
# Hunting Higgs at CDF

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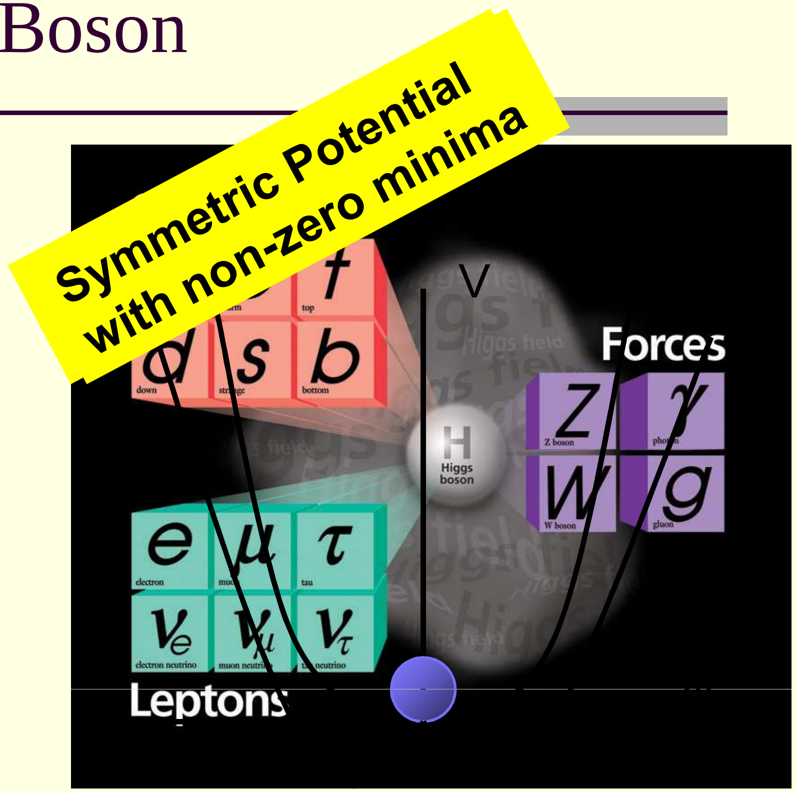
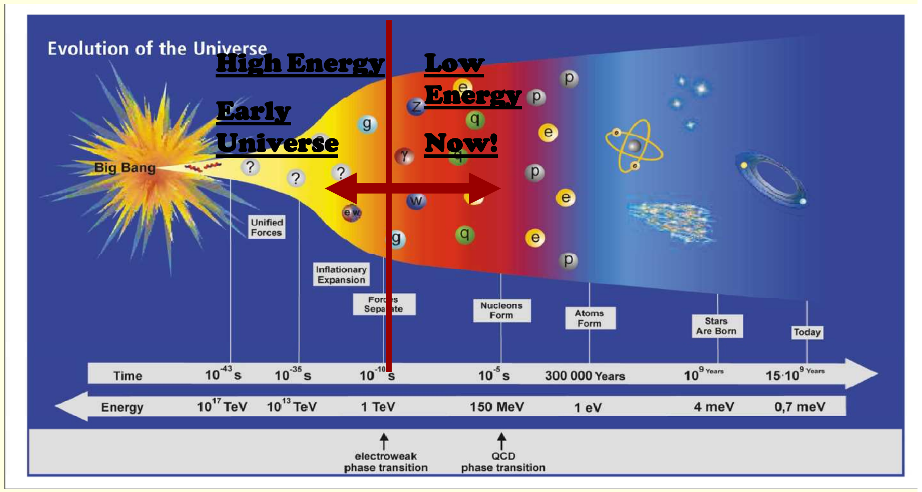
# The Higgs Boson

- Standard Model predicts the yet-to-be observed Higgs particle
- Why should we believe this particle exists?
  - Particles have mass
    - Unexplained without new field (i.e. Higgs)
  - Unification of Electromagnetic and Weak forces
    - Early particle theory with massive particles broke down when mass introduced
    - Problem solved by introducing a concept know as Electroweak Symmetry breaking
- At high energies, forces are unified and "ground state" value is zero
- Lower energy scale breaks the symmetry, producing non-zero vacuum expectation and giving particles mass!



# Predictions of Electroweak theory

- Theory predicts massive vector bosons W and Z
  - Electroweak couplings related by $\theta_W$
- $v=246$ GeV/$c^2$
- $g'/g=\tan\theta_W$
- Measured values predict $M_W$ and $M_Z$
- Predictions later confirmed by accelerator experiments
- Higgs mass not predicted by theory due to self-coupling

Measurement of Weinberg angle performed at CERN and Fermilab in early 1970's

Direct Measurement of W and Z at SPS by UA1 and UA2

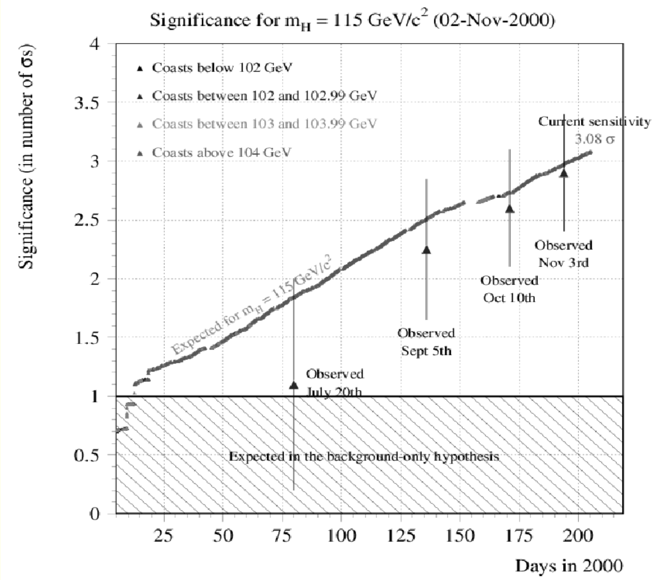
Precision Measurements of Z boson

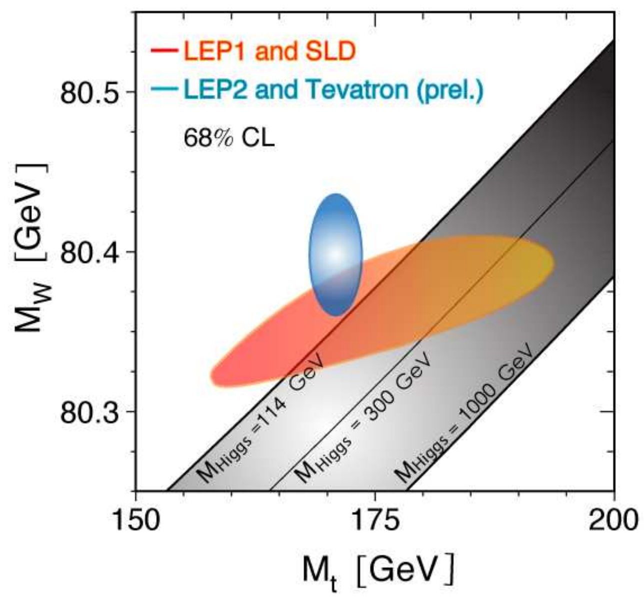
At LEP (CERN)

W boson measurements at LEP and the Tevatron

# Where Should We Be Looking?

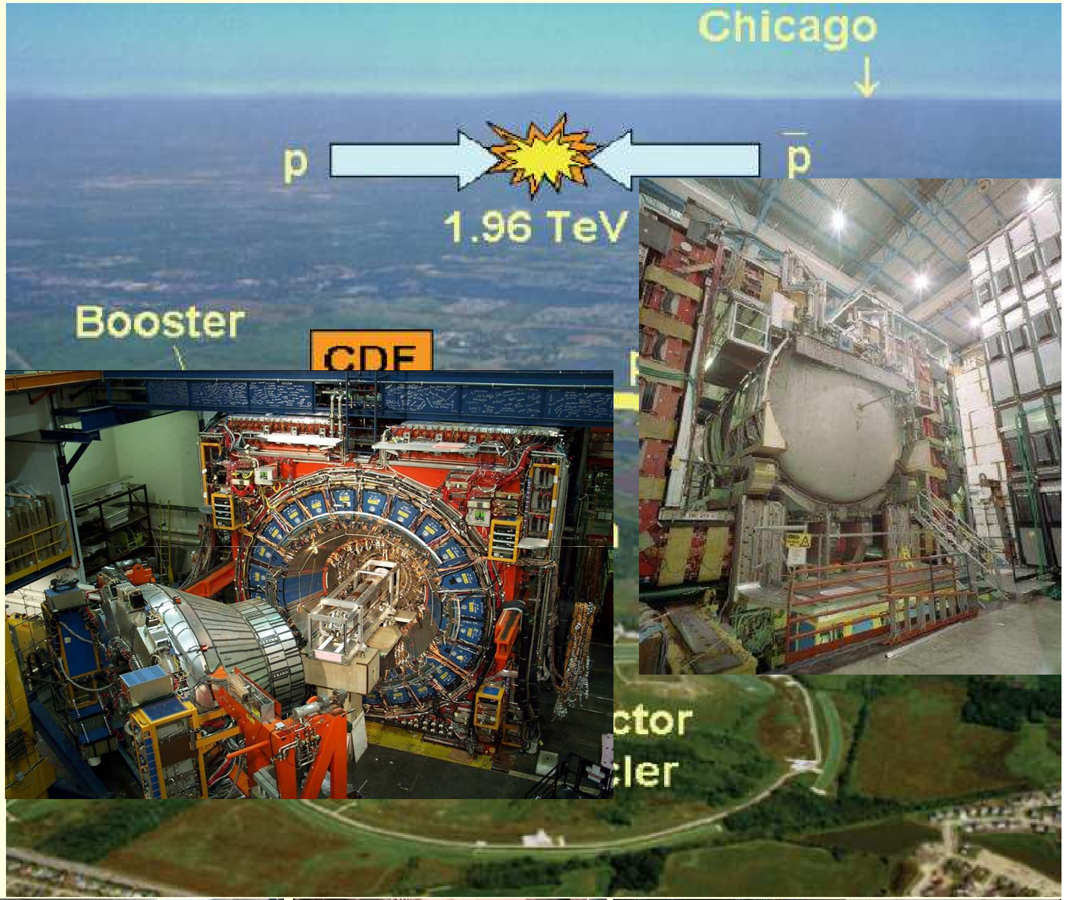
- Tevatron continues to improve SM measurement
  - W boson
  - Top
  - More precision, better constraining power
- LEP unable to discover Higgs
  - Some interesting hints right before shutdown
- Direct limits placed on mass
  - Current limit placed at 114.4 $GeV/c^2$
- SM theory unrenormalizeable if $M_H > 1$ $TeV/c^2$
  - Use current data to find “most likely” mass region
  - $M_H < 150$ $GeV/c^2$ at 95% Confidence
- Limits consistent with the excess of events seen at LEP

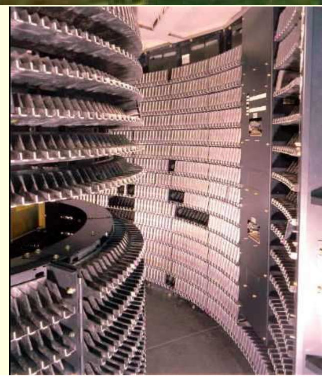


# The Tevatron and CDF

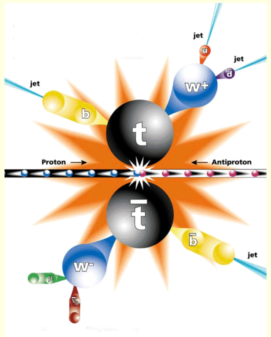
- So how do you produce a Higgs boson?
  - Step 1 – Build a huge accelerator
    - Must generate large energies
    - Directly produce massive particles
  - Step 2 – Build a detector
    - Many components, each performing a specific task
      - Tracking, Calorimetry
      - Hardware triggers
  - Step 3 – Must have large computing resources to store and analyze massive amounts of data
    - Trigger software
    - Production farms
    - Analysis farms



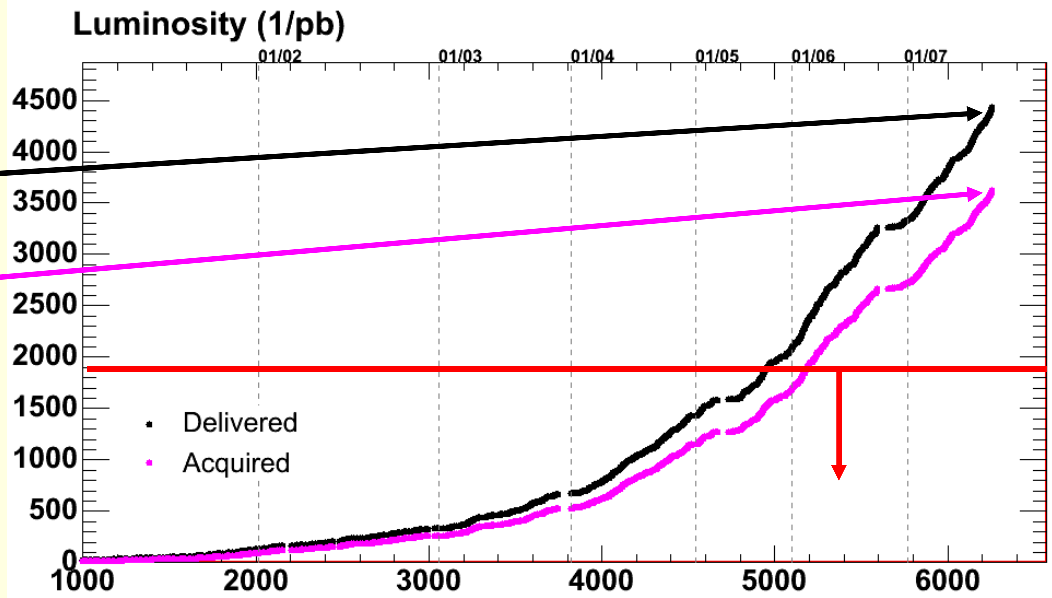



# The Tevatron

- The Tevatron at Fermilab provides high-energy proton-antiproton collisions
  - Center of mass energy 1.96 TeV!
- Collisions create lots of interesting physics that currently takes place nowhere else in the world
  - Top quarks
  - W,Z bosons
  - Diboson
  - Higgs?

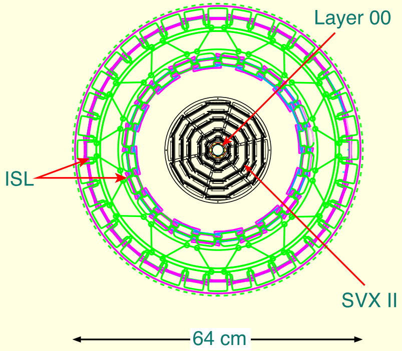


- Energies provided very large, but amount of data collected just as important
- Tevatron has run very well, continually providing record luminosities for a hadron collider
- <u>CDF Dataset</u>
  - Tevatron Delivered Lumi
    - 4.5 $fb^{-1}$
  - CDF Acquired Lumi
    - 3.6 $fb^{-1}$
  - Analysis Dataset
    - 1.7 $fb^{-1}$



# The Collider Detector at Fermilab

- Experimental particle physics requires an apparatus with many subdetectors




**Silicon Tracker**

Closest to beamline

Accurately measure position of primary vertex

Locate secondary vertices from hadron decay

**Central Outer Tracker**

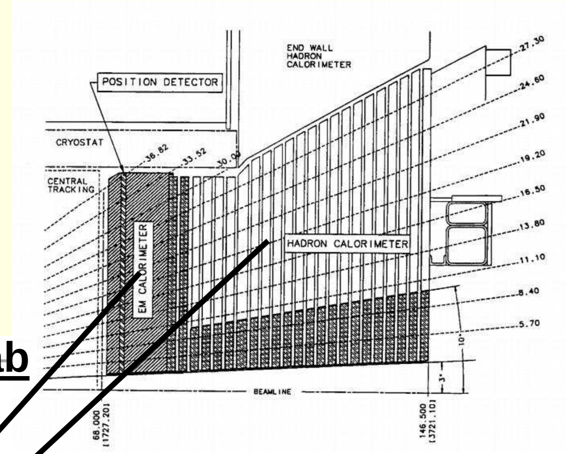
Provides tracking for charged particles

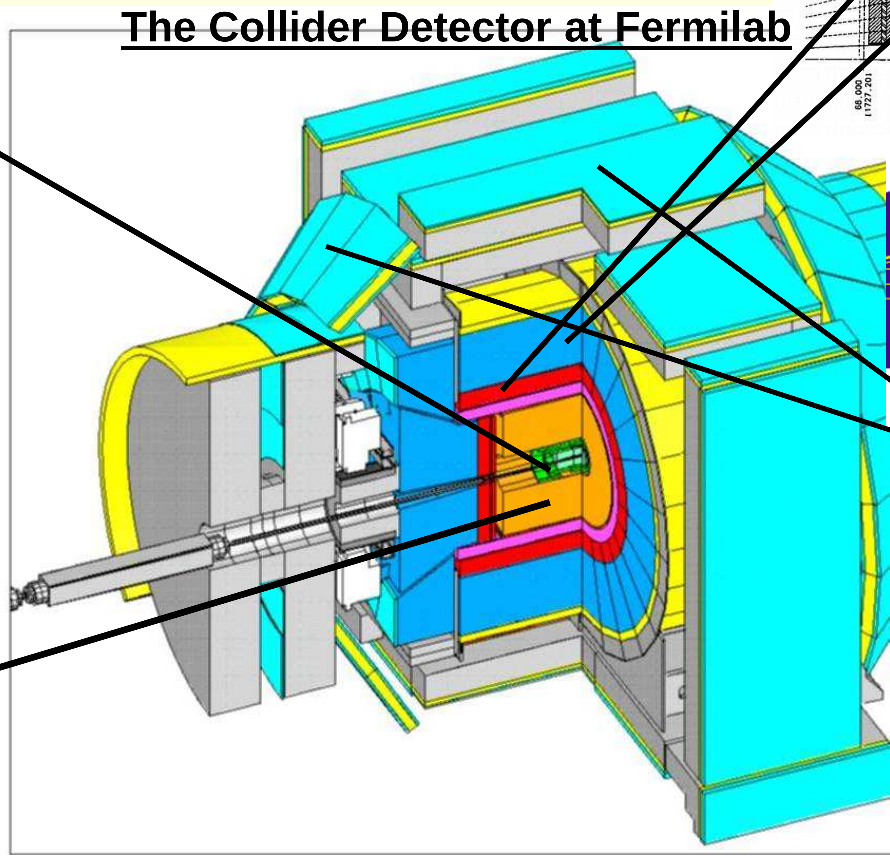
Lepton ID

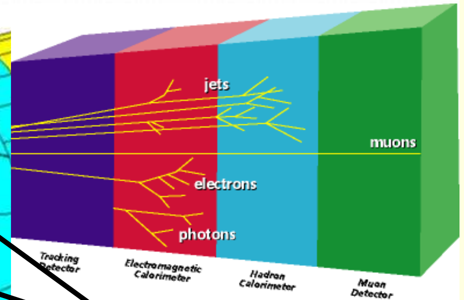
**Calorimeters**

EM and Had calorimeters

Collect energy of charged and neutral particles



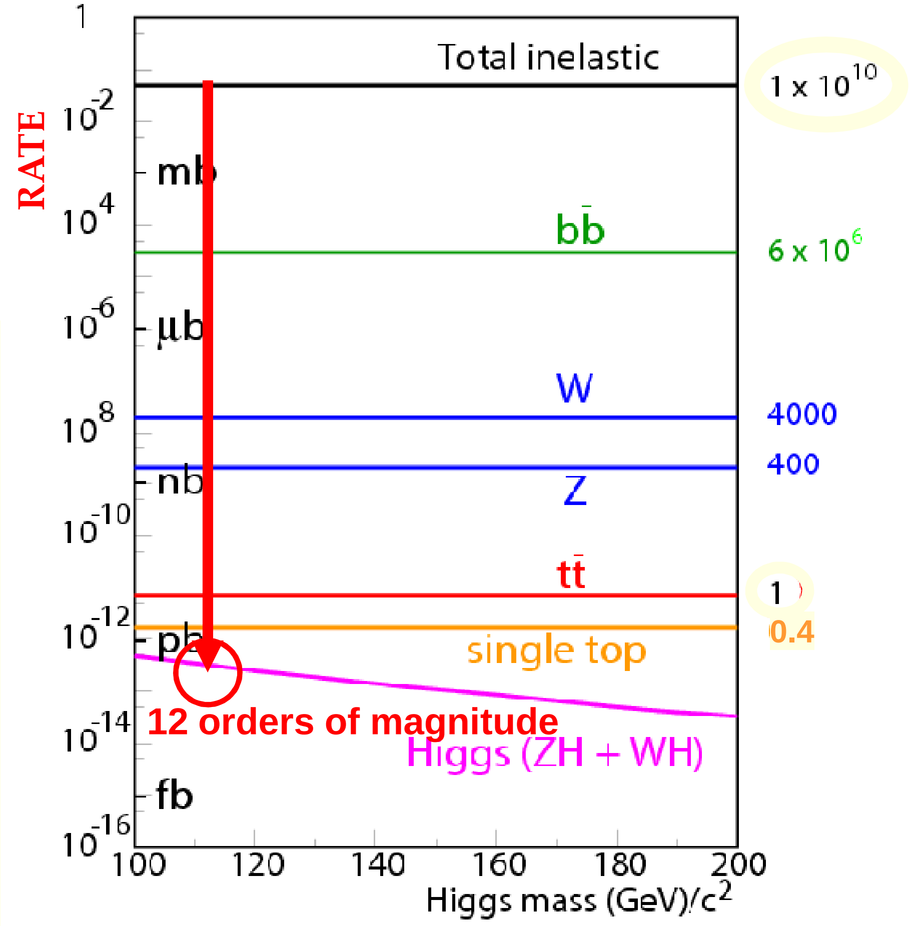




**Muon Chambers**

Muons typically escape detector

Small tracking chambers measure short track

# Getting to the Higgs




| |
|---|
| Energetic Accelerator ☑ |
| Sophisticated Detector ☑ |
| Computing Resources ☑ |

- Now the "hard" part begins
- Higgs particles are extremely difficult to produce
  - All known physical processes occur at rates much larger
  - Overwhelm any chance of seeing this new physics
- Must find ways to sift through the trillions of collisions and extract to physics of interest
  - How is this possible?

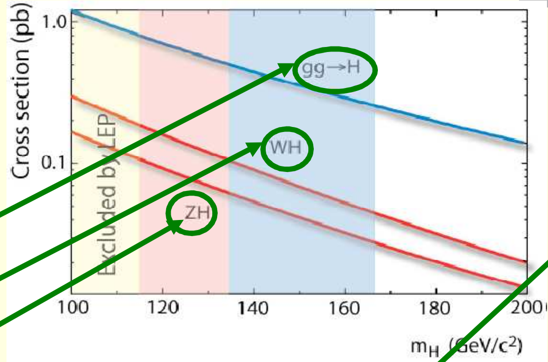
# Step 3 - Constructing an Analysis

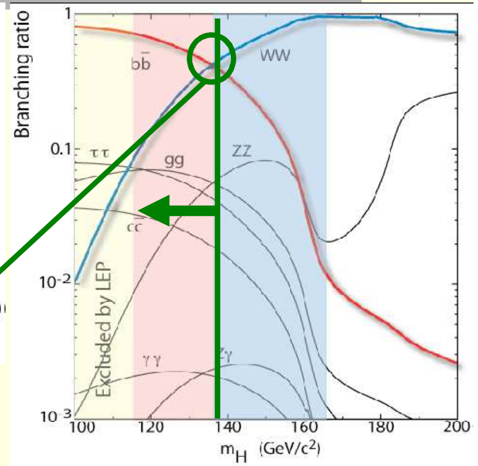
- Each analysis is unique
  - Must be uniquely designed
- Determine properties of your signal
  - Higgs has 3 primary modes of production

**Rate**

| | | |
|---|---|---|
| 1.00 | gg→H | |
| 0.15 | qq→WH | |
| 0.09 | qq→ZH | |

- Another piece of the puzzle
  - How does Higgs decay (i.e. What to look for in detector)
  - Dominant decay mode changes w/ mass
    - bb and WW largest
  - At low mass, bb mode optimal
- Remember from before the hierarchy of production rates

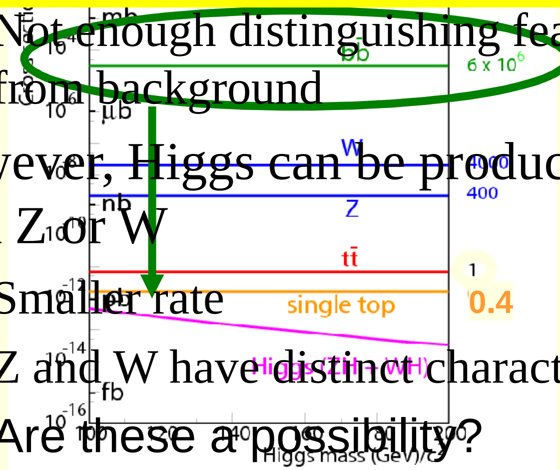



- So gg→H→bb is no good.

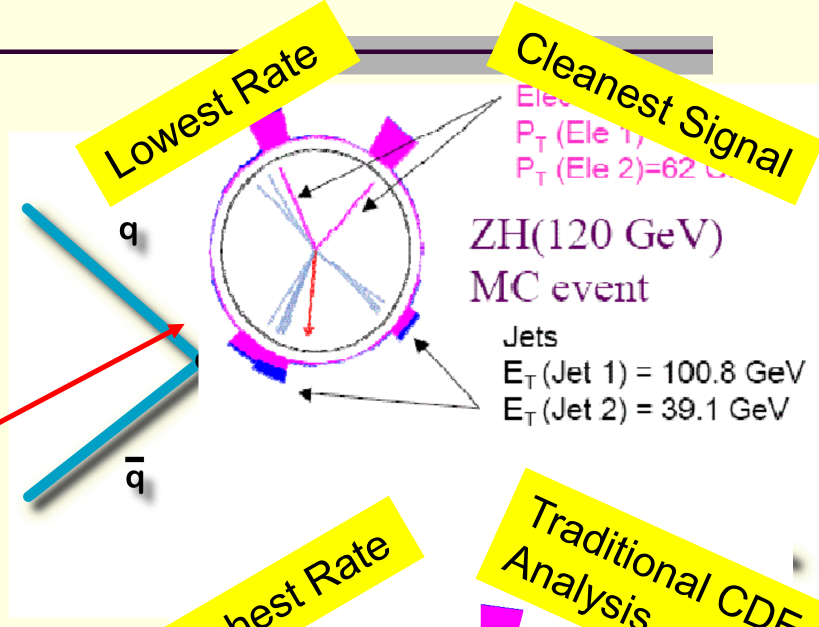
**Still many orders of magnitude away from generic b-production!**

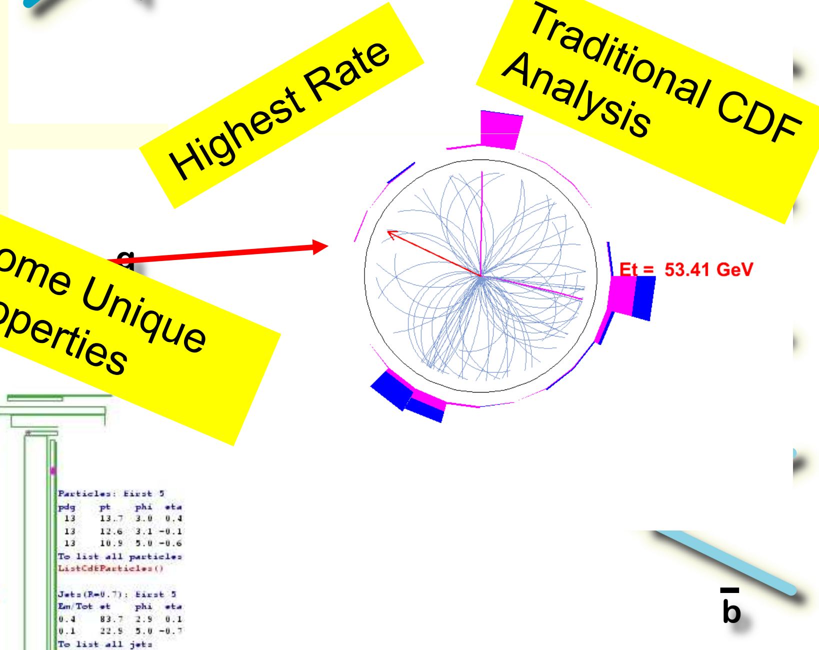
  - Not enough distinguishing features from background
- However, Higgs can be produced with Z or W
  - Smaller rate
  - Z and W have distinct characteristics
  - Are these a possibility?

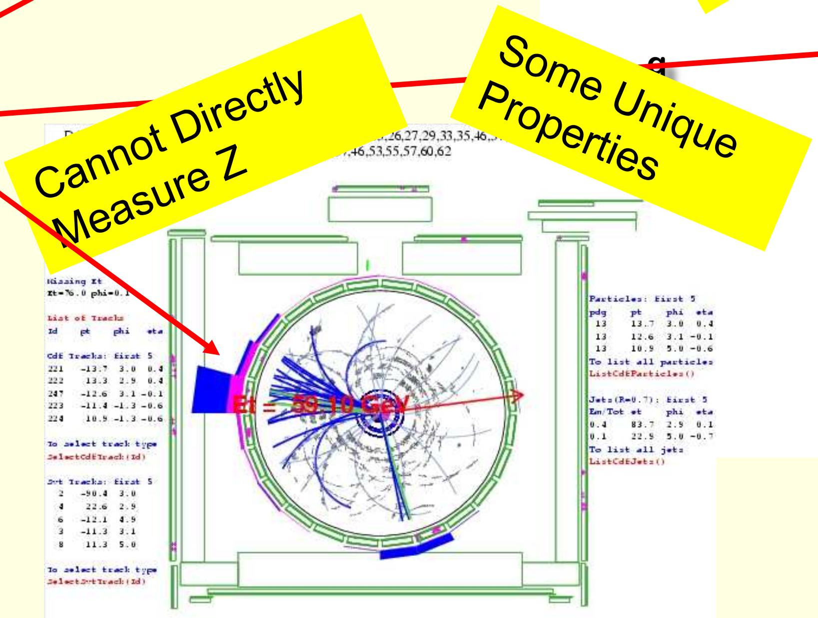


# Higgs Analysis Near the LEP Limit

- For low mass Higgs near experimental limit, associated production is best shot at discovery
- High energy electrons, muons and neutrinos leave very distinct signatures in detector
  - Good way to reduce background dramatically
- 3 main analyses at low mass
  - ZH→llbb
  - WH →lνbb
  - ZH → ννbb

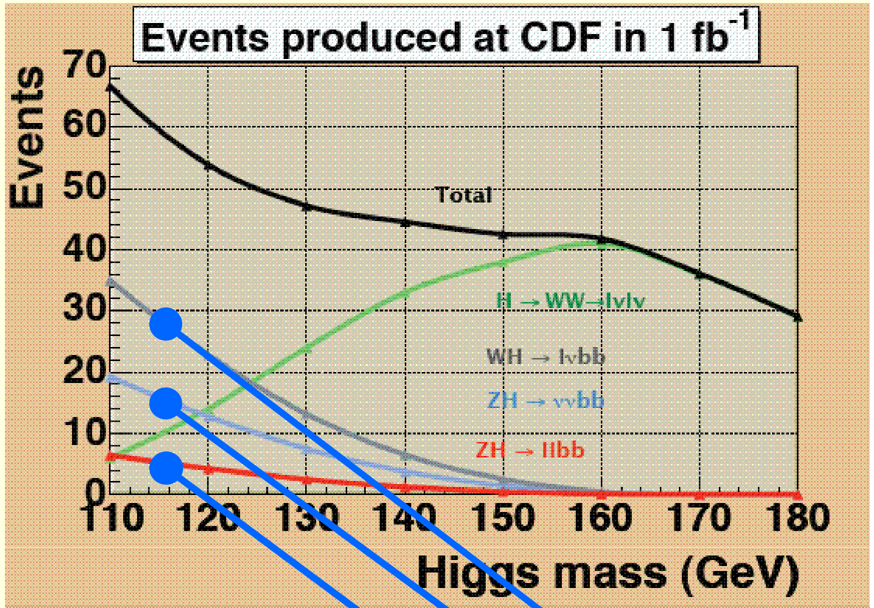


# Where is the Best Place to Look?

- Have three options with very different signatures and background compositions
  - Where should we spend time and resources?
- WH has largest event yield
  - Followed by Z→νν and Z→ll
- Is WH best to find Higgs at CDF?
  - Maybe, but Z channels have some interesting features



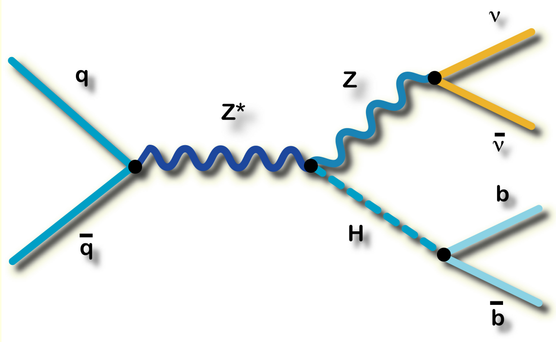

| Process | XSect | BR | $N_{EV}$/ fb$^{-1}$ |
|---|---|---|---|
| WH→lνbb | 0.19 pb | 0.21*0.73 | 29 |
| ZH→ννbb | 0.11 pb | 0.20*0.73 | 16 |
| ZH→llbb | 0.11 pb | 0.07*0.73 | 6 |

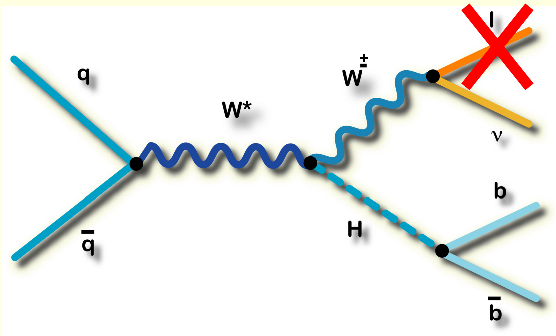
# The Missing $E_T$ Plus bb Channel

- The ZH channel, where Z→νν is very interesting prospect for Higgs measurement at CDF
  - Z→νν rate is 3 times higher than Z→ee+ Z→μμ
  - Often times in WH →lνbb events, lepton is unidentified
    - These events contribute to Higgs acceptance in this channel
    - Signal nearly doubles!

<u>However, there are difficulties!</u>

- Cannot detect neutrinos, so half of final decay products go unmeasured
- Large backgrounds from many different types of physics (Basically entire Standard Model )
  - Most backgrounds are mismeasured
  - All behave differently
- Two different signals means attempting to optimize analysis for two different processes



# First Step : Find Appropriate Data Sample

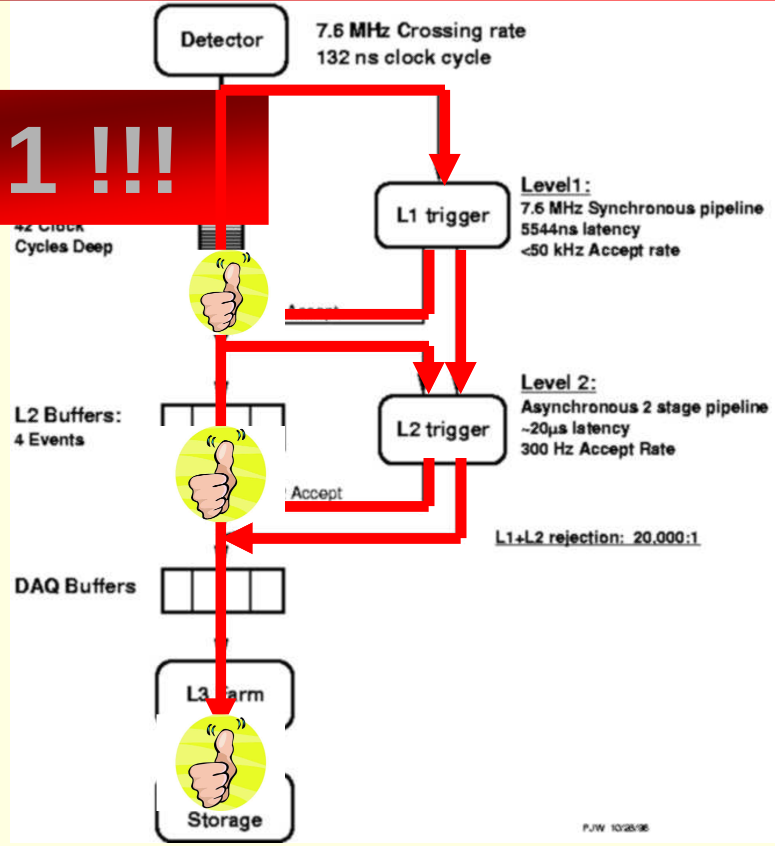
**Before**

**1,000,000,000,000 : 1 !!!**

- First step at quality mana
  select appropriate trigger
  - Background:Signal
- CDF utilizes 3 levels of triggers

**1,000,000,000,000 : 1 !!!**

    - Require 25 GeV of Missing Energy
      - Reduce data rate dramatically
  - Level Two – Reduce rate further with more sophisticated reconstruction
    - Require at least 2 jet candidates with at least 10 GeV of energy
    - One must be central
      - Heavy particles like Higgs typically produce at least one central jet
    - Reduction factor of 150 in data flow
  - Level 3 - Analysis farm with full reconstruction of events
    - Events must have at least 35 GeV of Missing Energy
    - These events are written to tape




**After**

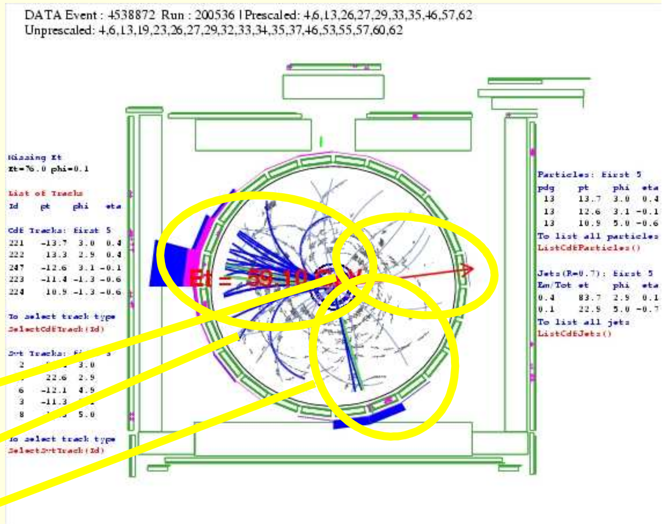
**40,000,000 : 1 !!!**

# Event Selection

- Given the overwhelming backgrounds to Higgs at the Tevatron, must develop set of quality cuts to reduce uninteresting physics further
  - Try to keep as high an efficiency for signal as possible
- Lots of interesting physics contained in samples with large missing energy, but lots of garbage as well!
  - Such data samples highly susceptible to instrumental effects
  - Mismeasurement of physics objects can cause Missing $E_T$
- Second, study properties of signal
  - 2 neutrinos means large missing energy
    - Require 50 GeV of missing transverse energy
      - Reduce large backgrounds
      - Avoid trigger biases
  - b quarks from Higgs decay will fragment into jets
    - 45 GeV for lead jet
    - 25 GeV for 2nd jet
    - Veto Lepton candidates
- These are the main requirements to identify a Z and Higgs

<u>Apply cleanup cuts to Missing ET data sample</u>

Remove beam halo, muon bremstralung, hot towers, noise




Is this sufficient to make backgrounds manageable?

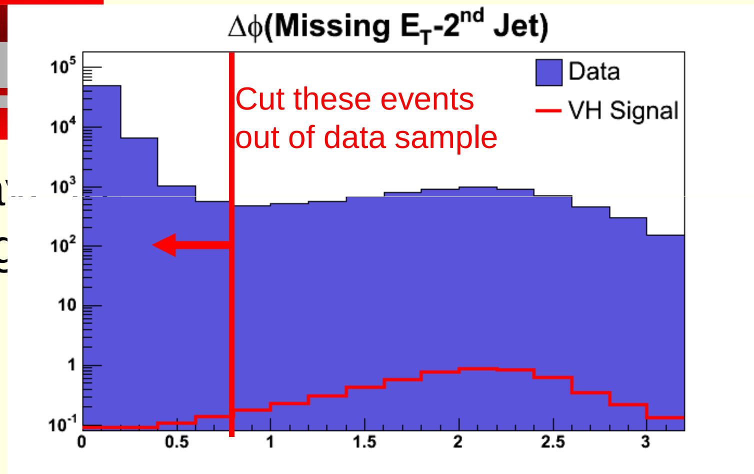
# Still Lots of Work To Do!

- So far we have applied only a general event selection based off of signal properties
  - Maybe we can do better by studying differences between the signal and its primary backgrounds
- Analysis of the data properties of the data sample
  - Large pileup o is aligned with Missing ET!?
    - What are these events?
    - Are they signal-like?
- We will cut these events out of the data sample
    - However, should try to understand what they are
    - May have some use later

**After Primary Event Selection**

**10,000 : 1 !**

Unfortunately, we will ha think much harder to g close to the Higgs



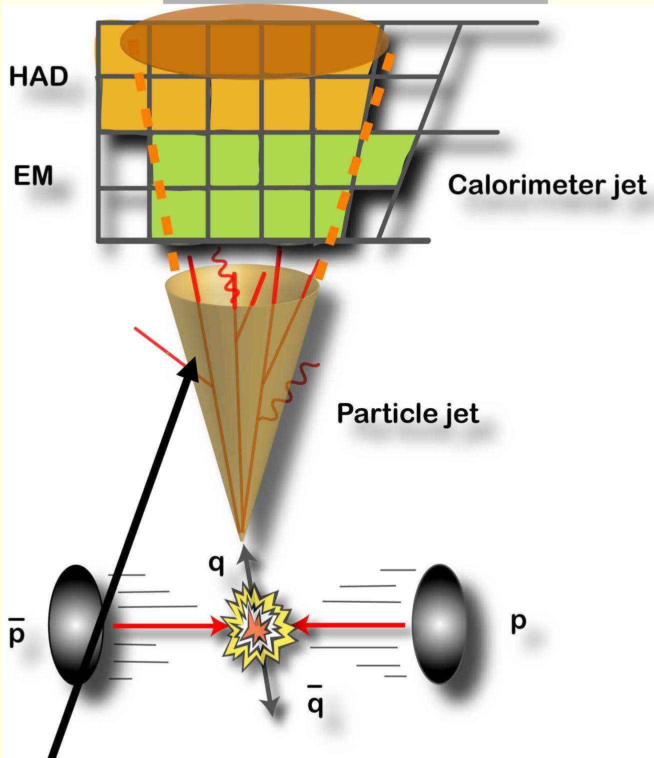

**After Δφ Removal**

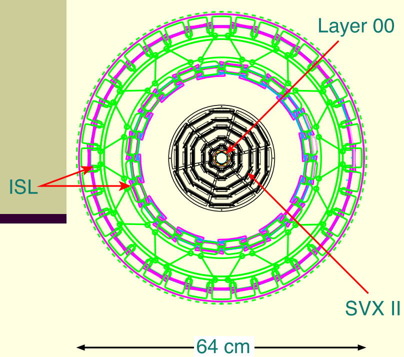
**1,500 : 1 !!!**

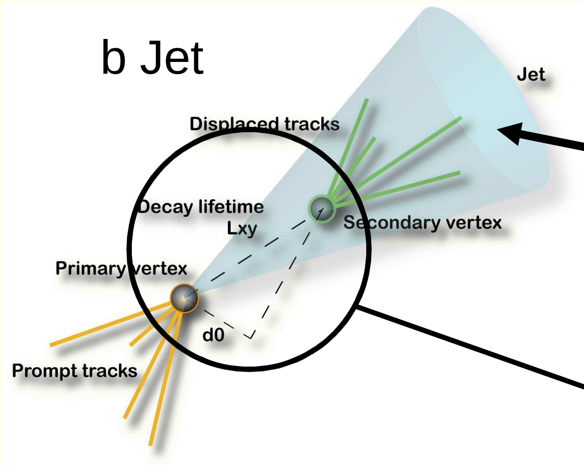
- This looks better, but not still not good enough

# b Tagging

- Jets at CDF will primarily be produced by a high-energy fragmentation process resulting from quark or gluon production
  - Jets are the most common brand of physics objects
- Higgs jets are the result of a specific type of quark production
  - b hadrons have special properties
  - Lifetime long enough to provide measurable vertex



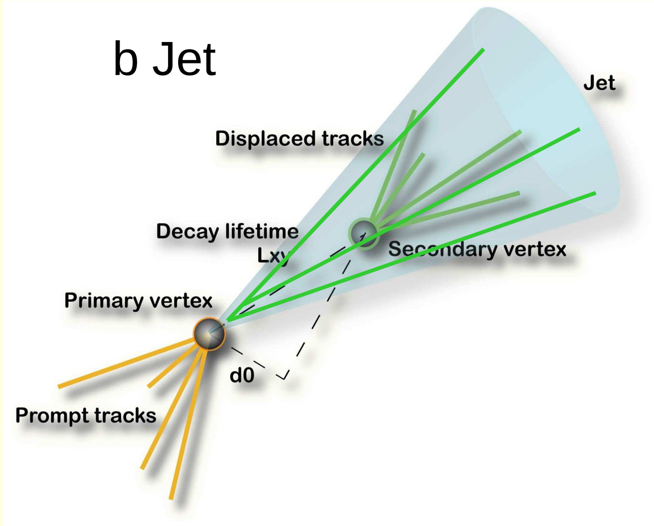

At first glance, b jets appear identical to gluon or light quarks jets

- **Silicon tracker very close to beamline**
- **Provides precise measurements of physics close to the primary interaction**

- **Secondary vertex can be located to identify heavy flavor quarks physics**
- **Highly efficient at rejecting light flavor jets**
- **Greatly increases signal significance in Higgs analysis**

# Tagging Algorithms

- Two separate tagging algorithms are employed in this analysis
  - Try to maximize amount of b tagged signal
- First Algorithm: **SecVtx**
  - Here, we are searching for 3 or more tracks that originate away from primary vertex
    - Somewhat loose selection on the tracks
  - If that doesn't work, look for two tracks consistent with a secondary vertex
    - Tighter quality cuts
  - This is the primary algorithm used at CDF
- Second Algorithm: **Jet Probability**
  - Uses a different strategy by considering probabilities that multiple tracks originated from primary vertex
  - The higher the probability, the less likely jet came from b hadron
- Use these algorithms in tandem to try and maximize b content in data sample




**This strategy greatly reduces the more common light flavor jets**

Our Starting Point

**1,000,000,000,000 : 1 !!!**

Where We Are Now

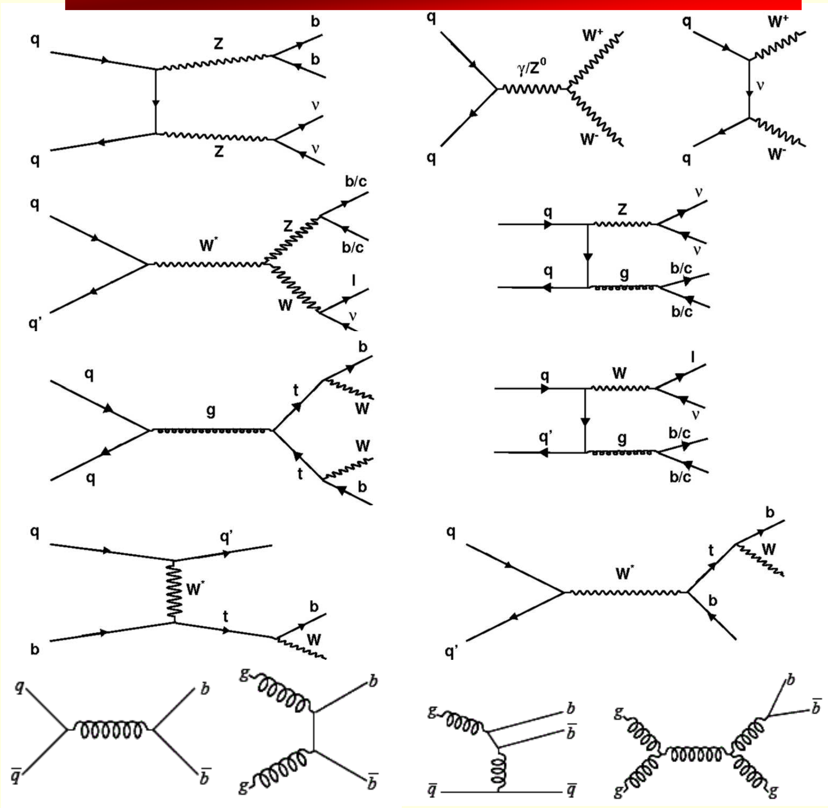
**55 : 1 !!!**

# Now the REAL work begins!

- Analysis currently has managed to greatly reduce the background while keeping good amount of signal (Relative to tiny amount there was to start with!)
- Background : Signal = 55 : 1
  - Infinitely better than staring point
  - Counting experiment still impossible
- Time to switch gears and focus on properties of all backgrounds
  - No easy task, given that just about all Tevatron physics contributes
- Must understand all physics contributing to data
  - Divide and Conquer strategy useful
- Look for data subsamples
  - Study properties individually
  - Apply studies to final analysis

Electroweak

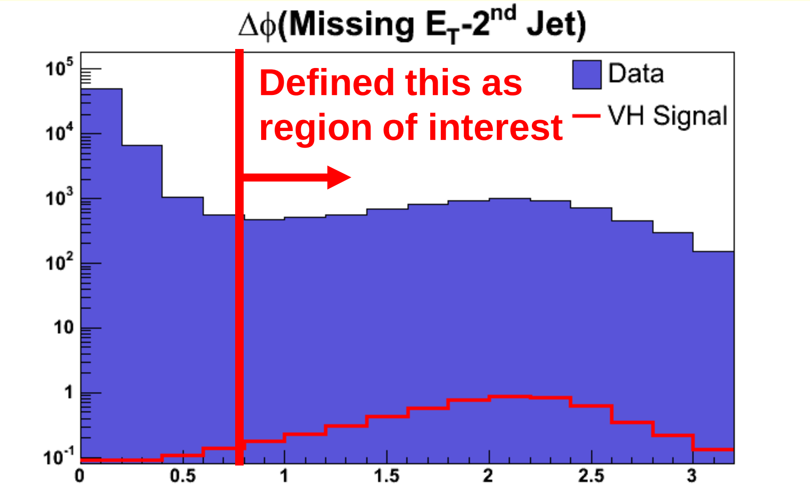
The Standard Model of Backgrounds

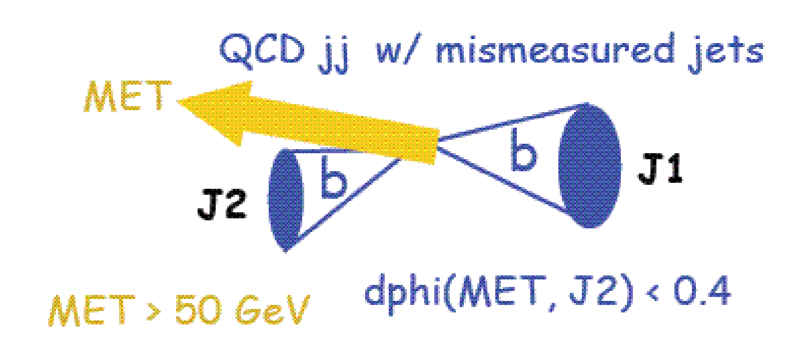


Heavy Flavor Multijet QCD

# Heavy Flavor QCD Multijet Background

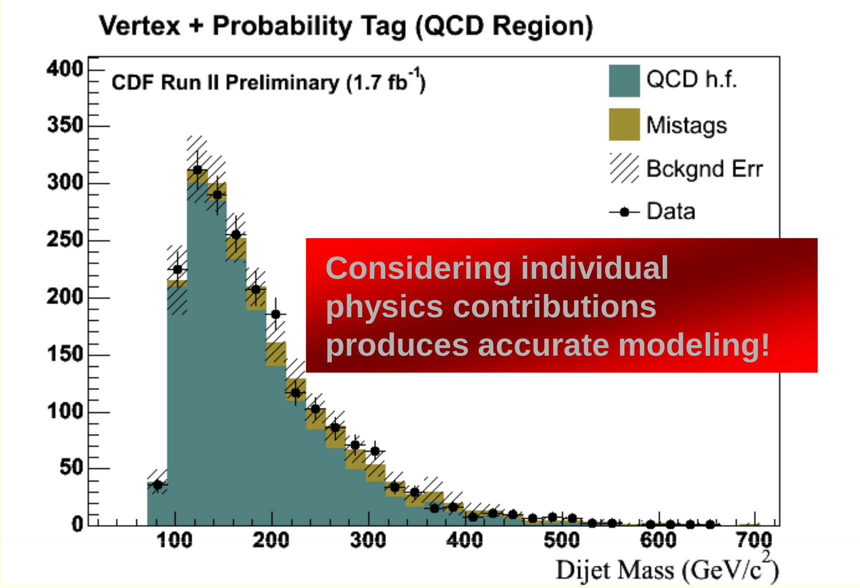
- Want to find a data subsample enriched in this background
  - Remember strange event pileup where Missing $E_T$ aligned with $2^{nd}$ jet
  - Study events that were originally removed
- Possible causes of these events
  - Severe mismeasurement of $2^{nd}$ jet
  - Severe mismeasurement of lead jet
  - Semi-leptonic decay in very energetic jet
- Want to be able to model this process
  - Apply studies here to mismeasured QCD in signal region
  - But how do you model mismeasurement?



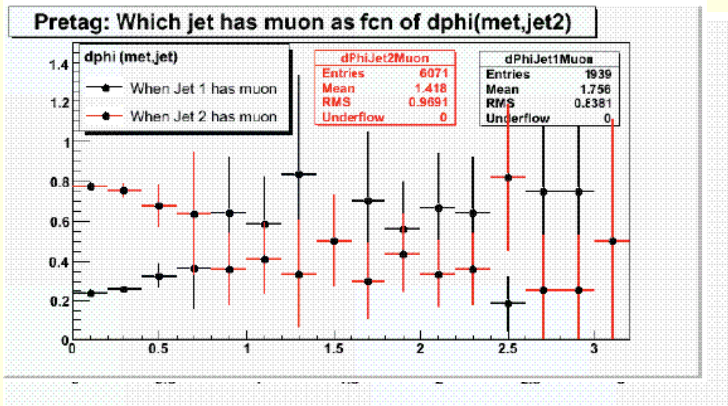
# Modeling the QCD

- Modeling backgrounds can be performed one of two ways
  - Generate Monte Carlo
  - Derive models directly from data
- Past versions of Missing $E_T$+Jets generating hundreds of millions of simulated events
  - Attempting to model outer "tail" of standard heavy flavor physics
  - Massive time and resources
  - Still limited statistics in modeling "signal-like" events
- Wish to pursue data-driven model
  - Success here circumvents many issues
  - Try 1: Use light flavor data without b tags?
    - Want to model data where both jets tagged
  - Try 2 : What about data with only 1 tag?
  - Try 3 : Single tag data also contains some "mistagged" light flavor physics
    - Estimate light flavor rate and shape
      - Subtract out of single tag data
    - Build heavy flavor QCD model and double mistagged light flavor model separately



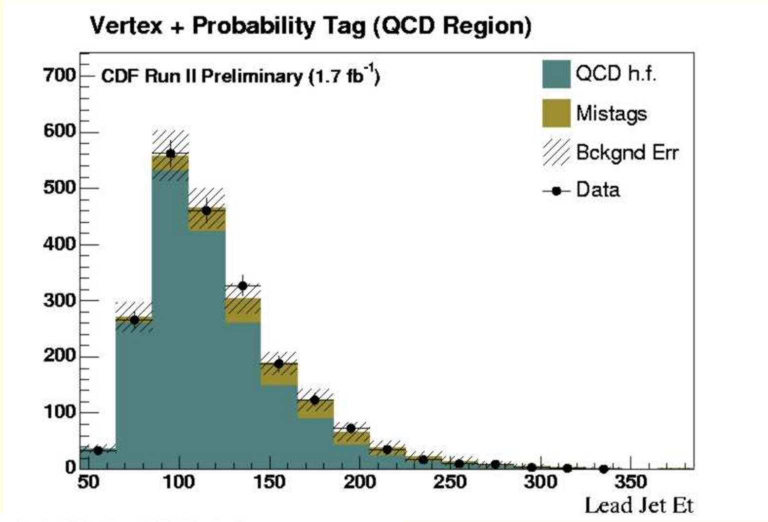

**<u>Are light and heavy flavor physics really that different here?</u>**

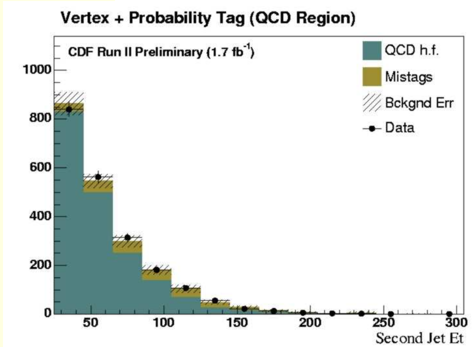
**Unfortunately, yes!**

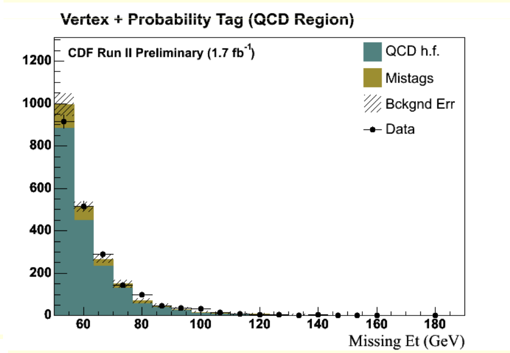


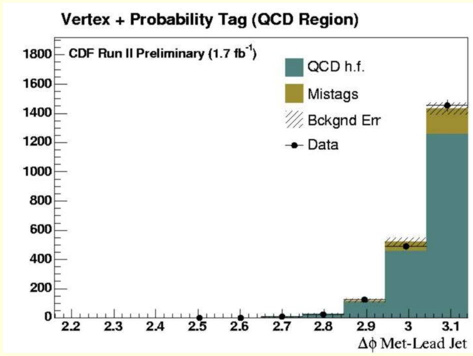
# More Modeling

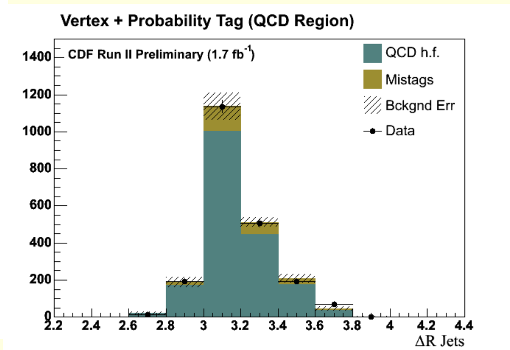
- Look at many kinematic features of data to understand quality of modeling
- Form additional plots involving physics between Missing $E_T$ and jets
  - Assign systematic uncertainties on shapes to compensate for differences
- Things look good, so propagate procedure to region of interest!
- We have now avoided the Monte Carlo problem with modeling mismeasurement
- Have confidence that shapes are accurate
  - Differences in signal region could be signal!



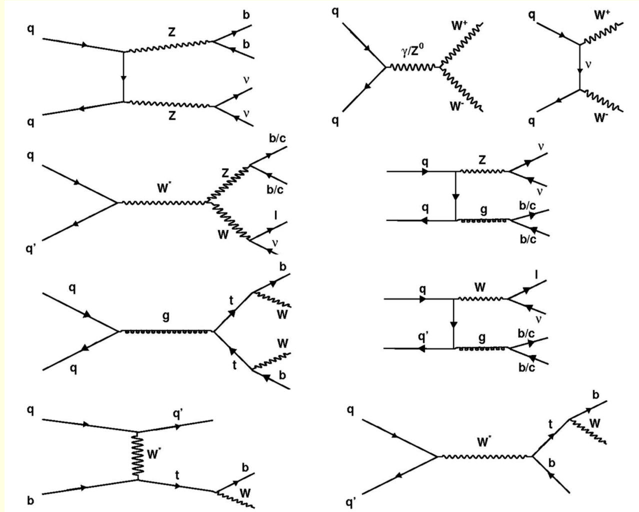



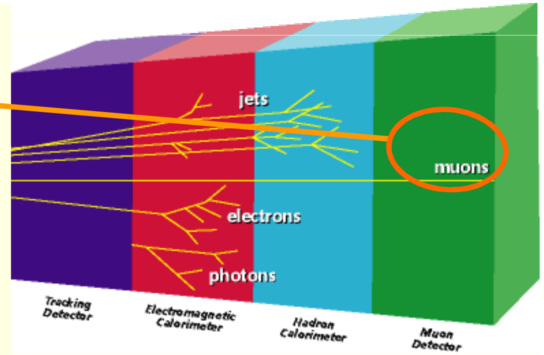



# Electroweak and Top Backgrounds

- Divide and Conquer has one of the major backgrounds pinned down
  - What about the others?
- Electroweak and Top backgrounds can be modeled with Monte Carlo
  - Develop sample to test this sample
- Trigger requires only 2 jets and Missing $E_T$
- Is there a subsample enriched in Electroweak physics?
  - One third of leptonic W's decay to muons
    - Recall features of muon
- Will leave only small amount of energy in calorimeters
  - Will appear almost like additional neutrino
    - Very signal-like!
- Muons very distinct
  - Very small fake muon rate
    - Fake muons usually show up at low Missing $E_T$
- Apply all cuts that define signal region
  - Change muon veto to ID
  - Now have sample for  signal-like background
- Test the procedure!



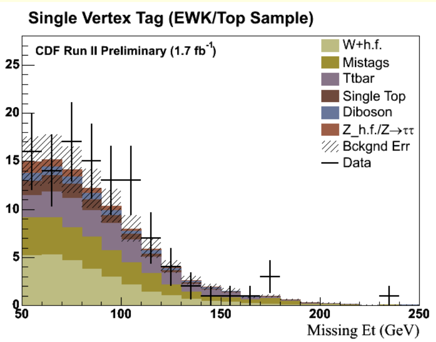


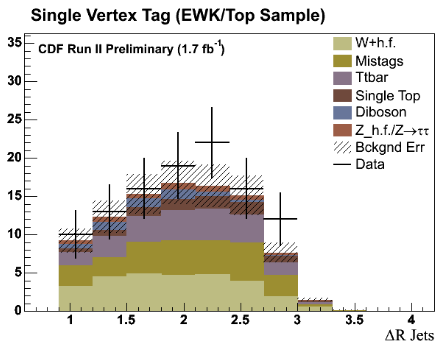
# Electroweak/Top Studies

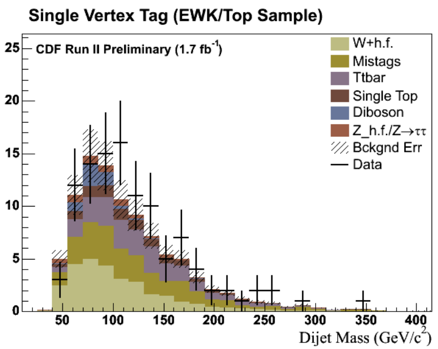
- Need large amount of Monte Carlo to get at physics of several processes
- Run analysis with all event selection
  - Get event expectations from acceptance
    - Know measured or theoretical cross-sections
    - Know Luminosity of data sample
    - NBackground = σ*ε*£
- Add up all contributing backgrounds and compare to data

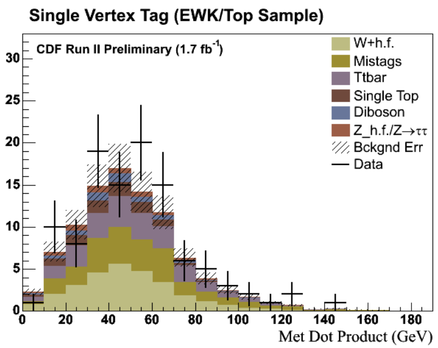
| Background | Event Expectation |
|---|---|
| Mistagged light flavor | 26.4 +/- 3.0 |
| Top pair | 22.1 +/- 2.9 |
| Single top | 8.2 +/- 1.1 |
| W+bb+np | 15.3 +/- 6.1 |
| W+c+np | 7.8 +/- 3.1 |
| W+cc+np | 5.8 +/- 2.3 |
| Z | 1.6 +/- 0.6 |
| WW | 3.0 +/- 0.4 |
| Z+bb/cc | 2.9 +/- 1.2 |
| WZ | 1.4 +/- 0.2 |
| ZZ | 0.5 +/- 0.1 |
| **Total** | **94.5 +/- 12.7** |
| **Data** | **108** |

## Physics appears well modeled



# Getting to the Higgs

- Now reliable models have been built for all relevant backgrounds
- Time to finally move forward!
- Background to signal ratio (55:1) daunting
  - Possible to reduce this further?

Let's think about possible options

- Option 1
  - Optimize tighter kinematic cuts
    - Improves background to signal ratio
    - Removes signal!
- Option 2
  - Fit for Higgs mass resonance
    - Could combine with option 1
    - Improve ability to discern signal from background
- Option 3
  - Develop new techniques
    - Find ways to reduce background w/out removing signal

# Reducing the QCD

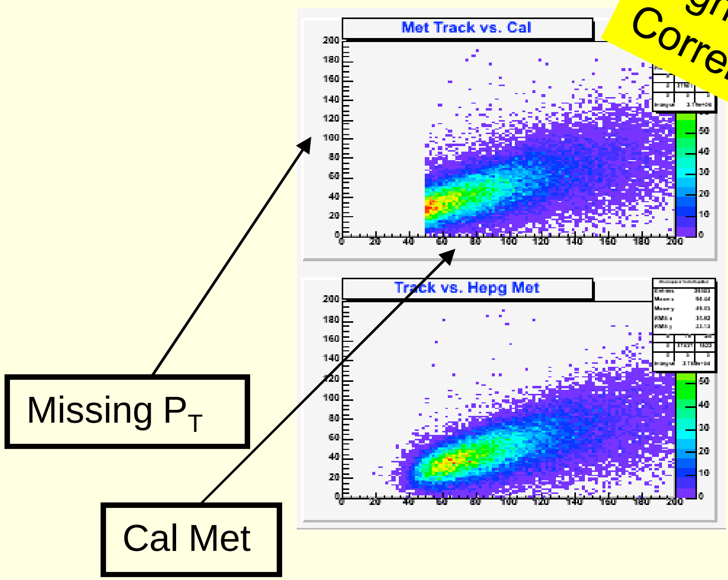
- Majority of kinematic quantities used derived from calorimeter measurements
  - Fake Missing $E_T$ in particular manufactured by cal mismeasurement
    - Primary cause of QCD background
- CDF provides accurate tracking as well
  - If cal is mismeasured, should be uncorrelated to tracking measurements

## The “Track Met” Procedure

- First form a Sum Pt of tracks in COT
- Obtain a vector of Missing PT from tracking information
  - How does this compare to Cal Met?

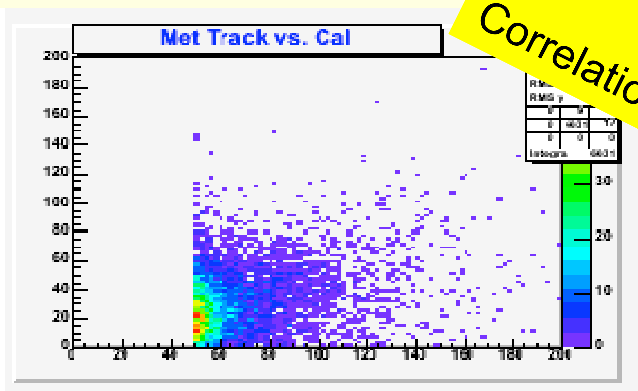
**ZH Signal**

Highly Correlated!



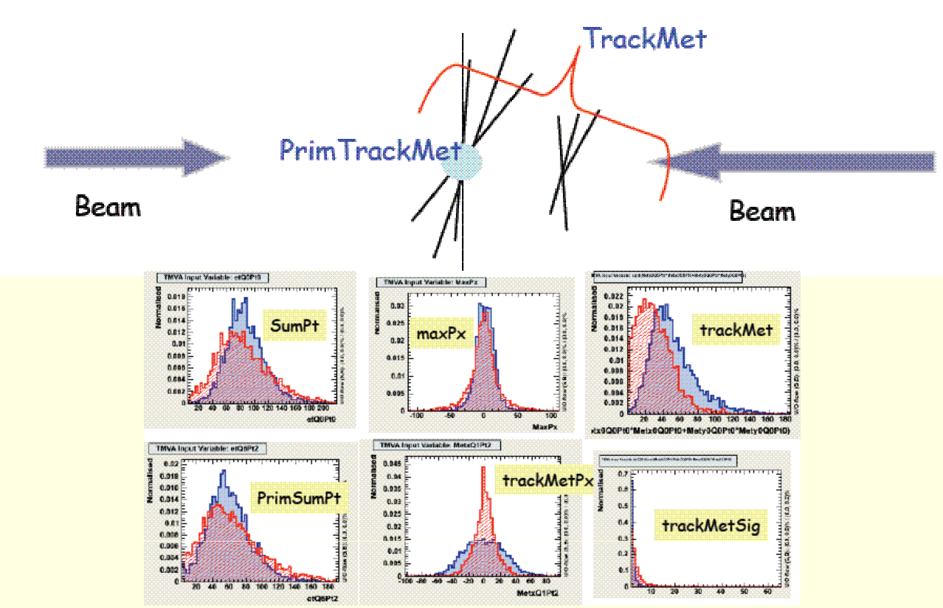

**QCD Data**

No Correlation!



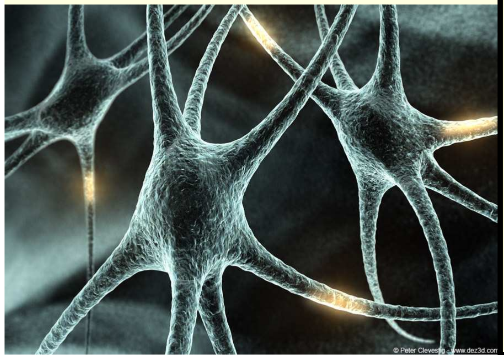
# Track-based Discriminant

- Can form multiple track-based variables
  - Apply various quality cuts
    - Define different quantities based on certain
      - Track PT
      - Origin relative to primary vertex
  - Variables will be more or less sensitive to primary interaction or underlying event
- How do we combine all this information?




**Separation provided solely by tracking information!**

**Artificial Neural Networks**



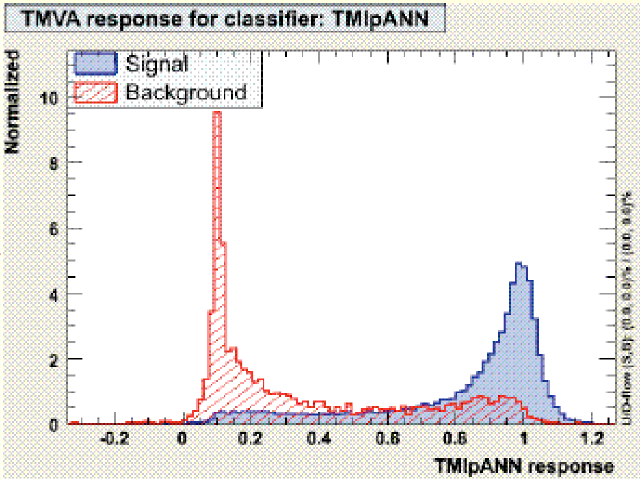
•Algorithm based loosely on leaning process in human brain

•Large datasets containing multiple variables trained against one another

•Iterative learning process begins

•Correlations between multiple variables compared between processes

•Multiple variables propagated into single discriminant



# Putting It All Together

- Have developed method to radically reduce QCD
  - What about other backgrounds?
- Must reduce Electroweak and Top backgrounds further
  - Have not taken full advantage of calorimeter measurements yet
- Neural network strategy worked well previously

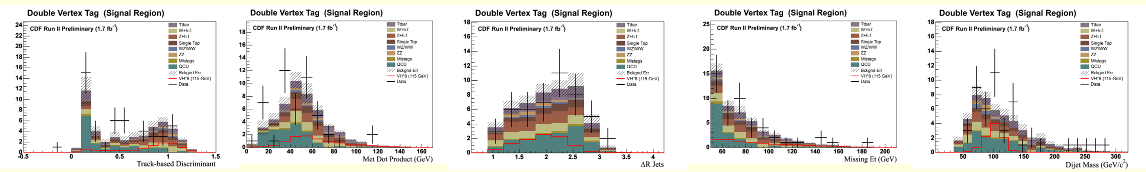
## Final Neural Net Discriminant

- •Study multiple quantities
- •Select variables showing separation (Higgs Vs Background)
- •Train NN with ZH/WH Vs. QCD/Top
- •Optimize NN configuration by adding one variable at a time
- •Continue until no improvement seen
- •5 final variables selected for NN

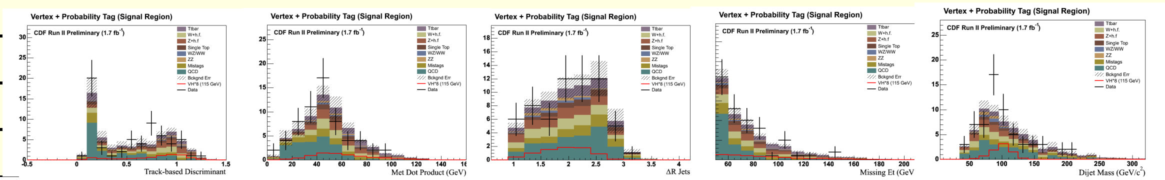
## Final Event Counts

| Background | Vtx + Prob Tag | 2 Vtx Tag |
|---|---|---|
| Mistagged l. f. | 8.3 +/- 2.4 | 1.5 +/- 0.3 |
| Top pair | 8.1 +/- 1.5 | 8.2 +/- 1.3 |
| Single top | 4.5 +/- 0.8 | 4.7 +/- 0.8 |
| W+h.f. | 8.8 +/- 3.8 | 6.9 +/- 2.9 |
| Z+h.f. | 8.2 +/- 3.6 | 8.0 +/- 3.4 |
| WZ/WW | 1.4 +/- 0.3 | 1.2 +/- 0.2 |
| ZZ | 2.0 +/- 0.4 | 2.3 +/- 0.4 |
| QCD Multijet h.f. | 20.7 +/- 10.4 | 15.6 +/- 8.6 |
| Total | 62 +/- 12.0 | 48.5 +/- 9.8 |
| Data | 62 | 48 |
| ZH+WH | 1.0 | 1.2 |

**Double Vertex Tag NN Inputs**



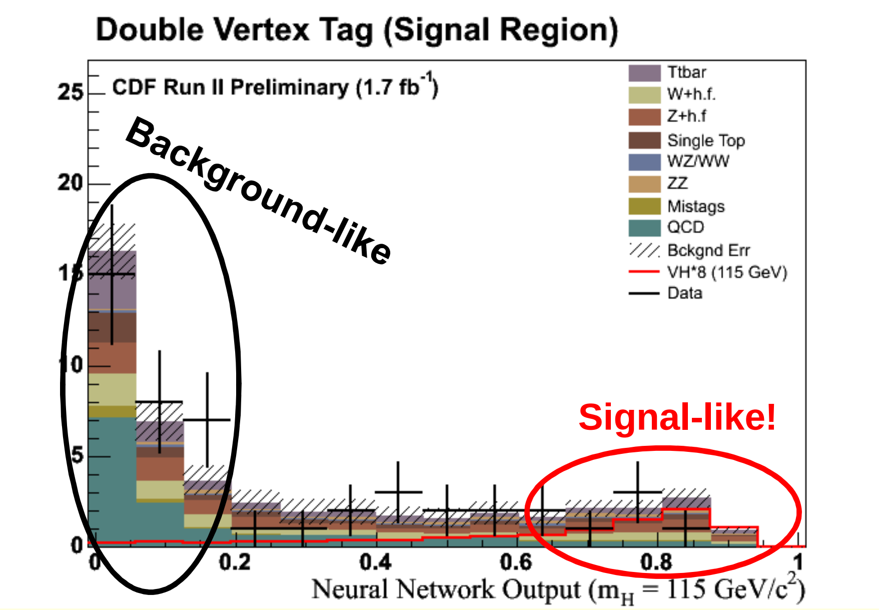

**Vertex + Probability Tag NN Inputs**

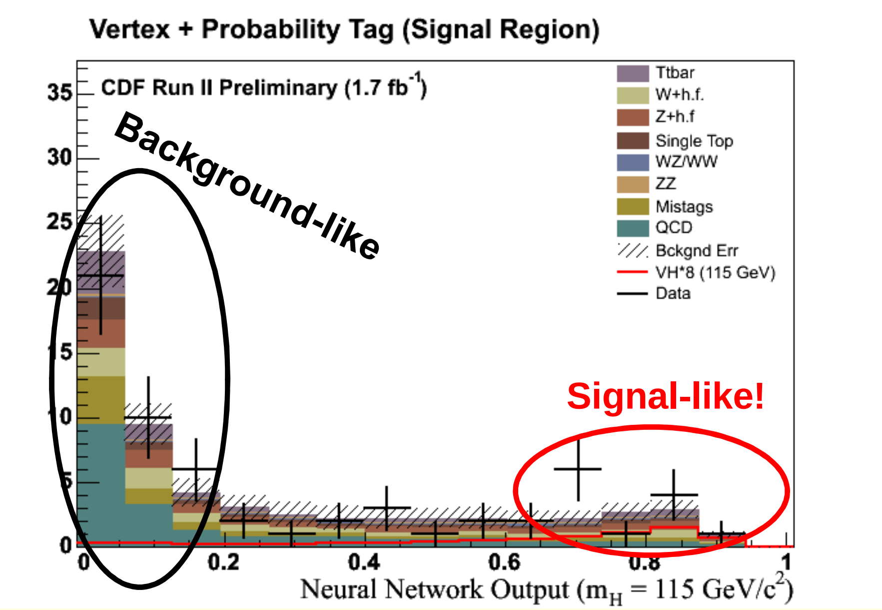


# Neural Network Output

- Now at the point where a measurement can be made!
- Add up Neural Network shape and event counts of all backgrounds
  - Expected shape and normalization for signal also
- Try to fit for Higgs signal in two separate tagging categories
  - Neural Network provides separation much greater than final event counts
- Compare data to background hypothesis
  - Look for significant deviations

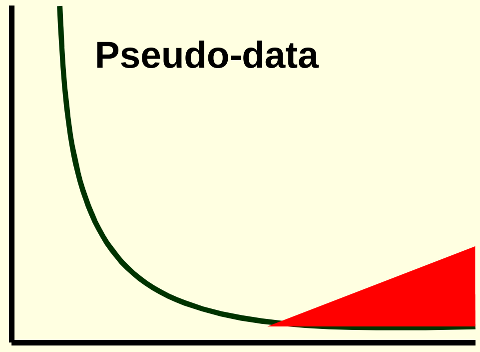
***Final Discriminating Distributions***



# Limit Calculations

- To extract a measurement, want to fit data to our various templates
  - How consistent is data with background hypothesis
- Run "pseudo-experiments"
  - Use templates for background and signal
  - Create pseudo-data from these
  - Fit to different possibilities
  - Background only
  - Signal + Background
- Vary amount of signal
  - Continually boost signal cross-sections
  - Signal-enhanced pseudo-data provides example of what actual signal in data looks like
- Likelihood ratio used as figure of merit
- If no signal is present, set a 95% Confidence Level limit
  - 95% certain that signal is not in data sample




**Systematics**

| Normalization | Shape |
| --- | --- |
| •40% W/Z+h.f. | •Jet Energy Scale |
| •50% QCD | •ISR/FSR Signal |
| •10-12% Top/Diboson | •QCD Model |
| •6% Luminosity | •Mistag Model |
| •9% b tagging | •Trigger Turn-on |
| •4% Trigger | |

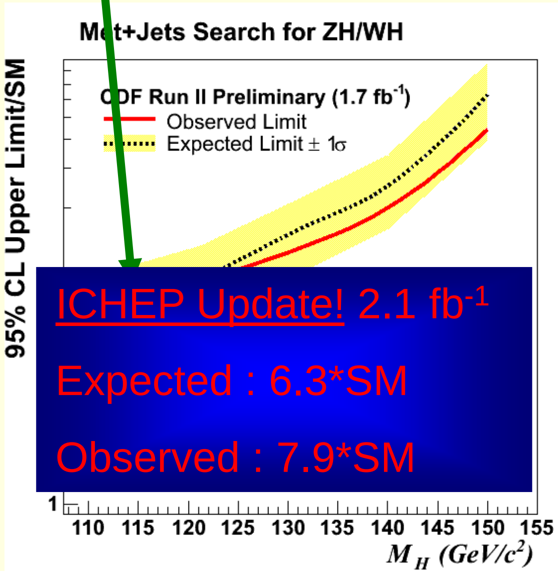
# Limits

- Expected 95% confidence level calculated considering all systematic and statistical uncertainties
  - One and two sigma “bands” calculated as well
- Observed limits are set using the actual data
  - Pseudo-experiments have determined ... experiment falls amongst thous... experimental outcomes
- If observed limit signifi... could be sign of ...
- Look at H...
- Expectati... that signal cross-secti... ndard model cross-section
  - Unfortunat... data tells us the expectation was accurate
- No signs of a signal in CDF data yet
- Have become closer to Standard Model expectation and developed large amount of knowledge which may be exploited further

However...

**σ(95% CL)/ σ(SM)**

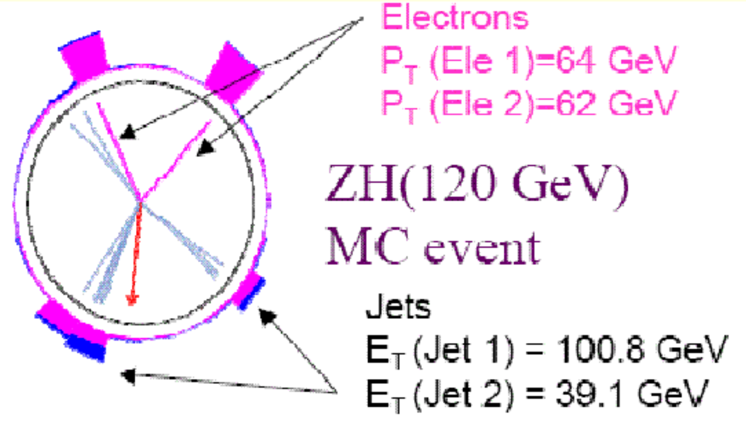
| Ma[illegible] | [illegible]ted | Observed |
|---|---|---|
| [illegible] | [illegible] | 9.6 |
| [illegible] | [illegible] | 8.0 |
| [illegible] | [illegible] | 9.5 |
| [illegible] | 15.3 | 12.8 |
| 140 | 25.1 | 20.0 |
| 150 | 63.3 | 44.3 |



# The ZH→llbb Channel

- This analysis has only exploited one mode of Higgs production at the Tevatron
  - Signal produced in Z to leptons channel small
- Are backgrounds large?
  - Two high energy electrons or muons
  - Distinct signature

No high energy neutrinos!




Electrons

| Sample | 2 Leptons | $Z$ Selected | $\geq$1 Jet | $\geq$ 2 Jets | 2 loose | 1 tight(!=2loose) |
|---|---|---|---|---|---|---|
| $ZH_{120GeV/c^2}$ | 0.83 | 0.76 | 0.73 | 0.63 | 0.13 | 0.25 |
| $t\bar{t}$ | 36.9 | 9.01 | 8.77 | 7.69 | $1.52 \pm .29$ | $2.91 \pm 0.56$ |
| $ZW$ | 46.3 | 40.8 | 25.89 | | | |
| $ZZ$ | 61.4 | 54.0 | 29.7 | | | |
| $WW2p$ | 33.5 | 7.93 | 4.36 | | | |
| $Z \to \tau\tau$ | 536 | 26.9 | 2.75 | | | |
| fakes | 1191 | 322.8 | 42.0 | | | |
| $Z^0 \to e^+e^-$ | 96,440 | 84,940 | 6943 | | | |
| ($b$ events) | 1019 | 908 | 209 | | | |
| ($c$ events) | | | | | | |
| (mistags) | Predicted mistags from data: | | | | | |
| Total | 98,340 | 85,400 | 7082 | 1673 | $7.36 \pm 1.56$ | $60.8 \pm 10.7$ |
| Data (1019 $pb^{-1}$) | 102,820 | 88242 | 6423 | 1794 | 6 | 54 |
| Negative Tags | Predicted: | | | | $0.44 \pm 0.04$ | $17.2 \pm 1.38$ |
| | Found | | | | 0 | 11 |

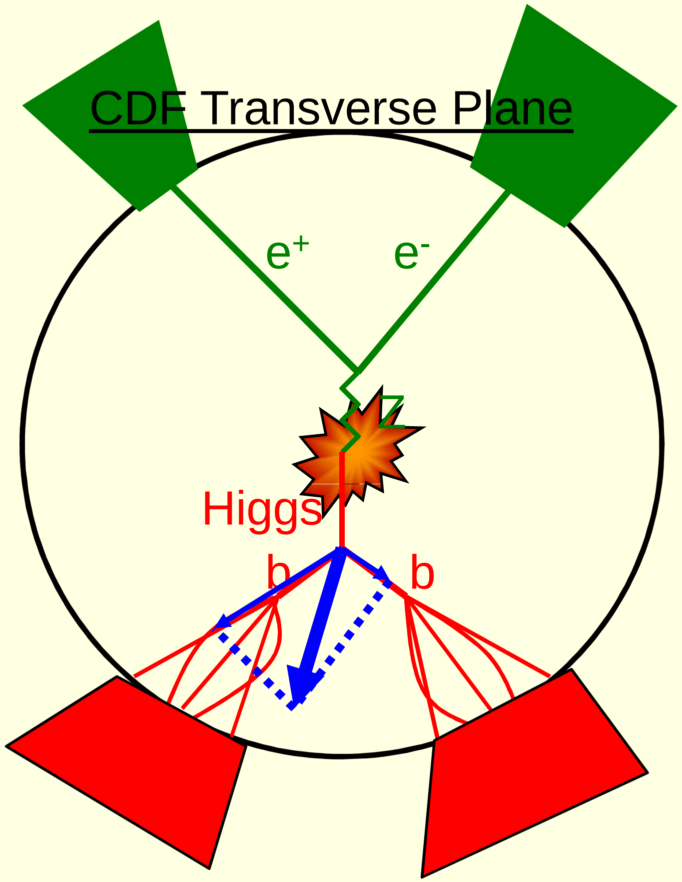
Muons

| Sample | 2 Leptons | $Z$ Selected | $\geq$1 Jet | $\geq$ 2 Jets | 2 loose | 1 tight (!=2loose) |
|---|---|---|---|---|---|---|
| $ZH_{120GeV/c^2}$ | 0.62 | 0.58 | 0.56 | 0.49 | 0.10 | 0.19 |
| $t\bar{t}$ | 29.3 | 7.0 | 6.9 | 6.00 | $1.32 \pm 0.27$ | $2.33 \pm 0.48$ |
| | | | | | | $0.51 \pm 0.10$ |
| | | | | | | $1.82 \pm 0.36$ |
| | | | | | | $0.020 \pm 0.004$ |
| | | | | | | 0.00 |
| | | | | | | $1 \pm 1$ |
| | | | | | | $35.1 \pm 7.0$ |
| | | | | | | $14.5 \pm 5.8$ |
| | | | | | | $8.2 \pm 3.3$ |
| | | | | | | $12.4 \pm 2.1$ |
| Total | 54,600 | 46,200 | 4320 | 1090 | $5.06 \pm 1.05$ | $40.8 \pm 7.1$ |
| Data (972 $pb^{-1}$) | 56,740 | 47,982 | 4128 | 1240 | 5 | 46 |
| Negative Tags | Predicted: | | | | 0.27 | $11.02 \pm 0.72$ |
| | Found | | | | 1 | 12 |

| Category | ZH | Bckgnd | $\frac{S}{\sqrt{B}}$ | $WH\ \frac{S}{\sqrt{B}}$ |
|---|---|---|---|---|
| Double Tag | 0.3 | 12.4 | .09 | .10 |
| Single Tag | 0.6 | 100.1 | .06 | .08 |

# Overcoming Low Signal Yield

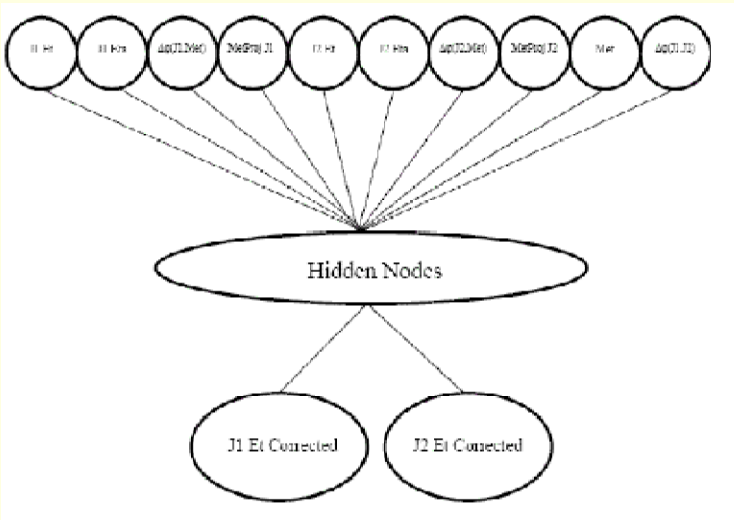
- All decay product of Z and Higgs directly measured
  - Places powerful constraints on system
- ZH event consists of Z recoiling against Higgs
- Z decay products directly measured in calorimeter and/or tracking chamber
  - Well measured
- Higgs decay products fragment
  - Less collimated
  - More difficult to measure
- Momentum conservation in transverse plane
  - Missing energy likely due to mismeasurement
- What if Met is projected onto jets?
  - May be able to improve energy resolution



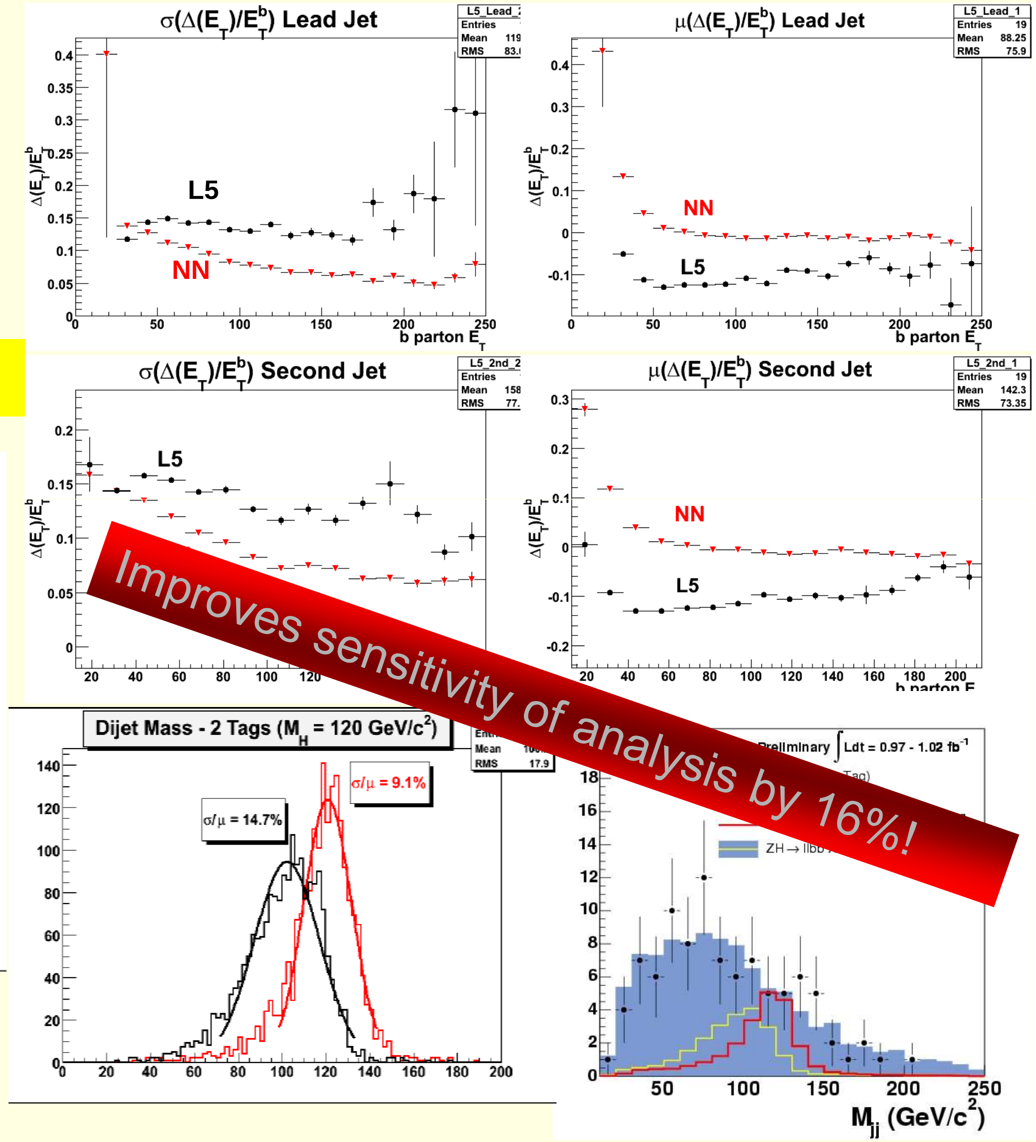
# Dijet Neural Network Corrections

- Develop correction function for jet energies
  - Use projected Met
  - Quantities associated with jets
- Want to combine information

Surprise! Another Neural Network



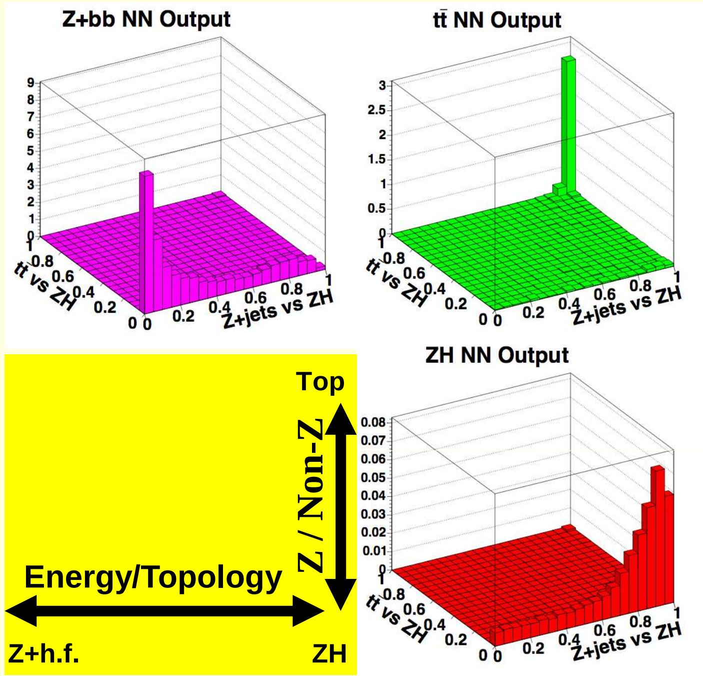

**Resolution** **Mean**



# Reducing different backgrounds

- Reconstructed mass powerful discriminant
  - However, more event info available
- Two major backgrounds to reduce
  - Top pair
    - More energetic
    - Met from neutrinos
    - No Z
  - Z+heavy flavor production
    - Less energetic
    - Similar final state
- Train NN in two dimensions to isolate different processes
  - Dramatically isolates top!
  - Greatly reduces Z backgrounds

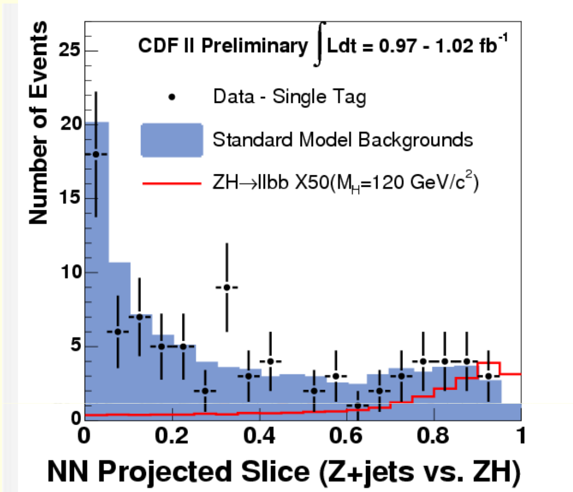
Separate in two dimensions

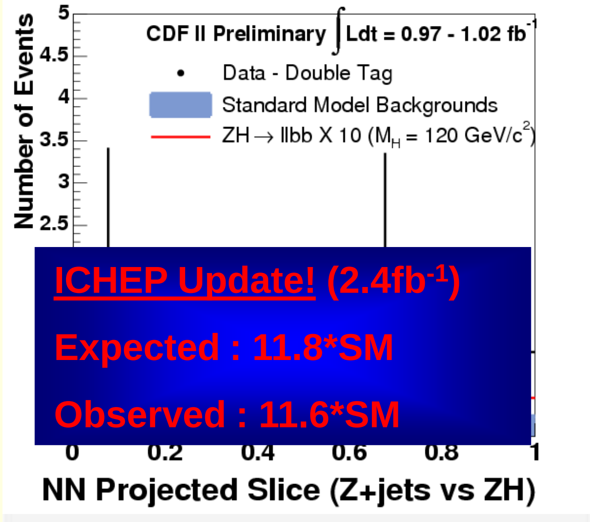


# Results

- Break data sample into single and double b-tagged categories
  - Improves sensitivity
- Look at data!
- A bit difficult to digest in 2D
  - Take slice of Z+jets Vs. ZH axis
- See agreement between data and background hypothesis
  - Calculate limits
- Set limit of 16*SM at 115 GeV/c$^2$
  - Result with 1 fb$^{-1}$ of data
- Remember raw signal production from before!

NN Output of Data




ICHEP Update! (2.4fb$^{-1}$)

Expected : 11.8*SM

Observed : 11.6*SM

**Comparable sensitivity despite tiny signal!**

| Process | XSect | BR | $N_{EV}$/ fb$^{-1}$ | 1 fb$^{-1}$ ExpectedLimit |
|---|---|---|---|---|
| WH→lνbb | 0.19 pb | 0.21*0.73 | 29 | 17*SM |
| ZH→ννbb | 0.11 pb | 0.20*0.73 | 16 | 15*SM |
| ZH→llbb | 0.11 pb | 0.07*0.73 | 6 | 16*SM |

# Combination

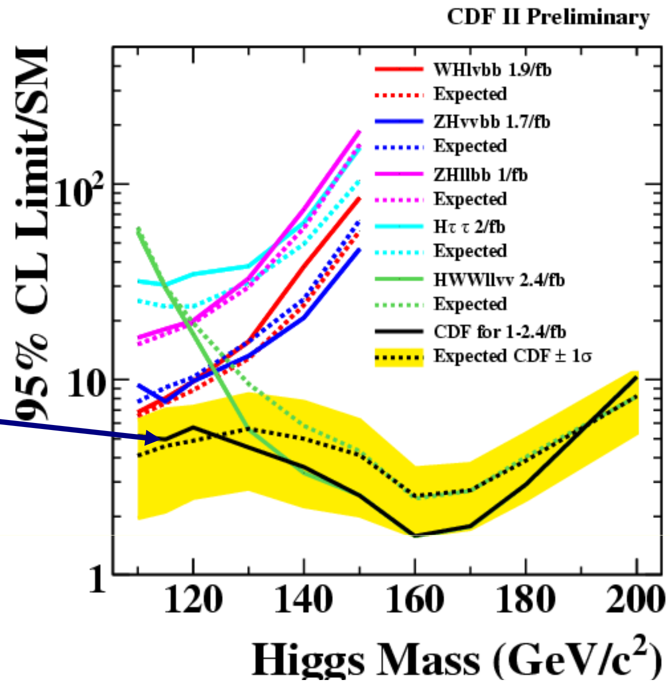
- There are several analyses contributing to the Higgs effort at CDF
  - Consider all analyses
  - Determine total limit on SM Higgs
- Combination of all CDF limits greatly increases sensitivity

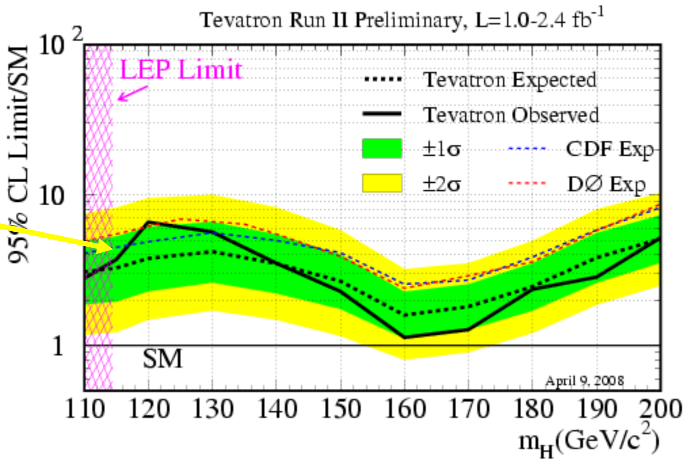
| CDF Limit | Obs (Exp) |
|---|---|
| 115 GeV/$c^2$ - | 5.0 (4.4) |

- In addition, statistical power of each analysis can be doubled!
  - Two Tevatron experiments
- Combination of CDF results with D0 push limit even closer to SM expectation

| Tevatron Limit | Obs (Exp) |
|---|---|
| 115 GeV/$c^2$ | 3.7 (3.3) |

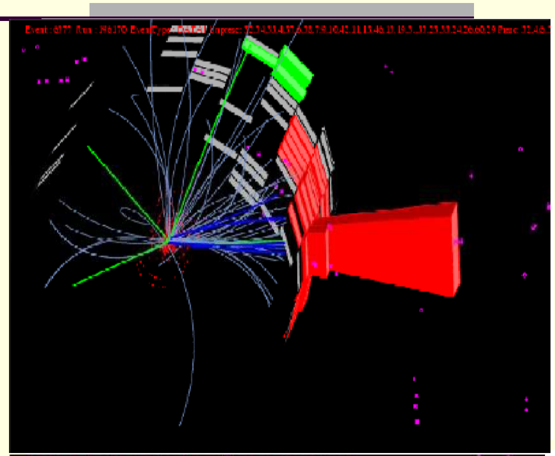
- Must squeeze out every ounce of sensitivity in each analysis at each experiment!

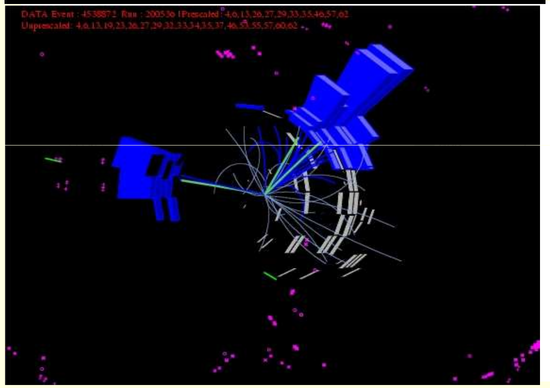


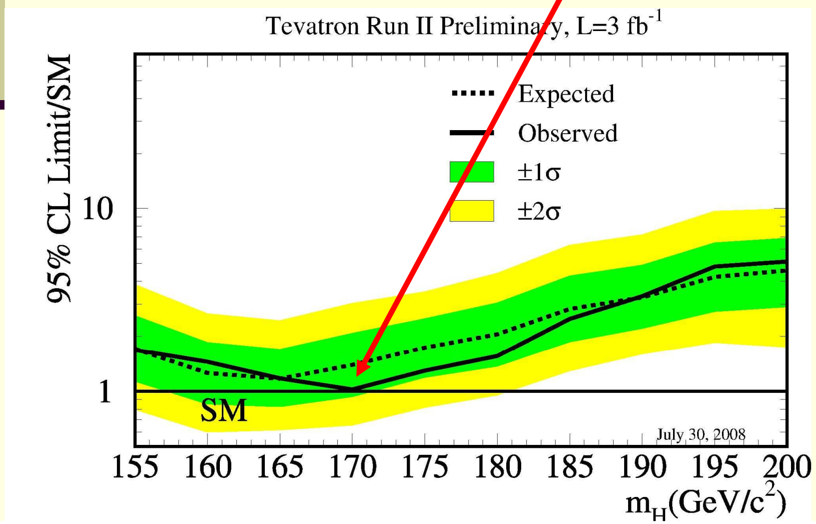



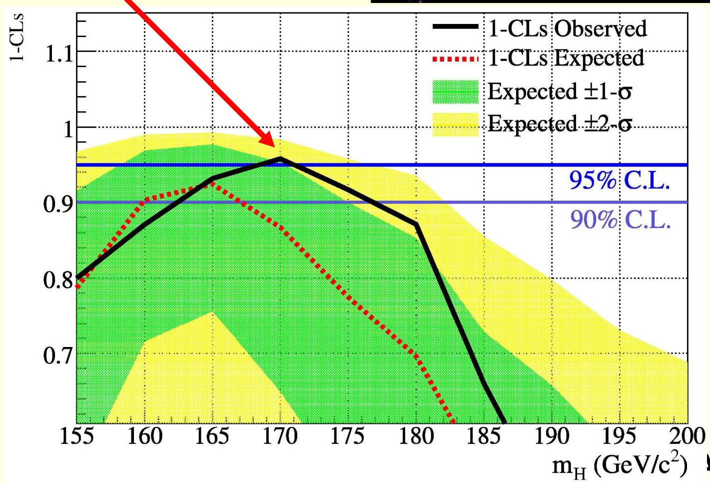
# Some Intriguing Hints

- No smoking guns in data sample
- Have identified a couple of candidates with high NN values
- S:B less than 1:10
  - Both events contain two tagged jets
  - Both events contain a muon in at least one jet
- CDF and D0 combination presented at ICHEP has excluded Higgs mass of 170 GeV/$c^2$
- Many signs pointing to lower mass Higgs!



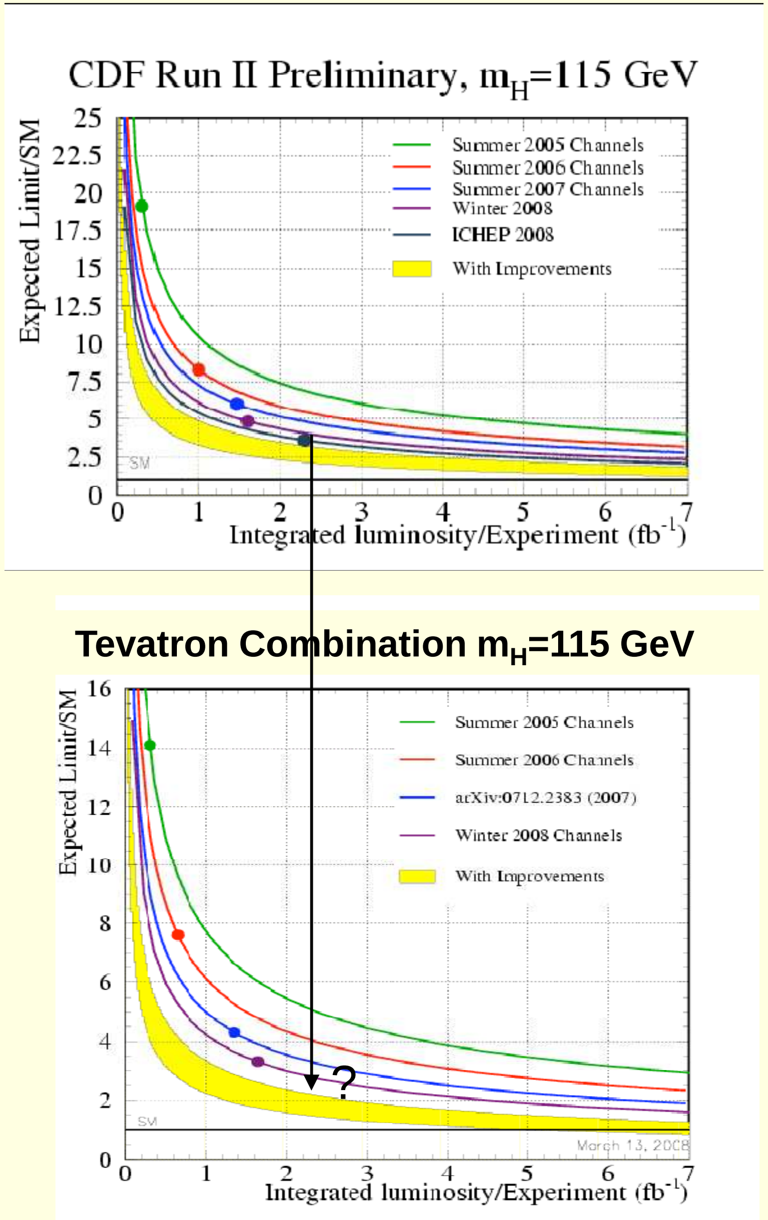




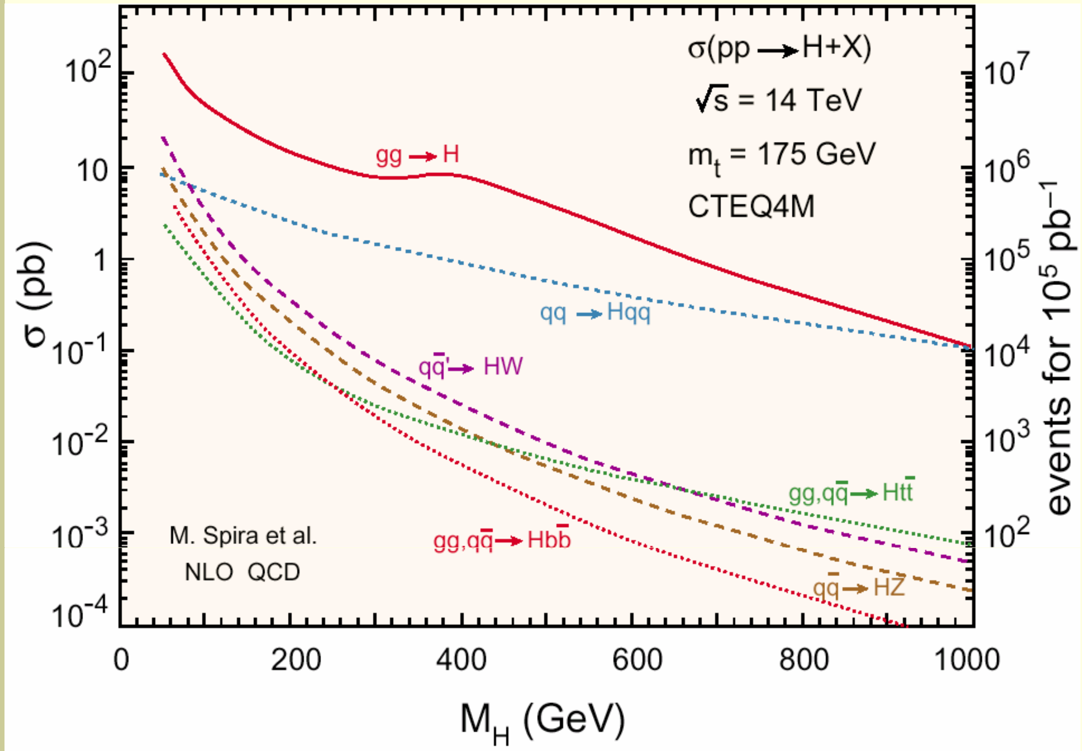
# Conclusion

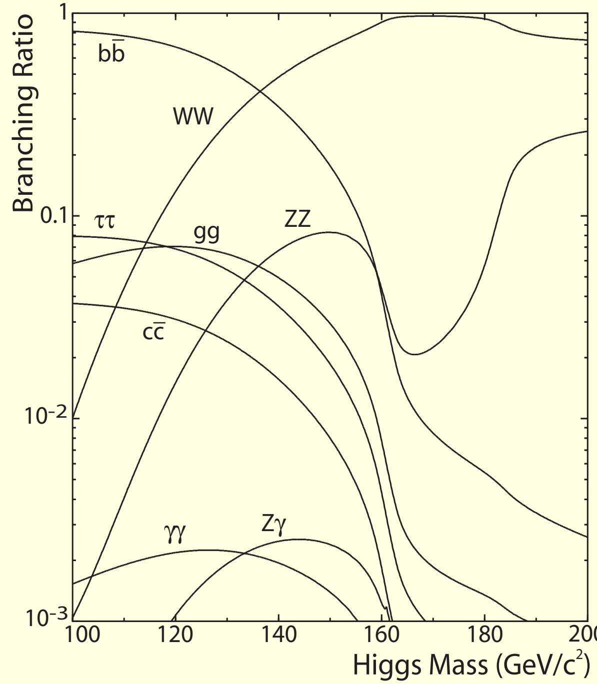
- The Standard Model Higgs boson predicted to exist by electroweak theory
  - Provides massive W and Z particles with mass
  - Theory has made predictions which were later confirmed experimentally
- Presented analysis designed to search CDF data for this elusive particle
  - Focus on the Met+bb signature
  - Developed several analysis techniques to reduce background and isolate signal
  - Set limit of 8.0*SM with 1.7 $fb^{-1}$ of data, consistent with expectation
- Additional sensitivity from $Z \rightarrow ll$ decays
  - Improved energy resolution
  - 2D Network
  - Limit of 16*SM in 1 $fb^{-1}$
- Have combined analyses with overall Tevatron effort to set current limit of 3.7*SM on Standard Model Higgs
  - Updated combination soon!



# Backups

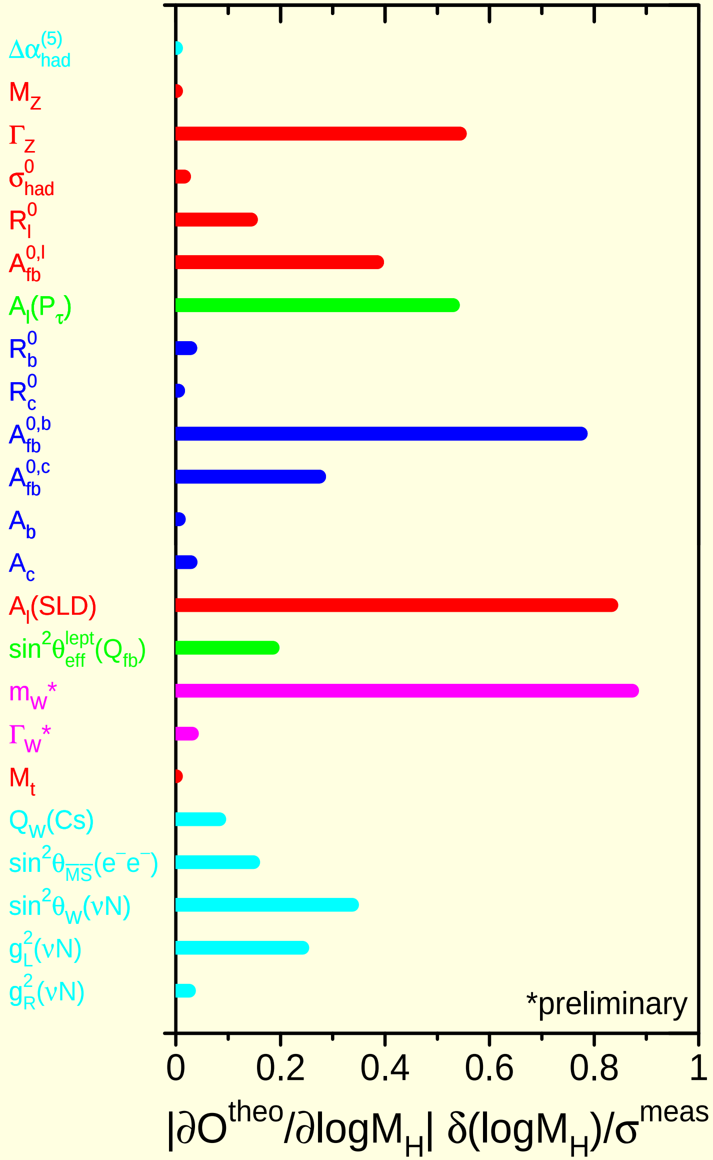
# Higgs Searches

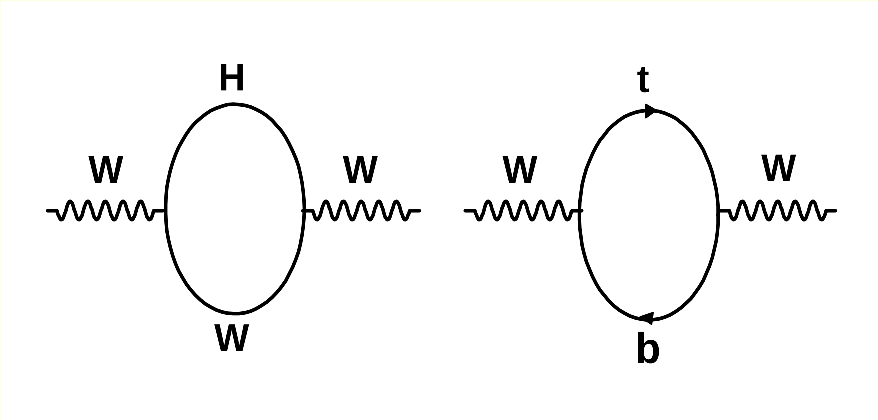



- Large beam energy changes production landscape
- LHC should be able to probe Higgs masses up to 1 TeV
  - Different techniques depending on mass
- Have many ways to search for Higgs in low mass region

# Standard Model quantities used in fit




$$M_W^2 = \frac{\pi\alpha}{\sin^2\theta_W\sqrt{2}G_\mu}(1+\Delta r)$$

$$\Delta r \sim \frac{3G_\mu}{8\pi^2\sqrt{2}}M_{top}^2 + \frac{2G_\mu}{16\pi^2}M_W^2\left[\frac{11}{3}\ln\frac{M_H^2}{M_W^2} + \cdots\right]$$