g_2^2 M_2^2 - \frac{3}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{e}_R} &= -\frac{24}{5} g_1^2 M_1^2 + \frac{6}{5} g_1^2 \mathrm{Tr}(Ym^2) \,,
\end{aligned}$$

where

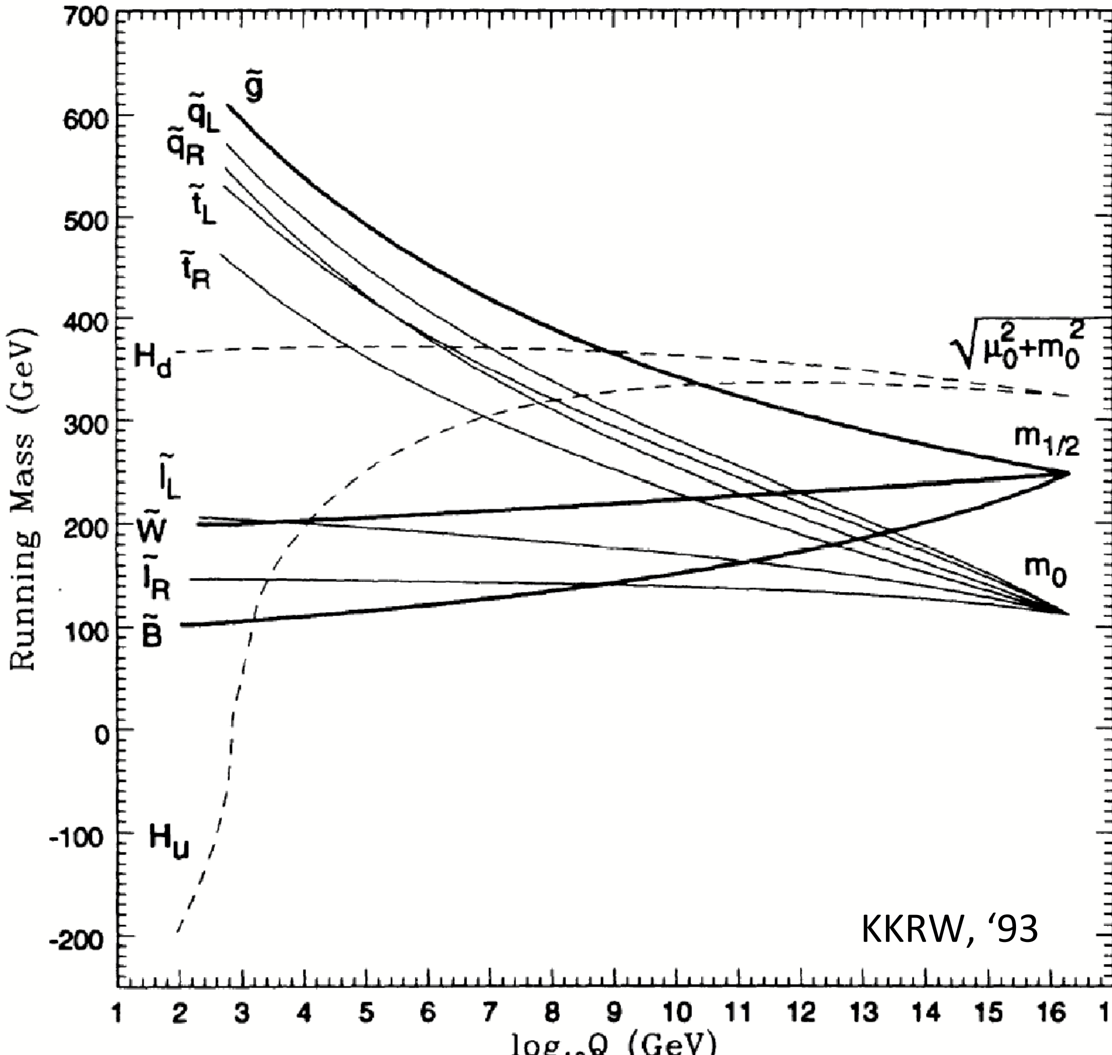
$$\mathrm{Tr}(Ym^2) = m^2_{H_u} - m^2_{H_d} + \sum_1^{n_f} \left(m^2_{\tilde{Q}_L} - 2 m^2_{\tilde{u}_R} + m^2_{\tilde{d}_R} - m^2_{\tilde{L}_L} + m^2_{\tilde{e}_R} \right) .$$

Third generation:

$$\begin{aligned}
16\pi^2 \frac{d}{dt} m^2_{\tilde{t}_L, \tilde{b}_L} &= 2 y_t^2 \Sigma_t^2 + 2 y_b^2 \Sigma_b^2 - \frac{2}{15} g_1^2 M_1^2 - 6 g_2^2 M_2^2 - \frac{32}{3} g_3^2 M_3^2 + \frac{1}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{t}_R} &= 4 y_t^2 \Sigma_t^2 - \frac{32}{15} g_1^2 M_1^2 - \frac{32}{3} g_3^2 M_3^2 - \frac{4}{5} g_1^2 \mathrm{Tr}(Ym^2) \,, \\
16\pi^2 \frac{d}{dt} m^2_{\tilde{b}_R} &= 4 y_b^2 \Sigma_b^2 - \frac{8}{15} g_1^2 M_1^2 - \frac{32}{3} g_3^2 M_3^2 + \frac{2}{5} g_1^2 \mathrm{Tr}(Ym^2) \,,
\end{aligned}$$

Martin, Ramond

Renormalization Group Flow



SUSY Limits at LHC

LHC running well, and has done many searches for SUSY.

Energy of 7 TeV makes search reach limited, yet still interesting.

Higgs search more likely/instructive perhaps at this stage (that is to come later)

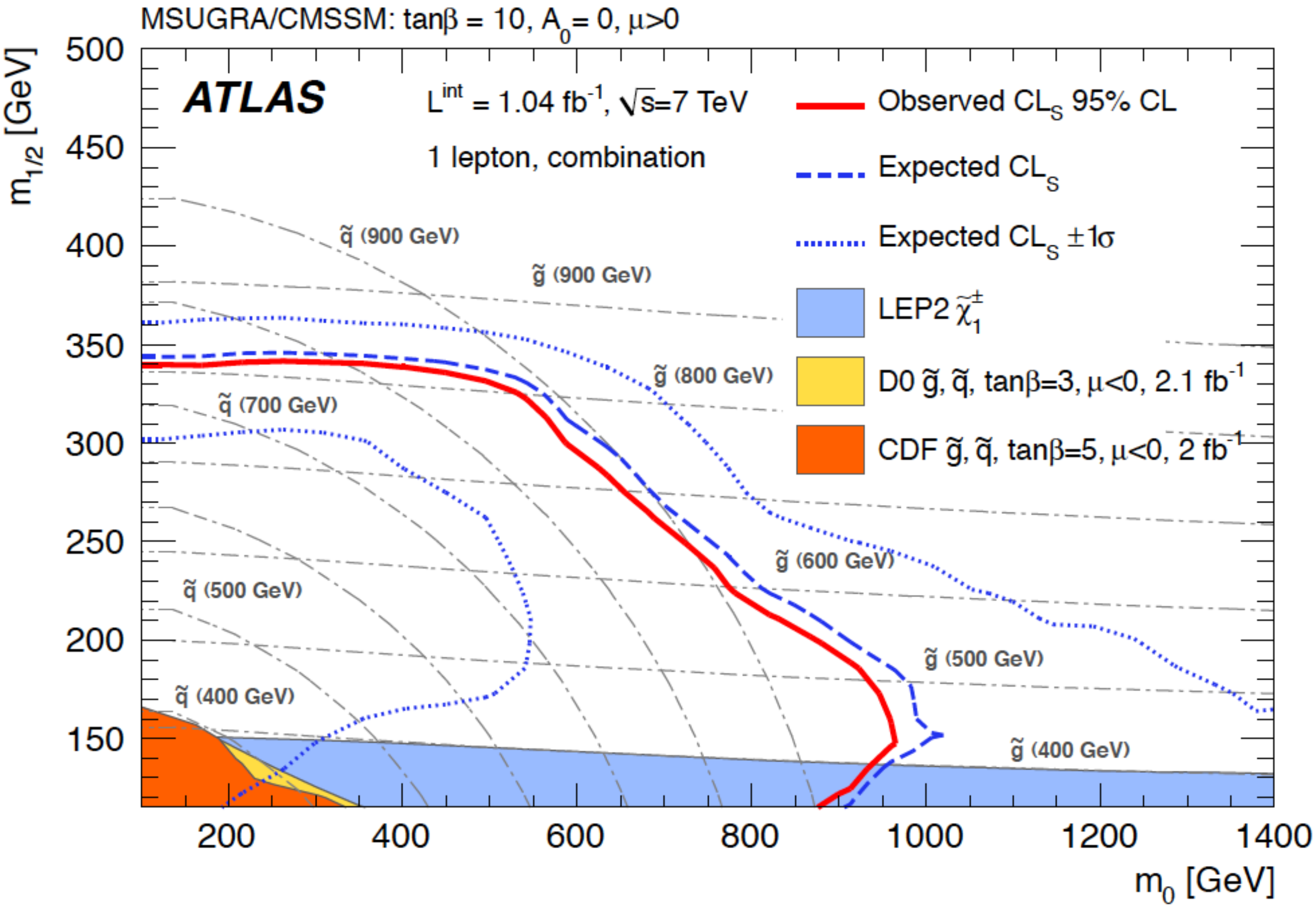


FIG. 7: Observed and expected 95% CL exclusion limits, as well as the $\pm 1\sigma$ variation on the median expected limit, in the combined electron and muon channels. The plots also show the published limits from CDF [60], D0 [61], and the results from the LEP experiments [62].

From arXiv:1109.6606

Two Higgs Doublets of Supersymmetry

Supersymmetry requires two Higgs doublets. One to give mass to up-like quarks (H_u), and one to give mass to down quarks and leptons (H_d).

8 degrees of freedom. 3 are eaten by longitudinal components of the W and Z bosons, leaving 5 physical degrees of freedom: $H^{\pm}$, A, H, and h.

As supersymmetry gets heavier ($m_{3/2}$ >> MZ), a full doublet gets heavier together (H±,A,H) while a solitary Higgs boson (h) stays light, and behaves just as the SM Higgs boson.

Coupling of the neutral scalar Higgses

$$\begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix} = \begin{pmatrix} v_u \\ v_d \end{pmatrix} + \frac{1}{\sqrt{2}} R_\alpha \begin{pmatrix} h^0 \\ H^0 \end{pmatrix} + \frac{i}{\sqrt{2}} R_{\beta_0} \begin{pmatrix} G^0 \\ A^0 \end{pmatrix} \quad R_\alpha = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix}$$

$\tan\beta = v_u/v_d$

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Haber et al. '01

Heavy Higgs

$$HVV: \quad \cos(\beta-\alpha) \to \boxed{0} + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \to \boxed{\frac{1}{\tan\beta}} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \to \boxed{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

Light Higgs

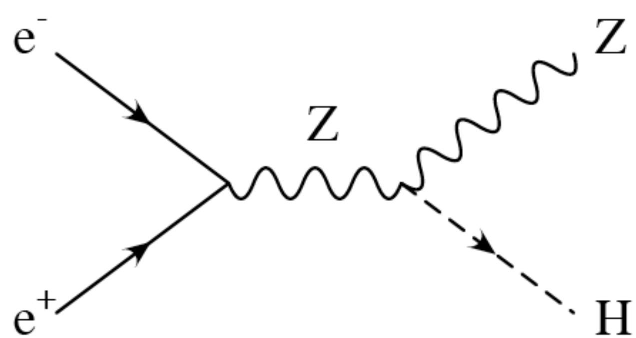
$$hVV: \quad \sin(\beta-\alpha) \to 1$$

$$htt: \quad \frac{\cos\alpha}{\sin\beta} \to 1$$

$$hbb: \quad \frac{-\sin\alpha}{\cos\beta} \to 1$$

Higgs mass limits

From LEP 2 $m_h > 114$ GeV

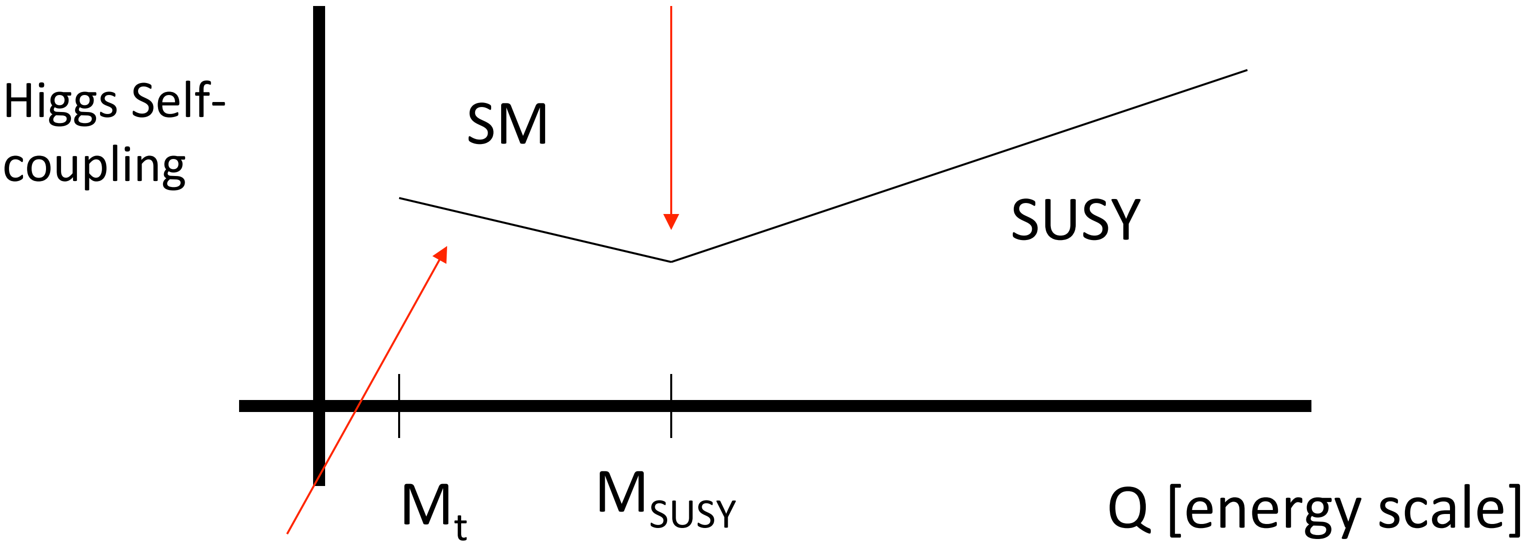


From LHC 114 < mh < 140 GeV (approximately)

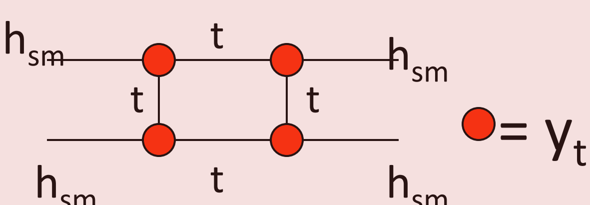
Perhaps a signal at ~ 125 GeV

Understanding Lightest Higgs Mass Computation

$$\lambda(M_{SUSY}) = \frac{1}{8}(g^2 + g'^2)\cos^2 2\beta$$



$$\frac{d\lambda}{d\log Q} = -\frac{3}{4\pi^2}y_t^4 + \cdots$$



$$\begin{aligned} m_h^2 &= 2\lambda v^2 = 2\left(\lambda(M_{SUSY}) + \frac{3}{4\pi^2}y_t^4 \log\frac{M_{SUSY}}{M_t}\right)v^2 \\ &= M_Z^2\cos^2 2\beta + \frac{3M_t^4}{\pi^2 v^2}\log\frac{M_{SUSY}}{M_t} \end{aligned}$$

Higgs boson mass

In minimal supersymmetry the lightest Higgs mass is computable:

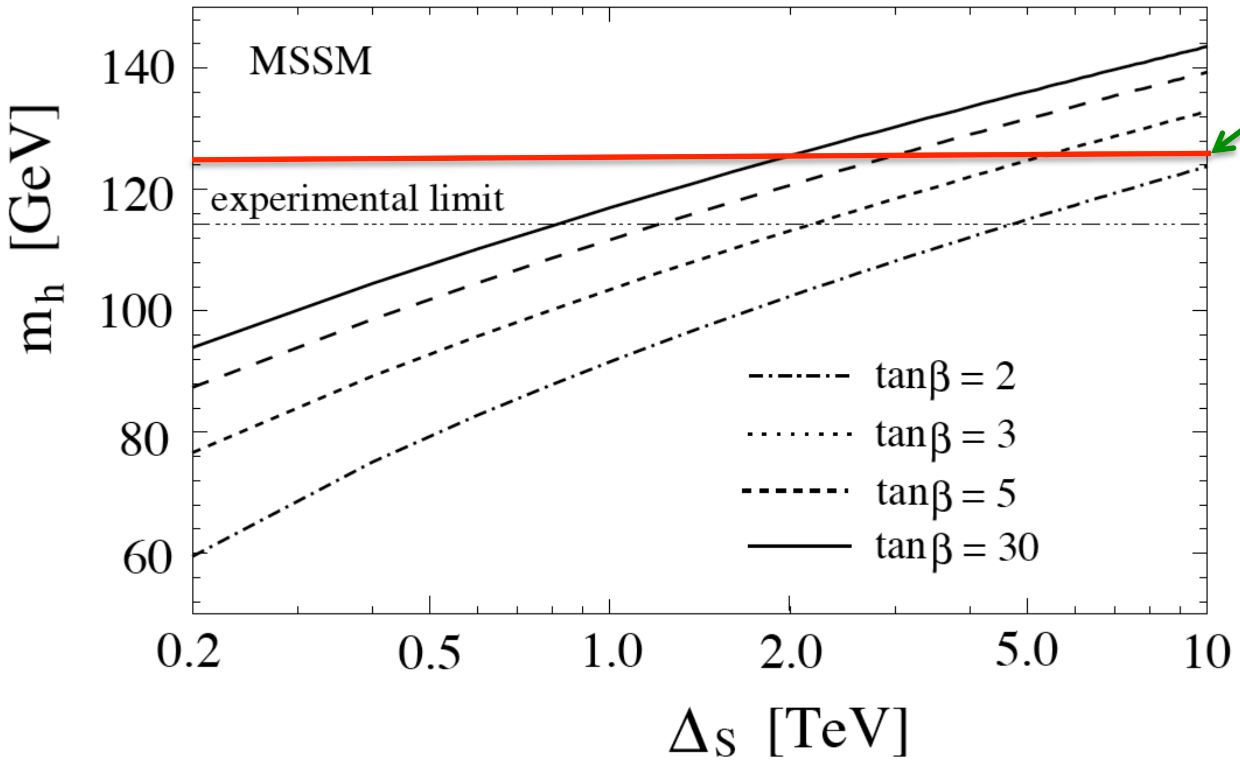
$$m_h^2 = m_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \log \frac{\tilde{m}_t^2}{m_t^2} + \cdots$$

Tree-level value is bounded by $m_Z = 91\,\mathrm{GeV}$. Current lower limit on Higgs boson mass is $114\,\mathrm{GeV}$. Thus, we need $\sim (70\,\mathrm{GeV})^2$ contribution from quantum correction.

Need $\tilde{m}_t \gtrsim 5\,\mathrm{TeV}(0.8\,\mathrm{TeV})$ for $\tan\beta = 2(30)$

Log-sensitivity keeps m_h below the Precision EW bound (~ 200 GeV)

Lightest Higgs Mass in the MSSM



m_h = 125 GeV?

SUSY scalar masses then > ~few TeV?

Tobe, JW, ‘02

$$
\begin{aligned}
m_h^2 &= M_Z^2 \cos^2 2\beta + \frac{3m_t^4}{2\pi^2 v^2} \ln \frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} + \frac{3m_t^2}{v^2} c_{\tilde{t}}^2 s_{\tilde{t}}^2 (m_{\tilde{t}_2}^2 - m_{\tilde{t}_1}^2) \ln \frac{m_{\tilde{t}_2}^2}{m_{\tilde{t}_1}^2} + \cdots \\
&\equiv M_Z^2 \cos^2 2\beta + \frac{3G_F m_t^4}{\sqrt{2}\pi^2} \ln \frac{\Delta_S^2}{m_t^2} \quad \text{where } \Delta_S^2 \gtrsim m_{\tilde{t}_1} m_{\tilde{t}_2}
\end{aligned}
$$

Naturalness

Naturalness is strained if M_{SUSY} becomes too large.

From the EW scalar potential of supersymmetry, the minimization conditions yield

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

This is of the generic form of one large number subtracting another and getting a small number:

$$\tilde{m}_1^2 - \tilde{m}_2^2 = m_Z^2$$

Example of extreme finetuning

Bush v. Gore Florida vote in 2000 U.S. Presidential election:

M_1^2 = Bush's votes = 2,912,790
M_2^2 = Gore's votes = 2,912,253

Normalizing $M_1^2 - M_2^2 = M_Z^2$ (multiply by 15.5) one gets the scale of 'supersymmetry masses' of this election to be

Sqrt[15.5* M_1^2] = 6.7 TeV [Well above Higgs mass needs.]

Obama-McCain a "250 GeV" election.

Sarkozy-Royal a "270 GeV" election.

What about ....

...making scalar superpartners (squarks and sleptons) much, much heavier than fermionic superpartners (charginos, neutralinos and gluinos).

This goes under the names of Split Supersymmetry (Arkani-Hamed, Dimopolous, Giudice, Romanino) or PeV Scale supersymmetry (JW).

Let's try to build a rationale for this "unnatural" approach.

EW-Scale Naturalness

Appeals to naturalness are murky and controversial. Incompatible views can be reasonable.

Agnostic approach: Delete all reference to naturalness and ask what is the “best” susy model consistent data.

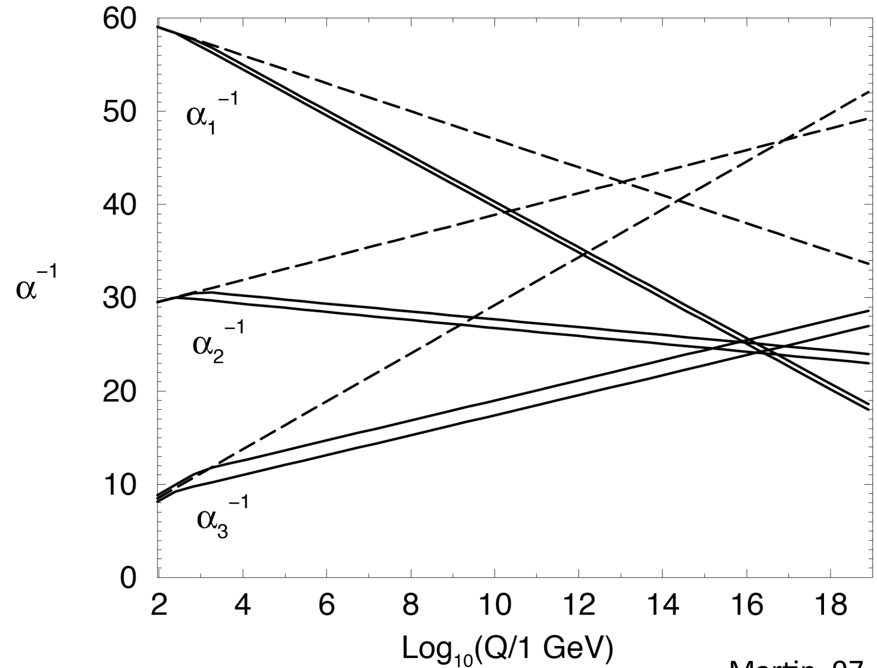
Arbitrary heavy SUSY?

After deleting naturalness from consideration, we should not conclude that SUSY is at some arbitrarily large scale, where it can't cause harm.

We wish to retain good things about SUSY:

- Gauge Coupling unification
- Light Higgs boson mass prediction
- Cold Dark Matter

Gauge Coupling Unification



Martin, 97

"Proximity Factor" for gauge coupling unification is defined to be the factor A needed such that

$$g_U = g_1(M_U) = g_2(M_U) = g_3(M_U) + A\frac{g_U^3}{16\pi^2}$$

Generic quantum correction

In weak-scale MSSM $M_U \simeq 2 \times 10^{16}\,\text{GeV}$ and $A \simeq 1$.

Unification success sensitive to -inos, but not scalars [Giudice, Romanino; etc.]

Relic Abundance

Weinberg ‘83 : LSP is stable -- Problem? No -- Might be good

Goldberg ‘83 : LSP Majorana -- Good CDM Candidate

LSPs annihilate as universe expands until they can’t find each other any more (freeze-out T ~ m/20)

$$\Omega h^2 = \frac{A}{\langle \sigma v \rangle} = \frac{A \tilde{m}^2}{\alpha}, \text{ where } \langle \sigma v \rangle = \frac{\alpha}{\tilde{m}^2}$$

CDM Limits and SUSY Mass

Experiment tells us

$$0.09 < \Omega_{CDM} h^2 < 0.13$$

Leads to upper bound constraint on lightest susy mass (neutralino), but others can be much heavier (squarks and sleptons).

$$\frac{A\tilde{m}^2}{\alpha} < 0.13 \quad \rightarrow \quad \tilde{m} < \sqrt{0.13\alpha/A} < \text{ few TeV}$$

Where we are at

Ignoring Naturalness

Eliminating bad things:

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

Preserving good things:

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

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

Good theory for this? Yes. The -ino masses charged under symmetries (R and PQ) whereas scalars are not. [Split SUSY literature.]

Supersymmetry Phenomenology

Lectures 2 & 3: Models and Unfication

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February 2012

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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

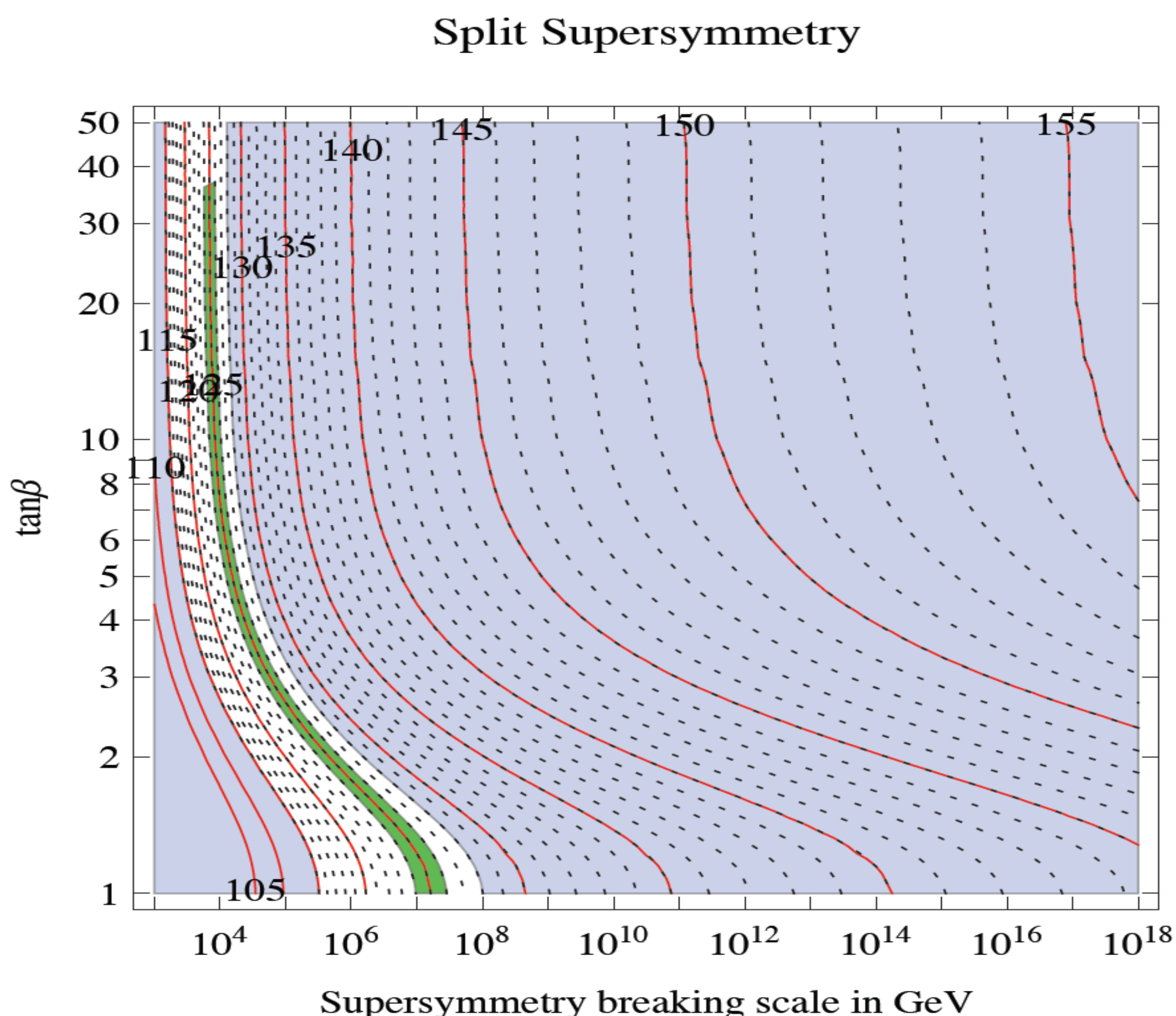
(light gauginos)

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

LSP is Wino!

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

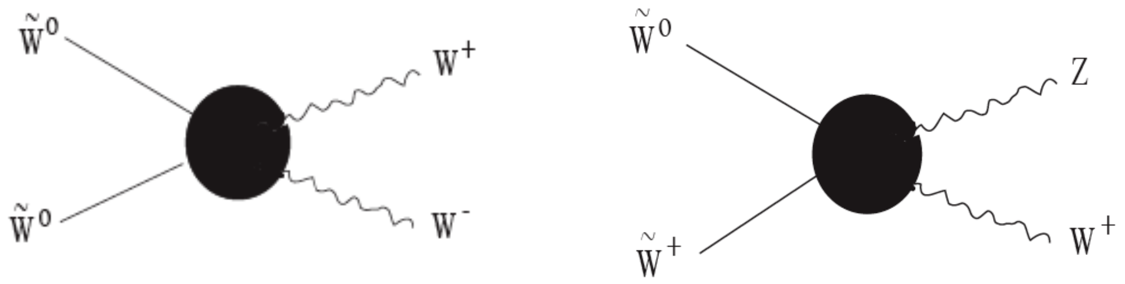
Higgs mass in Split SUSY



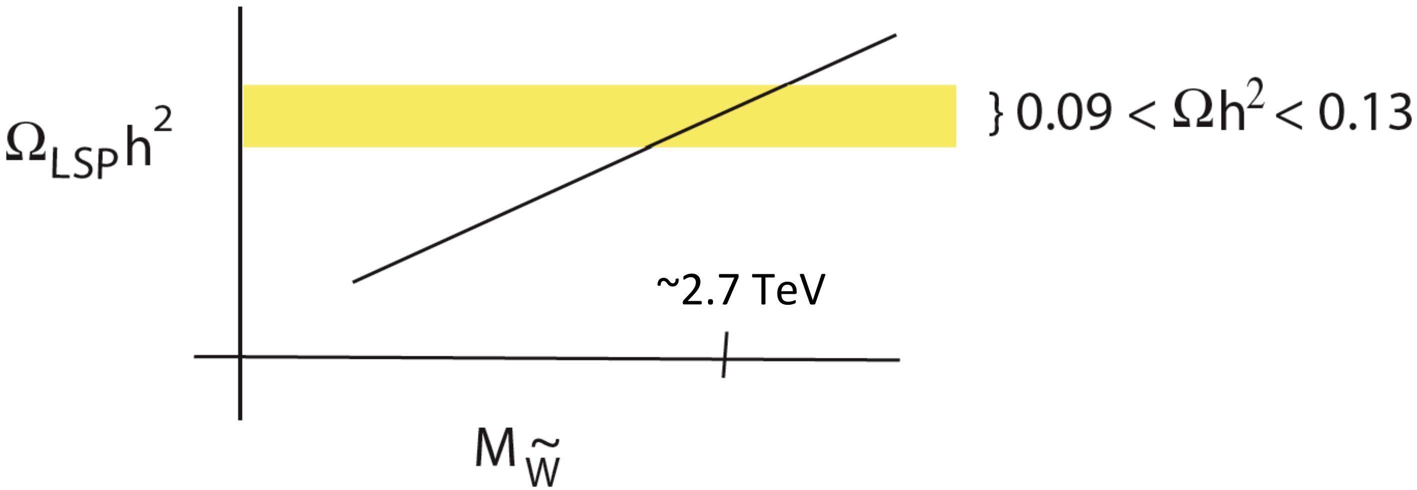
Giudice, Strumia, 1108.6077

Wino Dark Matter

Winos annihilate very efficiently



Mass must be quite high to be good CDM



Thermal CDM and PeV Scale SUSY

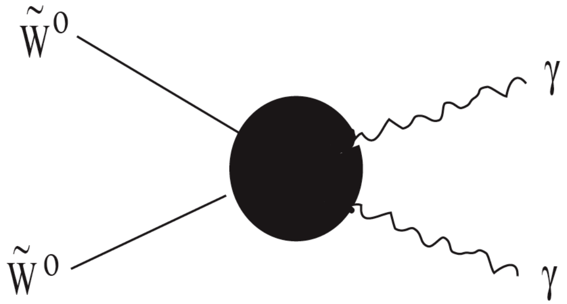
If Wino is the CDM, the SUSY breaking mass is about a PeV

$$m_{\tilde{G}} \sim m_{scalars} \sim 1\,PeV$$

$$M_2 \sim 2\,TeV,\, M_1 \sim 6\,TeV,\, M_3 \sim 14\,TeV$$

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)

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

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

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

Collider Implications of Heavy Flavor Supersymmetry

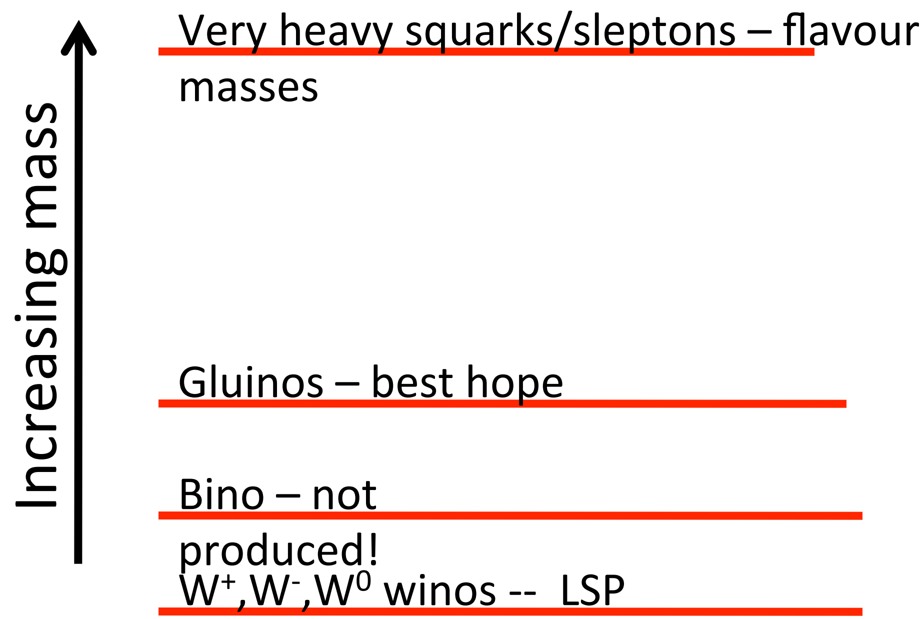
Example spectrum:

$$M_2 = 100\,GeV\ (wino)$$

$$M_1 = 300\,GeV\ (bino)$$

$$M_3 = 700\,GeV\ (gluino)$$

$$m_{\tilde{G}} \sim \mu \sim m_{scalars} \sim 36\,TeV$$



- 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

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

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

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

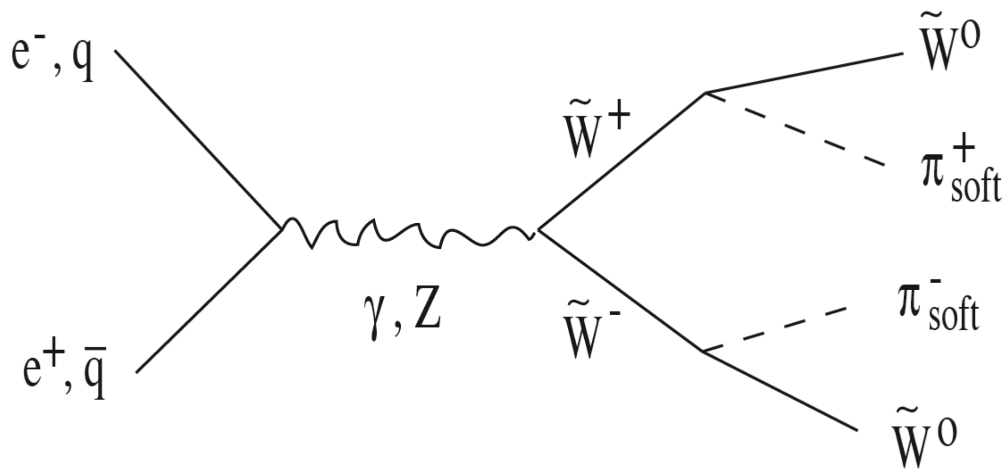
There are also important loop corrections. In the $\mu \to \infty$ limit,

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

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

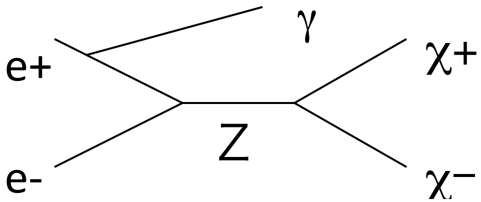
Wino Production and Decays

The mass splitting between charged and neutral is tiny.

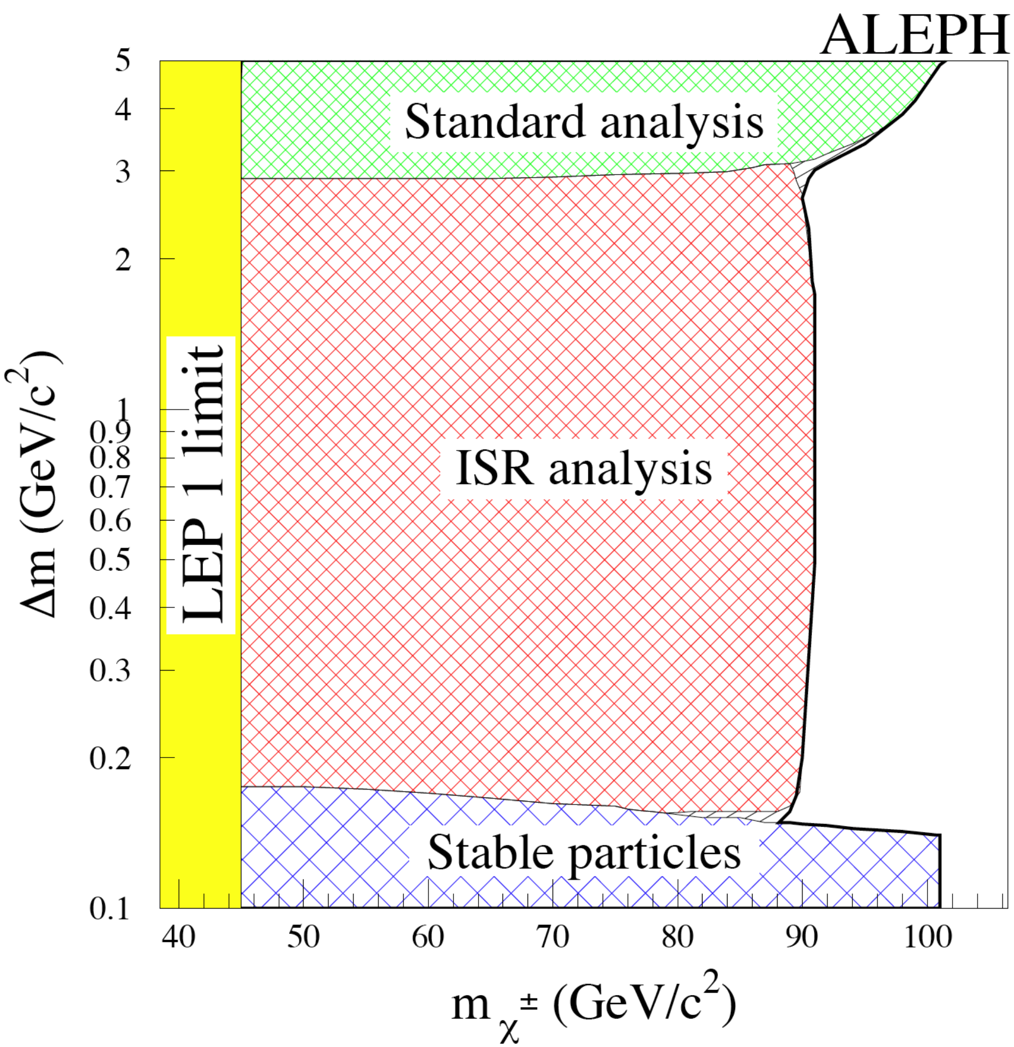


As it stands, difficult. LEP has limits (next slide).
Hadron colliders cannot trigger on soft pions.
Trigger on initial state gluon (Tevatron/LHC).
Can this be done?

ISR Analysis



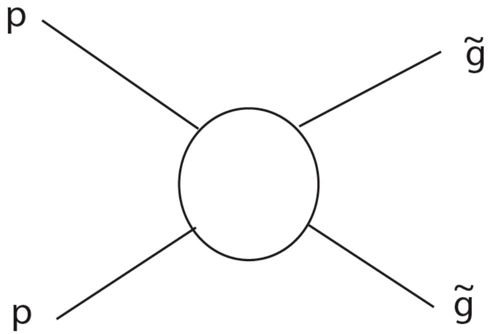
LEP Searches

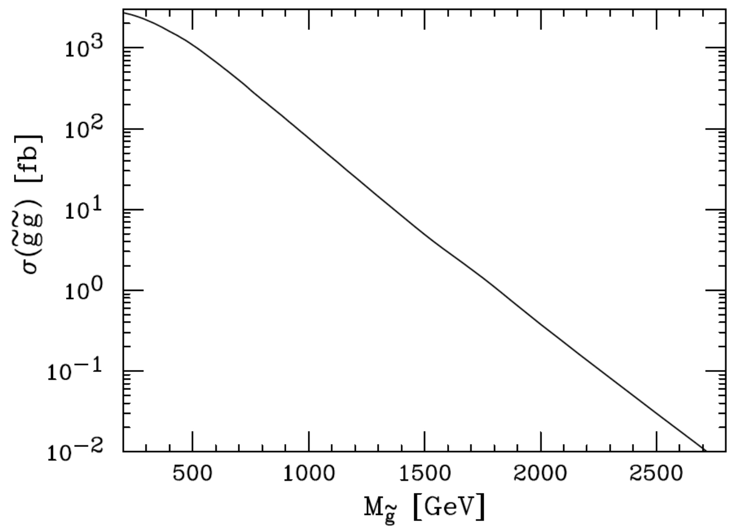


Wino mass limit
From LEP is
~ 90 GeV with
Small mass
Splitting.

ALEPH Collaboration,
hep-ex/0203020

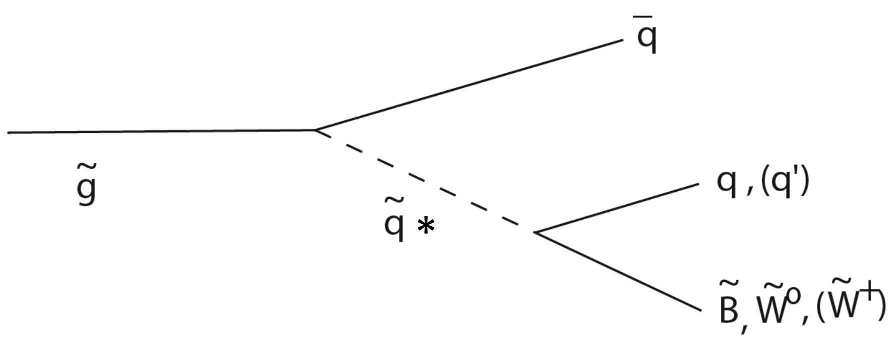
Gluino Production and Decays





Pythia output

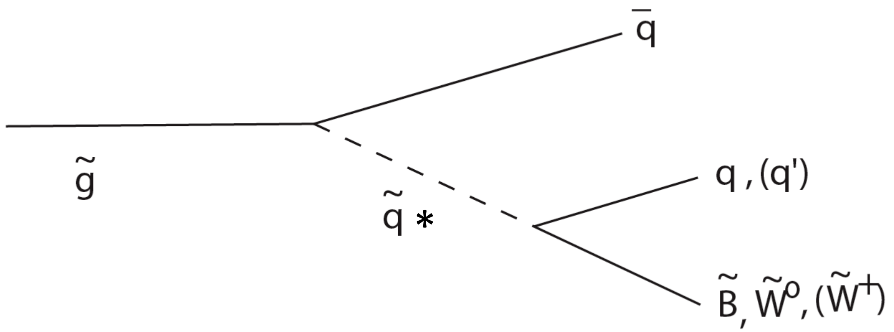
Main decay is three-body through off-shell squark



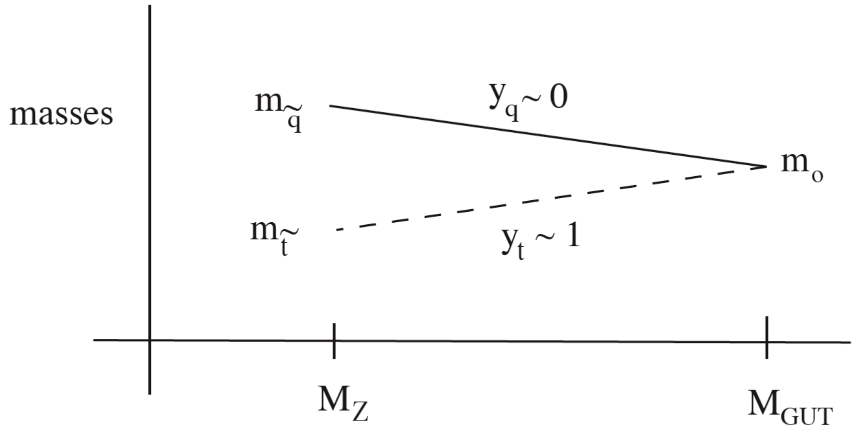
(Toharia, JW for more details on gluino decays within this scenario)

Preference for 3rd generation

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



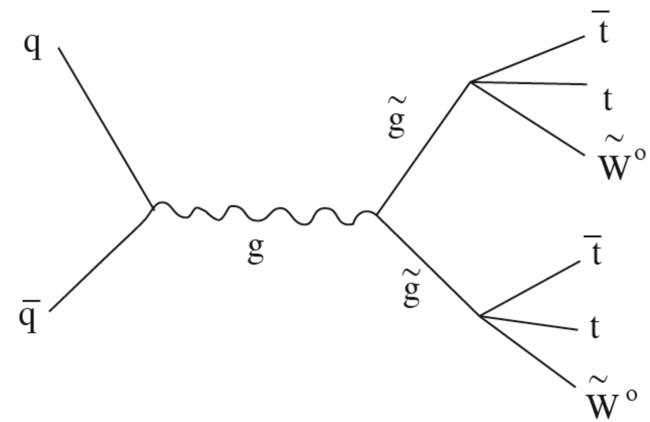
$$\frac{d\tilde{m}^2_{q_i}}{d\log Q} = -\frac{32}{3}M_3^2 + a_i y^2_{q_i}\tilde{m}^2_{q_i} + \cdots \quad (a_i \text{ is positive})$$

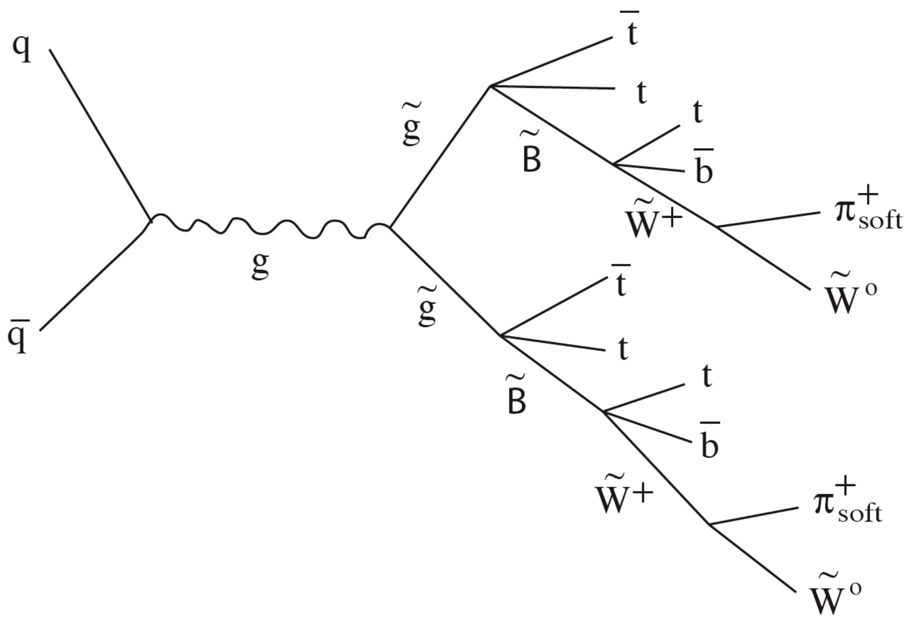


There is a generic preference for decays into 3rd generation quarks.

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

Comments

Inputs:

1. SUSY partners heavier than LHC 7
2. Direct limits suggest 114 < mhiggs < 140 GeV
3. Perhaps mhiggs = ~ 125 GeV

Outputs:

1. Perhaps high non-minimality for "natural SUSY"
2. Deleting naturalness as criterion -> Split SUSY
3. In case 2, LHC discovery hope likely rests in multi-top production

Supersymmetry Phenomenology

Studies in Unification

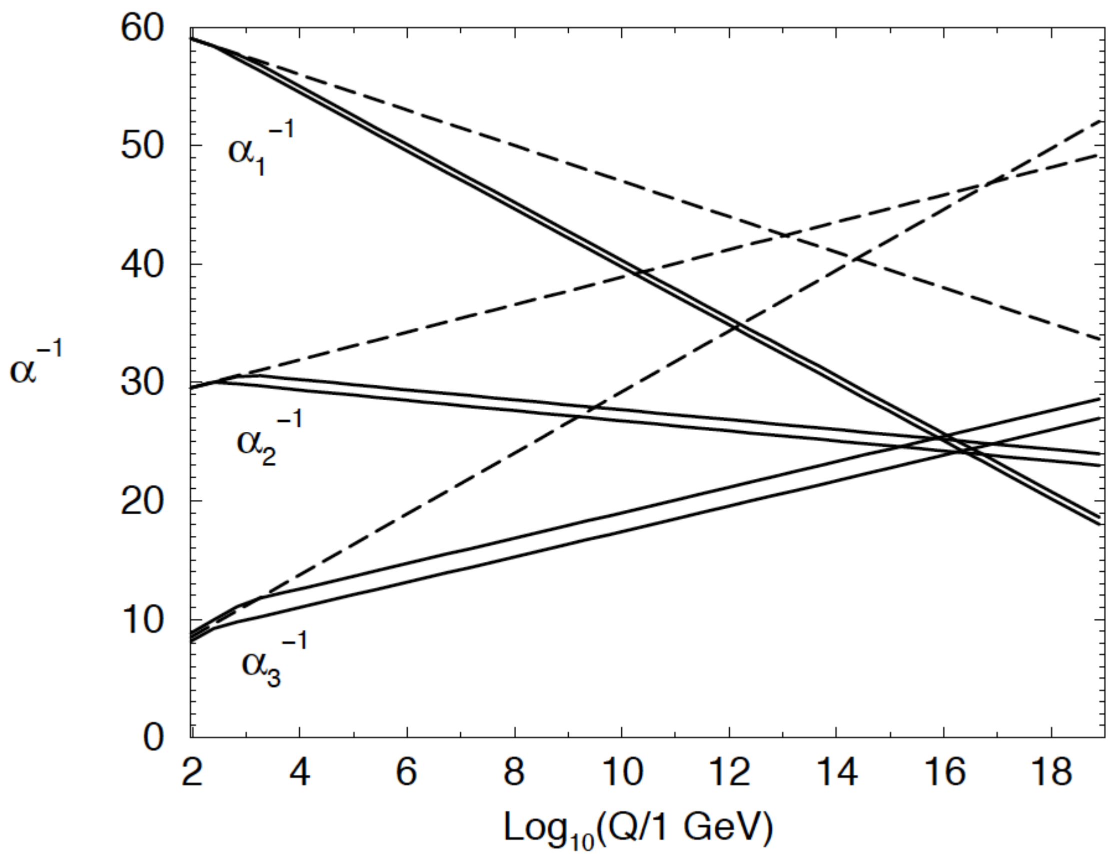
James Wells

CERN & Univ Michigan

February 2012

Gauge coupling unification

Gauge coupling unification possible in weak-scale susy



Martin

Third generation Yukawa unification

Gauge coupling unification implies that our low scale $SU(3) \times SU(2) \times U(1)_Y$ theory is unified somehow – either string unification and/or grand unification into a simple group like $SU(5)$ or $SO(10)$.

$SO(10)$ is especially powerful because all known SM states of each generation fit nicely into a 16 rep. E.g., all 3rd generation fermions in one rep.

The simplest model has third family Yukawa unification at the GUT scale: $y_b = y_\tau = y_t$ from $W = y 16_3 10_H 16_3$.

How rigorous is Yukawa unification?

So why isn't Yukawa unification on the "Supersymmetry Successes" list?

Lazy answer: Because we're not sure if it works.

Better answer: Because, unlike gauge coupling unification, Yukawa unification is *extremely* sensitive to low-scale superpartner masses and parameters which haven't been measured yet.

Bad news: We presently cannot have confidence in Yukawa unification for model building like we do for gauge coupling unification.

Good news: the extreme sensitivity is a great opportunity to test the idea. If all possible patterns of unification theories were insensitive to low-scale superpartner parameters we'd never make progress.

Goals of our Analysis

Two choices: (1) Wait for superpartner measurements and then revisit the question of Yukawa unification, or (2) Ask what the well-motivated hypothesis of Yukawa unification does to the requirements on the superpartner spectrum.

We did (2), and we will happily do (1) also when the time comes.

Why do (2)?

- Warns of possibly difficult superpartner spectrum patterns to measure at collider ...
- Determining the requirements, we can then apply our aesthetic judgement of whether the idea is likely to work or not ...
- Sets priorities on model building ...

Technical Remarks

Here is how we compute Yukawa couplings at high scale:

Find low-scale $\overline{DR}$ gauge couplings from experimental measurements

Compute $\overline{DR}$ Yukawa couplings from SM $\overline{MS}$ fermion masses:

$$\begin{aligned}
\bar{y}_t(m_Z) &= \frac{\sqrt{2}\bar{m}_t^{MSSM}(m_Z)}{\bar{v}(m_Z)\sin\beta} = \frac{\sqrt{2}\bar{m}_t^{SM}(m_Z)}{\bar{v}(m_Z)\sin\beta}(1+\delta_t(m_Z)),\\
\bar{y}_b(m_Z) &= \frac{\sqrt{2}\bar{m}_b^{MSSM}(m_Z)}{\bar{v}(m_Z)\cos\beta} = \frac{\sqrt{2}\bar{m}_b^{SM}(m_Z)}{\bar{v}(m_Z)\cos\beta}(1+\delta_b(m_Z)),\\
\bar{y}_\tau(m_Z) &= \frac{\sqrt{2}\bar{m}_\tau^{MSSM}(m_Z)}{\bar{v}(m_Z)\cos\beta} = \frac{\sqrt{2}\bar{m}_\tau^{SM}(m_Z)}{\bar{v}(m_Z)\cos\beta}(1+\delta_\tau(m_Z)).
\end{aligned}$$

where $\delta_f(m_Z)$ are the weak-scale corrections (both finite and log) due to SUSY particle loops.

Yukawa couplings and gauge couplings are then run up to high-scale using 2-loop RGEs.

Depending on what we do, sometimes δ_i are left unknown and fit to, so that a superpartner spectrum later must give those values. And sometimes δ_i are directly computed given a superpartner spectrum.

Demonstration of Gauge Coupling Unification

At a high scale $M \simeq M_{G_0}$ (M_{G_0} is where $g_1 = g_2$, the gauge couplings are

$$\begin{aligned}
g_1(M) &\simeq 0.734\,(1 + 3\delta_{g_1} - 0.007\delta_{g_2} + 0.02\delta_{g_3} - 0.02\delta_{y_t} - 0.005\delta_{y_b} \\
&\quad -0.002\delta_{y_\tau} - 0.007\delta_{\tan\beta} + 0.02\log\frac{M}{M_{G_0}} + \delta_{g_1}^{GUT} + O(\delta^2)\Big)\,,
\end{aligned}$$

$$\begin{aligned}
g_2(M) &\simeq 0.734\,(1 - 0.003\delta_{g_1} + \delta_{g_2} + 0.03\delta_{g_3} - 0.02\delta_{y_t} - 0.008\delta_{y_b} \\
&\quad -0.001\delta_{y_\tau} - 0.01\delta_{\tan\beta} + 0.004\log\frac{M}{M_{G_0}} + \delta_{g_2}^{GUT} + O(\delta^2)\Big)\,,
\end{aligned}$$

$$\begin{aligned}
g_3(M) &\simeq 0.722\,(1 - 0.001\delta_{g_1} - 0.002\delta_{g_2} + 0.4\delta_{g_3} - 0.01\delta_{y_t} - 0.005\delta_{y_b} \\
&\quad -0.0002\delta_{y_\tau} - 0.005\delta_{\tan\beta} - 0.01\log\frac{M}{M_{G_0}} + \delta_{g_3}^{GUT} + O(\delta^2)\Big)\,,
\end{aligned}$$

The success is very insensitive to even large weak-scale susy corrections from δ_{g_i} or δ_{y_i}.

We call susy gauge coupling unification a success because unnaturally large $\delta_{g_i}^{\mathrm{GUT}}$ are not needed.

Yukawa unification – basic results

We can do a similar exercise for Yukawa couplings at a high-scale M near M_{G_0} ($\tan\beta_0 = 50$):

$$y_t(M) \simeq 0.63\Big(1 + 0.9\delta_{g_1} + 3\delta_{g_2} - 3\delta_{g_3} + 7\delta_{y_t} + 0.7\delta_{y_b} + 0.02\delta_{y_\tau} + 0.7\delta_{\tan\beta} - 0.01\log\frac{M}{M_{G_0}} + \delta_t^{GUT} + O(\delta$$

$$y_b(M) \simeq 0.44\Big(1 + 0.7\delta_{g_1} + 2\delta_{g_2} - 2\delta_{g_3} + \delta_{y_t} + 3\delta_{y_b} + 0.2\delta_{y_\tau} + 3\delta_{\tan\beta} - 0.02\log\frac{M}{M_{G_0}} + \delta_b^{GUT} + O(\delta^2)\Big),$$

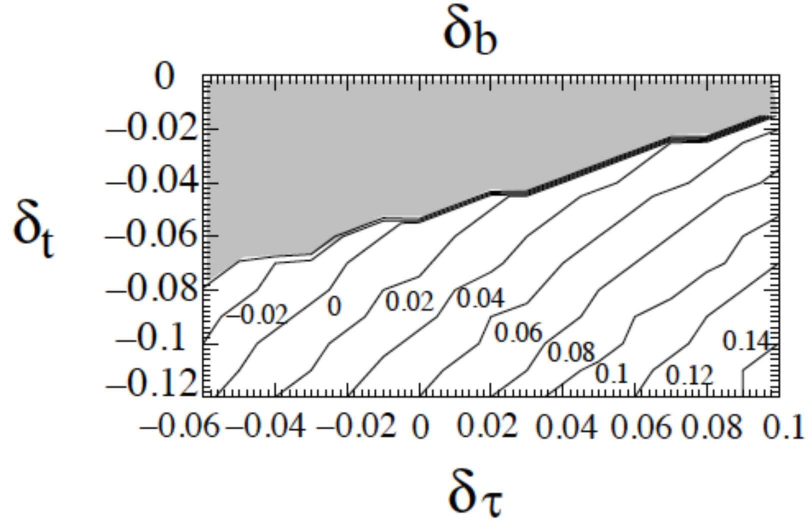
$$y_\tau(M) \simeq 0.52\Big(1 + 0.1\delta_{g_1} + \delta_{g_2} - 0.6\delta_{g_3} + 0.2\delta_{y_t} + \delta_{y_b} + 2\delta_{y_\tau} + 3\delta_{\tan\beta} - 0.005\log\frac{M}{M_{G_0}} + \delta_\tau^{GUT} + O(\delta^2)\Big),$$

Note extreme sensitivity to δ_{g_3} and $\delta_{y_{t,b}}$.

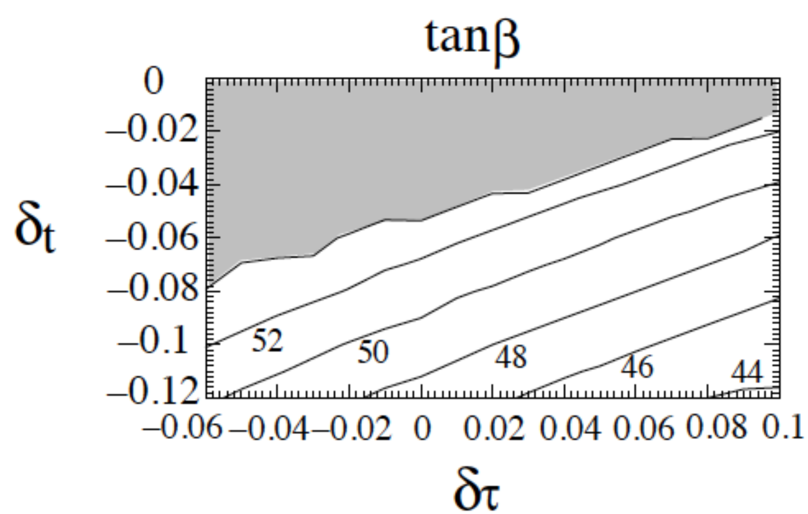
Unification gets better when $\delta_t < 0$ (check! log corrections) and $\delta_b > 0$ but not very big (check! finite corrections).

Must do things numerically, since above expansion is not precise.

Needed corrections for Yukawa unification



(a)



(b)

Typical top and tau corrections

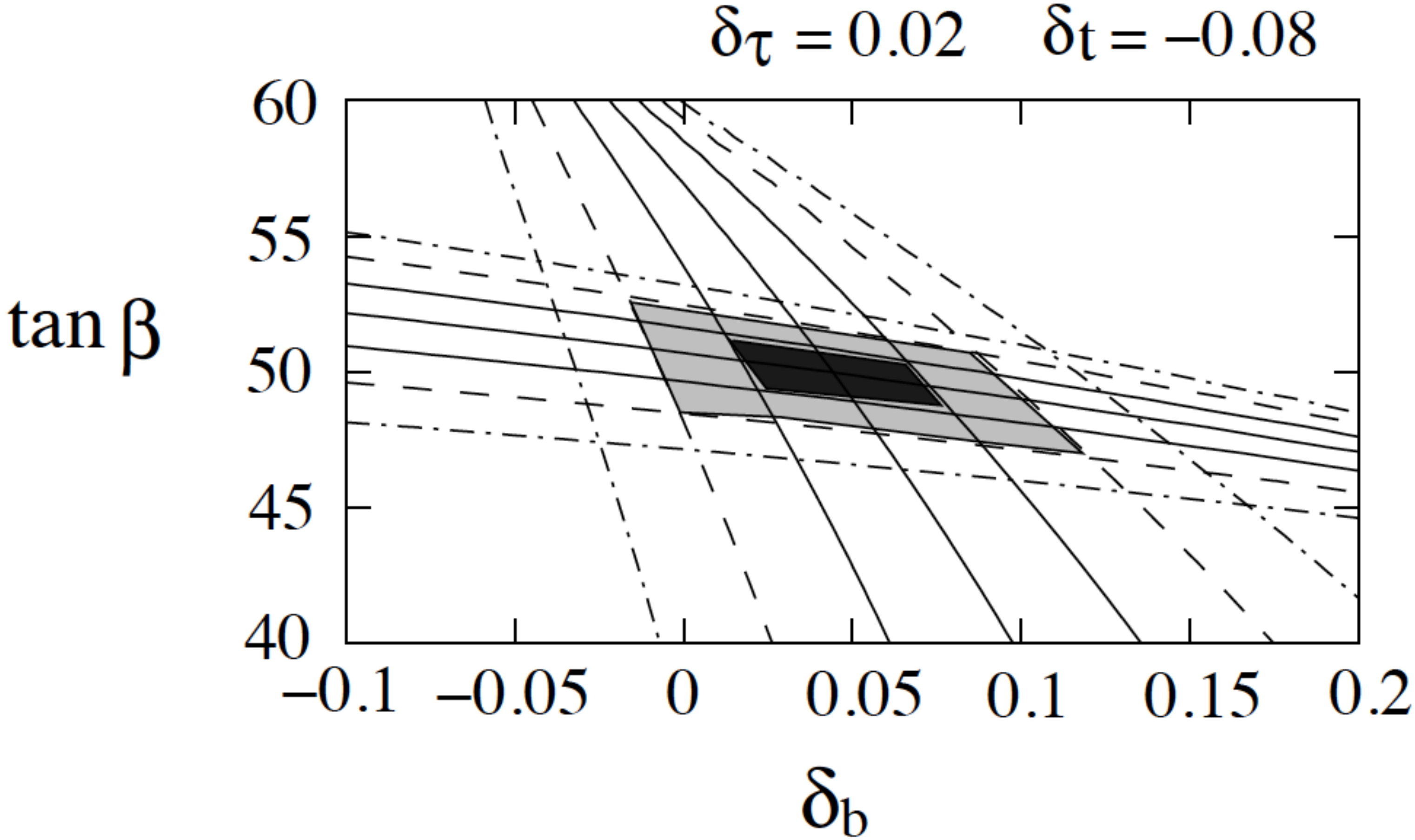
The size of corrections for δ_t and δ_τ in typical weak scale supersymmetric theories with $\tan\beta \sim 50$ are roughly

$$-\delta_t \simeq \frac{g_3^2}{6\pi^2}\log\left(\frac{M_{\rm SUSY}}{m_Z}\right) \lesssim 10\%, \quad \text{(negative correction)}$$

$$\delta_\tau \sim \frac{g_2^2}{32\pi^2}\frac{M_2\mu\tan\beta}{M_{\rm SUSY}^2} \lesssim \pm \text{ few}\%.$$

Therefore, from previous graph of relations needed between δ_i, only relatively small corrections are tolerated for the b-quark: $\delta_b \lesssim$ few%.

Expectation for δ_b corrections



Typical size for b quark mass corrections

At high $\tan\beta$, if all supersymmetry masses are roughly equal, the finite b-quark mass corrections are about:

$$\delta_b \sim \pm \frac{g_3^2}{12\pi^2} \tan\beta$$

Therefore, for b-τ-t unification, which is at large $\tan\beta$, we expect that typical b mass corrections are

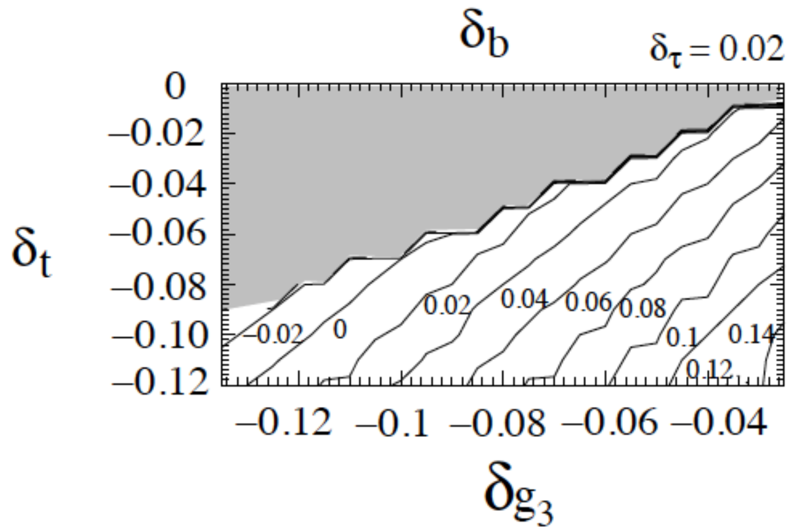
$$\delta_b \sim \pm 50\%$$

50% corrections are too big to allow Yukawa unification.

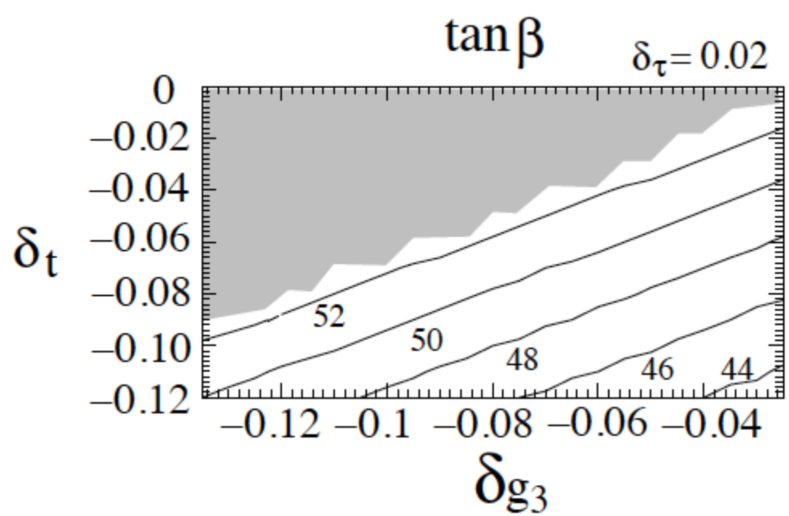
Therefore, basic conclusion: *b mass corrections must be smaller than naively is expected to allow 3rd generation Yukawa unification.*

(Conclusion survives a more detailed/numerical analysis.)

Things don't shift too much with g_3 shift



(a)



(b)

What does 3Y-unification tells us about susy mass

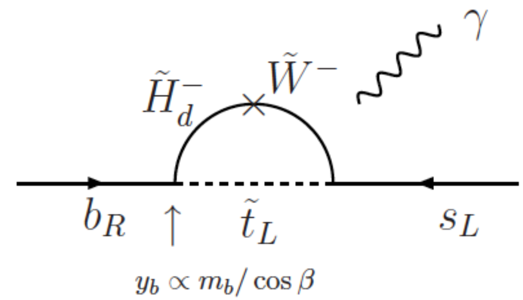
A more detailed expression for finite b quark mass corrections is

$$\delta_b^{\text{finite}} \simeq -\frac{g_3^2}{12\pi^2}\frac{\mu M_{\tilde{g}} \tan\beta}{m_{\tilde{b}}^2} + \frac{y_t^2}{32\pi^2}\frac{\mu A_t \tan\beta}{m_{\tilde{t}}^2} + \ldots$$

This suggests several ways to get the small but non-zero δ_b needed for 3Y unification.

- suppress by making R-charged masses (M_i and A_i) very small compared to scalar superpartners
- suppress by making PQ-charged masses (μ) very small compared to the scalar superpartners
- manufacture a cancellation between terms
- some combination of the above

The correlation with $b \to s\gamma$



Before going further, must point out corrrelation with $b \to s\gamma$

Even for super-KM=KM, this observable can be very large at high $\tan\beta$. The SUSY coefficient to the operator

$$\mathcal{O}_7 = m_b \bar{s}_L \sigma^{\mu\nu} b_R F_{\mu\nu}$$

is $\tan\beta$ enhanced, since chirality flips in supersymmetry can be done with $\lambda_b \propto m_b/\cos\beta \sim m_b \tan\beta$.

In general, we expect wildly HUGE contributions to $b \to s\gamma$ for low-scale susy with $\tan\beta \sim 50$.

The Blazek-Dermisek-Raby solution (BDR)

BDR's analysis is based on GUT $SO(10)$ with separate masses for m_{16} and m_{10}. They get 3Y unification by the following means:

1. $\tan\beta \sim 50$ for the third generation Yukawa couplings to approach unification.

2. $m_{1/2} \sim \mu \ll m_{16}$ to suppress, but not to zero, the gluino contributions to δ_b and $b \to s\gamma$.

3. Large A_0 such that the weak-scale A_t is larger than $M_{\tilde{g}}$ and the positive chargino-stop contributions to δ_b cancels, and slightly overcomes, the large negative contributions due to gluino-sbottoms finite and logarithmic corrections. (Note, we are expressing this criteria in our sign convention for b-quark corrections which is opposite to BDR sign convention: $\delta_b \propto -\Delta m_b^{\mathrm{BDR}}$).

4. $\mu > 0$ so that the large chargino-stop corrections to $b \to s\gamma$ can be opposite in sign to SM (and charged Higgs) contributions. This is necessary to be consistent with the large choice of A_0 term above, which when combined with the right sign of μ gives the chargino-stop loops a sufficiently large canceling contribution to change the sign of the $b \to s\gamma$ amplitude. This enables large $\tan\beta$ supersymmetry to be consistent with the $B(b \to s\gamma)$ measurements despite the SUSY contributions being much larger than the SM contributions.

Changing sign of $b \to s\gamma$?

Define ΔC_7 to be the susy contributions to the $\mathcal{O}_7$ operator.

The susy prediction can be approximated as

$$B(b \to s\gamma)_{\rm susy} = B(b \to s\gamma)_{\rm SM} \left| 1 + 0.45 \frac{\Delta C_7}{C_7^{\rm SM}} \right|^2$$

The experiment is nicely consistent with SM theory (within $\sim 10\%$). Therefore, either

$$\Delta C_7 \simeq 0, \quad \text{or}$$

$$1 + 0.45 \frac{\Delta C_7}{C_7^{\rm SM}} \simeq -1$$

thereby flipping the sign of the amplitude. But amplitude gets squared for $b \to s\gamma$, so satisfies experimental constraint.

Because ΔC_7 is expected to be so large, the latter possibility is real and is exploited by BDR.

Disquieting features of BDR solution

Main worry ... "finetuned cloaking of large $\tan\beta$ effects"

δ_b has to be suppressed by a combination of susy hierarchies and cancellation between gluino-sbottom and chargino-stop contributions.

$b \to s\gamma$ has to be cloaked by a just-so flipping of amplitude.

Is there a better way?

The partially-decoupled solution

We can suppress both δ_b, as is needed for 3Y unification, and $b \to s\gamma$, as is needed for consistency with experiment, by considering very massive scalars.

There are pluses and minuses to considering very massive scalars:

Main minus: EWSB breaking more tuned – heavy mass scales in potential have to eject a low-mass m_Z.

Main plus: FCNC and CP violating observables are ok no matter what super-KM angles are.

So...

Our framework: $\tilde{m}_i \gg M_\lambda, A_i, \mu$ such that no cancellations or cloaking of large $\tan\beta$ effects is necessary.

Roughly speaking $\tilde{m} \gtrsim \sqrt{\tan\beta}\, M_\lambda$, etc.

Example model approach to spectrum

Anomaly mediated supersymmetry breaking (AMSB) works well for our needs.

Ordinarily, mass of gauginos come from

$$\int d^2\theta \frac{S}{M_{\rm pl}} \mathcal{W}\mathcal{W} \to \frac{F_S}{M_{\rm pl}} \lambda\lambda$$

If there is no singlet in theory carrying susy breaking then gaugino mass very supressed. However, AMSB (via conformal anomaly) introduces susy breaking contributions at one loop:

$$M_\lambda = \frac{\beta_{g_\lambda}}{g_\lambda} \frac{m_{3/2}}{16\pi^2}$$

where $m_{3/2}$ is the gravitino mass.

Scalar masses generally arise at order $F^\dagger F/M_{\rm pl}^2$ and so are naturally of order $m_{3/2}$. They can be supressed (e.g., no scale) all the way to AMSB levels, but probably should not rely on that. We assume only a mild suppression at most

$$\tilde{m}^2 = \eta\, m_{3/2}^2$$

where η is maybe one-loop suppressed.

Illustration of 3Y-unification in pAMSB

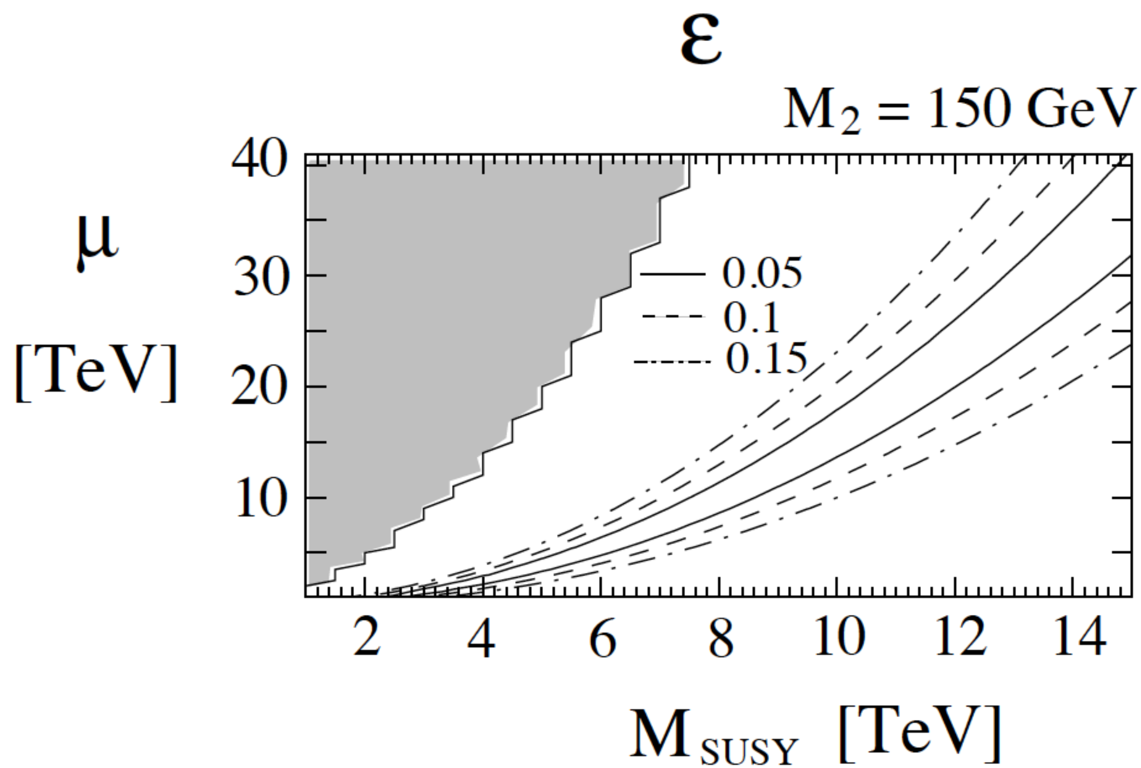
Choose AMSB spectrum normalized such that $M_2 = 150\,\mathrm{GeV}$ ($M_1 = 500\,\mathrm{GeV}$ and $M_3 = 1300\,\mathrm{GeV}$). Gravitino mass is near $600\,\mathrm{GeV}$ in this case.

For given value of μ and M_{SUSY} (defined to be all scalar masses except Higgs), compute the value of $\tan\beta$ (usually near 50) such that ϵ is minimized.

$$\epsilon = \sqrt{\left(\frac{y_b - y_\tau}{y_b}\right)^2 + \left(\frac{y_t - y_\tau}{y_t}\right)^2 + \left(\frac{y_t - y_b}{y_t}\right)^2} \quad \text{(computed at GUT scale)}$$

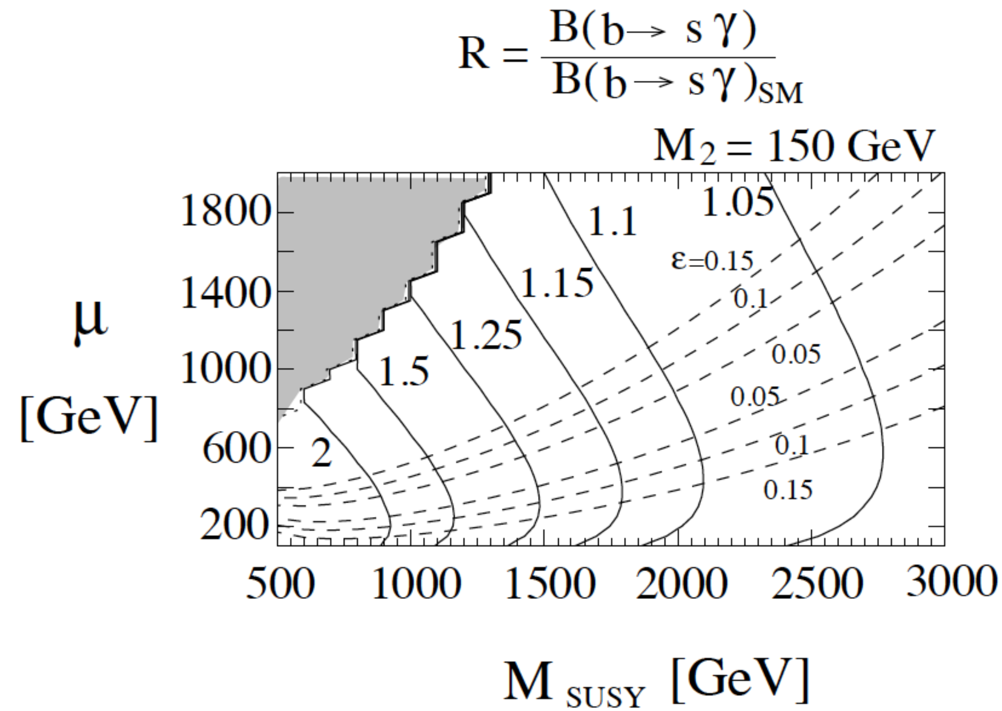
Plot contours of constant ϵ – values less than about 5% ($\epsilon \lesssim 0.05$) are reasonable requirements on the unification.

Contours of constant ϵ



Contours of $\epsilon = 0.05\ (0.1, 0.15)$ corresponds to about 5% (10%, 15%) GUT threshold correction needed to achieve Yukawa coupling unification. GUT-scale Yukawa corrections are expected to be less than about 1%. M_{SUSY} is the low-energy mass for all scalar superpartners. The gaugino and A-term masses are equal to their anomaly-mediated values normalized to $M_2 = 150$ GeV.

Is $b \to s\gamma$ ok?



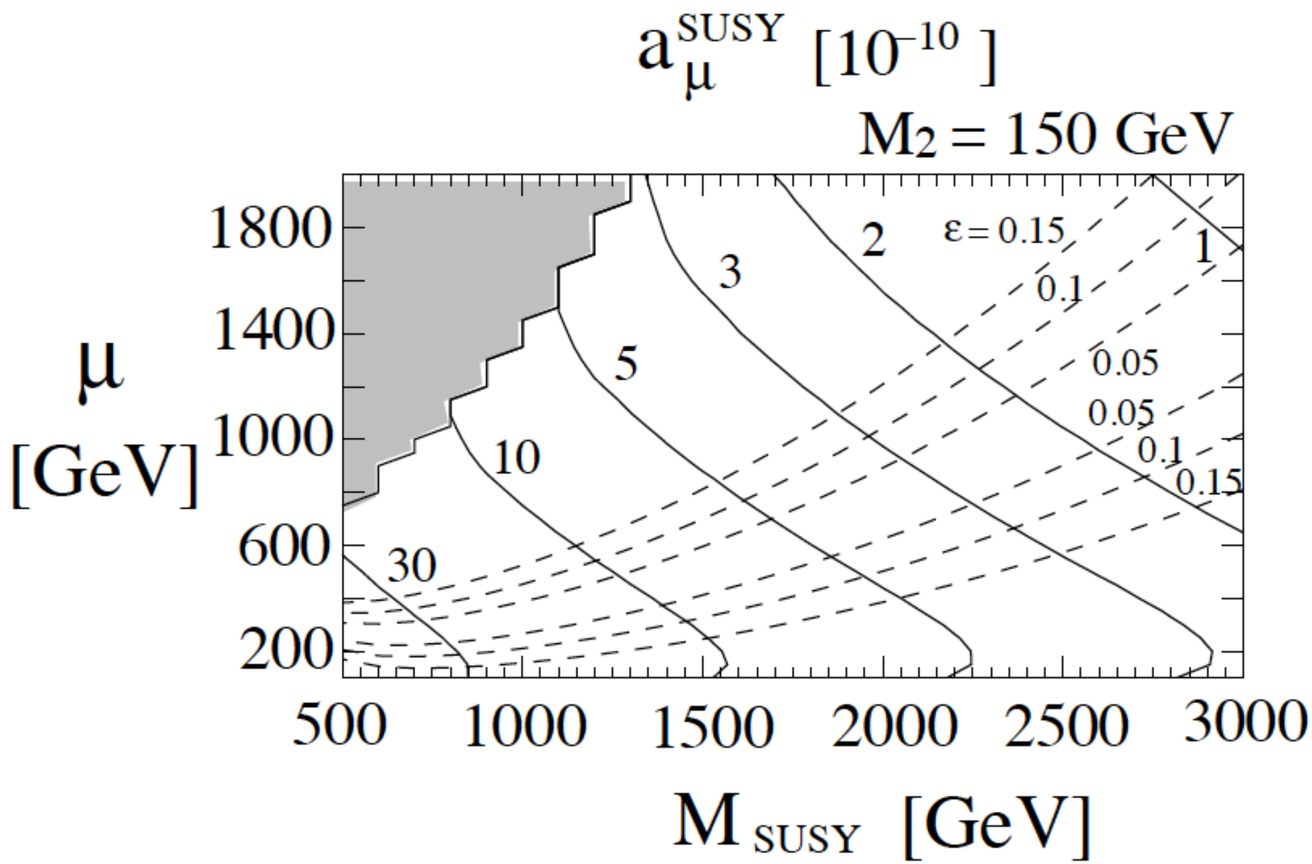
(a)

Kagan and Neubert say that $0.37 < R < 1.25$ where

$$R = \frac{B(b \to s\gamma)}{B(b \to s\gamma)_{\rm SM}}.$$

$M_{\rm susy}$ over a few TeV seems necessary. This graph was made under the most favorable FCNC assumptions (super-KM=KM), otherwise limit would be higher.

$g-2$ of the muon



(b)

A conservative view of the $g-2$ experimental uncertainties and theoretical uncertainties implies that $a_\mu^{\rm susy}/10^{-10}$ should be between about -37 and 90 (Martin and JW).

Comments on high-scale threshold corrections

Gravity effects yield order 1% corrections to gauge and Yukawa couplings:

$$\delta y, \delta g \sim \frac{M_G}{M_{\rm pl}} \sim 1\%$$

Heavy GUT-scale particles in loops generally do not contribute much to Yukawa corrections (but can contribute much to gauge coupling corrections).

If neutrino Yukawa y_ν is unified at the high scale than its Yukawa coupling affects the evolution of the other Yukawas. The correction can be expressed as a GUT-scale threshold correction:

$$\delta_t^{GUT} \simeq \delta_\tau^{GUT} \lesssim \frac{y_\nu^2}{16\pi^2} \log \frac{M_G}{10^{13}\,\mathrm{GeV}} \sim 4\%, \quad (1)$$

$$\delta_b^{GUT} \simeq 0. \quad (2)$$

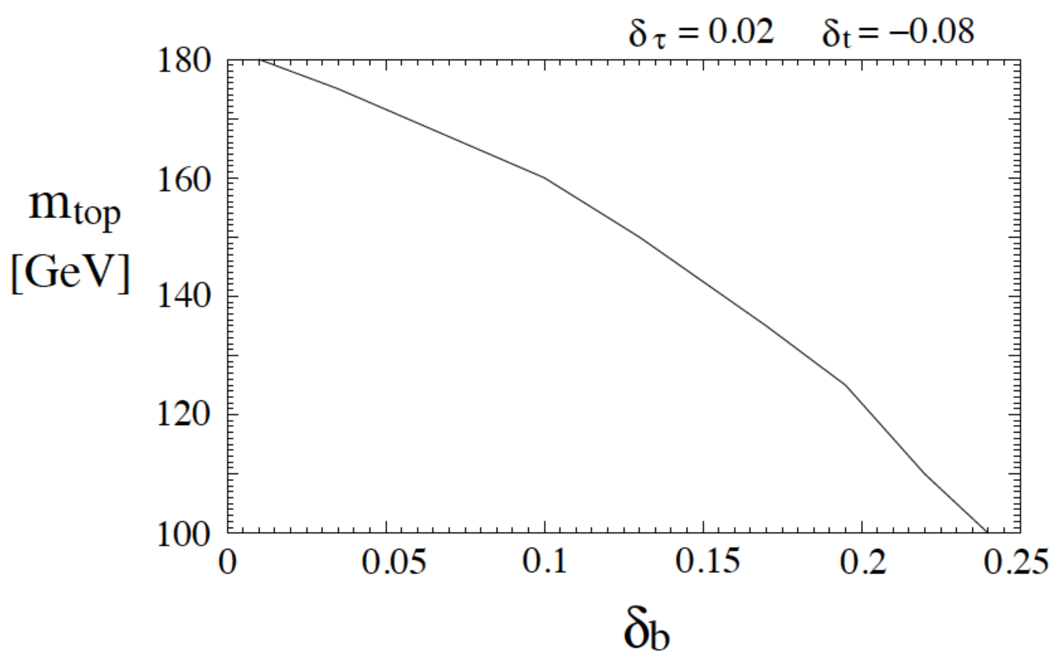
This correction is in the positive direction $\delta_t \simeq \delta_\tau$ direction which has almost no impact on needed δ_b. (Contours of constant "needed δ_b" are in $\delta_t \simeq \delta_\tau$ direction.)

Prediction of top mass

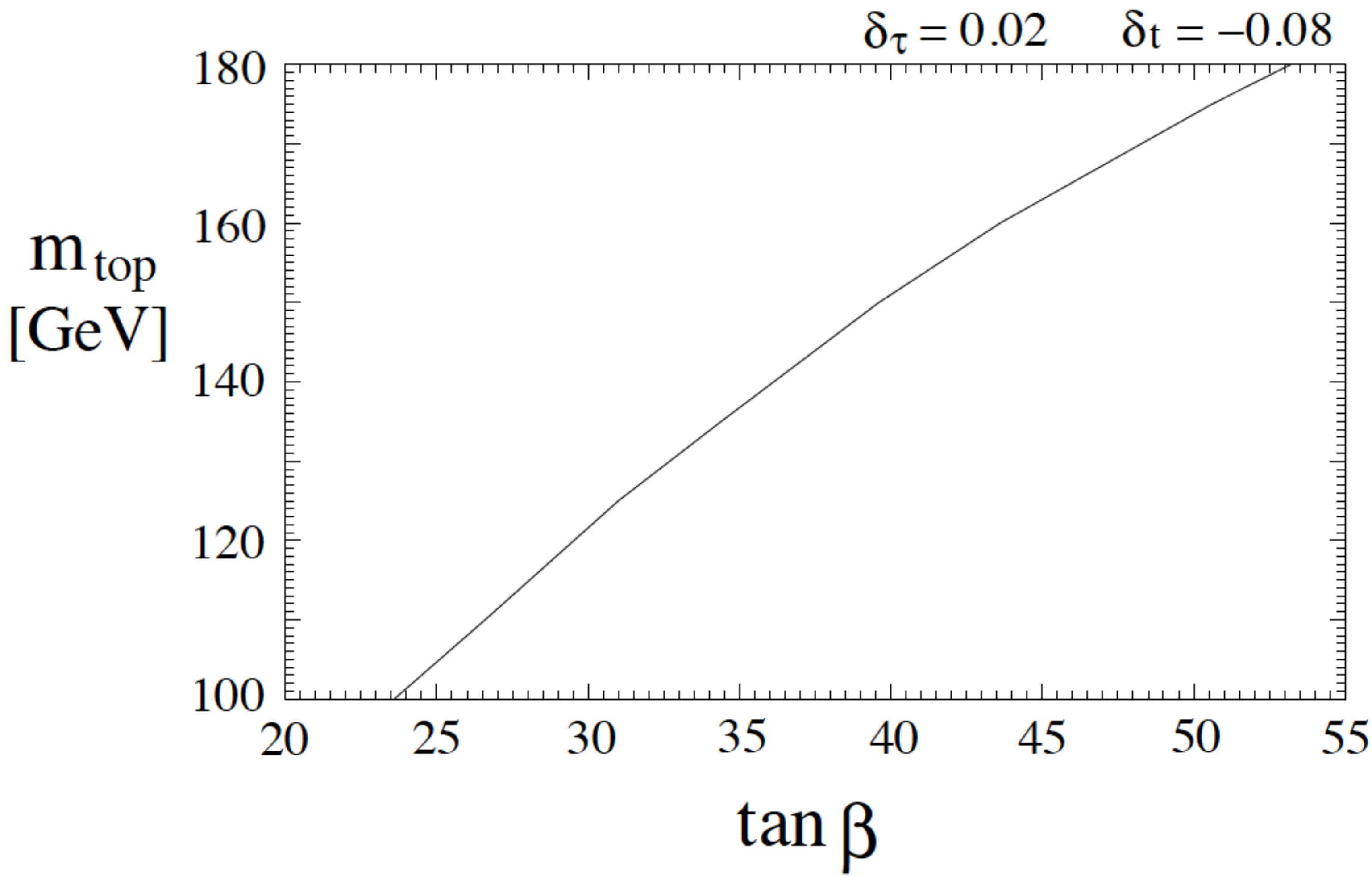
Old (and not so old) Claims: "$S0(10)$ 3Y unification predicts a top mass of 175 GeV, just like experiment shows."

That was derived assuming (either consciously or, usually, subconsciously) that $\delta_b = 0$ and doing a not-so-super-precise analysis.

Actually, any m_t would have been fine. In fact, perhaps a lower value of m_t would have been better since we naturally expect $\delta_b \sim$ tens of percent.



$\tan\beta$ dependence on top mass in 3Y unification



Yukawa unification discussion

- judging viability of $b - \tau - t$ unification is *highly* sensitive to the low-scale superpartner spectrum.
- b mass finite corrections must be much smaller than naively would be expected to make unification work out.
- BDR approach: cancellations to cloak unwanted large $\tan\beta$ effects
- Our approach: deep suppressions of unwanted large $\tan\beta$ effects at the possible expense of natural EWSB
- Experiment will tell! (The benefits of IR sensitivity)

Exact gauge coupling unification

We saw earlier that gauge couplings do not unify exactly, when applying only IR considerations.

Nor do we expect it! Rather, we expect high-scale threshold corrections to have an effect.

From minimal $SU(5)$ point of view, we can illustrate how important non-renormalizable operators (NROs) are to unification.

Minimal $SU(5)$ is dead...

Consider minimal $SU(5)$:

$$\{\mathbf{10}_i, \bar{\mathbf{5}}_i, \mathbf{1}_i\} \text{ matter sector}$$
$$\mathbf{24} \text{ gauge sector}$$
$$\{\mathbf{24}_H, \mathbf{5}_H, \bar{\mathbf{5}}_H\}$$

High scale threshold corrections come from the massive components of the these reps: $M_V,\ M_\Sigma,\ M_{H_c}$.

Gauge coupling running

The relationships between the GUT scale gauge coupling g_G and the low-scale gauge couplings $g_i(Q)$ of the MSSM effective theory are

$$\frac{1}{g_i^2(Q)} = \frac{1}{g_G^2(Q)} + \Delta_i^G(Q) + c_i\epsilon$$

The $\Delta_i^G(Q)$ functions are the threshold corrections due to heavy GUT states; $\Delta_i^G(Q) = 1/(8\pi^2)\sum_a b_{ai}\ln(Q/M_a)$ where b_{ai} and M_a are β function coefficient of a heavy particle and its mass, respectively. They are explicitly written by

$$\begin{aligned}
\Delta_1^G(Q) &= \frac{1}{8\pi^2}\left(-10\ln\frac{Q}{M_V} + \frac{2}{5}\ln\frac{Q}{M_{H_c}}\right)\\
\Delta_2^G(Q) &= \frac{1}{8\pi^2}\left(-6\ln\frac{Q}{M_V} + 2\ln\frac{Q}{M_\Sigma}\right)\\
\Delta_3^G(Q) &= \frac{1}{8\pi^2}\left(-4\ln\frac{Q}{M_V} + \ln\frac{Q}{M_{H_c}} + 3\ln\frac{Q}{M_\Sigma}\right).
\end{aligned}$$

Importance of Higgs triplet

One linear combination isolates M_{H_c} (Hisano et al.):

$$-\frac{1}{g_1^2(Q)}+\frac{3}{g_2^2(Q)}-\frac{2}{g_3^2(Q)}=\frac{3}{5\pi^2}\ln\frac{M_{H_c}}{Q}.$$

Evaluate at unification scale Λ_U, which we define to be the place where $g_1(\Lambda_U)=g_2(\Lambda_U)=g_U$,

$$\frac{1}{g_U^2}-\frac{1}{g_3^2(\Lambda_U)}=\frac{3}{10\pi^2}\ln\frac{M_{H_c}}{\Lambda_U}.$$

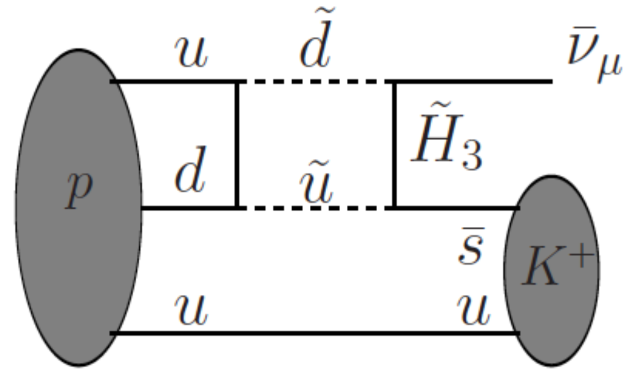
Λ_U depends mildly on the low-scale superpartner masses, but it is always within the range

$$1\times 10^{16}\,\mathrm{GeV}\lesssim\Lambda_U\lesssim 2\times 10^{16}\,\mathrm{GeV}$$

for superpartner masses at the TeV scale and below.

Conflict between unification and proton stability?

$$\frac{1}{g_U^2} - \frac{1}{g_3^2(\Lambda_U)} = \frac{3}{10\pi^2} \ln \frac{M_{H_c}}{\Lambda_U}.$$



$g_3(\Lambda_U) < g_U$, albeit by less than 1%.

This implies that the LHS of is necessarily negative. We see that

$$M_{H_c} < \Lambda_U \simeq 10^{16}\,\mathrm{GeV} \quad \text{(gauge unification)}$$

is required for the RHS to be negative and successful gauge coupling unification to occur.

But this is in conflict with the proton decay requirement that

$$M_{H_c} > 10^{17}\,\mathrm{GeV}(> \Lambda_U) \quad \text{(proton decay)}$$

NRO effects

We expect gravity to induce M_P operators of the type

$$\int d^2\theta \left[\frac{S}{8M_{\rm Pl}}\mathcal{W}\mathcal{W} + \frac{y\Sigma}{M_{\rm Pl}}\mathcal{W}\mathcal{W}\right]$$

where $\Sigma = \mathbf{24}_H$ and $\langle S\rangle = M_{\rm Pl}/g_G^2 + \theta^2 F_S$ contains the effective singlet supersymmetry breaking. The $SU(5)$ gauge coupling is g_G and the universal contribution to the masses of all gauginos is $M_{1/2} = -g_G^2 F_S/(2M_{\rm Pl})$.

Indeed, such interactions are necessary for gaugino masses from susy breaking.

The GUT symmetry breaking is accomplished by

$$\langle\Sigma\rangle = v_\Sigma \,\mathrm{diag}\left(\frac{2}{3}, \frac{2}{3}, \frac{2}{3}, -1, -1\right)$$

to break $SU(5)$ to $SU(3) \times SU(2)_L \times U(1)_Y$ at the GUT scale. The numerical value of v_Σ depends on details of the couplings but should be around the GUT scale of 10^{16} GeV.

Shifted gauge couplings

The NRO operator involving the **24** affects the $SU(3) \times SU(2) \times U(1)$ couplings. They are now

$$\frac{1}{g_i^2(Q)} = \frac{1}{g_G^2(Q)} + \Delta_i^G(Q) + c_i \epsilon$$

where

$$\epsilon = 8y \frac{v_\Sigma}{M_P} \quad \text{and} \quad c_i = \{-1/3, -1, 2/3\}$$

for groups $i = \{U(1)_Y, SU(2)_L, SU(3)\}$ respectively.

We can recompute the combination that isolated H_c:

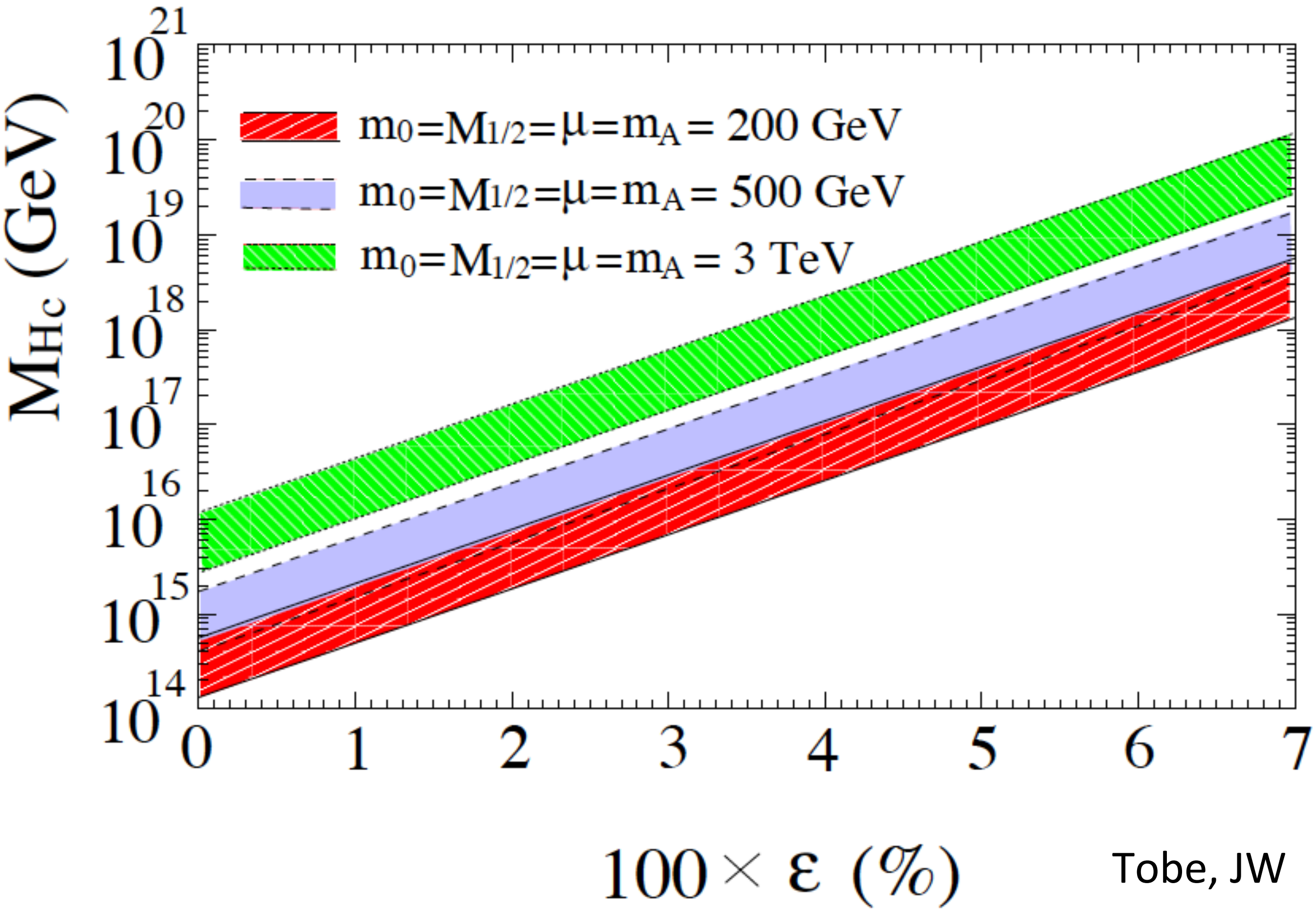
$$\begin{aligned} \frac{1}{g_U^2} - \frac{1}{g_3^2(\Lambda_U)} &= \frac{3}{10\pi^2} \ln \frac{M_{H_c}}{\Lambda_U} - 2\epsilon \\ &= \frac{3}{10\pi^2} \ln \frac{M_{H_c}^{eff}}{\Lambda_U}. \end{aligned}$$

where

$$M_{H_c}^{eff} = M_{H_c} \exp(-20\pi^2 \epsilon/3)$$

Thus, with $\epsilon \sim$ few percent, we can have $M_{H_c} > 10^{17}\,\mathrm{GeV}$ and $M_{H_c}^{\mathrm{eff}} < 10^{16}\,\mathrm{GeV}$.

Triplet Higgs mass for exact unification



Tobe, JW

SUSY breaking effects

VEVs usually develop in superspace

$$\langle\hat{\Sigma}\rangle \simeq (v_\Sigma + F_\Sigma\theta^2)\,\mathrm{diag}\left(\frac{2}{3},\frac{2}{3},\frac{2}{3},-1,-1\right)$$

The superpotential and soft lagrangian terms we assume are

$$W = \frac{1}{2}M_\Sigma \mathrm{Tr}\,\Sigma^2 + \frac{f}{3}\mathrm{Tr}\,\Sigma^3 + M_5\mathbf{5}_H\overline{\mathbf{5}}_H + \lambda\overline{\mathbf{5}}_H\Sigma\mathbf{5}_H + \cdots$$

$$-\mathcal{L}_{\mathrm{soft}} = \frac{1}{2}B_\Sigma M_\Sigma \mathrm{Tr}\,\Sigma^2 + \frac{f}{3}A_\Sigma \mathrm{Tr}\,\Sigma^3 + B_5 M_5\mathbf{5}_H\overline{\mathbf{5}}_H + A_\lambda\lambda\overline{\mathbf{5}}_H\Sigma\mathbf{5}_H + h.c. + \cdots$$

where upon minimizing the full potential we find

$$F_\Sigma \simeq v_\Sigma(A_\Sigma - B_\Sigma) = \frac{\epsilon M_{\mathrm{Pl}}}{8y}(A_\Sigma - B_\Sigma)$$

which generates a correction to gaugino masses via the NRO.

$$\int d^2\theta\left[\frac{S}{8M_{\mathrm{Pl}}}\mathcal{W}\mathcal{W} + \frac{y\Sigma}{M_{\mathrm{Pl}}}\mathcal{W}\mathcal{W}\right]$$

Gaugino mass spectrum

$$
\begin{aligned}
M_1(\Lambda_U) &= g_U^2\overline{M} + g_U^2\left[\frac{1}{6}\epsilon(A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2}\left(10g_U^2\overline{M} + 10\{A_\Sigma - B_\Sigma\} + \frac{2}{5}B_5\right)\right] \\
M_2(\Lambda_U) &= g_U^2\overline{M} + g_U^2\left[\frac{1}{2}\epsilon(A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2}\left(6g_U^2\overline{M} + 6A_\Sigma - 4B_\Sigma\right)\right] \\
M_3(\Lambda_U) &= g_3^2(\Lambda_U)\overline{M} + g_U^2\left[-\frac{1}{3}\epsilon(A_\Sigma - B_\Sigma) - \frac{1}{16\pi^2}\left(4g_U^2\overline{M} + 4A_\Sigma - B_\Sigma + B_5\right)\right]
\end{aligned}
$$

where $\overline{M} = -F_S/(2M_{\rm Pl}) \sim \mathcal{O}(m_z)$ is the supersymmetry mass scale from the singlet field F-term.

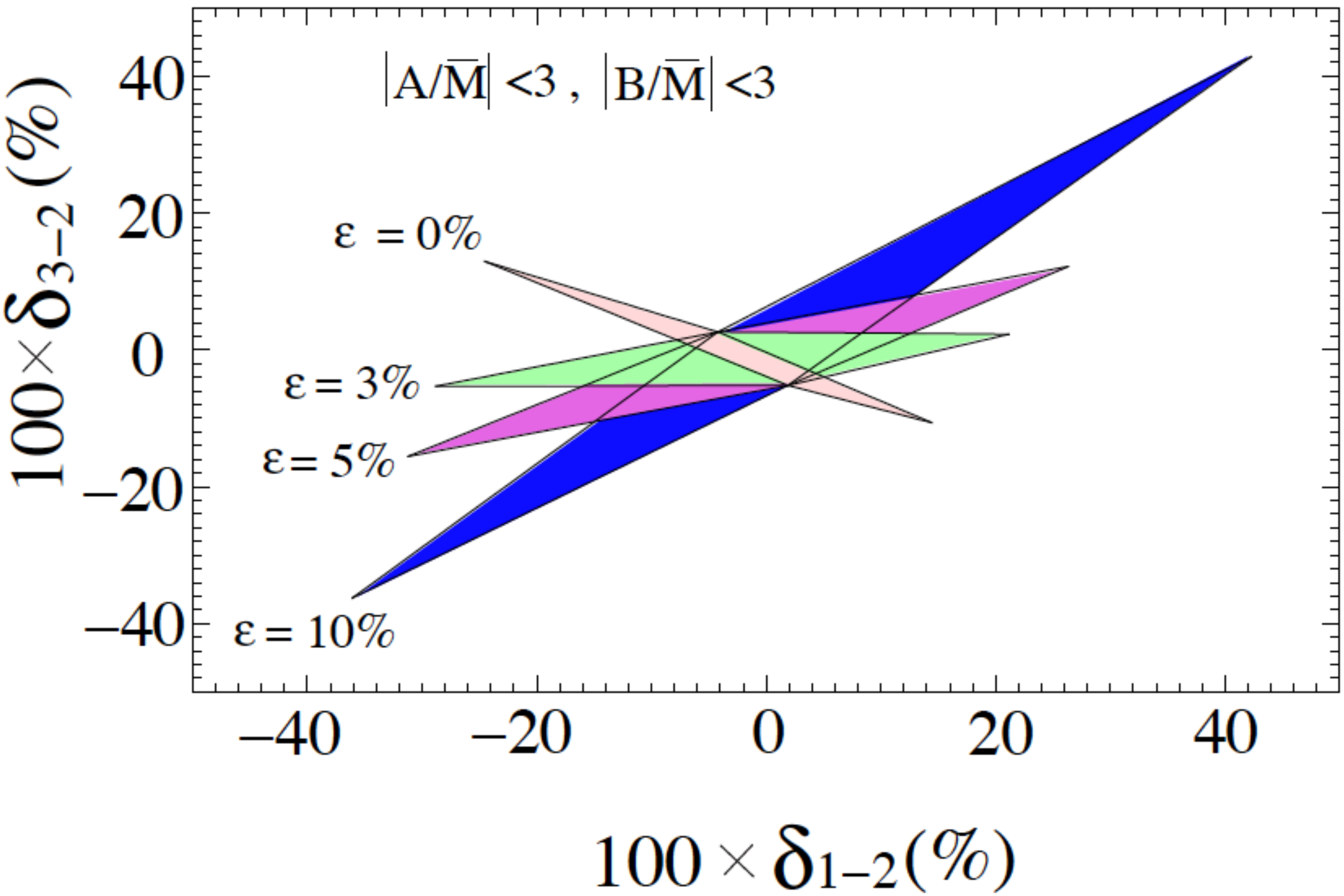
There are four parameters of the GUT theory that are affecting the ratios of the gaugino mass values at Λ_U,

$$\epsilon, \quad A_\Sigma/\overline{M}, \quad B_\Sigma/\overline{M}, \quad B_5/\overline{M}.$$

$$\delta_{1-2} = \frac{M_1(\Lambda_U) - M_2(\Lambda_U)}{M_2(\Lambda_U)} \quad \text{and} \quad \delta_{3-2} = \frac{M_3(\Lambda_U) - M_2(\Lambda_U)}{M_2(\Lambda_U)}.$$

The δ's are defined at the $g_1 = g_2$ unification scale Λ_U.

Relative shifts in gaugino mass boundary conditions



arXiv:1201.5668v1 [hep-ph] 26 Jan 2012

A heavier gluino from t-b-τ Yukawa-unified SUSY

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Abstract

Supersymmetric models with $t-b-\tau$ Yukawa coupling unification and unified gaugino masses at the GUT scale– with $\mu > 0$– show a mild preference for light gluino masses $m_{\tilde{g}} \lesssim 500$ GeV. This range of $m_{\tilde{g}}$ is now essentially ruled out by LHC searches. We show that a heavier gluino with $m_{\tilde{g}} \sim 0.5-3$ TeV can also be compatible with excellent $t-b-\tau$ Yukawa coupling unification in supersymmetric models with non-universal Higgs masses (NUHM2). The gluino in such models is the lightest colored sparticle, while the squark sector displays an inverted mass hierarchy with $m_{\tilde{q}} \sim 5-20$ TeV. We present some LHC testable benchmark points for which the lightest Higgs boson mass $m_h \simeq 125$ GeV. We also discuss LHC signatures of Yukawa-unified models with heavier gluinos. We expect gluino pair production followed by decay to final states containing four b-jets plus four W-bosons plus missing E_T to occur at possibly observable rates at LHC.

	Point 1	Point 2	Point 3	Point 4
m_{16}	21370	20230	18640	26130
$m_{1/2}$	93.41	364	579	1021
A_0/m_{16}	-2.43	-2.13	-2.09	-2.11
$\tan\beta$	57.2	51	50	52
m_{H_d}	22500.0	26770	24430	34210
m_{H_u}	13310.0	23260	21780	30590
m_h	126.7	125	124	124
m_H	9389	3192	3145	4066
m_A	9328	3171	3125	4040
$m_{H^\pm}$	9390	3193	3147	4067
$m_{\tilde{g}}$	750	1375	1853	2991
$m_{\tilde{\chi}^0_{1,2}}$	122, 285	232, 491	323,661	557,1114
$m_{\tilde{\chi}^0_{3,4}}$	19295, 19295	6048,6048	4570,4571	6315,6315
$m_{\tilde{\chi}^\pm_{1,2}}$	286, 19330	493,6021	664,4542	1118,6275
$m_{\tilde{u}_{L,R}}$	21389,21132	20230,20115	18653,18574	26187,26079
$m_{\tilde{t}_{1,2}}$	7389,8175	3465,5356	3089,5447	4376,7901
$m_{\tilde{d}_{L,R}}$	21389,21513	20230,20333	18653,18742	26187,26304
$m_{\tilde{b}_{1,2}}$	7836,8234	5417,6047	5534,6584	8038,9652
$m_{\tilde{\nu}_1}$	21196	20128	18565	26037
$m_{\tilde{\nu}_3}$	15502	15066	14032	19441
$m_{\tilde{e}_{L,R}}$	21193,21717	20123,20416	18559,18779	26027,26319
$m_{\tilde{\tau}_{1,2}}$	7490,15463	8048,15079	7796,14042	9984,19455
$\Omega_{CDM}h^2$	12642	190	972	1377
$R_{tb\tau}$	1.06	1.00	1.05	1.07
$BF(\tilde{g} \to b\bar{b}\tilde{\chi}^0_i)$	0.33	0.13	0.07	0.06
$BF(\tilde{g} \to t\bar{t}\tilde{\chi}^0_i)$	0.15	0.15	0.69	0.75
$BF(\tilde{g} \to t\bar{b}\tilde{\chi}^-_j + c.c.)$	0.45	0.33	0.22	0.18

Table 1: Sparticle and Higgs masses (in GeV). All of these benchmark points satisfy the various constraints mentioned in Section 2 and are compatible with Yukawa unification. Point 1 exhibits a solution near the current reach limit of LHC. Point 2 exhibits 'perfect' Yukawa unification. Point 3 displays an example of a relatively heavy gluino within reach of LHC14. Point 4 represents a solution with the heaviest gluino (~ 3 TeV) we have in our scans; it is likely beyond reach of LHC. The uncertainty in the Higgs mass (m_h) estimates is about ± 2 GeV.

Comments

General lesson: high-scale hypotheses can have very significant effect on low-scale phenomenology – even "subtle hypotheses".

Tri-Yukawa unification leaves distinctive implications on the low-energy spectrum.

The spectrum needed looks like a "split susy" or "partial split susy" scenario – independent of the Higgs boson mass issues!

Supersymmetry Phenomenology

Lecture 4: Hidden sectors and the Higgs boson

James Wells
CERN & Michigan

February 2012

SM Higgs Boson

EWSB accomplished by a single Higgs boson.

$$H = \begin{pmatrix} \frac{1}{\sqrt{2}}(h+v) + i\phi_1 \\ \phi_2 + i\phi_3 \end{pmatrix} \quad \text{where } v = 246\,\text{GeV}$$

$$\{W_T^\pm, Z_T^0\} + \{\phi_1, \phi_2, \phi_3\} \Rightarrow \{W_T^\pm, W_L^\pm, Z_T^0, Z_L^0\}$$

$$L = \left[m_W^2 W^{+\mu} W_\mu^- + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right] \cdot \left(1 + \frac{h}{v}\right)^2 - m_f \bar{f}_L f_R \left(1 + \frac{h}{v}\right) + h.c.$$

Higgs mass is only free parameter.

What is special about the Higgs Boson in the SM?

"It gives elementary particles their masses."

"It has not been found yet."

"It is the only fundamental Lorentz scalar particle in nature."

"It condenses."

All true, but there is another reason…

Relevant Invariant Operator

The $|H|^2$ operator is the only gauge-invariant, Lorentz invariant relevant operator in the Standard Model.

Other relevant operators include:

Neutrino physics.

$$B_{\mu\nu}, \qquad HL, \quad \nu_R^T i\sigma^2 \nu_R$$

Lorentz Tensor

Lorentz spinor

Lepton #
Not in SM.

Challenges of being sensitive to New Physics

The Standard Model matter and gauge states saturate dimensionality of the lagrangian.

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi + \frac{1}{4}W^{a,\mu\nu}W^{a}_{\mu\nu} + \cdots$$

Any new states coupled in may come with a large suppression scale:

$$\mathcal{L} = \frac{1}{\Lambda^{\#}}\mathcal{O}_{SM}\mathcal{O}_{hid}$$

Opportunities with Higgs Relevant Operator

The $|H|^2$ operator gives us a chance to see states that we would otherwise never see.

Generic couplings of Higgs to SM singlets, hidden sectors, etc

$|\Phi_{hid}|^2|H|^2$ (Generic coupling)

$X^{\mu\nu}B_{\mu\nu}$ (Possible coupling with extra $U(1)_{hid}$)

Why more stuff?

Copernicus (NASA photo)

Copernicus Monument in Toruń
by Christian Friedrich Tieck (1853)

"There are more things in heaven and earth, Horatio, than are dreamt of in your philosophy." -Hamlet

The SM is merely a description of the particles that make up our bodies, and copies of those particles, and the forces between those particles.

Why at our scale?

There is a definite scale in nature whose origin we do not understand: M_Z.

No strong reason to believe that SM is alone at that mass scale.

Simple, Non-Trivial Hidden World

Probably simplest theory is a Hidden-Sector Abelian Higgs Model.

A complex scalar charged under $U(1)_{X.}$ The particle spectrum is a physical Higgs boson and an X gauge field.

Lagrangian

Consider the SM lagrangian plus the following:

$$\mathcal{L}_X^{KE} = -\frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{\chi}{2}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu}$$

$$\begin{aligned}\mathcal{L}_\Phi \;=\; & |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2 \\ & -\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \kappa|\Phi_{SM}|^2|\Phi_H|^2.\end{aligned}$$

Canonical Kinetic Terms

First, we make kinetic terms canonical by

$$\begin{pmatrix} X_\mu \\ Y_\mu \end{pmatrix} = \begin{pmatrix} \sqrt{1-\chi^2} & 0 \\ -\chi & 1 \end{pmatrix} \begin{pmatrix} \hat{X}_\mu \\ \hat{Y}_\mu \end{pmatrix}$$

The covariant derivative is shifted to

$$D_\mu = \partial_\mu + i(g_X Q_X + g'\eta Q_Y)X_\mu + ig'Q_Y B_\mu + igT^3 W^3_\mu$$

$$\text{where } \eta \equiv \chi/\sqrt{1-\chi^2}$$

Gauge Boson Eigenstates

Diagonalize to mass eigenstates A, Z, and Z' by

$$\begin{pmatrix} B \\ W^3 \\ X \end{pmatrix} = \begin{pmatrix} c_W & -s_W c_\alpha & s_W s_\alpha \\ s_W & c_W c_\alpha & -c_W s_\alpha \\ 0 & s_\alpha & c_\alpha \end{pmatrix} \begin{pmatrix} A \\ Z \\ Z' \end{pmatrix}$$

Where,

$$\tan(2\theta_\alpha) = \frac{-2 s_W \eta}{1 - s_W^2 \eta^2 - \Delta_Z}$$

$$\Delta_Z = M_X^2 / M_{Z_0}^2, \; M_X^2 = \xi^2 g_X^2 q_X^2$$

$$\mathcal{L}_\Phi = |D_\mu \Phi_{SM}|^2 + |D_\mu \Phi_H|^2 + m^2_{\Phi_H}|\Phi_H|^2 + m^2_{\Phi_{SM}}|\Phi_{SM}|^2$$
$$-\lambda|\Phi_{SM}|^4 - \rho|\Phi_H|^4 - \boxed{\kappa|\Phi_{SM}|^2|\Phi_H|^2.} \qquad (3)$$

Higgs Masses and Mixings

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

The mixing angle and mass eigenvalues are

$$\tan(2\theta_h) = \frac{\kappa v \xi}{\rho\xi^2 - \lambda v^2}$$

$$M^2_{h,H} = (\lambda v^2 + \rho\xi^2) \mp \sqrt{(\lambda v^2 - \rho\xi^2)^2 + \kappa^2 v^2 \xi^2}$$

Feynman Rules

$$\bar{\psi}\psi Z \; : \; \frac{ig}{c_W}\left[c_\alpha(1-s_W t_\alpha \eta)\right]\left[T_L^3 - \frac{(1-t_\alpha\eta/s_W)}{(1-s_W t_\alpha\eta)} s_W^2 Q\right]$$

$$\bar{\psi}\psi Z' \; : \; \frac{-ig}{c_W}\left[c_\alpha(t_\alpha+\eta s_W)\right]\left[T_L^3 - \frac{(t_\alpha+\eta/s_W)}{(t_\alpha+\eta s_W)} s_W^2 Q\right]$$

$$\mathcal{R}_{AW^+W^-} = 1,\; \mathcal{R}_{ZW^+W^-} = c_\alpha \text{ and } \mathcal{R}_{Z'W^+W^-} = -s_\alpha$$

$$hff : -ic_h\frac{m_f}{v}\,, \qquad hWW : 2ic_h\frac{M_W^2}{v}$$

$$hZZ : 2ic_h\frac{M_{Z_0}^2}{v}(-c_\alpha+\eta s_W s_\alpha)^2 - 2is_h\frac{M_X^2}{\xi}s_\alpha^2\,,$$

$$hZ'Z' : 2ic_h\frac{M_{Z_0}^2}{v}(s_\alpha+\eta s_W c_\alpha)^2 - 2is_h\frac{M_X^2}{\xi}c_\alpha^2\,,$$

$$hZ'Z : 2ic_h\frac{M_{Z_0}^2}{v}(-c_\alpha+\eta s_W s_\alpha)(s_\alpha+\eta s_w c_\alpha) - 2is_h\frac{M_X^2}{\xi}s_\alpha c_\alpha\,.$$

Kinetic Mixing Origin

No position on how kinetic mixing occurs. Often,

$$\chi = \frac{\hat{g}_Y \hat{g}_X}{16\pi^2} \sum_i Q_X^i Q_Y^i \log\left(\frac{m_i^2}{\mu^2}\right)$$

“Kinetic messengers” can induce it if not there at the start.

Precision EW Effects of Kinetic Mixing

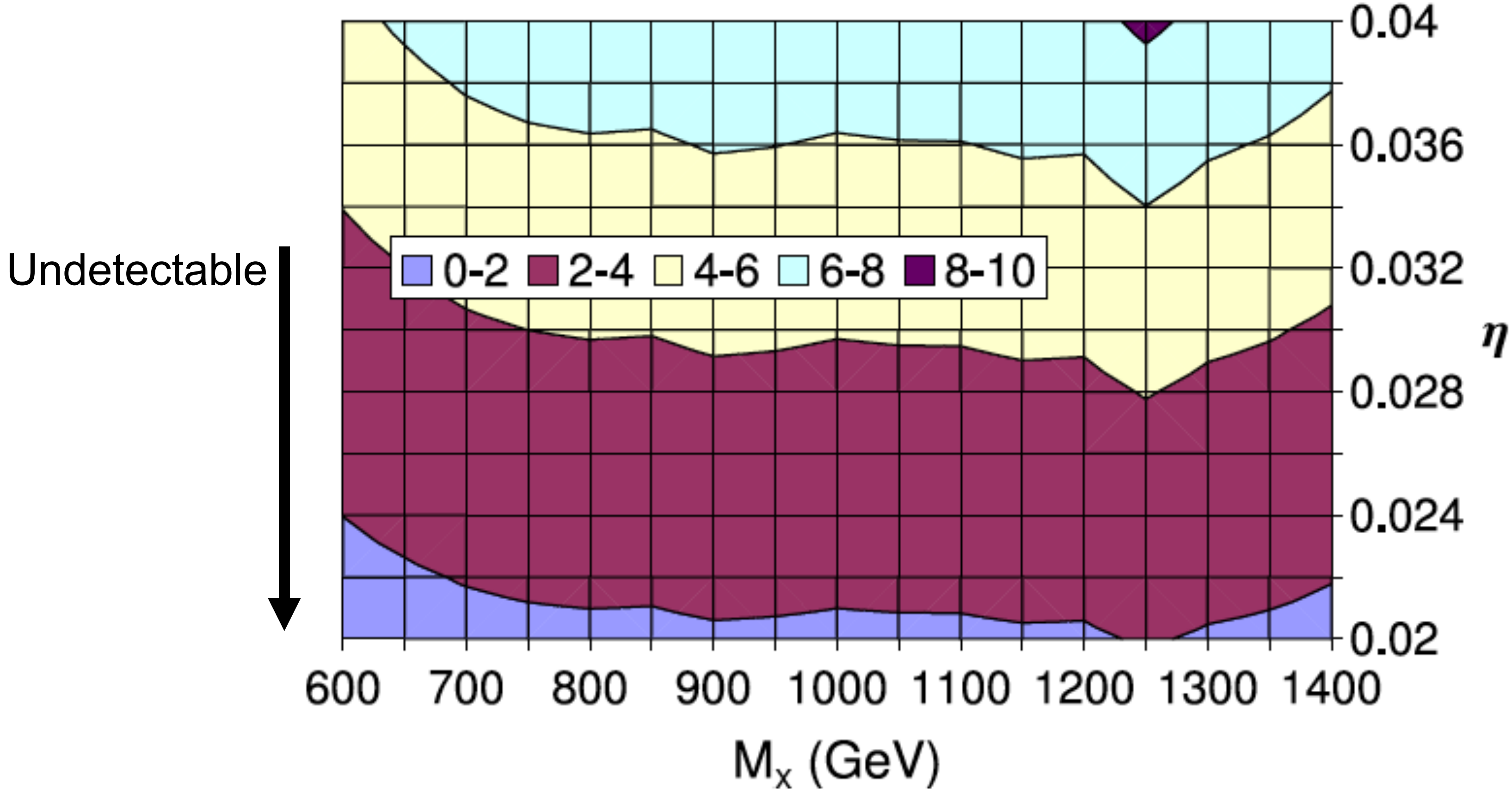
$$\begin{aligned} \Delta m_W &= (17\,\mathrm{MeV})\,\Upsilon \\ \Delta\Gamma_{l^+l^-} &= -(8\,\mathrm{keV})\,\Upsilon \\ \Delta \sin^2\theta_W^{eff} &= -(0.00033)\,\Upsilon \end{aligned}$$

$$\Upsilon \equiv \left(\frac{\eta}{0.1}\right)^2 \left(\frac{250\,\mathrm{GeV}}{m_X}\right)^2$$

Data limits suggest that $\Upsilon < 1$.

Kumar, JW

Collider Searches for Z'



Kumar, JW 0606183

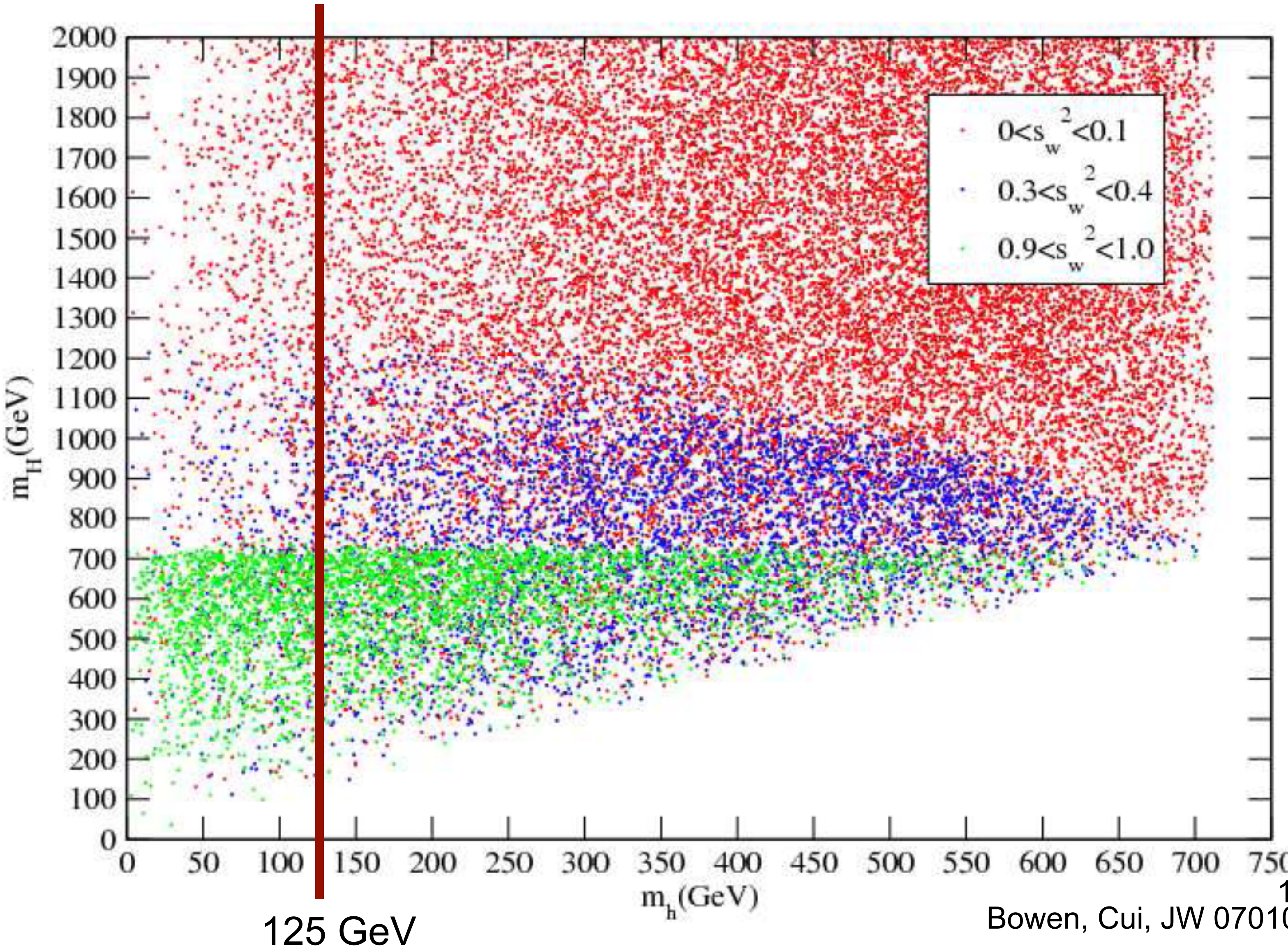
Higgs and Precision EW

When the Higgs bosons mix, neither state couples with full SM strength. The precision EW bound on the log is shared:

$$c_h^2 \log\left(\frac{M_h}{1\ \mathrm{GeV}}\right) + s_h^2 \log\left(\frac{M_H}{1\ \mathrm{GeV}}\right) \simeq 1.93^{+0.16}_{-0.17}$$

It is relatively easy to get high-mass Higgs when mixing angle is rather small. Precision EW can always be accommodated by adding new stuff.

Perturbative Unitarity of VV Scattering



Bowen, Cui, JW 0701035

Two Paths to LHC Discovery

Within this framework, we studied two ways to find Higgs boson at the LHC:

1) Narrow Trans-TeV Higgs boson signal

2) Heavy Higgs to light Higgs decays

Narrow Trans-TeV Higgs Boson

When the mixing is small, the heavy Higgs has smaller cross-section (bad), but more narrow (good).

	Point A	Point B	Point C
s_ω^2	0.40	0.31	0.1
m_h (GeV)	143	115	120
m_H (GeV)	1100	1140	1100
$\Gamma(H \to hh)$ (GeV)	14.6	4.9	10
$BR(H \to hh)$	0.036	0.015	0.095

Investigate Point C example

Two Signals

1) $$H \to WW \to l\nu jj$$

$$p_T(e,\mu) > 100\,\mathrm{GeV} \quad \text{and} \quad |\eta(e,\mu)| < 2.0$$

$$\text{Missing } E_T > 100\,\mathrm{GeV}$$

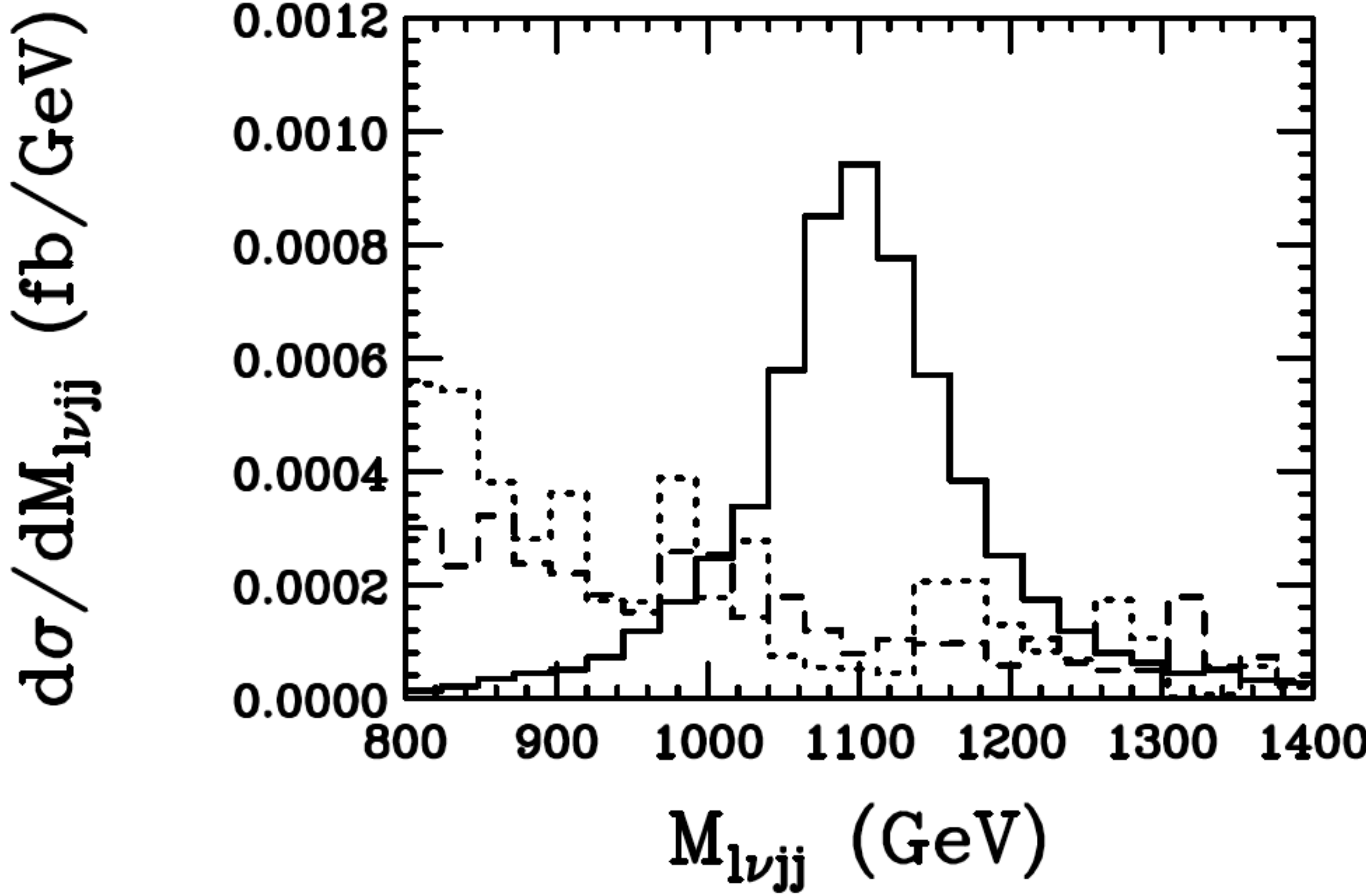
$$p_T(j,j) > 100\,\mathrm{GeV} \quad \text{and} \quad m_{jj} = m_W \pm 20\,\mathrm{GeV}$$

$$\text{“Tagging jets” with } |\eta| > 2.0$$

H->WW->jjlν

Techniques: Atlas & CMS TDRs and Iordanidis, Zeppenfeld, '97

Between 1.0 & 1.3 TeV 13 signal events in 100 fb^{-1} vs. 7.7 bkgd



H->WW (solid)

WWjj (dashed)

ttjj (dotted)

Difference from SUSY heavy Higgs boson

SUSY heavy Higgs has qualitatively different behavior:

ϕ		$g_{\phi\bar{t}t}$	$g_{\phi\bar{b}b}$	$g_{\phi VV}$
SM	H	1	1	1
MSSM	h^o	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\sin(\beta-\alpha)$
	H^o	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos(\beta-\alpha)$
	A^o	$1/\tan\beta$	$\tan\beta$	0

Haber et al. '01

$$HVV: \quad \cos(\beta-\alpha) \rightarrow \boxed{0} + \mathcal{O}(m_Z^4/m_A^4)$$

$$H\bar{t}t: \quad \frac{\sin\alpha}{\sin\beta} \rightarrow \boxed{\frac{1}{\tan\beta}} + \mathcal{O}(m_Z^2/m_A^2)$$

$$H\bar{b}b: \quad \frac{\cos\alpha}{\cos\beta} \rightarrow \boxed{\tan\beta} + \mathcal{O}(m_Z^2/m_A^2)$$

Heavy Higgs decays mostly into tops or bottoms (or susy partners) depending on tanβ.

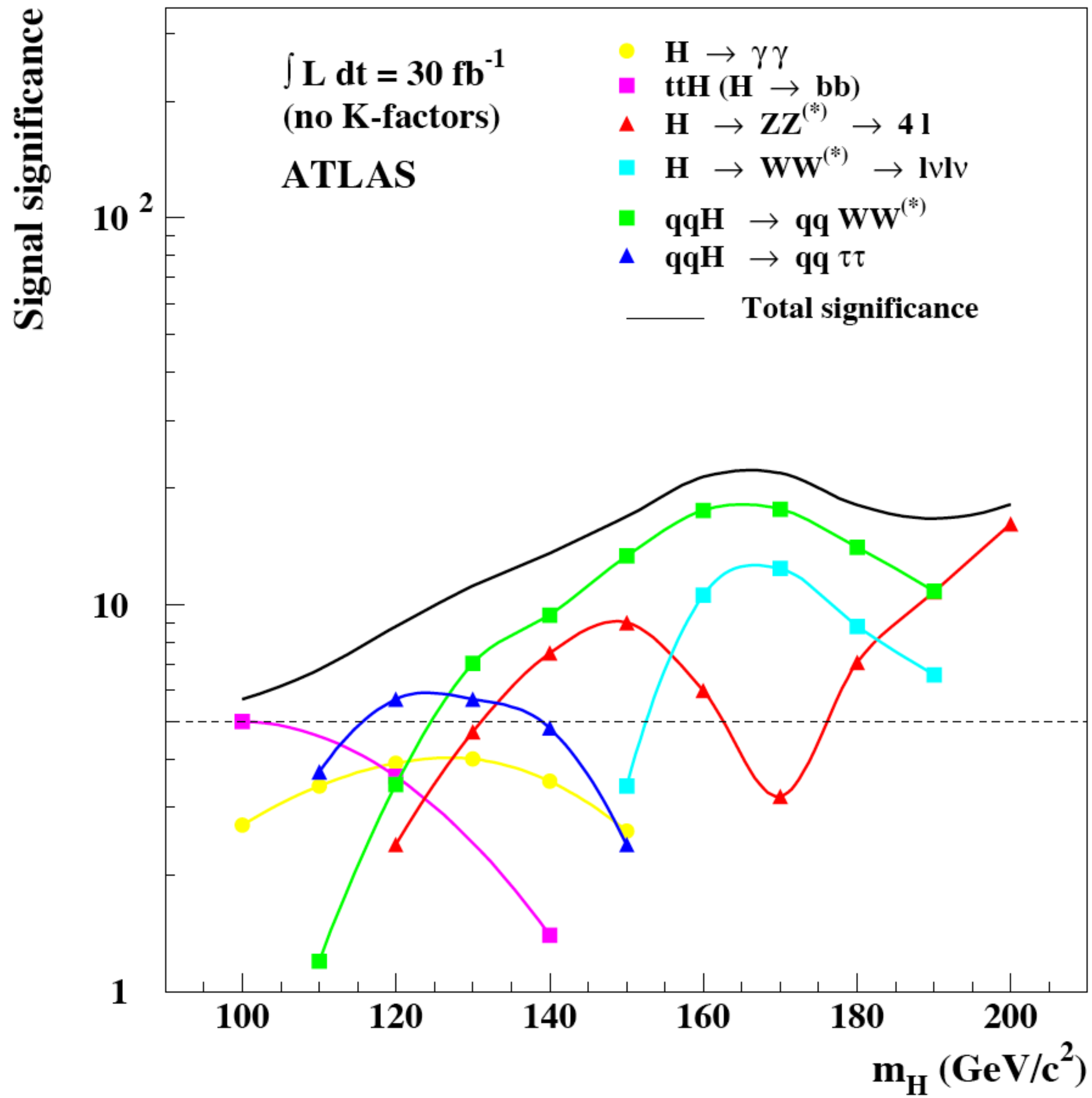
H decays to lighter Higgses

We can also have a heavier Higgs boson decaying into two lighter ones in this scenario.

	Point 1	Point 2	Point 3
s_ω^2	0.5	0.5	0.5
m_h (GeV)	115	175	225
m_H (GeV)	300	500	500
$\Gamma(H \to hh)$ (GeV)	2.1	17	17
$BR(H \to hh)$	0.33	0.33	0.33

Both Higgses suppressed with respect to SM Higgs.

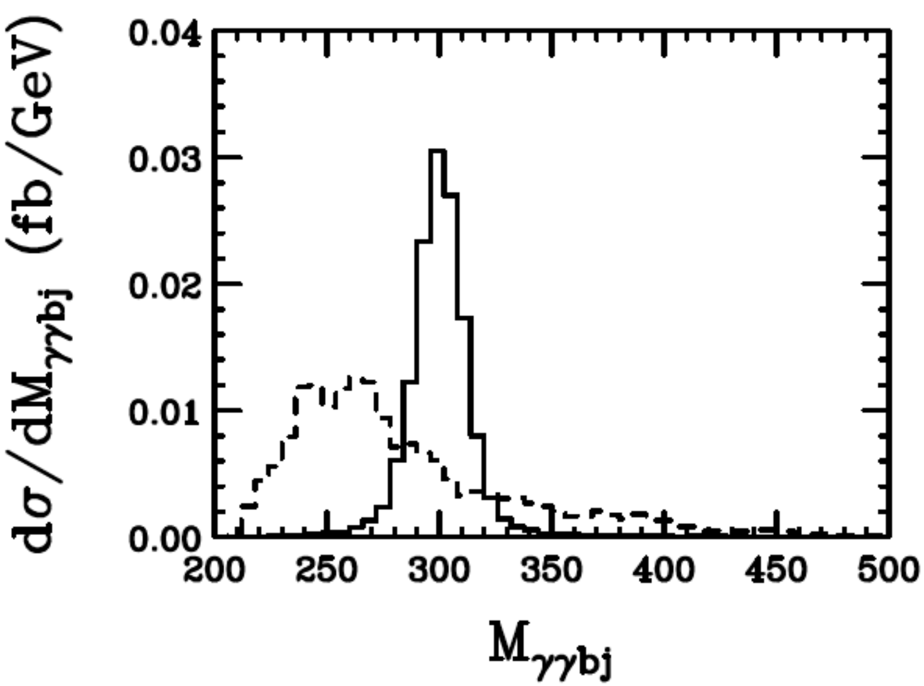
Higgs discovery significances



Heavy to Light Higgs rate

Considered discovery mode (Richter-Was et al.):

$$gg \to H \to hh \to \gamma\gamma\bar{b}b$$

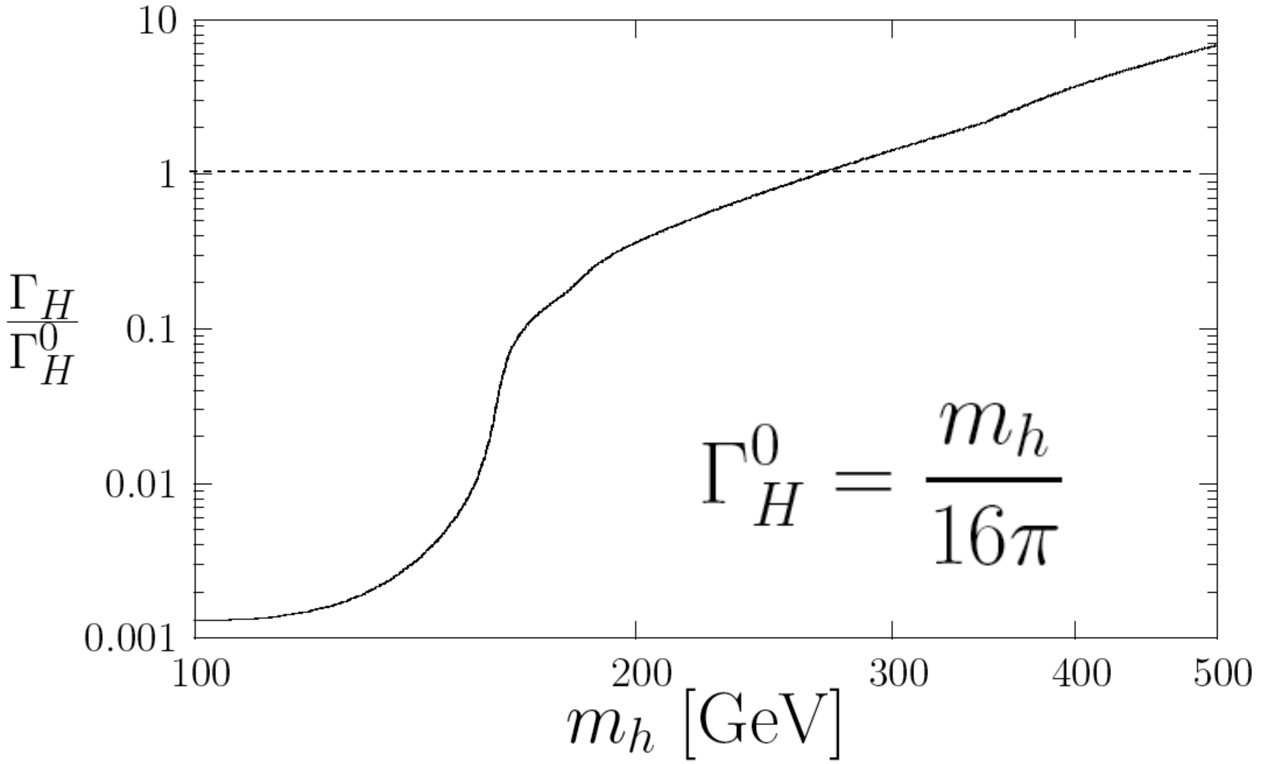


Channel	1 tag	2 tags
$H \to hh$	24	12
$\gamma\gamma bb$	0.4	0.2
$\gamma\gamma bc$	0.15	0.01
$\gamma\gamma bj$	1	0.009
$\gamma\gamma cc$	1.2	0.069
$\gamma\gamma cj$	3.6	0.042
$\gamma\gamma jj$	1.8	0.007
Total background	8.2	0.34

30 fb^{-1} bkgd estimates

Bowen, Cui, JW

Light Higgs accidentally narrow



Light Higgs boson especially susceptible to new decay modes.

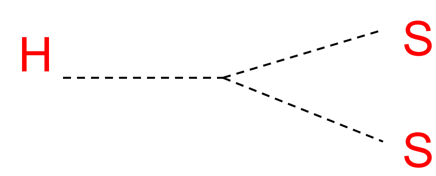
Sources of Invisible Decay

Many ideas lead to invisible Higgs decays -- possible connections to dark matter.

Joshipura et al. '93 ;
Binoth, van der Bij, '97, etc.

Simplest of all is the addition of a real scalar field with Z_2.

$$\mathcal{L} = \frac{M_S^2}{2} S^2 + \lambda S^2 |\Phi_{SM}|^2 + \cdots$$



Example from Abelian Higgs Model with fermions:

$U(1)_X$: $\{\Phi_H, \psi, \bar{\psi}, \chi, \bar{\chi}\} = \{3, -1, 1, -2, 2\}$ leads to

$$\mathcal{L} = y \Phi_H \psi \chi + y' \Phi_H^* \bar{\psi} \bar{\chi} + M_\psi \bar{\psi} \psi + M_\chi \bar{\chi} \chi \cdots$$

Invisible Higgs at LHC

$\not{p}_T$ cut	$m_h = 120$ GeV S/B	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (10 fb^{-1})	$m_h = 120$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 140$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})	$m_h = 160$ GeV S/$\sqrt{\text{B}}$ (30 fb^{-1})
65 GeV	0.22 (0.16)	5.6 (4.9)	9.8 (8.5)	7.1 (6.2)	5.2 (4.5)
75 GeV	0.25 (0.22)	5.7 (5.3)	9.9 (9.1)	7.3 (6.7)	5.4 (5.0)
85 GeV	0.29	5.7	9.8	7.4	5.6
100 GeV	0.33	5.4	9.3	7.3	5.7

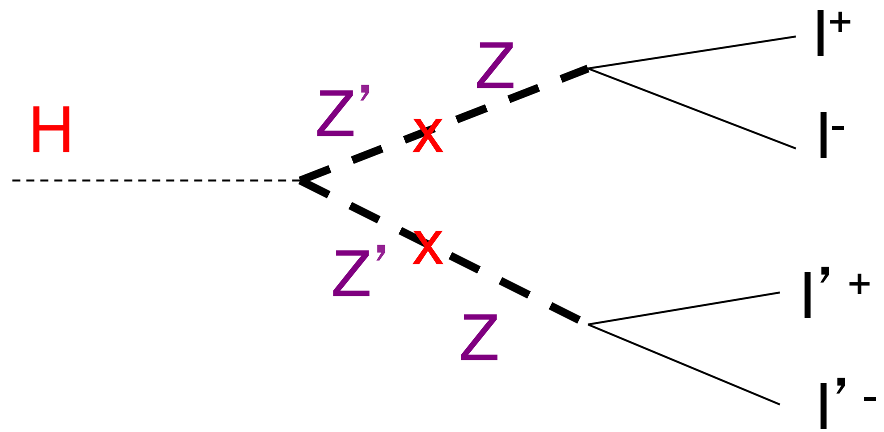
TABLE II: Signal significance for associated $\boxed{Z(\to \ell^+\ell^-) + h_{inv}}$ production at the LHC, combining the ee and $\mu\mu$ channels. The numbers in the parentheses include the estimated Z+jets background discussed in the text.

Davoudiasl, Han, Logan, ‘05

Light Z’ and Higgs Decays

With tiny kinetic mixing, a very low Z’ mass is possible in this framework. The light Higgs, however, could couple to it well with impunity. This leads to

H->Z’ Z’ -> 4 leptons signature



Gopalakrishna, Jung, JW, ‘08

Conclusions

Higgs boson is a unique object that is *especially* sensitive to new physics.

New physics comes from its “viability entourage”: supersymmetry, extra dimensions, etc., all which affect Higgs boson collider phenomenology.

New physics comes from its gauge- and Lorentz-invariant window to relevant operators, e.g. $|H|^2|\Phi|^2$.

Collider physics alterations can show up at low energies (e.g., Higgs to four lepton decays), and/or at much higher energy (e.g., heavy hidden sector fields with tiny mixings with the Higgs boson)