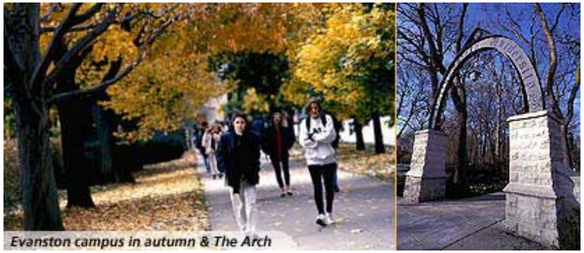
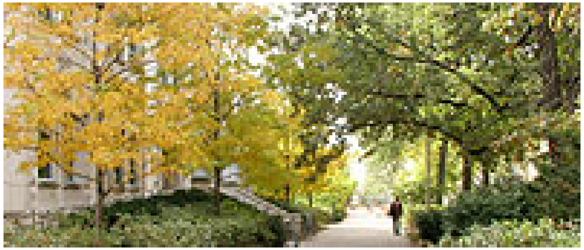
Searches for New Physics at High Energy Colliders





Colloquium
`Northwestern University`
3-October-2003

Michael Schmitt
Northwestern University

Outline

- What is “New Physics” and why is it so important?

  The Standard Model and its deficiencies

- What are particle “colliders” and why are they the right tool?

  LEP Tevatron LHC LC

- Theoretical Speculations – what might be the New Physics we find?

  Supersymmetry Strong Dynamics Extra Dimensions

- Closing remarks

What do I mean by "New Physics" (NP)?

(1) changes in our picture of fundamental particles and their interactions

i.e., things along the lines of:

- Are there new particles we have not yet observed?
- Do the iteractions among known particles change at high energies?
- Is there a new organzing principle which explains why we have three generations?

(2) changes in our appreciation of known processes

- Example: the obervation of "rapidity gaps" in diffractive scattering.

(Essentially this amounts to a collective behavior of the quarks and gluons inside protons which scatter at small angles.)

While such phenomena are interesting and sometimes beautiful, they do not change our picture of what are the fundamental particles and the forces among them.

In this talk we are concerned with the first item above.

(note: In principle, one can see NP though very rare processes, too – hopefully there will be another colloquium about this by another faculty soon!)

Why is it important to look for NP? – What is wrong with the "old physics" ?

The best explanation comes from an example from undergraduate physics –

the unification of electricity and magnetism.

Maxwell achieved this in the later 19th century. It was largely a theoretical triumph which led to the prediction of exciting new phenomena, namely, electro-magnetic waves. This was soon confirmed by Hertz.

So this advancement of the understanding of two fundamental forces of Nature, (electricity & magnetism) achieved BEAUTY and UTILITY.

It is also the first example of a field theory.

In Particle Physics we are following this same tradition.

(Of course, there have been many other advances since the days of Maxwell & Hertz. . .)

The Standard Model (SM) of Particle Physics

- four forces: electromagnetism, weak, strong, gravity
- electromagentism+weak = electro-weak (second unification)
- gravity not really included
- matter is made of spin-$\frac{1}{2}$ fermions: quarks and leptons
- there are three generations of fermions
- for every fermion particle, there is an anti-particle (eg., e^+ for e^-)
- the gauge forces are 'carried' by spin-1 bosons: γ, $W^\pm$, Z and g
- non-Abelian gauge structure
- there is a spin-0 boson, the 'Higgs,' (h) which unifies electromagnetism and the weak force, gives masses to the W and Z bosons, provides a basis for the masses of the (matter) fermions

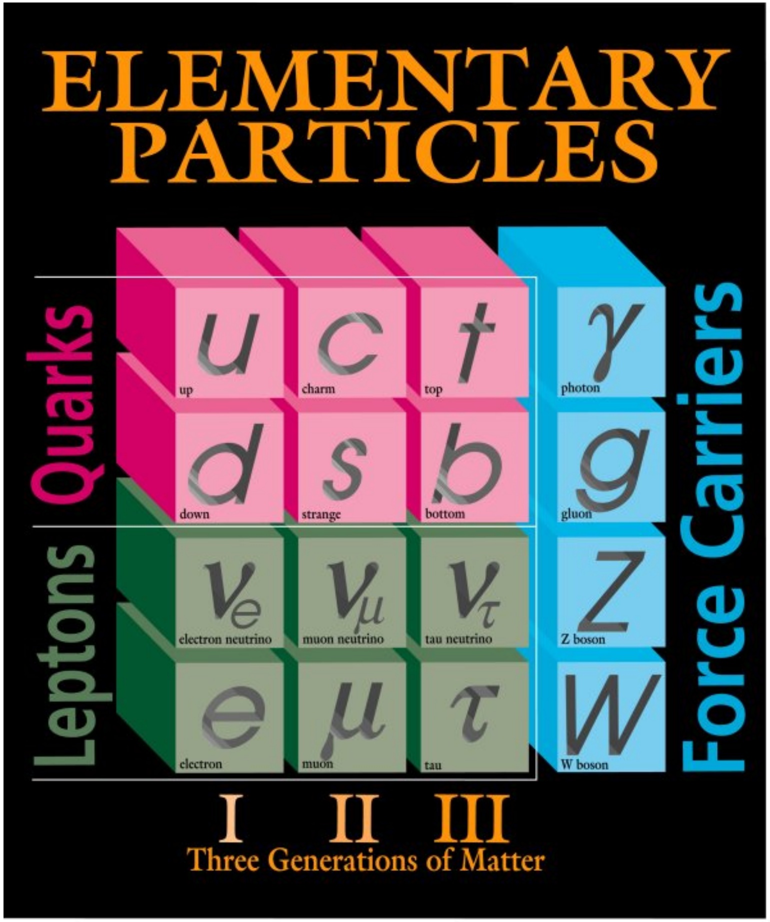
⋆ To date, the SM provides accurate predictions for a huge variety of processes, and all of these predictions are confirmed by experiments.

⋆ In fact, there is no direct evidence for physics beyond the SM (*i.e.*, no new particles or forces).

Yet we know the SM is deficient!

The particles of the SM are arranged as follows:

There is also a Higgs boson, not shown, which is responsible for 'separating' the weak and electromagnetic forces.



Fermilab 95-759

Deficiencies of the SM ("the old physics")

- The Higgs mechanism is ad hoc. – and unconfirmed
- no explanation for three generations (flavor, CP)
- gauge structure $\mathrm{SU(3)}_c \times \mathrm{SU(2)}_W \times \mathrm{U(1)}_Y$ is purely empirical
- no accounting for gravity
- Higgs boson is not stable wrt higher order quantum corrections

Generally we view the SM as the "low-energy" effective theory of a more fundamental theory which will explain some or all of the above.

We want to find the first evidence for that theory.

Of course we do not know what that might be, but theorists have made proposals which are worth considering seriously.

I will discuss three of these:

1. Supersymmetry
2. Strong Dynamics
3. Extra Dimensions

These are independent ideas, yet there are also hybrids. I will keep it simple. . .

What is a particle "collider" and why is it so useful for finding NP?

Our discoveries of NP climb a "ladder of mass."

$\longrightarrow$ New particles are heavier than old ones $(e, \mu, \tau$ and $u, c, t)$

To create particles with more mass, we need more (kinetic) energy in the initial state.

Recall: Einstein $\longrightarrow$ **MASS = ENERGY**

- If you have a beam of particles (say, protons) with energy $E_p \gg M_p$, you could collide them into a target (of, say, protons).
- The center-of-mass energy is then, approximately, $\sqrt{s}_{\mathrm{FT}} = \sqrt{2\,E_p\,M_p}$.
- If you have two such beams and collide them head-on, then $\sqrt{s}_{\mathrm{CB}} = 2\,E_p$.
- Clearly, when $E_p \gg M_p$ (and $M_p \approx 1$ GeV), $\sqrt{s}_{\mathrm{CB}} \gg \sqrt{s}_{\mathrm{FT}}$.
- So, if the beams are intense enough to give us a good rate, then colliding beams are the way to get high energies, and hence, high mass "reach."

It is usually most effective to collide beams of particles and antiparticles: e^+e^- and $p\bar{p}$.

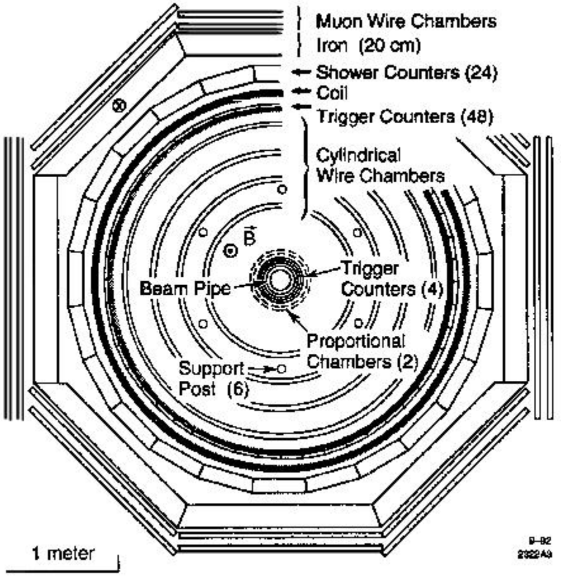
EXAMPLE 1: The discovery of the τ lepton at an e^+e^- collider.

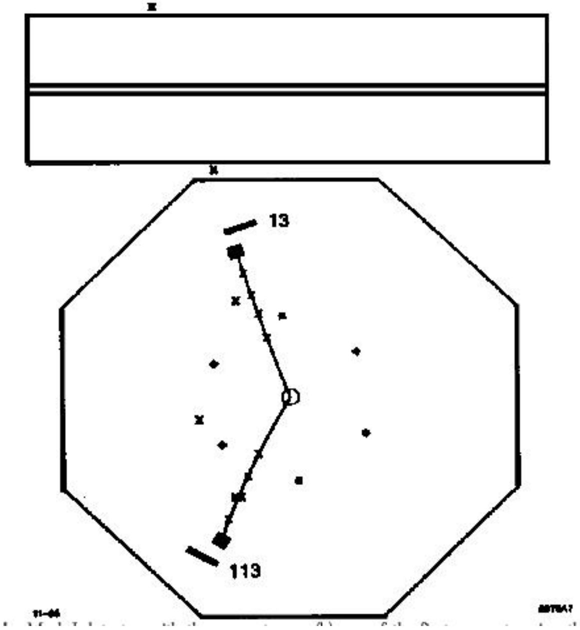
Martin Perl at SPEAR (Stanford) 1975 e^+e^- collisions at 0.005 GeV Nobel Prize (1995)

- ⋆ A big surprise, people did not believe it at first.
- ⋆ Key was the unexpected presence of “mixed” events containing an electron and a muon.

(Normally would be forbidden, ie, $e^+e^- \not\to e^+\mu^-$)

Interpretation: $e^+e^- \to \tau^+\tau^-$ $\quad \tau^+ \to \bar{\nu}_\tau\, e^+\, \nu_e$ $\quad \tau^- \to \nu_\tau\, \mu^-\, \bar{\nu}_\mu$





EXAMPLE 2: The discovery of the W and Z bosons at a $p\bar{p}$ collider.

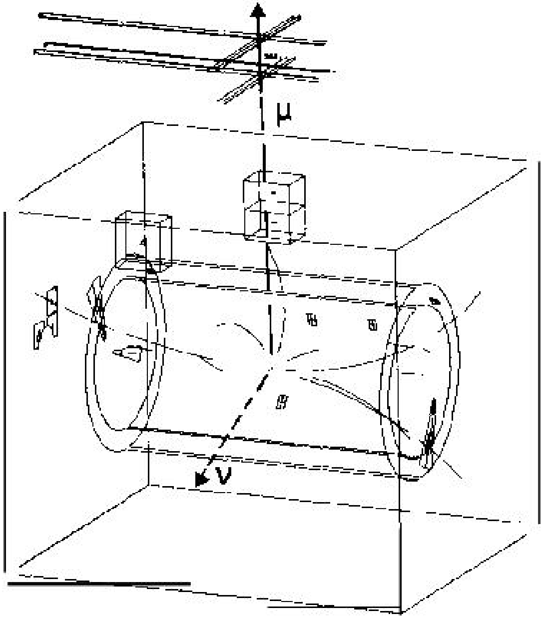
Carlo Rubbia & Simon van der Meer CERN SPS $\sqrt{s} = 540$ GeV Nobel, 1984

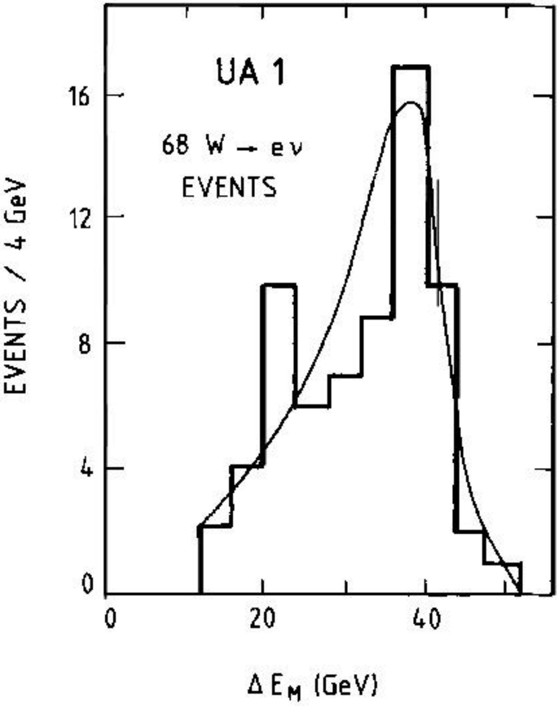
The electroweak bosons $W^{\pm}$ and Z were predicted by the then-new SM.

They carry the weak force in charged and neutral channels.

charged: $K^{+} \rightarrow \mu^{+}\nu_{\mu}$ and $\nu_{\mu}\, e^{-} \rightarrow \mu^{-}\, \nu_{e}$
neutral: $\nu_{e}\, e^{-} \rightarrow \nu_{e}\, e^{-}$

The new vector bosons were observed via their leptonic decays: $W^{\pm} \rightarrow e^{\pm}\, \nu_{e}$ and $\mu^{\pm}\nu_{\mu}$ and $Z \rightarrow e^{+}e^{-}$.





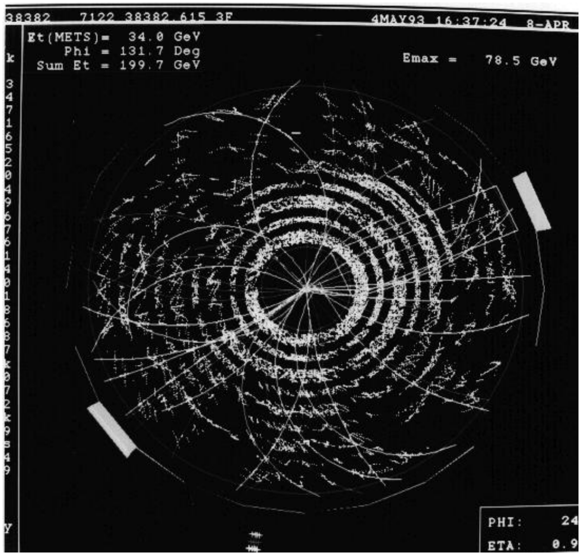
To achieve high enough beam intensities, a new technique called "stochastic cooling" was invented.

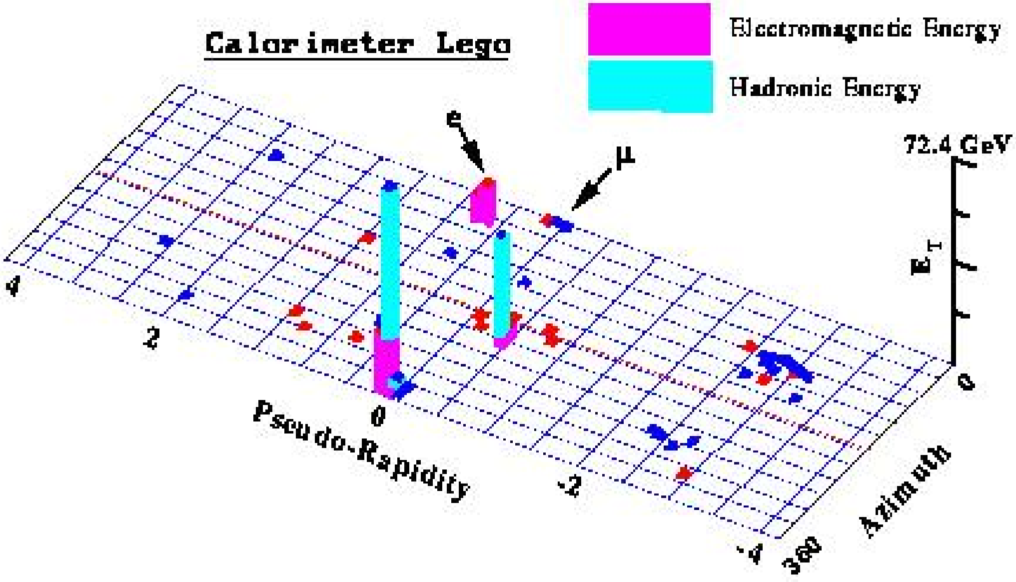
EXAMPLE 3: The discovery of the top quark.

The CDF & DØ Collaborations Fermilab Tevatron, $\sqrt{s} = 1800$ GeV 1994-96 No Nobel Prize

- ⋆ The top quark is special because it is so massive – 175 GeV.
- ⋆ Its decays are relatively complicated and the events are rare. . .

$$p\bar{p} \to t\bar{t} \quad t \to b\,W \quad W \to e\nu \ \ (\mu\nu)$$





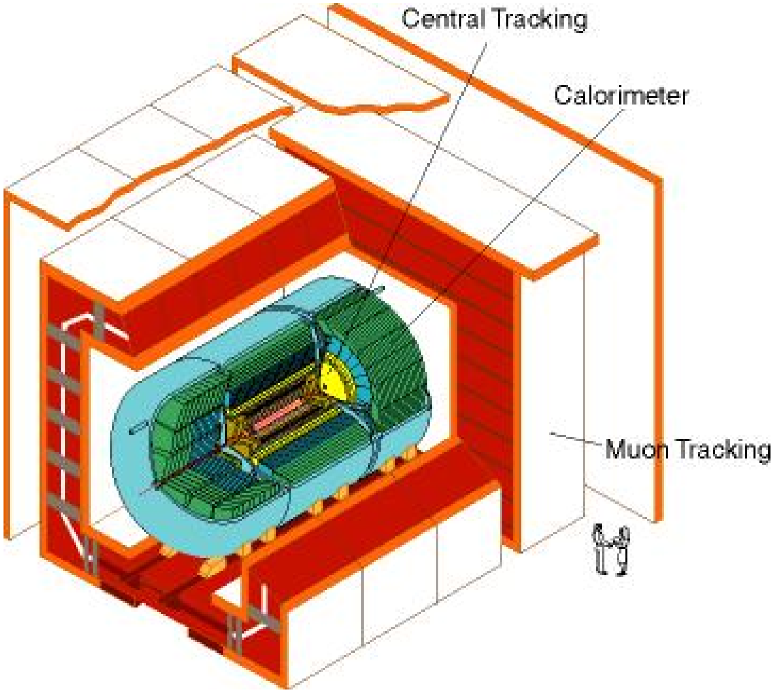
The analysis teams numbered in the dozens and it took $\mathcal{O}(2\text{ years})$ to complete the anlayses.

Note that Prof. Buchholz, Schellman & Gobbi were members of DØ at that time. (I joined CDF in 1998.)

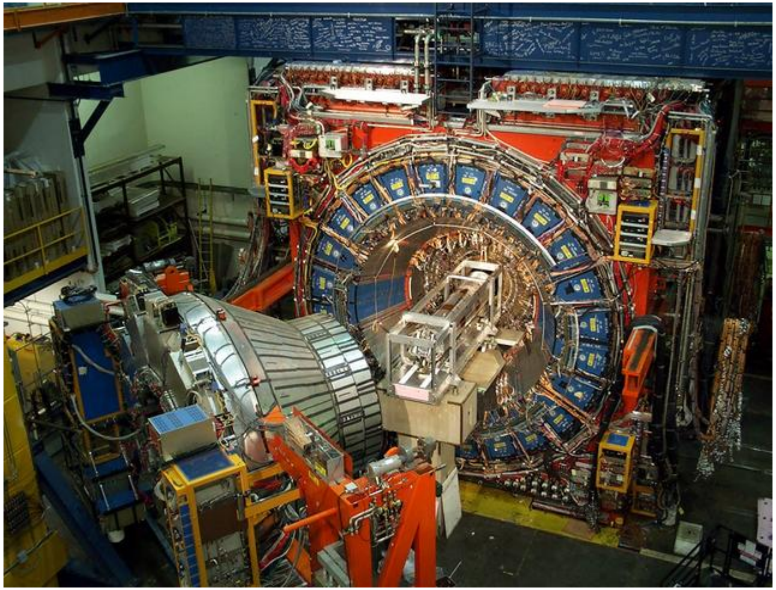
RECENT/CURRENT/FUTURE Colliders

$\boxed{\text{LEP}}$ – e^+e^- with $\sqrt{s}$ up to 209 GeV – shut down in 2000.

$\boxed{\text{Tevatron}}$ – $p\bar{p}$ with $\sqrt{s}$ up to 1980 GeV – going strong.

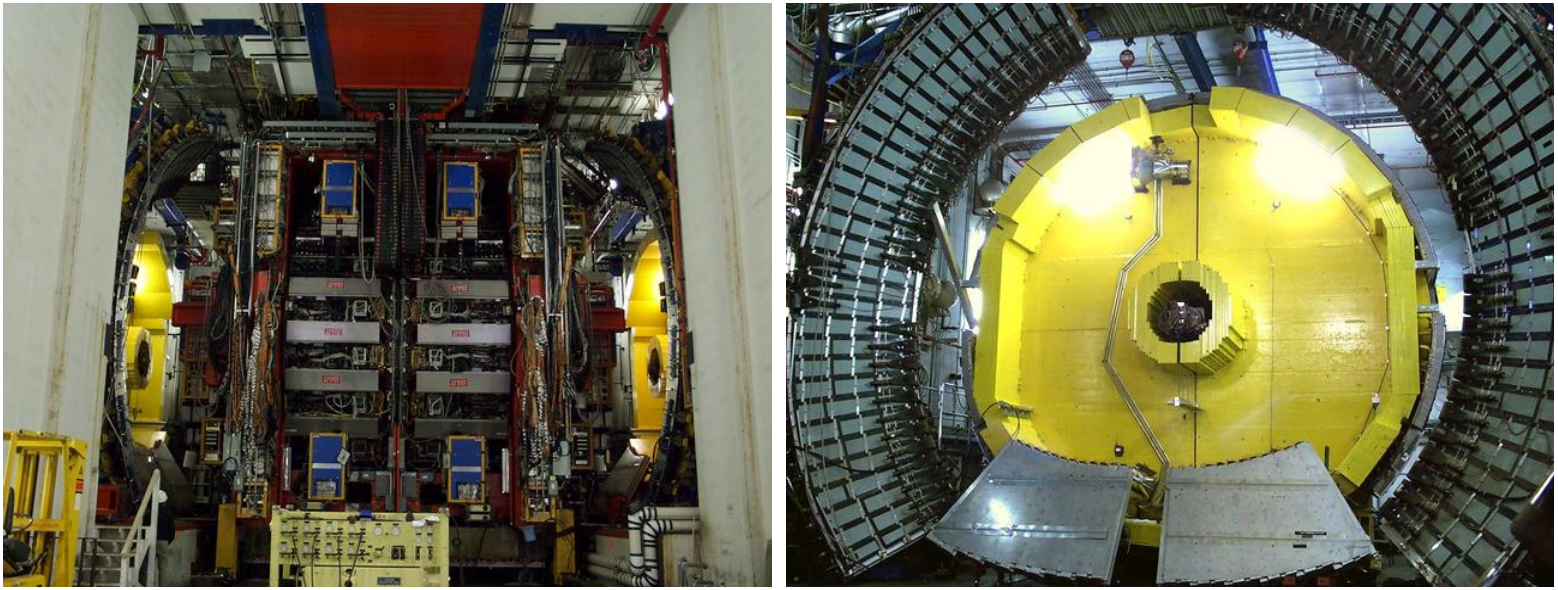


The DØ Detector



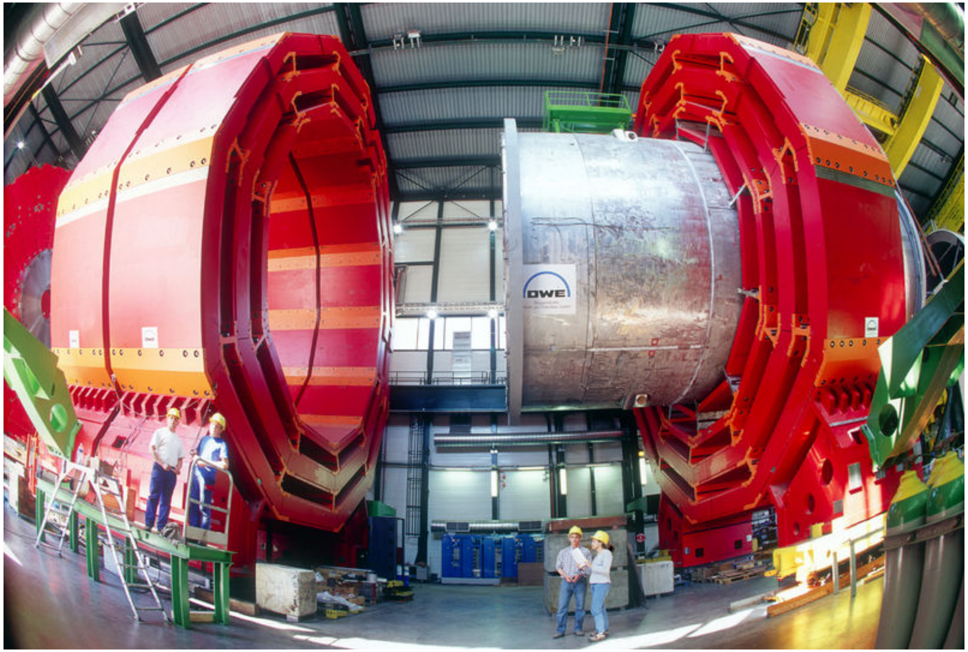
The CDF Detector

Two other pictures of the CDF Detector. . .



$\boxed{\text{LHC}}$ – pp with $\sqrt{s}$ up to 14 TeV in construction phase – starts in 2007–8

LHC Dipole Magnets



CMS Insertion Test

Prof. Gobbi is developing advances pixel devices for CMS.

$\boxed{\text{LC}}$ – proposals under consideration – different technologies, different locations, $\sqrt{s}$ =350 or 500 or 1000 or 2000 GeV

Prof. Velasco's group very active here.

Supersymmetry (SUSY)

- The only possible extension of the Poincaré group.

- Break down the rigid classification

  matter ↔ fermions   forces ↔ bosons

- Required by "String Theory"

  (possibly the ultimate theory of fundamental particles and interactions – but it is much too early to tell)

- Follows the same approach as most the SM *i.e.*, perturbativity at high energies.

- Solves some of the flaws of the SM

  ex: hierarchy problem, incorporation of gravity, particle physics explanation for dark matter

  (see lectures by John Ellis in November)

- Might already be wrong ⟶ no Higgs yet, no SUSY particles up to ∼100 GeV

SUPERSYMMETRY SEARCHES

What is a 'search' anyway? $\longrightarrow$ like designing a sophisticated, software SIEVE

We "reconstruct" each collision and pick out salient features:

leptons, photons, jets (which come from quarks and gluons), b-quark and c-quark jets, missing energy ($\not\!\!E_T$) and overall kinematic properties

We push literally millions of these events through and subject each to a 'decision tree.'

(*e.g.*, does it have an energetic lepton? yes → keep; no → reject)

- We are left with (typically) a handful of unusual events, N_O.
- The SM tells us to expect N_E (which we call the 'background.')
- If $N_O > N_W$ *significantly*, then we have a 'discovery.'
- The 'signal' would be any excess $N_S = N_O - N_E$.

For any given model (SUSY or otherwise), there will be a prediction for N_S.
In principle all models are falsifiable on this basis.

EXAMPLE 1: The Higgs Bosons

Signal:

$p\bar{p} \longrightarrow W\,h$

$W \longrightarrow e\nu$: energetic lepton and $\not{E}_T$

$h \longrightarrow b\bar{b}$: two b-quark jets

- basis for the sieve aka event selection

However, these events resemble the background

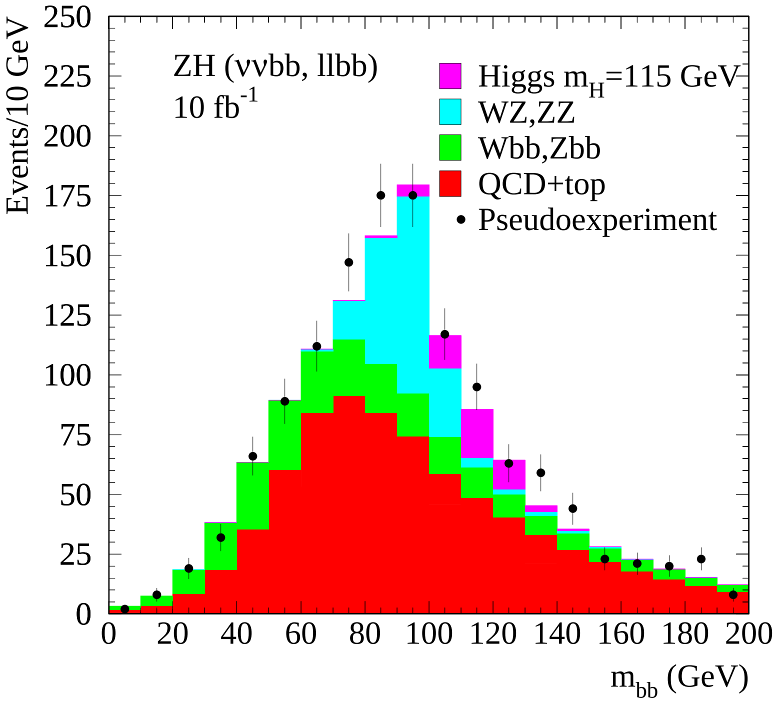
$p\bar{p} \longrightarrow W\,g^*$

$W \longrightarrow e\nu \qquad g^* \longrightarrow b\bar{b}$

Distinguish these using $M(b\bar{b})$

Tevatron has limited ability to find the Higgs.
But, could exclude it up to ∼130 GeV.

LHC will find Higgs within 2 years of running.



(Fake Tevatron signal – not real data.)

Why is the Higgs so important?

⟶ challenge the SM ⟶ crucial test of SUSY ($M_h <$ 135 GeV)

In fact, in SUSY there are four distinct Higgs bosons, h, H, A and $H^{\pm}$

EXAMPLE 2: Associated Chargino-Neutralino Production $p\bar{p} \longrightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$

'chargino' $\tilde{\chi}_i^\pm$ = fermionic partners of $W^\pm$ and $H^\pm$
'neutralino' $\tilde{\chi}_i^0$ = fermionic partners of γ, Z, h, H, A

These 'interaction eigenstates' mix to form 'mass eigenstates.'

(The mixing is determined by fundamental parameters of the theory which would have to be measured.)

Interactions are essentially the same as SM gauge interactions:

$$W^+ \longrightarrow e^+ \, \nu_e \qquad \Rightarrow \qquad \tilde{\chi}_1^\pm \longrightarrow \tilde{e}^{+(*)} \, \nu_e \longrightarrow e^+ \, \nu_e \, \tilde{\chi}_1^0$$

Several topologies are possible:

- 4 Jets and $\not{E}_T$
- 2 Jets and 2 leptons and $\not{E}_T$
- 2 Jets and 1 lepton and $\not{E}_T$
- 3 leptons and $\not{E}_T$

The last one has the lowest *a priori* rate from SM processes.

So we focus on the so-called 'tri-lepton' signal:

$$p\bar{p} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \qquad \tilde{\chi}_1^\pm \rightarrow \ell \tilde{\chi}_1^0 \qquad \tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$$

The leptons will tend to have a lot of energy from the decays of the charginos and neutralinos.

$\longrightarrow$ demand 2–3 energetic leptons. (usually, e or μ)

There is always one energetic neutrino which leaves no signal in the apparatus (this is always true for ν's) so there is at least a little $\not{E}_T$.

So far, this is all true for the SM process $p\bar{p} \rightarrow WZ$.

What we want is something that in some sense looks like $p\bar{p} \rightarrow WZ\tilde{\chi}_1^0\tilde{\chi}_1^0$

The key is missing energy $\not{E}_T$.

Also, since the decay $\tilde{\chi}_2^0 \rightarrow \ell^+ \ell^- \tilde{\chi}_1^0$ is 3-body, there is no peak in $M(\ell^+\ell^-)$.

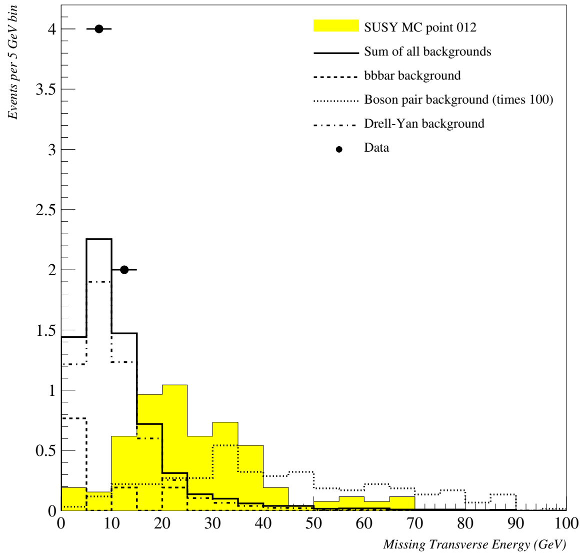
In a real search at CDF, the actual cuts (the “sieve”) is:

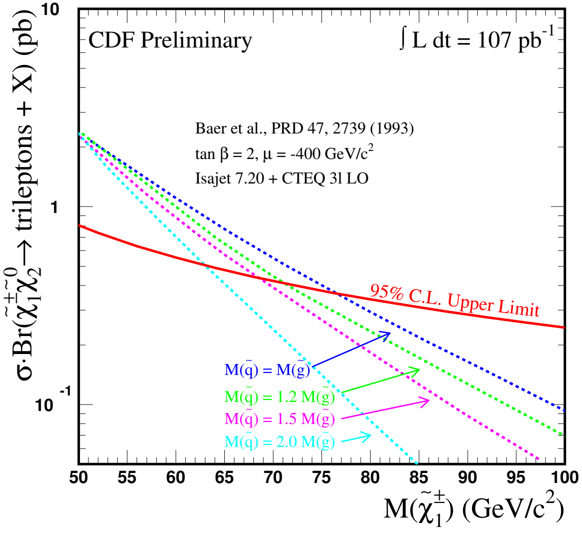
- require three identified leptons (e or μ), with $p_T > 11, 5, 5$ GeV
- they must be in well instrumented regions of the detector (reduce false leptons)
- $\Delta\phi_{12} < 170^\circ$ (removes SM process $p\bar{p} \to \ell^+\ell^-$)
- remove events when $M(\ell^+\ell^-) \approx M_Z$
- $\not\!\!E_T > 15$ GeV

The search from Run I (mid-nineties) found no evidence for SUSY chargino and neutralino production.

`Phys. Rev. Lett. 80 (1998) 5275`

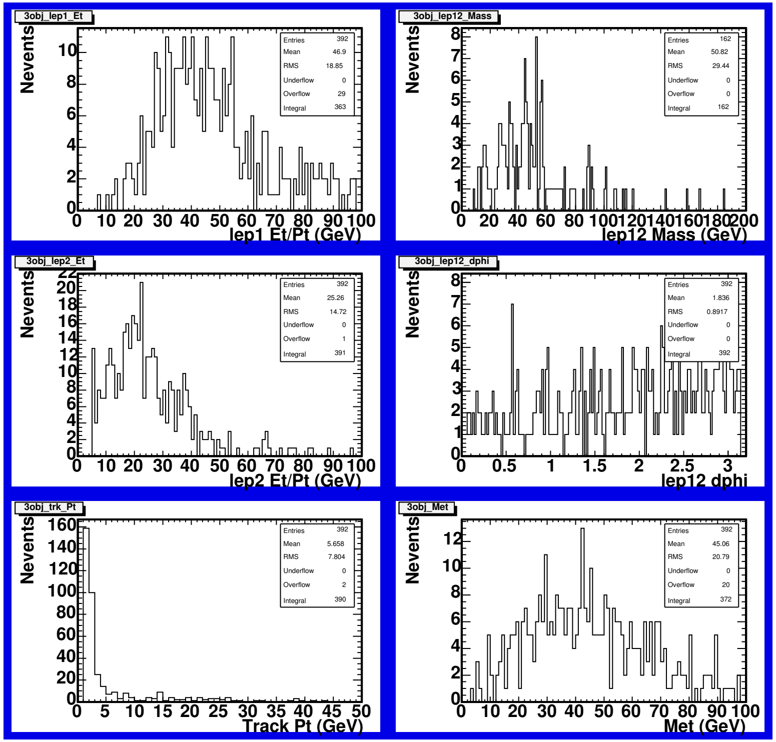
This search turned out to be less sensitive that the corresponding searches at LEP, which placed bounds $M(\tilde{\chi}_1^\pm) > 103$ GeV at 95% CL.

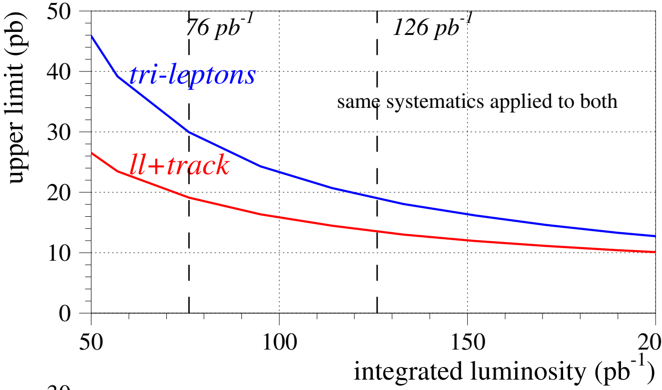


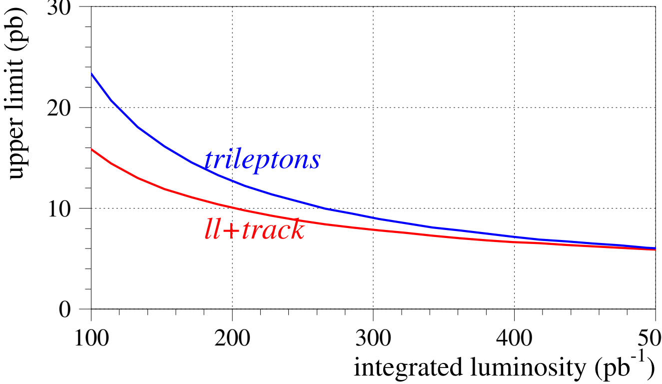


Now we have a chance to extend the sensitivity of this search in Run II (started in 2001 – lasts until ∼2009).

John Zhou (Rutgers) and I are extending the senstivity of this search by utilizing well understood data sets and accepting changing the search criteria slightly in order to accept τ decays.

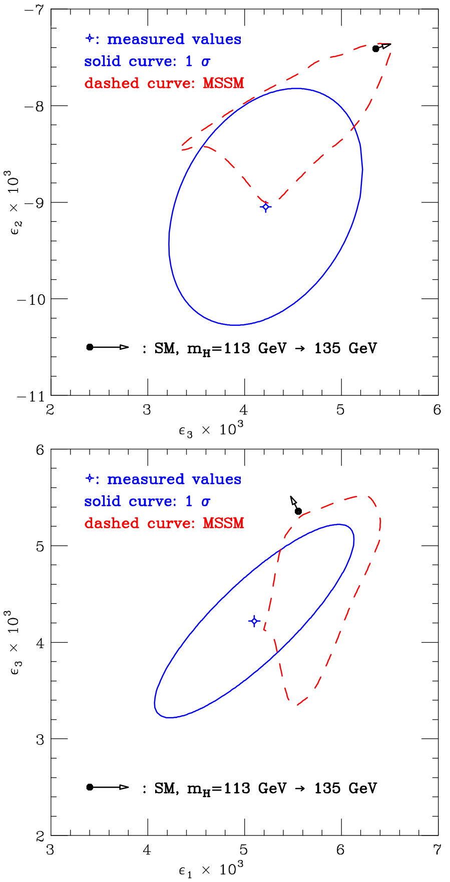




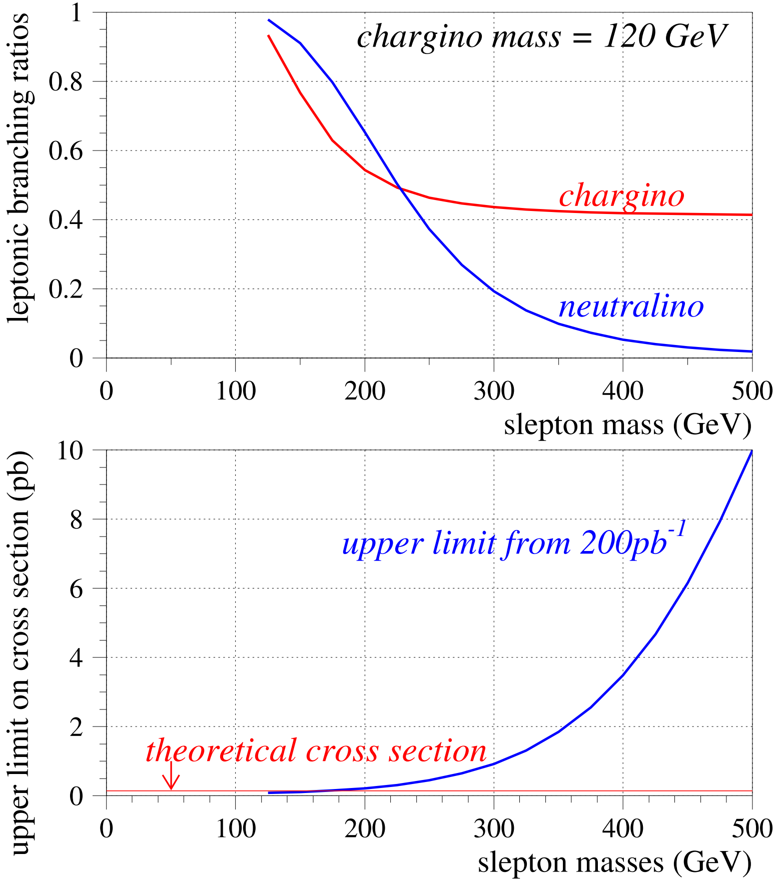


There is an important theoretical scenario which favors a discovery in this particular mode.

G. Altarelli has shown that precision electroweak measurements favor light sleptons. `hep-ph/0106029`



These ϵ_i are sensitive to the virtual effects of SUSY particles.



Light sleptons greatly enhance the tri-lepton signal.

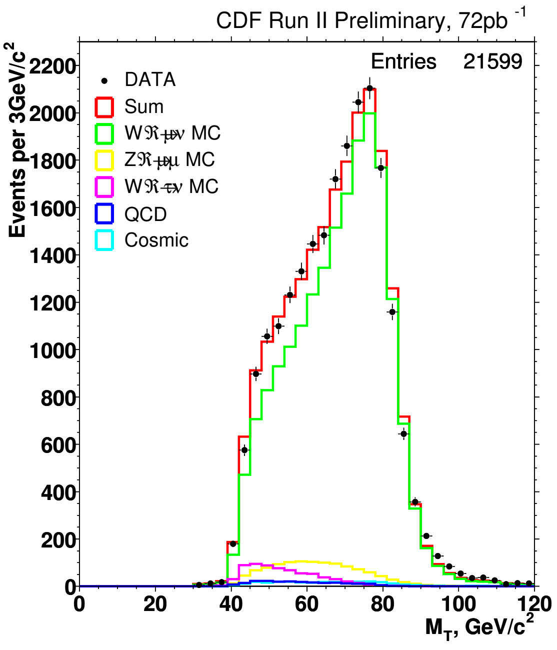
How do we know we understand lepton-based signals in the CDF data?

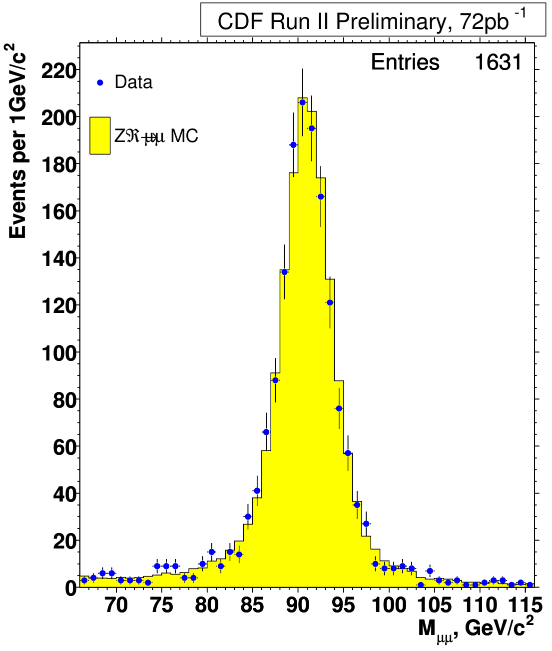
As in any experiment, you first have to establish known benchmarks.

One of the most basic and most useful is the energetic lepton signal coming from the inclusive production of W and Z bosons – the same process as Rubbia used in 1981 to discover these particles.

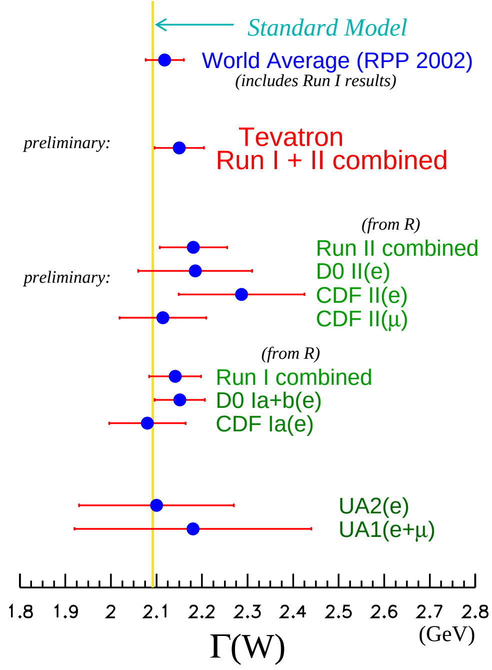
$$p\bar{p} \longrightarrow W^{\pm} \longrightarrow \ell^{\pm}\nu$$

$$p\bar{p} \longrightarrow Z \longrightarrow \ell^{+}\ell^{-}$$





TeVEWWG



(analysis projects with Victoria Martin)

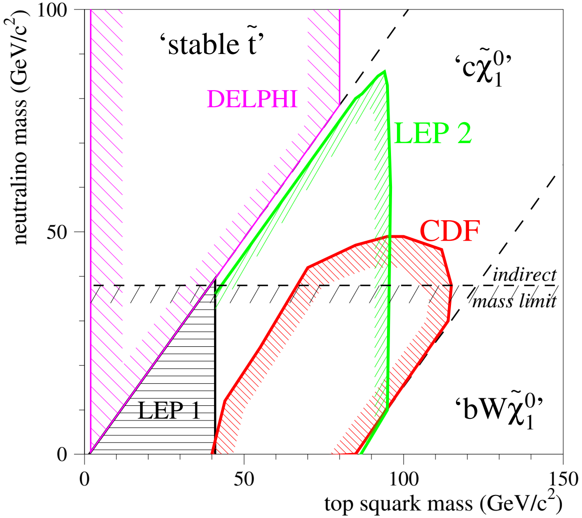
EXAMPLE 3: Scalar-top Production $p\bar{p} \longrightarrow \tilde{t}_1\tilde{t}_1^*$

The SUSY partner of the top quark is called the 'stop.'
It has spin-0.

The interaction eigenstates $\tilde{t}_L$ and $\tilde{t}_R$ will mix significantly, leading to a relative light mass eigenstate, $\tilde{t}_1$.

If it is not very heavy, then it will decay via a FCNC $\tilde{t}_1 \longrightarrow c\,\tilde{\chi}_1^0$.

The signature will be:
a pair of charm-quark jets and missing energy.



M.S. PDG Review Article

This analysis will be greatly improved in Run II.
Preliminary results on the jets+$\not\!\!E_T$ channel have been shown in the context of LQ searches.

We are working (NWU+U.Florida) to improve the sensitivity for stop signals in the Run II data. (Results not yet approved for public dissemination.)

There are several other important searches for squarks and gluinos based on jets and $\not\!\!E_T$.

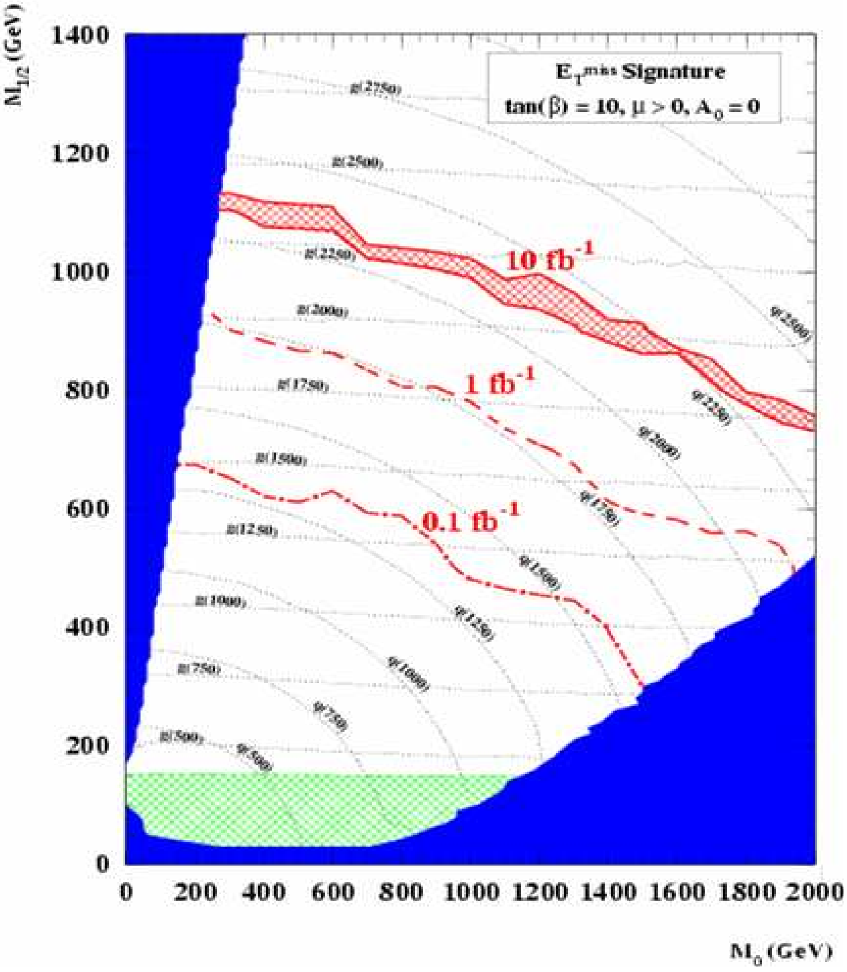
Any of these could turn up a signal in Run II.

At best, however, we would have a handful of events compared to an expected background of a couple. ⟶ not very stunning.

The LHC will have amazing signals for SUSY (if SUSY is the correct theory of Nature).

Signals at the limit of the Tevatron's capabilities ($\sqrt{s}$ = 2 TeV) would be found within days at the LHC ($\sqrt{s}$ = 14 TeV)

The signals are much larger and easier to distinguish from the background processes.



CMS Study

And why do we need a high energy Linear Collider, then?

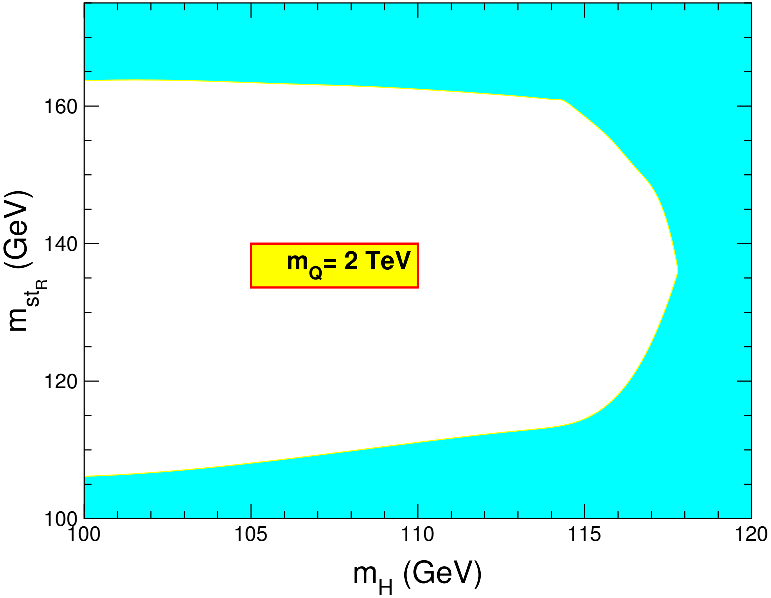
If SUSY particles are discovered at the Tevatron and the LHC, then a high energy e^+e^- collider will be needed to measure their properties accurately. This needed to fix the parameters of the theory and, ultimately, to understand its structure, *i.e.*, to distinguish among models.

Example: The baryon asymmetry of the universe cannot be explained by the SM.

SUSY can explain it through electroweak baryogenesis if the Higgs is not too heavy (less than 118 GeV) and if the lightest stop is also not too heavy (165 GeV). ('electroweak baryogenesis')

If these particles are observed at the Tevatron and LHC, it will be important to measure their properties in order to test this theory of EWBG.

A LC can measure the mass to ∼1% and the mixing angle, and test for CP violations.



Note: there are other theories of 'leptogenesis' which are closely connected with recent discoveries of the oscillations of neutrinos.

Strong Dynamics

Is SUSY too simple / naive / easy? ⟶ Let's not assume perturbativity.

Ansatz: High energy theory is like hadronic physics.
Use our understanding of that: quarks and gluons form bound states (π and ρ)

(Note: important ongoing work in this area by Prof. Seth and Prof. Rosen.)

Varietes of Strong Dynamics models:

1. composite Higgs –

   Higgs is a *composite* of the top quark and a new quark.

   Physics of the new quark and other composites appear at the TeV scale

   (just as the π and ρ appear somewhat above Λ_{QCD}).

   There should also be some new Z bosons.

2. 'Technicolor' –

   There is no Higgs particle at all.

   EWSB comes about through a new interaction which is strong at the TeV scale.

   There are new particles (π_{TC}'s and ρ_{TC}'s) which resemble an extended Higgs sector.

   There must be a WW resonance below 2 TeV.

But let's take a step back from the theoretical debate and think about the experimental view.

Suppose we discovered an excess of charm-jets and $\not\!\!E_T$.

We cannot be sure what is the source of the $\not\!\!E_T$ – it could just be a pair of ordinary neutrinos. We would need to **interpret** $p\bar{p} \longrightarrow 2$ Jets$+\not\!\!E_T$.

It might be $p\bar{p} \rightarrow X\bar{X}$ with $X \rightarrow c\,\nu_\mu$.

This X particle we call a 'lepto-quark' (LQ) and it arises in, for example, some versions of Technicolor.

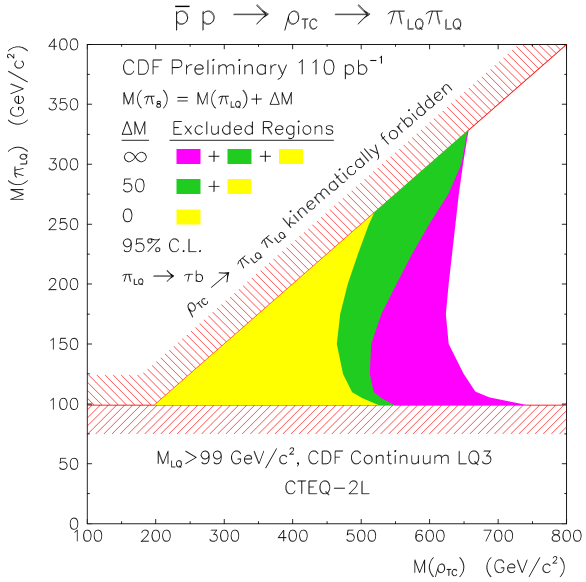
The point is that we can have a discovery, *i.e.*, proof of <u>some</u> physics beyond the SM, but it is another thing to say <u>which</u> theoretical model is correct.

This is one of the main arguments in favor of a high energy LC.

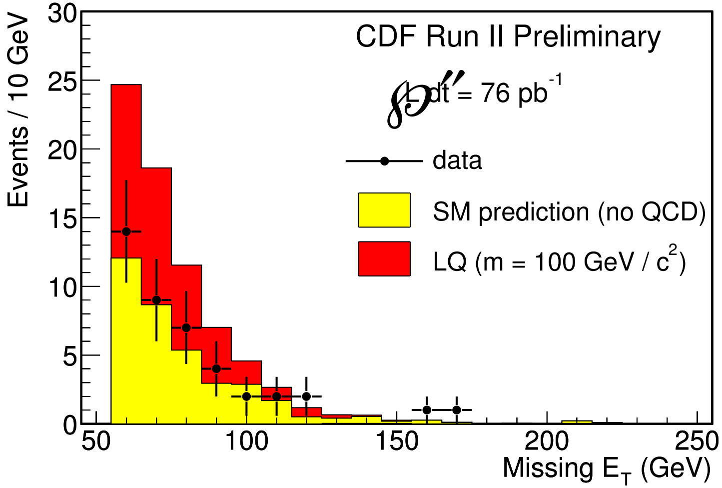
CDF Run II data have been used to search for LQ in the $q + \nu$ decay mode (among others).

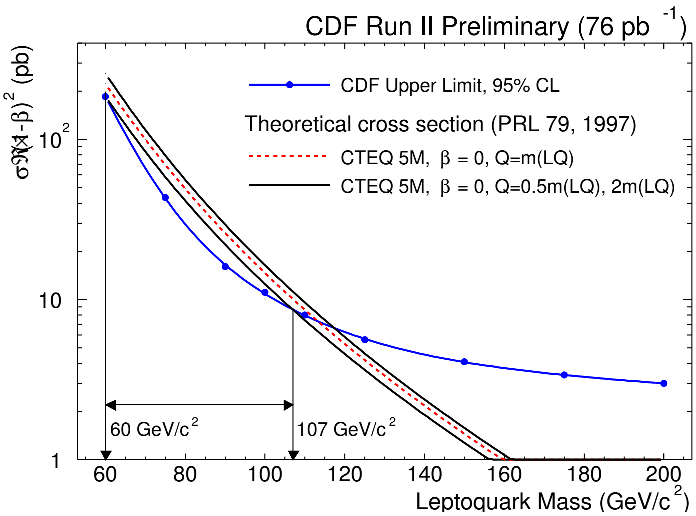
(This is the analysis were are improving for SUSY stop searches.)

The CDF searches for LQ have been used to test certain variants of techni-color theories.

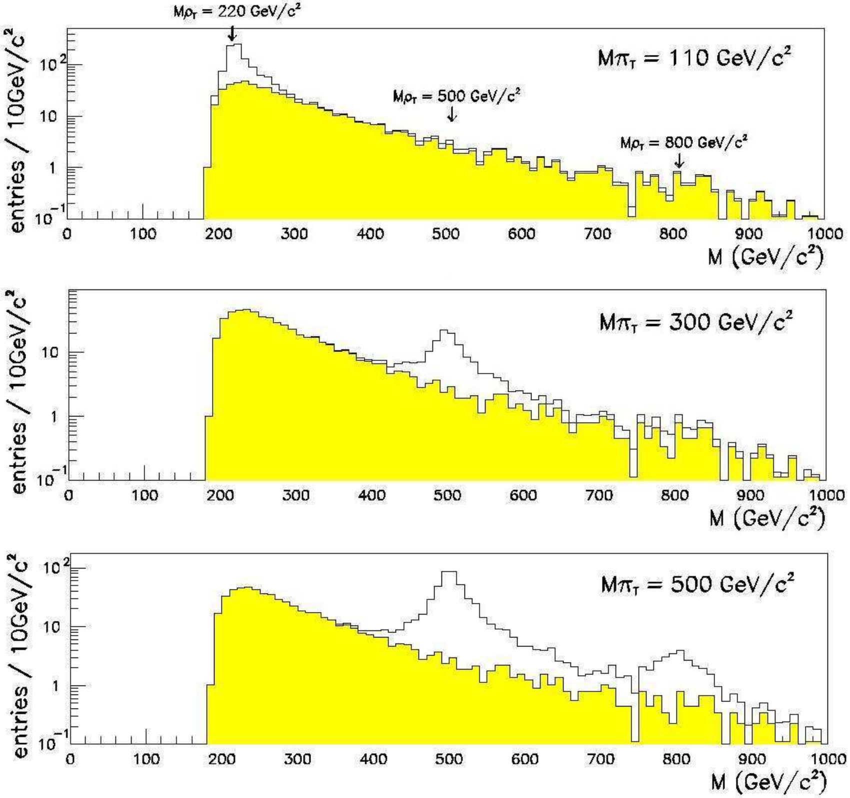


Phys.Rev.Lett. 82 (1999) 3206





At the LHC,
Technicolor signals such as $\rho_{\rm TC} \to WZ$ would be relatively clear.

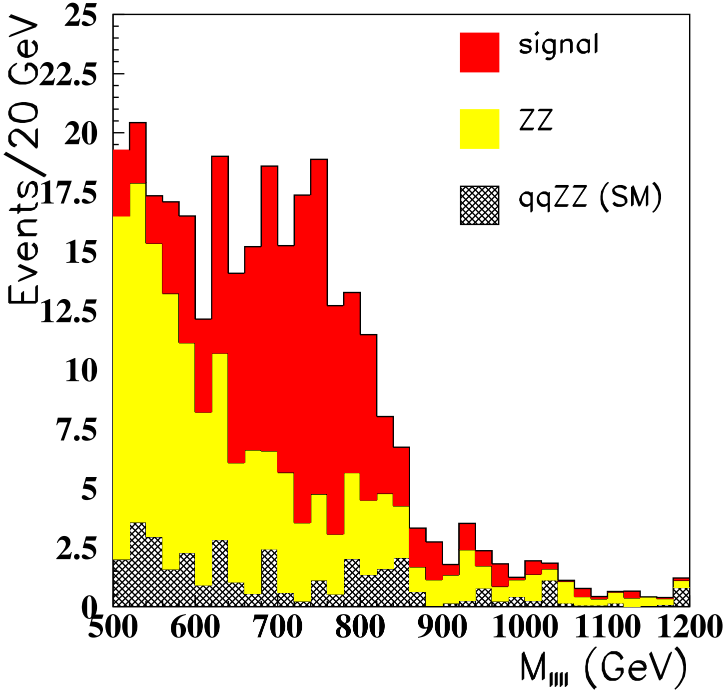


ATLAS study

However, of none of these new resonances is found, then the only real signal would come from a study of WW, ZZ and WZ scattering.

Here the signals are quite modest.

ex: vector resonance $\to ZZ \to 4\ell^\pm$



Extra Dimensions

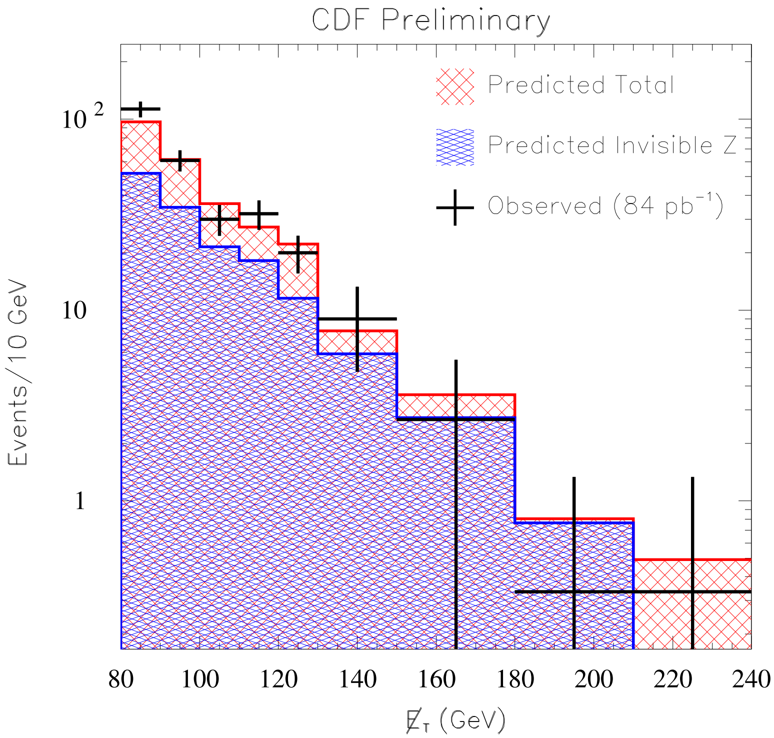
A fresh approach to the heirarchy problem – turns energy scales into geometry!

- Ansatz: there really are $3+1+\delta$ dimensions.
- gravity is weak because it propagates in $3+\delta$ while the other forces propagate in 3 dimenions.
  $\longrightarrow$ Novel prediction that gravity deviates from $1/r^2$ at small r!
- Gauss' Law gives a fundamental energy scale for gravity which can be close to the electro-weak scale.
  $\longrightarrow$ The hierarchy problem vanishes.
- String Theories demand extra dimensions.

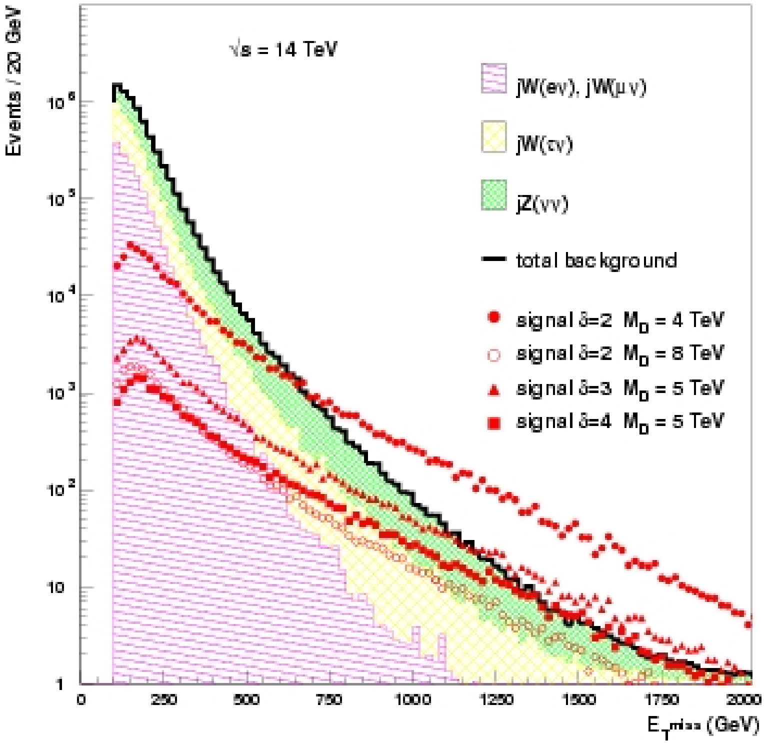
Two classes of theories:

1. 'flat'
   There are several extra dimensions, but they are very small.
   The higher-dimensional gravity field gives rise to new particles – "KK excitations."
   They can be produced directly in high energy collisions $\longrightarrow$ Jets $+\not{E}_T$
2. 'warped'
   Again there are exitations of the gravitational field
   but this time they are widely spaced $\mathcal{O}(1 \text{ TeV})$.
   The 'warping' comes from a non-flat metric for the extra dimension(s).
   The SM fields could propagate in the extra dimensions,
   and then they would have exitations, too. $\longrightarrow$ di-lepton resonances

A recent search for Jets+$\not{E}_T$ from CDF Run I shows no signs of a signal.



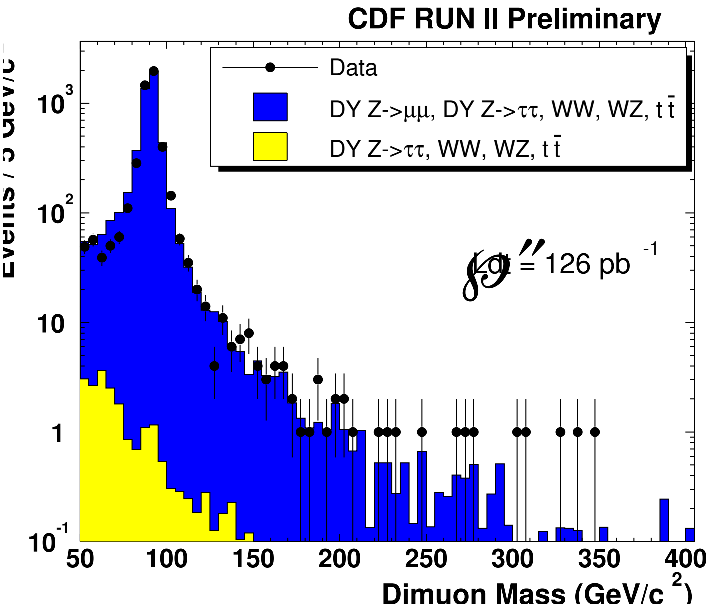
Here is a projection of how a signal could appear in this same channel, at the LHC.



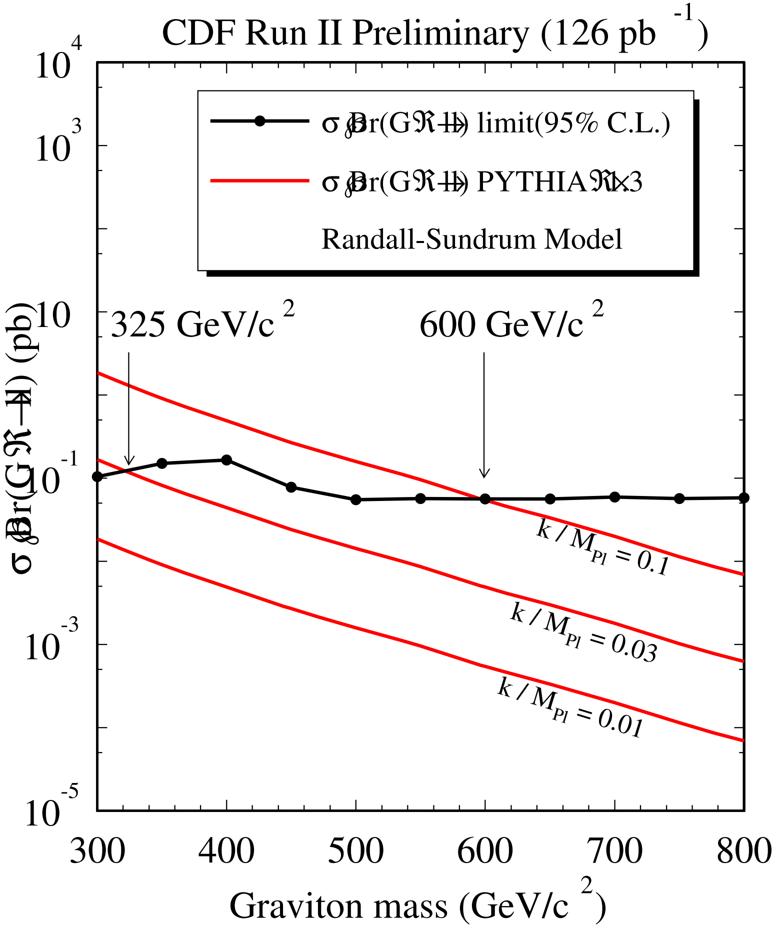
We have been searching for evidence of $Z' \rightarrow e^+e^-$ and $\mu^+\mu^-$.

A signal would appear as an additional peak well above the SM $Z \rightarrow \ell^+\ell^-$ one.

Limits have been placed in the context of warped extra dimenions (first proposed by Randall & Sundrum) – a first for Run II.



(thesis project of Muge Karagöz Ünel)



combined electron and muon channels

Concluding Remarks

Final Point: The biggest discoveries come from the Unexpected, exactly because they are unexpected.

This is true in all fields of science, not only high energy particle physics.

So, we must be alert and vigilant.

The primary goal of an experimenter is to keep her / his eyes open!