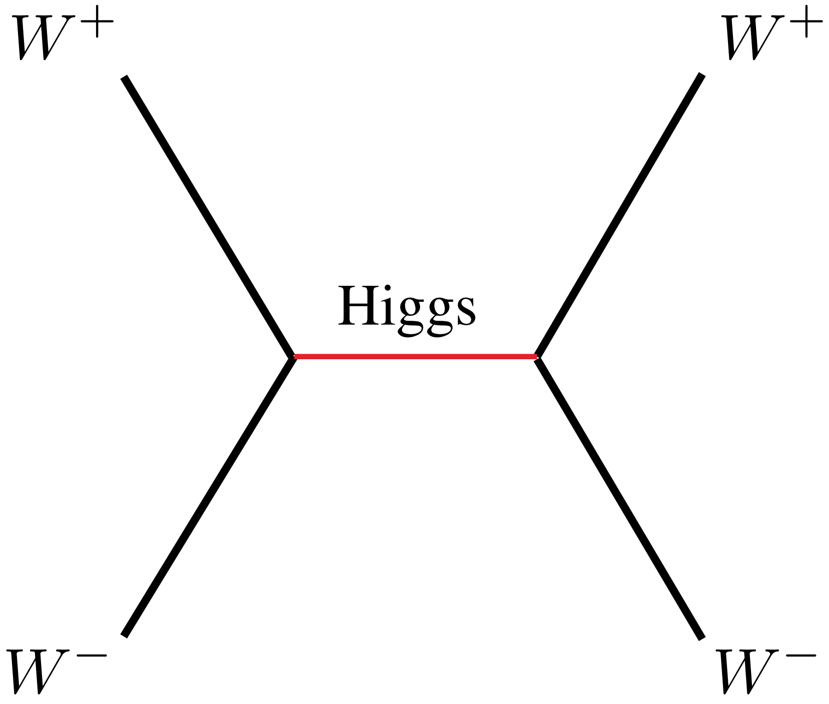
The Higgs Completes the Standard Model



$$\lim_{E\to\infty} \mathcal{A} \propto \text{const.}$$

With the inclusion of the Higgs particle, the theory remains predictive.

Theory requires a Higgs mass < 1 TeV

IV

Phenomenology of Supersymmetry: What Your Mother Never Told You

Biggest Problem for the MSSM

We didn't see the *Higgs*.
(not superpartners)

The Higgs Potential

$$\lambda|h|^4 \rightarrow \frac{g^2}{8}\left[|H_1|^2 - |H_2|^2\right]^2 \qquad m_h = M_Z|\cos 2\beta|$$

SUSY-breaking loop required - same size as tree.

$$(m_h^2)_{tree} + \delta m_h^2 > (114\,\mathrm{GeV})^2$$ (Big Susy-breaking in top sector)

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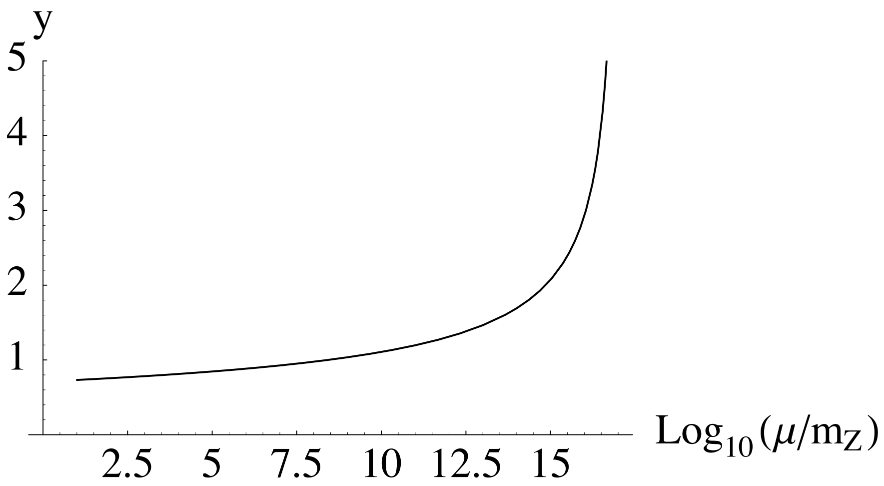
$$(m_h^2)_{tree} + \delta m_h^2 > (114\,\mathrm{GeV})^2$$ (Big Susy-breaking in top sector)

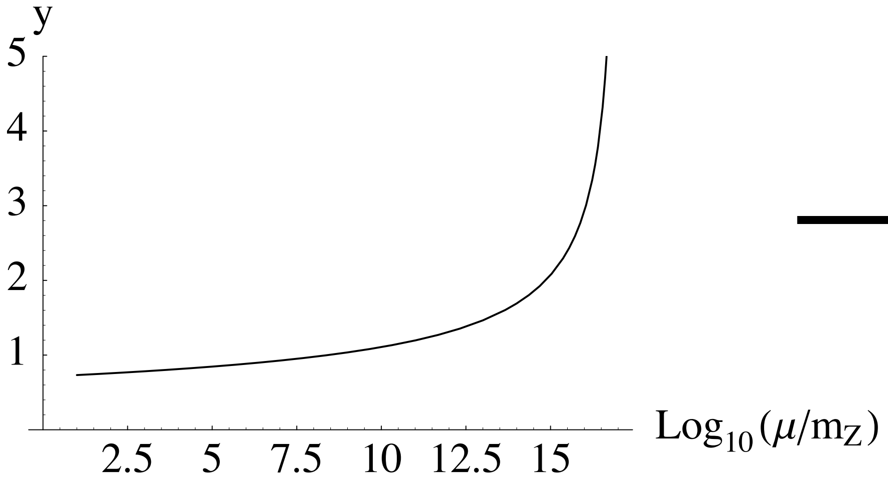
New tree-level contribution requires new fields:

$$W = ySH_1H_2 \rightarrow y^2\,|H_1H_2|^2$$

Limits on the New Quartic

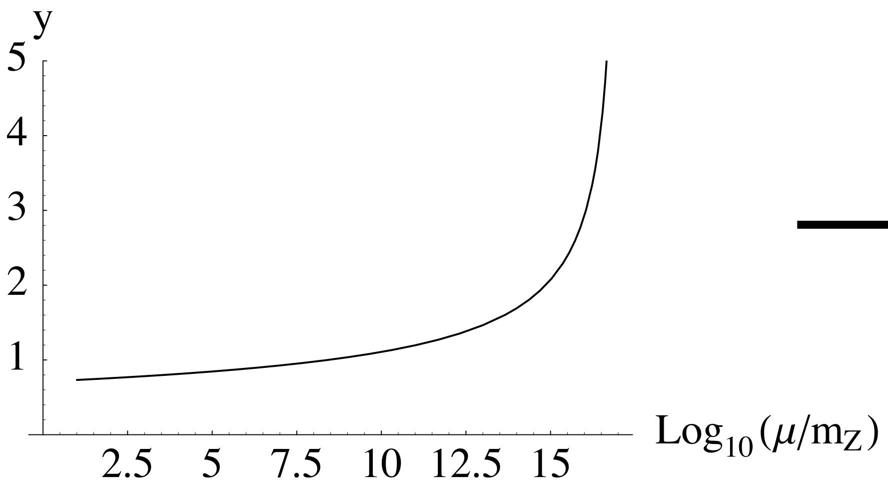


Limits on the New Quartic

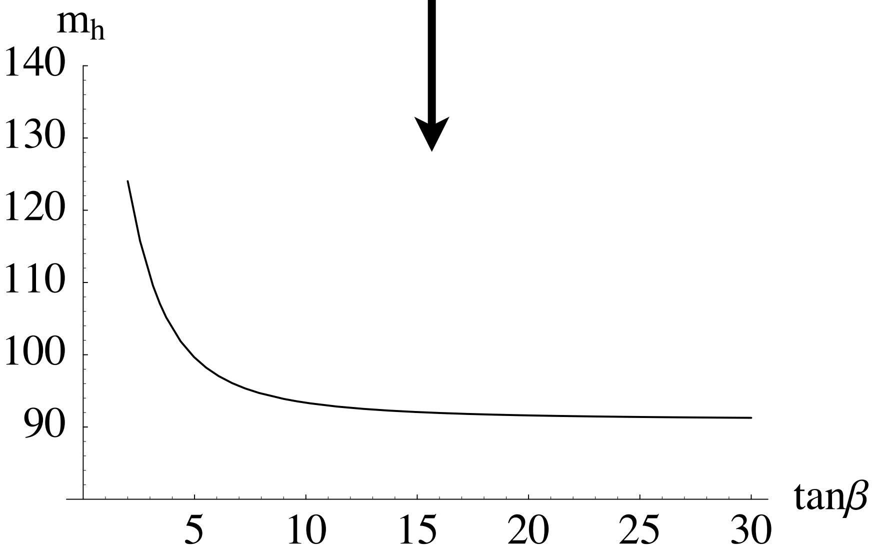


$y < 0.8$

Limits on the New Quartic



$y < 0.8$



More Higgses

$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3}\hat{S}^3$$

More Higgses

$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3}\hat{S}^3$$

$$M_{H_d}^2 = -\frac{\lambda^2}{2}\left(s^2 + v^2 \sin^2\beta\right) + \frac{\lambda\kappa}{2} s^2 \tan\beta - \frac{M_Z^2}{2}\cos 2\beta + m_\lambda s \tan\beta \ ,$$

$$M_{H_u}^2 = -\frac{\lambda^2}{2}\left(s^2 + v^2 \cos^2\beta\right) + \frac{\lambda\kappa s^2}{2\tan\beta} + \frac{M_Z^2}{2}\cos 2\beta + \frac{m_\lambda s}{\tan\beta} \ ,$$

$$M_S^2 = -\frac{\lambda^2}{2} v^2 + \frac{\lambda\kappa}{2} v^2 \sin 2\beta - \kappa^2 s^2 + \frac{m_\lambda v^2}{2s}\sin 2\beta + m_\kappa s \ .$$

More Higgses

$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3}\hat{S}^3$$

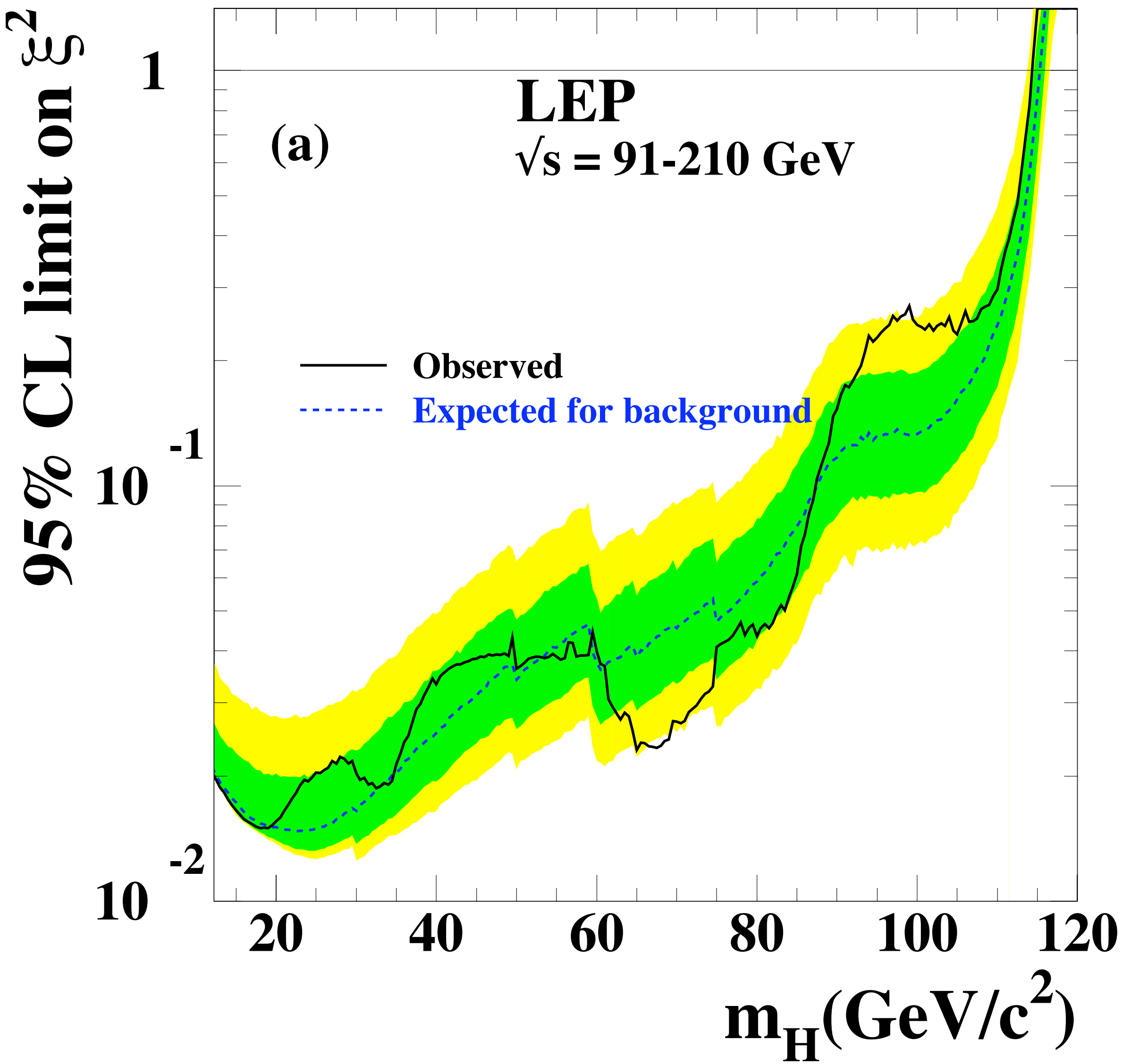
$$h_v^0, H_v^0, h_s^0 \qquad A_v^0, A_s^0$$

New Higgs Decay

$$h^0 \rightarrow a^0 a^0$$

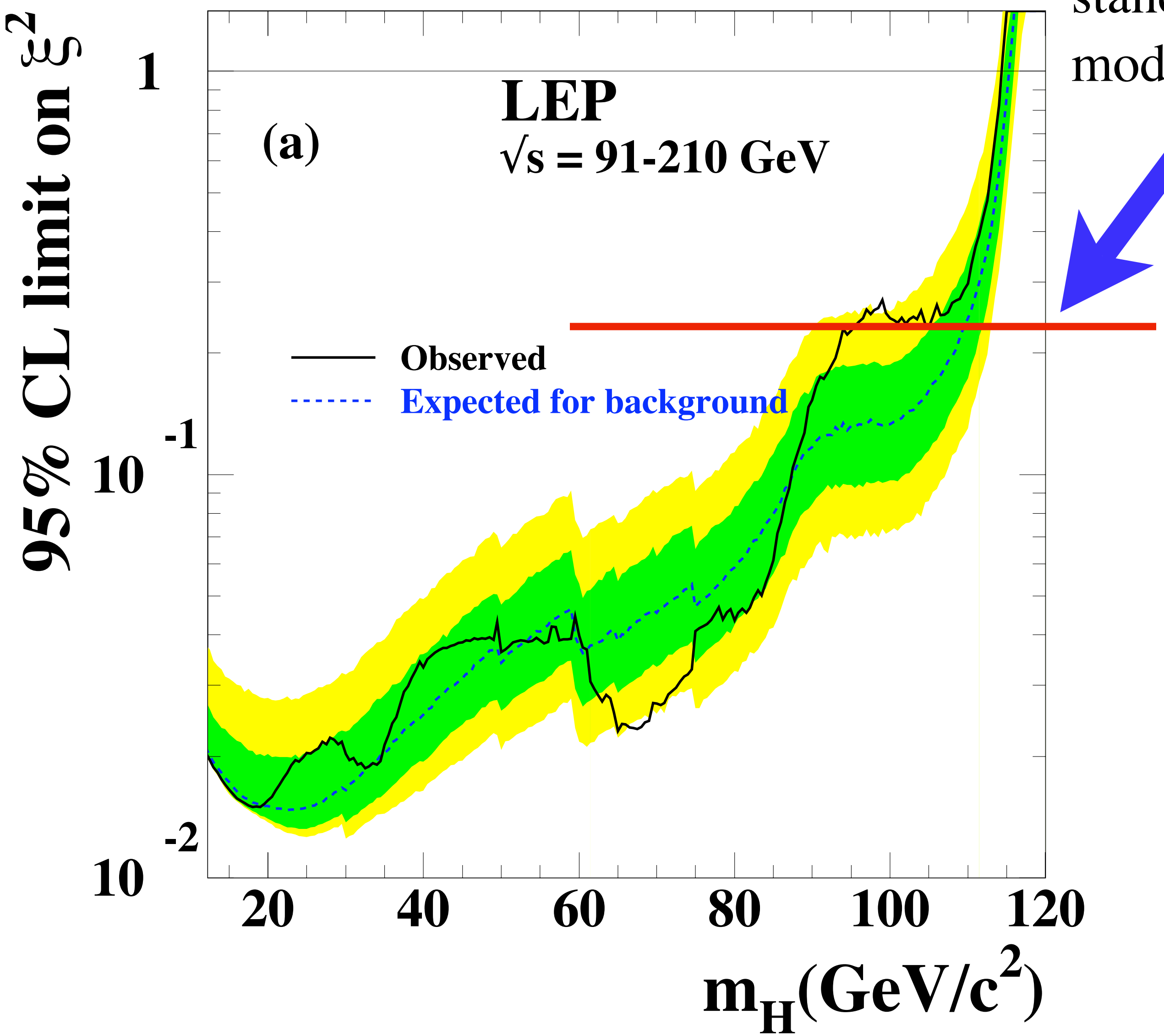
And then the pseudo-scalars decay.

SM Higgs



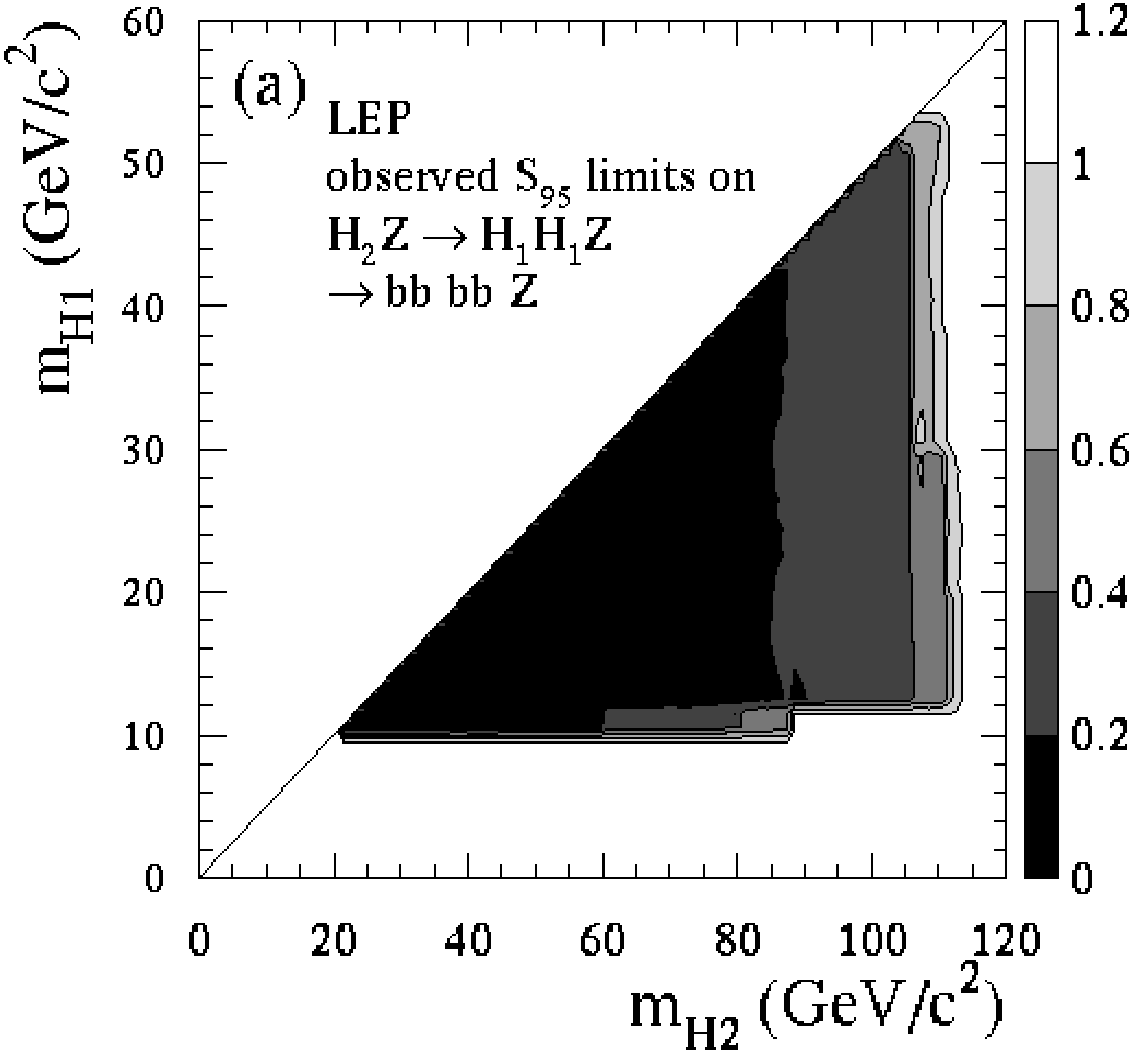
95% CL limit on ξ^2
1
10^{-1}
10^{-2}
LEP
$\sqrt{s}$ = 91-210 GeV
(a)
Observed
Expected for background
20
40
60
80
100
120
m_H(GeV/c^2)

SM Higgs



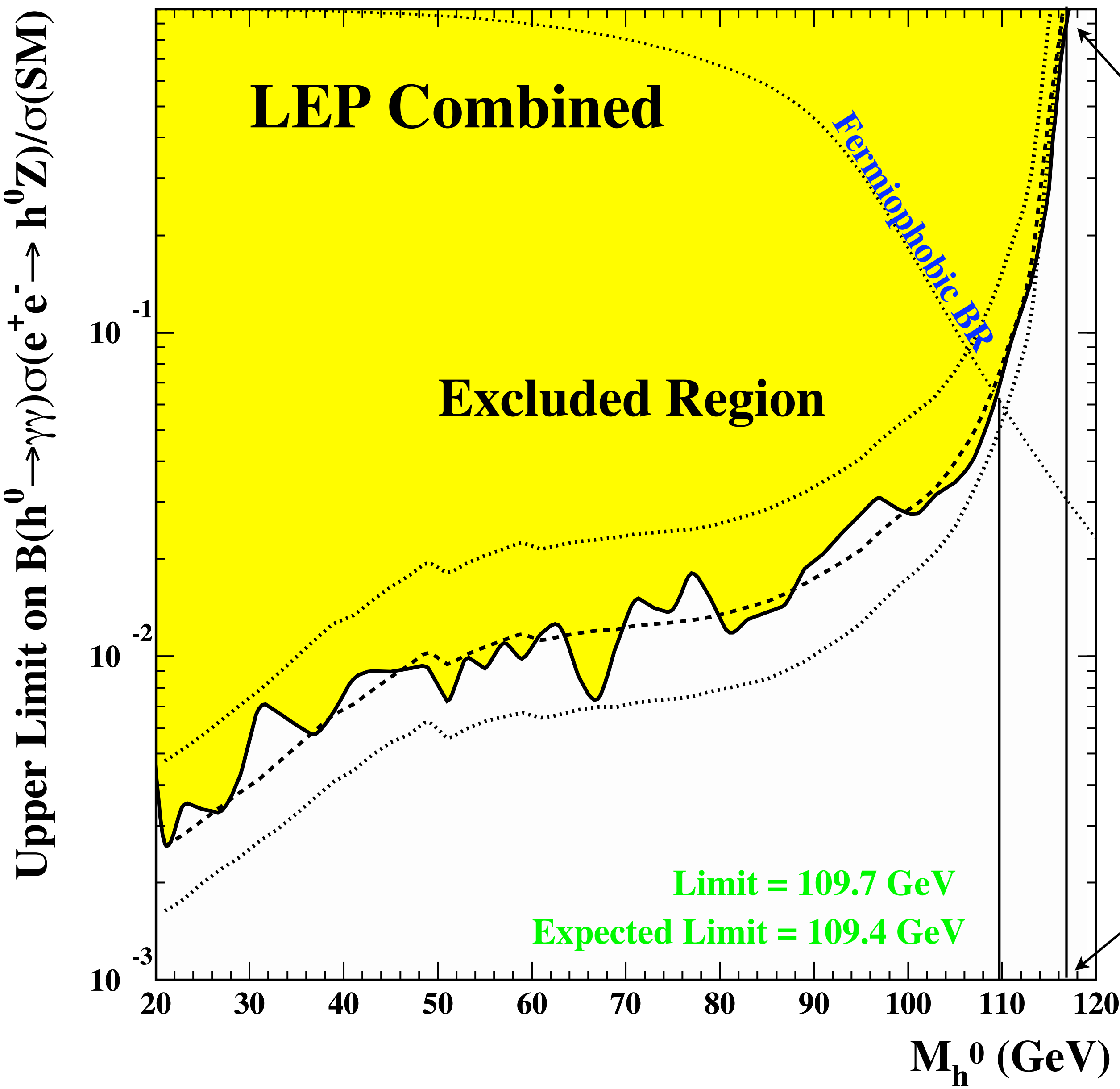
Suppress cross section or BR to standard model modes to ~20%

Higgs to 4b's



But NOT 4 taus!

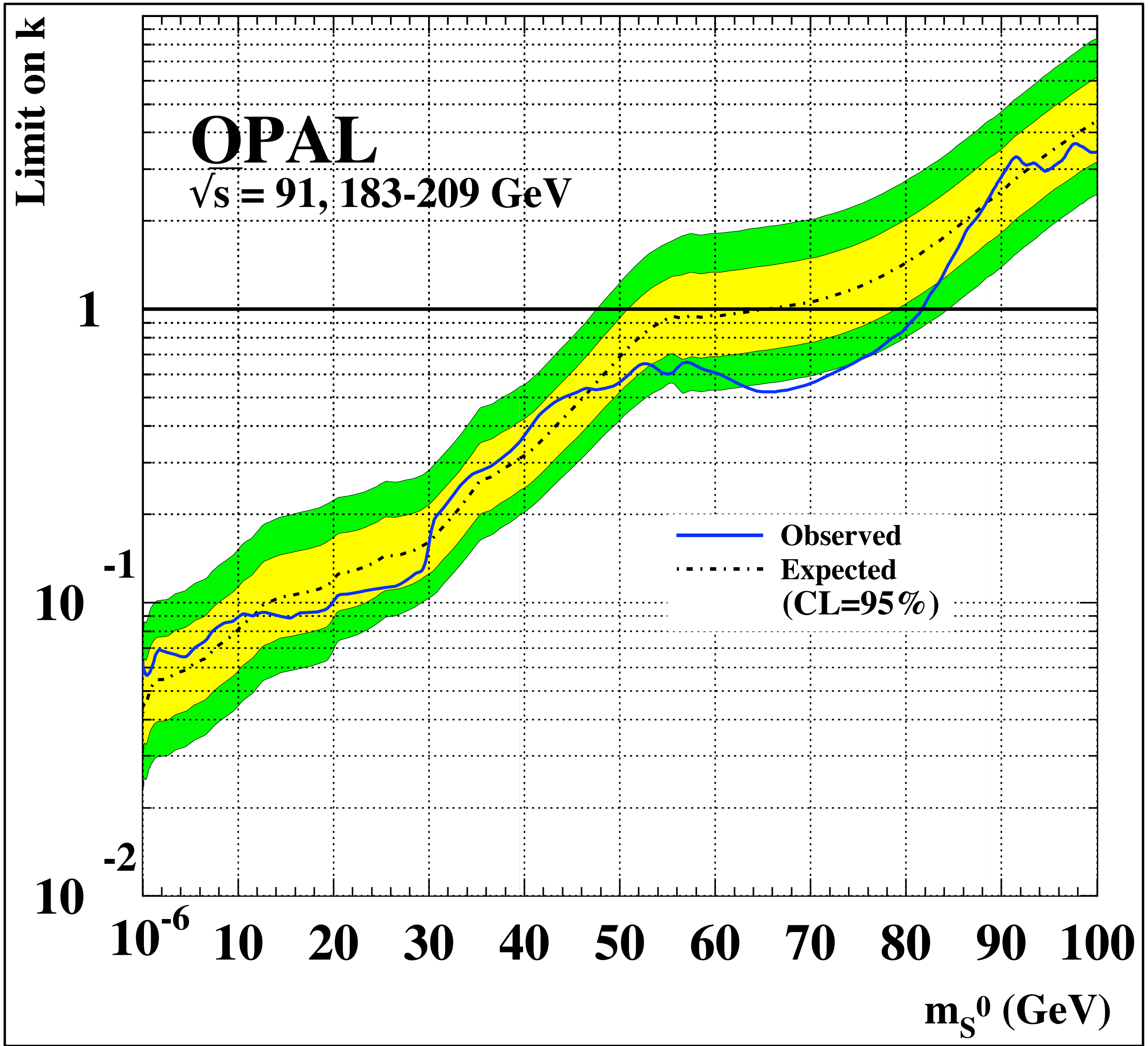
Fermiophobic



Exclusively
2 photons

117 GeV

Non-standard Higgs Decays



New Higgs Decays

$$h \to a^0 a^0 \to b\bar{b}b\bar{b} \qquad m_h > 110 \text{ GeV}$$

$$h \to a^0 a^0 \to \tau\bar{\tau}\tau\bar{\tau} \qquad m_h > 86 \text{ GeV}$$

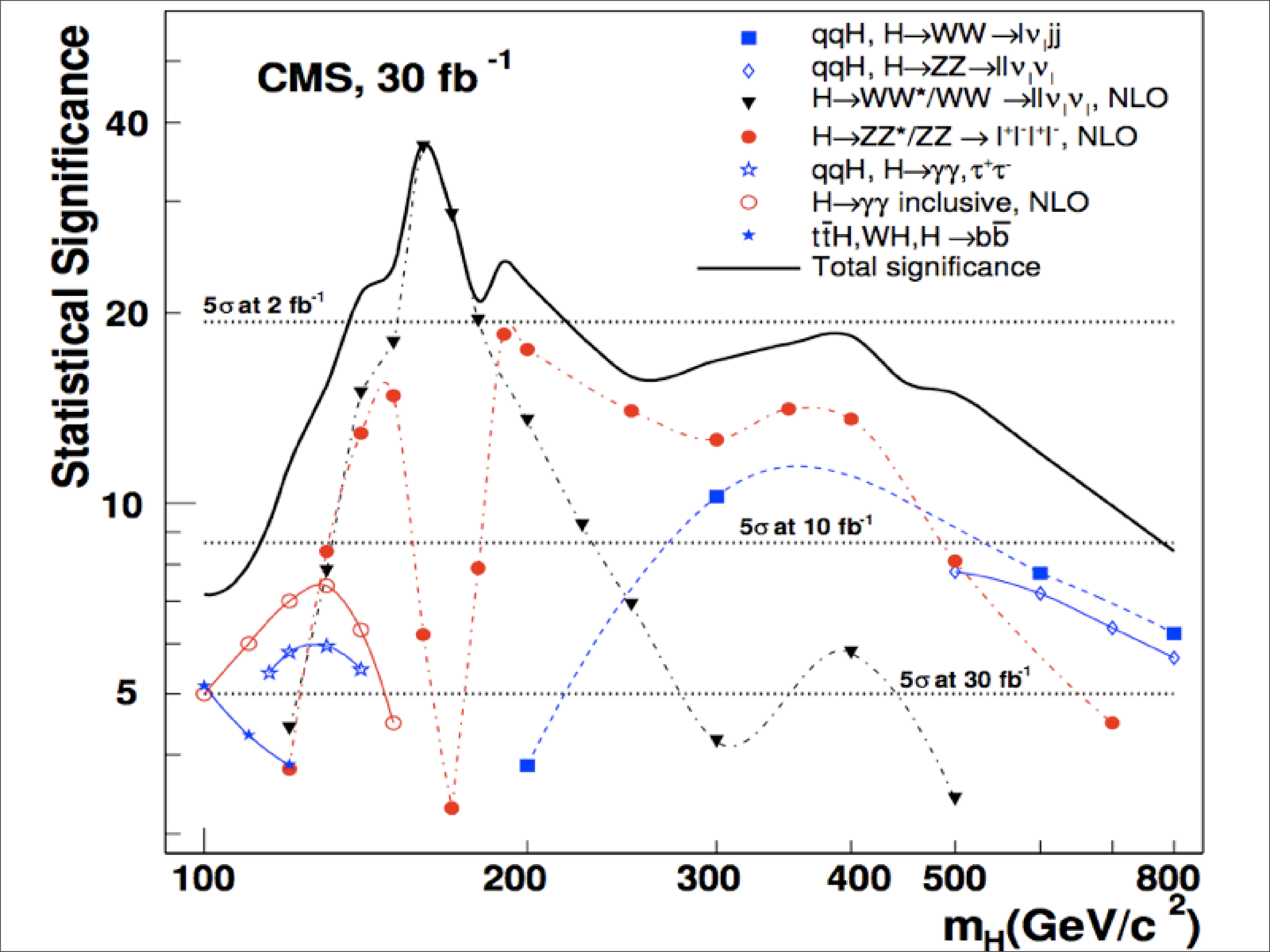
$$h \to a^0 a^0 \to gggg \qquad m_h > 86 - 100 \text{ GeV?}$$

$$h \to a^0 a^0 \to 6\pi^0 \qquad m_h > 117 \text{ GeV}$$

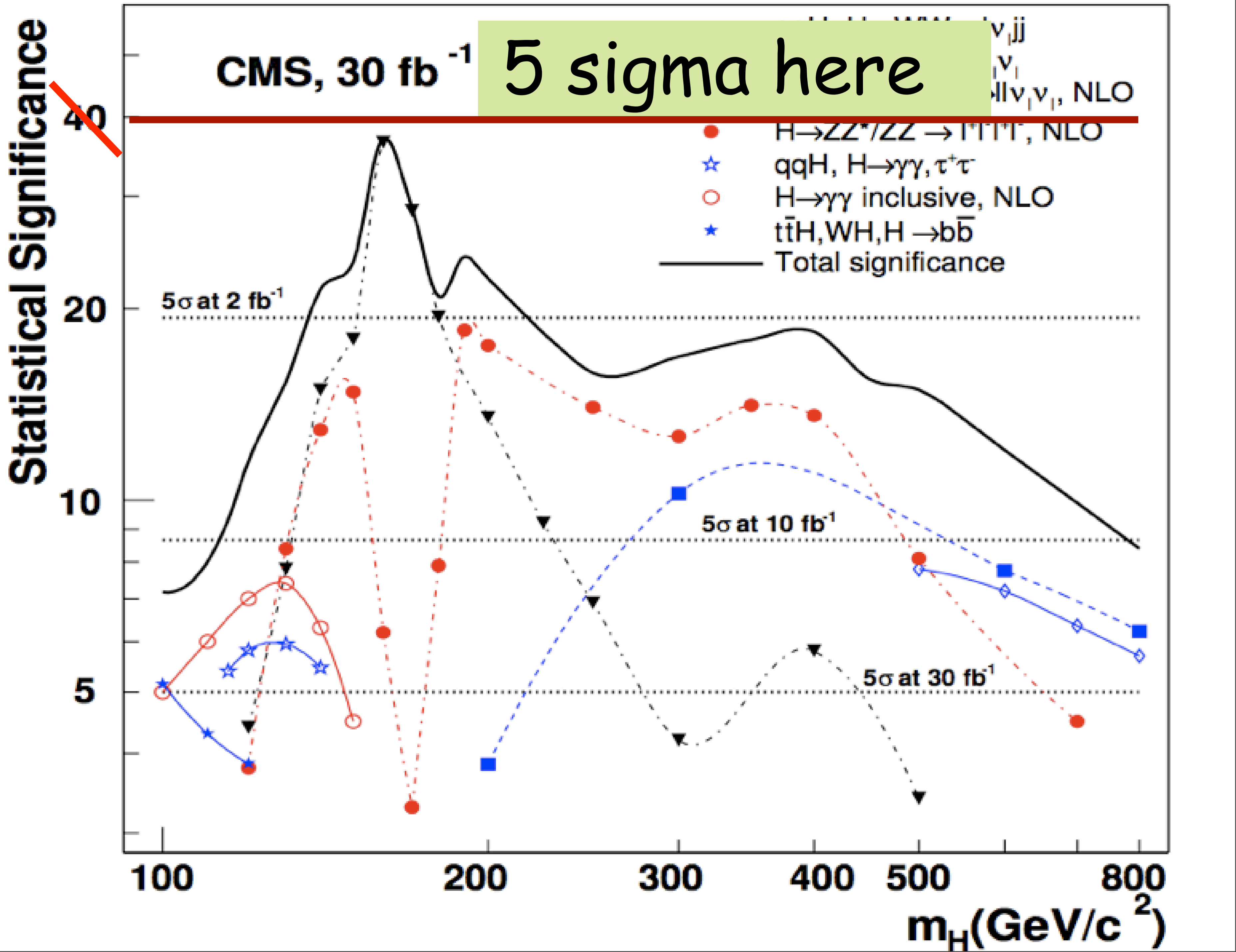
$$h \to a^0 a^0 \to 4\gamma \qquad m_h > 117 \text{ GeV}$$

$$h \to ss \to a^0 a^0 a^0 a^0$$

$$\to b\bar{b}b\bar{b}b\bar{b}b\bar{b} \qquad m_h > 82 \text{ GeV???}$$



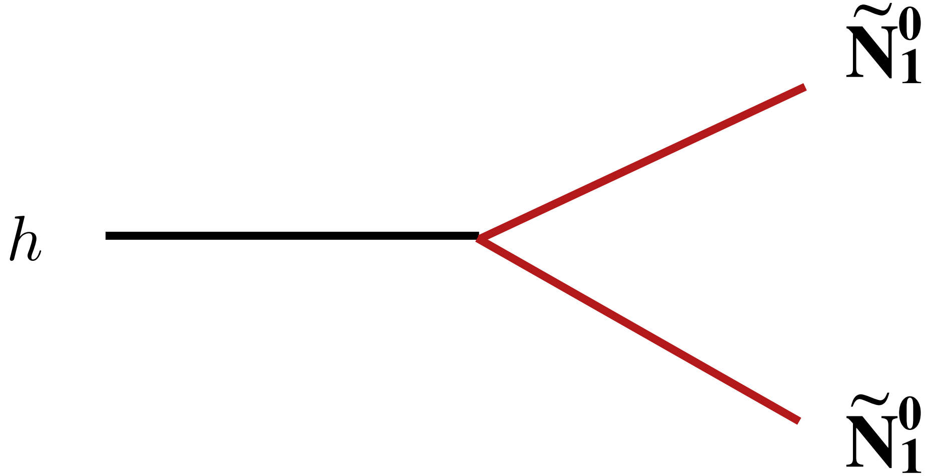
CMS, 30 fb -1
Statistical Significance
qqH, H→WW→lν jj
qqH, H→ZZ→llνν
H→WW*/WW →llνν, NLO
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ, τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
40
20
10
5
100
200
300
400
500
800
mH(GeV/c 2)



Statistical Significance
CMS, 30 fb-1
5 sigma here
H→ZZ*/ZZ → l+l-l+l-, NLO
qqH, H→γγ, τ+τ-
H→γγ inclusive, NLO
tt̄H,WH,H →bb̄
Total significance
5σ at 2 fb-1
5σ at 10 fb-1
5σ at 30 fb-1
40
20
10
5
100
200
300
400
500
800
mH(GeV/c2)

Higgs Decays to Superpartners

Most robust possibility:

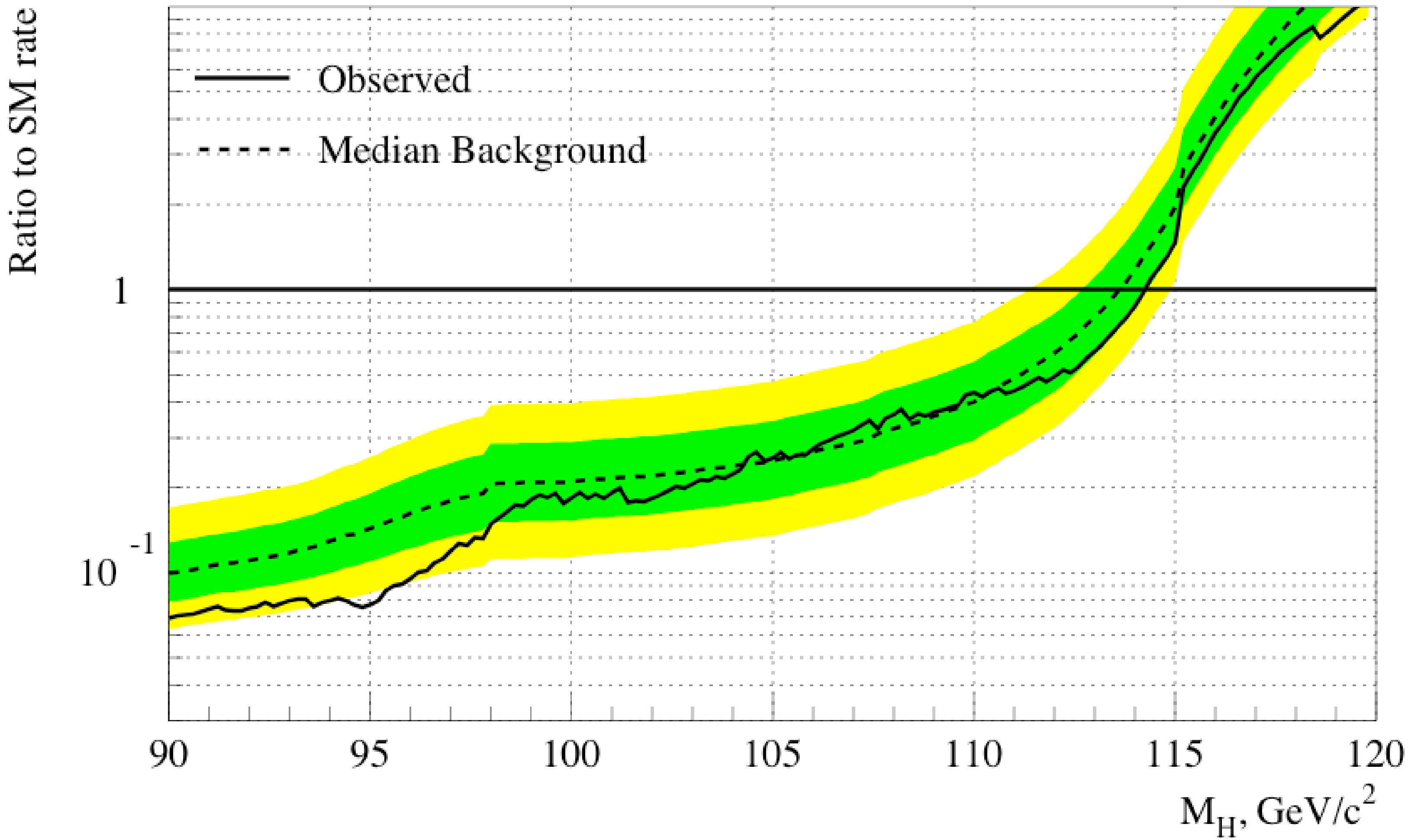


Neutralinos (like neutrinos) are invisible.

$$\tilde{\mathbf{N}}_1^0 = \tilde{\chi}_1^0$$

Invisible Higgs

114 GeV - same as SM Higgs



LEP Combined - '01

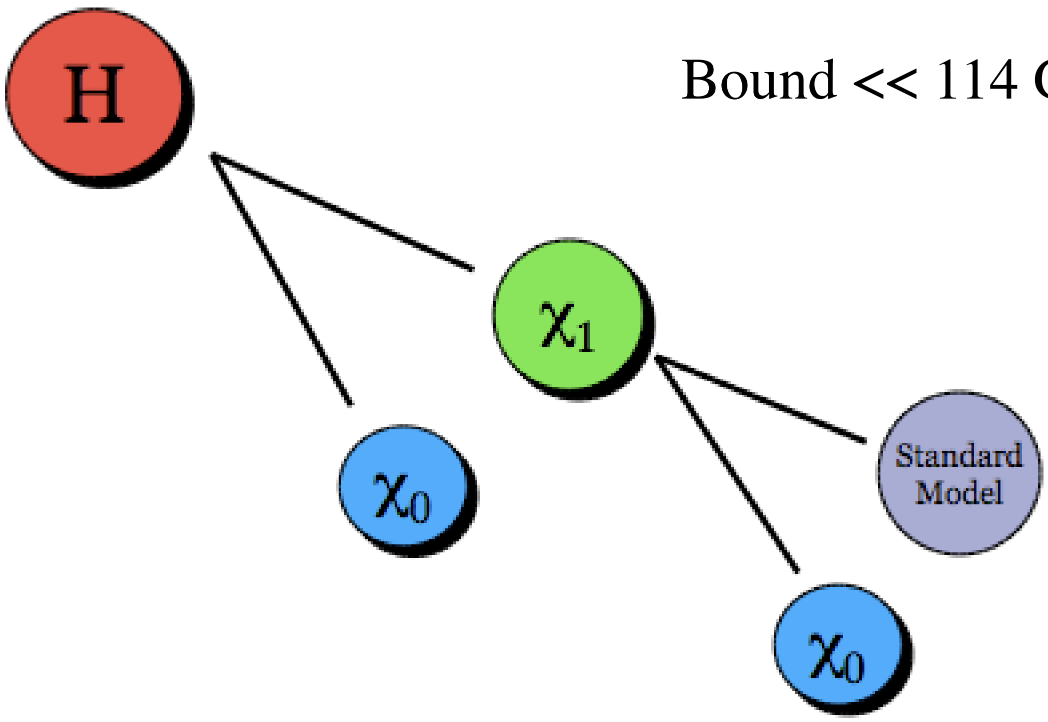
Extra Singlet -> Extra Neutralino

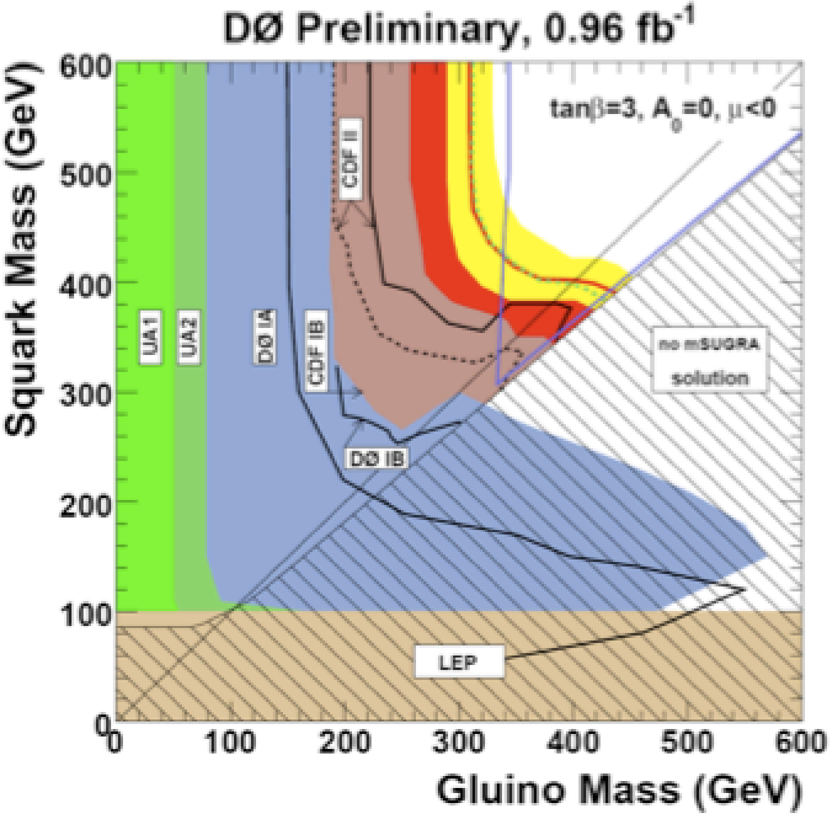
$$W = \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3} \hat{S}^3$$

$$\mathbf{M}_{\tilde{N}} = \begin{pmatrix} M_1 & 0 & -g' v_d/\sqrt{2} & g' v_u/\sqrt{2} & 0 \\ 0 & M_2 & g v_d/\sqrt{2} & -g v_u/\sqrt{2} & 0 \\ -g' v_d/\sqrt{2} & g v_d/\sqrt{2} & 0 & -\lambda s & -\lambda v_u \\ g' v_u/\sqrt{2} & -g v_u/\sqrt{2} & -\lambda s & 0 & -\lambda v_d \\ 0 & 0 & -\lambda v_u & -\lambda v_d & 2\kappa s \end{pmatrix}$$

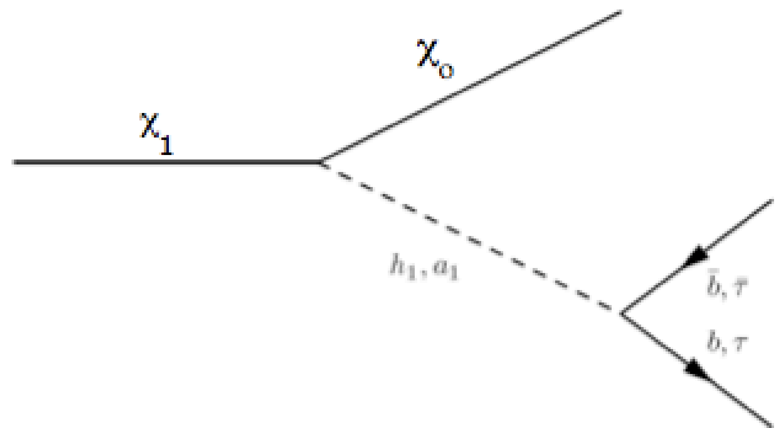
Higgs to Neutralino Cascade

Bound << 114 GeV ??





Missing Energy signature suppressed, e.g.



As m_a approaches m_{χ_1}, missing energy is reduced

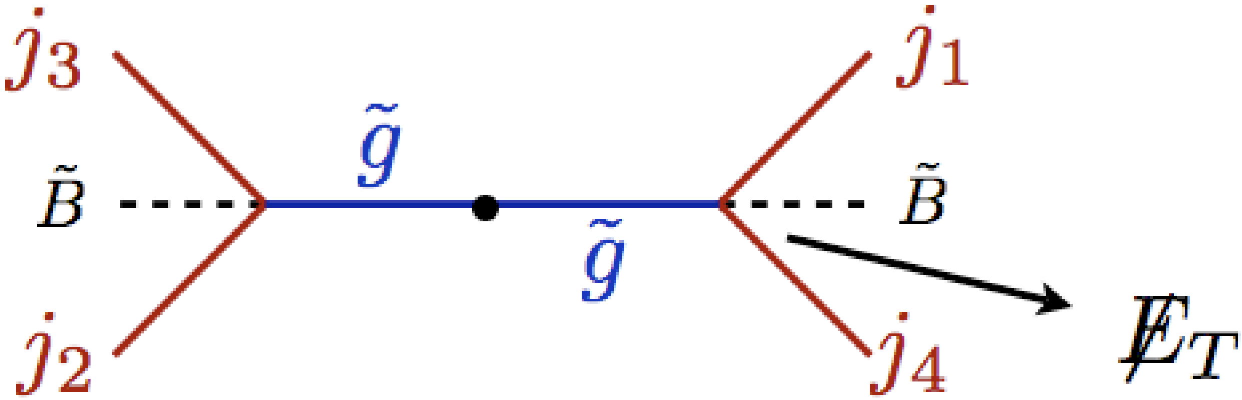
Generalizing This Ratio

$$M_3 : M_2 : M_1 \simeq 7 : 2 : 1$$

What if, for example, $M_2 > M_3 \gtrsim M_1$?

Generalizing This Ratio

What if, for example, $M_2 > M_3 \gtrsim M_1$?



$Q = M_{\tilde{g}} - M_{\tilde{B}}$

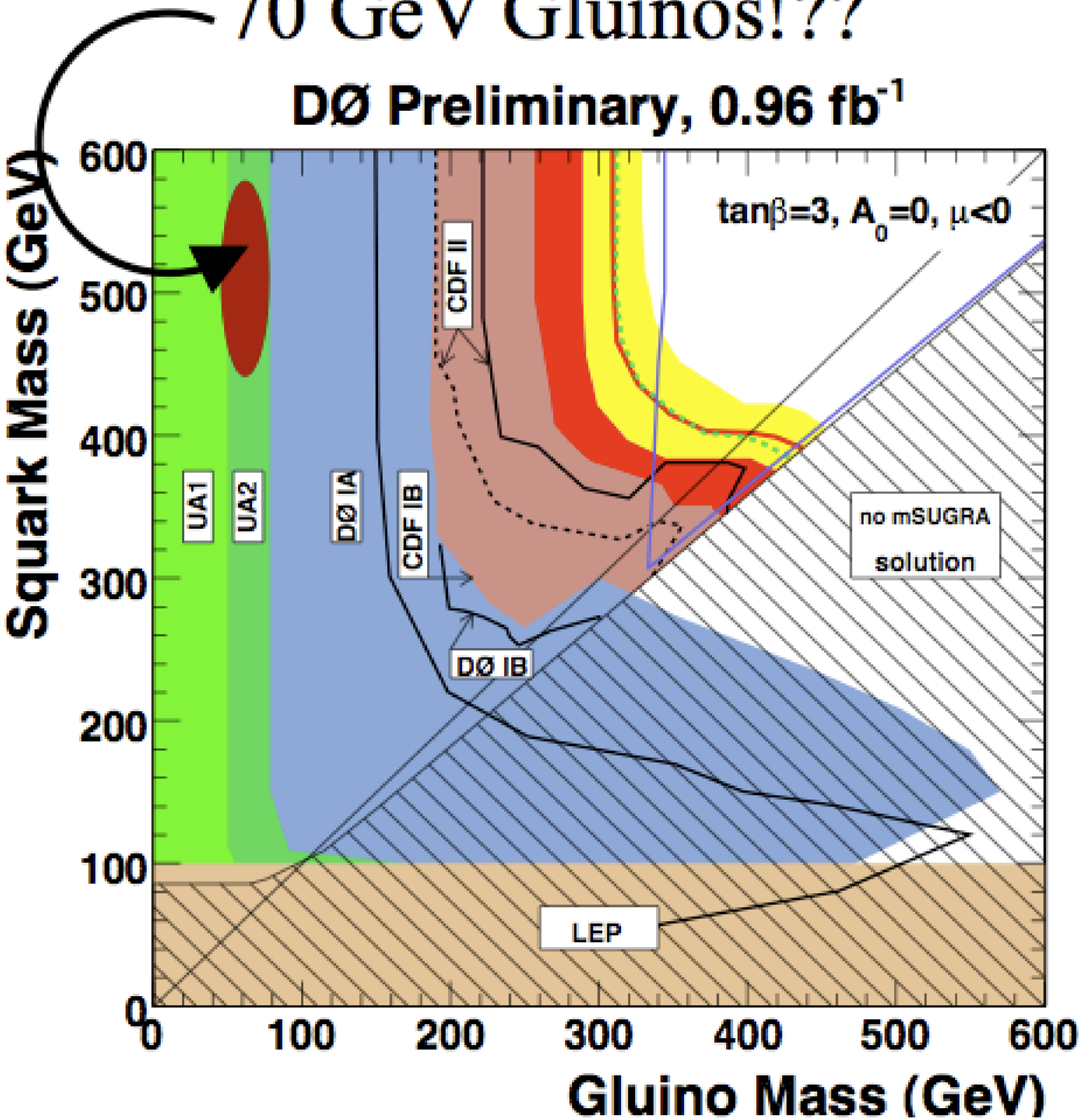
If $Q < M_{\tilde{B}}$

Bino carries away energy but not momentum

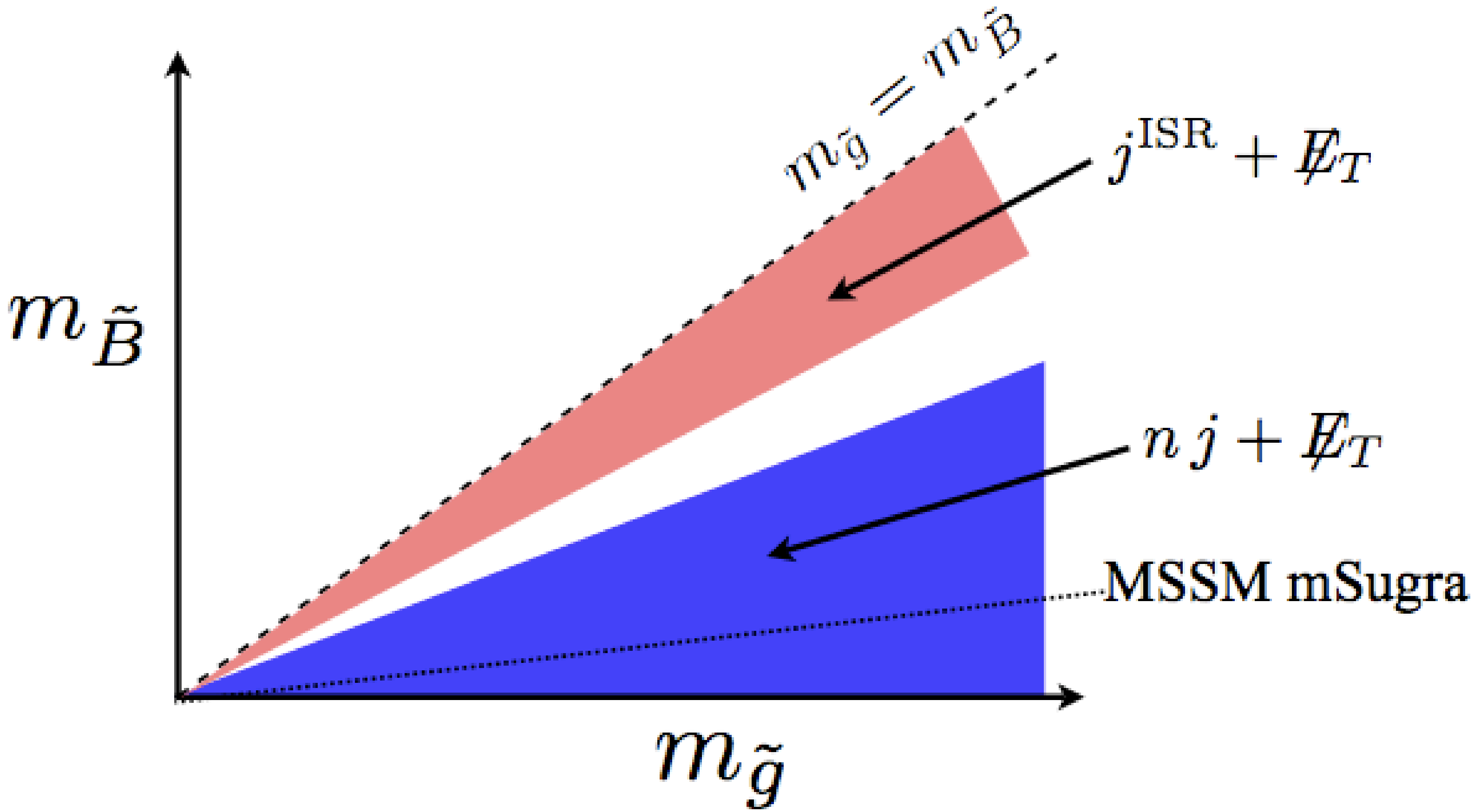
$$\not{E}_T \sim \frac{Q^2}{M_{\tilde{B}}}$$

Take $M_{\tilde{B}} = 60$ GeV...

70 GeV Gluinos!??



Motivates a Gluino-Bino Plot



Wacker, et. al.

Ratios of 'inos'

$M_3 > M_1 > M_2$	AMSB - cascades with leptons. LL charged particle
$M_2 > M_3 > M_1$	Only jets + missing E_T
$M_1 > M_3 > M_2$	Jets plus missing E_T and/or LL charged particle
$M_2 > M_1 > M_3$	Gluino may be long lived - at least 4-body decay

Violation of R Parity

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

Violation of R Parity

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

$$+ L Q D^c \cancel{+ U^c D^c D^c} + L L E^c + \mu_L L H_2$$

Could have “Baryon Parity”.

Violation of R Parity

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

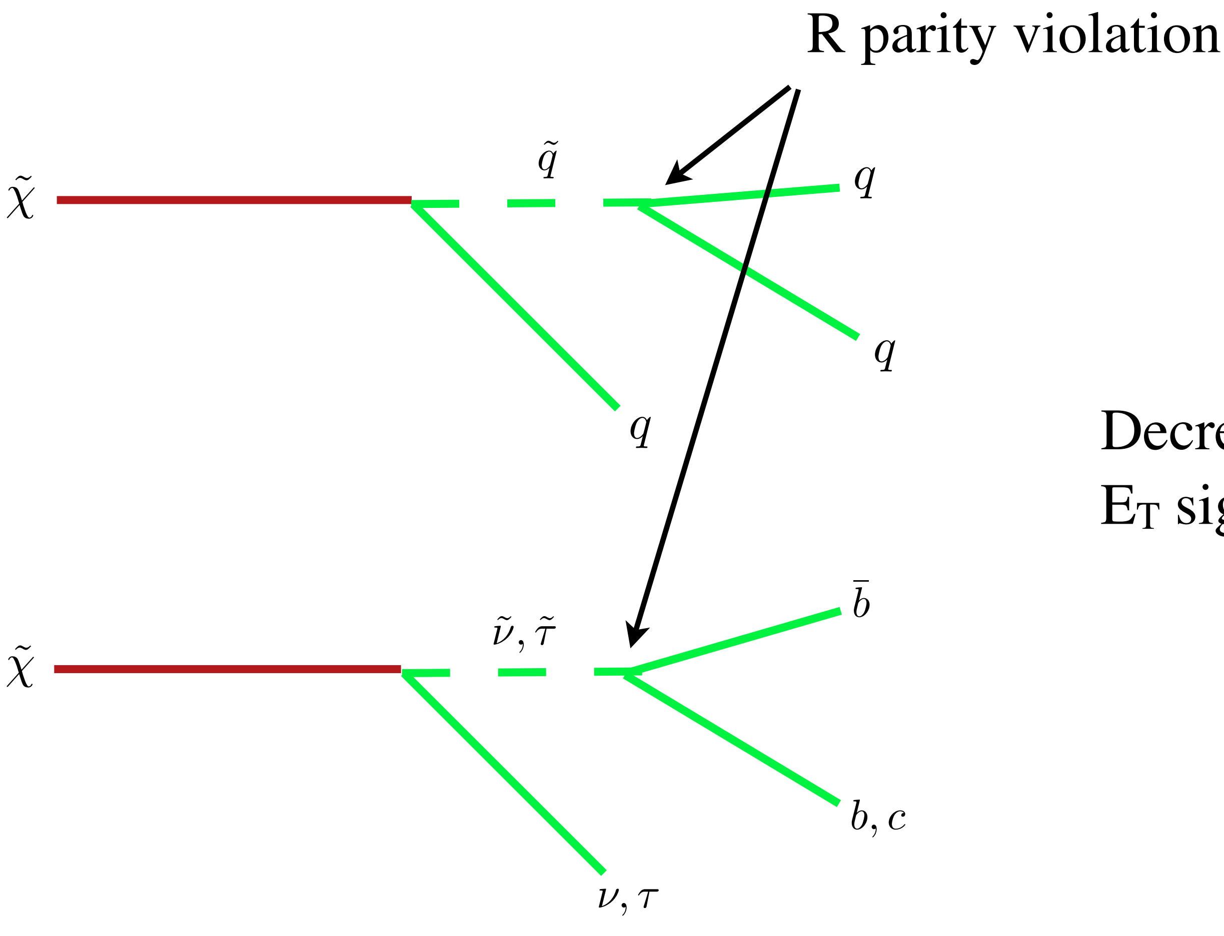
$$+ L Q D^c + U^c D^c D^c + L L E^c + \mu_L L H_2$$

or “Lepton Parity”

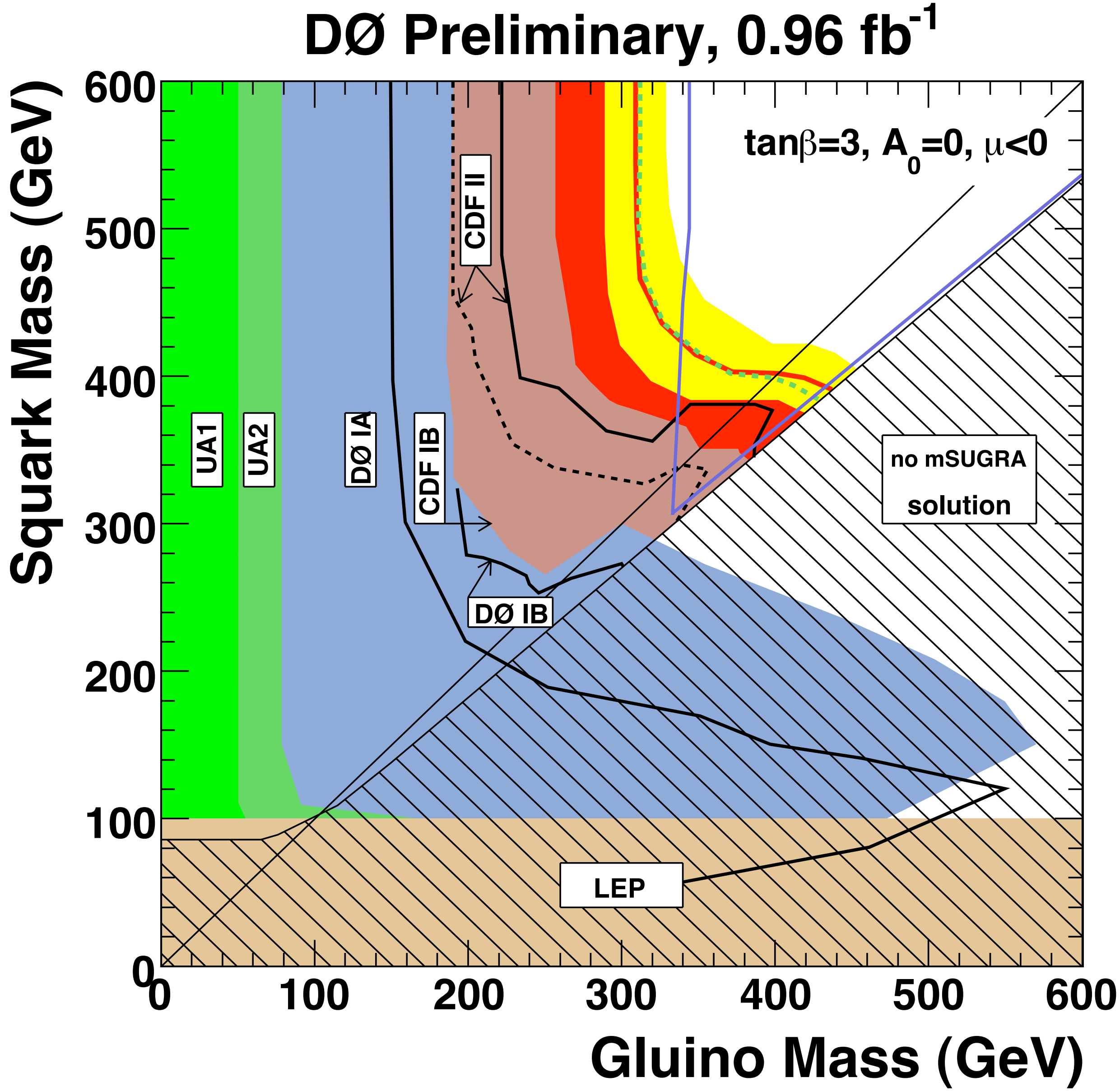
$$p \not\to X$$

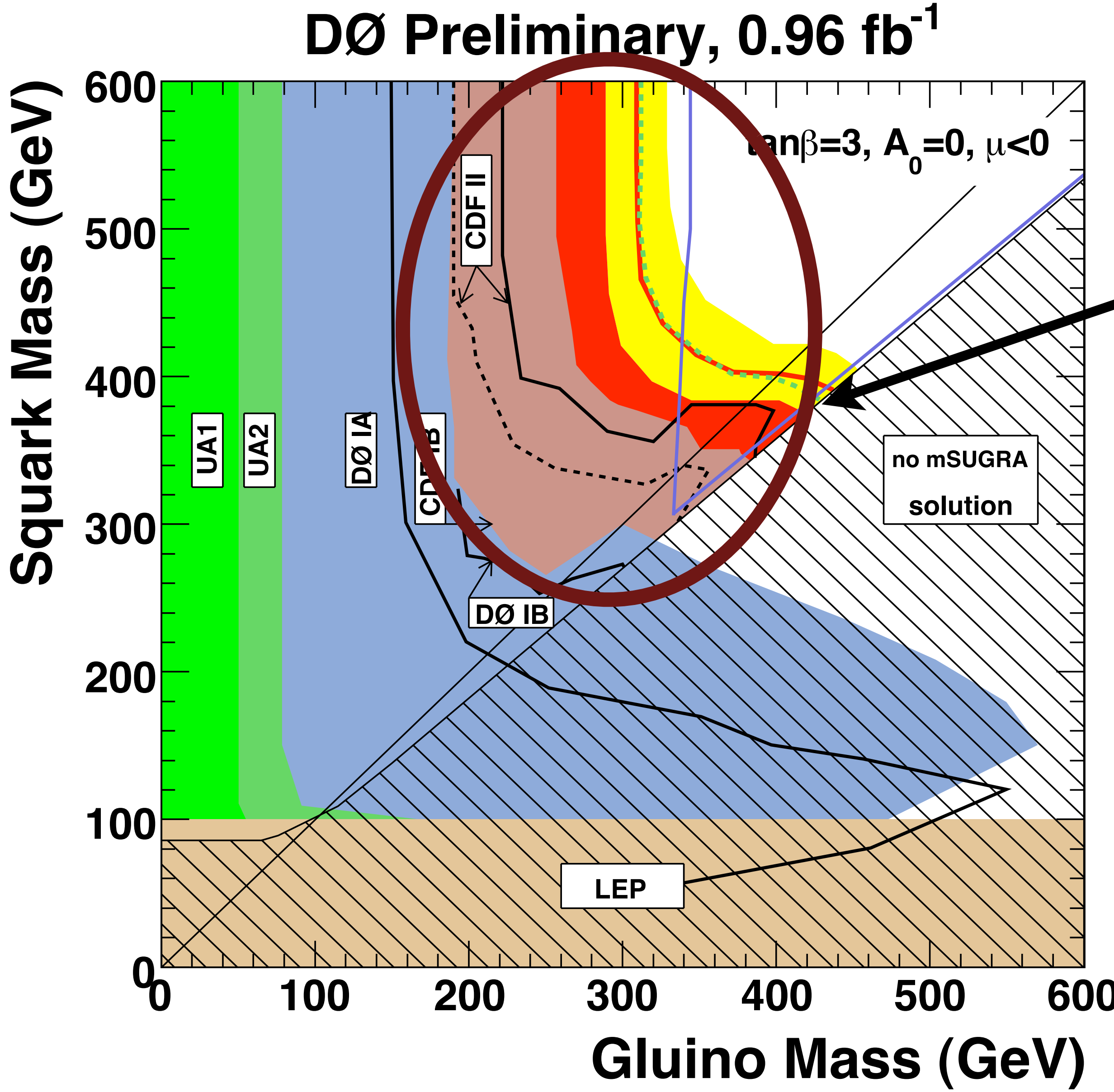
X must have an odd number of fermions, thus its lepton number $L = 2n + 1$. No lepton parity violation, no decay.

LSP decays



Decreases missing E_T signal


DØ Preliminary, 0.96 fb-1
tanβ=3, A0=0, μ<0
UA1
UA2
DØ IA
CDF IB
CDF II
DØ IB
no mSUGRA solution
LEP
Squark Mass (GeV)
Gluino Mass (GeV)
0
100
200
300
400
500
600



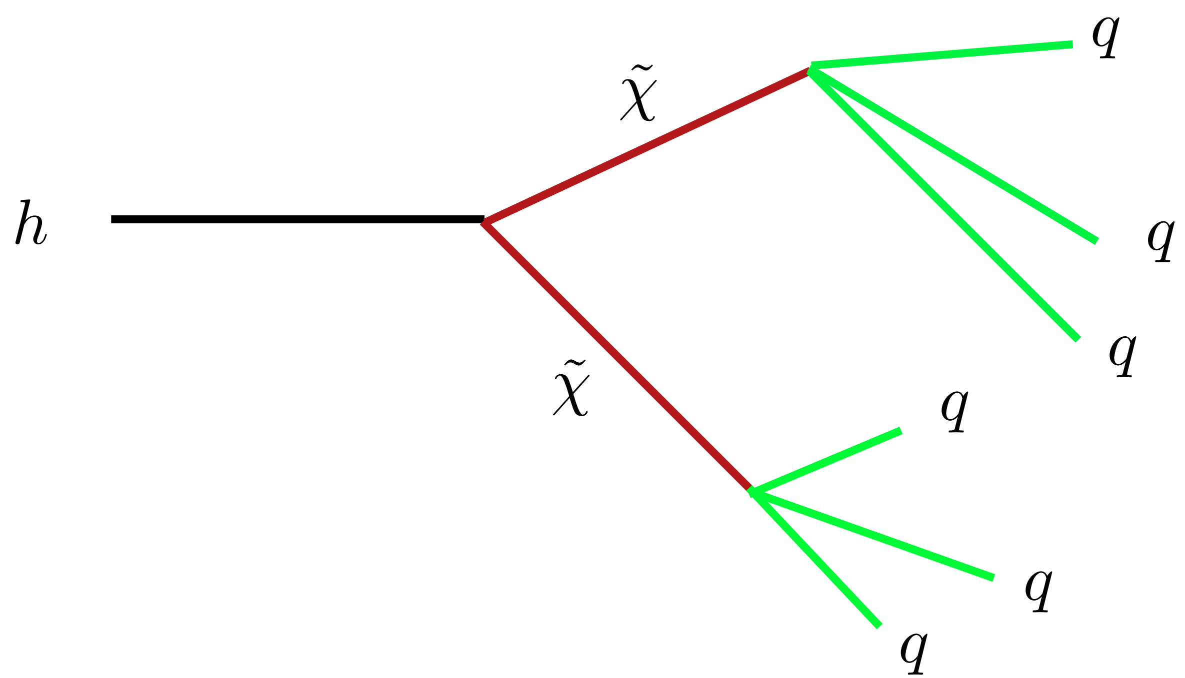
Required missing E_T > 100 GeV

Typical Bounds on Superpartners with B Violation

Sleptons (R)	94,85,70 GeV (A)
Sneutrinos	88,65,65 GeV (A)
Squarks ($u_{L/R}$,$d_{L/R}$)	87,80,86,56 GeV (L)
Stop	77 GeV (O,D,L)
Sbottom	7.5 (>55, <30) GeV (L)
Gluino	80 GeV ? (UA2)

Only Chargino bound roughly the same (102.5 GeV)

Higgs decays with B-violation



higgs -> 6 jets!

$m_h > 87$ GeV

Could be a source of new displaced vertices.

L. Carpenter, D. Kaplan, E.J. Rhee

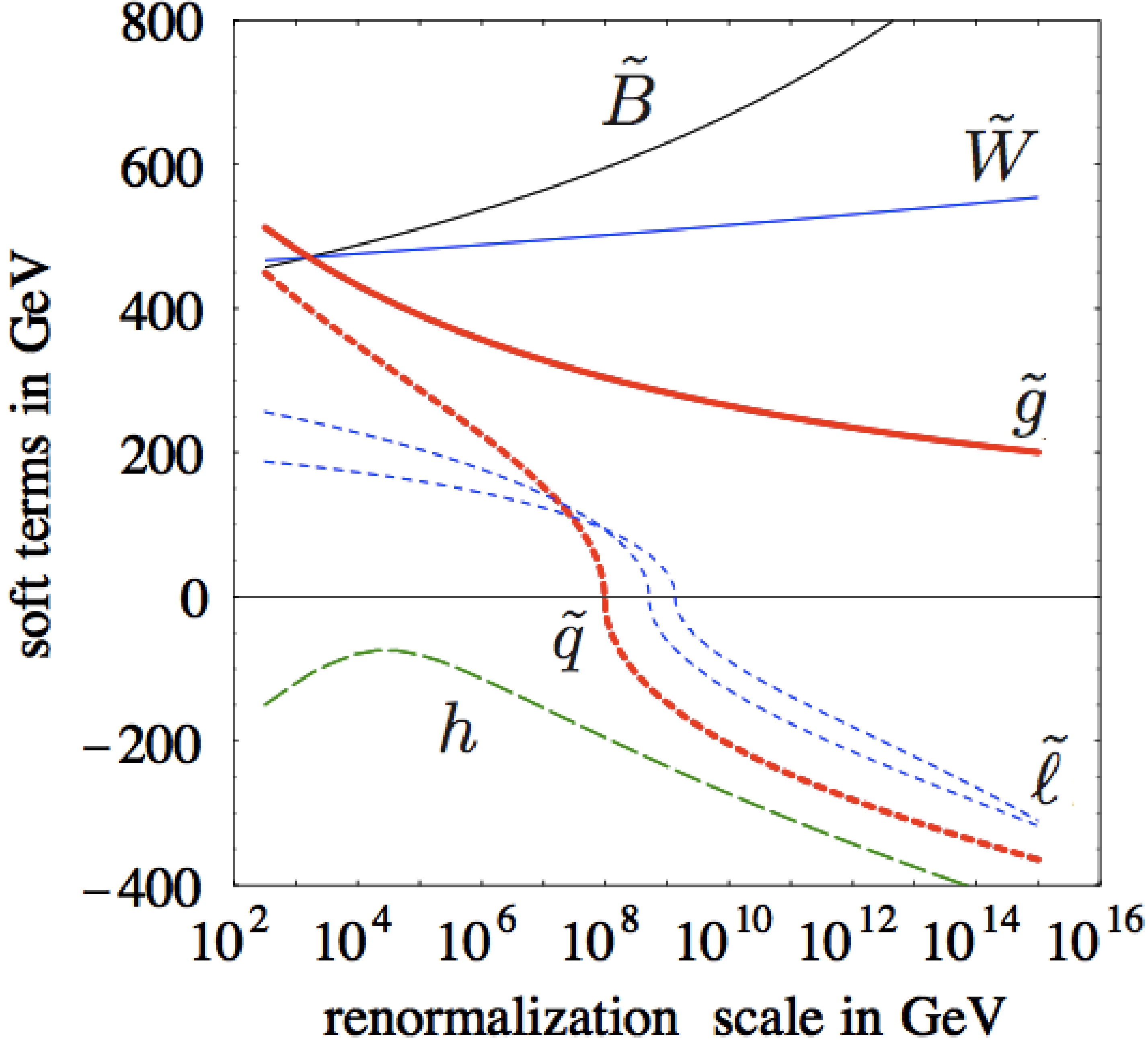
Supersymmetry Breaking with 'Squashed' Spectrum

Deflected Anomaly Mediation

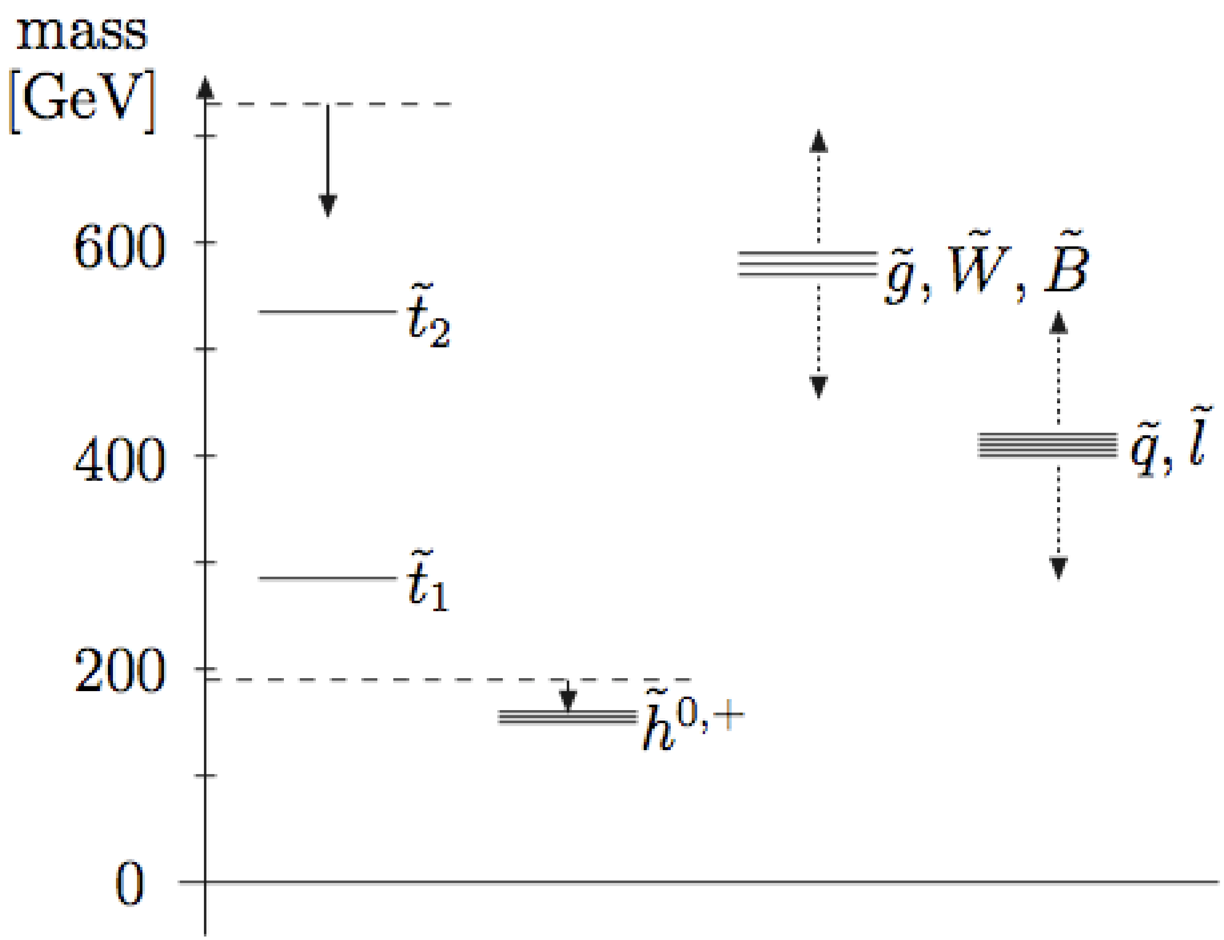
Mirage Mediation

Dirac Gauginos

DAMSB


soft terms in GeV
800
600
400
200
0
−200
−400
$\tilde{B}$
$\tilde{W}$
$\tilde{g}$
$\tilde{q}$
$\tilde{\ell}$
h
10^2 10^4 10^6 10^8 10^{10} 10^{12} 10^{14} 10^{16}
renormalization scale in GeV

Mirage Mediation



Supersymmetry Breaking with 'Squashed' Spectrum

Deflected Anomaly Mediation

Mirage Mediation

Dirac Gauginos vs. Majorana Gauginos

"New" Parameter Set At the Weak Scale

$$
\begin{aligned}
\mathcal{L}_{\rm soft}^{\rm MSSM} = & -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right) \\
& -\left(\widetilde{\overline{u}}\,\mathbf{a_u}\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\widetilde{L}H_d + \text{c.c.}\right) \\
& -\widetilde{Q}^\dagger\mathbf{m^2_Q}\widetilde{Q} - \widetilde{L}^\dagger\mathbf{m^2_L}\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m^2_{\overline{u}}}\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m^2_{\overline{d}}}\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m^2_{\overline{e}}}\widetilde{\overline{e}}^\dagger \\
& - m^2_{H_u}H_u^*H_u - m^2_{H_d}H_d^*H_d - \left(bH_uH_d + \text{c.c.}\right).
\end{aligned}
$$

parameter x identity matrix

Use this to fix the Z mass.

$\tan\beta$

μ sets higgsino mass

"New" Parameter Set At the Weak Scale

$$\mathcal{L}_{\rm soft}^{\rm MSSM} = -\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)$$
$$-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\widetilde{L}H_d + \text{c.c.}\right)$$
$$-\widetilde{Q}^\dagger\,\mathbf{m_Q^2}\widetilde{Q} - \widetilde{L}^\dagger\,\mathbf{m_L^2}\widetilde{L} - \widetilde{\overline{u}}\,\mathbf{m_{\overline{u}}^2}\widetilde{\overline{u}}^\dagger - \widetilde{\overline{d}}\,\mathbf{m_{\overline{d}}^2}\widetilde{\overline{d}}^\dagger - \widetilde{\overline{e}}\,\mathbf{m_{\overline{e}}^2}\widetilde{\overline{e}}^\dagger$$
$$-\,m_{H_u}^2 H_u^* H_u - m_{H_d}^2 H_d^* H_d - (bH_uH_d + \text{c.c.})\,.$$

$\mathbf{a_u} = \mathbf{y_u}\,A_u$

parameter x identity matrix

Use this to fix the Z mass.

$\tan\beta$

μ sets higgsino mass

Should the world be "Natural"?

$$(m_h^{phys})^2 = M^2_{planck} + M^2_{qtm\,corr}$$

Cancellation of one part in 10^{34}

This doesn't happen in condensed matter system unless we force it to happen.

The Cosmological Constant

Fine tuning of one part in 10^{120}!

(one part in 10^{60} with SUSY)

In 1987 Weinberg suggested that if our universe was one of a large selection, we would live in one where the cosmological constant was *just small enough* to allow for structure to form, and if we don't measure one, we can rule out the anthropic principle.

The Cosmological Constant

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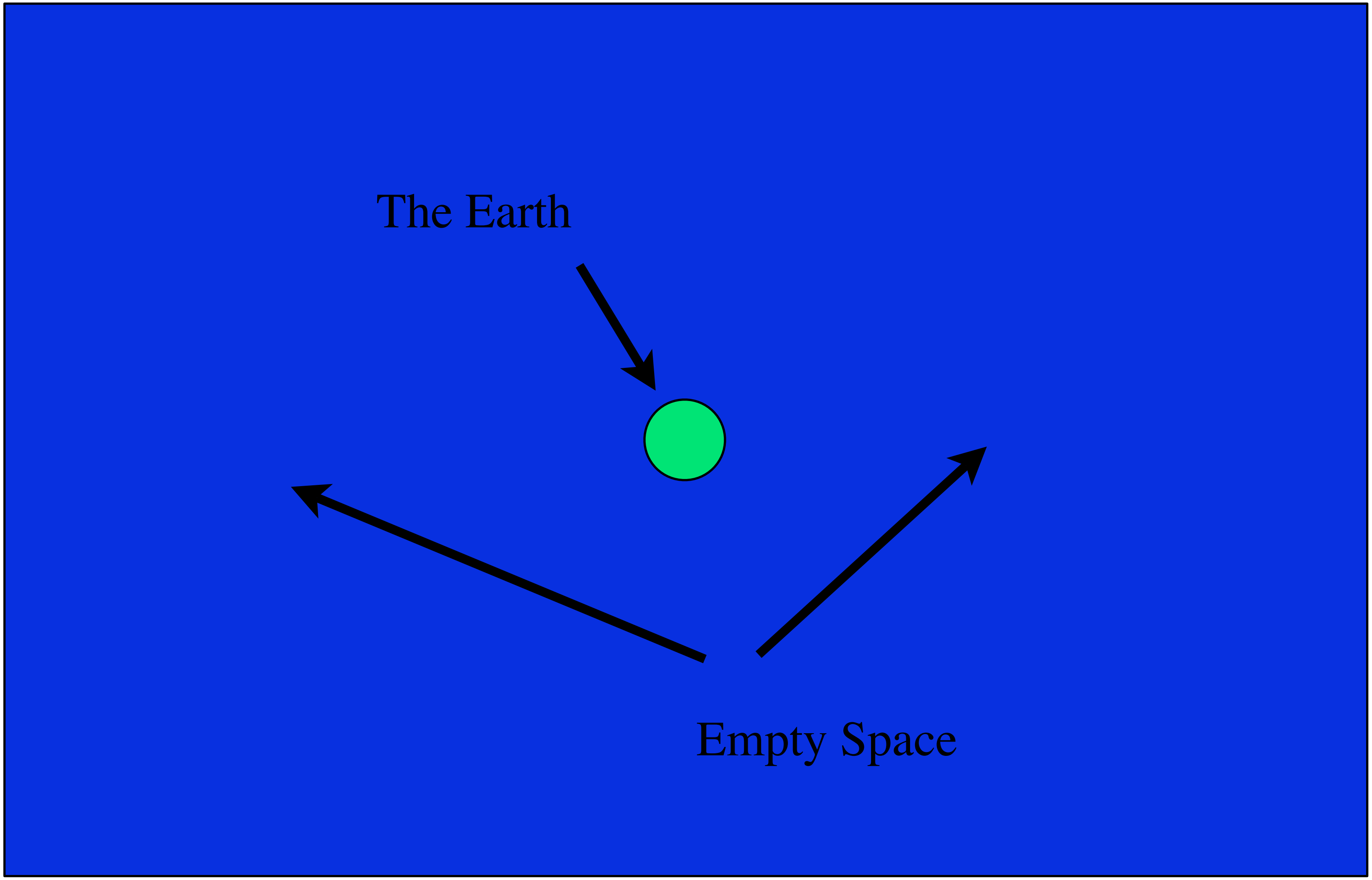
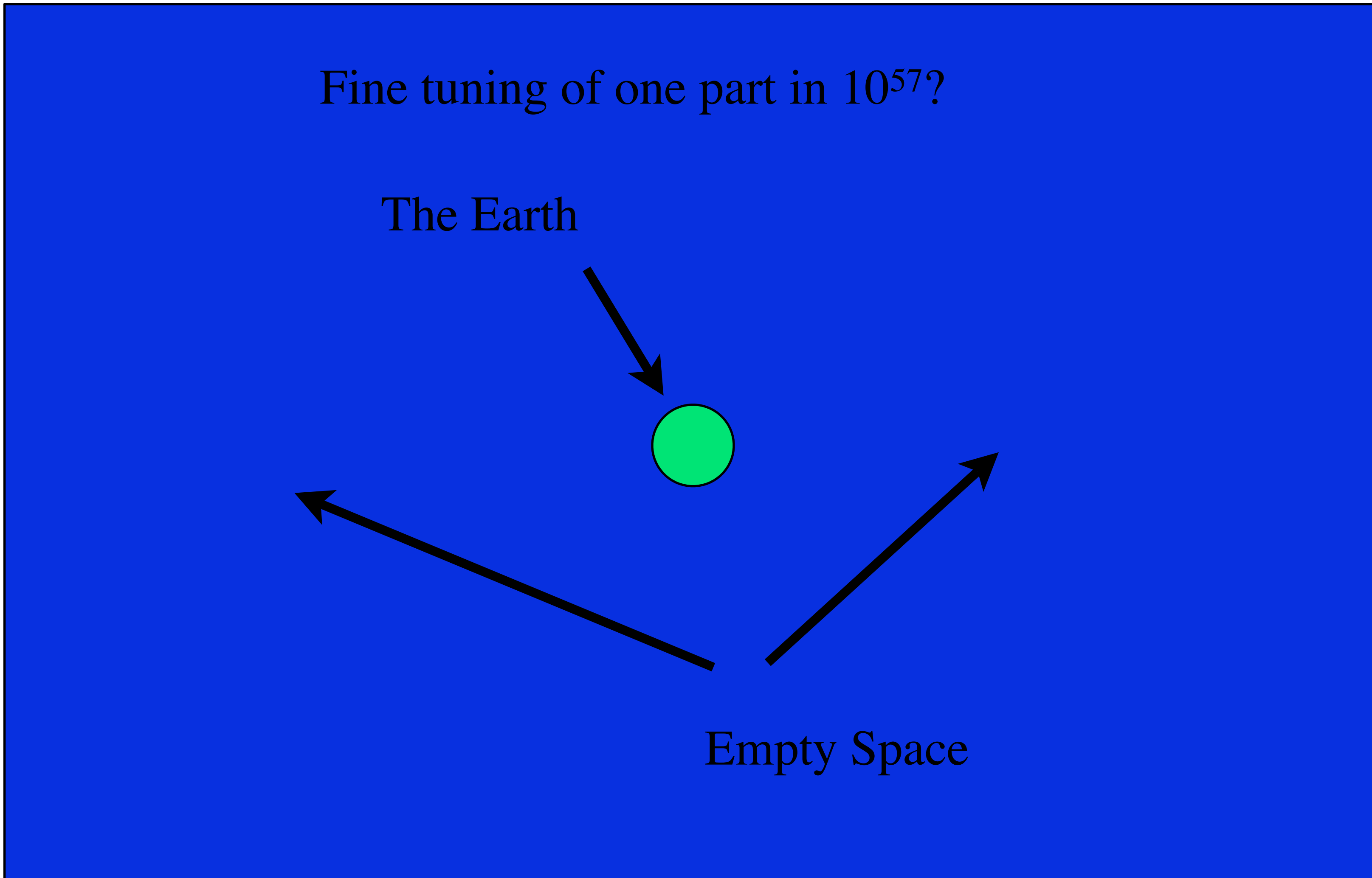
In 1987 Weinberg suggested that if our universe was one of a large selection, we would live in one where the cosmological constant was *just small enough* to allow for structure to form, and if we don't measure one, we can rule out the anthropic principle.

But then we did measure one...

Environmental Selection



Environmental Selection



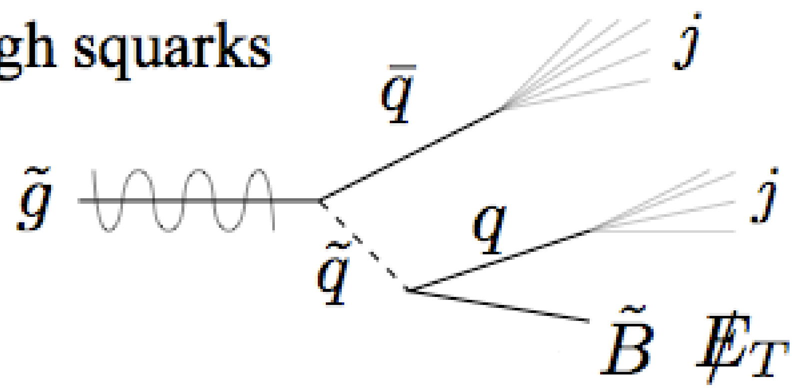
Split Supersymmetry

	$M_{\rm Pl.}$		10^{16} TeV
Scalars (Squarks, sleptons, ...)	$M_{\rm susy}$	?	10^{15} TeV 10 TeV
Fermions (Higgsinos, gauginos) +SM Higgs	$M_{\rm weak}$		~ 1 TeV
	$M_{\rm CC}$		10^{-15} TeV

Preserves Unification and Dark Matter

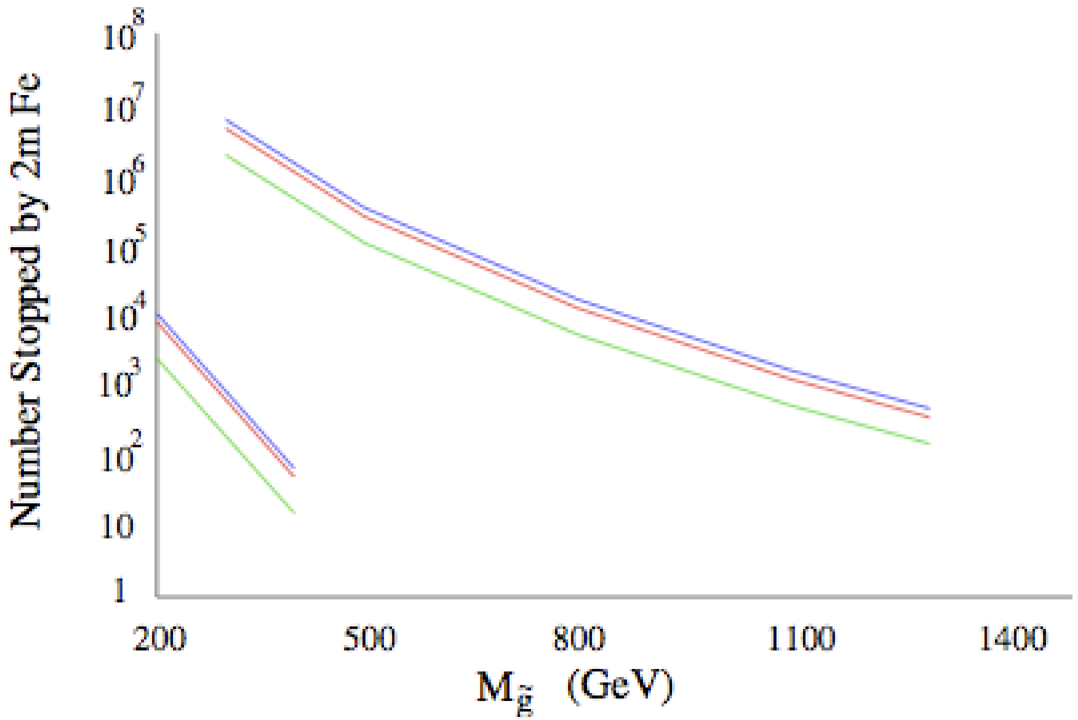
Gluinos are Long-Lived

Must decay through squarks



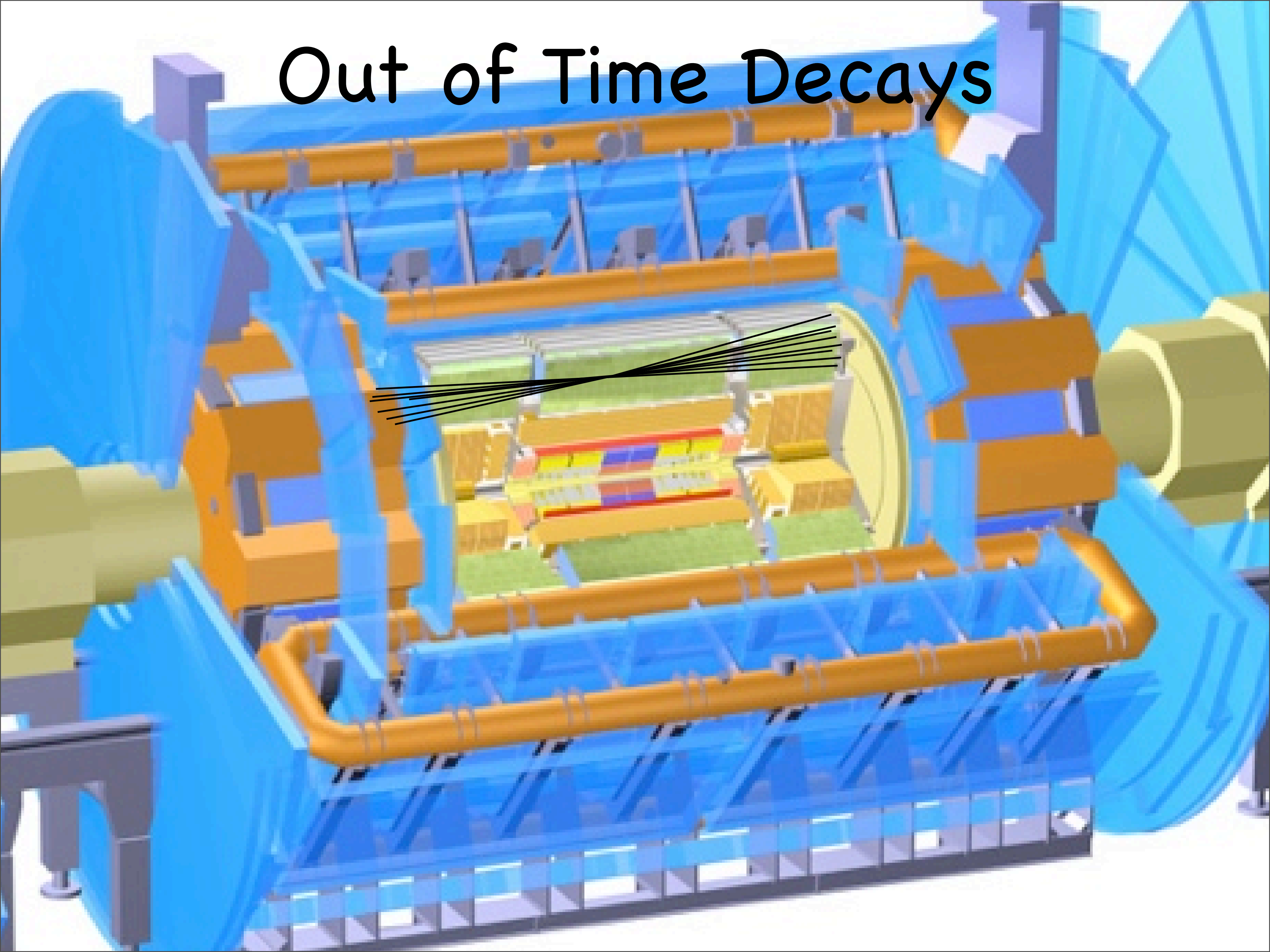
$$\tau_{\tilde{g}} \simeq 2 \text{ sec.} \left(\frac{350 \text{ GeV}}{m_{\tilde{g}}}\right)^5 \left(\frac{M_{\text{Susy}}}{10^6 \text{ TeV}}\right)^4$$

Stopped Gluinos



2 fb^{-1}	200 GeV	300 GeV	400 GeV
CDF	4.1×10^3	3.1×10^2	3.3×10^1
D0	4.5×10^3	3.3×10^2	3.4×10^1
100 fb^{-1}	300 GeV	800 GeV	1300 GeV
ATLAS	5.8×10^6	1.8×10^4	6.2×10^2
CMS	3.7×10^6	1.2×10^4	3.9×10^2

Out of Time Decays



Even if you HATE use of the anthropic principle...

Is pointed us to a new signal to look for - very long lived stopped particles.