Searches for New Physics at the TEVATRON

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OUTLINE

I will start with the most straight-forward of searches, and end with the most challenging...

- Introducing the TEVATRON
- Searches for Extra Gauge bosons
- Resonances in the top – anti-top mass spectrum
- Searches for Supersymmetric Particles
- Searches for Higgs bosons
- Summary, Outlook & Conclusions

I must make a selection of topics – it would be impossible to cover all Tevatron results even if I were to speak all morning long – apologies for what I have left out...

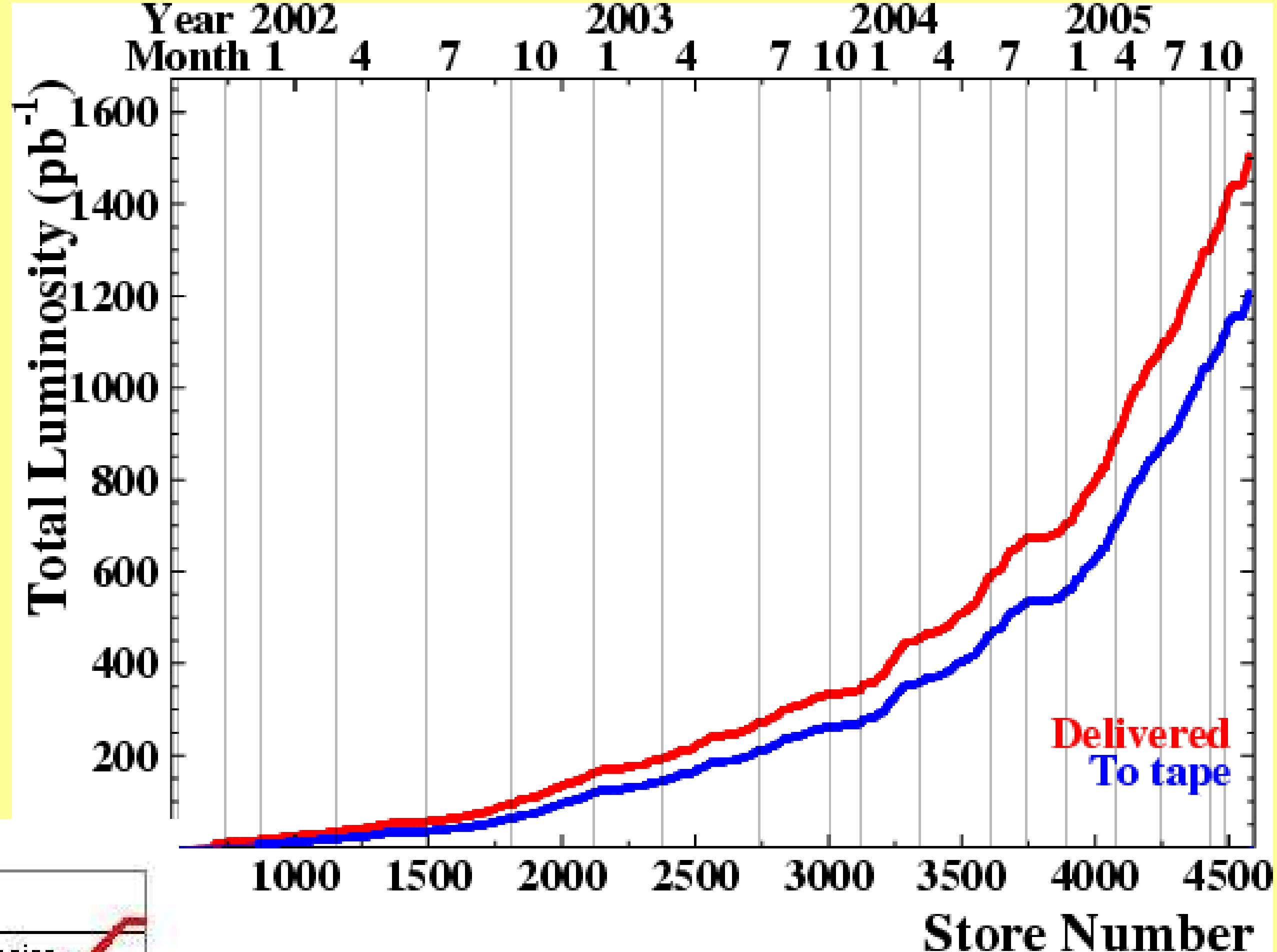
The TEVATRON

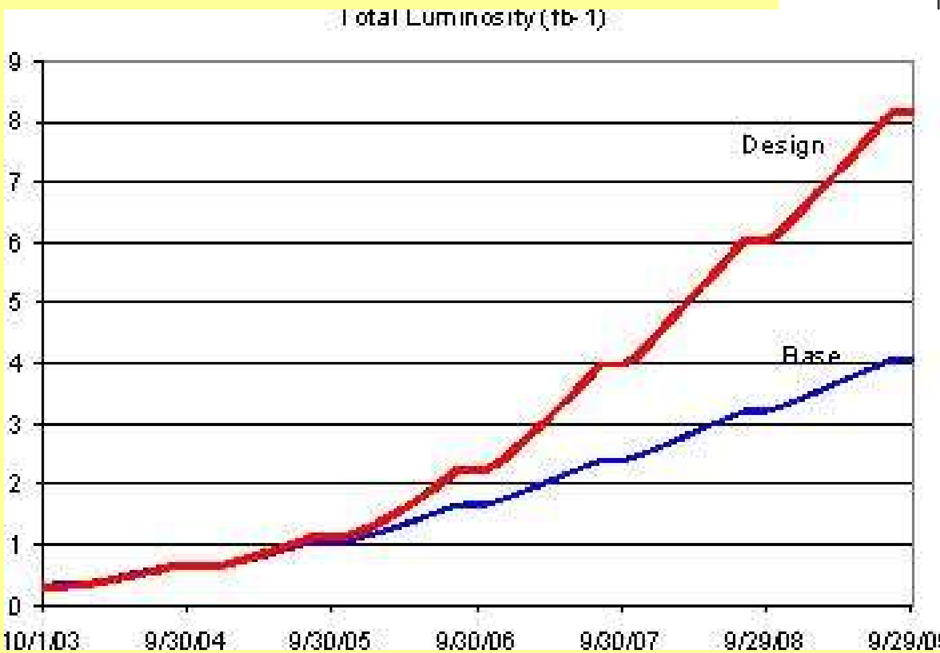
The Tevatron is the world's largest and highest-energy collider, operated near Chicago, USA.

Luminosities are now at or beyond design level.

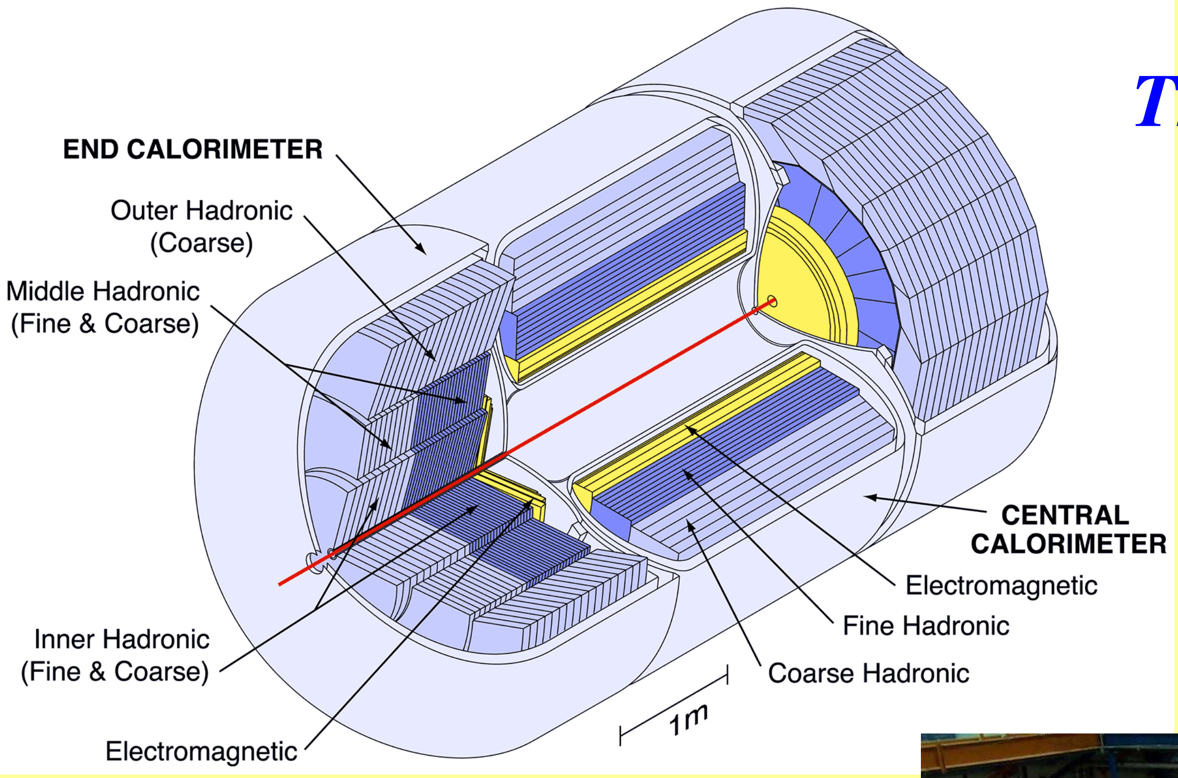
Experimental efficiencies are high (> 85%).

Over 1 fb^{-1} has been recorded on tape, and is waiting to be analyzed.





Projections for the end of Run II in 2009 call for at least 4 fb^{-1} / expt, or, more likely, 8 fb^{-1}.

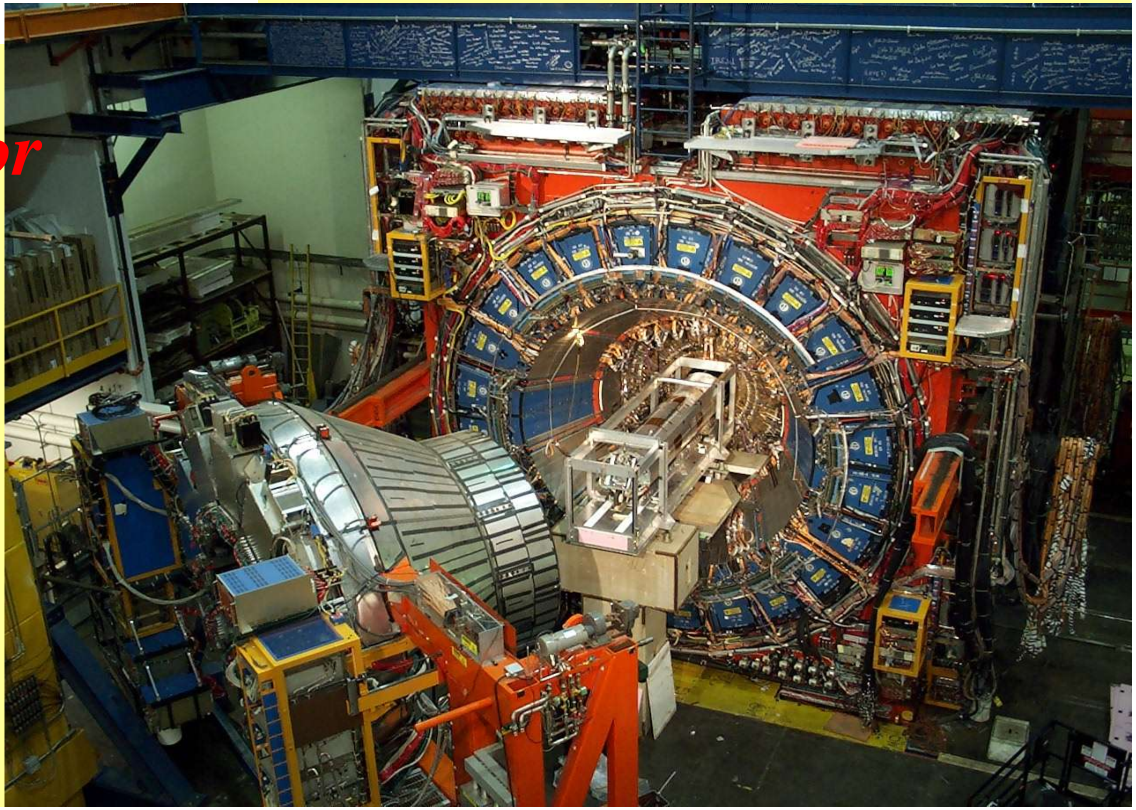


The DØ Detector

A general-purpose detector with particularly good calorimetry.

Several upgrades for Run II, including new tracker, magnetic field, and Si vertex detector.

The CDF Detector



Strongest point is the tracking.

Run II upgrades included advanced Si-based triggering, improved vertex reconstruction & tracking, and improvements to "endcap" calorimetry and muon systems.

Extra Gauge Bosons

The quest for Grand Unified Theories leads to models with an extra U(1) gauge group (often there are many other ingredients but they don't concern us here).

A direct consequence is the existence of an extra neutral gauge bosons: ***Z′***

Such a particle should be relatively heavy, and decay at least some of the time to leptons.

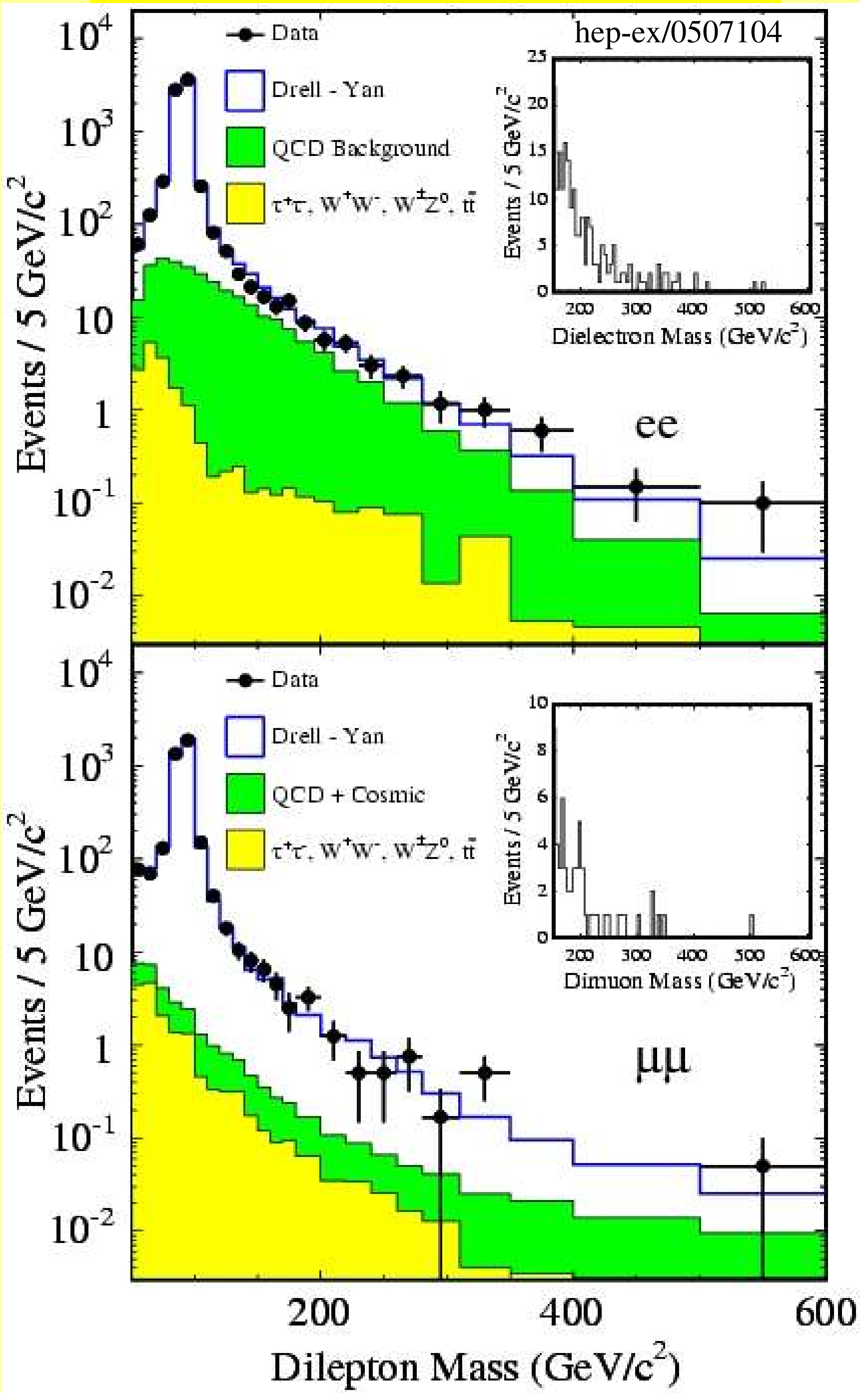
Experimental Approach:

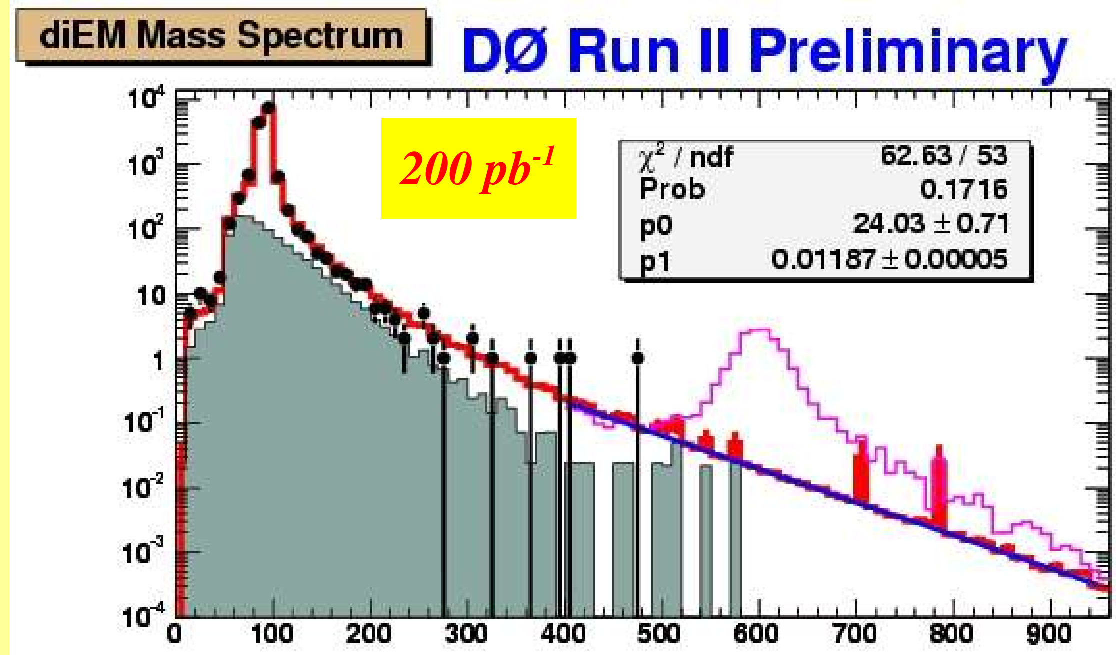
Select events with two isolated high-p_T leptons of the same flavor (e or μ) and opposite charge.

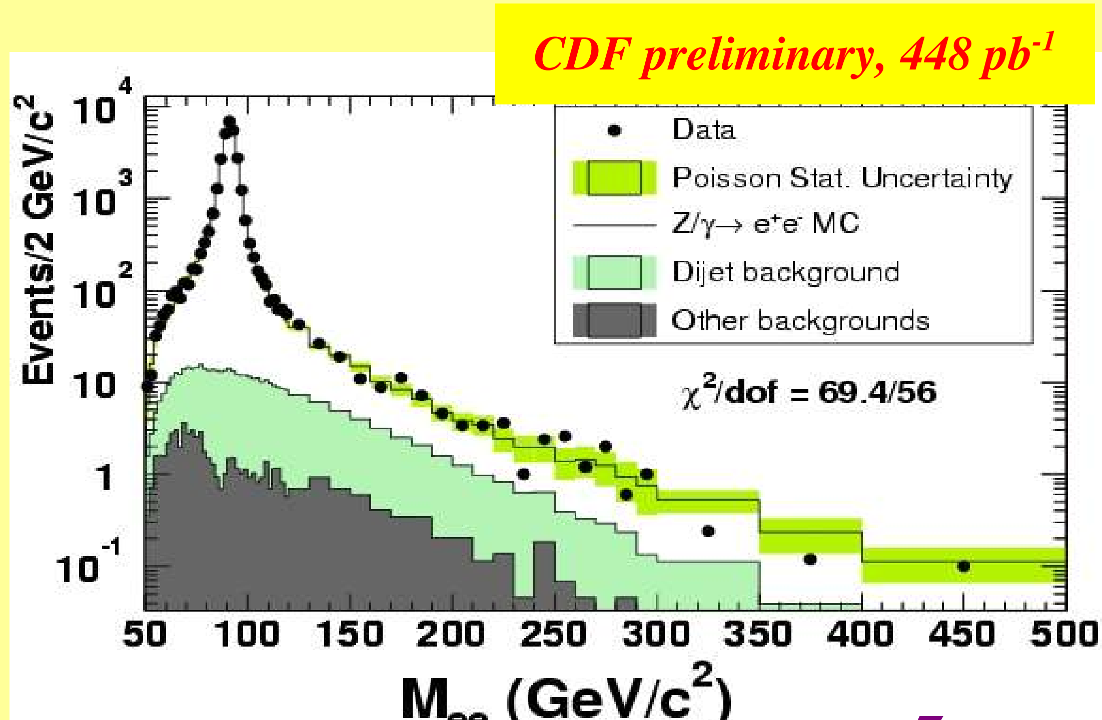
Examine the di-lepton invariant mass distribution:

- dominated by the Z peak and Drell-Yan
- worry about fake leptons
    * QCD di-jets with two jets looking like leptons
    * W + jet(s) with a leptonic W decay and one jet looking like a lepton
    * γ + jet(s) with the photon looking like an electron and the jet faking an electron
- "electroweak" backgrounds (WW, WZ, ZZ, tt) are tiny and can be estimated w/ simulations

CDF Run II, 200 pb^{-1}, published.







How do DØ and CDF Set Limits?

First, is there any overall excess?

minimum mass	CDF ee		CDF mm		D0 mm	
	exp.	obs.	exp.	obs.	exp.	obs.
150	213 +/- 99	205	55 +/- 2	58	85	73
200	78 +/- 33	84	21 +/- 1	18	-	-
210	-	-	-	-	25	24
300	14 +/- 4	22	5.2 +/- 0.3	6	6.4	5

If not, then compute the upper limit on the signal:

- define mass windows assuming very small natural width
- compute the 95% CL upper limit on the number of signal events
- convert into σ x BR using acceptance and efficiency estimates
- combine e and μ channels

From the point of view of the experimenter, this is the end result!

- one might compare this to $(\sigma \text{ x BR})_{\text{model X}}$ to constrain the model...

(but the models are not the important thing, (σ x BR) is....)

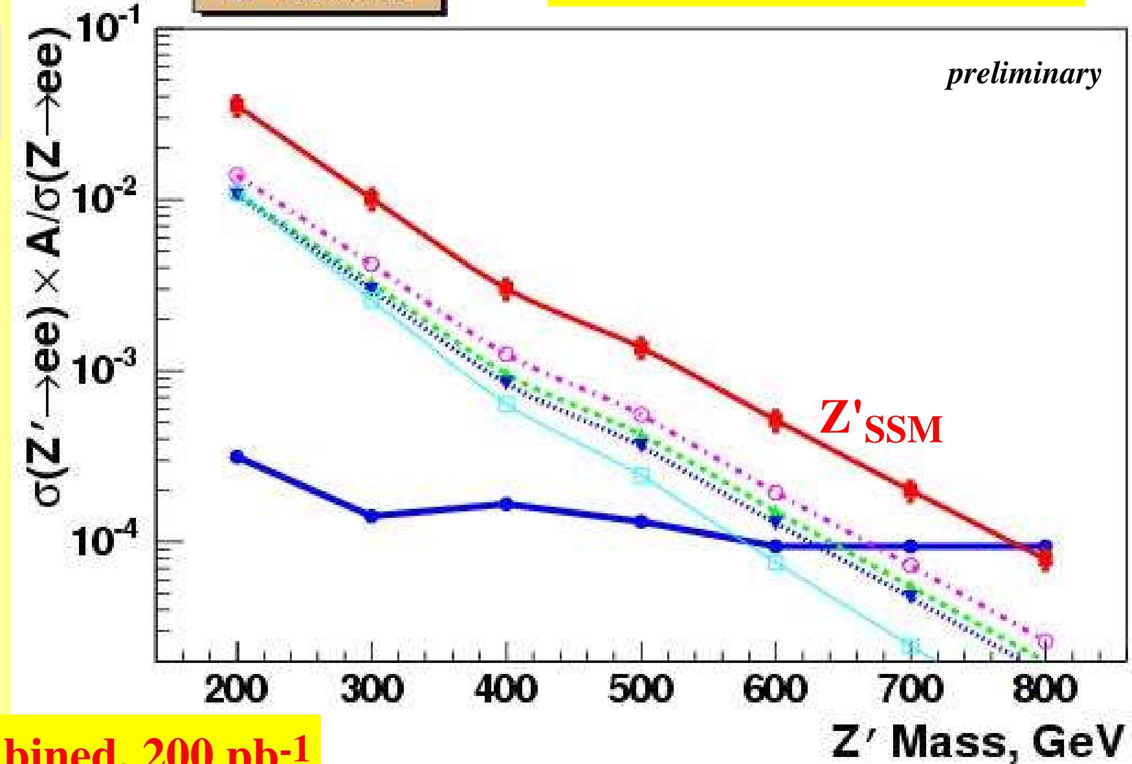
Actual

upper limits on Z' production

DØ works with the ratio of signal to SM Z cross sections.

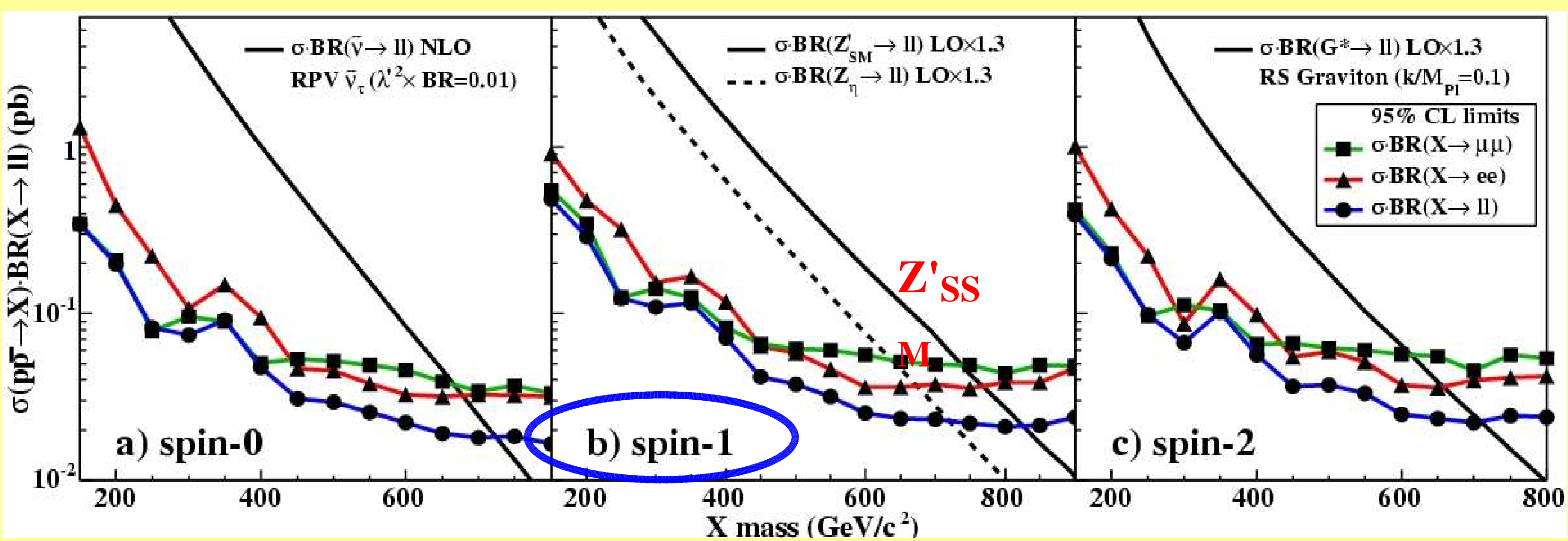
Both experiments achieve
σ x BR < 24 fb at 95% CL

DØ di-electrons, 250 pb^{-1}



CDF, di-electrons and di-muons combined, 200 pb^{-1}

hep-ex/0507104



How do we use these limits to constrain theories predicting a $\boldsymbol{Z'}$?

The traditional approach is to test certain benchmark models:

- "sequential" Z' - one like the SM only heavier – unrealistic!
- certain GUT-inspired special cases

But this is not general and does not bring out the full utility of the analysis.

A more general approach has been put forth recently:

Carena, Daleo, Dobrescu and Tait (CDDT) - Phys. Rev. D70 (2004) 093009

Applying only a few very general theoretical considerations, they identify four distinct "model lines" which cover broad classes of Z' models.

Each model line depends only on a few parameters:

- the mass of the resonance ($M_{Z'}$)
- the overall coupling constant (g_z)
- a free dimensionless parameter, x, which determines the fermion charges

Instead of testing 1, or 4, or 6, or 7 different specific Z' models, one places constraints on g_z and x for a given $M_{Z'}$.

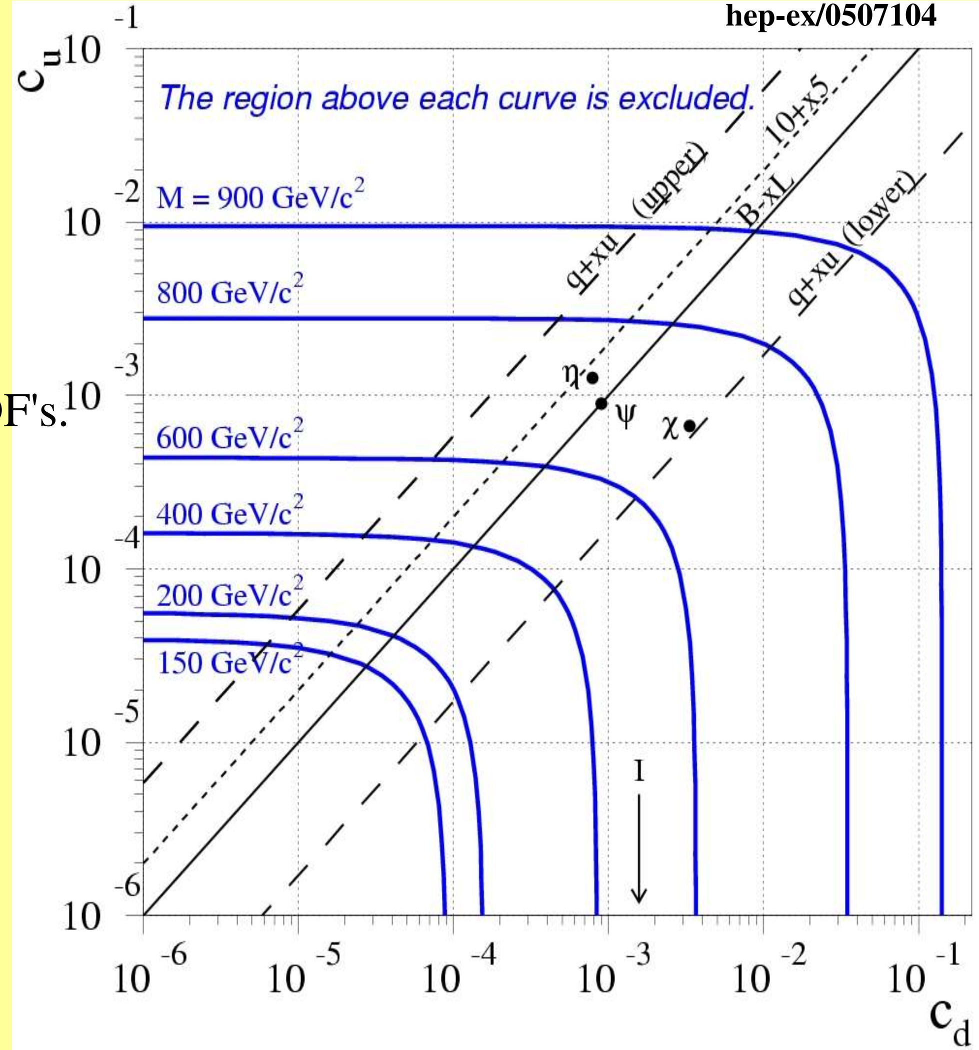
CDF constraints coming from the upper limit on the cross section:

CDDT factorize the cross section in terms of model parameters and kinematic factors:

$$\sigma(Z')=\frac{\pi}{48\,s}\left[c_u w_u(s,M_{Z'})+c_d w_d(s,M_{Z'})\right]$$

$$c_{u,d}=g_z^2\,(z_q^2+z_{u,d}^2)\,Br(Z'\to l\,l)$$

The factors w_u and w_d encapsulate the integrals over the parton fluxes.
They can be computed and depend only on the PDF's.



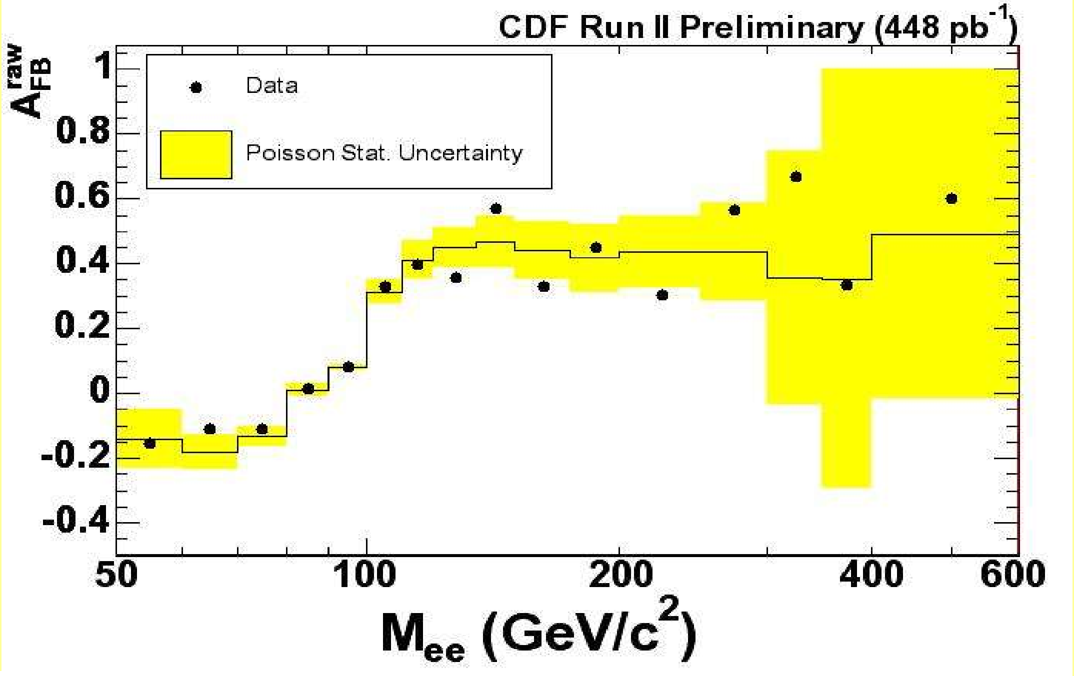
An upper limit on $\sigma(Z')$ translates directly into limits on the "charge factors" c_u and c_d.

CDF recent di-electron results:

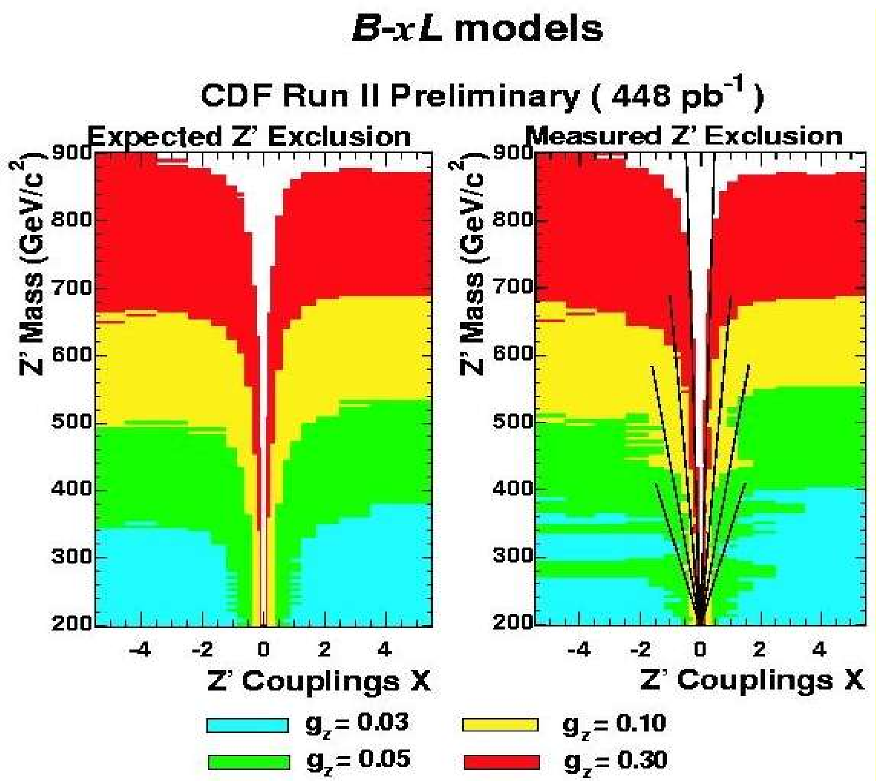
The forward-backward asymmetry has been measured as a function of M_{ee}.

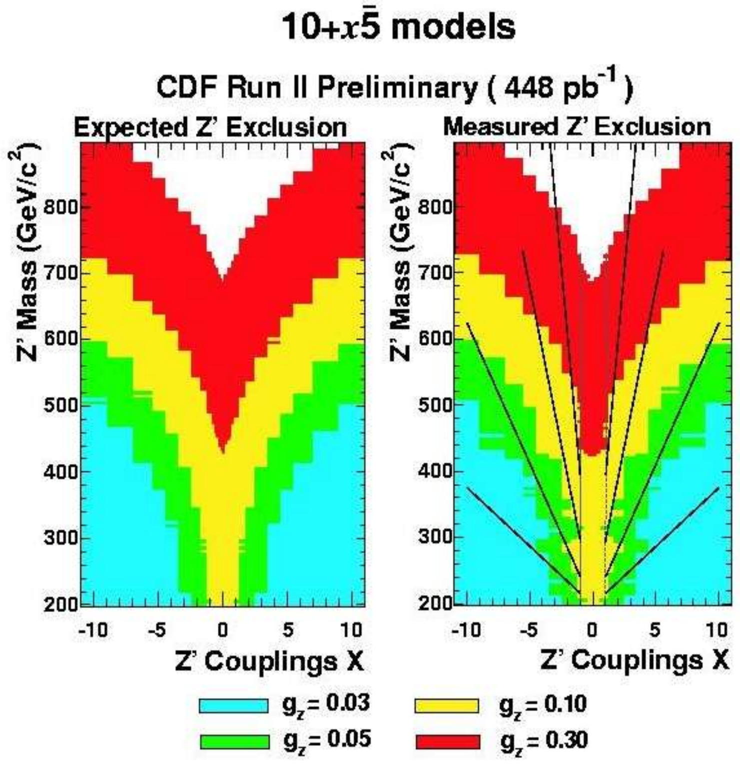
The presence of a Z' generally shifts A_{FB} depending on couplings and the Z' width.

A "model-independent" formulation is quite helpful here...



These are two out of four examples.





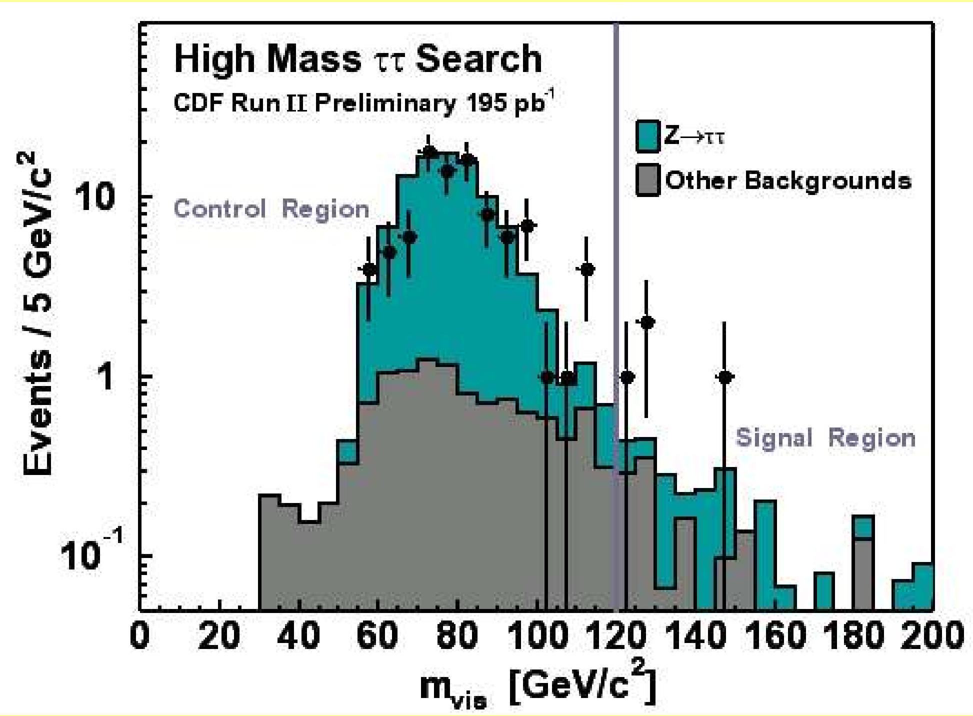
Just a quick word about τ's ....

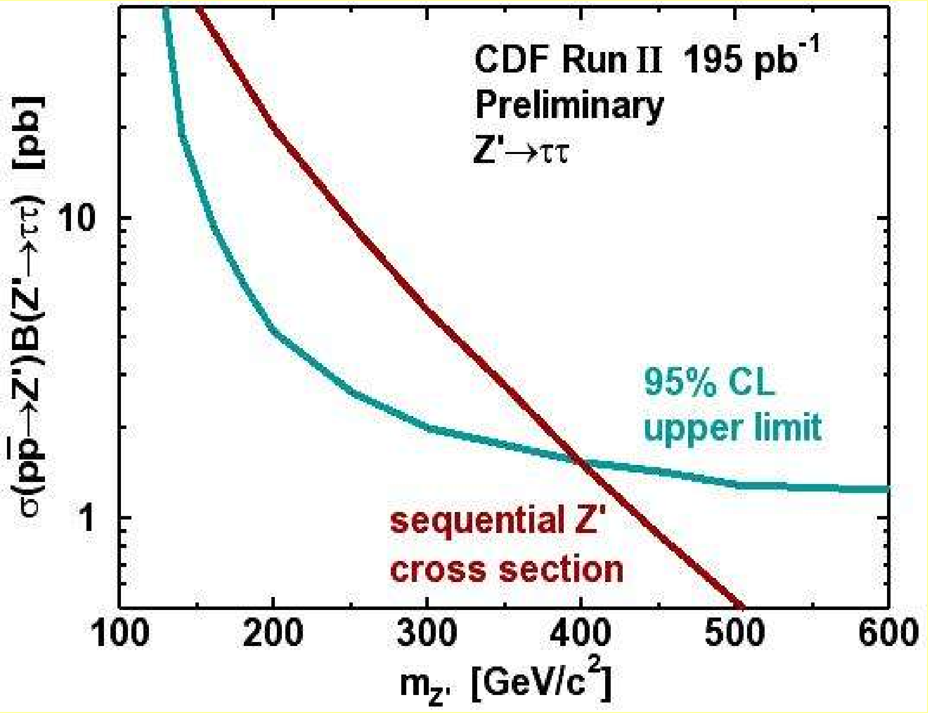
Z' decays to tau's are much harder to identify, of course, so this channel does not play a central role in the search for Z' bosons.

That said, it would be extremely important if couplings were not generation-independent!

CDF published, 195 pb^{-1}

hep-ex/0506034





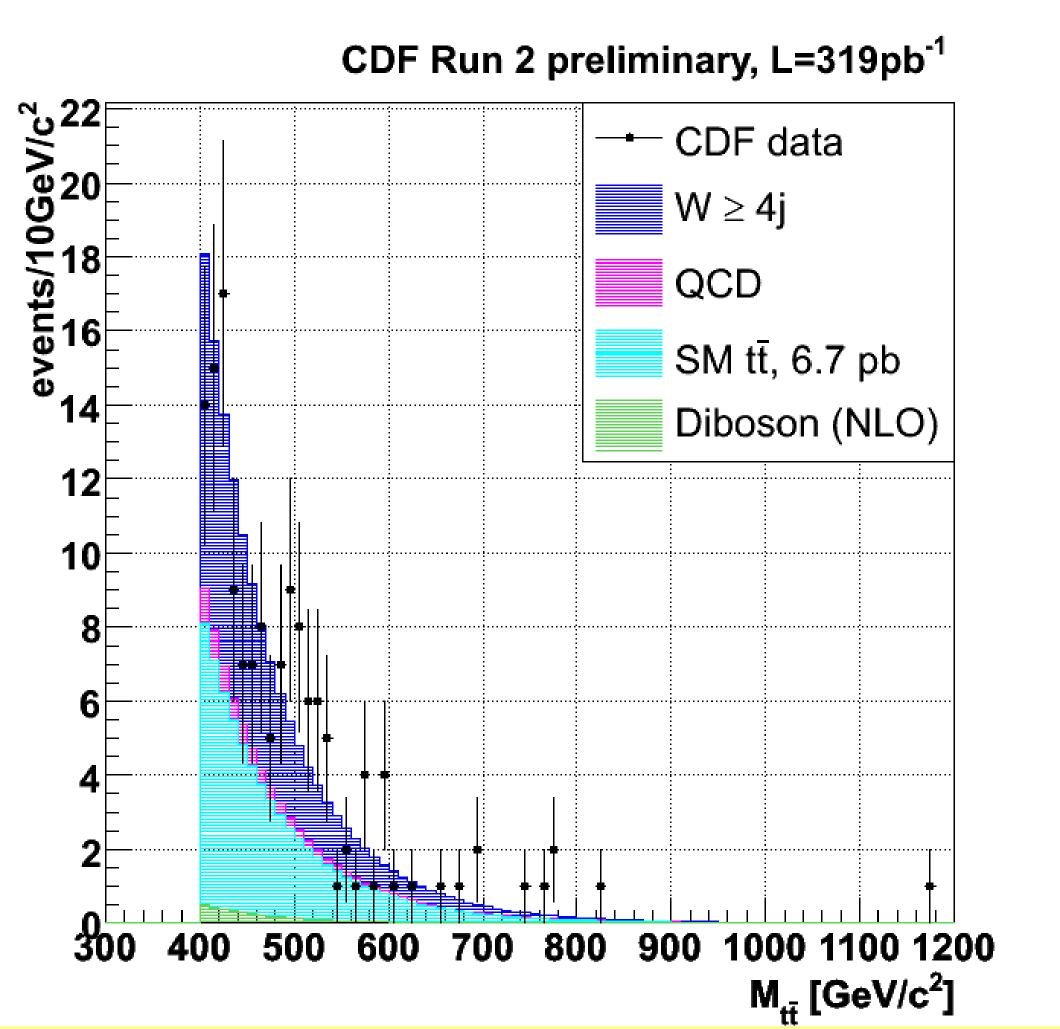
top – anti-top Resonances

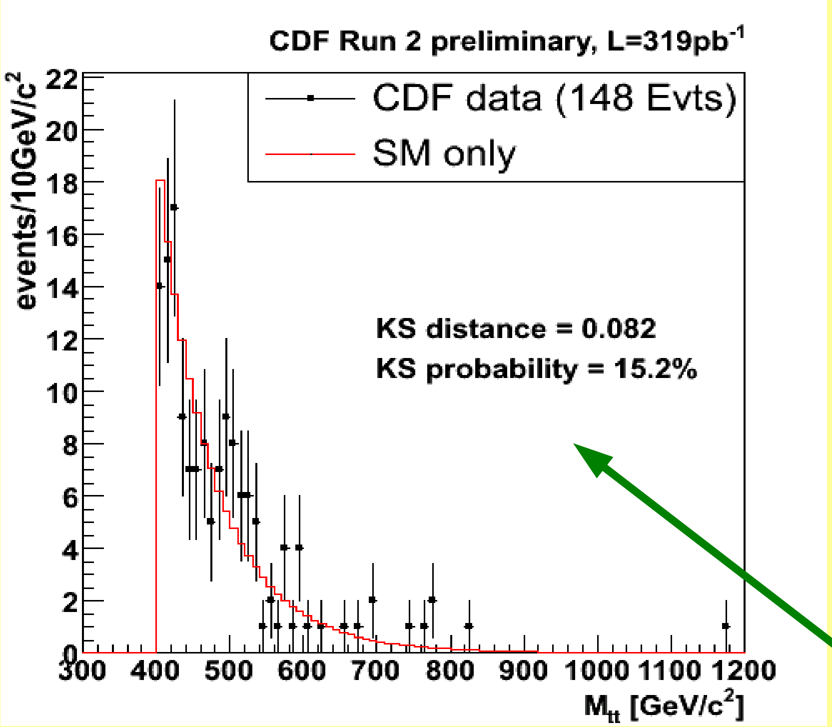
Look for other di-fermion resonances

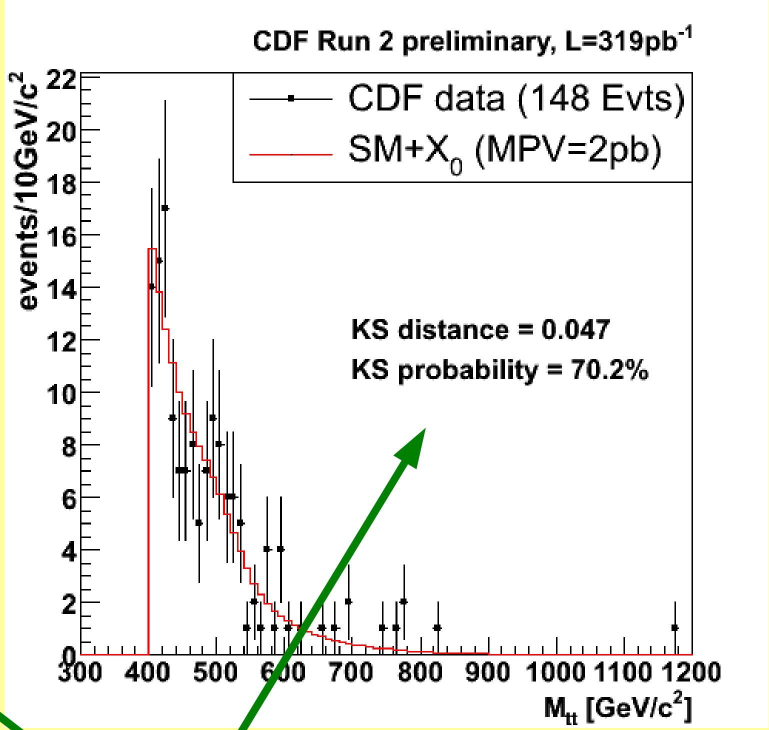
The top quark is a great place to look for new physics.

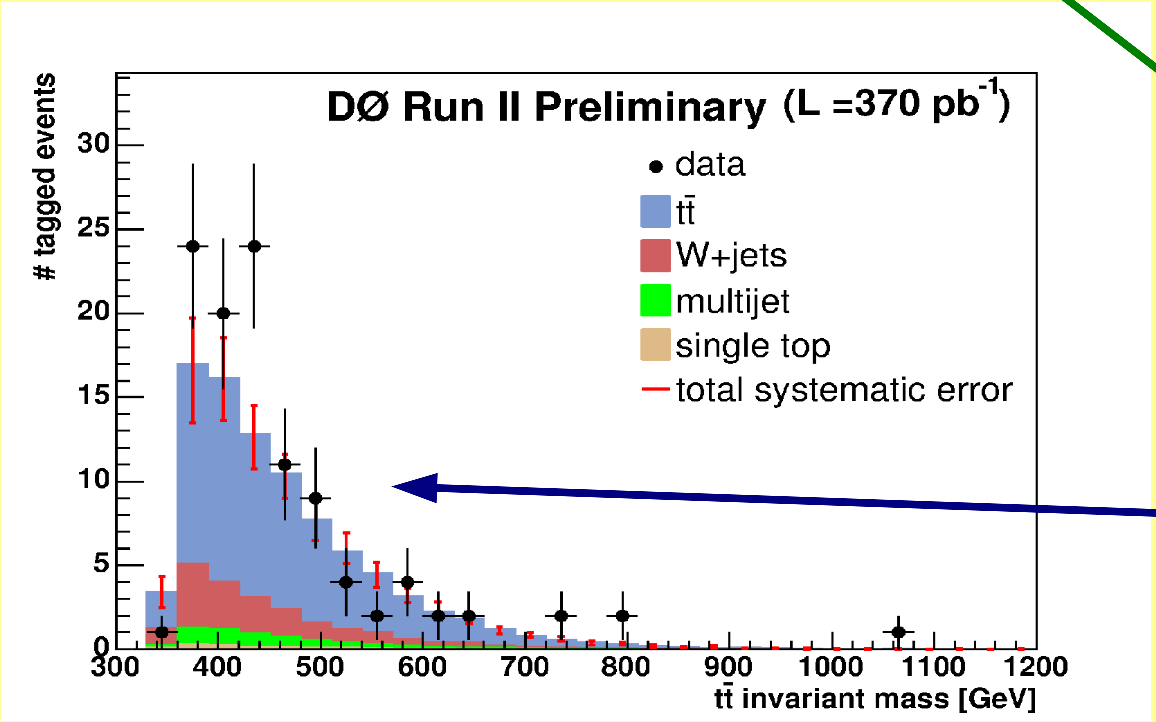
Reconstruct top-quark pairs in the lepton+jets channel, and then form the $M_{t\bar{t}}$ spectrum.

An intriguing “bump” is observed in the CDF data near 500 GeV…









Statistical treatment shows slight improvement if "signal" is included, but significance is mild: $\approx 2\ \sigma$

The DØ data show no signs of any excess at 500 GeV.

Supersymmetric Particles

Supersymmetry is the best-motivated model for physics beyond the SM.

The phenomenology can be explicitly calculated and is very rich.

- For every SM particle, there is a SUSY partner of different spin.
- The SUSY partners must be relatively heavy (with a couple of exceptions).
- The exact mass spectrum (& other properties) depends on unknown parameters, but once these have been specified, everything can be calculated.
- R-parity distinguishes SM from SUSY particles, and is often assumed to be exact.
- The lightest SUSY particle (LSP) is stable, and might be the stuff of dark matter.

There have been *many* searches for SUSY particles – none has been found.

The discovery of any SUSY particle would be momentous!

SUSY 1: squarks and gluinos

Since the TEVATRON is a hadron collider, it makes sense to look for squarks & gluinos.

The missing transverse energy $\vec{E}_T$ from the neutralinos $\tilde{\chi}_1^0$ is the key to isolating a signal.

Consider the kinematics:

- if **M(squarks) < M(gluinos)** then
  - ★ squarks decay to quarks and LSP's → *2 jets + MET*
  - gluinos decay to squarks and gluons
- if **M(squarks) > M(gluinos)** then
  - ★ gluinos decay to a pair of quarks and an LSP → *4 jets + MET*
  - squarks decay to a quark and a gluino

We expect M(squarks), M(gluinos) to be > 300 GeV or so.

The JETS that come from the SUSY decays will always be **energetic**, in distinction to ordinary jets which tend to have less energy.

→ Require high energies for the jets, and require the sum of jet energies (H_T) to be high.

Both DØ and CDF pre-select events with >2 jets, and MET > 40 GeV or so...

(dictated by the experimental "trigger")

Actual cuts in the CDF selection:

- at least 3 jets, $E_T > 30$ GeV
- MET > *165* GeV
- $H_T > 350$ GeV

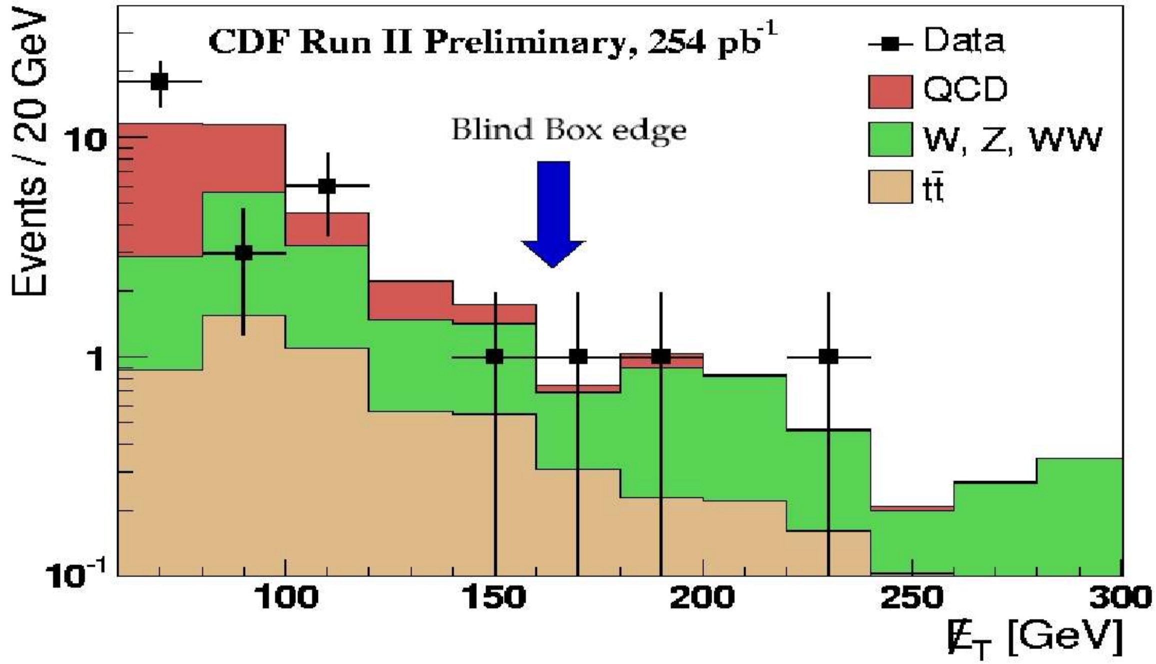
- expect 4.1 ± 1.4 events from SM
- observe 3 events

Actual cuts in the DØ selection:

The DØ cuts depend on the "scenario" - on the relative masses of squarks and gluinos.

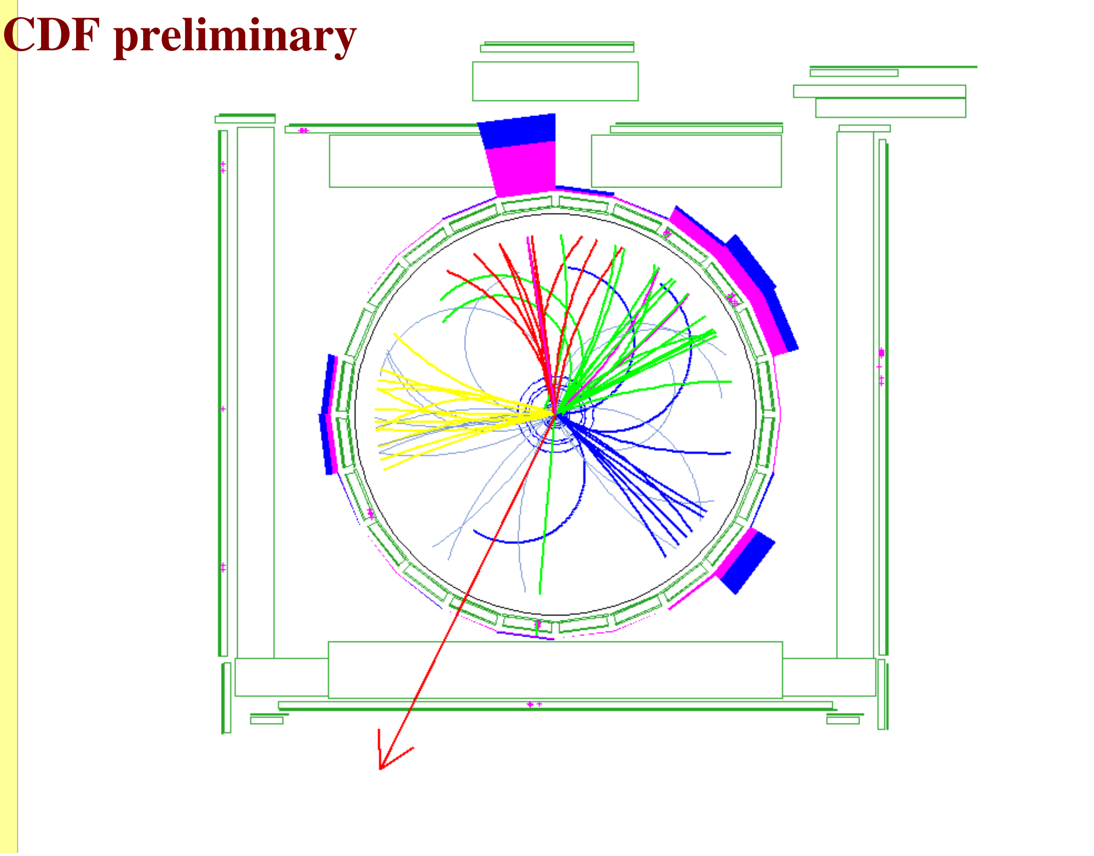
- 2 Jets + MET: gluinos heavier than squarks MET > *175* GeV, $H_T > 250$ GeV
  expect 12.8 ± 5.4 events, observe 12 main background: $Z \to \nu\nu$
- 3 Jets + MET: gluinos close to squarks MET > *100* GeV, $H_T > 325$ GeV
  expect 6.1 ± 3.1 events, observe 5 main background: $W \to \tau\nu$ + jets
- 4 Jets + MET: gluinos lighter than squarks MET > *75* GeV, $H_T > 250$ GeV
  expect 7.1 ± 0.9 events, observe 10 main background: **t t**

These results were obtained using about 300 pb^{-1} of data.



After lots of hard work, one can examine the last few events in the MET distribution.

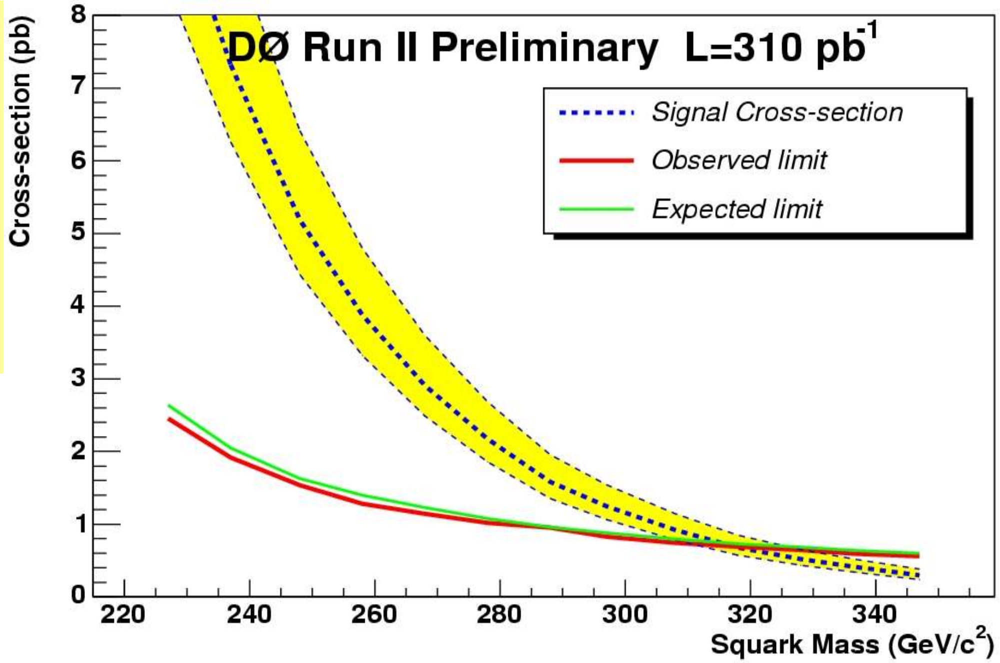
We see no evidence for any excess of events above those expected from SM processes...

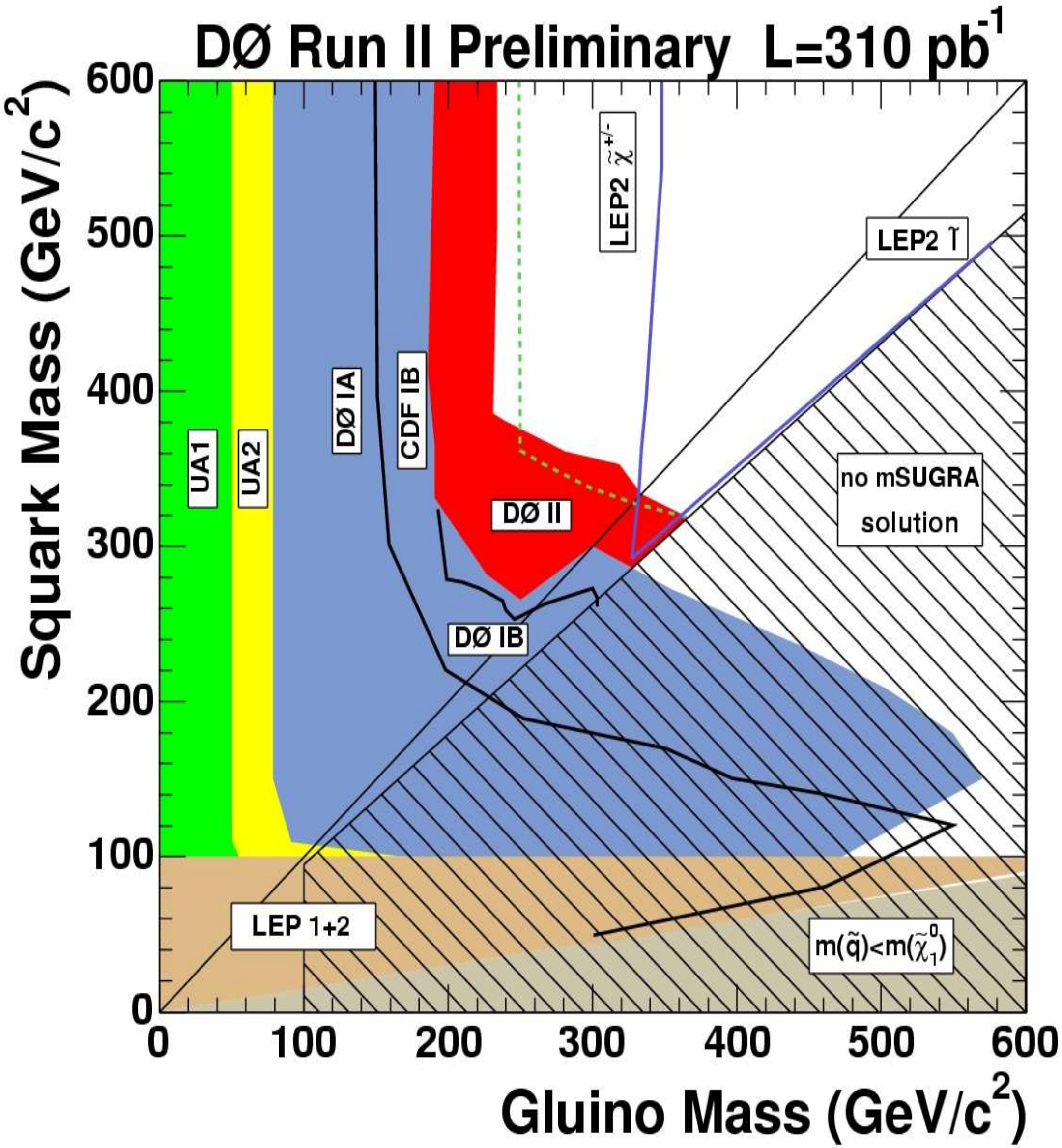


Here is the event with the highest missing energy.

One clearly sees four energetic jets, and a large MET (red arrow).

No evidence for squarks or gluinos.





In view of the negative results of these searches, one can only say that squarks and gluinos do not exist, provided they would have been produced at a rate which would have been visible...

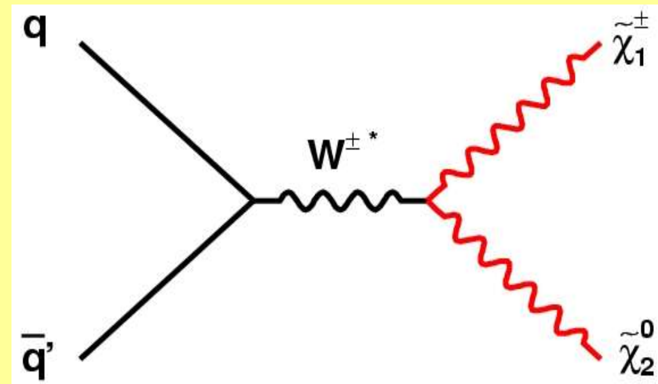
In practice this is translated into excluded ranges for the squark and gluino masses.

$$M(\tilde{g}) > 233\,GeV \quad , \quad M(\tilde{q}) > 318\,GeV$$

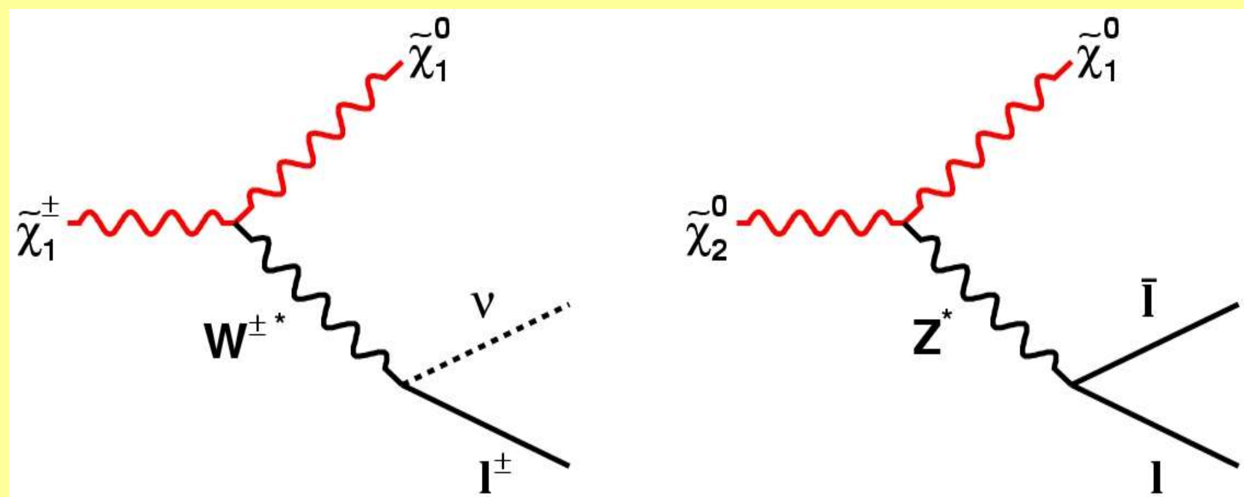
SUSY 2: The "tri-Lepton" Search

Charginos and neutralinos are the spin-1/2 SUSY partners of (W and charged Higgs), and (γ, Z and neutral Higgs bosons).

production:



decay:



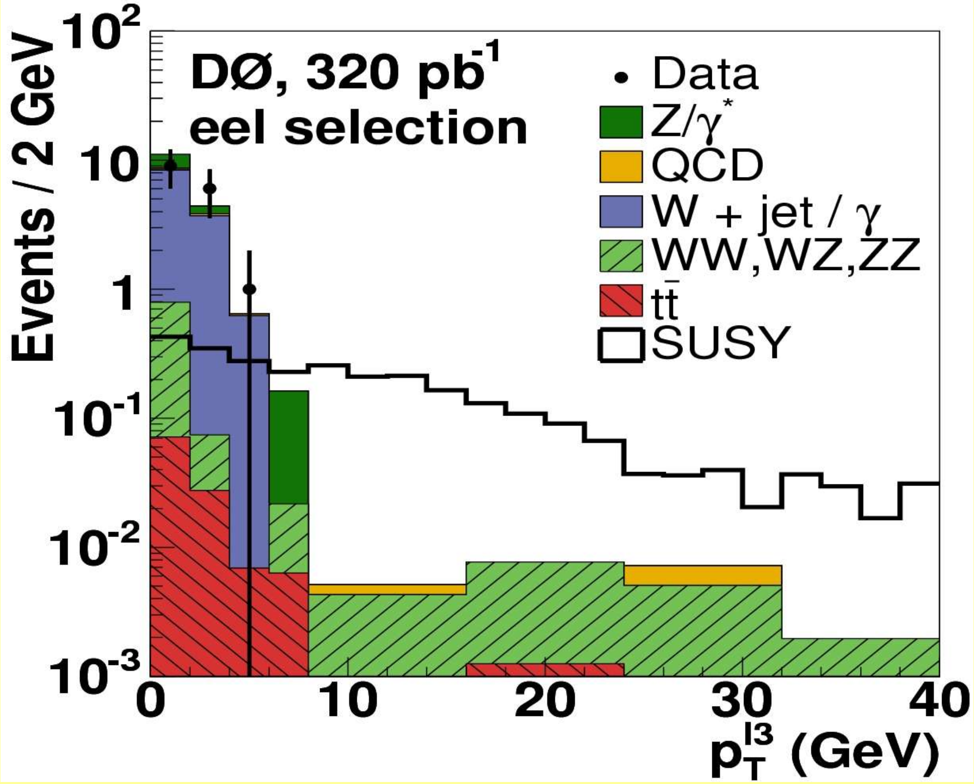
One lepton comes from the chargino, and two leptons come from the neutralino.
There is lots of missing transverse energy, too!

Again, we know that charginos and neutralinos are heavy (> 100 GeV).

This ensures that the leptons will be **energetic.**

They will also tend to be **isolated** in the sense that they will not be part of a jet.

(A troublesome source of leptons are jets with b-hadrons or c-hadrons, which sometimes decay semileptonically, giving us a lepton and a neutrino (=MET). The key point is that the leptons from b- or c-decays come associated with hadrons that are produced with the b- or c-quarks, and also in the b- and c-decays. So, we veto any leptons which have hadrons near by.)



This plot shows the discriminating power of the energy cuts (p_T) on the third lepton.

The SUSY curve corresponds to an optimistic but not crazy scenario.

DØ published! hep-ex/0504032

In a little more detail, the CDF analysis runs like this:

- e^+e^- + (e or μ)
- $\mu^+\mu^-$ + (e or μ)
- e^+e^- + (isolated track)

these two have very low backgrounds

this one accepts some tau decays

The isolation of the leptons is crucial. There is a jet veto.

More than a dozen "control regions" (where no signal is expected) are scrutinized...

About 0.7 ± 0.1 events are expected, and 2 are selected. (346 pb^{-1})

And the DØ analysis is roughly as follows:

- e^+e^- + (isolated track)
- $e\mu$ + (isolated track)
- $\mu^+\mu^-$ + (isolated track)
- like-sign $\mu\mu$
- e + (hadronic τ) + (isolated track)
- μ + (hadronic τ) + (isolated track)

The kinematic selections are complex in order to reject surgically individual background sources.

The hadronic-τ selections help maintain good acceptance at moderate $\tan\beta$.

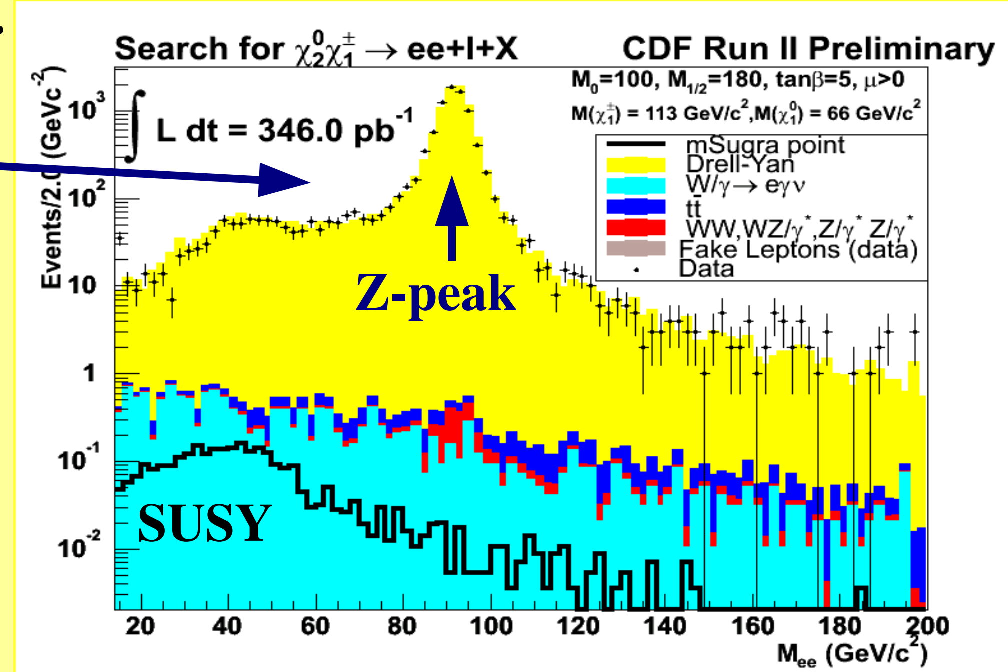
From these 6 selections, 3.8 ± 0.8 events are expected, and 4 are observed. (320 pb^{-1})

In both analyses, p_T thresholds are kept quite low. Remember these are 3-body decays...

And of course, significant MET (> 15 to 22 GeV) is required!

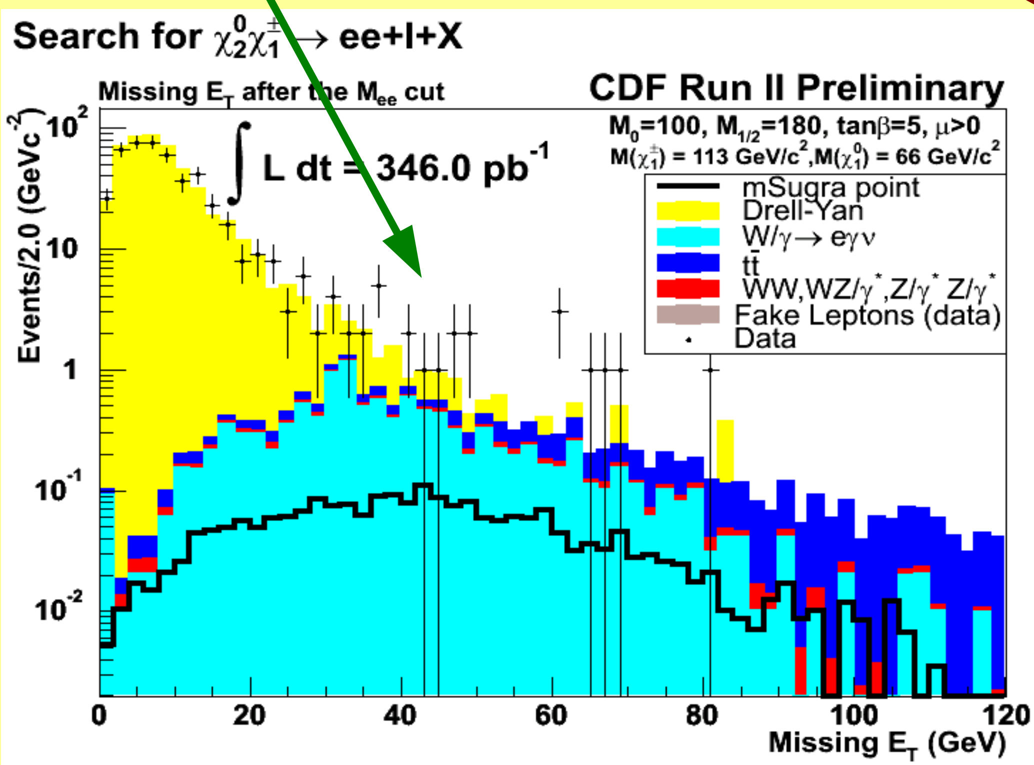
These plots show the power of the other cuts.

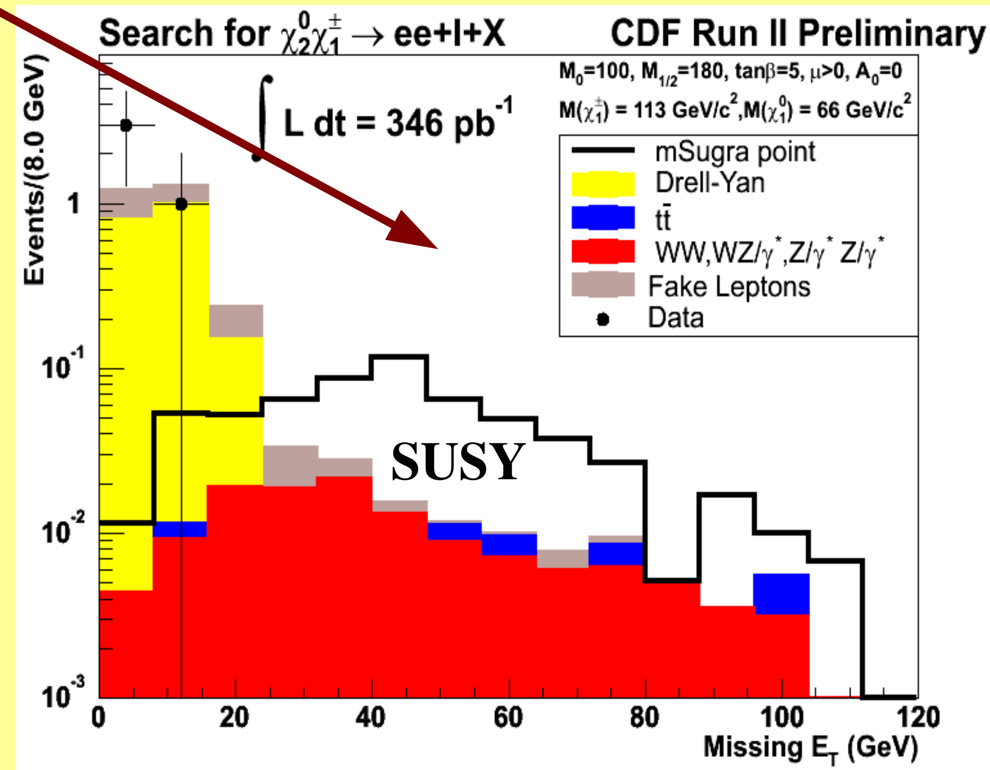
Overall di-electron mass spectrum.



MET distribution after cutting out the Z-peak.

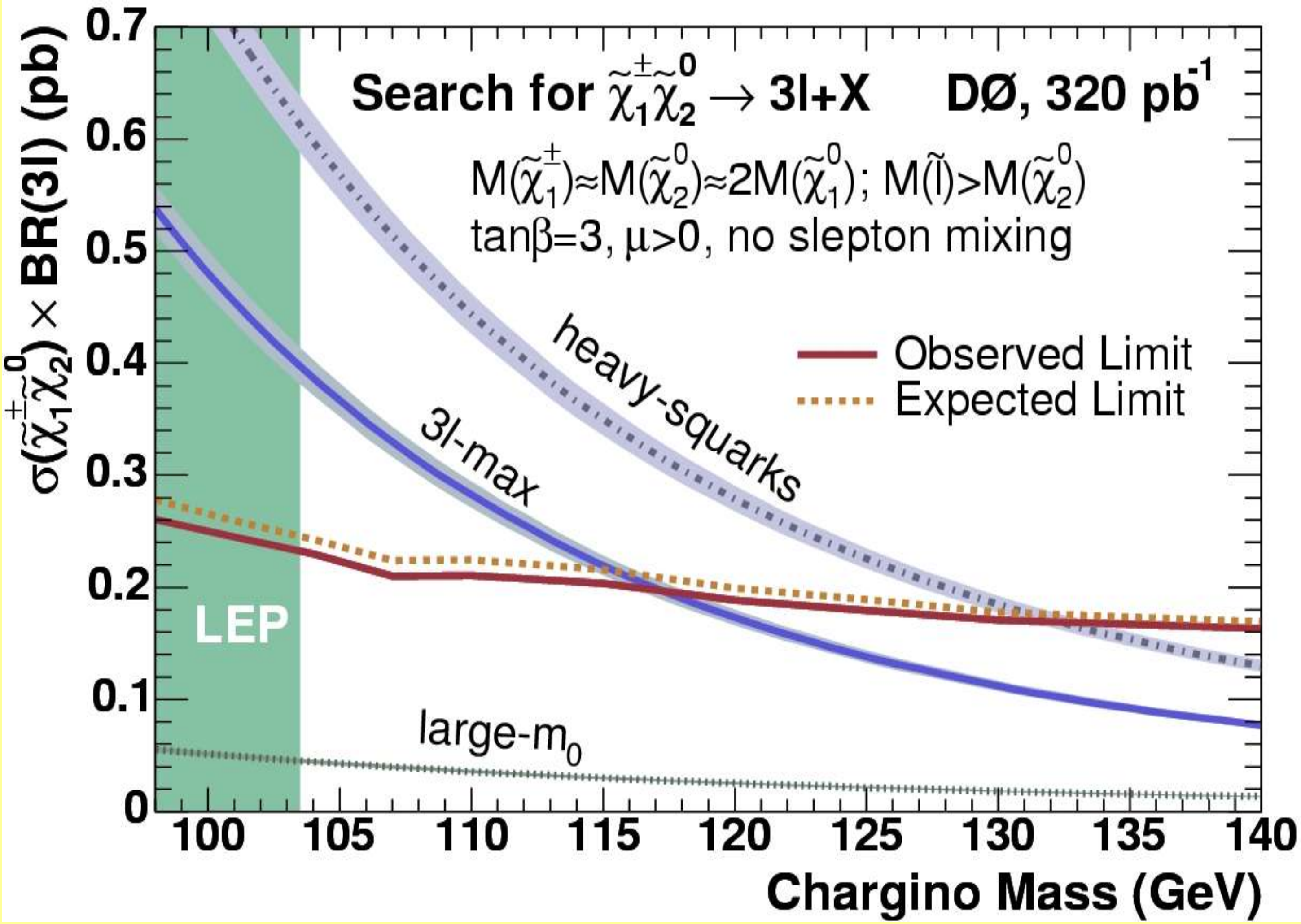
MET distribution after all cuts.





Limits from the tri-Lepton Search

Again, no evidence for any excess, so we can only place limits on SUSY cross sections, equivalently, masses.



Three scenarios are depicted:

all scalar masses large:

- cross section is maximal
- BR is not so optimistic
- very difficult to see a signal
- most realistic?

maximal leptonic BR:

- bring scalar masses down
- enhances BR
- but cross section reduced (*t*-channel)
- some extension of LEP bounds

light leptons, heavy squarks:

- best of both worlds
- highly contrived ?
- would eventually cover past 200 GeV

hep-ex/0504032

$\sigma \times$ Br upper limits will improve by factor 20 by end of Run II.

SUSY 4: "GMSB"

Most of the examples above are based on the MSSM with or without constraints coming from gravity mediation.

There are other variants of supersymmetry in which other mechanisms induce SUSY-breaking, and their phenomenology can be quite different.

One example is "gauge-mediated supersymmetry" (GMSB).

In these models, the LSP is the **gravitino** which is quite light.

Other SUSY particles can decay electromagnetically to the gravitino, and of particular importance is the lightest neutralino:

$$\tilde{\chi}_1^0 \rightarrow \tilde{G} + \gamma$$

(There are other scenarios in which the $\tilde{\tau}^{\pm}$ is lighter than the $\tilde{\chi}_1^0$.)

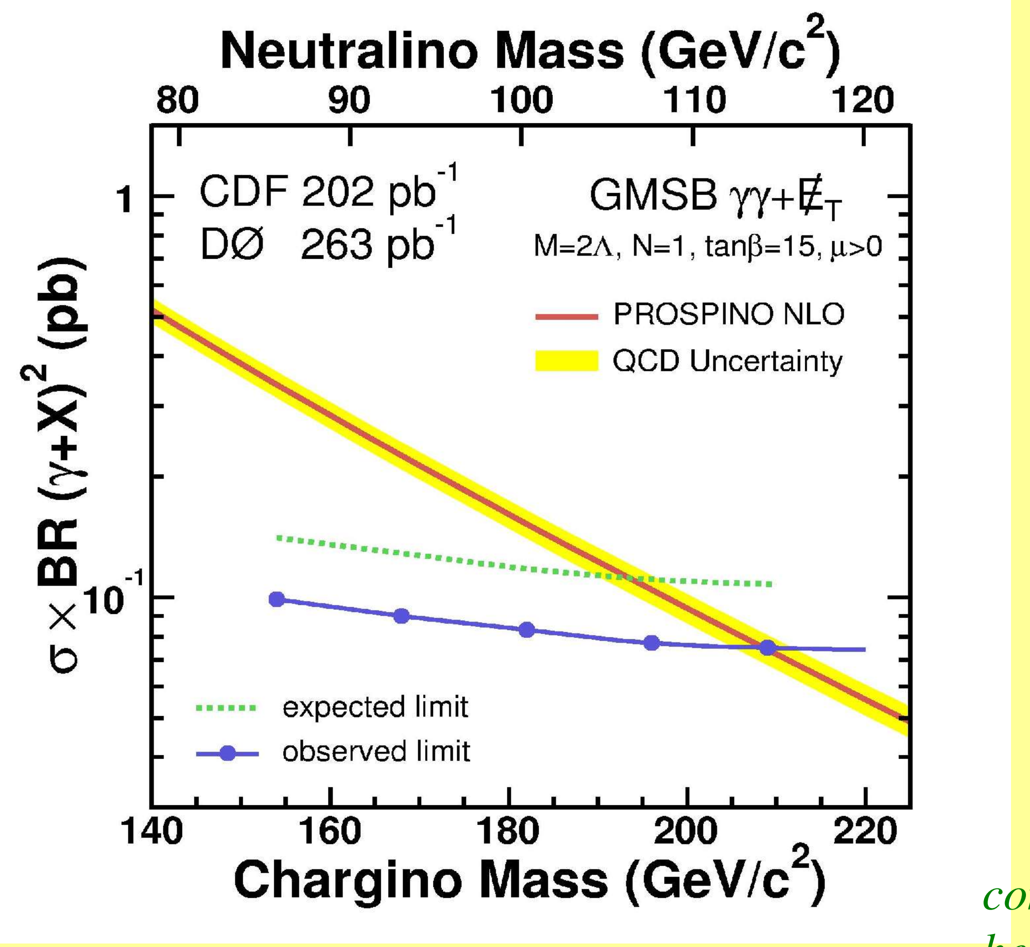
This leads to a very distinctive signature: high-energy photons and MET!

CDF and DØ have searched for charginos and neutralinos in this scenario.

$$p\,\bar{p} \;\rightarrow\; \tilde{\chi}_1^{\pm}\;\; \tilde{\chi}_2^{0} \;\rightarrow\; \gamma\,\gamma\,\vec{\not{E}}_T\,X$$

- ask for two high-ET photons (thresholds at 13 and 20 GeV, respectively)
- the photons have to be isolated
- ask for significant MET (45 and 40 GeV, respectively)

The signature is so distinctive that no other requirements are needed.



The reach in chargino mass is much higher than in the tri-leptons analysis.

This result is independent of the chargino and neutralino decay mode.

Clearly the Tevatron has access to much higher states than does LEP - the challenge is to dig the signal out from background.

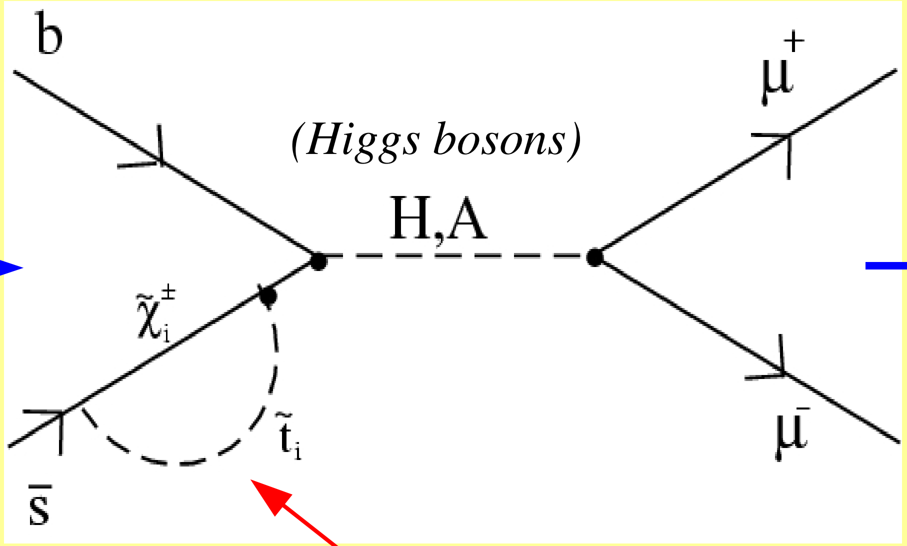
There other model parameters which have to be specified – the cross section will be different for other values.

combined result from DØ and CDF
hep-ex/0504004

SUSY 4: Rare B_s Decays

Let's switch gears and look into the possibility of **virtual effects**...

B_s meson



$\mu^+\mu^-$ final state

virtual SUSY particles in loops

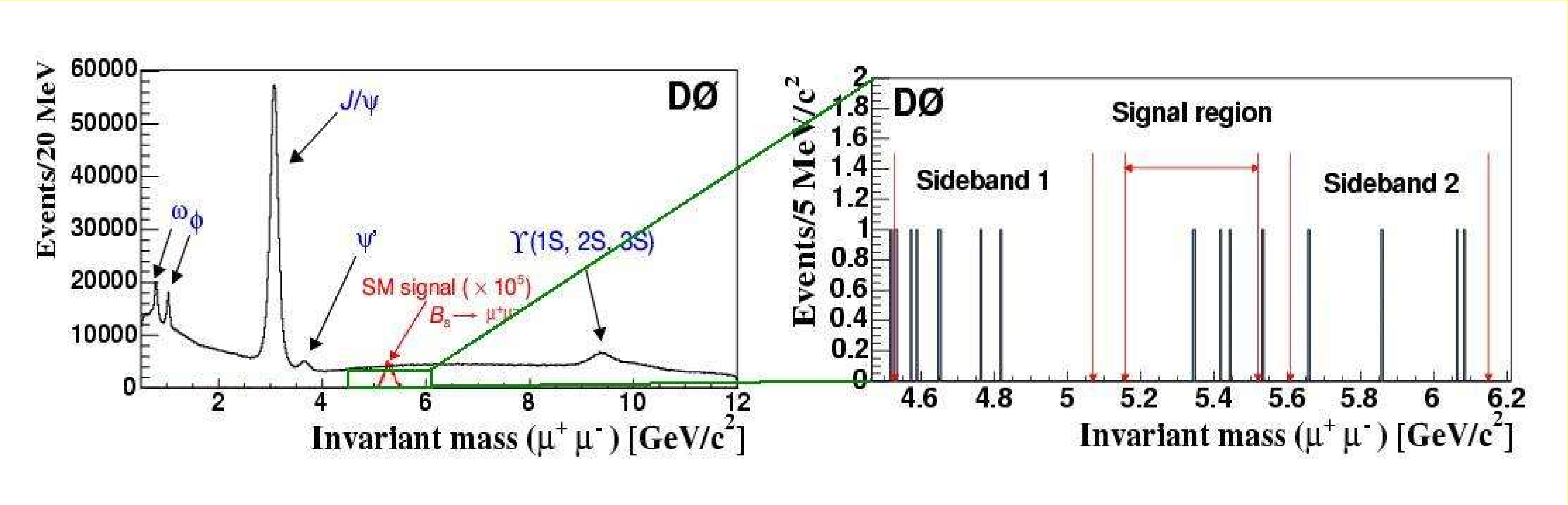
This is extremely rare in the SM, since it constitutes a FCNC decay

→ *special "window" onto virtual SUSY effects...*

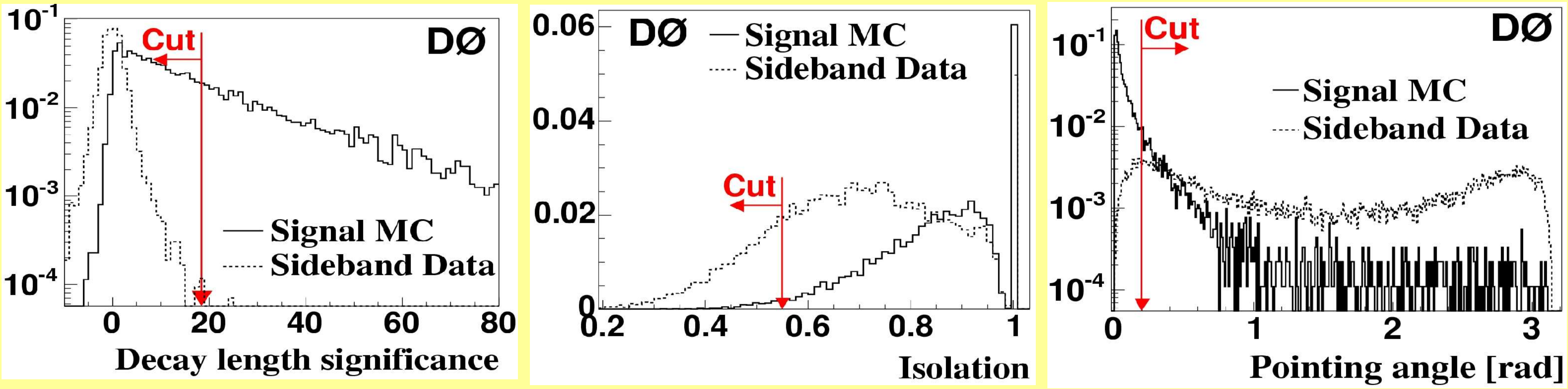
In the MSSM, this decay width is proportional to $\frac{\tan^6\beta}{M_A}$

a huge enhancement!

We are looking for a ***tiny*** bump in the $\mu^+\mu^-$ invariant mass spectrum:



Some of the "handles" we can use to isolate any signal include:



DØ and CDF results for $B_s \to \mu^+\mu^-$:

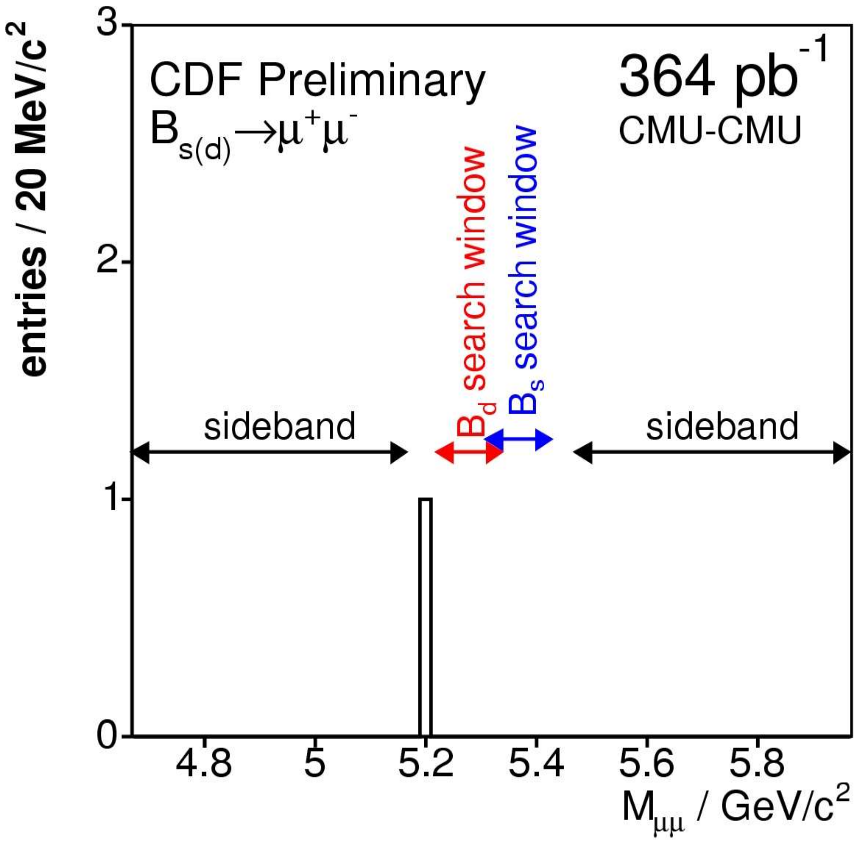
DØ: $Br(B_s \to \mu^+\mu^-) < 3.7\times10^{-7}$

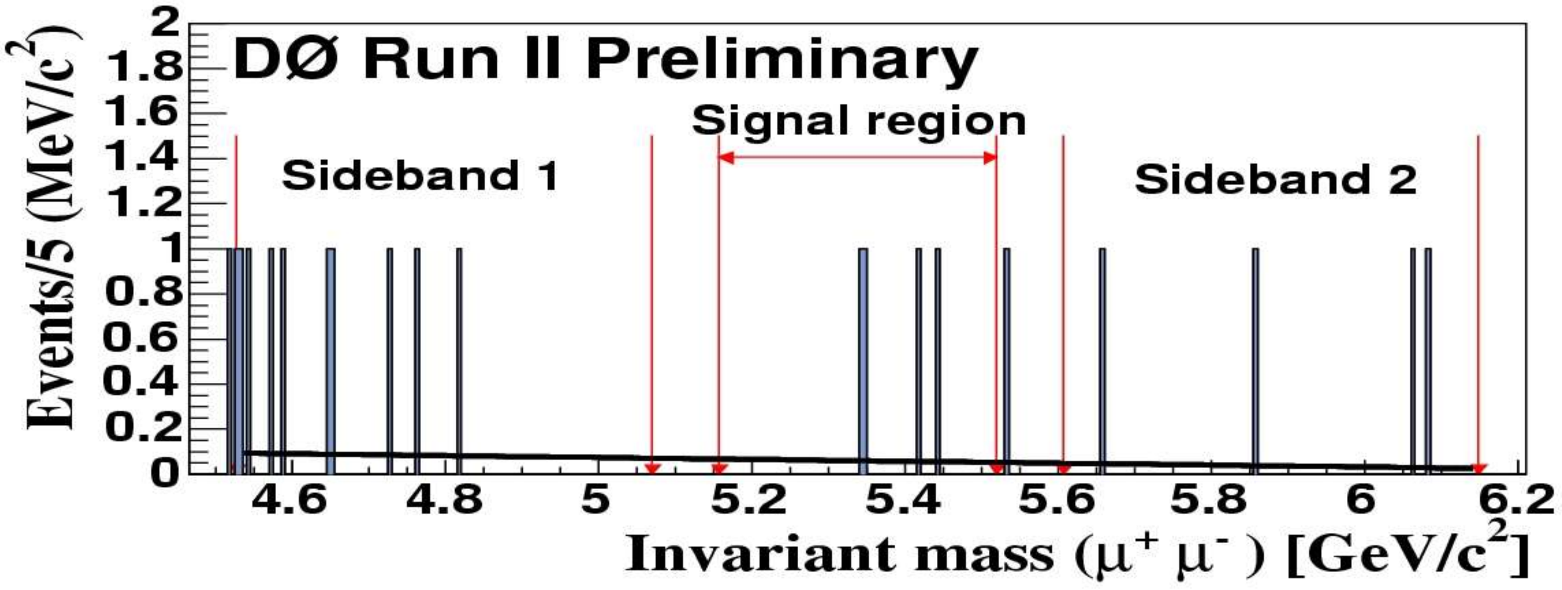
CDF: $Br(B_s \to \mu^+\mu^-) < 2.0\times10^{-7}$

combined: $Br(B_s \to \mu^+\mu^-) < 1.5\times10^{-7}$

The combined result already cuts into unexplored SUSY parameter space.

Ultimate sensitivity will be at the level of $\approx 2\times10^{-8}$.





Higgs Bosons

This Higgs boson is the agent of EWSB, we believe...

There is an intimate connection with M_W and M_t via R.C.

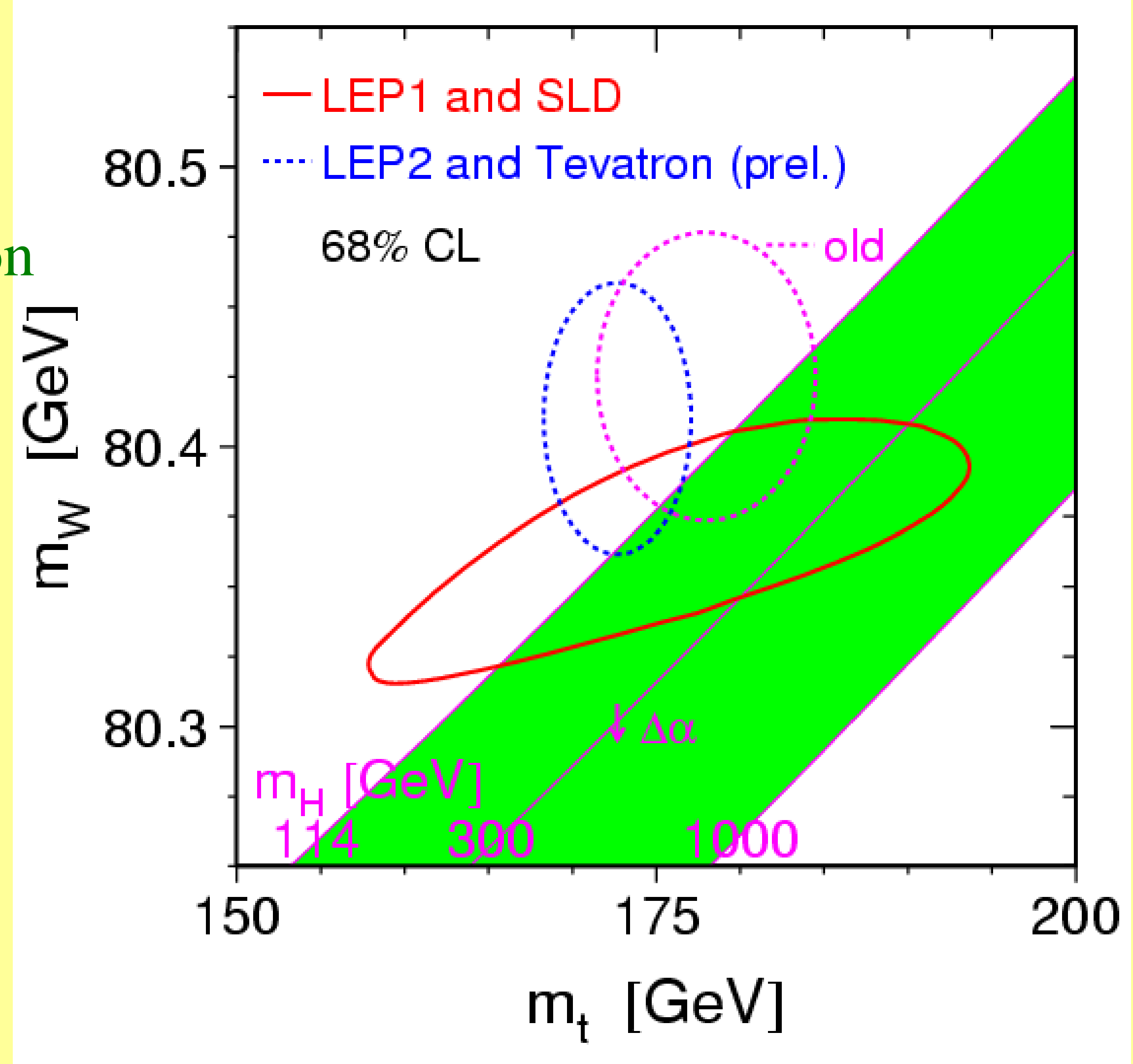
Tevatron will provide the best measurements for many years.

$$\delta M_t \rightarrow 1.5\,GeV$$

$$\delta M_W \rightarrow 30\,MeV$$

(by end of Run II)

Data favor a "light" Higgs!



Cross sections at the Tevatron are not large compared to, e.g., $\sigma(tt)$

Consider two main decay channels: $h \rightarrow b\bar{b}$ and $h \rightarrow W^{+} W^{-}$

Work out several relevant event topologies:

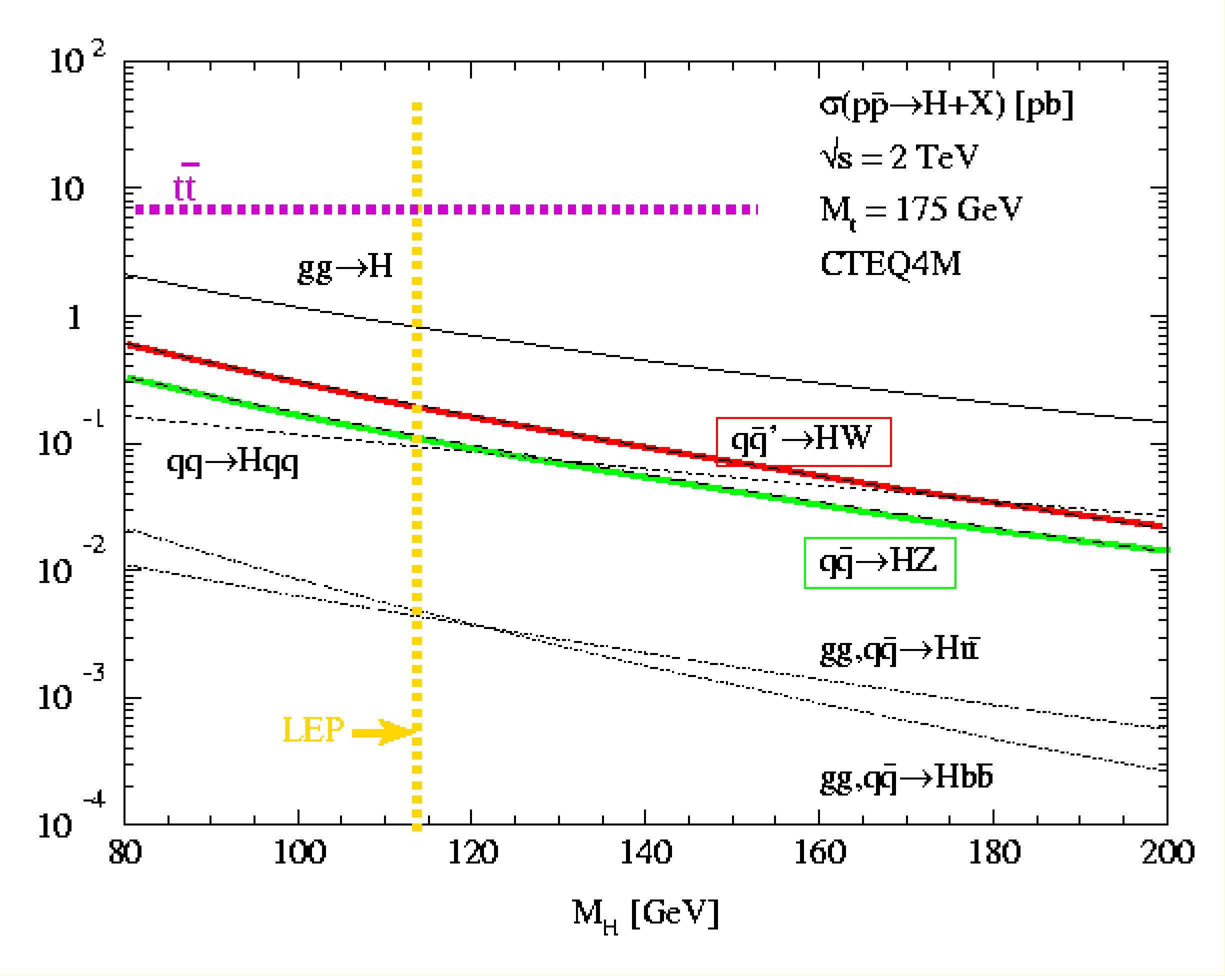
$$Wh \rightarrow l\,\nu\, b\,\bar{b}$$

$$Zh \rightarrow \nu\,\bar{\nu}\, b\,\bar{b}$$

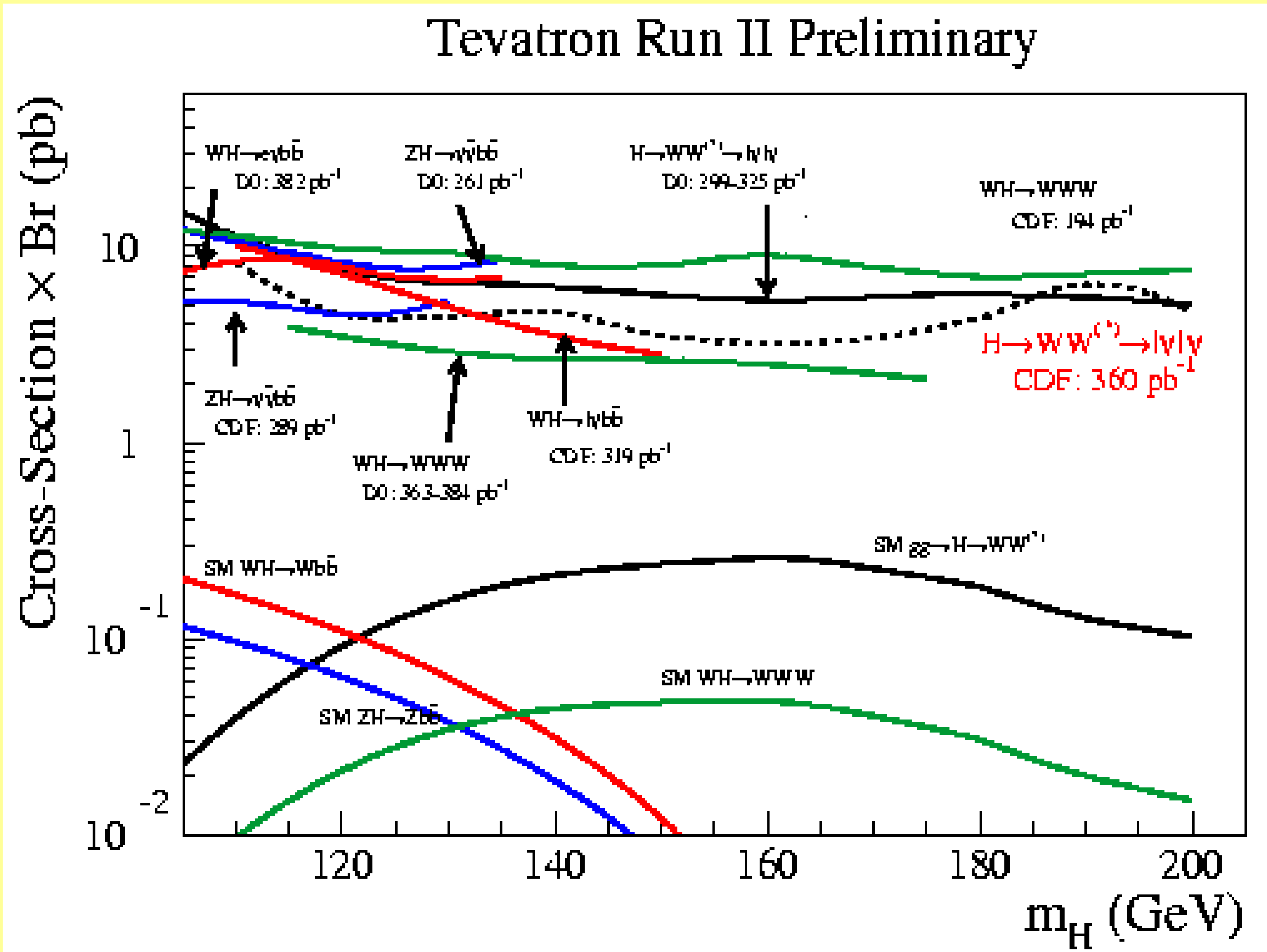
$$Wh \rightarrow WWW \rightarrow \mu^{+}\,\mu^{+}\,X$$

$$g\,g \rightarrow h \rightarrow l^{+}\,\nu\, l^{-}\,\bar{\nu}$$

CDF and DØ have active efforts in these and other channels.



These searches cover a wide range of SM-like Higgs masses, but currently lie far above SM production rates:



With the Tevatron ever have a chance of finding the Higgs?

Luminosities will increase by a factor of 25 or more,
bringing an improvement in sensitivity of a factor > 5.

Recent studies show that a number of possible improvements to these main channels can bring a factor of 5 – 10.

If there is a Higgs with a mass of 115 GeV,
then expect strong evidence ($\approx 4\ \sigma$) by end of Run II.

Otherwise, expect 95% CL with about 2 fb^{-1}.

Exclusions limits could extend over most of the range 100 – 180 GeV.

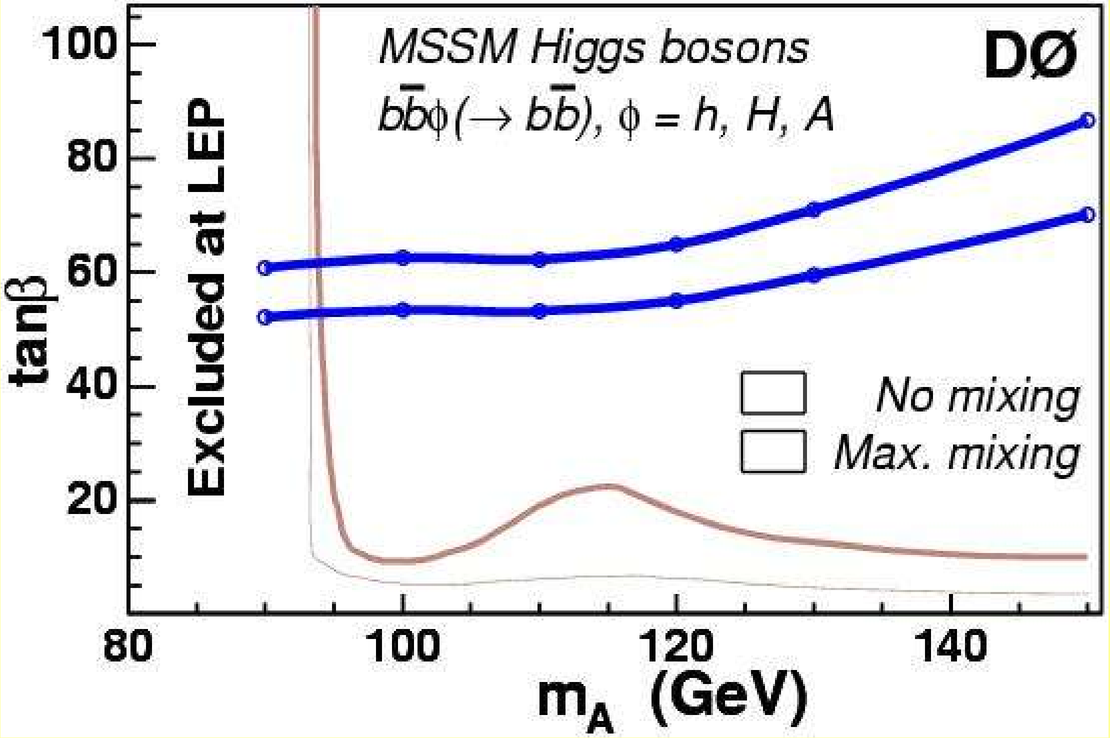
In the MSSM, there is a more extended Higgs sector.

New channels open up which can be larger than SM channels by orders of magnitude when tanβ is large.

The first example is $p\,\bar{p} \;\rightarrow\; b\,\bar{b}\,H\,,A \;\rightarrow\; 4\,b-jets$

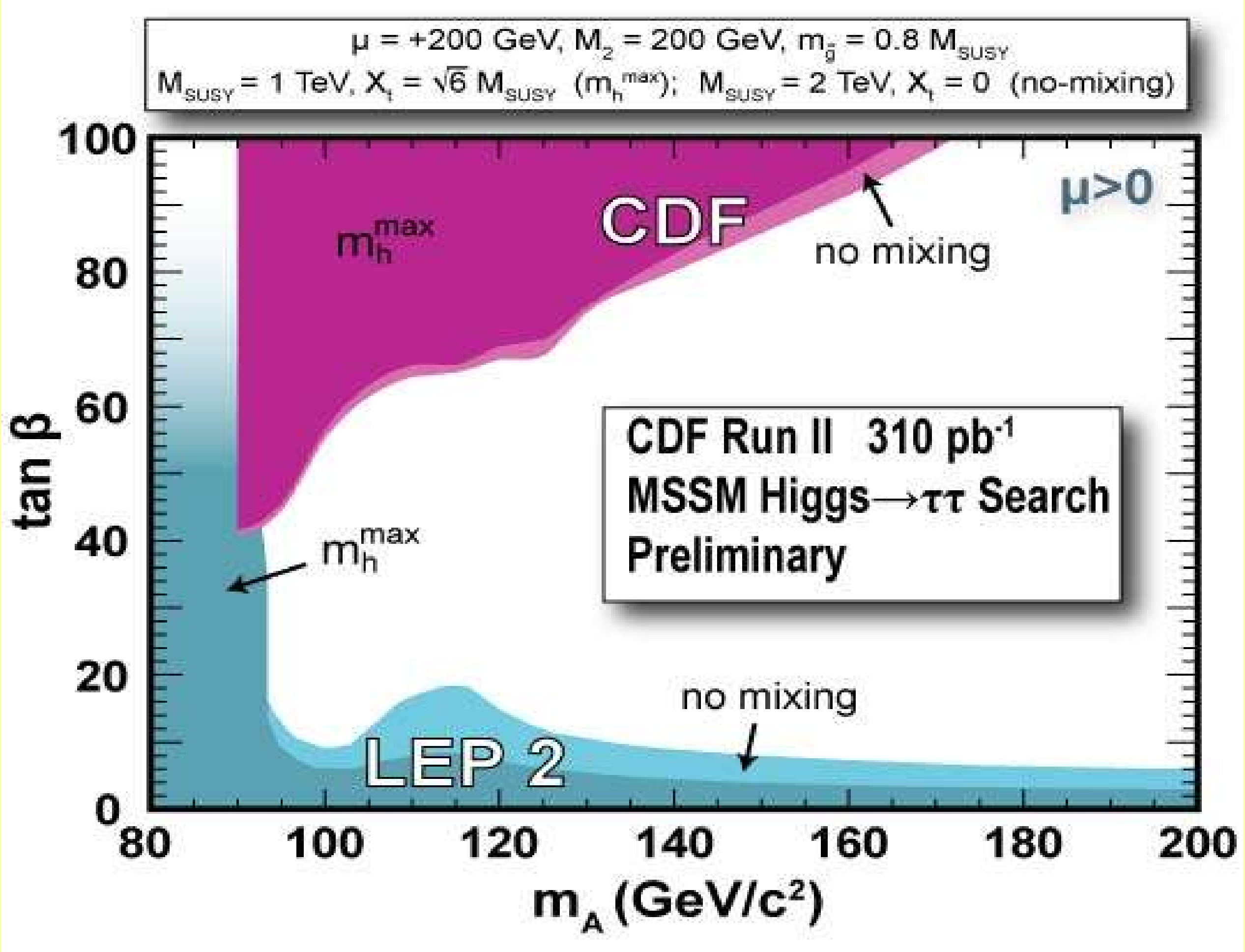
D0 analysis selects 4 clean b-jets and forms the invariant mass distribution.

Constraints already are significant and will improve with more data.



CDF have searched in the H,A $\rightarrow$ $\tau\tau$ channel, inclusive.

In these MSSM searches, the results depend on the scenario, ie on the other theoretical parameters parameters $\rightarrow$ benchmark cases.



Prospects for the end of Run II are also very good.

This is a relatively robust search since it depends only on the $\tau\tau$ system in the final state.

Conclusions

- Searches from the TEVATRON are very active and easily surpass the results from Run I.
- No compelling signal has yet been seen.
- Limits and constraints are interesting in many cases.
- Expect much stronger results by the end of Run II.