Higgs and SUSY Searches at CDF

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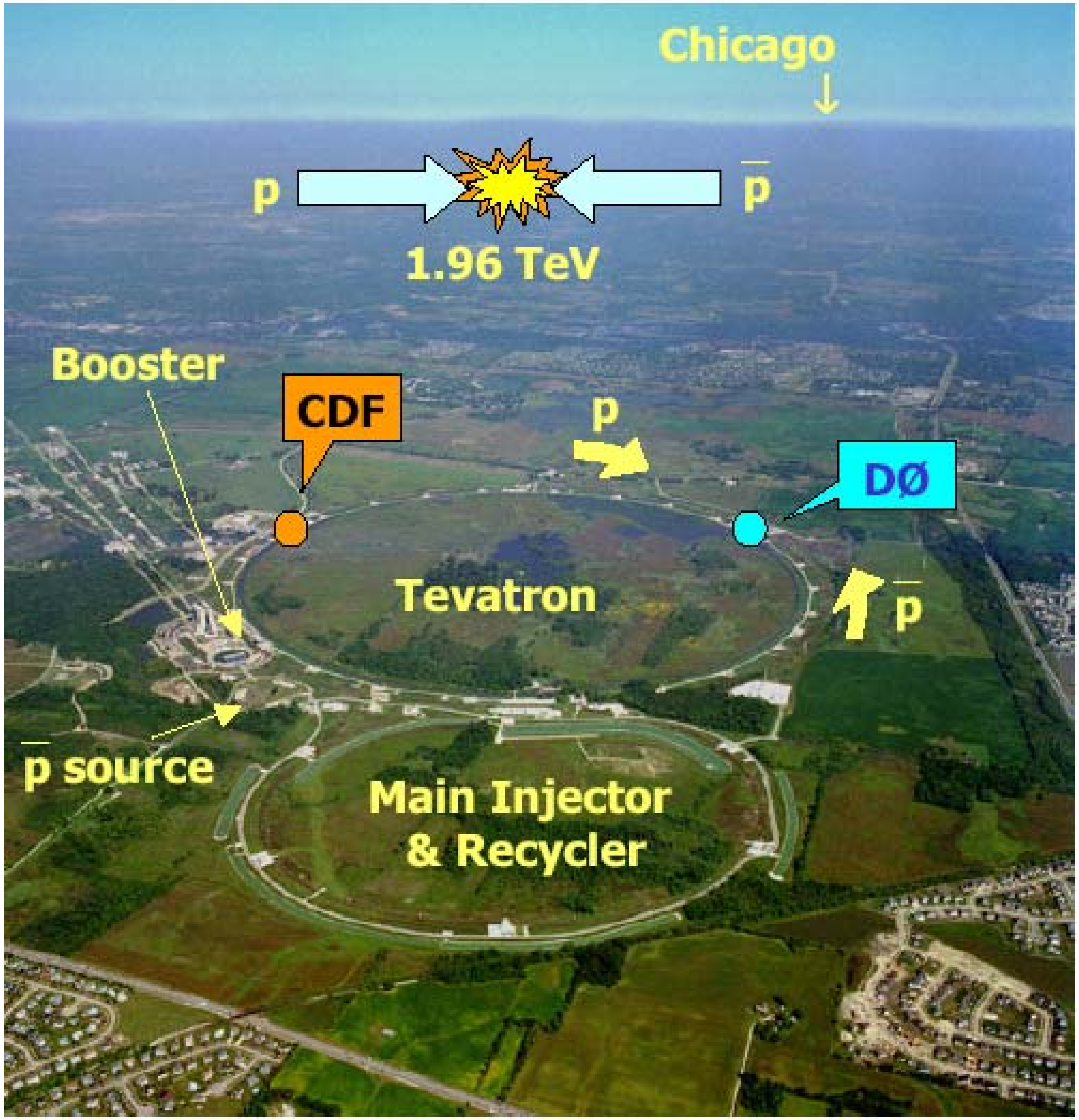
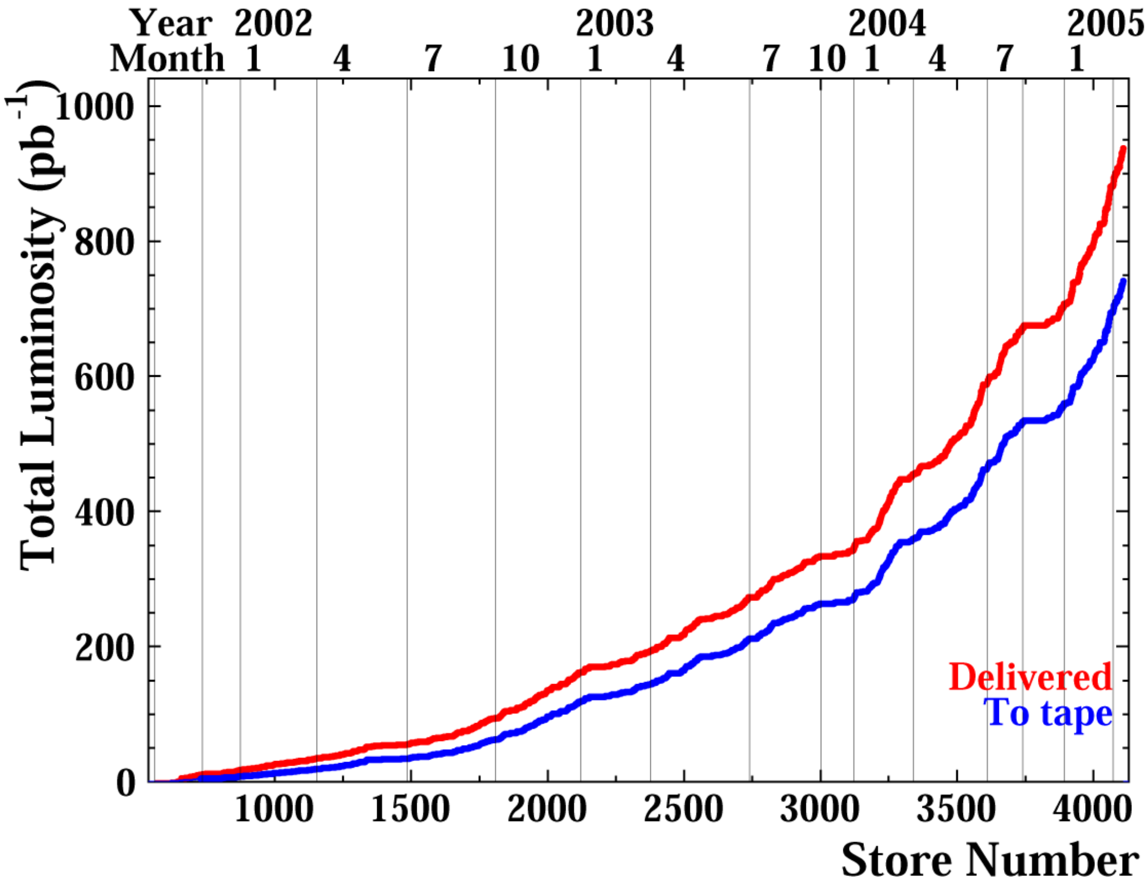
Fermilab Tevatron

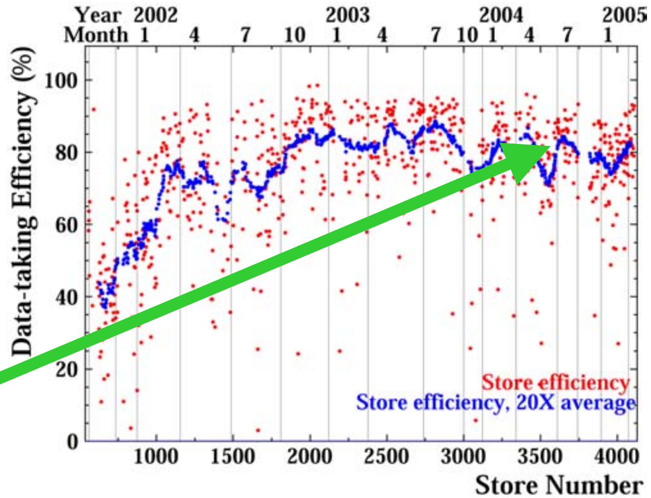


- Particle beams collide at experiment sites (CDF, DØ) every 396 ns
  - C.M. Energy: 1.96 TeV
- Over 700 pb^{-1} of data on tape
  - Current analyses 200-390 pb^{-1}
- Run 2 goal: 4.4-8.5 fb^{-1}
  - Take data until 2009
- *Energy Frontier* until LHC turn-on

Luminosity



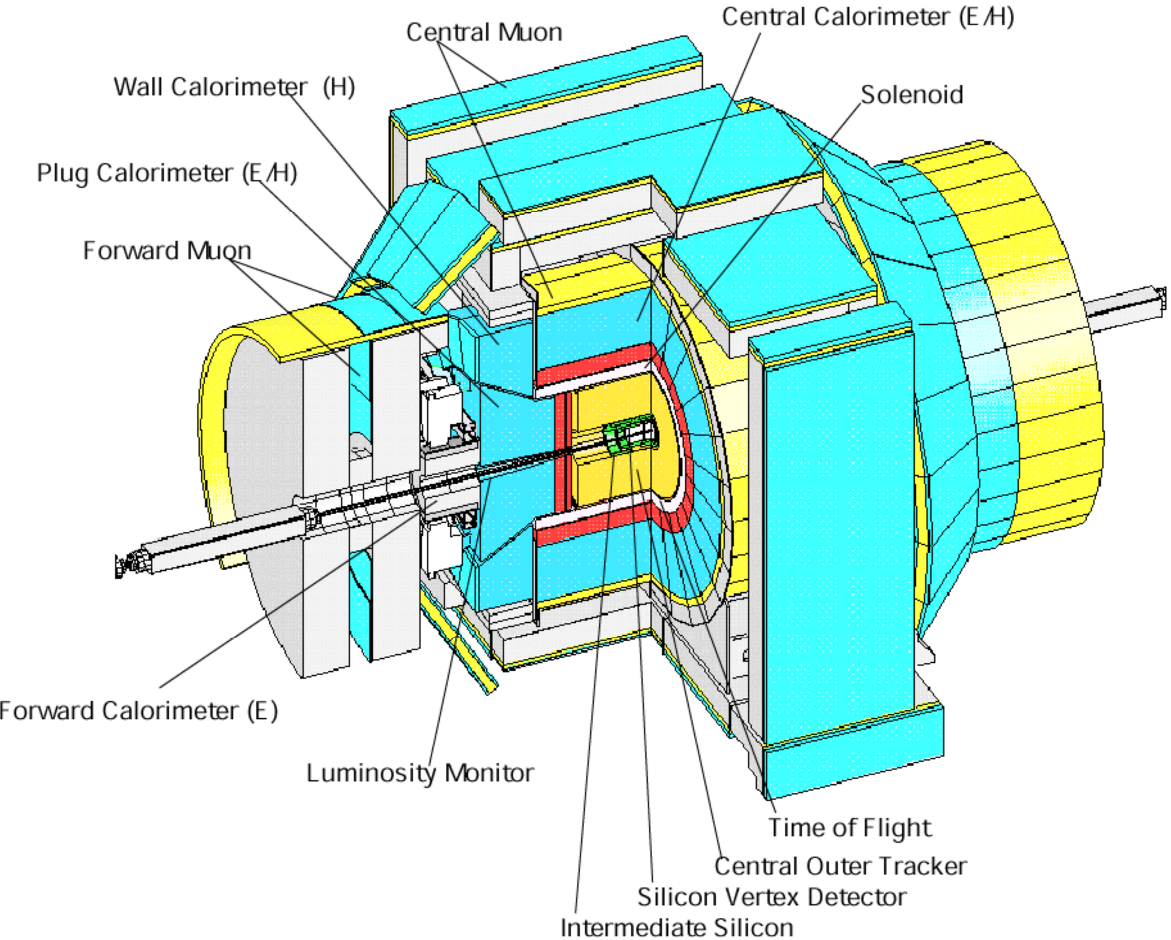
- Troubles of the early days of Run 2 seem to be behind
- Luminosity profile follows optimistic scenario
- If lucky, expect over 8 fb^{-1} of data in Run2



- Data taking efficiency ~80%

CDF Detector

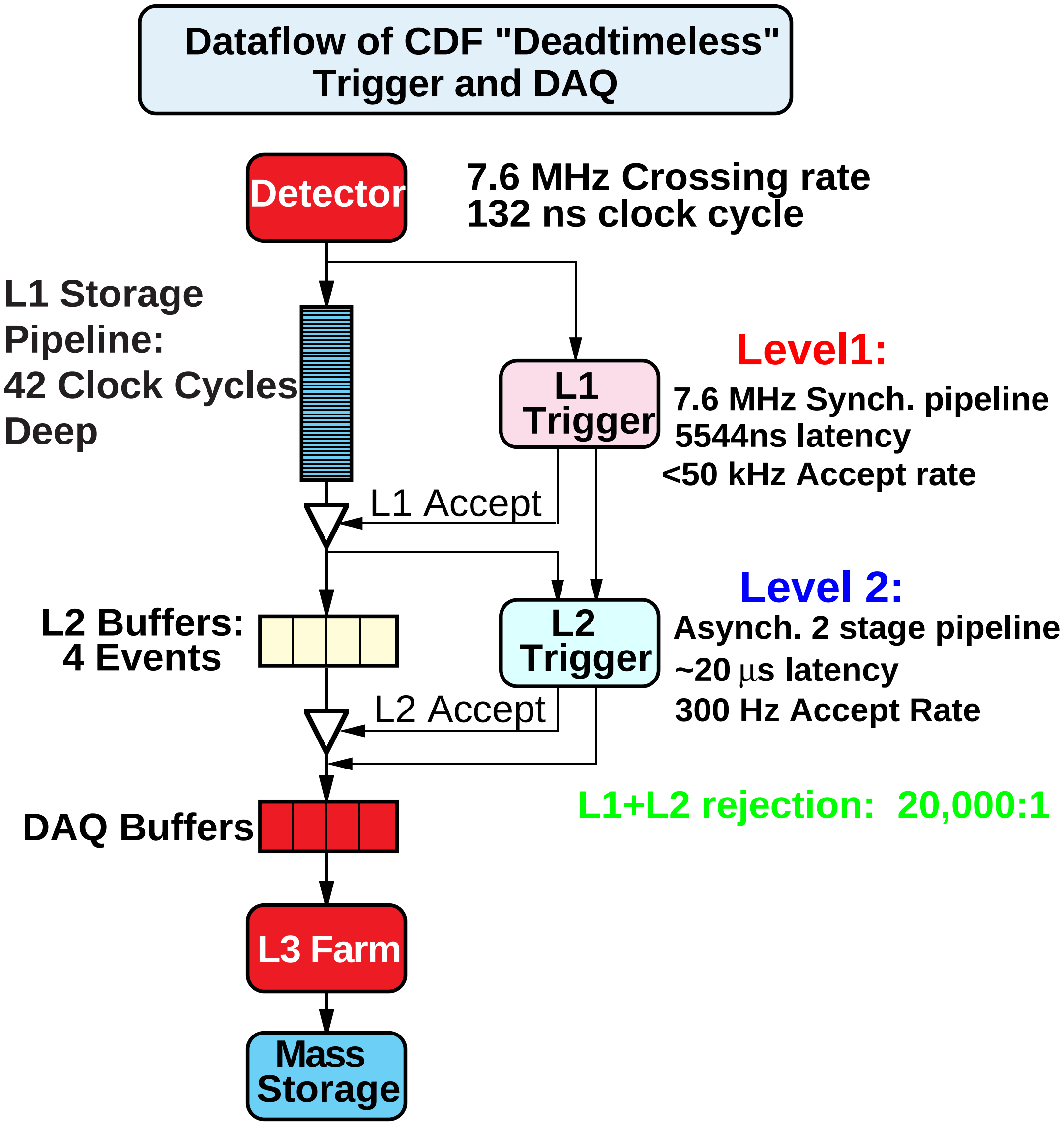
- **Significant upgrades for Run II**



- **Highlights:**
  - **Excellent central tracking**
    - Drift chamber, η~1.2
  - **Silicon tracking up to η~2.0**
  - **Calorimeter: HAD+EM**
    - Towers $15^0(\Delta\phi)$ x $0.1(\Delta\eta)$
    - Extends to η~3.8
  - **Robust Central Muon system**

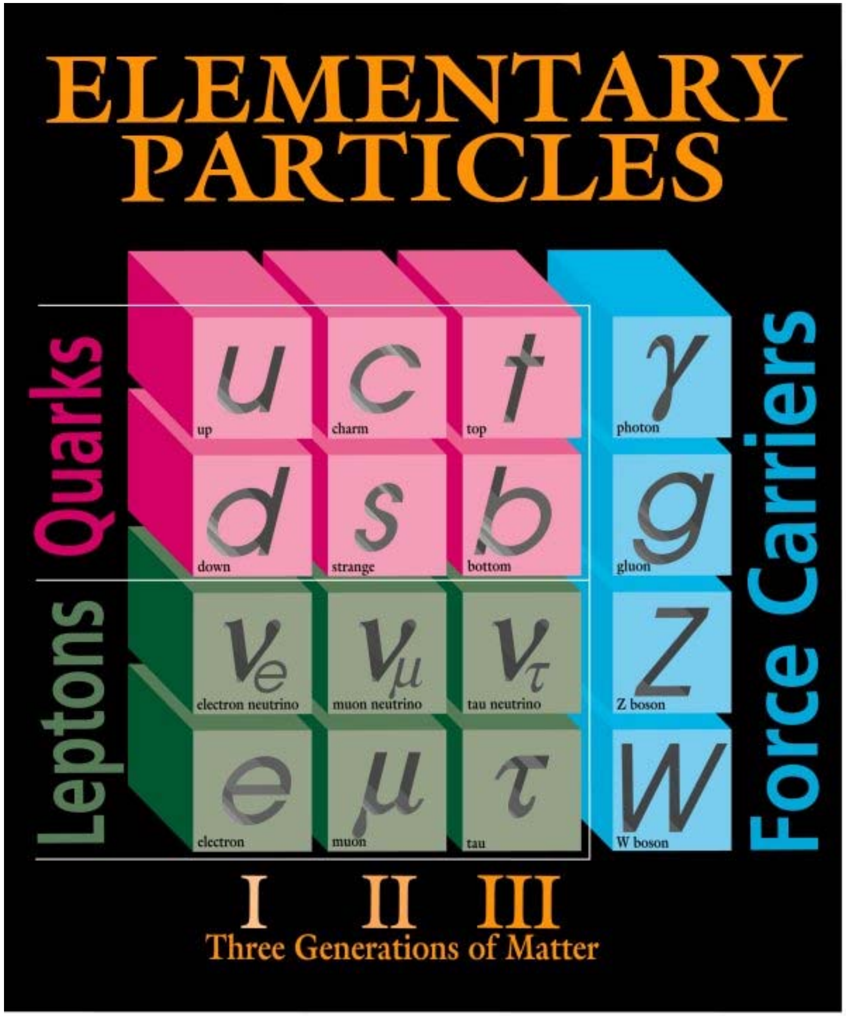
CDF Trigger System

- Rate of incoming events:
  - Every 396 ns
- Design specs: maximum rate of accepting events:
  - L1: 50 kHz
  - L2: 300 Hz
  - L3: 30 Hz
- L2 currently is the bottleneck
  - Exceeded design specs to operate at 380 Hz



Why Even Go Beyond SM?

- **Likes:**
  - **Standard Model (SM) has been a major success**
    - Good old renormalizable theory
    - Confirmed by precision measurements
- **Dislikes:**
  - **Not “beautiful” enough:**
    - Why particle masses vary wildly?
    - Unification not possible
  - **Can it even work?**
    - Divergences at high energy scales
    - Huge Higgs mass corrections
  - **And more**
    - No Higgs so far
    - Neutrino mass not zero
    - Does not explain dark matter



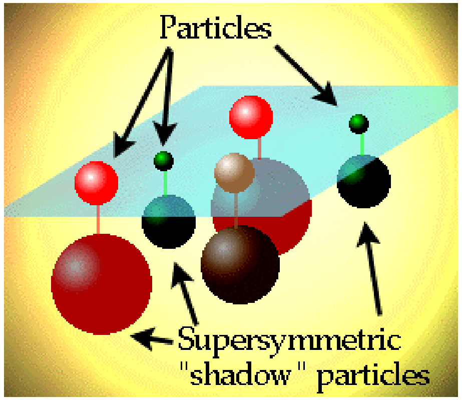
Fermilab 95-759

What is The Ultimate Theory?

- **Requirements:**
  - **Should be simple and natural:**
    - Few input parameters
    - No "fine tuning"
  - **Should explain everything**
    - All particles and interactions
    - Particle masses and hierarchy
    - Unification of interactions
    - Dark matter and anti-matter

- **Any candidates? Some…**
  - **SuperSymmetry (SUSY)**
  - **Little Higgs**
  - **Strings**
  - **Extra Dimensions**
  - …

SuperSymmetry (SUSY)



- New symmetry:
  - fermions ↔ bosons
  - Doubles number of particles

Particle	Super-partner
e,ν,u,d	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$
γ,W,Z,h	$\tilde{\chi}_1^{\pm},\tilde{\chi}_2^{\pm},$ $\tilde{\chi}_1^0 \ldots \tilde{\chi}_4^0$

Dark Matter Candidate → $\tilde{\chi}_1^0$

- Almost "beautiful":
  - Hierarchy problem resolved and Higgs mass stabilized
  - LSP is a candidate for dark matter
  - Unification possible

$$m_{\tilde{l}} > 100\ {}^{\mathrm{GeV}}\!/_{\mathrm{c}^2}$$

$$m_{\tilde{\chi}_1^0} > 43\ {}^{\mathrm{GeV}}\!/_{\mathrm{c}^2},\ m_{\tilde{\chi}_1^{\pm}} > 104\ {}^{\mathrm{GeV}}\!/_{\mathrm{c}^2}$$

$$m_{\tilde{g}/\tilde{q}} > 195(300)\ {}^{\mathrm{GeV}}\!/_{\mathrm{c}^2}$$

Many Faces of SUSY

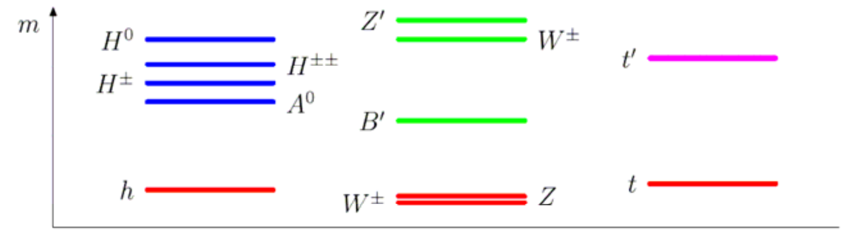
- Ain't easy to find, e.g. SUSY:
  - Many parameters, different symmetry breaking scenarios and particle mass spectra
  - Experimental signatures vary wildly
- Benchmark "model lines"

Scenario	LSP	Signature
MSSM	$\tilde{\chi}_1^0$	*leptons, jets+MET*
mSUGRA	$\tilde{\chi}_1^0$ $\tilde{\nu}$	*leptons, jets+MET*
High tanβ		light stop/stau, many taus in final state
RPV	varies	*more leptons, less MET*
GMSB	G	*Leptons/photons+ MET*
AMSB	$\tilde{\chi}_1^{\pm}$ $\tilde{\chi}_1^0$	special treatment

- Or even better, look for signatures:
  - Bumps in the mass spectrum (new particles): e.g. Higgs(es)
  - Excess of events over SM prediction: e.g. tri-leptons

A Convenient Target

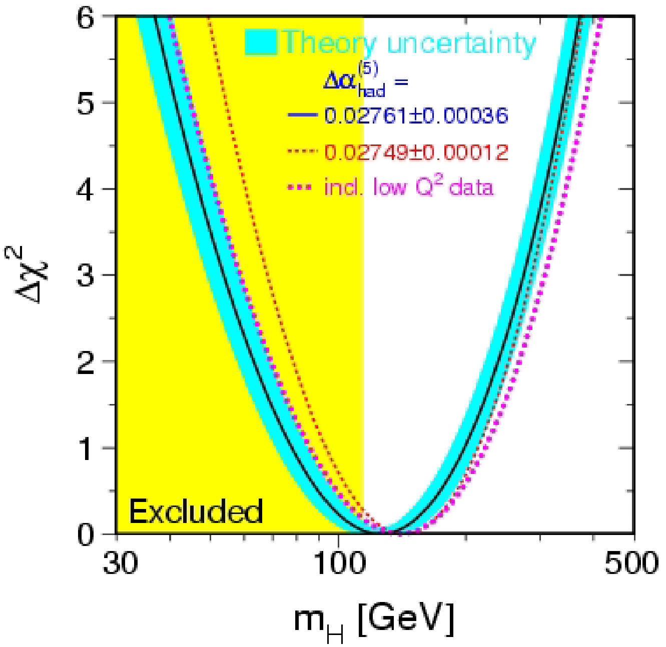
- **Standard Model:**
  - **EWK symmetry breaking via Higgs mechanism generates particles masses**
  - **Single physical scalar H, coupling ~m_f**
  - **m_H from 114 to a couple of hundred GeV**
- **Higgs is unavoidable in most extensions of SM**
  - **SUSY:**
    - Similar mechanism, several Higgs particles: h, H, H+/-, A
    - Production is enhanced if tanβ is large
  - **Little(st) Higgs:**
    - Three-scale model, radiatively generated Higgs mass
    - Light Higgs h
    - Also heavier A,H,H+/-,H++/--



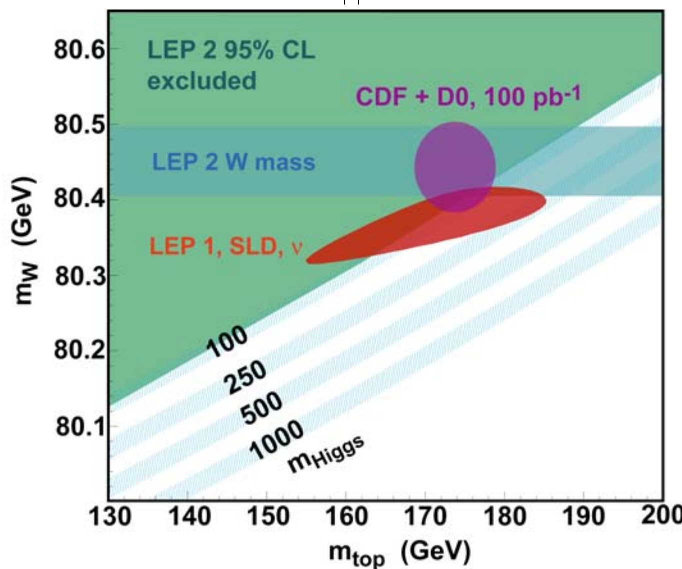
- **Hence, Higgs is a convenient target for searches**
  - **At least we know what to look for**

What we know about the Higgs

- **Precision EWK:**
  - **Mass known within about 60 GeV, e.g. latest LEP results:**
    - M_H=126+73-48 GeV
    - M_H<280 GeV @ 95% CL
    - Direct limit M_H>114 GeV



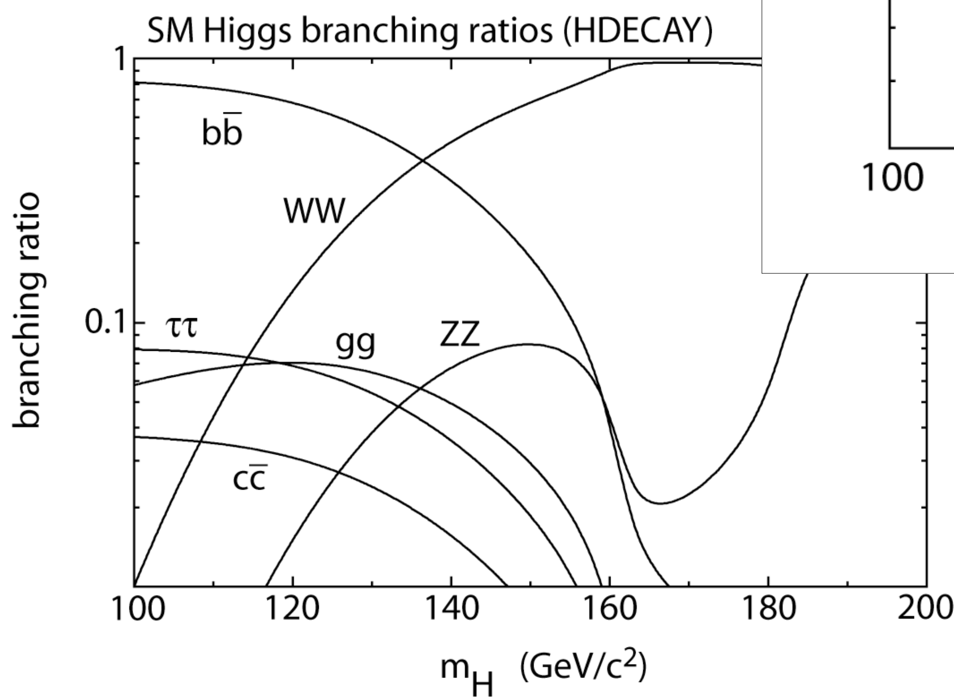
- **While preparing for direct searches, focus on measuring the mass of the W and top quark**
  - **Tight constraints on Higgs mass**
  - **This is what CDF and D0 do best!**

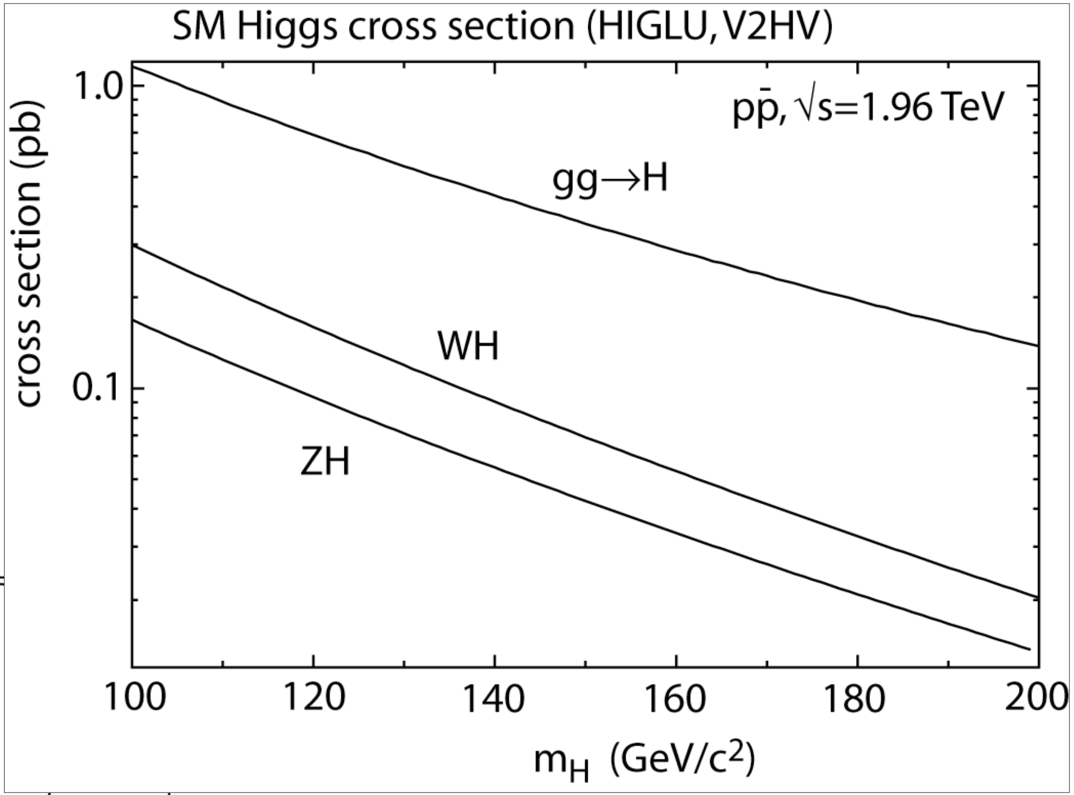


SM Higgs at the Tevatron

- gg→H dominates but dijet background too big…

- bb decay modes are best!





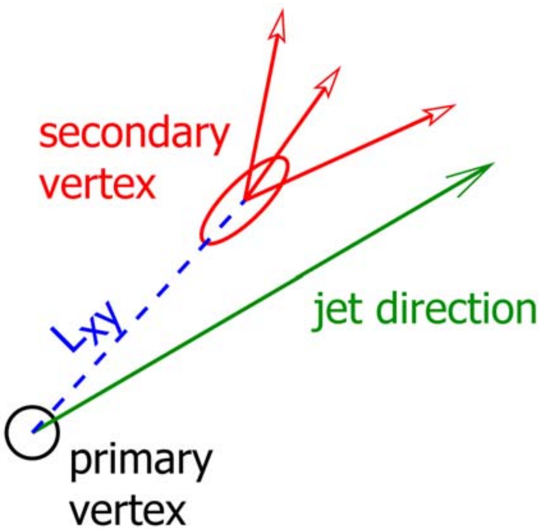
WH+ZH ~300 fb at 115 GeV

typical efficiencies ~ 2%

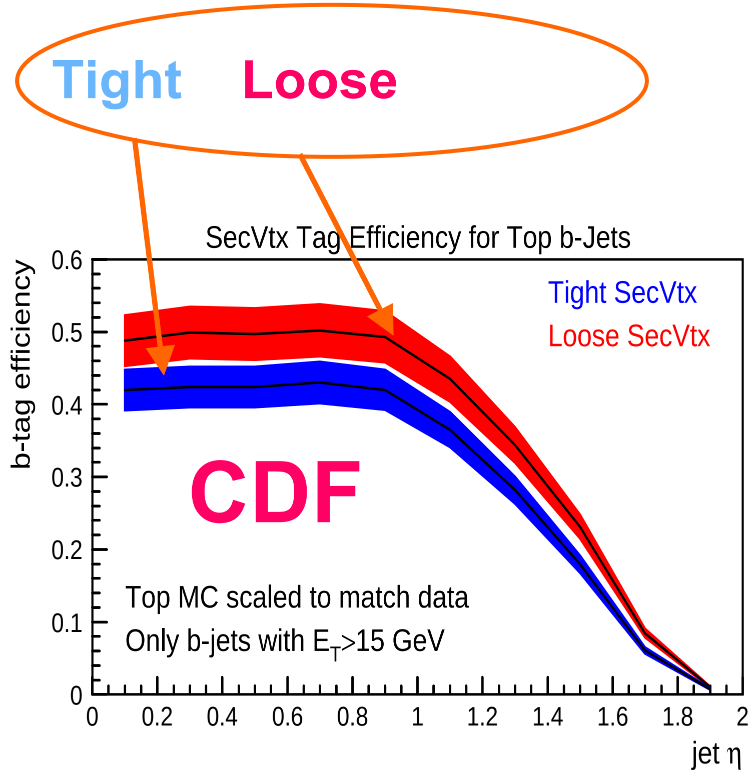
A daunting proposition!

CDF - b tagging

- Identifying b-jets is the key for low-mass Higgs boson searches.
- Layer 00, SVX-2 and ISL
  - Double-sided silicon microstrips: 800k channels!
  - r ~1.5 cm out to ~50 cm



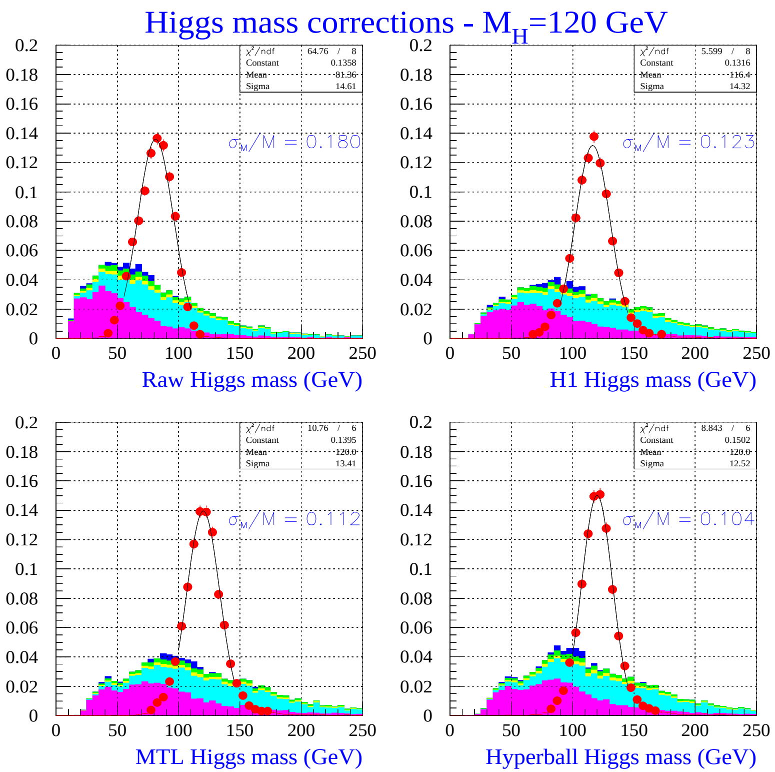
- Extrapolation resolution:
  - 10~15 mm

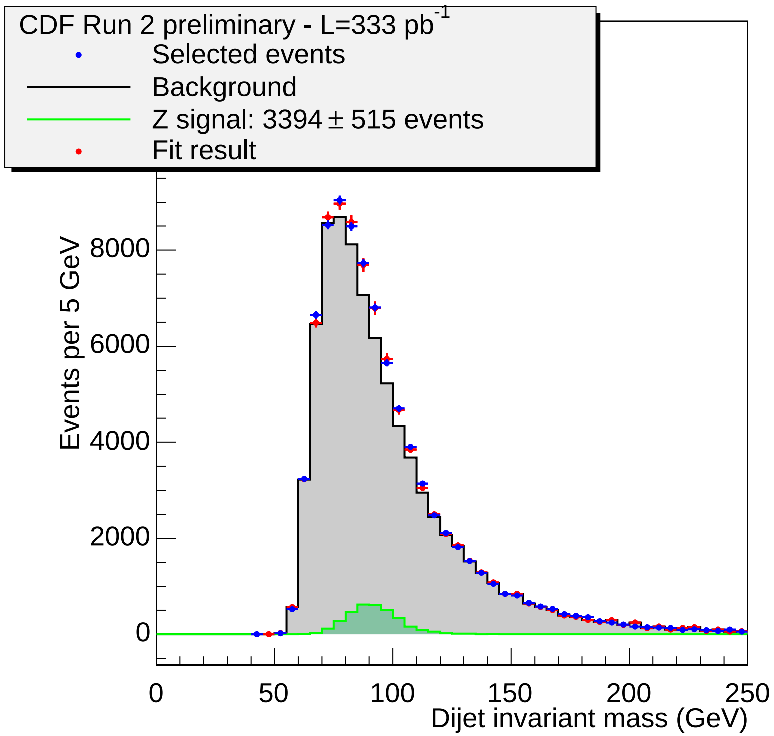


$\varepsilon_b \sim 45\%$ at high p_T

Mistag rates are typically at 0.5%

b-jet Resolution

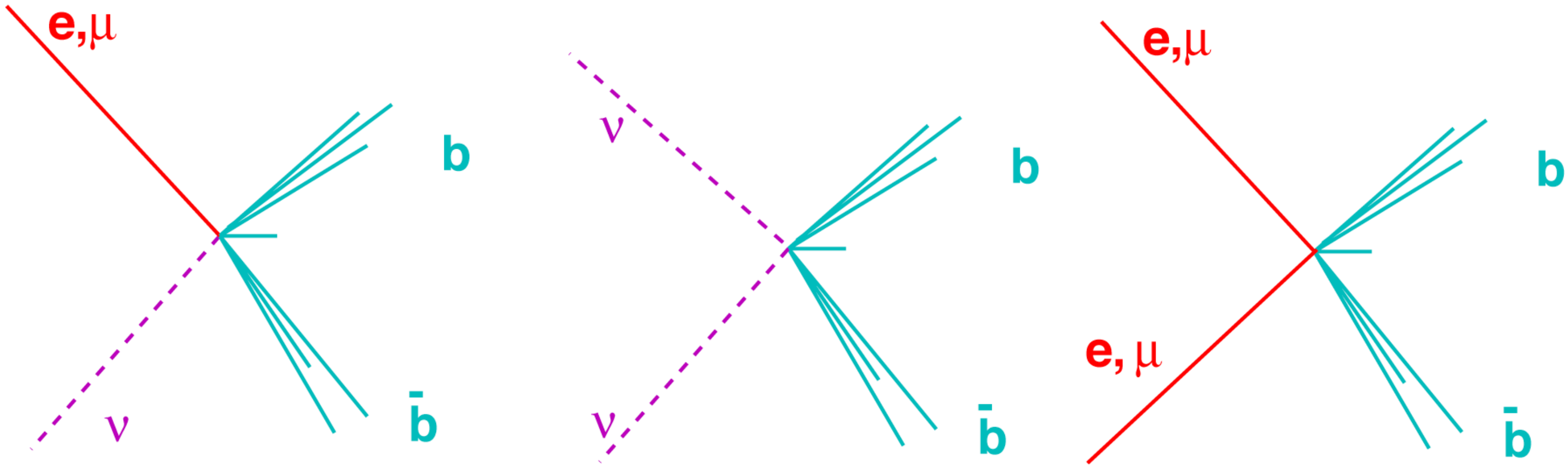




- Mass resolution improvements:
  - $\delta M/M \sim 10\%$
- Can see $Z \rightarrow bb$ events:
  - signal size ok
  - resolution as expected
  - jet energy scale ok!

Search Channels - Low Mass

For m_H<135 GeV, bb decays dominate:

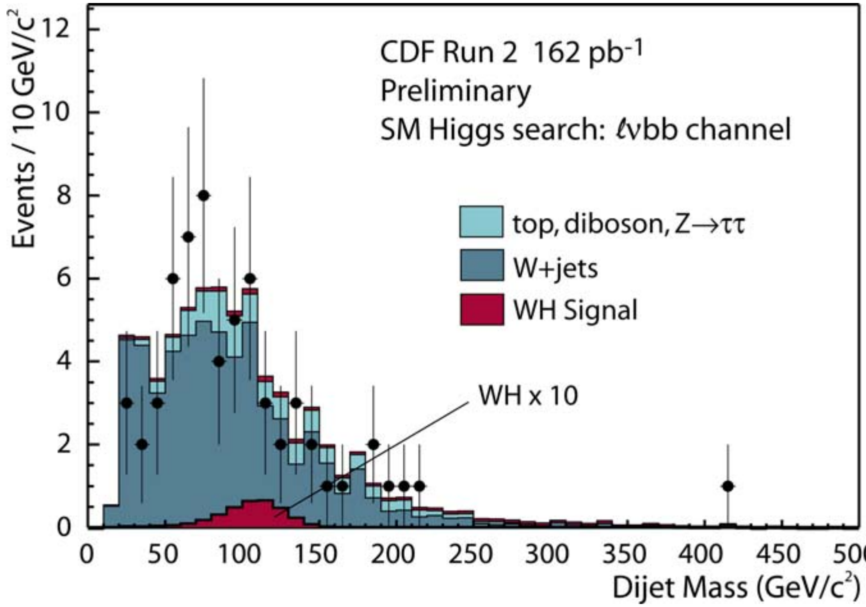


WH ZH

- clearly need excellent b tagging!
- need optimal bb mass resolution!
- need to understand background shapes!

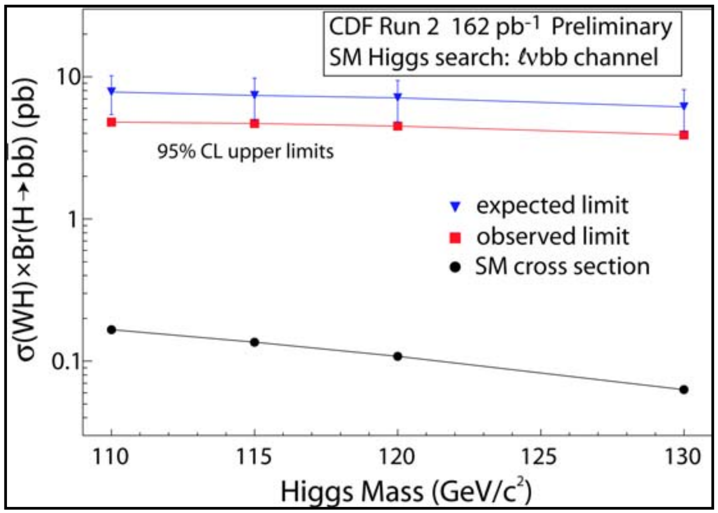
WH Search Results

- Select events with p_T>20 GeV lepton triggers
- Require lepton, missing E_T, two jets with E_T> 15 GeV
- Demand at least one b-tagged jet
- Use bb mass distribution for signal sensitivity

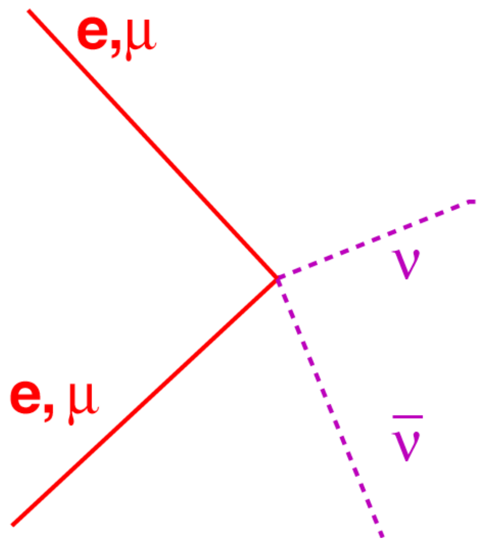


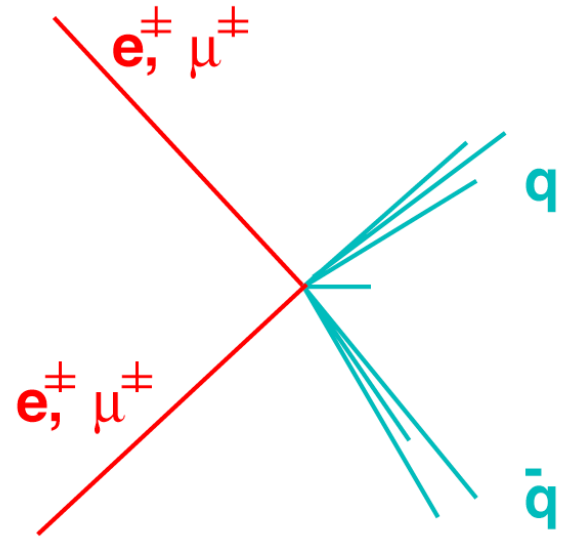
Not yet challenging the Standard Model:

- better resolution
- improved tagging
- need ννbb channel



Search Channels - High Mass

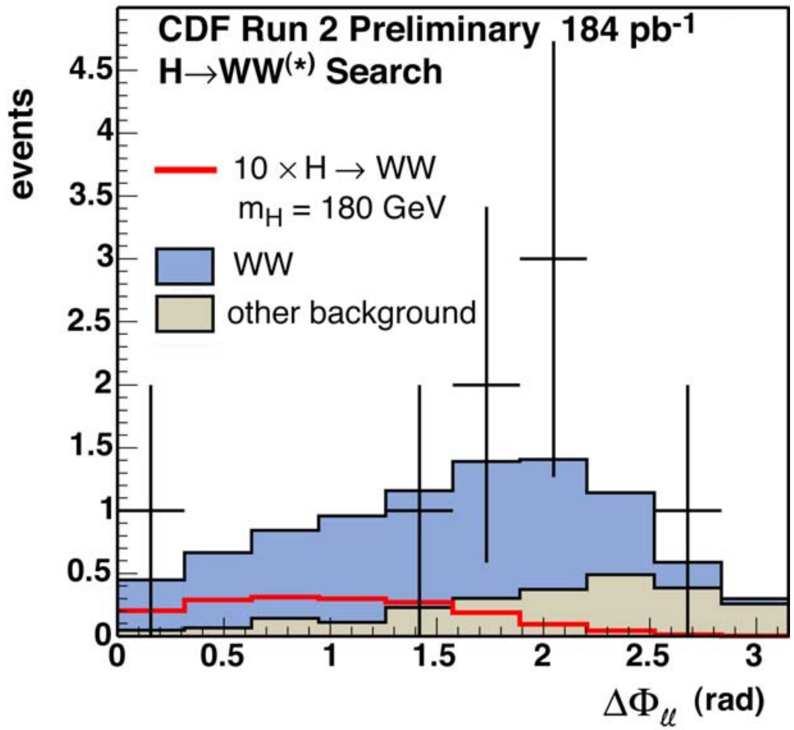




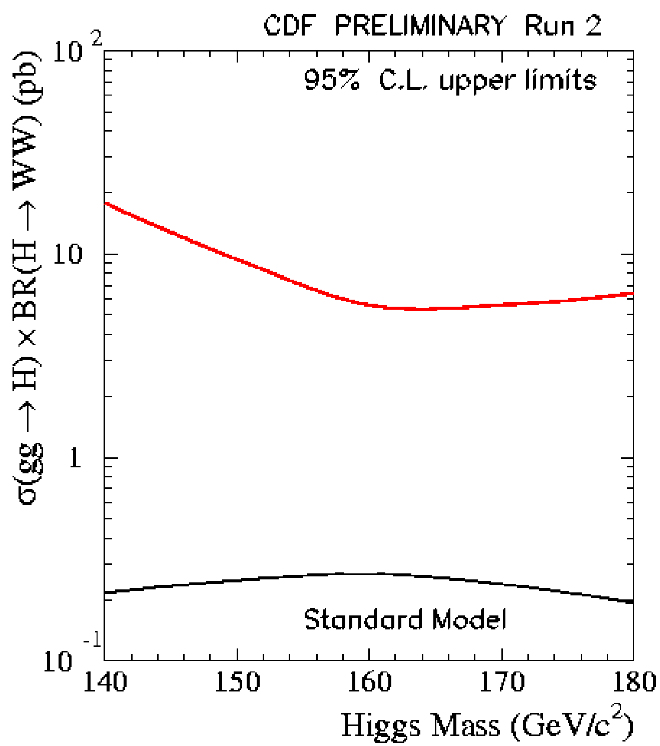
gg→H→WW →ℓℓνν **ZH/WH→WWW/ZWW**

(trileptons: rate too low)

H→WW Search



- Select events with two high-p_T leptons (ee, eμ, μμ)
- Main background: WW

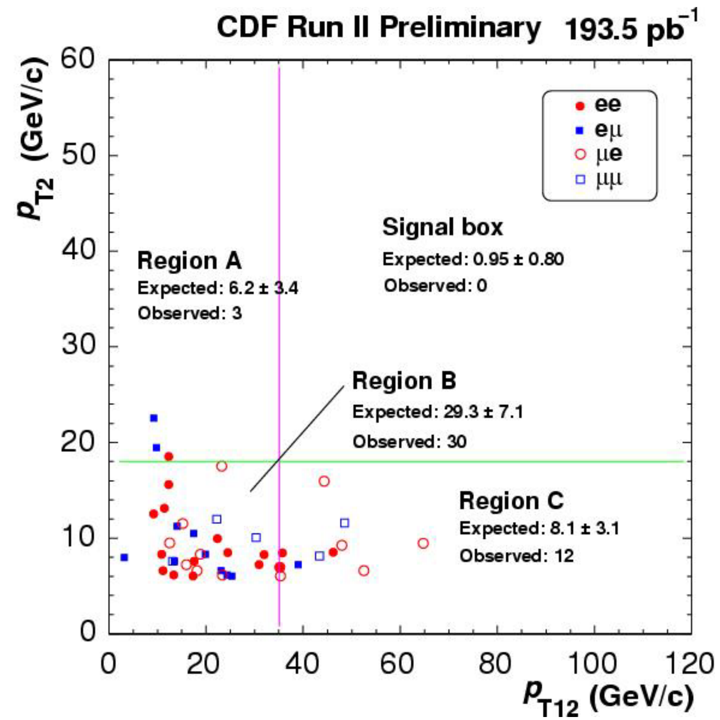


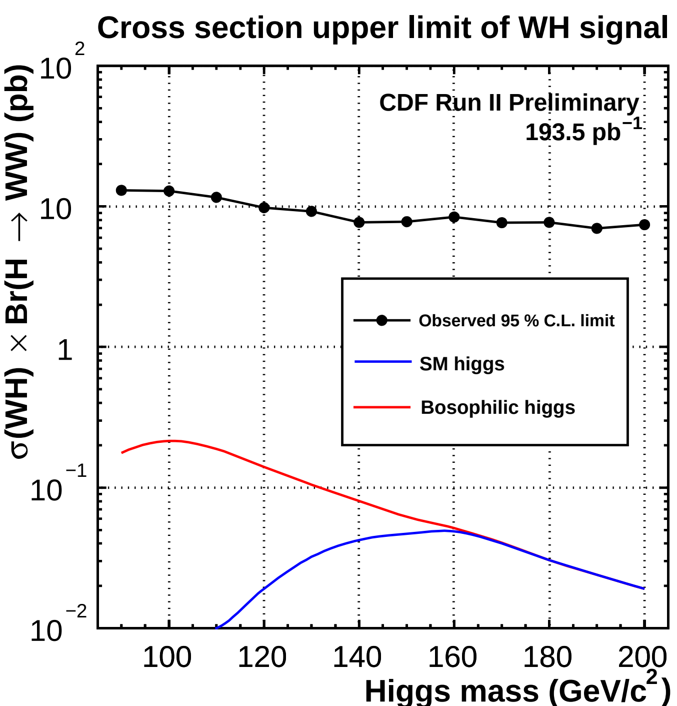
Perform likelihood fit using angular distribution

Extract 95% CL upper limit using Bayesian approach

WH→WWW* Search

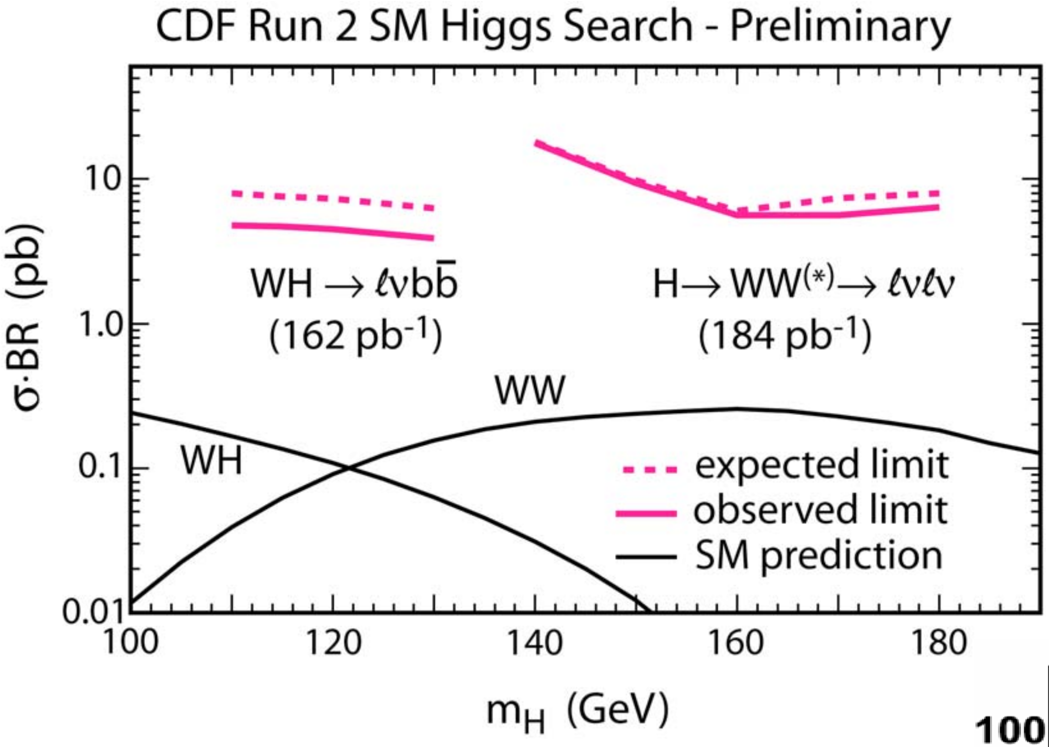
- Two LS leptons
- One lepton with P_T>20 GeV
- Optimize cuts on the second lepton:
  - P_T>18 GeV (for MH>160 GeV)
  - Vector sum of leptons transverse momenta ($P_T$ll>35 GeV).



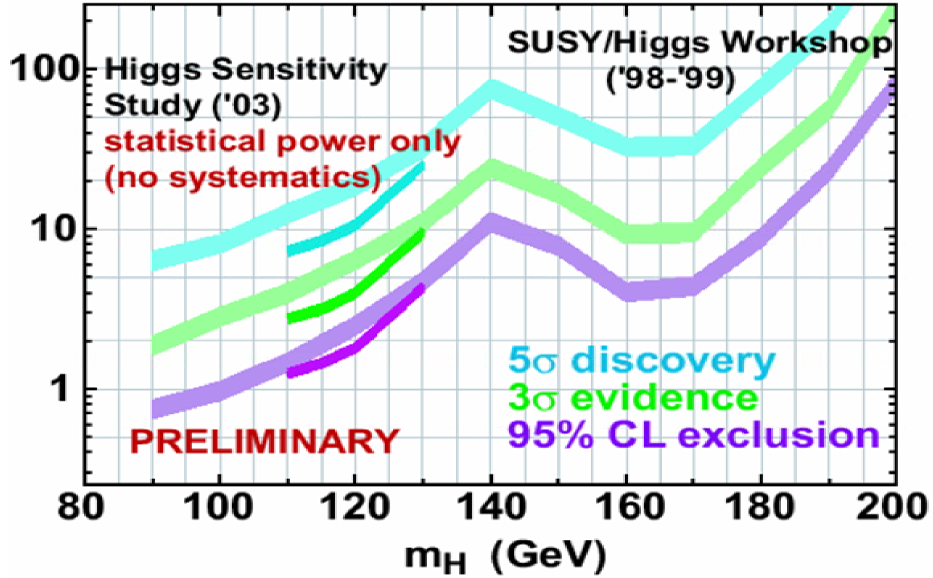


- No events observed
- Expected 0.95±0.61± 0.18 from SM sources
- 95% CL limits are thus set at 12 (8) pb for M_H=110 (160) GeV

CDF Run 2 SM Higgs Limits

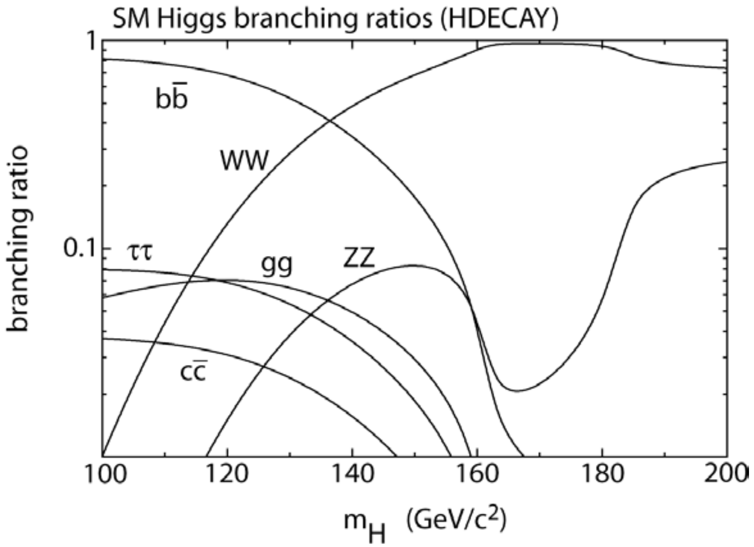


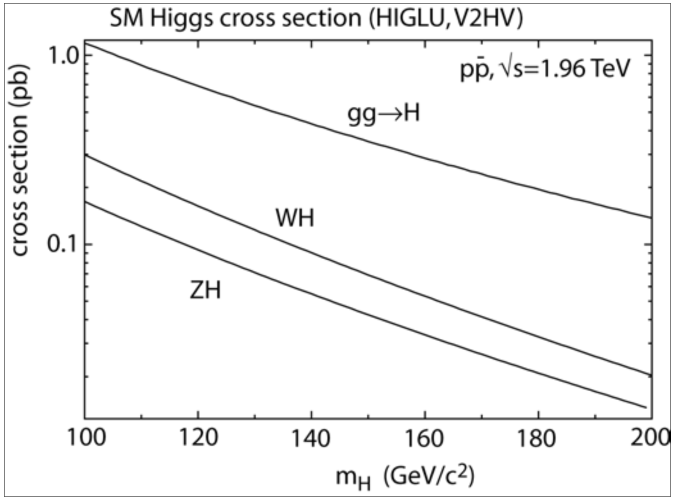
2003: Tevatron re-evaluated Higgs reach potential in Run 2



Aren't We Forgetting Something?

- **Taus:**
  - **Low-to-intermediate mass Higgs:**
    - Second highest Br after b's
    - Much cleaner signatures – can use $gg \rightarrow H$
- **So far, a bit exotic at hadron machines**
  - **Need to prove we know how to handle them**
- **$Z \rightarrow \tau\tau$ – Standard candle for taus**
  - **And also the largest irreducible background**

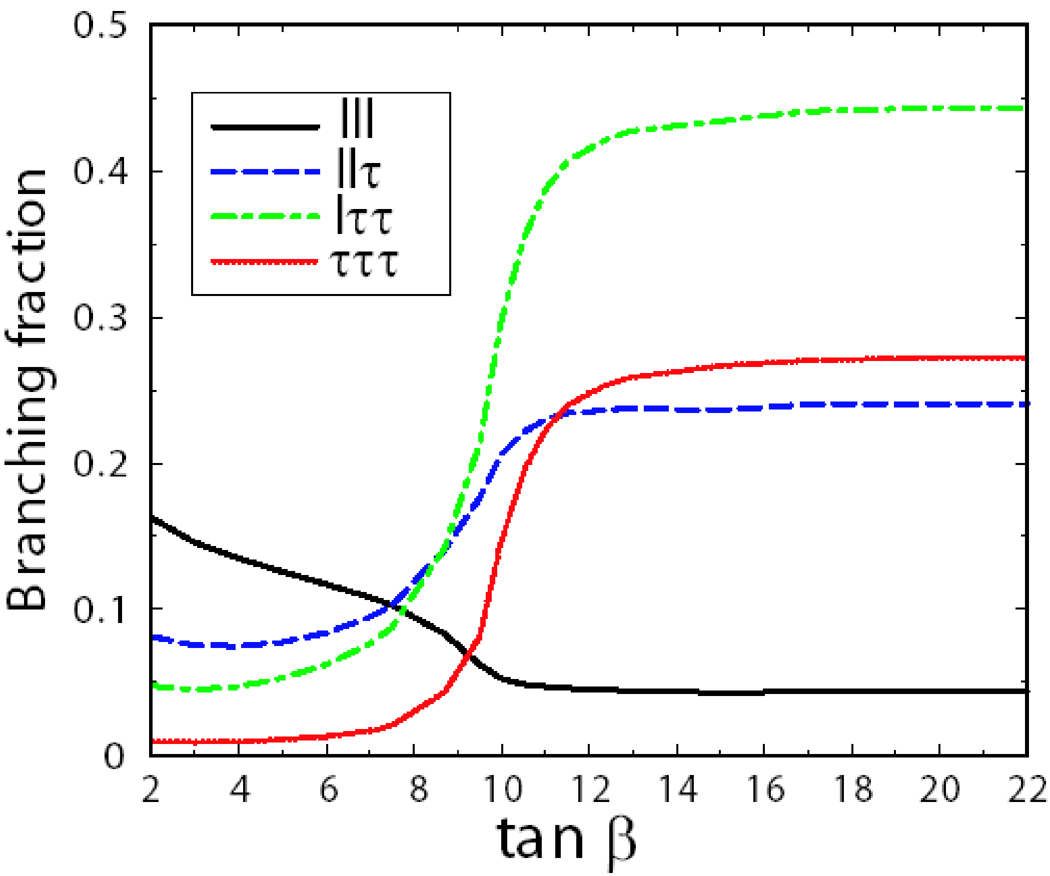




Where Else Taus Get In?

- **Consider standard trilepton search:**

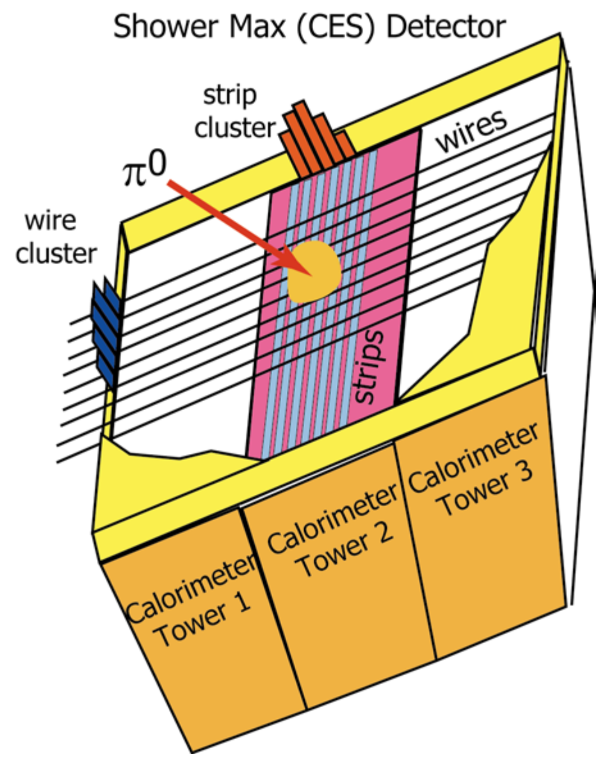
$$p\bar{p} \rightarrow \tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \rightarrow (\nu\tilde{l})(l\tilde{l}) \rightarrow (\nu l\tilde{\chi}_1^0)(ll\tilde{\chi}_1^0)$$



- **At tanβ >8 final state leptons are dominated by τ's.**
- **Very important at low tanβ too!**

Hadronic Tau Reconstruction

- **Main ingredients:**
  - **Charged tracks:**
    - Excellent tracking (efficiency in high 90's, $|\eta|<1$)
  - **Calorimeter (energy) clusters:**
    - Segmentation ($\Delta\eta=0.1$) x ($\Delta\varphi=15^0$)
      - Typical tau size: $\Delta\theta \sim 5\text{-}10^0$
    - Poor resolution for hadronic energy measurement ($\delta E / E \sim 40\% / \sqrt{E}$)
  - **Neutral pions:**
    - Use ShowerMax (CES) Detector
      - strip/wire chamber inside EM calorimeter
      - Spatial resolution ~few mm
    - Reconstruct π^0s as 2D matches in CES
    - Assign energy from EM calorimeter

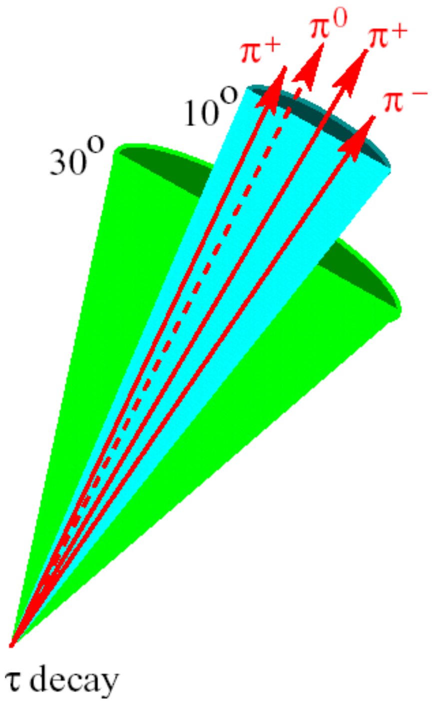


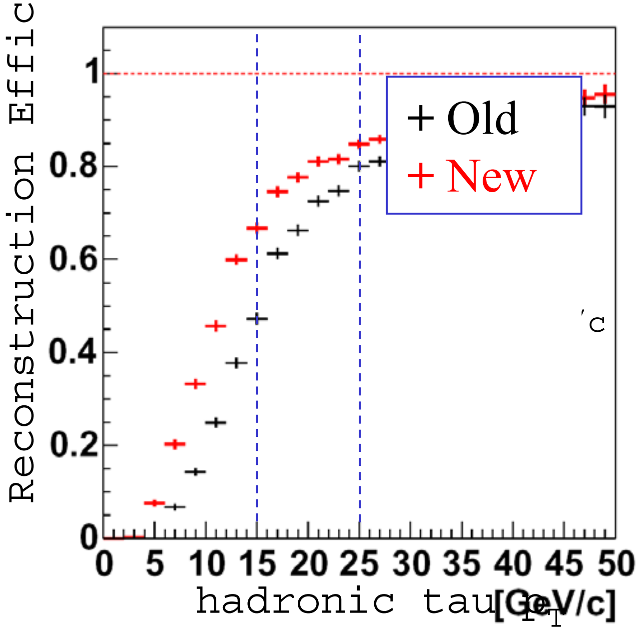
- **Energy: use tracks and π^0's, avoid calorimeter**

$$E^{\tau} = \sum E^{trk} + \sum E^{\pi 0}$$

Tau Reconstruction in Numbers

- A concept of a pencil-like jet:
  - Particles in the core, nothing in the annulus
  - Isolation is the key
- Choices for isolation:
  - Nparticles=0 in the isolation annulus
  - Small SET of all particles
- Reconstruction efficiency:
  - 70-95% for pT 15-50 GeV

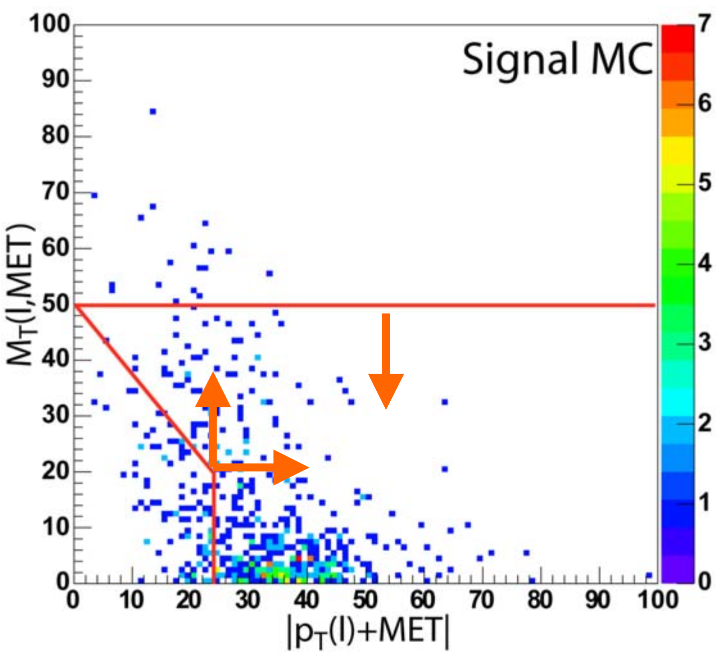


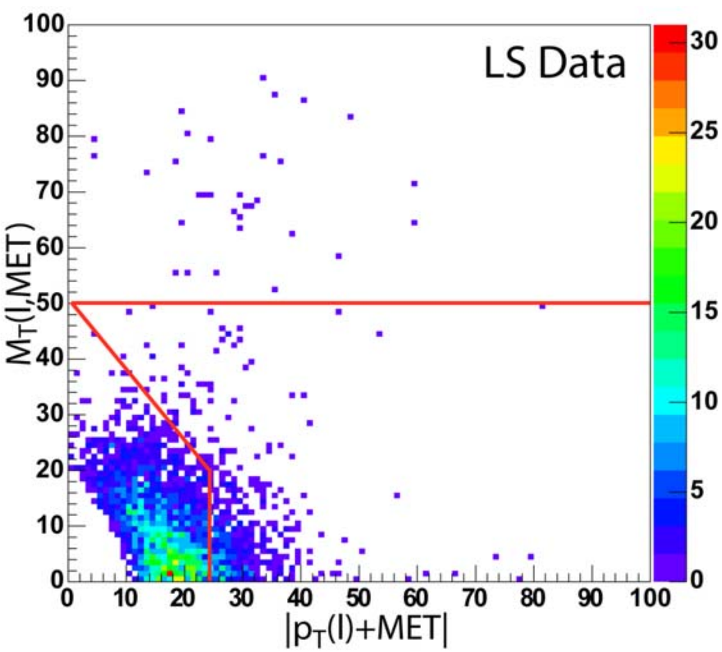


- Full selection efficiency = reconstruction x identification
  - Typical CDF tau ID efficiency is ~60%
  - Jet fake rate ~0.3-0.7%

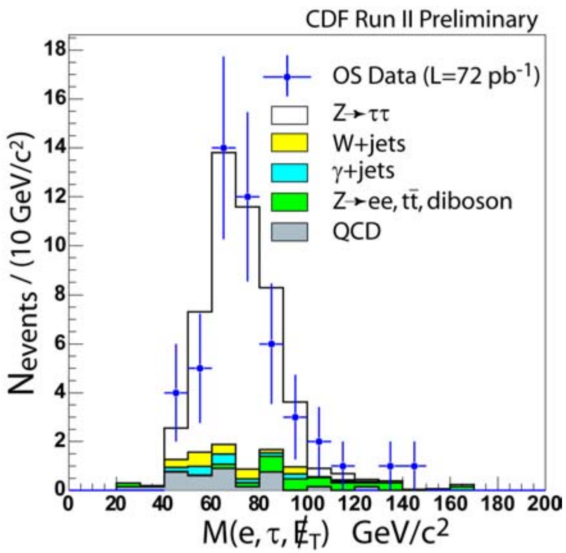
Z→ττ: Event Selection

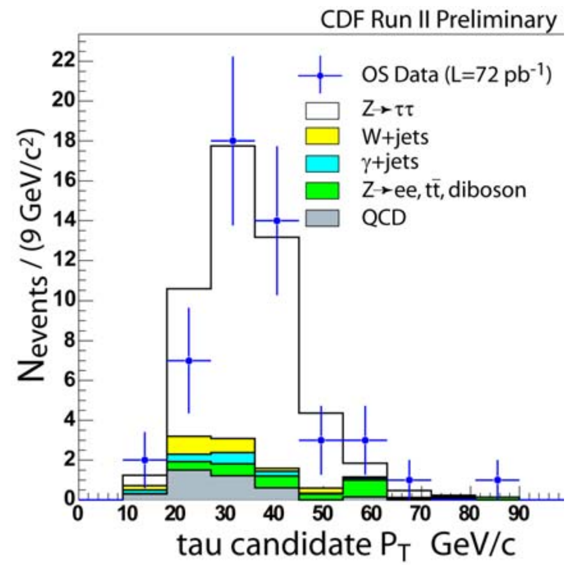
- Central electron: E_T>10 GeV
- Hadronic tau: p_T>15 GeV
- Suppress DY(ee) and other "technical" backgrounds
- Optimize in M_T(l,MET) vs (p_T(l)+MET) plane

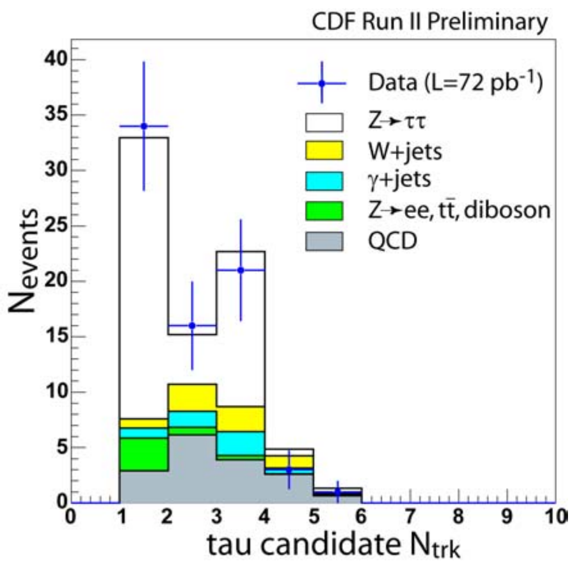




Z→ττ: Proof of Principle



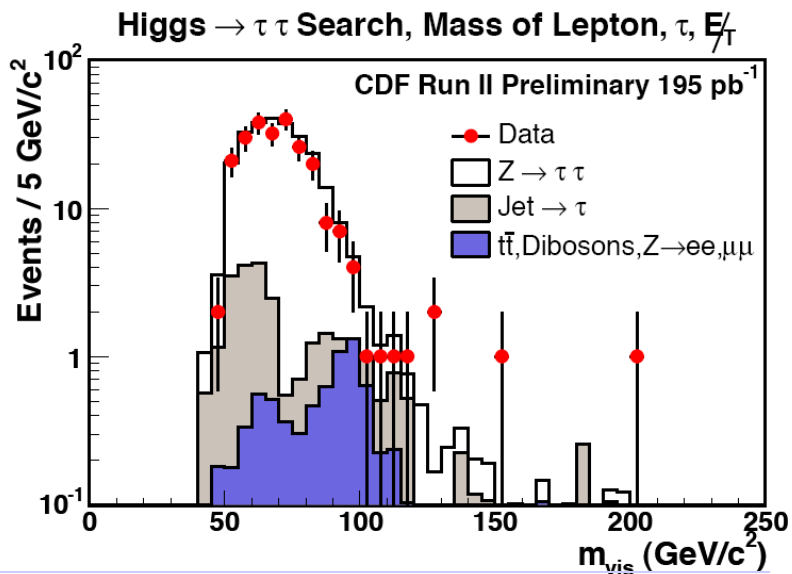


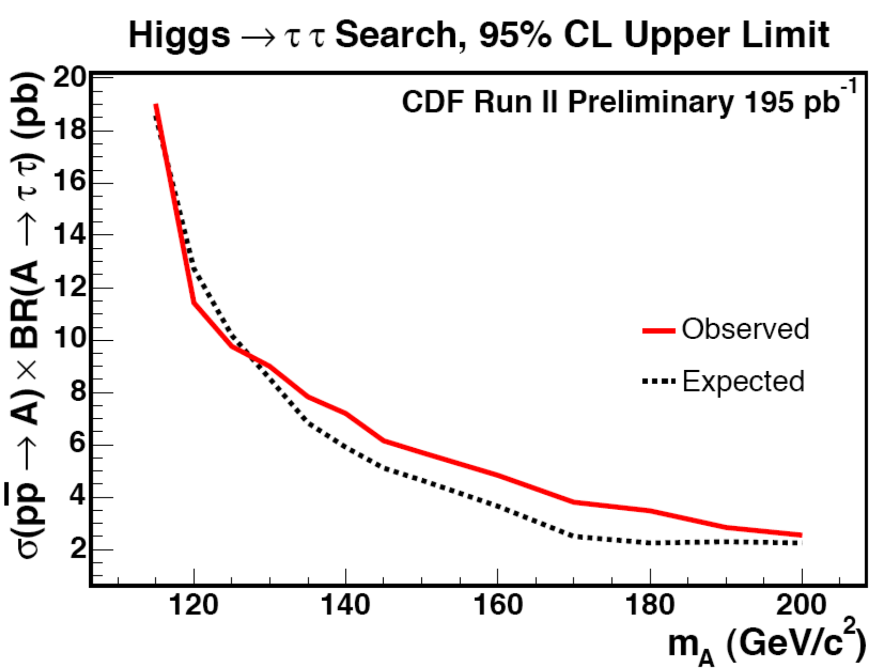


- **Good agreement**
- **An updated and optimized measurement is going through the CDF review**
  - **320 pb-1 of data, ~350 Z events**
- **Our tools for identifying taus work!**

Search for H→ττ

- Selections similar to Z→ττ
  - Slightly tighter cuts
  - Electron and muon channels combined
  - Fake rate technique for jet backgrounds

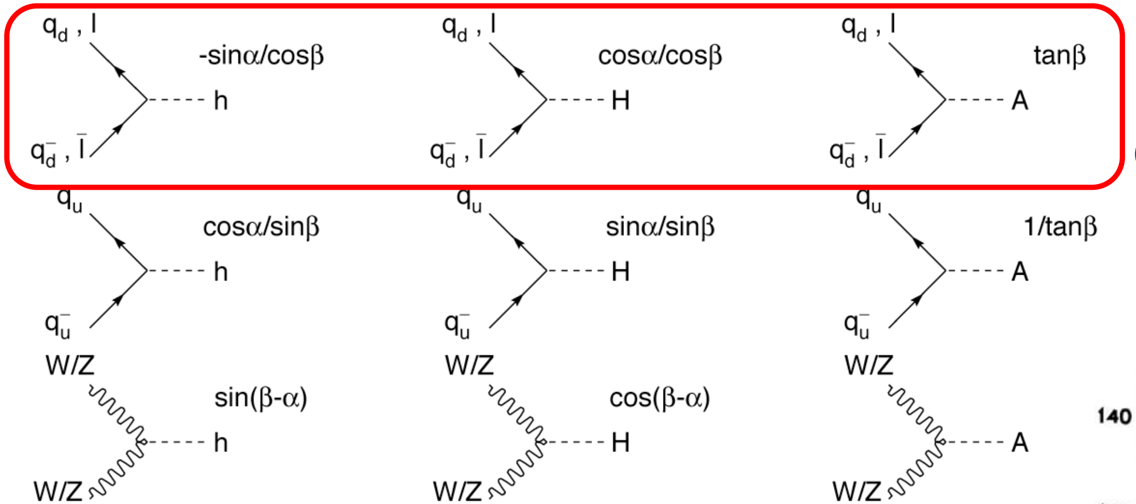




Fit mass spectrum to combination of Higgs, Z, and background

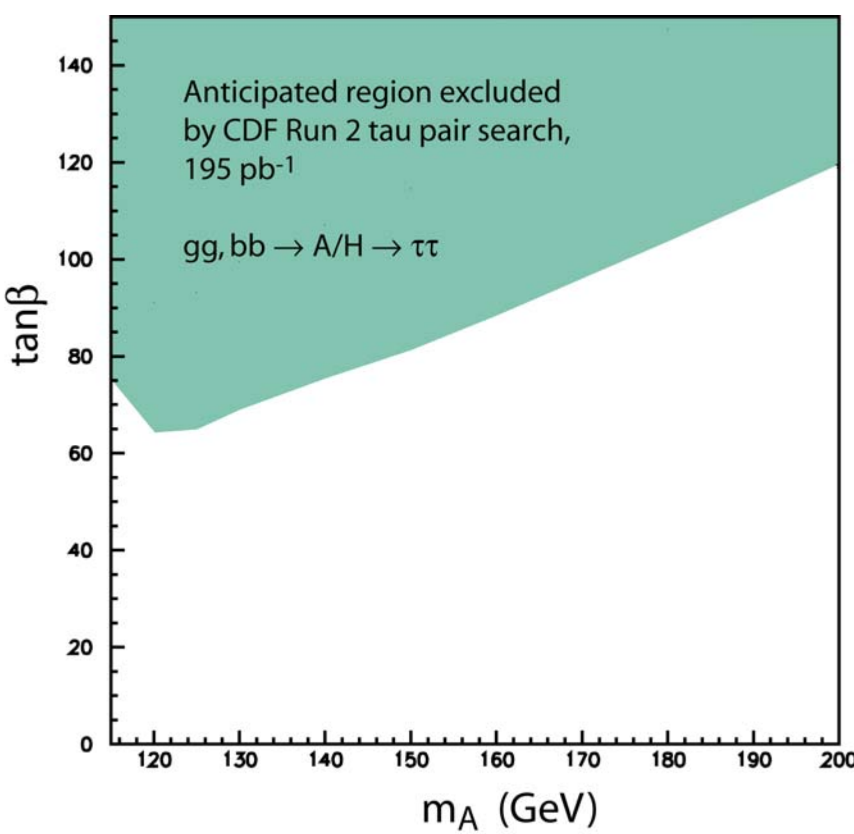
- Not too bad for a first shot
  - Updated measurement in in the CDF pipeline
  - Have a few tricks to use
  - Expect to do better soon

Limits on MSSM Higgs→ττ

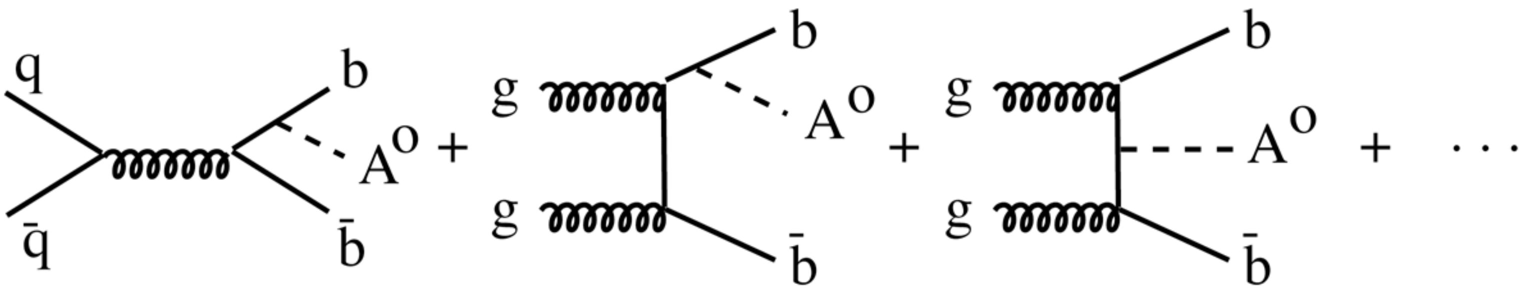


Top row leads to enhanced production at large tanβ

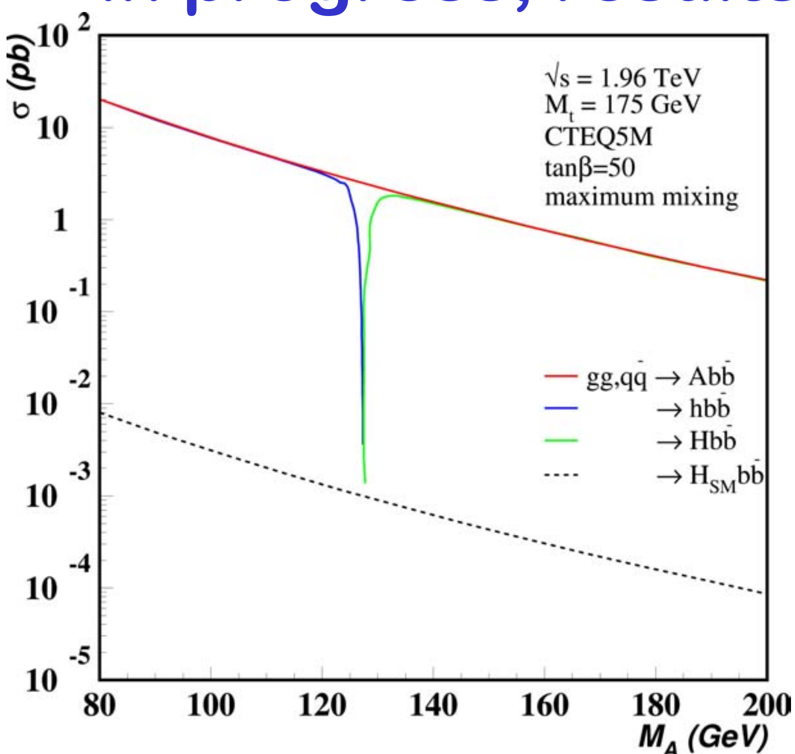
- **Set Limits on MSSM Higgs in tanβ vs m_A plane**



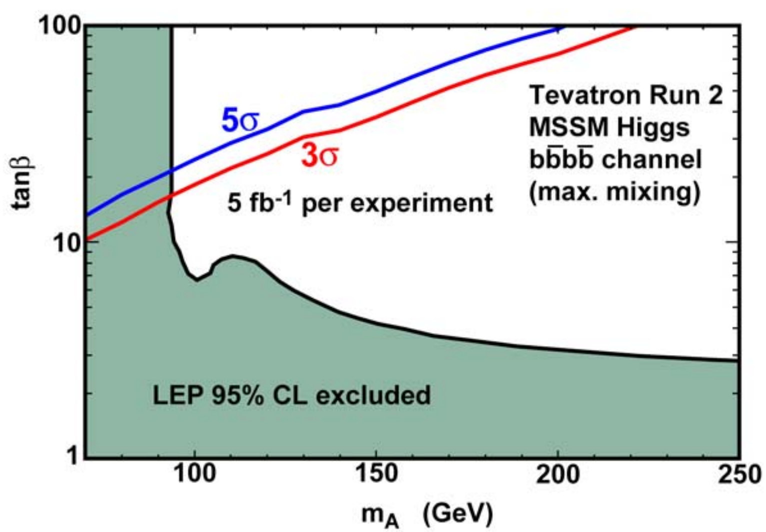
MSSM Higgs + b(b)



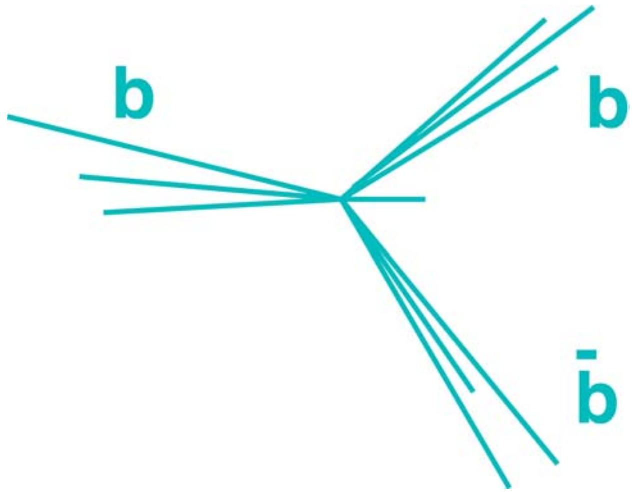
- **Analysis in 4b channel is in progress, results soon**

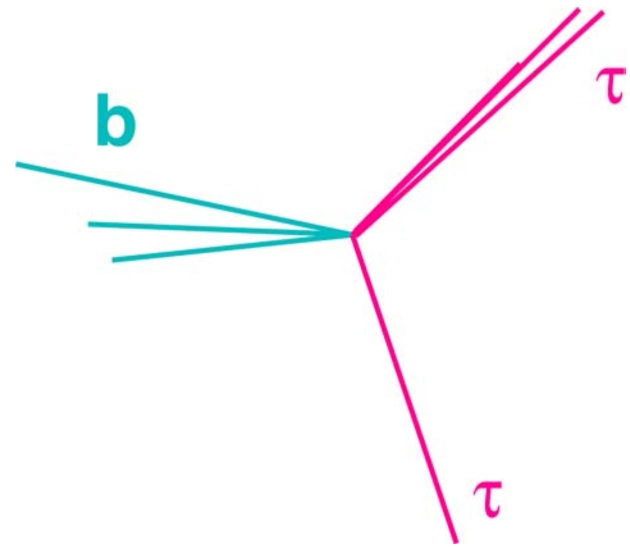


Projections based on the Run 1 four-jet trigger; will likely do better with new three-jet trigger



bH/bA/bh $\rightarrow \tau\tau b$





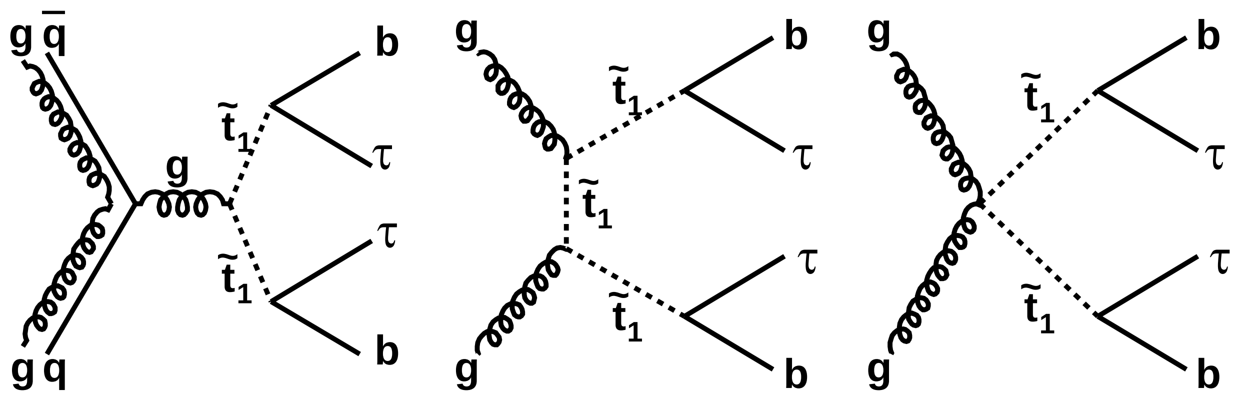
- 90% branching ratio
- difficult to trigger
- don’t know which pair
- lots of background

- trigger exists
- can reconstruct mass
- low background (Zb)
- 8% branching ratio

- Can use full mass reconstruction technique
  - Improve S/B
  - Details later in the 2τ+2jet stop search

Search for RPV Stop

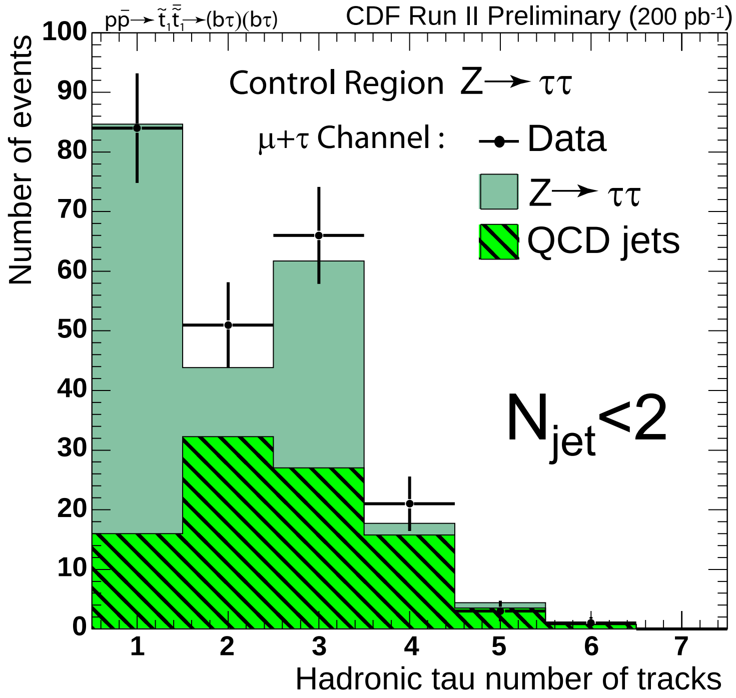
- If exists, stop should be pair-produced at the Tevatron
- R-parity: $R_p = (-1)^{3B+L+2S}$
- If R-parity is violated, stop can decay into tau and a b-jet
  - for wide range of parameters $Br(\tilde{t} \to \tau b) = 1$
- Signature to look for: (e or μ) + τ_h + 2 jets



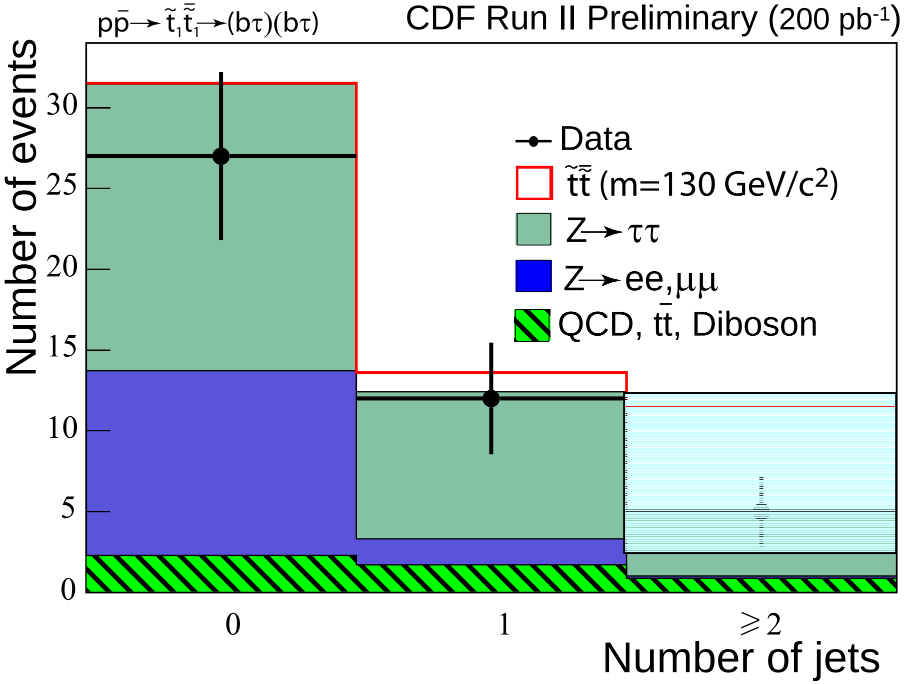
- Identical to the scalar LQ_3 in the limit of high gluino mass.
- Same signature (dataset, cuts) as for SUSY Hbb
- Existing Limits:
  - LQ_3: m>99 GeV (LEP / CDF Run I)
  - RPV stop: m>122 GeV (CDF Run I)

Stop Search: Control Regions

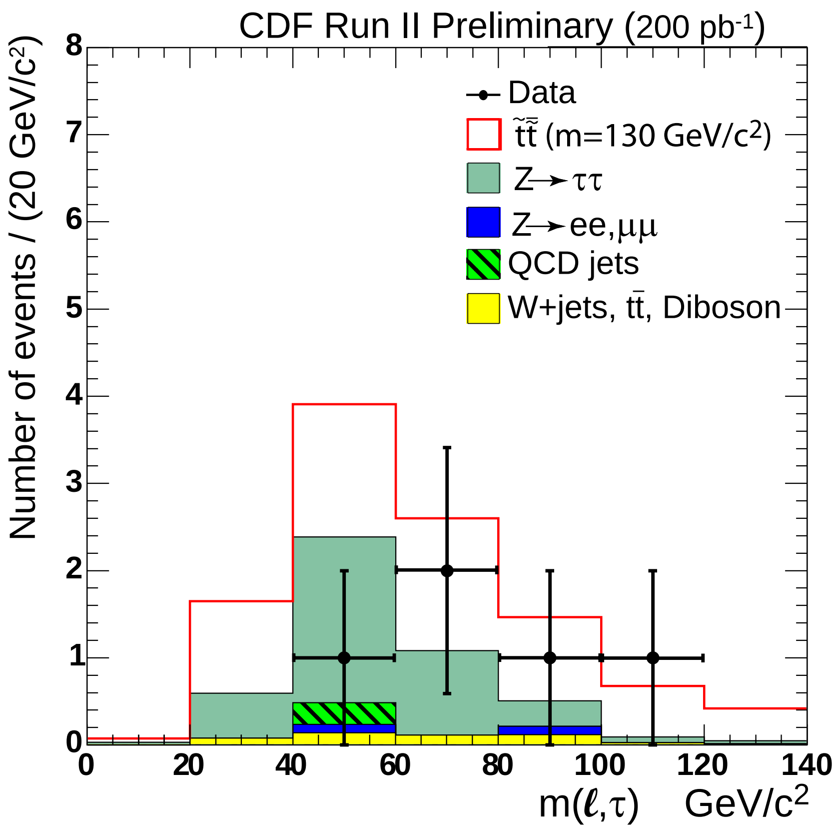
- **Tau ID: $Z \rightarrow \tau\tau$**
- $\left|\vec{p}_T^{\,l} + \vec{\not{E}}_T\right| > 25\ GeV$

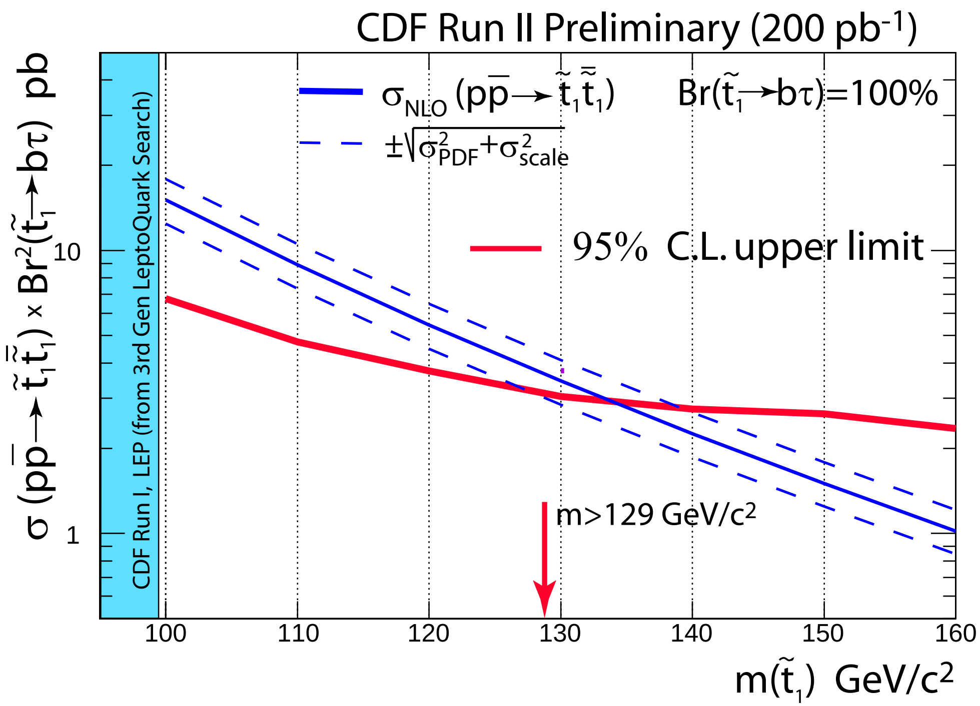


- **Agreement in Njet=0, 1 bins**
- **$N_{jet} \geq 2$ was looked at later**



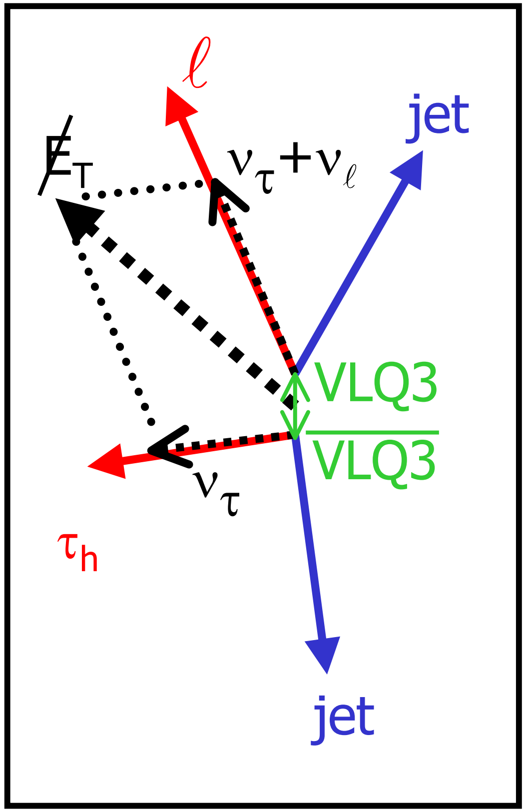
Stop Search: In-the-Box





- **No excess – set a limit**
- **Result: world best mass limit: m>129 GeV**
- **Byproduct: world best limit on 3rd gen. scalar LQ: m>129 GeV**

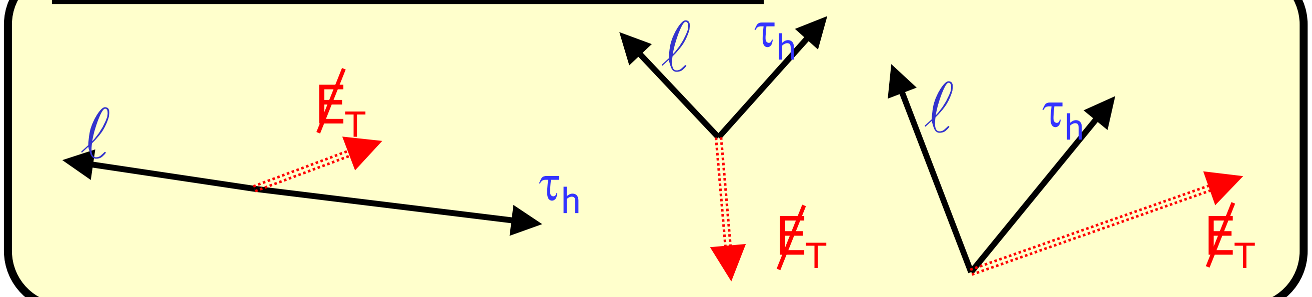
Mass Reconstruction with Taus



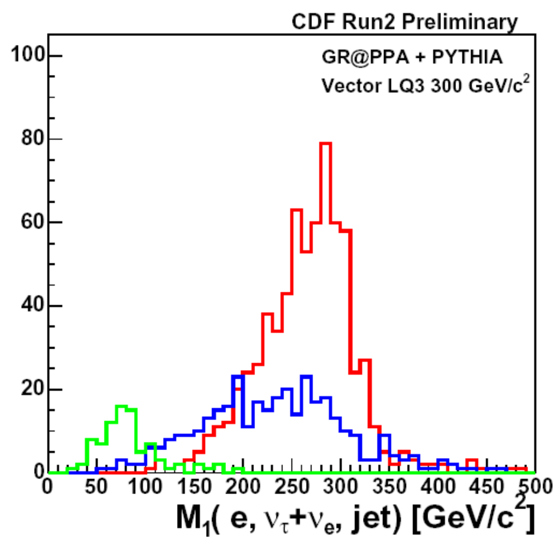
CDF search for vector LQs decaying to bτ

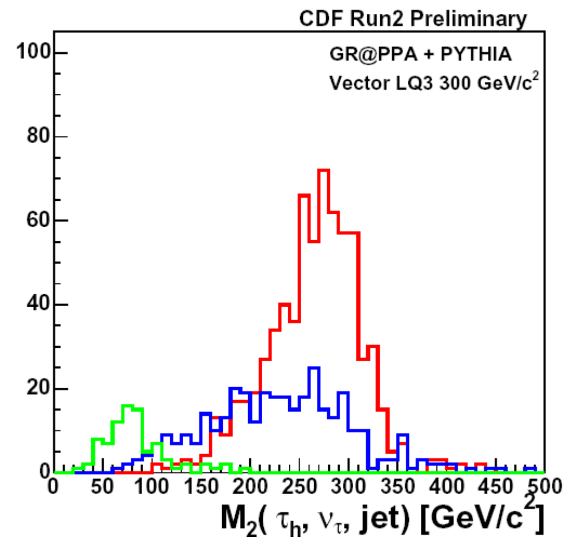
- **Challenging because of escaping neutrinos, but possible:**
  - **Un-Project $\not{E}_T$ on directions of ℓ, τ_h**
  - **Potentially helpful to fight backgrounds**
    - e.g. require $M(\ell, \nu_\tau+\nu_\ell, \text{jet}) \sim M(\tau_h, \nu_\tau, \text{jet})$
    - Even more useful in Hb, Hbb
  - **Setback: some events are not "reconstructable"**
    - Reconstructable fraction ~ 80%

Non-reconstructable events



Mass Reconstruction with Taus



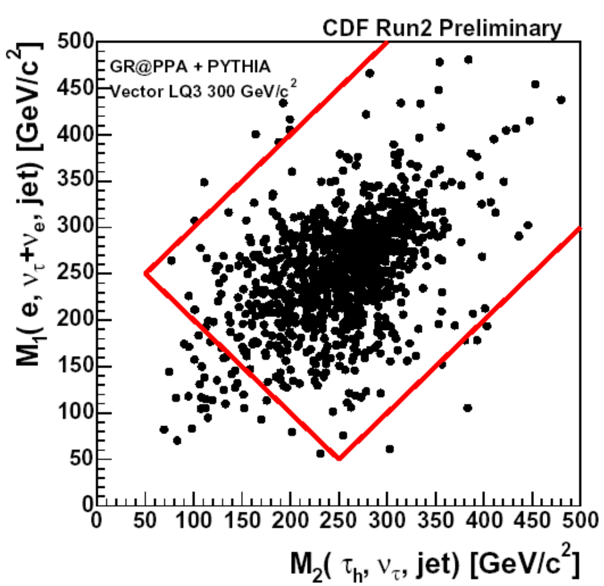


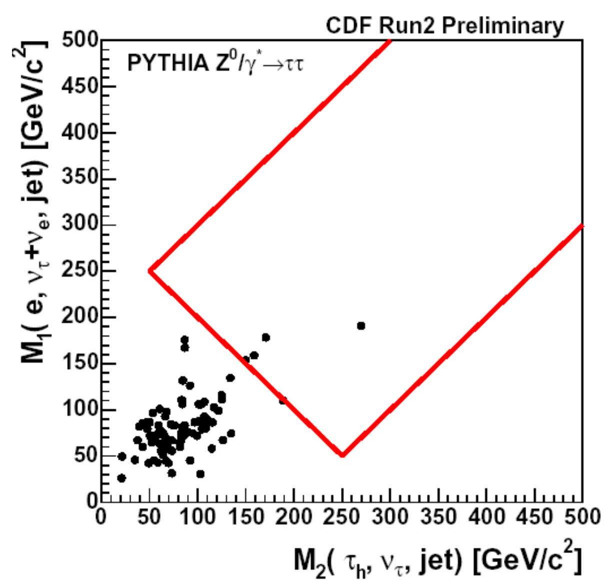
e+τ_h channel only

Good Combinations

Bad Combinations and Bad matchings

PYTHIA $Z^0/\gamma^* \to \tau\tau$





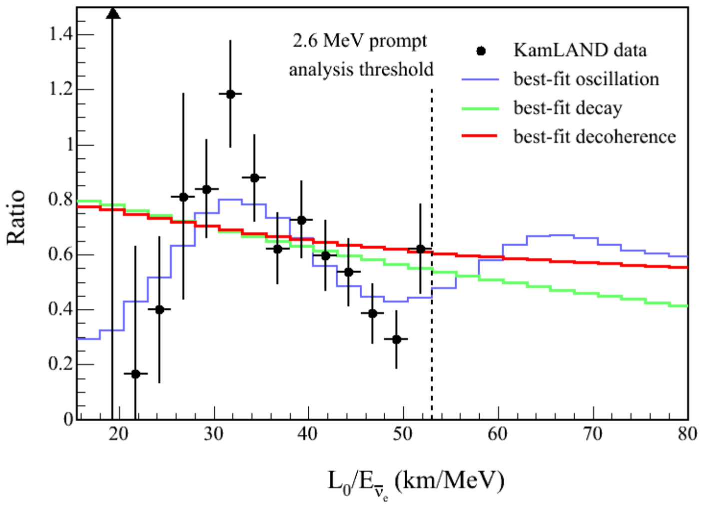
$|M_1-M_2| < 200$ GeV/c^2

& $M_1+M_2 > 300$ GeV/c^2

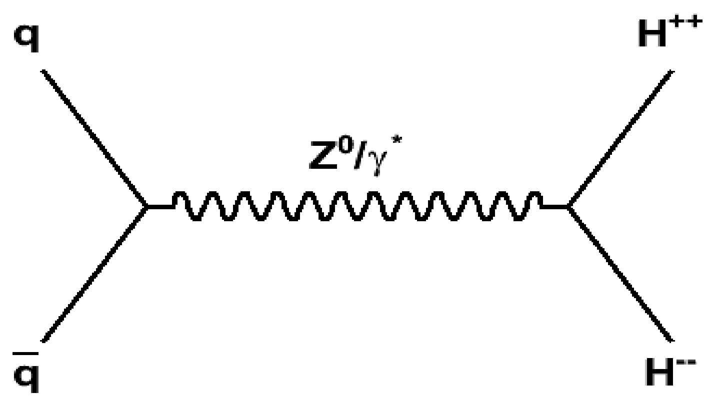
Method works!
Resolution is dominated by jets
Less of a problem for M($\tau\tau$) case

Search for H^{++}

- Natural expansion of Higgs sector
  - Frequent in models with additional gauge groups
    - e.g. Little Higgs, SUSY LR-models
  - Left-right symmetric models:
    - $SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$
    - See-saw mechanism for light ν masses
    - $v_R \sim 10^{10}$ GeV, $m(H^{\pm\pm}) \sim 100$ GeV

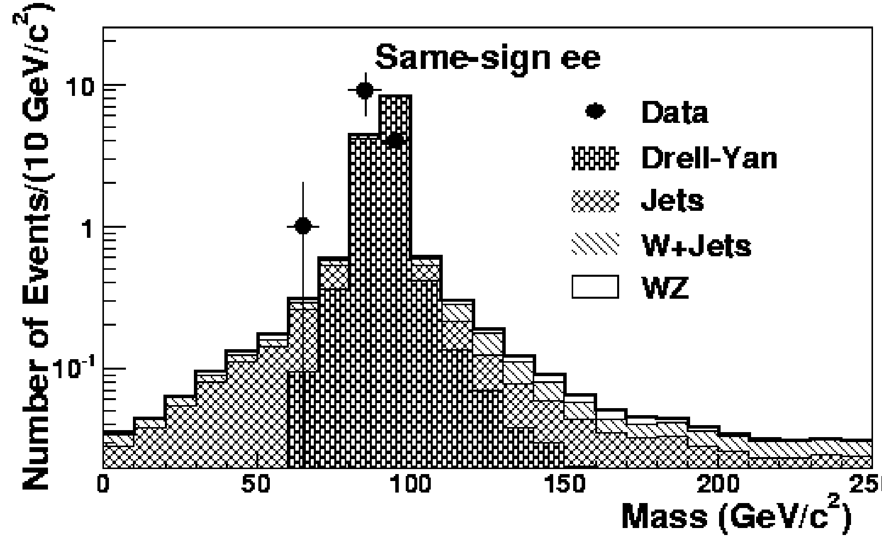


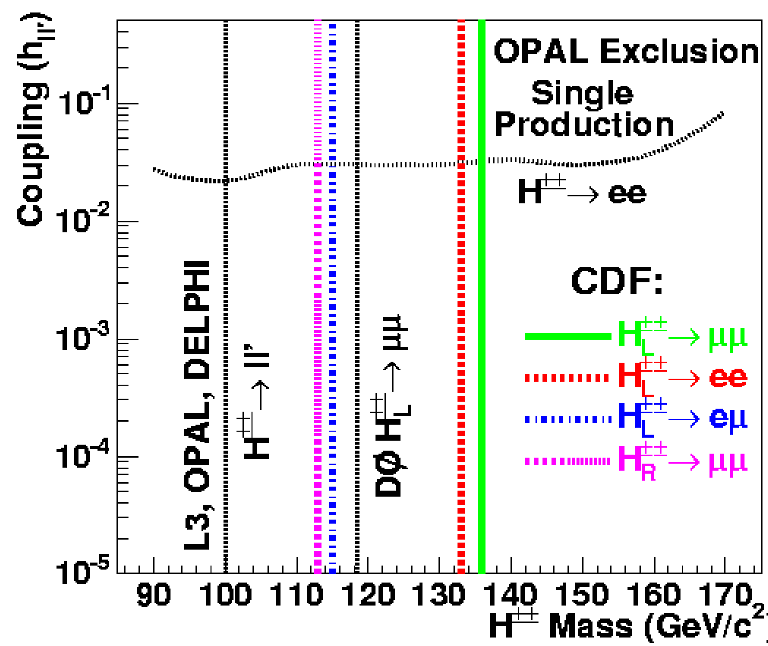
- At Tevatron, DY-like production:
  - $\sigma(m = 100\text{ GeV}) = 0.12$ pb
- Expect H++ to decay into leptons
  - WW decay constrained by ρ parameter
  - LFV is possible
  - σ=0.12 pb at mH=100 GeV



Search for H++

- Require 2 leptons (e or μ) with p_T>20 GeV
  - High acceptance
  - Still very clean signature
- Test in various control regions
- Open the box:
  - No events
  - Hence set a limit
- CDF exceeded LEP-2 sensitivity
  - Results in e/μ channels published
- Analysis with taus
  - More complicated due to ~x10 higher backgrounds
  - Start with LFV H++ (best sensitivity)
  - Results soon



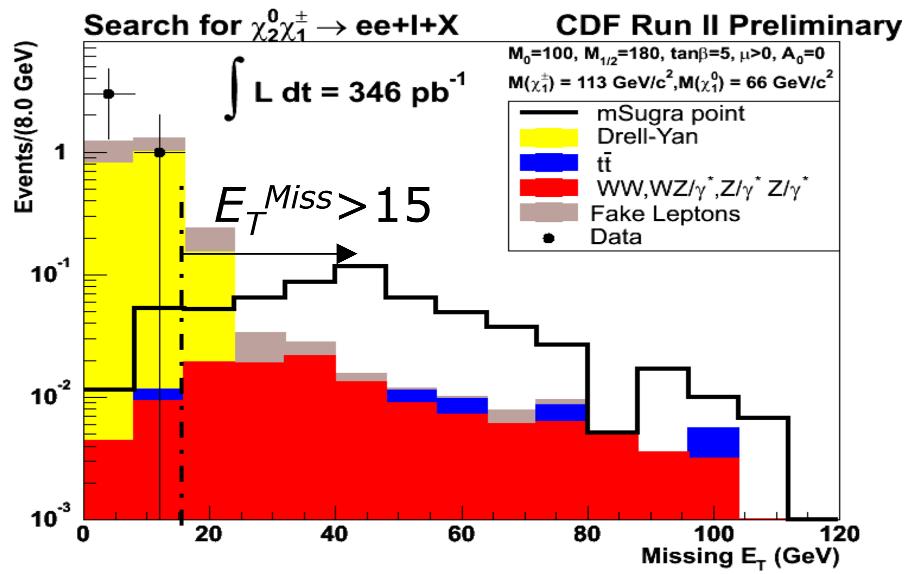


First CDF Tri-Leptons: Low tanβ

Chargino-neutralino in eeℓ channel

SELECTION:

- -2 electrons+ ℓ (ℓ =e,μ) $|\eta| < 1$
- large E_T^{Miss}>15 GeV/c²
- - 15<M_{ll}<76, >106 GeV/c²
- - |Δφ|< 160
- - Njets(20 GeV) <2



Process	
mSugra eeℓ	0.5
Bkgnd Expected	0.16±0.07
OBSERVED	0

- In progress:
  - Add forward electrons
  - Add muon channels
- Next steps:
  - Need to add taus!

CP-violation in Higgs Sector

- Add CP-violation in Higgs sector
  - Need a few more particles:
    - CP-even h, CP-odd h, one more neutralino
  - Much less fine tuning than in MSSM
  - Could well be that $h \to aa$ is dominant
  - If $2m(\tau)<m(a)<2m(b)$, 4-tau mode
- Interesting signature: two pairs of close or even overlapping taus
  - E.g. a good muon sitting inside a good tau can lead to a very clean experimental signature
- On our to-do list

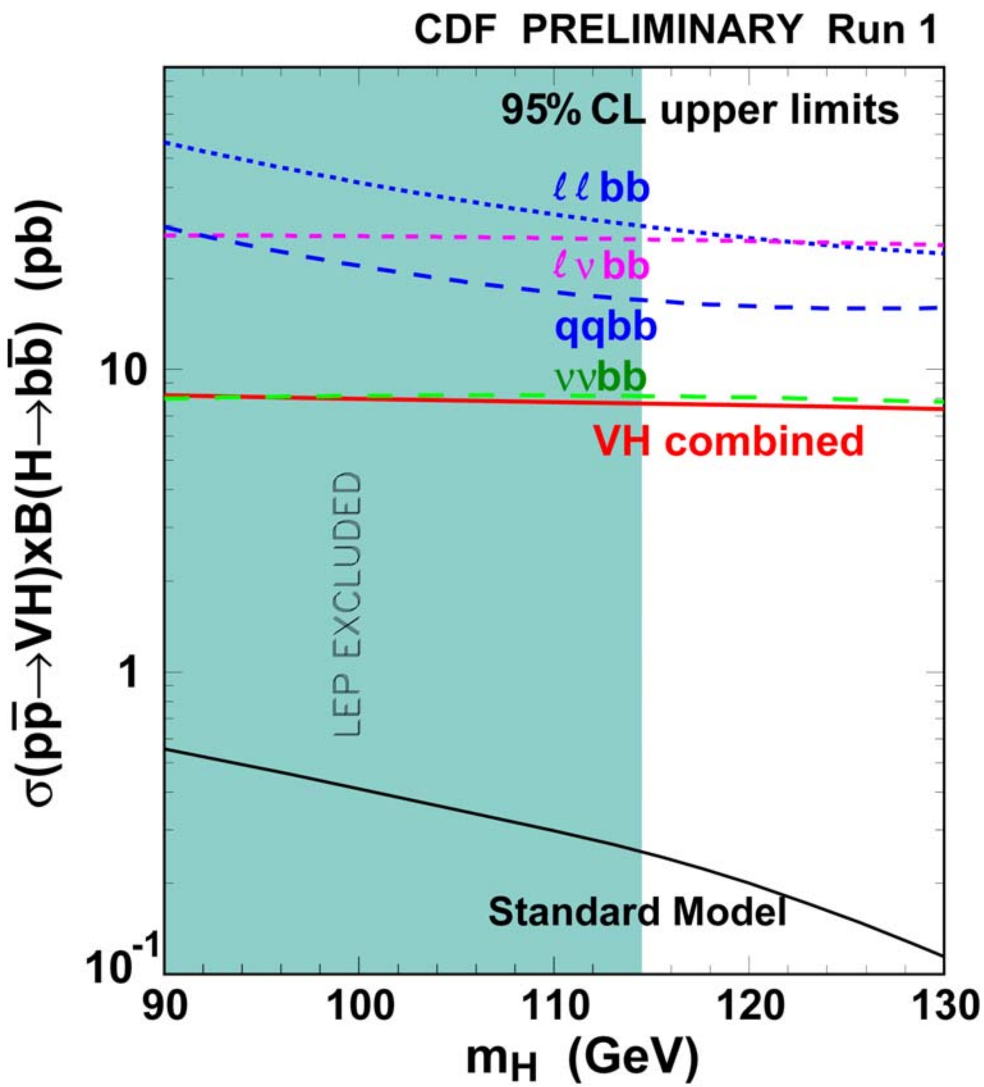
Summary and Outlook

- The Higgs boson is being hunted at the Tevatron
  - D0 and CDF are competing, will soon start combining results
  - No smoking gun with analyzed data, but already 2-3 times more on tape
- Taus are getting into the game
  - Important for Higgs and SUSY
  - Several searches are mature, a few more in the pipeline
  - May well turn out to be very useful both for SM-like and SUSY Higgs
- SM Higgs Search:
  - On track to supersede the LEP2 lower limit on M_H in 2007
  - By the end of 2009, may see a MH=115 GeV Higgs at 5σ, or exclude up to 180 GeV.
  - Require both luck and the Tevatron delivering according to the design plan!

Run 1 combined limits - CDF

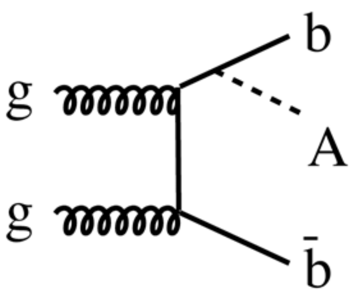
Slight fluctuation up in $\ell\nu bb$ channel led to higher limit…

Still very far from SM cross section



"Forward enhancement" ?

Willenbrock et al: enhancement for Higgs+b (hep-ph/0304035, hep-ph/0312024)



Pole in cross section (related to b structure function) in case where one b goes forward.

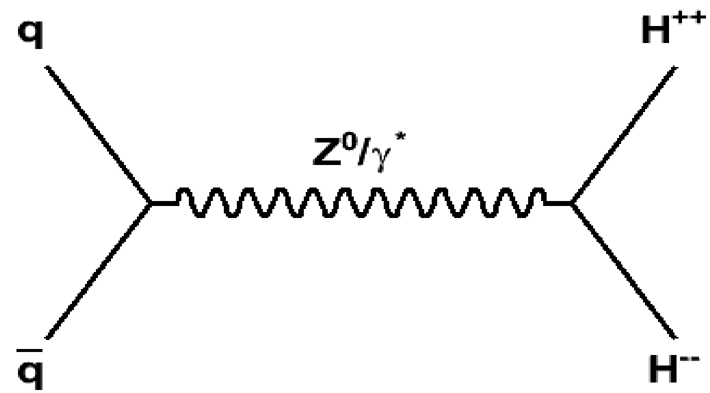
σ(bbb) / σ(bbbb) = 10 !

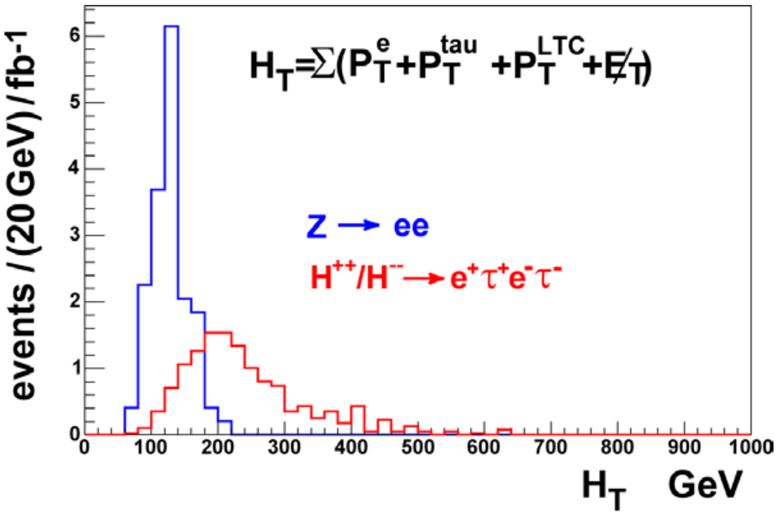
Similar enhancement predicted for Z+b !

σ(Zb)•B(Z$\rightarrow\ell\ell$) = 0.9 pb

Search for $H^{++} \to \tau\tau / e\tau / \mu\tau$

- Dominant mechanism: pair production
  - H++'s are produced with high PT
- Start with LFV $H^{++} \to e\tau$ case:
  - 3p channel: e+tau+LTC
  - 4p channel: e+tau+LTC+LTC
- For M_H=100 GeV (LEP limit)
  - Expect 3-4 signal events in existing data virtually no backgrounds
  - Sufficient for initial observation or exclusion
- Similar sensitivity in the muon channel
- Results in a few weeks

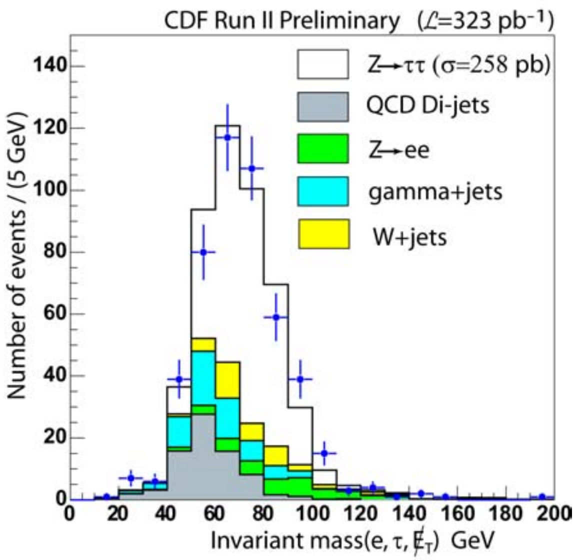


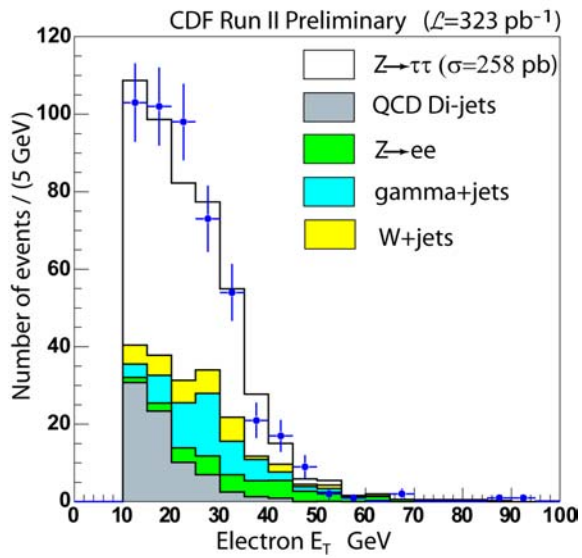


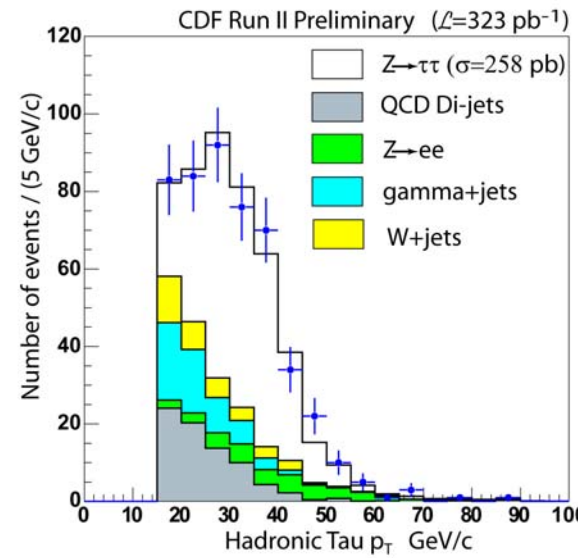
LTC = Loose Tau Candidate – narrow isolated jet

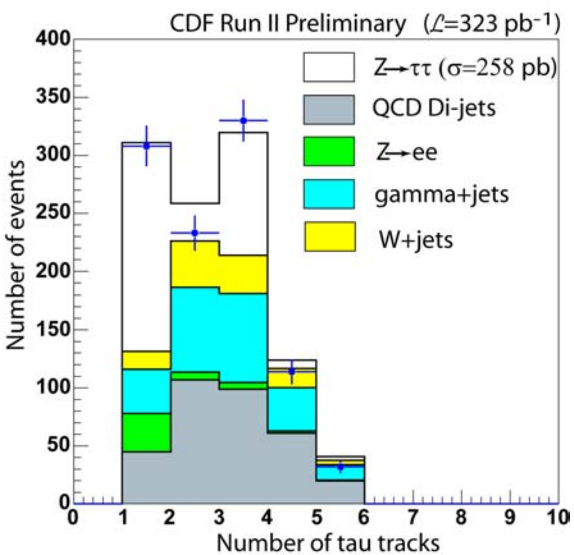
Selects both electrons and hadronic taus

$Z \rightarrow \tau\tau$: Kinematics









- **Good agreement**
- **Our tools for identifying taus work!**