# Supersymmetry, Baryon Number Violation and a Hidden Higgs

David E Kaplan
Johns Hopkins University

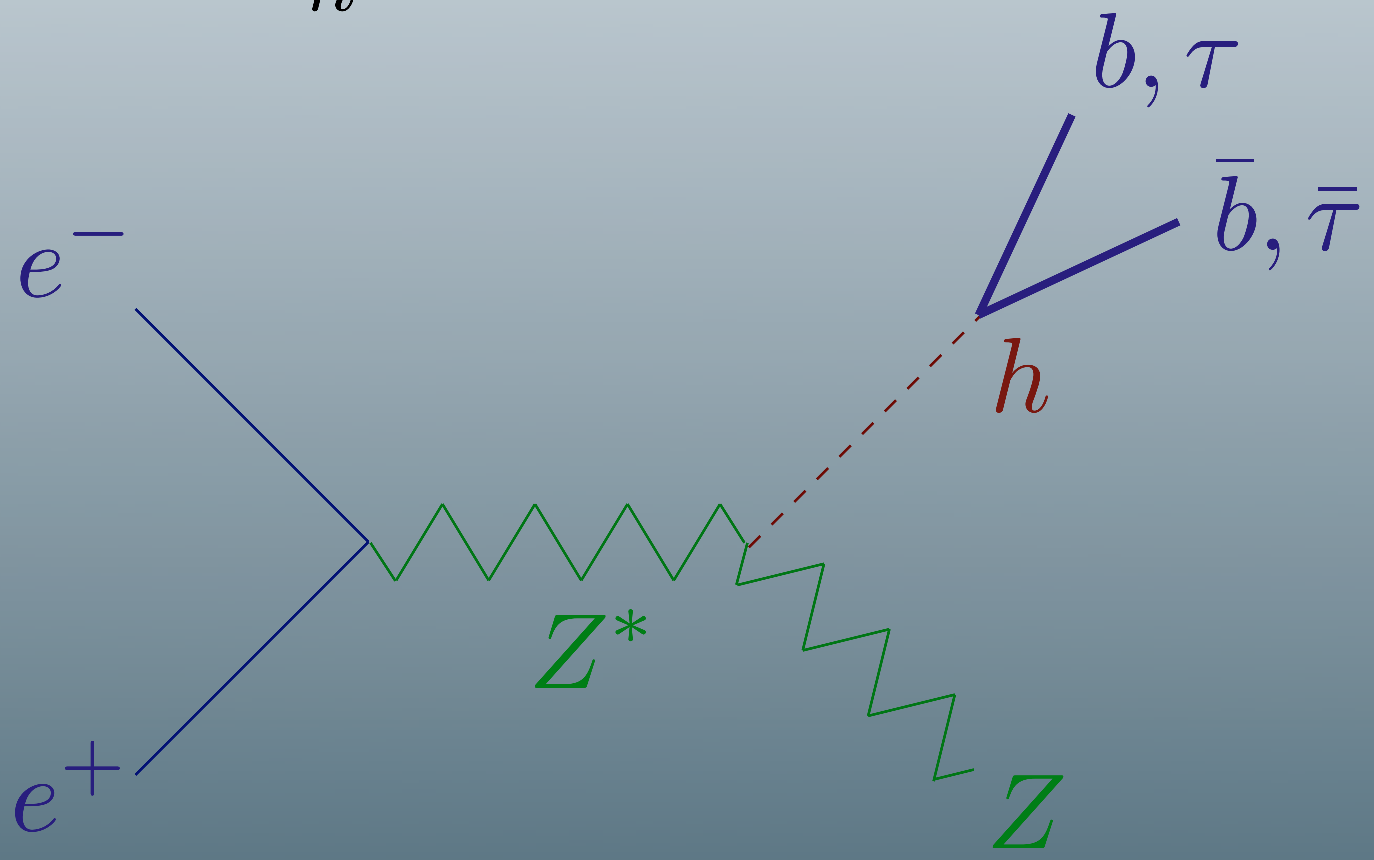
# Summary

- LEP looked for a SM Higgs and didn't find it.
- Both electroweak precision measurements and supersymmetric theories prefer a Higgs mass *lighter* than the LEP bound.
- Non-standard decays of the Higgs severely weakens current bounds and opens up SUSY parameter space
- New LEP(!) analyses are warranted.  Higgs searches at the Tevatron and the LHC in these channels are a challenge...

# Higgs: Direct Search

Dominant bound from LEP II

SM: $m_h > 114.4\,\mathrm{GeV}$



# Decay modes of the Higgs

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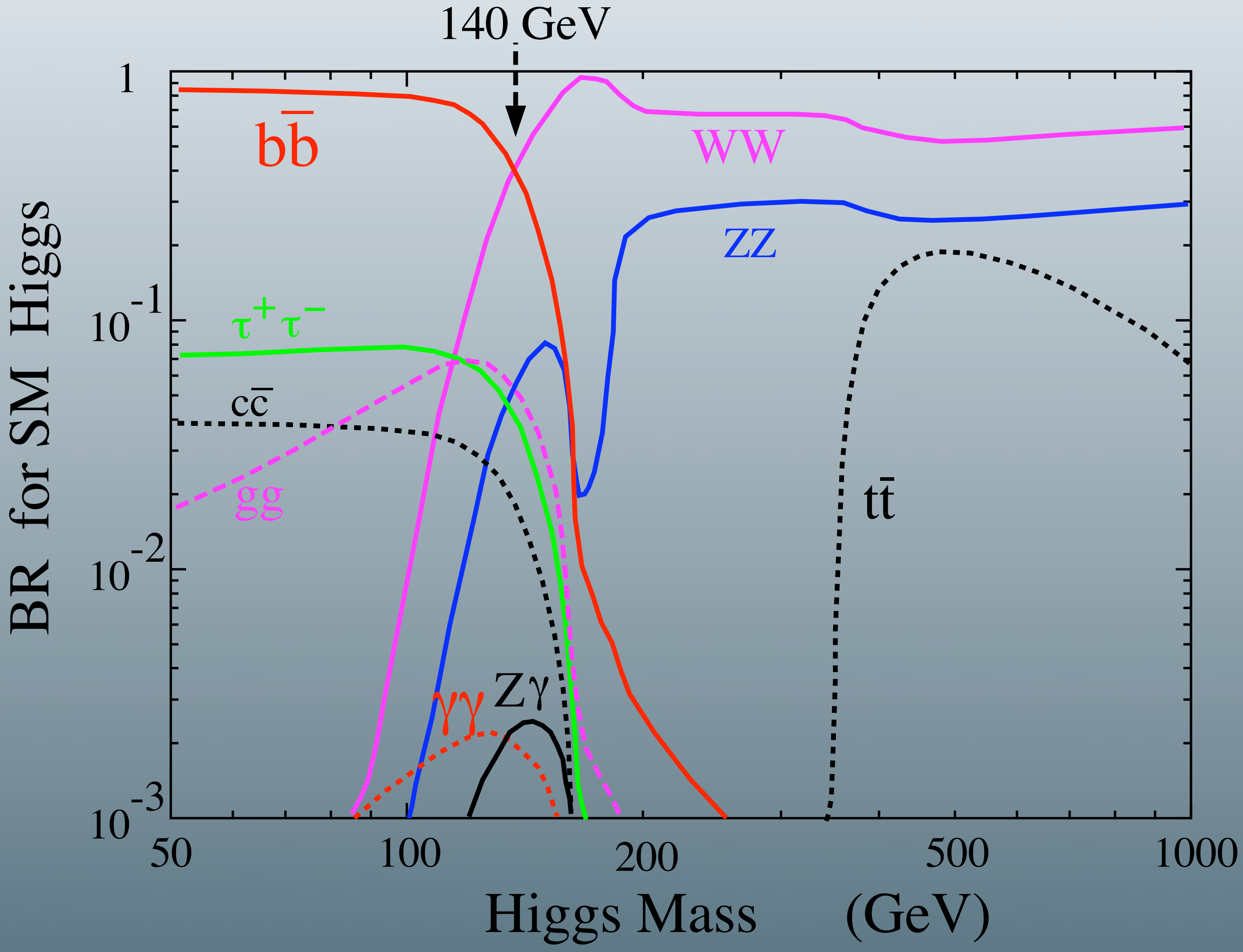
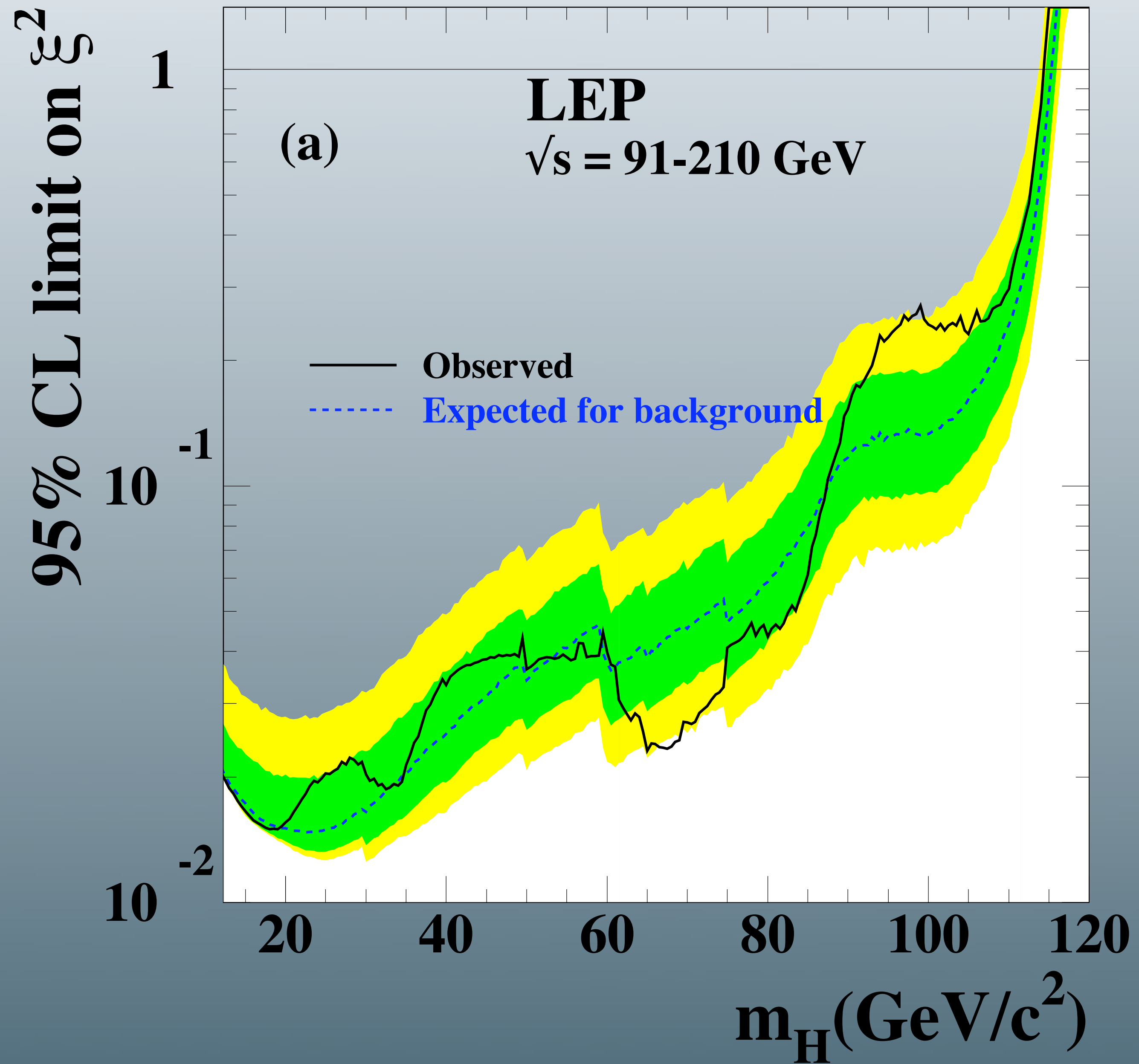


# SM Higgs



95% CL limit on $\xi^2$
1
$10^{-1}$
$10^{-2}$
LEP
$\sqrt{s}$ = 91-210 GeV
(a)
Observed
Expected for background
20
40
60
80
100
120
$m_H(GeV/c^2)$

# A light Higgs is preferred by data

**Preliminary**

| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02768 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
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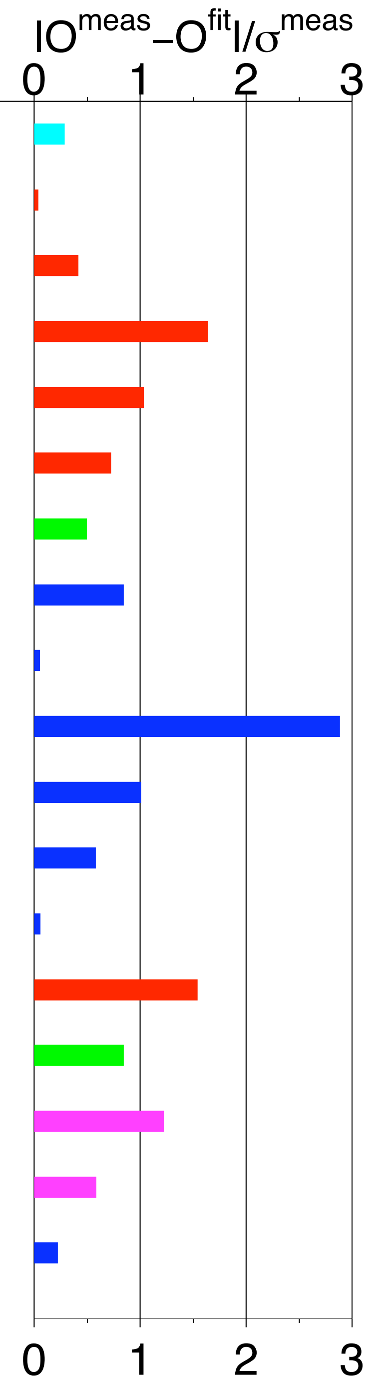

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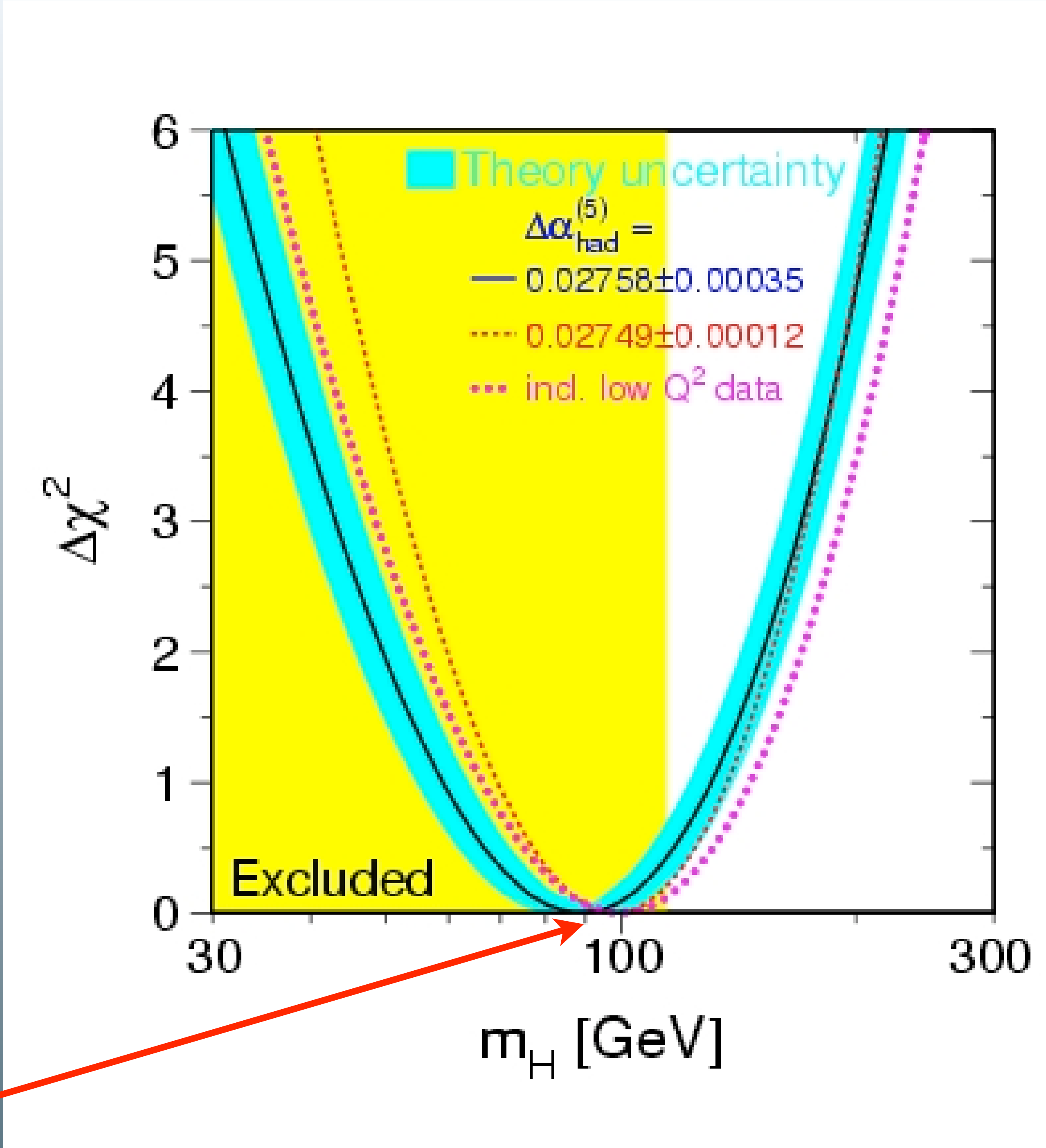


Central value

at 92 GeV.

# Strained Standard Model

TIFR-EHEP/97-01
March 11, 1997

受入
97-05-033
高エ研図書室

## Asymmetry measurements at LEP/SLC revisited

Tariq AZIZ

Tata Institute of Fundamental Research, Bombay 400005, India

**Abstract.** We examine the fermion asymmetry measurements at LEP and SLC leading to effective weak mixing angle, $\sin^2\theta_{\rm eff}$. We notice very interesting regularity in these measurements. All asymmetry measurements fall in two classes. Class A measurements where hadronisation effects are not relevant for the final result and class B measurements where hadronisation effects can not be avoided and can only be corrected with whatever understanding of these phenomena we have. In each of these classes there is excellent agreement between LEP and SLC results. However the two classes are distinctly apart by more than $3\sigma$. We suggest that for precision test of the standard model the class A measurements should be preferred.

During last few years the standard model has been subjected to very tight precision tests through a variety of measurements at LEP and SLC on one hand and direct confirmation and further tests by another set of measurements at Tevatron on the other [1, 2, 3]. An extremely important measurement at LEP/SLC has been the measurement of the effective weak mixing angle parameter, $\sin^2\theta_{\rm eff}$[1]. Whereas in the case of LEP, production of Z bosons takes place using unpolarised electron/positron beam, in the case of SLC it happens using almost 80% polarised electron beam. For measuring $\sin^2\theta_{\rm eff}$ the

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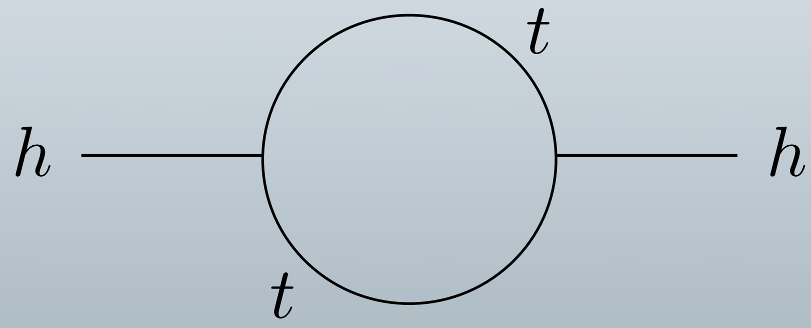
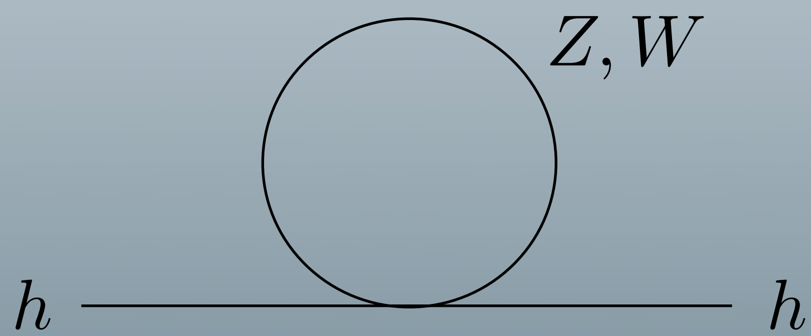
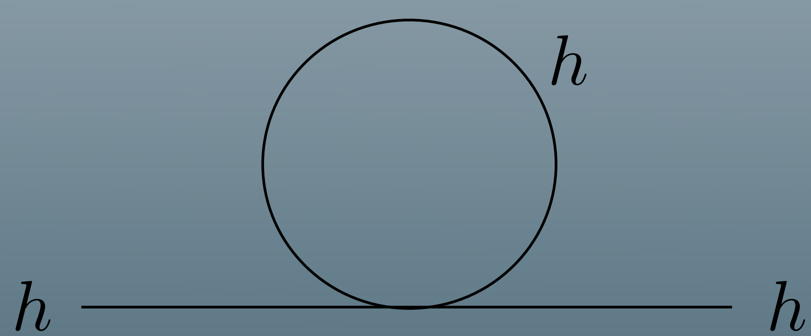
# Higgs Mass Contributions




$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$$

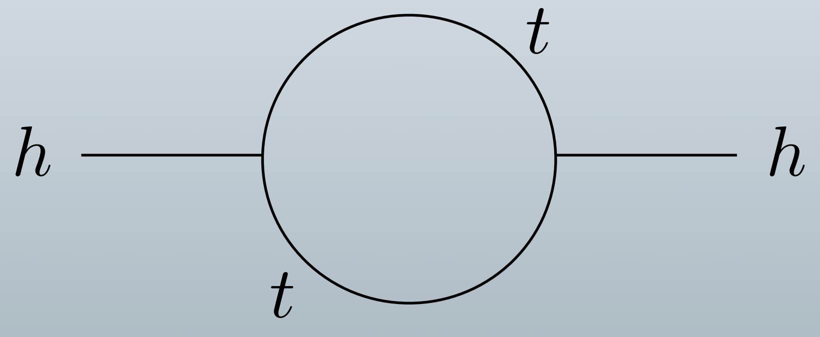



$$\delta m_h^2 \sim \frac{9}{64\pi^2}g^2\Lambda^2$$

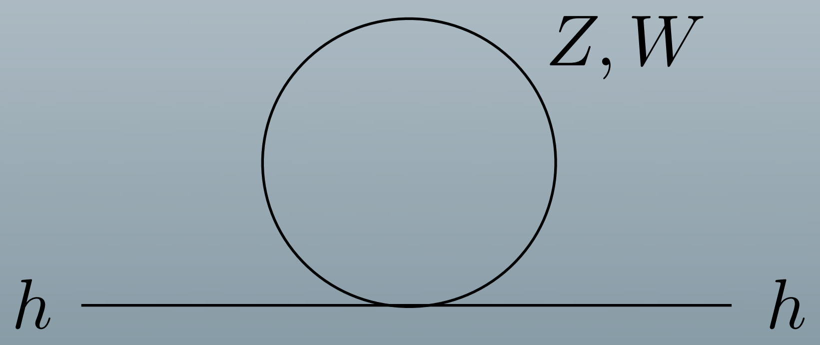



$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2\Lambda^2$$

# Softly Broken SUSY




$$\delta m_h^2 \sim -\frac{3}{8\pi^2}\lambda_t^2 m_{susy}^2$$

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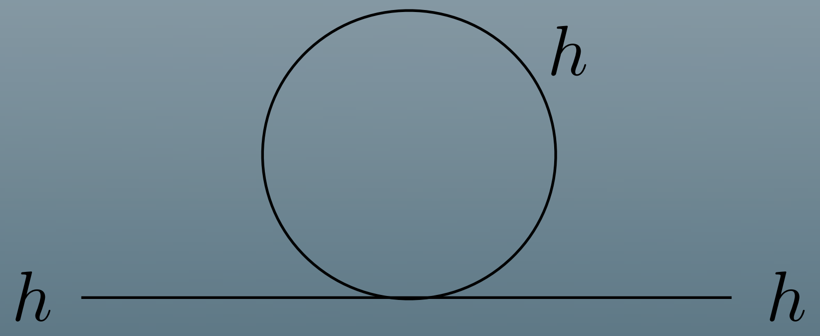



$$\delta m_h^2 \sim \frac{1}{16\pi^2}\lambda^2 m_{susy}^2$$

# Corrections to the Higgs mass

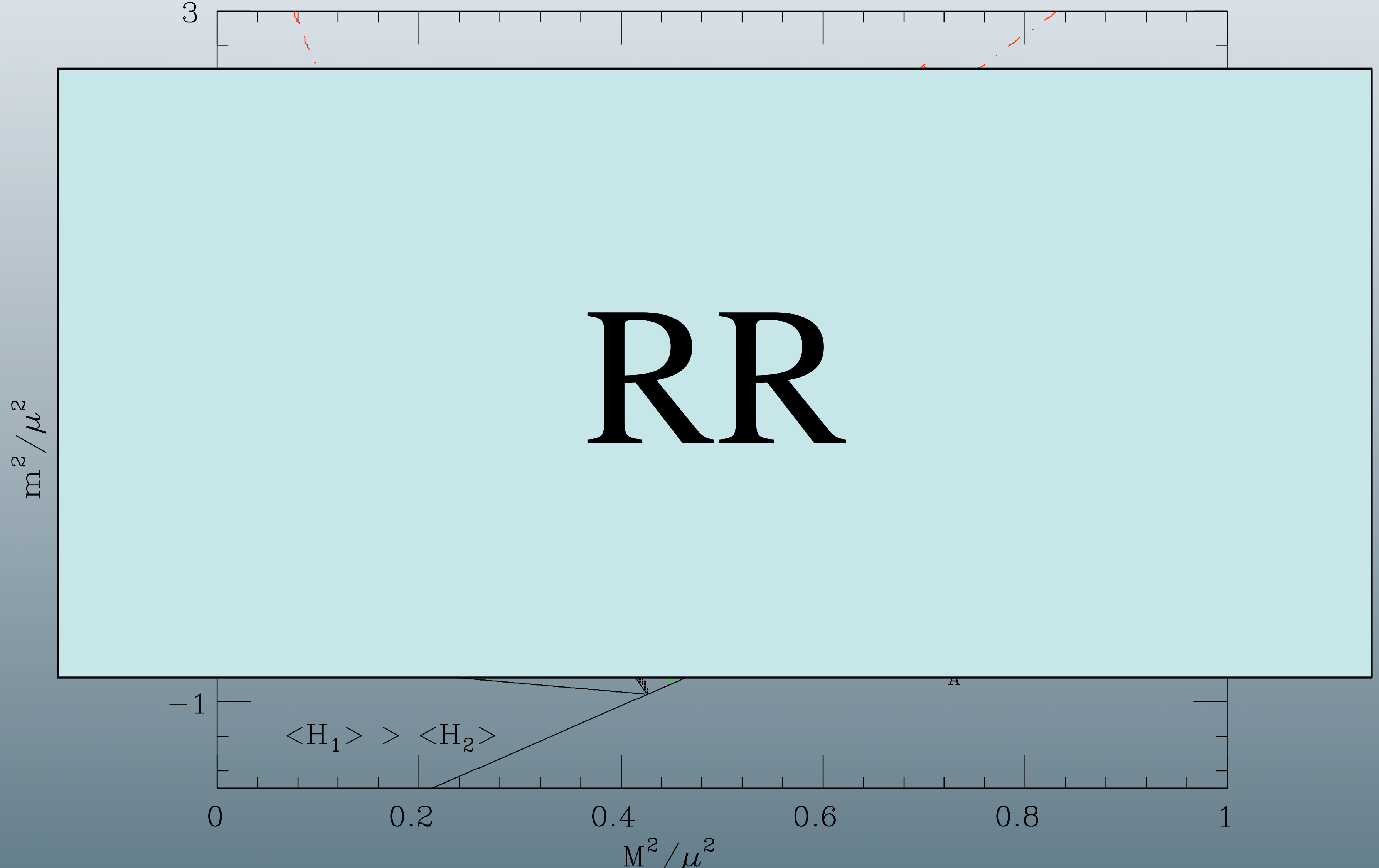
$$m_Z^2 + \delta\lambda\, v^2 = m_{phys}^2 = 2\mu^2 + m_{soft}^2$$

$$\delta\lambda \propto y_t^4 \ln(m_{\tilde{t}}/m_t)$$ grows as a log

$$\delta m_{soft}^2 \propto y_t^2 m_{\tilde{t}}^2 \ln(\Lambda/m_{\tilde{t}})$$ grows as a power

Typically need stop masses near 1 TeV

# State of mSUGRA




Arkani-Hamed, Giudice, Rattazzi '06

# SUSY: Where to Look

"Sweet spots" in parameter space

Choi, et. al. (2004), Kitano and Nomura (2005)

Radical shift in view of naturalness

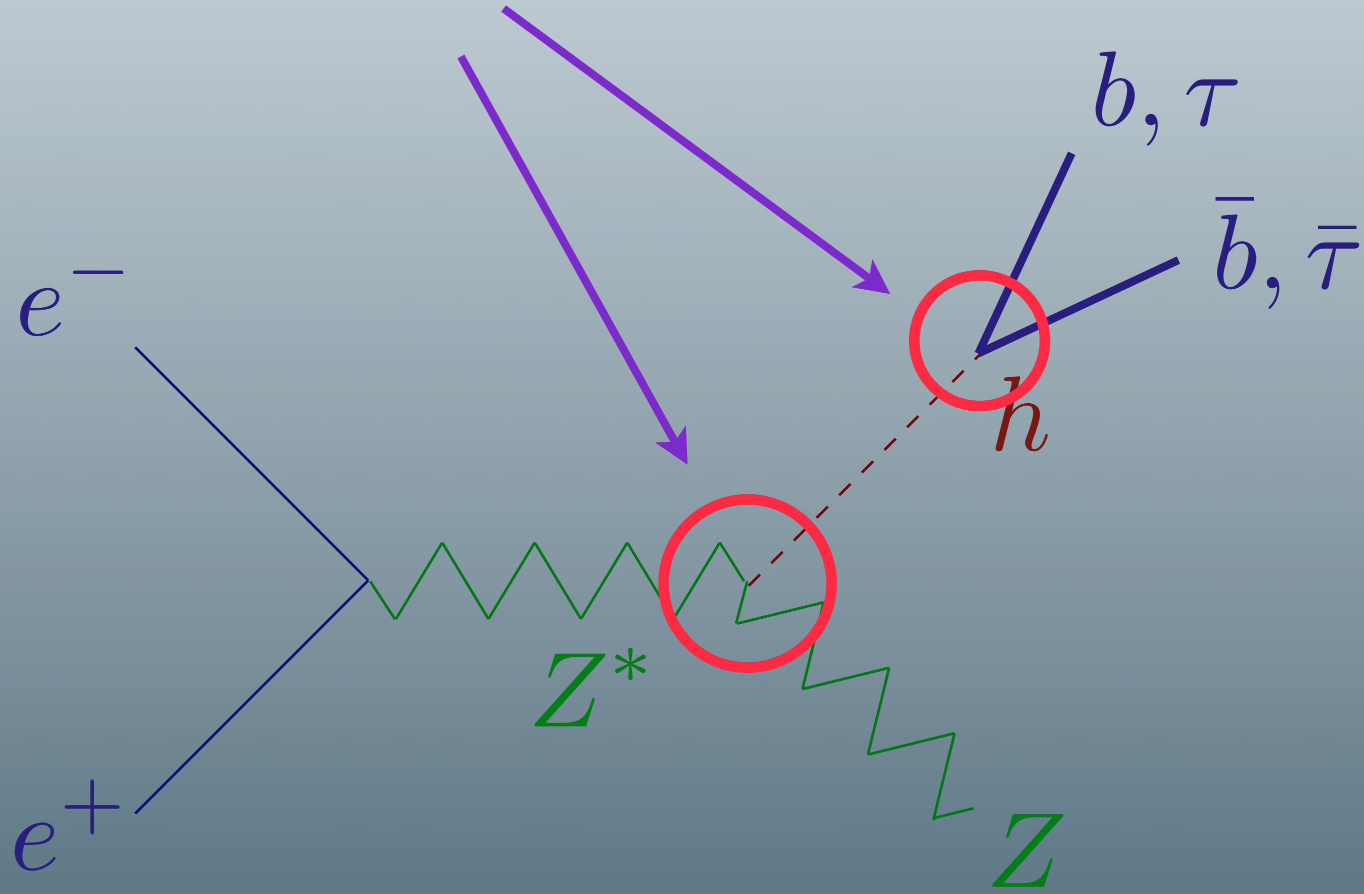
Arkani-Hamed and Dimopoulos (2004)

Mild shift in assumptions of low energy theory

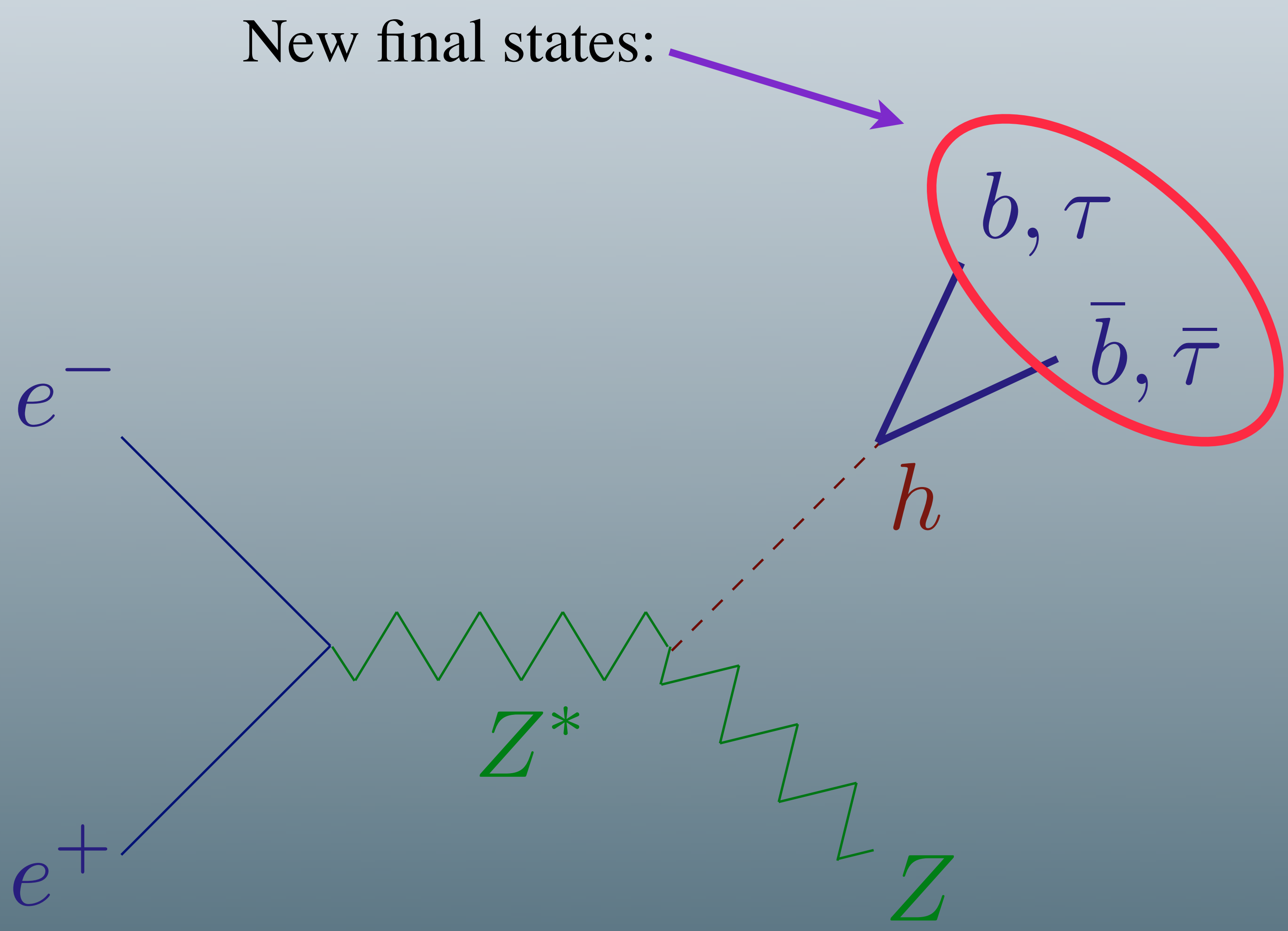
Dermisek and Gunion (2005), S. Chang, et.al. (2005)

# Alternative phenomenology of the Higgs

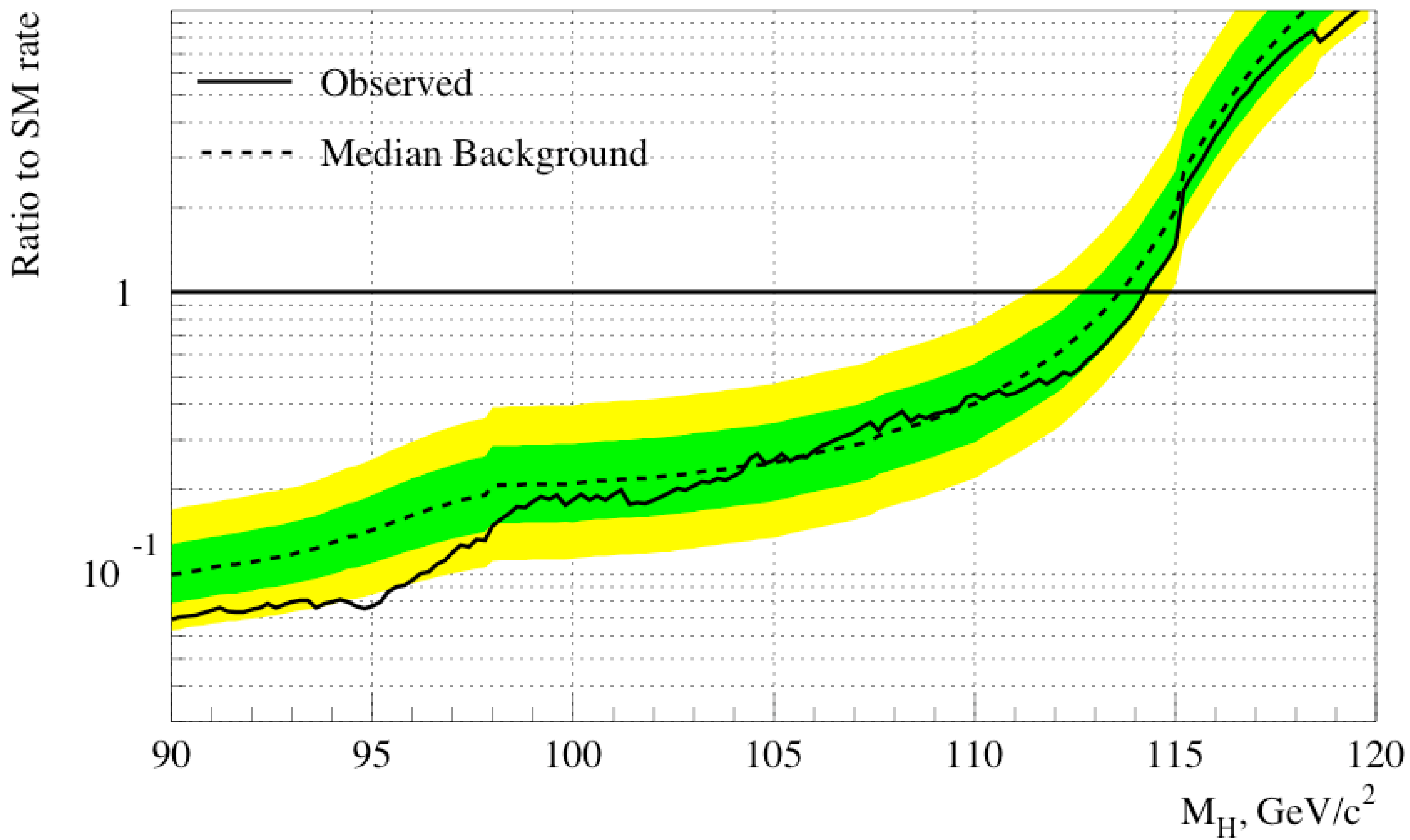
New couplings for the Higgs:



# Alternative phenomenology of the Higgs

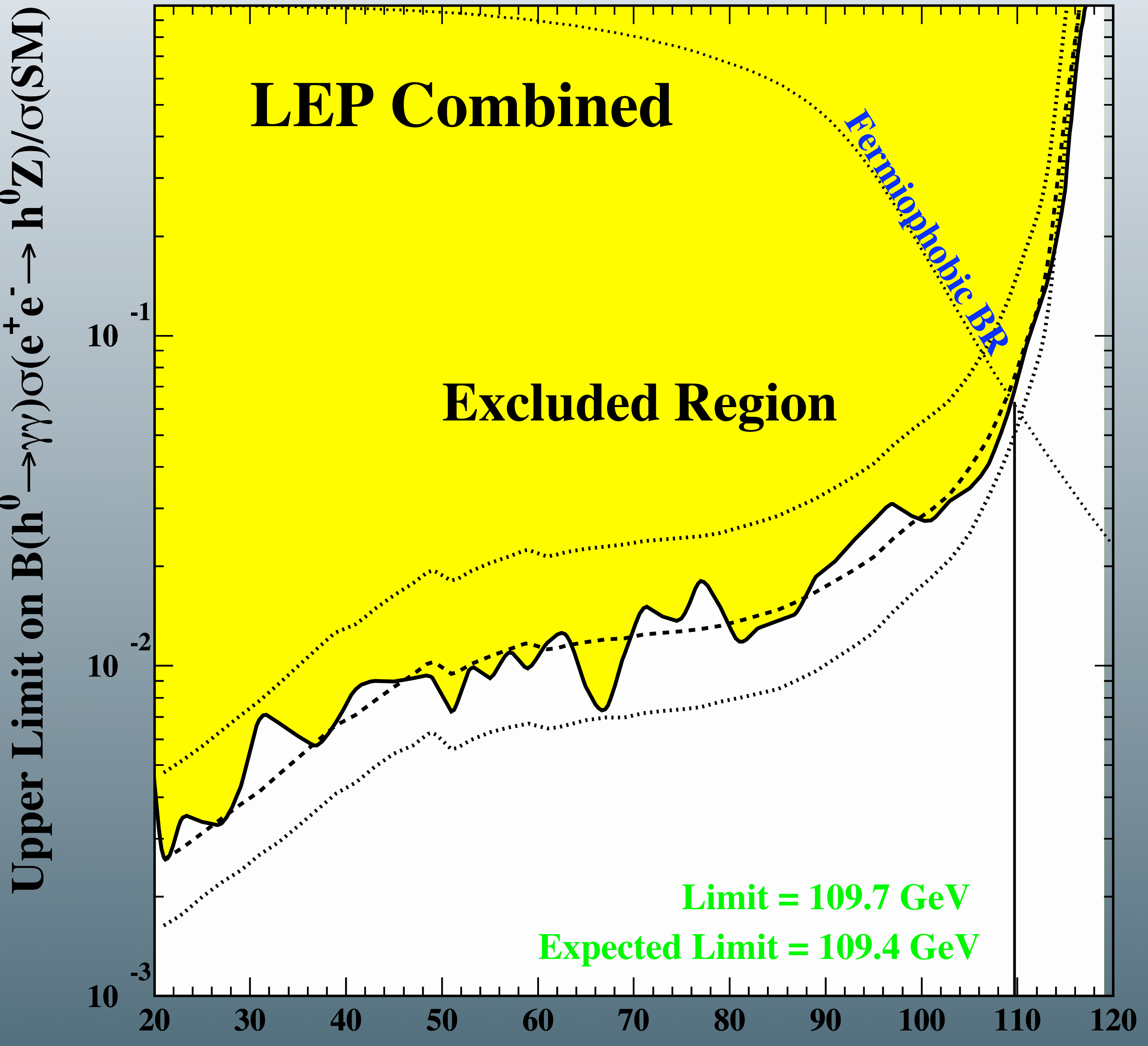


# Invisible Higgs




LEP Combined - '01

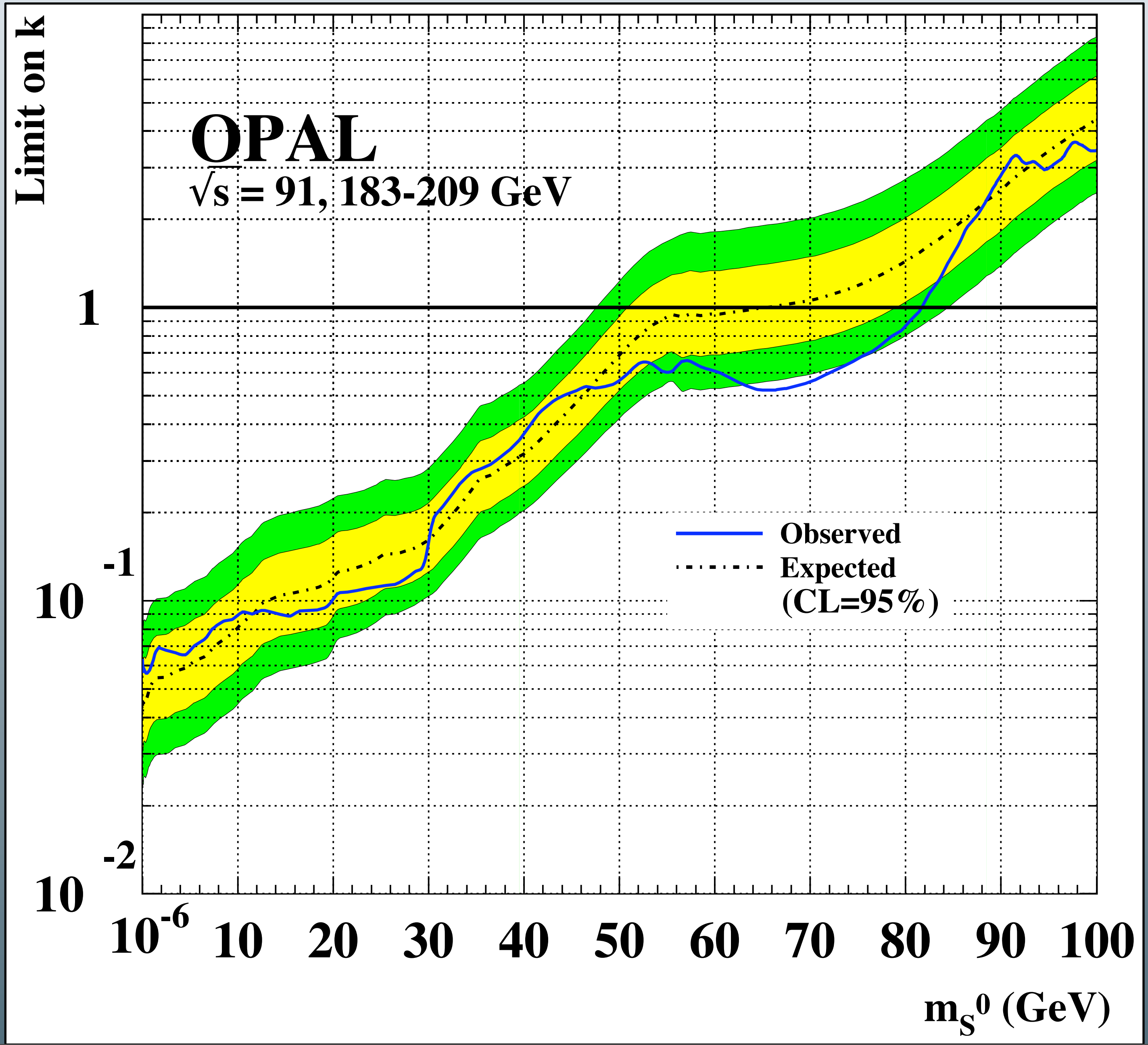
# Fermiophobic



# Only Searches so far...

| | Excludes: |
| --- | --- |
| $h \to$ invisible | $m_h < 114\,\mathrm{GeV}$ |
| $h \to jj$ | $m_h < 113\,\mathrm{GeV}$ |
| $h \to VV$ | $m_h < 109.7\,\mathrm{GeV}$ |
| $h \to \gamma\gamma$ | $m_h < 117\,\mathrm{GeV}$ |
| $h \to 2\phi \to 4b$ | $m_h < 110\,\mathrm{GeV}$ |
| $h \to X$ (leptonic $Z$) | $m_h < 82\,\mathrm{GeV}$ |

# Non-standard Higgs Decays



# Non-standard Higgs Decays

Most problematic decay:

$$h \rightarrow \mathrm{N}\; jets$$

At the LHC, one would still look for SM decays to $\gamma\gamma$, $VV^*$, with $S/\sqrt{B} \sim 8, 5 - 20$ (SM values) reduced.

E. Berger, C.-W. Chiang, J. Jiang, T. Tait, C. Wagner - '02

# Alternative phenomenology of the Higgs

NMSSM (generalized):

Add a singlet superfield to the spectrum - helps add to the Higgs mass and adds the possibility of

$$h \to aa \to XX$$
$$h \to ss \to XX$$
$$h \to ss \to 4a \to 4X$$

where the X is 2b's, 2 taus or 2 unflavored jets.

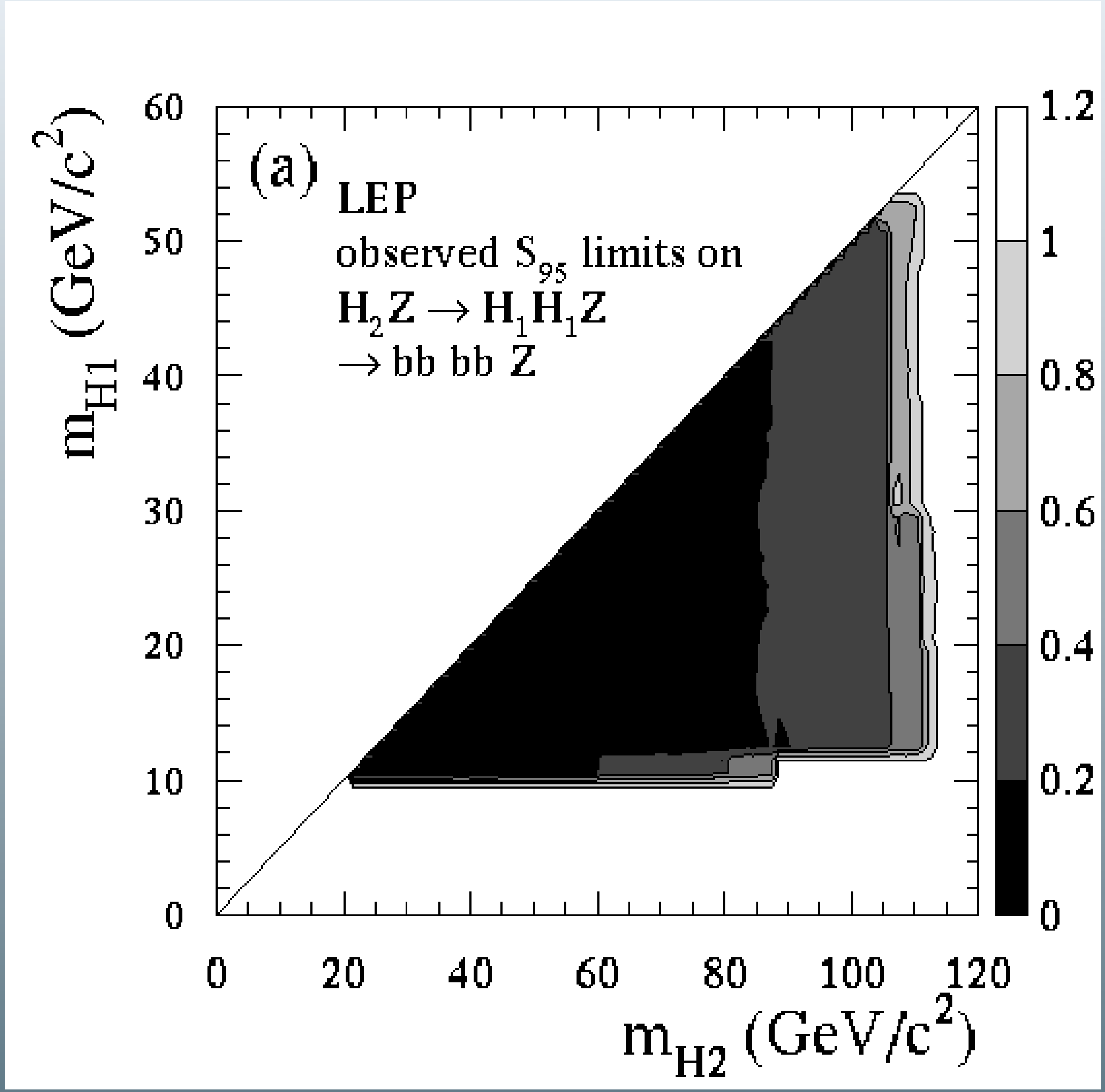
J. Gunion, H. Haber, T. Moroi - '96

B. Dobrescu and K. Matchev - '00

R. Dermisek and J. Gunion - '04

S. Chang, P. Fox, N. Weiner - '05

# Higgs to 4b's




But NOT 4 taus!

# Time to loosen up

# Unified Gaugino Masses

$$\frac{M_1}{M_2} = \frac{5}{3}\tan^2\theta_w \simeq \frac{1}{2}$$

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Anomaly Mediation: $$\frac{M_1}{M_2} = \frac{\beta_{g'}/g'}{\beta_g/g} \simeq 3$$

Dirac Gauginos: $$\frac{M_1}{M_2} = \left(\frac{\alpha_2(\mu)}{\alpha_2(M_{GUT})}\right)^{\frac{2}{b_2}} \left(\frac{\alpha_1(\mu)}{\alpha_2(\mu)}\right)^{\frac{1}{2}} \simeq \frac{3}{8}$$ [for SU(5)]

"Orbifold GUTs": $$\frac{M_1}{M_2} = \text{arbitrary}$$

# A Supersymmetric Standard Model

$$W = H_1 Q D^c + H_2 Q U^c + H_1 L E^c + \mu H_1 H_2$$
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

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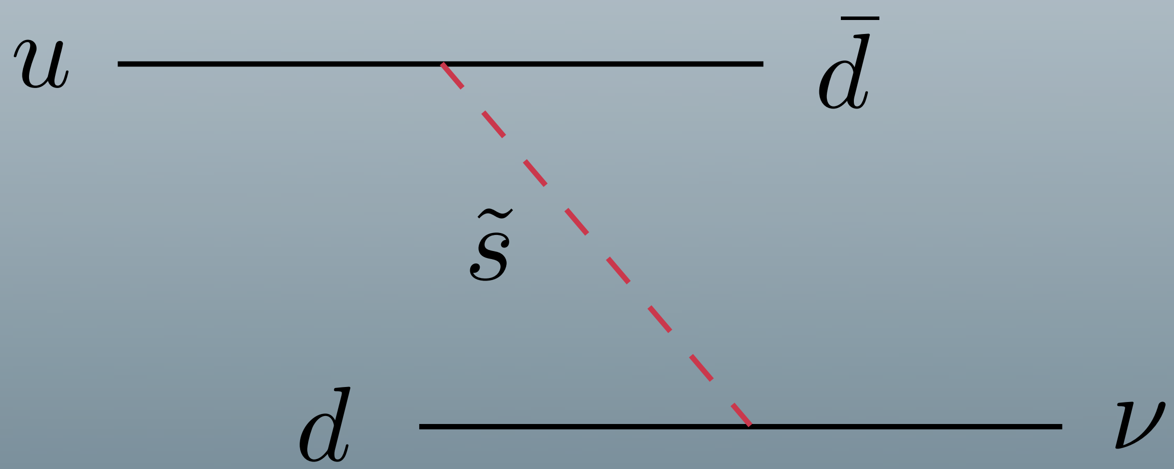


$$p \rightarrow \pi^+ \nu$$

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Introduce a parity

$$Q \longrightarrow -Q$$
$$H \longrightarrow +H$$

Equivalent to:

$$\phi_{SM} \longrightarrow +\phi_{SM}$$
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R Parity

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Could have "Baryon Parity".

# A Supersymmetric Standard Model

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$$\cancel{+LQD^c} + U^c D^c D^c \cancel{+ LLE^c + \mu_L L H_2}$$

or "Lepton Parity"

$$p \not\to X$$

$X$ must have an odd number of fermions, thus its lepton number $L = 2n + 1$. No lepton parity violation, no decay.

# Bounds on R-parity violation

$$\lambda''_{ijk} U^c_i D^c_j D^c_k$$

$$\lambda''_{uds}, \lambda''_{udb} < 10^{-7}, 10^{-4}$$

double nucleon decay ,
n - n̄ oscillations

$$\lambda''_{usb}, \lambda''_{cds}, \lambda''_{cdb}, \lambda''_{csb} < 1$$

unitarity...

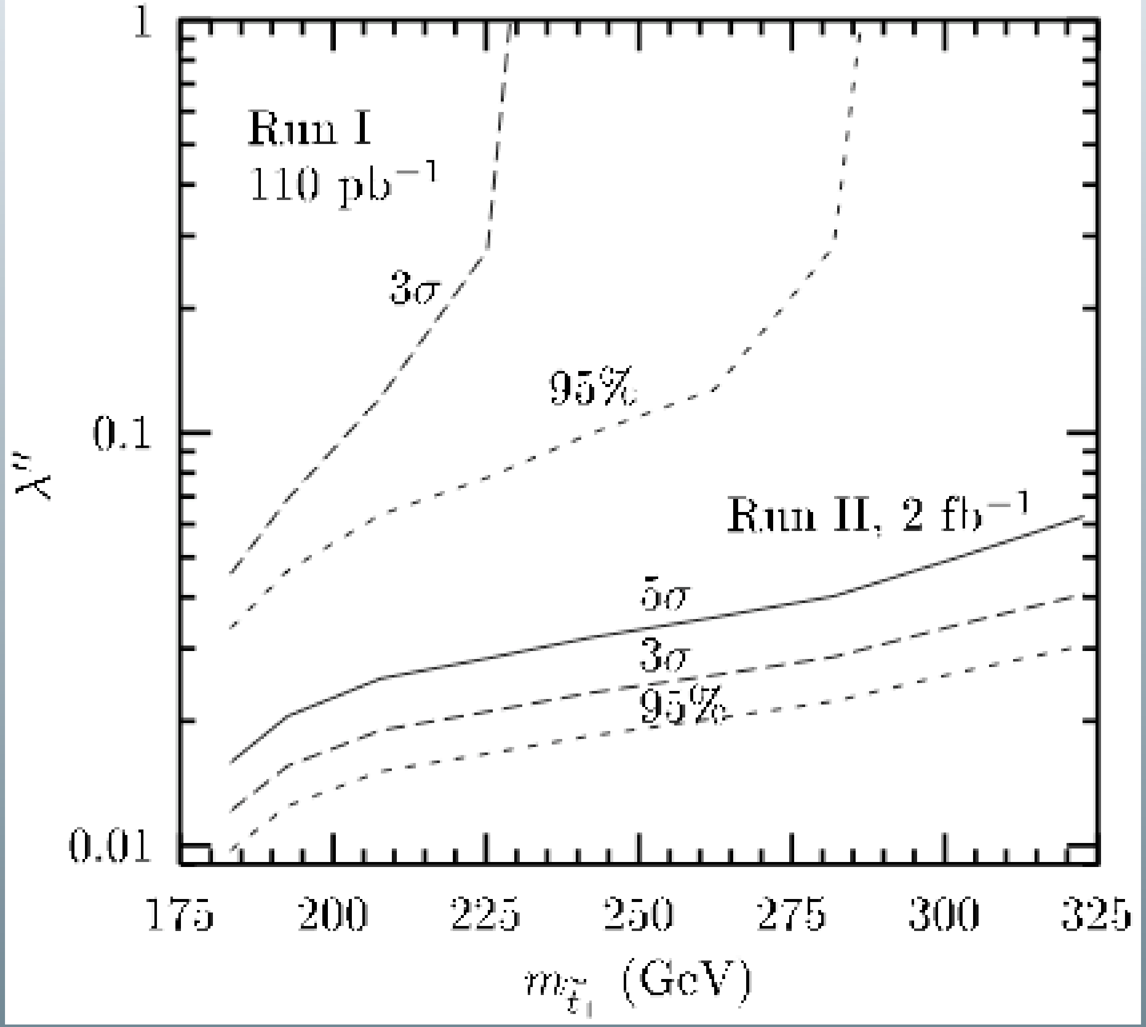
$$(\lambda''_{ijk} \lambda''_{i'j'k'}) < 10^{-2} \sim 10^{-4}$$

rare decays,
e.g., hadronic B's

assuming 100 GeV squarks

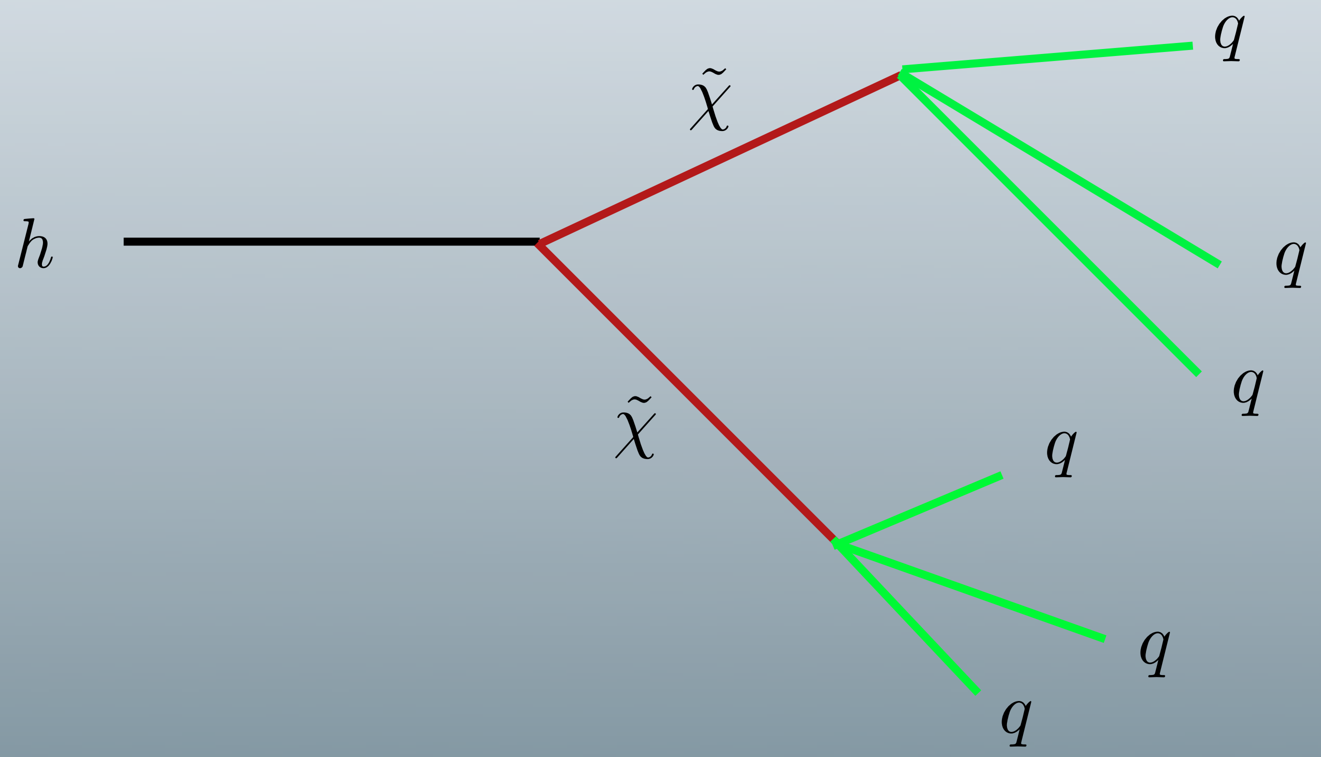
easily allows the "spurion mnemonic" $\lambda''_{ijk} \sim \sqrt{y_i y_j y_k}$

# Single Stop Production




E. Berger, B. Harris, Z. Sullivan - '99

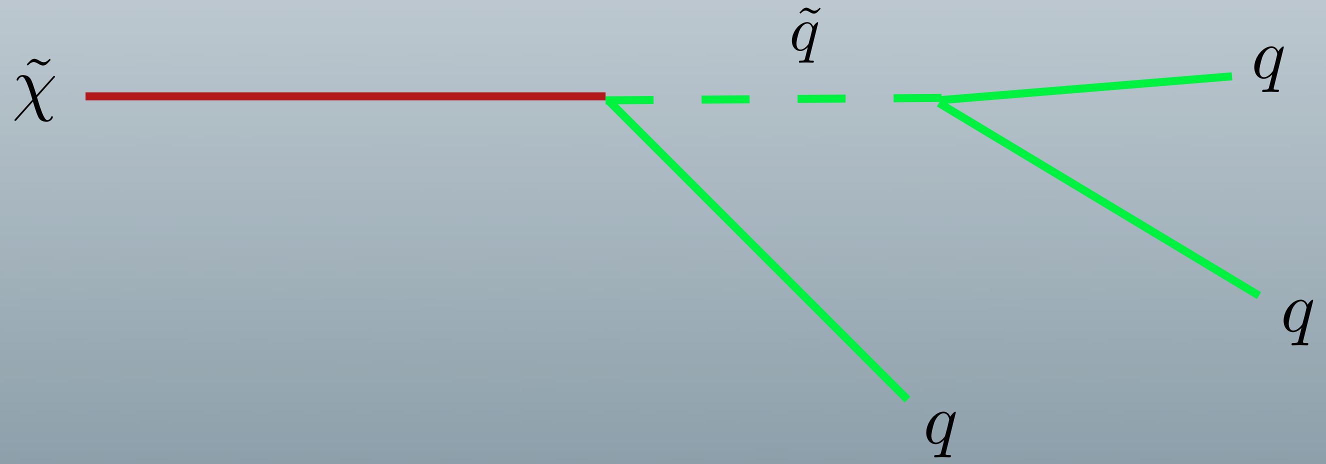
# Higgs decays with B-violation




higgs -> 6 jets!

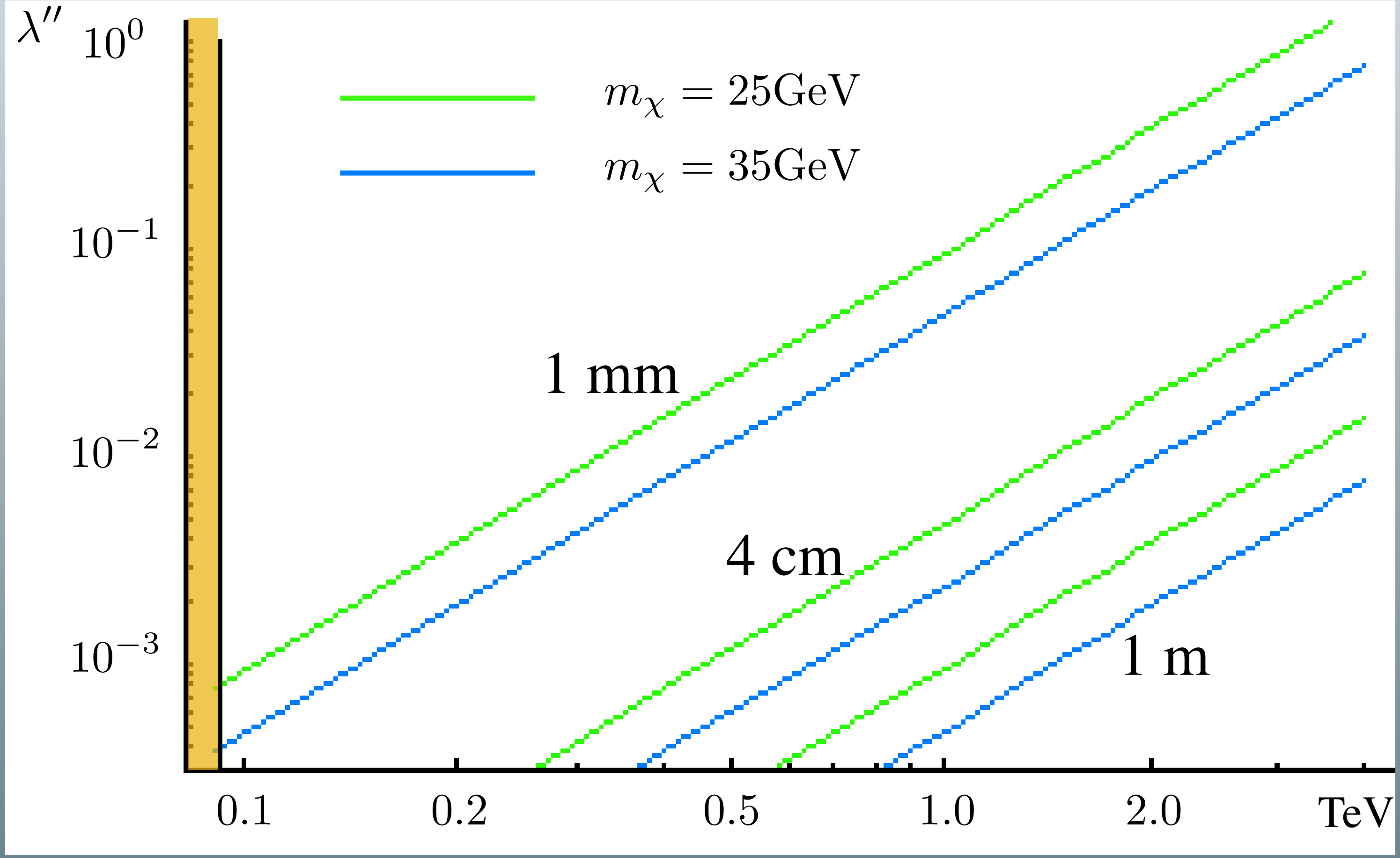
$m_h > 82\,\mathrm{GeV}$

# Neutralino Decay

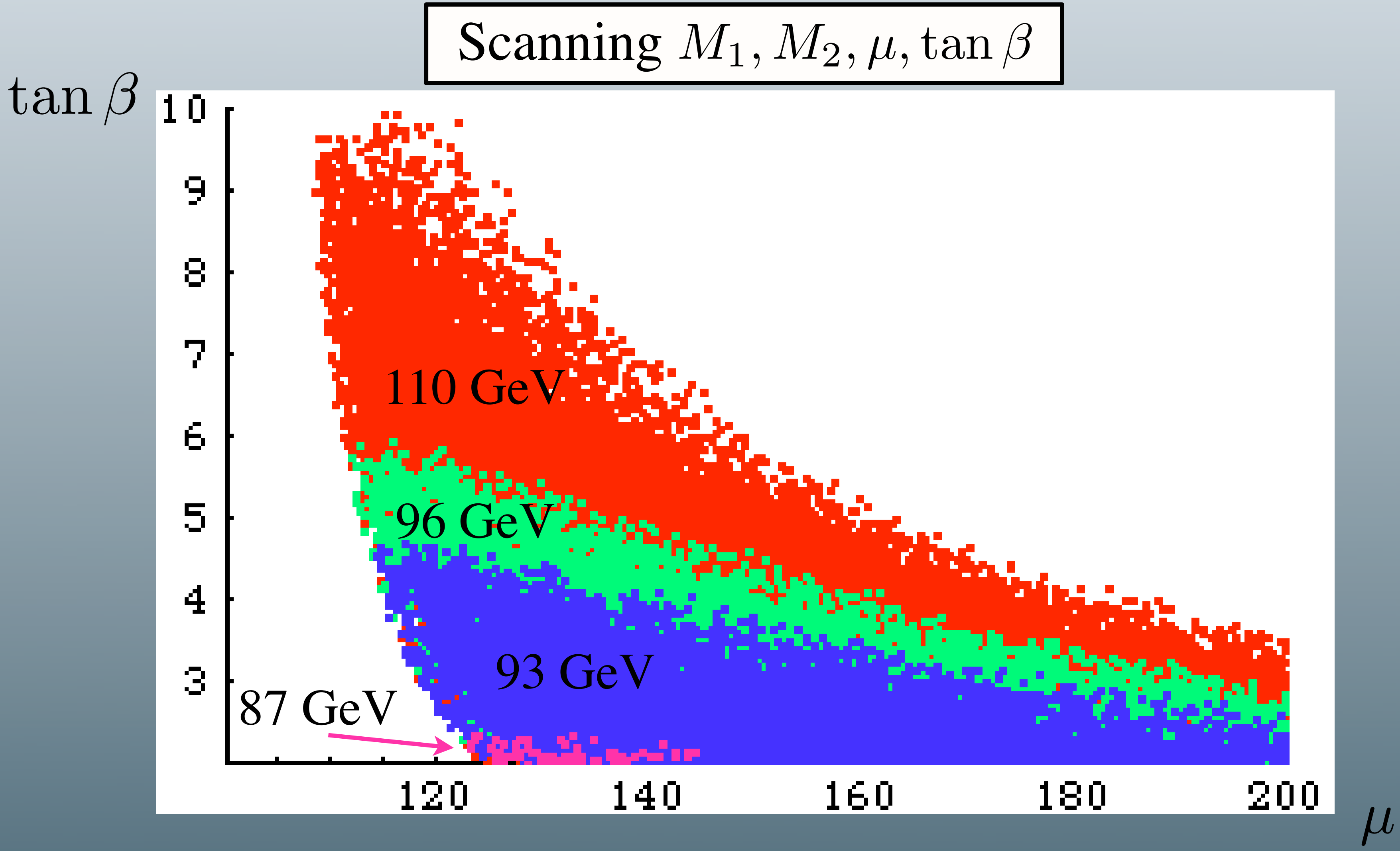



$\lambda'' > 0.01$ and squark masses < 600 GeV for fast decays

# Neutralino Decay Length



# Allowed Higgs Masses



# LEP I Constraints

Z couples due to mixing of neutralinos. Typically add about 2 MeV to the width.

$$\Delta\chi^2 \sim 1$$

(Thanks Tim!)

## Preliminary

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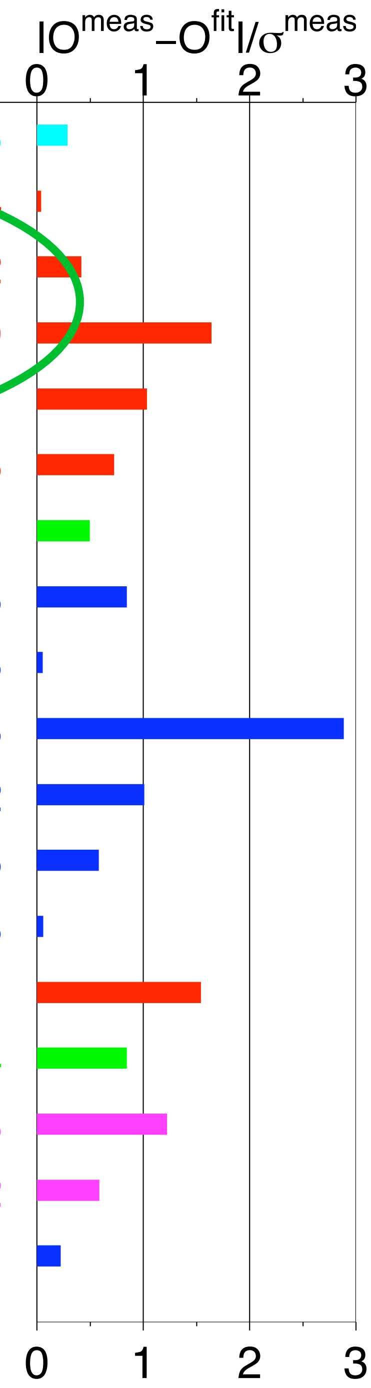
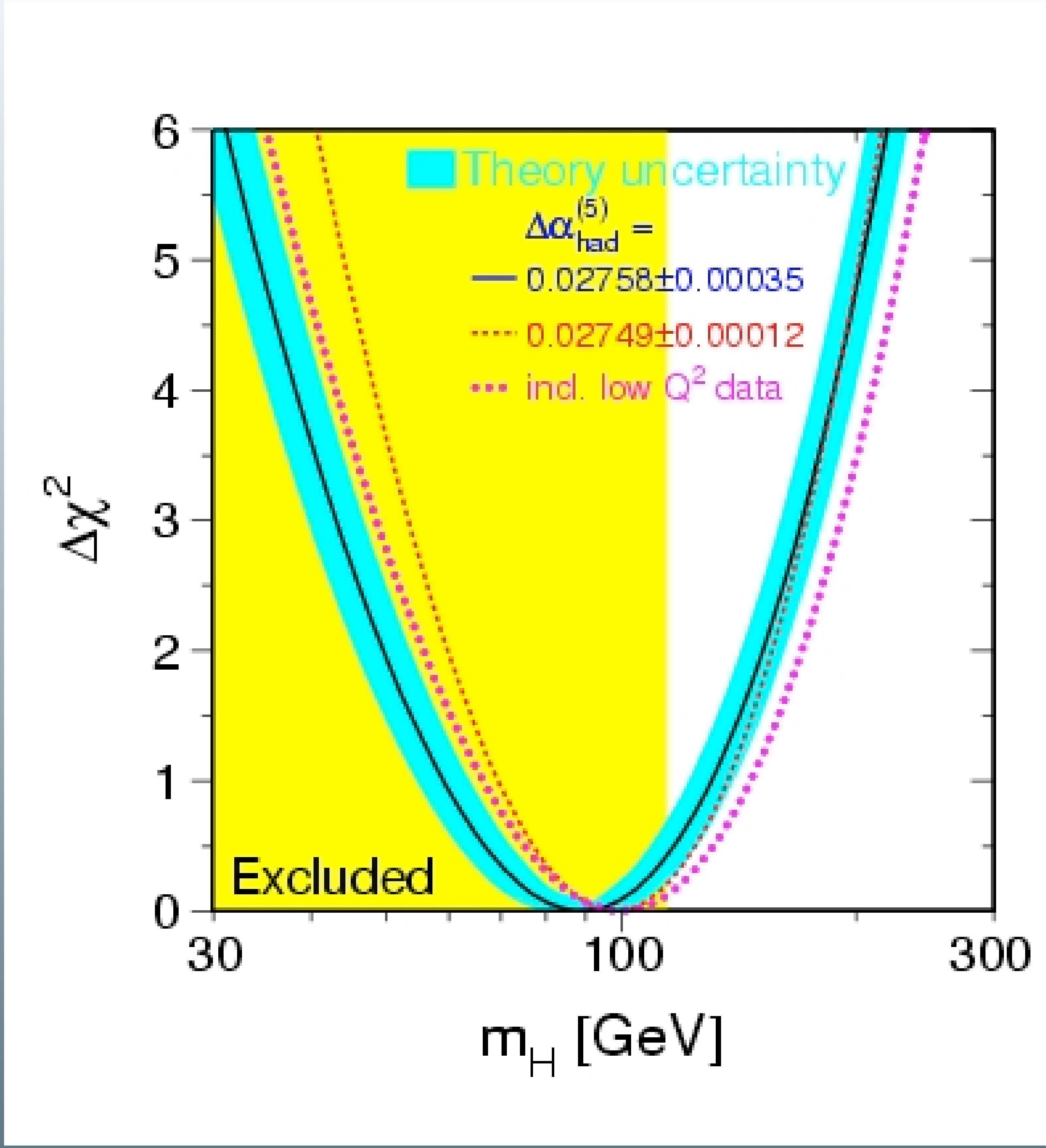
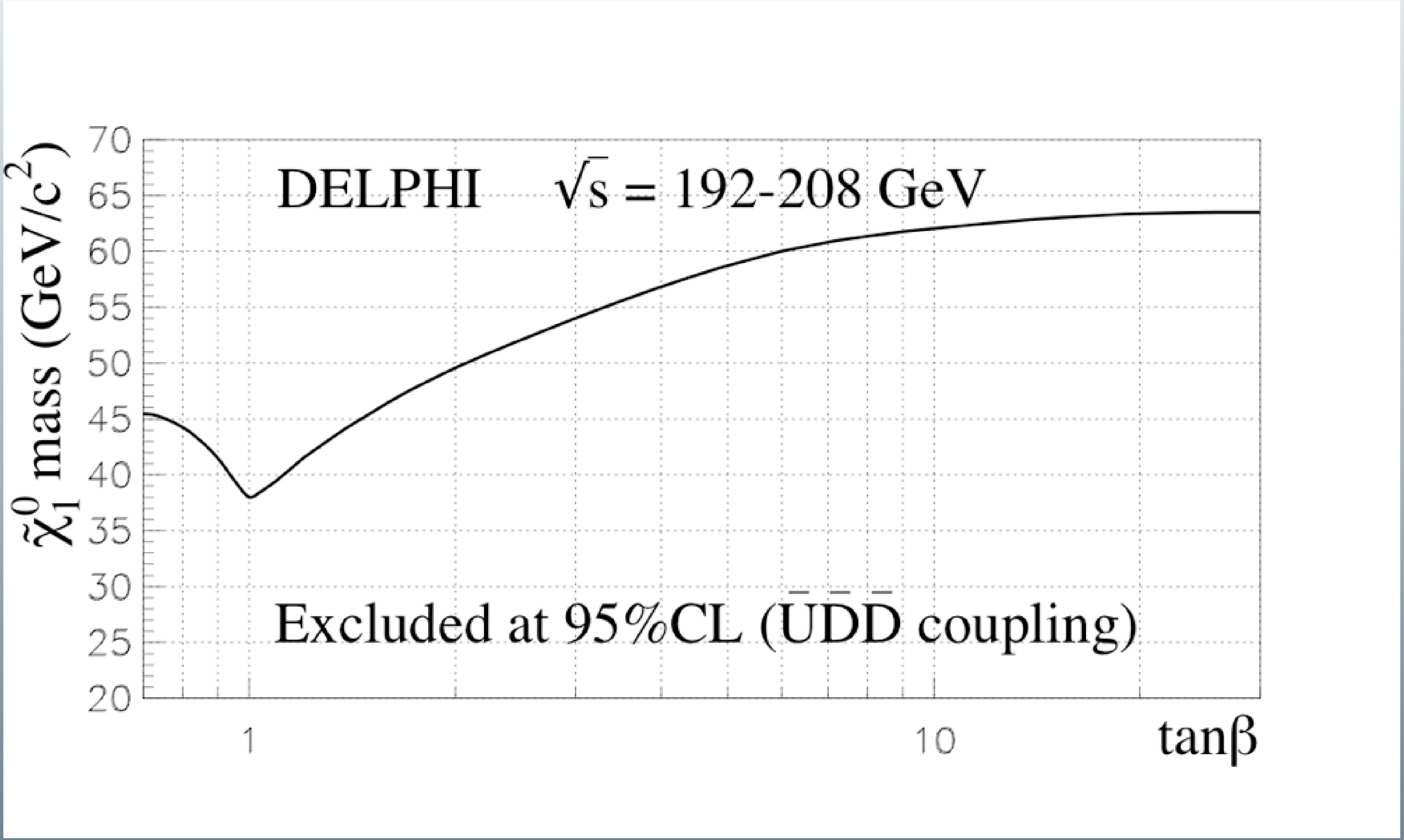


# Allowing a Lighter Higgs Improves the Fit

$$\Delta\chi^2 \sim -0.5$$



# Search for RPV SUSY (Delphi)



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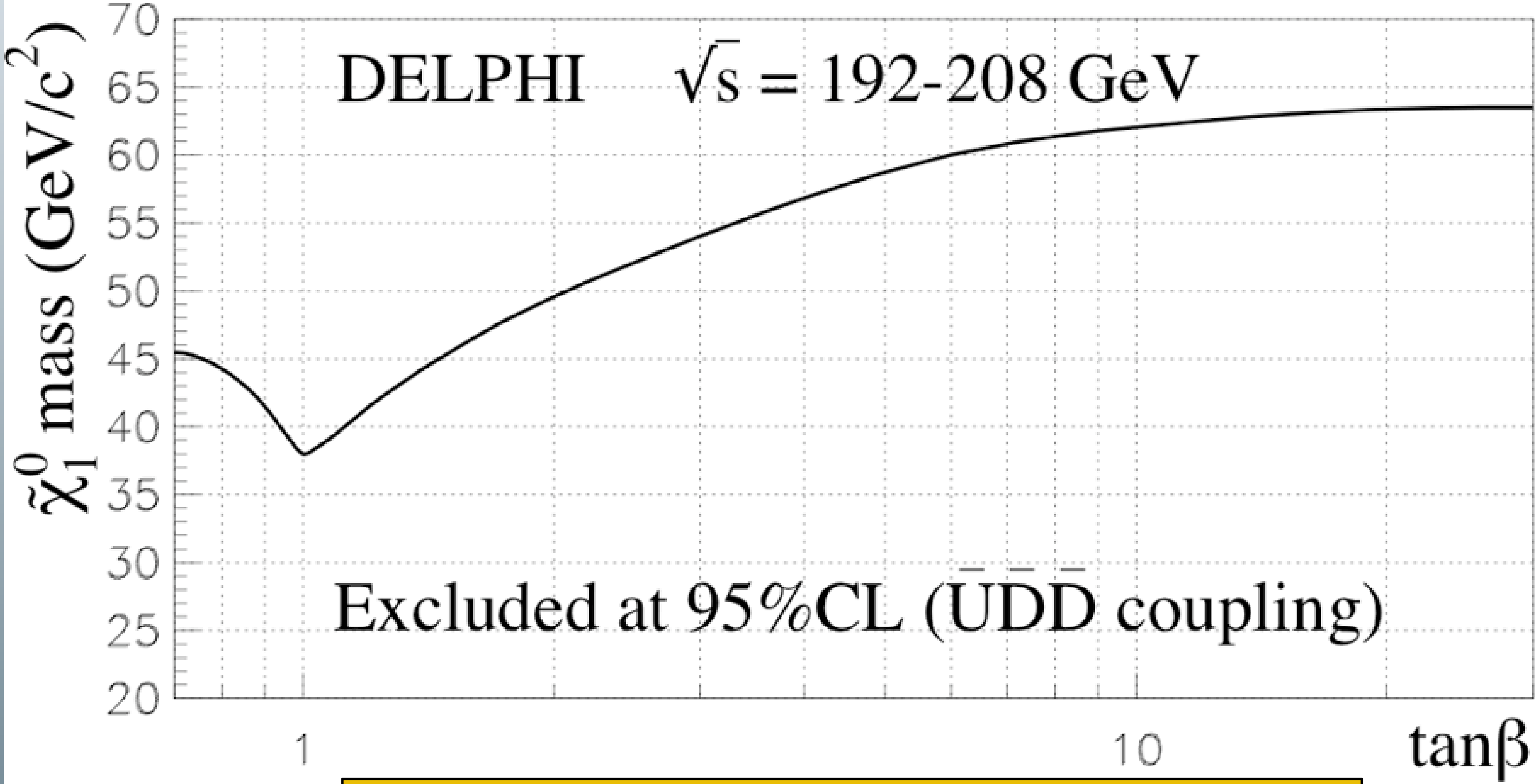


Assumed Gaugino Mass Unification:

$$M_1 = \frac{5}{3} \tan {\theta_W}^2 M_2$$

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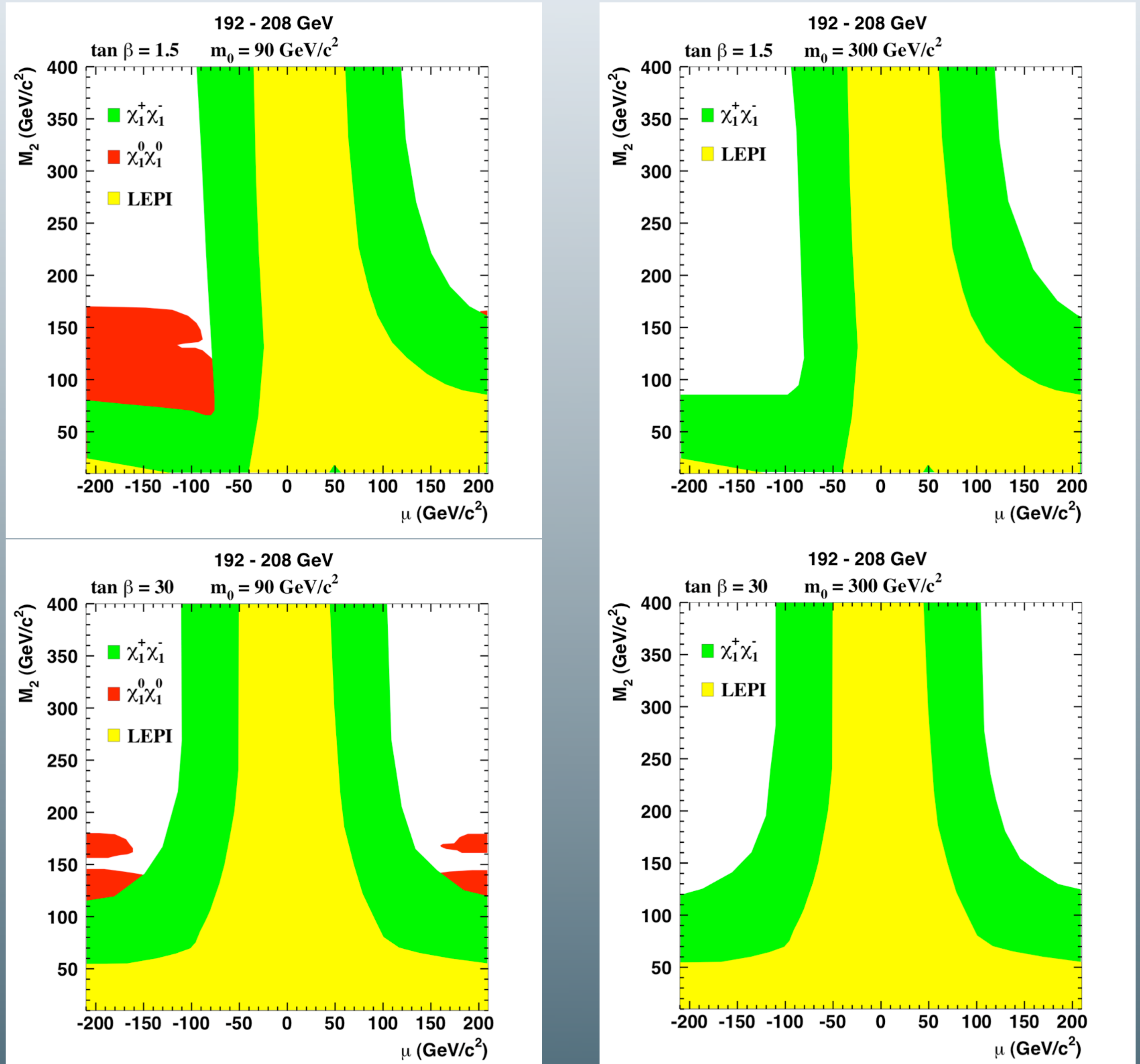
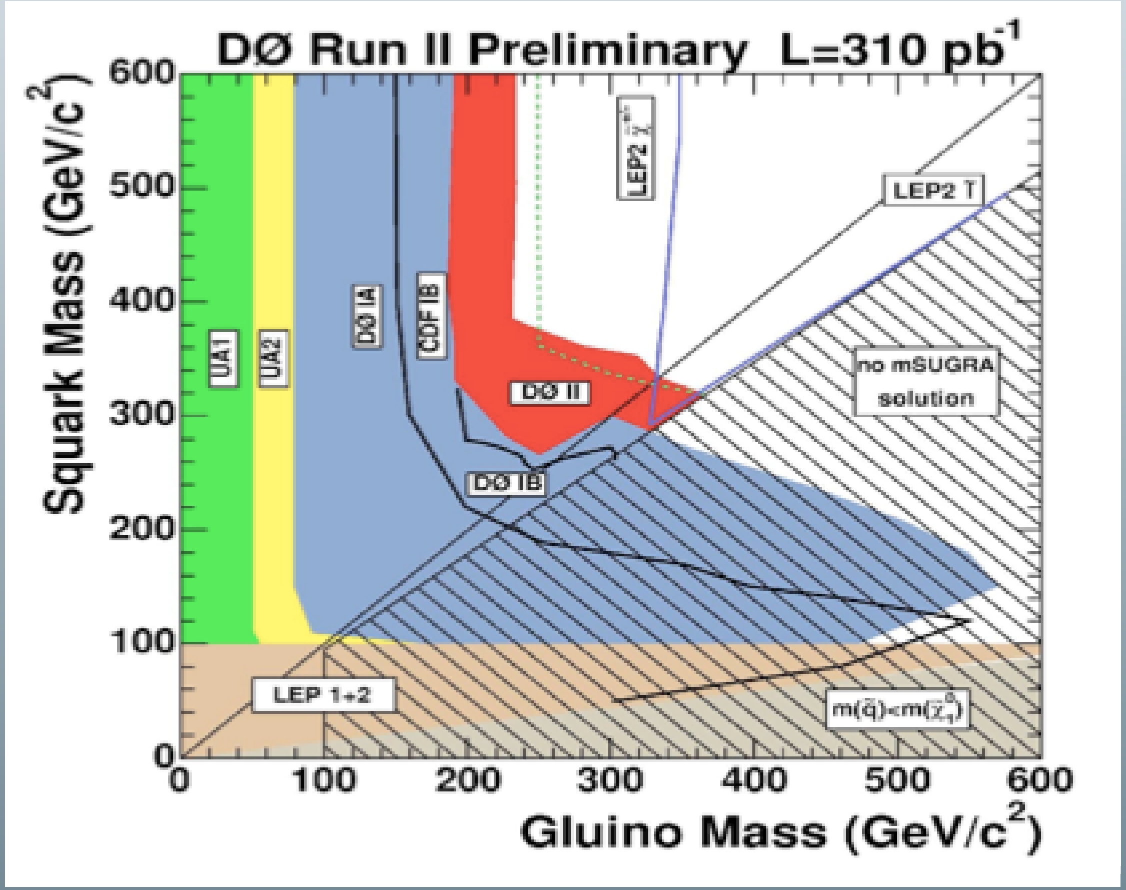
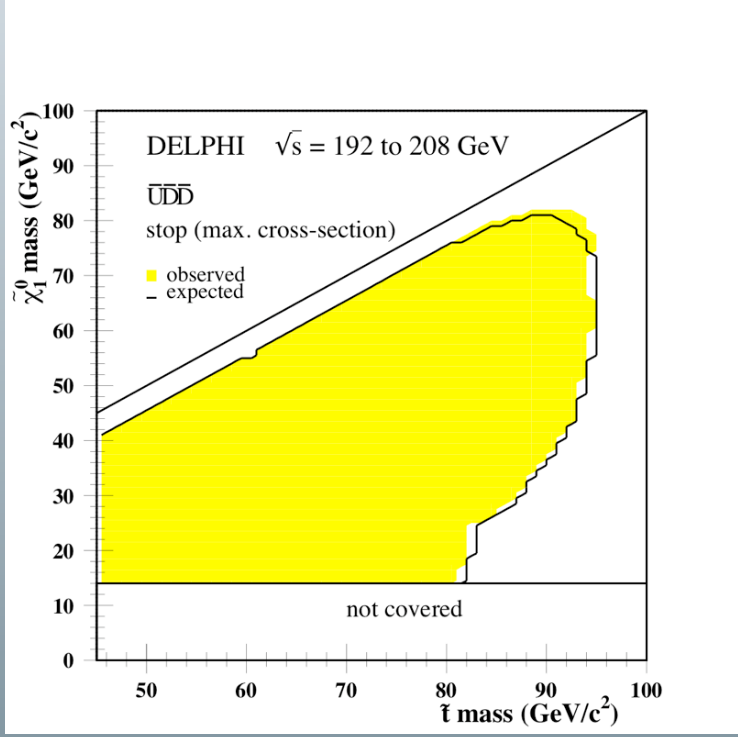


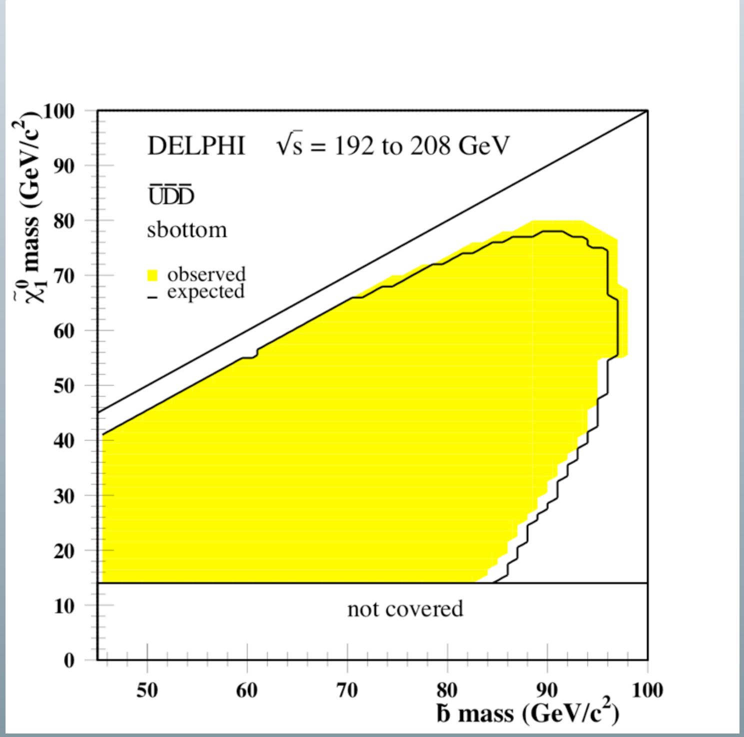
# Squark Searches



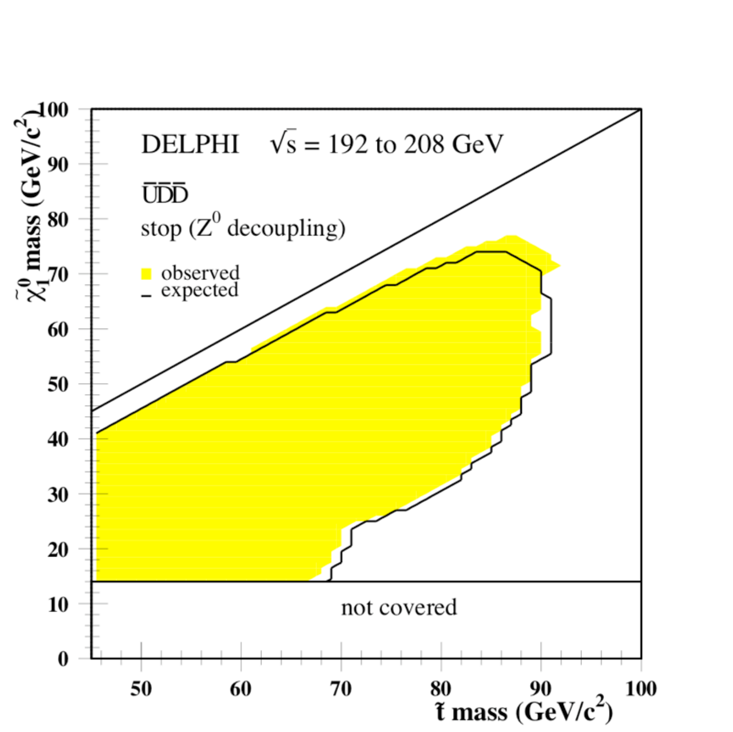

Require large missing energy cuts (>100 GeV)!

# Squark Search with B-violation



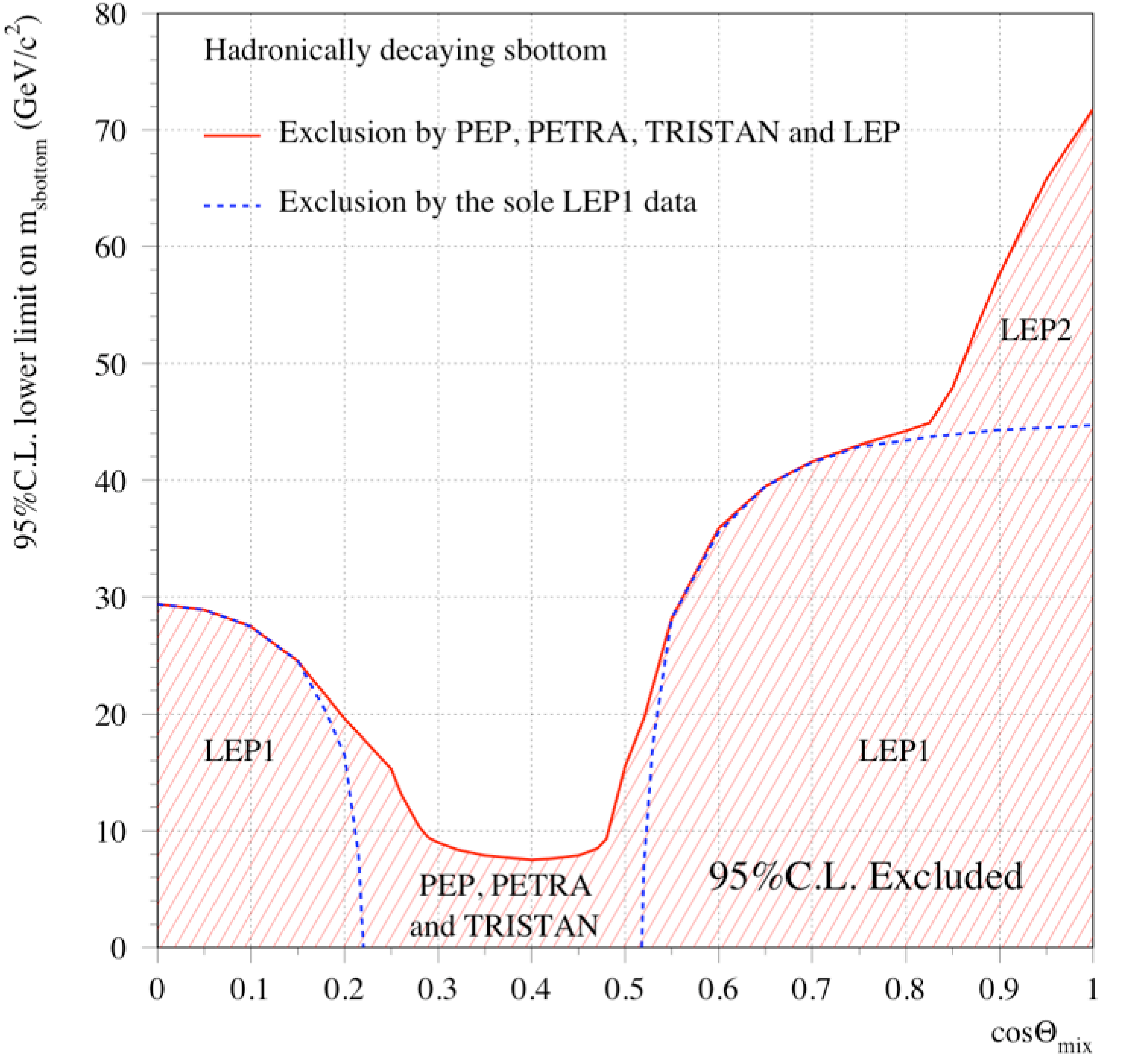
# Squark Search with B-violation




No sensitivity for sbottoms

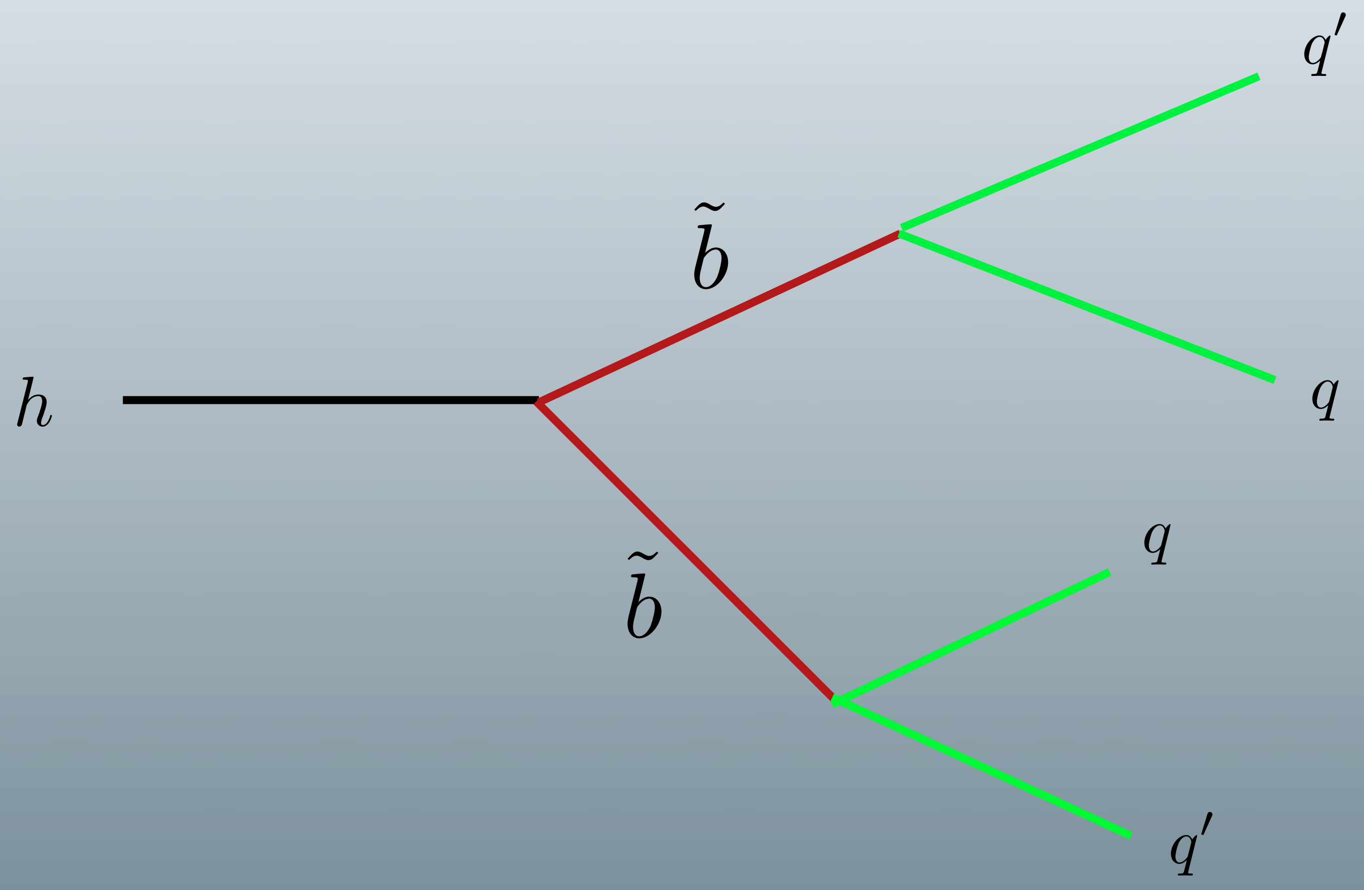
Mixed to decouple from the Z boson

# Light Sbottoms ???




Patrick Janot, 2004

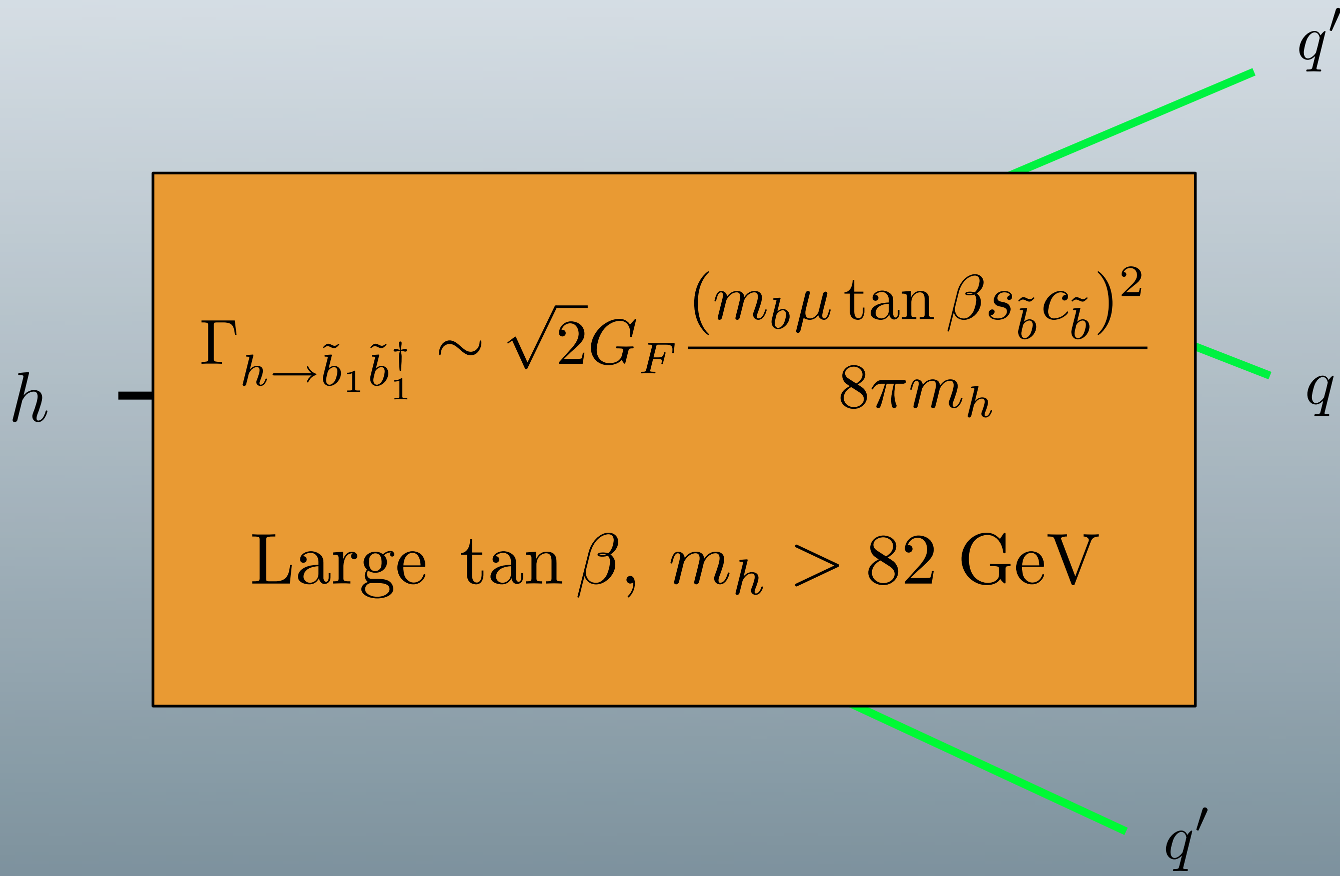
# Higgs to Light Sbottoms




$$q = s, d$$

$$q' = c, u$$

# Higgs to Light Sbottoms




$$\Gamma_{h\to\tilde{b}_1\tilde{b}_1^\dagger} \sim \sqrt{2}G_F\frac{(m_b\mu\tan\beta s_{\tilde{b}}c_{\tilde{b}})^2}{8\pi m_h}$$

$$\text{Large }\ \tan\beta,\ m_h > 82\ \text{GeV}$$

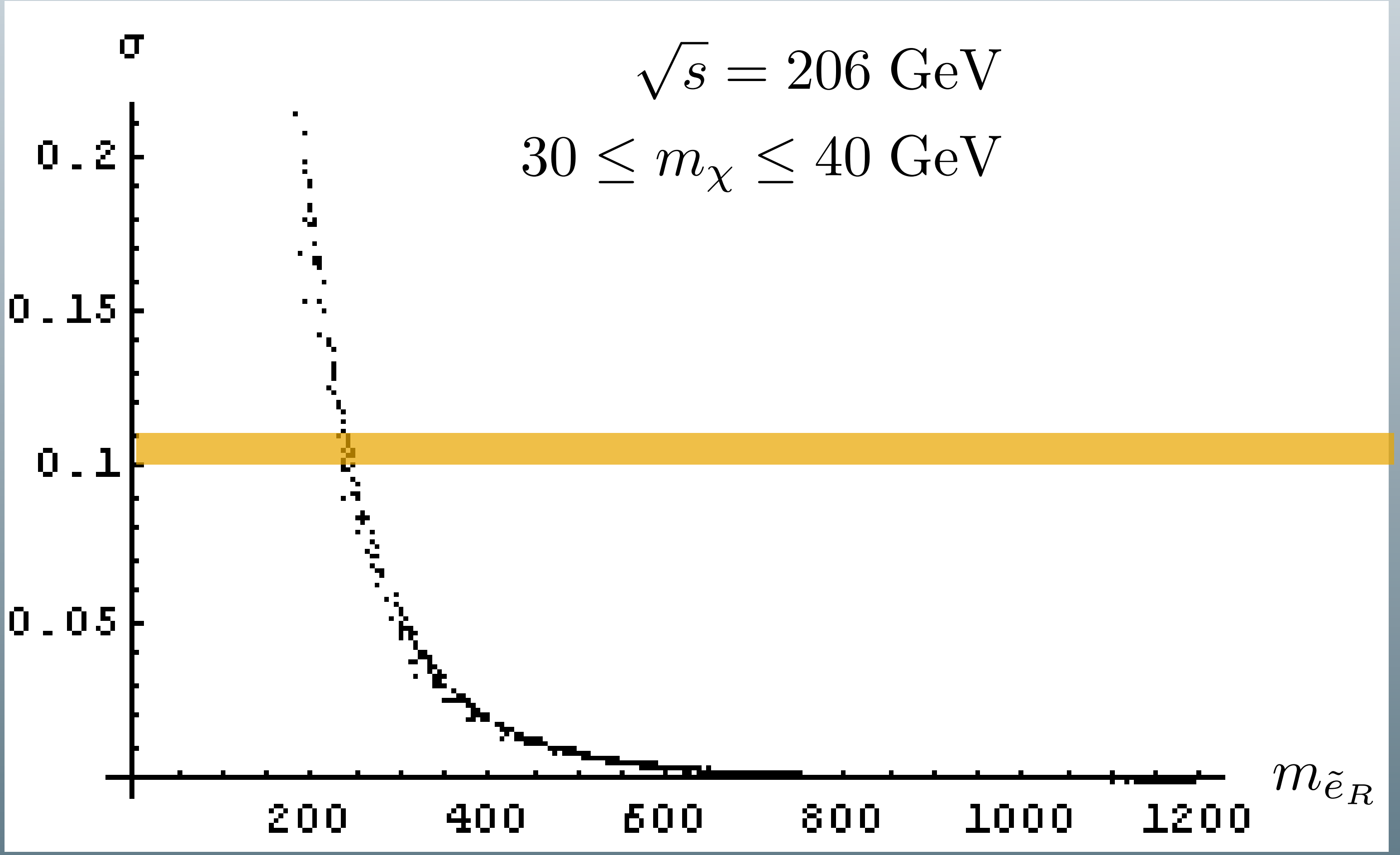
Carena, Heinemeyer, Wagner, Weiglein (2000)

# Sbottom Mass Matrix

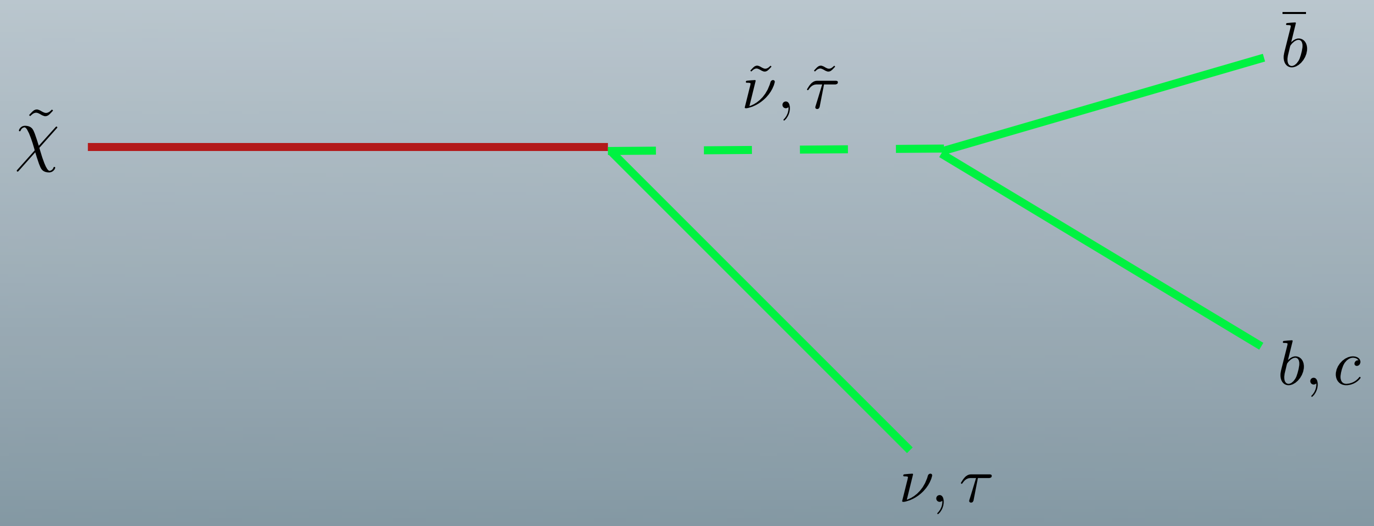
$$\begin{pmatrix} m_L^2 & m_b(A_b + \mu \tan\beta) \\ m_b(A_b + \mu \tan\beta)* & m_R^2 \end{pmatrix}$$

Diagonal terms 100-200 GeV (squared) requires few-10% tuning to get light enough sbottom.

# Slepton Bounds from Neutralino Production



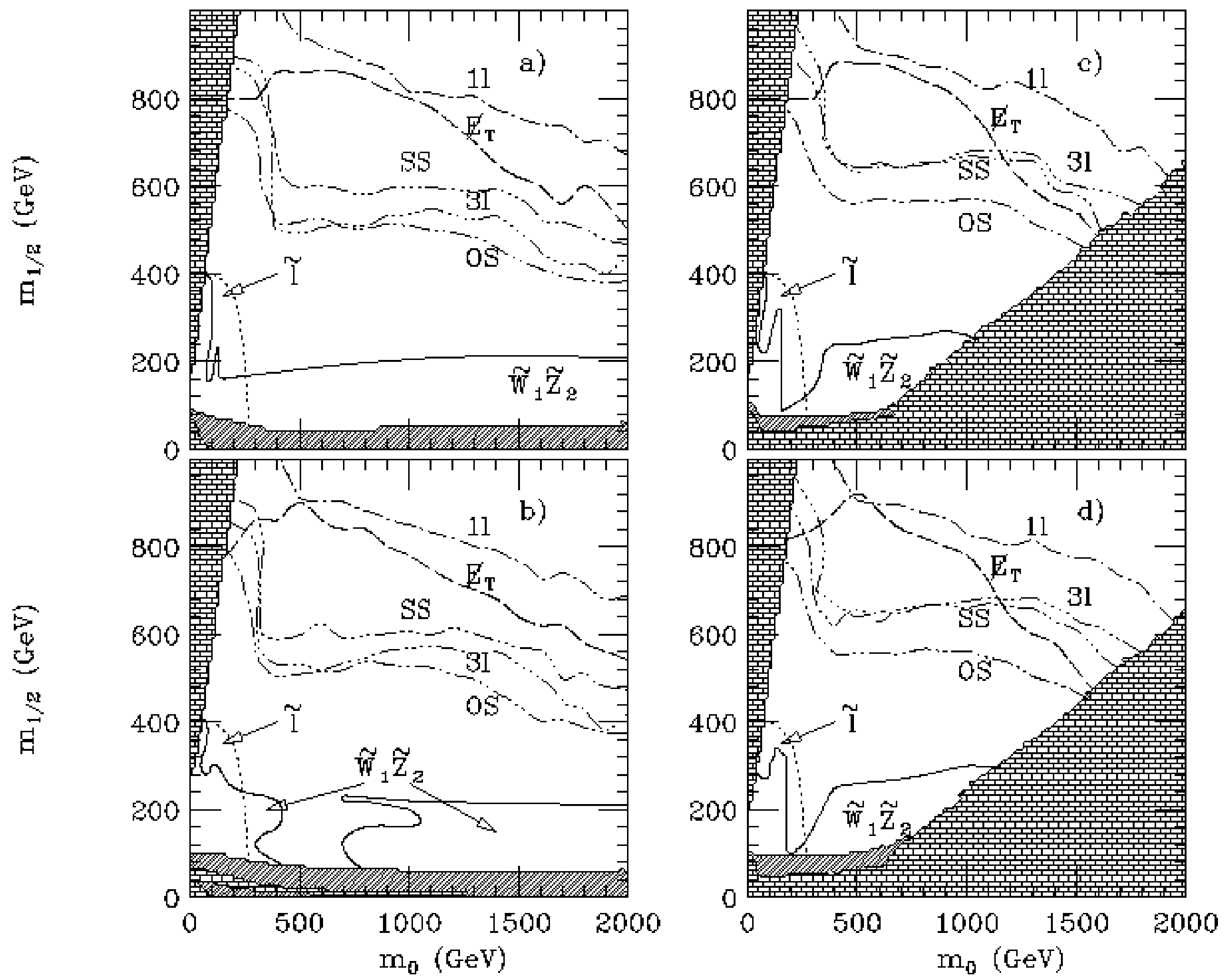
# Lepton Number Violation



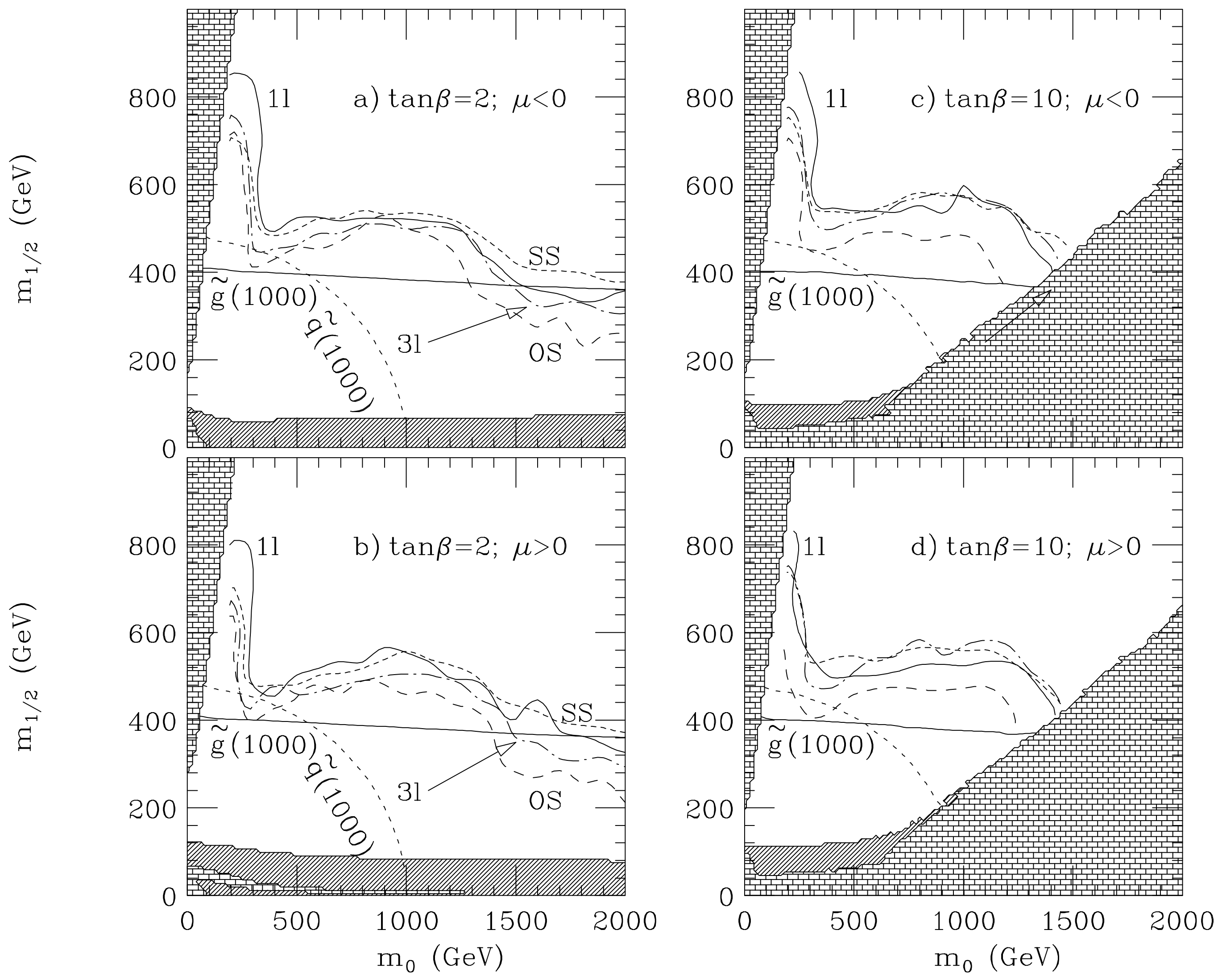
# Typical Bounds on Superpartners with B Violation

| | | |
|---|---|---|
| $\tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$ | $94, 85, 70$ | (A) |
| $\tilde{\nu}$ | $88, 65, 65$ | (A) |
| $\tilde{u}_{L,R}, \tilde{d}_{L,R}$ | $87, 80, 86, 56$ | (L) |
| $\tilde{t}_1, \tilde{b}_1$ | $77(88), -(78)$ | (O, D) |
| $\tilde{t}_1, \tilde{b}_1$ | $77, 55$ | (L)* |

# R-parity preserving SUSY at the LHC



# R-parity violating SUSY at the LHC



# Conclusions

Did we miss the Higgs at LEP?

A Higgs which decays to a multi-jet final state happens in SUSY parameter space and allows $m_h \sim m_Z$.

LEP analyses should continue!

There are Higgses that LEP can see and the LHC can't. We are now exploring a Tevatron study.