# Associated Higgs boson production in events with MET and b-jets at CDF

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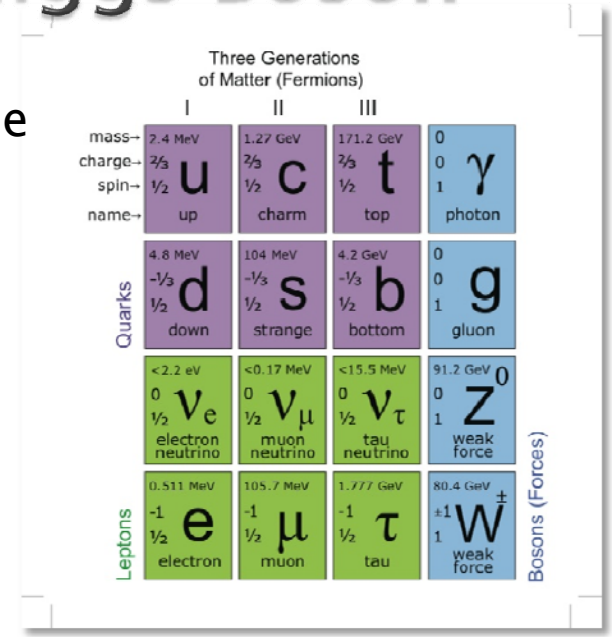
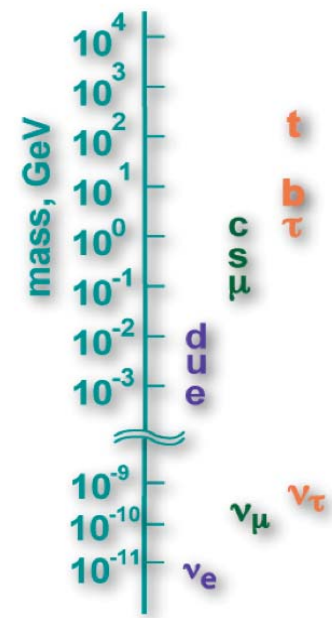
# The Standard Model and the Higgs Boson

- Quarks and leptons interact via an exchange of force carriers:
  - Gluons and Electroweak boson: g, $\gamma$, W, Z
  - A very diverse mass spectrum of particles in SM

- Gauge theories predicts that all gauge bosons and fermions are massless!
  - Putting masses by hand breaks gauge invariance
  - The theory becomes not renormalizable
  - Symmetry must be spontaneously broken

- Most economic solution in SM: Higgs mechanism
  - Self-interacting scalar field $\Phi=(\Phi^{+},\Phi^{0})$
  - Non-zero vacuum expectation value breaks the symmetry
  - Three massless Goldstone bosons: absorbed to give mass to $W^{\pm}/Z^{0}$
  - One scalar degree of freedom is left over: the Higgs boson
  - The mass of the Higgs boson is not determined by theory



# The searches for the Higgs boson

- The Higgs mechanism is testable in experiments
  - Direct observation of the Higgs boson is needed
  - The interactions of the Higgs boson are predicted by theory, but not its mass

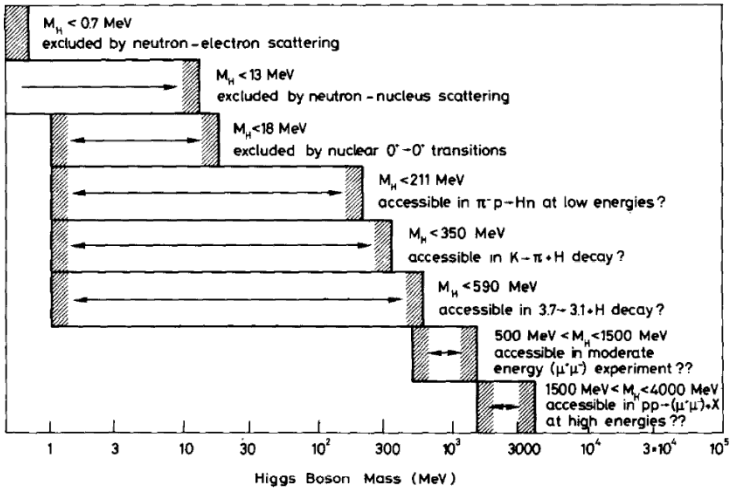
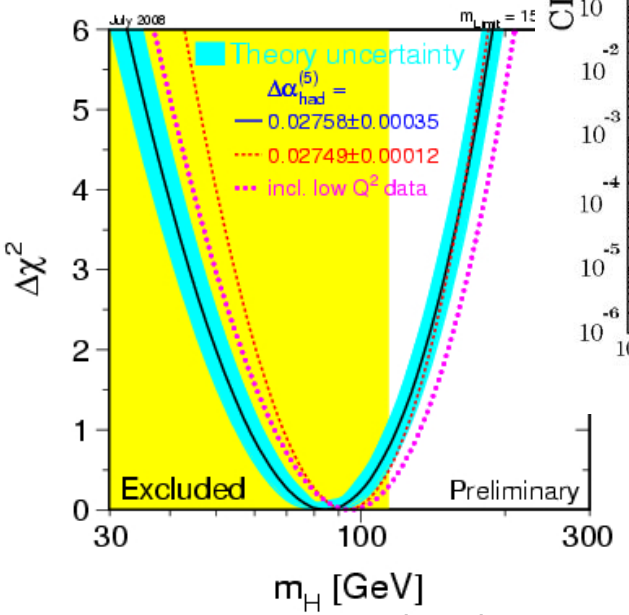
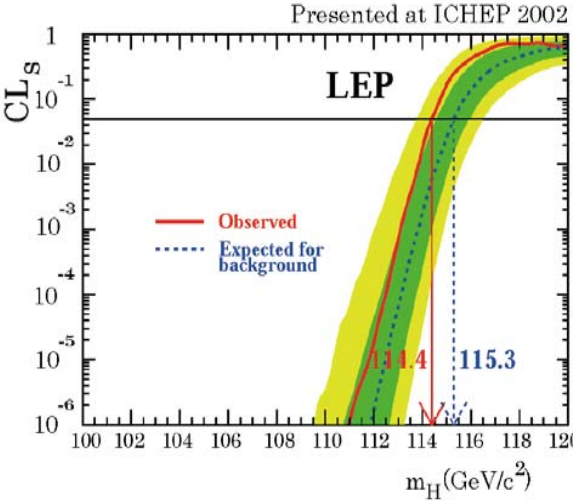



Fig. 3. Present and possible future limits on the Higgs boson mass.

- Searches for the Higgs boson in 70's–80's
  - Before the LEP era searches were sensitive to $M_H \lesssim 5$GeV
- LEP provided the most stringent bounds for SM Higgs: $M_H > 114.4$GeV



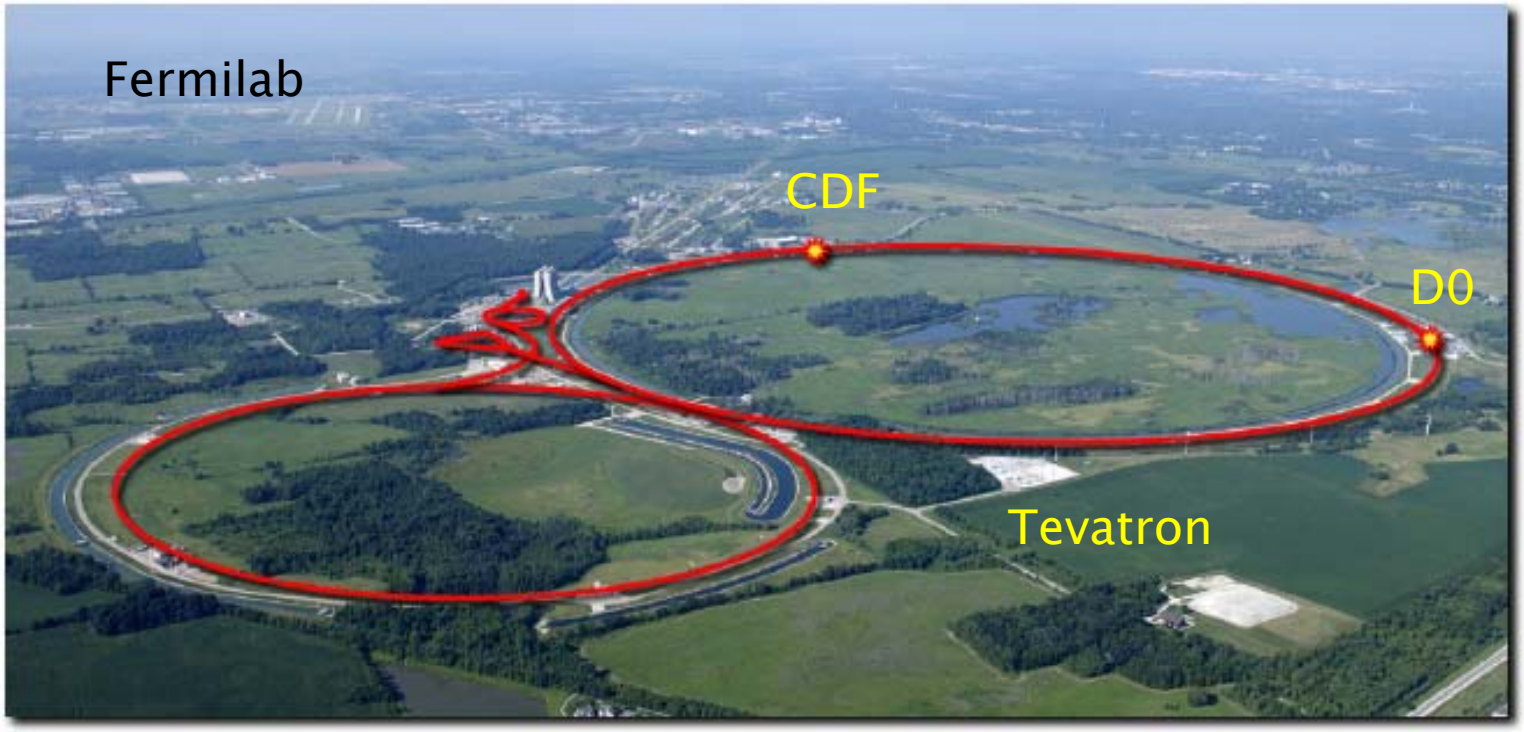




- Indirect searches:
  - Constraints from fitting EW data
  - $M_H = 84^{+34}_{-26}$ GeV
  - $M_H < 154$GeV at 95%CL
- Indirect constraints provided first hints of top mass before discovery
  - Predicted to be 180±12GeV

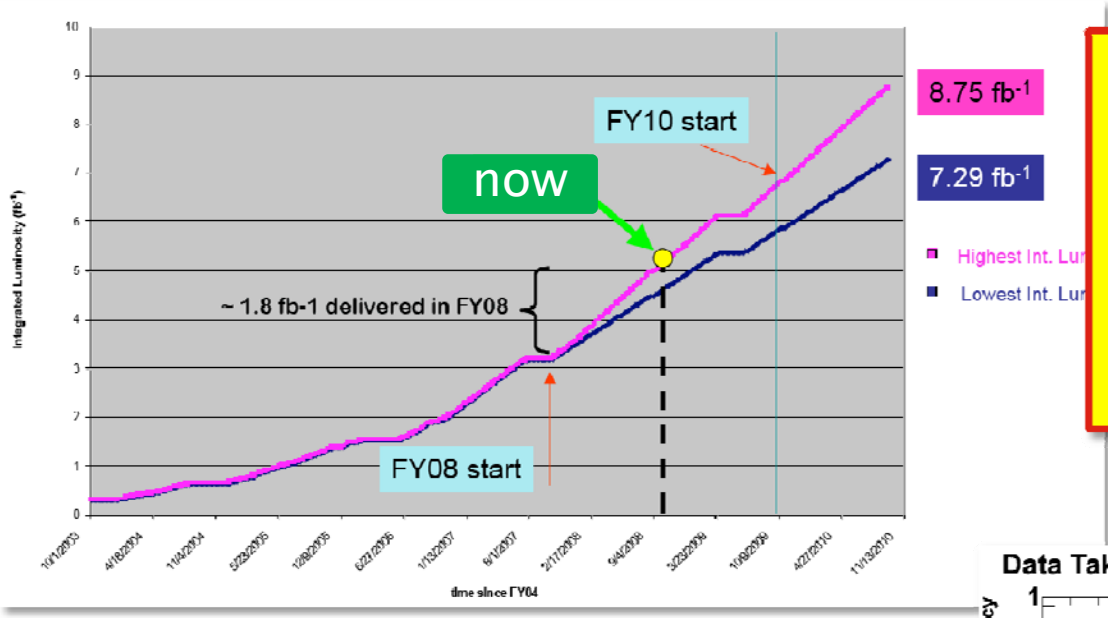
# Tevatron

- The only machine capable to directly probe the Higgs sector above LEP limit
  - Proton-antiproton collisions at 1.96 TeV center-of-mass energy
  - Reached the design luminosity in the end of 2006: $2\times10^{32}$ $cm^{-2}s^{-1}$
  - Keep surpassing the design goals: $3.5\times10^{32}$ $cm^{-2}s^{-1}$ achieved Nov 26th 2008

- Two-multipurpose detectors: CDF and D0
  - Well understood machines, stable operations

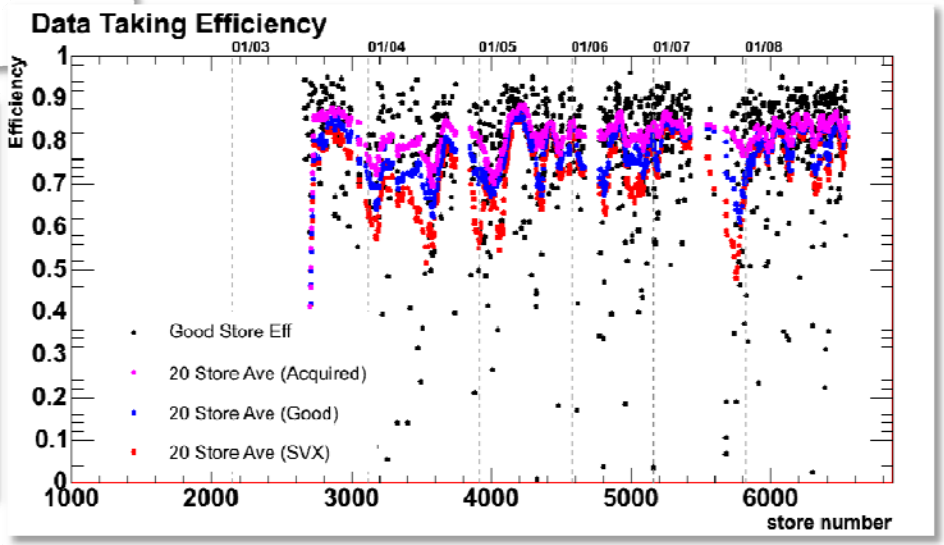


# Tevatron performance



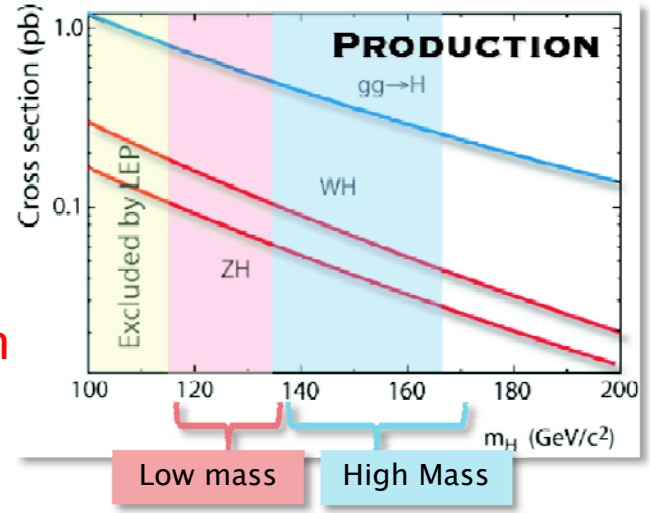

- Expect to have up to almost 9fb$^{-1}$ at the end of 2010
- More than 4fb$^{-1}$ available now on tape
- 2.1fb$^{-1}$ used in the following result

- CDF data taking efficiency ~85-90%
- Increased inst. Luminosity
  - Good for physics
  - Bad for triggers
- Recently upgraded CDF triggers to accommodate for higher rates



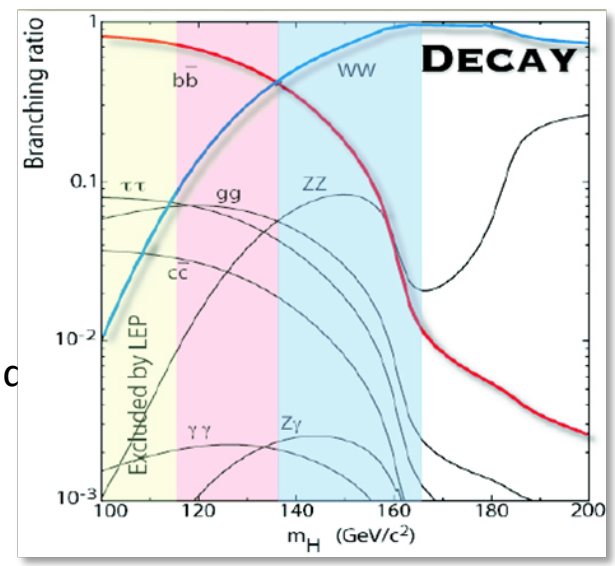
# SM Higgs production at Tevatron

- At the Tevatron the most probable production mode for Higgs is by gluon fusion
  - For $M_H \lesssim 135$ GeV: low sensitivity, QCD bb production is a huge and irreducible background.
  - For $M_H \gtrsim 135$ GeV: dominant decay is to $W^+W^-$:, most sensitive if using the leptonic decays of W's



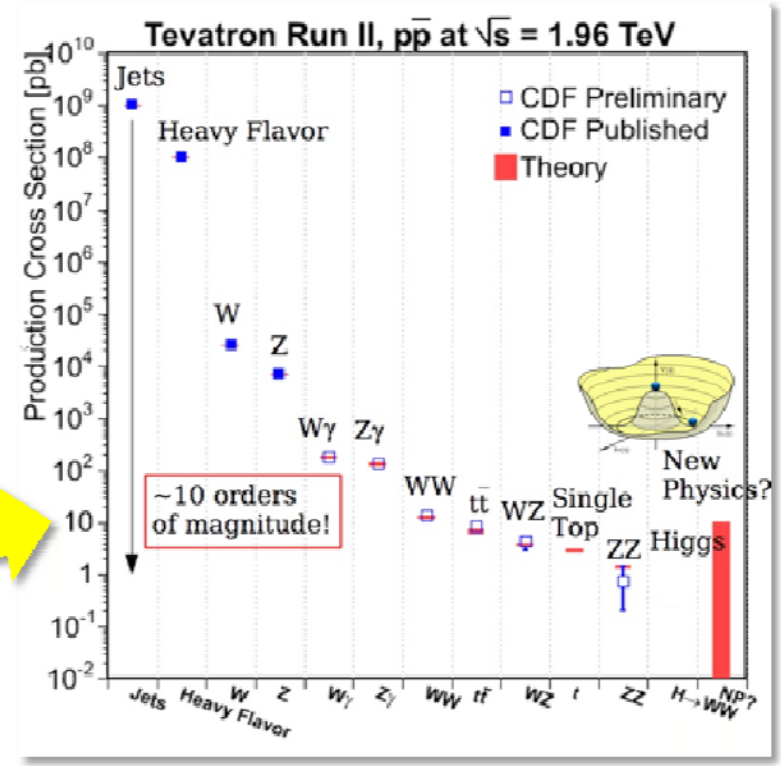

- Next most frequent mode: associated production
  - Decay products of W/Z bosons: separate signal from backgrounds
  - Focus of the rest of the talk is on this mode

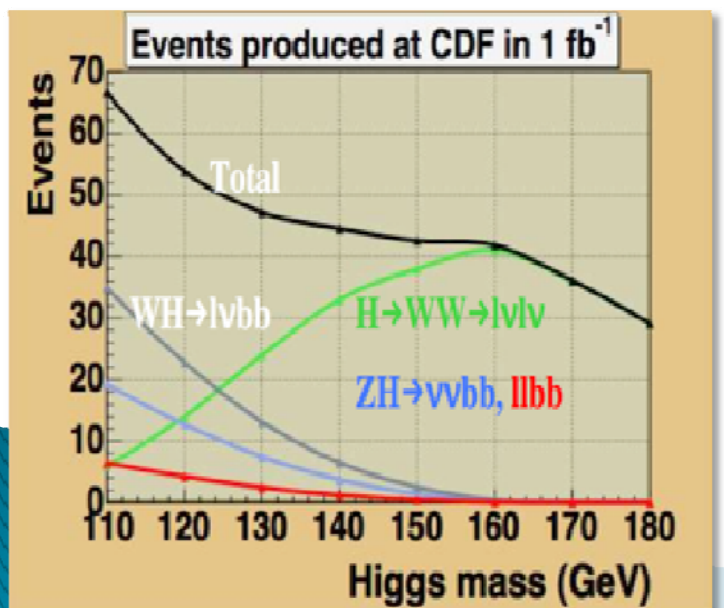
- Require the W/Z signature to improve S/B
  - Z→ll: fully reconstructed final state, low σXBR
  - W→lν: golden channel, high σXBR
  - W/Z→MET: various W/Z decay modes, large backgrounds
    - Z →νν, Z→(ll), W→(l) ν
  - W/Z→qq': fully hadronic, largest σXBR, huge QCD backgroun



# The challenges of the Higgs searches

- Hadron colliders: most promising for discovery
  - A wide range of energies is available at collision
  - Challenging experimental environment
  - QCD production: orders of magnitude higher than signals
- Many background processes are not yet well-measured/understood
  - Continuously reaching new landmarks
  - Single top evidence.
  - Observations of diboson production: WW, WZ, ZZ
  - Production of h.f. jets in association with W/Z
- Higgs boson production is **very rare**!

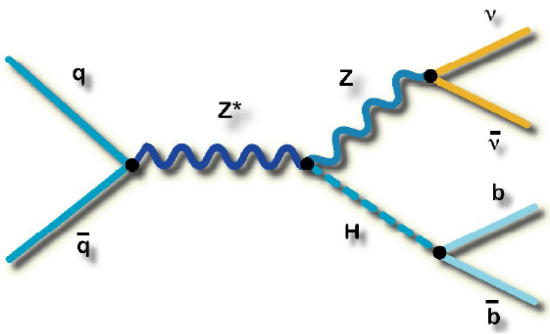


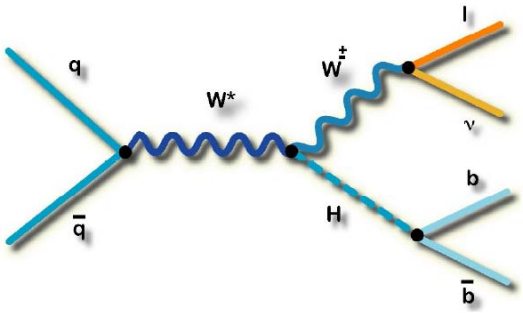

- Only a handful of Higgs events is produced
  - Need to fine-tune analysis for specific modes
- Still, single channels are not sensitive alone
  - A combination of results in various **channels** and BOTH CDF and D0 **experiments** is necessary

# The $\not{E}_T$+jets channel

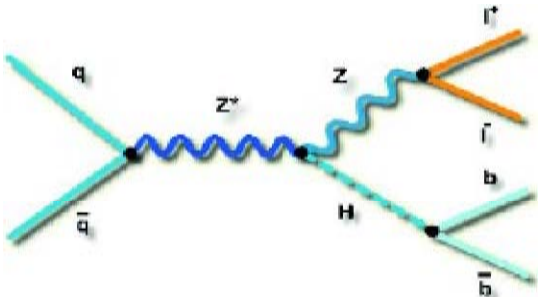
- Acceptance to various decay modes:
  - Large σXBR for ZH→ννbb: about 16 events per $fb^{-1}$
  - Events in WH→lνbb where the charged lepton is missed: about as many events as in ZH→ννbb
  - Additional (*small*) acceptance to llbb mode




- Same signature for various decay modes of the *W*
  - Non-identified muon+neutrino: MET
  - Non-isolated electron+neutrino: jet+MET
  - Hadronic tau+neutrino: jet+MET

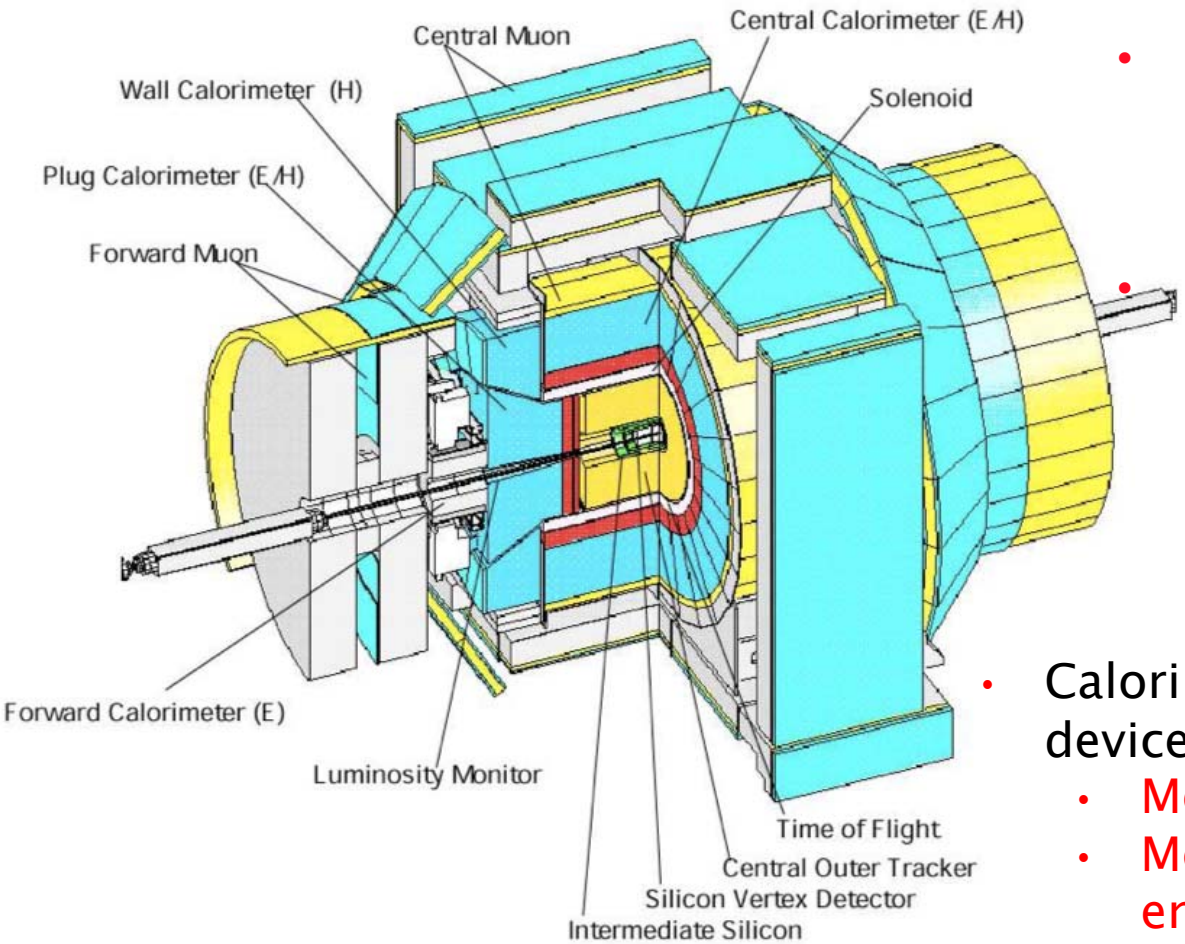



- *b*-quarks from the Higgs decay
  - Detected as jets: collimated sprays of hadrons
  - Identify using *b*-tagging algorithms




- No well-identified leptons
  - QCD contribution **huge**!
  - The information about the vector boson is **completely lost!**
  - The same signature can be mimicked by many SM processes

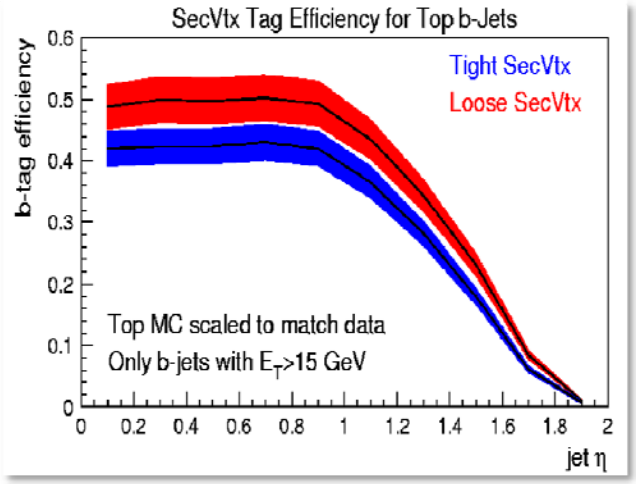
# The CDF detector

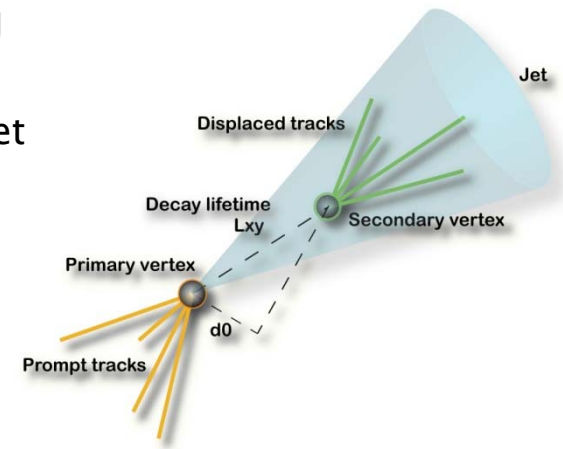



- Tracking:
  Drift chamber $|\eta|<1$
  measure charged particle $P_T$
- Silicon tracker allows precision vertex detection $|\eta|<2$
  - Identify *b*–decays
- Calorimeter split in EM and HAD devices $|\eta|<3.6$
  - Measure the energies of jets
  - Measure the amount of missing energy
- Muon chamber outside calorimeter
  - coverage $|\eta|<1.5$

# *b*–tagging in CDF

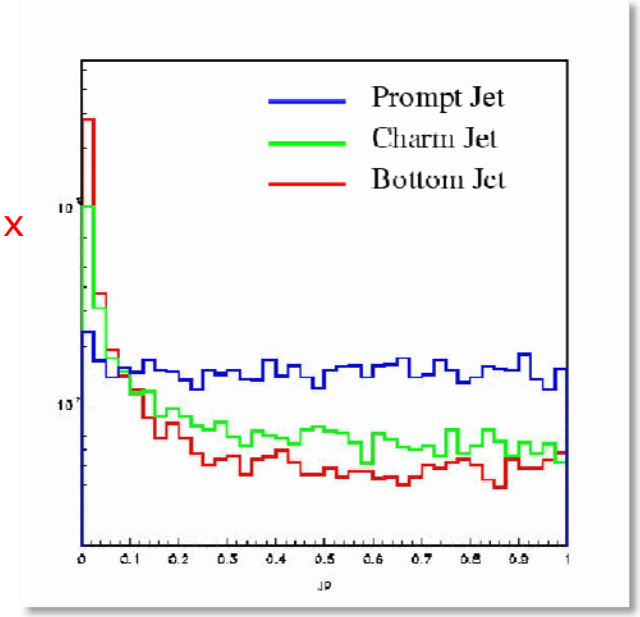
- SecVTX: *b*–quark can be identified due to the long lifetime of the B hadrons:
  - identification through search of a secondary vertex within a jet




- *b*–tag eff: ~40–50%
- fake rate: ~0.5–1.5%

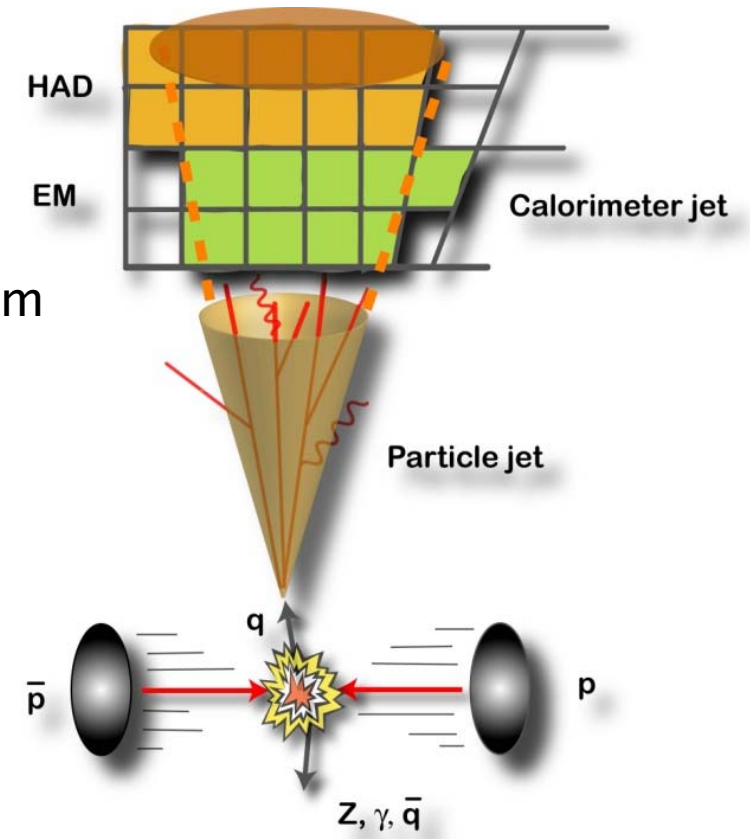
- JetProb: tagging probability algorithm
  - Probability that observed set of tracks is from a primary vertex
  - Variable operating point
  - *b*–tag eff: ~50% used in this analysis, fake rate ~5%

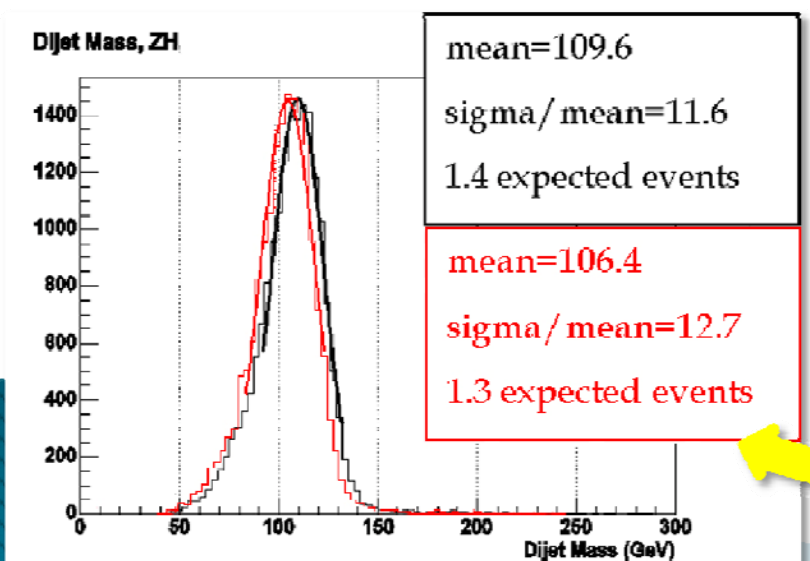



- Complimentary algorithms
  - Use both to maximize the selection efficiency

# Jet reconstruction at CDF

- Quarks and gluons are detected in calorimeters as collimated sprays of hadrons
- The CDF Seeded Cone clustering algorithm is used with a jet cone of radius 0.4
- Jet energy scale known at 3-5%
- Cracks in the calorimeter
  - Underestimate the jet energy



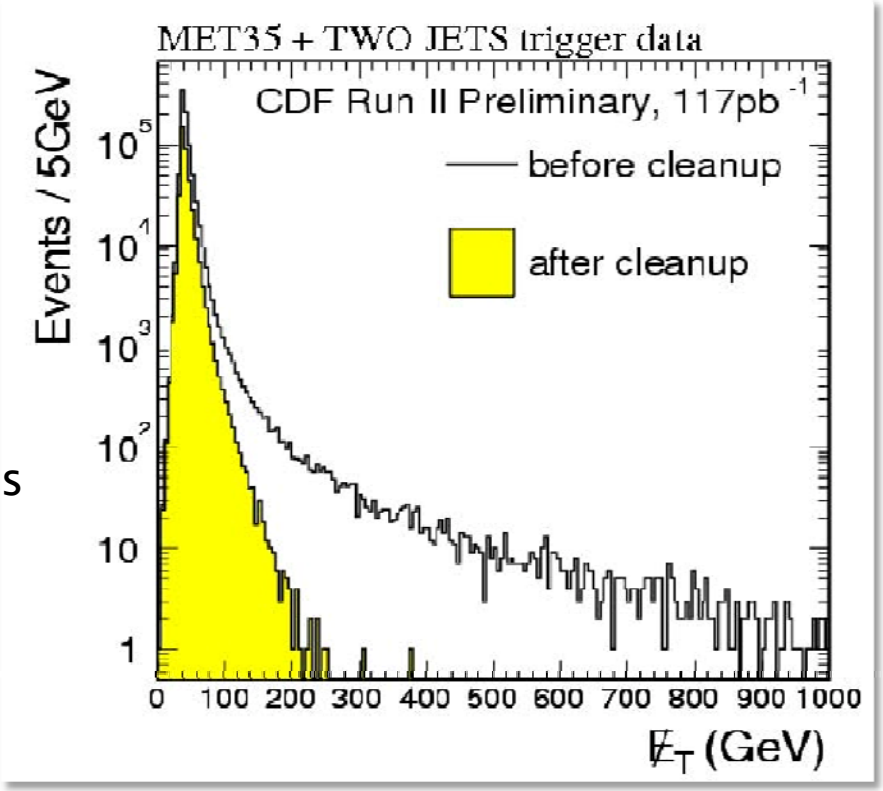

- Jet energy resolution limited
  - Driven by HAD calo: 80%/$\sqrt{E_T}$
- Use tracking information
  - Track resolution is far better
  - 10% improvement in Mjj resolution

New at CDF

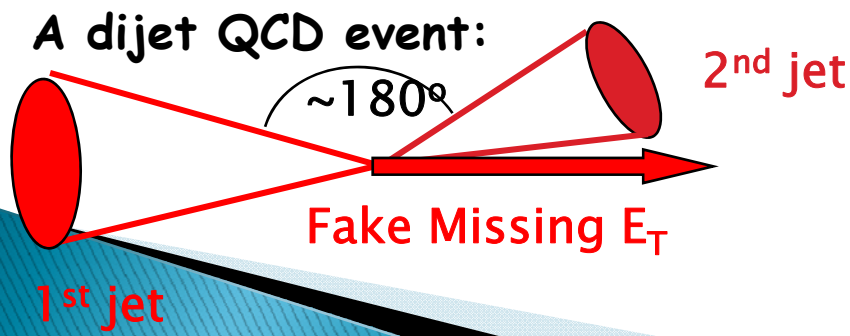
# Missing $E_T$ reconstruction

- Reconstructed Missing $E_T$ has various origins:
  - undetected particles (*neutrinos, semi-leptonic b-decays*)
  - beam/detector effects (*un-instrumented regions, beam halo muon*)
  - mis-measured jets faking Missing $E_T$

- Mis-measured jets in QCD dijet events can cause an apparent large MET
  - The largest backgrounds because of huge cross-section




- Cleanup cuts help eliminate fake MET



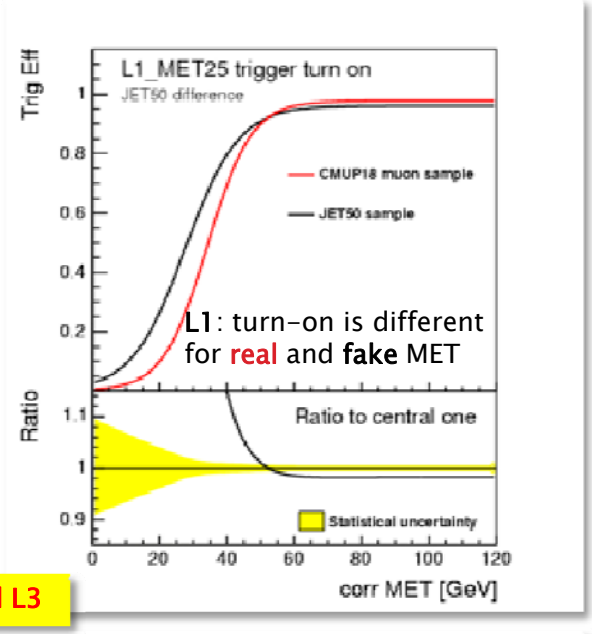
# Triggering on MET

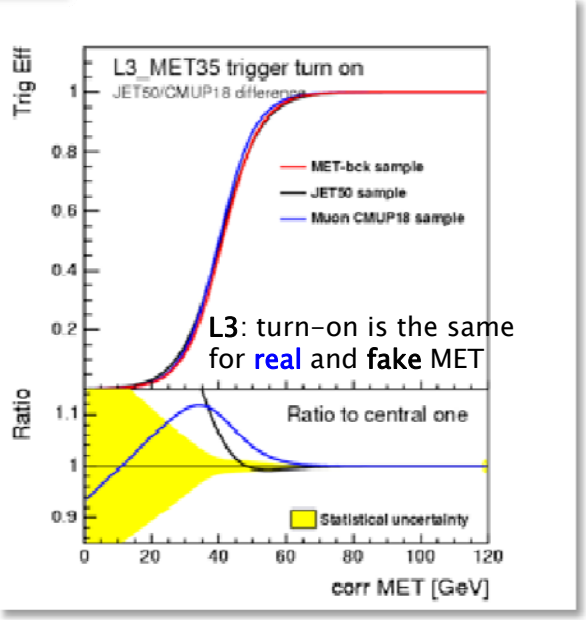
- Choose a trigger to **efficiently** collect interesting events:
  - Level1: L1_MET>25 GeV
  - Level2: Two clusters with ET>10 GeV
  - Level3: L3_MET>35 GeV
- Trigger efficiency depends on:
  - Offline corrected MET and jet $E_T$'s: $\varepsilon(1^{st}$ jet $E_T$, $2^{nd}$ jet $E_T$, MET$)$

Determined by L2

Function of L1 and L3

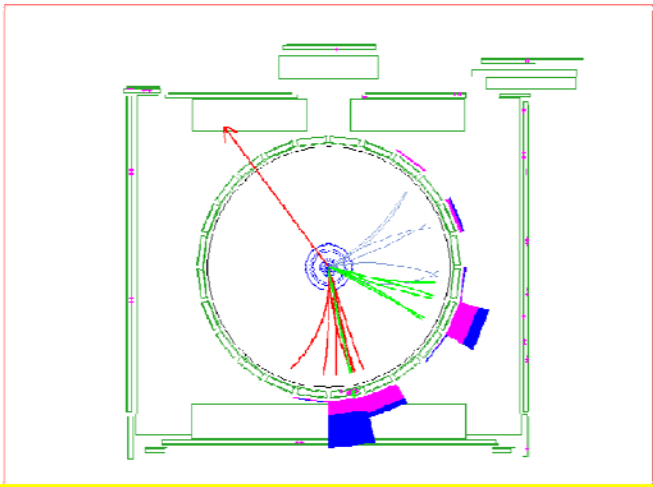
- Select a phase space where the Level2 is fully efficient:
  - $1^{st}$ jet $E_T$>35 GeV
  - $2^{nd}$ jet $E_T$>25 GeV
  - Level2 is now fully efficient
  - Express trigger efficiency as a function of MET alone
- MET reconstruction at Level1 is not very reliable
  - Large systematic uncertainty at low MET values: keep **MET>50 GeV**
  - The upgraded CDF trigger makes Level3 calorimeter resolution available for the Level1 and Level2: better reconstruction



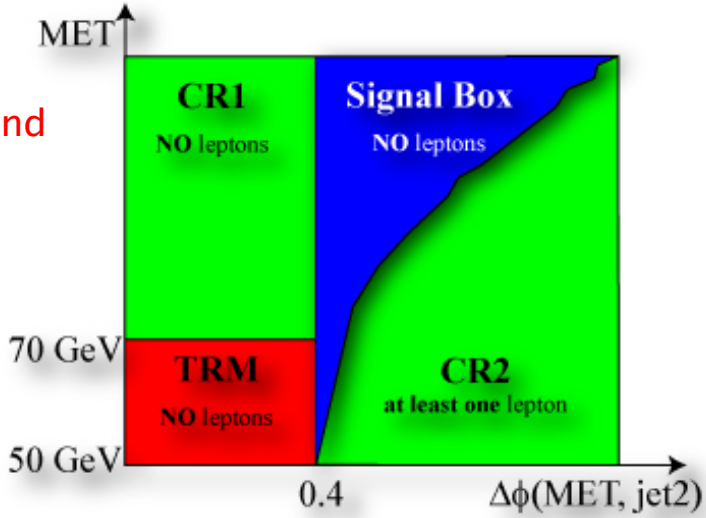
# The search strategy

- Interested in events with:
  - High MET: "*signature* " of the missing W/Z bosons
  - Low jet multiplicity:
    - two jets from the decays of the Higgs
    - additional jet from initial/final state radiation
    - electron/tau faking a jet
  - No identified leptons: a sample independent from channels with an identified lepton



A sample Higgs event with MET+jets

- Perform a statistically unbiased search:
  - Define a set of Control Regions and a Signal Region
  - Check the background modeling in the Control Regions
  - Signal Region : increase signal acceptance, low background
  - "*Open the Box*" to perform the measurement

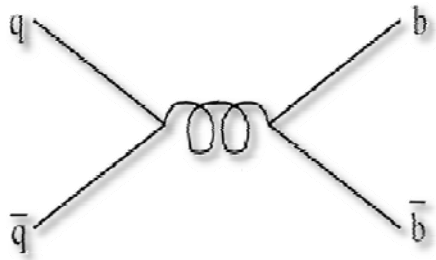


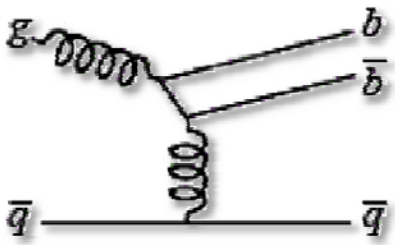

- Seek for a sign of Higgs in the Signal Region
  - Claim a discovery if signal is found
  - Set 95% C.L. upper limits on Higgs boson production cross-section

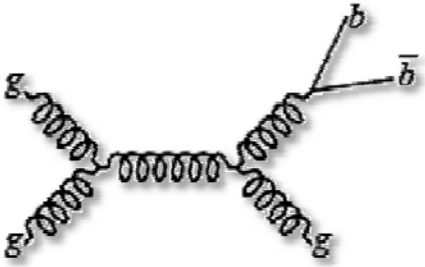
# The data-sample and its features

- Due to the signature, many processes contribute:

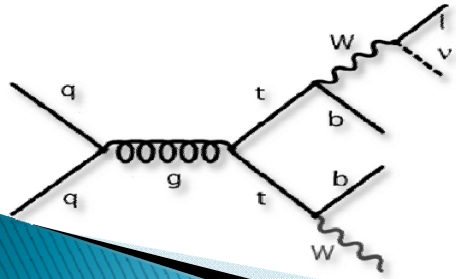
- QCD multijet production: <u>largest background</u>
  - Cross-section is $10^9$ times larger than signal
  - Fake MET from mismeasured jets
  - Semi-leptonic b-decays

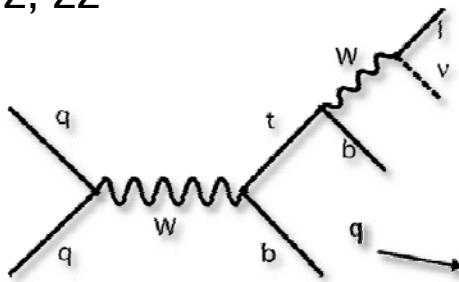


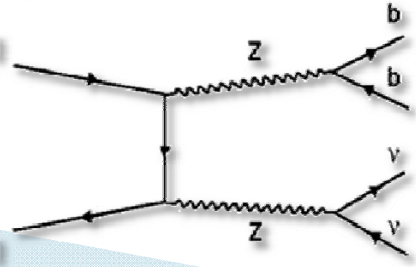



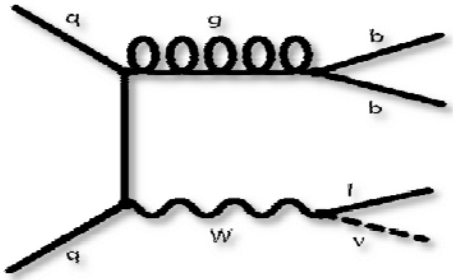




  - Events with real MET
    - Top pair and single top production: energetic jets and MET from W's
    - W/Z associated production with jets: MET from missed leptons
    - Diboson: WW, WZ, ZZ



# Baseline selection

- Require orthogonality in lepton cuts to channels with identified lepton
  - Various channels can be combined as statistically independent

- Require low jet multiplicity, 2 *b*–jets from Higgs
  - Increase acceptance by allowing an additional jet, maybe coming from:
    - Initial/Final state radiation
    - electron or tau reconstructed as a jet

New at CDF

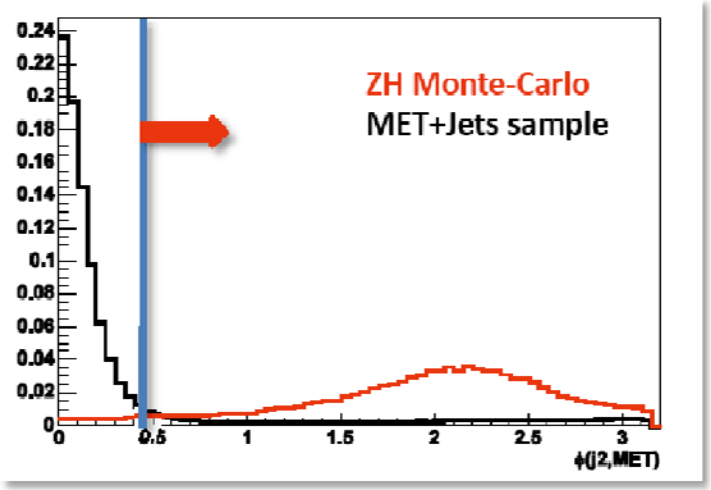
- To avoid the region of trigger turnon
  - 1st jet $E_T$>35 GeV
  - 2nd jet $E_T$>25 GeV
  - $\Delta R$(1st jet, 2nd jet)>1.0: avoid jet merging at L2
  - Missing $E_T$>50 GeV

- Trigger driven requirements result in a loss of 50% signal
  - Devise a sophisticated event selection: keep most of the signal, remove most of backgrounds
  - The S/B after this selections is ~1/20,000
  - Analysis with lepton usually have a "*reasonable*" S/B after basic requirement: events with leptons are much more rare…

# Removing the QCD background

- Main background source is <u>instrumental</u>
  - QCD events with mismeasured jets will appear as events with high MET

- Requiring MET and jets to be misaligned is very effective in removing the QCD backgrodunds:




- rejects 1 order of magnitude of backgrounds
- loss of only a few % of signal
- At this point we have ~16 Higgs events if $M_H$=115GeV (*with 2.1fb$^{-1}$*)

- Use *b*–tagging to reject QCD production of light flavor jets
  - Both leading jets are *b*–tagged: reduce background by ~2 orders of magnitude
  - Only one of the leading jets is *b*–tagged: reduce background by ~1 order of magnitude

# QCD background modeling

- QCD multijet production is the major background even after the trigger and kinematic selections:
  - S/B is still bad: around 1/3,500

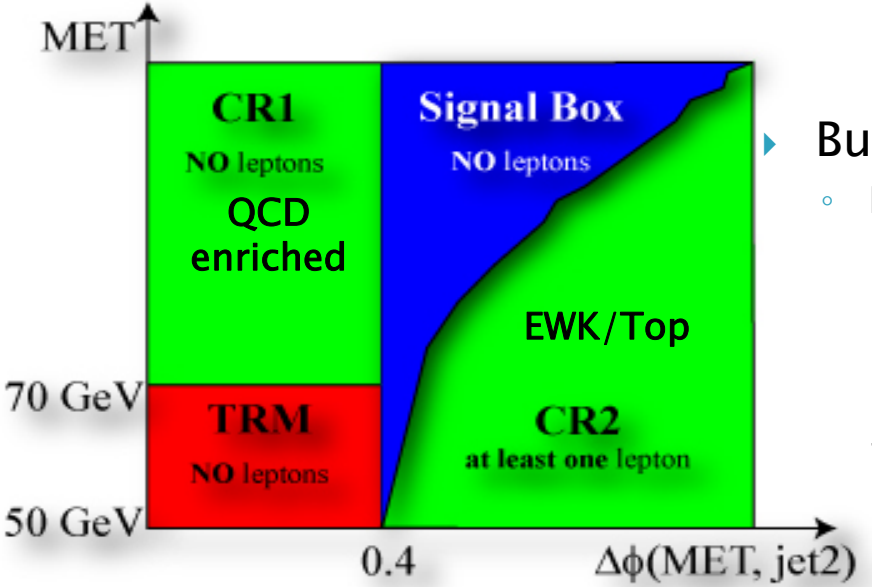
- Monte-Carlo based techniques to model QCD are challenging
  - Huge cross-section: to generate high statistics is a very time consuming process
  - Models are usually unreliable, difficult to compute high order corrections
  - CDF used MC models in the past: cut very hard on MET to reduce the QCD
    - Gets rid of QCD, but also kills a lot of signal
    - Large systematic uncertainty was assigned to QCD

- Need to devise a data-driven model:
  - The future of the analysis: cannot keep producing the huge amounts of MC
  - Data-driven technique would allow to release MET cuts: increase the signal acceptance
  - Remove systematics associated with MC modeling
  - Overall systematics of QCD modeling much smaller
    - The remaining systematics will reduce with luminosity

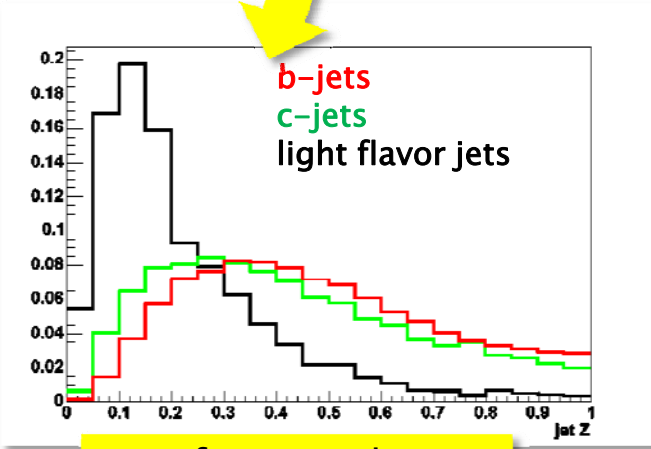
# Mulitjet background estimation

New at CDF

- Obtain QCD shapes using the Tag Rate Matrix (TRM)
  - Probability to tag a jet from pre-tagged sample ➡ **Single Tagged Bckg**
  - Probability to tag a jet when the other jet is tagged ➡ **Double Tagged Bckg**




- Build the matrix in TRM region
  - Matrix is parameterized in 4-dimenstions:
    - **Jet $E_T$**: more energetic jets are more likely to tag
    - **Jet η**: detector coverage drops with η
    - **Event $H_T$**: scalar sum of jet $E_T$'s: energy content of the event
    - **Jet Z**: (sum of good track pt's)/(Jet $E_T$): distinguish *light* from *heavy* flavor jets




Jet Z for tagged jets

- Inclusion of the jet Z
  - Distinguish between h.f jets and mistags
  - Predict the shapes of single tagged QCD backgrounds
  - Treat the two types of processes together
  - Reduce overall systematic uncertainty

# Electroweak and Top backgrounds

- The data sample contains a large amount of events with real MET
  - Top pair and single top production: energetic jets and MET from W's
  - W/Z associated production with jets: MET from missed leptons
  - Diboson production: WW, WZ, ZZ, one boson decays hadronically, the other one to leptons which escape detection

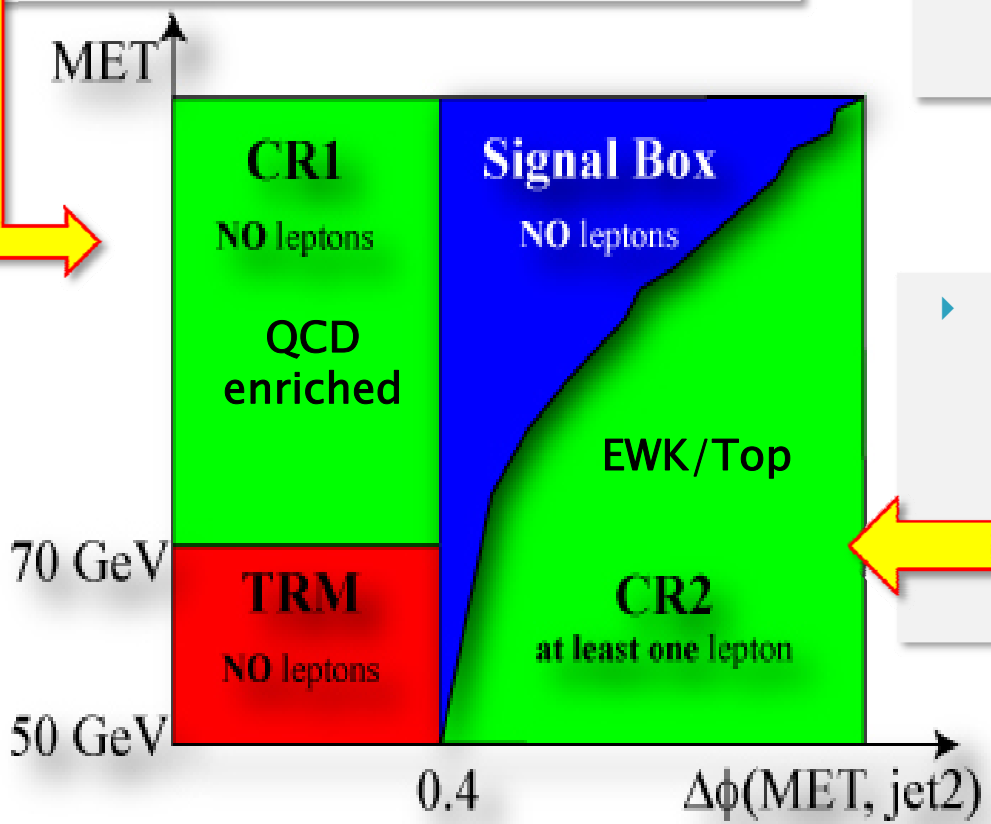
- Estimate these processes using Monte-Carlo techniques
  - We use Pythia program for the majority of the processes
  - Use MadEvent for single top production
  - Simulate only events with *taggable* objects: b/c-quark or tau

- Veto leptons: how to test if we model these backgrounds well?
  - Reverse the lepton **veto** into charged lepton **ID**: e or μ
  - Check the model in the same kinematic region, but requiring a lepton

# Cross-check the model

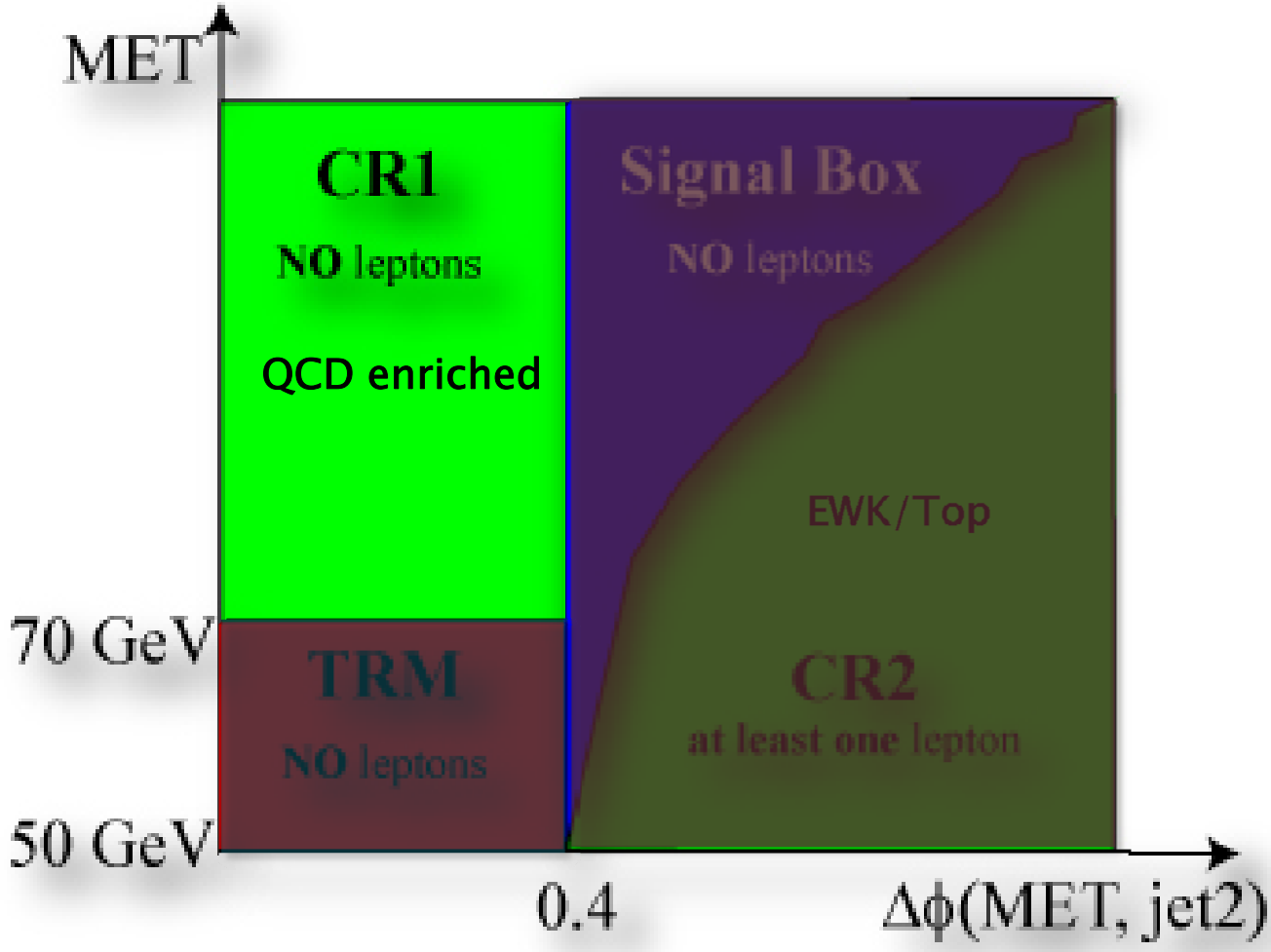
- MET aligned with 2nd jet, high MET:
  - *Veto all leptons*
  - **Check** the Multijet model

- Keep the signal region *blind*
  - Open only when the background modeling is validated



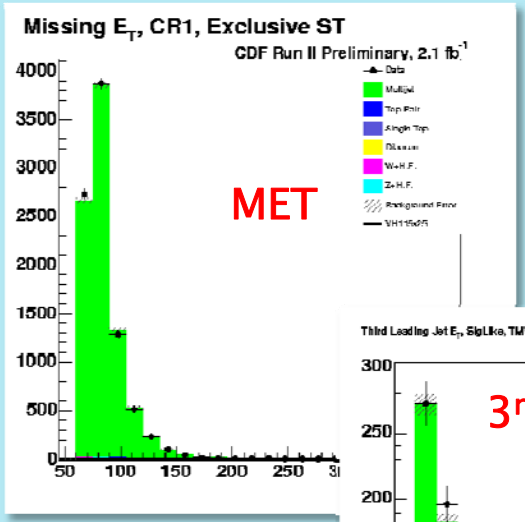

- MET is not aligned with jets
  - Require *at least one lepton*
  - Check EWK and Top models
  - *Single tagged sample*: mixture of all backgrounds
  - *Double tagged sample*: rich in top pair produced events

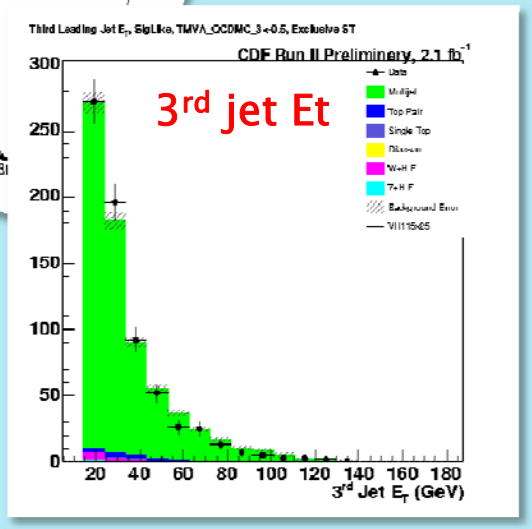
# Cross-checks in QCD control region



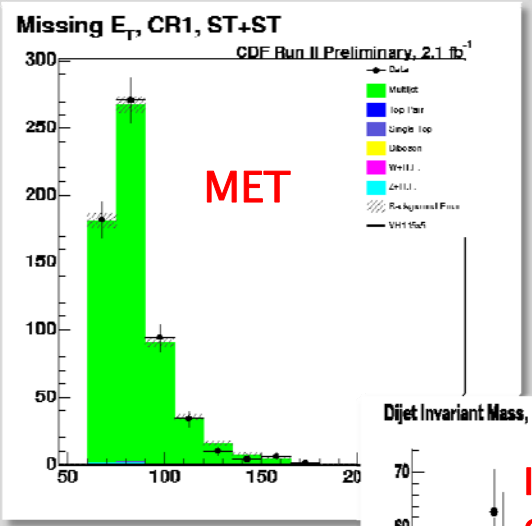
# Cross-checks in QCD control region

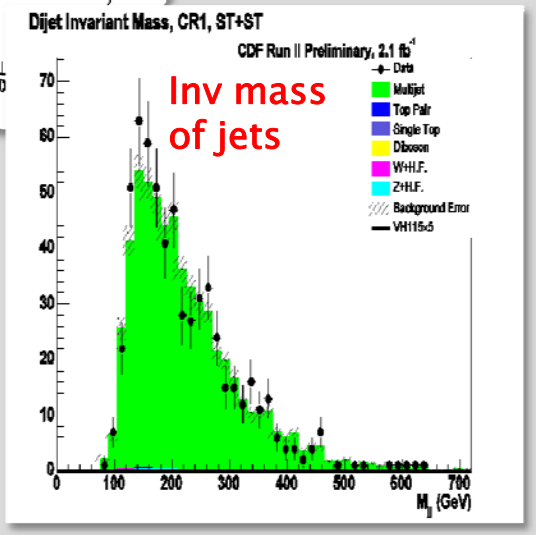
- Check in single tagged sample:
  - High statistics sample
  - Can spot discrepancies in modeling
- Large fake MET



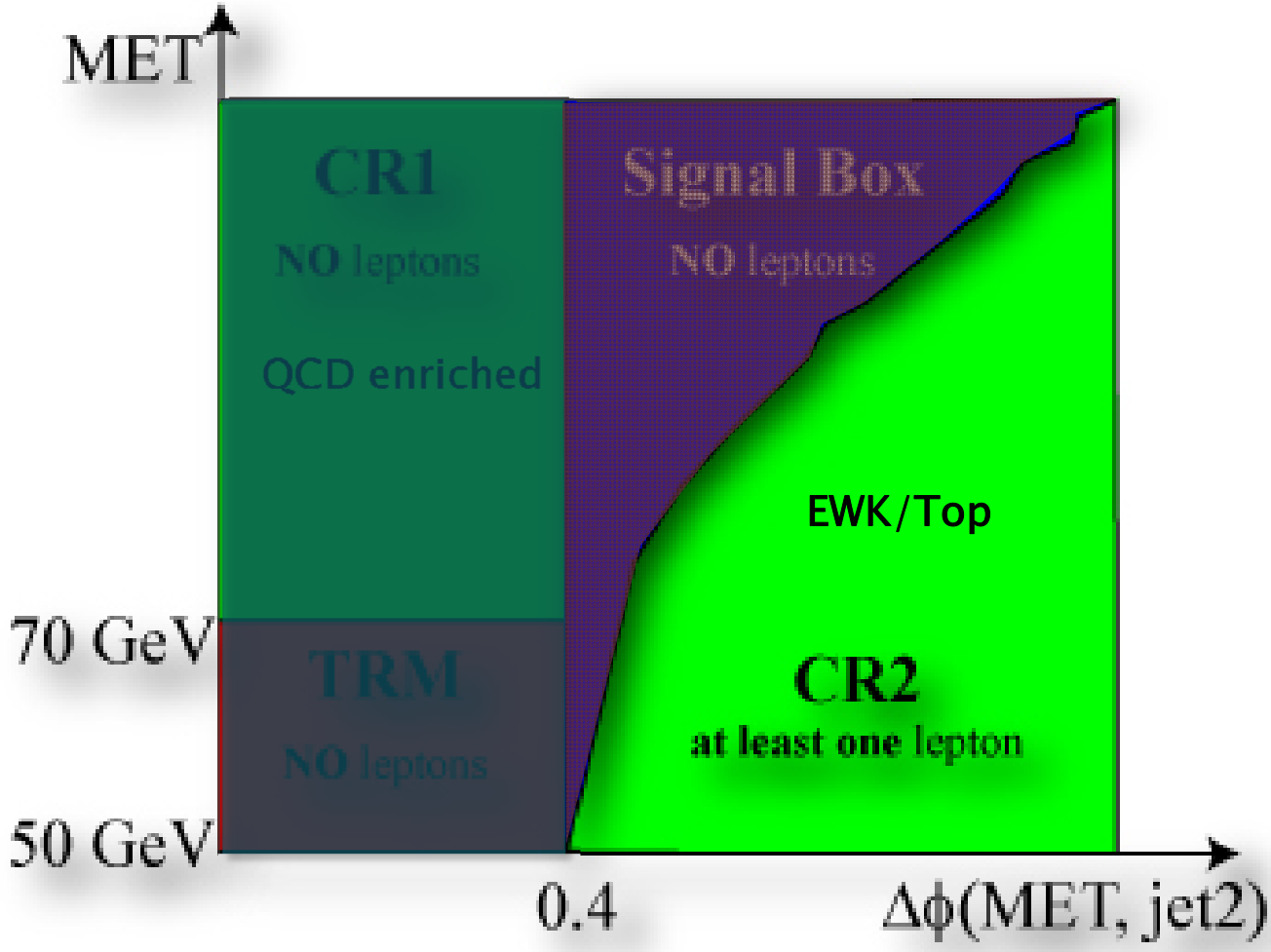




- Check in double tagged sample:
  - Lower statistics
  - Most sensitivity comes from double-tags



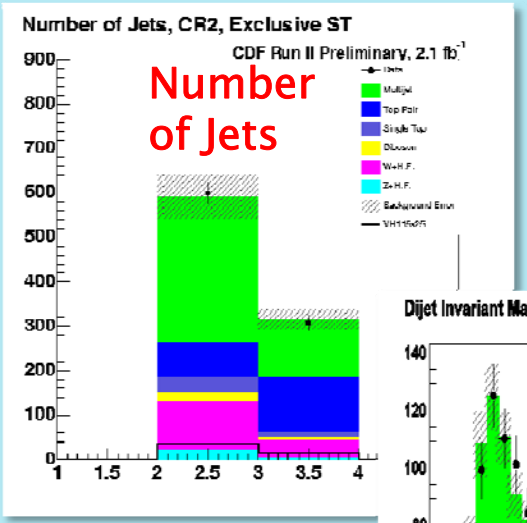



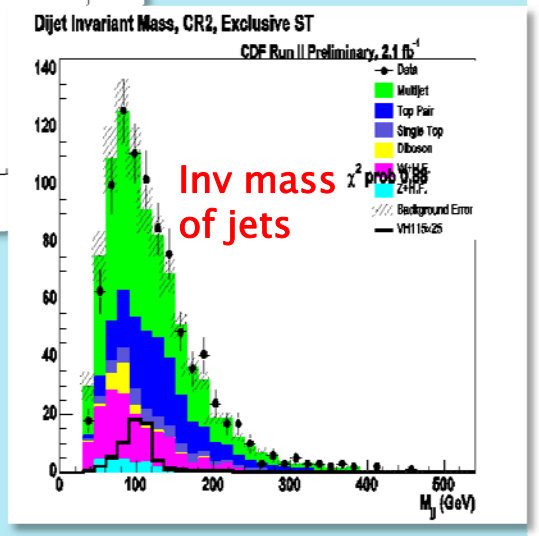
# Cross-checks in EWK control region



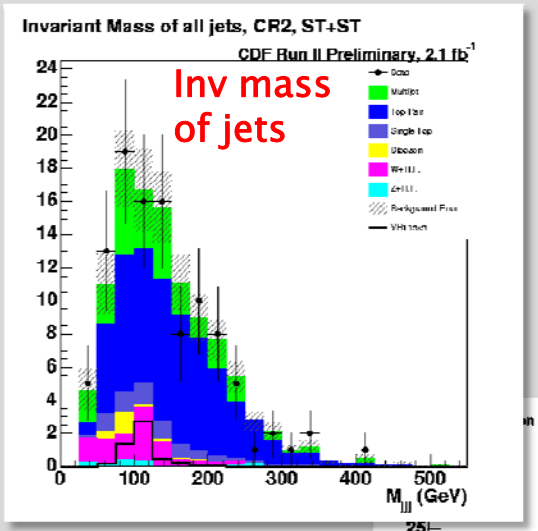
# Cross-checks in EWK control region

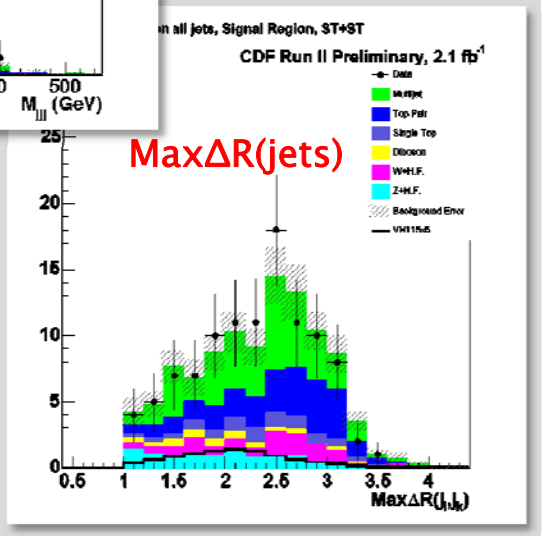
- Check in single tagged sample:
  - High statistics sample
  - Rich in various EWK processes
  - Almost equally split among top and W/Z+jets




- Check in double tagged sample:
  - Rich in top pair events

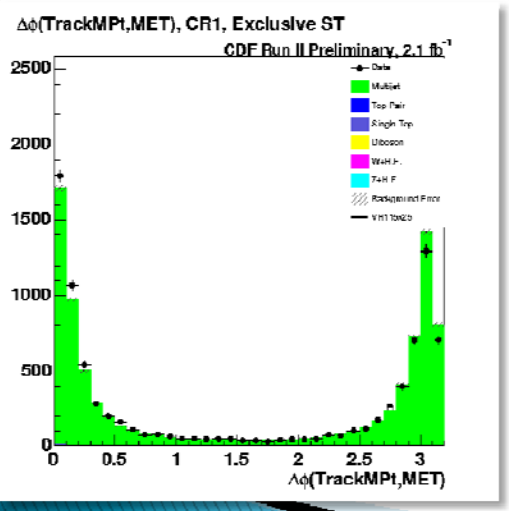


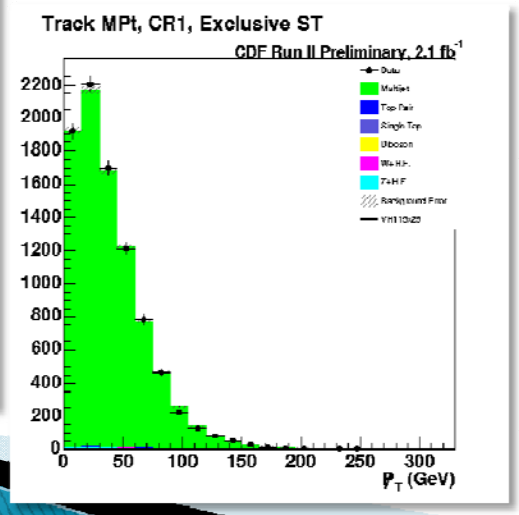



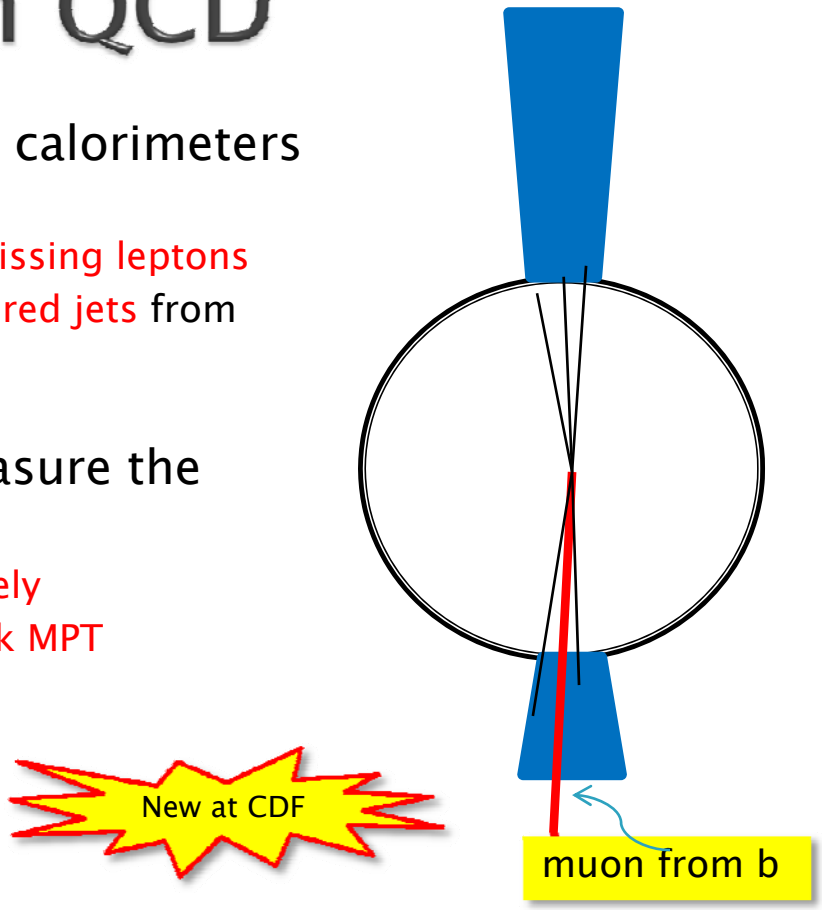
# Additional handles on QCD

- So far the analysis used information from calorimeters
  - Missing $E_T$ and jets
  - The signal events contain "*real*" missing $E_T$ from missing leptons
  - Large amount of background caused by mismeasured jets from QCD

- Can we find an alternative method to measure the amount of energy escaping the detector?
  - $P_T$'s of charged particles are measured very precisely
  - Compute the complimentary quantity to MET: track MPT



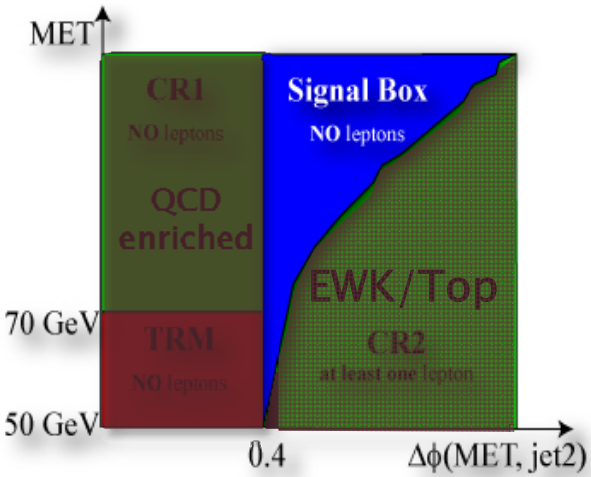



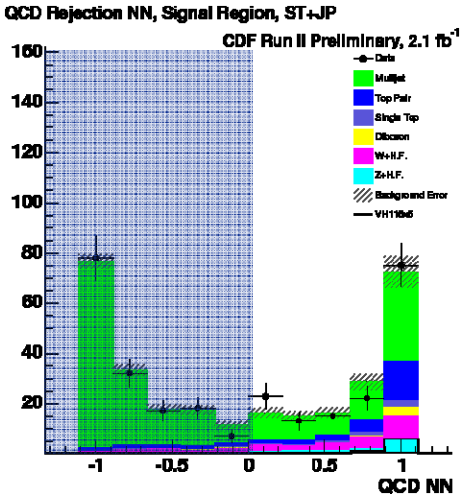

- MET from mismeasurements:
  - MET and MPT are <u>not correlated</u>
  - In events with mismeasured jets the MPT is small

# Signal Selection

- Several handles on QCD background
  - Robust QCD modeling: release the selection cuts
  - Additional handles on QCD: track based quantities
- Use all possible information to reduce the major background
  - Could define selection cuts to define SR: e.g. high MET
  - Combine all possible information using a multivariate technique
    - Much higher signal purity with respect to cut based definition




New at CDF



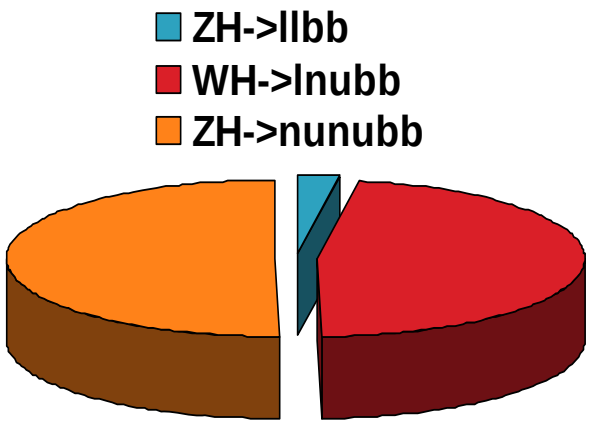

| | Preselection | After QCD cut | Gain |
|---|---|---|---|
| S | 7.6 | 7.5 | *-0.5%* |
| B | 4010 | 1800 | *-50%* |
| S/B | ~1/500 | ~1/240 | *times 2!* |
| S/√S+B | 0.12 | 0.18 | *+50%* |

Now the S/B is as good as in WH searches with identified lepton, and the acceptance is larger

# Three tagging categories

After all cuts, we maximized acceptance to Higgs in Signal Region

Almost 4 events per $fb^{-1}$




New at CDF

- WH events accepted in the selection:
  - Around 50% WH→e/μν bb
  - Around 50% WH→τν bb
    - Half of the time τ is reconstructed as a jet

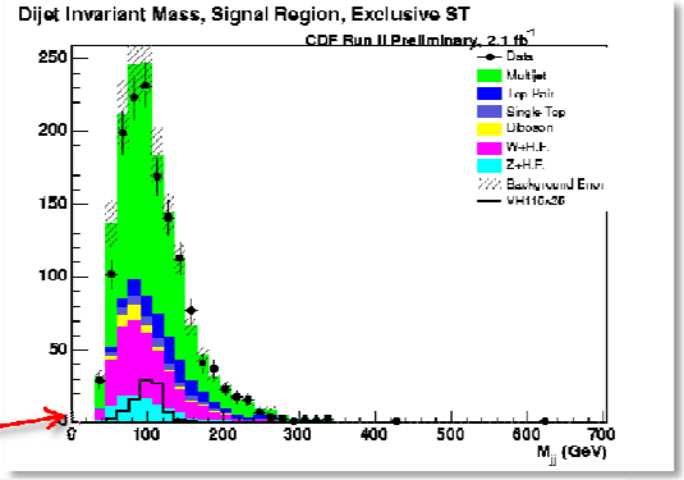
- In terms of $S/\sqrt{S+B}$
  - ~40% improvement by splitting into 3 categories
  - ~10% improvement by including single tagged channel

| Higgs | Signal Evts | Bckg Events | $S/\sqrt{(S+B)}$ |
|---|---|---|---|
| All | 7.5 | 1802 | 0.18 |
| 1 SecVTX | 4.0 | 1548 | 0.10 |
| SecVTX+JP | 1.5 | 149 | 0.12 |
| 2 SecVTX | 2.0 | 105 | 0.20 |
| Quadrature sum of three categories | | | 0.25 |

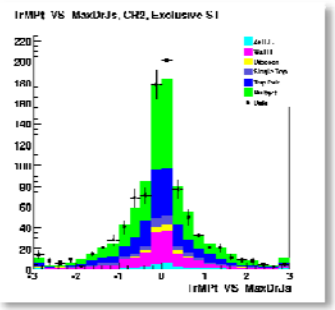
# Improving the sensitivity

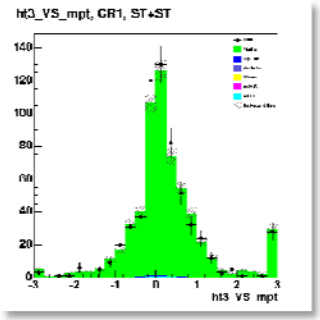
- Still, the amount of Higgs signal is small
  - Backgrounds are much larger
  - Any possible excess has a small significance
  - Some backgrounds have a large systematic uncertainty
    - Can easily hide the signal

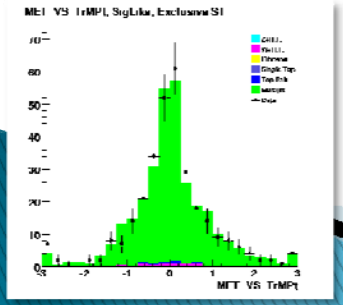
- The most distinguishing feature of the signal:
  - Two *b*–jets from the Higgs decay
  - Invariant Mass of two jets: Higgs Boson mass

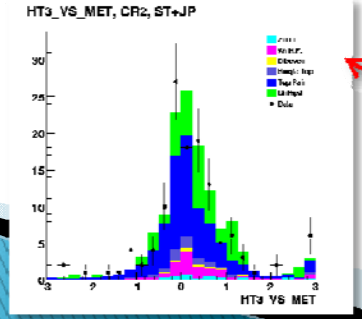



But, the signal is buried under a huge bckrd



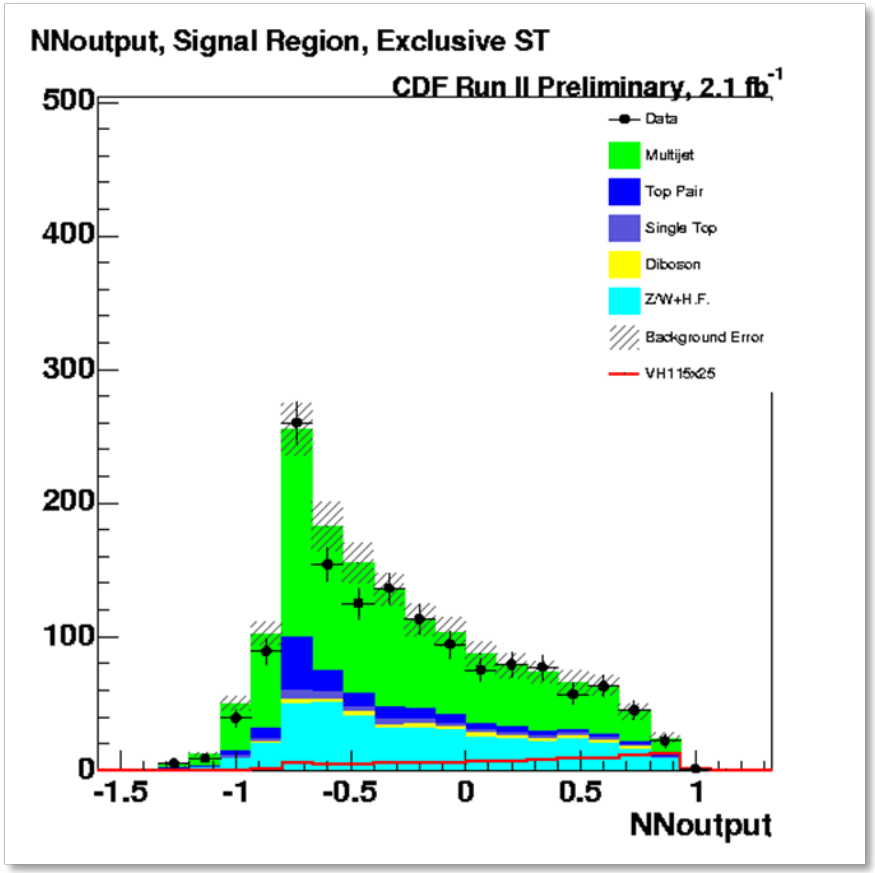

- Exploit various features of signal and bckgs
  - Multivariate technique, e.g. a Artificial Neural Network
  - Different correlations between signal and bckgs

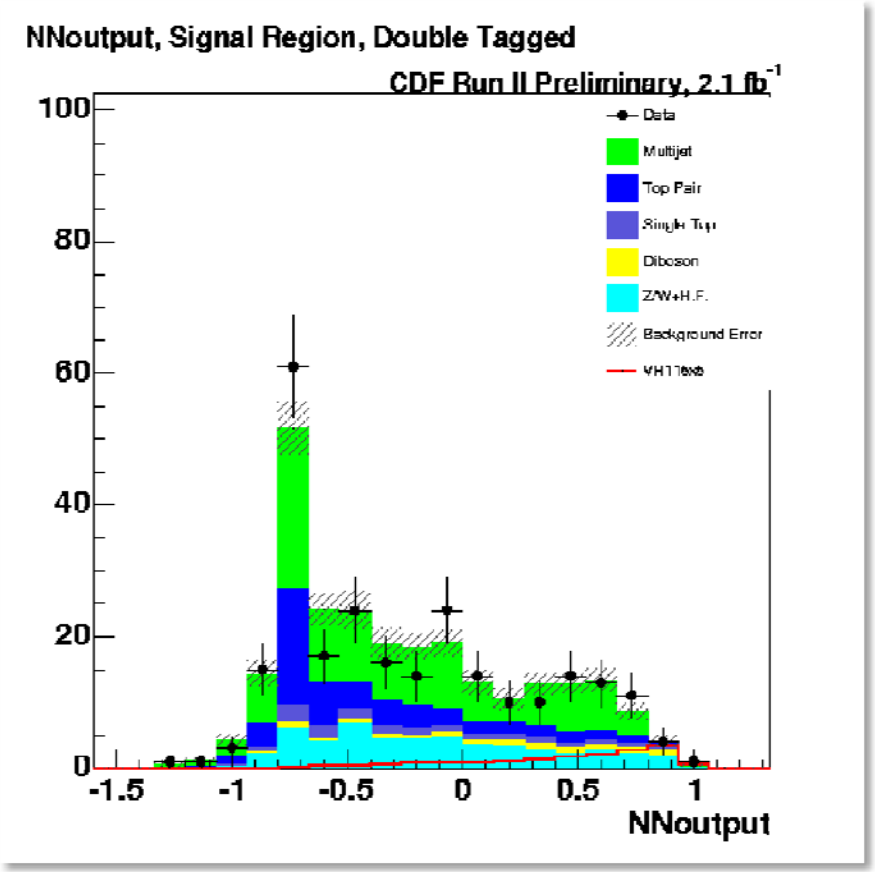
- Inputs to the NN need to be well-modeled
  - Correlations between input variables: NN can pick up on badly modeled correlations
  - Validate that the correlations between input variables are well modeled

$$r_{XY} = \frac{(X_i - \overline{X})(Y_i - \overline{Y})}{\sigma_X \cdot \sigma_Y}$$

# Final discriminant

- Discriminant to scan for the presence of the Higgs boson signal
  - Six input variables: *Mjj, $M_T$(j1,j2,MET), HT-MET, MHT-MET, MaxΔR(jets), TrackMET_NN*
  - Separate training for events with 2 and 3 jets: different S/B



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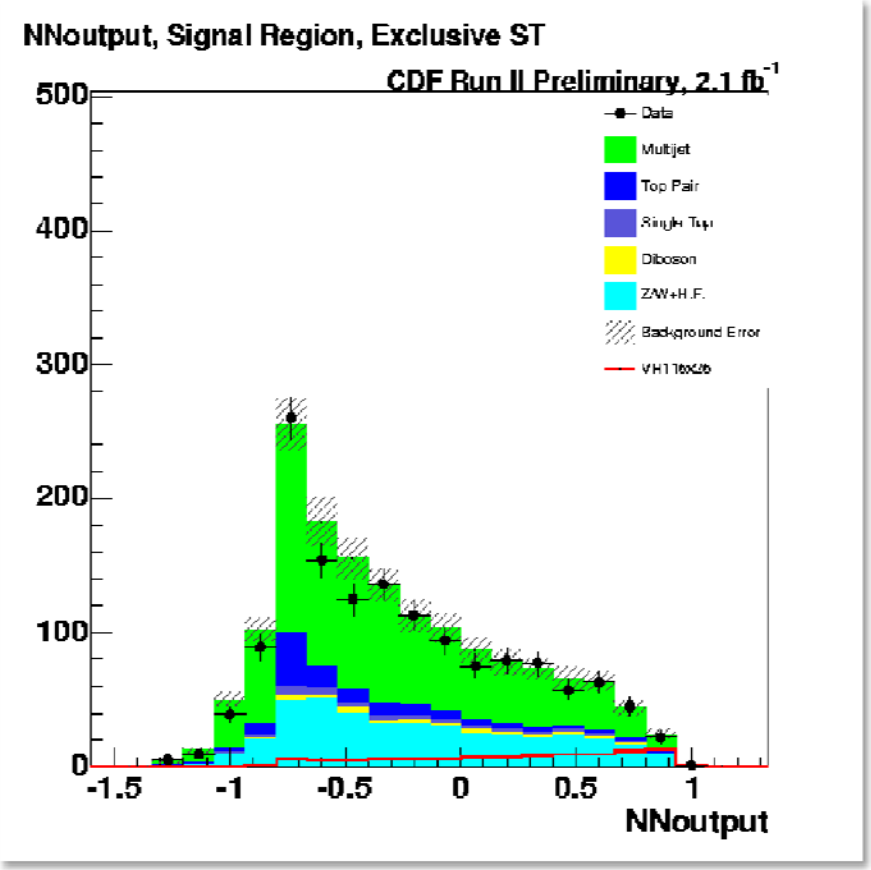
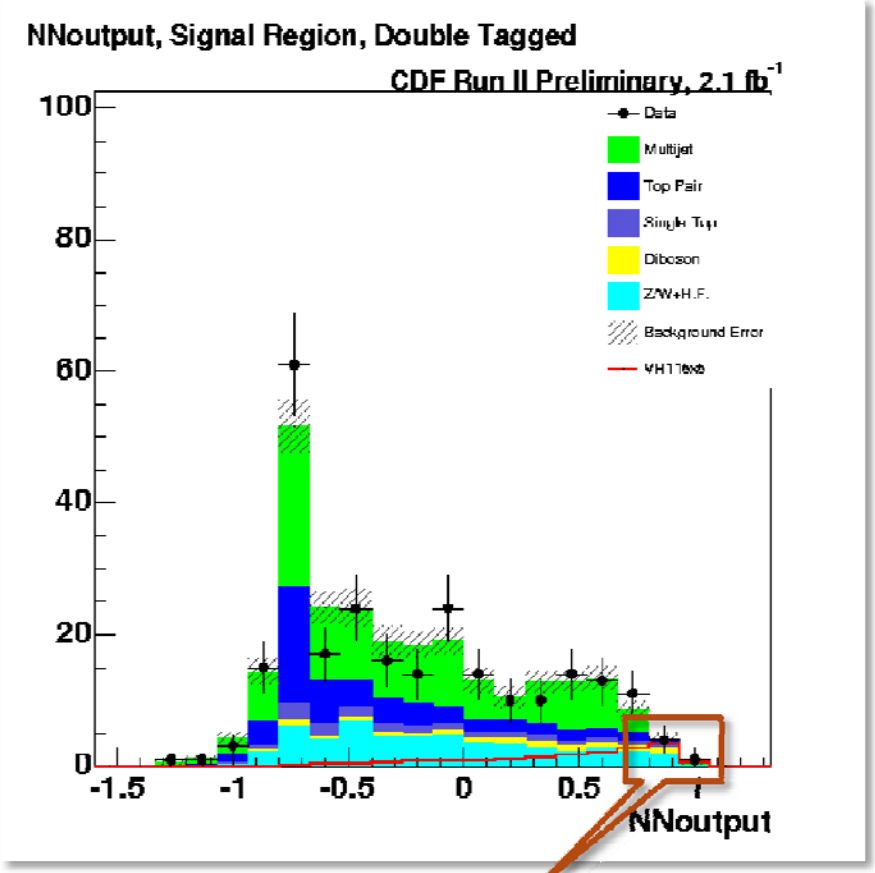


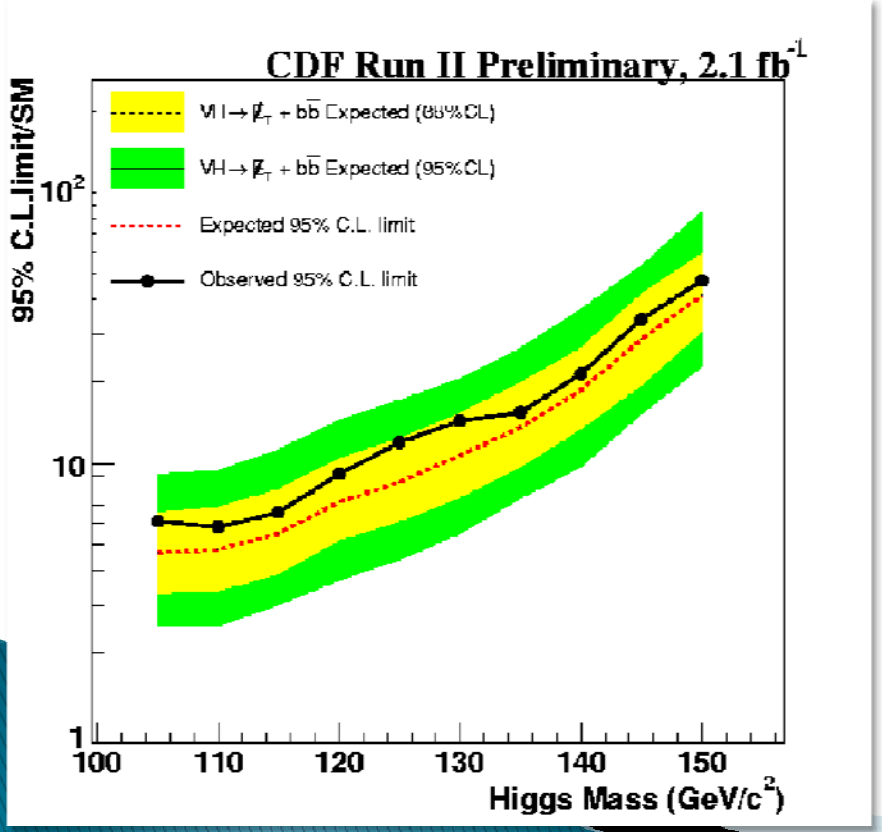




- S/B in the most sensitive bin: 1/5!
- Expect 0.4 signal events ($M_H$=115 GeV)

# Final results in MET+*b*-jets

- CDF observed data is consistent with background expectation
  - Set a 95% C.L. upper limit on Higgs boson production cross-section

- Scan the output of the Neural Net using binned likelihood
  - All systematics uncertainties treated as nuisance parameters with truncated Gaussian constraints



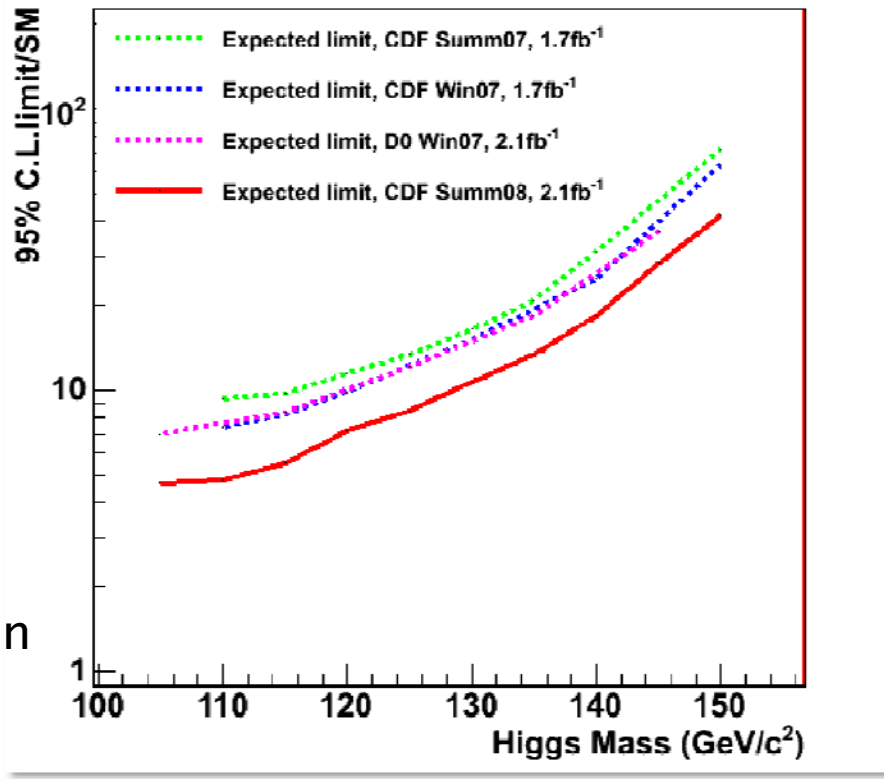

- Assuming MH=115 GeV/c$^2$
  - Expected limit: 5.5×SM cross-section
  - Observed limit: 6.6×SM cross-section

- Improvement of a factor of two since Summer 2007
  - Only 20% more luminosity

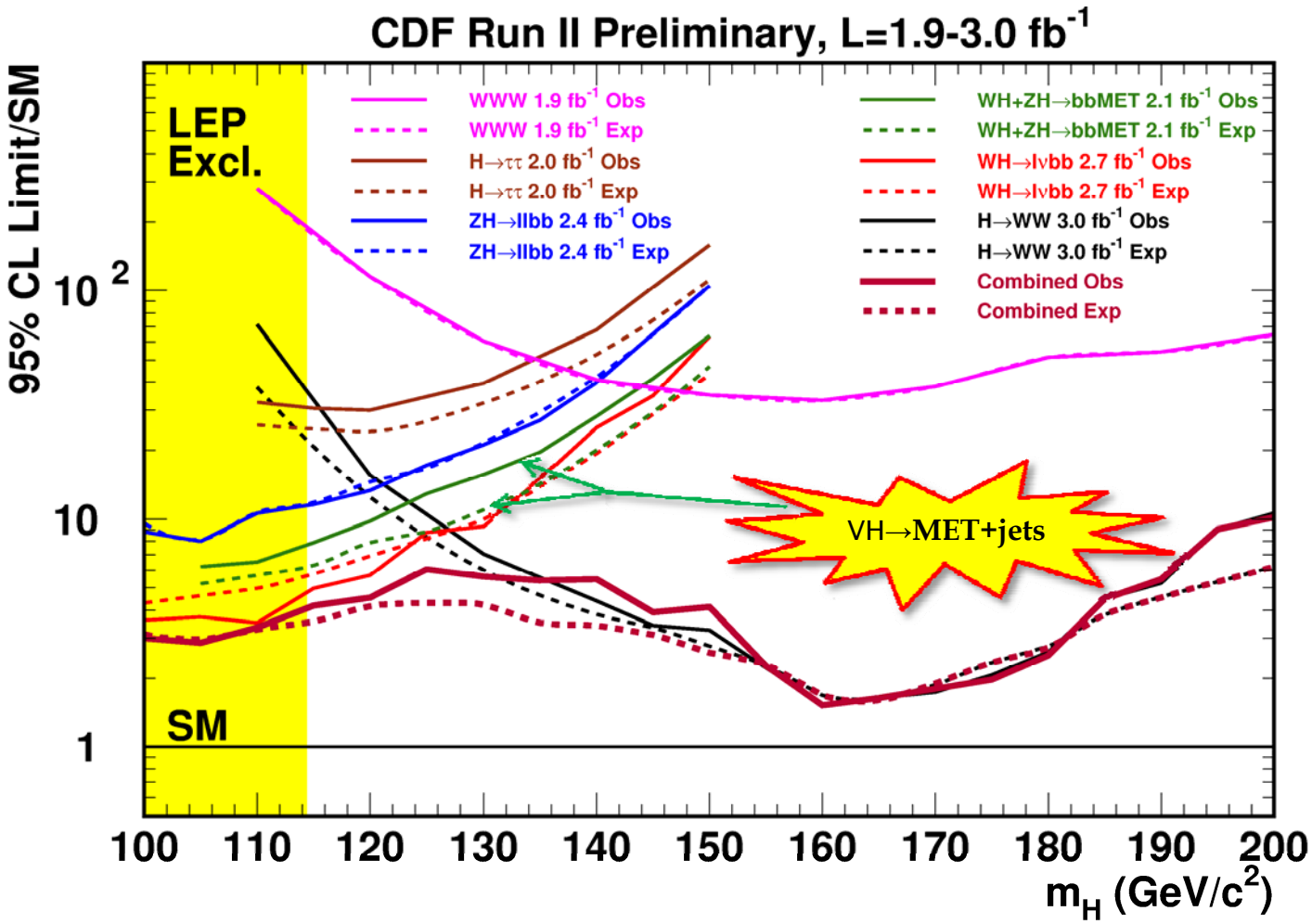
- One of the most sensitive search channels at Tevatron

# Key improvements of the analysis

- Acceptance!: Looser event selection
- Doubled the acceptance
  - Backgrounds increase much faster!
  - Use NN to select events
- Data-driven background modeling
  - Reduce systematics on the largest background
- Track related variables
  - MPT to discriminate signal from QCD
  - Correct jet $E_T$ to improve $M_{jj}$ resolution
- Multivariate discriminant to enhance sensitivity



# CDF combination



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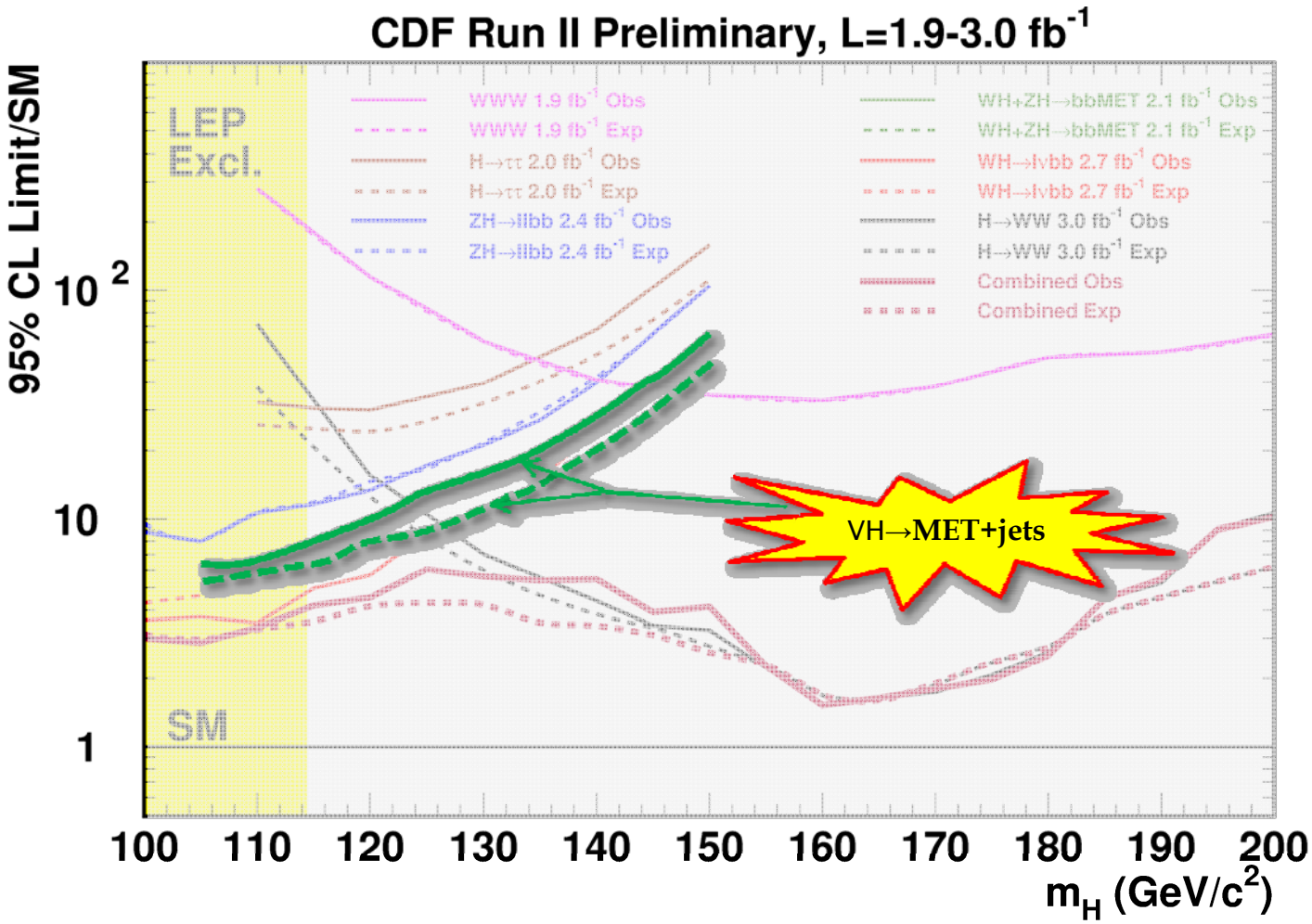
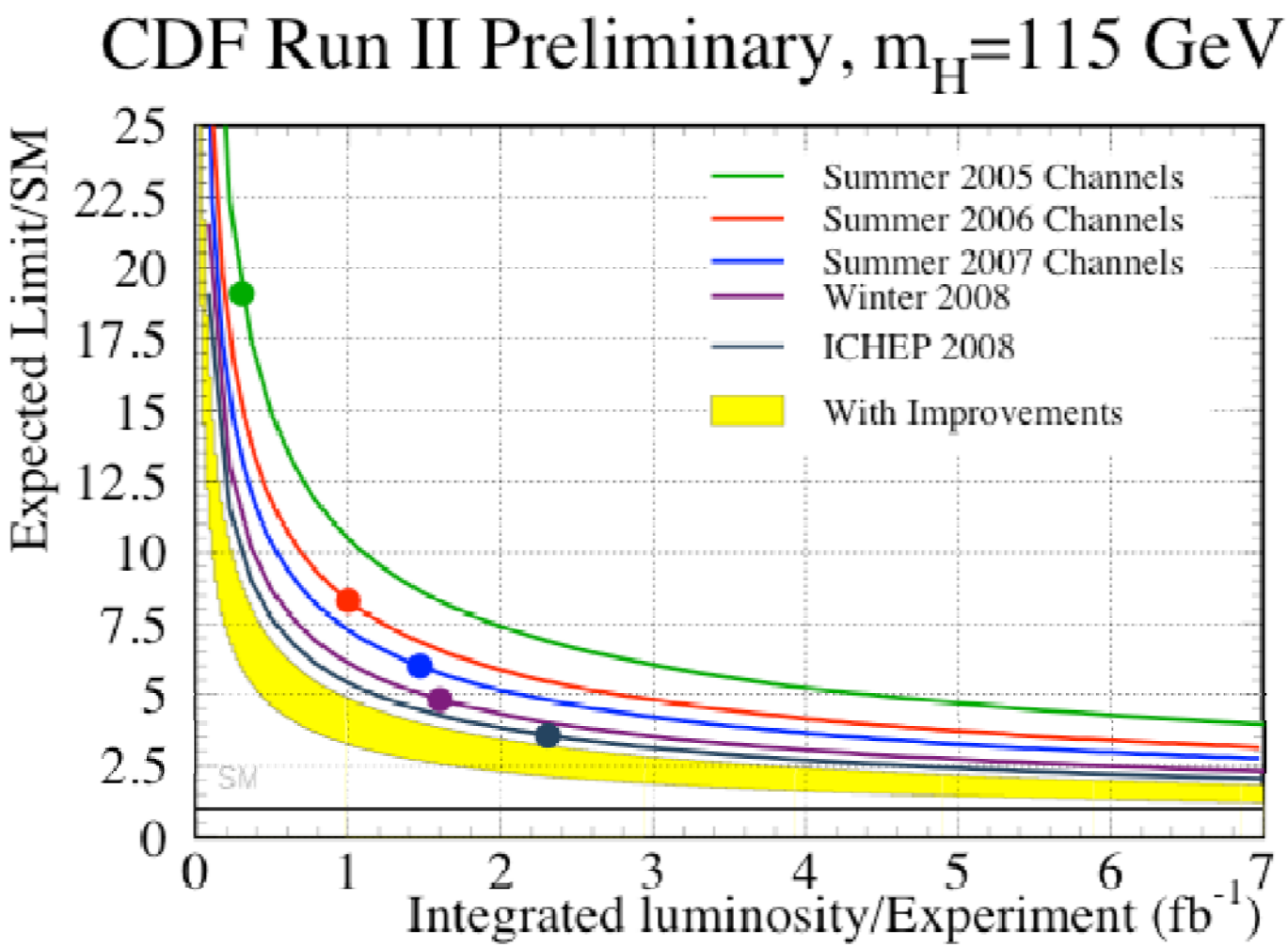


# Higgs sensitivity projections




- All analysis are improving faster than 1/sqrt(L) !

# Tevatron Low mass Higgs

| Channel | CDF<br>95% C.L. Limits<br>$\sigma\cdot$BR/SM obs (exp) | DØ<br>95% C.L. Limits<br>$\sigma\cdot$BR /SM obs (exp) |
|---|---|---|
| VH→MET+*b*-jets | 6.6 (5.5) 2.1fb$^{-1}$ | 7.5 (8.4) 2.1fb$^{-1}$ |
| WH→lνbb | 5.0 (5.8) 2.7fb$^{-1}$ | 9.3 (8.5) 1.7fb$^{-1}$ |
| WH→lνbb | 5.7 (5.6) 2.7fb$^{-1}$ | |
| WH→τνbb | - | 35.4 (42.1) 0.9fb$^{-1}$ |
| VH→qqbb | 37.0 (36.6) 2.0fb$^{-1}$ | - |
| ZH→llbb | 11.6 (11.8) 2.4fb$^{-1}$ | 11.0 (12.3) 2.3fb$^{-1}$ |
| ZH→llbb | 14.2 (15.0) 2.0fb$^{-1}$ | |
| ttH→lνbbbbqq | - | 63.9 (45.3) 2.1fb$^{-1}$ |
| H→γγ | - | 30.8 (23.2) 2.7fb$^{-1}$ |
| H→ττ | 30.5 (24.8) 2.2fb$^{-1}$ | - |

# Future of the analysis

- Still a lot of room for improvements:
  - Improve the rejection power of QCD NN
  - New method developed at CDF to improve MET resolution
- Acceptance gain:
  - The upgraded CDF trigger: improved jets and MET resolution
  - Use complimentary triggers: recover events in orthogonal samples
  - Improved understanding of the trigger: loosen the baseline selections
- Improved b-tagging:
  - Neural Net based tagger developed recently at CDF: higher efficiency with the same fake rate as SecVTX

# Benchmarking the tools

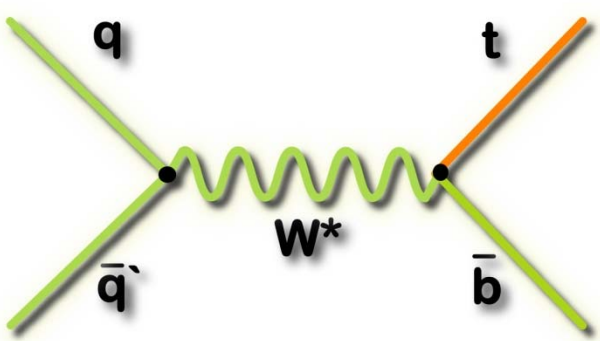
- Want to benchmark the tools used in the Higgs boson searches
  - Can we observe larger cross-section processes?

| Process | Exclusive 1Tag | ST+ST | ST+JP |
|---|---|---|---|
| QCD + Mistags | $941.2 \pm 44.0$ | $42.1 \pm 8.7$ | $78.2 \pm 11.5$ |
| Single Top | $43.2 \pm 7.9$ | $8.5 \pm 1.7$ | $7.2 \pm 1.5$ |
| Top Pair | $124.5 \pm 17$ | $27.4 \pm 4.3$ | $27.1 \pm 4.6$ |
| Di-boson | $35.6 \pm 6.8$ | $4.9 \pm 1.2$ | $4.3 \pm 1.1$ |
| W + h.f. | $296.9 \pm 129.5$ | $11.0 \pm 6.5$ | $21.0 \pm 10.6$ |
| Z + h.f. | $107.0 \pm 45.8$ | $10.8 \pm 5.0$ | $11.3 \pm 5.2$ |
| Total Exp | $1548.4 \pm 145.6$ | $104.6 \pm 12.9$ | $149.1 \pm 17.2$ |
| Observed | 1443 | 105 | 148 |
| $ZH \to \nu\nu bb$ (MH115GeV) | 2.1 | 1.0 | 0.8 |
| $WH \to (l)\nu bb$ (MH115GeV) | 1.8 | 0.9 | 0.7 |
| $ZH \to (ll)bb$ (MH115GeV) | 0.09 | 0.04 | 0.03 |

- Diboson production well known from LEP
- Acceptance to WZ and ZZ to bbar and missed leptons: 45 signal events
- Similar to WH/ZH due to the Z reconstructed mass
  - Discrimination similar to Higgs
- Work in progress to optimize the analysis to measure Diboson cross-section

# Benchmarking the tools

- Single top production not observed yet
  - Waiting to integrate more luminosity
- Recover events without identified leptons
  - Same baseline event selection as for Higgs

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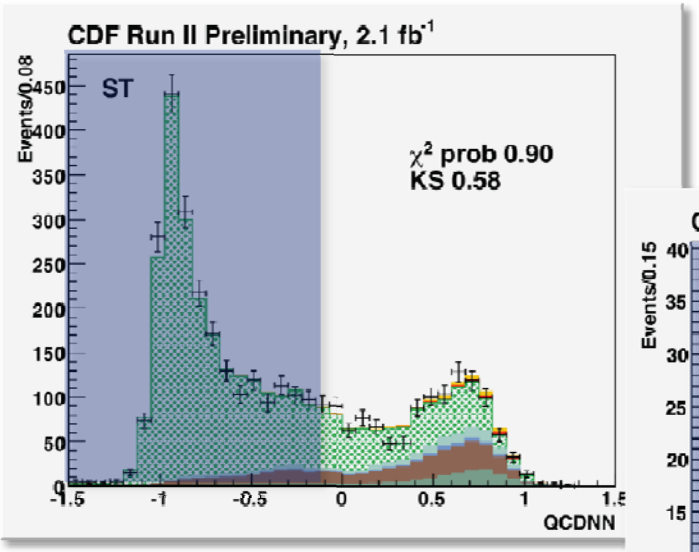
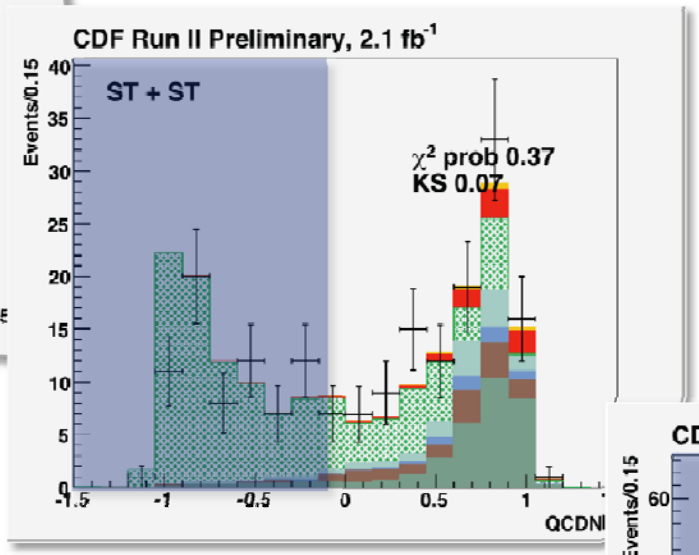
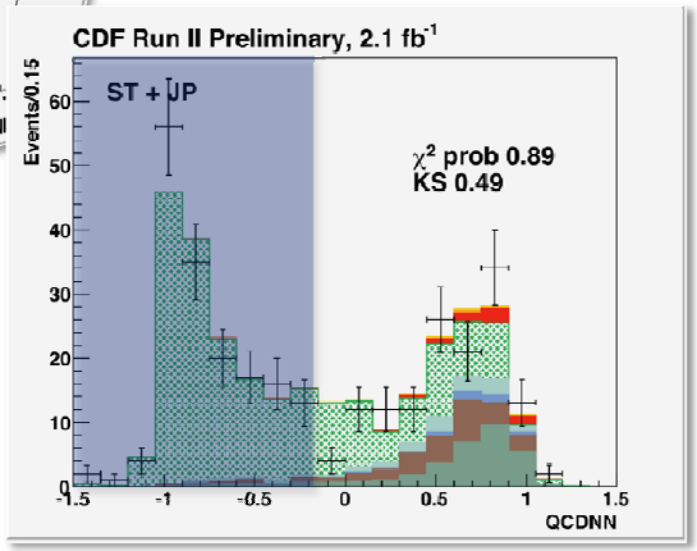
- MET+jets channel:
  - Acceptance to events with escaping e/μ, hadronic τ
- Dedicated event selection: ~70 signal events!
- S/B ranges from 1/10 to 1/30
  - Similar to leptonic channels
- Difficult to discriminate
  - Top four momentum not reconstructed: W boson is not identified
- Analysis almost finalized
  - Results in time for winter conferences

# Single top production in MET+jets




- Dedicated final event selection
  - Signal is the red and yellow

# Summary

- Developed a framework to analyze the MET+JETS sample
  - Applied to a Higgs boson search: PRL is being written
  - The technique is applied to a single top search: results will be released soon
  - A goal is to apply this technique to measure the diboson production cross-section
- Many novel ideas used for the first time in Higgs searches in CDF
  - Some are being used in other searches: e.g. searches for SUSY
- Improvements in Higgs search sensitivity:
  - A factor of two with 20% additional data-sample
  - Crucial factor for the Higgs program at Tevatron: increasing the integrated luminosity only will not be enough to scan the mass range
- CDF-only limit at $M_H$=115 GeV is nearing 3*SM
  - With the upcoming updates from DØ can get to 2*SM
  - SM Higgs can be within the reach of Tevatron

# Backup

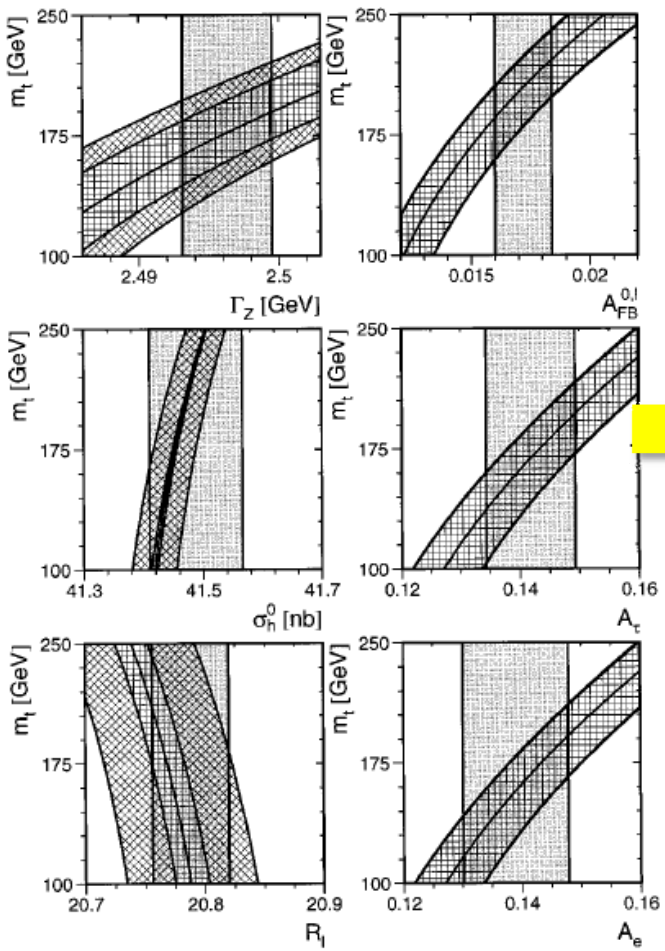
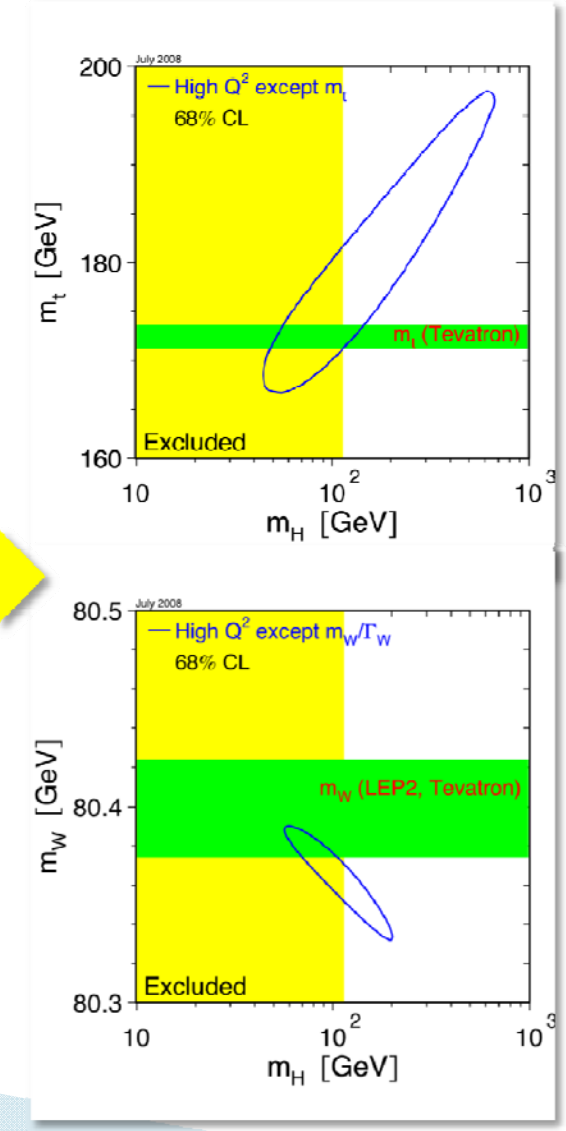
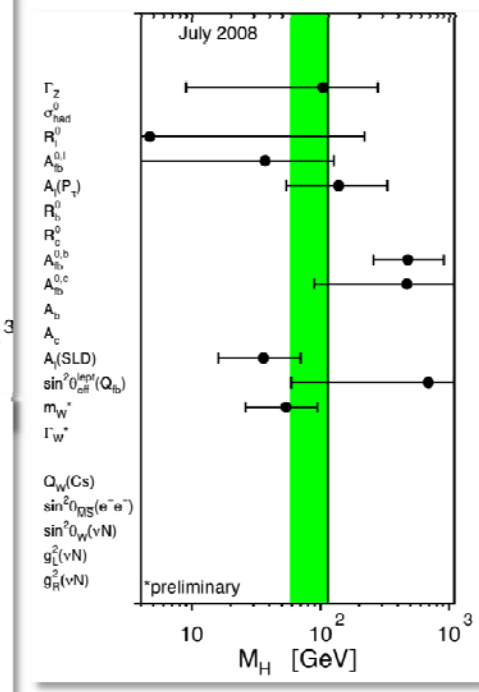
# Systematic uncertainties

- Luminosity uncertainty: 6%
- PDF acceptance: 2%
- JES uncertainty: varying JES correction by $\pm$ 1 s.
- ISR/FSR uncertainty on signal
- b-tagging scale factor:4.3% for SecVTX Tight Tagger, and 8.1% for JetProb(<5%) Tagger
- W/Z h.f. and Diboson NLO Corrections: 40% on W/Z+h.f. and 11.5 on Diboson
- Lepton ID: 2%
- Trigger efficiency as an uncertainty on the NN shape for all backgrounds and Signal.
  - Also rate uncertainty.
- Multijet SF uncertainty

# Setting the limit

- Use Bayesian and frequentist approach:
  - Bayesian $L(R,\vec{s},\vec{b}|\vec{n},\vec{\theta})=\prod_{i=1}^{Nc}\prod_{j=1}^{Nbins}\mu_{ij}^{nij}e^{-\mu_{ij}}/n_{ij}!\times\prod_{k=1}^{n}e^{-\theta_k^2/2}$
  - Frequentist($CL_s$) $LLR_n=2\sum_{i=1}^{N}(s_i-n_i Log(1+\frac{s_i}{b_i}))$

- If the excess is significant after combination, do more checks to make sure not statistic fluctuation.
- If no excess, set 95% CL upper limit vs mH

# Electroweak fits

- Indirect constrains from EW parameter fits provided first hints of top quark mass
  - Will this repeat for Higgs?