Searches for Supersymmetry at The Tevatron Collider

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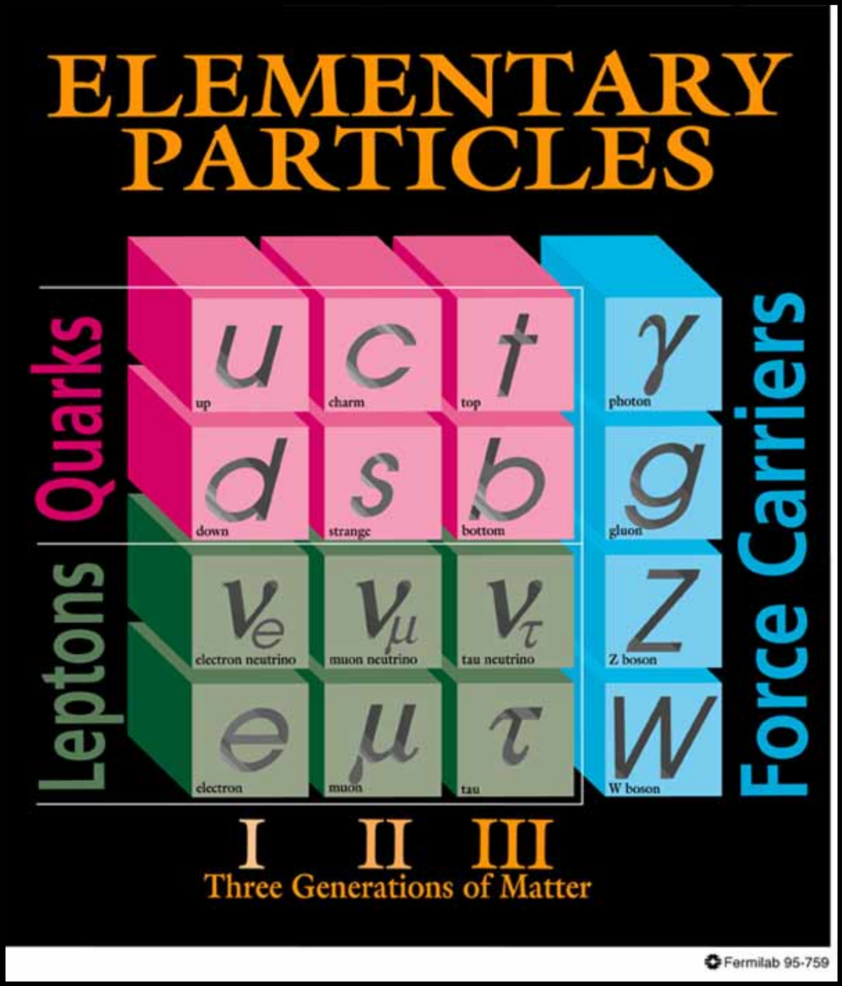
- The Standard Model (SM) Particles
- The Hierarchy Problem in the SM
- Supersymmetry
- The Minimal Supersymmetric Standard Model (MSSM)
- Search for Supersymmetry
- Conclusions

The Standard Model Particles

- All matter is made up of spin ½ *fermions:* *quarks* and *leptons*
- Four forces
  - (Gravity)
  - Electromagnetic
  - Weak
  - Strong
- Forces mediated by spin 1 *gauge bosons*
- Particle masses acquired by *Higgs Bosons* (predicted)



Electroweak Theory

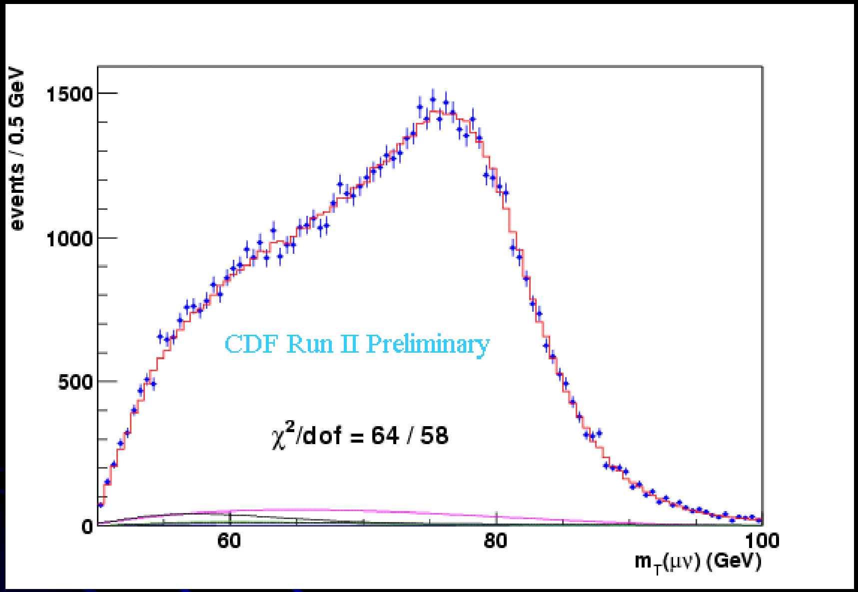
The theory begins with four massless mediators for the electroweak force: $W_\mu^{1,2,3}$ and B_μ.

$$\mathbf{W_\mu^{1,2,3}, B_\mu \longrightarrow W^+, W^-, Z^0, \gamma}$$

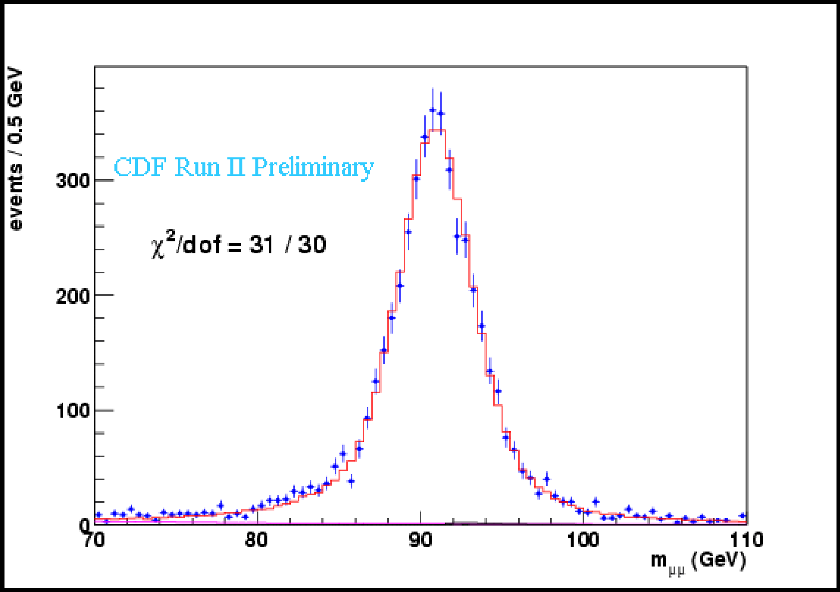
This transformation is the result of a phenomenon known as Spontaneous Symmetry Breaking. In the case of the electroweak force, it is known as the Higgs Mechanism.

The SM: Experimental Success

$W \rightarrow \mu\nu_\mu$ (CDF)



$Z \rightarrow \mu^+\mu^-$ (CDF)



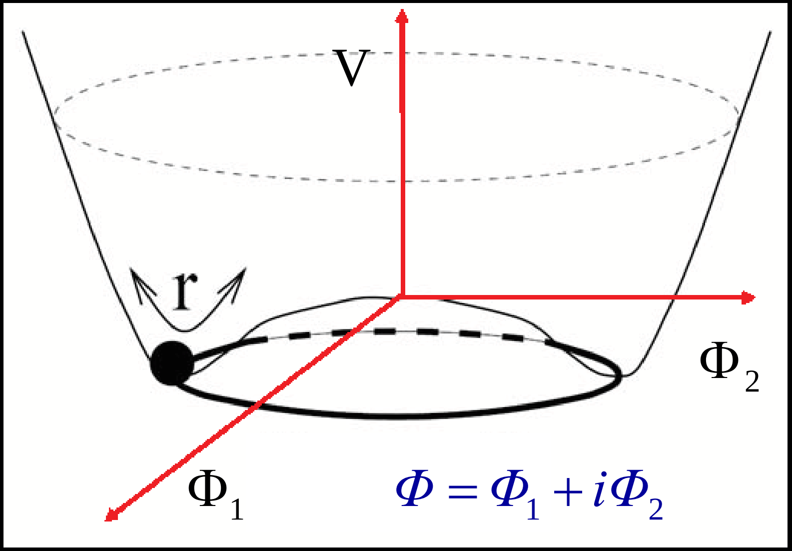
	SM Predicted (GeV)	The Tevatron	World Average
M_W	80.390 ± 0.018	80.452 ± 0.063	80.425 ± 0.038
M_Z	91.1874 ± 0.0012		91.1876 ± 0.0021

Electroweak Symmetry Breaking and the Higgs Mechanism

- Particle Masses arise through the Spontaneous Symmetry Breaking

$$SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_{EM}$$

- A potential induces a vacuum expectation value (VEV) in the Higgs, breaking the EW symmetry
- VEV related to the W and Z boson masses
- Problems
  - Higgs not discovered yet
  - Mass parameter is unstable under quantum corrections



$$V_{Higgs} = -\mu^2 |\Phi|^2 + \lambda |\Phi|^4$$

Higgs "mass" parameter — Higgs "quartic" interaction

$$\langle \Phi \rangle = \mathrm{v} = \sqrt{\frac{\mu^2}{2\lambda}}$$

$$M_W^2 = g_W^2 \mathrm{v}^2$$

$$M_h^2 = 2\lambda \mathrm{v}^2$$

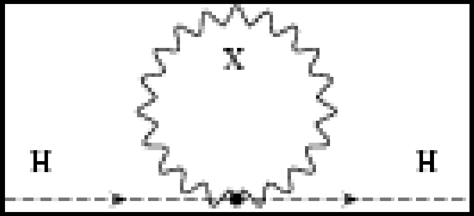
The Hierarchy Problem in the SM

- Want to unify Electroweak and Strong interactions
  $\rightarrow$ Grand Unified Theories (GUT)
- The GUT scale is believed to be $E_{GUT} = 10^{16}\,GeV$
- Once we admit to the higher mass scales, difficulties arise in the SM.
  : The Hierarchy Problem

  1) Imagine the one loop correction to the Higgs mass parameter from a heavy particle ($M \approx M_{GUT}$)

  2) If the mass of the (EW) Higgs particle is driven by this heavy particle of the GUT scale, its value will be unstable (divergent)

$$\frac{M_{GUT}}{M_W} \approx 10^{14}$$

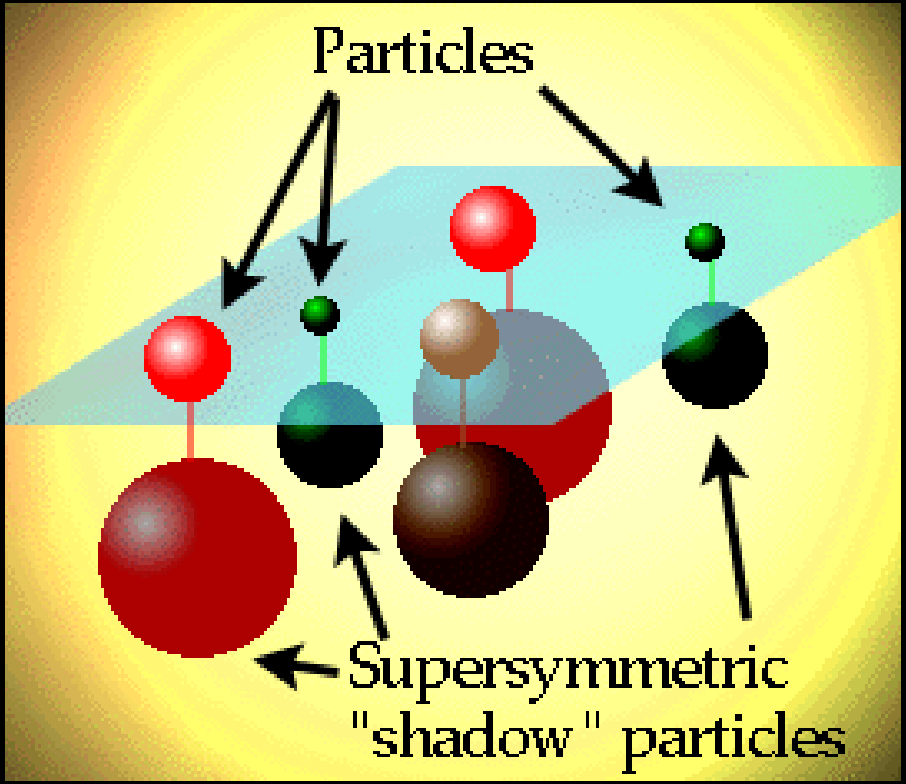


- Supersymmetry is designed to solve this problem

$$\Rightarrow \frac{g^2}{16\pi^2} M_X^2$$

Supersymmetry

Postulates a fermion-boson symmetry, according to which new fermion (boson) partners are postulated for all known fundamental bosons (fermions)
The hypothesis of supersymmetry can provide a solution to the hierarchy problem

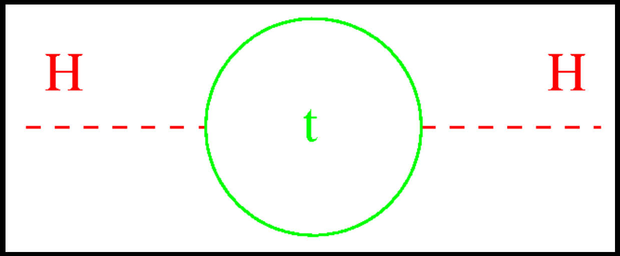


- How: double the particle spectrum! (Worked before: postulate positron for QED)
- Introduce "super-partners" with different spin

: makes theory self-consistent

How does Supersymmetry solve the hierarchy problem

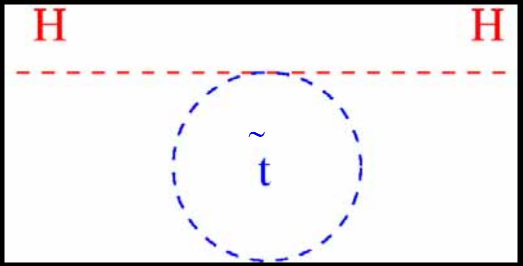
The Standard Model



Corrections to Higgs boson mass not only finite, but large in addition (divergent)

$$\delta m_H^{\ 2} \approx \Lambda^2 >> m_H^{\ 2}$$

Supesymmetry



Fermion and Boson contributions to m_H cancel in exact supersymmetry (finite)

$$\delta m_H^{\ 2} \approx O(\frac{\alpha}{\pi}) \times (m_B^{\ 2} - m_F^{\ 2})$$

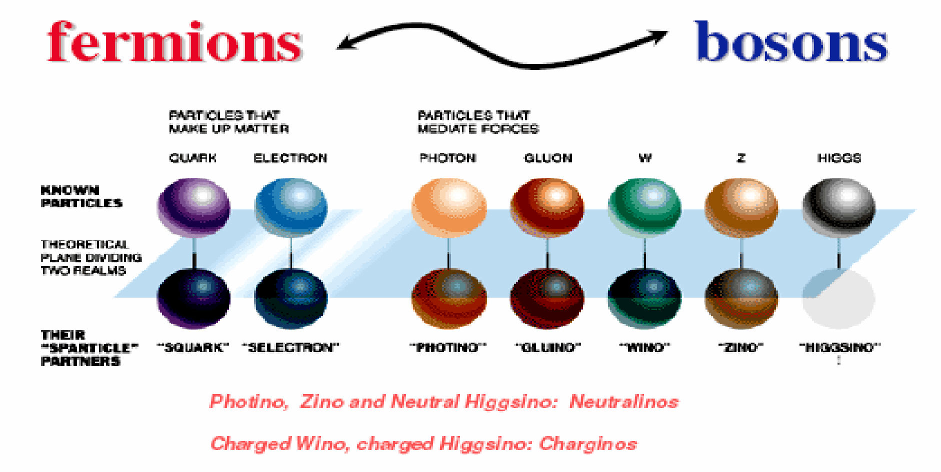
The one loop divergences will cancel, provided that the SUSY particles have masses below the Fermi scale $| m_B^{\ 2} - m_F^{\ 2} | < 1Tev^{\ 2}$

- The SUSY particle masses expected to be the same order as m_W, m_Z and m_H

Minimal Particle Content

The Minimal Supersymmetric Standard Model (MSSM)

Where are they?
m (positron) = m (electron)
But not so for selectron
→ SUSY is broken!



Gauge / Gaugino Sector

Standard Bosons	Supersymmetric Partners
$W^{\pm}$, $H^{\pm}$	Charginos $\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_2^{\pm}$
γ, Z h, H, A	Neutralinos $\tilde{\chi}_1^0$ $\tilde{\chi}_2^0$ $\tilde{\chi}_3^0$ $\tilde{\chi}_4^0$
g_i	Gluinos $\tilde{g}_i$

[Two Higgs doublets] [All fermions]

Particle / Sparticle Sector

Standard Particles	Supersymmetric Partners
Leptons ℓ	Sleptons $\tilde{\ell}_{R,L}$
Neutrinos ν_ℓ	Sneutrinos $\tilde{\nu}_\ell$
Quarks q	Squarks $\tilde{q}_{R,L}$

[All scalars]

The Search for Supersymmetry

- In most versions of the theory SUSY particles can only be created or destroyed in *pairs*
  - the decay of a SUSY particle → one SUSY particle in the final state
  - the stable *lightest* SUSY particle (the LSP-Dark Matter candidate)!
- Most models assume the LSP is a *neutralino*

- Typical production reaction ~

$$e^+ e^- \rightarrow \tilde{e}^- \tilde{e}^+$$ (selectron-antiselectron pair)

- … and decay

$$\tilde{e}^\pm \rightarrow e^\pm \tilde{\chi}^0$$ (stable LSP - the neutralino)

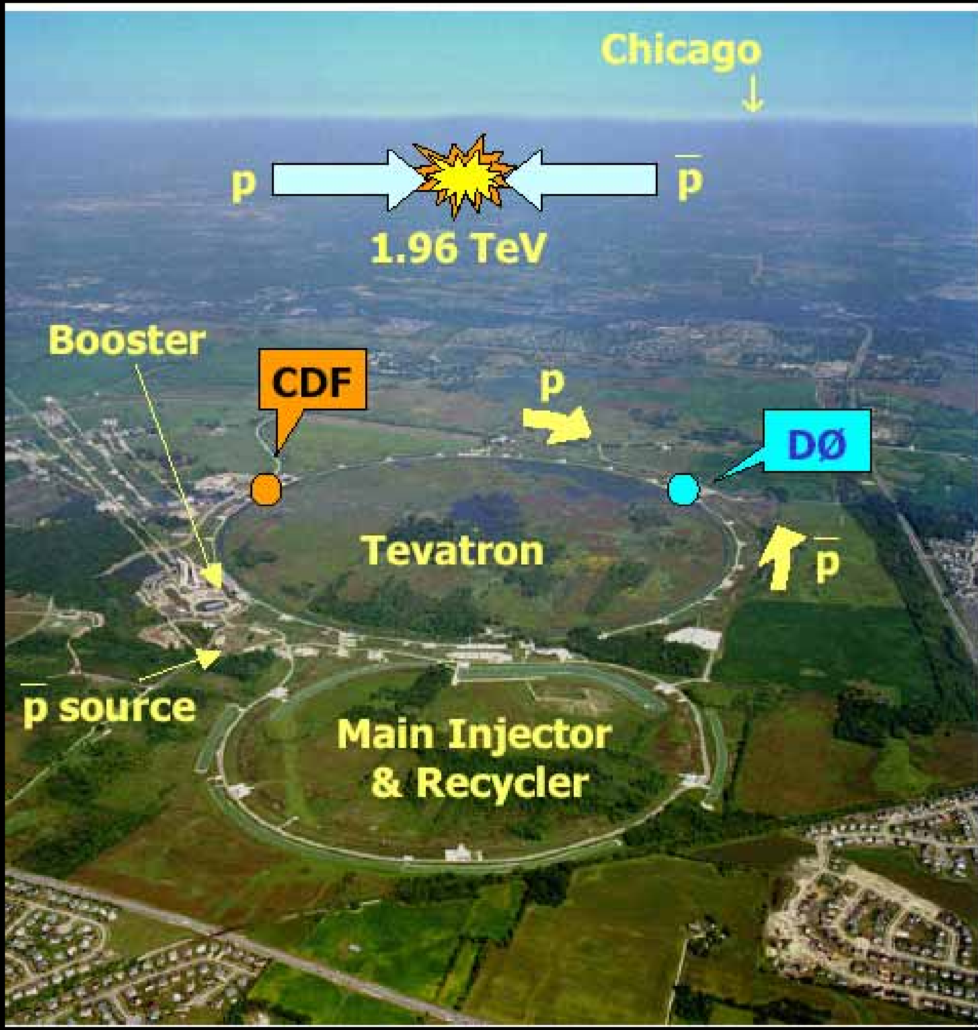
- Since the neutralino is not detected (because it is very weakly interacting) there will be a large amount of *missing energy and momentum* in these events

Success or Failure?

- SUSY signatures have been searched for exhaustively at particle colliders during the past10-15 years, so far without any evidence…
- LEP and The Tevatron has placed quite stringent limits on the allowed values of some of the parameters of the theory…
- Most SUSY particle masses are believed to be greater than ~100 GeV from their non-observation in current experiments…
- However, the masses of SUSY particles are predicted to be below 1 TeV and hence it is a fairly safe bet that if they exist they will be found at the Tevatron or the LHC

Tevatron at Fermi National Accelerator Lab

- The tevatron circulates protons and anti-protons
- Particle beams collide at experiment sites (CDF, DØ)
  - Energy in C.O.M.: ~2 TeV
- Now have > 600 pb^{-1} of data on tape
- Current analyses 200-390 pb^{-1}
- Run II goal: 4400-8500 pb^{-1}
  - Take data until 2009
- The tevatron is *Energy Frontier* until LHC turn-on



An example SUSY Search at hadron collider : Scalar-Quarks

- **Smaller cross sections than sleptons at** $e^{-}e^{+}$ collider
- **Signatures may not be the most favorable**
- **But, only if they happen to be lighter than other superpartners, they would be the first to be observed**

- **Decays**
- **Productions and Signatures**
- **Limits**
- **Pre-Run II SUSY Limits**

Decays

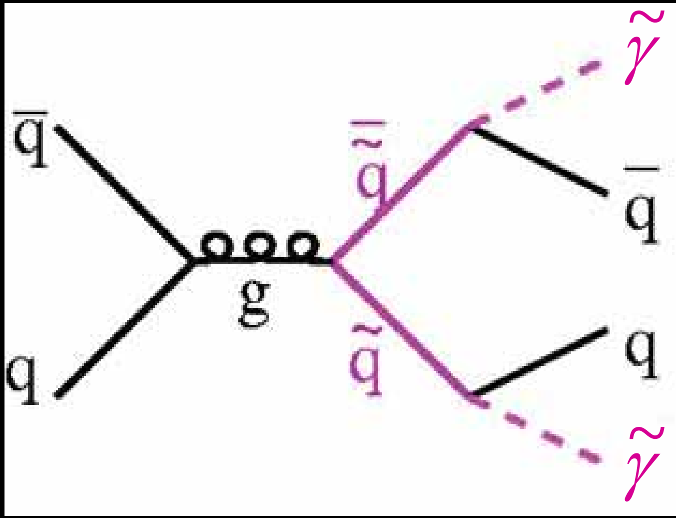
- Squarks always have a coupling to $\tilde{g}$, $\tilde{\gamma}$
- If the decays $\tilde{q} \to q\tilde{g}$, $\tilde{q} \to q\tilde{\gamma}$ are kinematically allowed, they will occur and dominate (strong pair production)

1. $\tilde{q} \to q\tilde{\gamma}$ can give a good signature of a quark jet and missing P_T (but small cross section)
2. $\tilde{q} \to q\tilde{g}$ can give a complicated signature from $\tilde{g} \to q\bar{q}\tilde{\gamma}$ but large strong interaction cross sections – one golden mode at the Tevatron

Productions and Signatures

- In hadron collisions there are several ways to produce squarks

  - One example of the Feynman diagram →
  - The signatures depend on the sizes of cross sections, on detector capabilities, and on the SM background



- While the $\tilde{q}\overline{\tilde{q}}$ cross section decreases for heavy $\tilde{q}$, if both squarks decayed via $\tilde{q} \rightarrow q\tilde{\gamma}$ the signature may be quite good
- It is important to identify the regions to identify $\tilde{q}\tilde{\gamma}$ or $\tilde{q}\overline{\tilde{q}}$ on an event-by-event basis…
- Since then a small number of events needed and large masses can be produced

Limits

- Squarks cannot be too light or we would have entirely new hadrons :

  $q q \tilde{q}, \tilde{q} \bar{q}$, etc. (must be 1 GeV scale)
- If Squarks rather light, we would have :

  $\tilde{q} \bar{\tilde{q}}$ (like *J/ψ, γ, etc.)*
- *But, these are not found…*
- *Squarks must be heavy!!*
- Now it is believed that

$$M_{\tilde{g}(\tilde{q})} > 195(300)\, GeV$$

Pre-Run II SUSY Limits

Need TEV limits

LEP2

- Limits:
  - e^+e^-: LEP 2, $\sqrt{s}$=130 - 208 GeV/c^2.
  - $p\bar{p}$: Tevatron Run 1, $\sqrt{s}$=1.8 TeV
- Take these into account in new searches

TEV

LEP2

Channel	M > (GeV)
$\tilde{\nu}$	43.7
$\tilde{e} \rightarrow e\tilde{\chi}_1^0$	99
$\tilde{\mu} \rightarrow \mu\tilde{\chi}_1^0$	95
$\tilde{\tau} \rightarrow \tau\tilde{\chi}_1^0$	85
$\tilde{t} \rightarrow c\tilde{\chi}_1^0$	95
$\tilde{t} \rightarrow bl\tilde{\nu}$	96
$\tilde{b} \rightarrow b\tilde{\chi}_1^0$	94
$\tilde{g},\tilde{q} \rightarrow j + E_T^{miss}$	195(300)
$\chi_1^{\pm} \rightarrow W\tilde{\chi}_1^0$	103.5

Conclusions

- **The Standard Model has been very successful**
- **Notwithstanding these successes, the Standard Model suffers from conceptual diseases, which can be cured in practice (with today's theoretical knowledge) by Supersymmetry**
- **The Tevatron Collider has a huge potential for new physics discoveries and for precision measurements - Higgs, SUSY parameters**
- Direct evidence for SUSY is expected to show up soon (Tevatron, LHC)
- **Discovery of SUSY, if it occurs, would be a revolution of physics in the 21st century**