CDF Higgs Results
Winter 2012

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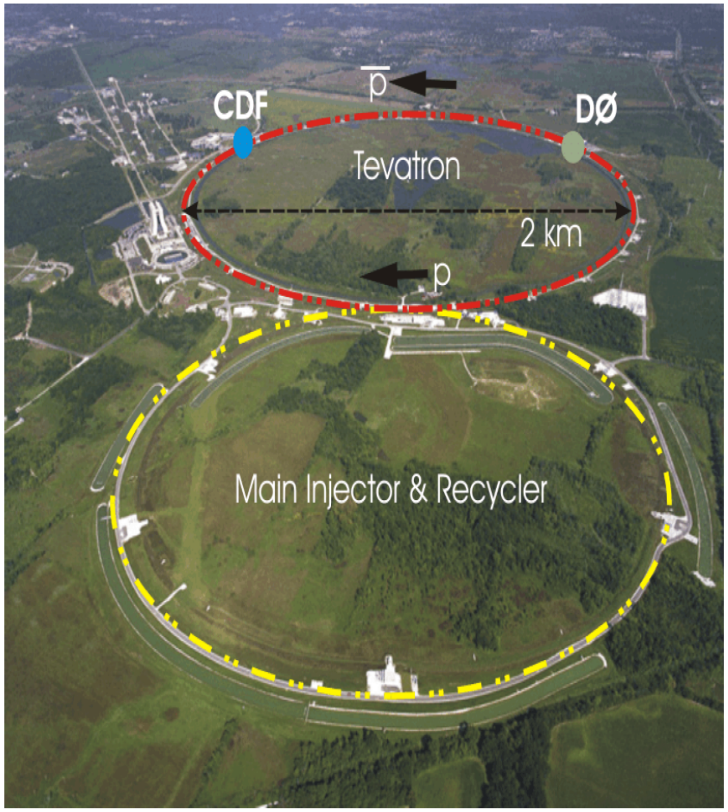
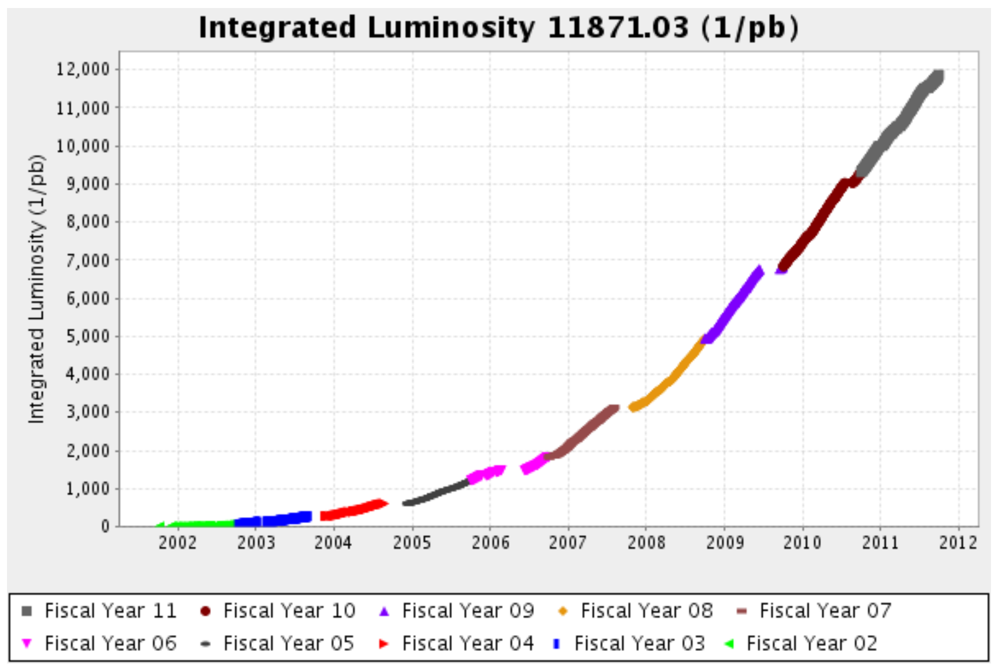
Fermi National Accelerator Laboratory

On behalf of the CDF collaboration

The Tevatron

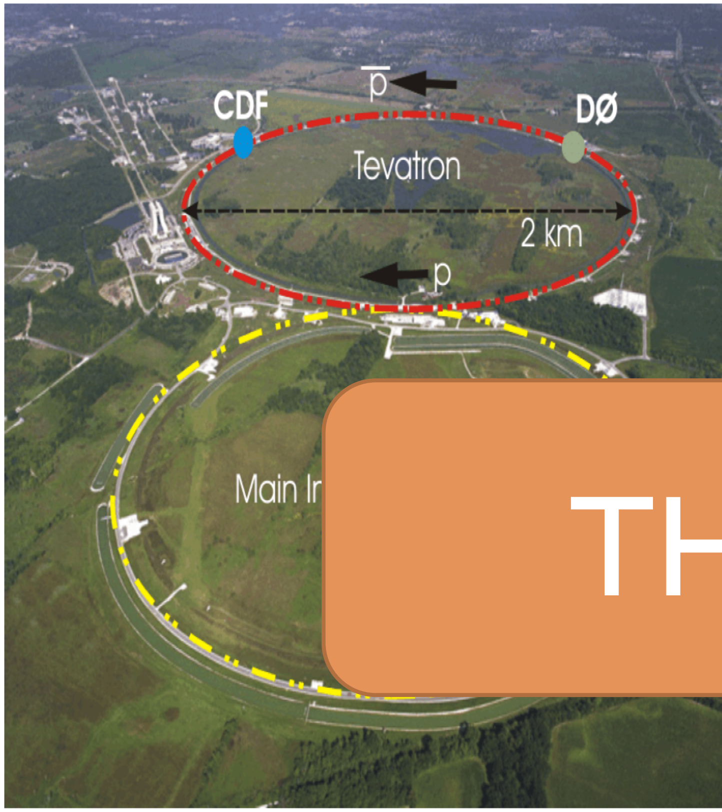


- proton-antiproton collider at
  $\sqrt{s}$ = 1.96 TeV
- Two multi-purpose detectors: CDF & DØ
- Antiproton Accumulation rate:
  ~25x10^{10} /hr
- Initial luminosity record:
  4.31 x10^{32} $cm^{-2}s^{-1}$



- Record week: 85 pb^{-1}
- Run II: 2001-2011
  12 fb^{-1} delivered
  10 fb^{-1} recorded

The Tevatron – 25+ years



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THANK YOU!

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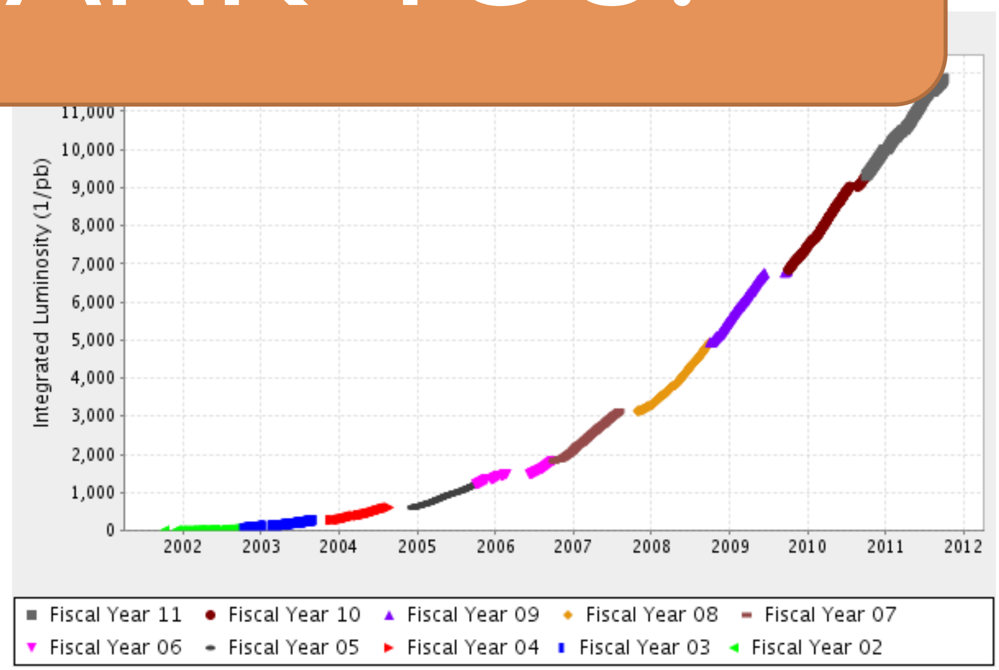
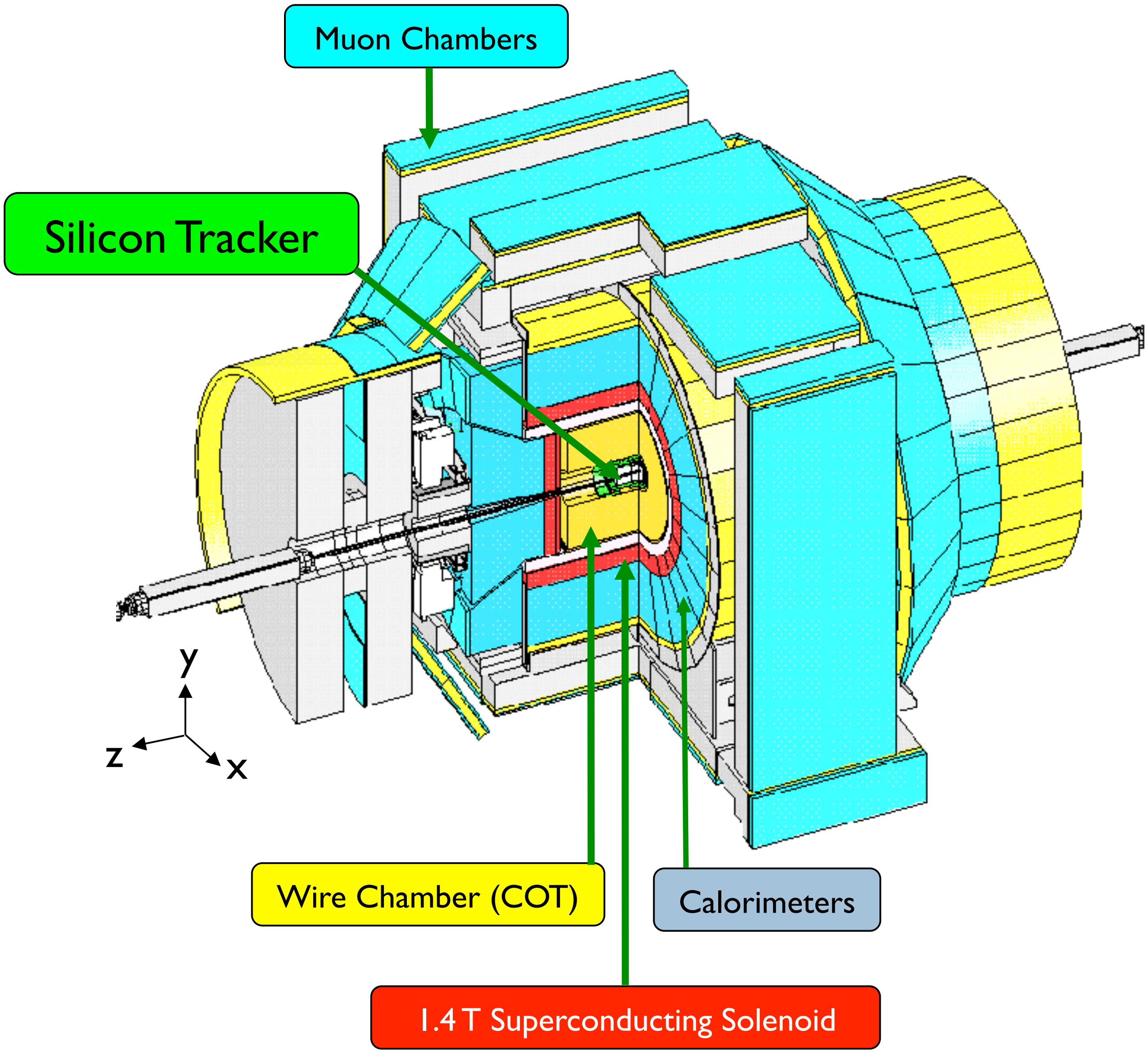
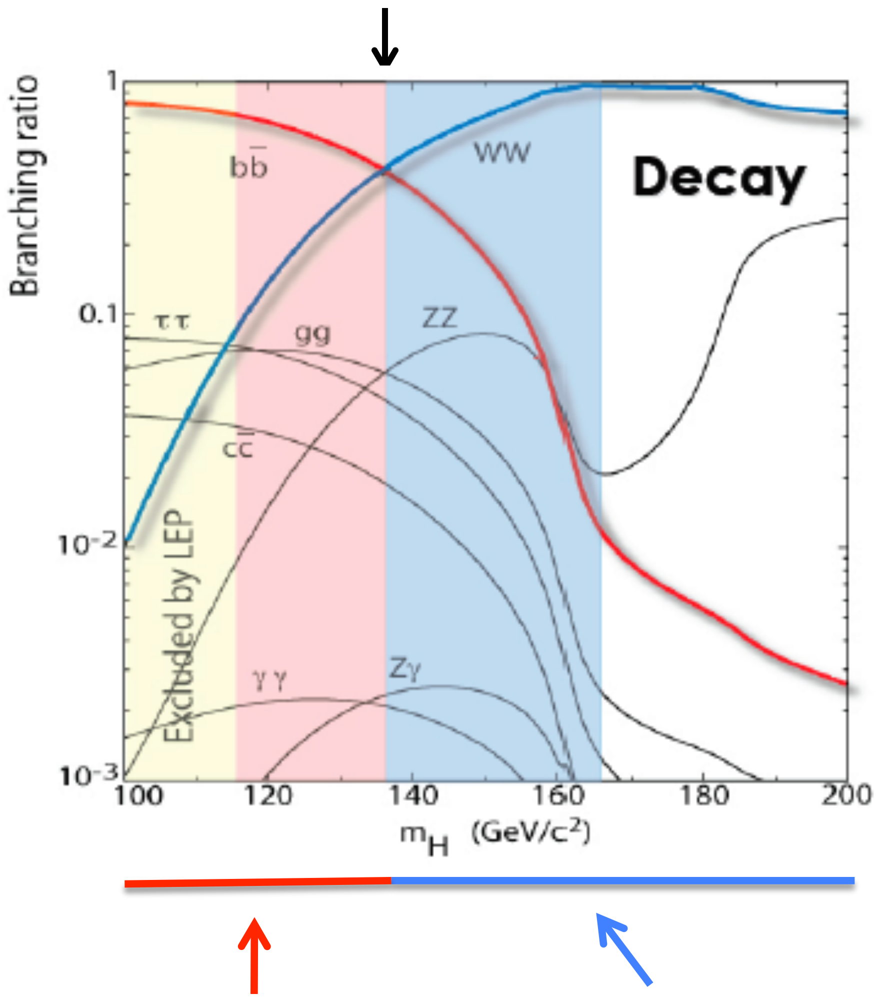


CDF II Detector



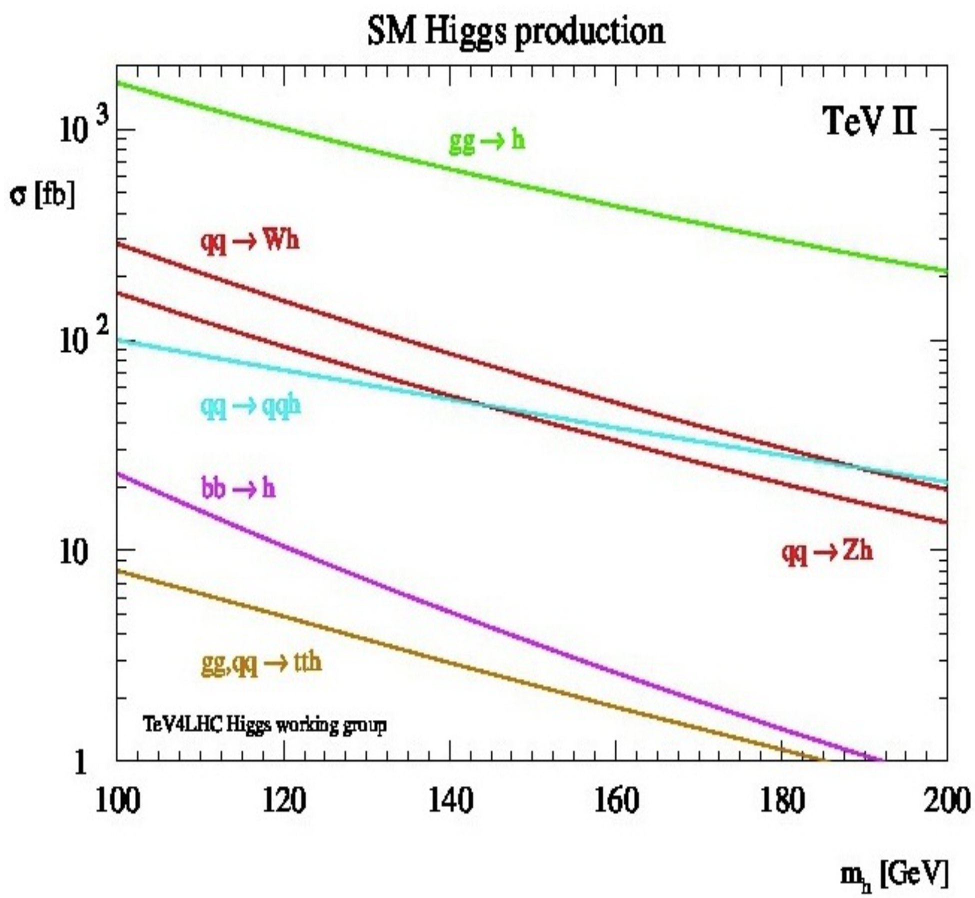
SM Higgs decay and production modes

135 GeV/c²

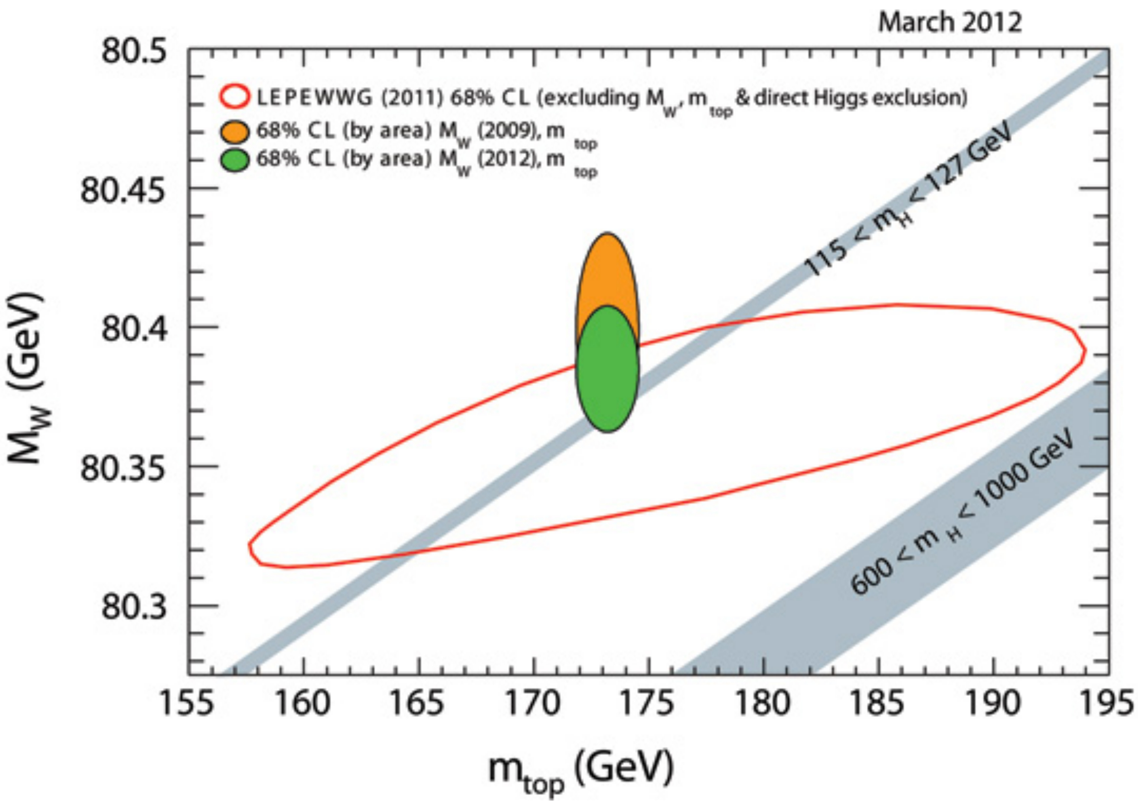


H→bb

H→WW

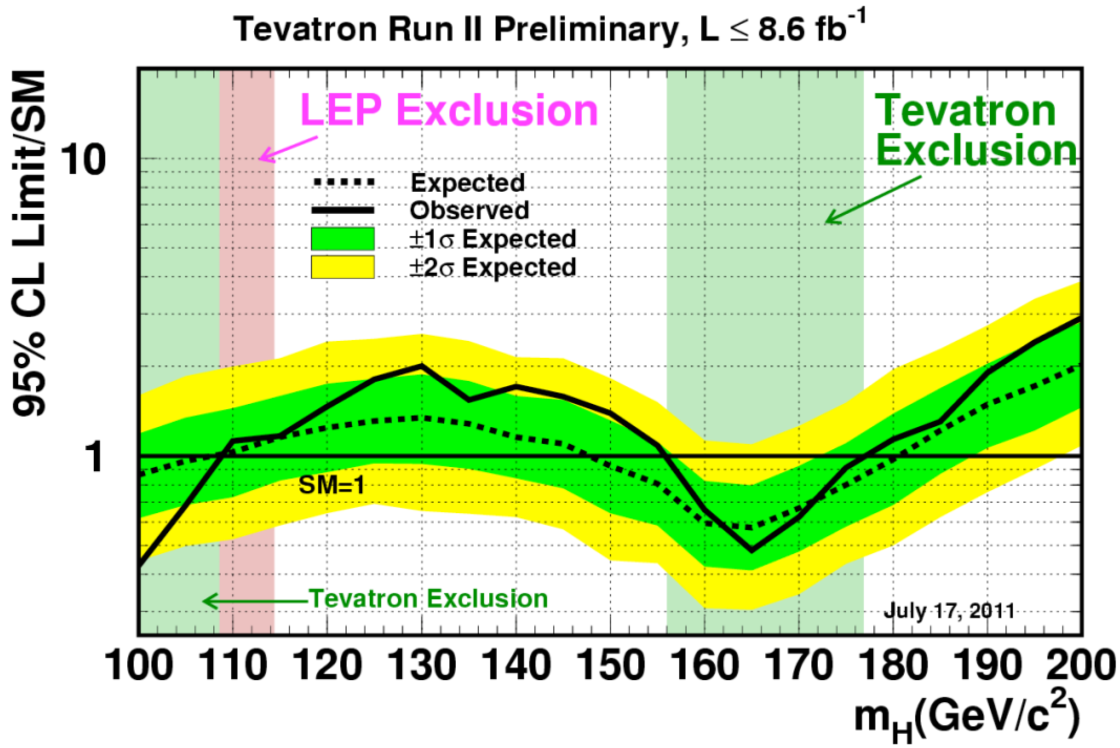


Latest W mass results



- New measurements from CDF and D0
- $m_W = 80385 +/- 15$ MeV/c^2 (World Average – Mar 2012)
- Updated SM indirect fit gives $m_H < 152$ GeV/c^2 at 95% C.L.

Tevatron Combination Summer 2011



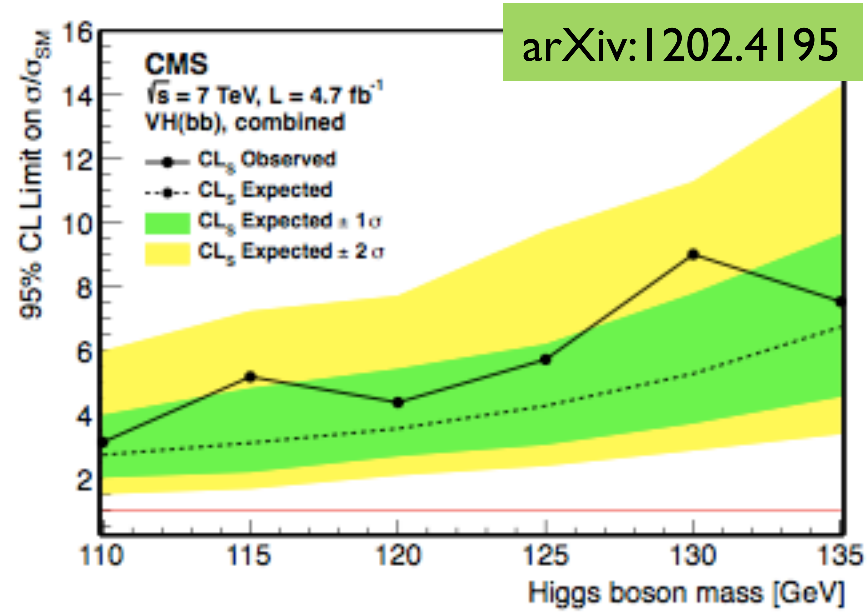
- Expected limit <=1.3*SM from 100-185 GeV/c^2
- Tevatron Exclusion: 100-108 & 156-177 GeV/c^2
- Broad 1 σ excess between 125-155 GeV/c^2 compatible with signal plus background and background-only hypotheses

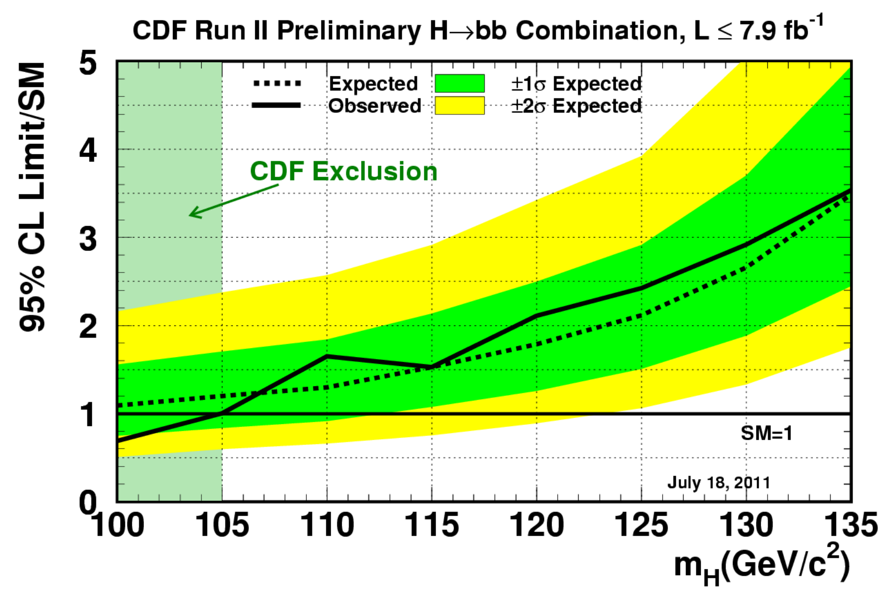
Strength of Tevatron is H→bb

Single experiment sensitivity
Feb 2012, M_H=125 GeV

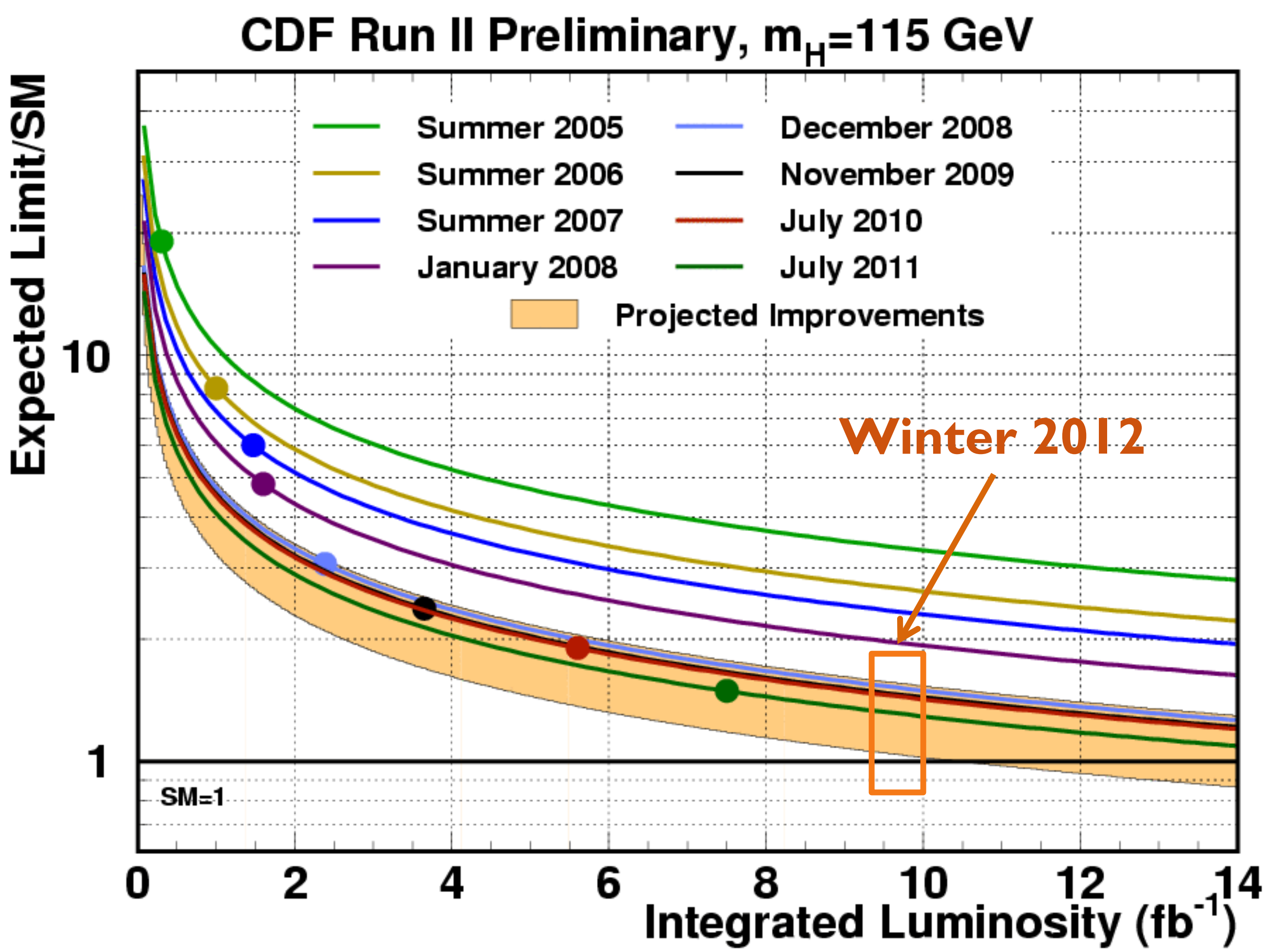
	CDF, D0	Atlas, CMS
H→γγ	10-13*SM	1.5-2*SM
H→WW	~3.5*SM	1-2*SM
H→bb	~2*SM	~3.5*SM

arXiv:1202.4195





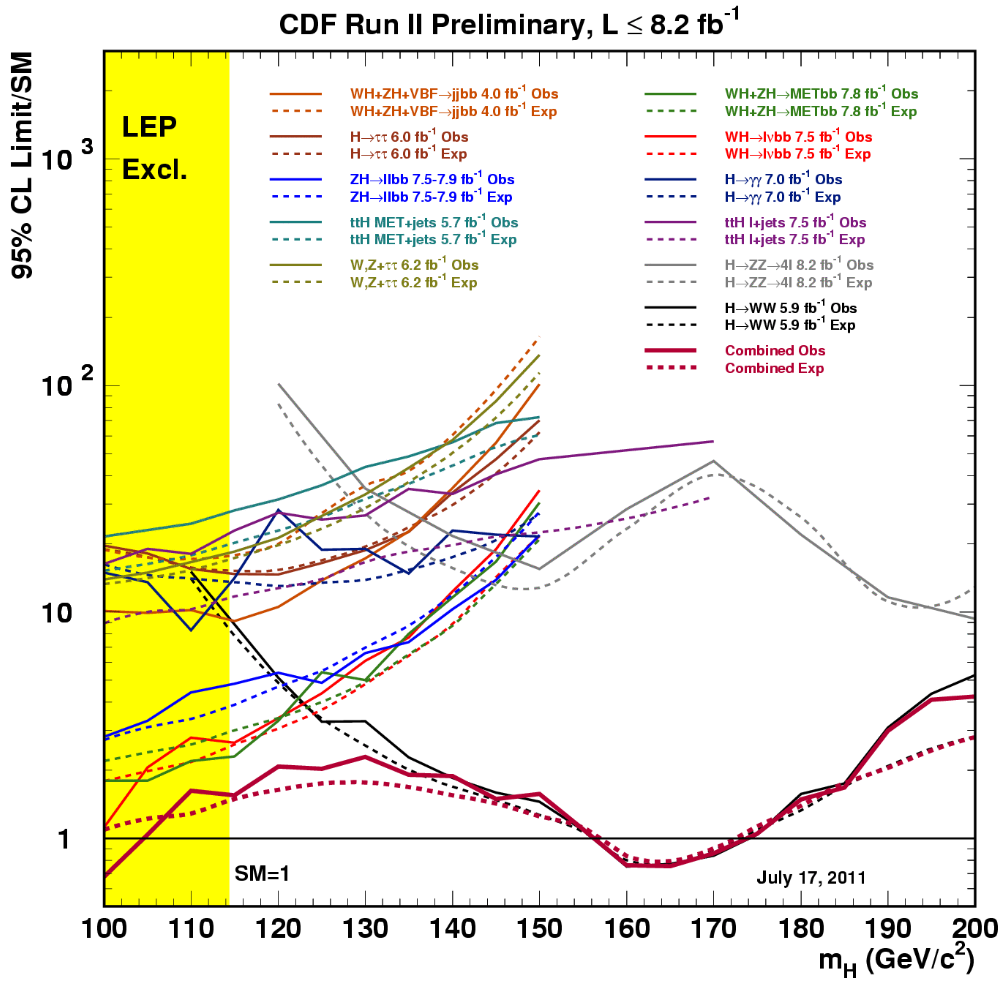
CDF Sensitivity Projections



CDF Higgs Search

Four channels contribute almost equally in the interesting region - need to improve all 4!

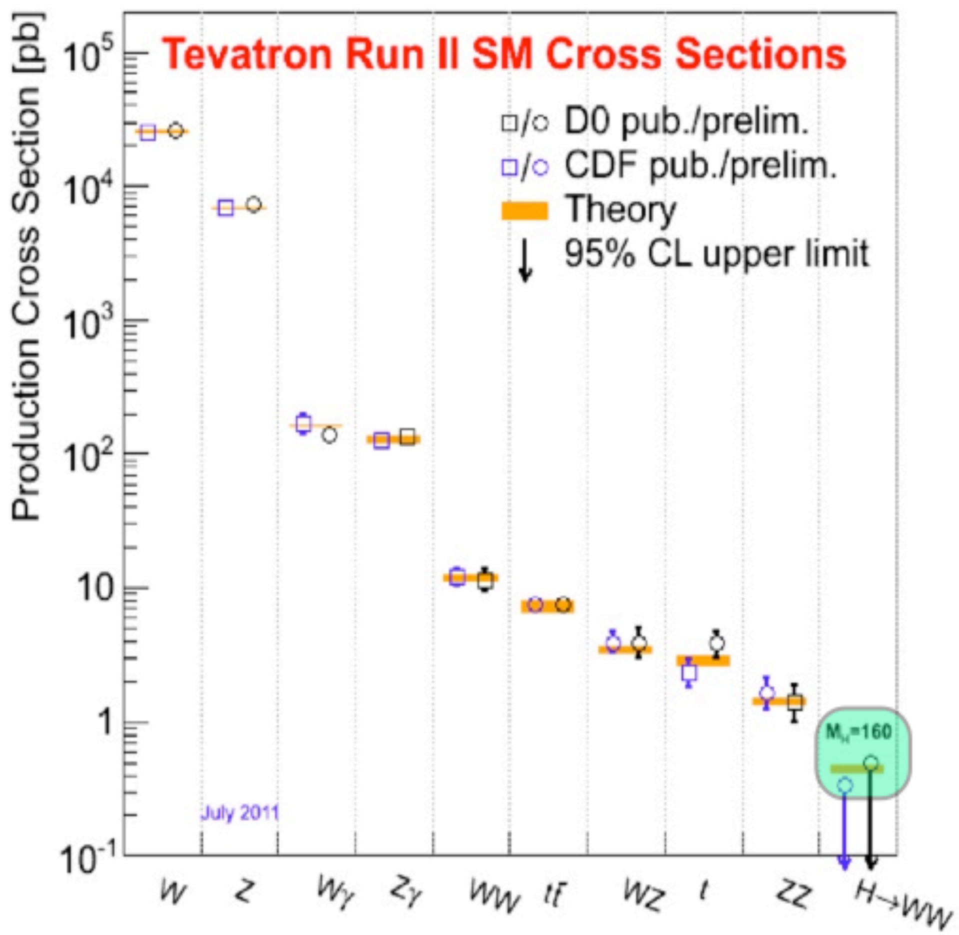
- ZH→llbb
- WH→lνbb
- ZH→ννbb
- H→WW→lνlν
- Remaining channels have a combined weight of ~10%



How to find a needle in a haystack

Potential Higgs signal is TINY and buried under more common SM processes with same final states

- Maximize signal acceptance
- Model all signal and background processes well
- Use multivariate analysis (MVA) to exploit all kinematic differences



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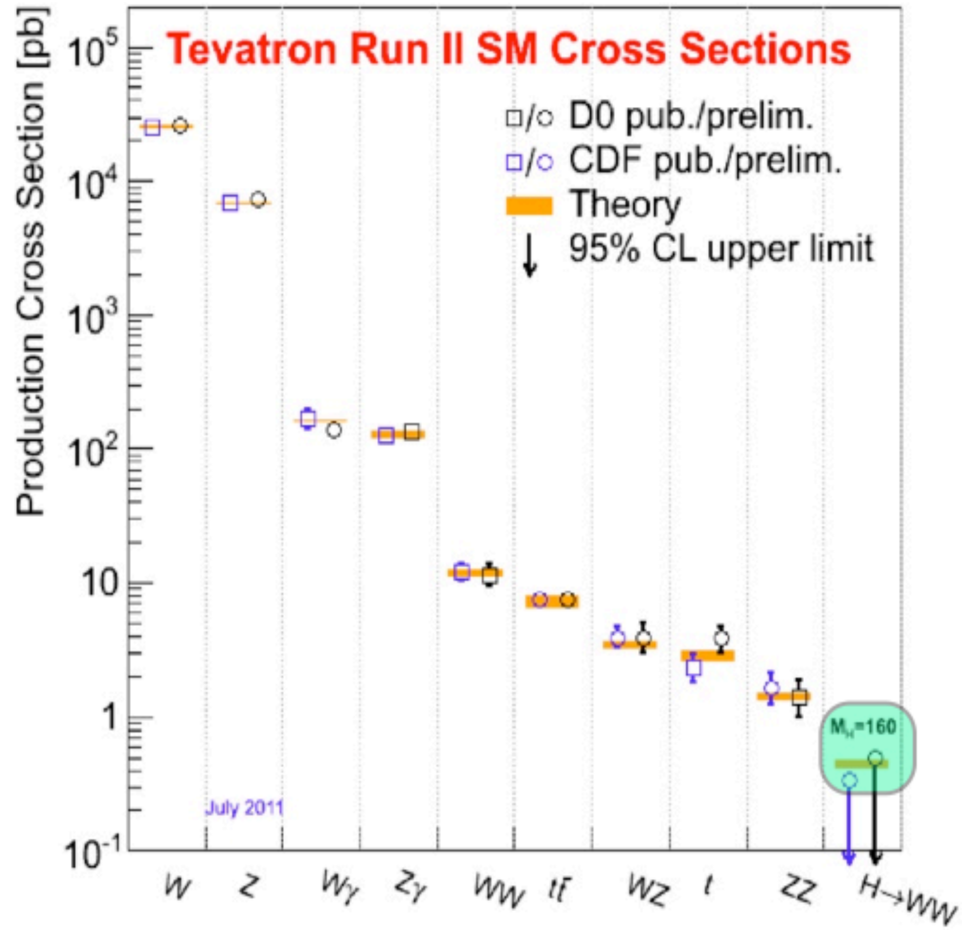
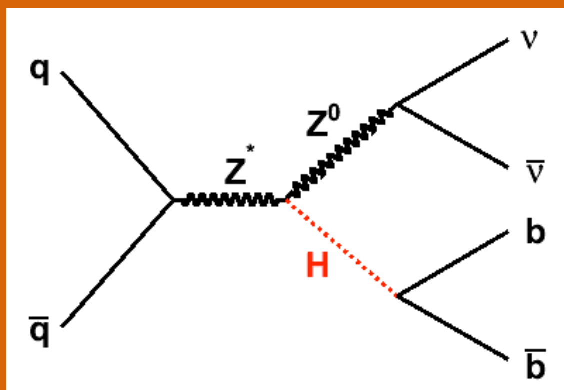
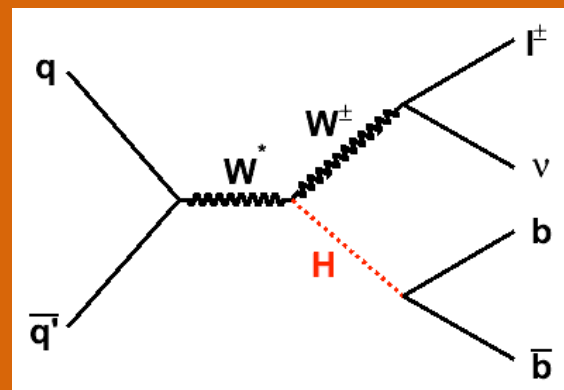
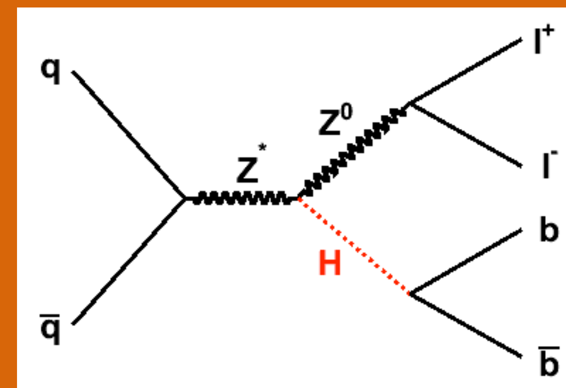


Expect 167 SM Higgs events (reconstructed and selected) and ~200,000 events from SM backgrounds for m_H=125 GeV/c^2

"Low Mass" Searches







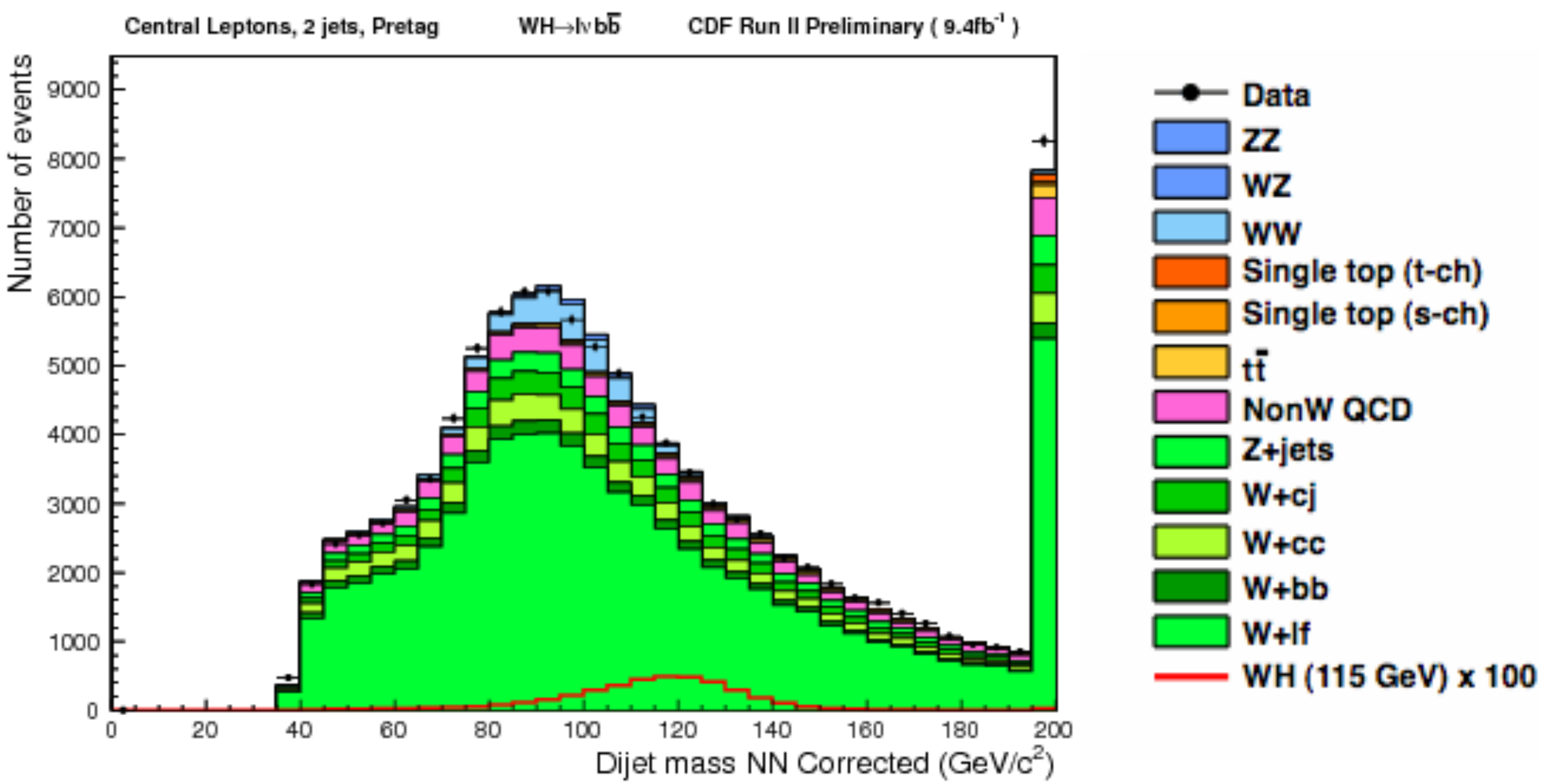
ZH→ννbb	WH→lνbb	ZH→llbb

Select:
- 0,1,2 leptons and/or missing E_t
- Two high E_t jets

Strategy:
- Maximize lepton reconstruction and selection efficiencies
- Maximize efficiency for tagging b-quark jets
- Optimize dijet mass resolution

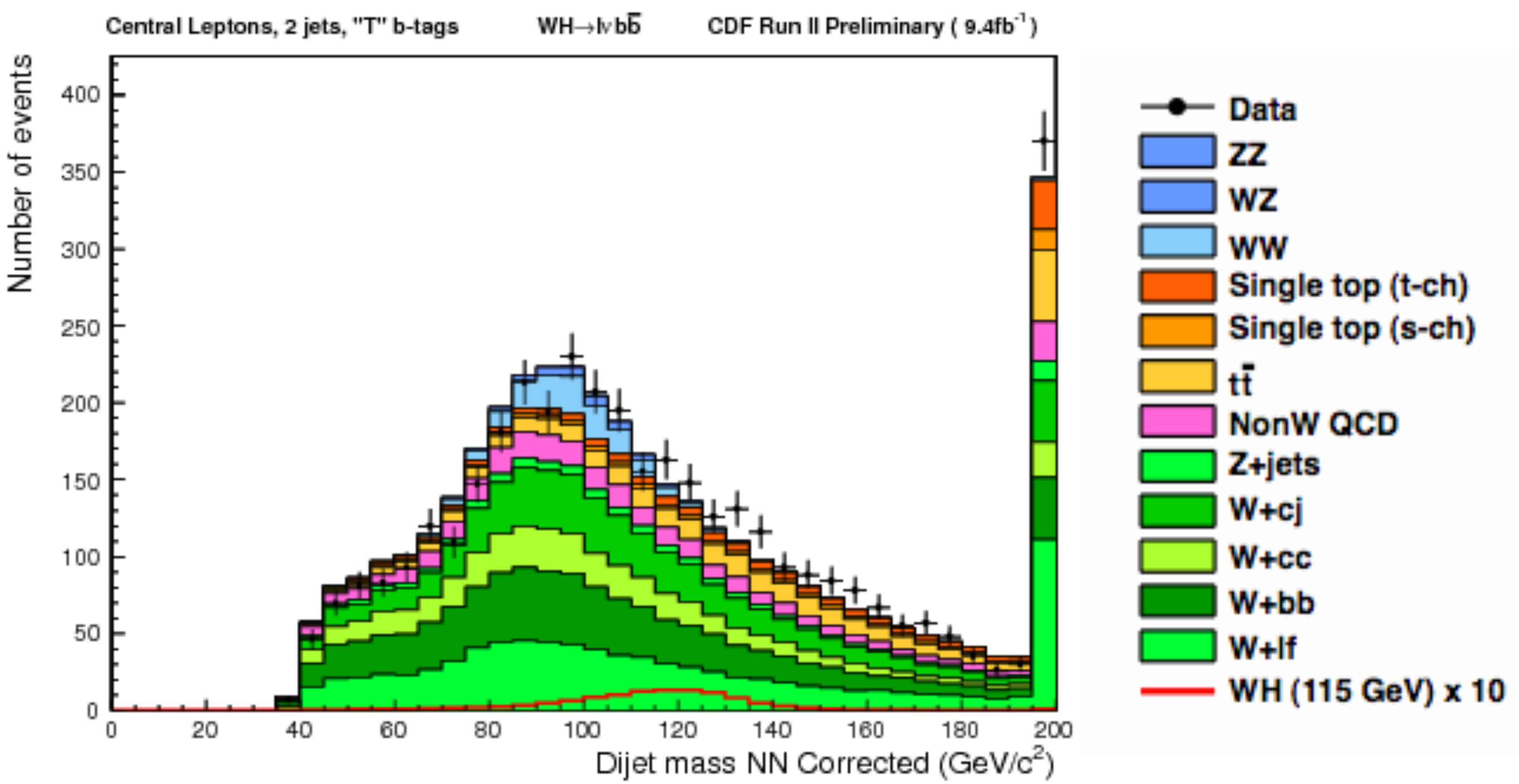
In pictures . . .

- Loose event selection: 1 high-pt lepton, MET, and 2 jets



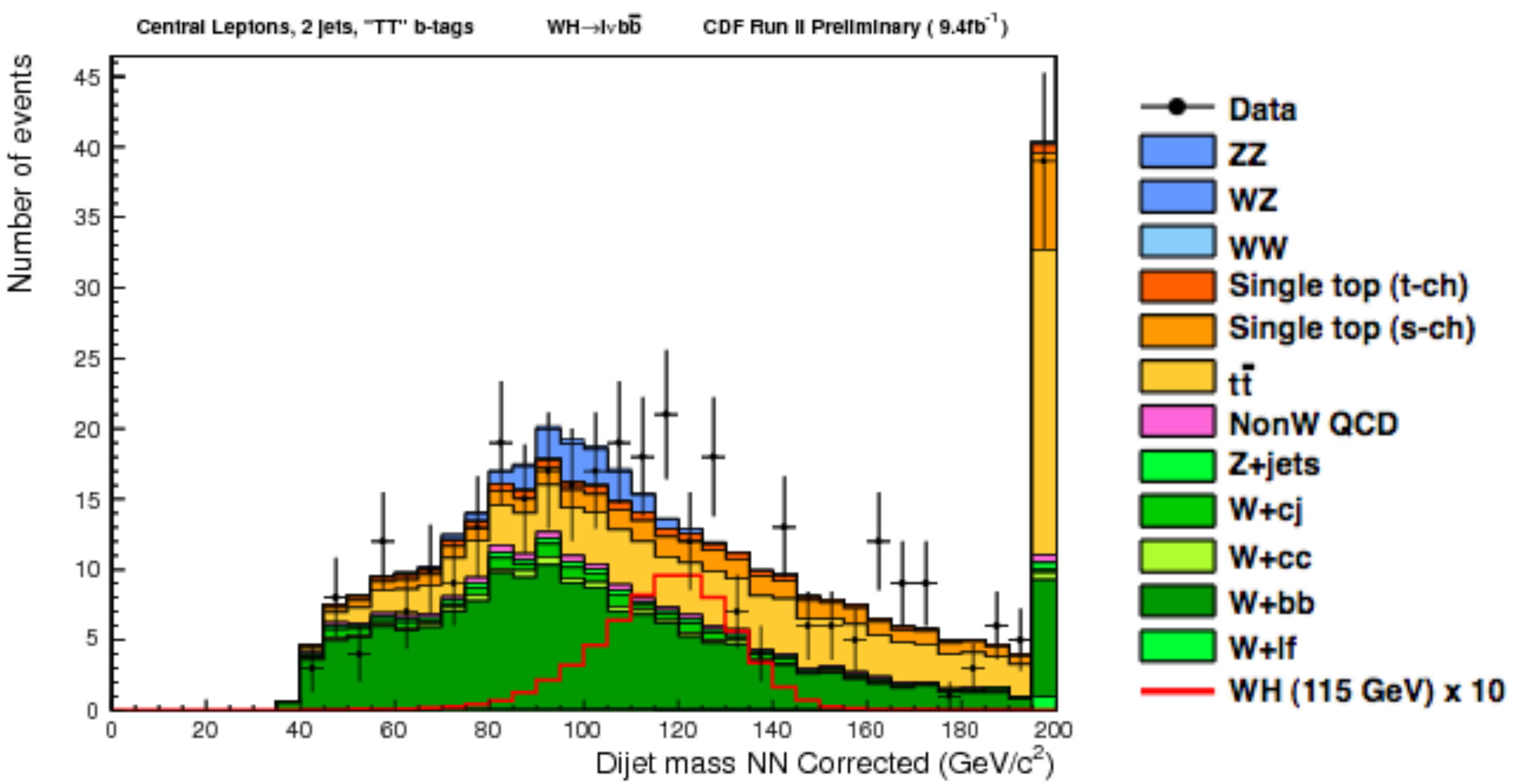
In pictures . . .

- Loose event selection plus one tightly tagged b-quark jet



In pictures . . .

- Loose event selection plus two tightly tagged b-quark jets



Improvements Since Summer 2011

- 25% more luminosity
  - Most recent data
  - Use every last pb^{-1} of data with component specific quality requirements
- New multivariate b-tagger optimized for $H \rightarrow bb$ jets
  - ~20% more acceptance
- Additional triggers and leptons
- Improved dijet invariant mass resolution
- Improved MVA
- Improved modeling

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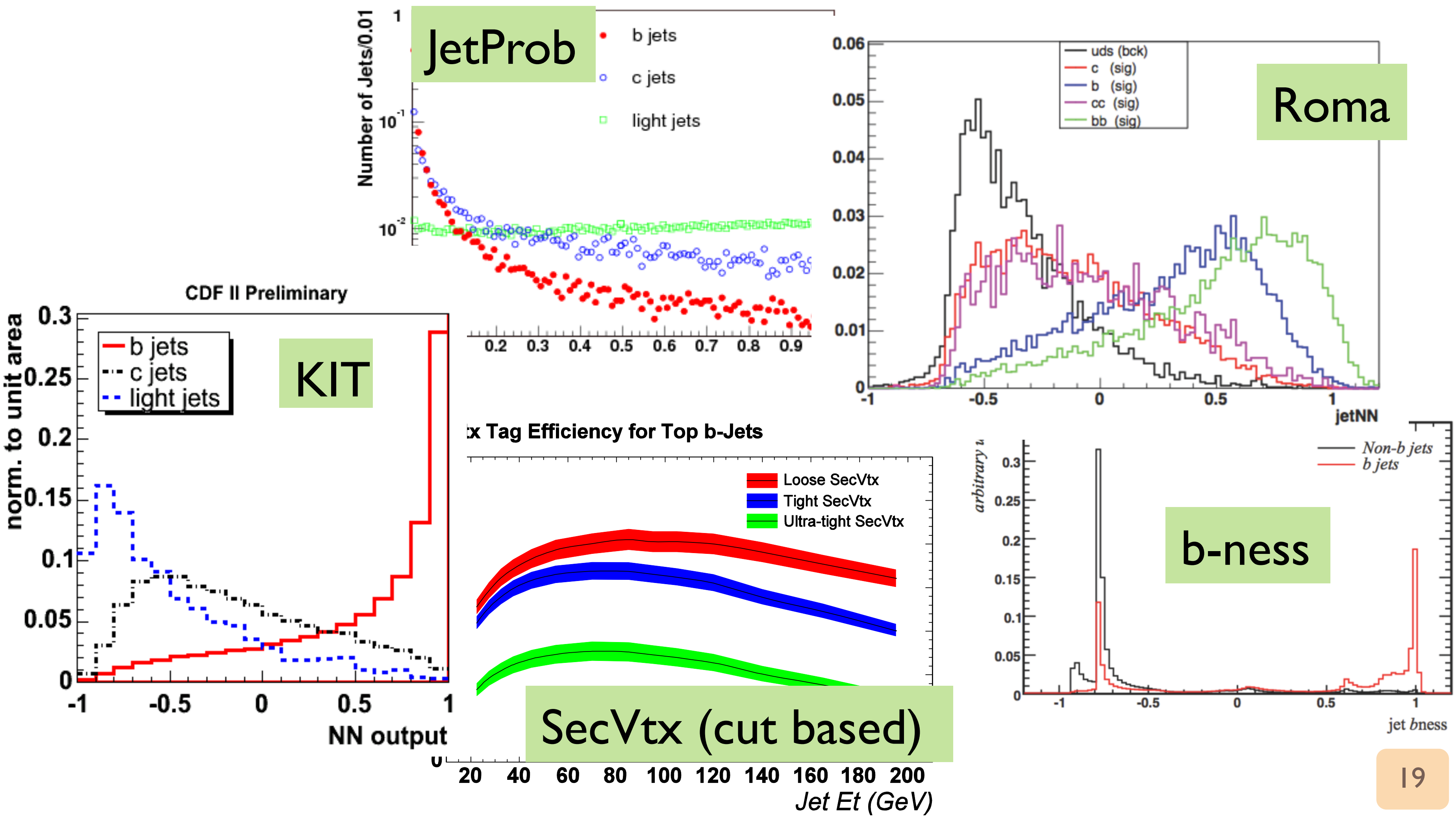
↑ More events

- Improved dijet invariant mass resolution
- Improved MVA
- Improved modeling

↓ Signal vs. background separation

Road to improved b-tagging

In 2010, CDF had 5 b-tagging algorithms with different strengths, weaknesses and applications



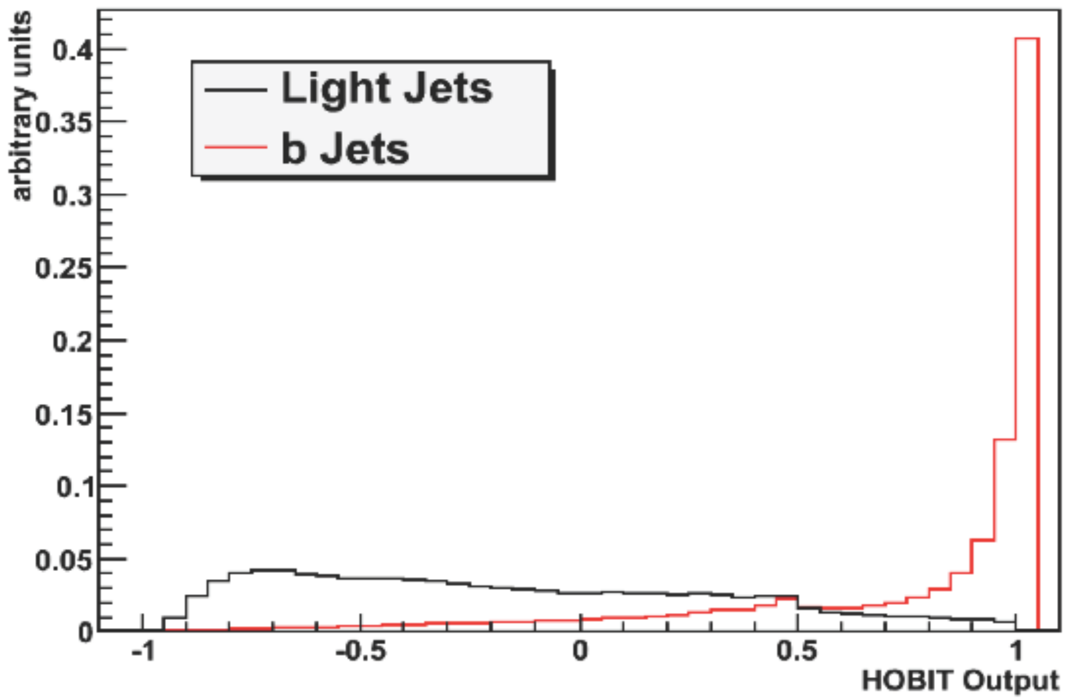
Road to improved b-tagging

Can we unify the strengths of each of these into a single Higgs-optimized network?

- Study of tagger performance says that we . . .
  - Need maximum acceptance
  - Can afford an increase in fake rates
- Need multiple operating points
  - allows separation of high S/B data (two "tight" tagged jets) and low S/B data (two "loose" tagged jets) into independent analysis channels
- Train with jets from $H \rightarrow bb$ MC

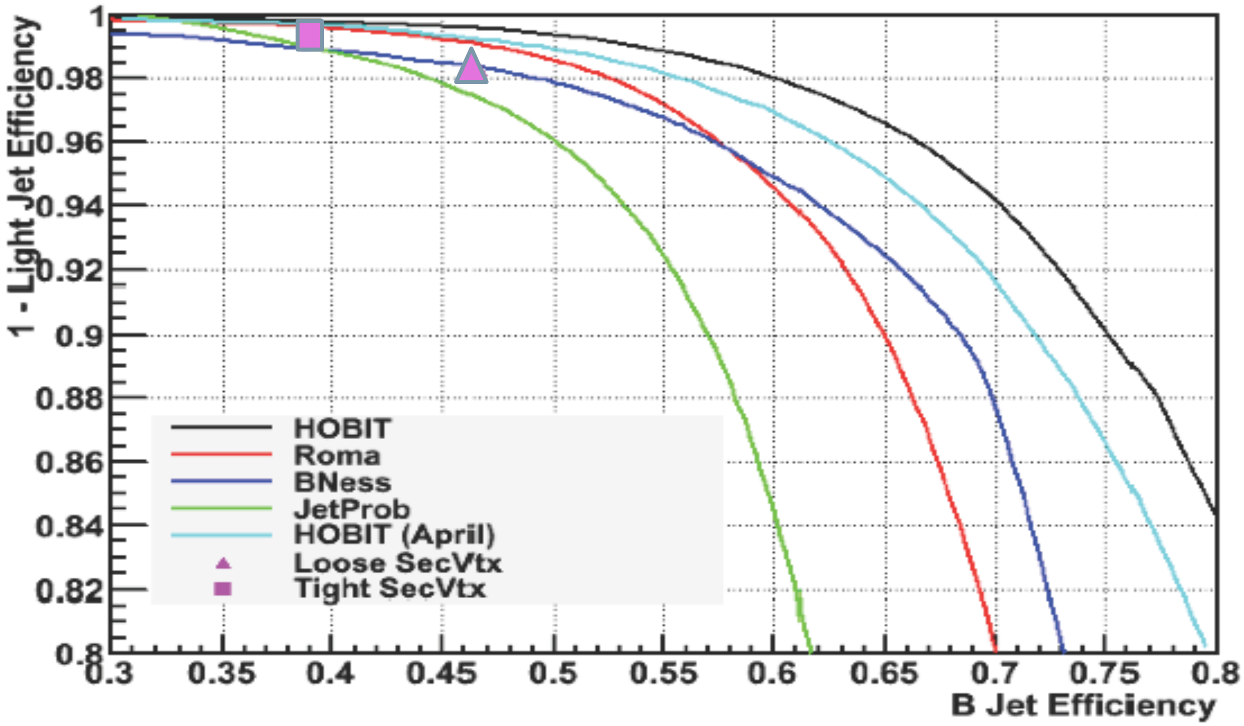
Higgs Optimized b Identification Tagger

HOBIT



- Multivariate, continuous output
- 25 input variables (most sensitive inputs to earlier taggers)
- Trained with jets from H→bb MC
- Validated with ttbar and soft electron samples

HOBIT performance



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

HOBIT in WH->lνbb

OLD – Multiple Taggers

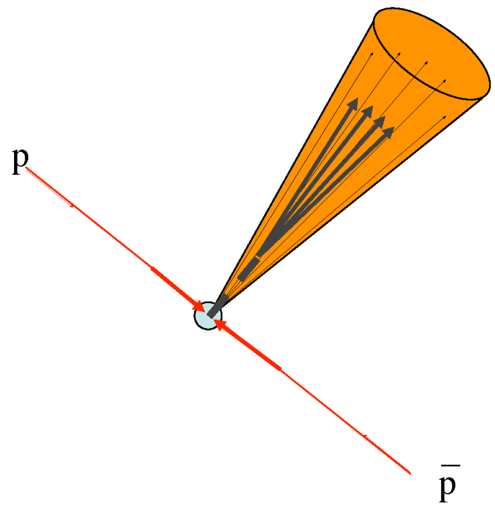
Tagging Category	S/√B
SecVtx+SecVtx	0.228
SecVtx+JetProb	0.160
SecVtx+Roma	0.103
Single SecVtx	0.146
Sum	0.331

NEW - HOBIT

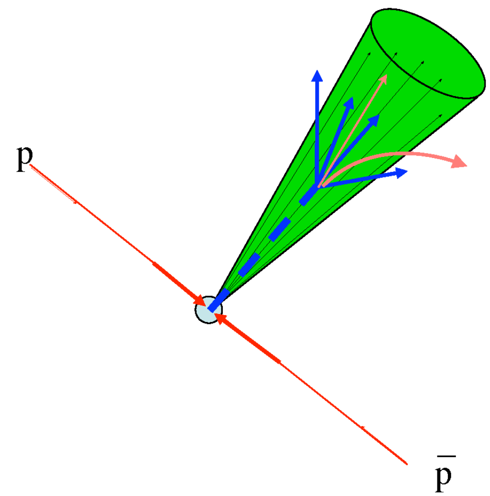
Tagging Category	S/√B
Tight-Tight	0.266
Tight-Loose	0.200
Single Tight	0.143
Loose-Loose	0.053
Single Loose	0.044
Sum	0.369

- 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

Jet Resolution Improvements



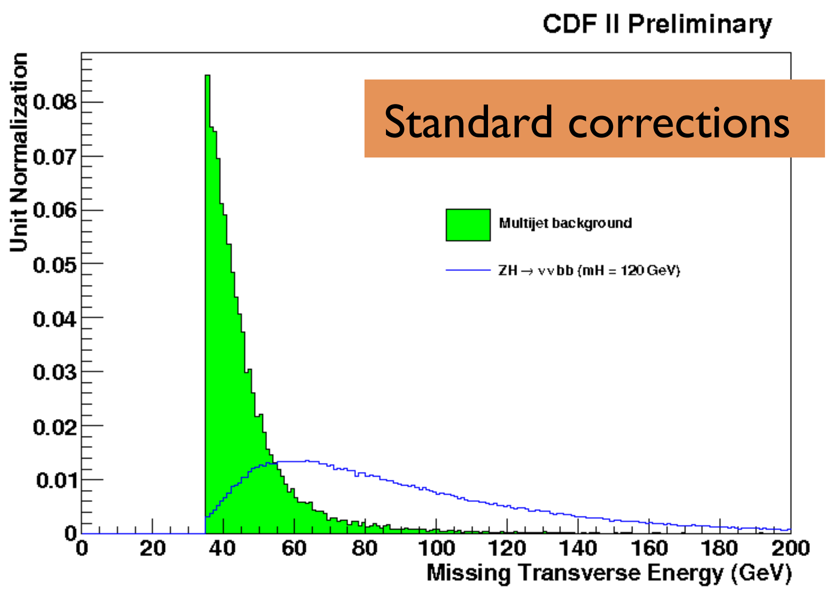
light flavor quark jet

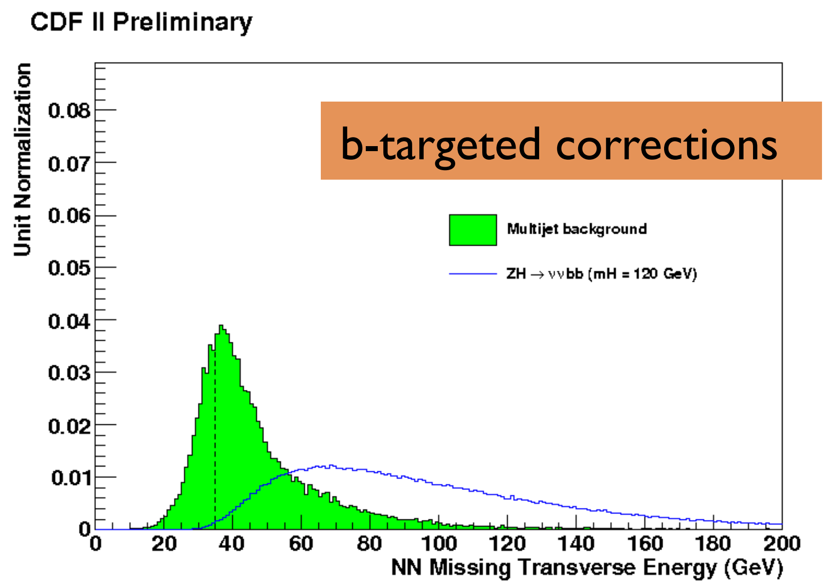


bottom quark jet

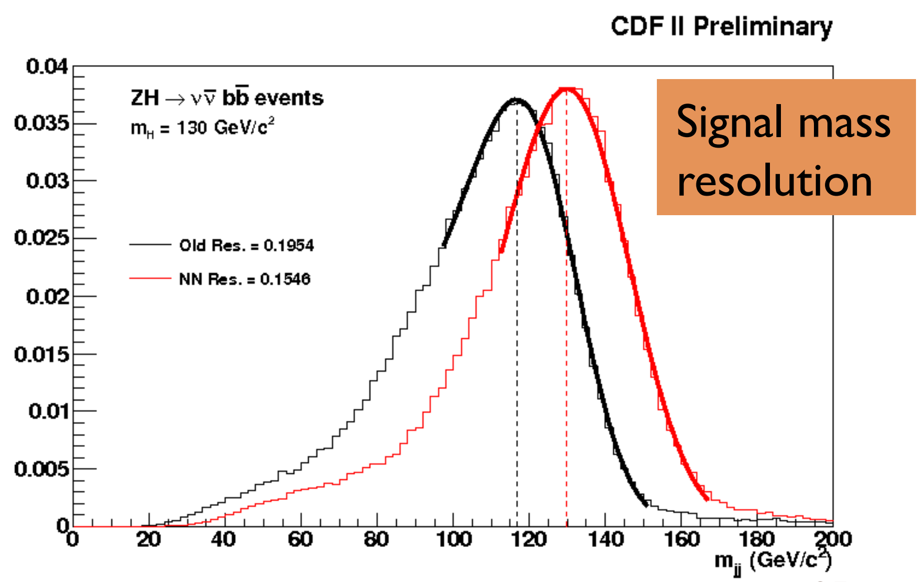
- Bottom quark jets have properties which are very different from standard light flavor quark jets
- Specialized jet energy scale corrections focused on bottom quark jets improve our dijet invariant mass and missing transverse energy measurements

Jet Resolution Improvements in ZH->ννbb





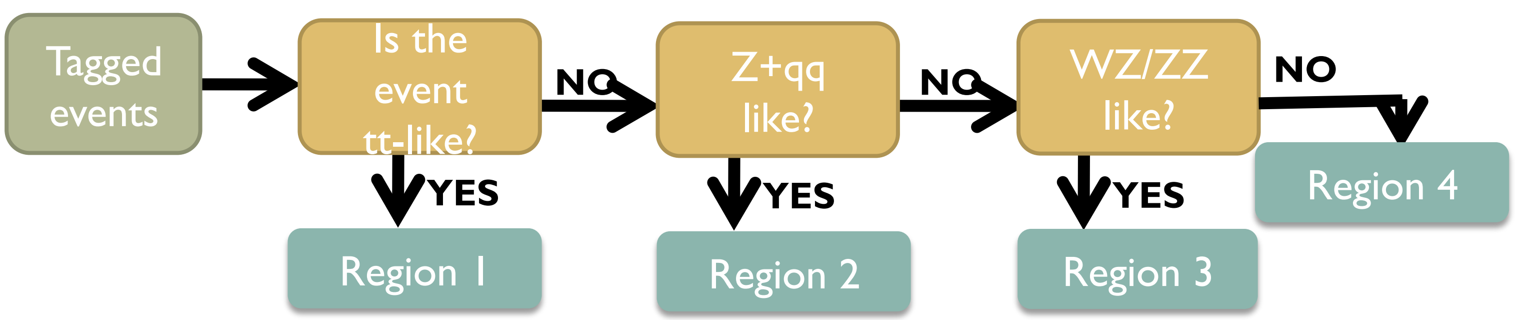
- Neural network correlates all jet-related variables and returns most probable jet energy based on bottom quark hypothesis – better signal/background separation



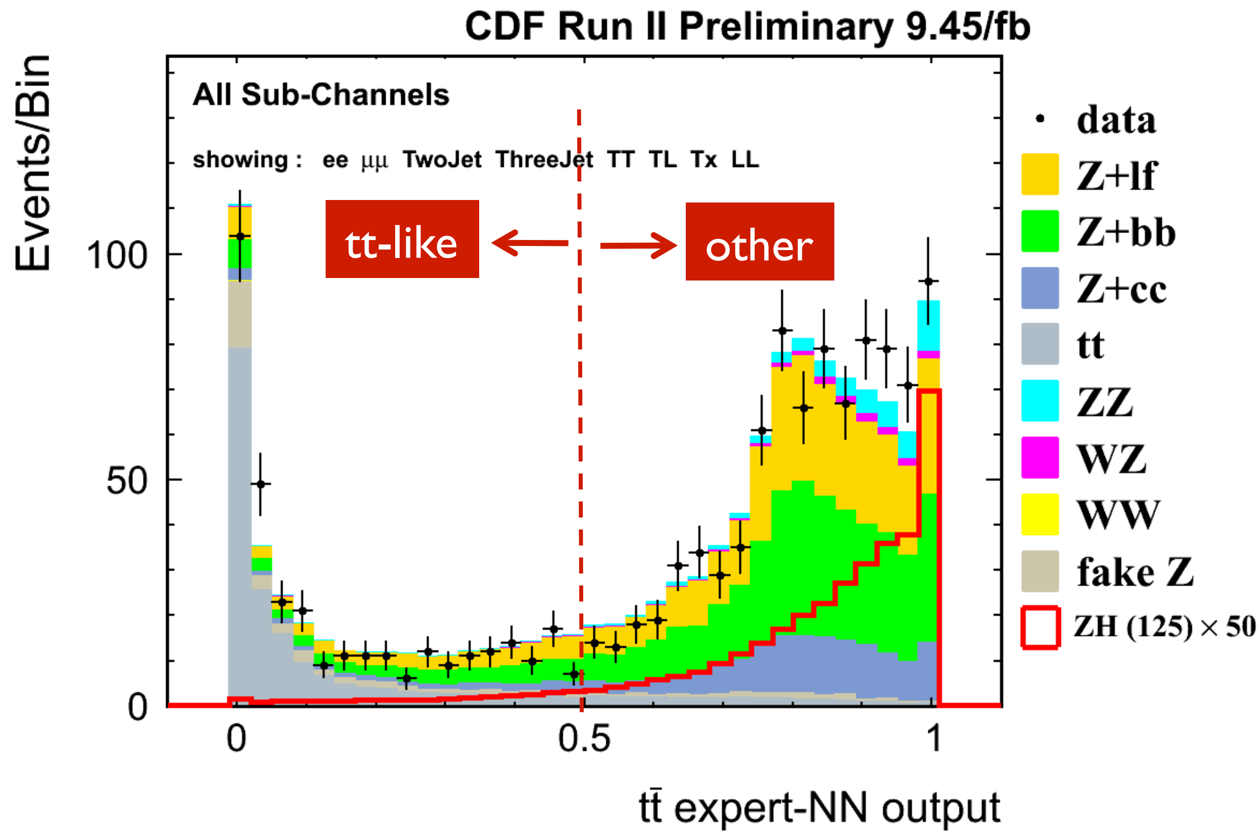
MVA improvements

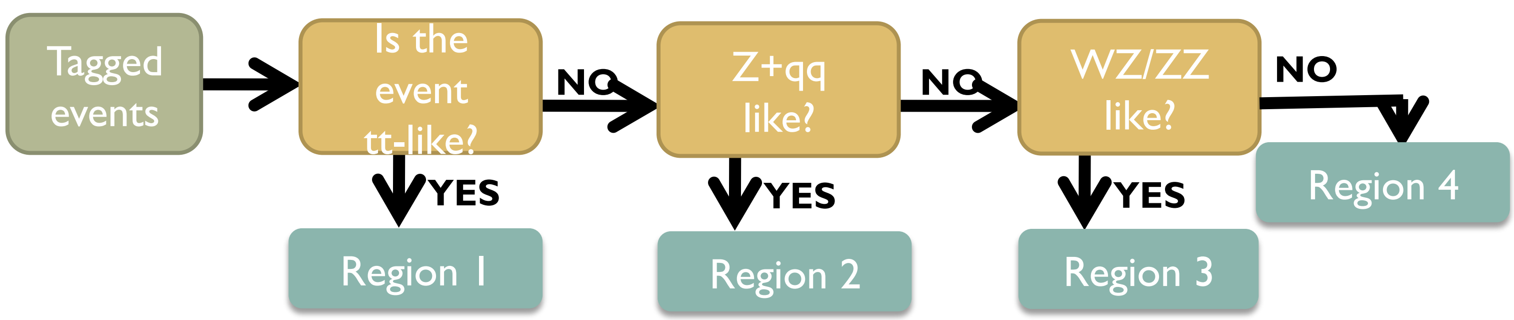
- Small MVA improvements in many channels
- Example from ZH→llbb to illustrate

• Many backgrounds processes are present the llbb selection
• The individual processes have different kinematics
• A single neural net trained to select signal out of a mix of backgrounds can be improved.

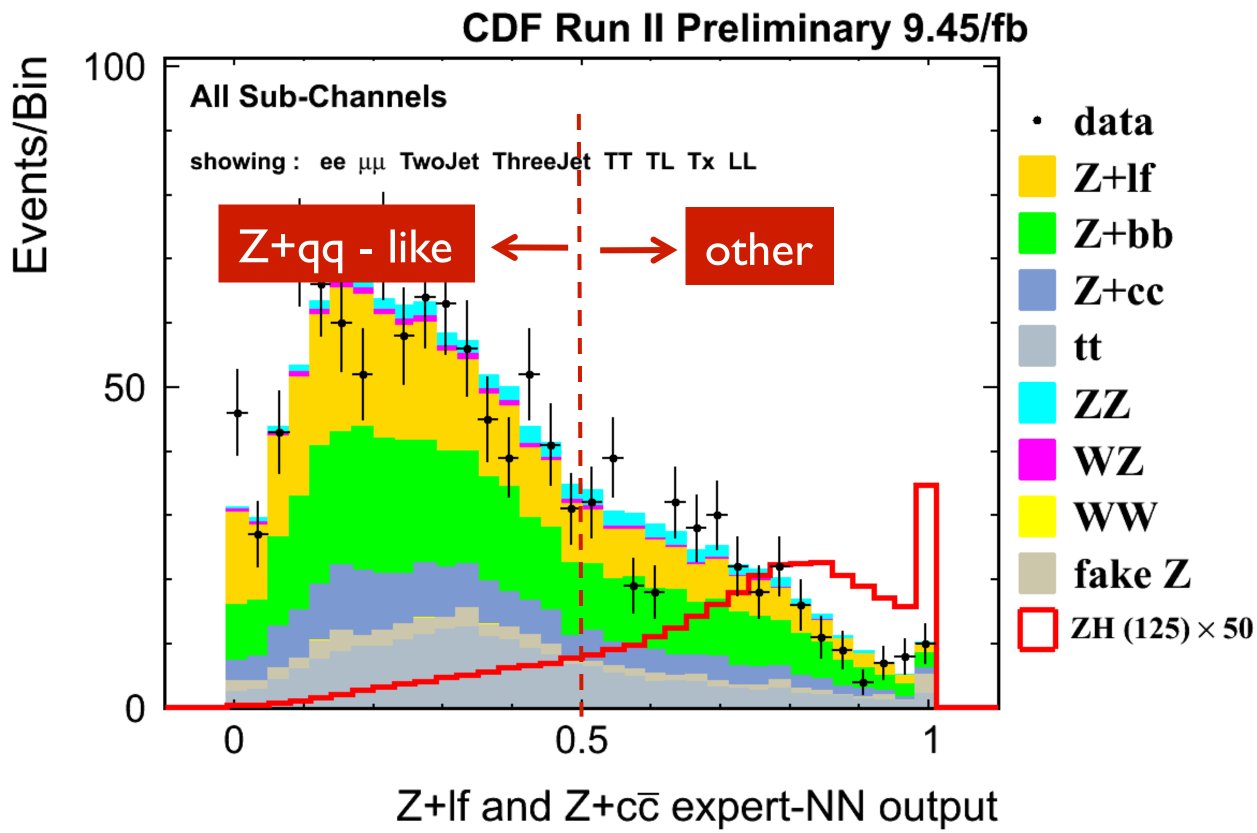


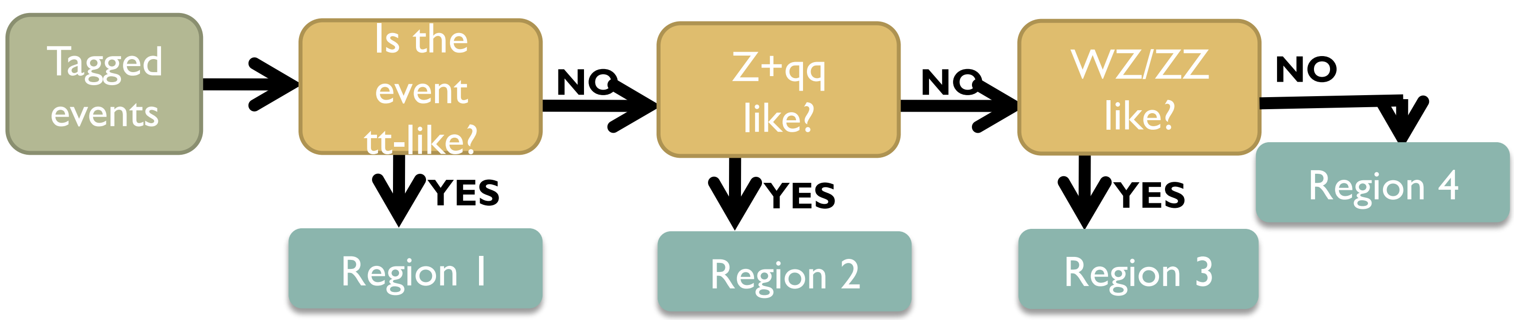
MVA improvements in ZH→llbb



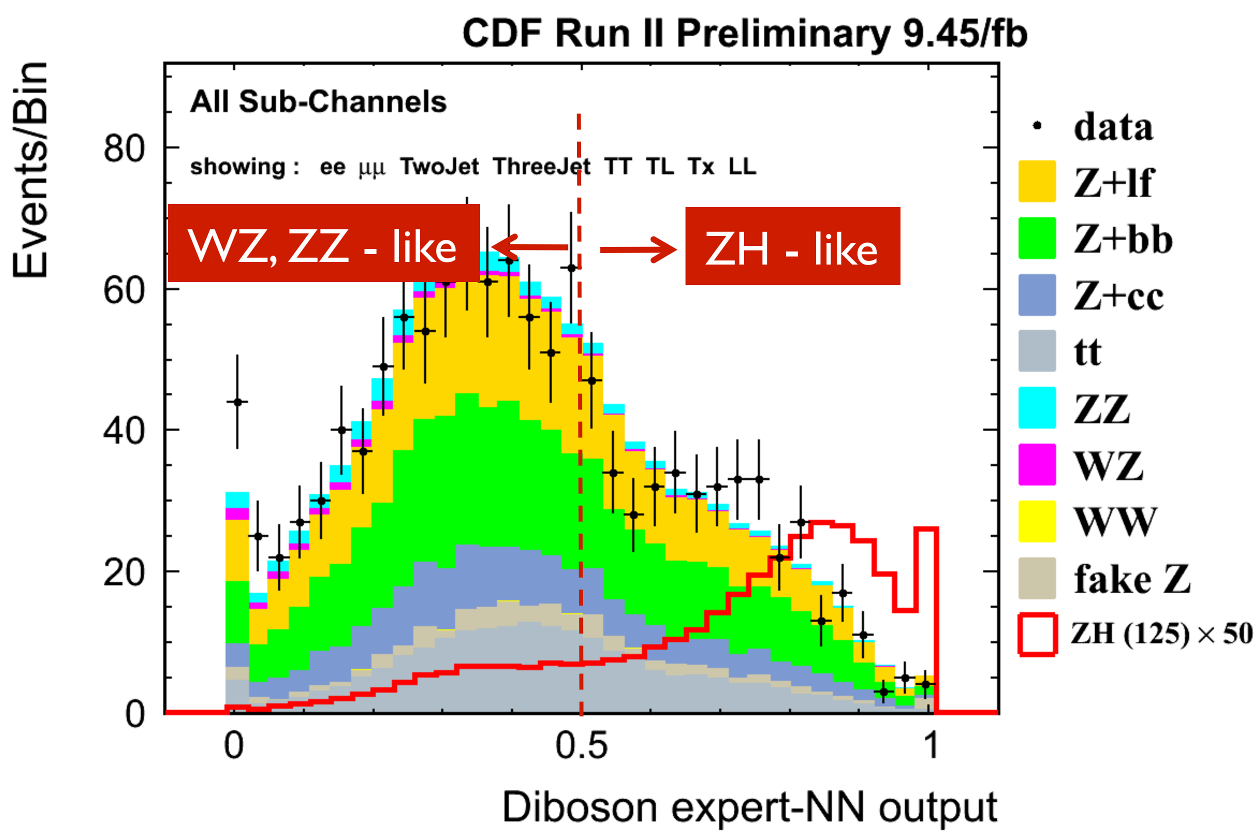


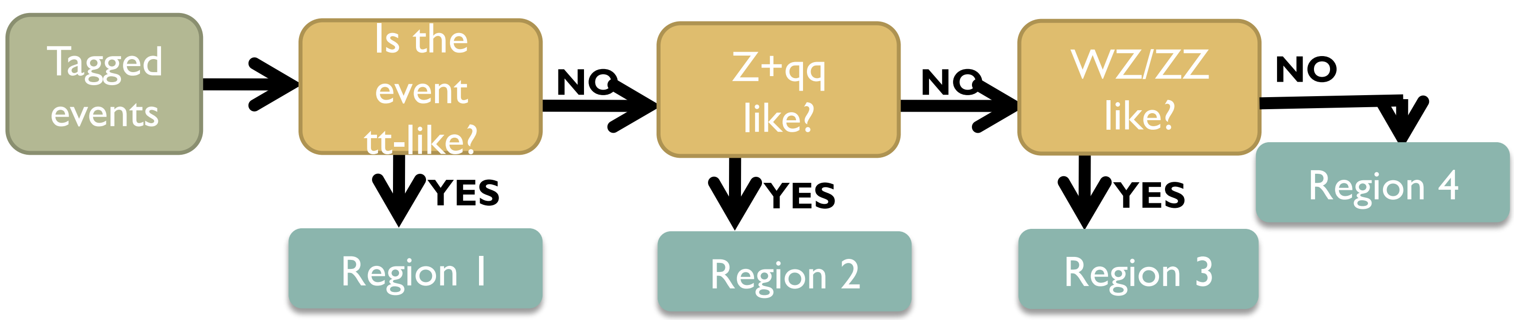
MVA improvements in ZH→llbb





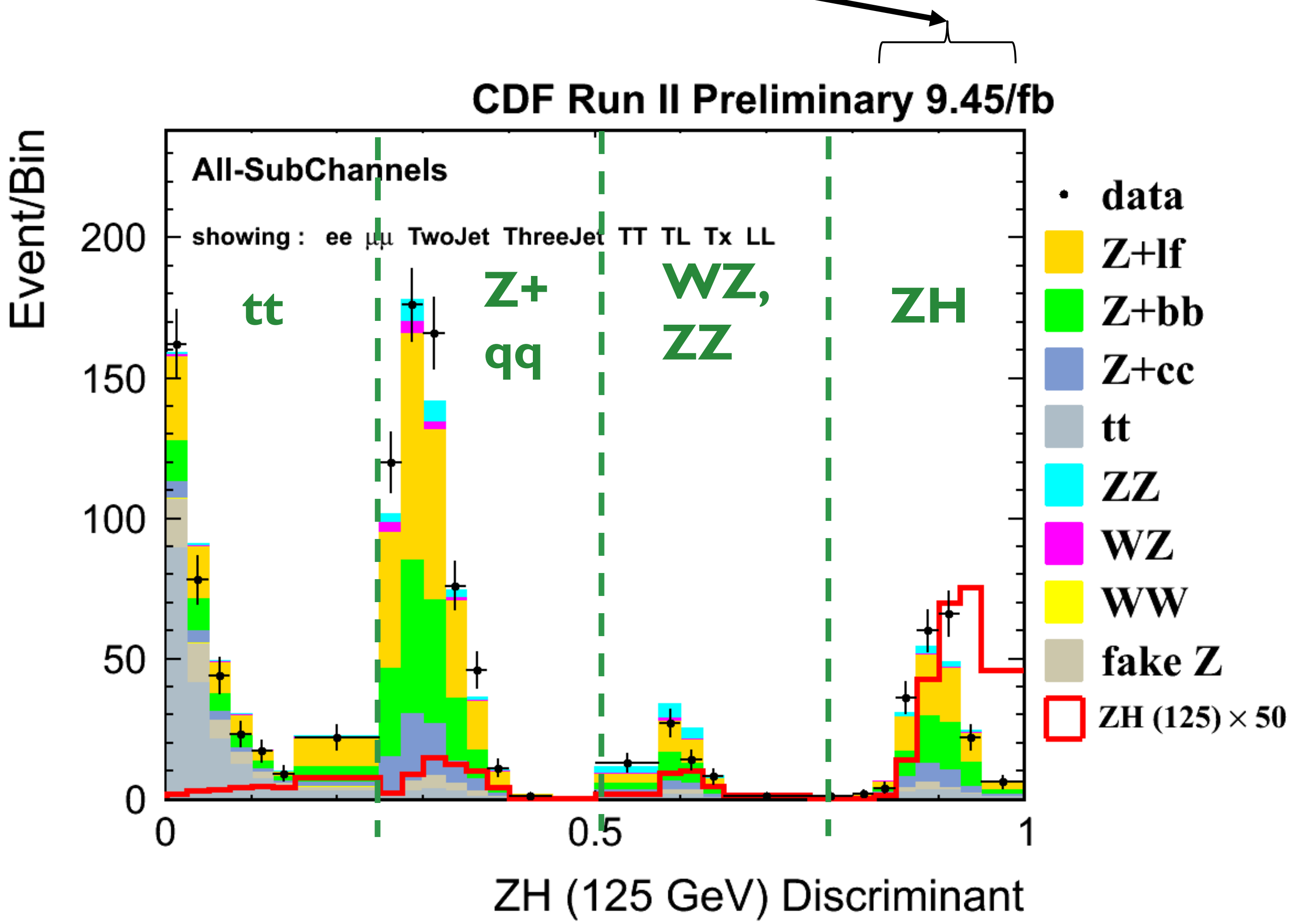
MVA improvements in ZH→llbb





MVA Improvements in ZH→llbb

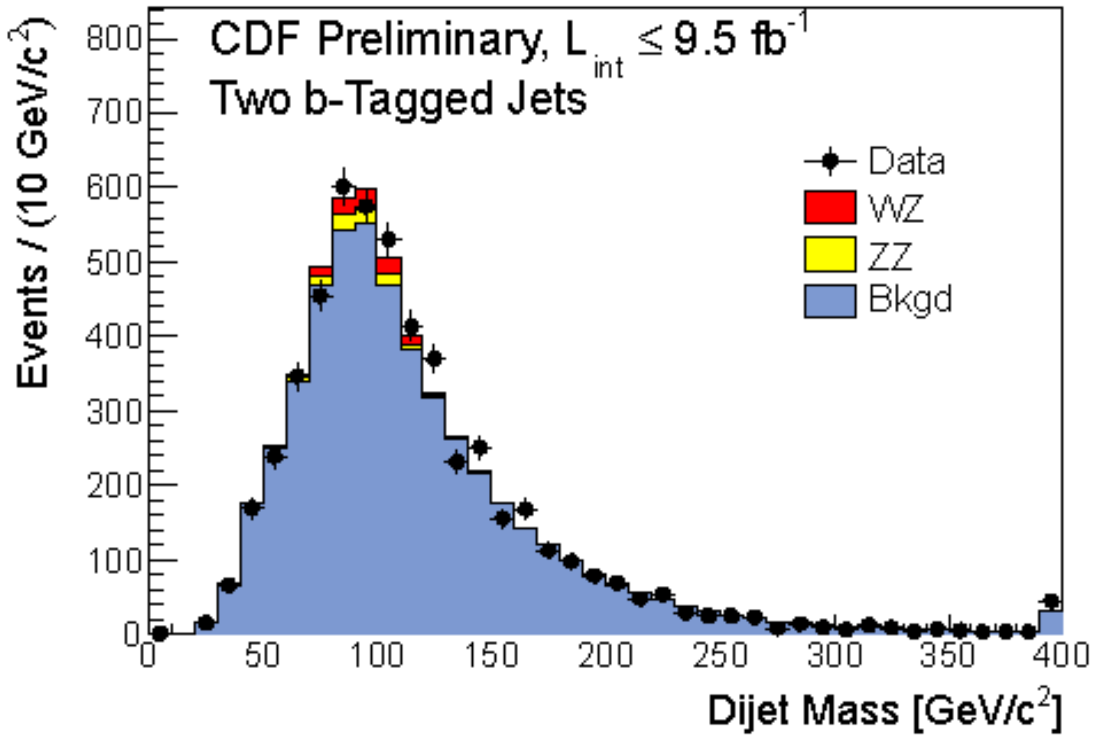
- No events are discarded, only shuffled
- Result is a handful of bins with enhanced S/B



How good is our modeling?

Do we see WZ and ZZ events ?

- same final state
- well known SM process
- same set of tagged events
- same background model
- different MVA optimized for WZ and ZZ events



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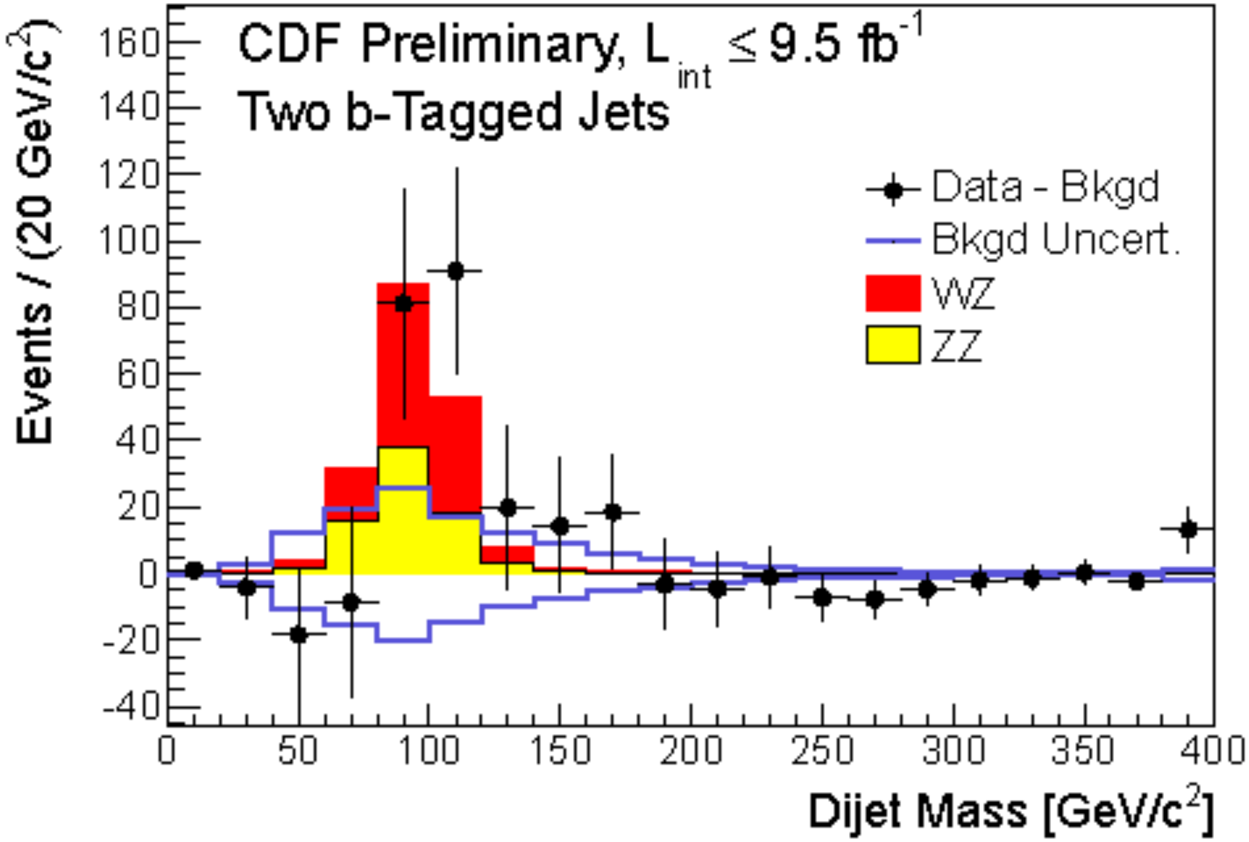
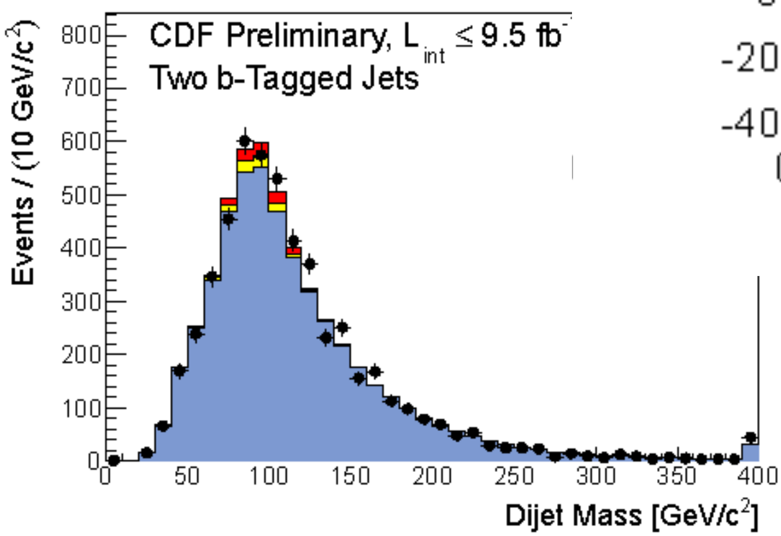
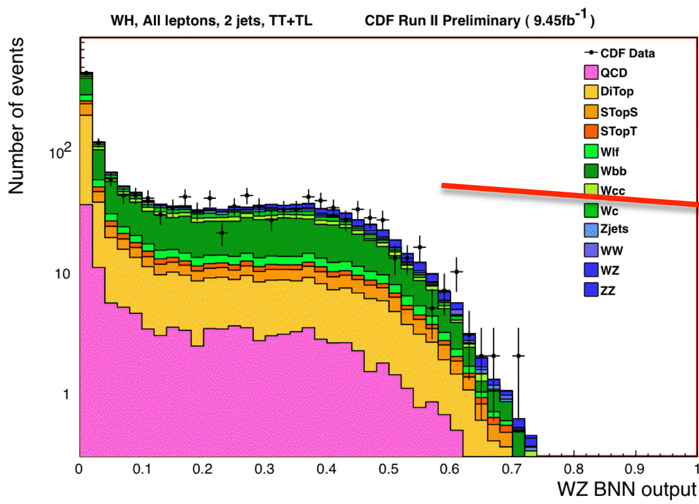


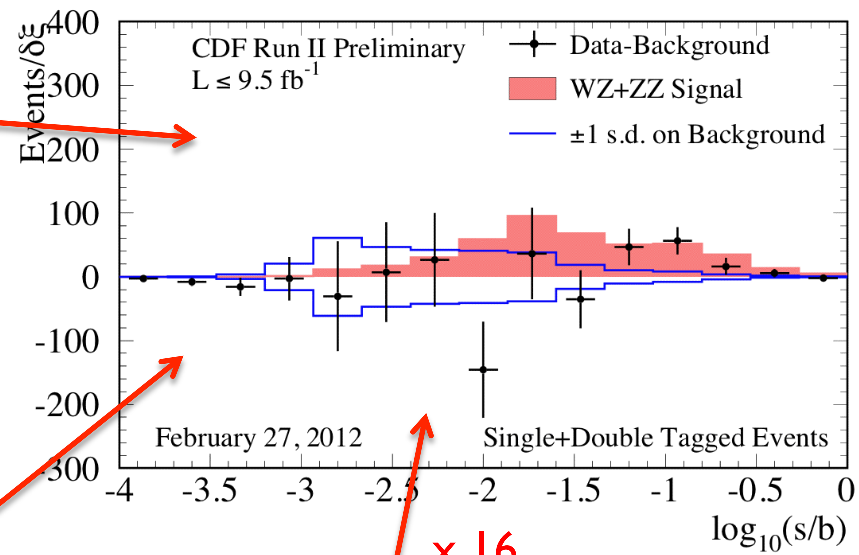


MVA-based Search

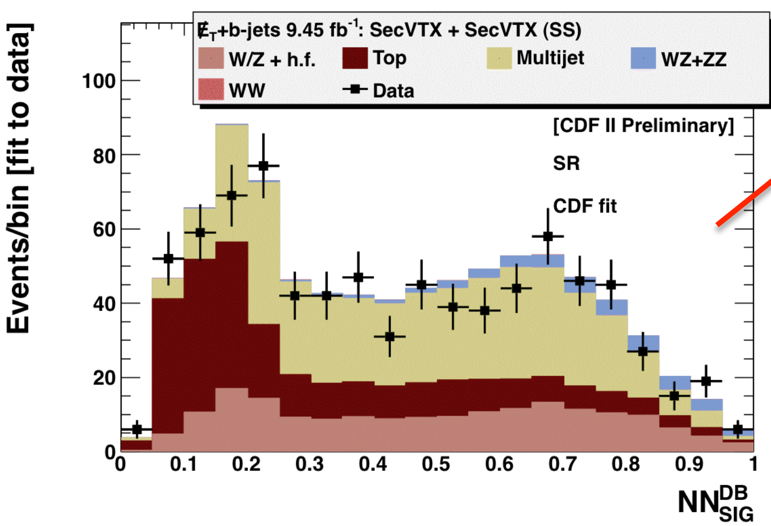
440 signal events and ~35,000 background



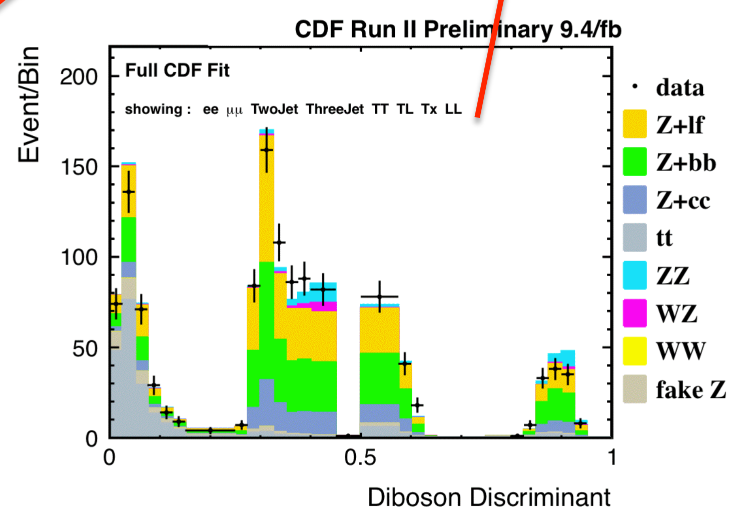
x 20



x 3



x 16



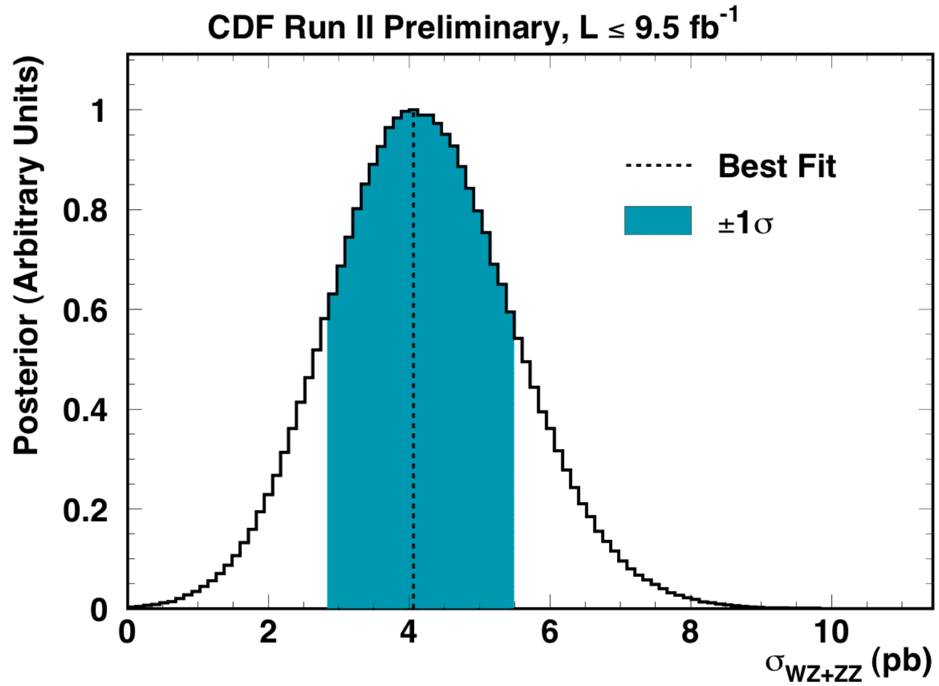
From Discriminants to Limits

- Combined binned likelihood function

$$L(R, \vec{s}, \vec{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

- Incorporate uncertainties as nuisance parameters
- Uncertainties taken on both the shapes and normalizations of signal & background templates
- Additional constraints on background model obtained directly from fit!!

Extracting σ(WZ+ZZ)

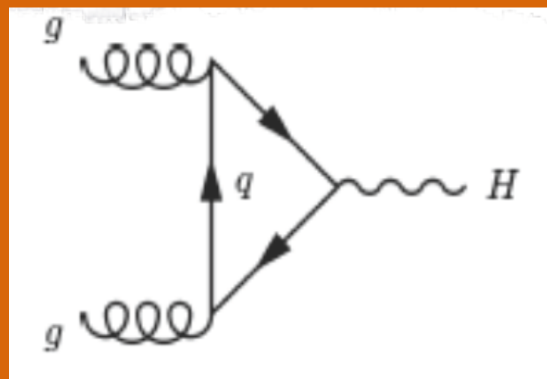


σ(WZ+ZZ)= 4.08 +/- 1.32 pb

with approximate significance of 3.2 σ

SM Prediction = 4.4 +/- 0.3 pb

"High Mass" channel



H→WW→lνlν

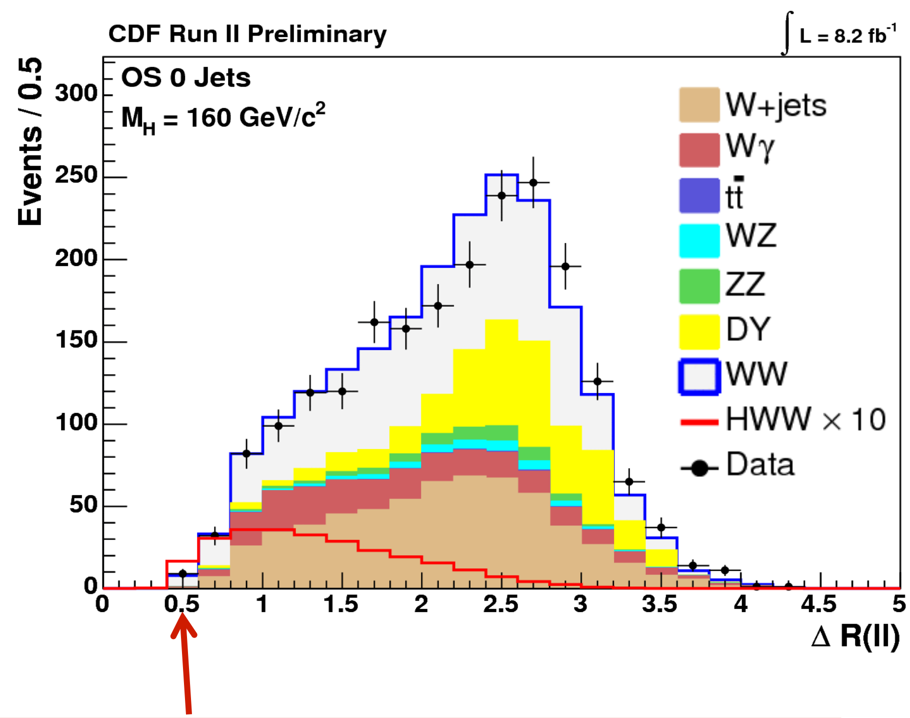
Select: 2 high E_T leptons and missing E_T

Strategy:
- Maximize lepton reconstruction and selection efficiencies
- Separate events into multiple analysis channels (e.g. 2 jets and opposite sign leptons)
- Best possible choice of kinematic event variables for separating signal and background

H→WW→lνlν

Improvements:

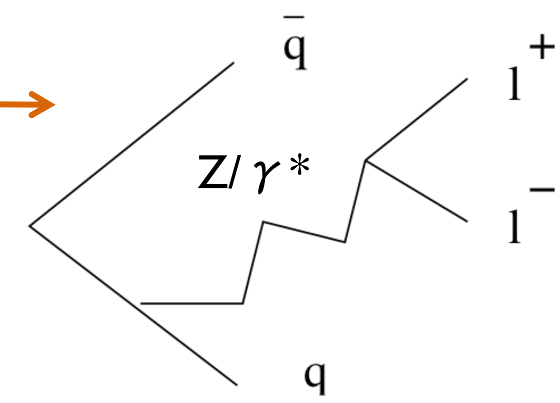
- 8.2→9.7 fb^{-1}
- M_H dependent optimization of neural network inputs
- Increased acceptance for low invariant mass dilepton pairs ($0.1 < \Delta R_{ll} < 0.2$)

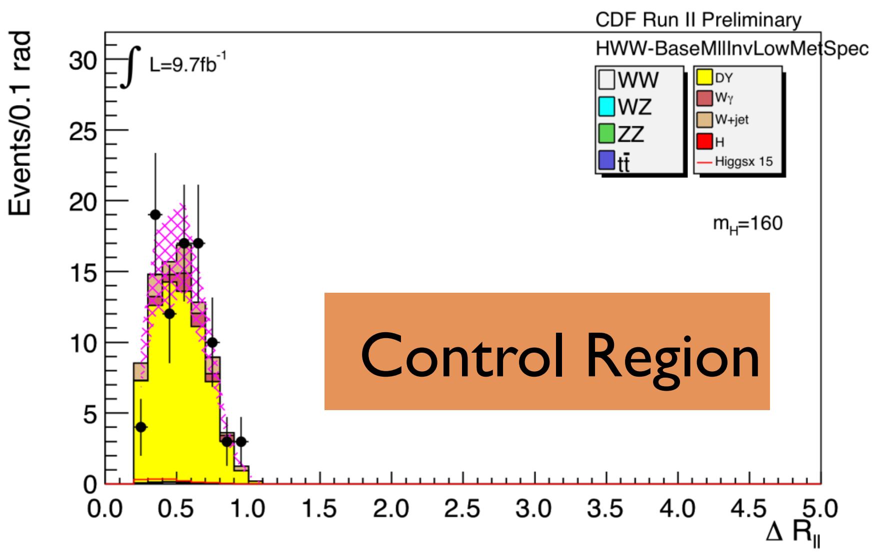


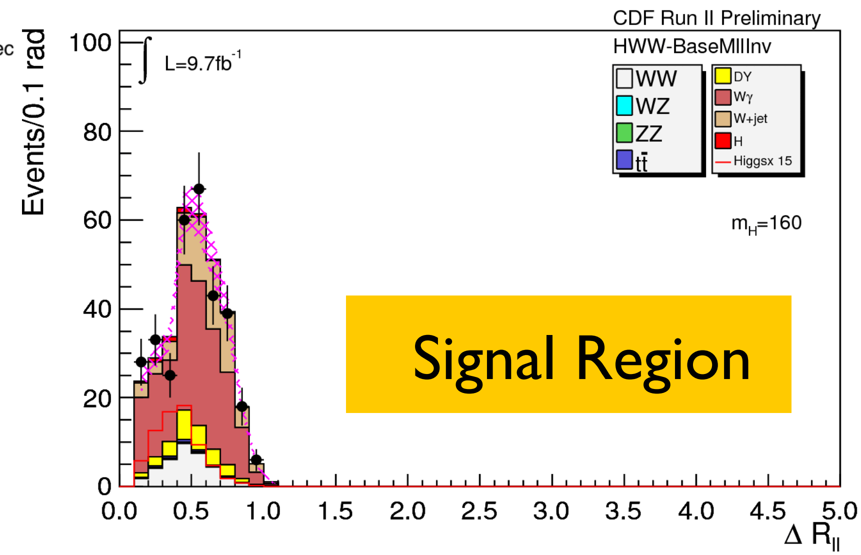
H→WW signal events are peaked at low ΔR_{ll} because spin 0 Higgs boson anti-correlates the spin of the Ws, favoring a small opening angle of the leptons

Improved ΔR_{ll} acceptance

- Include region $0.1 < \Delta R_{ll} < 0.2$
  - special Drell-Yan modeling (MADGRAPH)
  - new Wγ modeling (MADGRAPH)
  - cuts to remove J/ψ and ϒ resonances

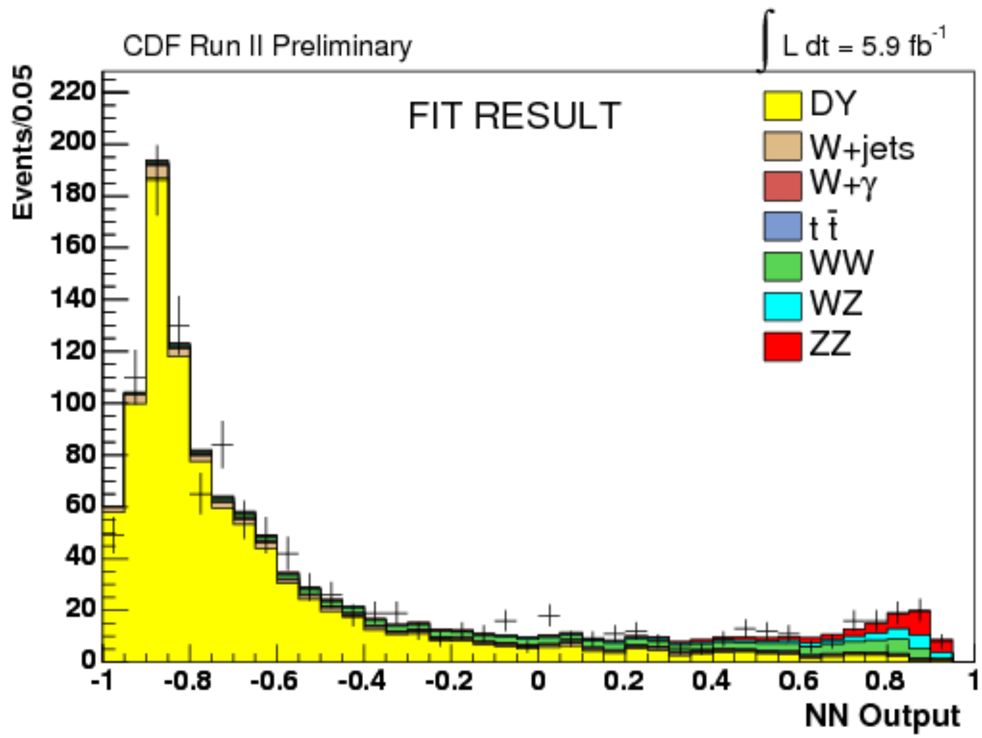






Validate high mass technique with σ(ZZ)

- Same tools and data samples
- Different neural network optimized for $ZZ \rightarrow ll\nu\nu$



$\sigma(ZZ) = 1.45^{+0.60}_{-0.51}$ pb

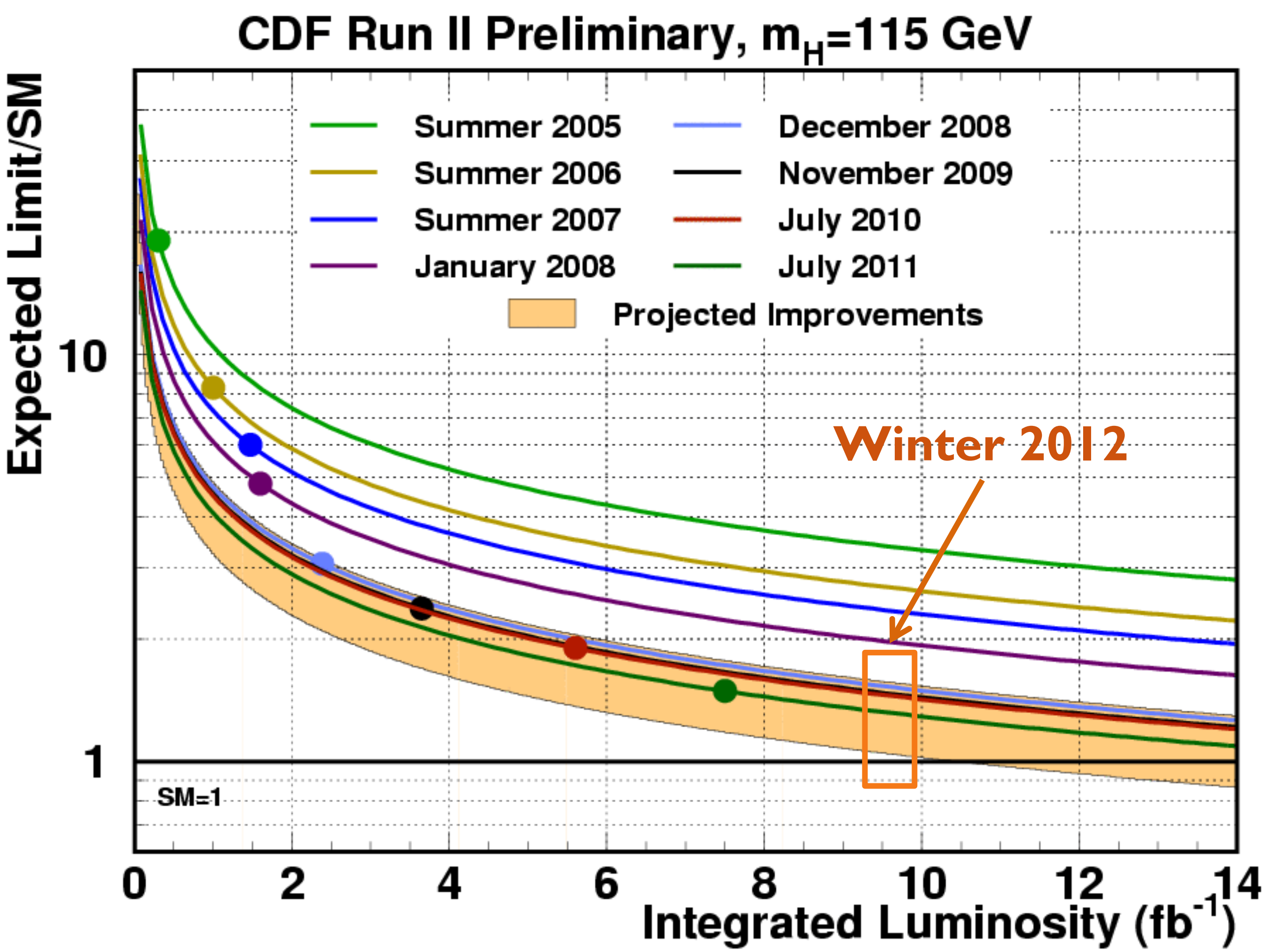
SM pred: 1.2±0.1 pb

No channel left behind!

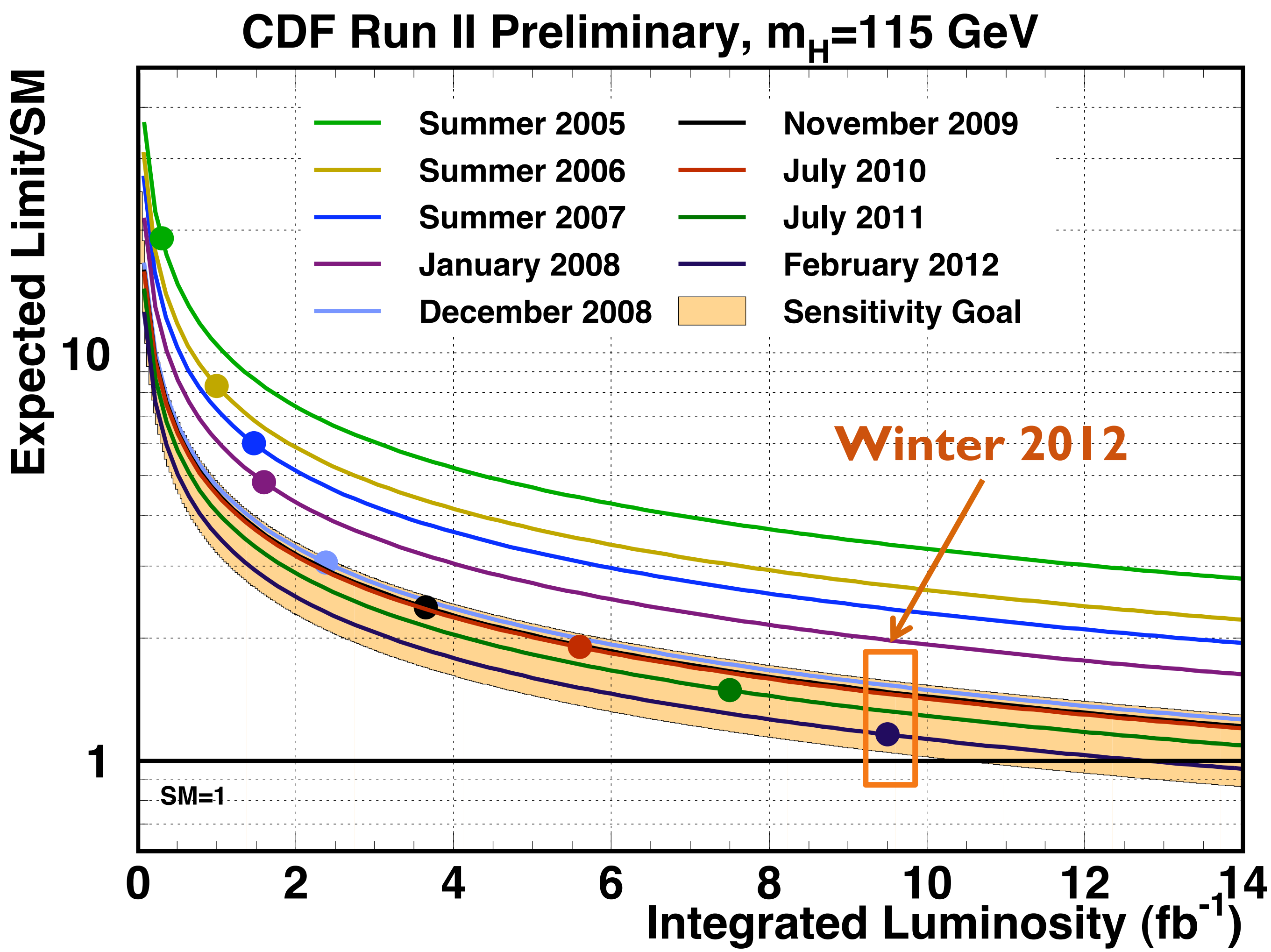
Channel	Luminosity	95% CL limit M_H=125 GeV
$H \to \gamma\gamma$	10.0 fb^{-1}	10.8 x SM
$VH \to bb$+jets	9.45 fb^{-1}	11.0 x SM
$ttH \to l\nu$+jets	9.4 fb^{-1}	12.4 x SM
$H \to \tau\tau$+jets	8.4 fb^{-1}	14.8 x SM

Channel	Luminosity	95% CL limit M_H=150 GeV
$H \to ZZ \to llll$	9.7 fb^{-1}	9.4 x SM

CDF Sensitivity Projections



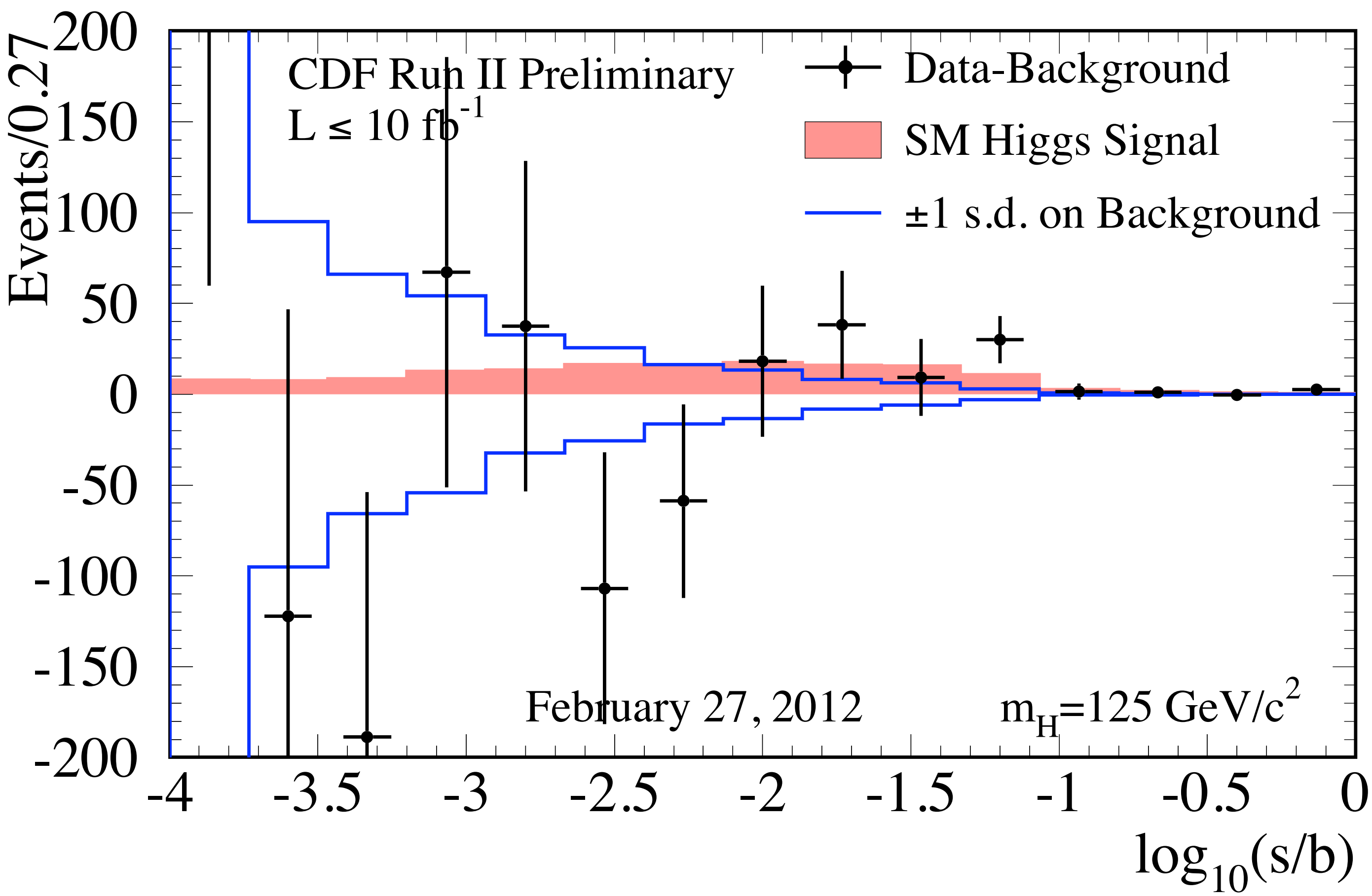
CDF Sensitivity Accomplishments!



Results

Combined Higgs Discriminants

- Combine 16 analyses, 93 orthogonal channels



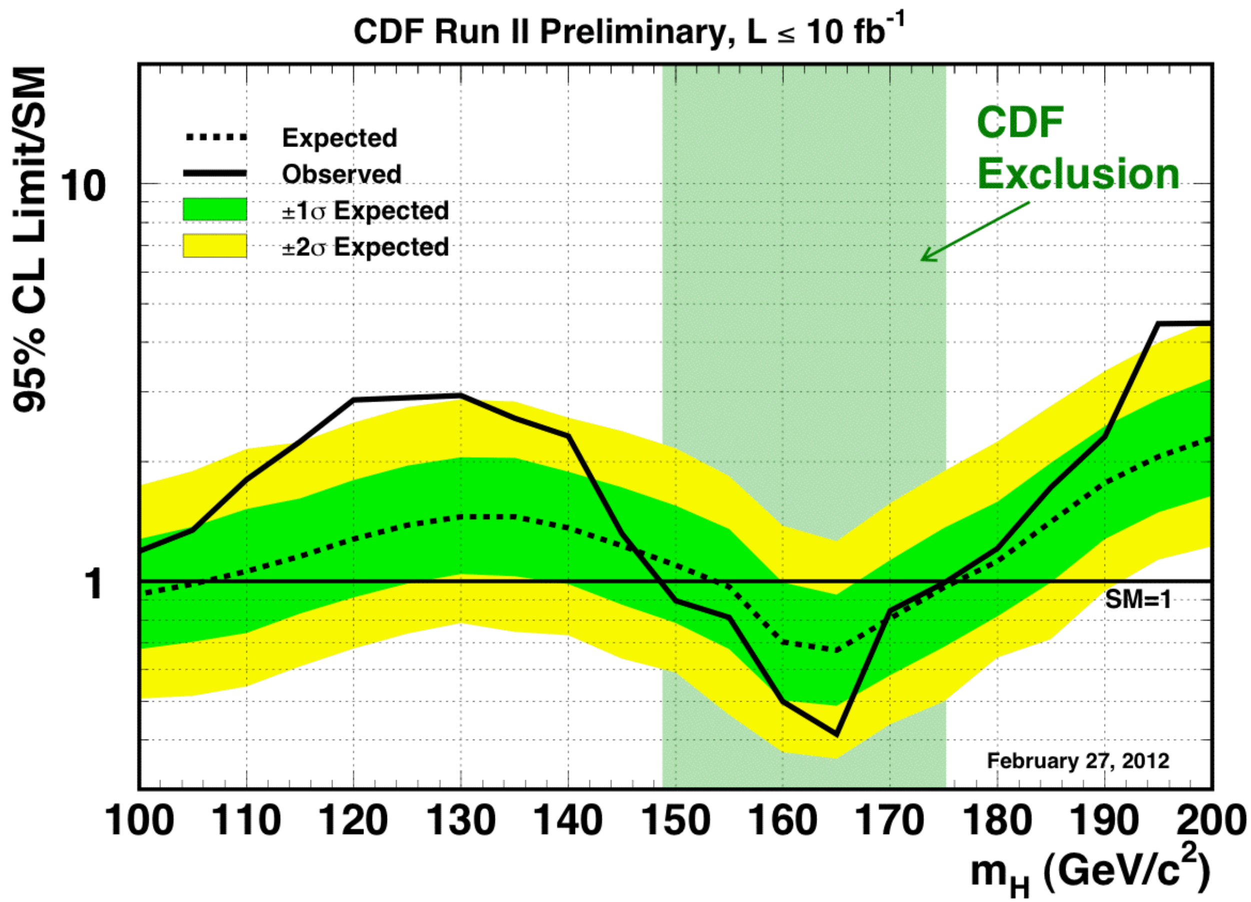
From Discriminants to Limits

- Combined binned likelihood function

$$L(R, \vec{s}, \vec{b}|\vec{n}) = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bin}}} \frac{\mu_{ij}^{n_{ij}} e^{-\mu_{ij}}}{n_{ij}!}$$

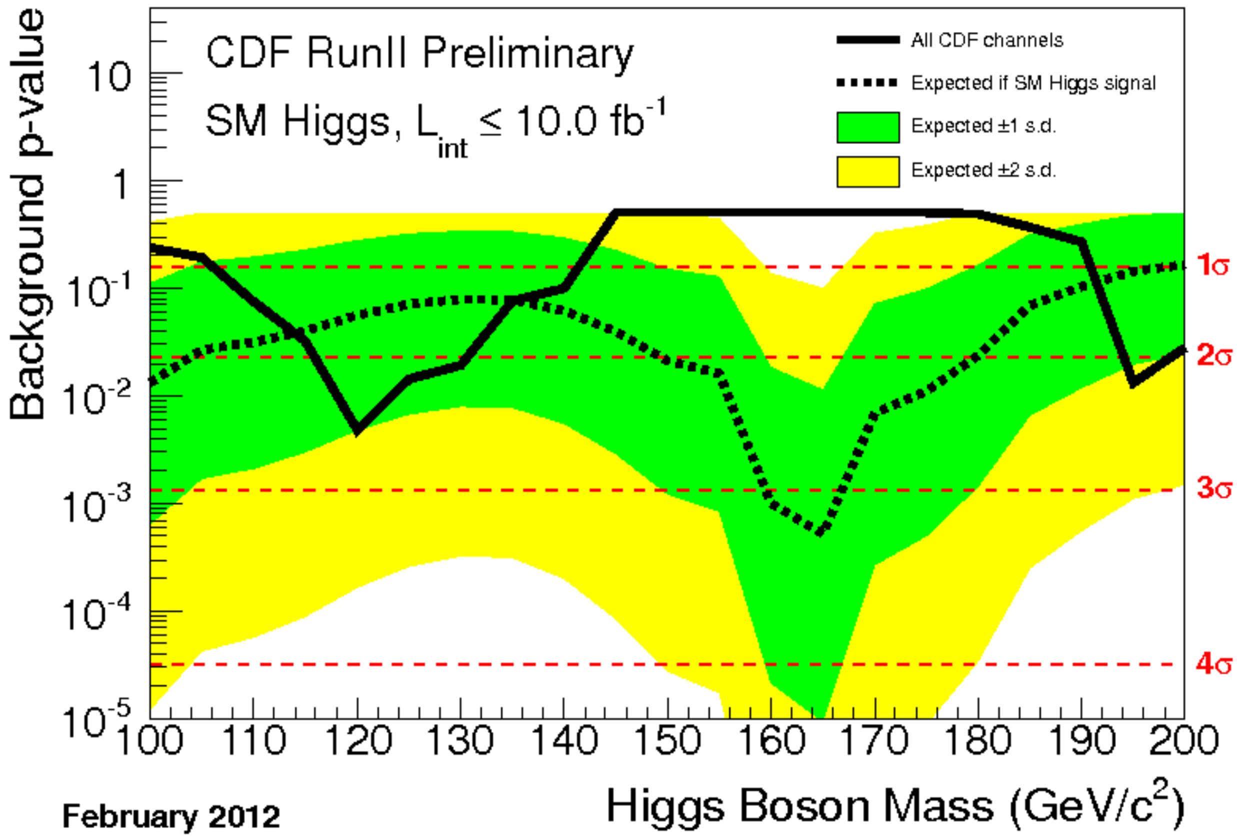
- Incorporate uncertainties as nuisance parameters
- Uncertainties taken on both the shapes and normalizations of signal & background templates
- Additional constraints on background model obtained directly from fit!!

New CDF combination



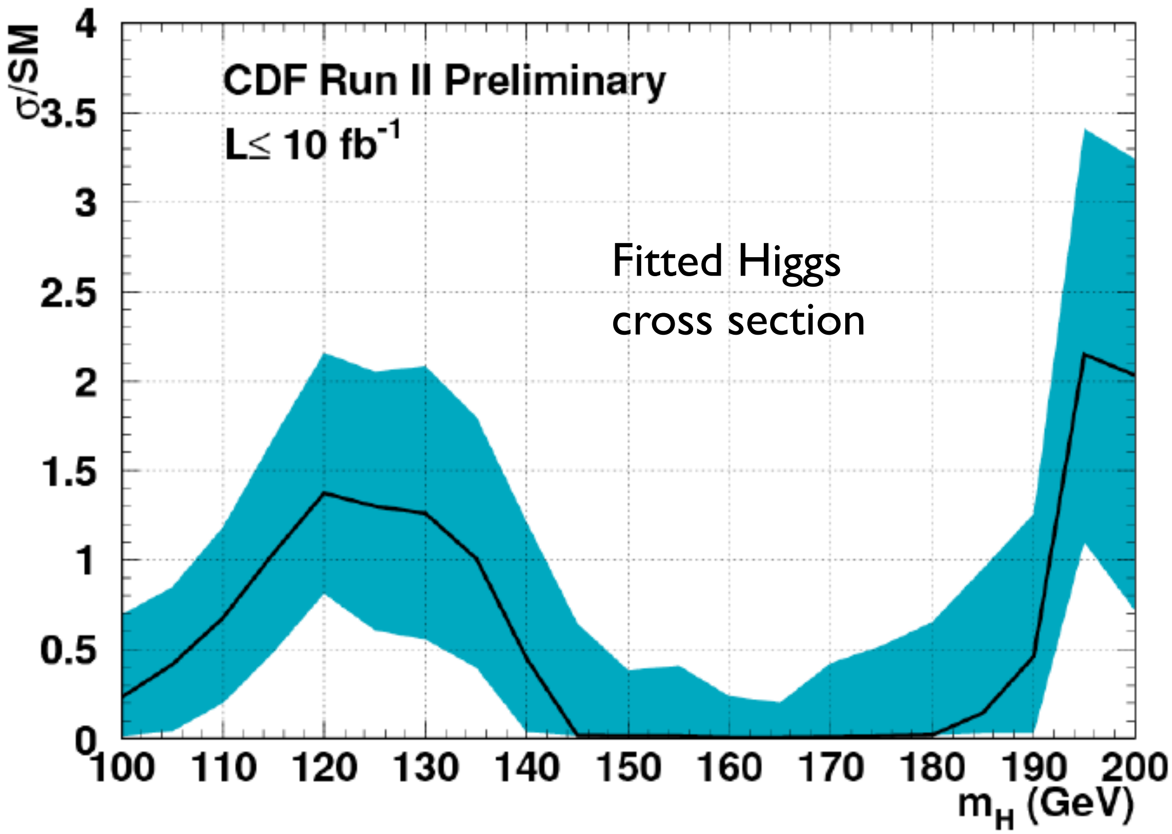
- Exclude SM Higgs at 95% C.L. : $147 < m_H < 175$ GeV/c^2
- Expect to exclude: $100 < m_H < 106$ GeV/c^2 & $154 < m_H < 176$ GeV/c^2

Compatible with background-only?



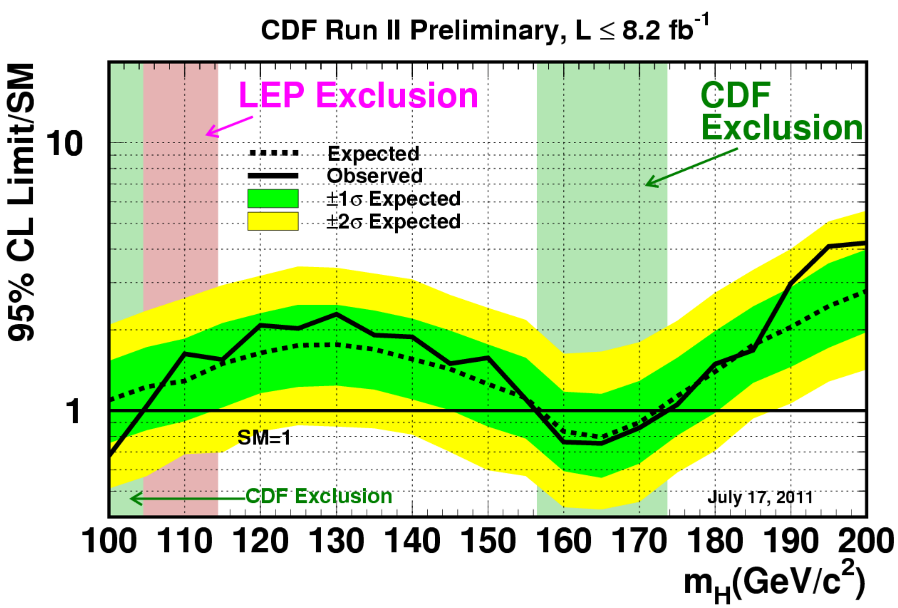
- Highest local p-value, 2.6σ, is found at m_H = 120 GeV/c^2

Is the excess compatible with a SM Higgs?

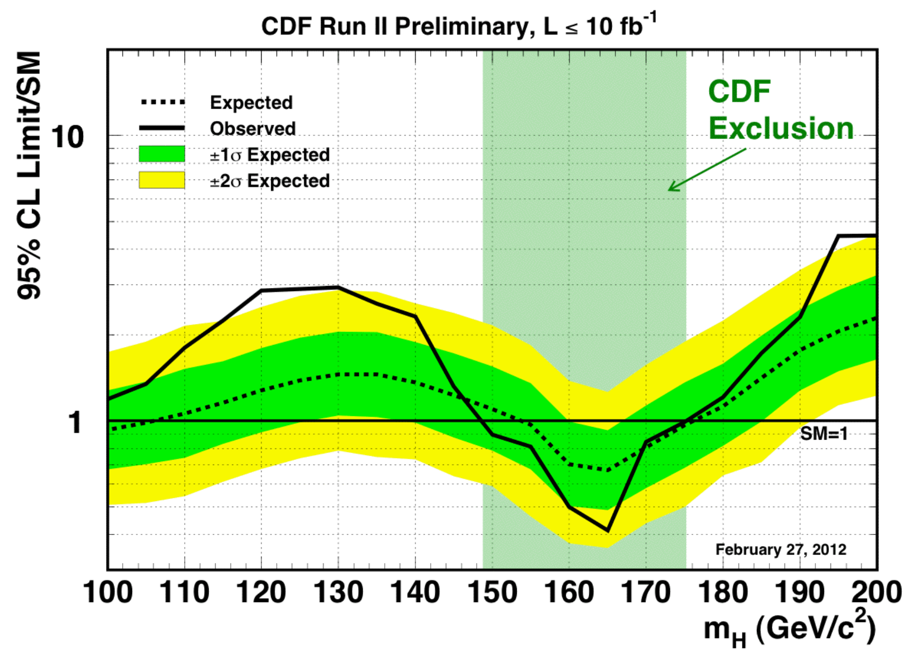


Consistent with SM Higgs at 1 σ level for mass range between 107 and 142 GeV/c^2

How much did things change?



Summer 2011

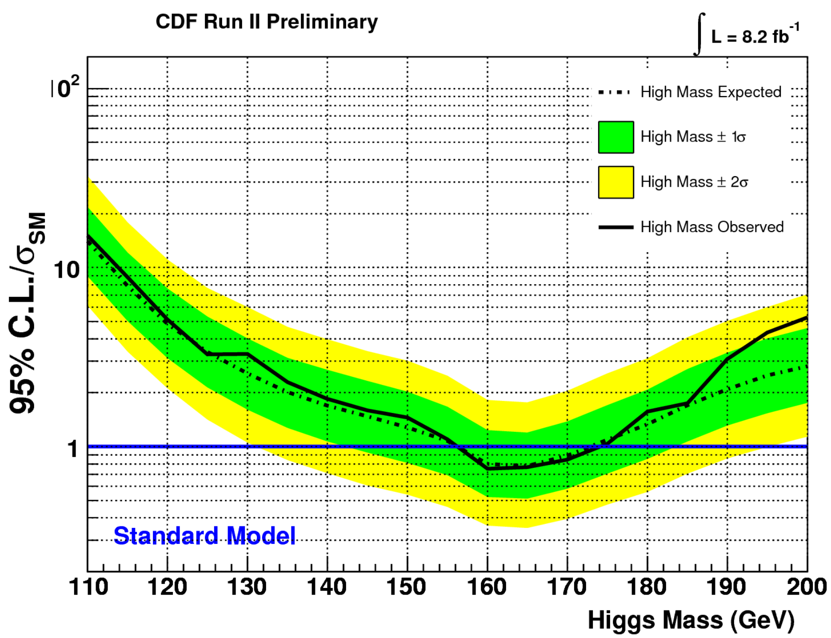


Winter 2012

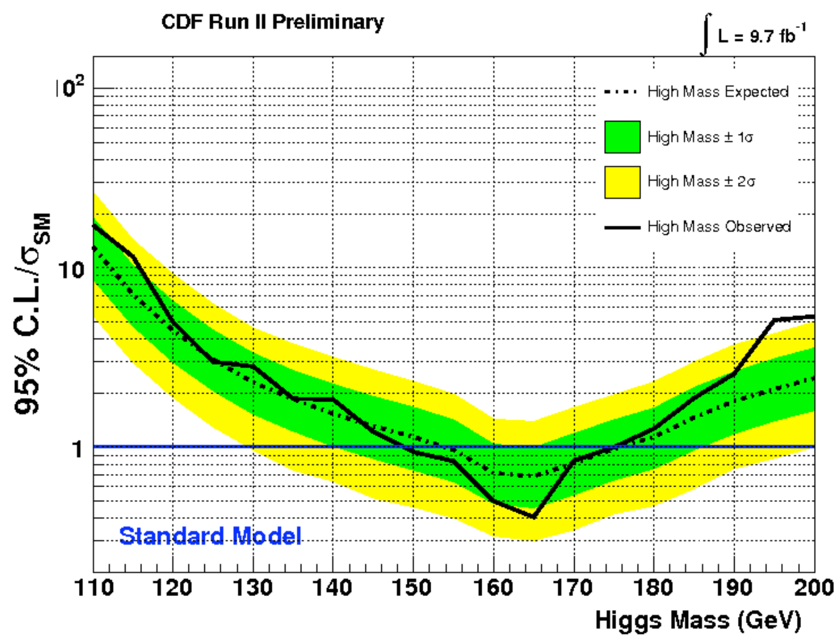
A ~0.5 σ excess in mass range from 115 to 135 GeV/c^2 has become a ~2 σ excess. How can this happen?

H→WW →lνlν

- 18% additional data
- Small signal acceptance improvements ($0.1 < \Delta R_{ll} < 0.2$)
- No appreciable change in behavior of limits



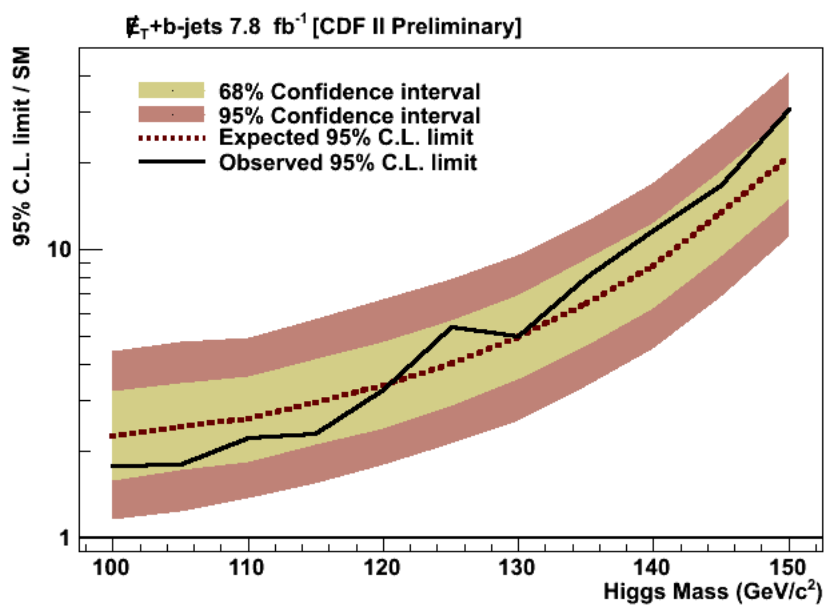
Summer 2011



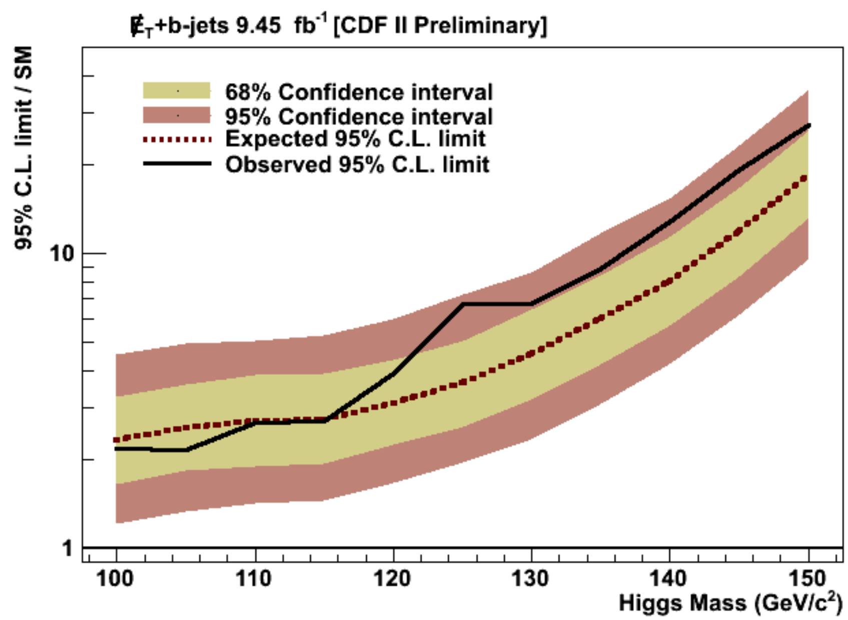
Winter 2012

ZH→ννbb

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



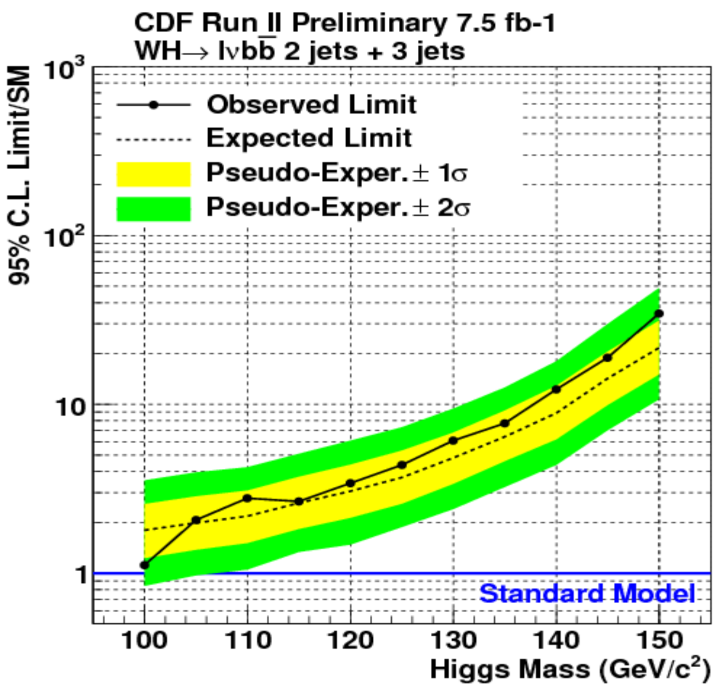
Summer 2011



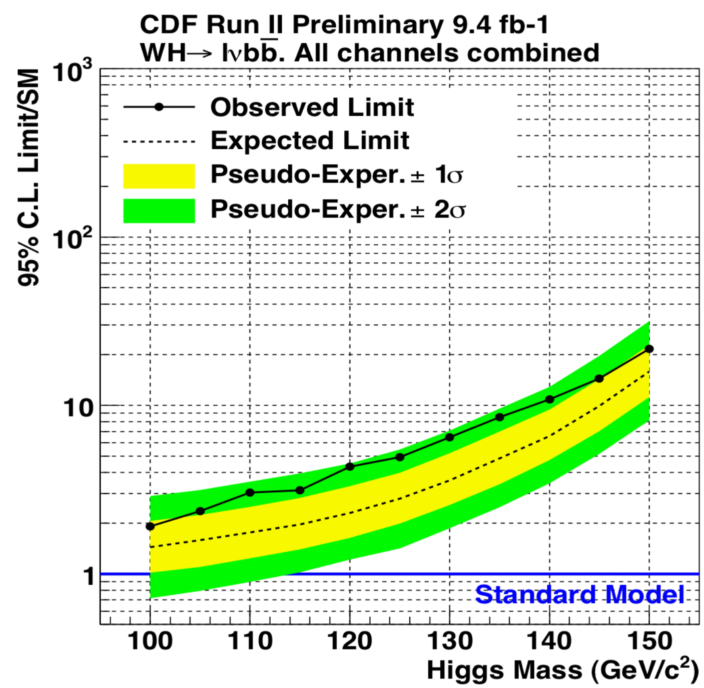
Winter 2012

WH→lνbb

- 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 1.5 σ increases in significance of excess



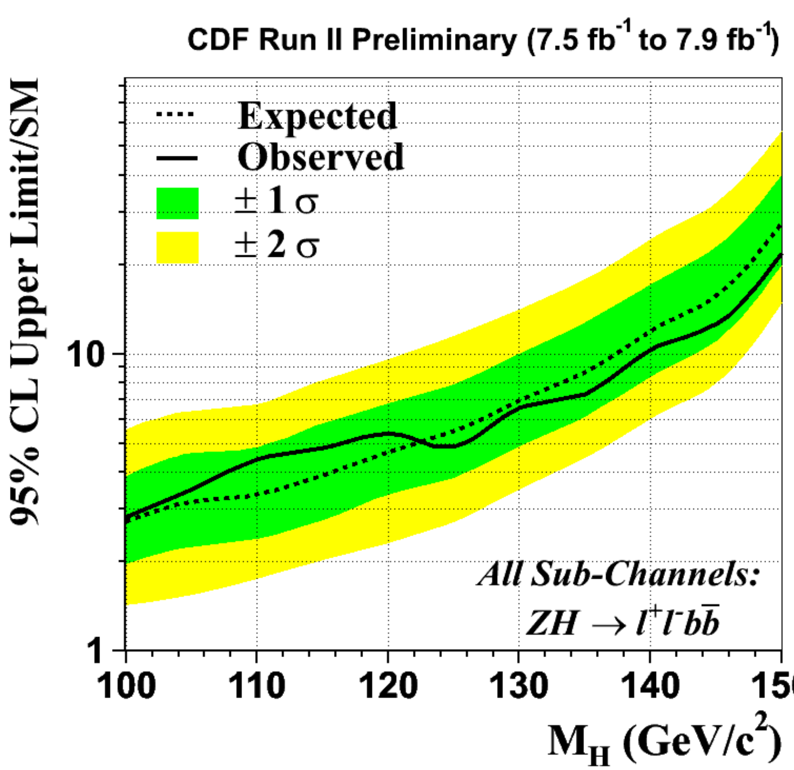
Summer 2011



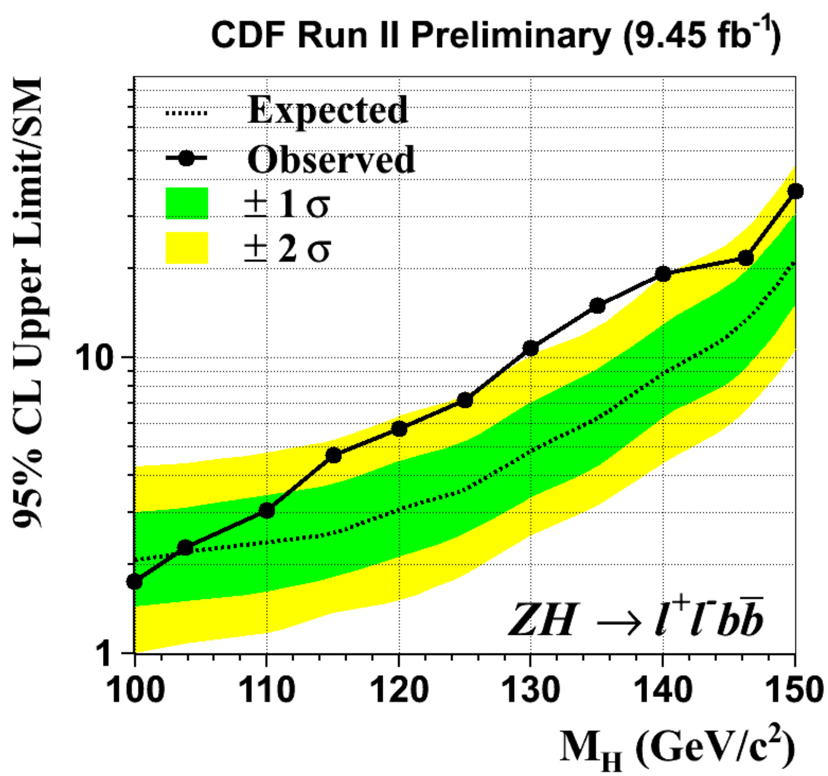
Winter 2012

ZH→llbb

- 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 m_H=120 GeV/c^2)



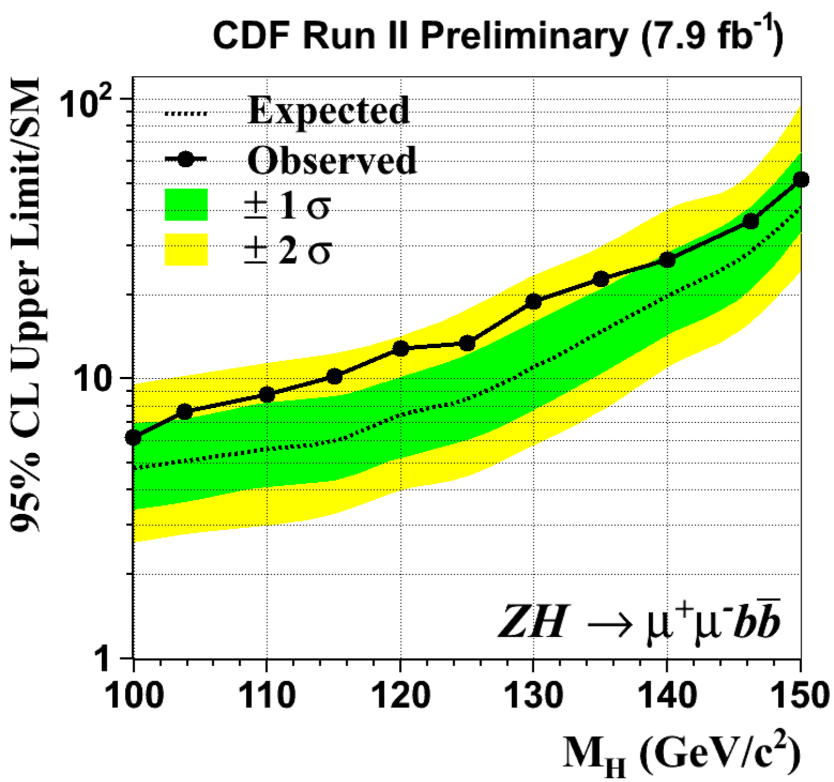
Summer 2011



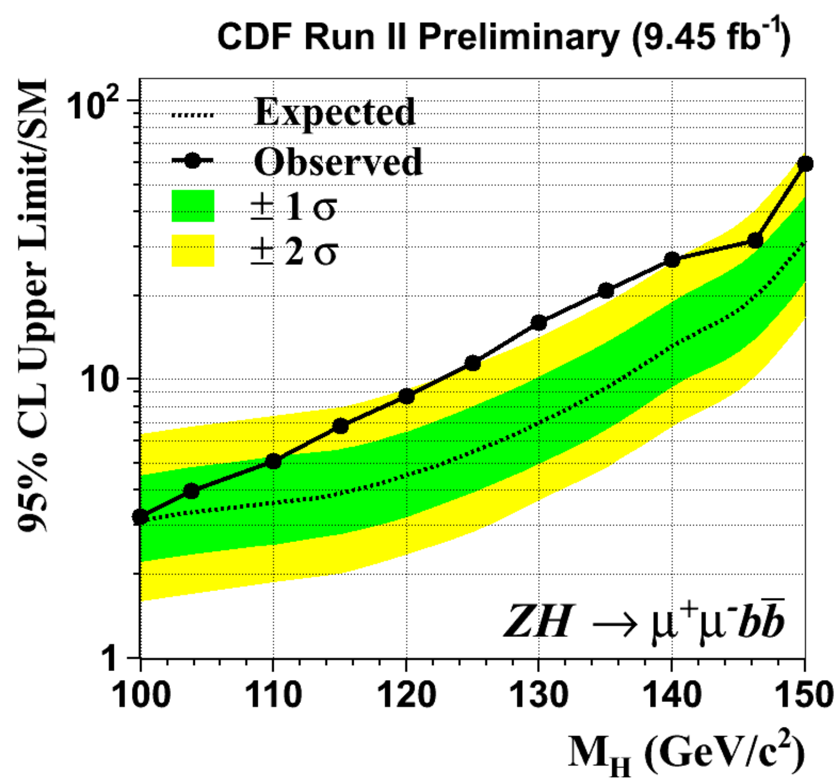
Winter 2012

ZH→llbb

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



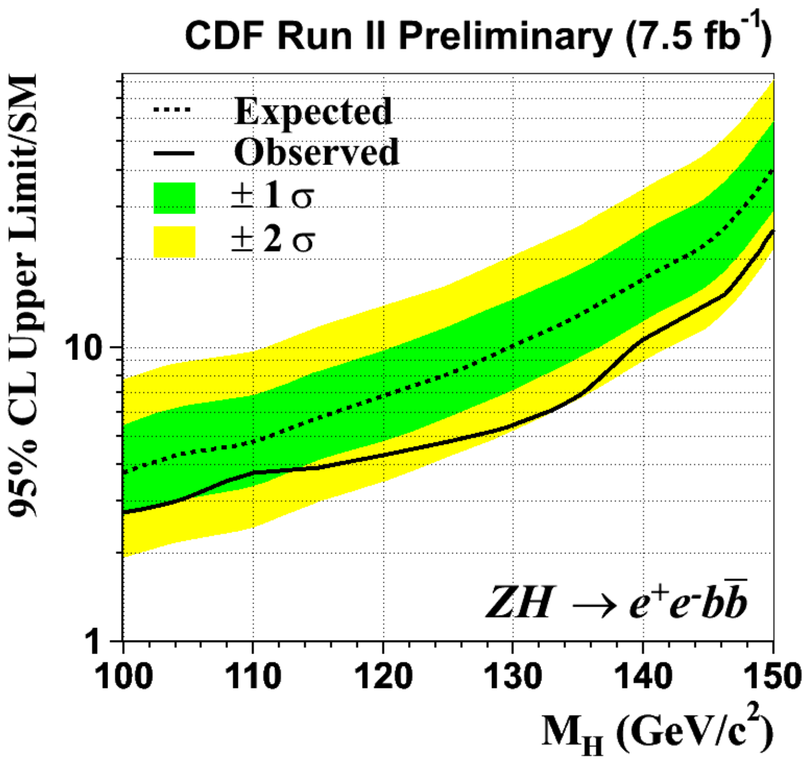
Summer 2011



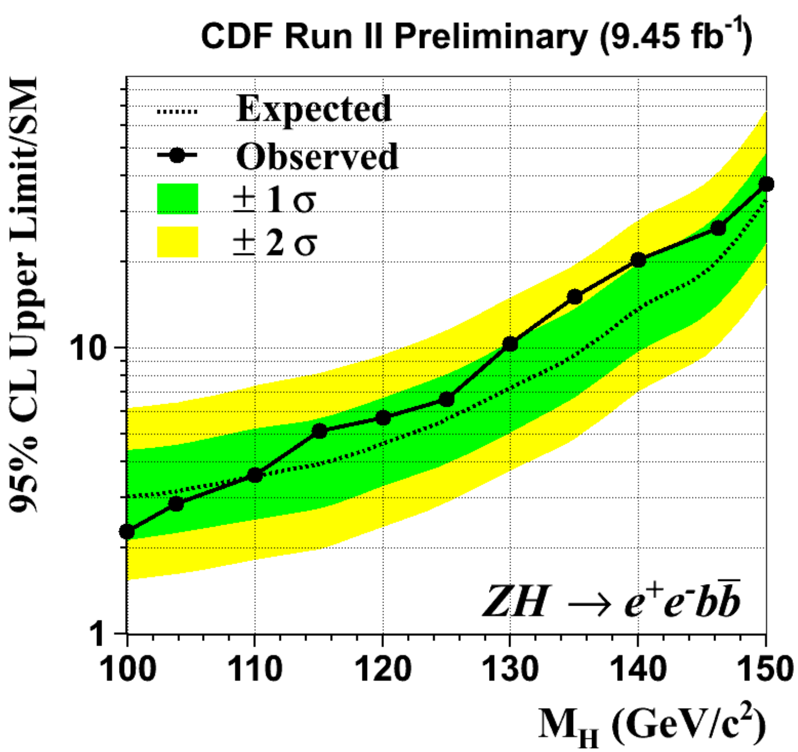
Winter 2012

ZH→llbb

- Electron channels
- Here we observe a significant change



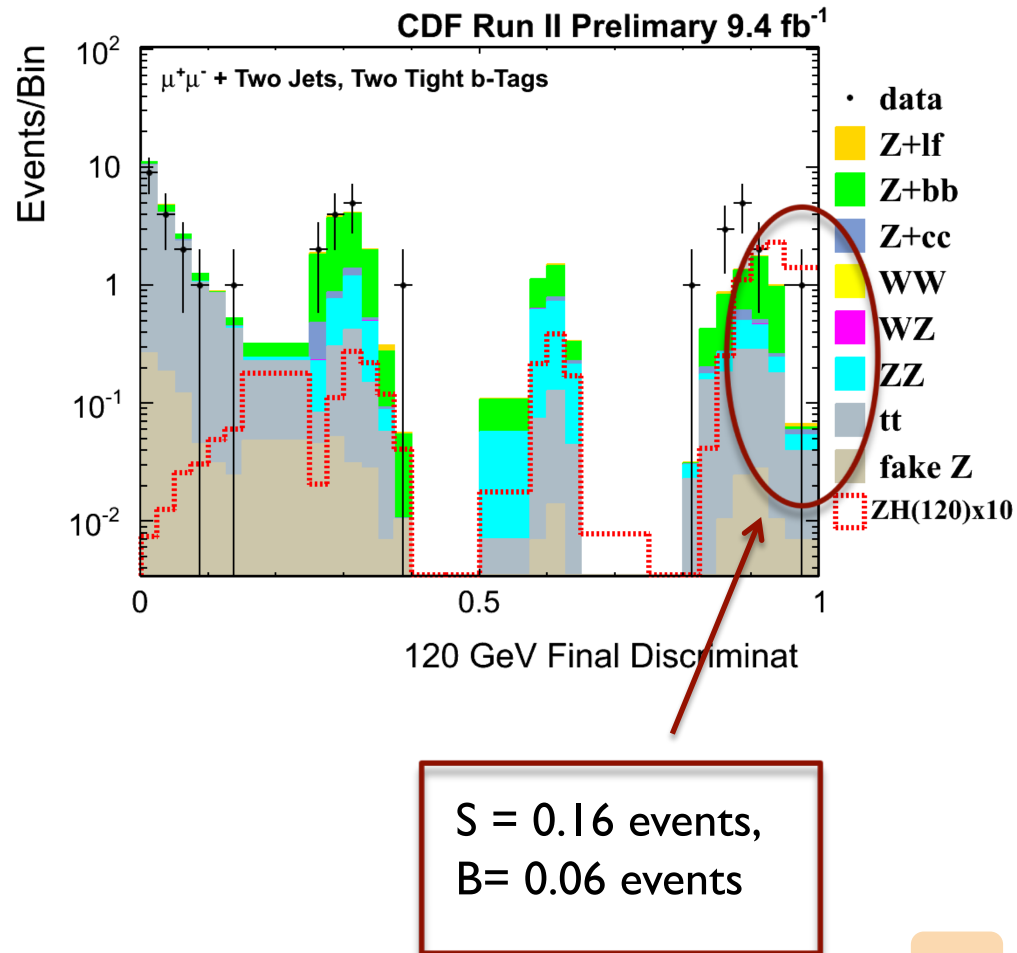
Summer 2011



Winter 2012

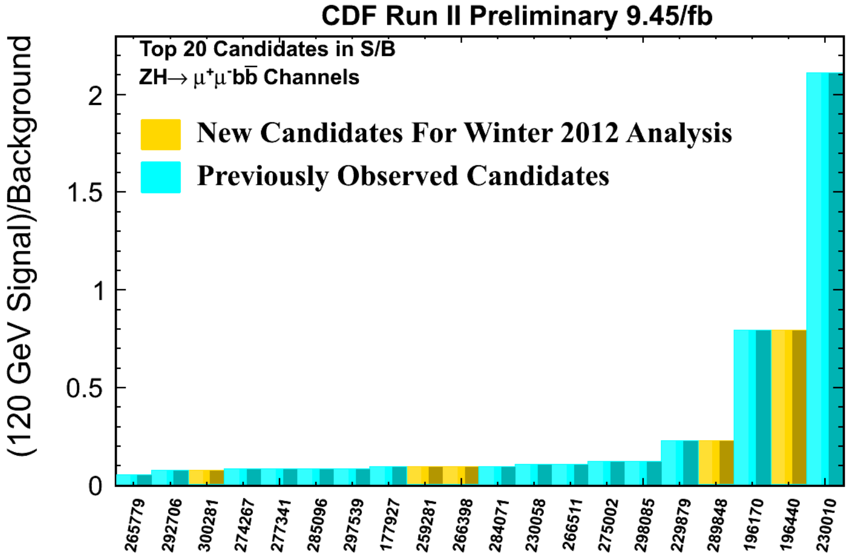
ZH→llbb

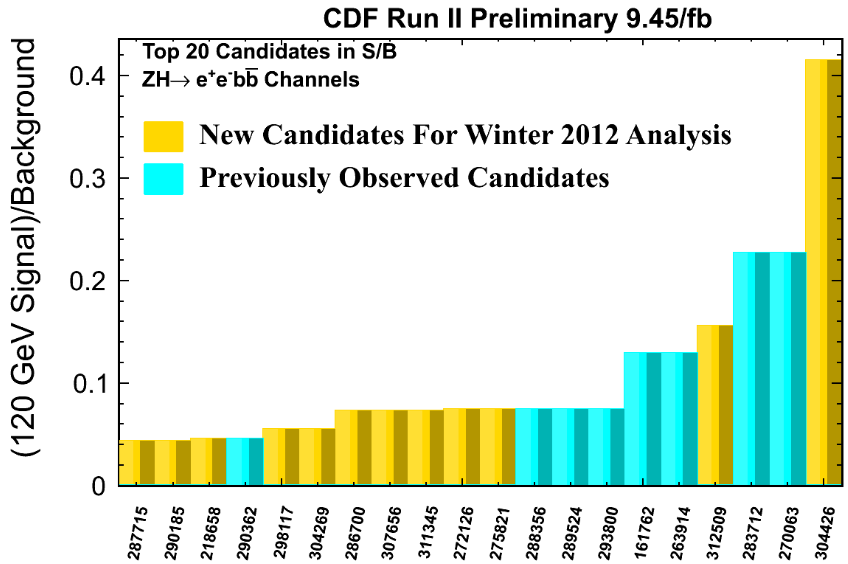
- ZH→llbb channel has …
  - lowest backgrounds
  - smallest expected signal yields (9 events for m_H=120 GeV/c^2)
- Some discriminant bins with large S/B
  - Low probability for observing events in these bins
  - A few such events can have substantial effects on observed limits



ZH→llbb

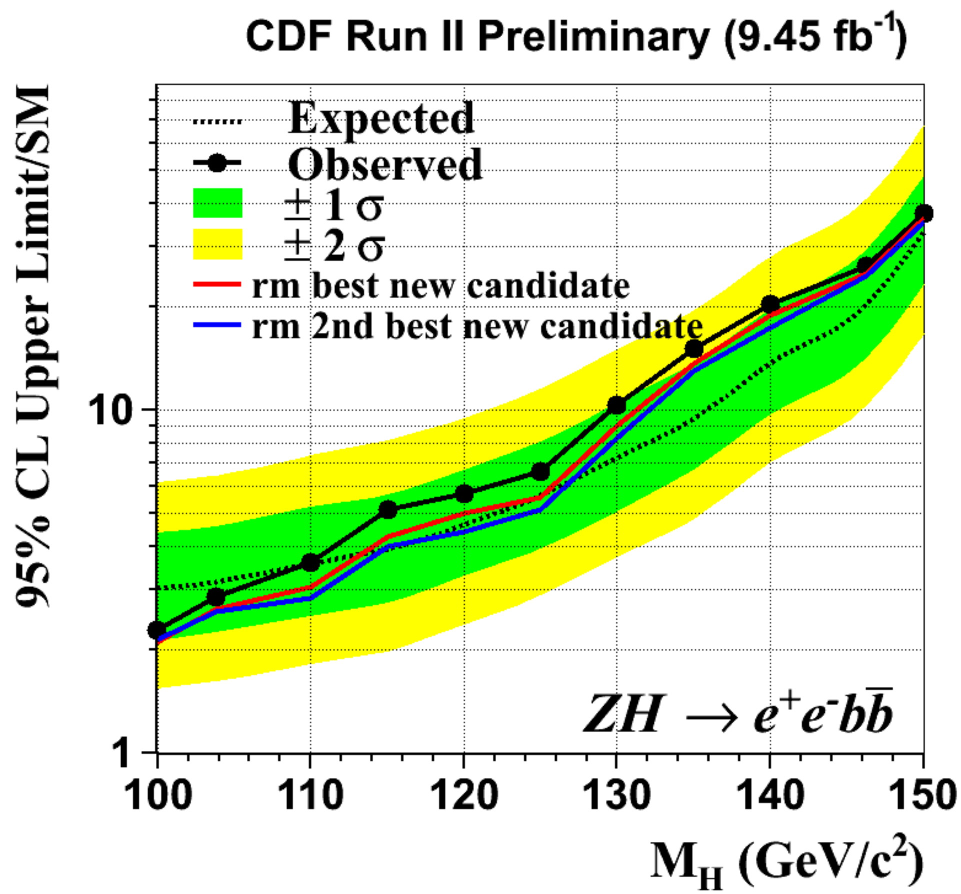
- Examine top 20 events in both channels based on S/B of the discriminant bin in which it's located
- The electron channel contains 12 new candidates within this high score region, while muon channel has 5





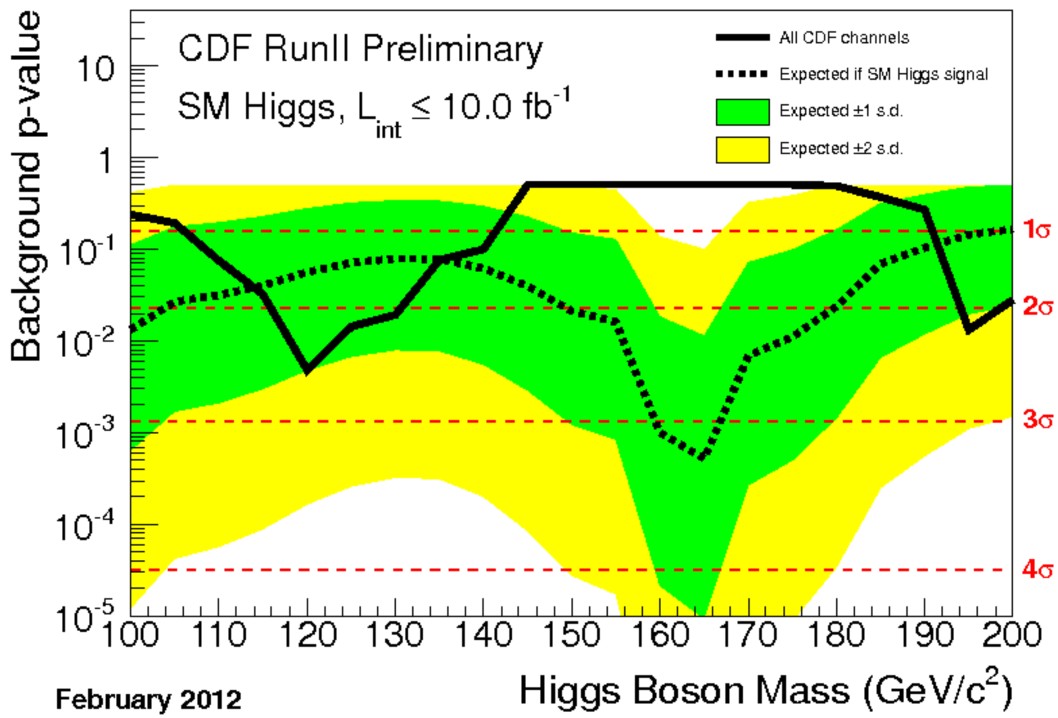
ZH→llbb

- To study the effect of high S/B events on our observed limits, we remove our best new and best two new events from the e^+e^- channel and re-run the limits
- Gives one sigma level changes in the limits at 120 GeV/c^2



Global Significance of Excess

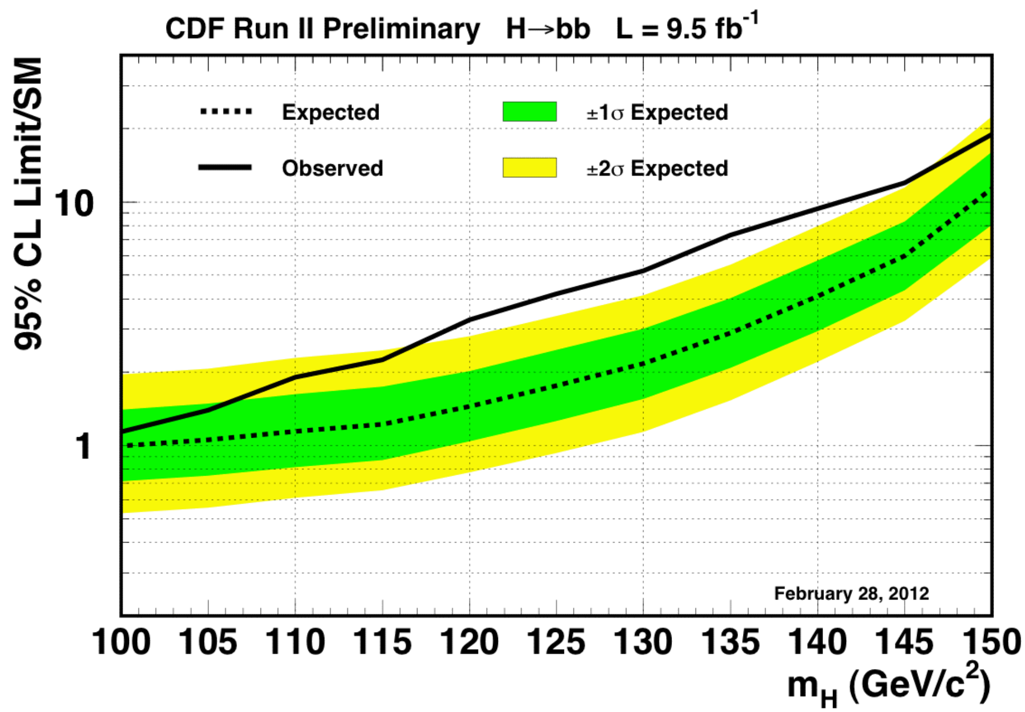
- Highest local p-value at m_H = 120 GeV/c²
- mass resolution of searches, dominated by bb at low mass and WW at high mass, is broad
- Estimate LEE of 4 for our entire SM search range from 100 to 200 GeV/c²



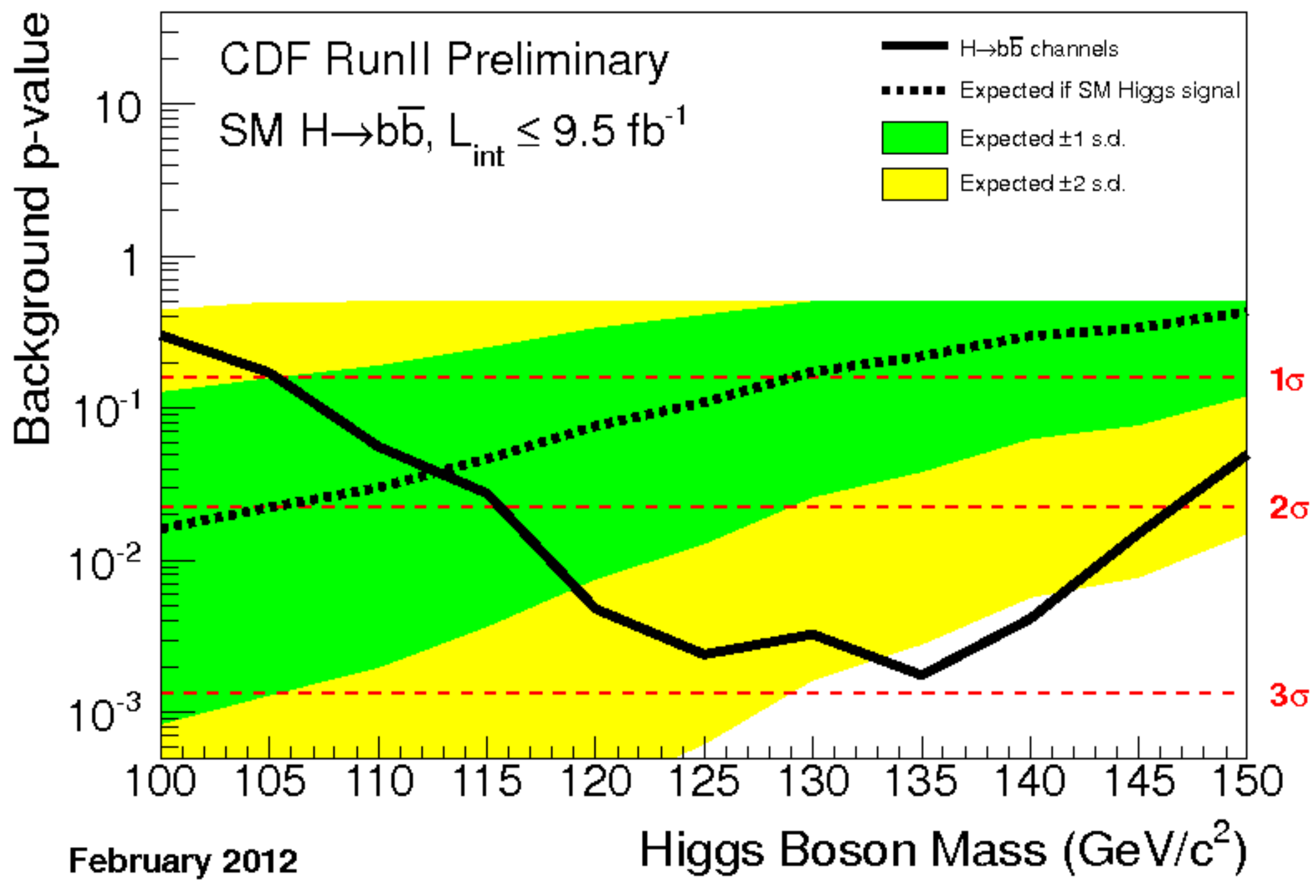
SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF	2.6 σ	2.1 σ
ATLAS	3.5 σ	2.2 σ
CMS	3.1 σ	2.1 σ

Tevatron strength: H→bb

- Combine our three primary low mass search channels
  - WH→lνbb
  - ZH→ννbb
  - ZH→llbb
- Allows for a quasi-model independent search for associated Higgs production with H→bb

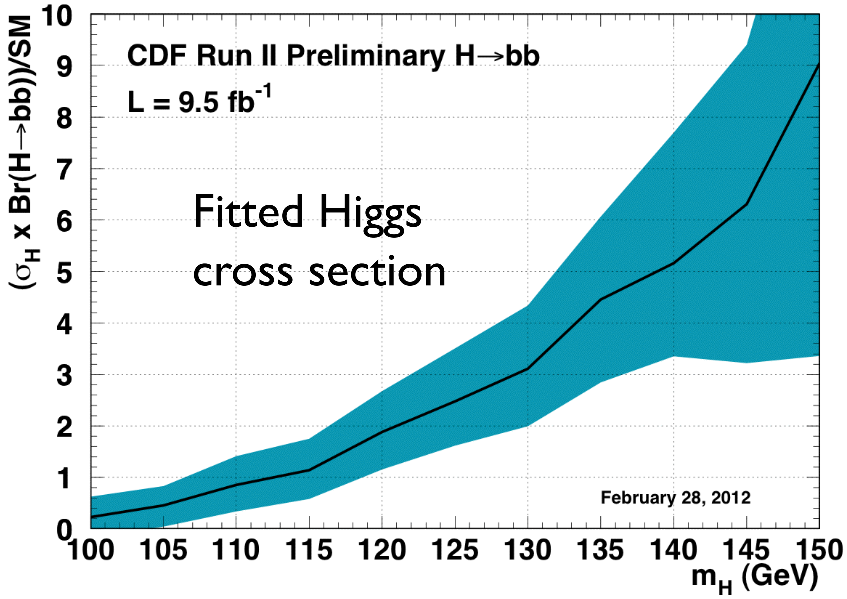


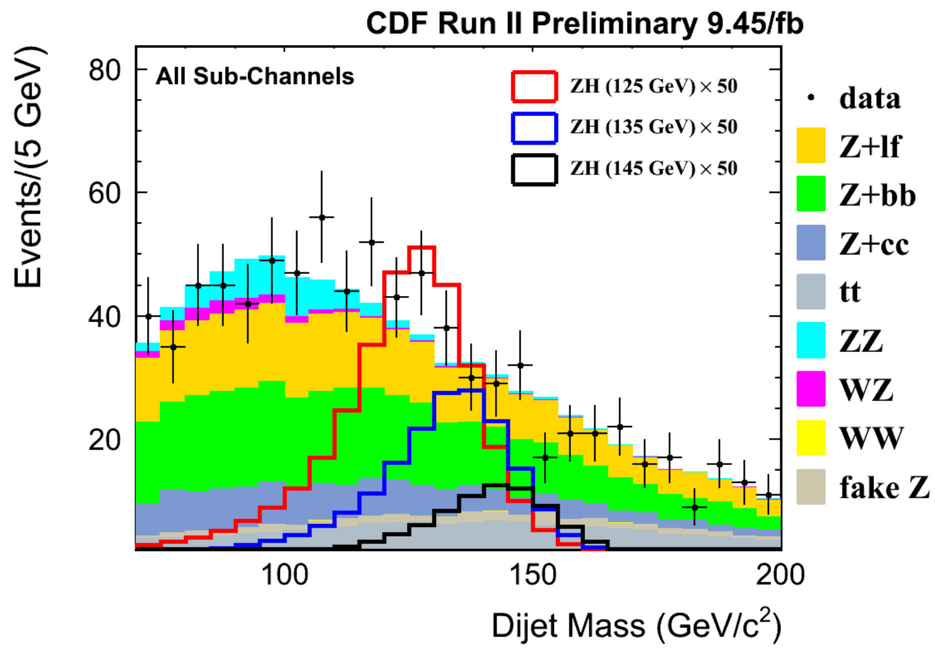
Consistent with background-only?



- Highest local p-value of 2.9σ is found at m_H = 135 GeV/c^2

Compatible with SM Higgs?

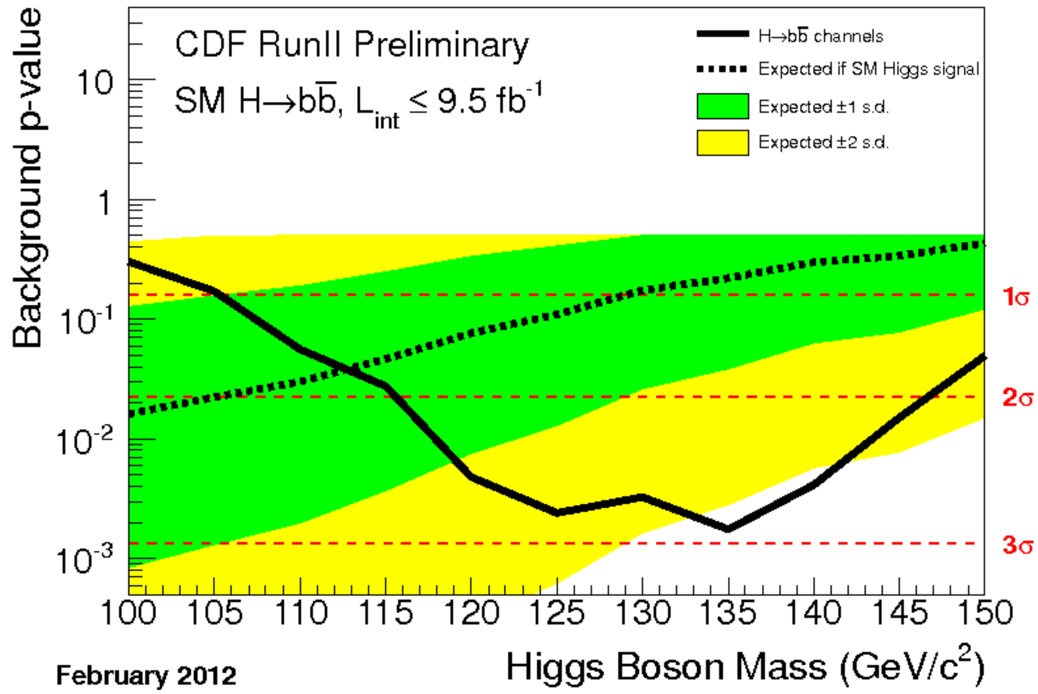




- Data are most consistent with SM in mass range from $105 < m_H < 120$ GeV/c^2
- Behavior at higher m_H values is consistent with the expectation from a lower mass Higgs

Global Significance of H→bb alone

- Highest local p-value is found at m_H = 135 GeV/c^2
- These searches are performed in the mass range between 100 to 150 GeV/c^2
- Estimate LEE of 2



Single Channel Searches			
Experiment	Channel	Local P-value	Global P-value
CDF	H->bb	2.9 σ	2.7 σ
ATLAS	H->γγ	2.8 σ	1.5 σ
CMS	H->γγ	3.1 σ	1.8 σ

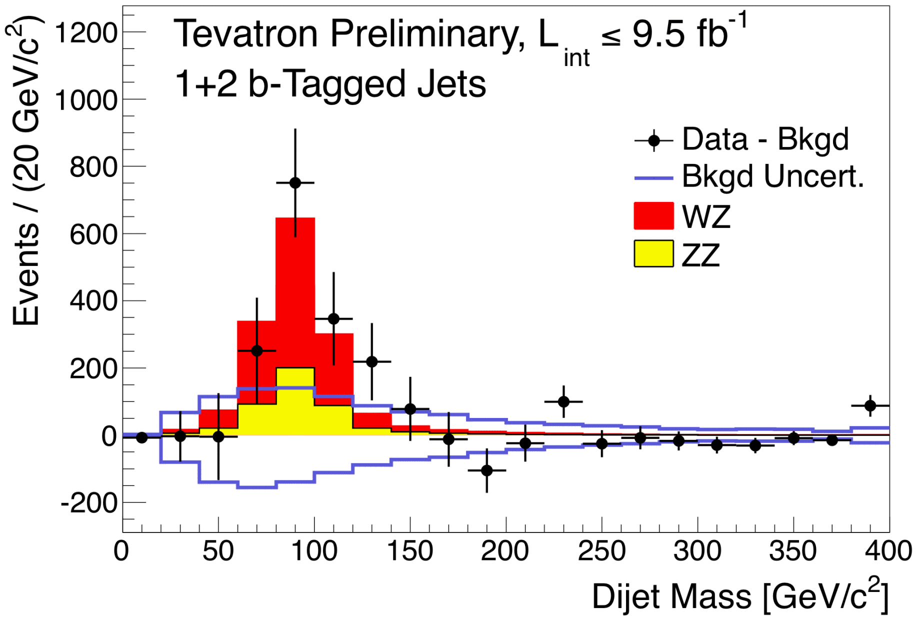
CDF Conclusions

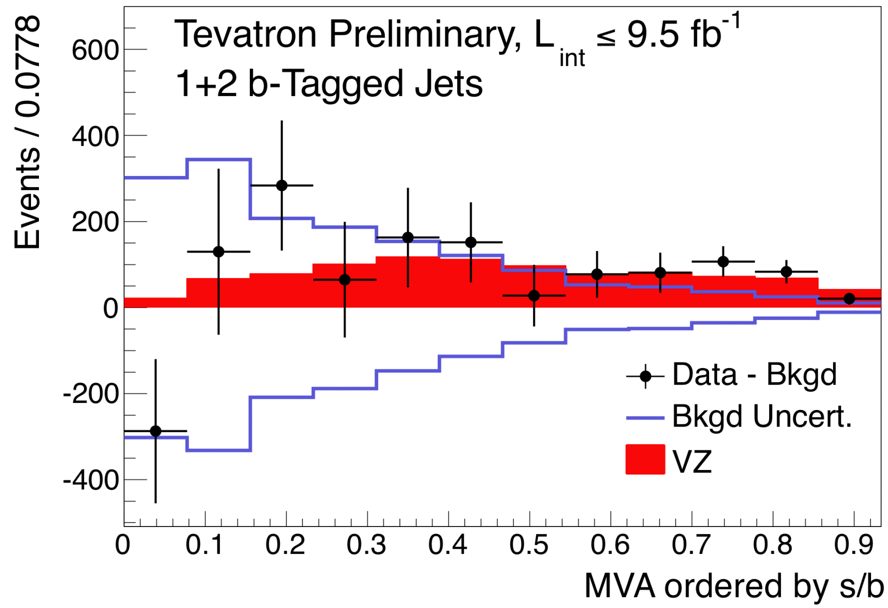
- CDF has significantly increased the sensitivity of its Higgs searches by incorporating the full 10 fb^{-1} dataset and a wide range of analysis improvements
- All SM searches combined
  - excess of Higgs-like events observed
  - consistent with SM Higgs production in the mass range from 107 to 142 GeV/c^2.
  - global significance of 2.1 σ
- Associated Higgs production in the decay mode $H \rightarrow bb$
  - excess of Higgs-like events observed, again consistent with SM Higgs production
  - global significance of 2.7 σ

Combined Tevatron Results
Winter 2012

CDF and DØ Collaborations

Verify modeling with σ(WZ+ZZ)



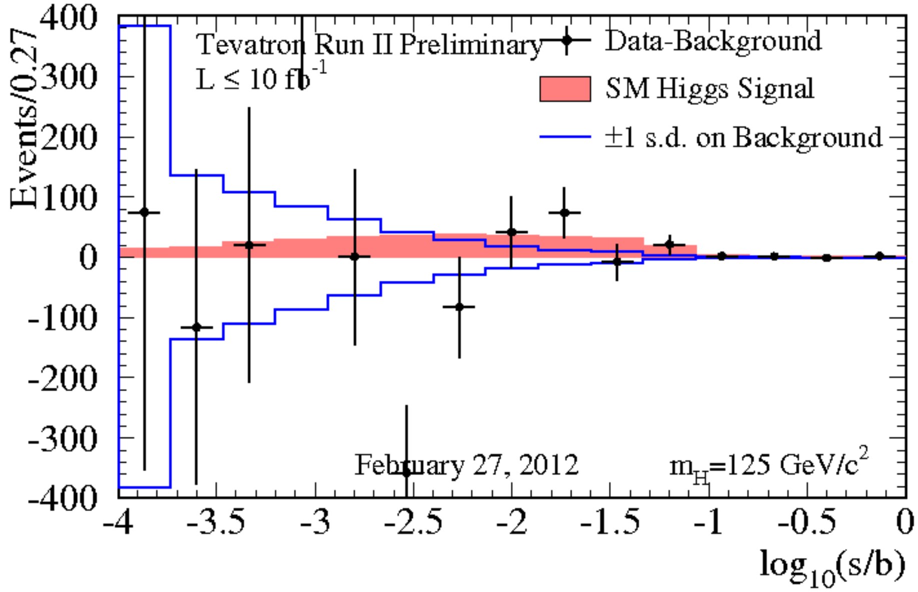


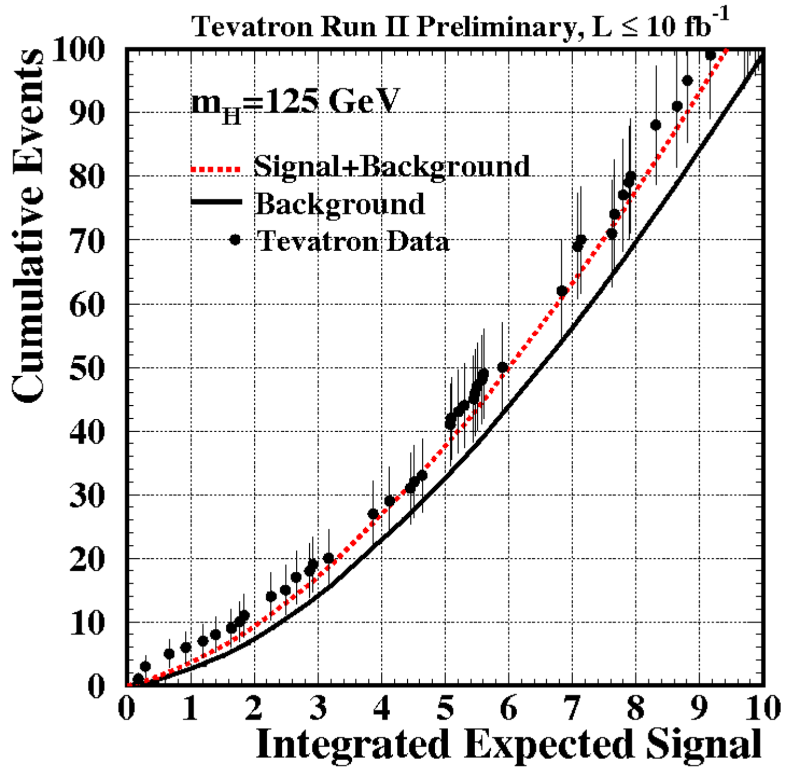
σ(WZ+ZZ)= 4.47 +/- 0.64 (stat) +/- 0.73 (syst) pb

with approximate significance of 4.6 σ

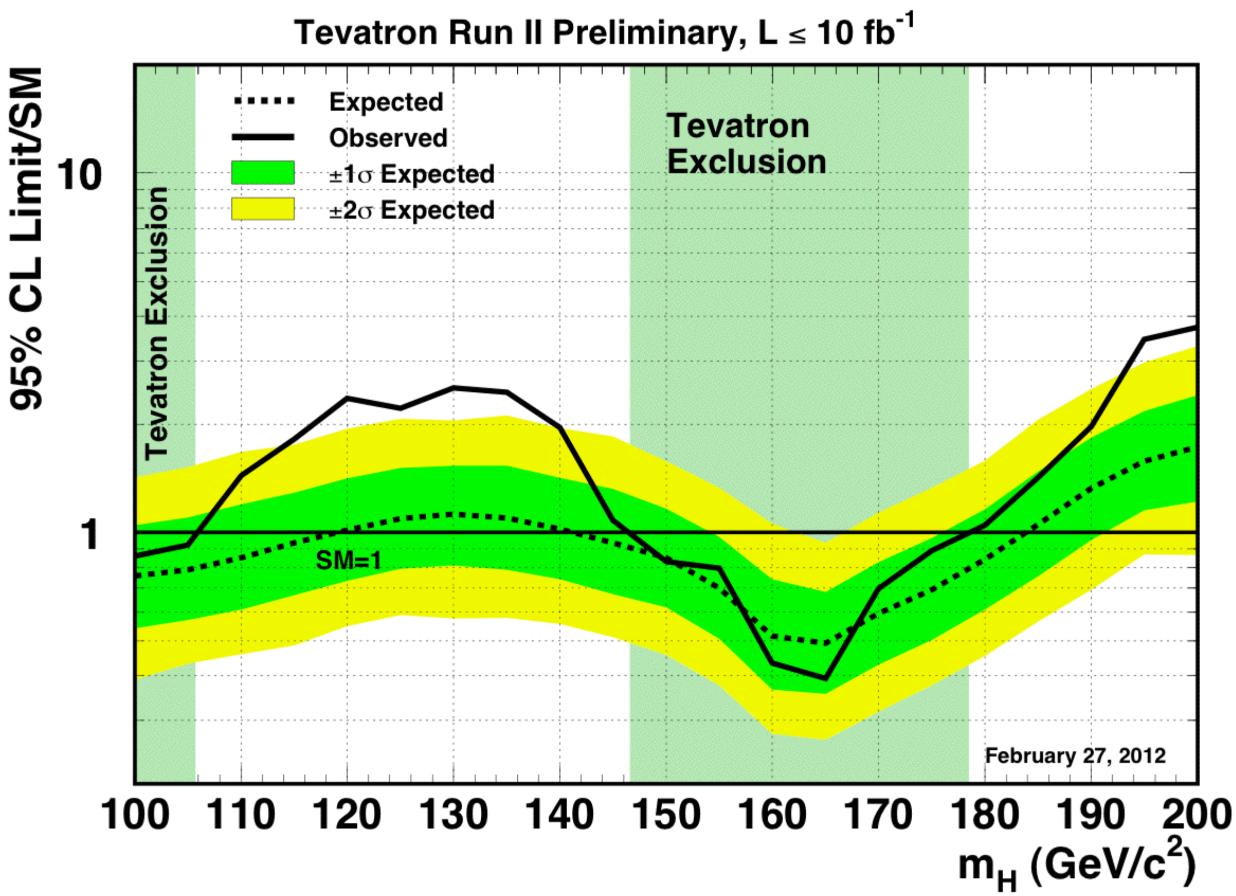
SM Prediction = 4.4 +/- 0.3 pb

Combined CDF and D0 discriminants





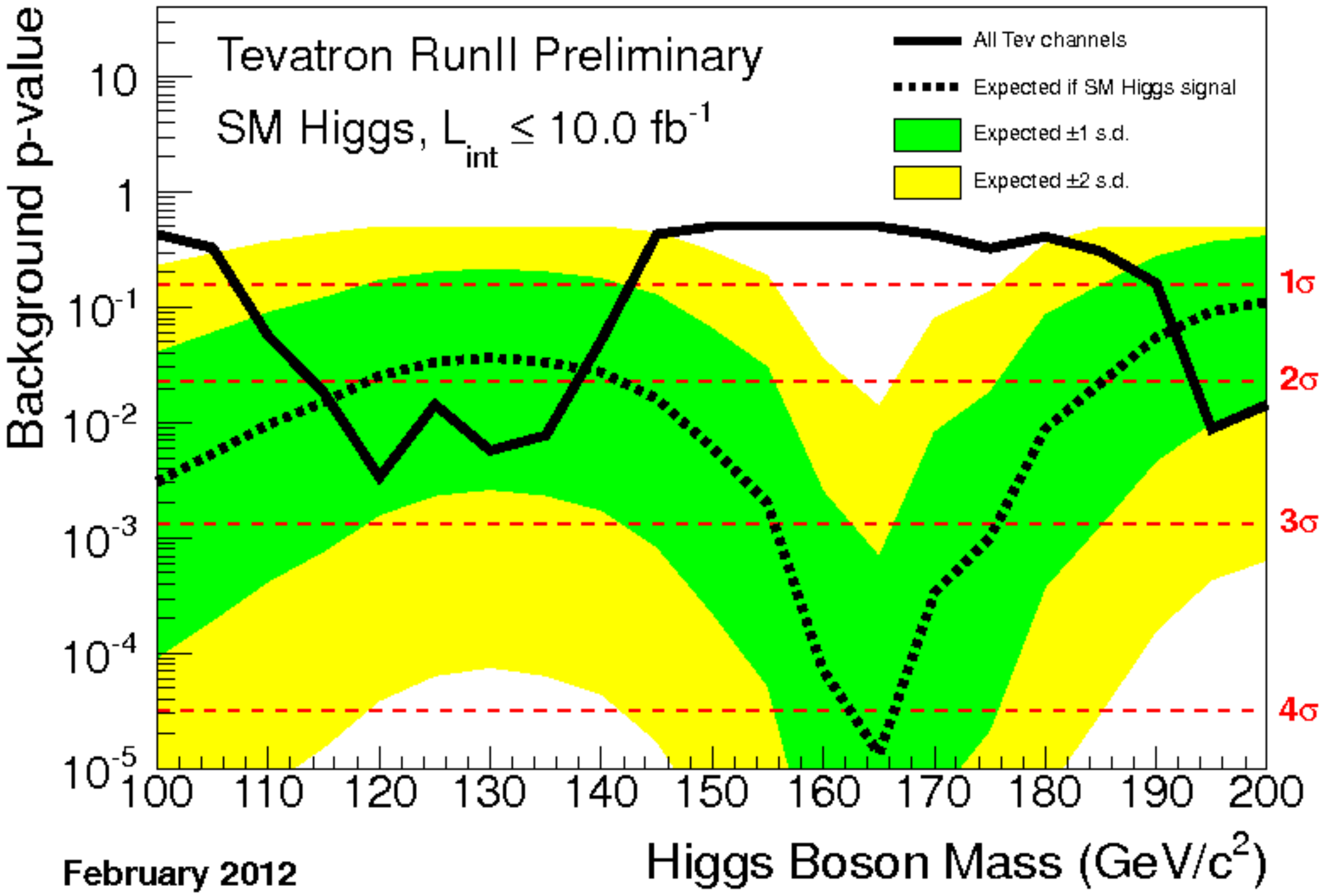
Combined Tevatron SM Higgs Limits



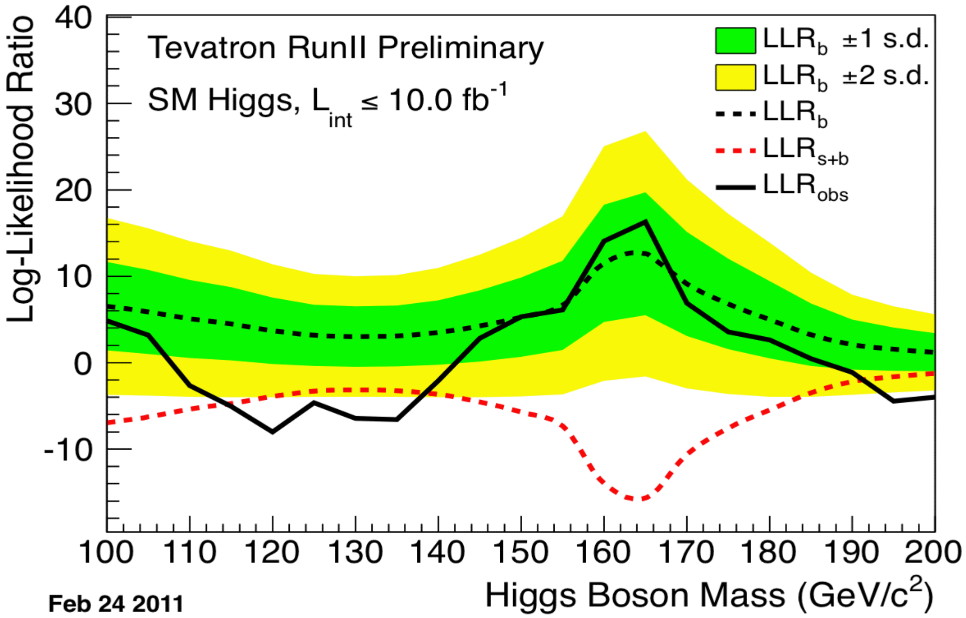
Exclude SM Higgs at 95% C.L. for $147 < m_H < 179$ GeV/c^2

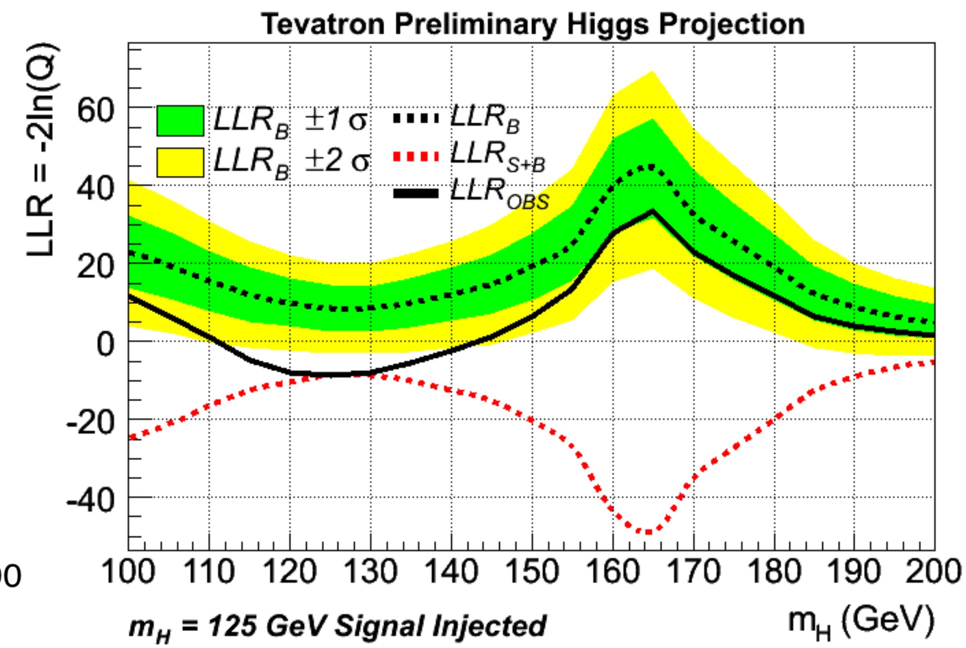
Expect to exclude $100 < m_H < 120$ GeV/c^2 & $141 < m_H < 184$ GeV/c^2

Compatible with background-only?



Compatible with SM Higgs?

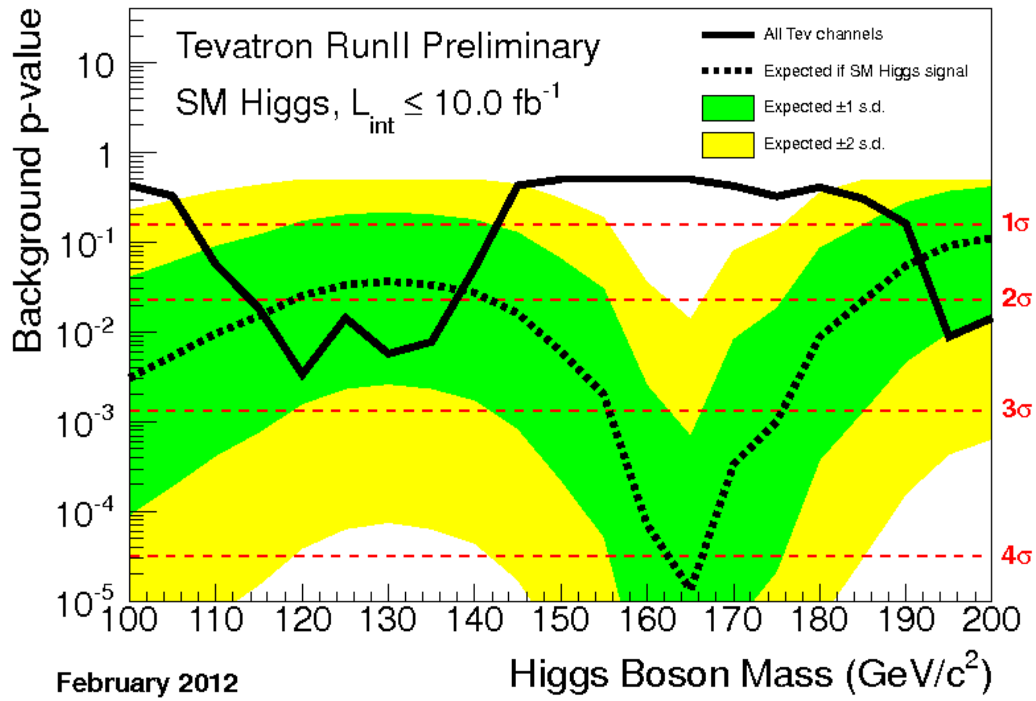




- Consistent with SM signal plus background hypothesis over Higgs mass range from 110 to 140 GeV/c^2

Global Significance

- Highest local p-value is found at m_H = 120 GeV/c^2
- Same LEE of 4 for entire SM search range from 100 to 200 GeV/c^2



SM Higgs Searches		
Experiment	Local P-value	Global P-value
CDF+D0	2.8 σ	2.2 σ
ATLAS	3.5 σ	2.2 σ
CMS	3.1 σ	2.1 σ

Tevatron Conclusions

- CDF and D0 have significantly increased the sensitivity of their Higgs searches by incorporating the full 10 fb^{-1} dataset and a wide range of analysis improvements
- We measure σ(WZ+ZZ) with a significance of 4.6σ and a value compatible with SM
- We observe an excess of Higgs-like events consistent with SM Higgs production in the mass range from 115 to 140 GeV/c^2.
- The global significance of this excess is 2.2 σ

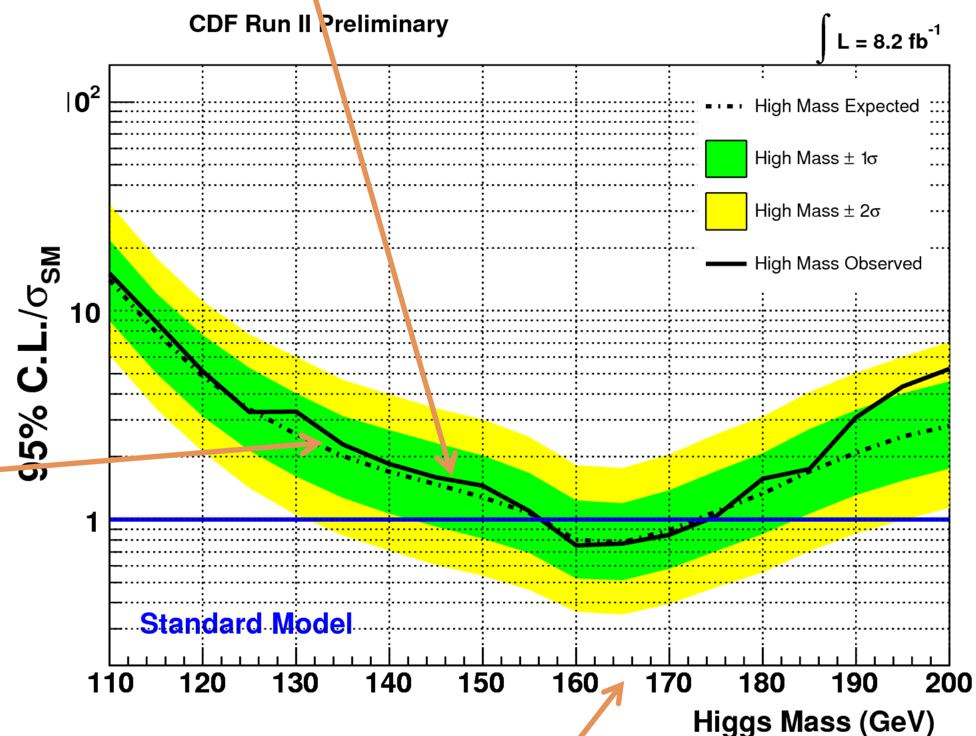
Backup Slides

Anatomy of a Limit Plot

1. Upper cross section limit for Higgs production relative to SM prediction

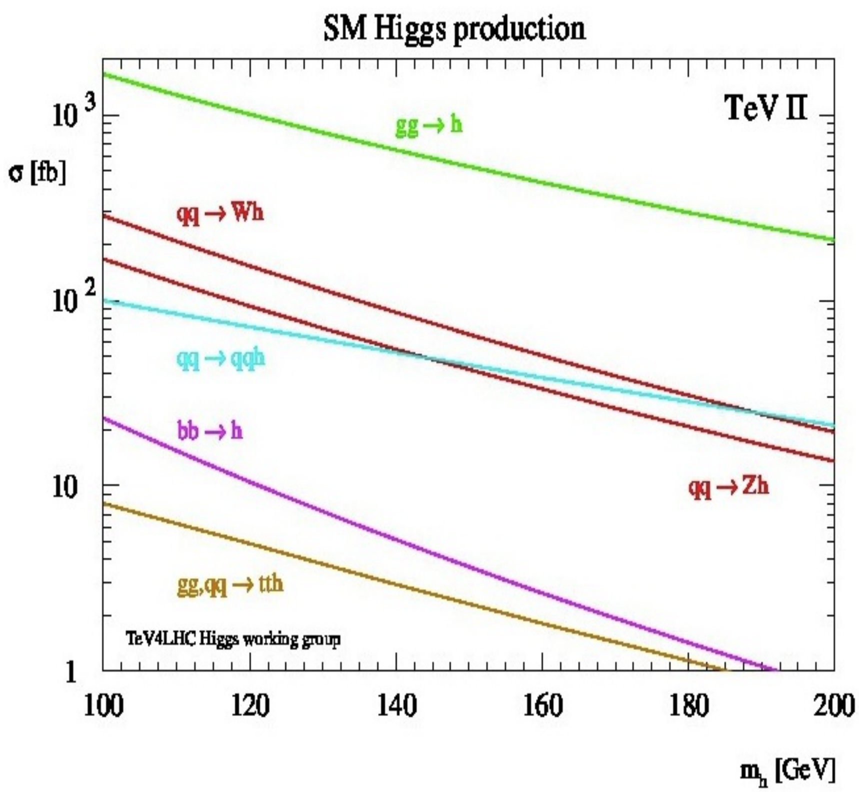
2. Observed limit (solid line) from data

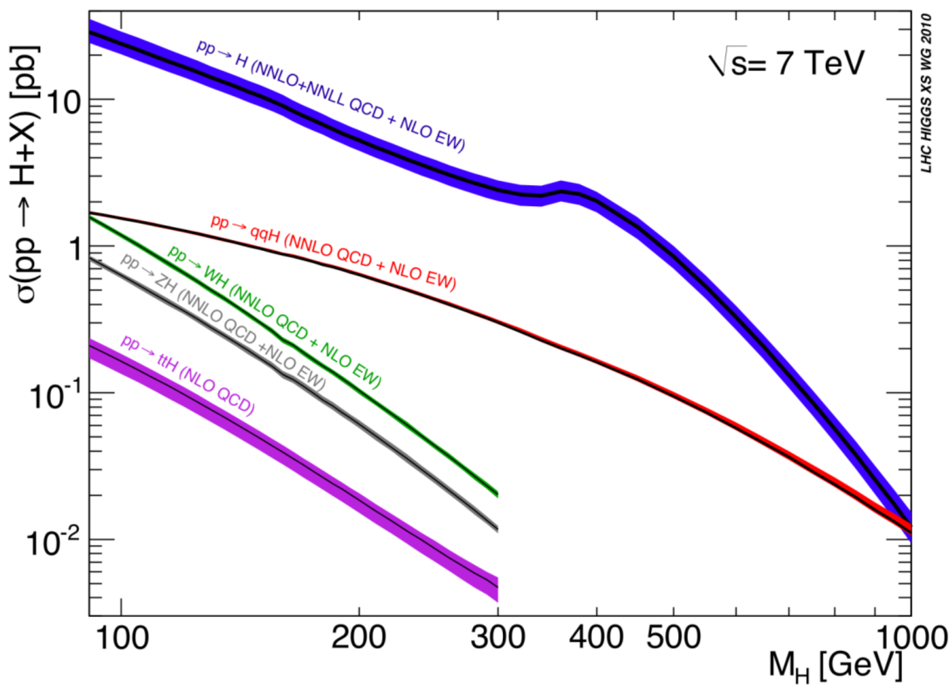
3. Median expected limit (dot-dashed line) and predicted 1 σ /2 σ (green/ yellow bands) excursions from background only pseudo-experiments



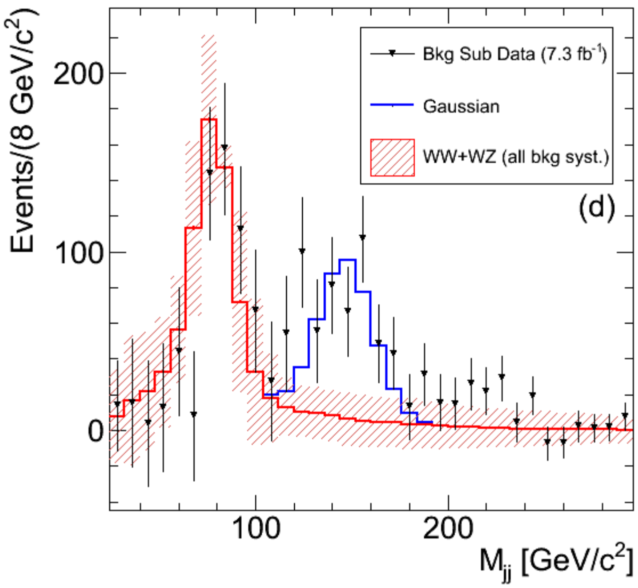
4. Analysis repeated using different signal templates for each m_H between 110 and 200 GeV in 5 GeV steps

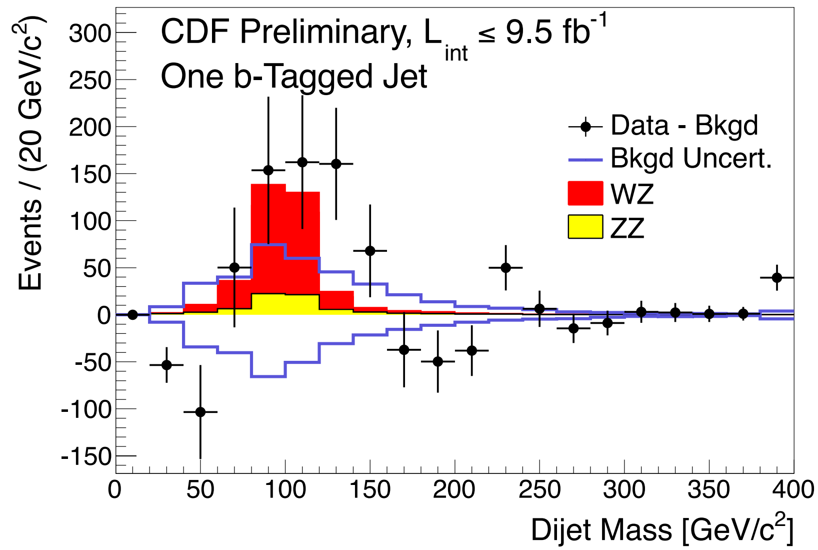
Tevatron/LHC production cross sections

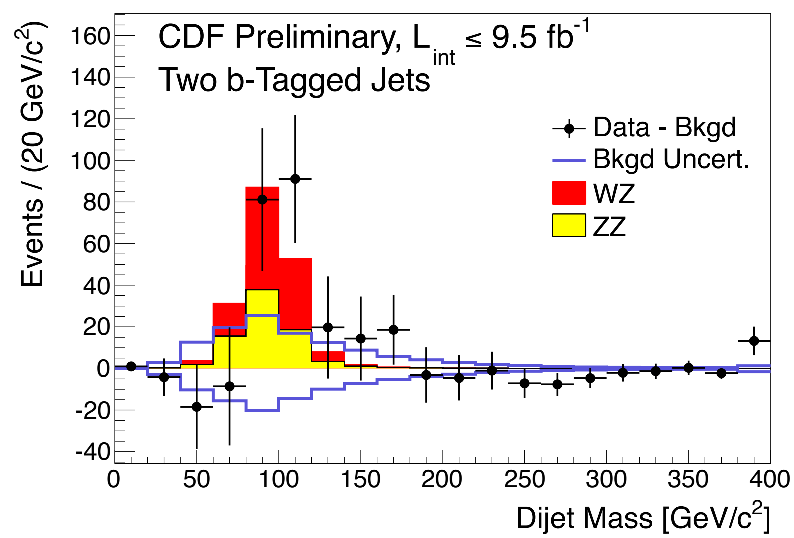




CDF Wjj



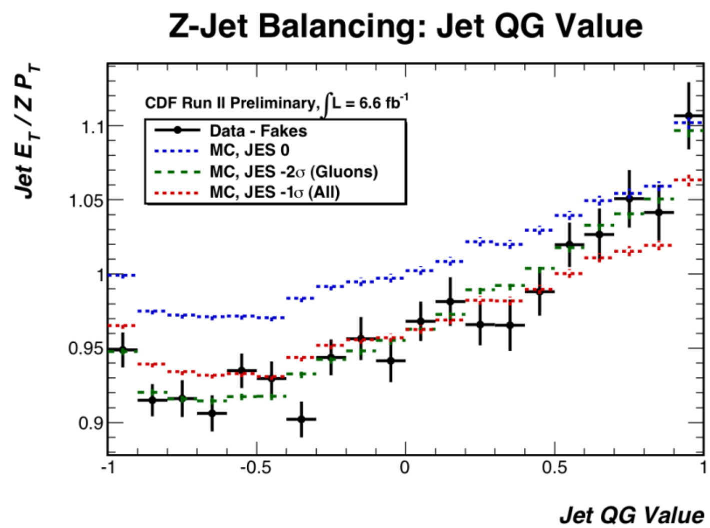


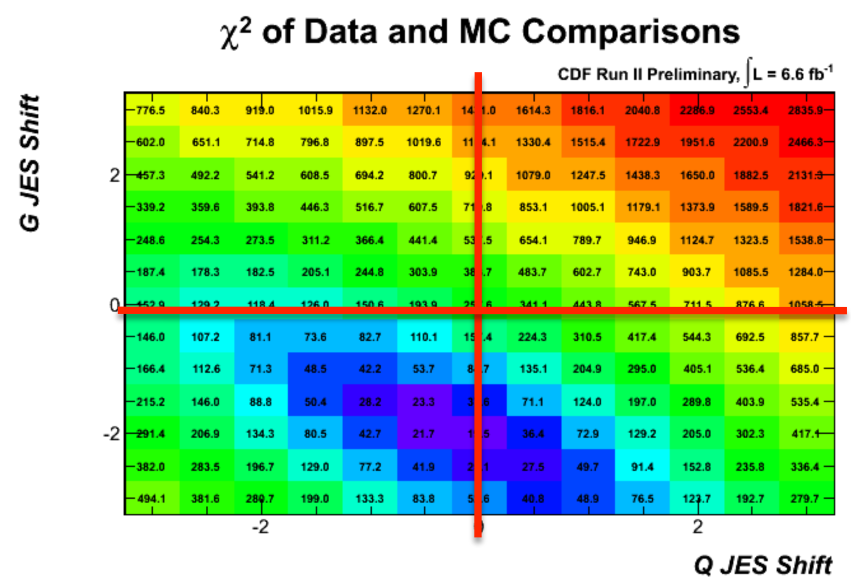


- Tagged samples used for Higgs searches do not contain any sign of abnormalities that were seen previously in pre-tagged region

CDF Wjj

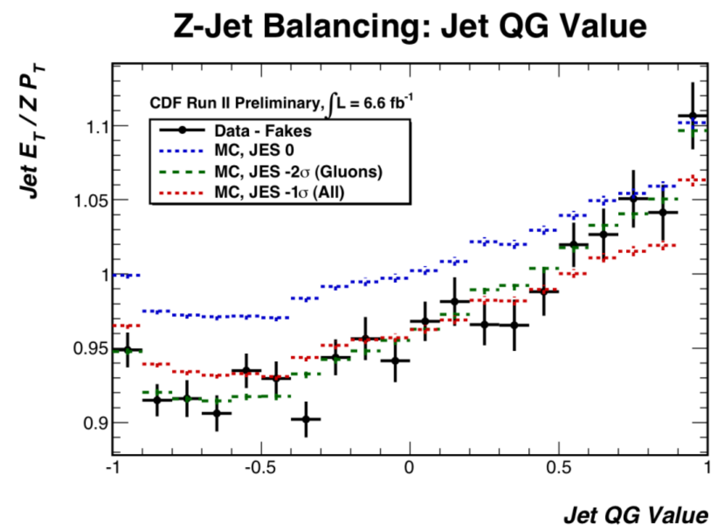
- Lots of studies to try to understand what's going on in the pre-tag region
- Detailed studies in Z + 1 jet events to understand potential differences in quark and gluon jet energy scales

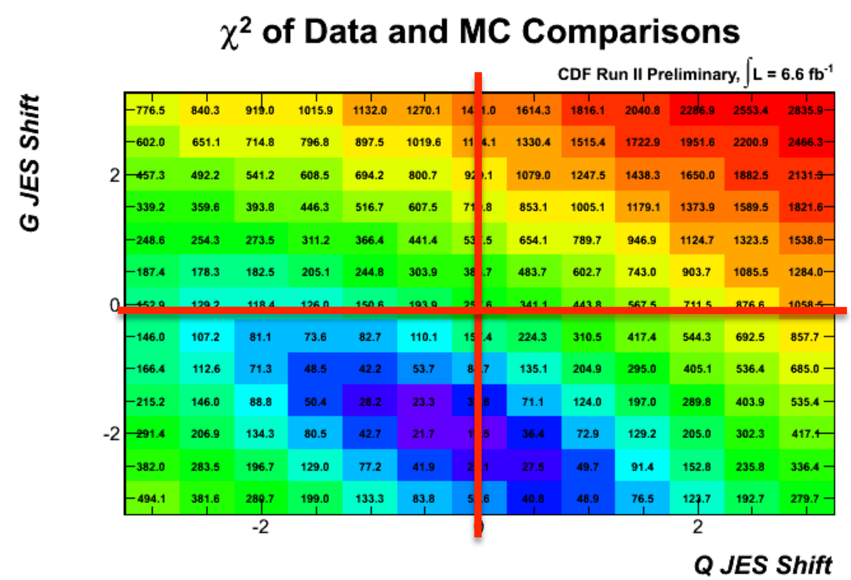




CDF Wjj

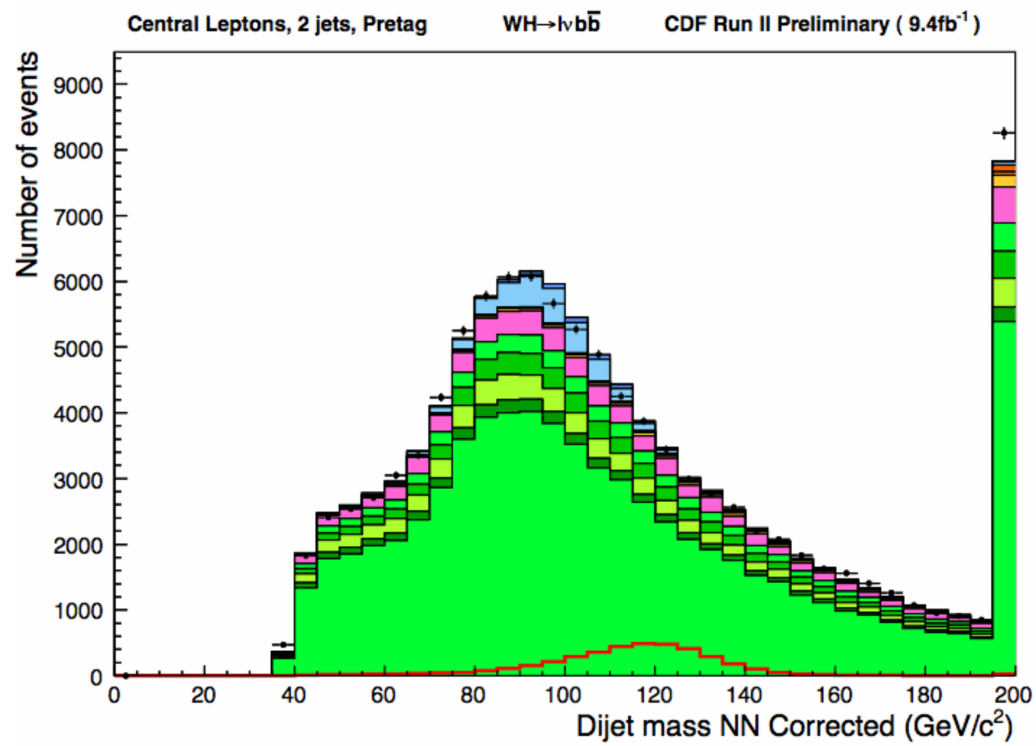
- Bottom line of these studies is that the JES for gluon jets needs to be shifted by 2 σ in MC to match with data
- The JES for quark jets is good – not surprising since well constrained by top mass measurements





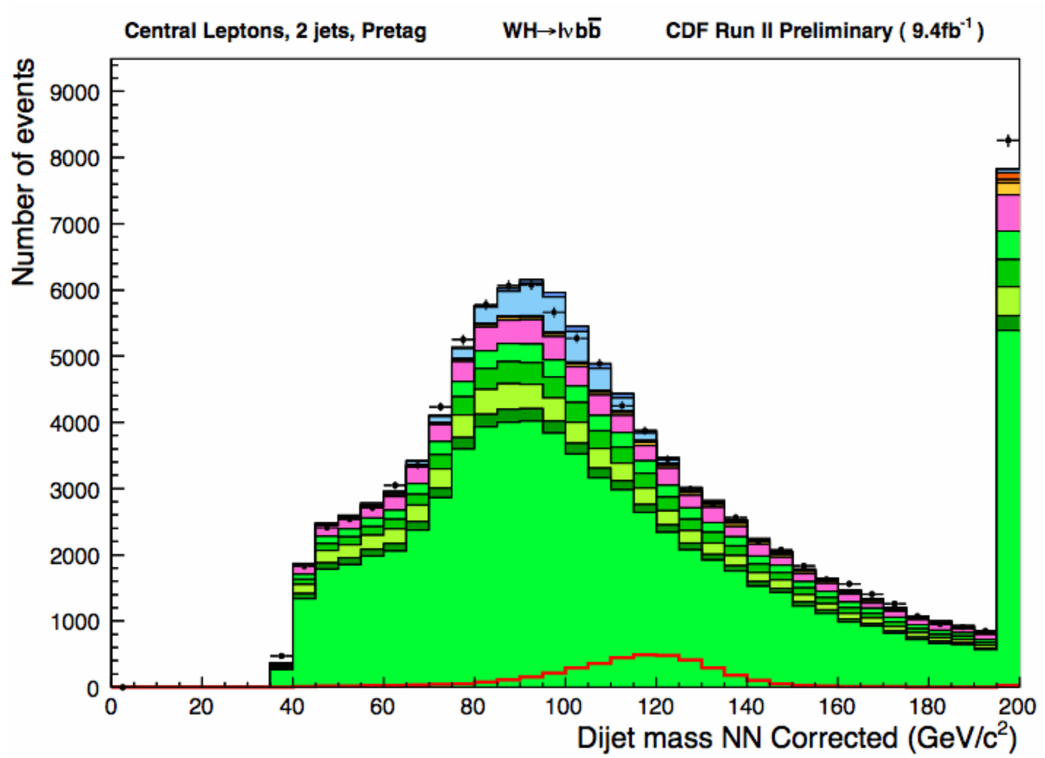
CDF Wjj

- In CDF Higgs searches we apply -2 σ 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

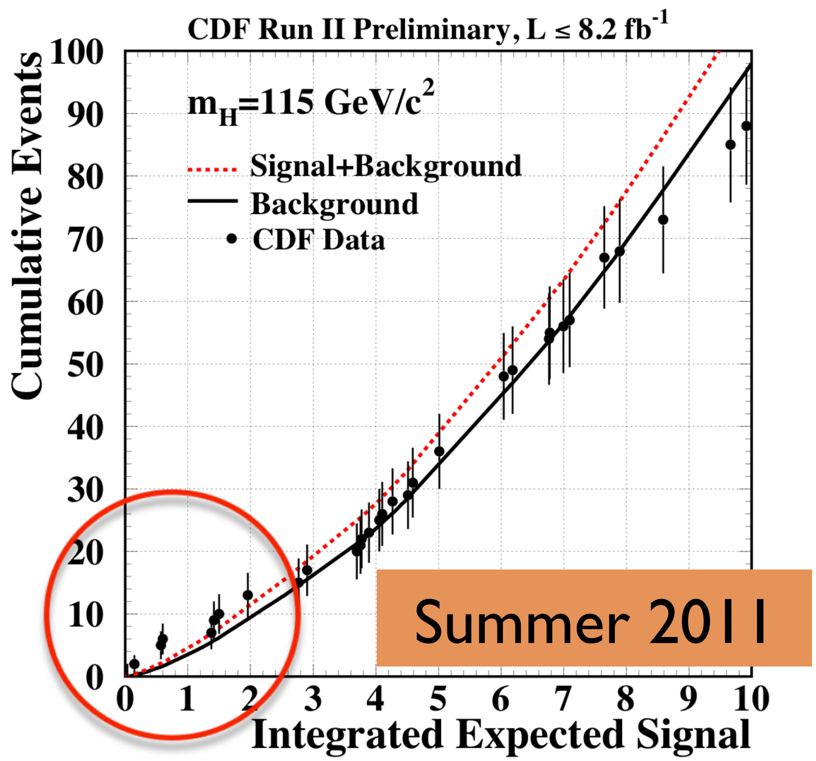


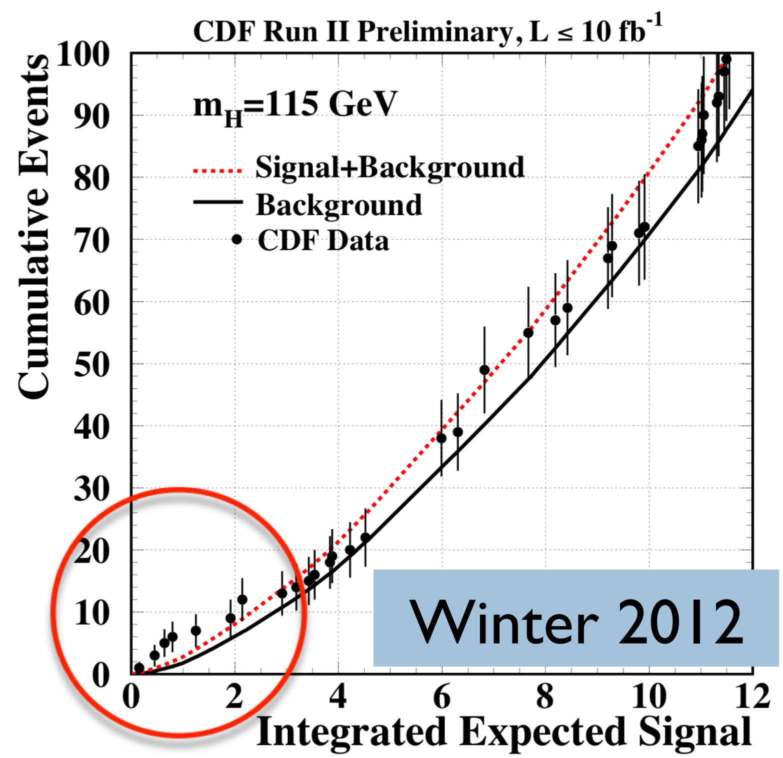
CDF Wjj

- With these corrections in place we do not observe mis-modeling in the pre-tag region of our l ν jj Higgs search
- Caveat is looser cuts are applied than in the "bump" search analysis
- No official statement from CDF regarding "bump" at this time



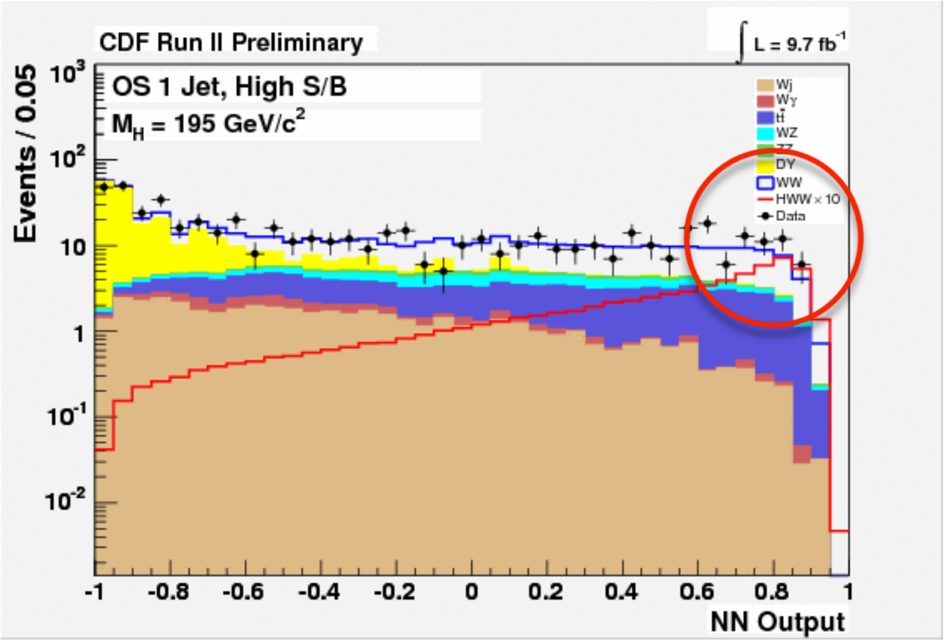
Change in Limits at m_H = 115 GeV/c^2

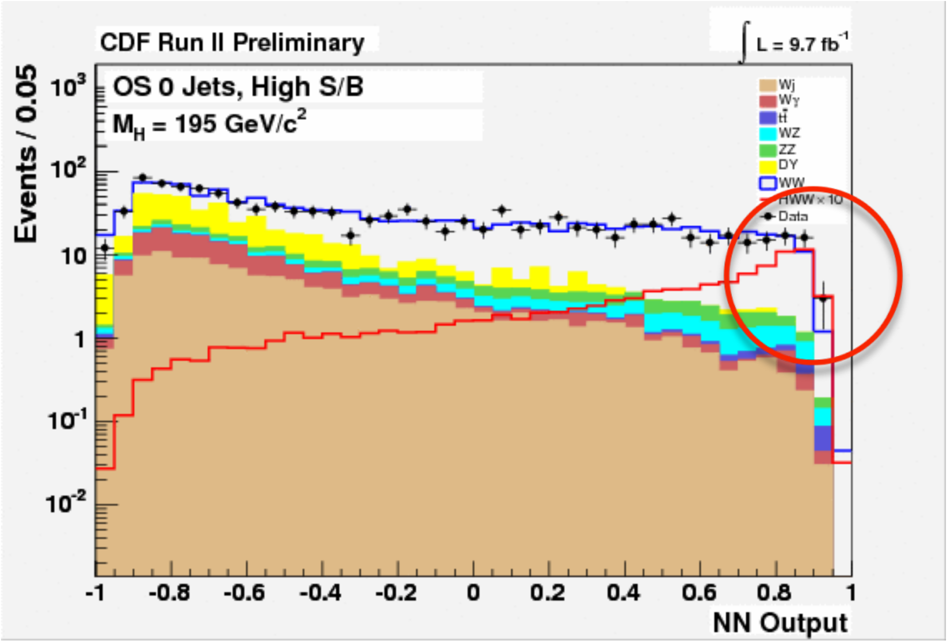




- Excess of high S/B events was present in previous analysis
- Change is that the lower S/B event region has become more consistent with S+B hypothesis

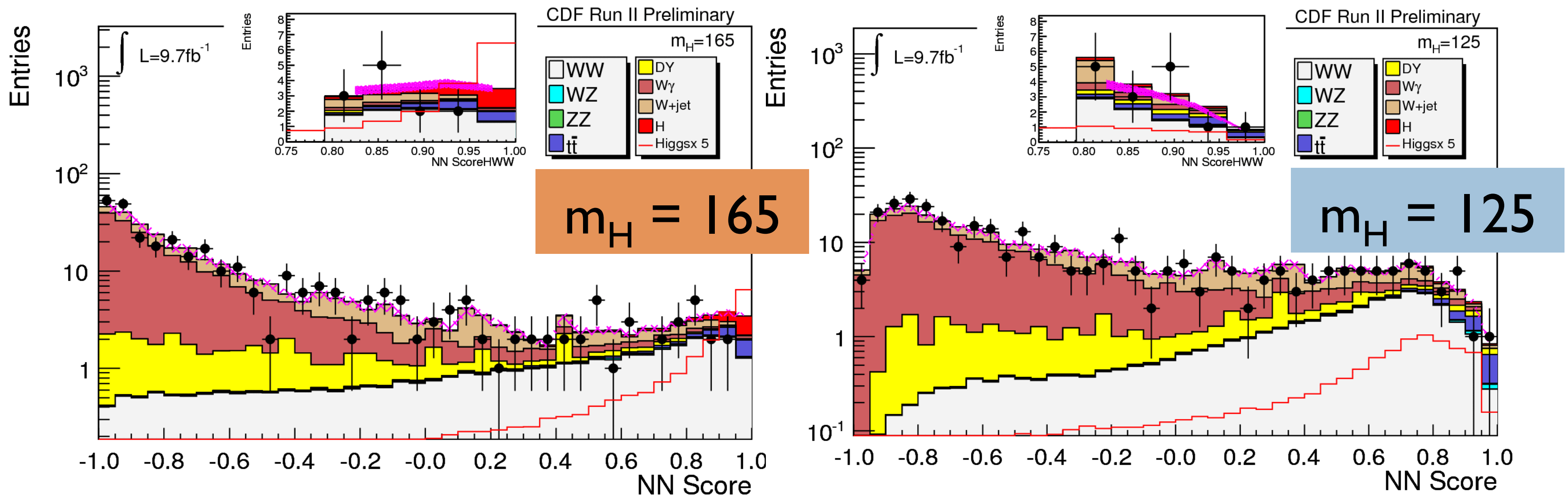
Excess at m_H = 195 GeV/c^2





- 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 m_H = 195 GeV/c^2 SM Higgs based primarily on equivalent searches in H->WW

Deficit at m_H = 165 GeV/c^2



- Driven by deficit of events in high S/B region of our opposite-sign, low invariant mass dilepton channel
- This is the channel in which we obtain increased acceptance from low ΔR_{ll} events
- Nothing peculiar in the overall modeling of this distribution and deficit is not spread over a wide mass range

Signal Injection study

The figure on right shows the results of a previous study where we injected a m_H = 115 GeV/c^2 Higgs signal into background-only pseudo-experiments to study the potential effect on our observed limits

Because our neural network discriminants are optimized for separation of signal and background rather than mass reconstruction, we expect to observe (in the presence signal) higher than expected observed limits over a broad mass range