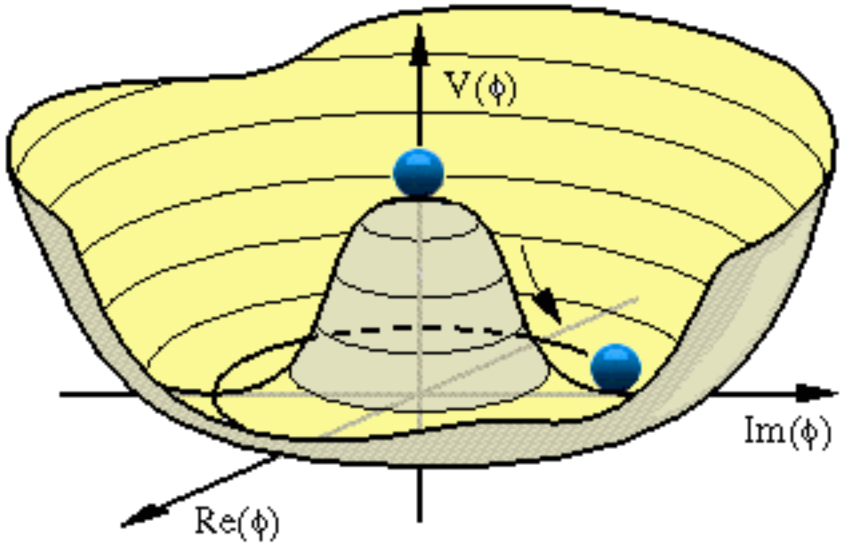
The hierarchy problem

(On the origin of the Higgs potential)

Electroweak symmetry breaking (EWSB) in the SM is triggered by the Higgs VEV:

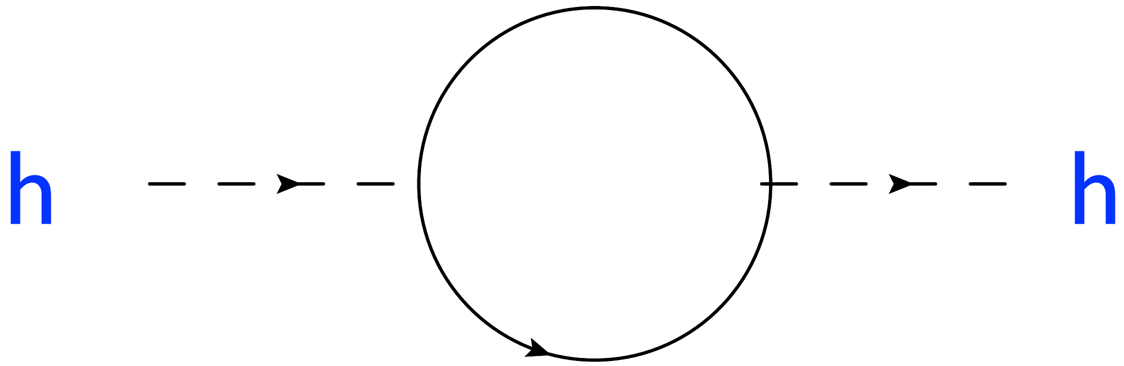
$$V(h) = -\frac{1}{2}\mu^2 h^2 + \frac{1}{4}\lambda h^4$$



$$\mu^2 = \lambda v^2 = \frac{\lambda}{g^2} 4 M_W^2 \sim 10^4 \text{ GeV}^2 << M_P^2 \sim 10^{38} \text{ GeV}^2$$

Why so different?

Even worse, at the quantum level, scalar masses are extremely sensitive to heavy states



$$\sim \frac{1}{16\pi^2} M^2$$

mass of the particle in the loop

Not the same situation for fermions or gauge bosons
➠ **gauge symmetries can protect them**

No symmetry in the SM protects the Higgs mass

In general: $m\bar{\Psi}_L\Psi_R$ vs $\mu^2|H|^2$

$\underbrace{m\bar{\Psi}_L\Psi_R}$: Not a singlet if Ψ_R transform:

$$\Psi_R \rightarrow e^{i\theta}\Psi_R$$

(chiral symmetry)

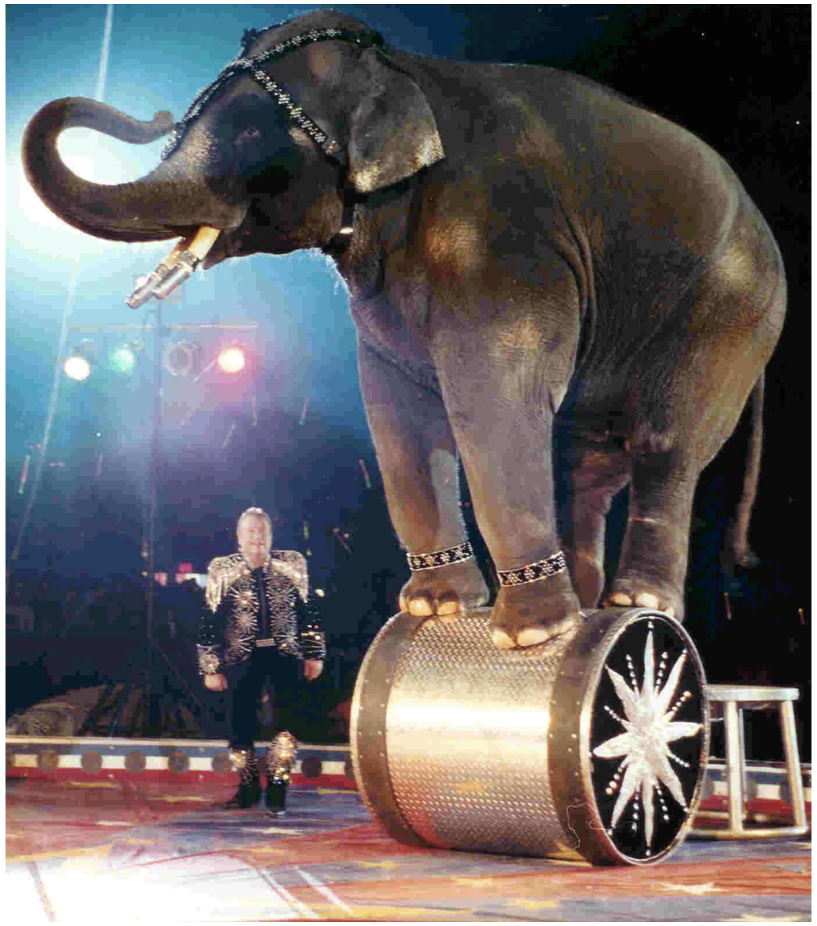
$\underbrace{|H|^2}$: Always a singlet under phase transformations

Expected: $\mu^2 \sim$ heavier scale^2 ~ M_{GUT}^2, M_P^2, M_{string}^2

➥ **This is the hierarchy problem**

Let me emphasize that is not a problem of consistency but of naturalness

Example:

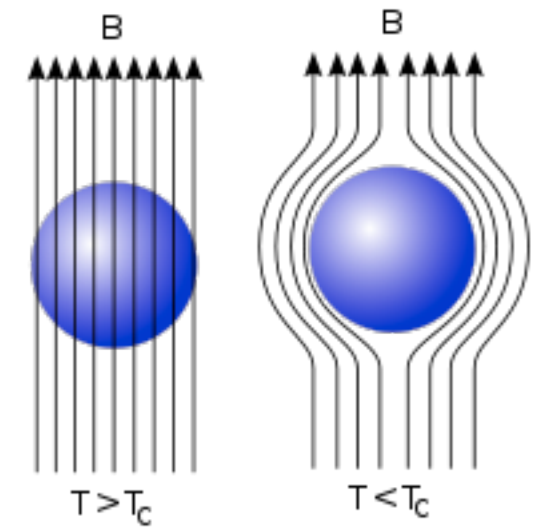


Fine-tune system

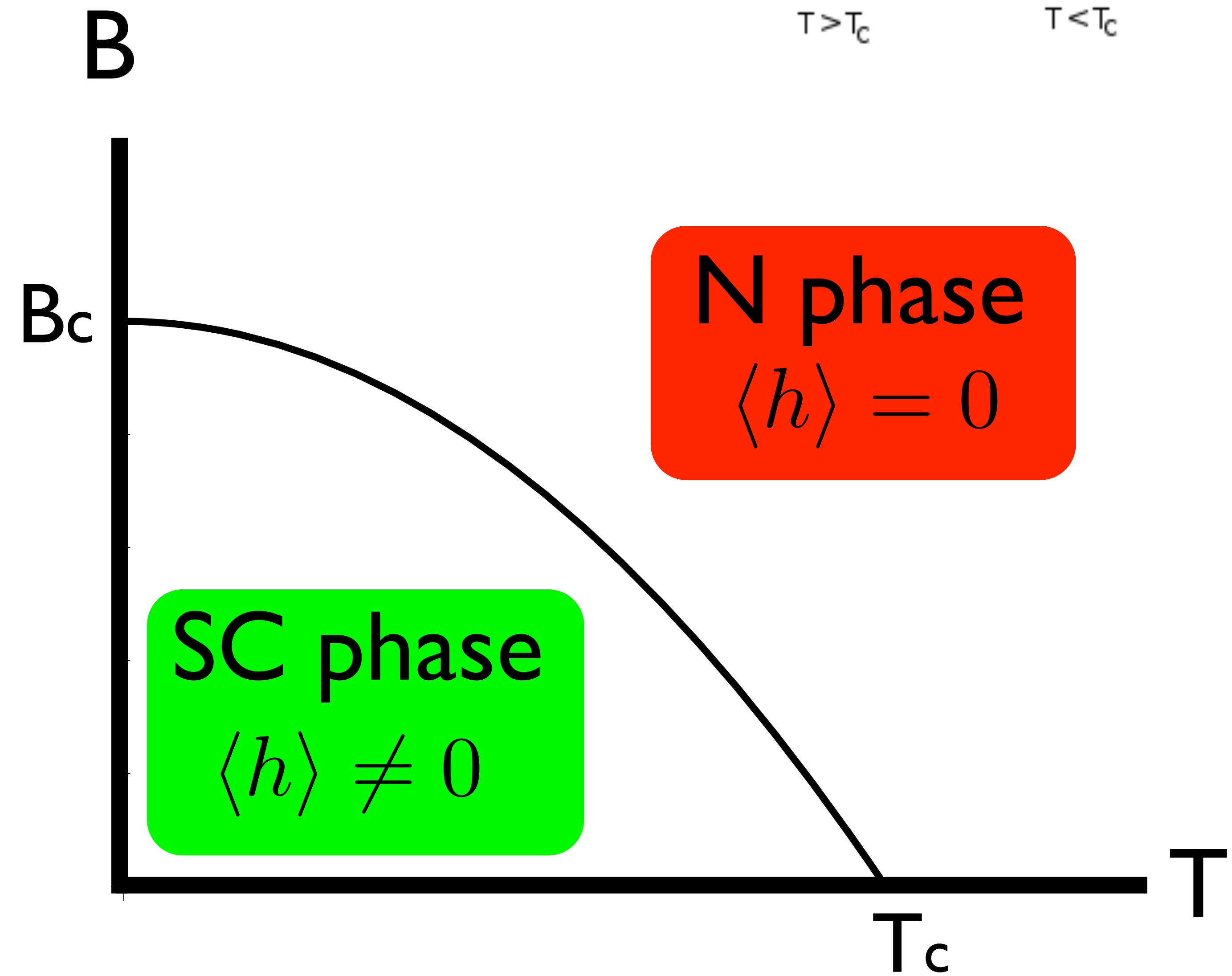
Analogy with Superconductivity

EWSB ⇔ Breaking of U(1)$_{EM}$

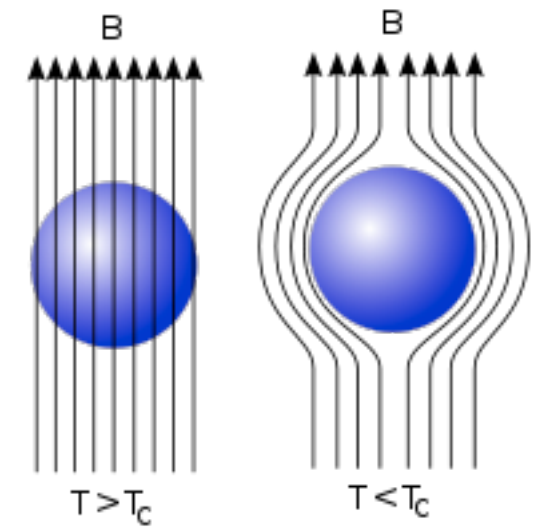
Higgs Model ⇔ GL Model $\langle h \rangle = \langle e^- e^- \rangle$



Give the GL Model a good description of superconductors?



Analogy with Superconductivity



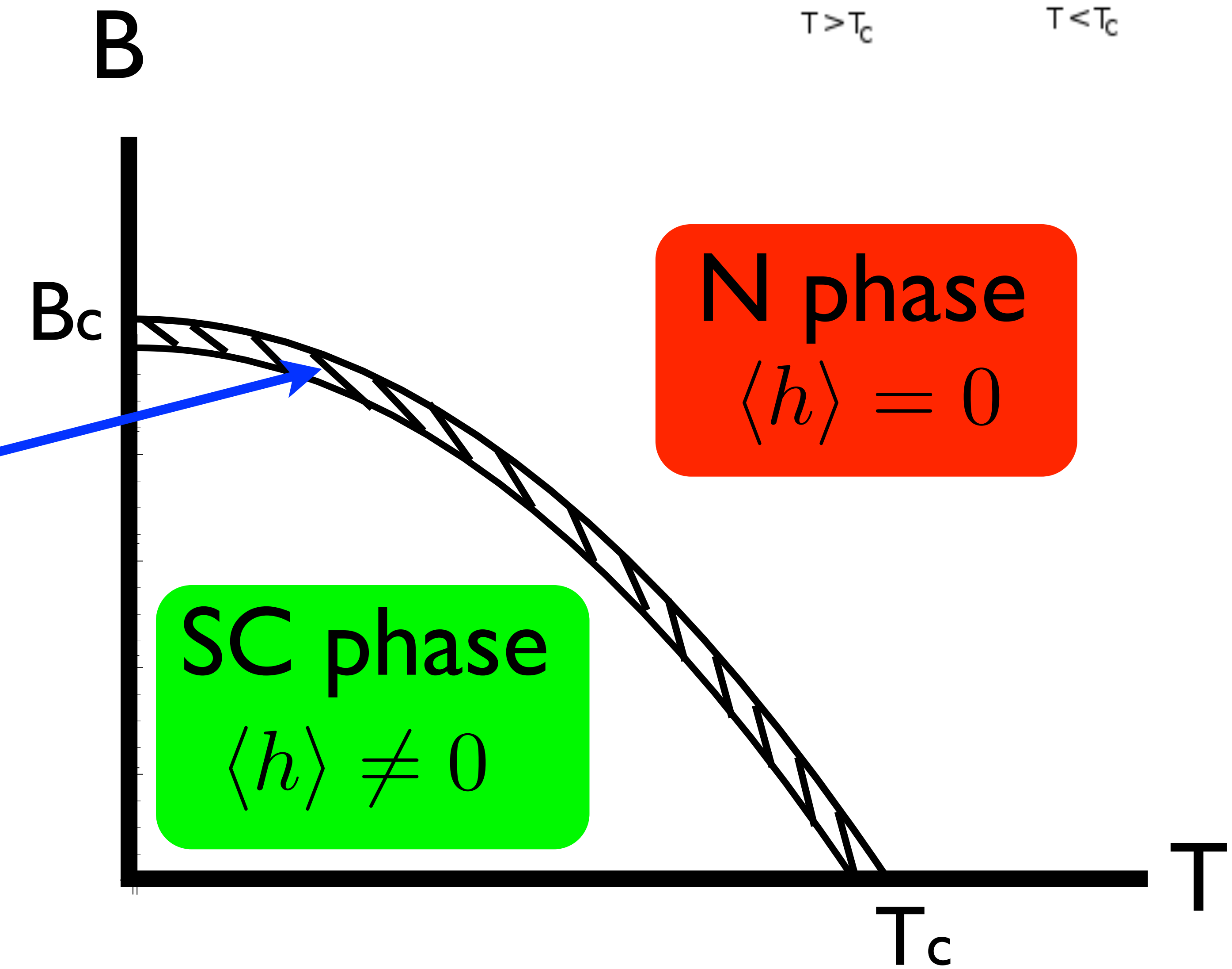
EWSB ⇔ Breaking of $U(1)_{EM}$

Higgs Model ⇔ GL Model $\langle h \rangle = \langle e^- e^- \rangle$

Give the GL Model a good description of superconductors?

NO, it only works close to the critical line

only there $\langle h \rangle$ is small and it makes sense to Taylor-expand the potential:



$$V(h) = m^2|h|^2 + \lambda|h|^4 + \cdots$$

Possibilities that theorists envisage to tackle the Hierarchy Problem:

1) **Supersymmetry**:
Protecting the Higgs mass by a symmetry

2) **Composite Higgs:** The Higgs is not elementary:

As in superconductivity: h ~ ee
or QCD: pions ~ $q\bar{q}$

3) **Large extra dimensions**:
Gravity strong at the EW-scale: $\Lambda \sim M_{string} \sim$ TeV

➥ **In all cases New Physics at ~TeV**

Strong motivation for the LHC !

Supersymmetry

Following notation and formulae of
"A Supersymmetry Primer", Stephen P. Martin
(hep-ph/9709356)

We want a symmetry to protect the Higgs mass:

Idea: Scalar ⟶ Fermion

symmetry trans.

since fermion masses protected by chiral symmetry

It exists, it is a ***Super***symmetry:

Simplest case:

$$\mathcal{L} = |\partial_\mu \Phi|^2 + i\frac{1}{2}\bar{\Psi}\partial\!\!\!/\Psi$$

Ψ = Majorana fermion

Φ = Complex scalar

Invariant under:

$$\Phi \to \Phi + \delta\Phi \qquad \delta\Phi \to \bar{\xi}(1-\gamma_5)\Psi$$

$$\Psi \to \Psi + \delta\Psi \qquad \delta\Psi \to i(1-\gamma_5)\gamma^\mu \xi \partial_\mu \Phi$$

Parameter of the trans. being a Majorana fermion

The scalar must be massless!!

Supersymmetry Algebra

(Maximal extension of Poincare in a QFT)

Minimal SUSY (*N*=*1*): One extra generator Q

$$Q|\mathrm{Boson}\rangle = |\mathrm{Fermion}\rangle, \qquad Q|\mathrm{Fermion}\rangle = |\mathrm{Boson}\rangle$$

Schematic form:

$$[Q, M_{\mu\nu}] = Q$$
$$\{Q, Q^\dagger\} = P^\mu,$$
$$\{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0,$$
$$[P^\mu, Q] = [P^\mu, Q^\dagger] = 0,$$

Q commutes with P^2 and any generator of the gauge symmetries:

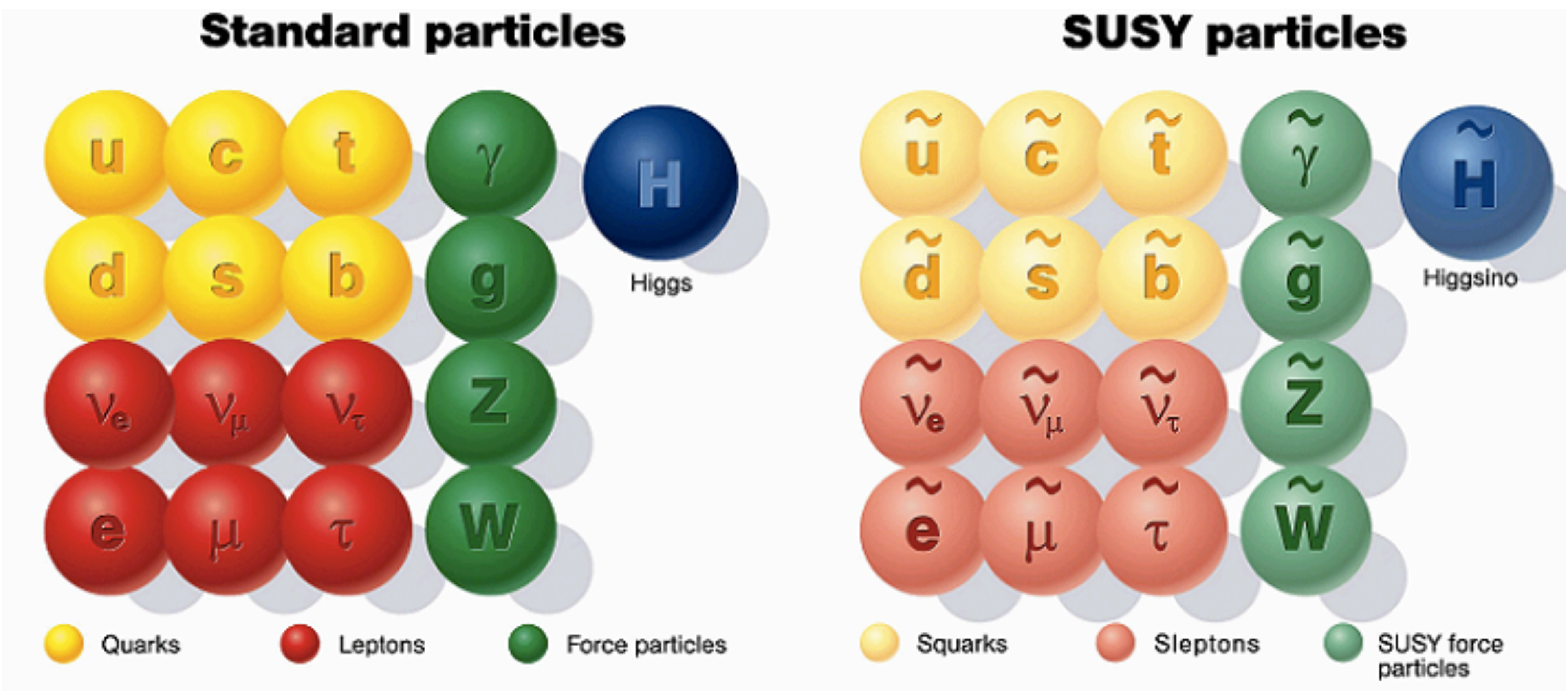
The Fermion and Boson have equal masses and charges

Minimal Supersymmetric SM (MSSM)

Imposing supersymmetry to the **SM ➡ MSSM**

The spectrum is doubled:

SM fermion ➡ New scalar (s-"...")
SM boson ➡ New majorana fermion ("...-ino)



... but not yet realistic:

The model has a quantum anomaly (due to the Higgsino) and the down-quarks and leptons are massless

Extra Higgs needed

➡ Two Higgs doublets:

$H_u : \ (1, 2, 1)$ → give mass to the up quarks

$H_d : \ (1, 2, -1)$ → give mass to the down quarks and leptons

+ two Higgsino doublets:

$\widetilde{H}_u : \ (1, 2, 1)$

$\widetilde{H}_d : \ (1, 2, -1)$

MSSM Spectrum

Squarks	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$
	$\widetilde{u}_R^*$	$u_R^\dagger$
	$\widetilde{d}_R^*$	$d_R^\dagger$
Sleptons	$(\widetilde{\nu} \ \ \widetilde{e}_L)$	$(\nu \ \ e_L)$
	$\widetilde{e}_R^*$	$e_R^\dagger$
Higgsinos	$(H_u^+ \ \ H_u^0)$	$(\widetilde{H}_u^+ \ \ \widetilde{H}_u^0)$
	$(H_d^0 \ \ H_d^-)$	$(\widetilde{H}_d^0 \ \ \widetilde{H}_d^-)$
Gauginos	$\widetilde{g}$	g
	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$
	$\widetilde{B}^0$	B^0

particles: *R-parity* = 1

superpartners: *R-parity* = -1

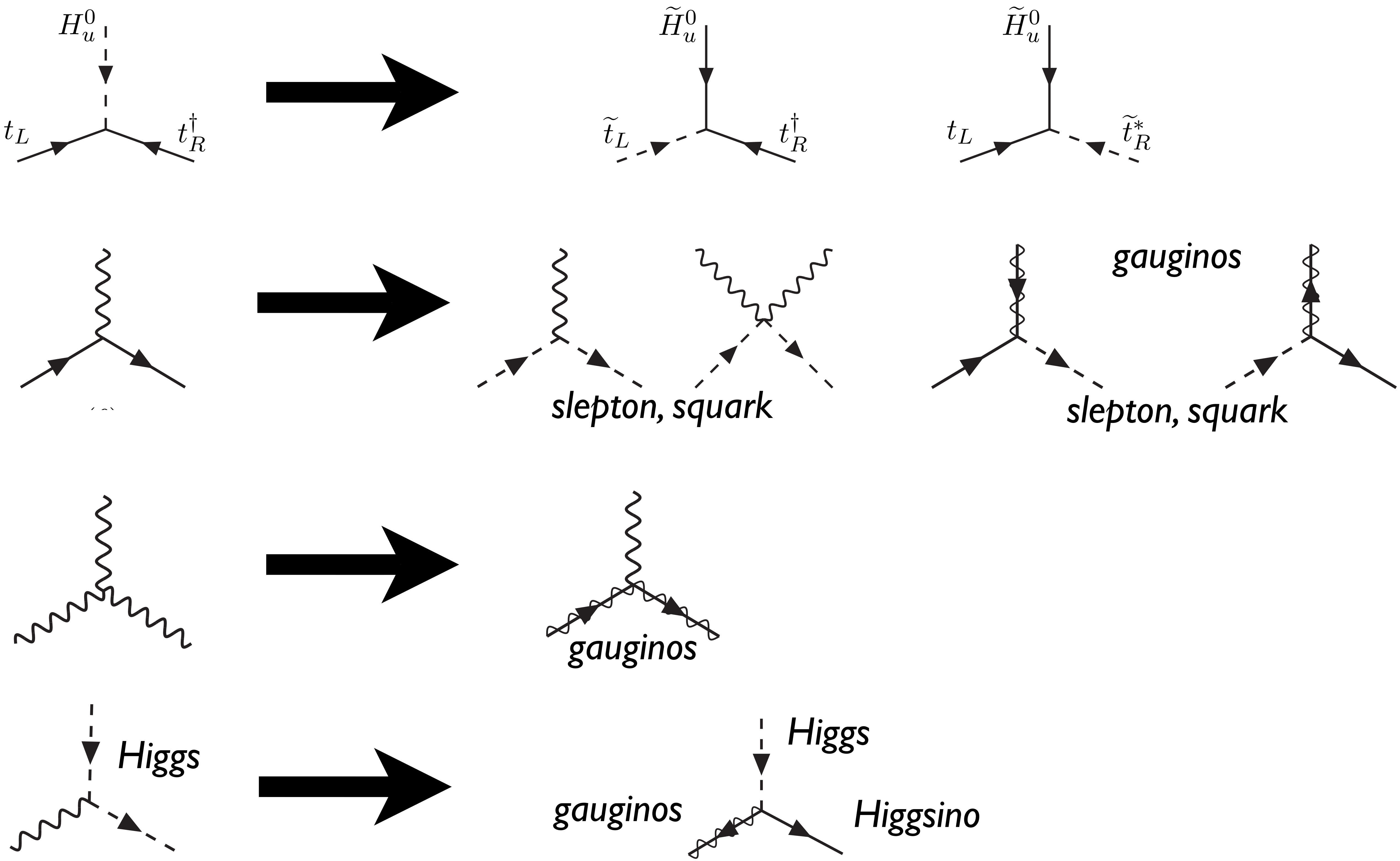
→

1) Superpart. interact in pairs

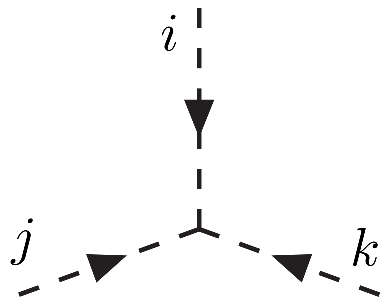
2) Lightest superpart. stable

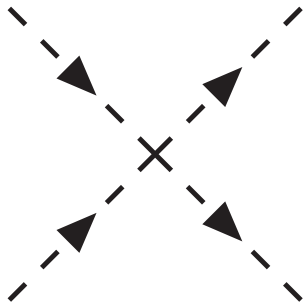
Type of interactions

Getting them from "supersymmetrization":

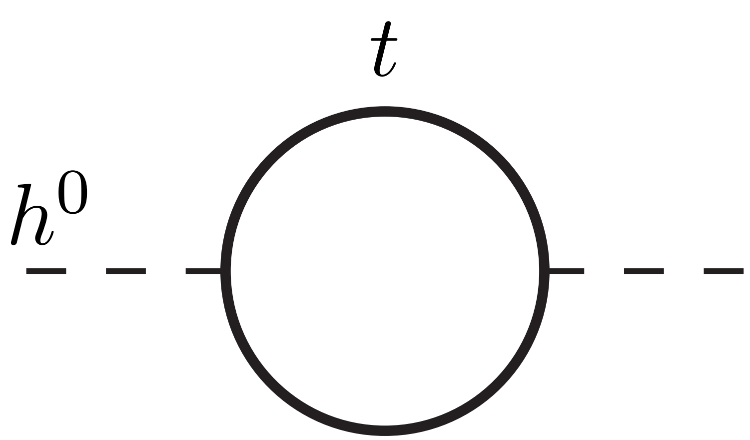


Up to scalar trilinear and quartics:

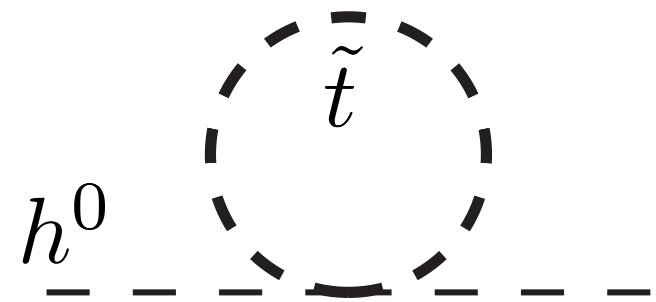




How supersymmetry works?



+



Fermion loop

$\mu^2 = +A$

Boson loop

$\mu^2 = -A$

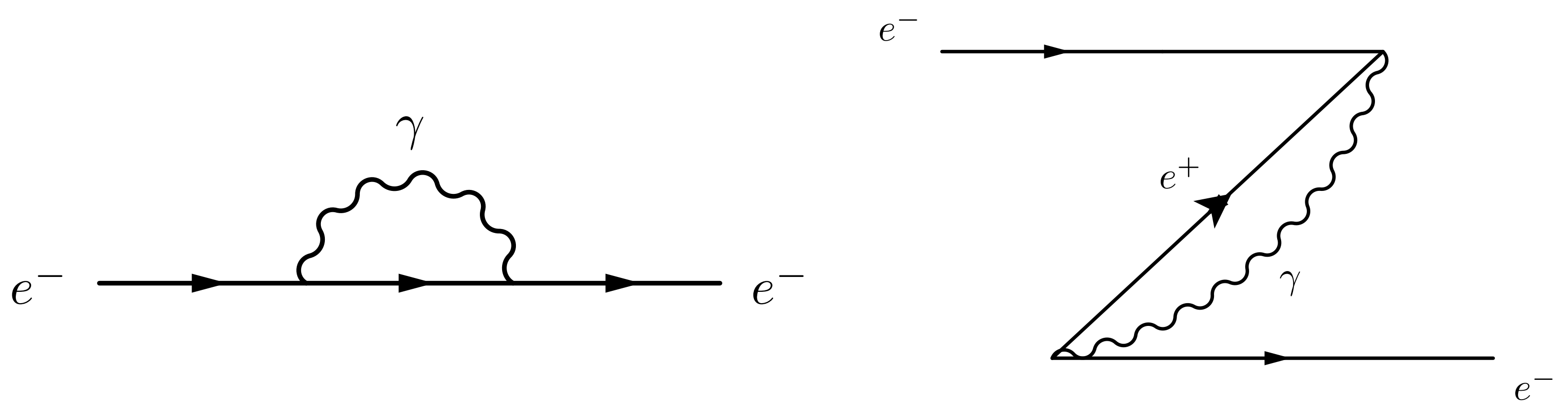
$\mu^2_{total} = 0$

Its not the first time that symmetries force doubling the known spectrum:

Relativistic quantum field theories:

Particle → Antiparticles

Made the electron-mass corrections not linearly divergent:



$$\Delta m_e \propto m_e$$

But if supersymmetry is exact:

MF = MB ➡ e.g. $M_e = M_{\tilde{e}}$

It must be broken to give masses to the superpartners

Supersymmetry breaking must afford "soft terms":

(terms that do not spoil the good UV properties of the Susy)

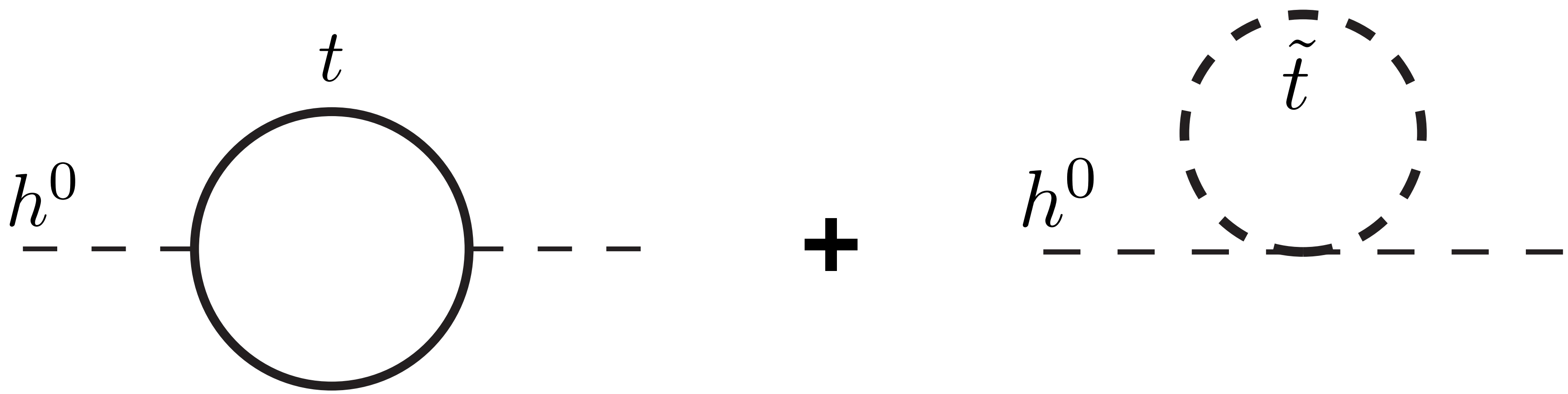
$$
\begin{aligned}
&-\frac{1}{2}\left(M_3\widetilde{g}\widetilde{g} + M_2\widetilde{W}\widetilde{W} + M_1\widetilde{B}\widetilde{B} + \text{c.c.}\right)\\
&-\left(\widetilde{\overline{u}}\,\mathbf{a_u}\,\widetilde{Q}H_u - \widetilde{\overline{d}}\,\mathbf{a_d}\,\widetilde{Q}H_d - \widetilde{\overline{e}}\,\mathbf{a_e}\,\widetilde{L}H_d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

$$+\mu\tilde{H}_u\tilde{H}_d$$

for 3 families, more than 100 terms are possible!!

How supersymmetry works?

(including soft-masses)



Fermion loop

Boson loop

$\mu^2 = +A$

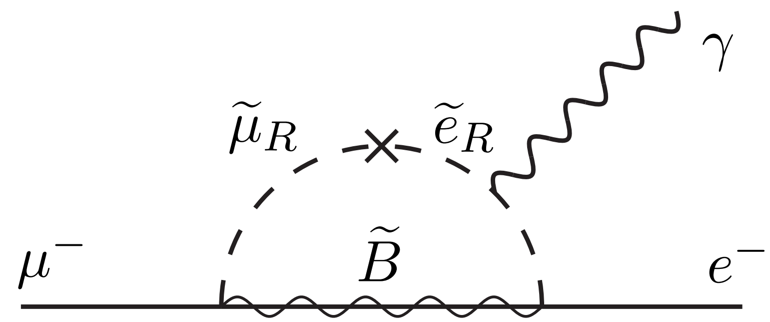
$\mu^2 = -A + m_{stop}^2 \ B$

$\mu^2_{total} \sim m_{stop}^2$

Superpartners expected around v ~ 100 GeV

Constraints on superpartner masses from flavor physics:

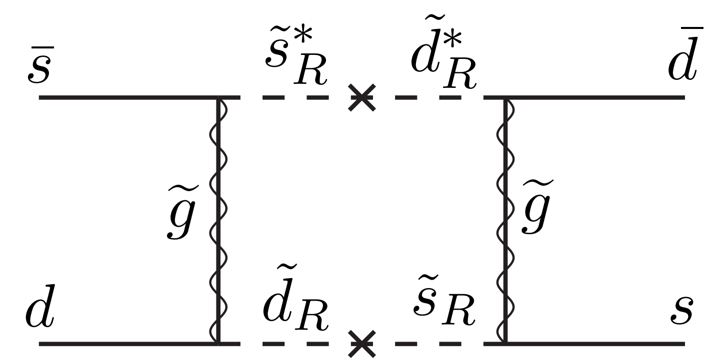
Breaking of lepton symmetry:



Exp: $BR(\mu \to e\gamma) < 10^{-11}$ ➡ $m_{\tilde{e}} \simeq m_{\tilde{\mu}}$

up to 1% - 0.1%

Large contributions to K-$\overline{\text{K}}$ mixing:



➡ $m_{\tilde{s}} \simeq m_{\tilde{d}}$ up to 0.1% - 0.001%

Soft terms must be generated in a clever way

Most interesting possibilities:

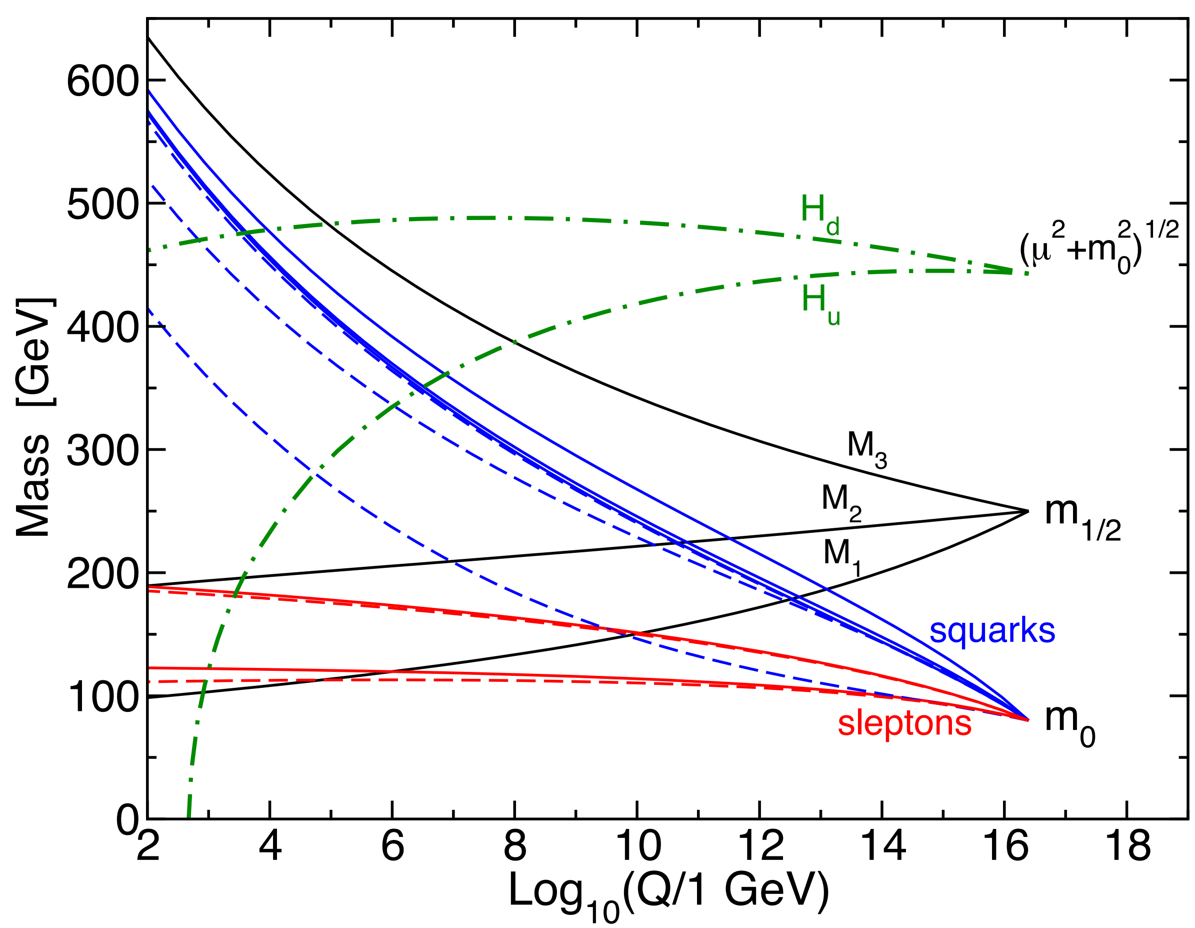
1) Gauge mediation

2) Gravity/Moduli/Extra-dim mediation

The famous scenario **"minimal sugra"**
not a model, just an Ansatz:

At $Q=M_{GUT}$ $\left\{ \begin{array}{l} \text{All gaugino masses equal} = M_{1/2} \\ \text{All scalar masses equal} = M_0 \\ \text{All trilinear equal} = A_0 \end{array} \right.$

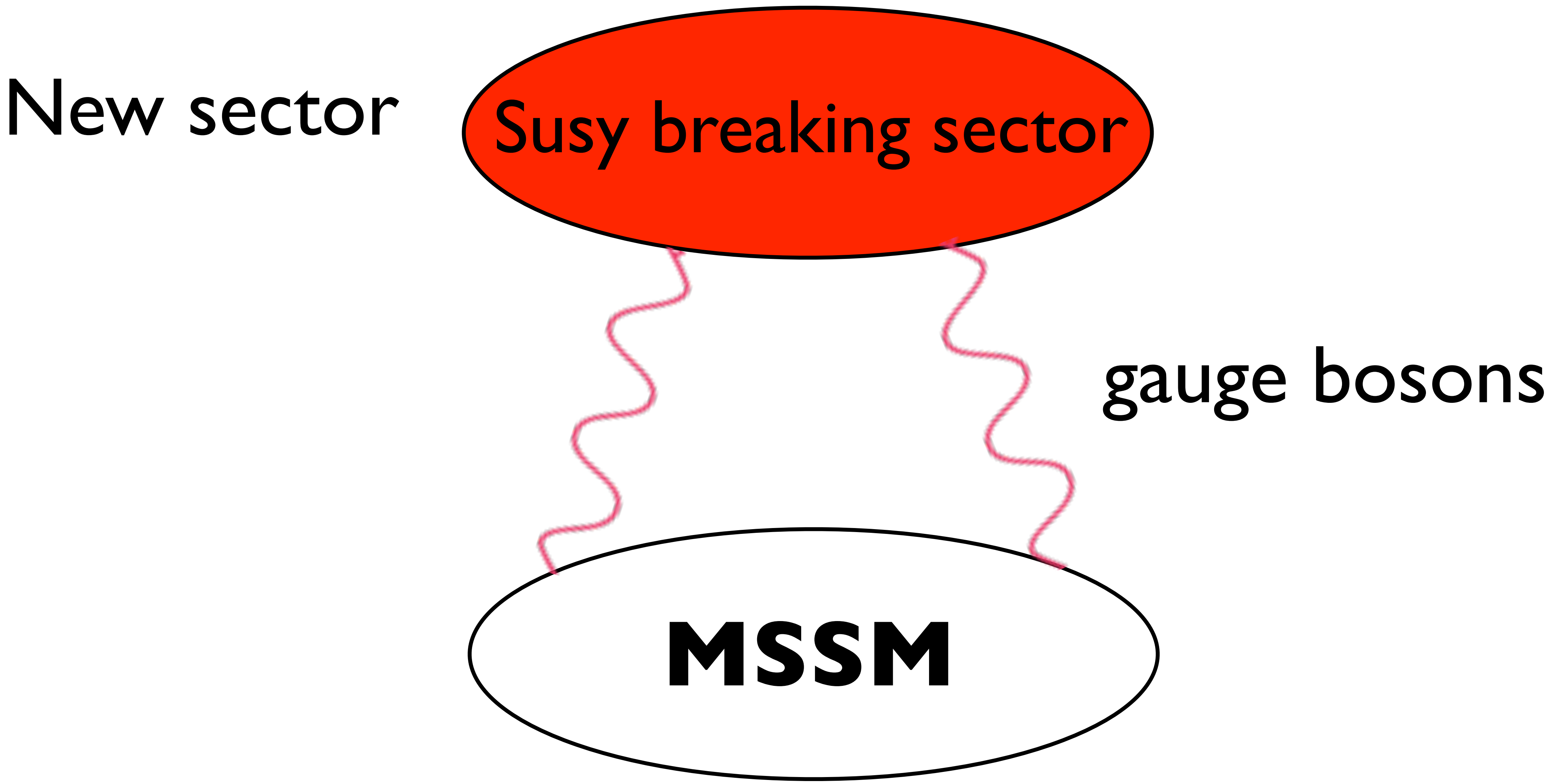
At $Q=M_Z$



➥ **Why?**

I don't know,
but experimentalists
like it a lot!

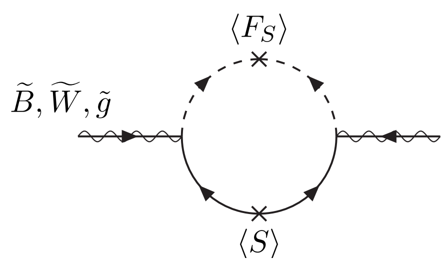
1) Gauge mediation



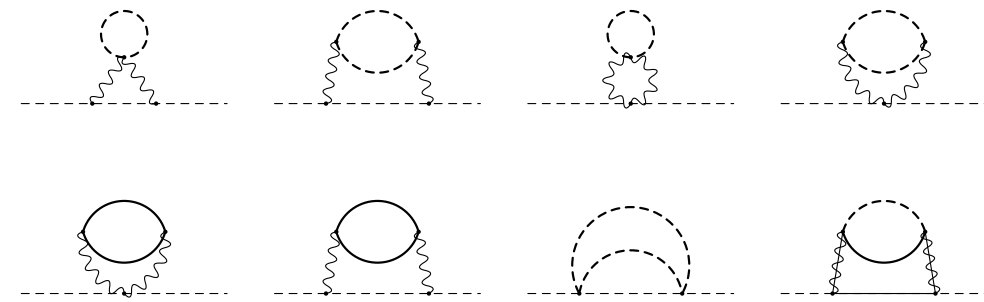
Gauge interactions are “flavor blind”:

Universal masses for squarks/sleptons with equal charges

Very predictive (in the minimal case).
Just calculate loops:



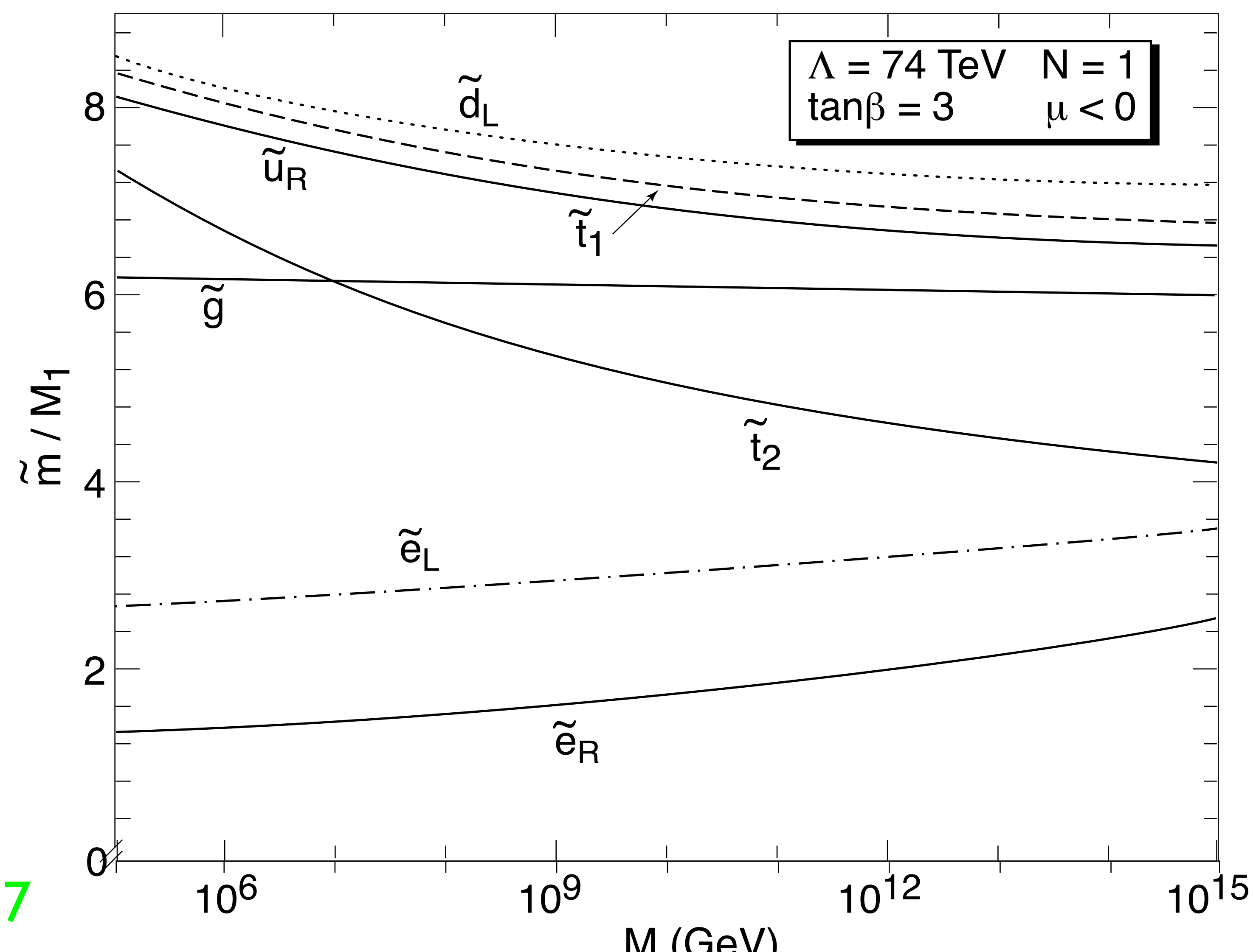
gaugino masses



scalar masses

Depends on 3 parameters:

1) μ-term: Higgsino mass
2) Susy-breaking scale: F
3) Scale where the soft-terms are induced: M



Giudice,Rattazzi 97

Predicts a very light **gravitino** = Mass suppressed by M_P:

➥ partner of the graviton

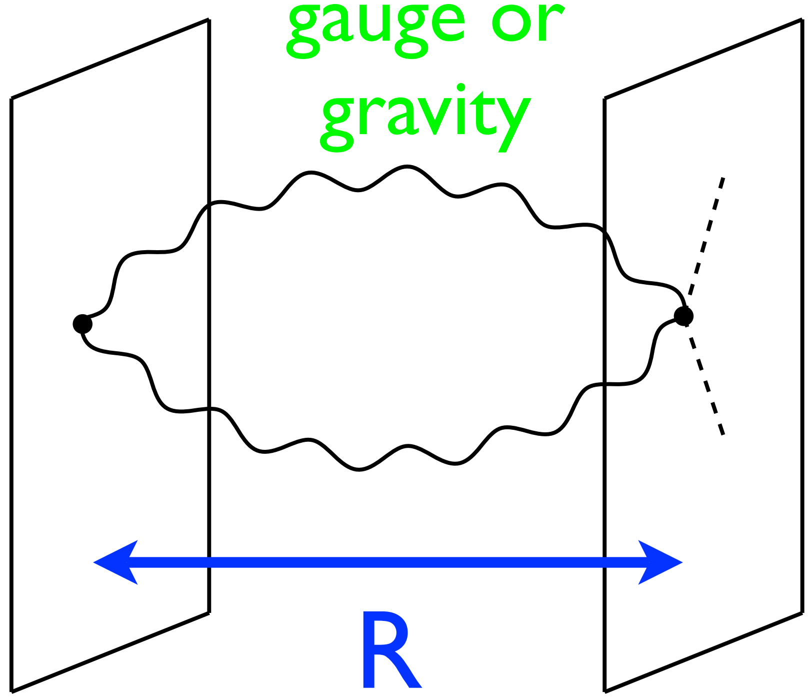
$$m_{3/2} = \frac{F}{k\sqrt{3}M_P} = \frac{1}{k}\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^2 2.4\ \mathrm{eV}$$

k = model-dependent coefficient

➥ Lightest Superparticle

2) Gravity/Moduli/Extra-dim mediation:

...to be discussed later



Spectrum at high-energies ($Q \sim 1/R$) model dependent

An example: Scalar masses = 0 (at tree-level)

Gaugino masses = $M_{1/2} \neq 0$

Lightest superpartner:

Neutralino (mixture of gaugino and Higgsino)

Higgs sector

Only 3 parameters:

$$V = (|\mu|^2 + m_{H_u}^2)(|H_u^0|^2 + |H_u^+|^2) + (|\mu|^2 + m_{H_d}^2)(|H_d^0|^2 + |H_d^-|^2)$$
$$+ [b(H_u^+ H_d^- - H_u^0 H_d^0) + \text{c.c.}]$$
$$+ \frac{1}{8}(g^2 + g'^2)(|H_u^0|^2 + |H_u^+|^2 - |H_d^0|^2 - |H_d^-|^2)^2 + \frac{1}{2} g^2 |H_u^+ H_d^{0*} + H_u^0 H_d^{-*}|^2.$$

quartic coupling
related to gauge-couplings

Spectrum:

2 x 4 = 8 scalars = 3 Goldstones (eaten by W, Z)
+3 neutral Higgs = h, H, A
+ Charged Higgs = H^+, H^-

2 unknown parameters (since $v^2 = \langle H_u \rangle^2 + \langle H_d \rangle^2$):

1) $\tan\beta = \frac{\langle H_u \rangle}{\langle H_d \rangle}$ 2) m_A

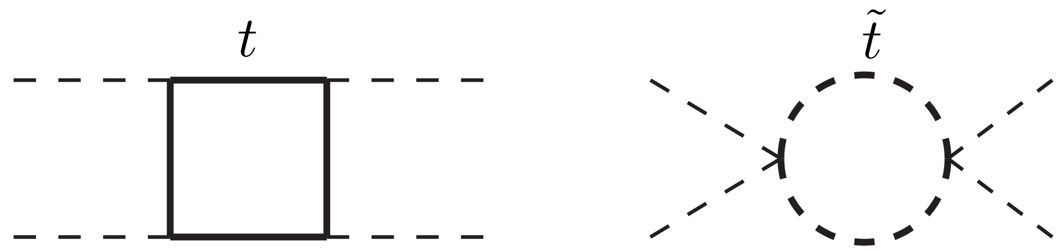
At tree-level:

$$\begin{cases} m^2_{H^+} = m^2_A + m^2_W \\ m^2_{h,H} = \frac{1}{2}\left\{ m^2_A + m^2_Z \pm \sqrt{(m^2_A - m^2_Z)^2 + 4\sin^2 2\beta\, m^2_A m^2_Z} \right\} \end{cases}$$

$$m_h \leq m_Z$$

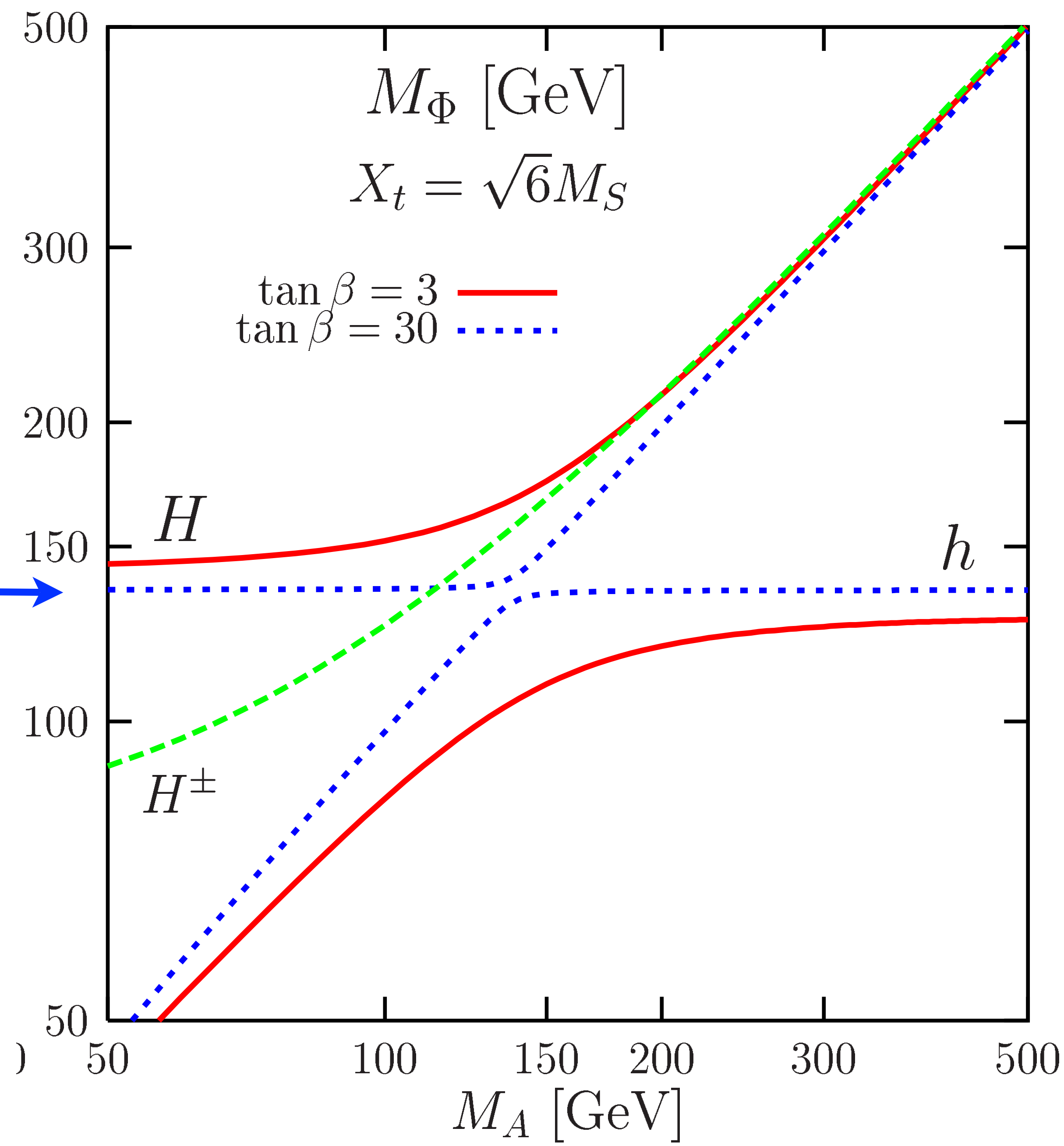
Was a great prediction for Higgs hunters at LEP!

... but quantum effects (mostly loops of top/stop)



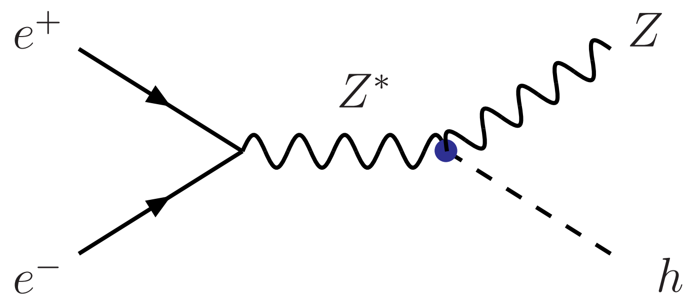
modify the bound:

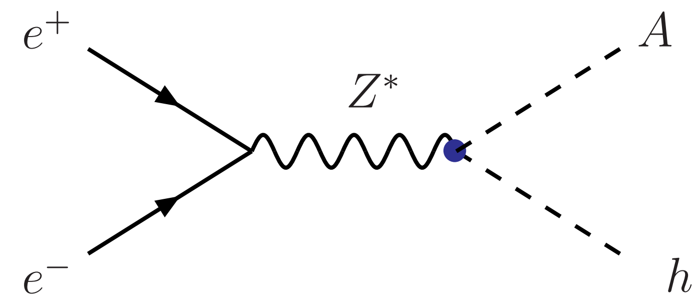
Upper bound
~130 GeV



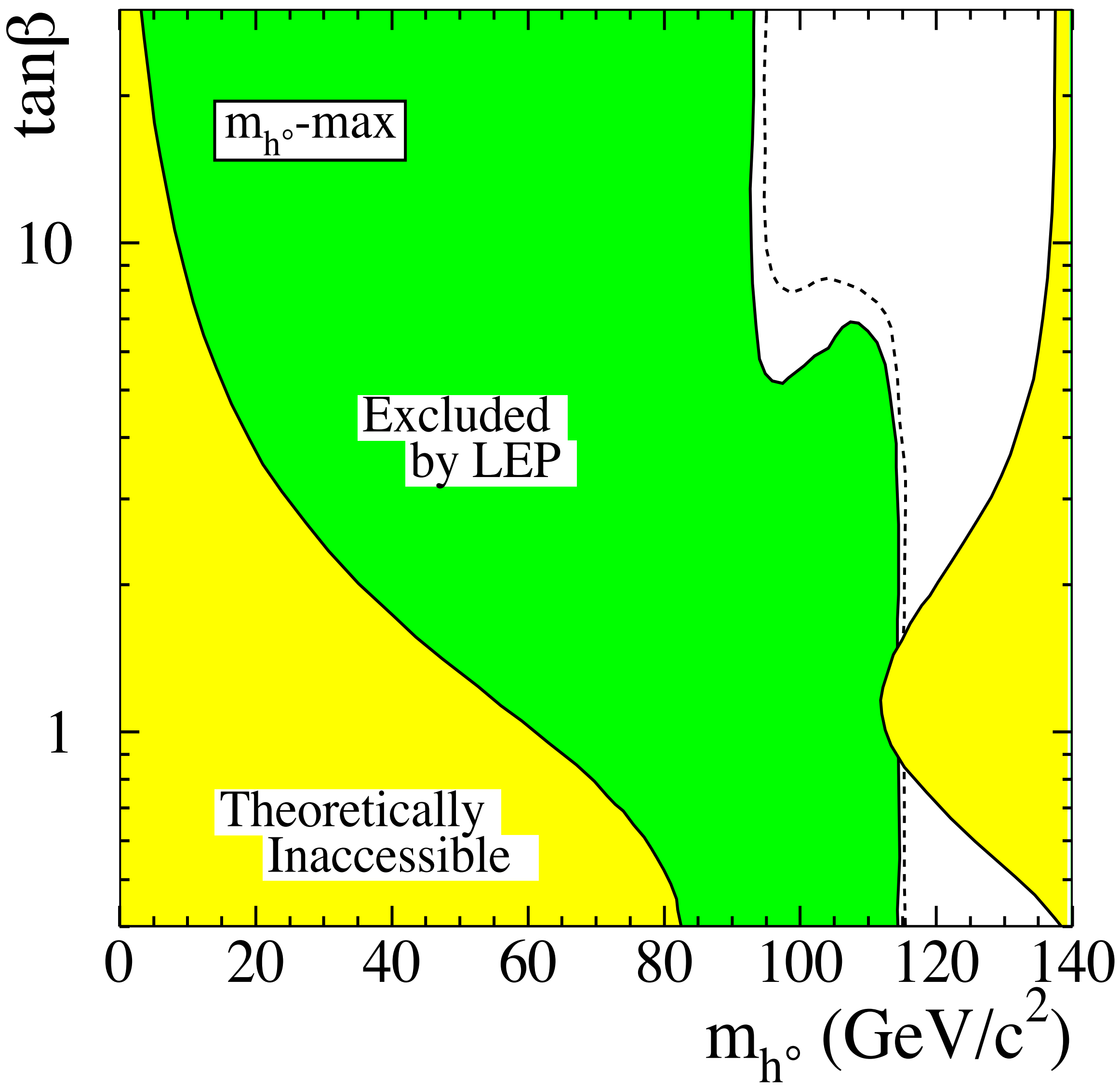
Djouadi 05

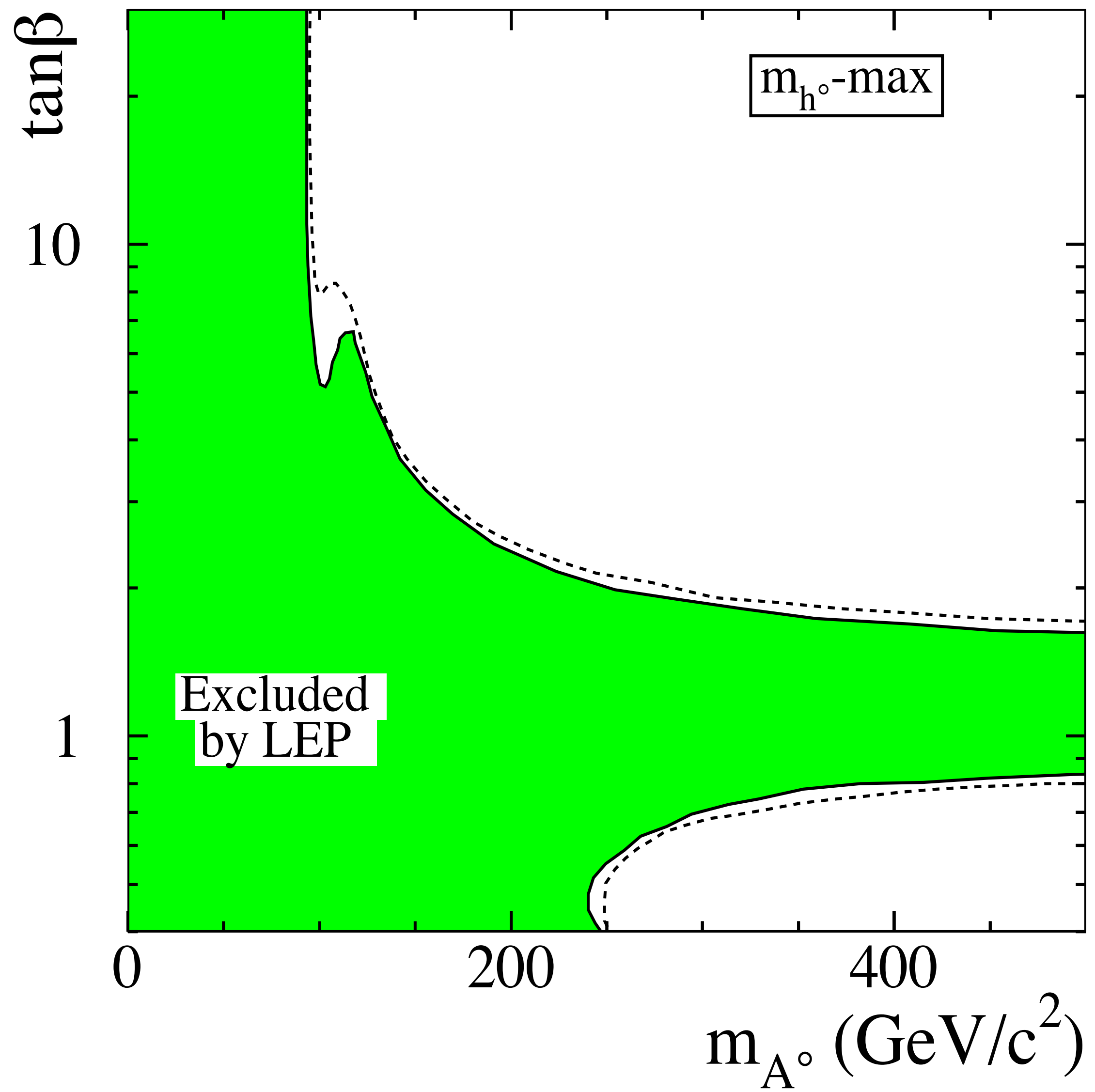
LEP searches:





with decays to taus and bottoms





After LEP, a heavy stop is essential to keep the MSSM alive

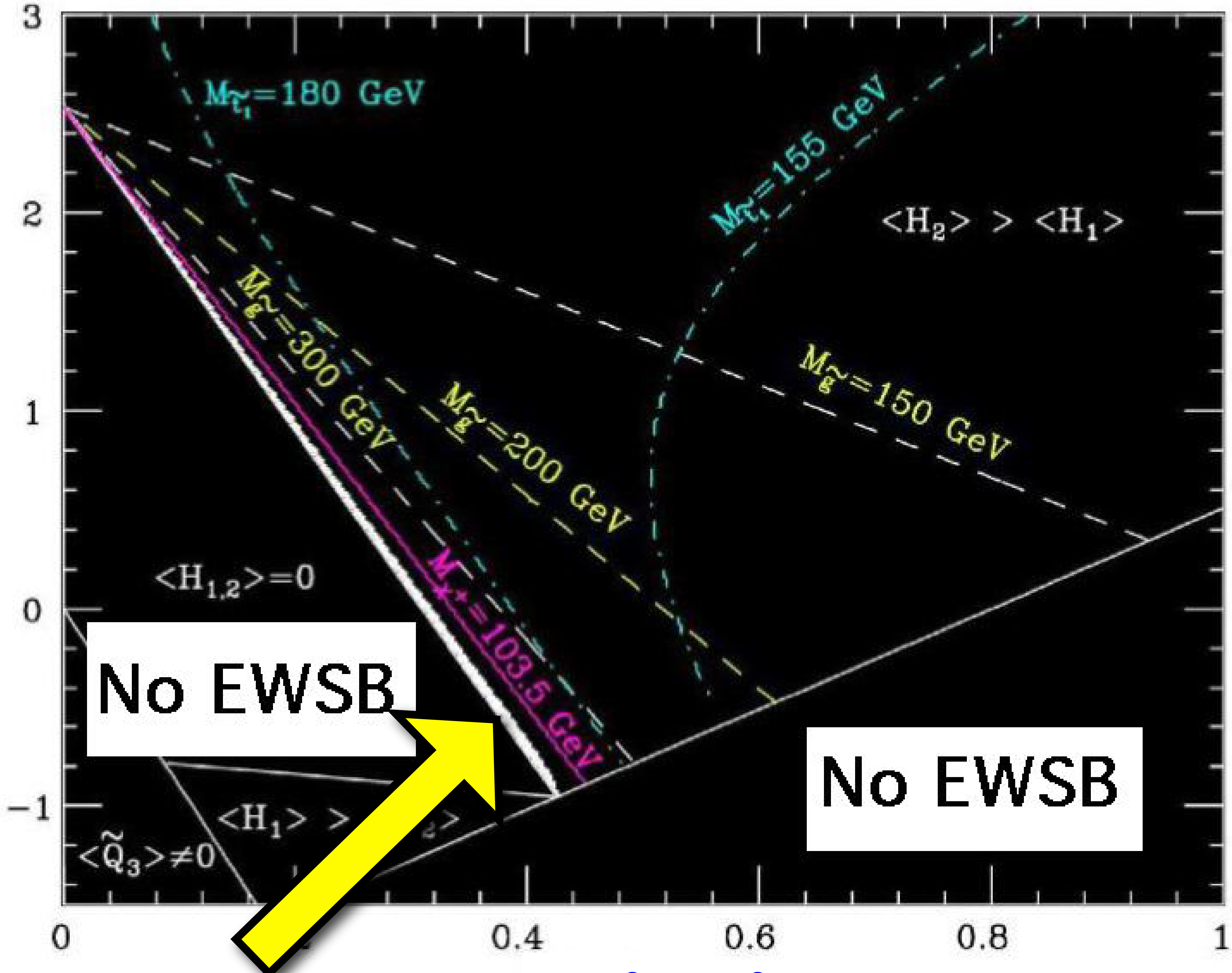
Higgs bound:

$$m_h^2 < m_Z^2 + \frac{3m_t^4}{2\pi^2 v^2}\ln(m_{\rm stop}/m_t) + \cdots$$

Needed to be large to be above the experimental bound

Higgs searches rules out a big chunk of the parameter space of the MSSM!

In minimal Sugra:



M_0^2/μ^2

$M_{1/2}^2/\mu^2$

Only the thin "withe spike" is left!

Giudice, Rattazzi

MSSM Higgs hunting at the LHC

Bad news: h too light to decay to WW/ZZ

A, H^{+} have very small couplings to WW/ZZ

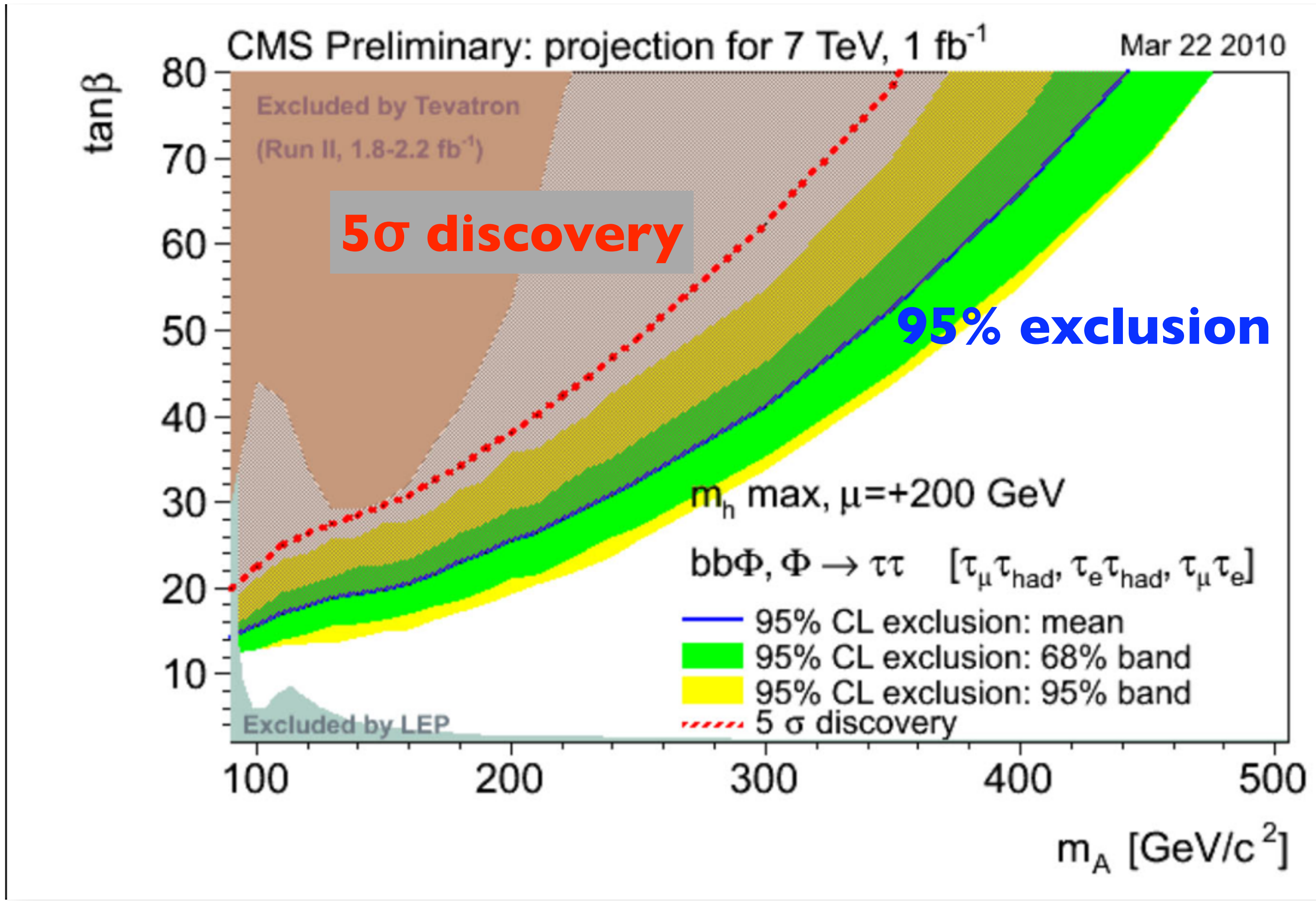
H small regions with sizable couplings to WW/ZZ

Good news: Regions where the decays of H, A, H^{+} to leptons are enhanced (Large Tanβ region)

Due to: $m_\tau = Y_\tau \langle H_d \rangle$

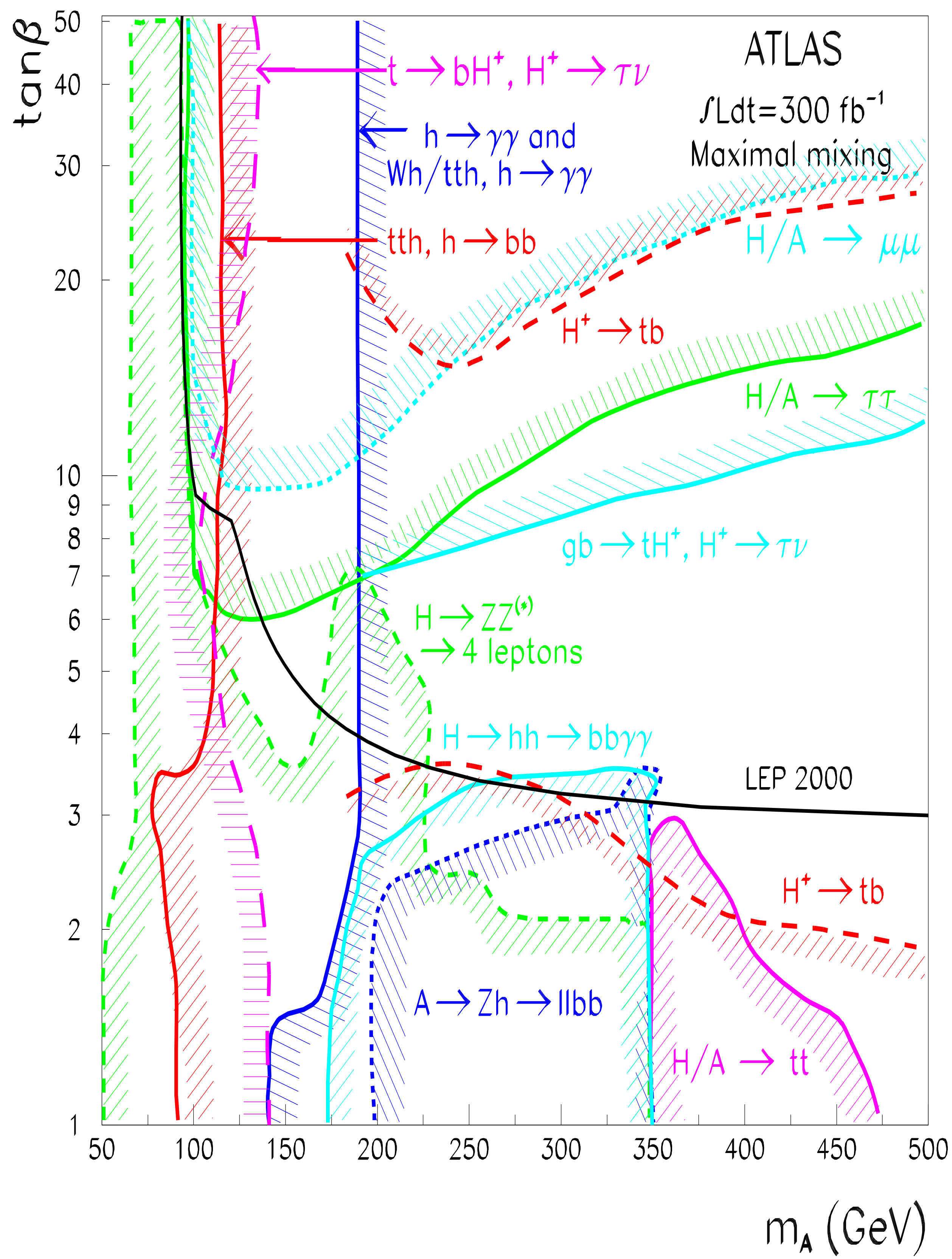
Y_τ can be larger than in the SM, if $\langle H_d \rangle$ is smaller than v

Near future:



More interestingly: MSSM could be ruled out if a Higgs → WW/ZZ with mass ~160 GeV is discovered in the first LHC run

In the long run....



Superpartners at Hadron Colliders

Superpartners at Hadron Colliders

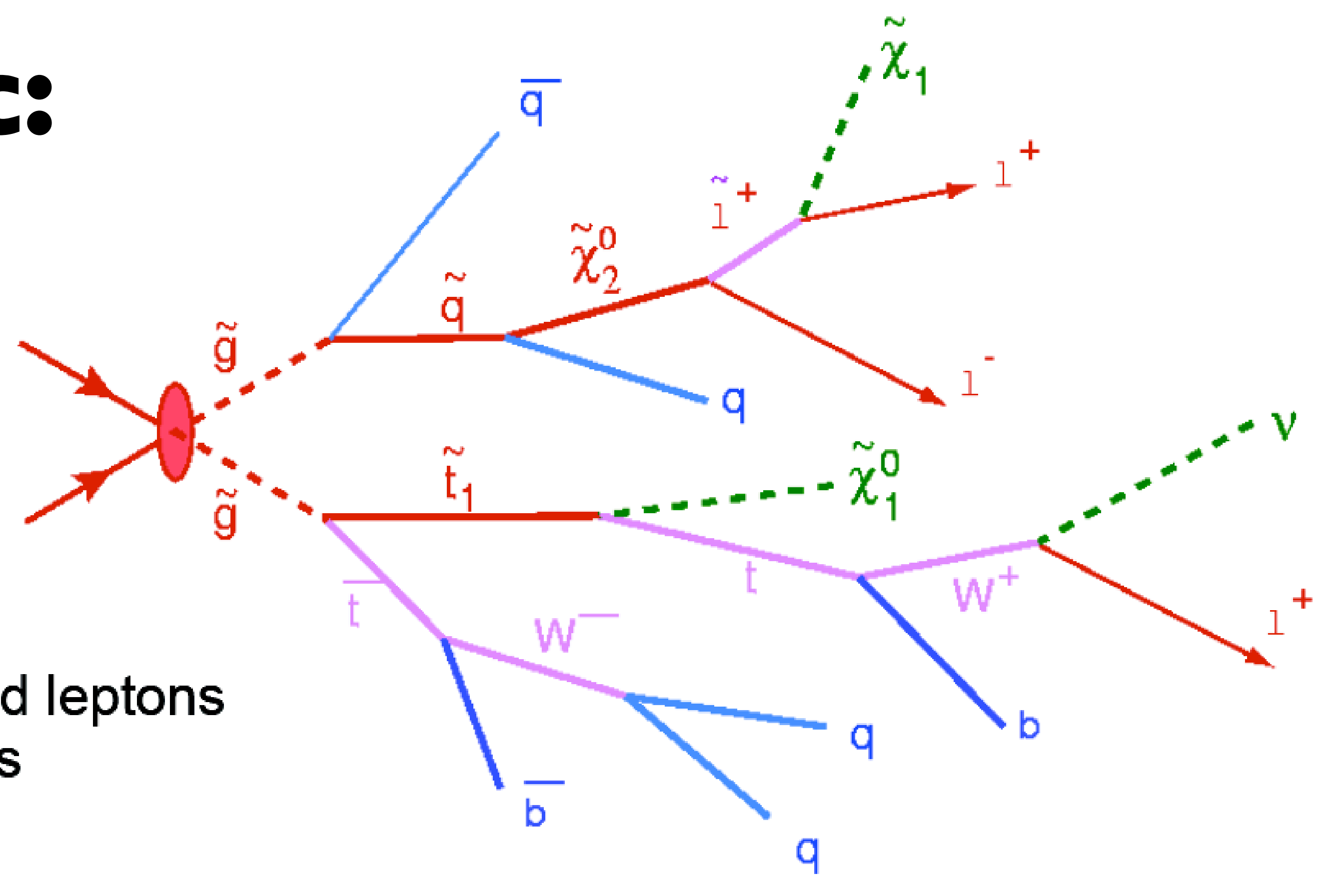
Neutral gaugino + Higgsino mix:
Mass-eigenstate = χ^0 neutralino

Charged gaugino + Higgsino mix:
Mass-eigenstate = χ^+ chargino

Main consideration:

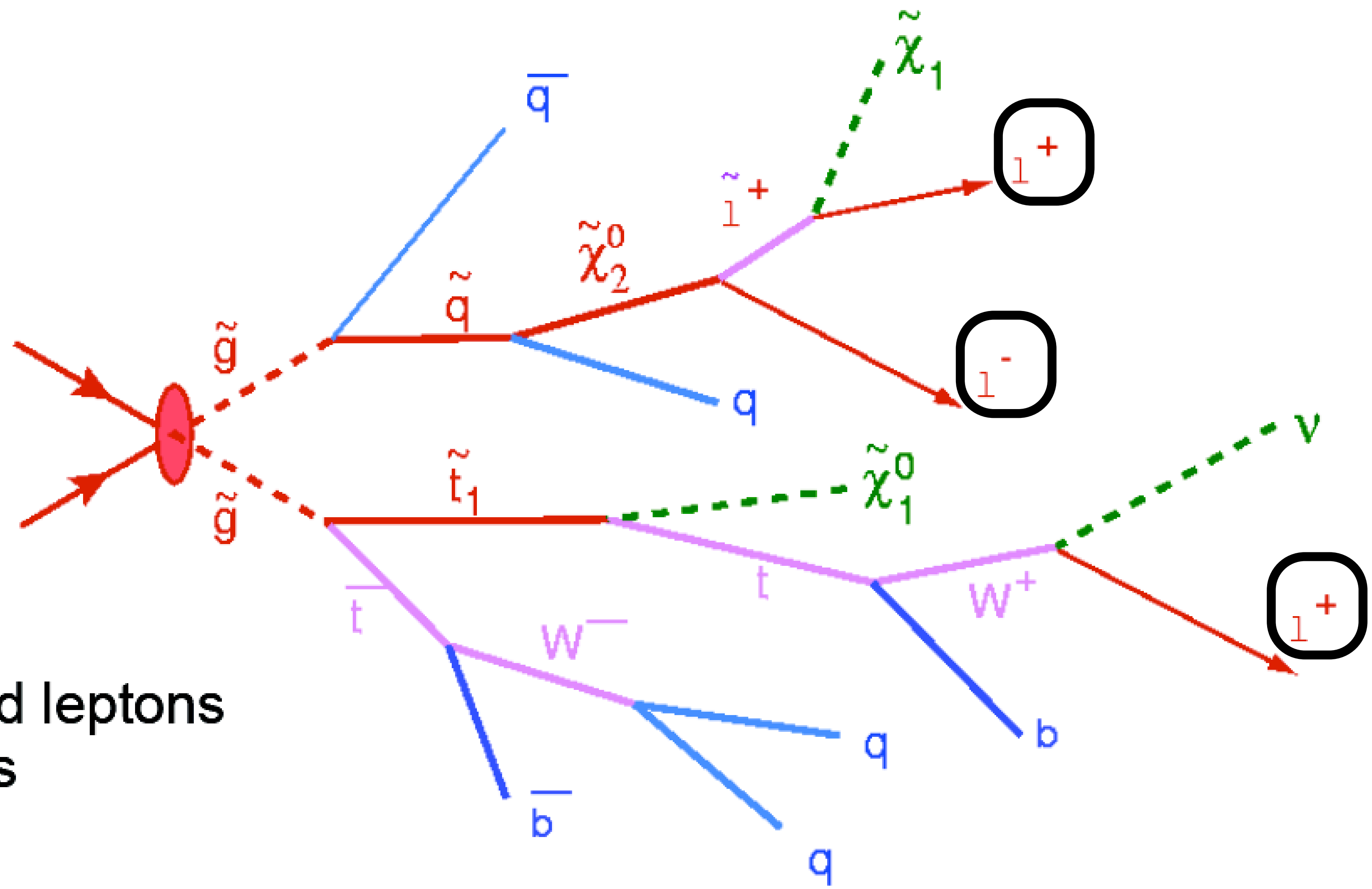
Due to *R-parity* superpartners are produced in pairs, and decay, in cascade, down to the lightest one (neutral) that, being stable, goes away from the detector

A classic:



3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_T^{miss}

Strategy: Detect leptons or jets + Missing E_T



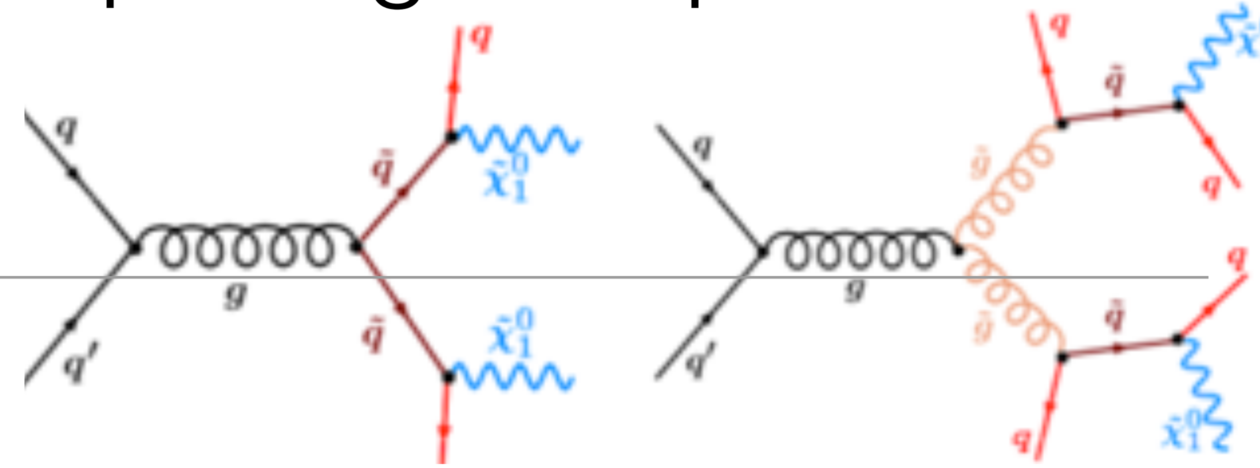
3 isolated leptons
+ 2 b-jets
+ 4 jets
+ E_T^{miss}

Final states with same-charge dilepton due to the Majorana nature of the gluino

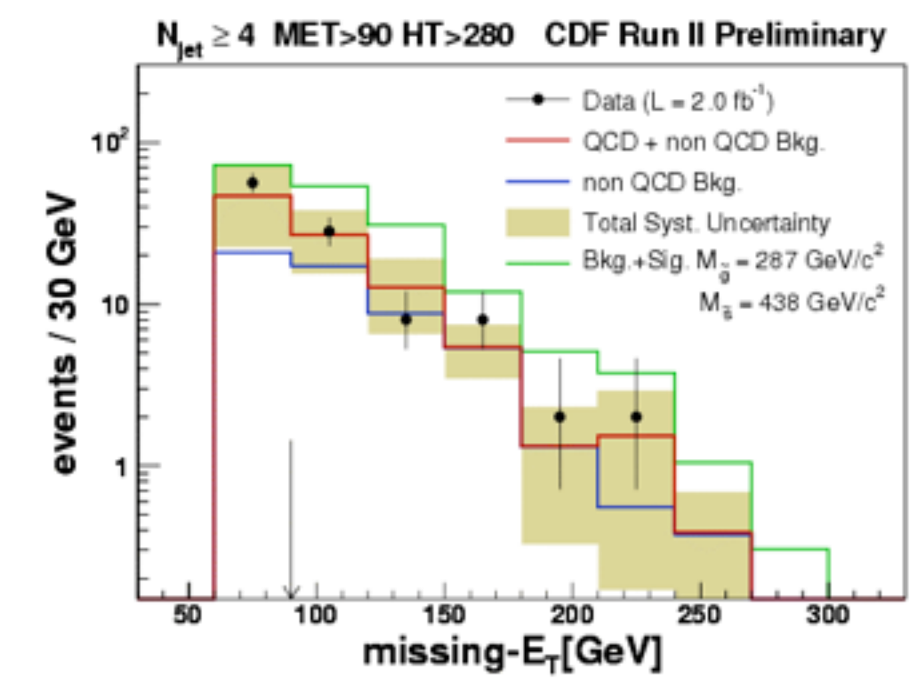
Tevatron

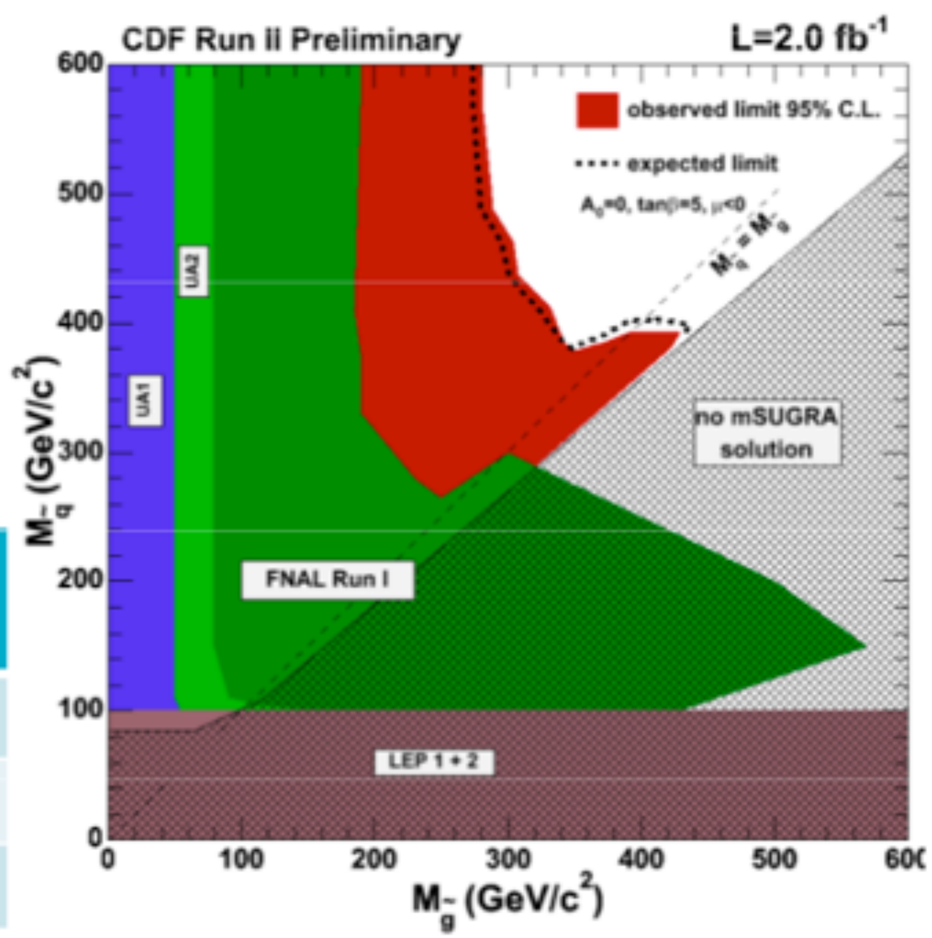
From P. Wittich at
"Physics at the LHC 2010" conference

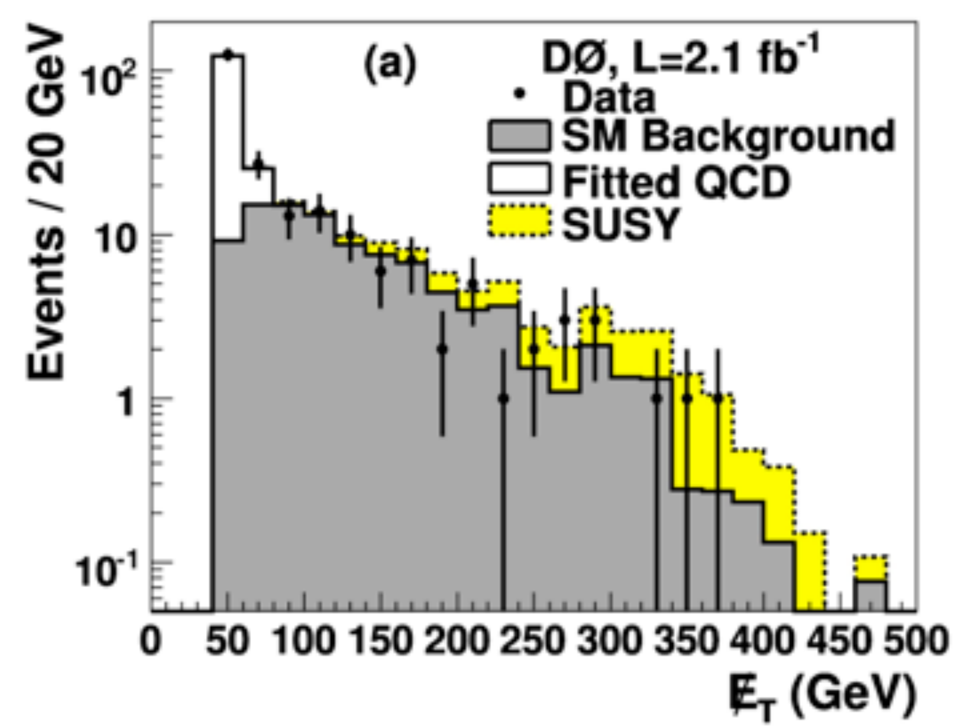
susy in jets + met:generic squark/gluino production



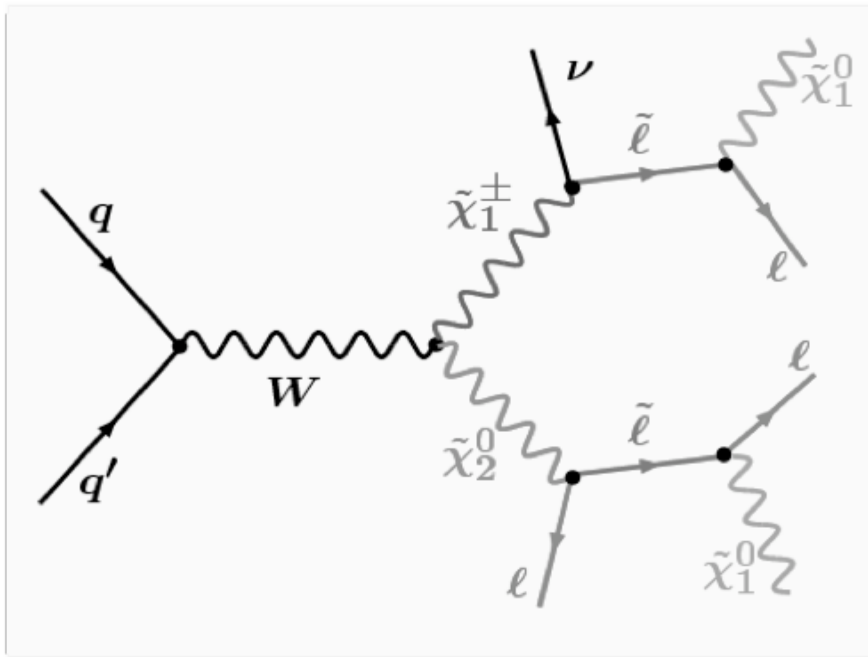
- Large production cross section, bkgnds from multi-jet, $Z \rightarrow \nu\nu$, top
- Optimize searches as a function of (Missing E_T, $n_{\rm jet}$)
- No excess seen so far
- Limits for 2 (2.1)/fb of data for CDF (D0)
- interpret results in mSUGRA-like SUSY scenario







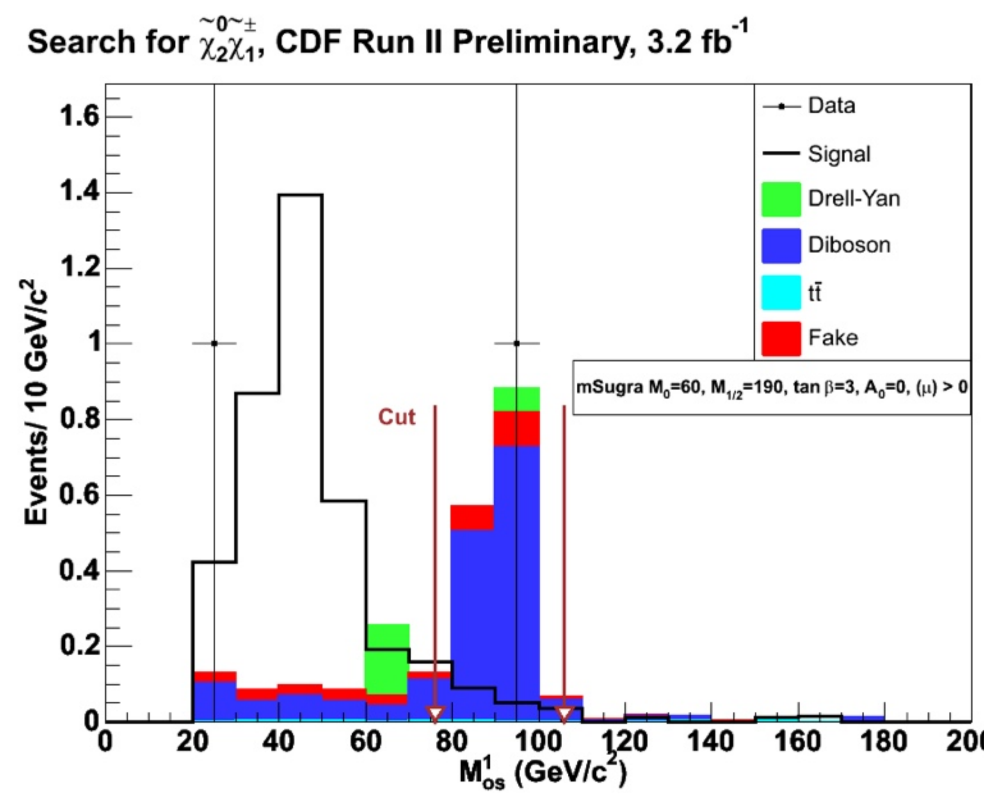
Trileptons: Chargino-Neutralino Search, 3.2/fb



- 3 identified leptons (e,μ)
- 2 identified leptons + track (ℓ)
- "Tight" and "loose" e,μ categories

- Very clean signature:
  - Missing E_T due to undetected ν, $\tilde{\chi}^0_1$
  - 3 isolated leptons, *lower momentum*

- Rejection using kinematic selections on: m_{l+l-}, n_{jets}, Missing E_T, Δφ between leptons...



Good agreement between data and SM prediction → **set limit**

Channel	SM expected	Data
Trilepton	1.5 ± 0.2	1
Lepton+trk	9.4± 1.2	6

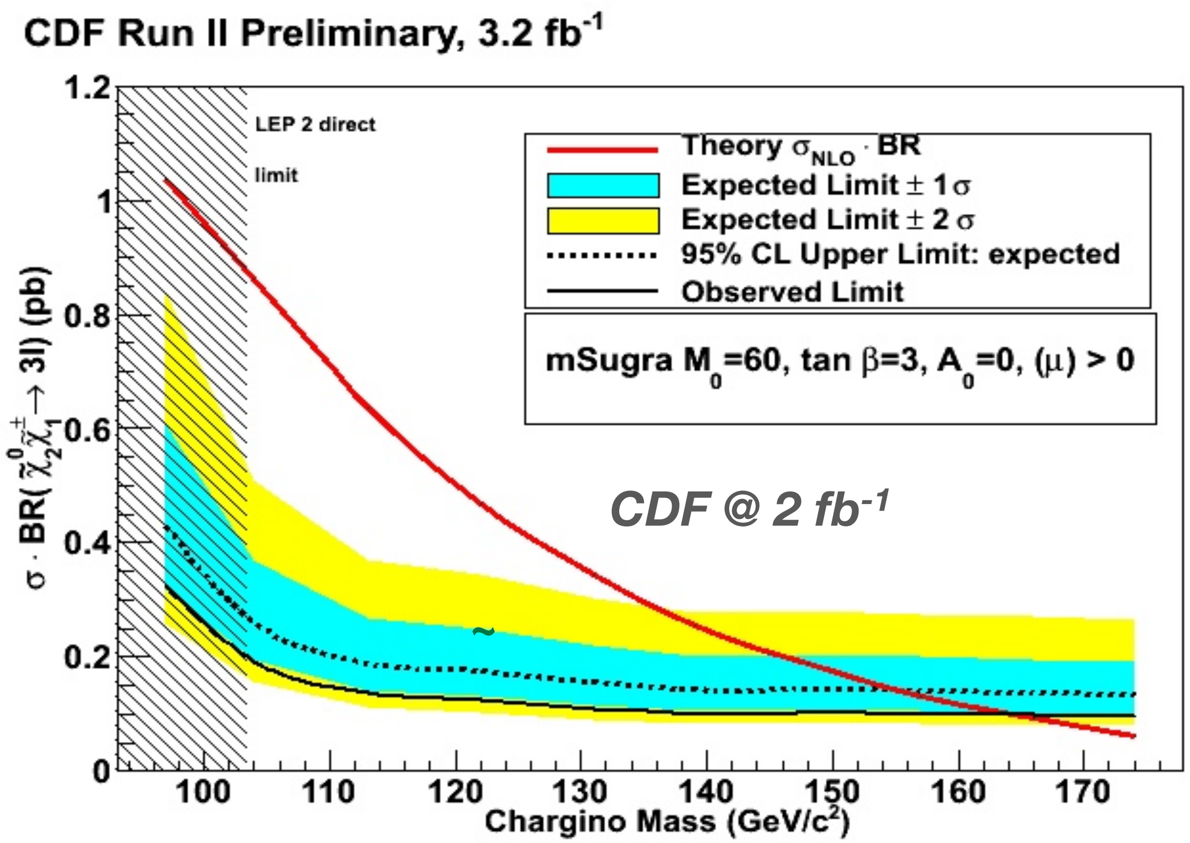
Chargino-neutralino results

PRL 101, 251801 (2008)

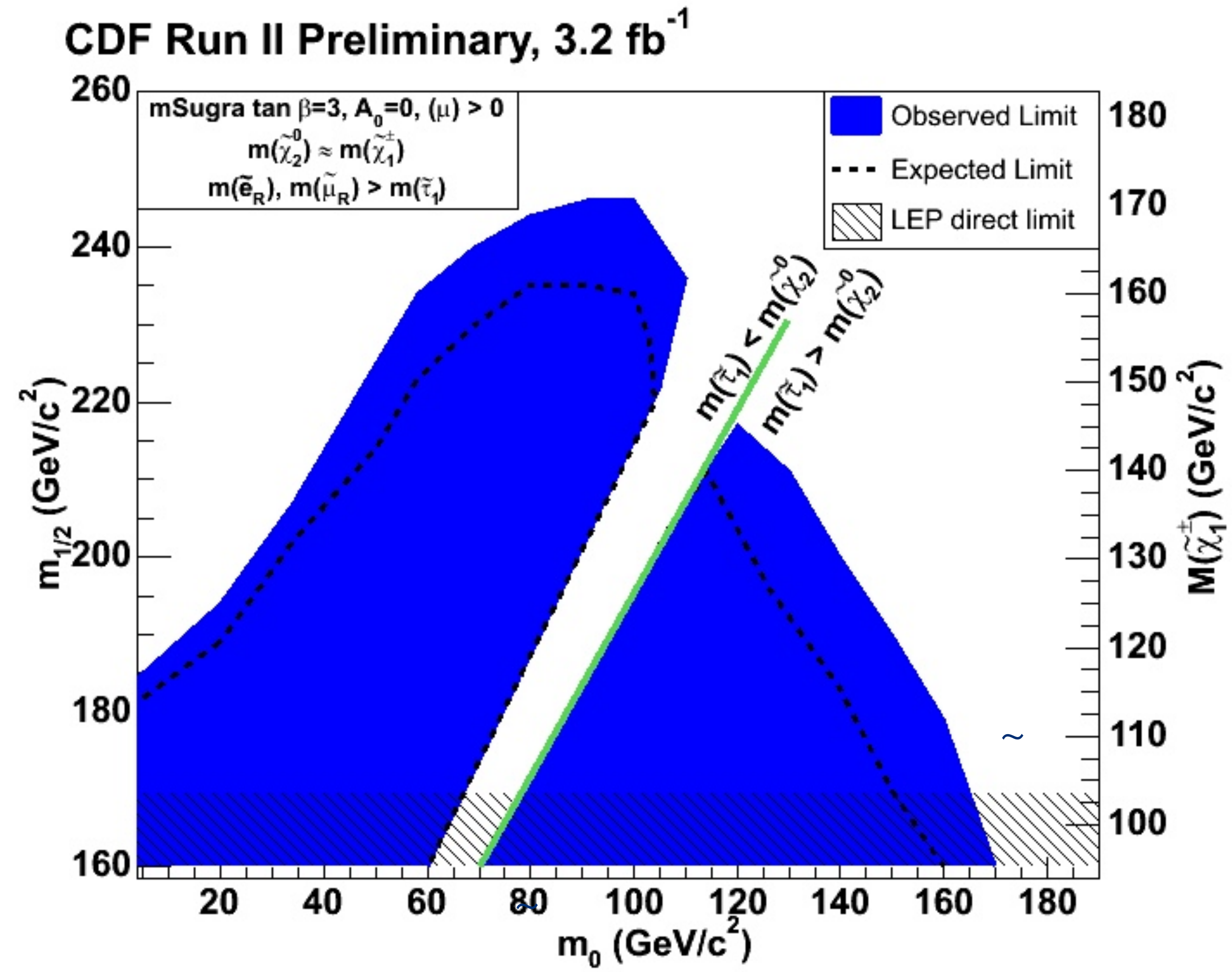
- interpret null result in mSugra SUSY scenario as a convenient/conventional benchmark

excluded region in mSUGRA m_0-$m_{1/2}$ space

m_0 = 60 GeV, tan β=3, A_0=0, μ>0



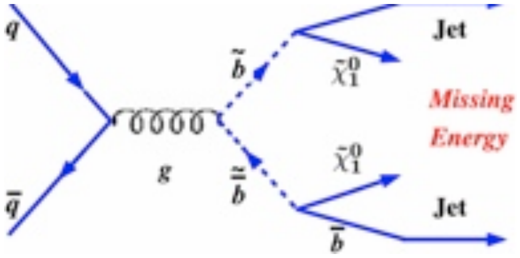
Excludes $m\chi^{\pm}_1$ < 164 (154 Exp.) **GeV/c²**



Limits depend on relative χ^0_2-$\tilde{\ell}$ masses

- $m_{\chi 2} > m_{\tilde{\ell}}$ increases $\mathcal{BR}$ to e/μ
- $m_{\chi 2} \approx m_{\tilde{\ell}}$ reduces acceptance

D0 limit in 2.3/fb: Phys. Lett. **B** 680, 34 (2009)



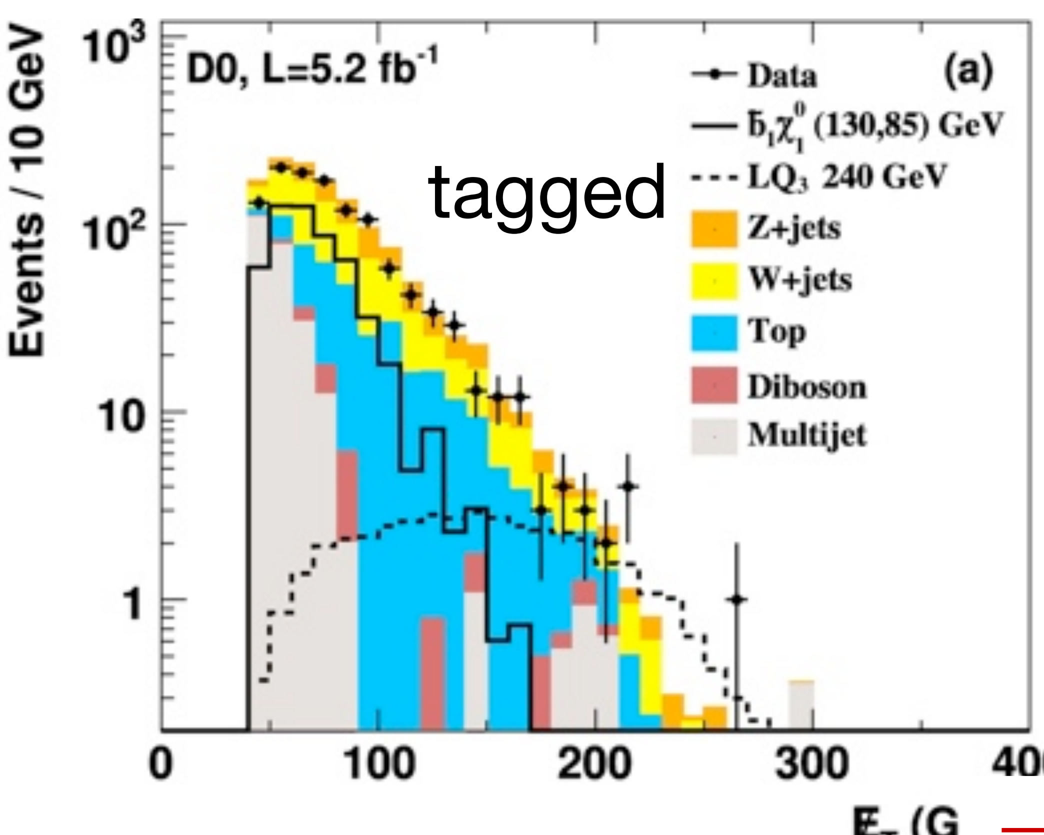
2 b jets + E_T^{Miss} - ~q and LQ

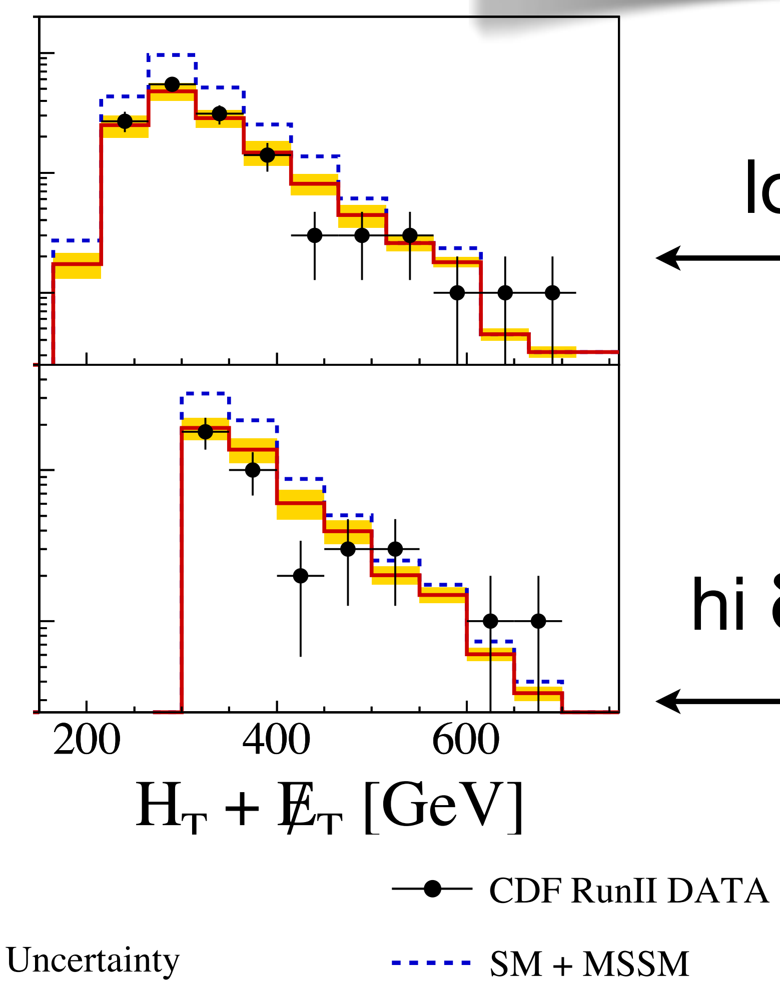
$$ZH \to \nu\bar{\nu}b\bar{b}$$

- Final state familiar from Higgs searches
  - missing E_T and b quarks
- Also good signal for leptoquarks and SUSY
- event selection:
  - b tagging (D0: neural-net algo)
  - two b-tagged jets, E_T^{miss}, Sign., ΣE_T
  - optimize p_T, E_T^{miss}, H_T, X_{jj} for SUSY/LQ3 signals

$$p\bar{p} \to \tilde{b}_1\bar{\tilde{b}}_1 \to b\tilde{\chi}_1^0\bar{b}\tilde{\chi}_1^0$$
$$LQ_3 \to \nu_\tau b$$

$$X_{jj} = \frac{p_T^{\mathrm{jet1}} + p_T^{\mathrm{jet2}}}{H_T}$$





low $\delta M_{(LSP,\ b\ squark)}$

hi $\delta M_{(LSP,\ b\ squark)}$

Supersymmetric top in the e+μ+bb+MET, 3.1/fb

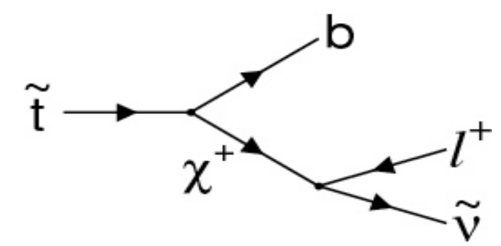
- 3rd generation again - special role in SUSY
- Look for decay mode in e μ final state with E_T^{Miss} >18 GeV
  - Low SM backgrounds (Z→ττ,ttbar)
  - Reject with δΦ(lepton, E_T^{Miss}) cuts
- no explicit b tag required

$$p\bar{p} \rightarrow \tilde{t}_1 \bar{\tilde{t}}_1$$

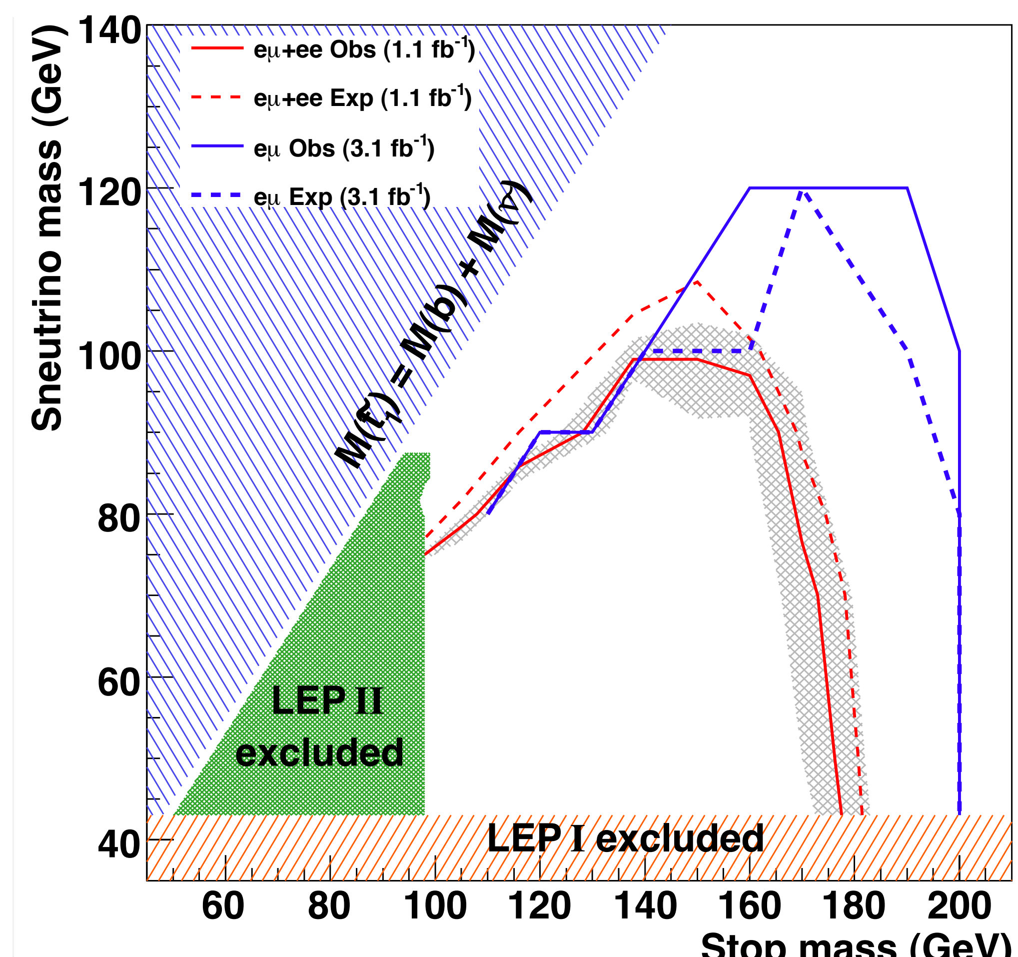
$$\mathcal{B}(\tilde{t}_1 \rightarrow \tilde{\nu} b \ell) = 100\%$$

R parity conserving

- Consider *small* and *large* δm(stop, sneutrino)
  - drives kinematics of accepted events



- Bin events in two kinematic variables
  - HT: scaler sum of jet p_T
  - ST: scalar sum of lepton p_T, E_T^{Miss}
- Null result: set limits in sneutrino/stop mass plane



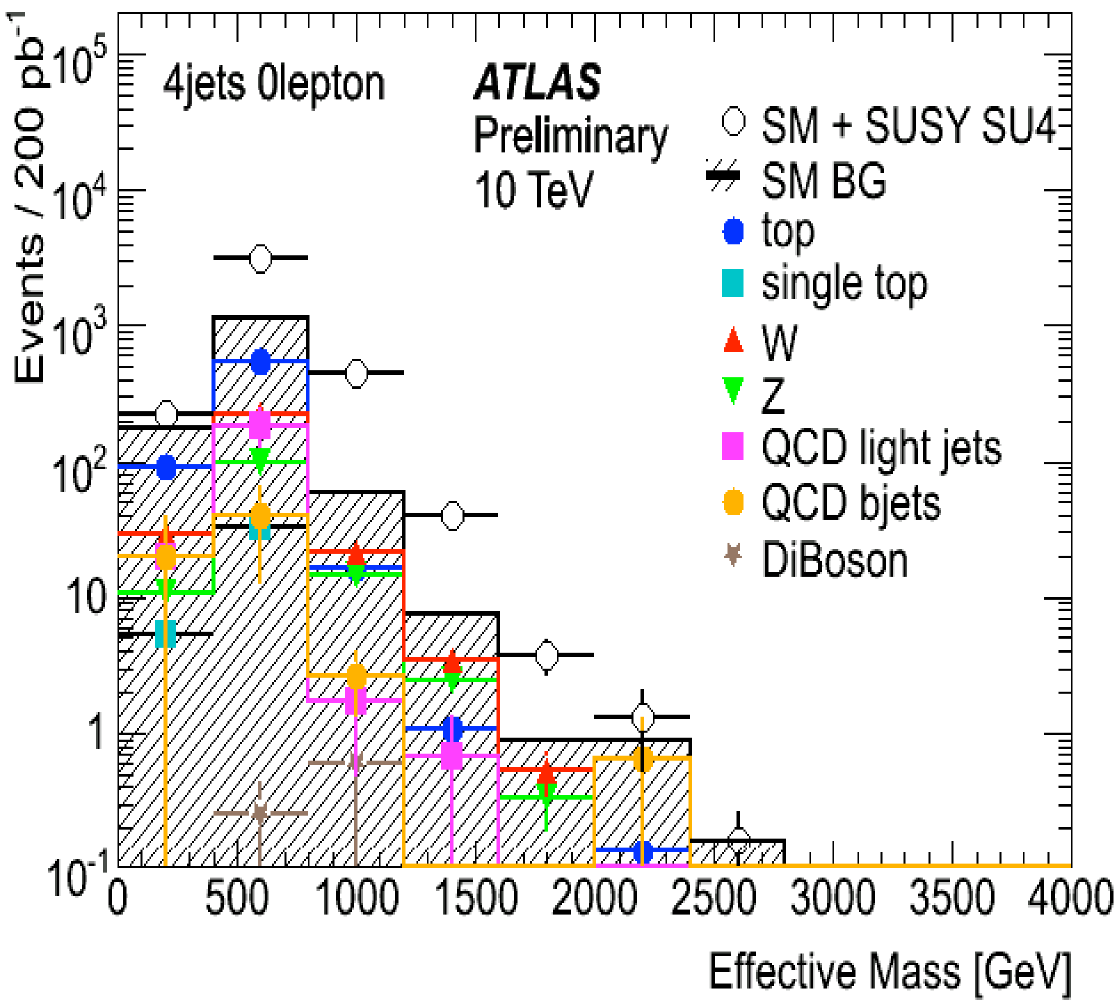
Blue: this result

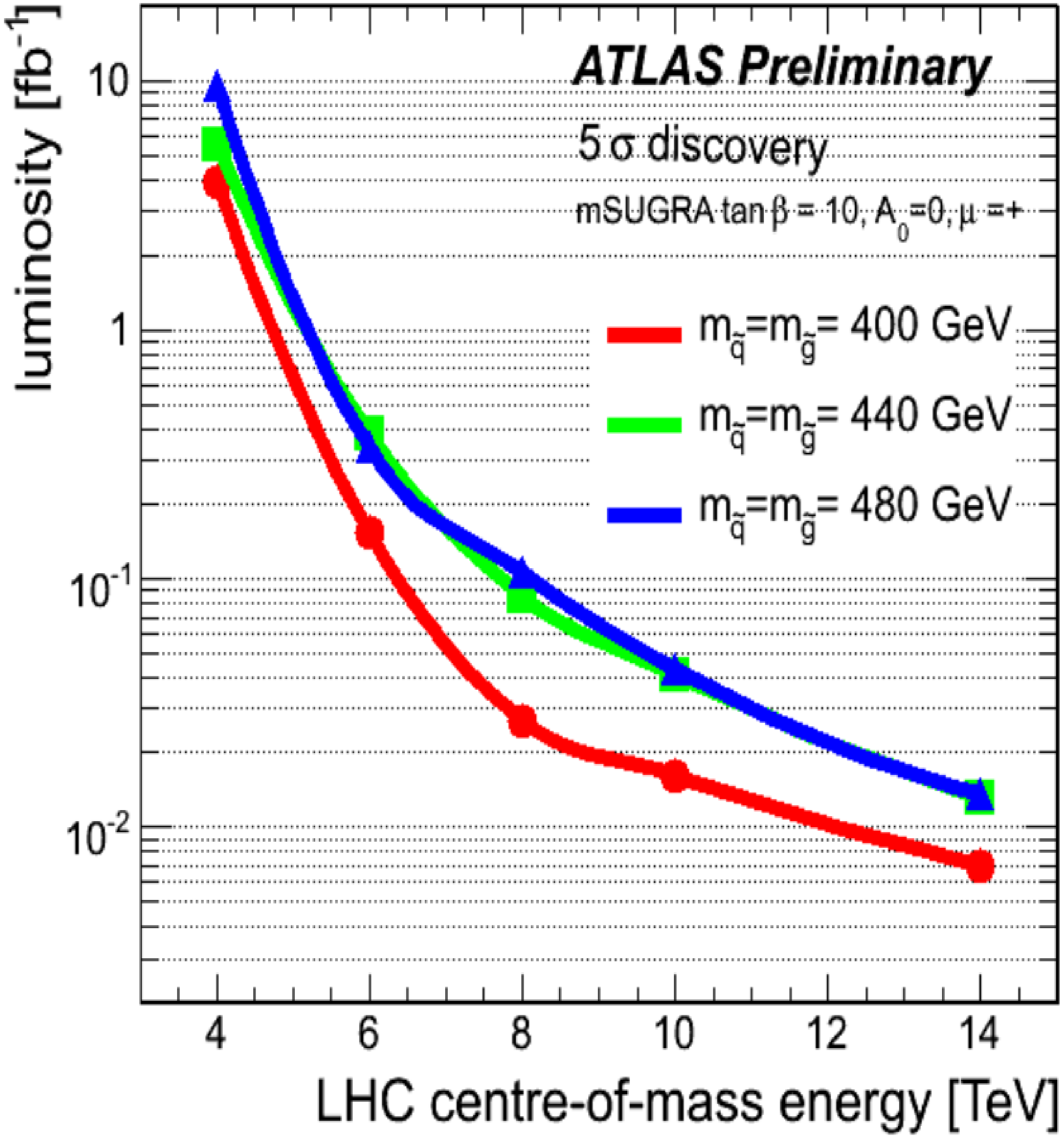
[D0 Conference Note 5937-CONF]

LHC

From P. Jenni at
"Physics at the LHC 2010" conference

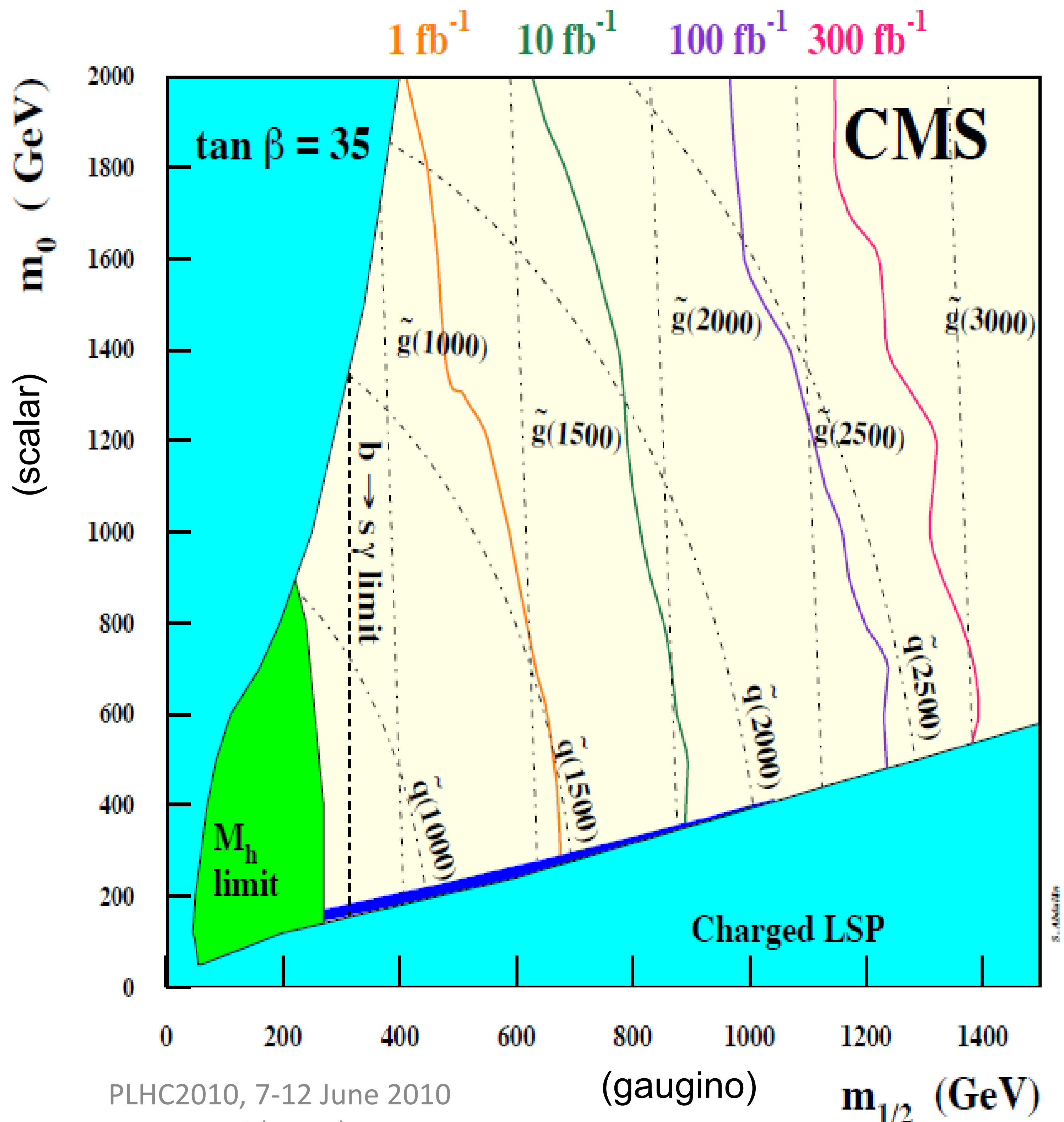
The initial LHC running will already match (maybe exceed) end 2010 the Tevatron reach

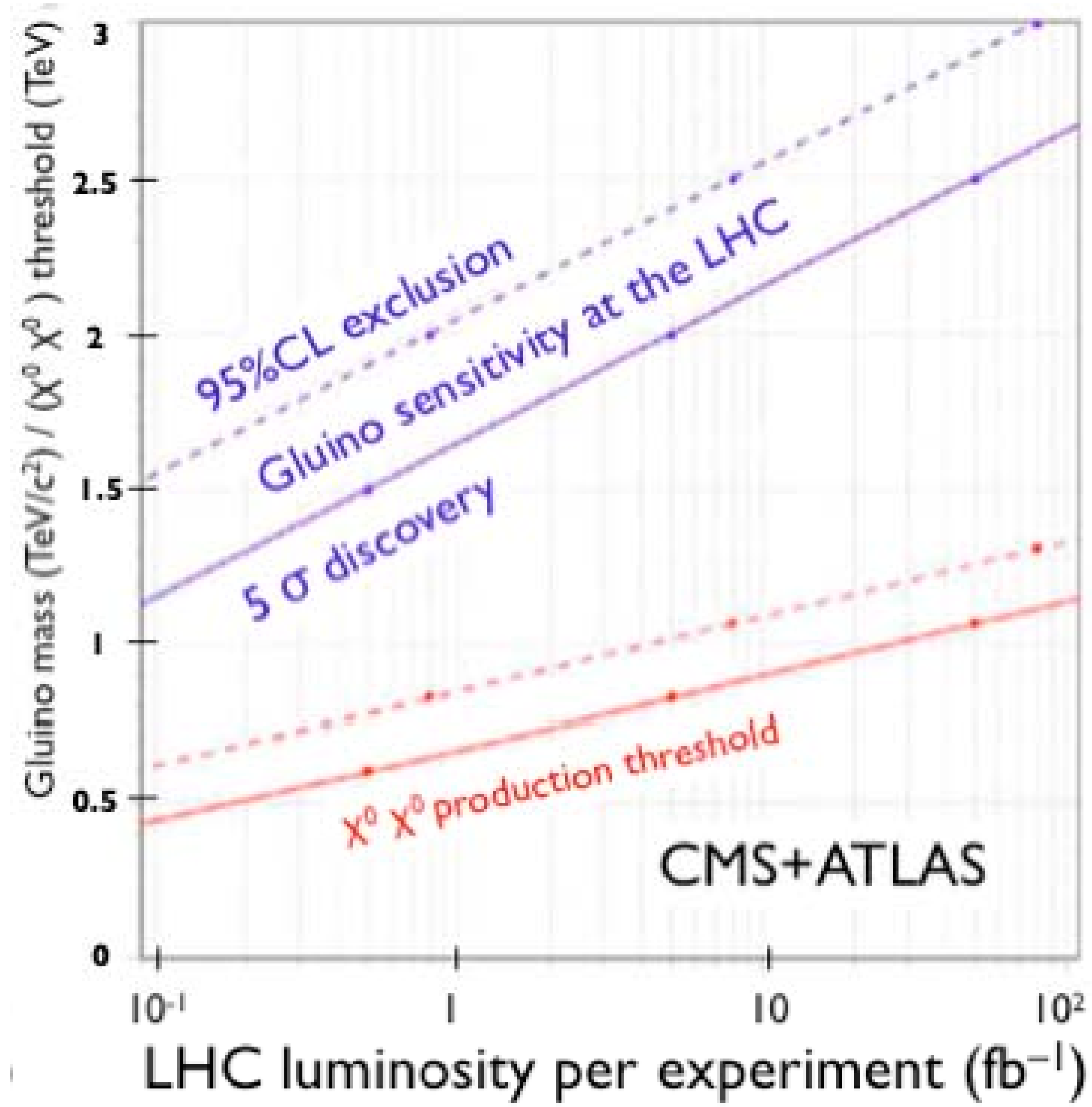




A typical example; note that the missing transverse energy performance enters directly the 'Effective Mass', detectors must be well understood for these measurements

Ultimate discovery reach for SUSY particles at the LHC (indicative plots, model-dependent…)





The mass scale probed for squarks and gluinos will be typically 2.5 TeV by 2017

Other MSSM goodies:

- Gauge coupling unification
- The lightest supersymmetric particle (LSP) can be Dark matter
- Local supersymmetry must incorporate gravity:

$$\{Q, Q^\dagger\} = P^\mu$$

- Fits well EWPT from LEP/Tevatron

➥ It has allowed us to write more than 20,000 papers