# Higgs and Supersymmetry

*at Collider Experiments*

**Lepton-Photon 2003**

Fermilab

11-August-2003

*Michael Schmitt*
*Northwestern University*

## *Higgs:*

- concentrate on MSSM scenarios
- usually expect a light SM-like Higgs
- non-standard scenarios
  - invisible Higgs $h \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_1^0$
  - bosophilic Higgs
  - peculiar BR scenarios
  - CP-violations
- LEP is done with the SM-like Higgs, presently investigating non-standard scenarios with rigor
- TEVATRON is getting started on SM-like signals

*for a recent review, see:*
*Carena & Haber, hep-ph/0208209*

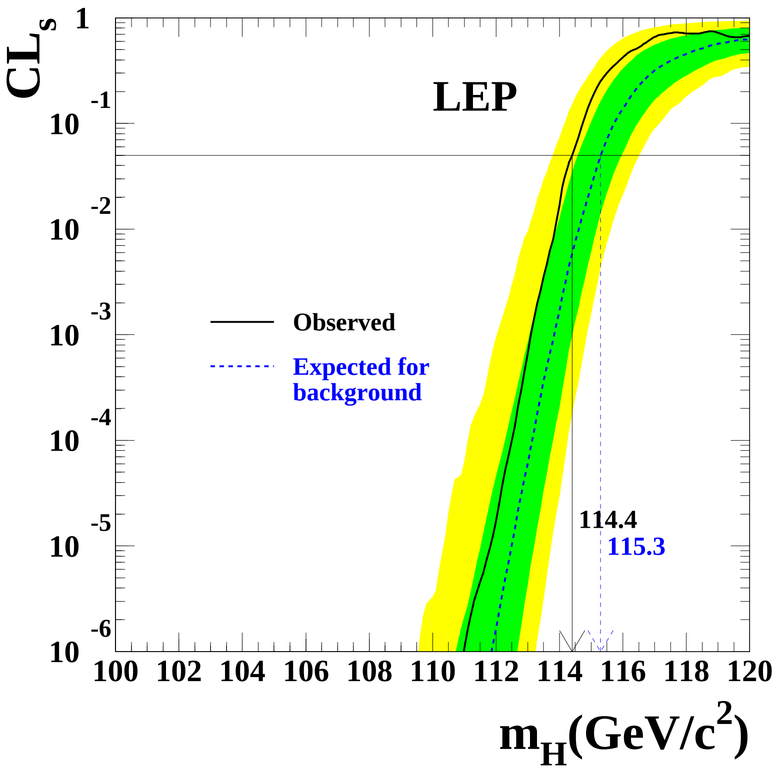
## *Supersymmetry:*

- generic MSSM

  *vs.*
- the multitude of special cases: SUGRA/cMSSM (standard for comparisons), R-parity violation (RPV), gauge-mediated SUSY (GMSB), anomaly-mediated SUSY (AMSB)
- There are no absolute exclusions in Supersymmetry. . .
- emphasize the experimental signatures – not the models
  *After all, the hope is to find something in real data, and theory is only a guide!*

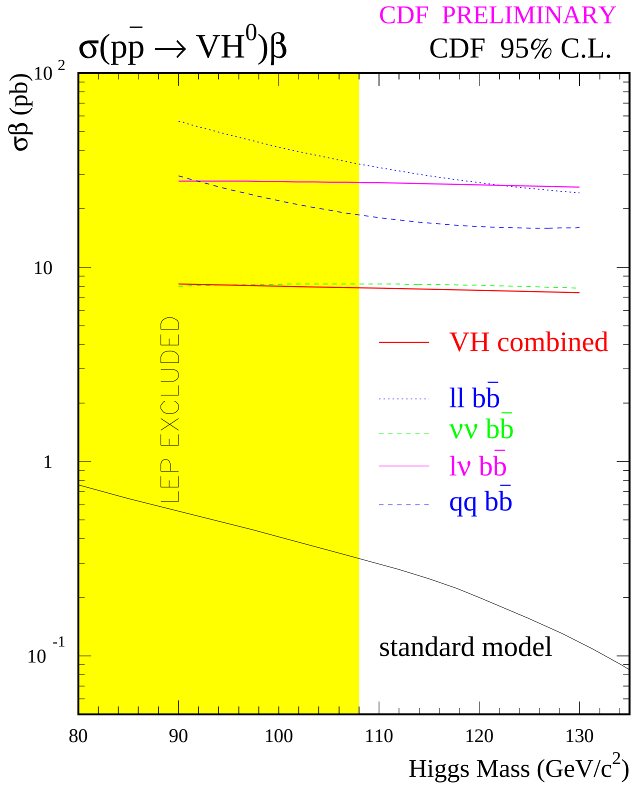
*for a recent review, see:*
*Steve Martin, hep-ph/9709356*

# Standard Model Higgs Searches




Basic SM Higgs, $m_h > 114$ GeV

*no more discussion of 'hints'*




No real sensitivity –

*yet we hope to observe the Higgs in* RUN II...

As we will see, the baton is passing from LEP to the TEVATRON...

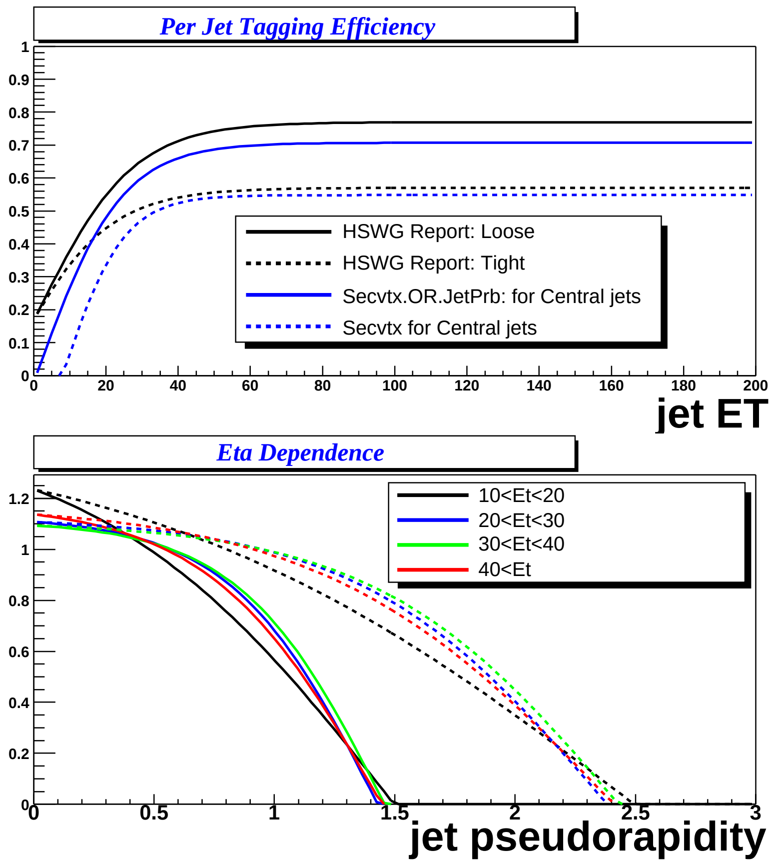
# A New Study of Higgs Sensitivity

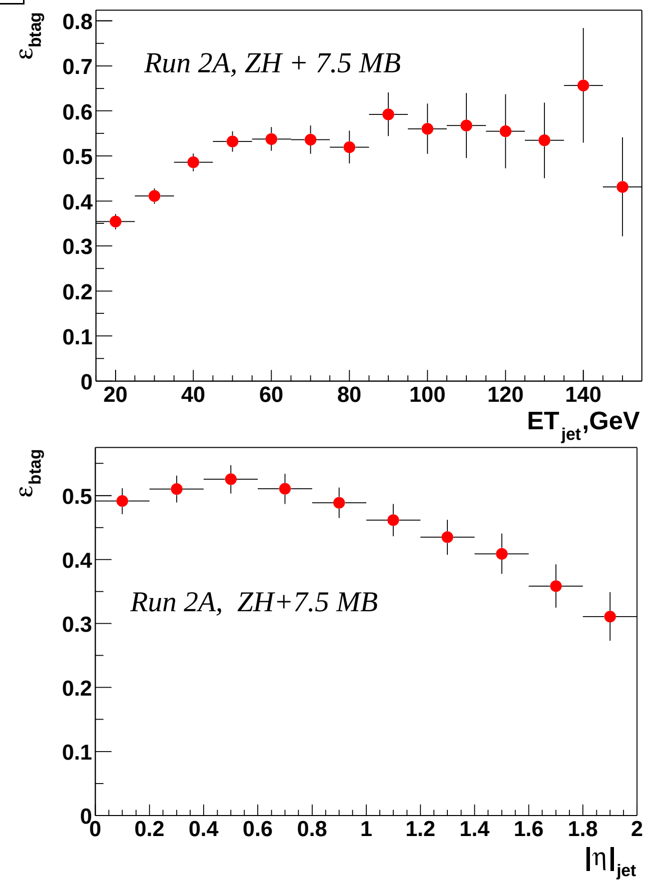
- *Goal:* update the results of the 1998-99 FNAL WS study
  "Were the central assumptions on detector performance too optimistic?"
- *Scientific Justification:*
  - CDF & DØ now have tuned, hit-level simulations.
  - event selections can now be based on actual top & electroweak analyses
  - current analysis techniques (*e.g.*, for key background estimates) can be employed
  - can – must – examine impact of multiple interactions
  - some background processes known to be higher ($\sim 20\%$)
  - what can one achieve if integrated luminosity is low?
- *Practical Approach:*
  - concentrate on $115 < m_h < 140$ GeV
  - concentrate on the two main channels:
    CDF studied $p\bar{p} \to Wh$ with $W \to \ell\nu$ and $h \to b\bar{b}$
    DØ studied $p\bar{p} \to Zh$ with $Z \to \nu\bar{\nu}$ and $h \to b\bar{b}$
  - results combined for both channels and experiments

# Findings:

- Despite some optimistic assumptions in the old study, the conclusions are supported by this new study.
- Central $b$-tagging is almost as good as assumed. *-see plot-*
  Some improvements should still be possible.
  Hope to be able to extend to large $|\eta|$ as indicated. . .
- Optimistically, di-jet mass resolution will have a 11% core.
  Perhaps it will be possible to achieve 10% with advanced techniques.
  ($Z \to b\bar{b}$ calibration signal will require $\sim 400\ \mathrm{pb}^{-1}$)
- *Fitting* the mass distribution amounts to a gain of $\sim 20\%$ in luminosity, compared to counting in a mass window.
- In the $\mathrm{CDF}$ $Wh$ analysis, study di-jet mass resolution and understand in detail differences w.r.t. the old baseline study.
  $\longrightarrow$ hope for some improvement from cut optimization, *etc.*
- In the $\mathrm{D\emptyset}$ $Zh$ analysis, employ dedicated artificial neural networks for certain backgrounds, and cut optimization of discriminating kinematic quantities. *-see plot-*
  $\longrightarrow$ rely on $\mathrm{CDF}$ study for di-jet mass resolution.

# $b$-jet tagging



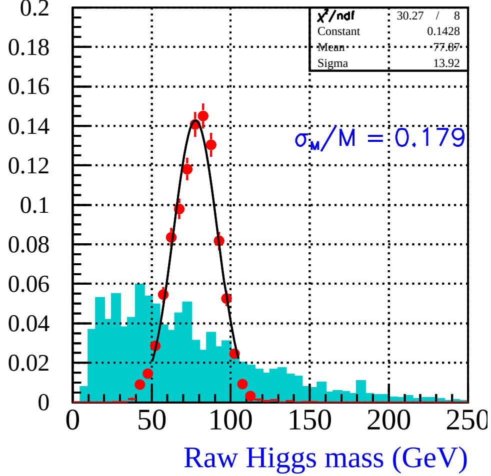



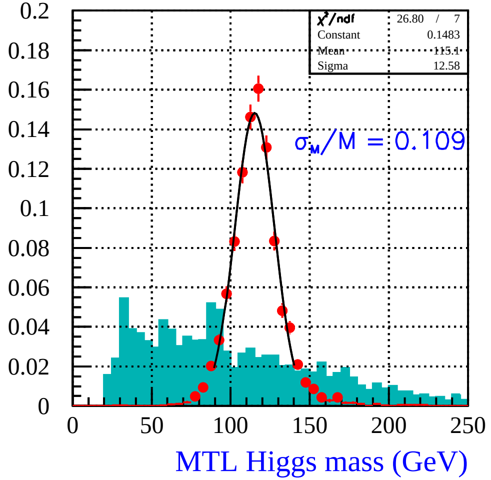

CDF study shows central jets well-tagged & considers extensions to higher $\eta$

DØ study shows some degradation for many multiple interactions

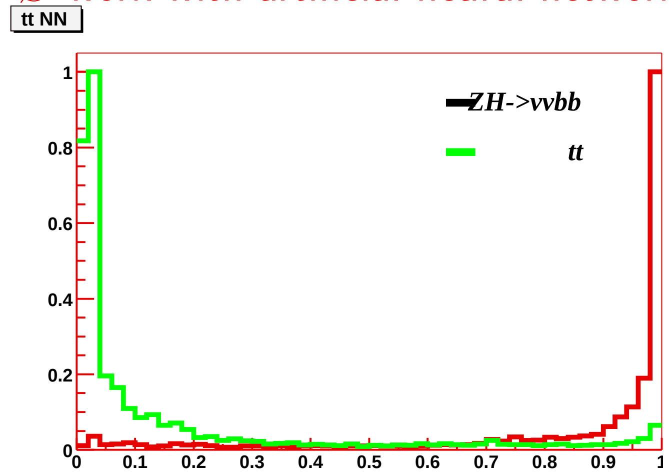
## CDF work on mass resolution:

### Higgs mass corrections

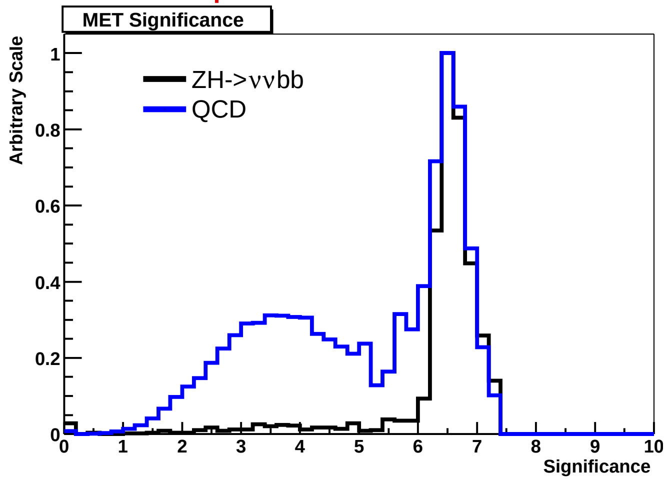


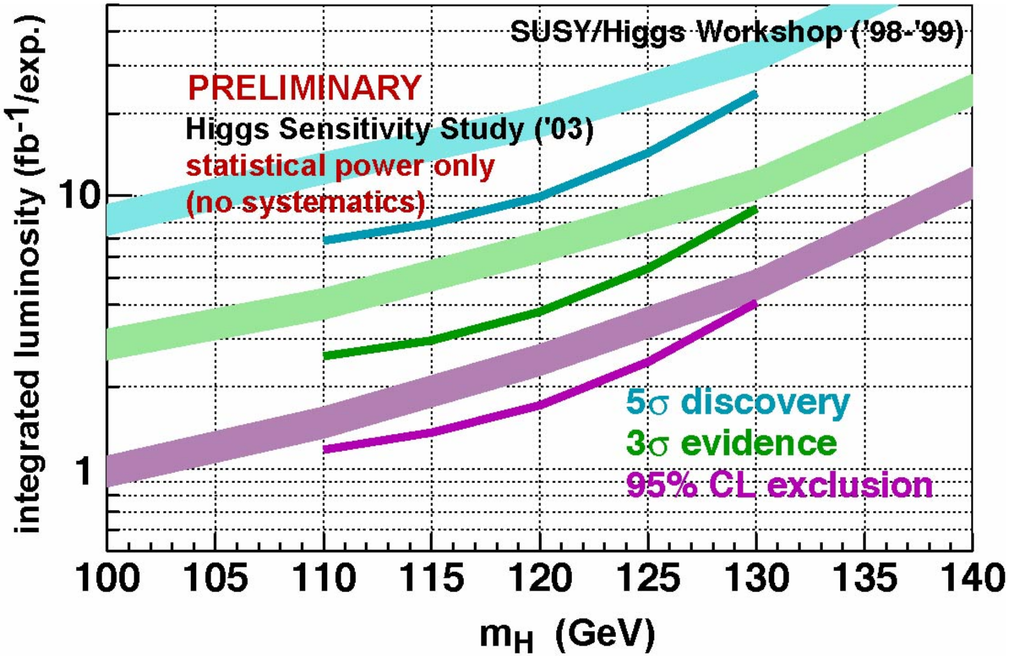

## DØ work with artificial neural networks




## and optimization of cuts:



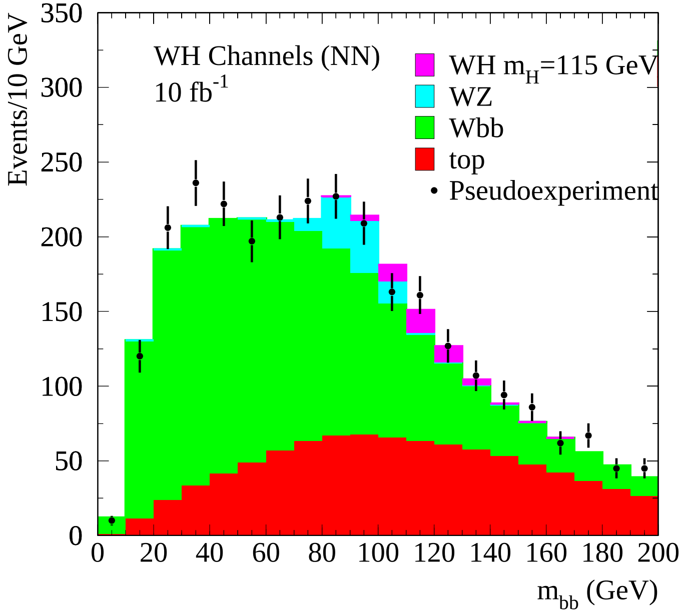
Basic conclusion: the 1998-99 study was not seriously wrong.




- Note that systematics have <u>**not**</u> been taken into account.
- It appears that with $\mathcal{L} \sim 4-5$ fb$^{-1}$, CDF+DØ would exclude SM Higgs if not there up to $m_h \sim 130$ GeV – the range dictated by the MSSM.
- For $\mathcal{L} \sim 8-10$ fb$^{-1}$, might find $3\sigma$ evidence.
- *This is not final – joint report coming very soon.*

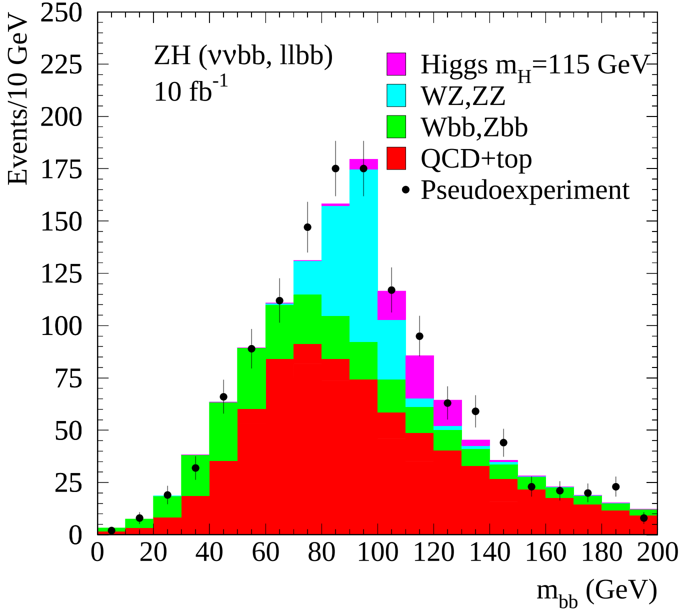
## *The signals, however, will not be dramatic:*

$p\bar{p} \to W\, h$ with $W \to \ell\nu$




*This is a statistically 'unlucky' case...*

$p\bar{p} \to Z\, h$ with $Z \to \ell^+\ell^-, \nu\bar{\nu}$




*This is a statistically 'typical' case...*

(but sometimes they aren't so visual – as we will see...)

## Luminosity Expectations for the TEVATRON

Currently,

- We have $\sim 190\ \mathrm{pb}^{-1}$ on tape –
- this is >80% of the data delivered.
- Physics running started in February, 2002

*projections for fiscal year 2009:*

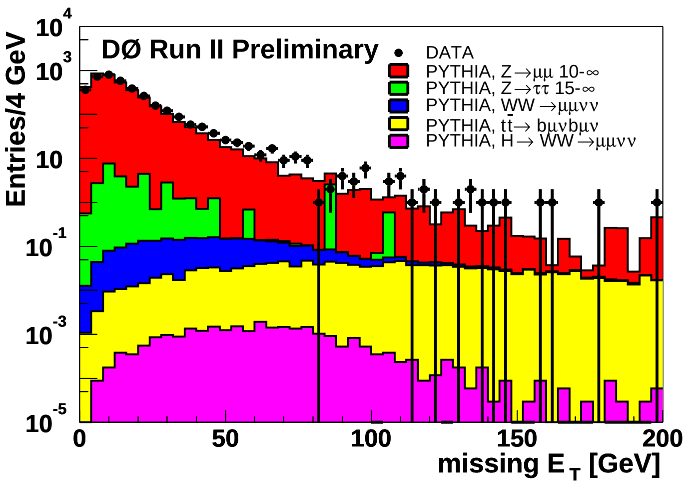
$$\text{`base'}\ \mathcal{L} \sim 4.4\ \mathrm{fb}^{-1}$$
$$\text{`design'}\ \mathcal{L} \sim 8.6\ \mathrm{fb}^{-1}$$

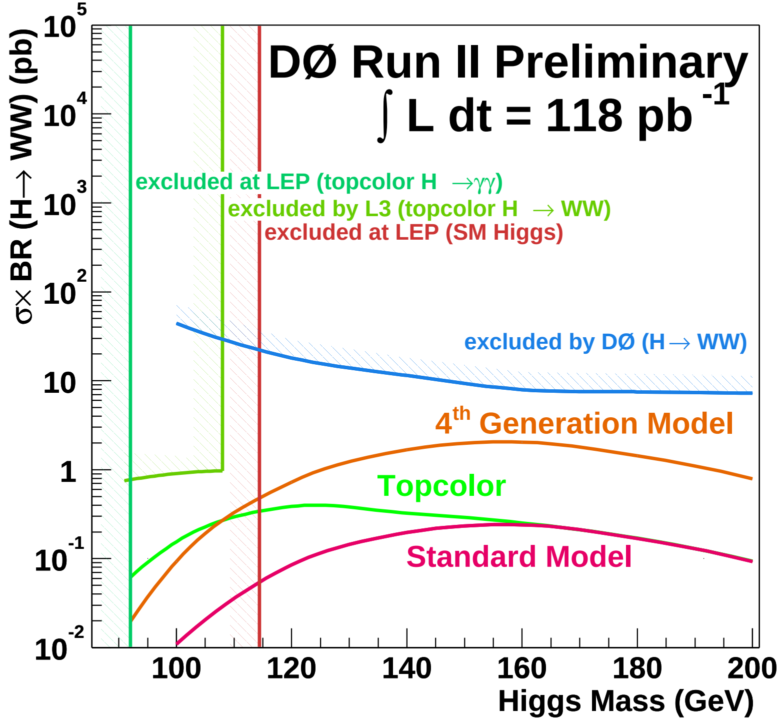
$\longrightarrow$ anticipate achieving $\mathcal{L} \sim 1\ \mathrm{fb}^{-1}$ in 2005.

# New Higgs Results from the TEVATRON

From DØ: Search for $h \to W^+W^-$ with $W \to e\nu$ or $\mu\nu$.
...important in high mass region $140 < m_h < 190$ GeV.

- two energetic, isolated leptons + large $\not{E}_T$
- large SM rates eliminated by topological cuts
- note similarity with continuum $p\bar{p} \to W^+W^-$
- limit $\sigma \times Br < 8$ pb about $100\times\sigma(h)$



# From CDF: $A \to \tau^+\tau^-$ in Run I.

The MSSM provides an opportunity at low $m_A$ and high $\tan\beta$ –
$\sigma \times Br$ in the hundreds of pb!

*(not all cuts applied for this plot)*

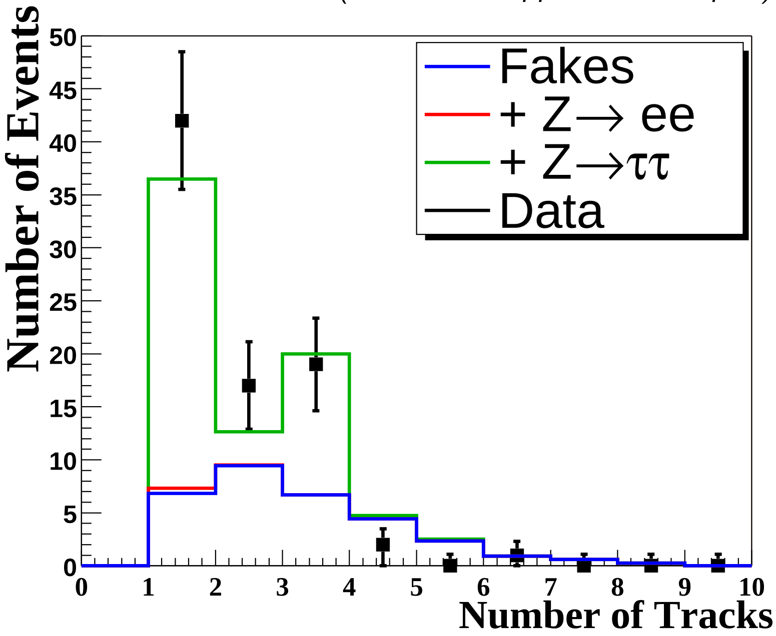
Experimentally, this is a very challenging analysis.

CDF extracted a clear sample of hadronic $\tau$'s.

Expect 53±7 (half QCD & half $Z \to \tau^+\tau^-$)
Observe 47.

Unfortunately, sensitivity is far from the $m_A \to \tau^+\tau^-$ signal, even for $\tan\beta = 50$.

Will be much better in Run II thanks to dedicated triggers.




*(more on taus later)*

# DØ is making the first steps toward a Higgs limit in $h \to Wb\bar{b}$

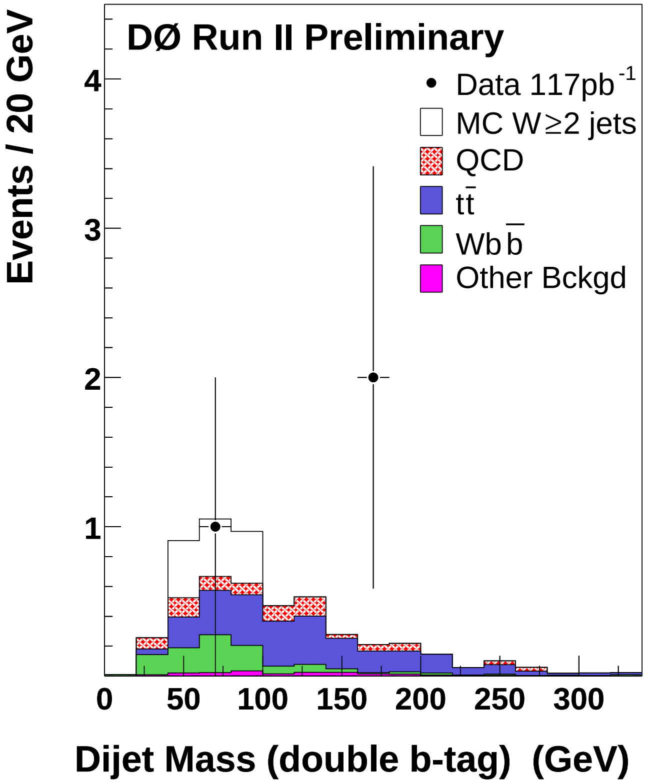
*Higgs is on the other side of Top.*

Select events with a high-$p_T$ lepton and two b-tagged jets.

expect 5.5±1.6 events,
including ~1 event from $Wb\bar{b}$
observe 3 events

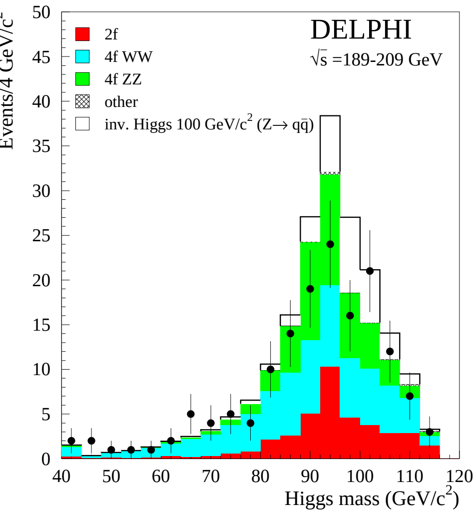
upper limit of 33.4 pb at 95% C.L.

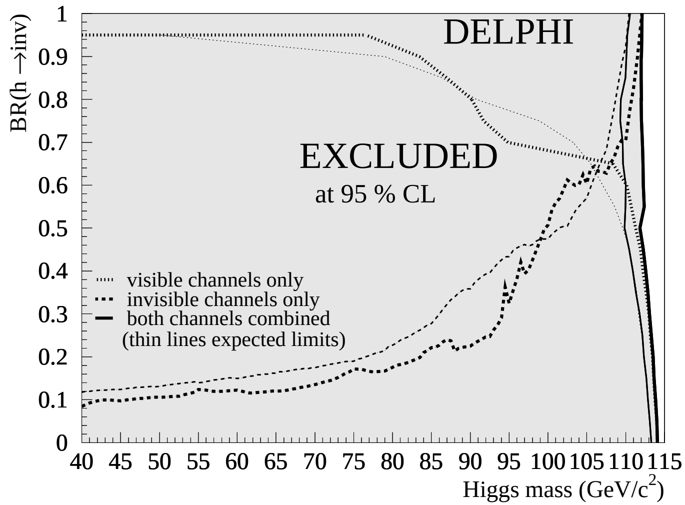
*(SM Higgs cross section < 1 pb.)*

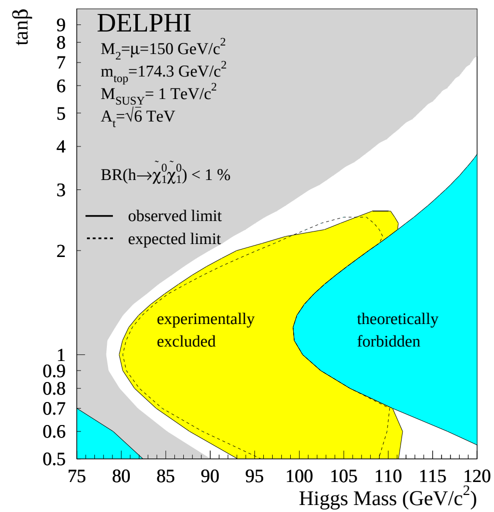


# New Higgs Results from LEP

While the TEVATRON experiments focus on the 'standard' Higgs signatures and channels, the efforts at LEP have been concentrated on stranger scenarios. . .




$h \to \tilde{\chi}_1^0 \tilde{\chi}_1^0$ can dominate for some choices of MSSM parameters.

DELPHI searched for *invisible* Higgs. Analysis relates to $e^+e^- \to Z\,h$ with $Z \to \nu\bar{\nu}$.
The DELPHI limit is nearly as stringent as SM Higgs!

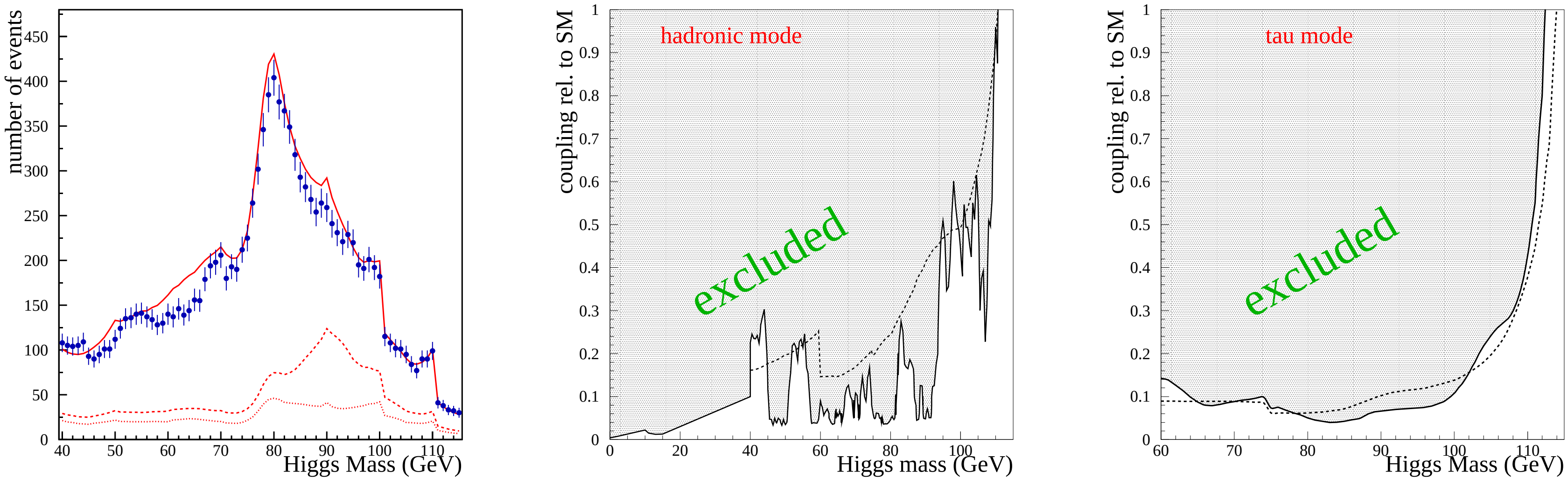
# Flavor-Independent Higgs Searches

A Higgs with $m_h < 140$ GeV decays mainly to $b\bar{b}$ at tree-level.

However, radiative corrections can change this dramatically.

$\longrightarrow$ perform a flavor-independent search: abandon b-tagging and rely on kinematics.

example: ALEPH $\ell^+\ell^- q\bar{q} + \tau^+\tau^- q\bar{q} +$ 4-jet channels




lower limit on $m_h$ is 110 – 112 GeV

*(See also: DELPHI and OPAL contributions to this conference.)*

# Searches for Bosophilic Higgses

In a similar vein, consider Higgs which decay primarily to boson pairs $h \to VV$.

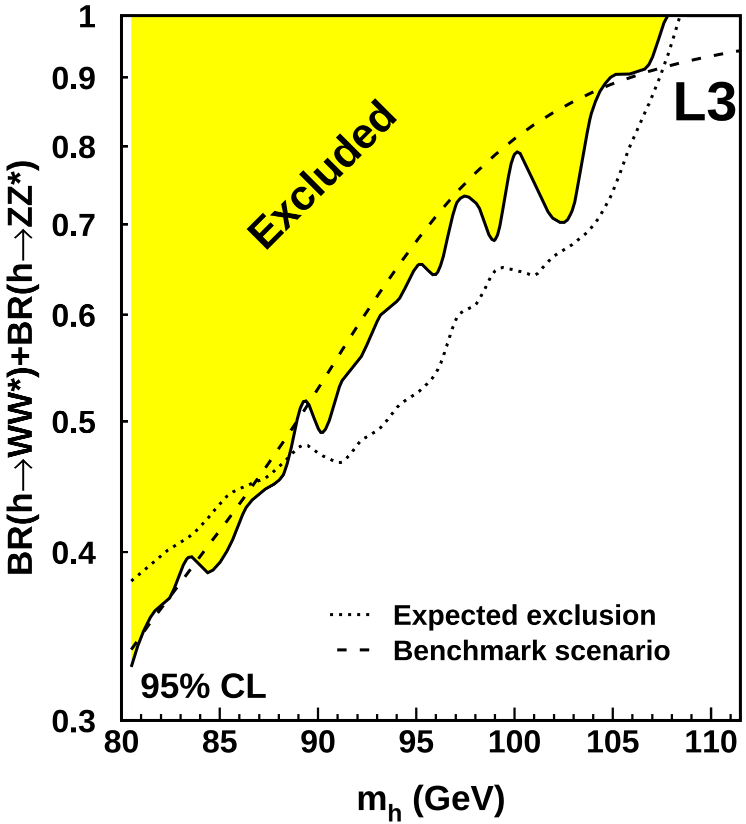
example: L3

benchmark scenario: assume $\sigma_{\mathrm{SM}}$, 'turn off' all decays to fermions

$h \to \gamma\gamma$ dominates for $m_h$ <40 GeV.

combine many channels depending on decays of $Z$ and of $V$'s.

$m_h >$ 108 GeV
for Br$(h \to WW + ZZ)$ =1.



# CP-Violation in Higgs Decays

CP violation may be induced through radiative corrections (esp. $\tilde{t}_i$)
This may help explain the baryon asymmetry of the universe. (Pilaftsis & Wagner, 1999) (Carena *et al.* 2000)
In general, three mass eigenstates $\{H_1, H_2, H_3\}$ are mixtures of the CP eigenstates $\{h, H, A\}$.
Couplings to gauge bosons can vary widely, and the lightest one $H_1$ might not be produced at LEP at all!

New OPAL analysis of 'Higgsstrahlung,' 'Associated Production,' and 'Yukawa Production' →
CP-conserving scenarios already well known:

$m_h, m_A > 84$ GeV and $\tan\beta \sim \mathcal{O}(2)$ is excluded

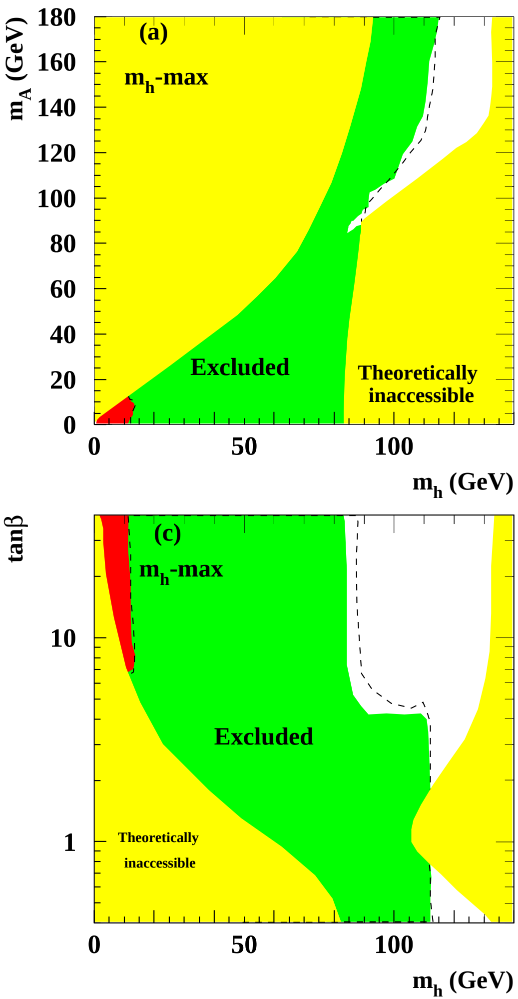
But there are some interesting special cases:

- "large $\mu$" – suppressed decays to $b\bar{b}$ due to large negative corrections from SUSY loops
  flavor-independent searches are important here.
- "gluophobic" – stops and tops cancel in $g - g - h$ loops (a big problem for LHC).
- "small $\alpha_{\rm eff}$" – suppression of decays to $b\bar{b}$ and $\tau^+\tau^-$ due to additional mixing in Higgs sector

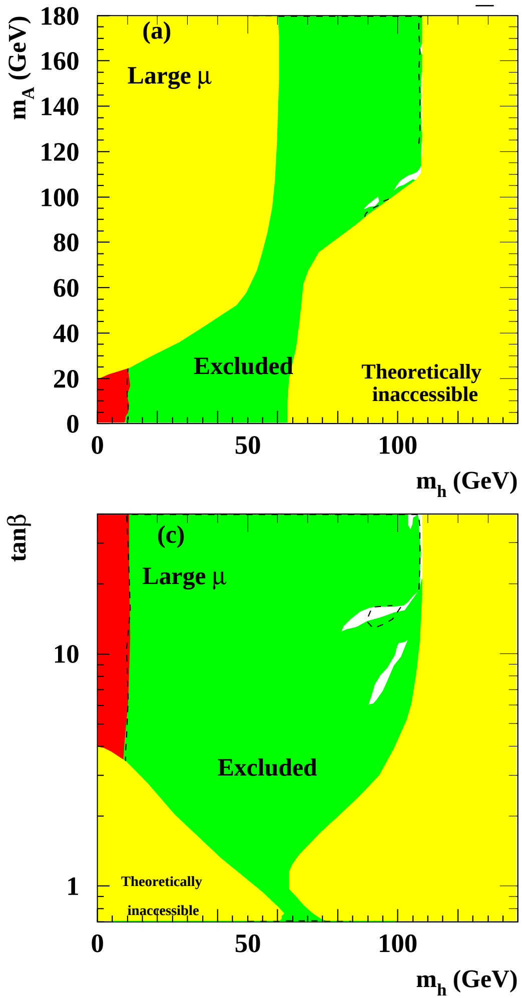
<u>CP-violating scenario:</u>

- mixing effects in Higgs sector are large when $\mathrm{Im}(\mu A_t)$ is large and/or $m_S$ is small.
- dramatically different phenomenology when $\arg(A_t) \sim 90°$

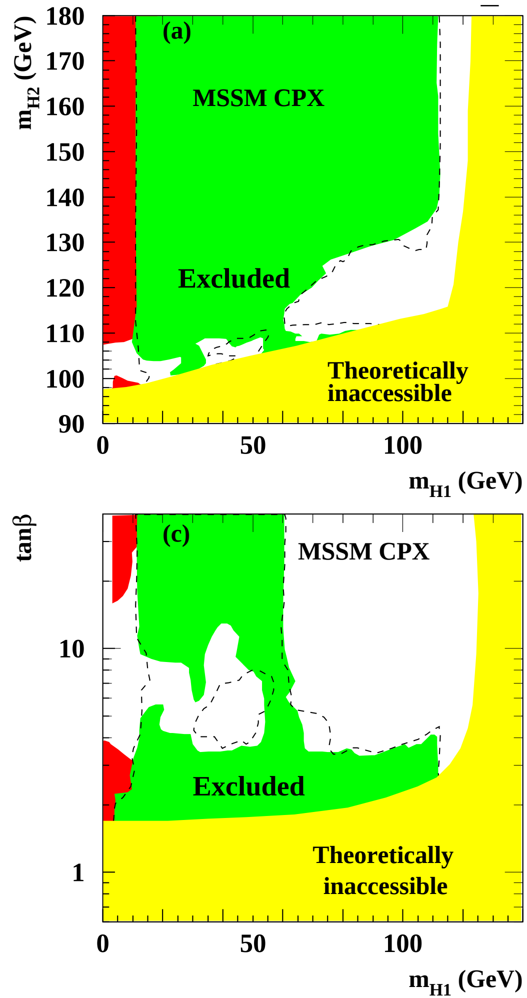
(Benchmarks suggested in Carena, Ellis, Pilaftsis & Wagner, 2000)




maximum $m_h$ scenario




large $\mu$ scenario




a tough CP-violating case

## Super⋆Symmetry⋆Searches

We have many many scenarios to consider.

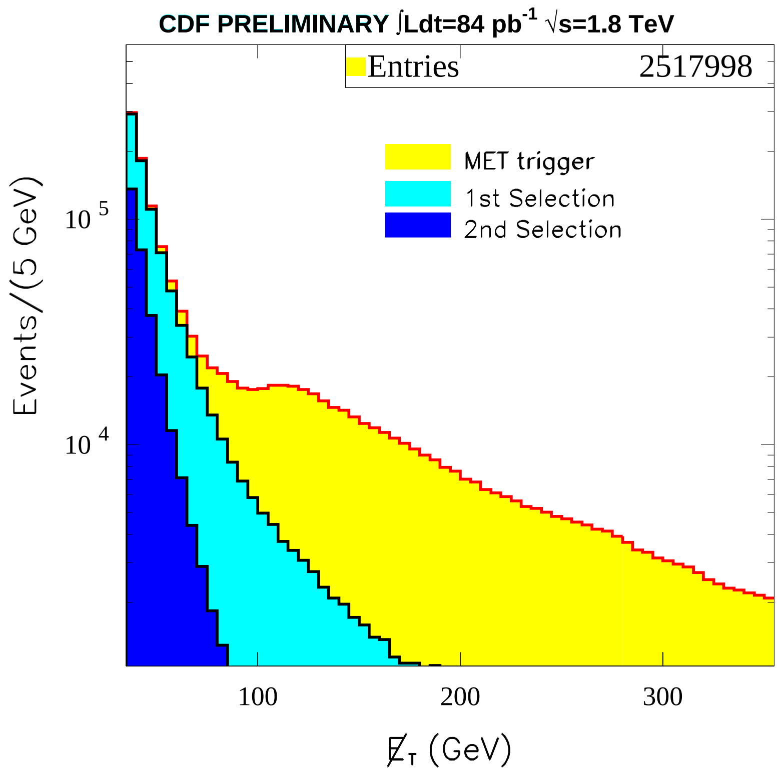
In different cases, the experimental signatures are similar.

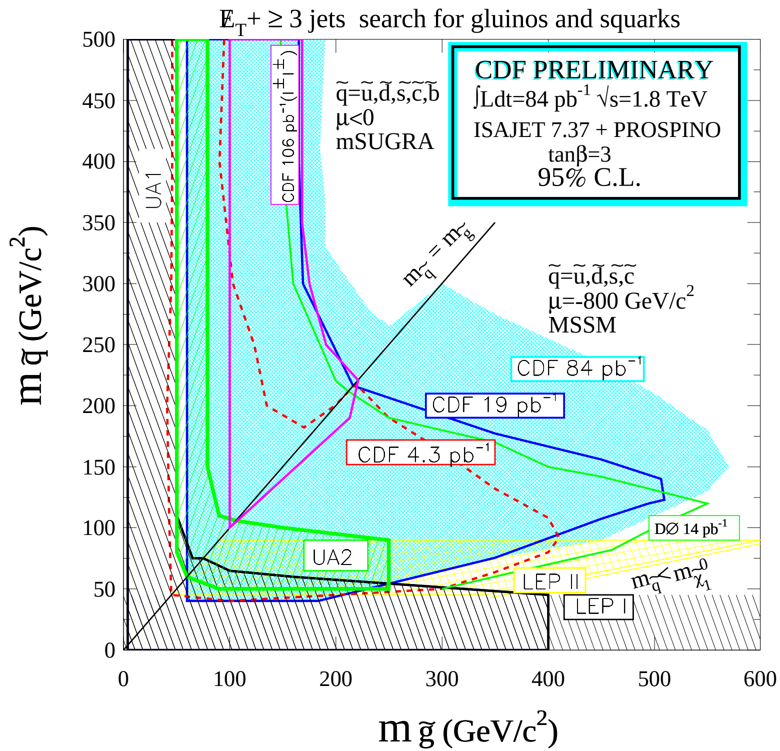
So, we will organize the discussion around the elements of the searches, namely

*jets, missing energy, leptons, taus, photons,*
*and strange tracks!*

# Jets ( + Missing Energy) ( + Leptons)

From Run I, the lessons on reducing a huge MET sample to a few, constraining events:



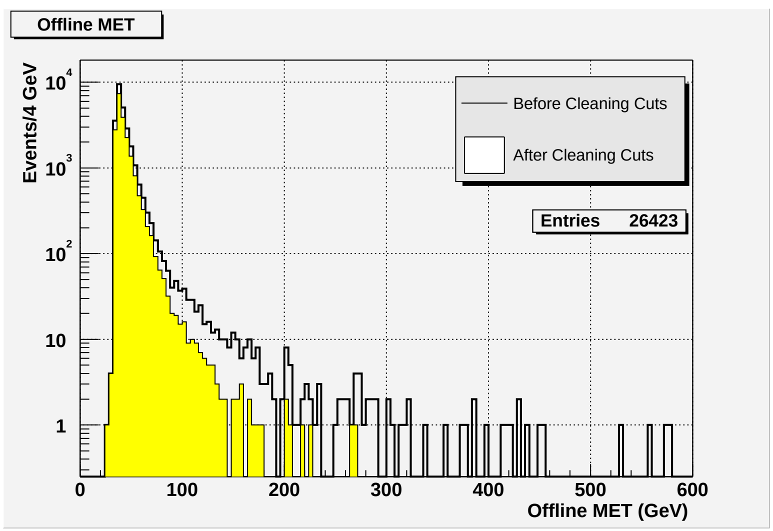

Most stringent bounds in mSUGRA $\longrightarrow m_{\tilde{g}} >$195 GeV, and $>$ 300 GeV when $m_{\tilde{q}} \approx m_{\tilde{g}}$.

**NB:** *much better than expected a priori. . .*

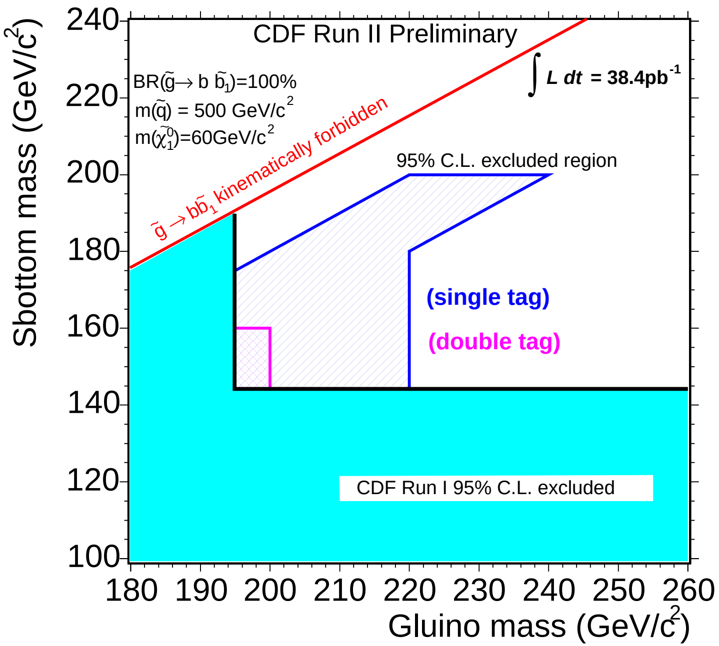
# From Run II, a new analysis looking for $\tilde{g} \to b\,\tilde{b}_1$ (CDF)

Take advantage of the large cross sections for the production of gluinos at a hadron machine.

- much better b-jet trigger, greatly improved acceptance
- $b$-tagging (SVX algorithm)
- currently using only a fraction of available data




*Note how much cleaner than in* Run I.



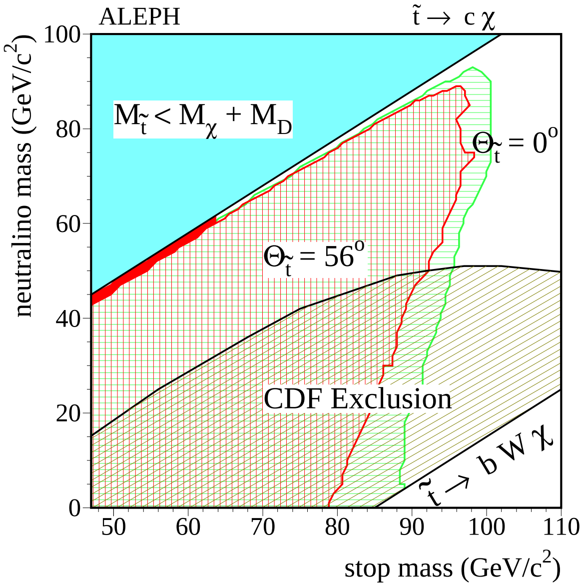
# Stop & Sbottom searches at LEP – many varieties...

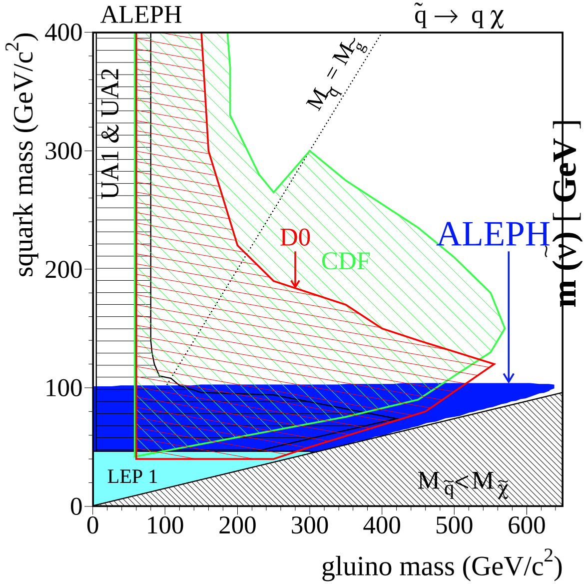
several $\tilde{t}_1$ searches from ALEPH:

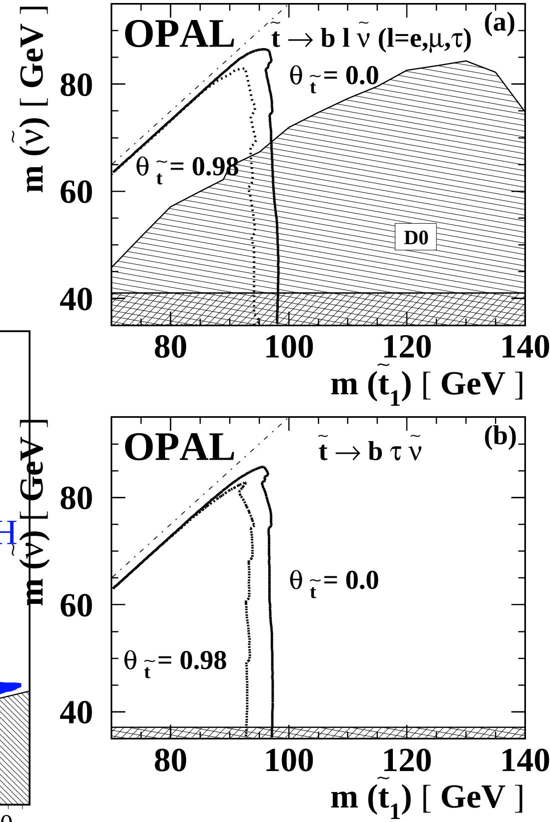
- $\tilde{t}_1 \to c\tilde{\chi}^0_1$ (and $\tilde{b}_1 \to b\tilde{\chi}^0_1$)
- $\tilde{t}_1 \to b\ell\tilde{\nu}$
- $\tilde{t}_1 \to bf\bar{f}\chi$

special effort from OPAL on $\tau$ channel $\tilde{t}_1 \to b\,\tau\,\tilde{\nu}_\tau$.

ALEPH result reinterpreted for generic $\tilde{q}$:

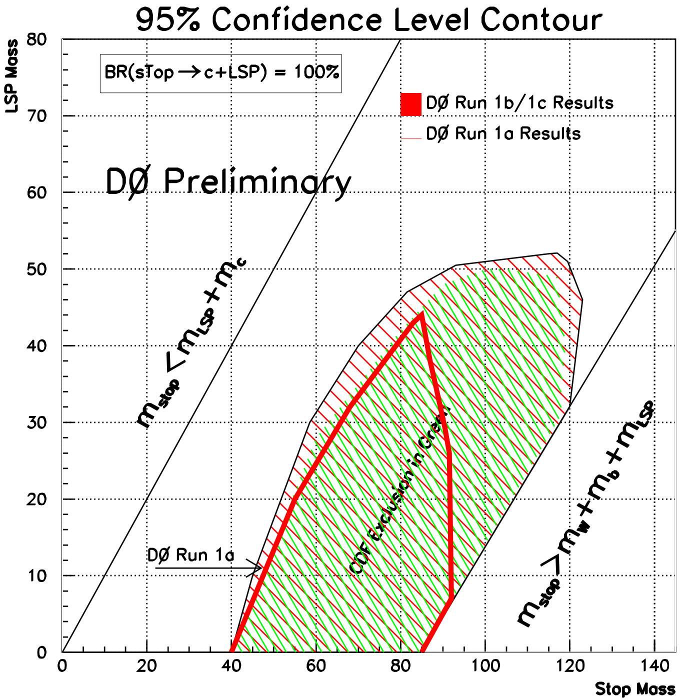


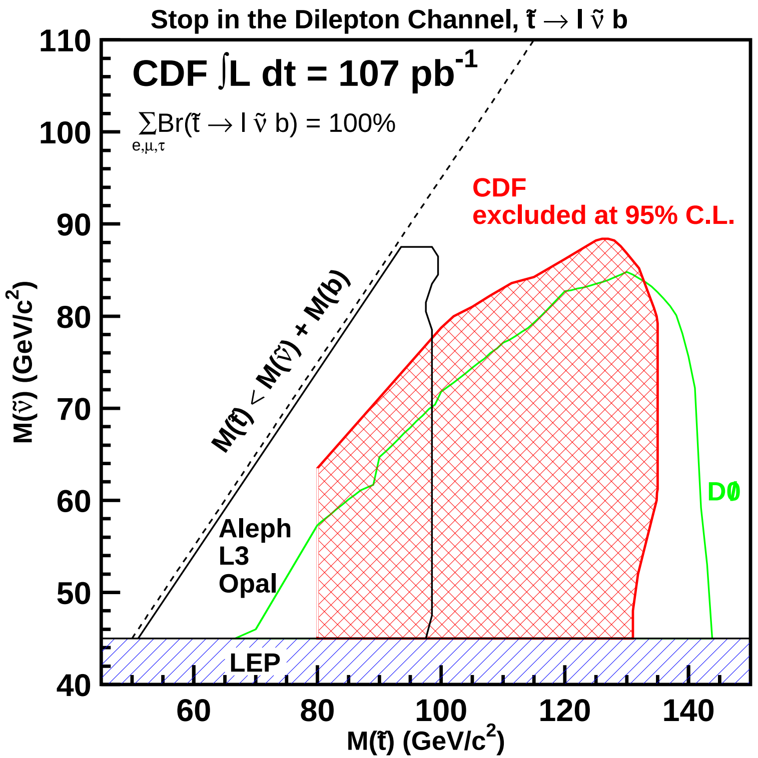



## (. . . *finishing-up stop searches from Run I* . . . )

New DØ analysis of $\tilde{t}_1 \rightarrow c\tilde{\chi}_1^0$




New CDF analysis of $\tilde{t}_1 \rightarrow b\ell\tilde{\nu}$




*Stay tuned for updates from the Run II data. . .*

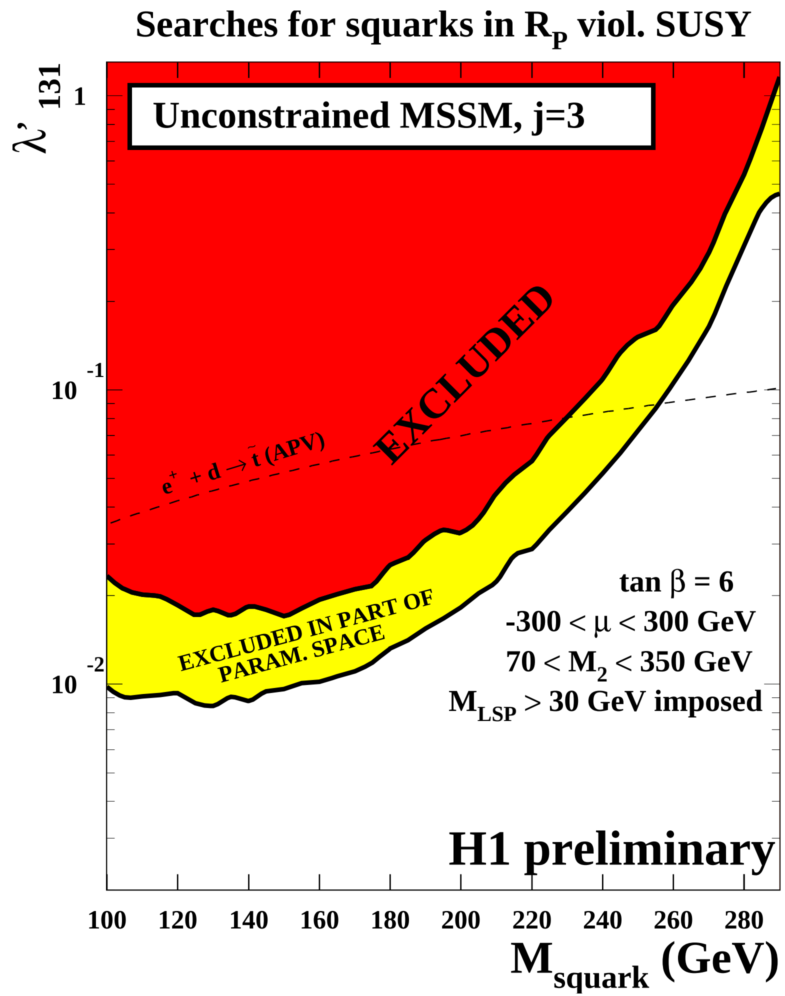
# Jets, Lepton & $\not\!\!E_T$ at HERA

A nice analysis from H1 considers $R$-parity violating production and decay of squarks.

Examine several signatures with jets and either high-$p_T$ electrons or missing energy, as appropriate for the assumed $R$-parity violating couplings.

Search is similat to that for leptoquarks.

Several cases considered, and limits placed on the coupling $\lambda'$ as a function of the squark mass.



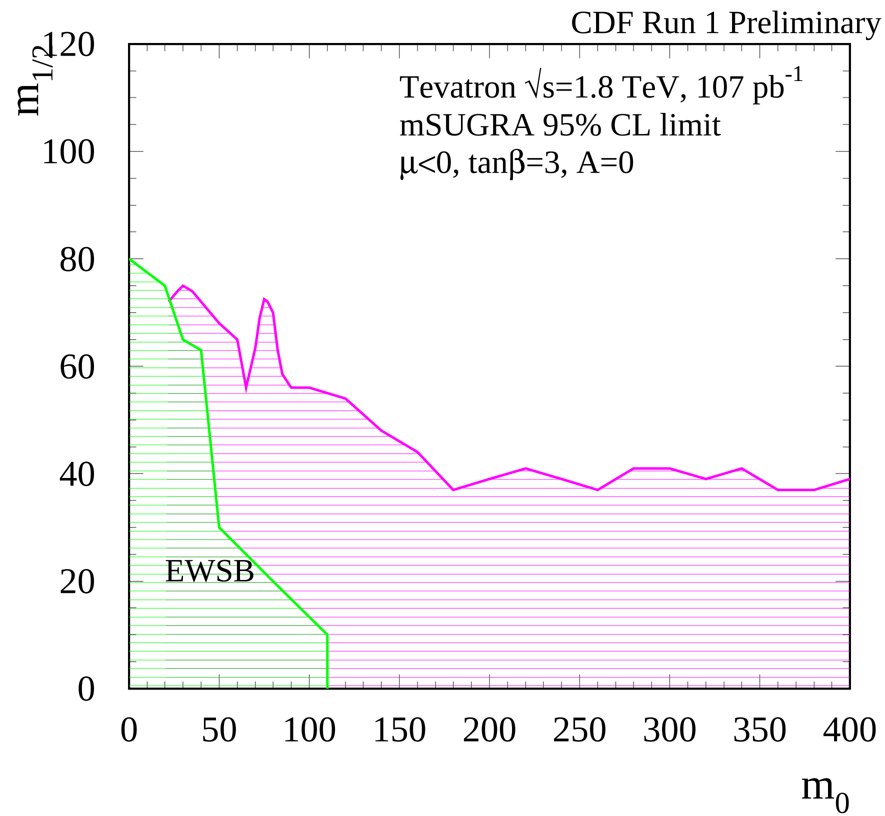
# More about Leptons

Lepton-based signatures are useful for finding $p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0$ (*e.g.*'tri-lepton' analysis)

CDF is completing an extension of the search for gauginos in the "like-sign di-lepton" channel

$$p\bar{p} \rightarrow \ell^{\pm}\ell^{\pm} + X$$

from Run I.




After a careful removal of non-isolated leptons and a study of fakes, zero events were observed where ~0.6 were expected.

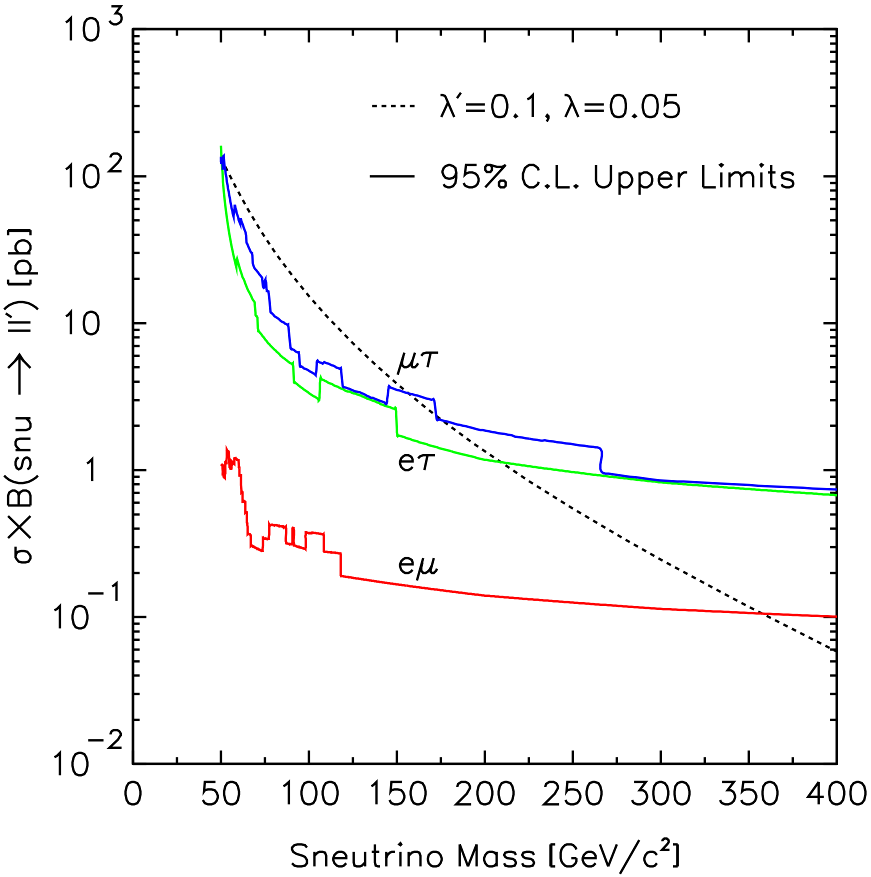
Derive limits in the mSUGRA model, accept small contributions from other processes. Not as constraining as Jets+$\not{E}_T$. Look forward to Run II, combined with tri-leptons.

A related sample is the "opposite-sign, different-flavor" channel which has been used to constrain $R$-parity violating $\tilde{\nu}$ production.

$$d\bar{d} \to \tilde{\nu} \to \ell^+ \, \ell'^-$$

The actual limits depend on the assumed values of the $R$-parity violating couplings, $\lambda$ and $\lambda'$.

CDF Run I

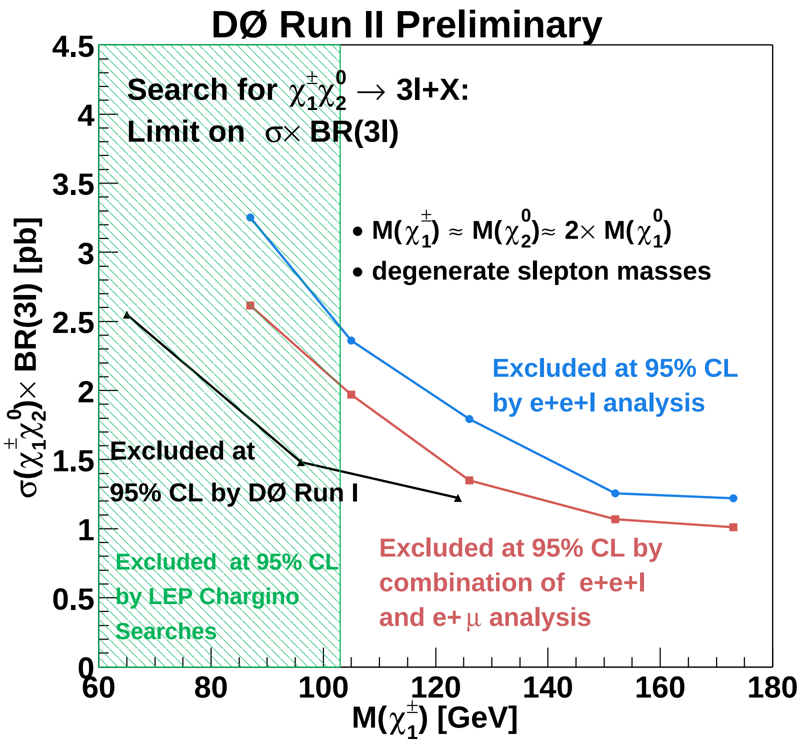


# Lepton-based Searches in Run II

## DØ has the first Run II result in the *tri-lepton* search!

- dedicated search in $e\,e$ +track sample
- reinterpret model-indep. $e\,\mu$ +track search
- both require high-$p_T$, well identified & isolated leptons, large missing energy, *and a single isolated track*
- SM backgrounds are low, dominated by $W$+jets & $W^+W^-$
- combine results to constrain

$$p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow \ell e e \nu \tilde{\chi}_1^0\tilde{\chi}_1^0$$
$$\rightarrow \ell e \mu \nu \tilde{\chi}_1^0\tilde{\chi}_1^0$$

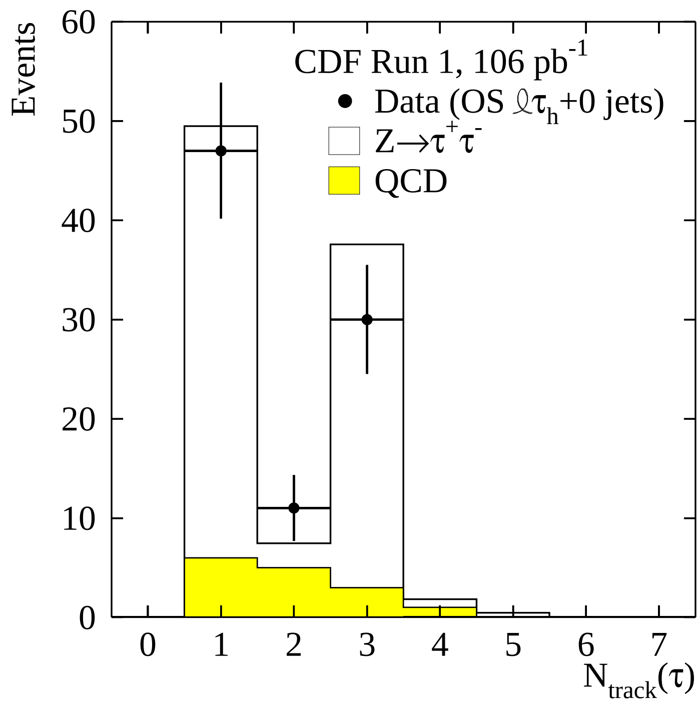


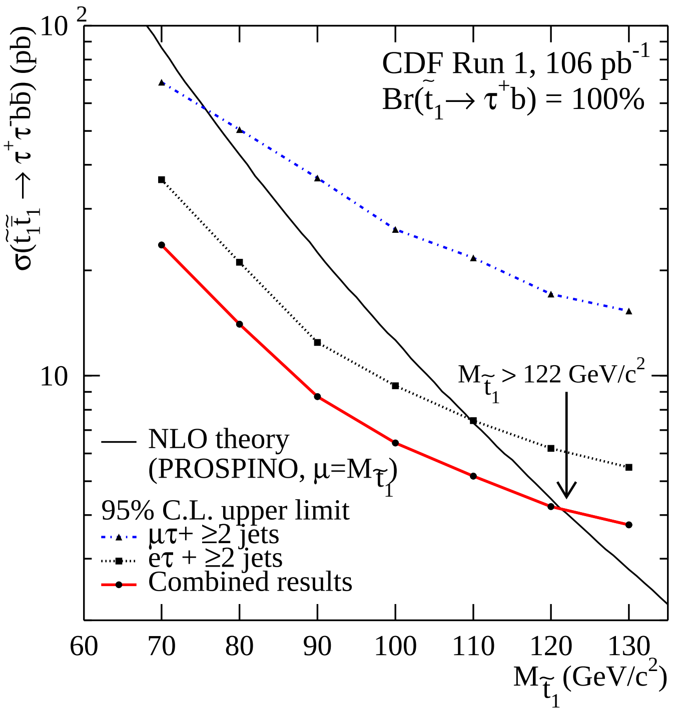

limits compare well to Run I, but are a factor 10 above mSUGRA predictions

# Taus, Taus, Now Everyone has Taus

One of the more difficult challenges in Run I was to search for new particles based on $\tau$-signatures. It was pointed out that these signatures might be crucial.

$\tau$-based searches did eventually succeed – here is a good example from Run I: $R$-parity violating $\tilde{t}_1 \to b\tau$ decays $(\mathrm{CDF})$.

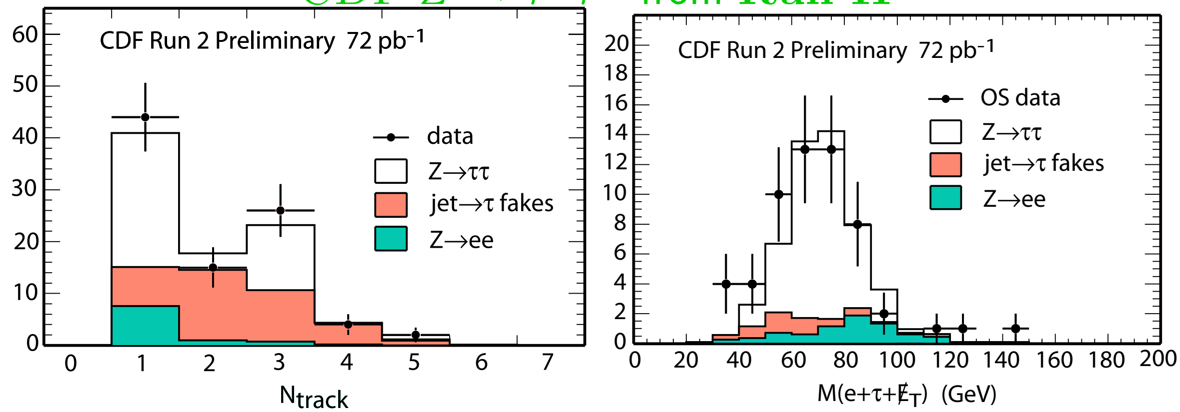


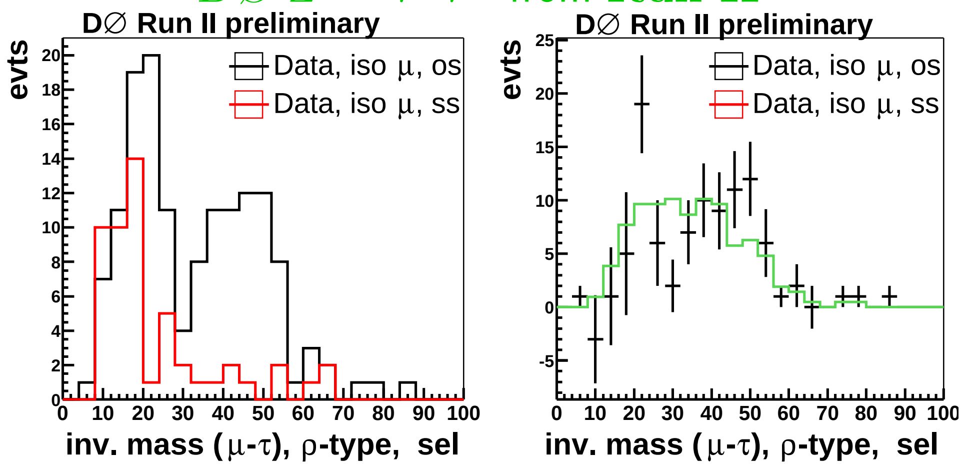

*(Recall also the $A \to \tau^+\tau^-$ result quoted earlier.)*

For Run II, the TEVATRON collaborations put special emphasis on better triggers for $\tau$ signals. Much has already been achieved in establishing good $\tau$ signals (from SM processes).

## CDF $Z \to \tau^+\tau^-$ from **Run II**



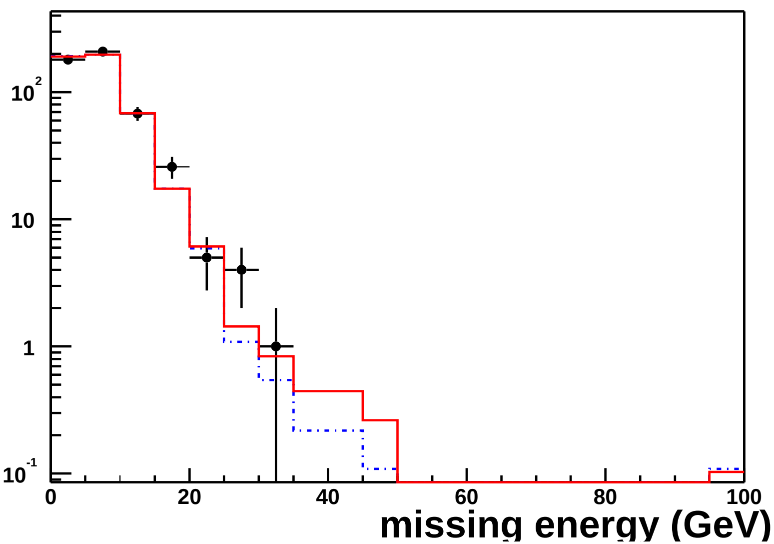

## DØ $Z \to \tau^+\tau^-$ from **Run II**

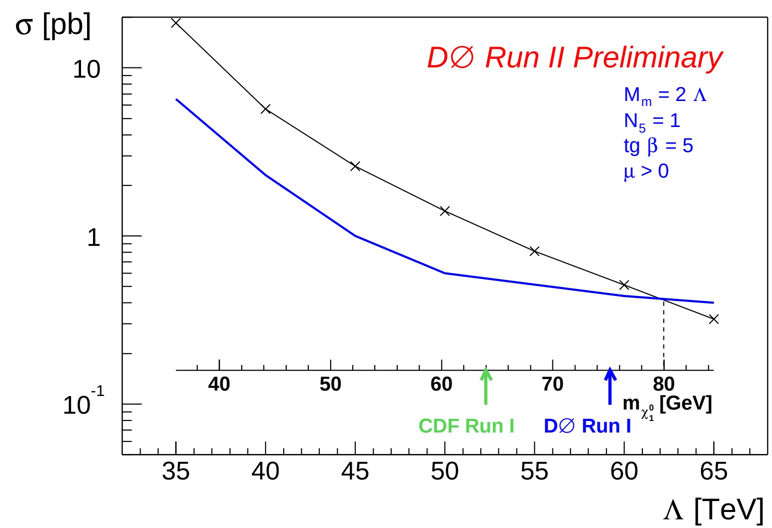


This case is motived mainly by the gauge-mediated scenario, which has many theoretical virtues. In truth, it received a lot of attention some years ago when a single spectacular event was publicized by the CDF Collaboration.

Naturally there has been lots of attention to photon-based searches in Run II.

DØ is ready with $\gamma\gamma + \not{E}_T$:



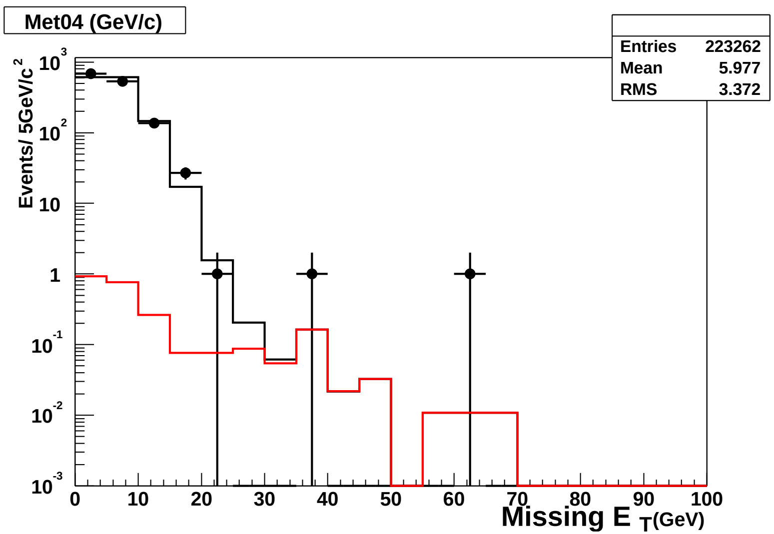



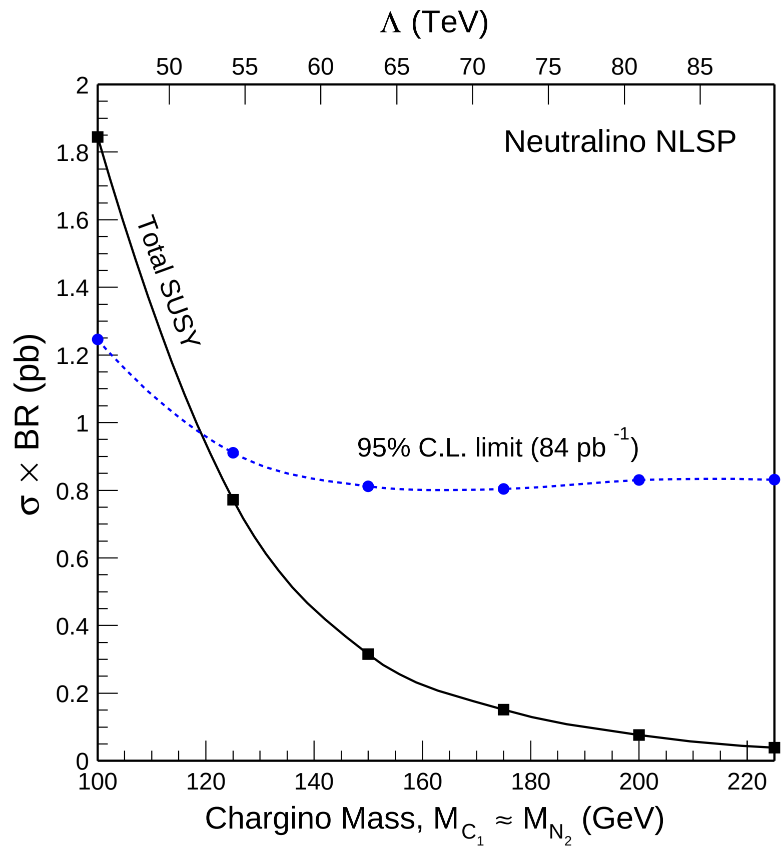

Select two central EM clusters, $E_T > 20$ GeV, & $\not{E}_T$ should not point along photon (or jet) directions. Normalize QCD background in $\not{E}_T < 15$ GeV region. Optimal cut is $\not{E}_T > 35$ GeV.

Expect $1.4 \pm 0.3$, observe zero.

# CDF has obtained very similar results:

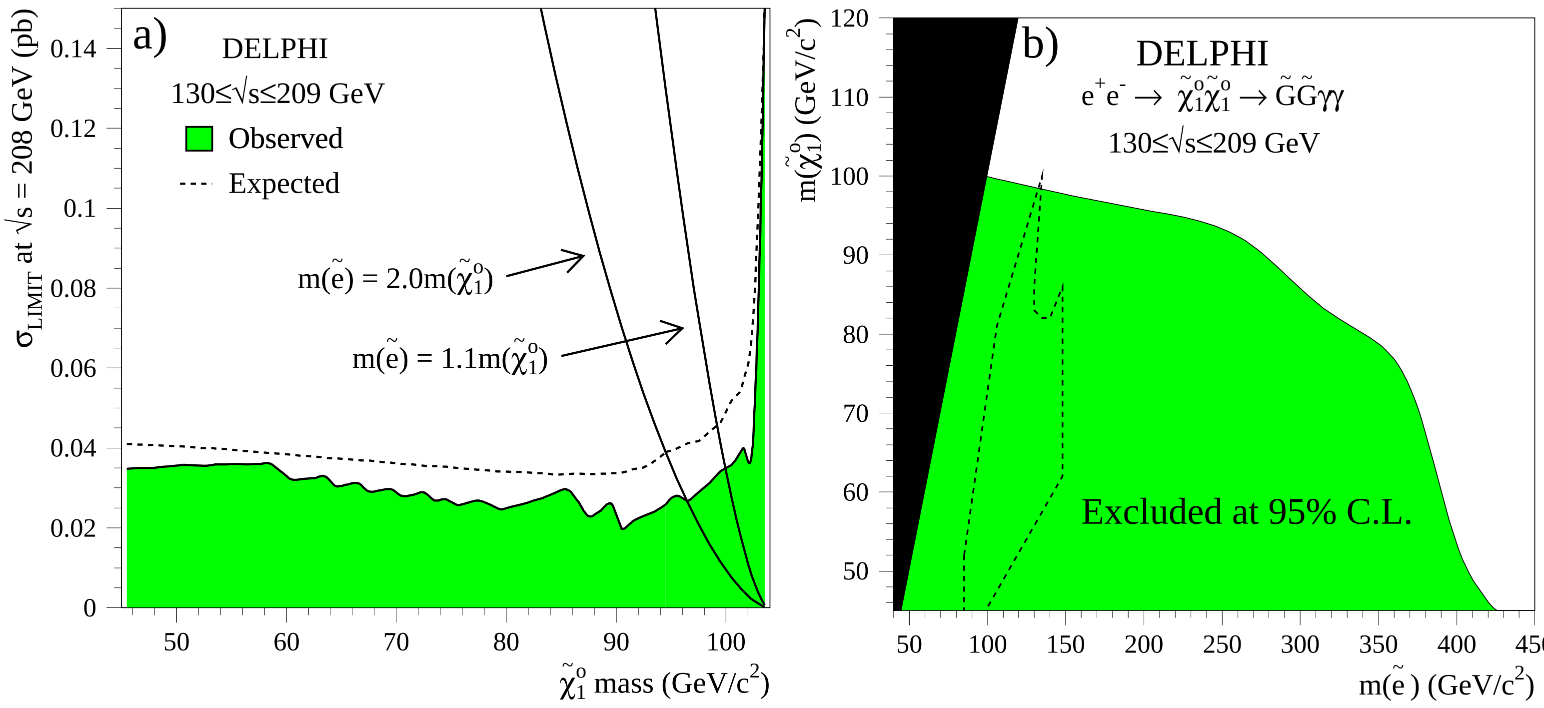
- 2 isolated photons, $E_T > 13$ GeV
- $\not{E}_T$ separated from photons & jets
- require $\not{E}_T > 25$ GeV
- expect 0.6 events, observe 2 (84 pb$^{-1}$)
- highest $\not{E}_T$ is 64.6 GeV



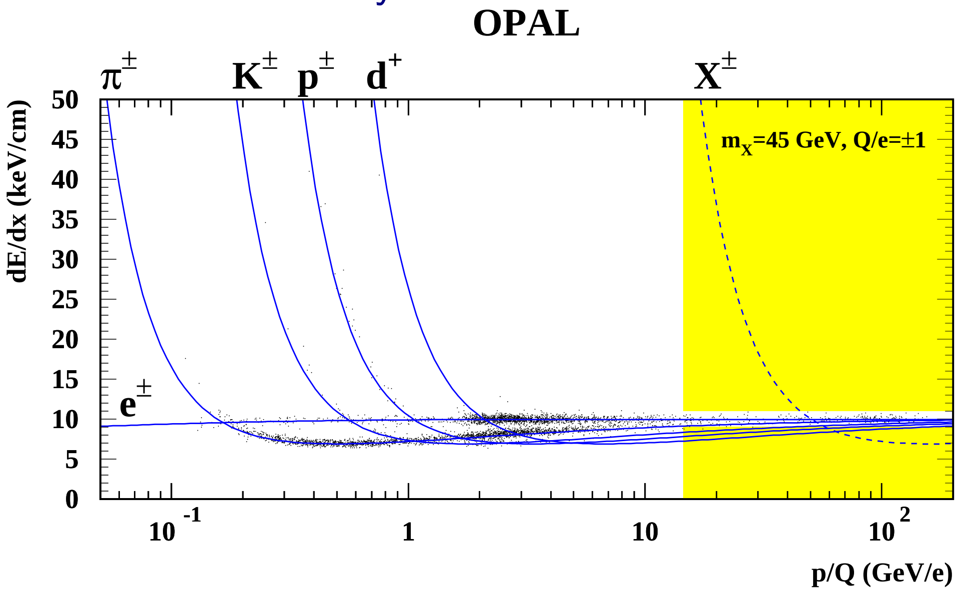
The LEP collaborations continue to investigate these channels, too.

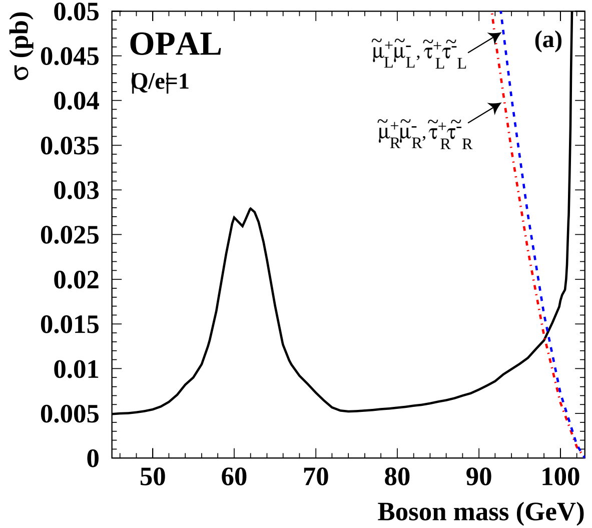
The final state is $2\gamma + \not{E}_T$.




Enough data have been collected that the entire parameter region favored by the one famous CDF event ($ee\gamma\gamma\not{E}_T$) is excluded. Here is the result from DELPHI data.

If a new particle (*e.g.*, $\tilde{\mu}$, $\tilde{\tau}$ or $\tilde{t}_1$) is stable and heavy, it will ionize the gas in the tracking chambers anomalously. Here are the latest bounds from OPAL:



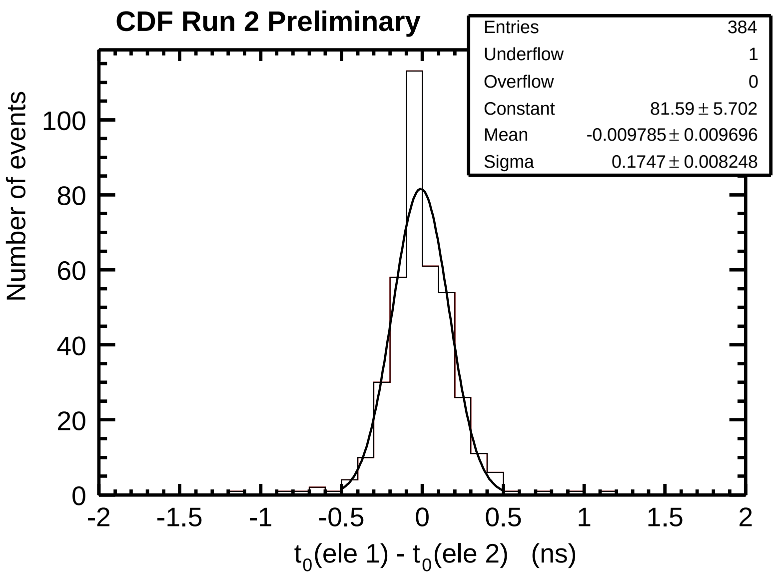



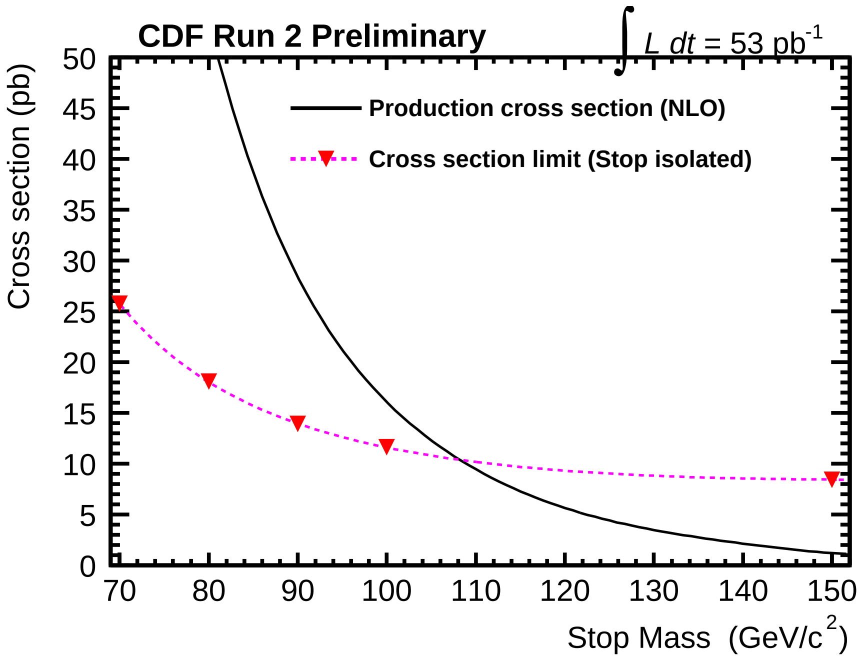

Also from LEP, and along these lines, are

- OPAL search for particles decaying at large distances from the IP
- ALEPH search for stable squarks and gluinos

CDF have also pursued this kind of search using ionization measurements in their upgraded & improved central outer tracker, and the new time-of-flight system –

They applied their results to the stable-stop case.



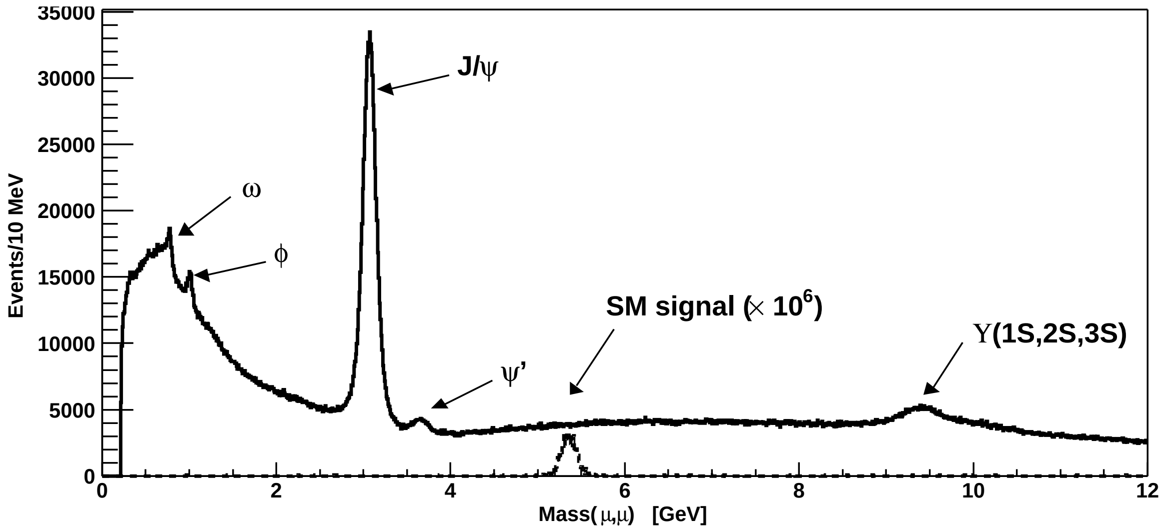




- ToF system gives resolution of ∼125 ps
- analysis with 53 $\mathrm{pb}^{-1}$ is sensitive to $M_{\tilde{t}_1} \approx 110$ GeV

Finally, there are excellent new TEVATRON results on the decay $B_s \to \mu^+\mu^-$:

(The old CDF result from Run I is $\mathrm{Br}(B_s \to \mu^+\mu^-) < 2.0 \times 10^{-6}$ at 90% C.L.)

*The challenge is formidable (see plot from DØ):*

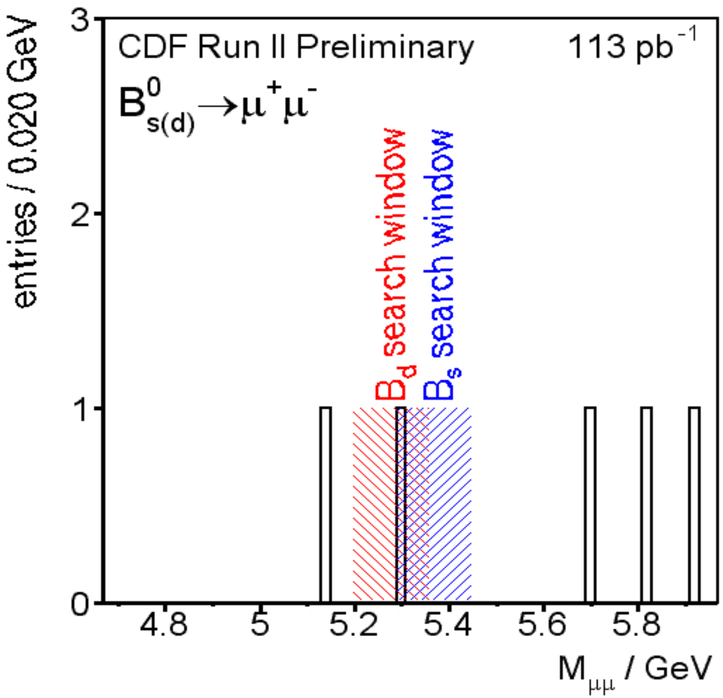


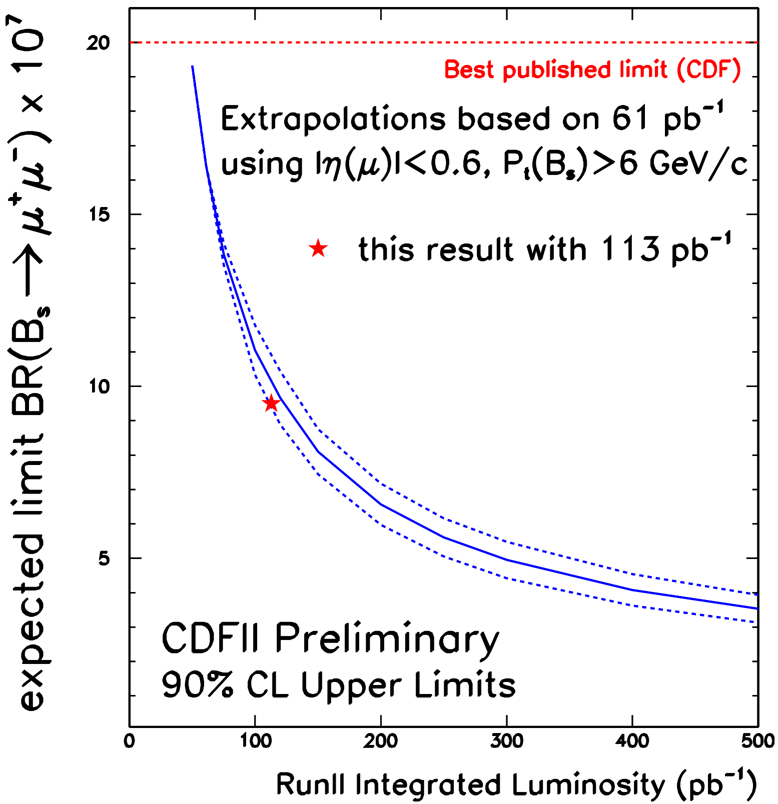

To tackle this, require:

- a good, displaced vertex pointing back to the IP
- relatively high $p_T$ for the muon pair
- good muon isolation

find 3 events in window, expect ∼3.4
$\Longrightarrow \mathrm{Br}(B_s \to \mu^+\mu^-) < 1.6 \times 10^{-6}$ at 90% C.L.

In the CDF analysis, find one event, expect $\sim 1/2$




CDF bound: $\mathrm{Br}(B_s \to \mu^+\mu^-) < 0.95 \times 10^{-6}$ at 90% C.L. ($1.2 \times 10^{-6}$ at 95% C.L.)

– more than a factor two lower than Run I!

*Light $A^0$ could lead to* $\mathrm{Br}(B_s \to \mu^+\mu^-) \sim 10^{-7} \ldots$

# Conclusions

- The field of Higgs and SUSY Searches is super-active!
- Higgs and SUSY searches at LEP are filling in holes (and uncovering them, too).
- The TEVATRON collaborations are cautiously positive about the Higgs search.
  – there can still be a real impact for SM-like Higgses.
- SUSY searches at the TEVATRON are getting over the bar – some first real results are now available with many others soon to appear. The TEVATRON collaborations are looking forward to a wide variety of new particle and new phenomena searches. (See talk by E.Perez for many other interesting results.)
- What we need now is more data!

*thanks to:*

Bill Orejudos, Boaz Klima, Nigel Lockyer, Doug Glenzinski, Marcela Carena, Joe Kroll, Brian Winer and John Conway