# Standard Model Higgs Searches at the Tevatron

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*on behalf of CDF and D0 collaborations*

THE UNIVERSITY OF WARWICK

24th Recontres de Blois
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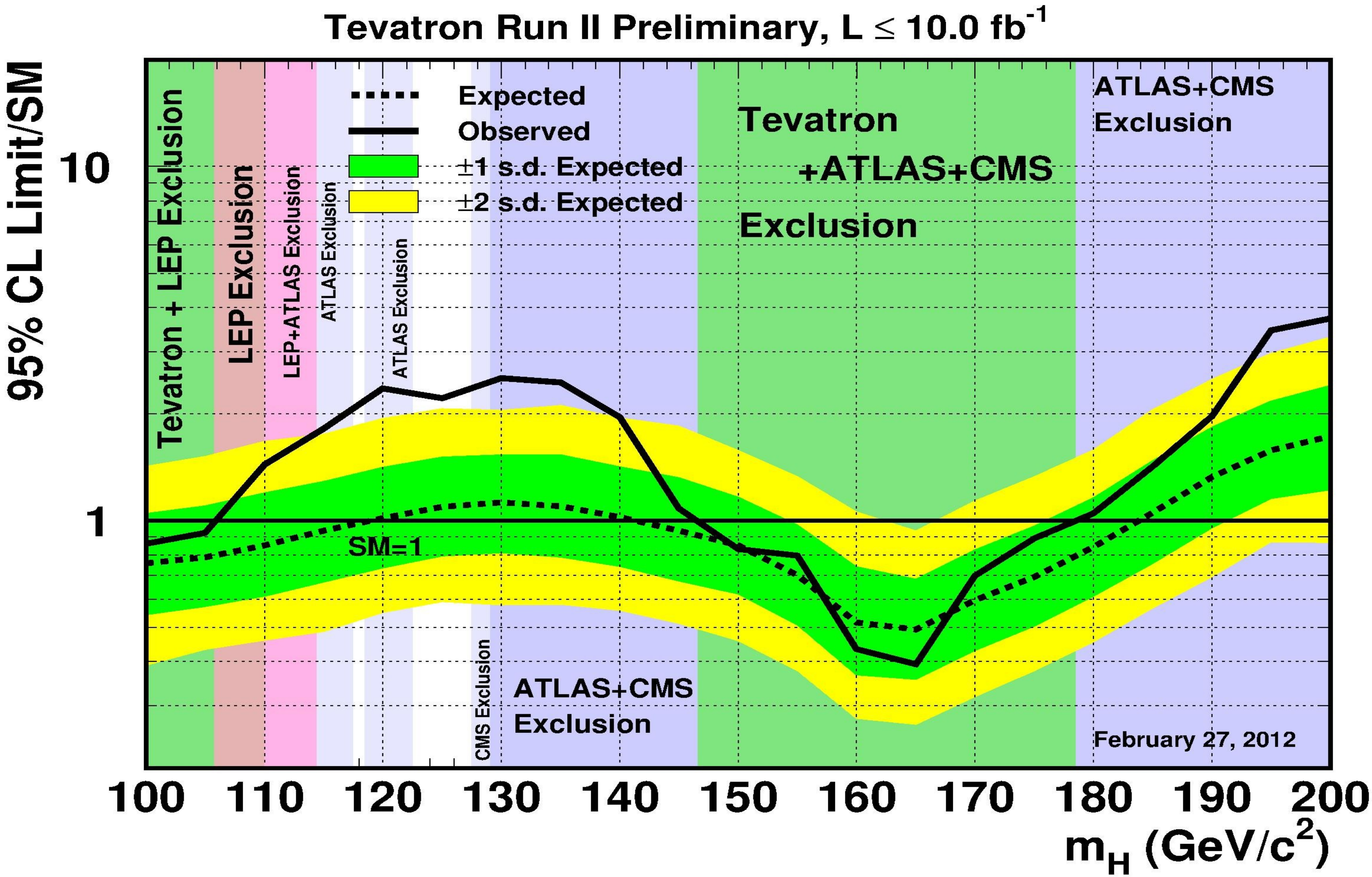
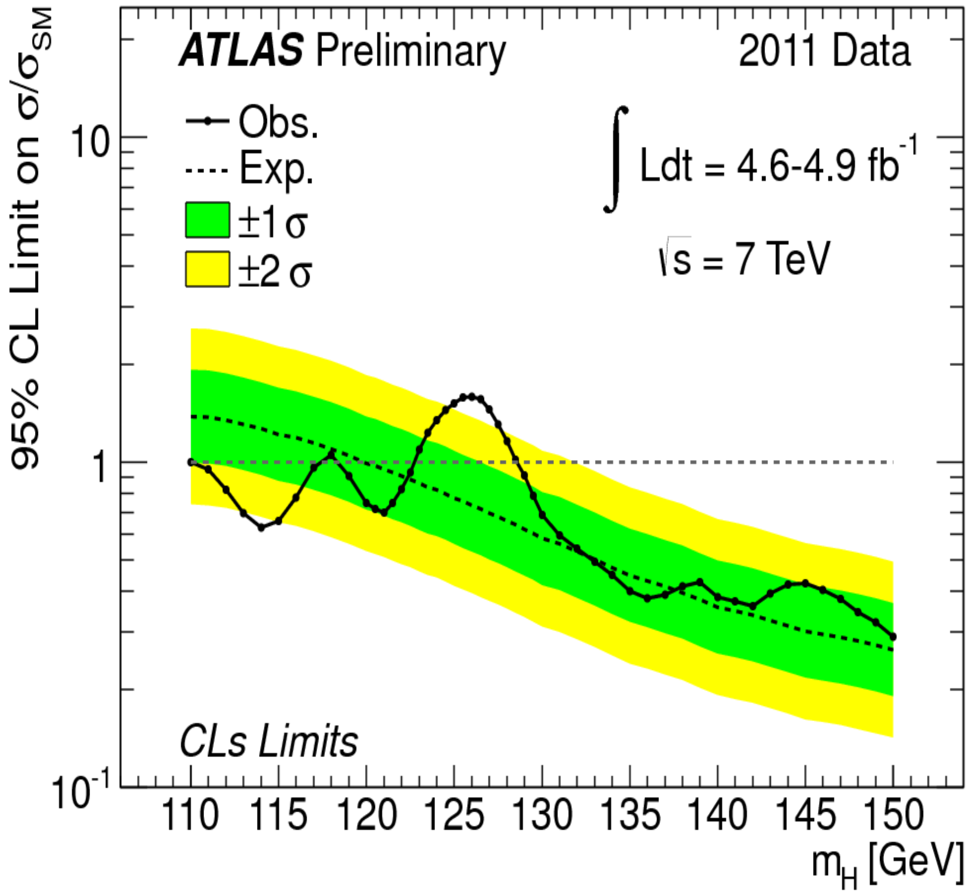
# Status of Higgs direct searches

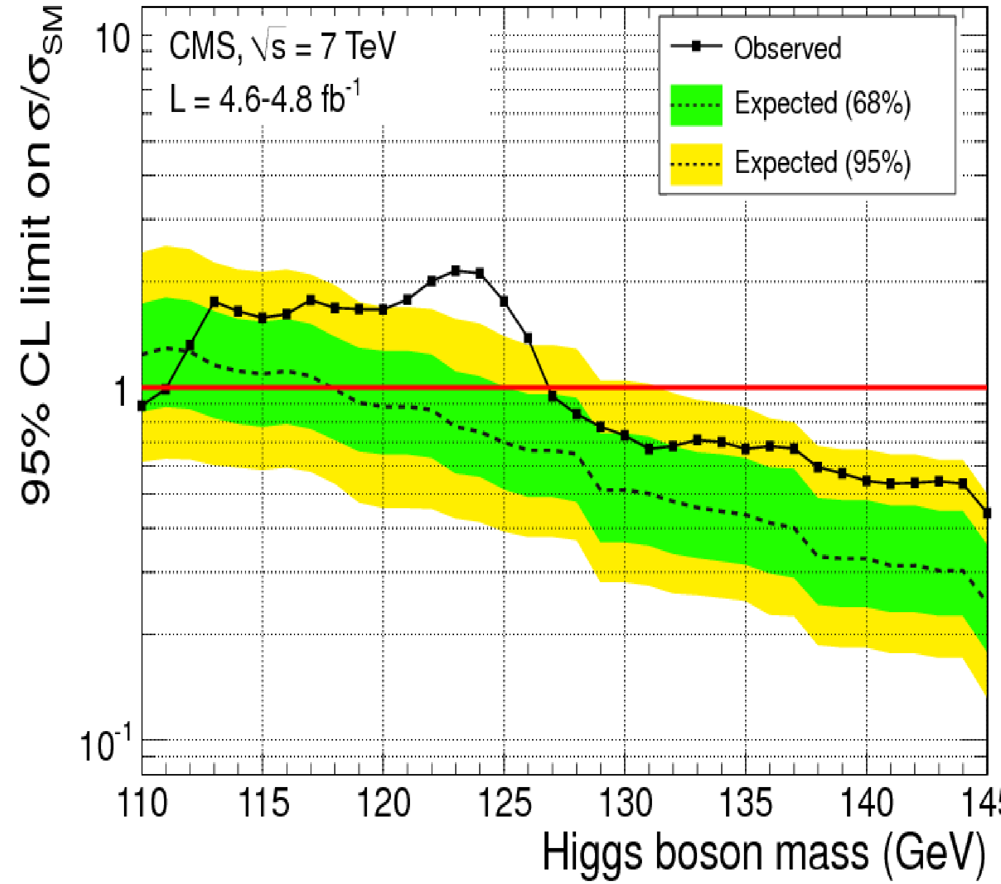



**World Exclusion:**

**$m_H < 117.5$ , $118.5 < m_H < 122.5$, $127 < m_H < 600$ excluded at 95% C.L.**

# Status of Higgs direct searches



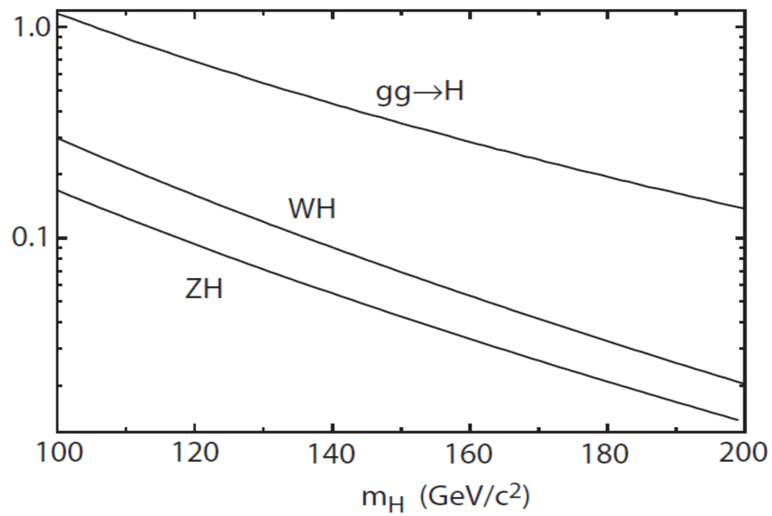



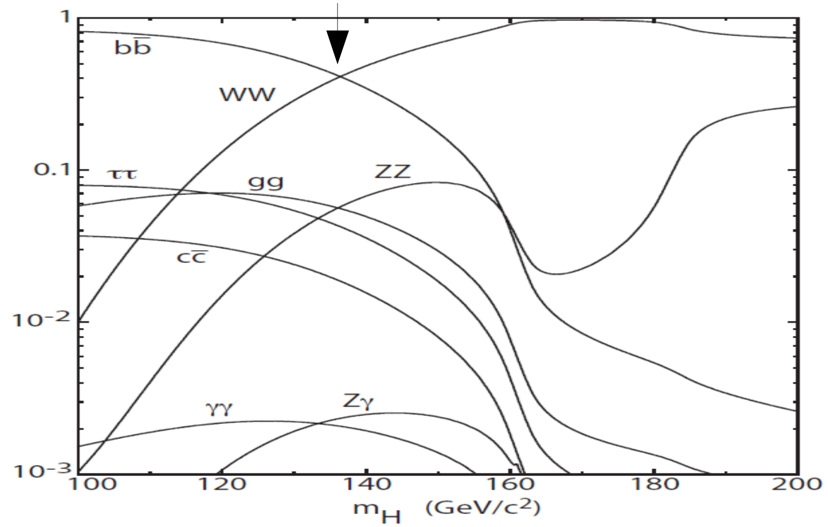

**Excess Global significance: 2.2 σ**

**Excess Global significance: 2.1 σ**

**Most of the sensitivity from H → γγ, H → ZZ or H → WW**

# Higgs searches at the Tevatron




$\sigma(H) \times B\,(H \rightarrow b\bar{b}) \sim 0.5$ pb
- overwhelmed by QCD
- other rare decay modes (γγ, ττ) less sensitive

$\sigma(VH) \times B\,(H \rightarrow b\bar{b}) \sim 0.1$ pb
- leptons from W/Z decays help to reduce background

| | CDF, D0 | Atlas, CMS |
|---|---|---|
| H→γγ | 10-13*SM | 1.5-2*SM |
| H→WW | ~3.5*SM | 1-2*SM |
| H→bb | ~2*SM | ~3.5*SM |

*Feb 2012 $m_H = 125$ GeV/c²*

→ **Associated production: main low mass channel**

**Complementary to LHC current analyses:**
Higgs-fermion coupling necessary to determine nature of a signal

**H → bb final states : topic of this talk**

# The Tevatron

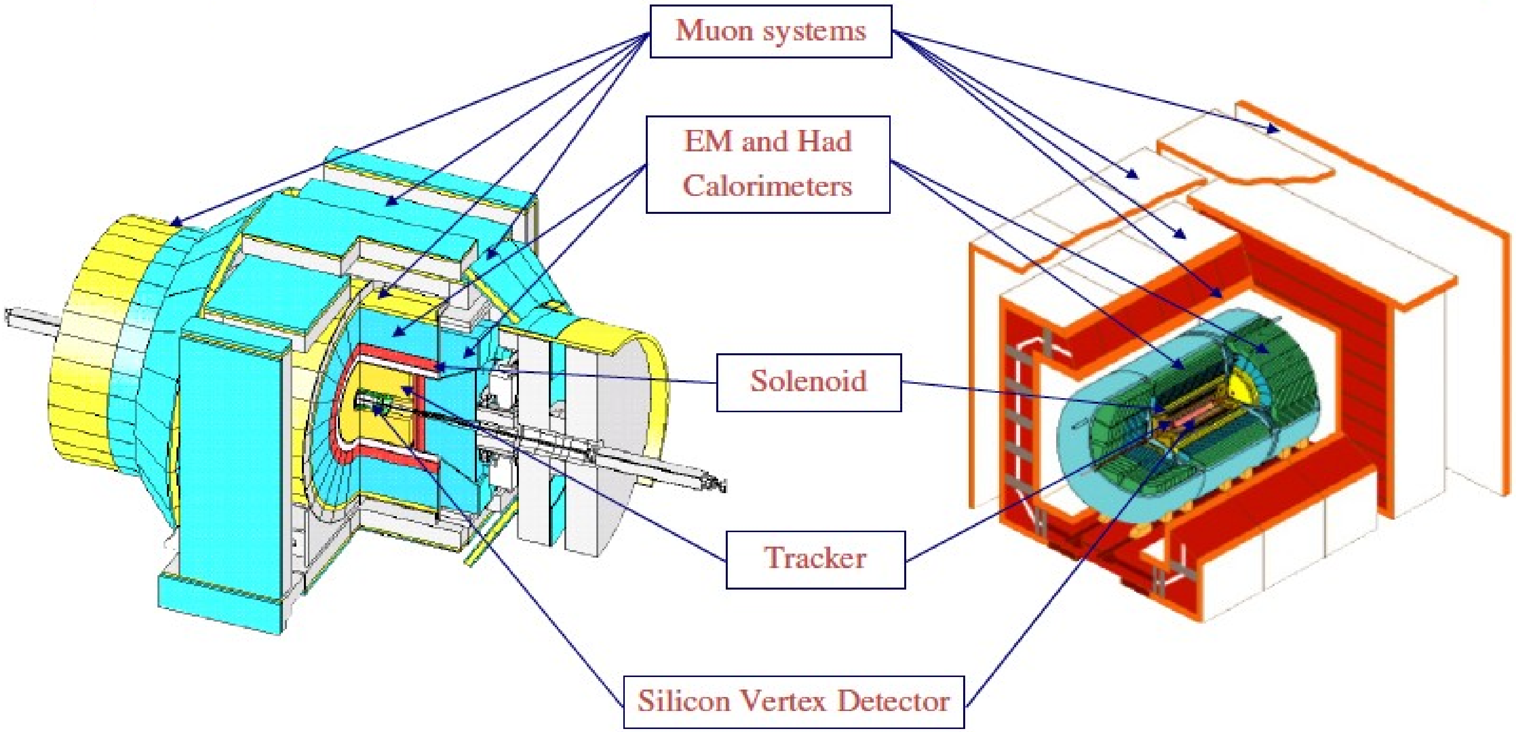
**$p\bar{p}$ collider, $\sqrt{s}$ = 1.96 TeV**

- 12 $fb^{-1}$ delivered
- ~90% data collected per experiment

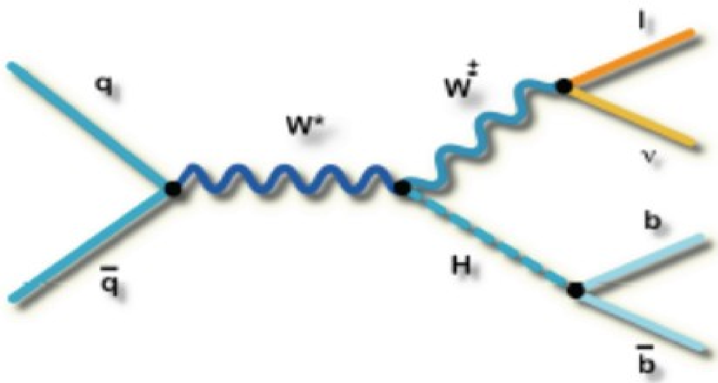
**Analyses presented today use full dataset**

CDF: $\int L = 9.45\ fb^{-1}$

D0 : $\int L = 9.7\ fb^{-1}$

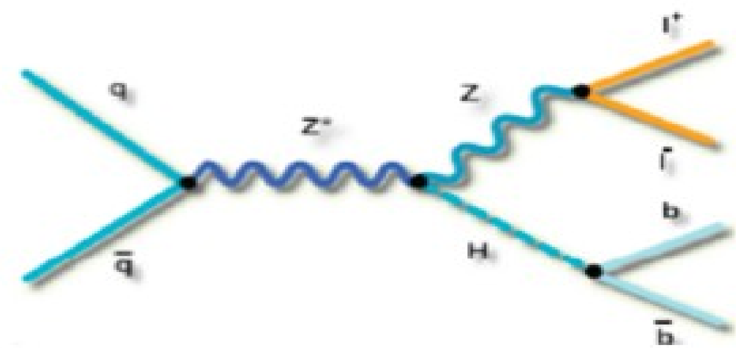


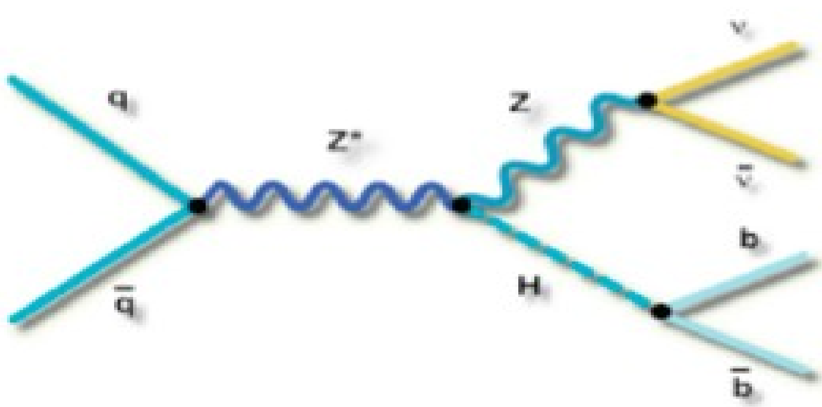
# $H \rightarrow b\bar{b}$ channels




WH→lνbb
Large production cross section
Backgrounds:
W+bb, ttbar and single top, Multijet production

ZH→llbb
Fully constrained
Small Signal
Backgrounds:
Z+jets, ttbar, Diboson




ZH→ννbb
3xsignal of ZH→llbb(+ contributions from WH)
Dominated by instrumental background

# Changes since last summer

- **Use full RunII dataset**
  +15%-50% of data

- **Inclusive triggering**
  use logical OR of multiple triggers : high pt leptons, MET, multiple objects
  → increase acceptance to both signal and background

- **Relax Event Selection**

- **Improved b-tagging techniques**

**Improving Signal-to-Background separation**

- **Improved dijet invariant mass resolution**

- **Improved multivariate discriminants**

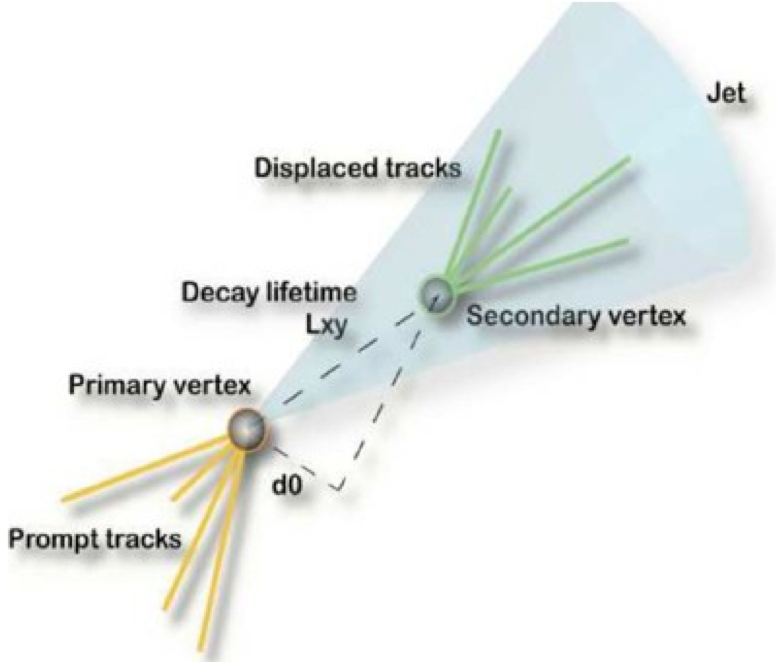
- **Improved background modeling**

# B-quark jet tagging

**Identify b's exploiting long life-time and large mass of b-hadrons**

**MVA approach,** using as input variables:
- secondary vertex
- track impact parameter
- jet mass
- distribution of tracks in jet cone

Etc..




**Pro's:** continuous output can be optimized

New

- CDF – HOBIT NN
  - NN discriminant trained using properties of H→ bb decays

| | New Tag Efficiency | Old Tag Efficiency |
|---|---|---|
| B-jets | 54 – 59% | 39 – 47 % |
| LF jets | 1 – 2% | 1 – 2 % |

- D0 – $L_b$ BDT
  - Continuous output ranked into 12 operating points, based on purity

| | New Tag Efficiency | Old Tag Efficiency |
|---|---|---|
| B-jets | 50 – 70% | 45 – 65 % |
| LF jets | 0.5 – 4.5% | 0.5 – 4.5 % |

B-jet tagging efficiency can not be directly compared between CDF and D0

# B-quark jet tagging in action

**Optimized b-tagger:** → **increase in acceptance**

CDF: >10% sensitivity improvement due to HOBIT

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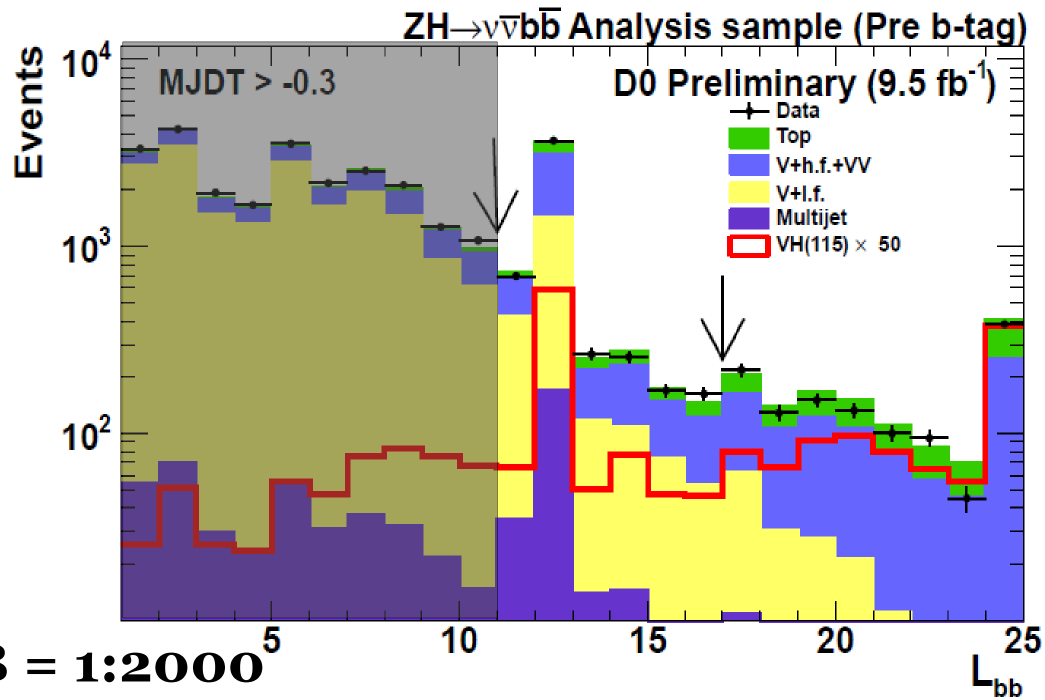
**Sort events in orthogonal samples according to purity of b-tagged jets:**
improve sensitivity




**S:B = 1:2000**

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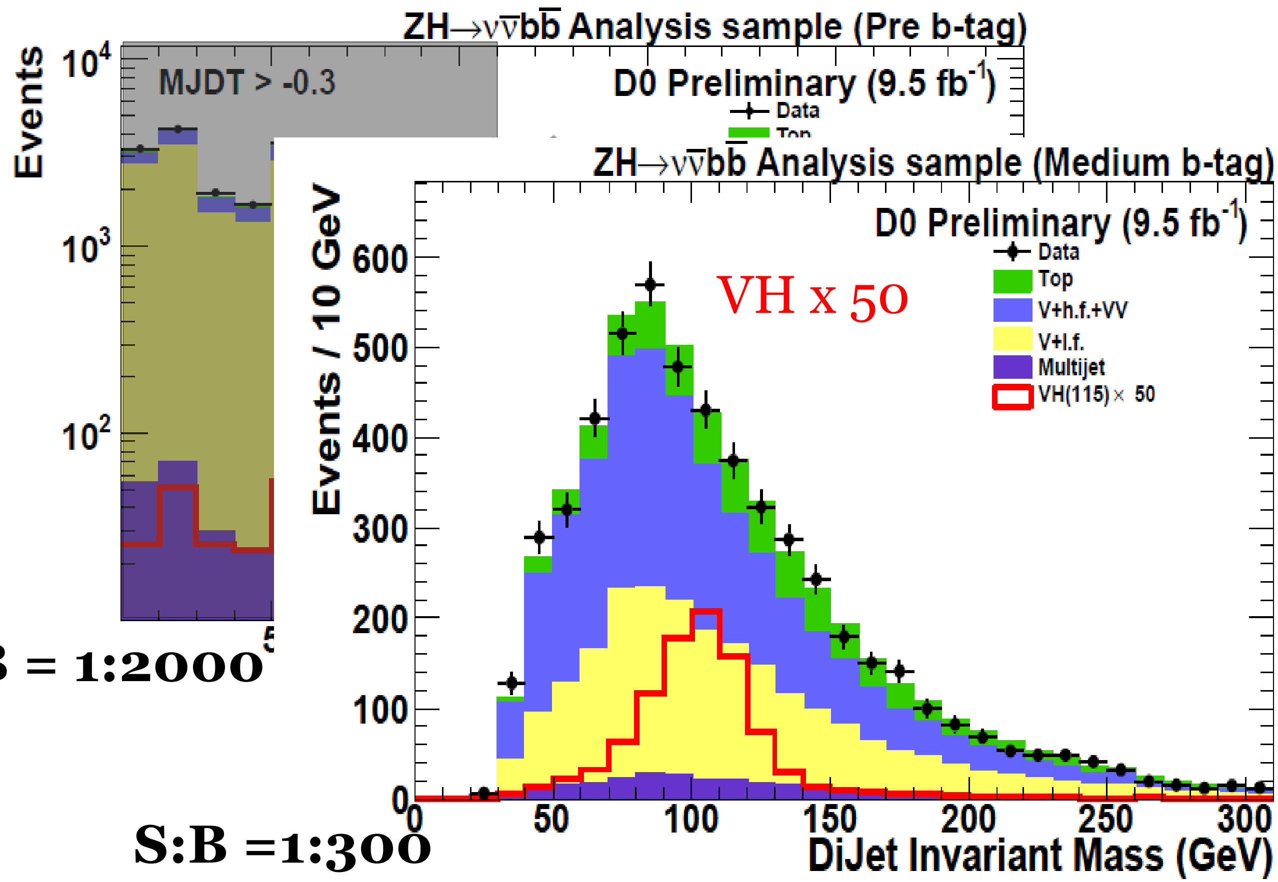


S:B = 1:2000

S:B =1:300

# B-quark jet tagging in action

**Optimized b-tagger:** → **increase in acceptance**

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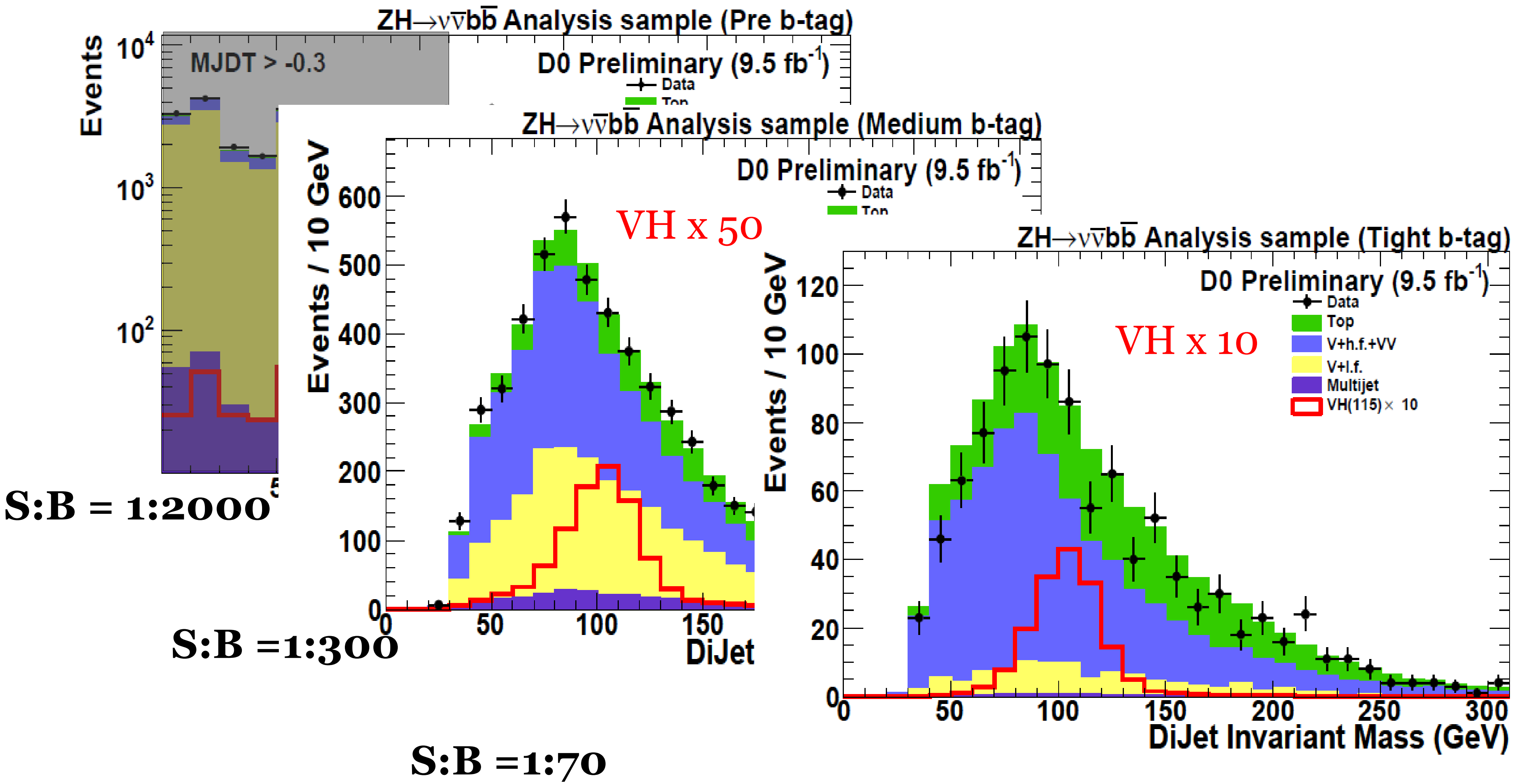
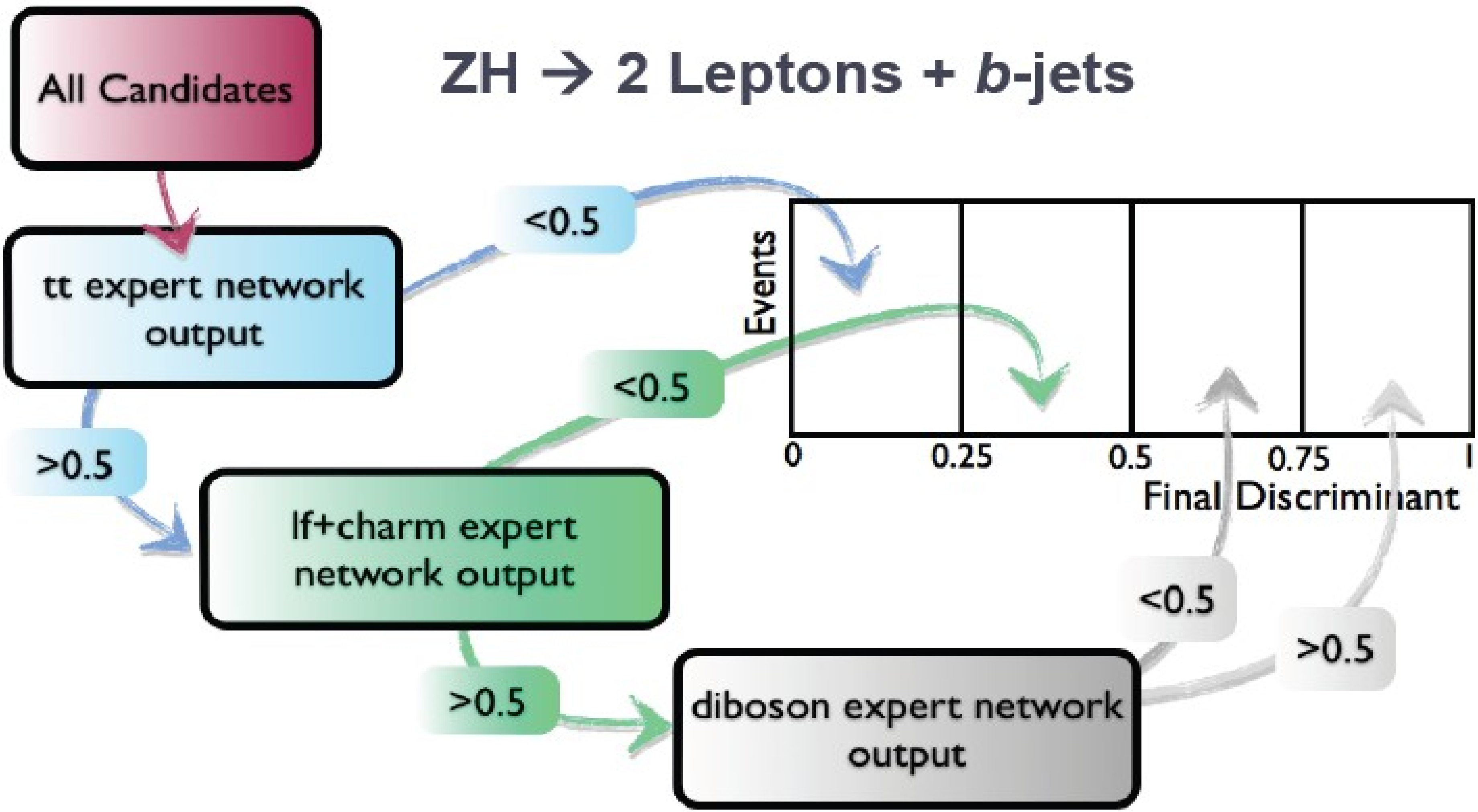


# Signal-to-background separation

- Classify events in regions with increasing S/B ratio
- Use MVA to discriminate background from signal



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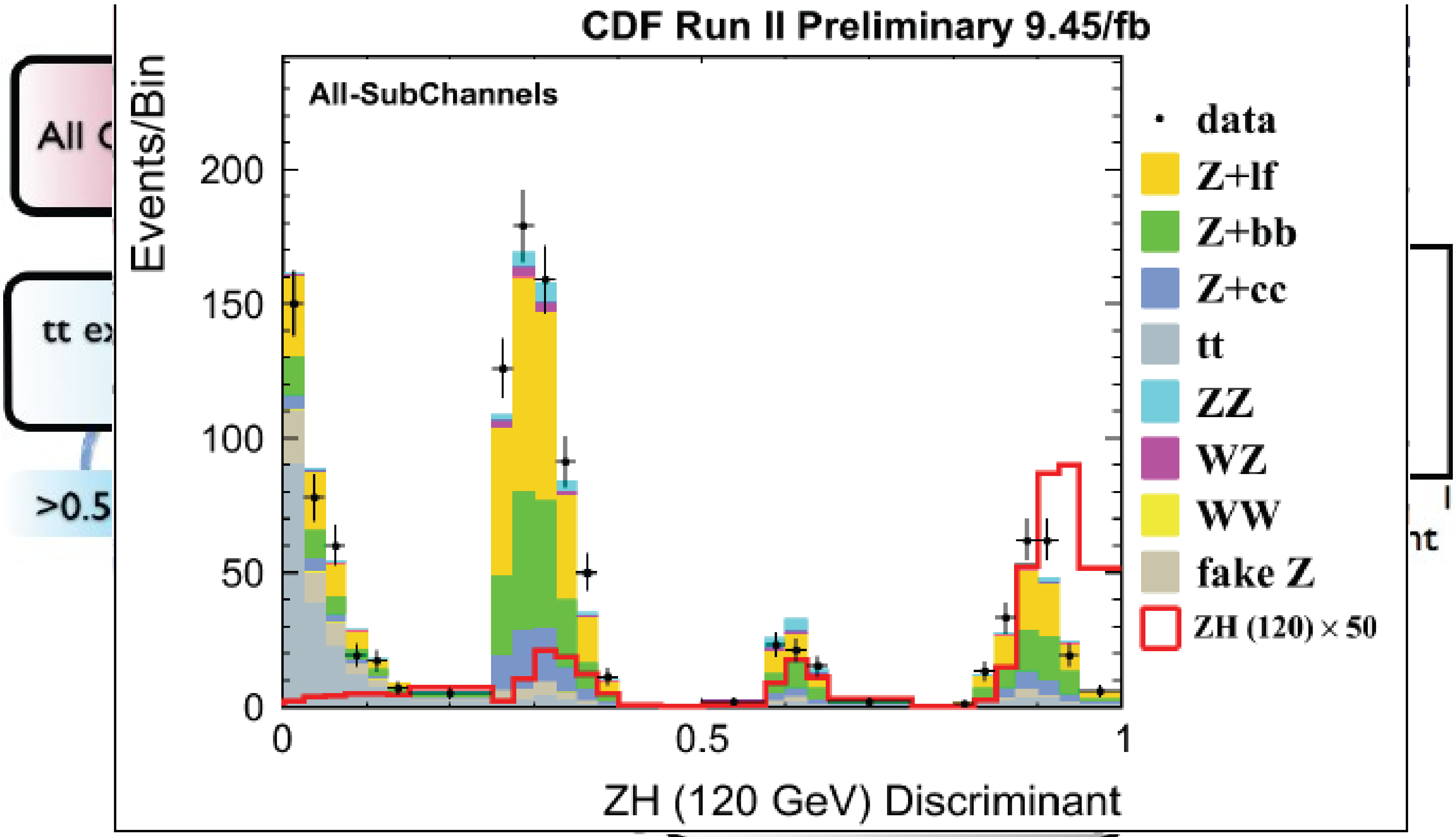
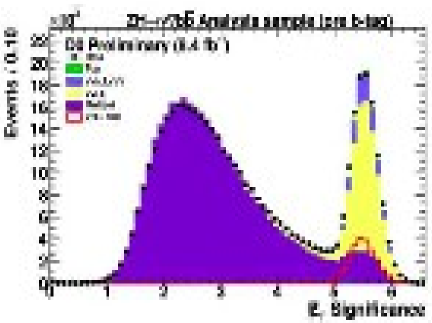


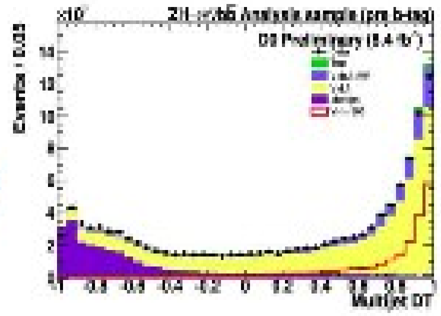

**+ 15% in sensitivity**

# Validation of Higgs Searches

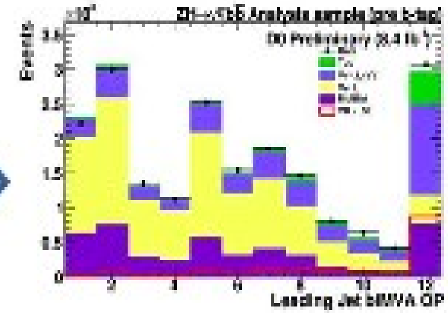
Reminder of what we have  done:



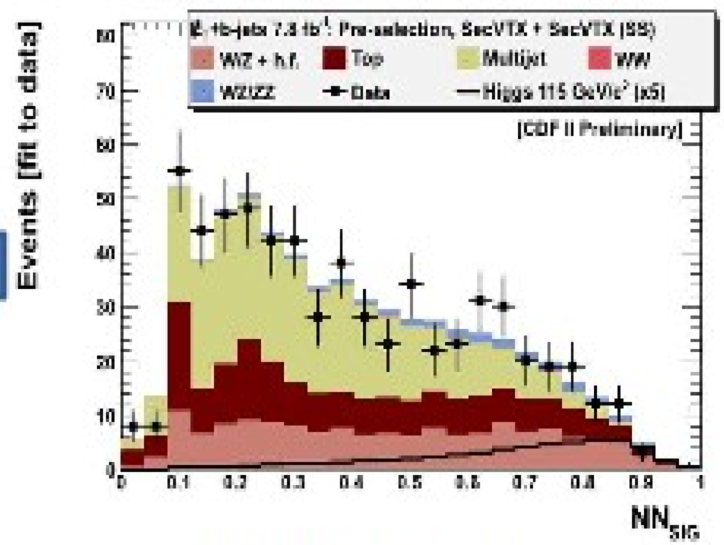
**Kinematic event selection**



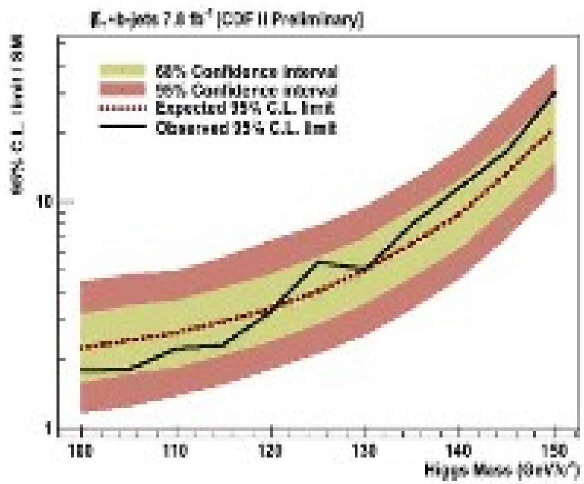

**Multijet removal**




**b-tagging**



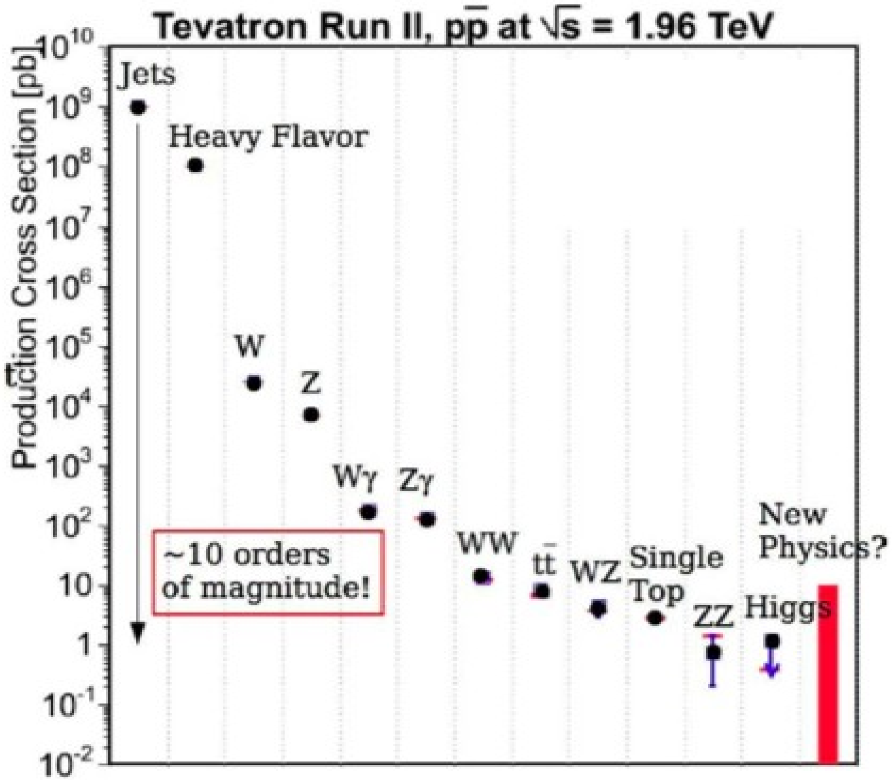

**Final discriminant**
**SVM, BDT, RF…**

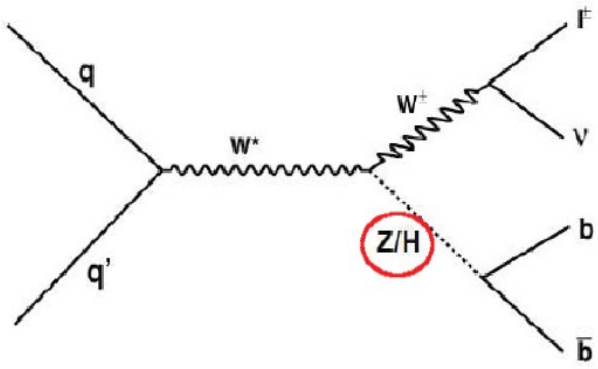



**Statistical analysis**
**Log Likelihood Ratio (LLR)**
**Marginalization of nuisance parameters**

# Validation of Higgs Searches

- WZ/ZZ $\rightarrow b\bar{b}$ signal is ~4 x VH $\rightarrow b\bar{b}$
  $\rightarrow$ use σ(WZ/ZZ) to validate methods for VH search



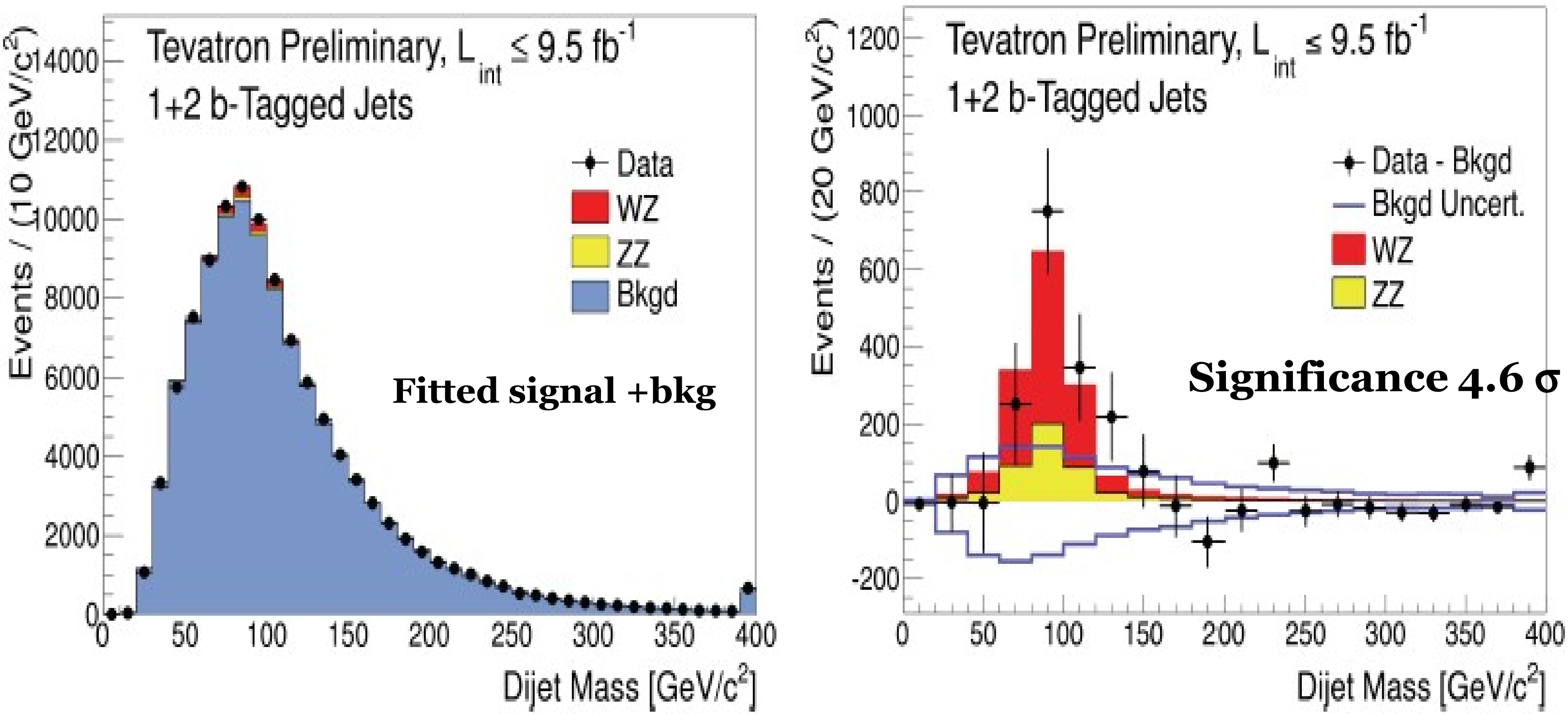




$$\sigma(W^{\pm}Z^{0}) = 3.22^{+0.20}_{-0.17}(\text{scale})^{+0.11}_{-0.08}(\text{PDF})\ \text{pb}$$

$$\sigma(Z^{0}Z^{0}) = 1.20^{+0.05}_{-0.04}(\text{scale})^{+0.04}_{-0.03}(\text{PDF})\ \text{pb}$$

**Use current VH analysis event selection/bkg model/event classification**
**Train final discriminant for WZ/ZZ $\rightarrow$ $b\bar{b}$ signal .**

# Validation of Higgs Searches

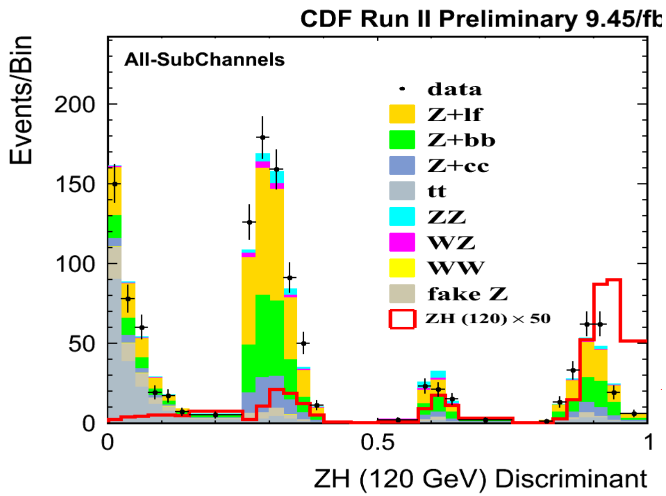


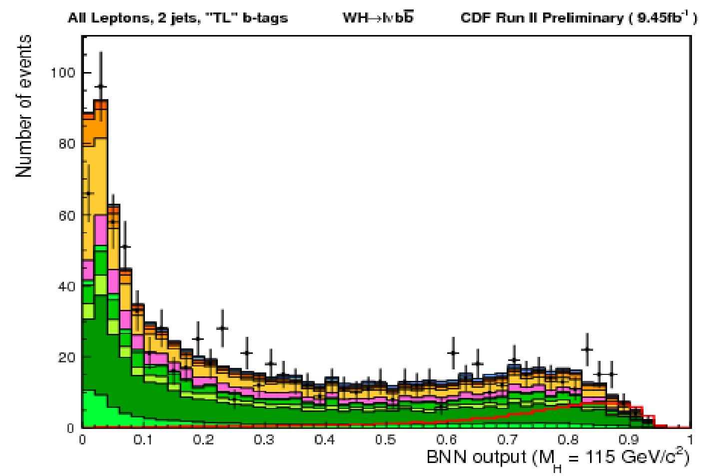

$\sigma(WZ + ZZ)$ = 4.47 ± 0.64 (stat) ± 0.73 (stat) pb

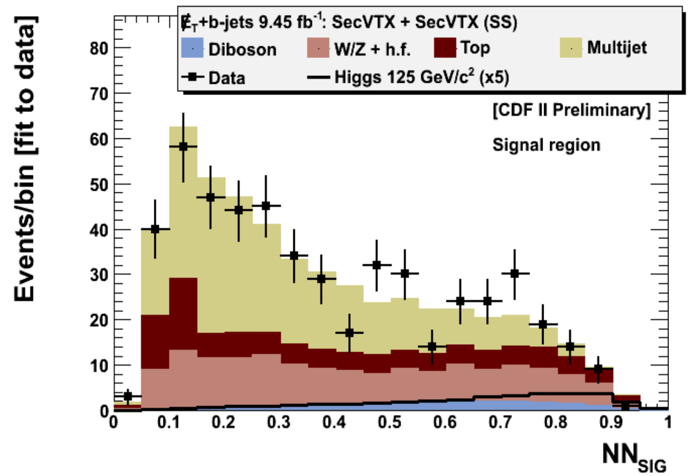
SM prediction = 4.4 ± 0.3 pb

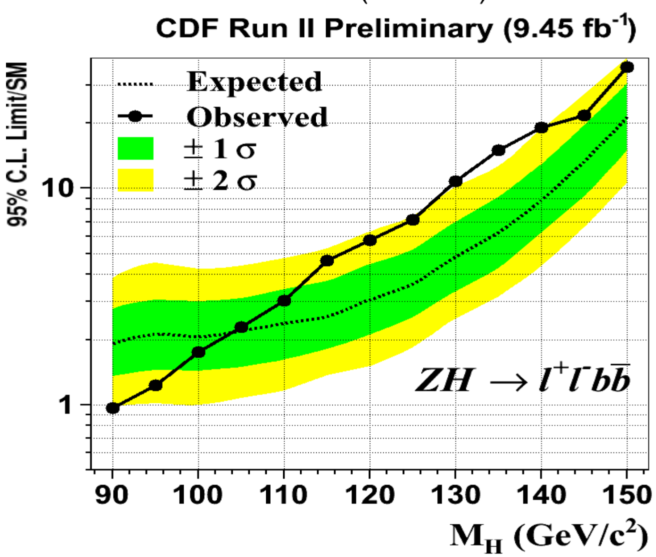
# CDF Low Mass Exclusion Limit

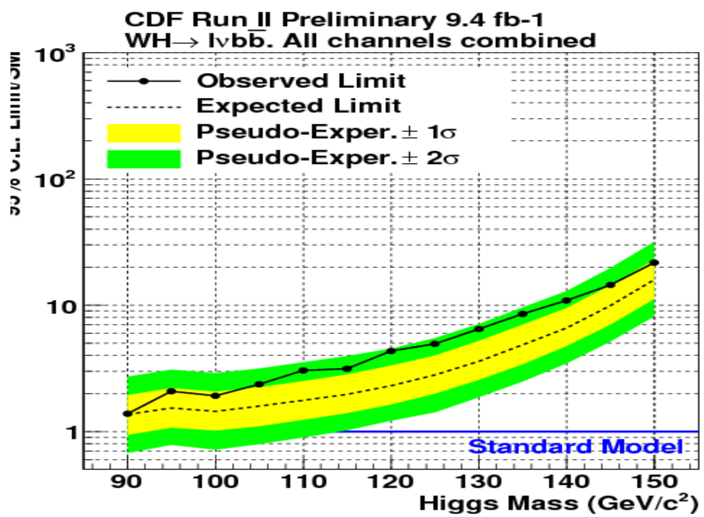
| $ZH \to ll\, b\bar{b}$ | $WH \to l\nu\, b\bar{b}$ | $ZH \to \nu\nu\, b\bar{b}$ |
|---|---|---|

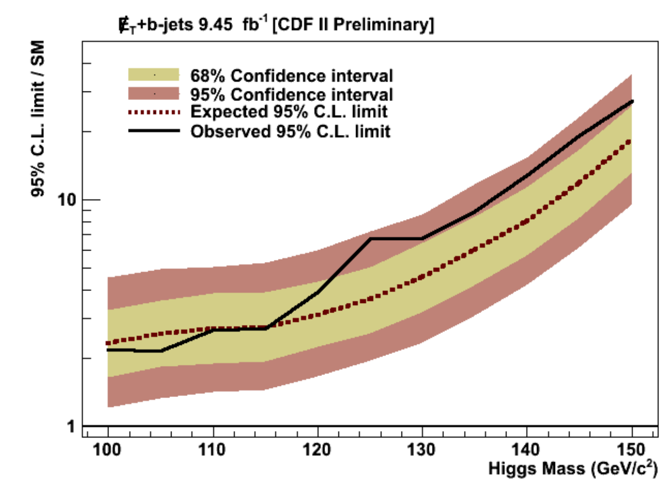


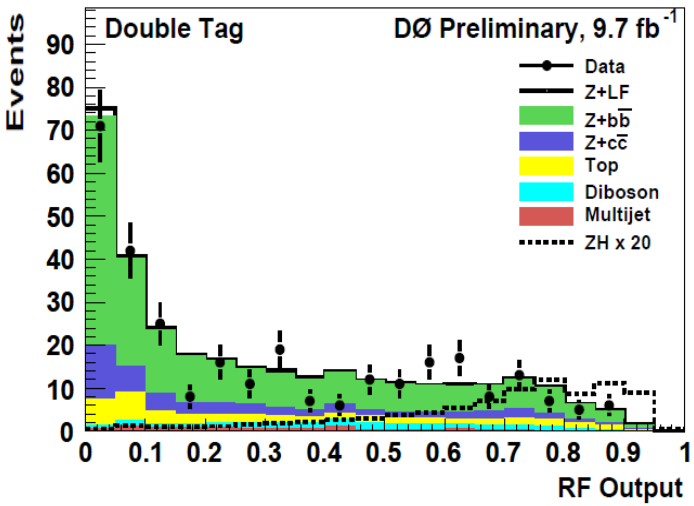



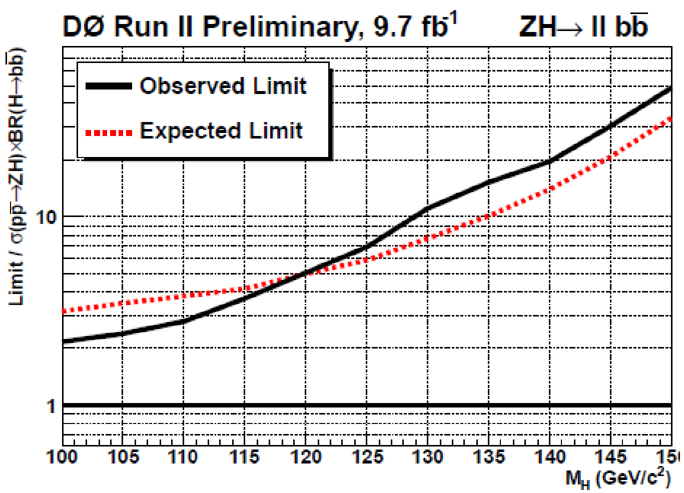

@ $m_H$ =125 GeV/c²

| | $ZH \to ll\, b\bar{b}$ | $WH \to l\nu\, b\bar{b}$ | $ZH \to \nu\nu\, b\bar{b}$ |
|---|---|---|---|
| Exp (x $\sigma_{SM}$) | 3.6 | 2.79 | 3.6 |
| Obs(x $\sigma_{SM}$) | 7.2 | 4.93 | 6.75 |

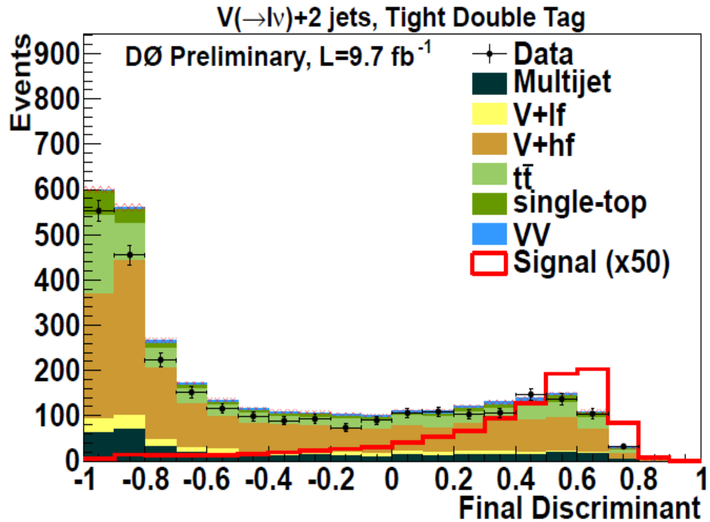
# D0 Low Mass Exclusion Limit

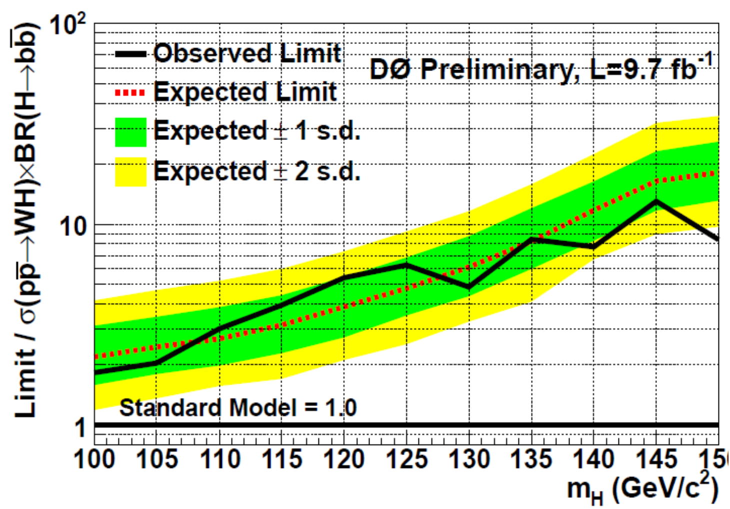
## $ZH \rightarrow ll\, b\bar{b}$



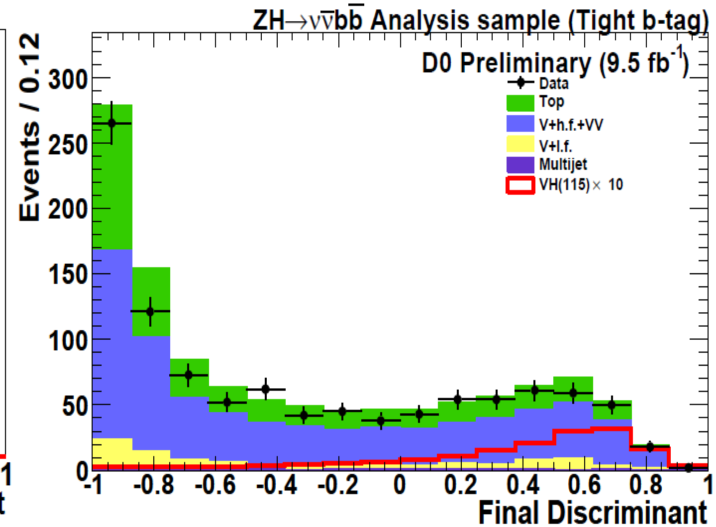



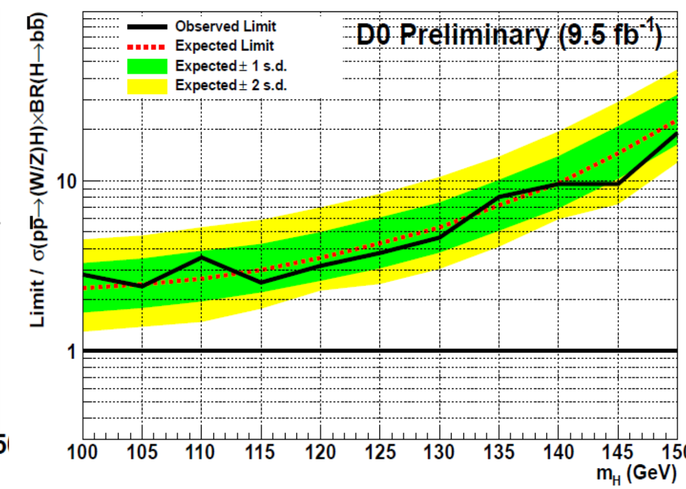

## $WH \rightarrow l\nu\, b\bar{b}$




## $ZH \rightarrow \nu\nu\, b\bar{b}$

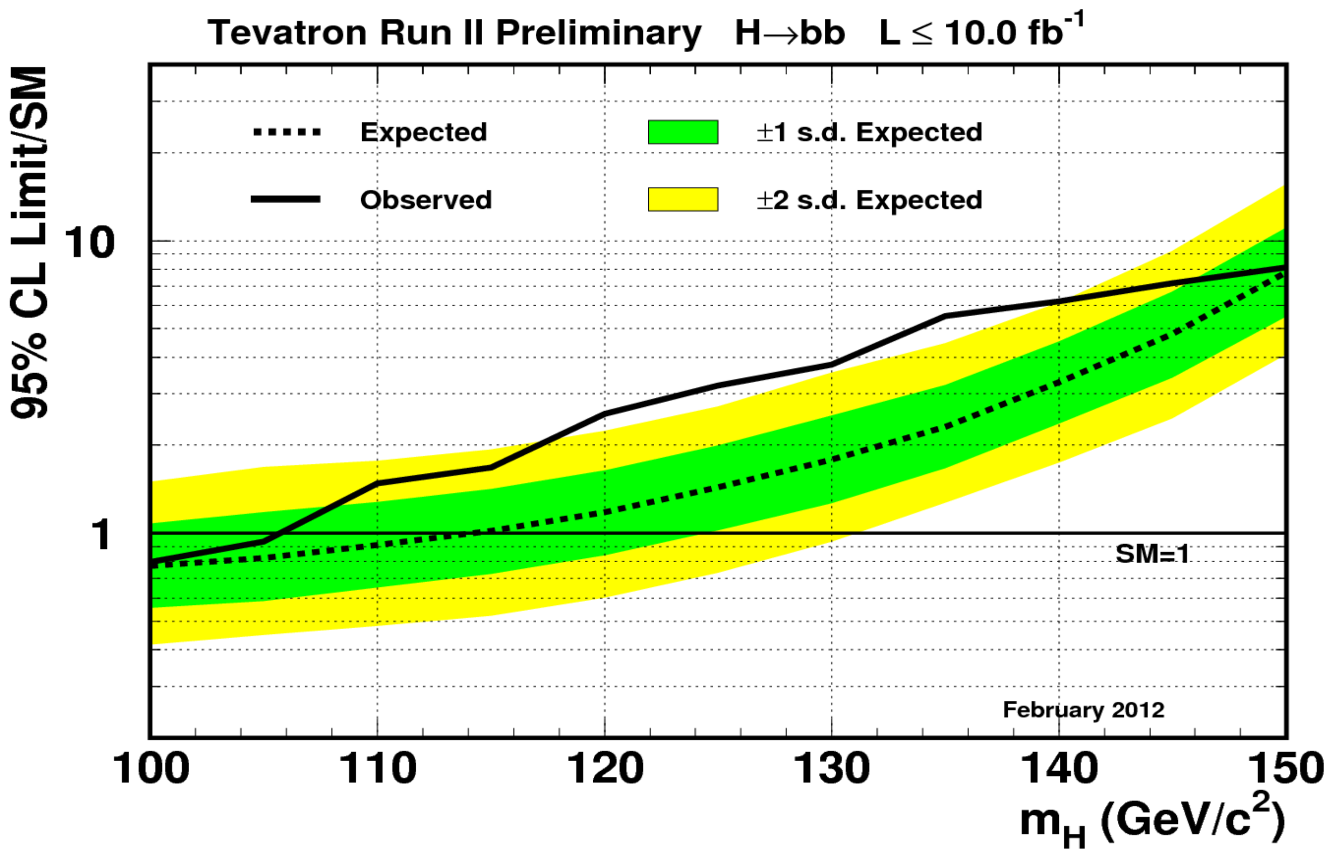



@ $m_H = 125\ \mathrm{GeV}/c^2$

| | $ZH \rightarrow ll\, b\bar{b}$ | $WH \rightarrow l\nu\, b\bar{b}$ | $ZH \rightarrow \nu\nu\, b\bar{b}$ |
|---|---|---|---|
| Exp (x $\sigma_{SM}$) | 5.9 | 4.81 | 4.3 |
| Obs(x $\sigma_{SM}$) | 6.9 | 6.26 | 3.8 |

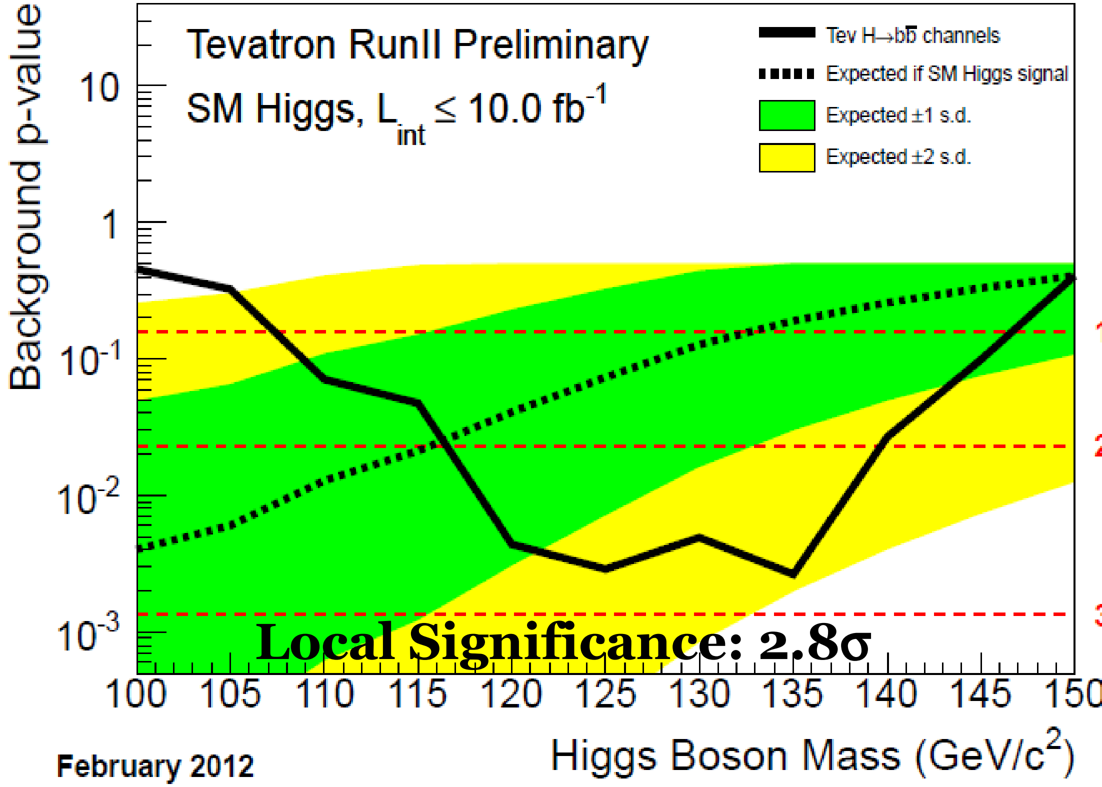
# Tevatron Low Mass Exclusion Limit



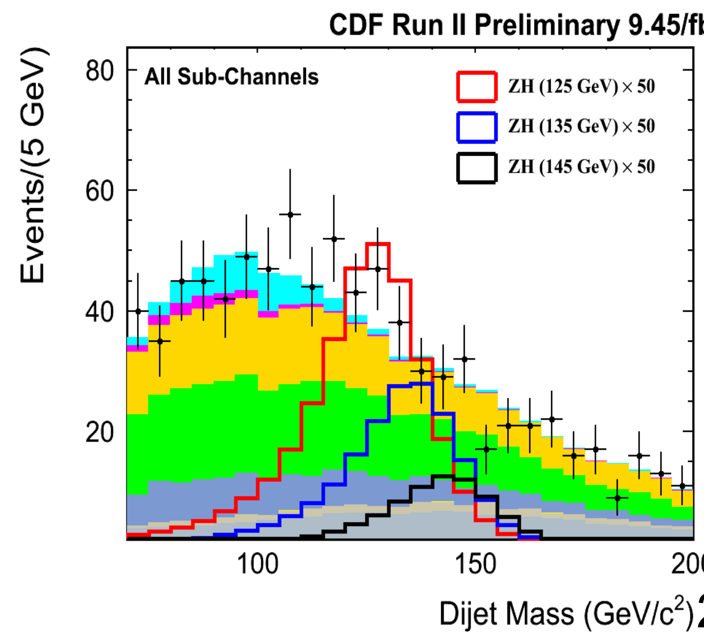

Observed(Expected) @ $m_H$ =125 GeV/$c^2$

3.2(1.44) $\sigma_{SM}$

# Low Mass Excess Significance




**Local Significance: 2.8σ**




Local significance is diluted by look elsewhere effect

**Look Elsewhere Effect at the Tevatron:**

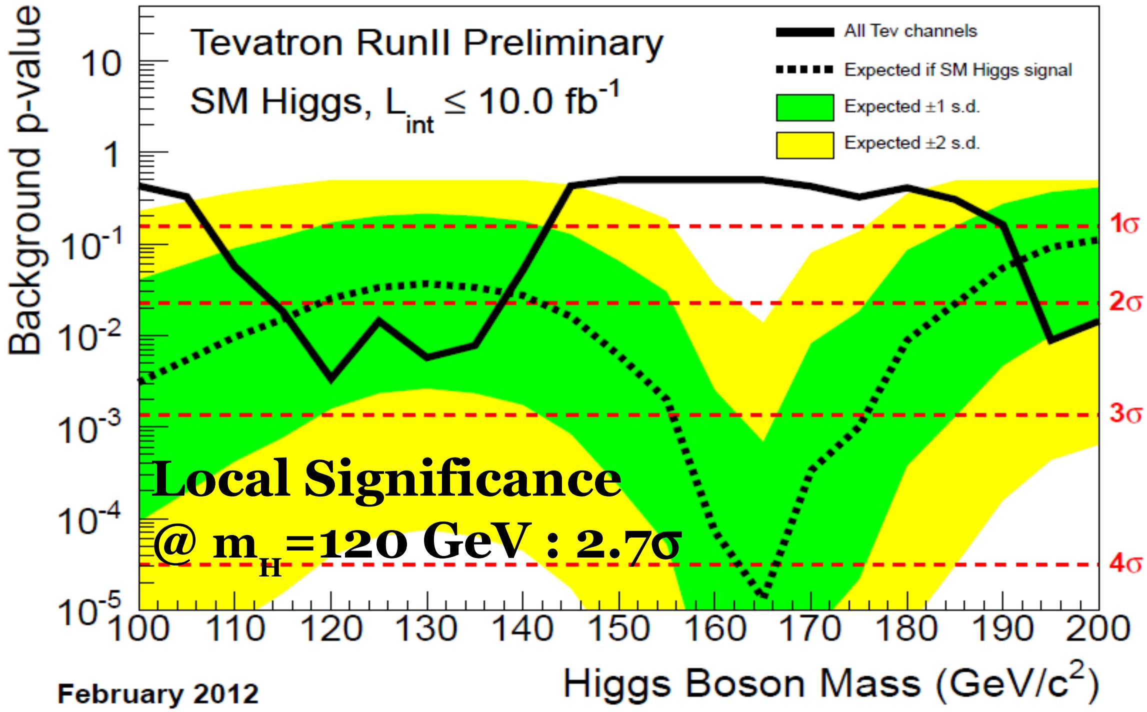
Di-Jet Mass resolution ~ 15 GeV/c$^2$

~ 2 independent searches in $100 < m_H < 150$ GeV/c$^2$

→ LEE factor ~ 2

**Global Significance: 2.6σ**

# Tevatron All Channels Combination




| | $M_H$ [ GeV/c²] | Local Significance | Global Significance |
|---|---|---|---|
| Tevatron | 120 | 2.7**σ** | 2.2**σ** |
| Atlas | 126 | 2.5**σ** | 2.2**σ** |
| CMS | 124 | 3.1**σ** | 2.1**σ** |

# Summary

• **LHC experiments will reach sensitivity to rule out SM Higgs boson or see a significant excess in the next few months**

• **Currently, low mass Higgs searches at the Tevatron show comparable sensitivity and similar excess to LHC:**

Expected 95 C.L. limit (in absence of Higgs signal) < .15 x $\sigma_{SM}$ for $m_H$< 180 GeV/$c^2$

Broad excess in observed data compared the the bkg-only hypothesis
105 < $m_H$ < 145 GeV/$c^2$ with global significance ~ 2.2σ

• **Tevatron searches currently provide a unique test of Standard Model**

• **In the near future:**
D0 expect to incorporate significant improvements
CDF working on implementing new b-tagger in MET+$b\bar{b}$ analysis

→ **more new interesting results from the Tevatron for the summer**

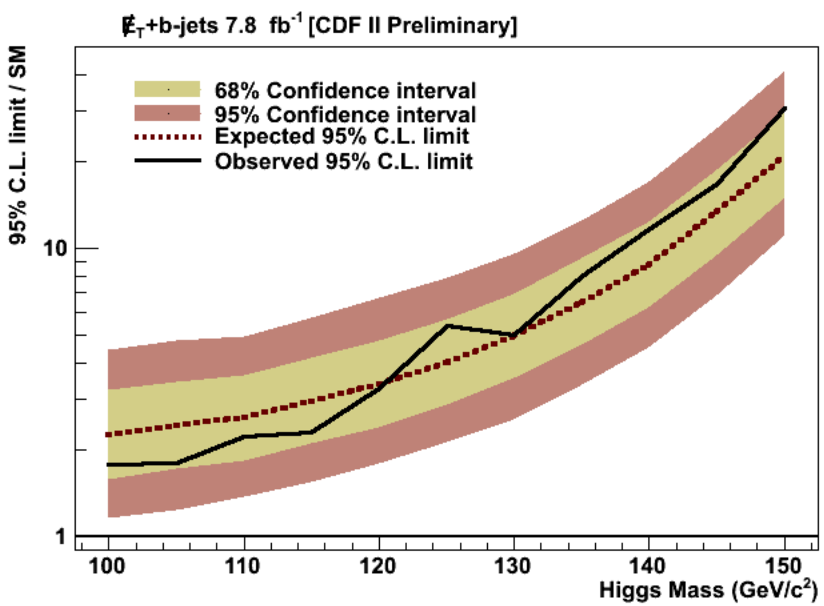
• **For additional details see:**

- **Tevatron:** http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/
- **CDF:** http://www-cdf.fnal.gov/physics/new/hdg/Results.html
- **D0:** http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

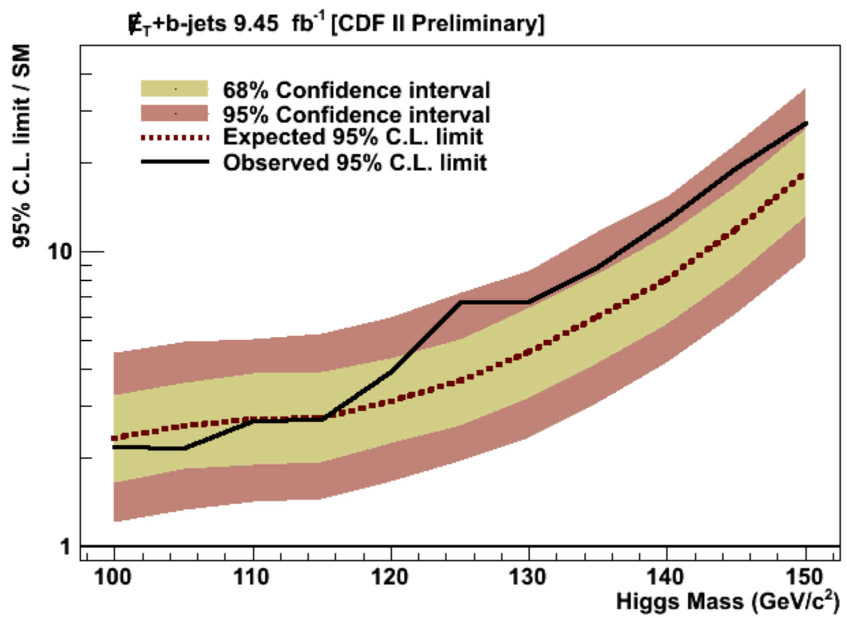
# Back Up

# CDF ZH $\rightarrow \nu\nu\, b\bar{b}$

- 21% additional luminosity
- Small improvements in background rejection
- Limits show same basic behavior with 0.5 to 1.0σ increases in significance of excess



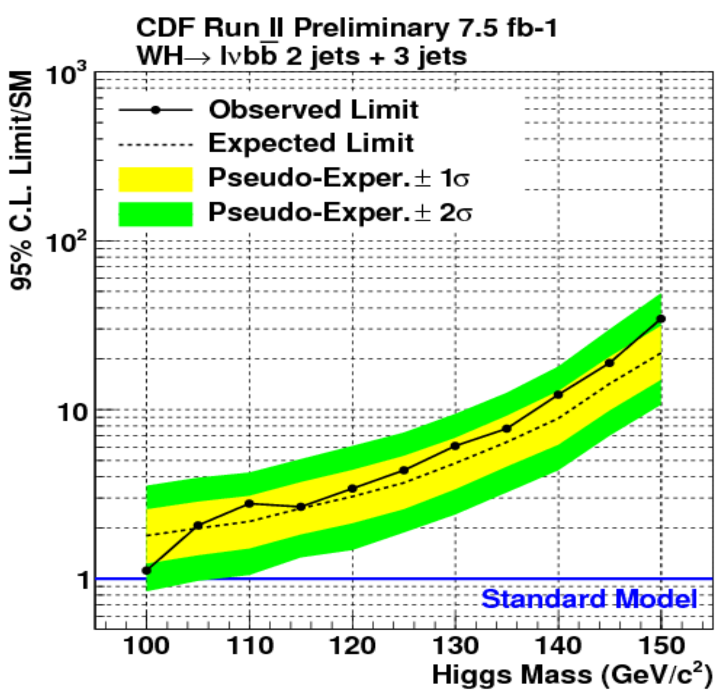

Summer 2011



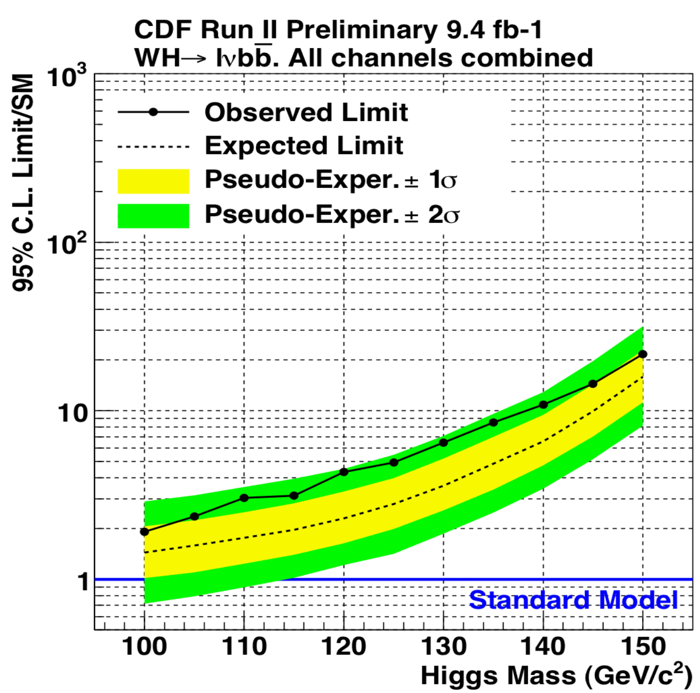

Winter 2012

# CDF WH →lν b$\bar{b}$

- 26% (69%) additional luminosity for 2-jet (3-jet) channels
- 5-10% level lepton acceptance/trigger efficiency improvements
- New HOBIT b-tagger equivalent to adding another 20% in additional luminosity
- Limits show same basic behavior with 1.0 to 1.5σ increases in significance of excess

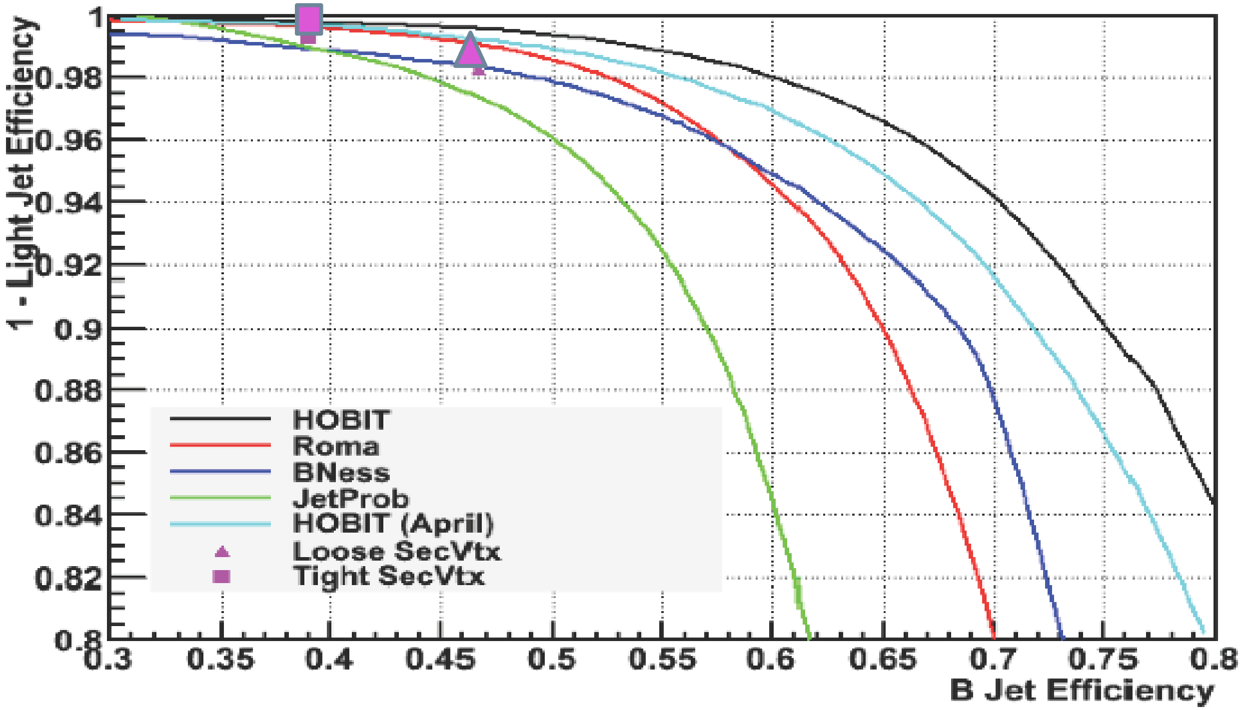



Summer 2011




Winter 2012

# Hobit Performance




| mistag rate | SecVtx efficiency | HOBIT efficiency |
|---|---|---|
| ~1% | 39% | 54% |
| ~2% | 47% | 59% |

# Hobit Performance in WH → lν bb

OLD

| Tagging Category | S/√B |
|---|---|
| SecVtx+SecVtx | 0.228 |
| SecVtx+JetProb | 0.160 |
| SecVtx+Roma | 0.103 |
| Single SecVtx | 0.146 |
| Sum | 0.331 |

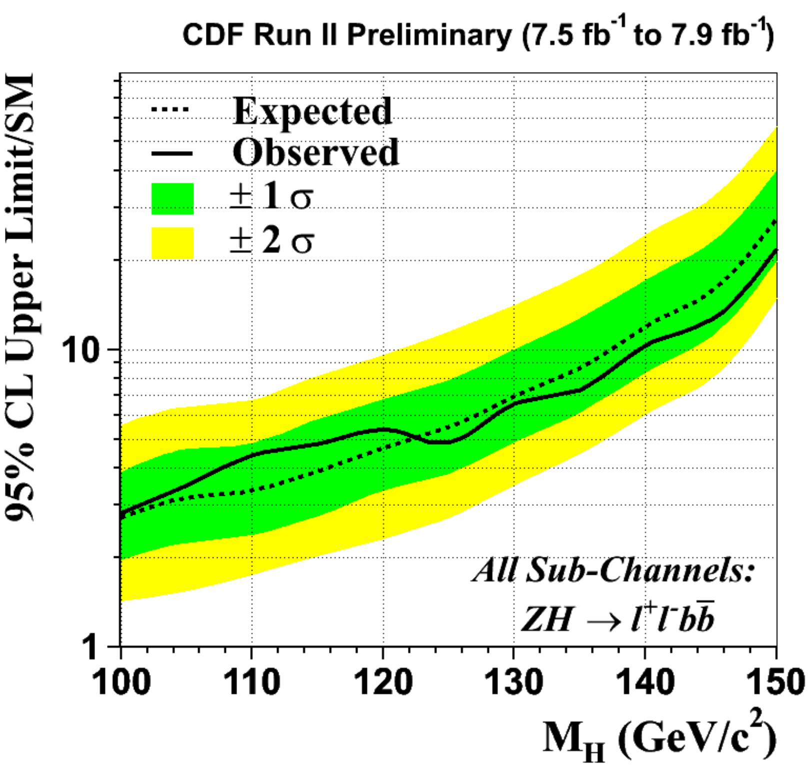
NEW - HOBIT

| Tagging Category | S/√B |
|---|---|
| Tight-Tight | 0.266 |
| Tight-Loose | 0.200 |
| Single Tight | 0.143 |
| Loose-Loose | 0.053 |
| Single Loose | 0.044 |
| Sum | 0.369 |

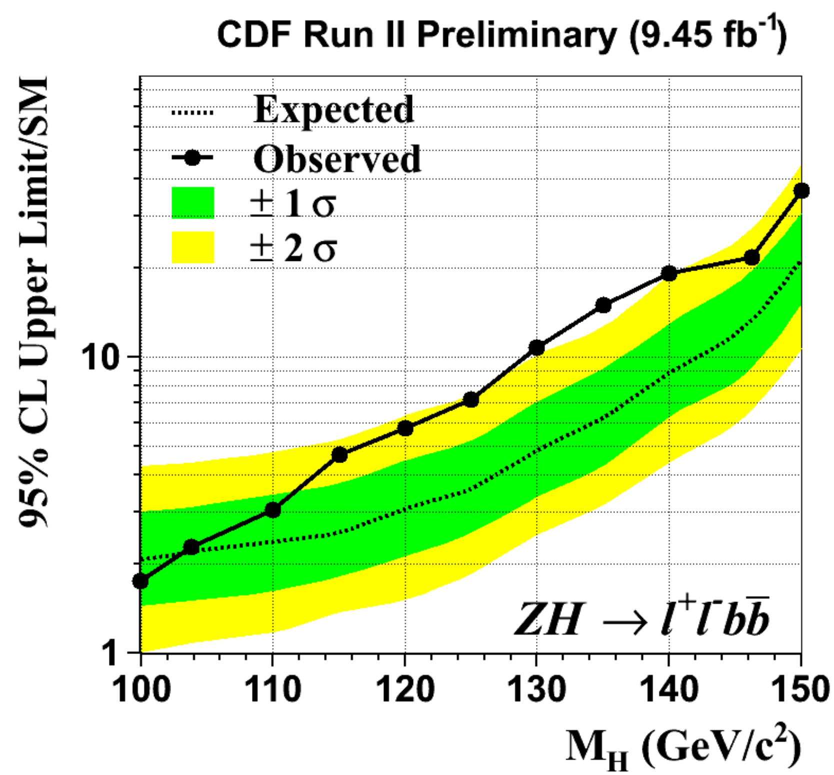
- Significant effort to optimize tagging categories and thresholds for loose/tight HOBIT selections
- 11% gain in S/√B translates directly into increase in overall search sensitivity

# CDF ZH →ll b$\bar{b}$

- 23% additional luminosity
- More gain from HOBIT in this analysis than WH (original tagging not as sophisticated)
- 56% of data events in current analysis were not included in previous analysis!
- 37% sensitivity improvement (4.67 →2.95 at mH=120 GeV/c2)



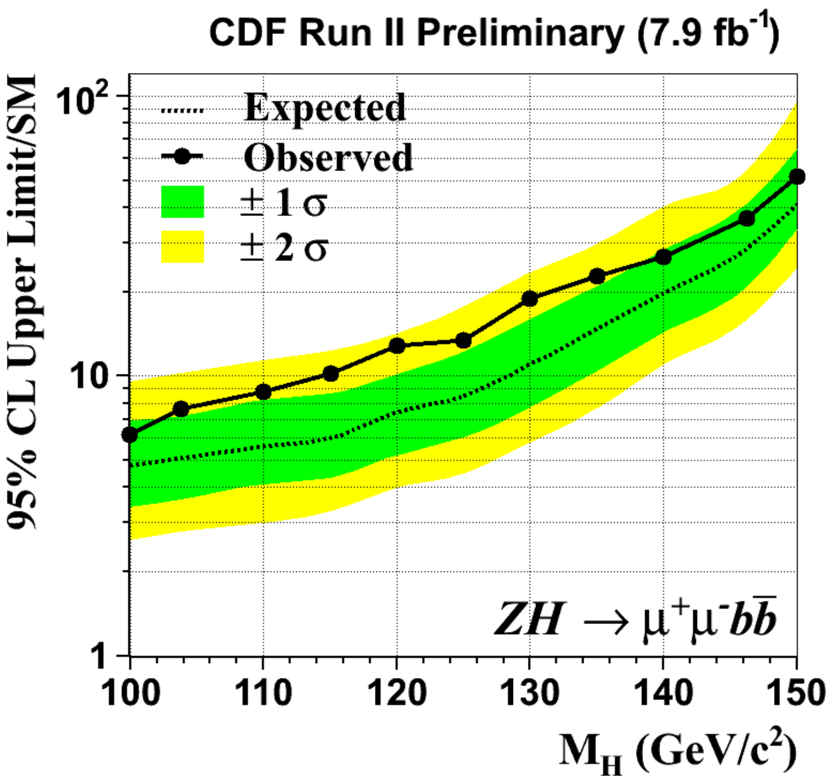

Summer 2011



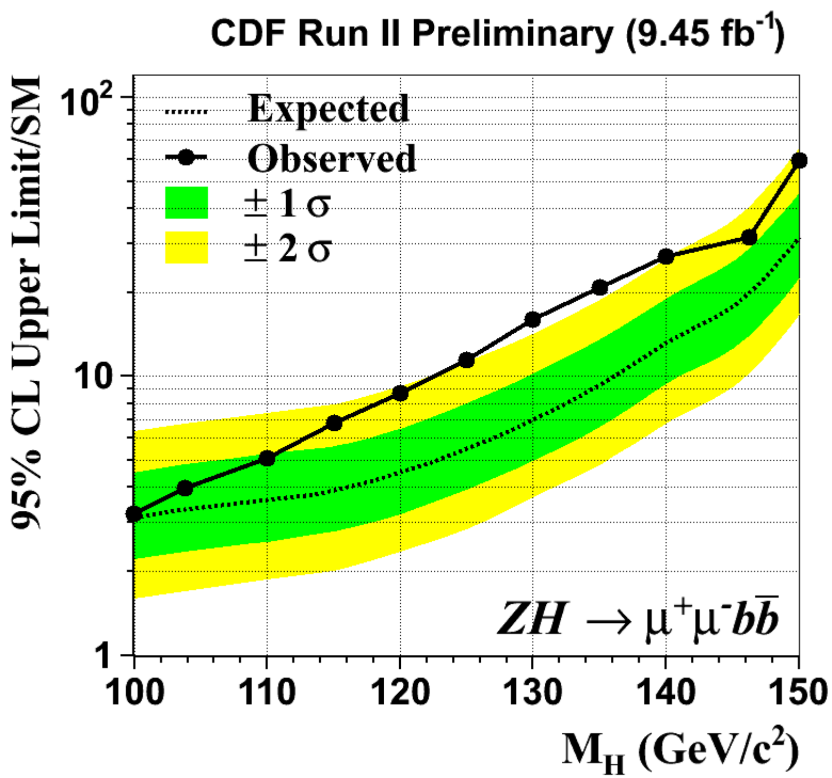

Winter 2012

# CDF ZH $\rightarrow \mu\mu\ b\bar{b}$

- Muon channels
- See only a slight change in behavior of limits (~0.5σ)



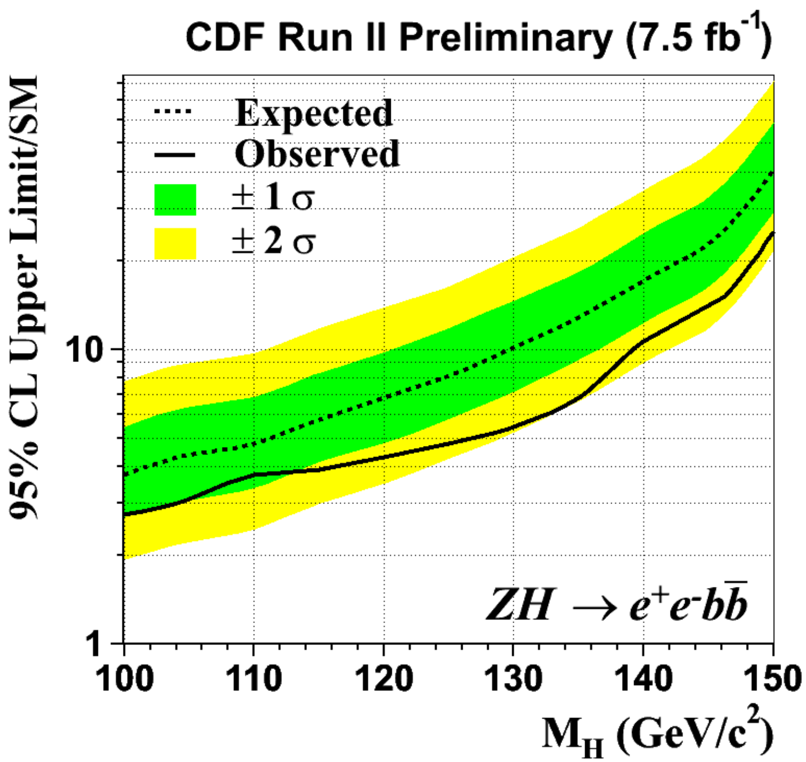

Summer 2011



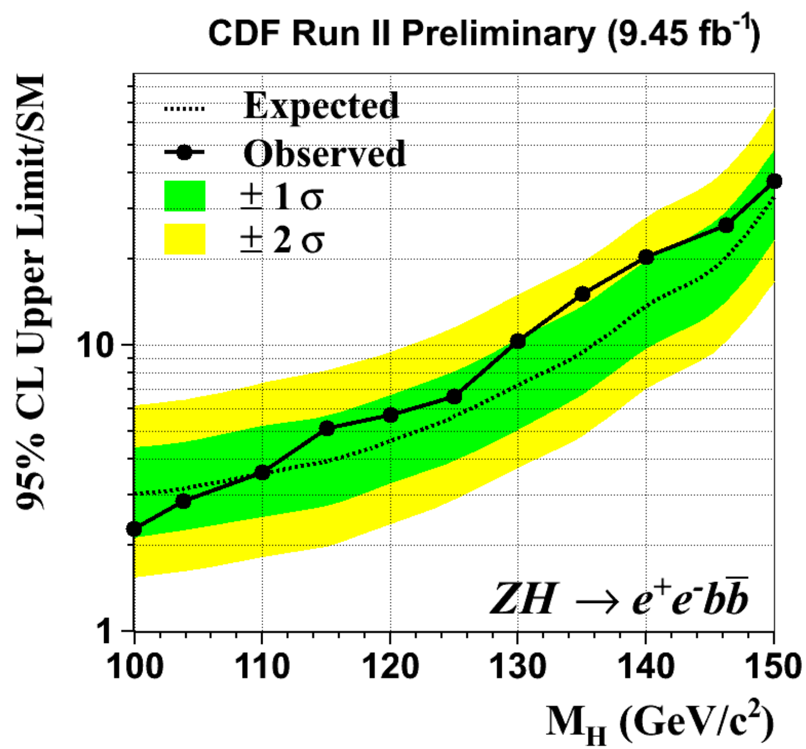

Winter 2012

# CDF ZH →ee $b\bar{b}$

- Electron channels
- Here we observe a significant change




Summer 2011




Winter 2012

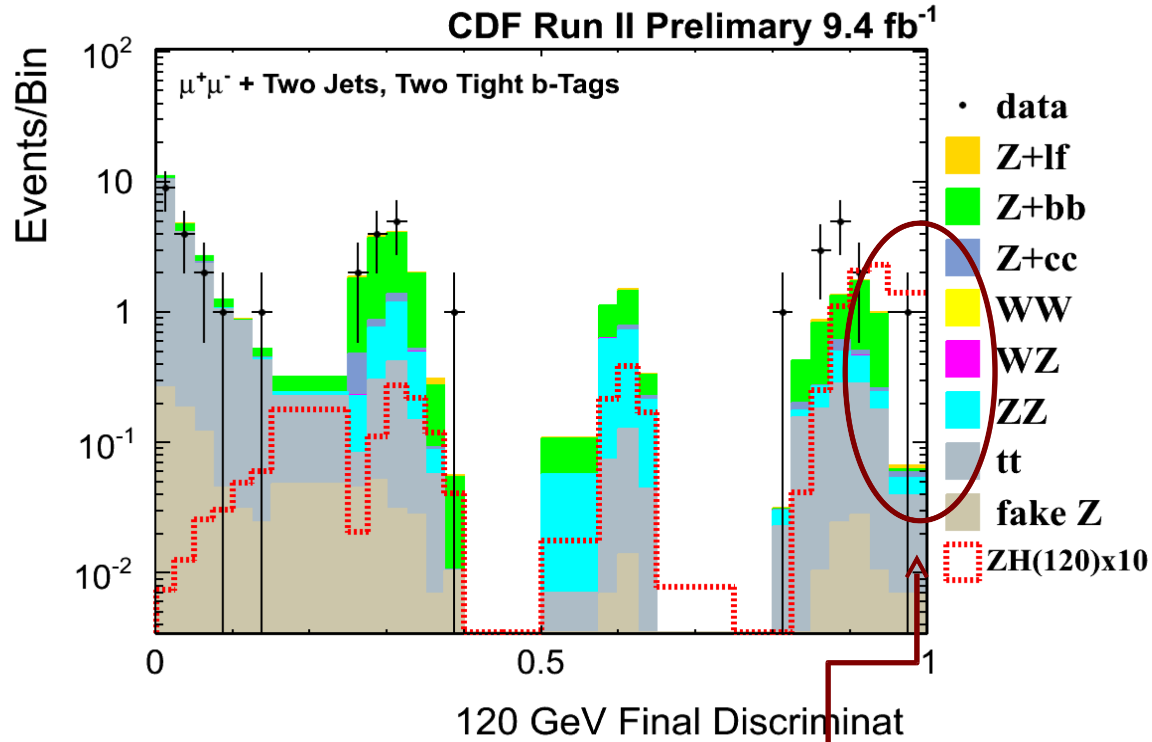
# CDF ZH →ll b$\bar{b}$

ZH → llbb channel has :

- lowest backgrounds
- smallest expected signal yields (9 events for mH=120 GeV/c²)

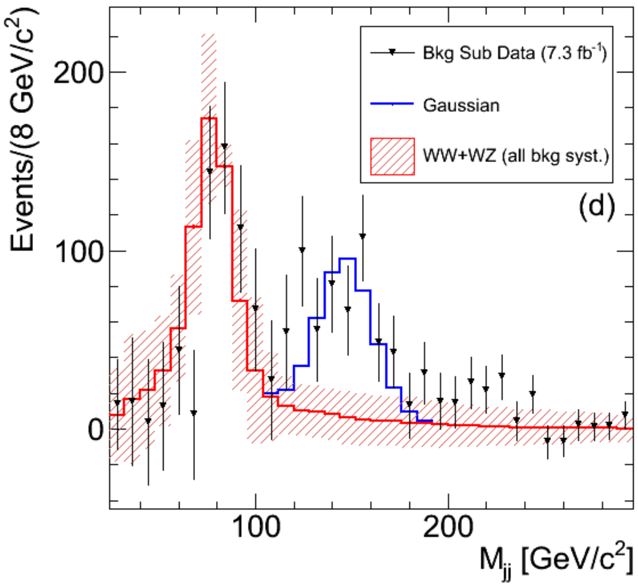
Some discriminant bins with large S/B

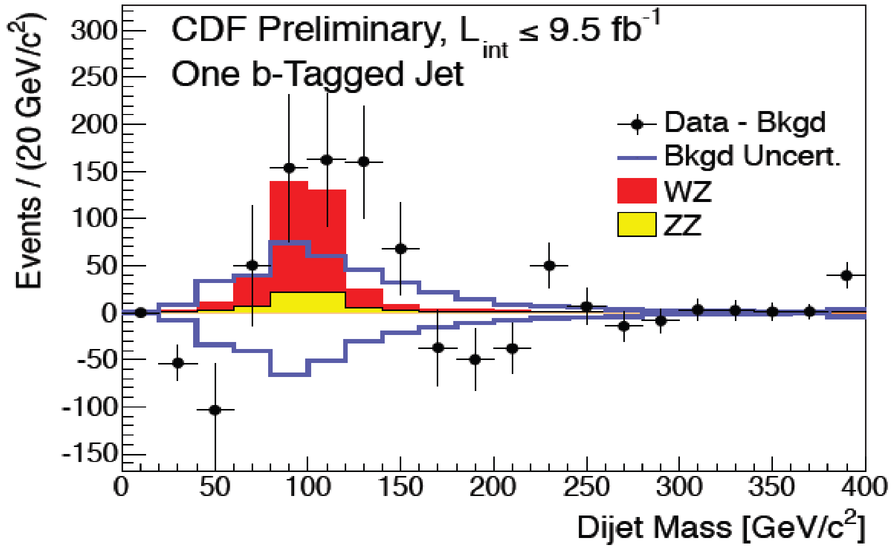
- Low probability for observing events in these bins
- A few such events can have substantial effects on observed limits

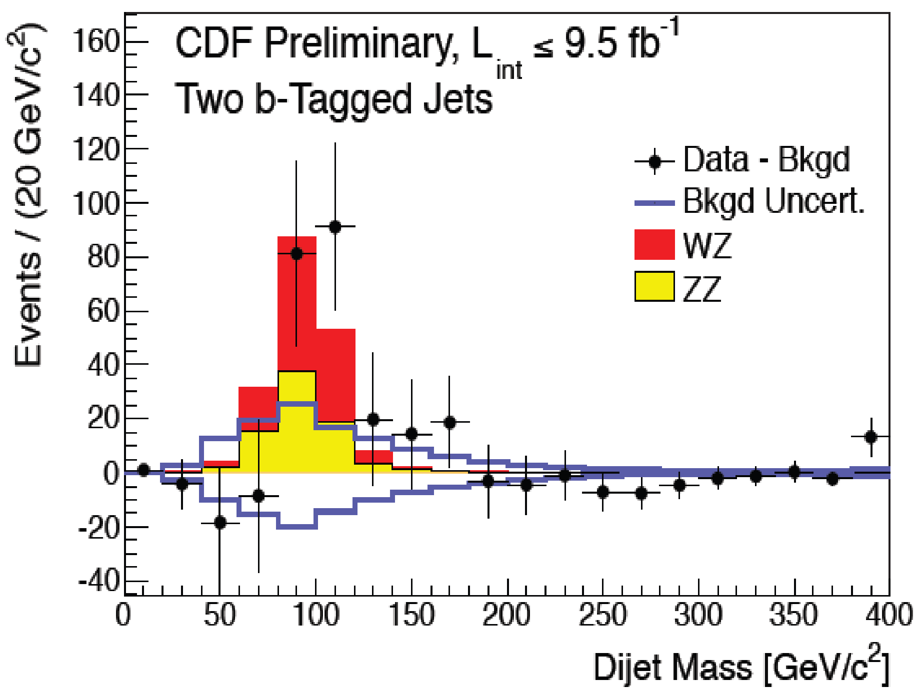



S = 0.16 events, B = 0.06 events

# CDF W+jets



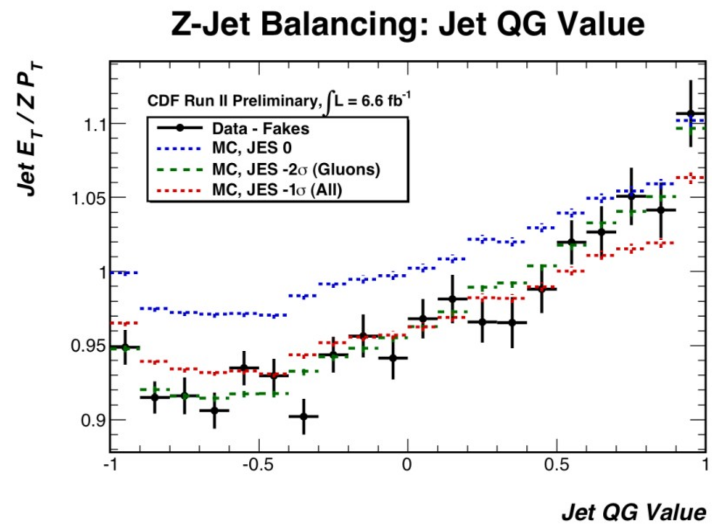



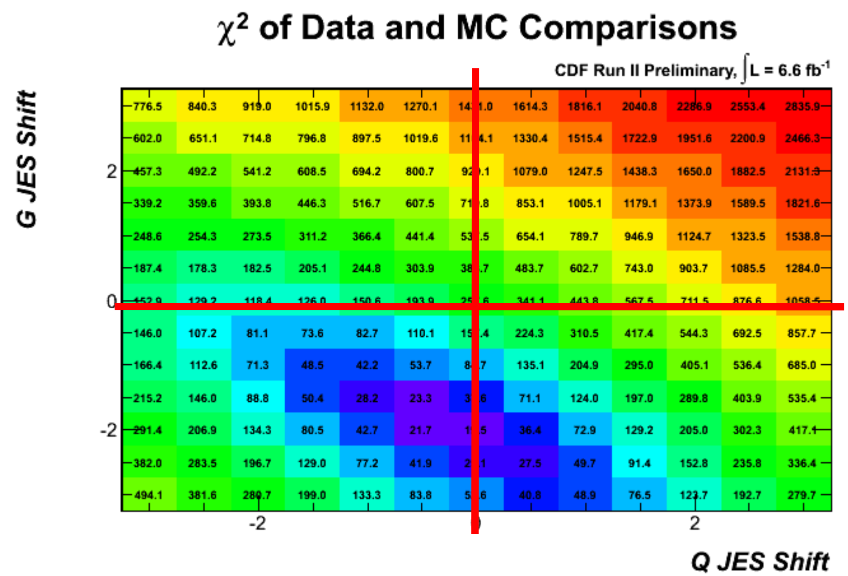




- Tagged samples used for Higgs searches do not contain any sign of abnormalities that were seen previously in pre-tagged region

# CDF W+jets

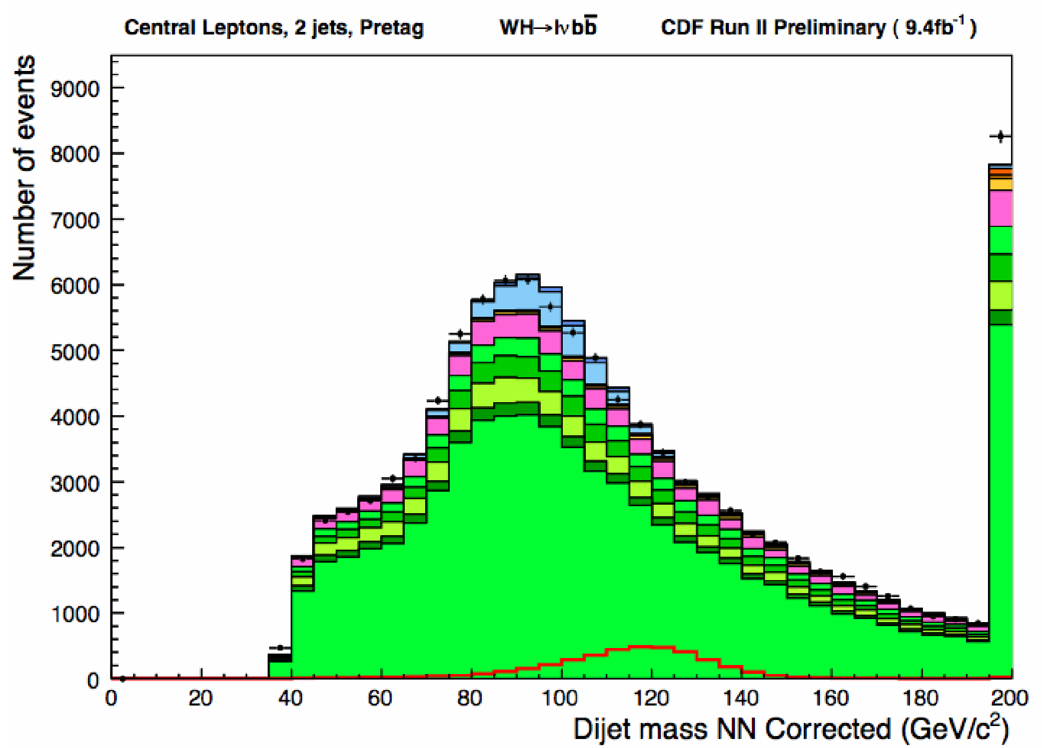
- Lots of studies to try to understand what's going on in the pre-tag region
- Detailed studies in Z + 1 jet events to understand potential differences in quark and gluon jet energy scales
- Bottom line of these studies is that the JES for gluon jets needs to be shifted by 2σ in MC to match with data
- The JES for quark jets is good – not surprising since well constrained by top mass measurements



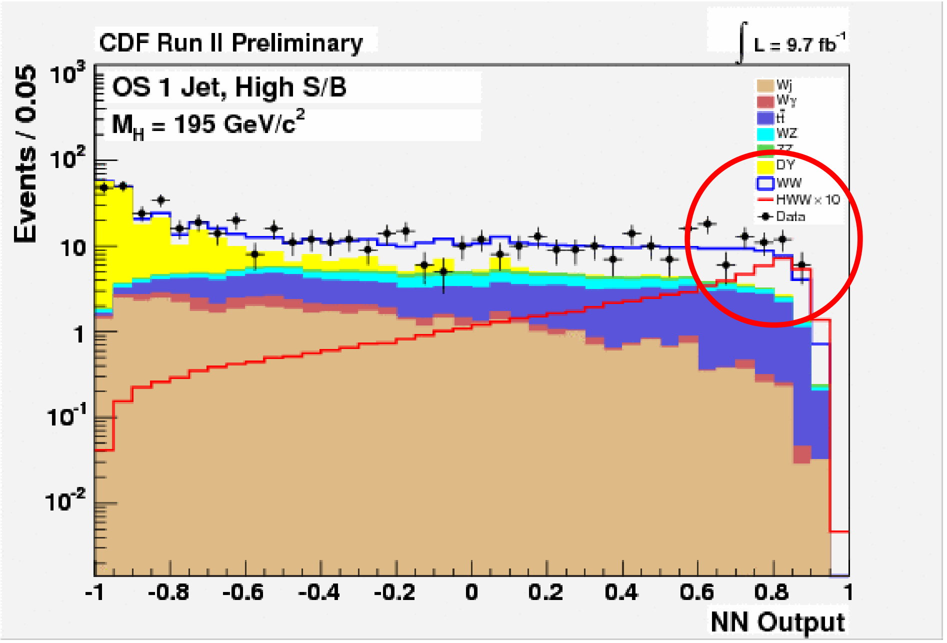
# CDF W+jets

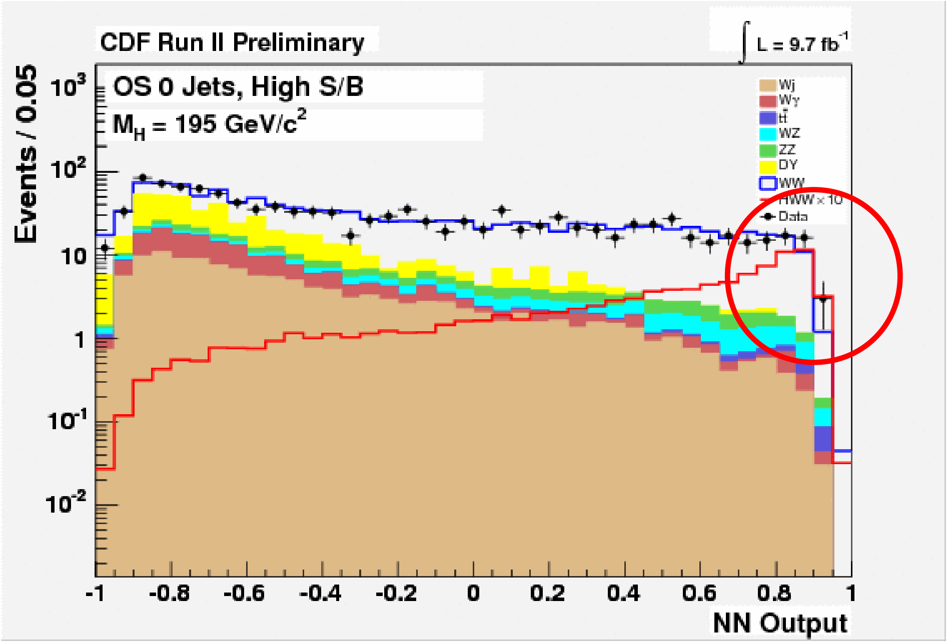
- In CDF Higgs searches we apply -2σ JES corrections to the gluon jets in our MC samples
- In the end, the effect of this is small since there are few gluon jets in our tagged event samples
- With these corrections in place we do not observe mis-modeling in the pre-tag region of our lvjj Higgs search




Caveat is looser cuts are applied than in the "bump" search analysis
No official statement from CDF regarding "bump" at this time

# CDF Excess at $m_H$ =195 GeV




- Behavior of observed limits driven by small event excesses in the high S/B regions of opposite-sign dilepton 0 and 1 jet channels
- Nothing peculiar in the modeling of these distributions
- Of course, ATLAS and CMS have ruled out a mH = 195 GeV/c² SM Higgs based primarily on equivalent searches in H->WW

# D0 improvements

~12% more data ⇒ ~6% improvement

Increased lepton efficiency / acceptance

- $WH \rightarrow l\nu b\bar{b}$: new multivariate electron identification ⇒ ~5% improvement
- $WH \rightarrow l\nu b\bar{b}$: increased muon acceptance ⇒ 5-10% (in progress)
- FSR and semi-leptonic jet corrections ⇒ ~1%

Improved multivariate discrimination

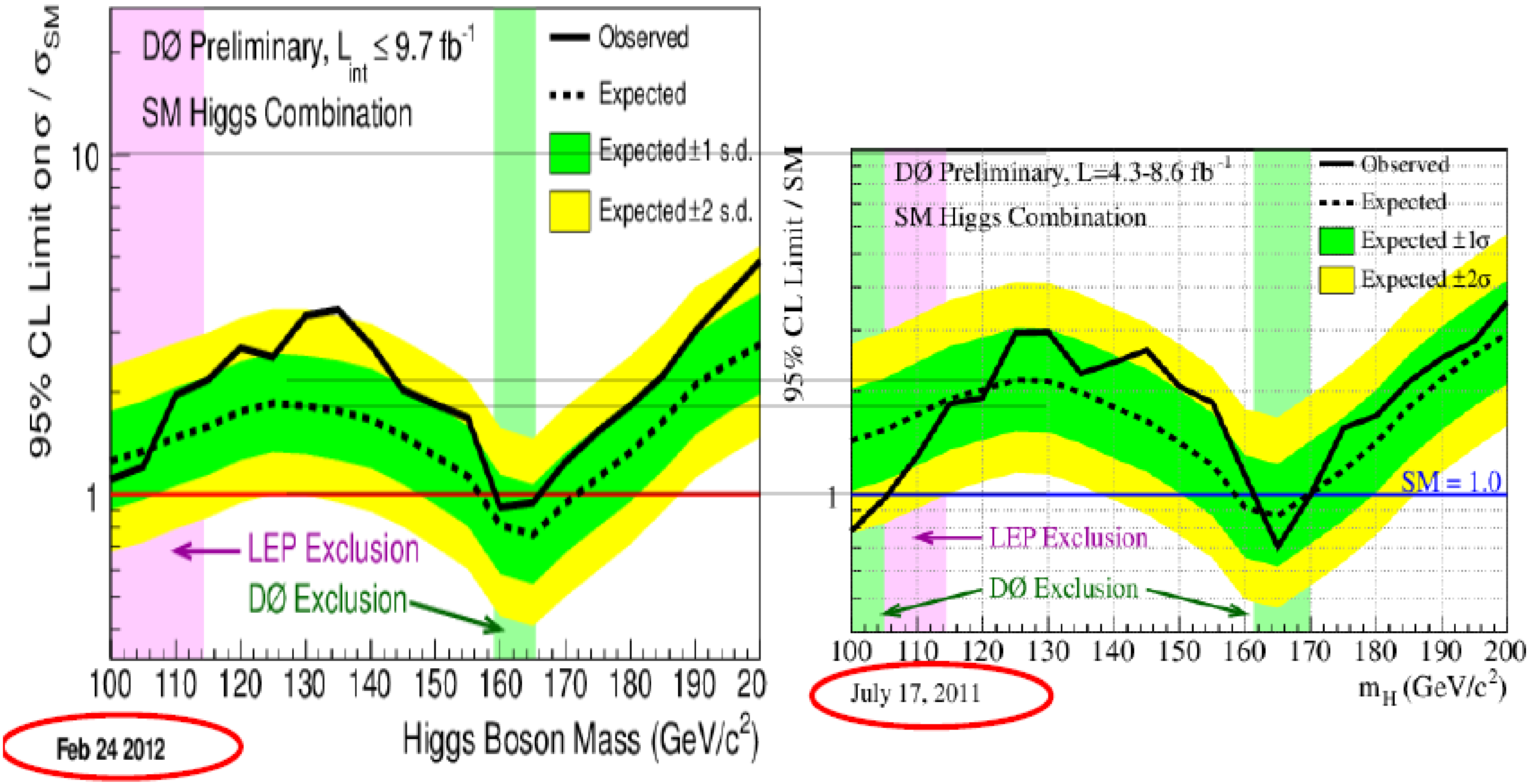
- 2–10% depending on analysis (room for more in the future)

More optimized b-tag categories

- $ZH \rightarrow \nu\bar{\nu}b\bar{b}$: b-tag outputs sum to define b-tag bins ⇒ ~15%
- $WH \rightarrow l\nu b\bar{b}$: three b-tag channels ⇒ ~5%

  (Future improvements with c-jet discrimination)

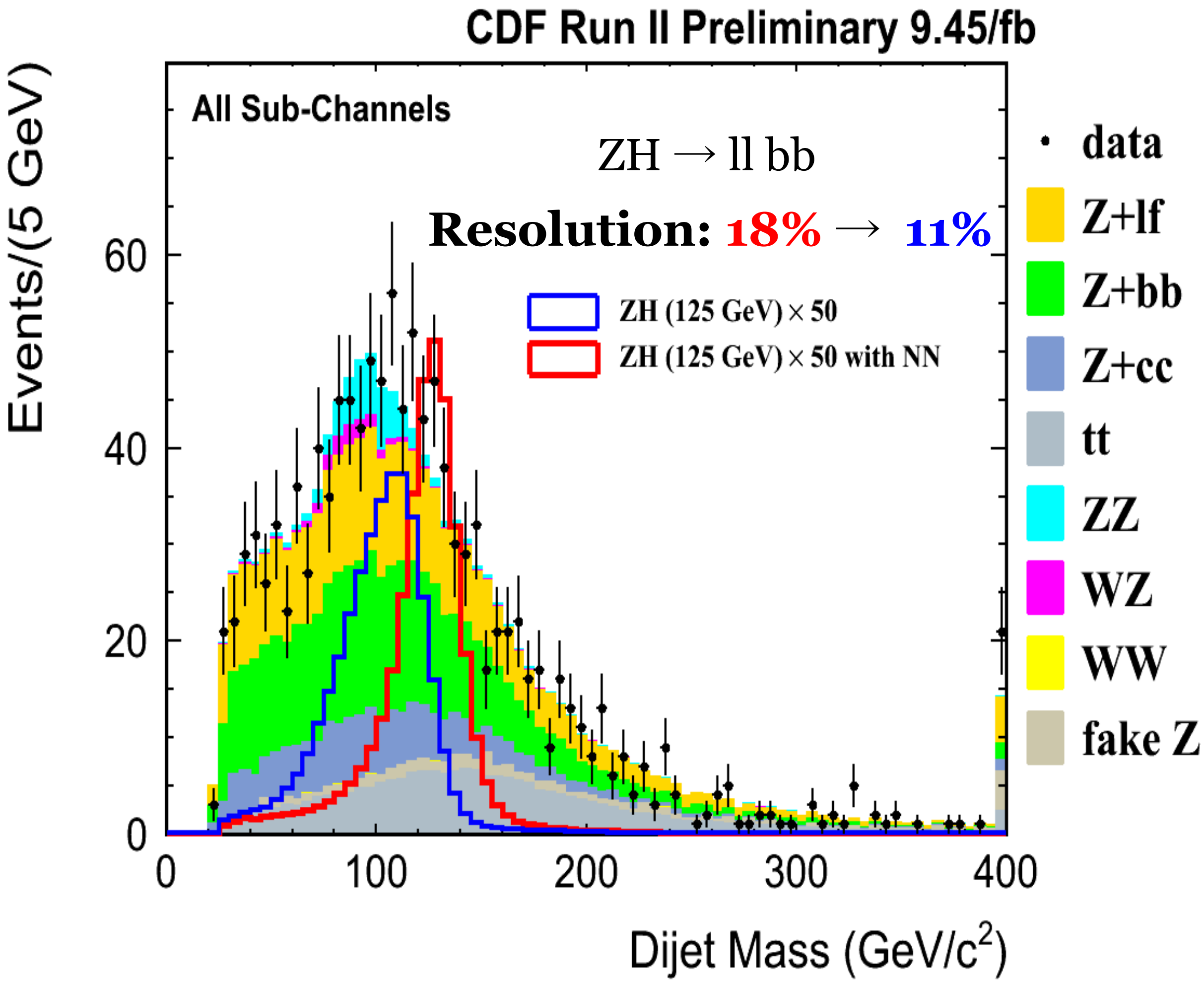
# D0 improvements



# Di-jet Invariant Mass Resolution

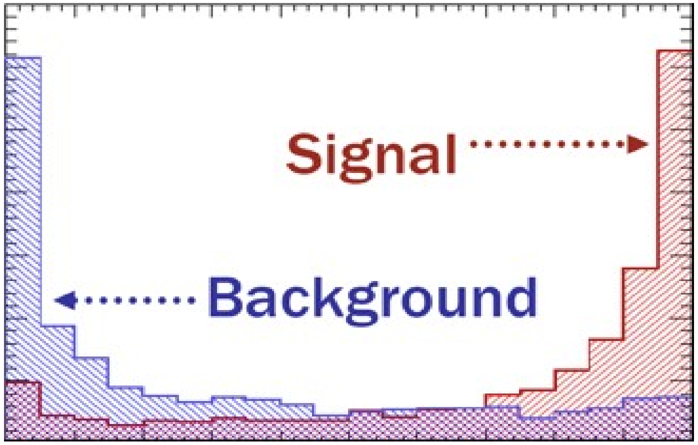
**Higgs signal appears as a resonance over a falling background**
**→di-jet mass is the single most discriminating variable**

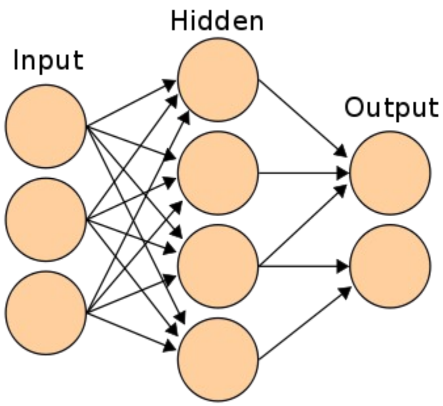
B-quark jets have very different properties from light quark jets
→ develop NN b-jet specific energy corrections



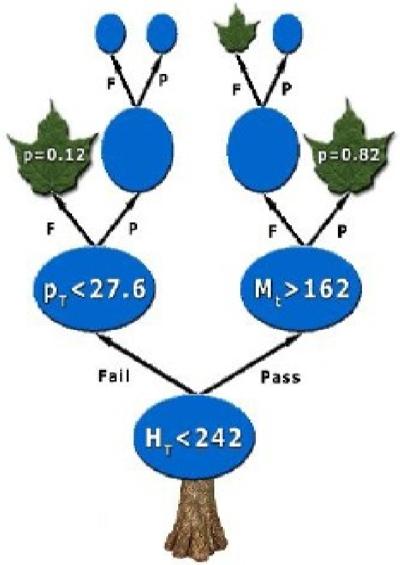
# Multivariate Methods

- Look at many variables simultaneously
  → exploit non-linear correlation between variables
- Choose well modeled, separating variables
- Neural Networks (NN) , Decision Trees (DT)
- DT arboretum: Random Forest (RF)
- Typically see ~ 10 - 20% sensitivity improvement w.r.t. single best variable Mjj

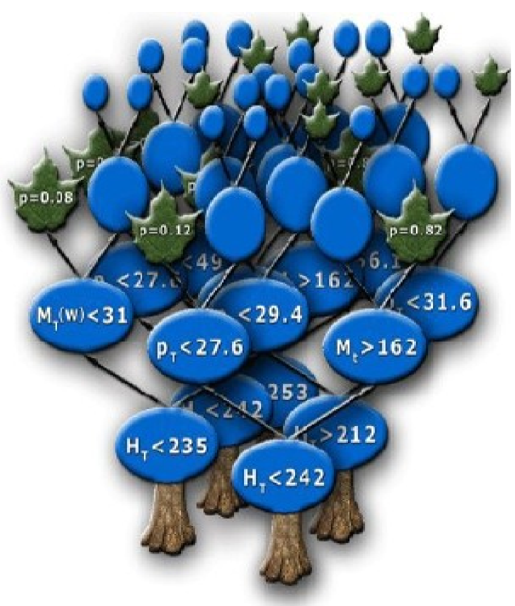



NN

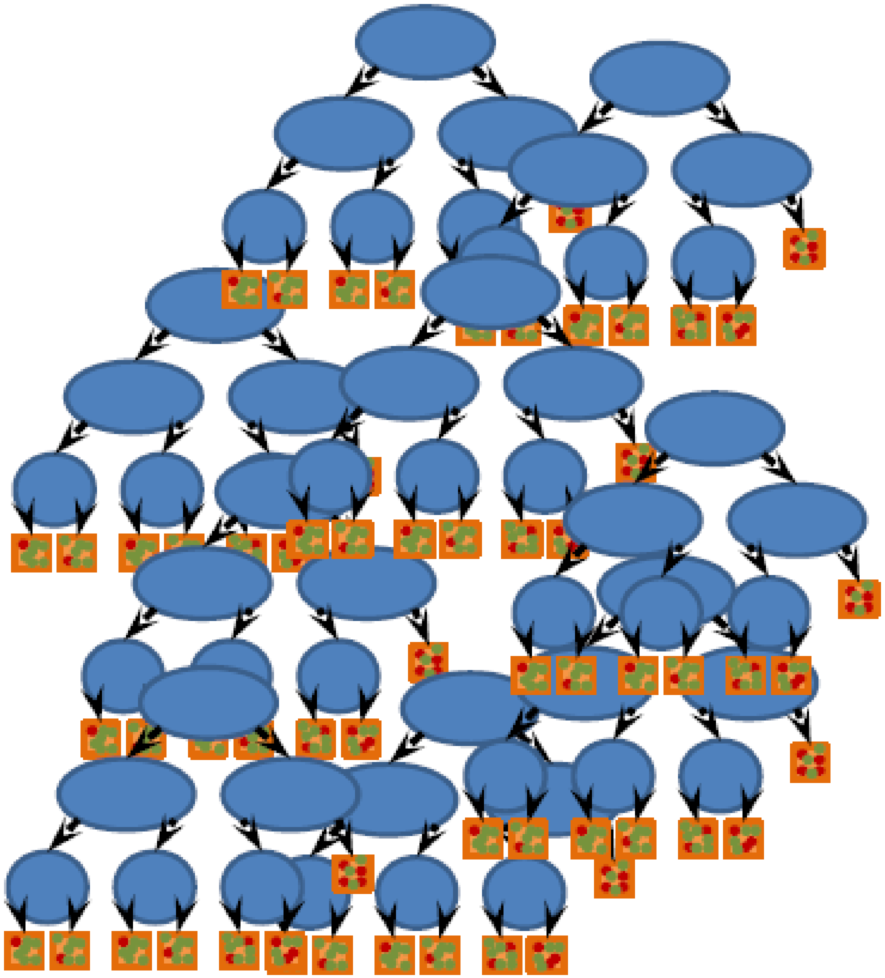



DT




RF

# Random Forest



- Can do even better
- Train lots of decision trees
  - Each tree gets a random subset of events
  - At each node check a random subset of variables
  - Take the performance weighted average
- Need to take care...