Searches for the Higgs Boson at CDF using the full Run-II dataset

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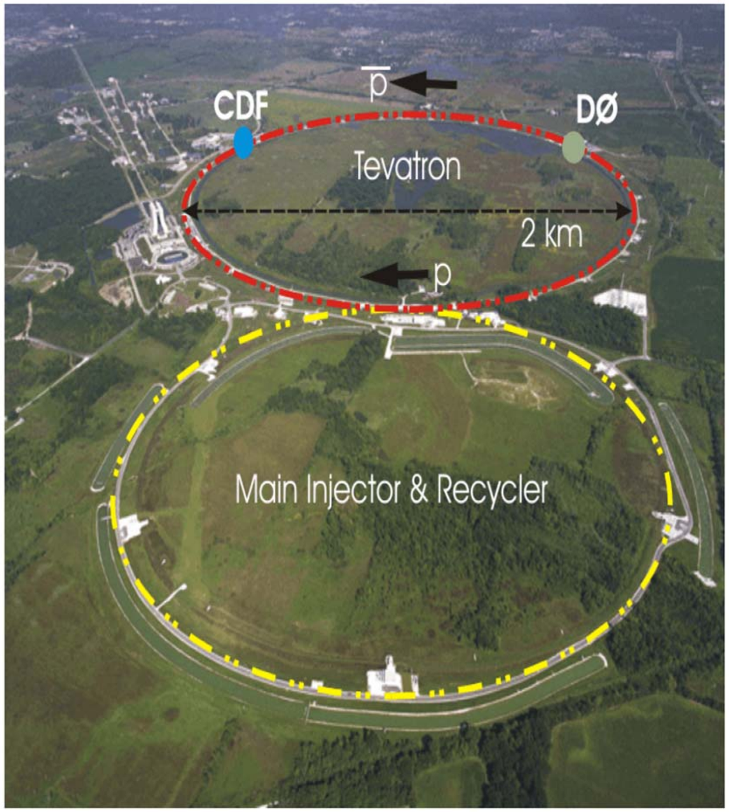
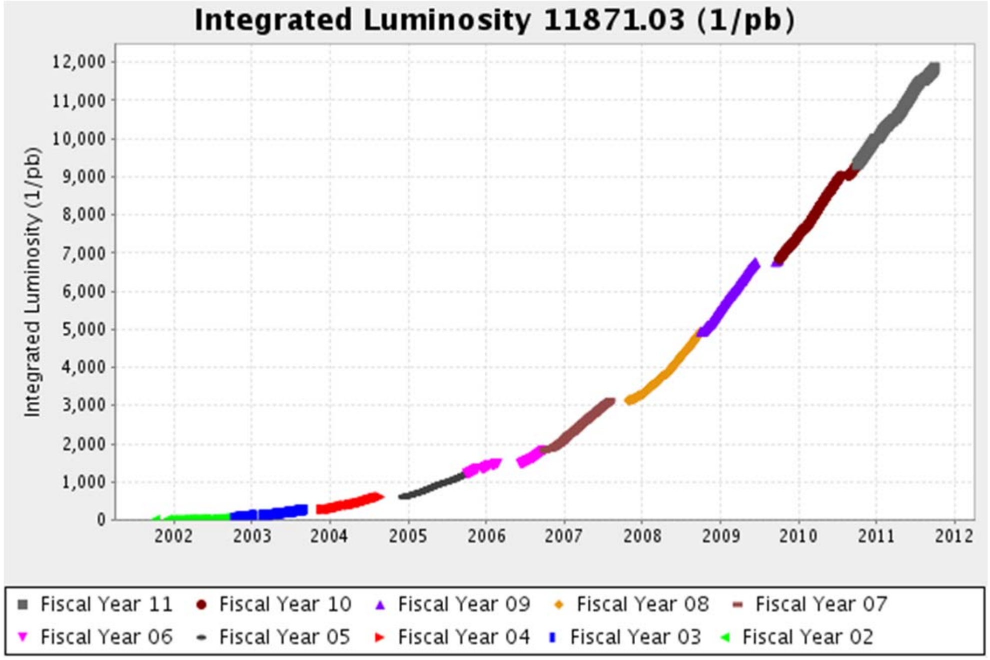
On behalf of the CDF collaboration

The Tevatron

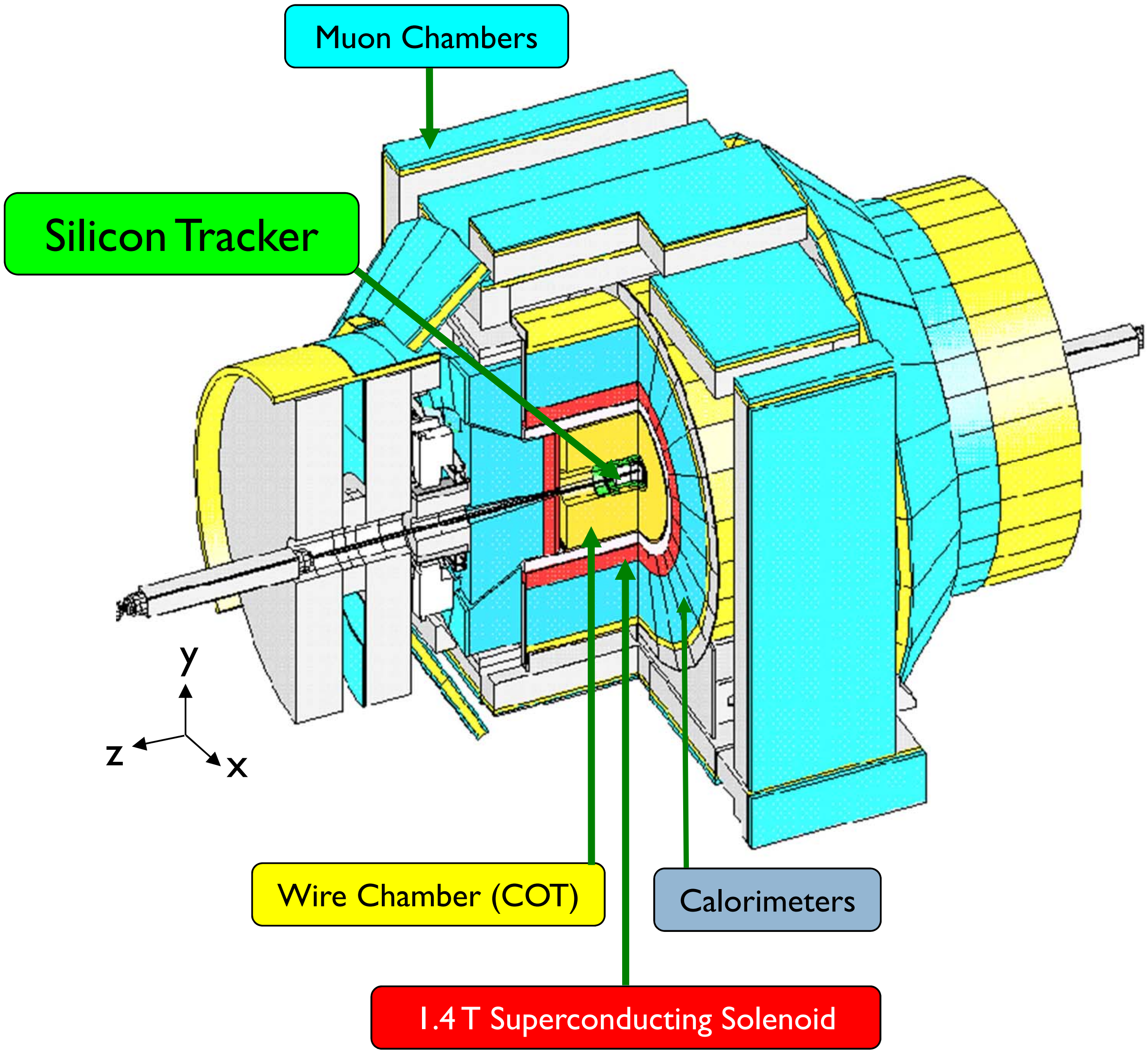


- proton-antiproton collider at
  $\sqrt{s}$ = 1.96 TeV
- Two multi-purpose detectors: CDF & DØ
- Antiproton Accumulation rate:
  ~25x10^{10} /hr
- Initial luminosity record:
  4.31 x10^{32} cm^{-2}s^{-1}

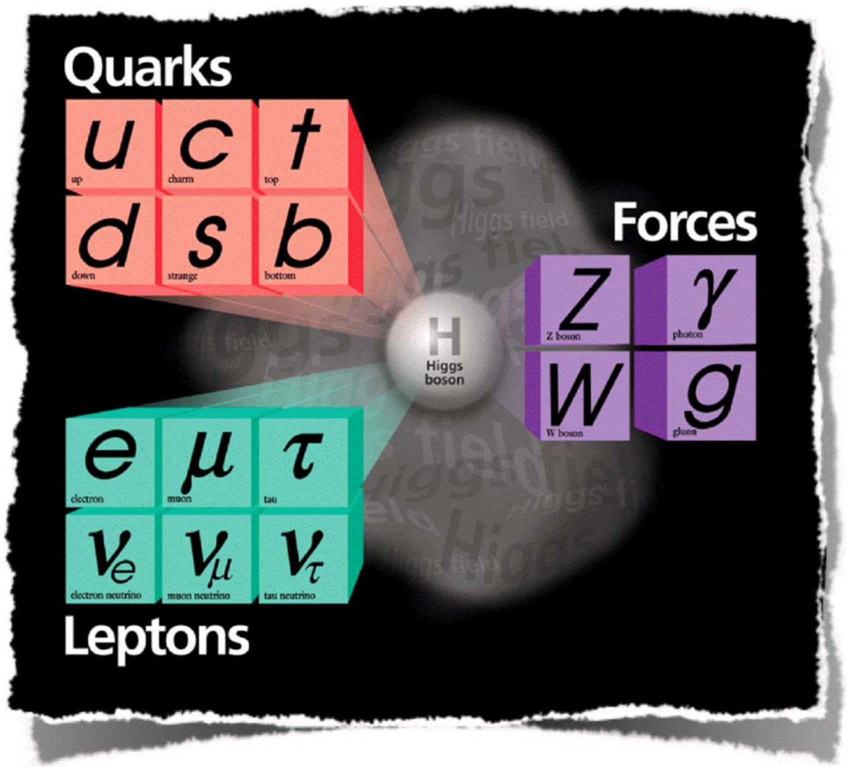


- Record week: 85 pb^{-1}
- Run II: 2001-2011
  12 fb^{-1} delivered
  10 fb^{-1} recorded

CDF II Detector

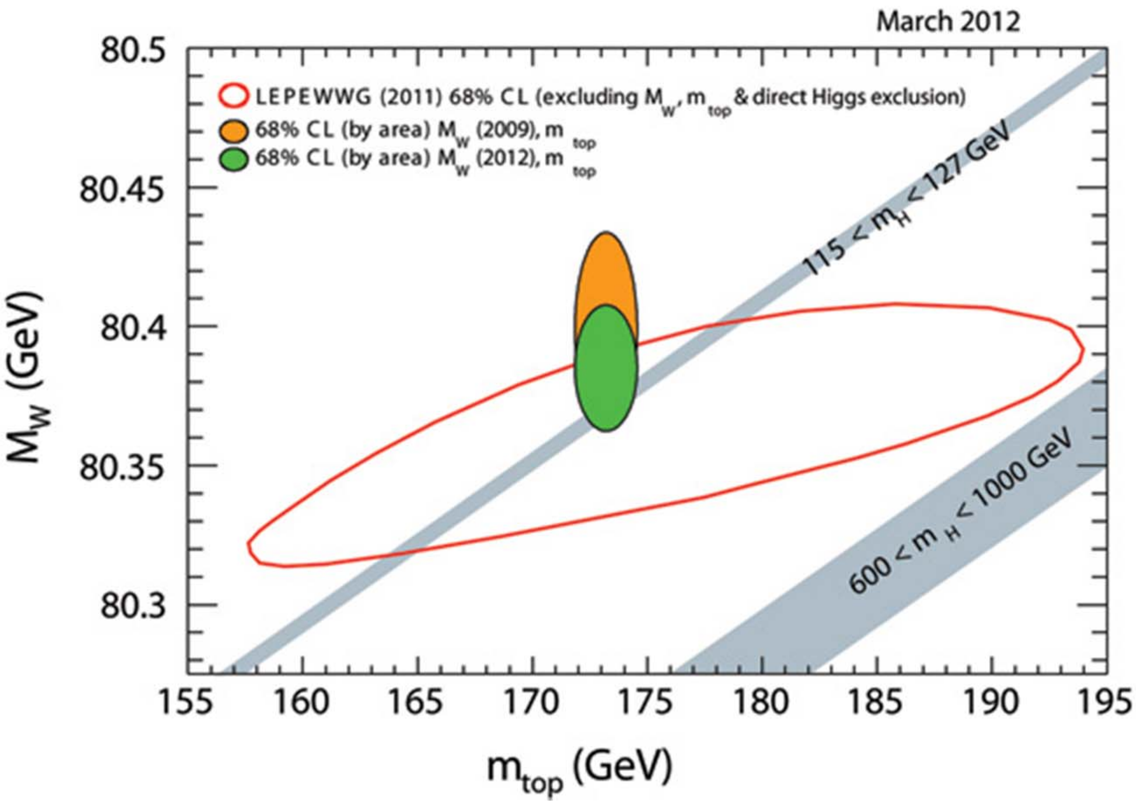


Standard Model Basics



- In the standard model, the Higgs field is the favored mechanism to produce electroweak symmetry breaking
- Elementary particles obtain mass by interacting with the Higgs field
- The boson associated with the Higgs field ~~is~~ **was?** the last undiscovered fundamental particle predicted by the standard model.

Latest W mass results from the Tevatron

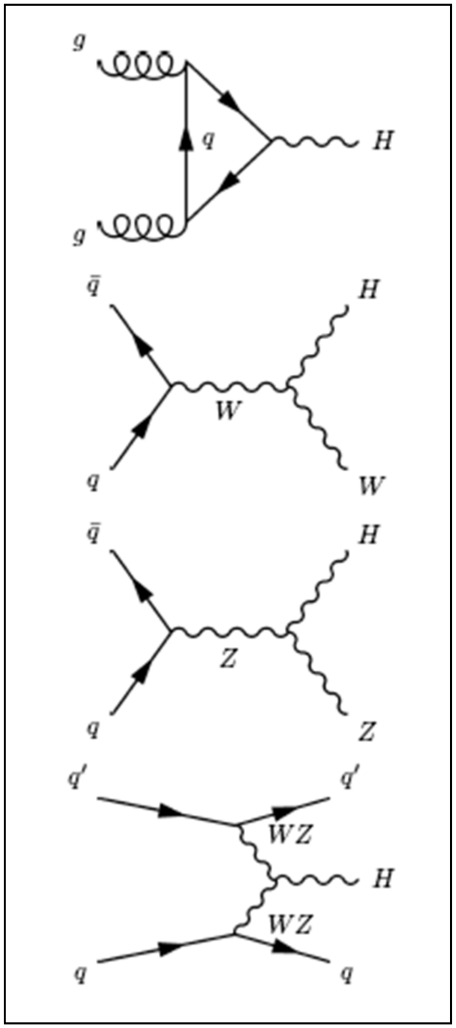


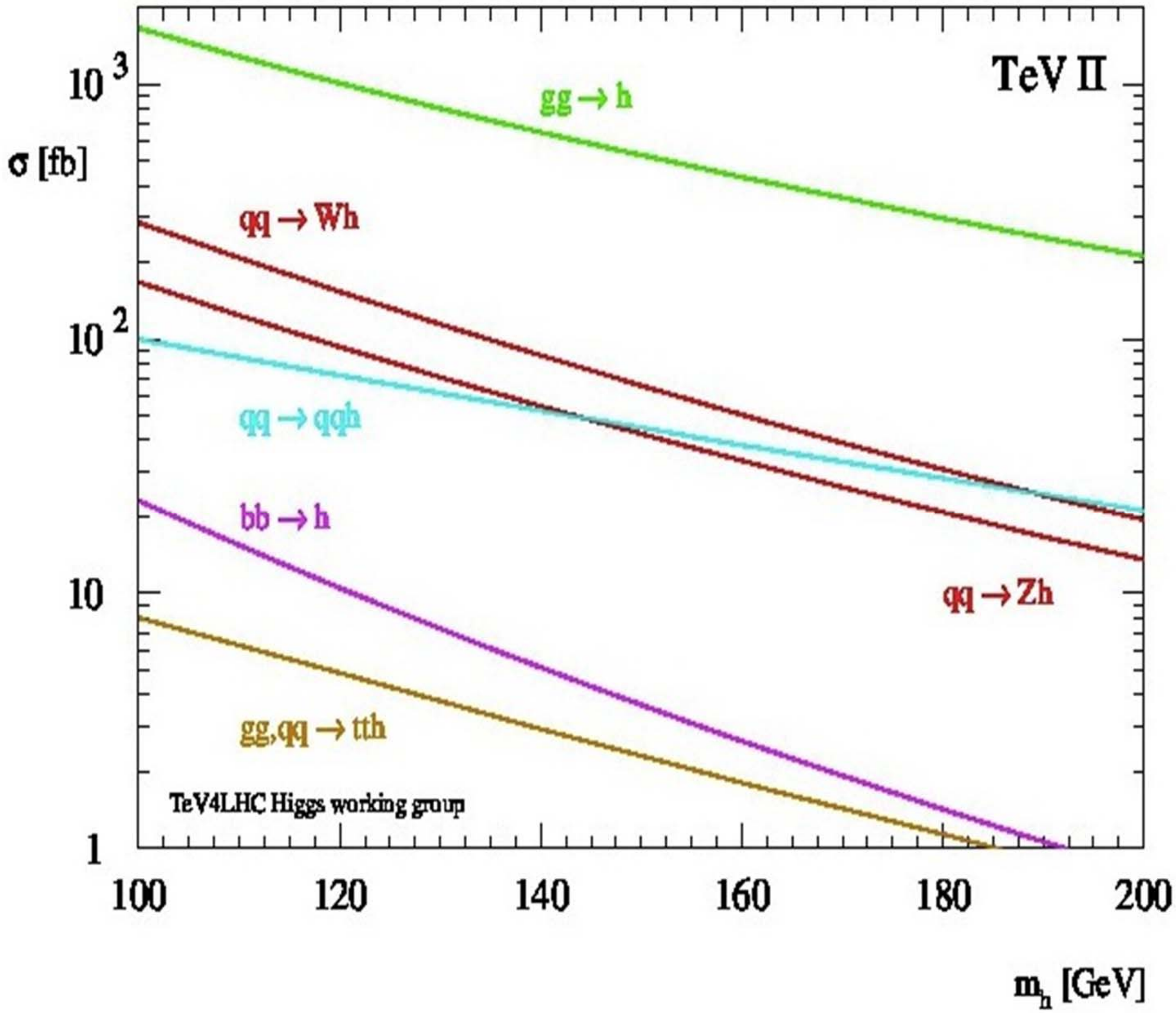
- New measurement from CDF and D0 (March 2012)
  $m_W = 80385 \pm 15$ MeV/c^2
- Updated SM fit gives $m_H < 152$ GeV/c^2 at 95% C.L.
- LHC exclusions from Dec 2011: $m_H < 115$; $m_H > 127$ GeV/c^2

Higgs mass constraints (before July 2012)

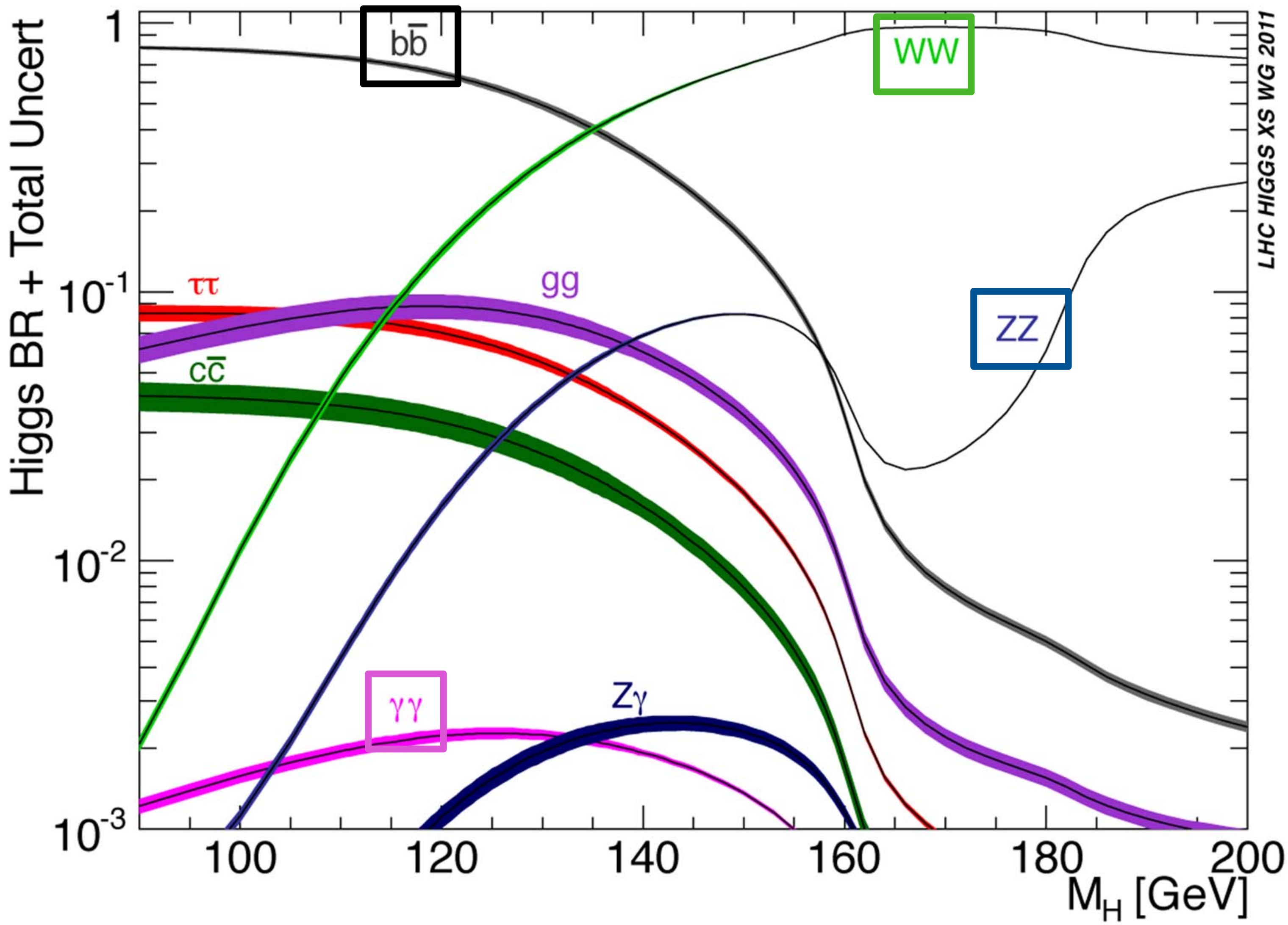
- Direct searches have excluded much of the accessible m_H range.
  - **LEP** : $m_H > 114.4$ GeV/c^2 @ 95% CL
  - **Tevatron** : Exclude $149 < m_H < 179$ GeV/c^2 @ 95% CL
  - **LHC** : Exclude region up to 600 GeV/c^2 @ 95% CL EXCEPT $115 < m_H < 127$ GeV/c^2
- Indirect constraints from W & top masses + other precision measurements
  - $m_H < 152$ GeV/c2 @ 95% CL

SM Higgs production at the Tevatron





SM Higgs Decay



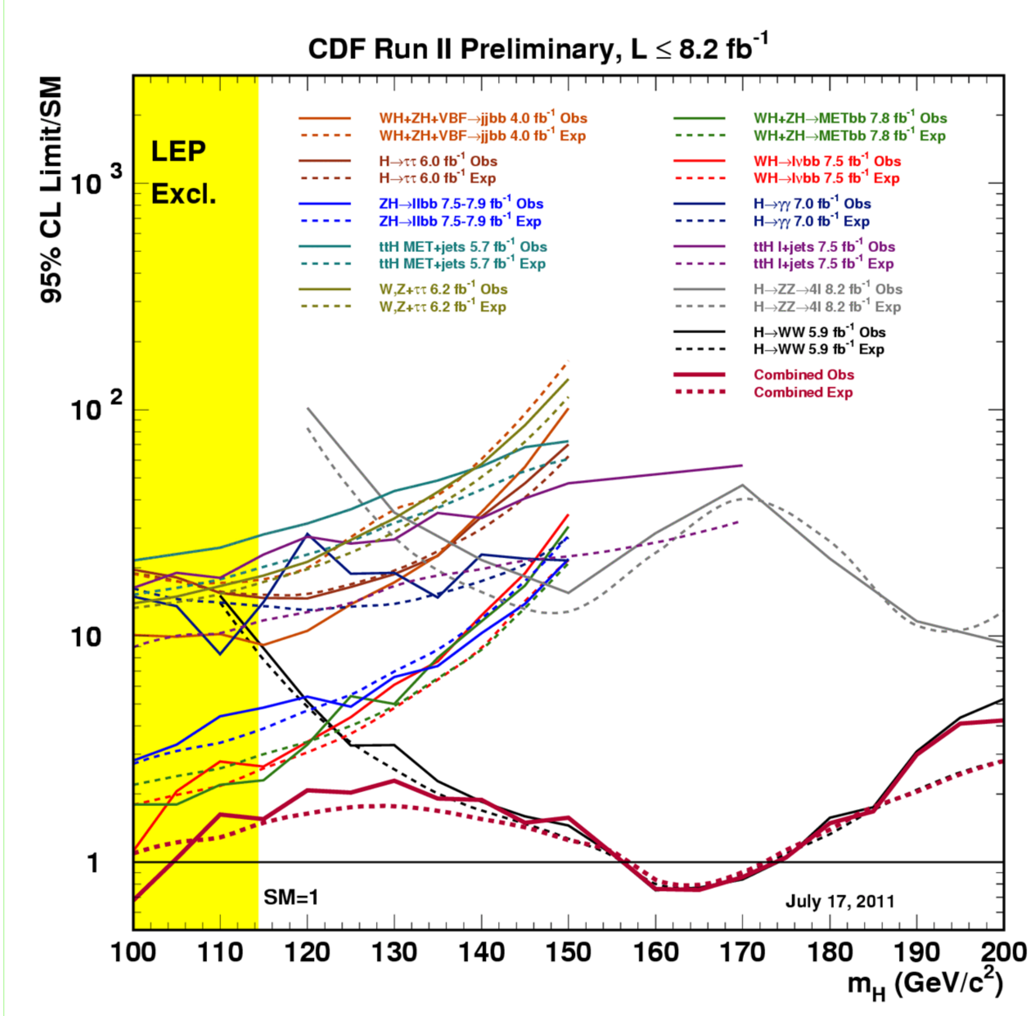
Individual channel sensitivity

Four channels contribute almost equally in the interesting region!

- qq→ZH→llbb
- qq→WH→lνbb
- qq→ZH→ννbb
- gg→H→WW→lνlν

Remaining channels have a combined weight of ~10%

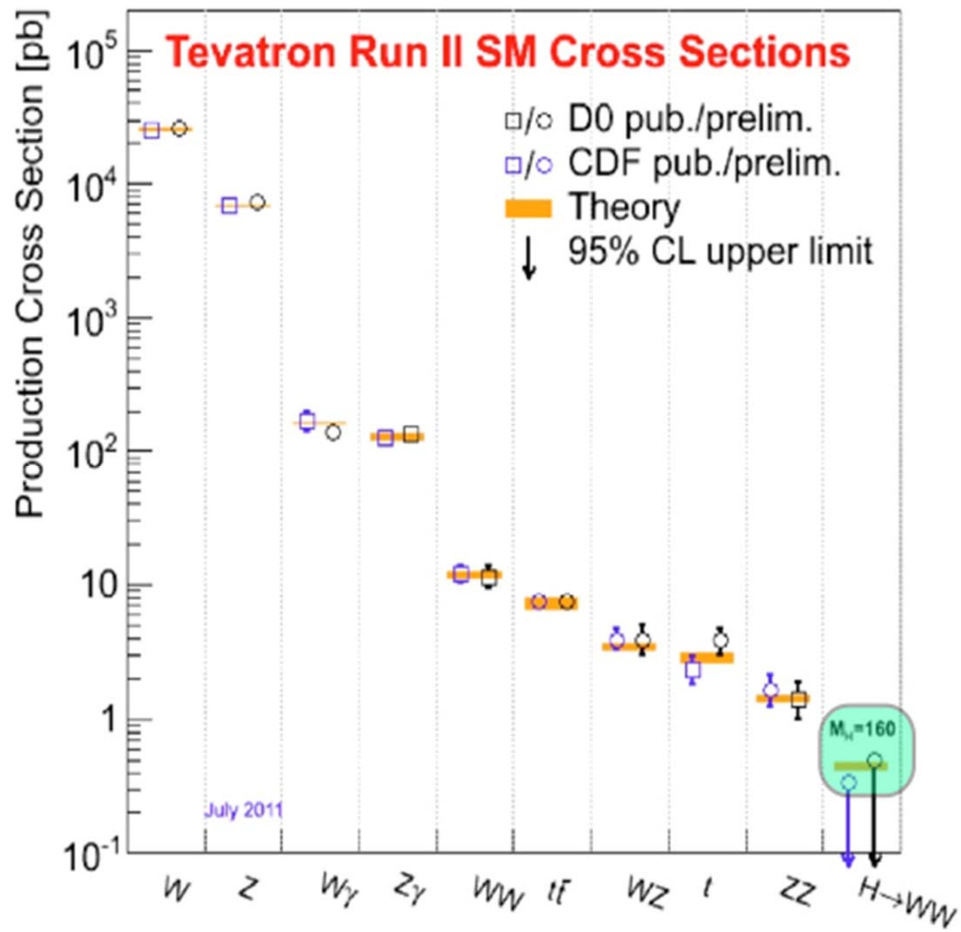
- gg→H→ZZ→llll
- gg→H→γγ
- …and others



How to find a needle in a haystack

<u>Potential Higgs signal is TINY</u> 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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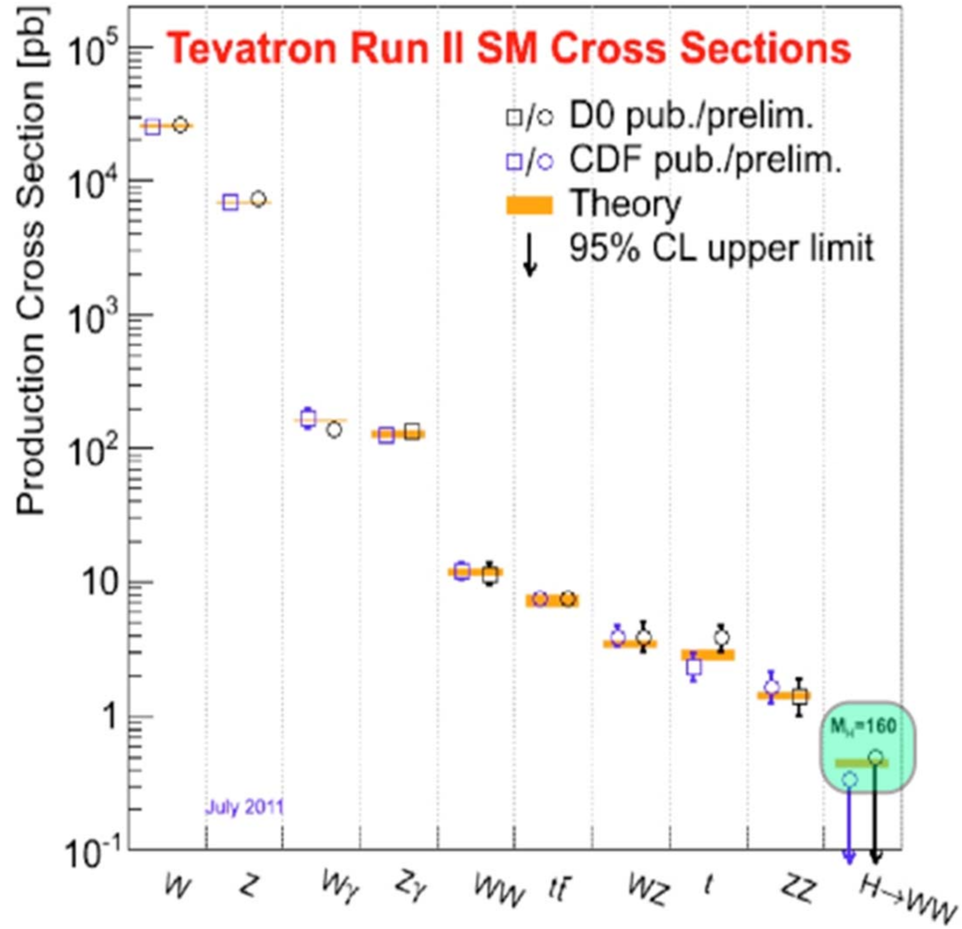
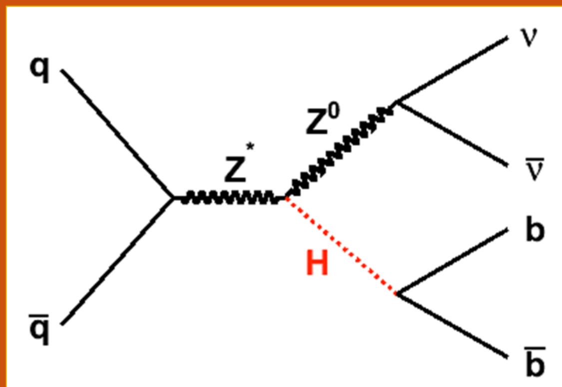
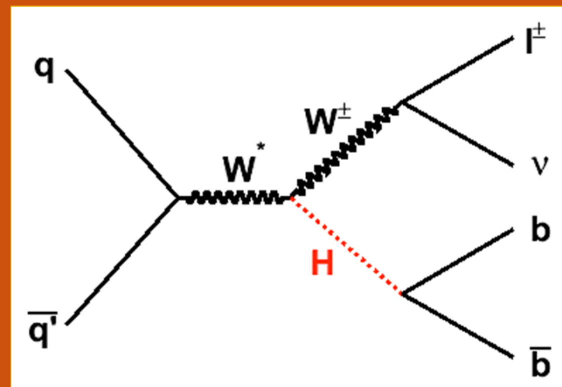


We expect 167 SM Higgs events (reconstructed and selected) and ~200,000 events from SM backgrounds for m_H=125 GeV/c^2

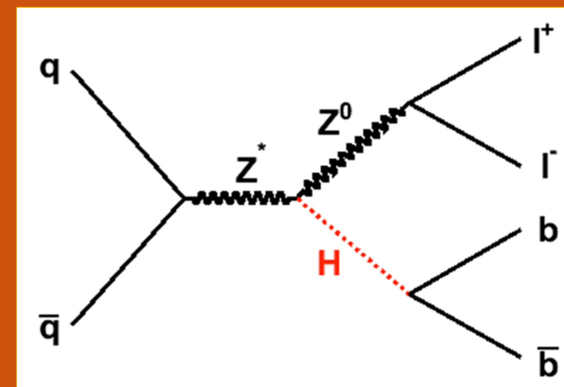
Associated Production: $VH \to Vbb$



$ZH \to \nu\nu bb$



$WH \to l\nu bb$



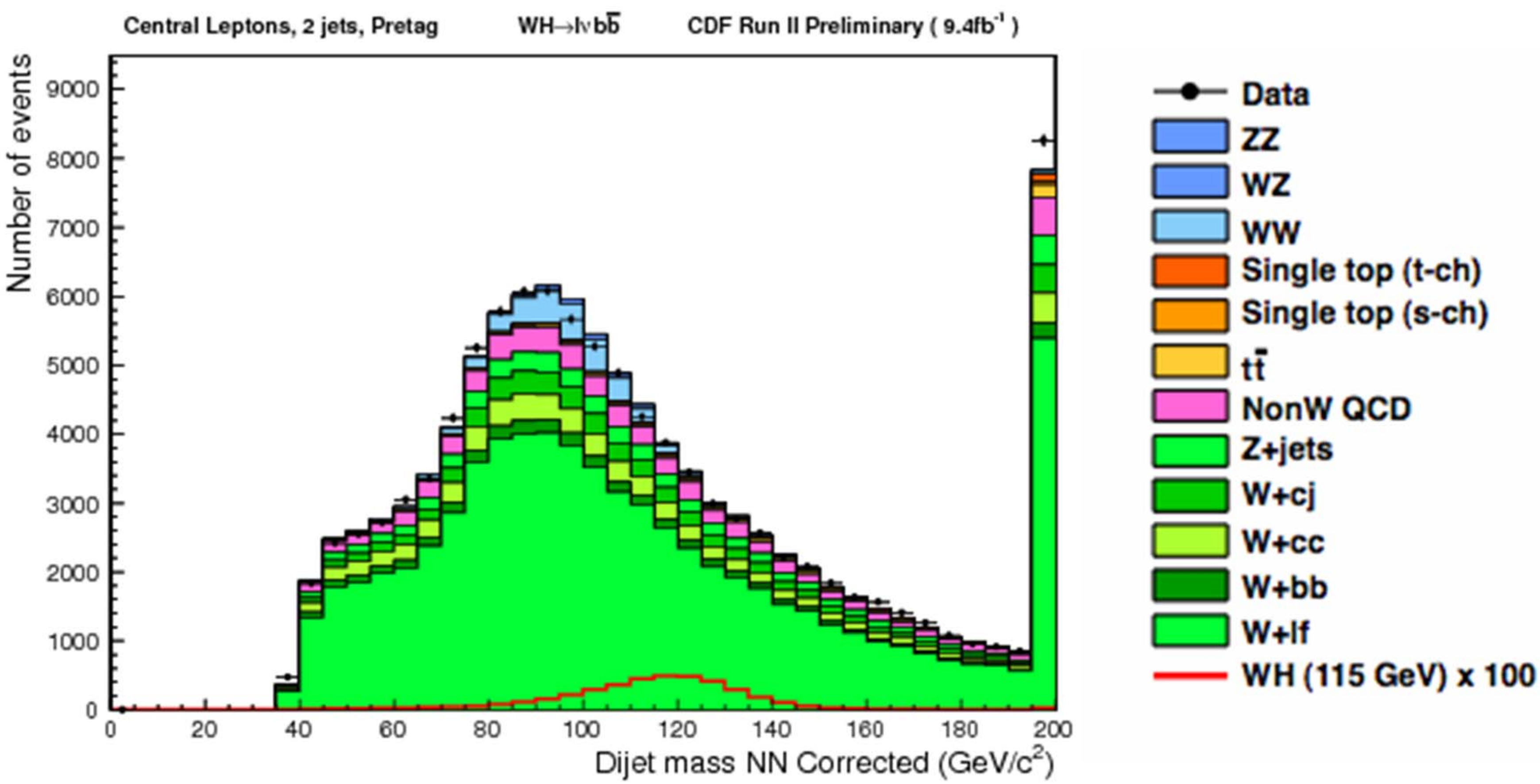
$ZH \to llbb$

Select:
- 0,1,2 charged 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

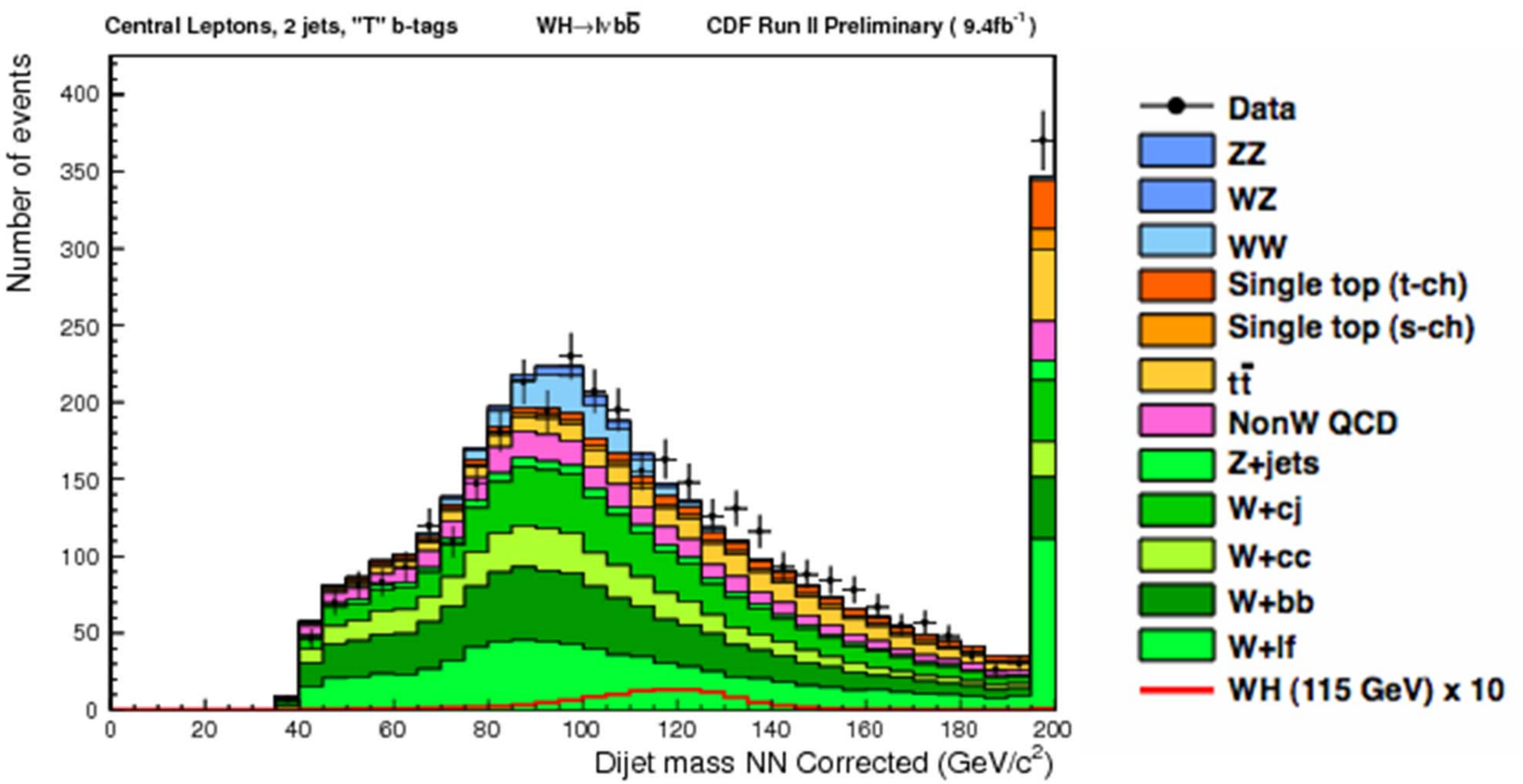
In pictures . . .

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



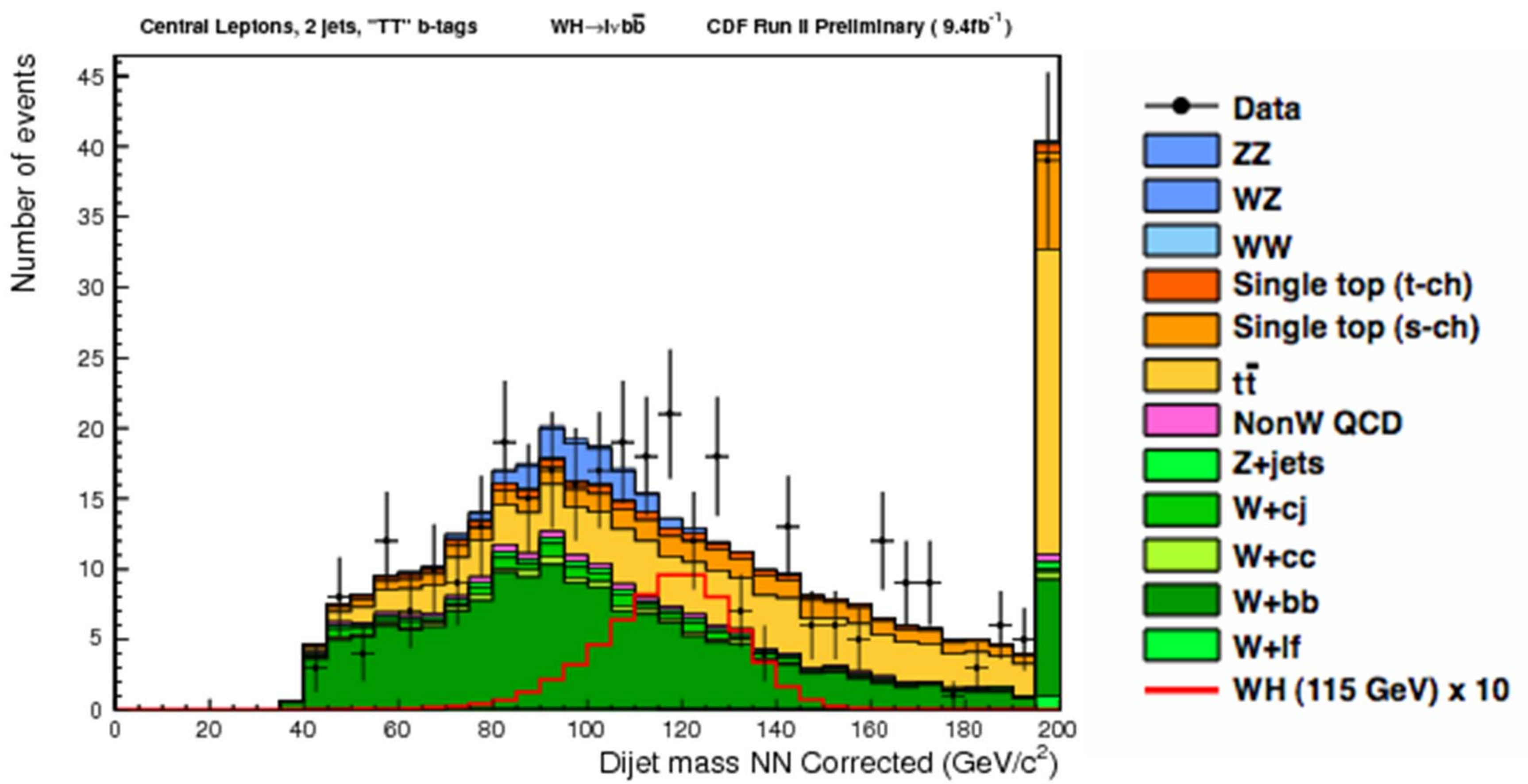
In pictures . . .

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

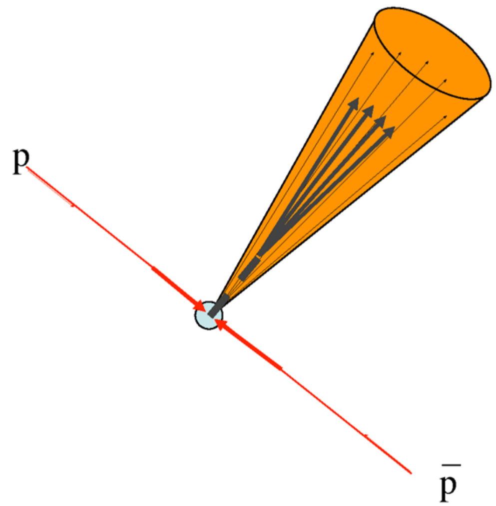


In pictures . . .

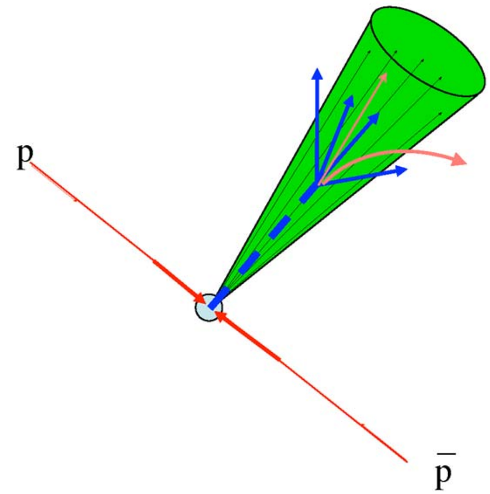
- Loose event selection plus two tightly tagged b-quark jets



Optimize Mjj resolution



light flavor quark jet



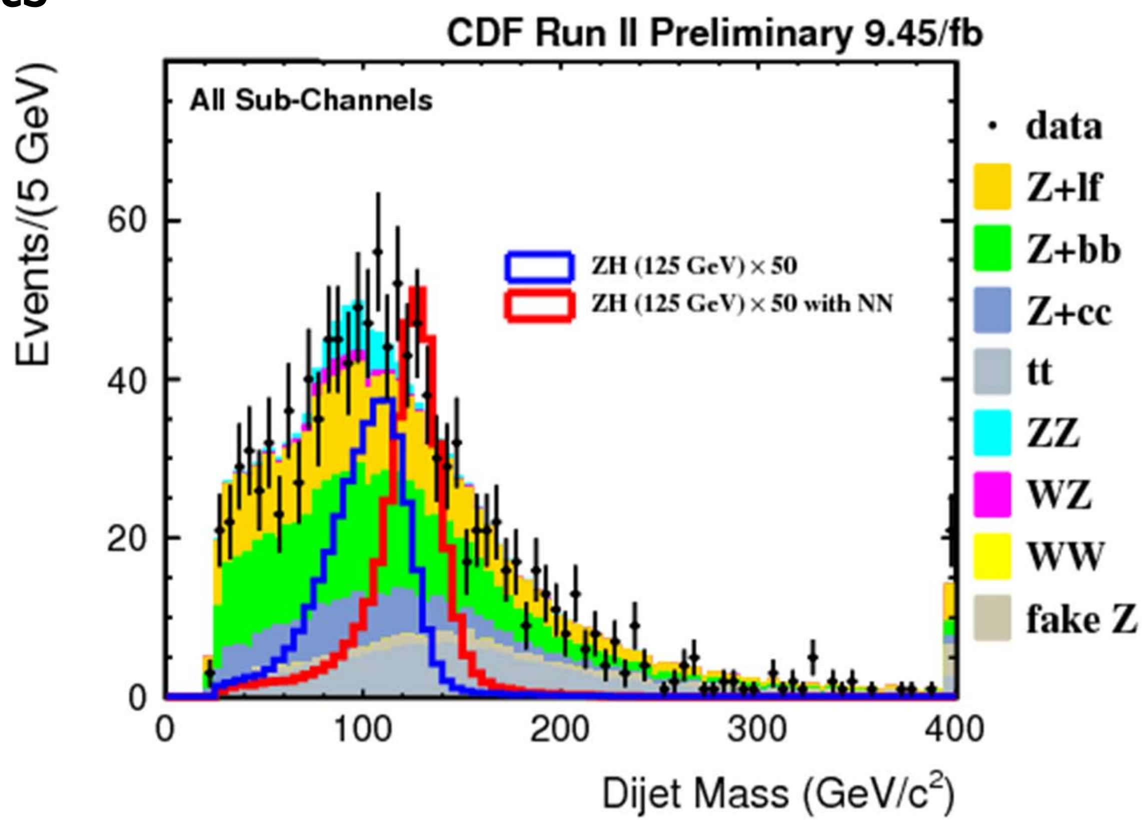
bottom quark jet

- 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

NN corrected jet energies

Train neural network to determine the energy of original b-quark from measured jet quantities using MC generated signal events

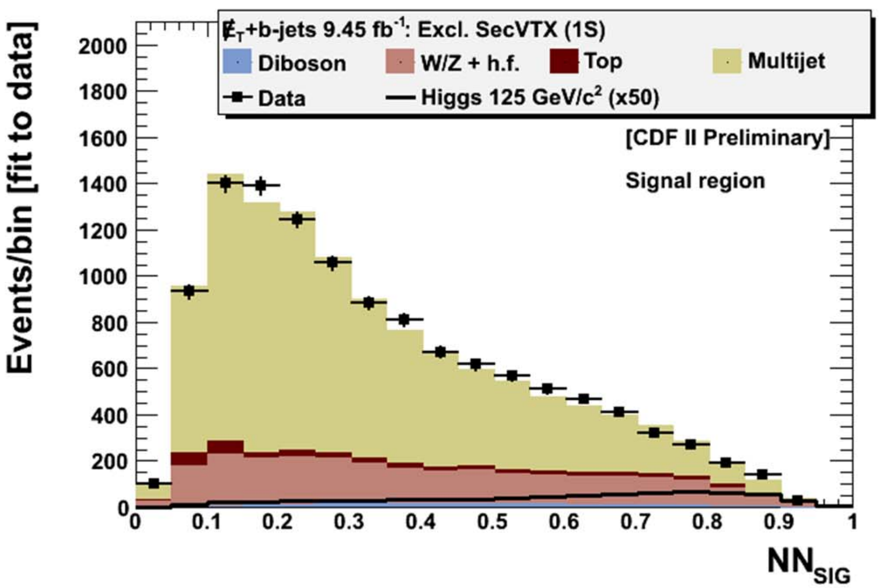
- Use the event kinematics when possible to improve the measured jet energies
- Example: ZH→llbb when both leptons are detected. Strong kinematic constraint on jet energies.



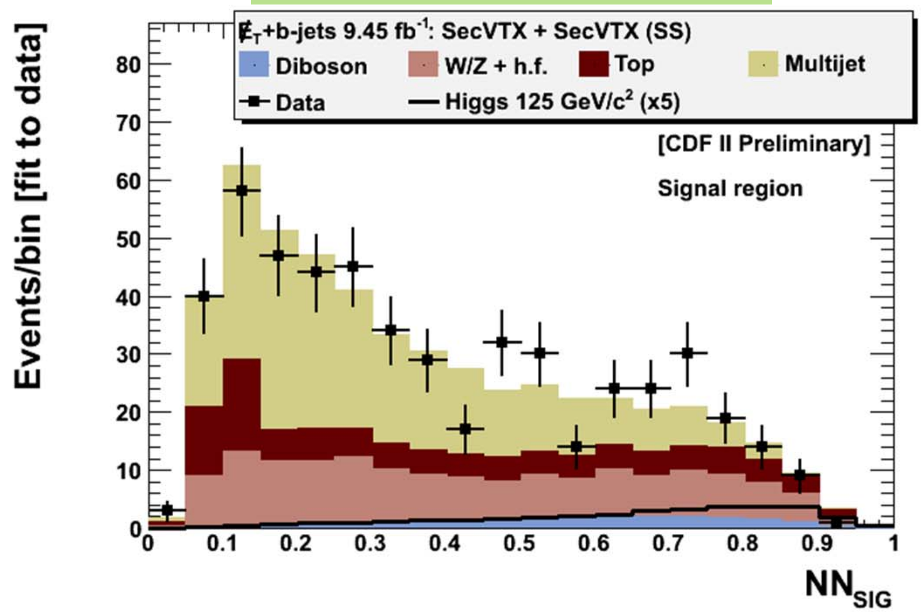
MVA example from ZH→ννbb

- Divide data into sub-channels using b-tag "tightness" to isolate a low background sample
- Each sub-channel has separate MVA output

One "tight" b-tagged jet



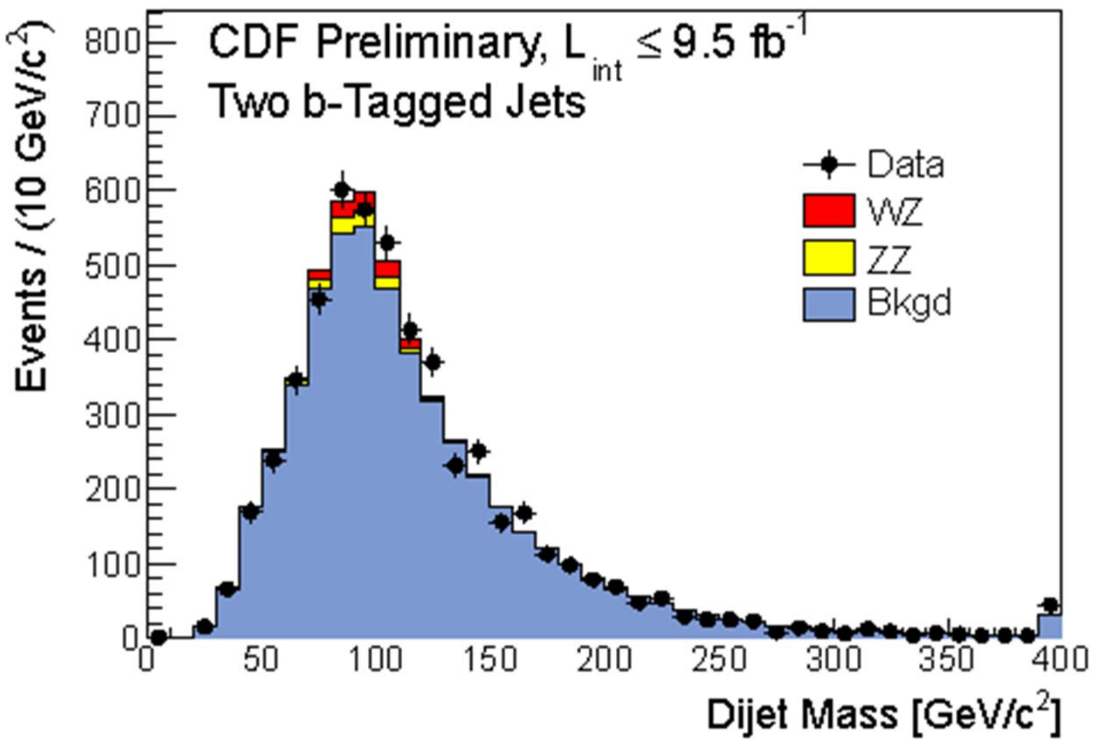
Two "tight" b-tagged jets



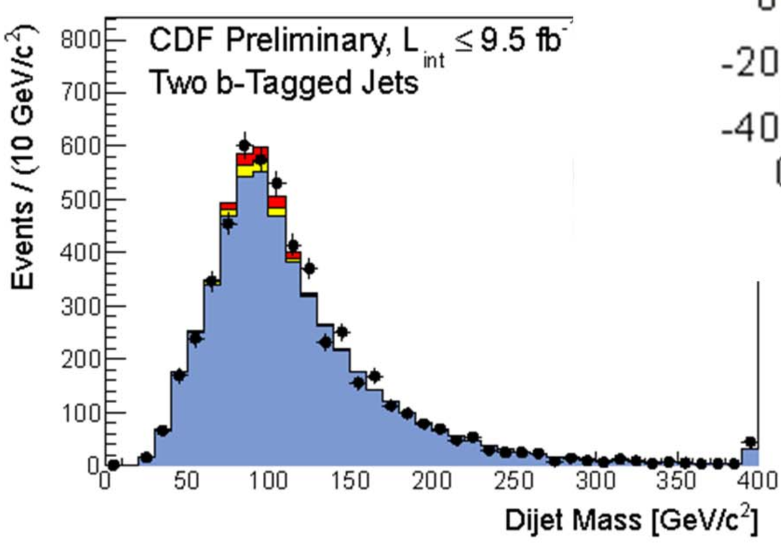
How good is our modeling?

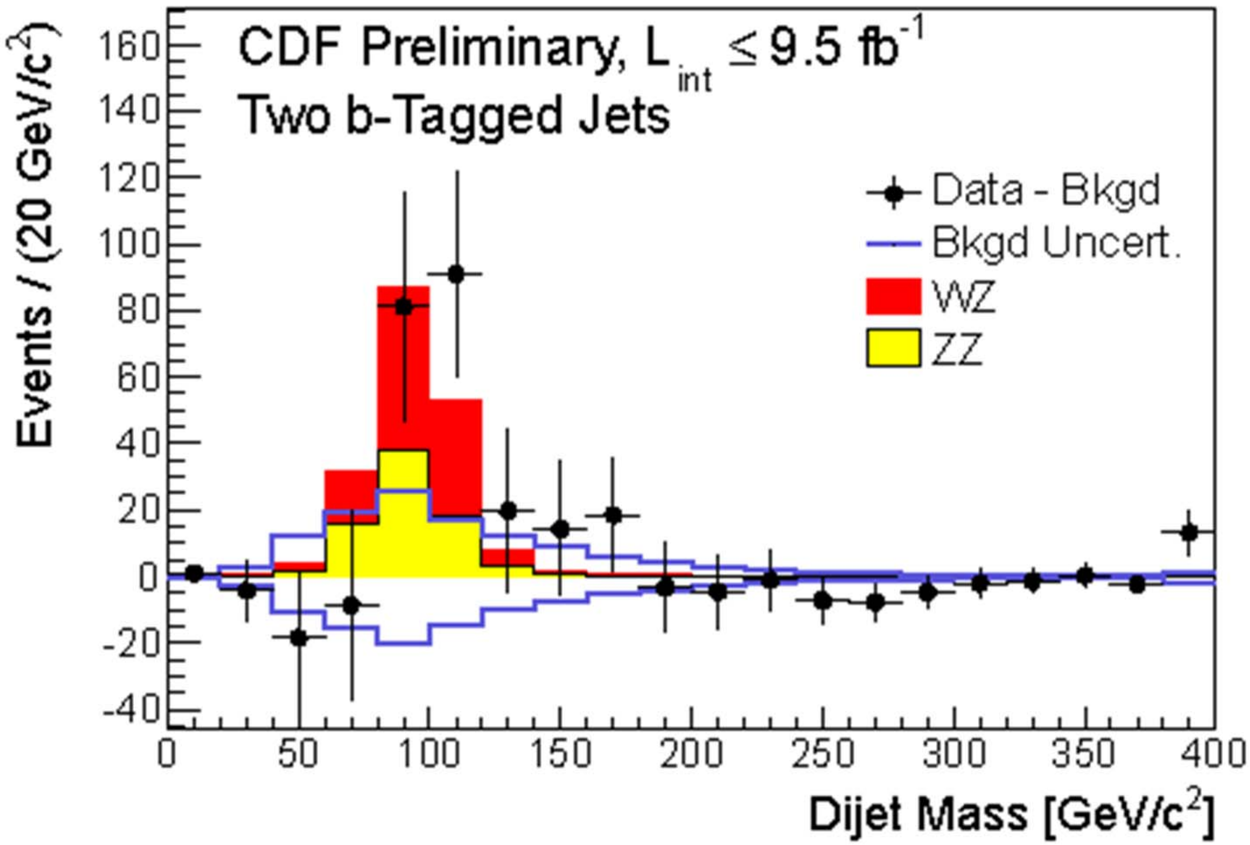
Do we see WZ and ZZ events ($Z \rightarrow bb$) ?

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



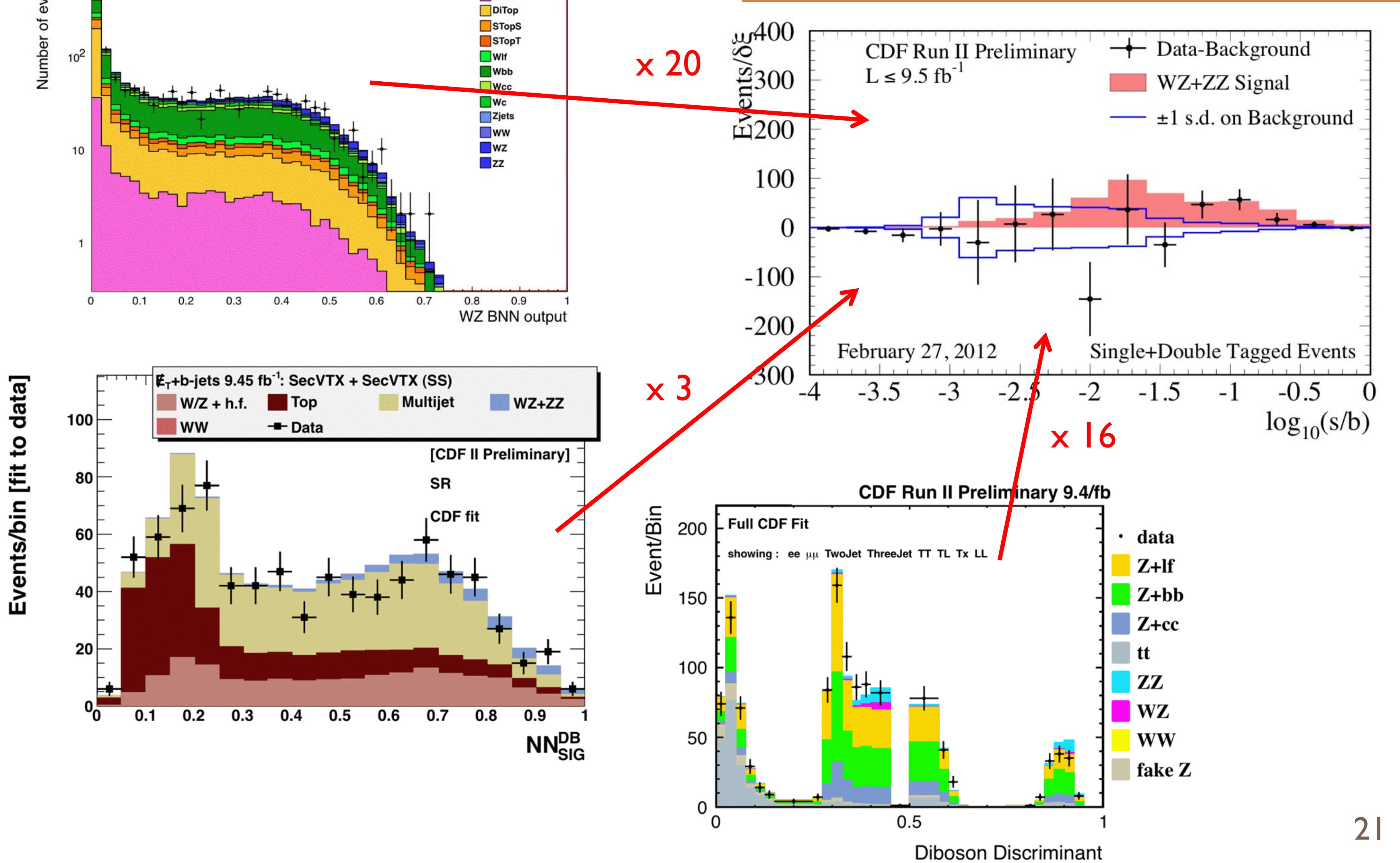
How good is our modeling?





MVA-based Search

440 signal events and ~35,000 background



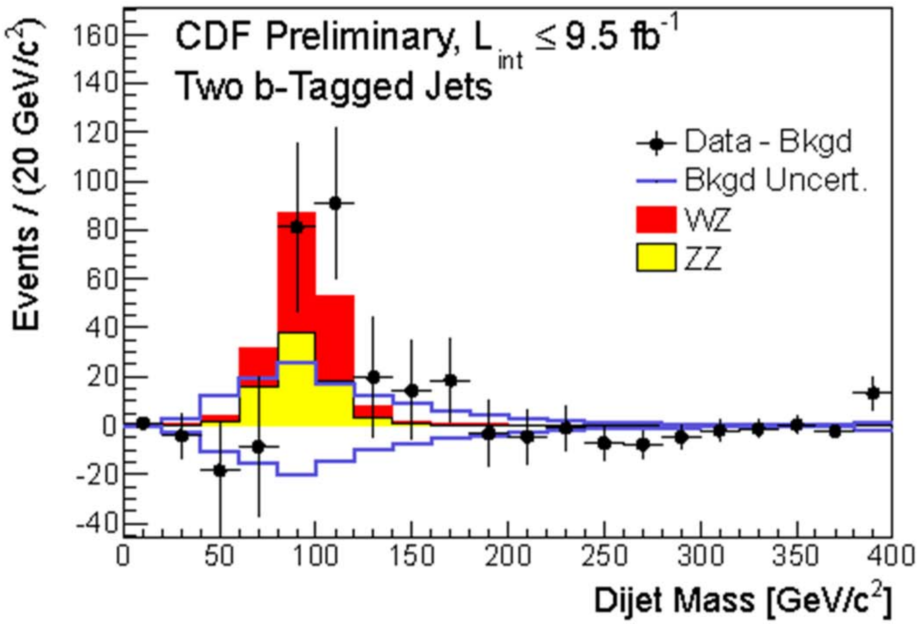
From Discriminants to Limits

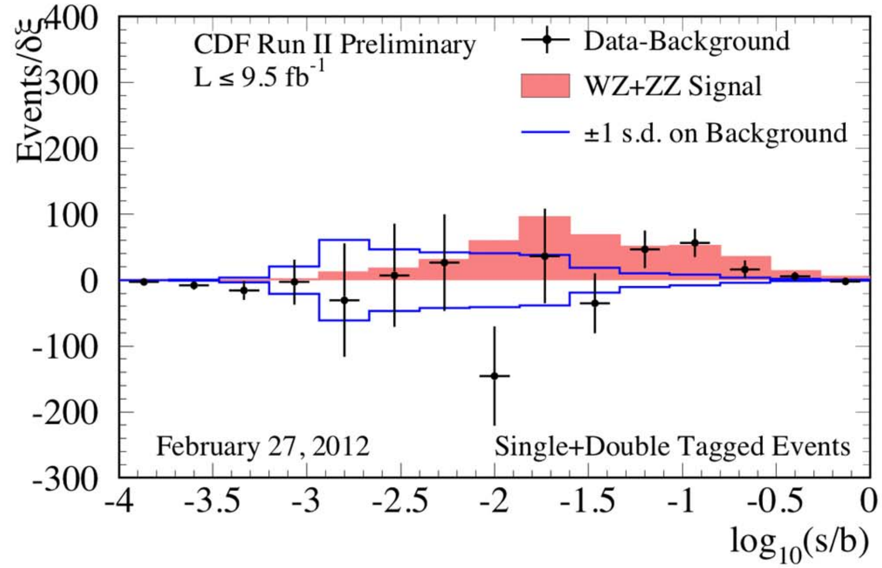
- Combined binned likelihood function

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

- 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)





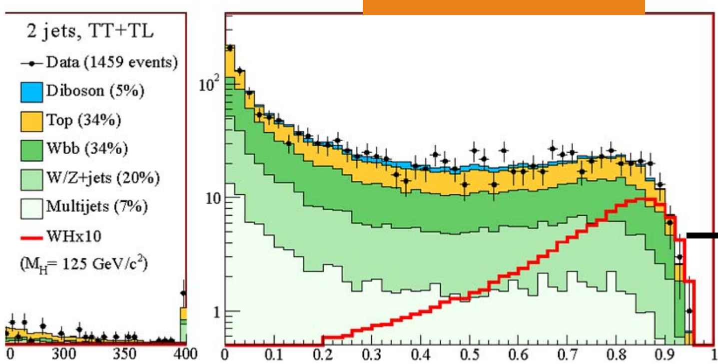
σ(WZ+ZZ)= 4.08 +/- 1.32 pb

significance of 3.2σ

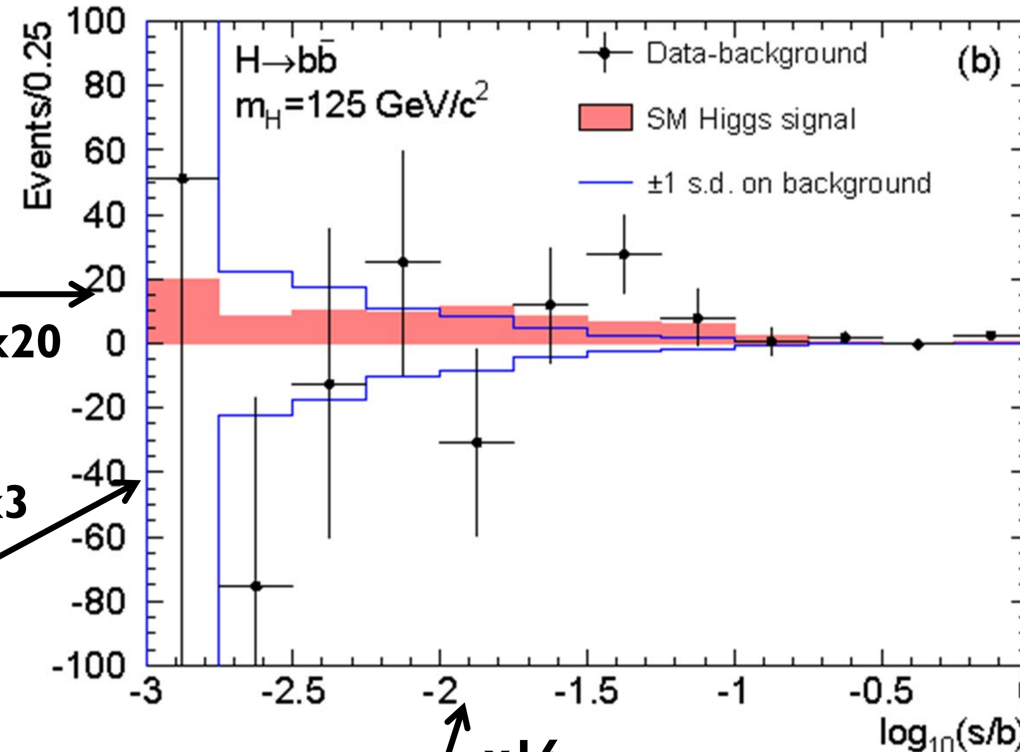
SM Prediction = 4.4 +/- 0.3 pb

VH→Vbb results from CDF

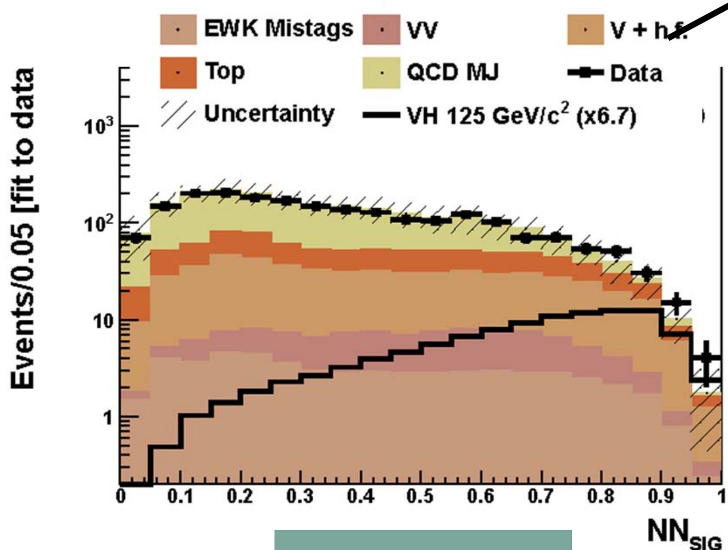
WH→lνbb



x20

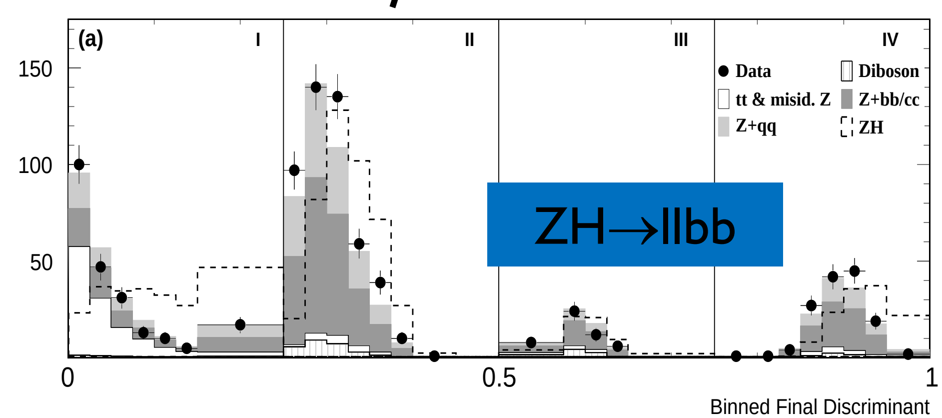


x3



ZH→ννbb

x16



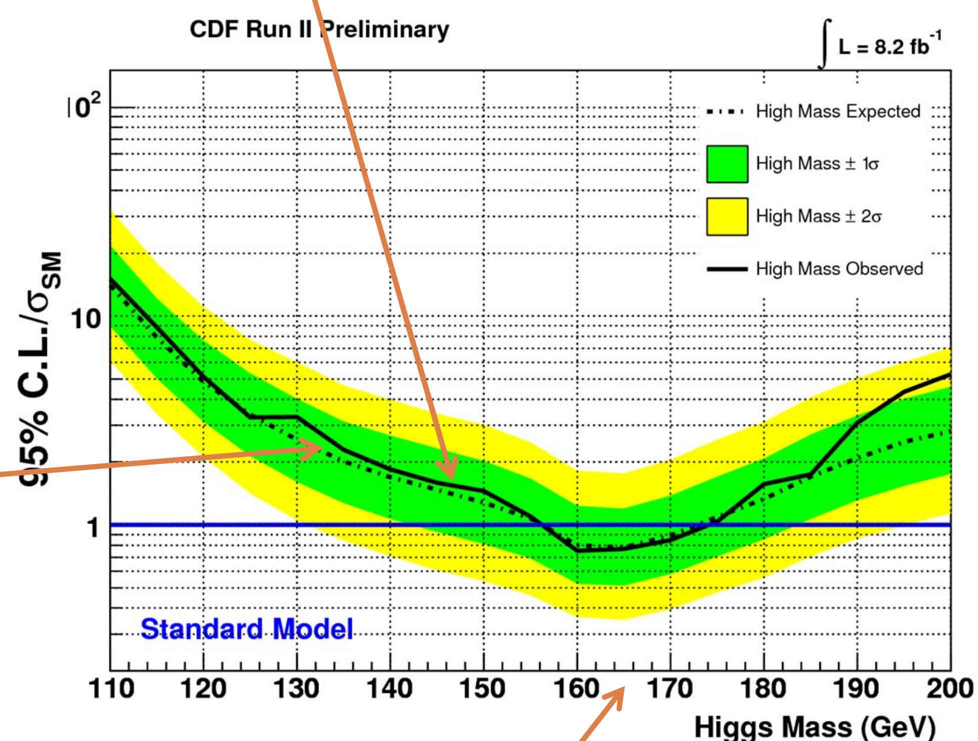
ZH→llbb

Anatomy of a Limit Plot

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

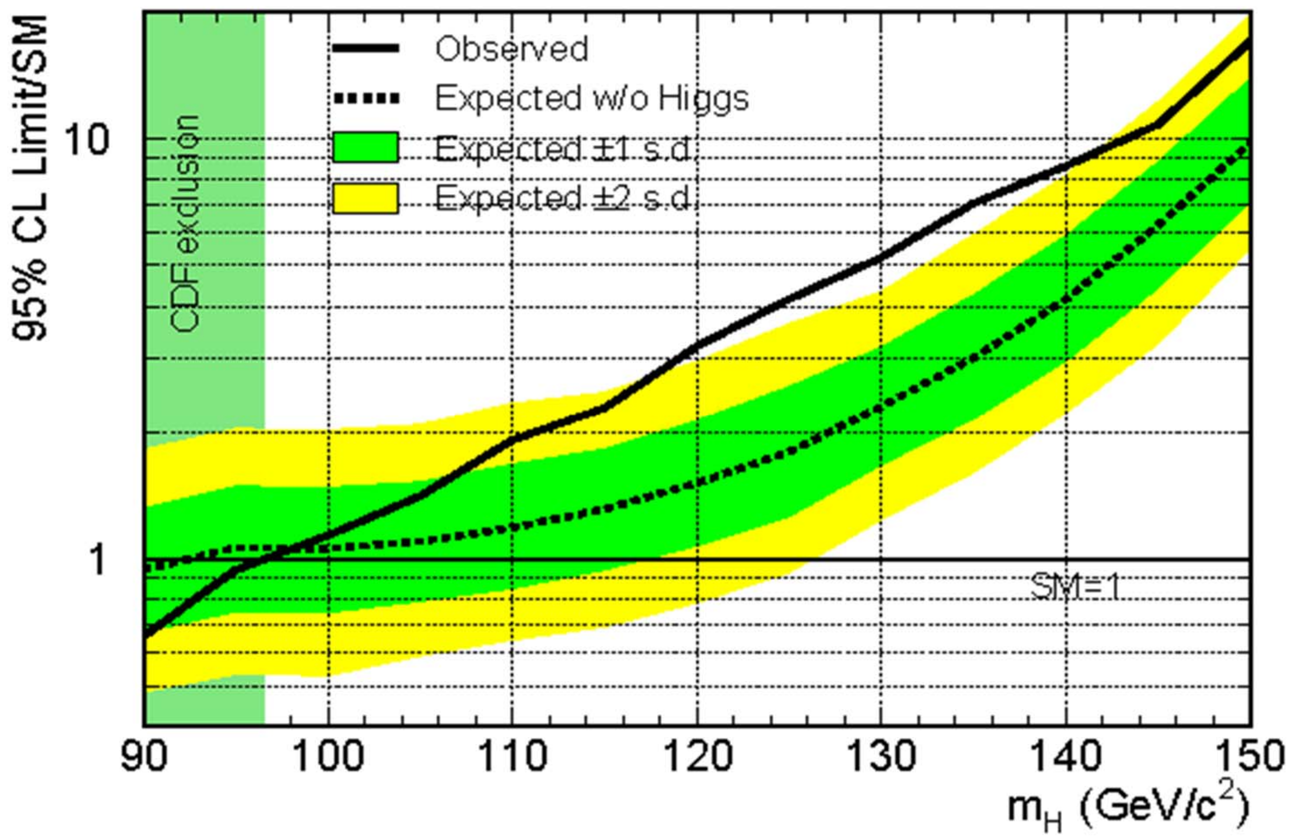
3. Observed limit (solid line) from data

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



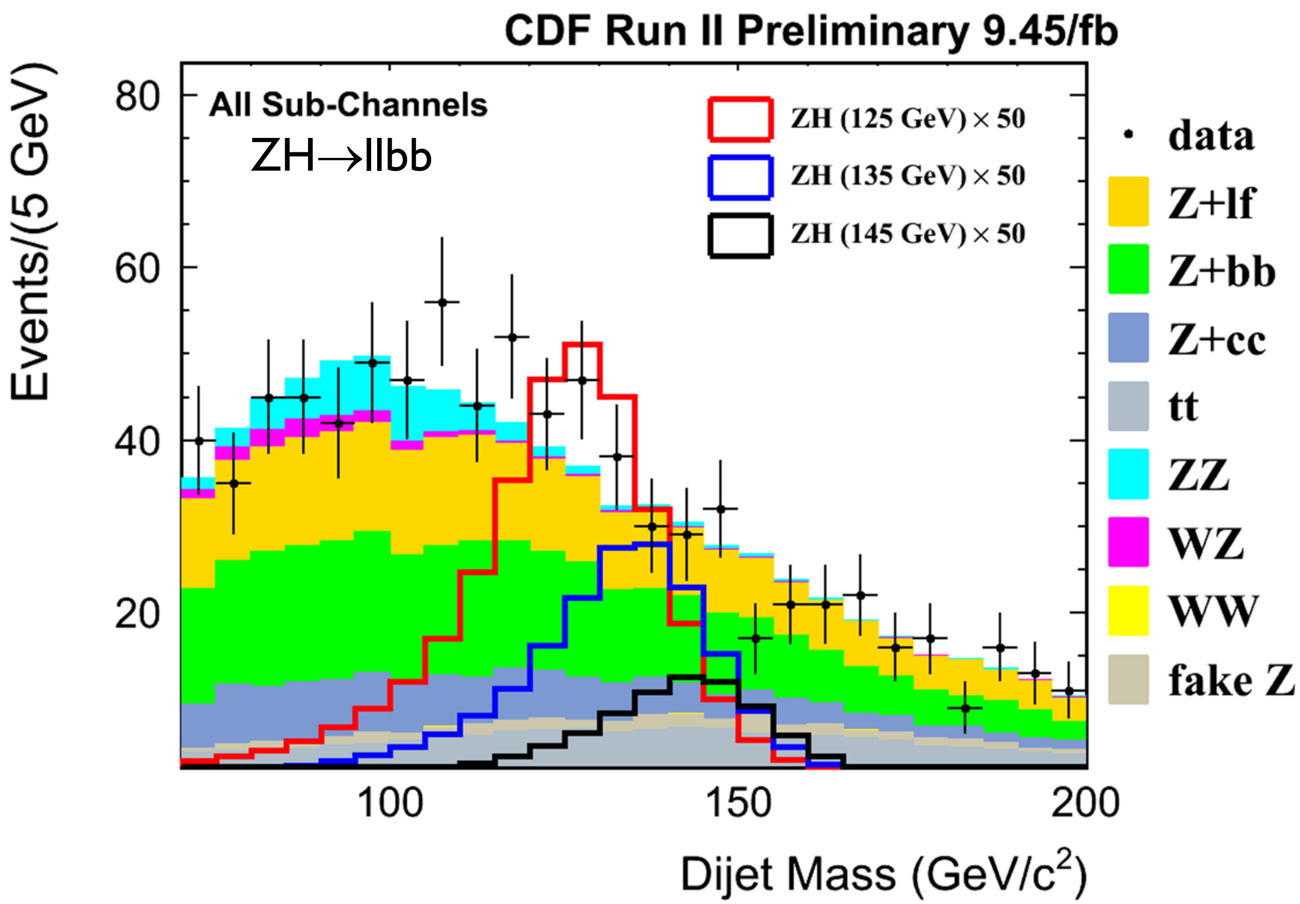
4. Analysis repeated using different signal templates for each m_H between 100 and 200 GeV in 5 GeV steps

Consistent with background-only hypothesis?



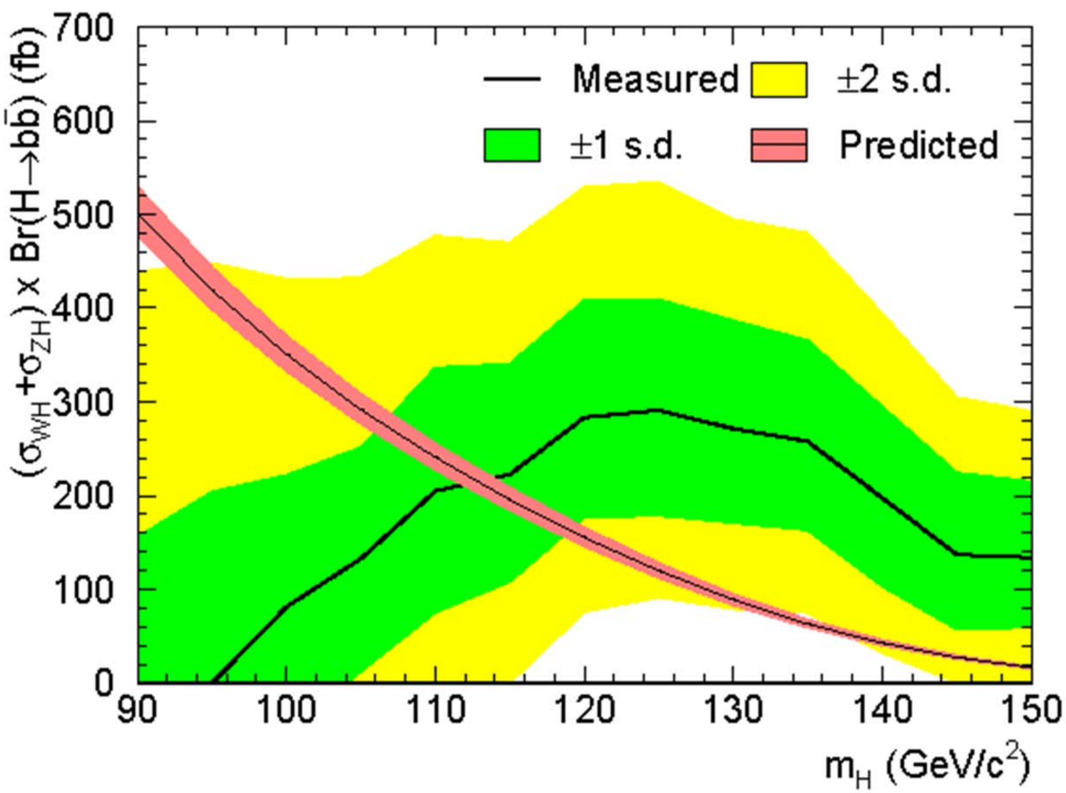
- Exclude m_H<96 GeV/c^2
- Sensitivity at 125 GeV/c^2 is 1.8*SM
- Broad excess of events in the range 120-140 GeV/c^2

Why we expect a real excess to be broad



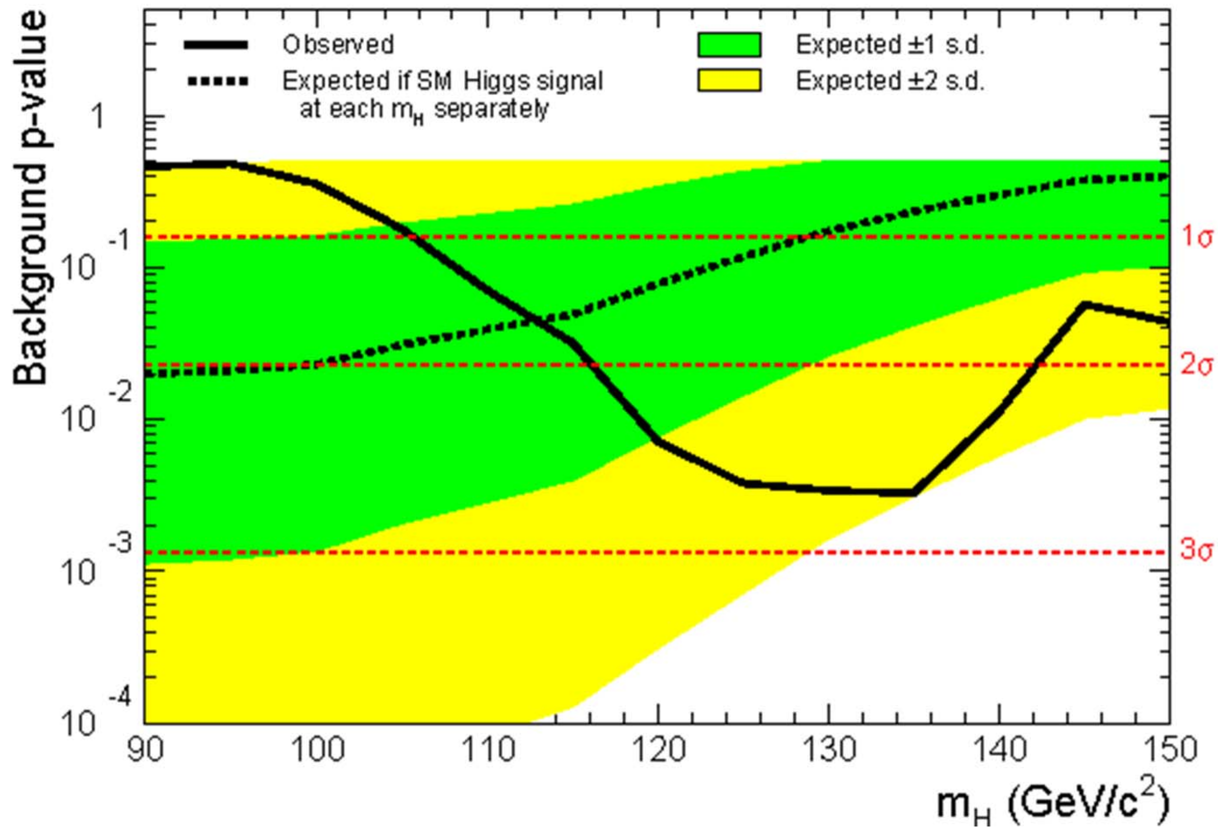
Consistent with SM Higgs?

- Quasi-model-independent search for associated Higgs production with $H \to b\bar{b}$



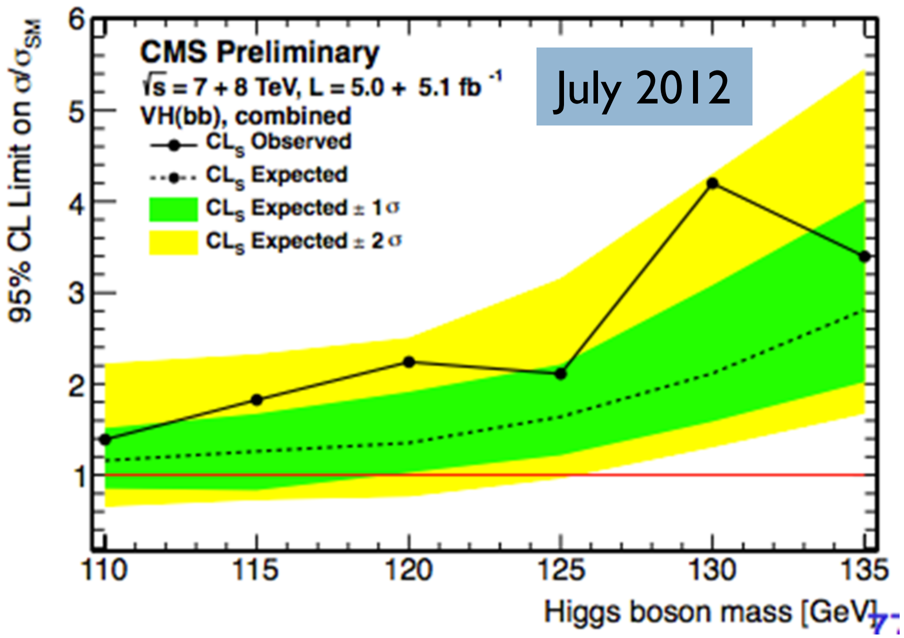
For m_H=125 GeV: $\sigma(WH+ZH) \times B(H \to b\bar{b}) = 291^{+118}_{-113}$ fb (stat+sys)

Consistent with background-only hypothesis?

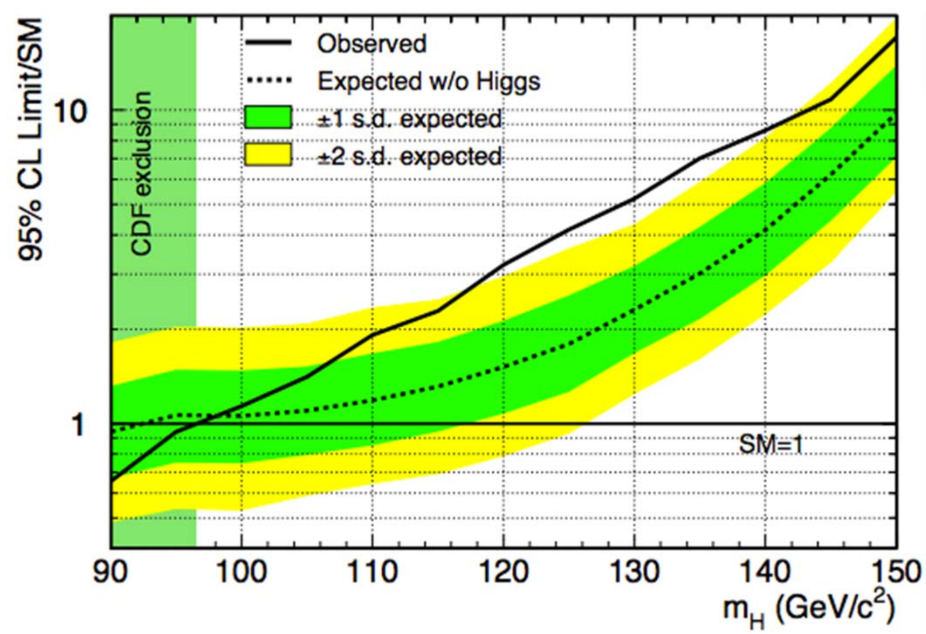


- Highest local p-value of 2.7σ is found at m_H = 135 GeV/c^2
- Correcting for a LEE of 2, the global p-value is 2.5σ
- At 125 GeV/c^2, p-value is 2.7σ

Single experiment sensitivity comparison



CDF Run-II Full dataset - March 2012



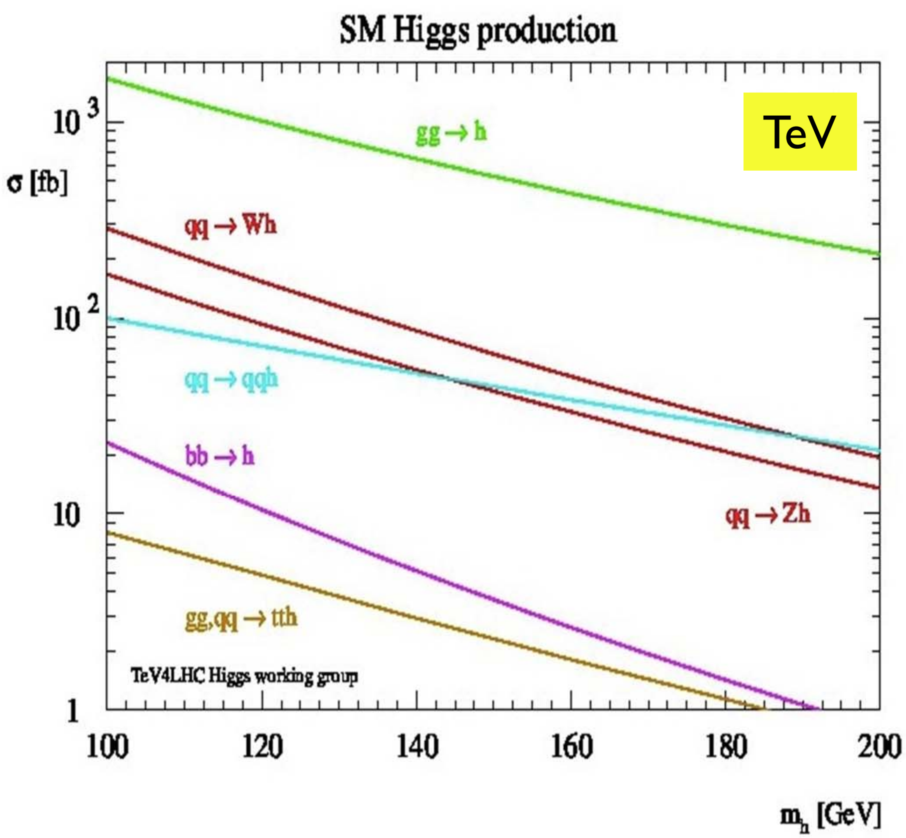
At m_H=125 GeV/c^2		
	CDF	CMS
H→γγ	~10*SM	0.5-1*SM
H→WW	~3.5*SM	~1*SM
H→bb	~1.8*SM	~1.4*SM

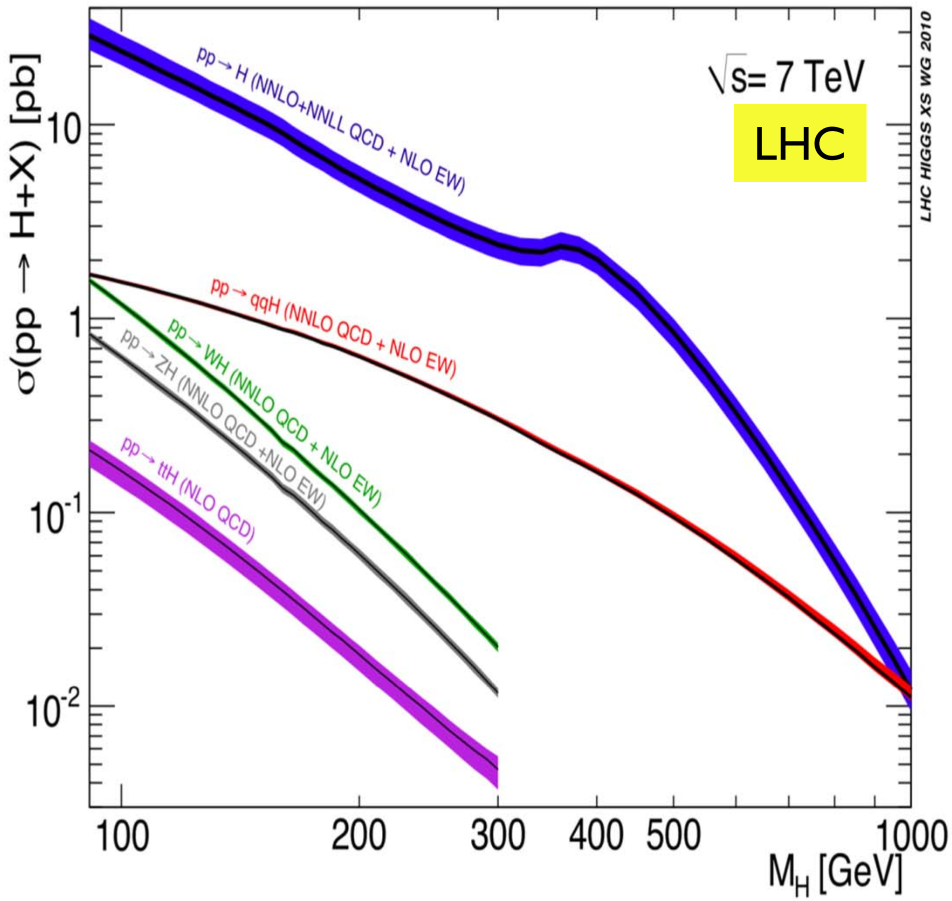
CDF: arXiv:1207.1707 [hep-ex], submitted to PRL

CMS: Presentation by J. Incandela July 4, 2012
CMS PAS HIG-12-019

Tevatron/LHC production cross sections

Strength of the Tevatron is H→bb!



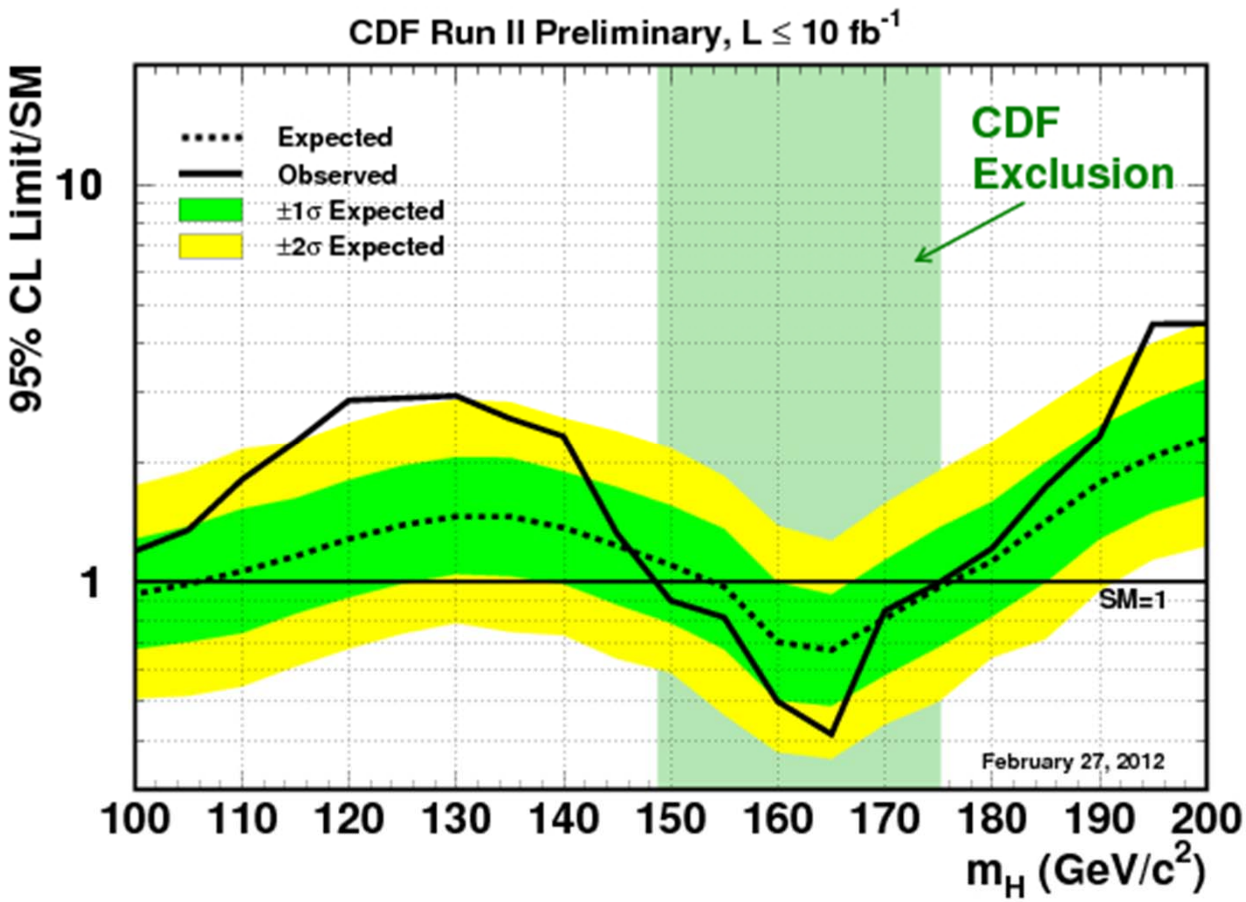


No channel left behind!

Channel	Luminosity	95% CL limit M_H=125 GeV
$H \to WW$	9.7 fb^{-1}	3.1 x SM
$H \to \gamma\gamma$	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

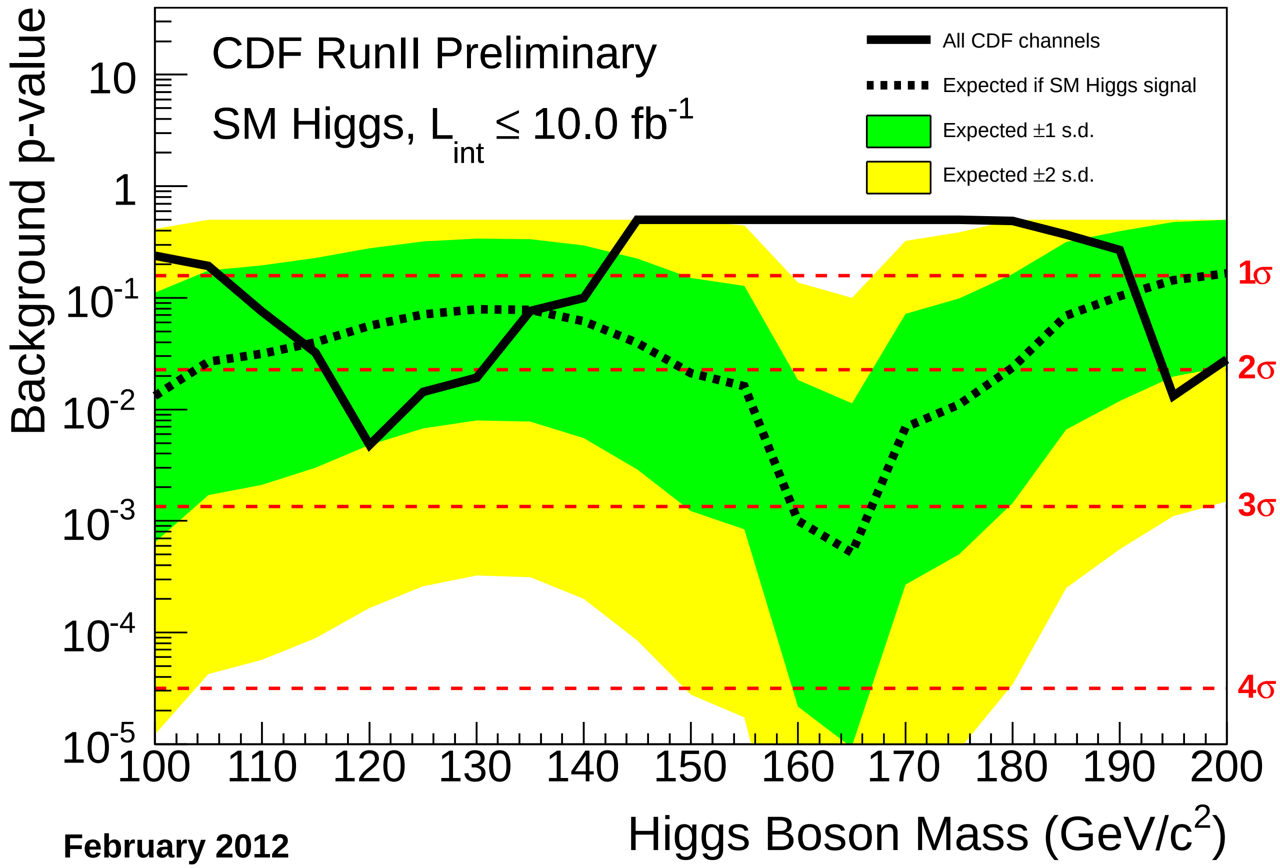
Channel	Luminosity	95% CL limit M_H=150 GeV
$H \to ZZ \to llll$	9.7 fb^{-1}	9.4 x SM

All channels combined

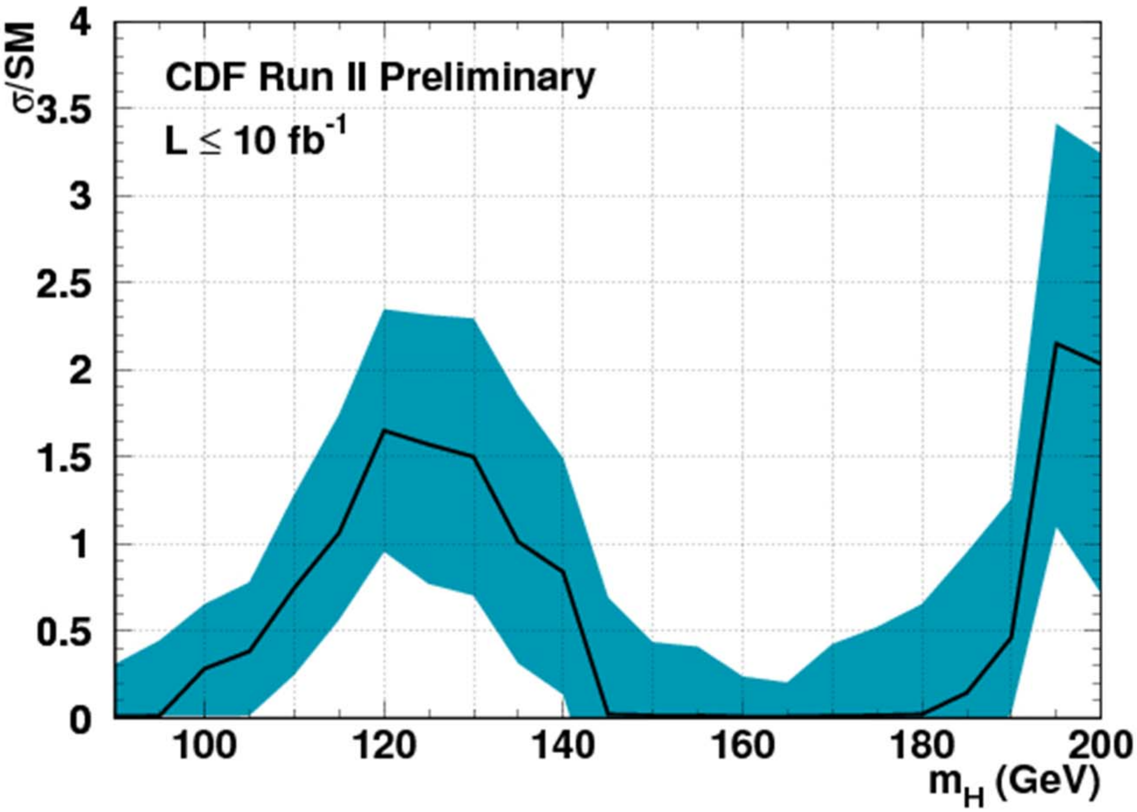


- CDF data alone exclude SM Higgs at 95% C.L. : $149 < m_H < 175$ GeV/c^2
- Expect to exclude: $100 < m_H < 105$ GeV/c^2 & $155 < m_H < 175$ GeV/c^2
- Excess of events in the range 105-145 GeV/c^2

All channels combined



All CDF channels combined



Consistent with SM Higgs at 1σ level for mass range between 105 and 150 GeV/c^2

Conclusions

- CDF has 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 $\sigma(WZ+ZZ)$ with a significance of 3.2σ and a value compatible with SM
- Combining all search channels, 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 significance of this excess is **2.5σ**.
- In the single decay mode H->bb, we observe an excess of Higgs-like events consistent with SM Higgs and a global p-value of **2.7σ**. We measure

  $\sigma(WH+ZH) \times B(H \to bb) = 291^{+118}_{-113}$ fb (stat+sys)

  at m_H=125 GeV (arXiv:1207.1707 [hep-ex], submitted to PRL)

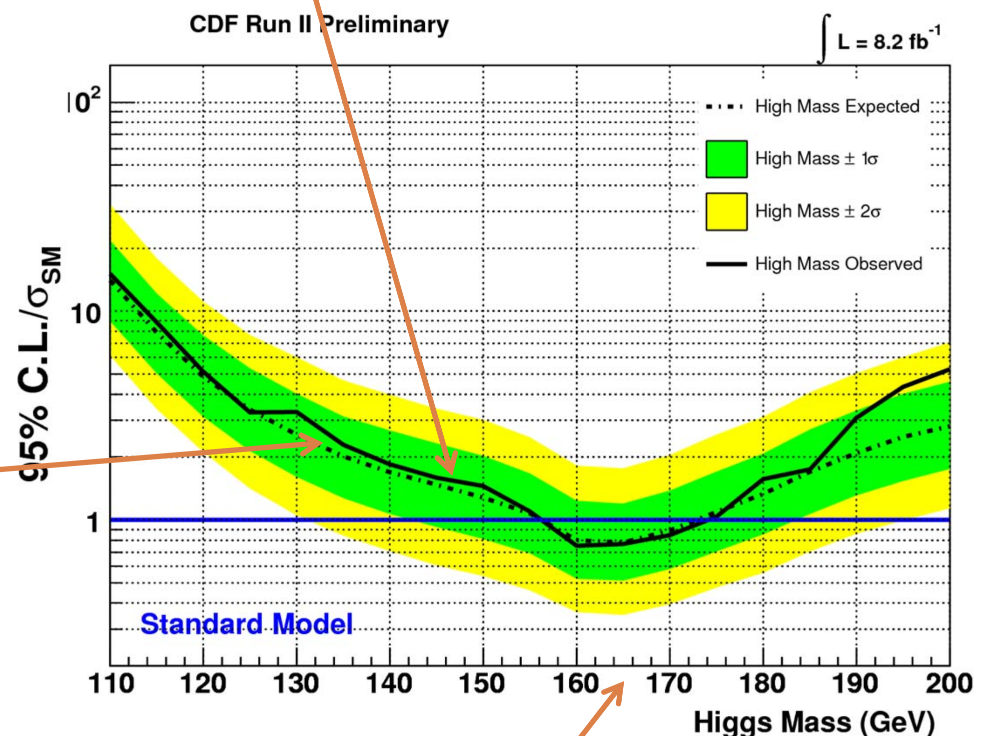
Backup Slides

Anatomy of a Limit Plot

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

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

3. Observed limit (solid line) from data



4. Analysis repeated using different signal templates for each m_H between 100 and 200 GeV in 5 GeV steps

H→ZZ→4 leptons

- Small expected signal rates
- Low SM backgrounds
- Narrow Higgs boson mass resonance easy to separate from nonresonant background contributions

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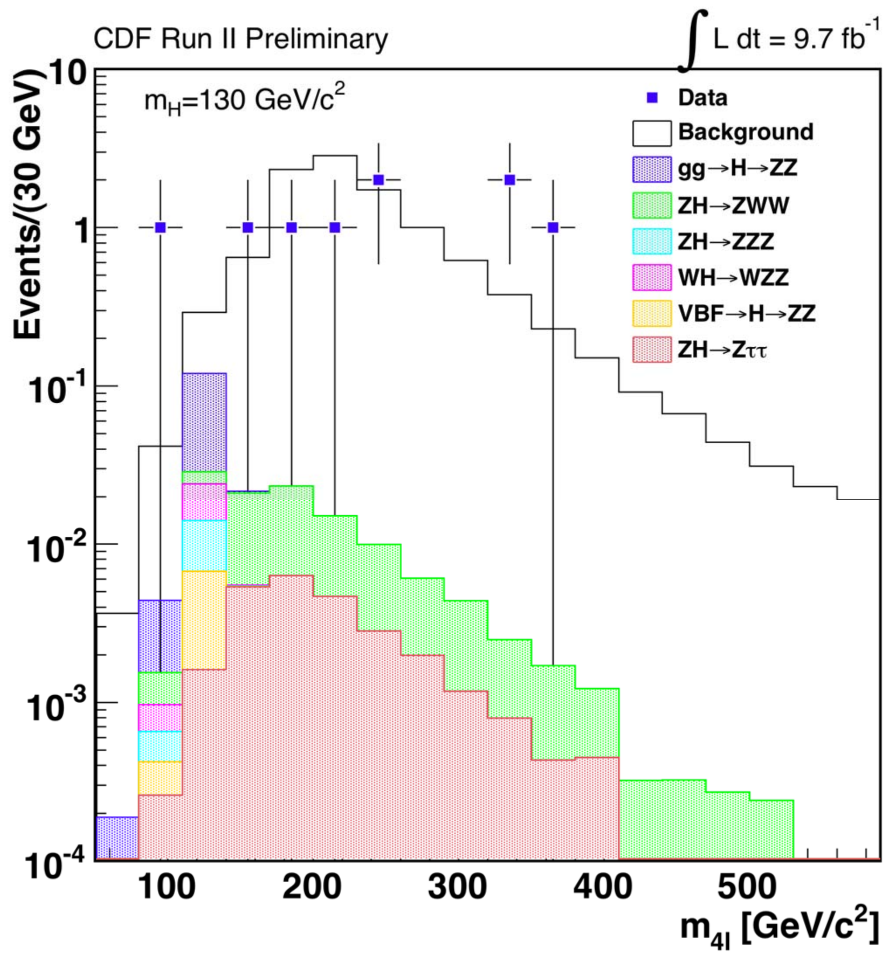
- Expect 2.1 Higgs events (0.2 after selection) for CDF alone
- Expected sensitivity 18xSM for CDF alone



$H\to\gamma\gamma$

- Large nonresonant SM backgrounds
- Signal appears as narrow mass resonance on top of falling background spectrum

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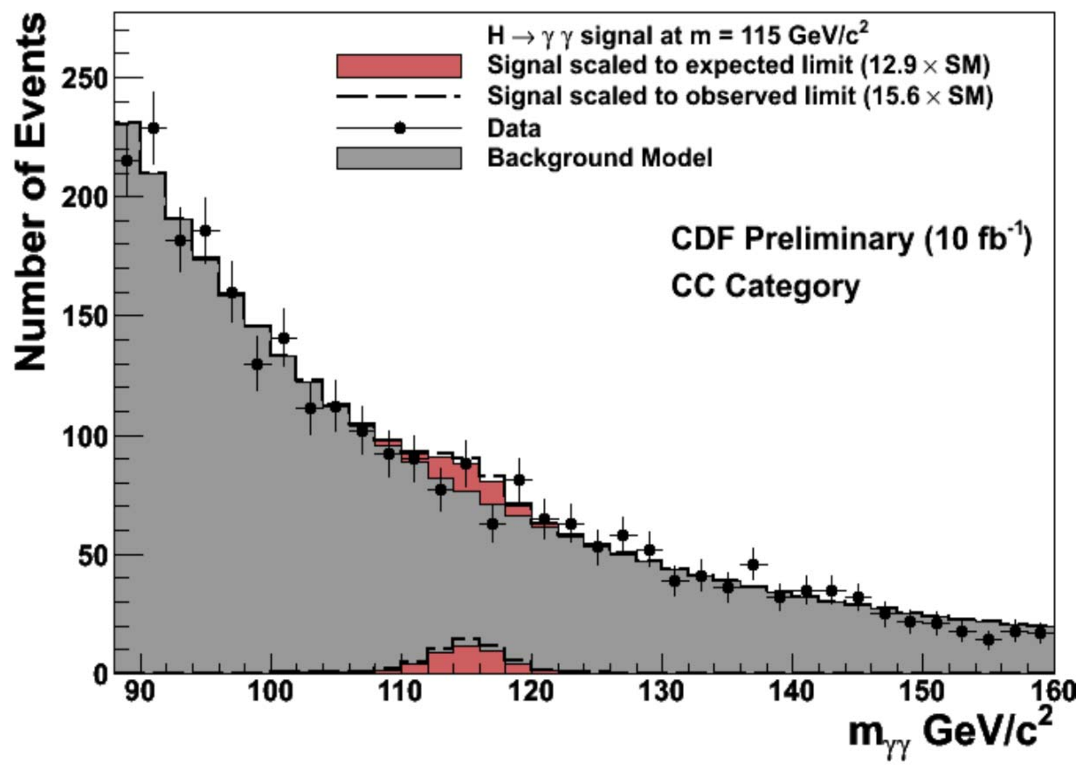
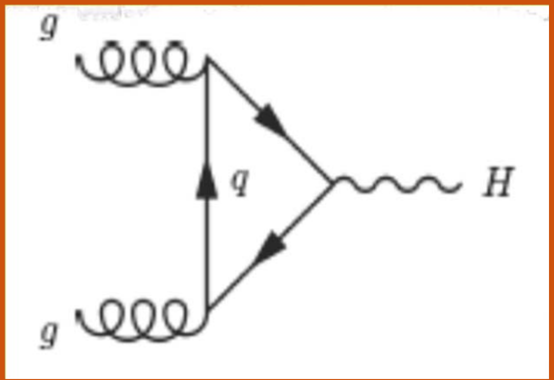
- Expect 28 events (7 after selection) at m_H = 125 GeV



"High Mass" channel



$H \rightarrow WW \rightarrow l\nu l\nu$

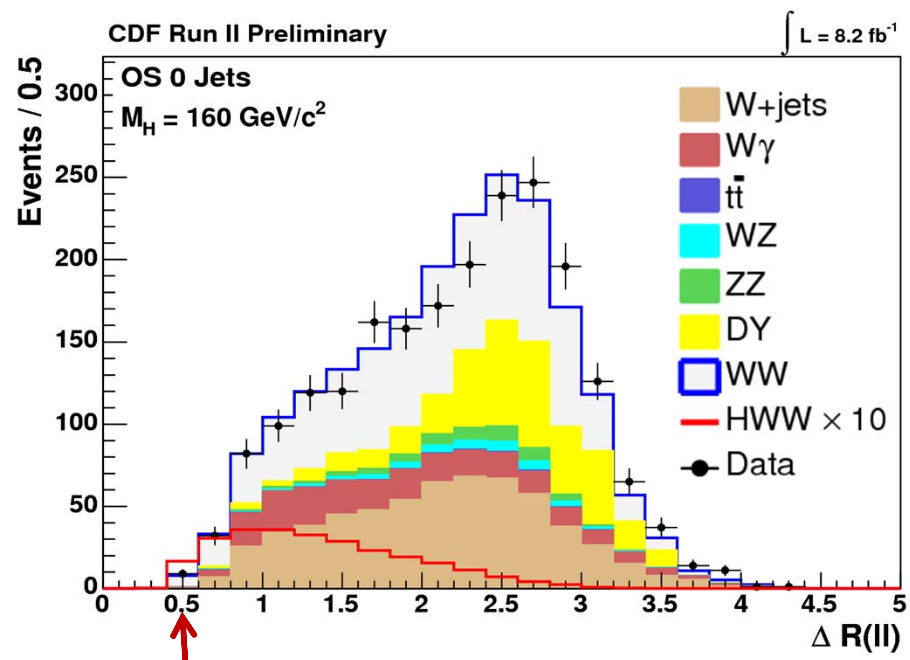
Select:
- 2 high E_T leptons and missing E_T

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

$H \to WW \to l\nu l\nu$

Improvements:

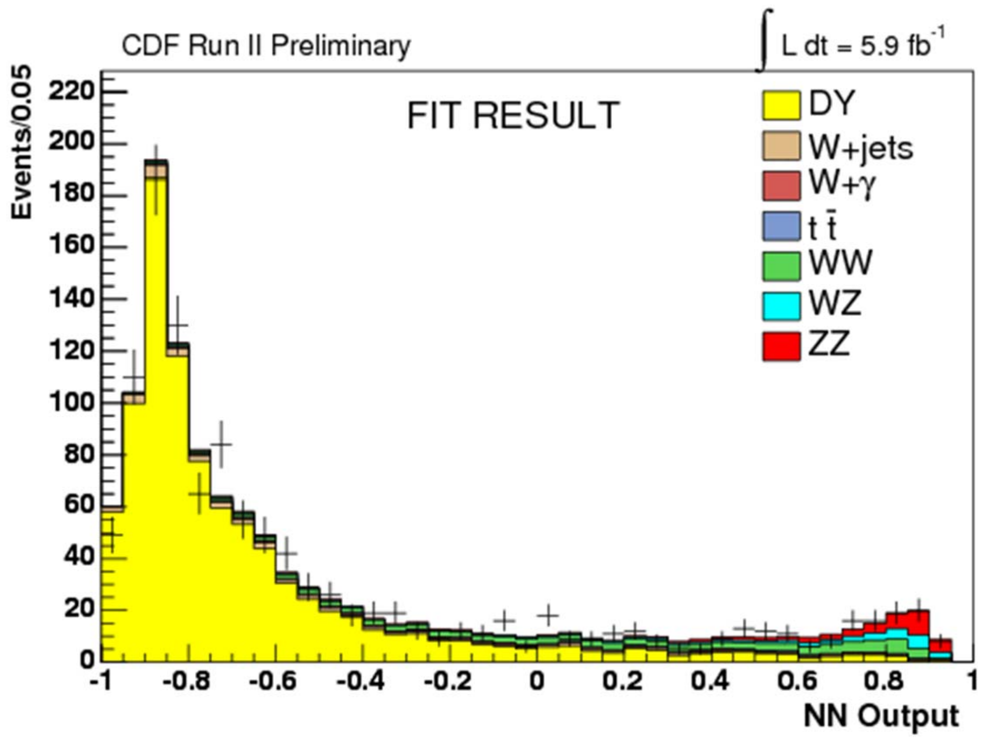
- $8.2 \to 9.7\ fb^{-1}$
- M_H dependent optimization of neural network inputs
- Increased acceptance for low invariant mass dilepton pairs ($0.1 < \Delta R_{ll} < 0.2$)



$H \to WW$ 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

Validate high mass technique with σ(ZZ)

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



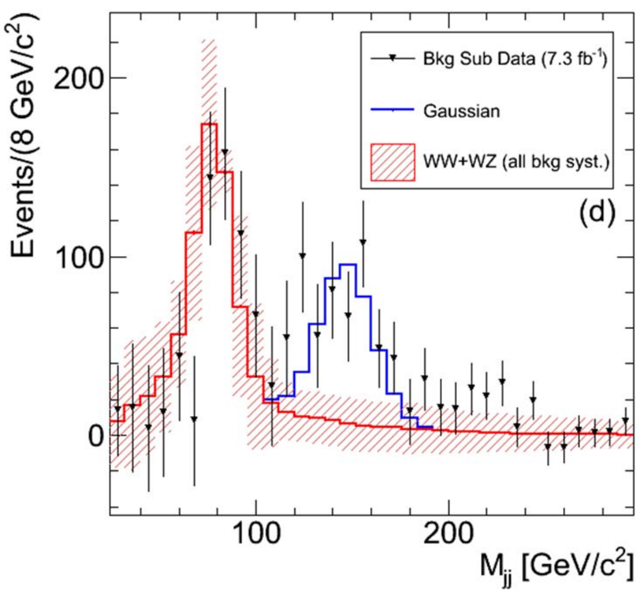
$\sigma(ZZ) = 1.45^{+0.60}_{-0.51}$ pb

SM pred: 1.2 ± 0.1 pb

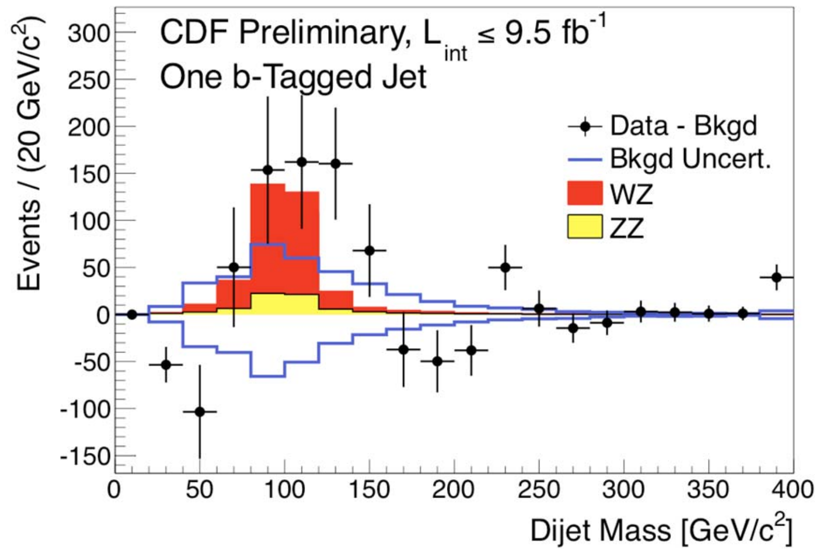
m_H=125 GeV	Sqrt(s) /Lumi	2 TeV / 10 fb^{-1}	7 TeV / 5 fb^{-1}	8 TeV / 5 fb^{-1}
H→gg m_H=125 GeV	Detector	CDF	CMS	CMS
	Signal Events	28	200	255
	Signal Yield	7	75	
	Sensitivity	11xSM	1.4xSM	
H→ZZ→4l m_H=130 GeV	Detector	CDF	ATLAS	ATLAS
	Signal Events	2.1	16	20
	Signal Yield	0.2	2.7	
	Sensitivity	18*SM	1.5*SM	
H→WW m_H=125 GeV	Detector	CDF	ATLAS	ATLAS
	Signal Events	170	1215	1550
	Signal Yield*	7	32	
	Sensitivity	3.1*SM	1.2*SM	
H→bb m_H=125 GeV	Detector	CDF	CMS	CMS
	Signal Events	315	670	820
	Signal Yield*	13.7	5	
	Sensitivity	1.8*SM	4.3*SM	

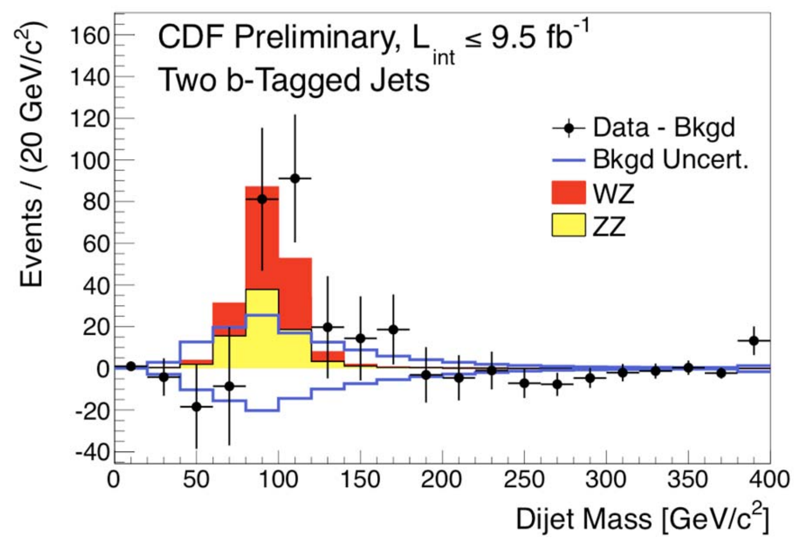
*Yield in high S/B bins only

CDF Wjj



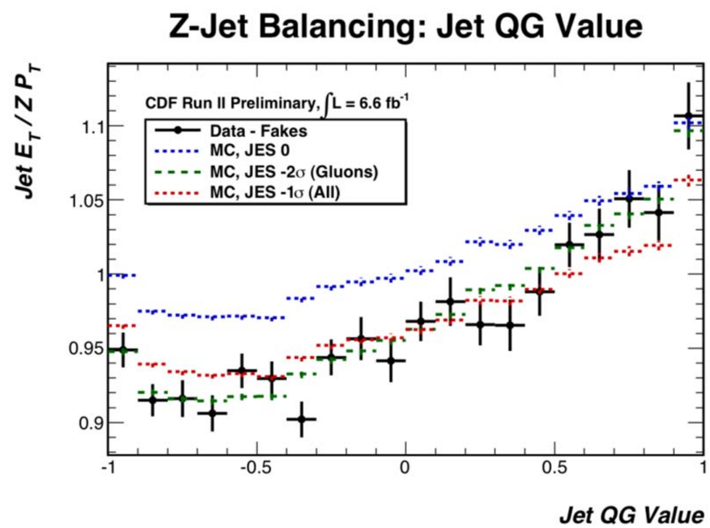
- Tagged samples used for Higgs searches do not contain any sign of abnormalities that were seen previously in pre-tagged region

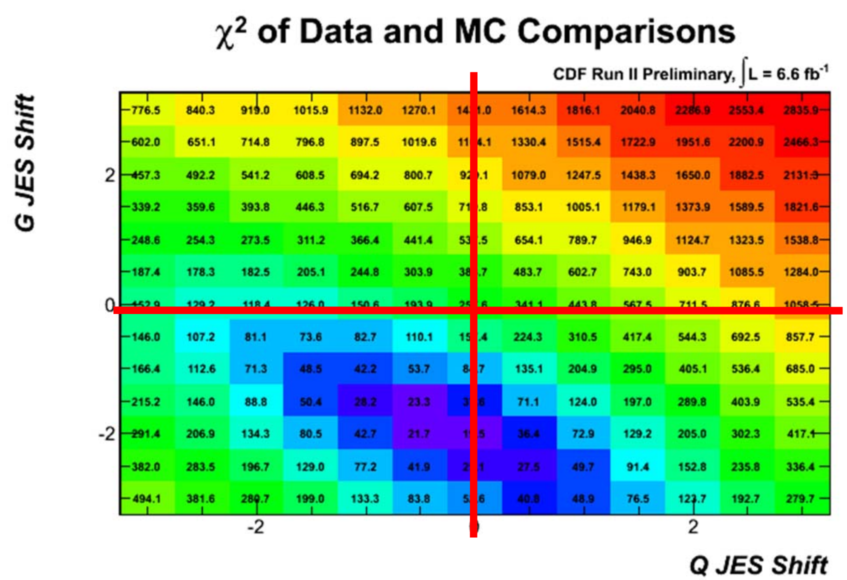




CDF Wjj

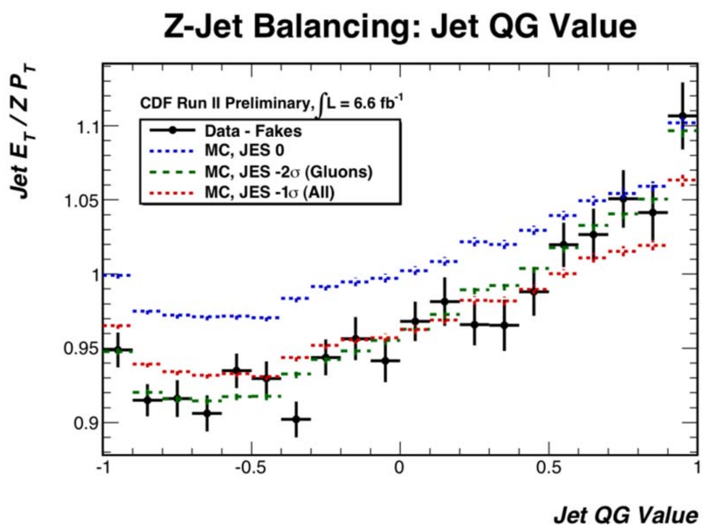
- Lots of studies to try to understand what's going on in the pre-tag region
- Detailed studies in Z + 1 jet events to understand potential differences in quark and gluon jet energy scales

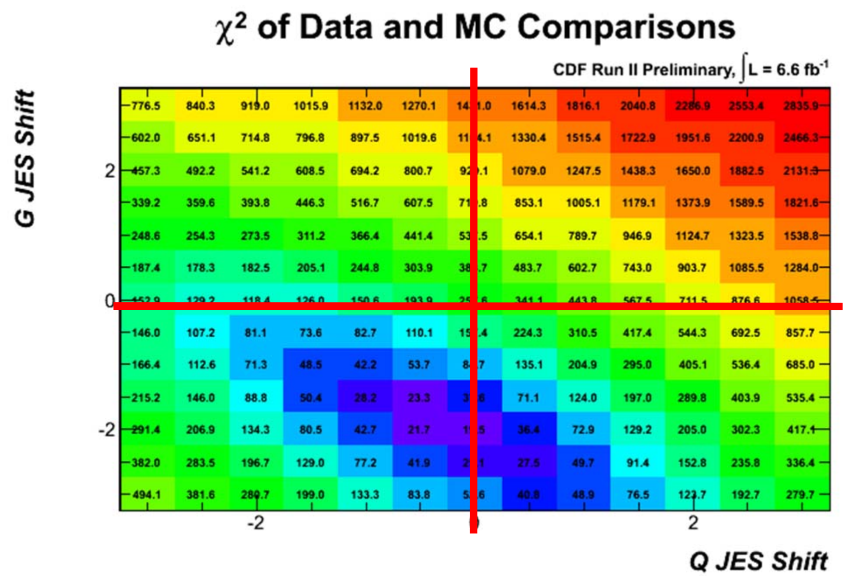




CDF Wjj

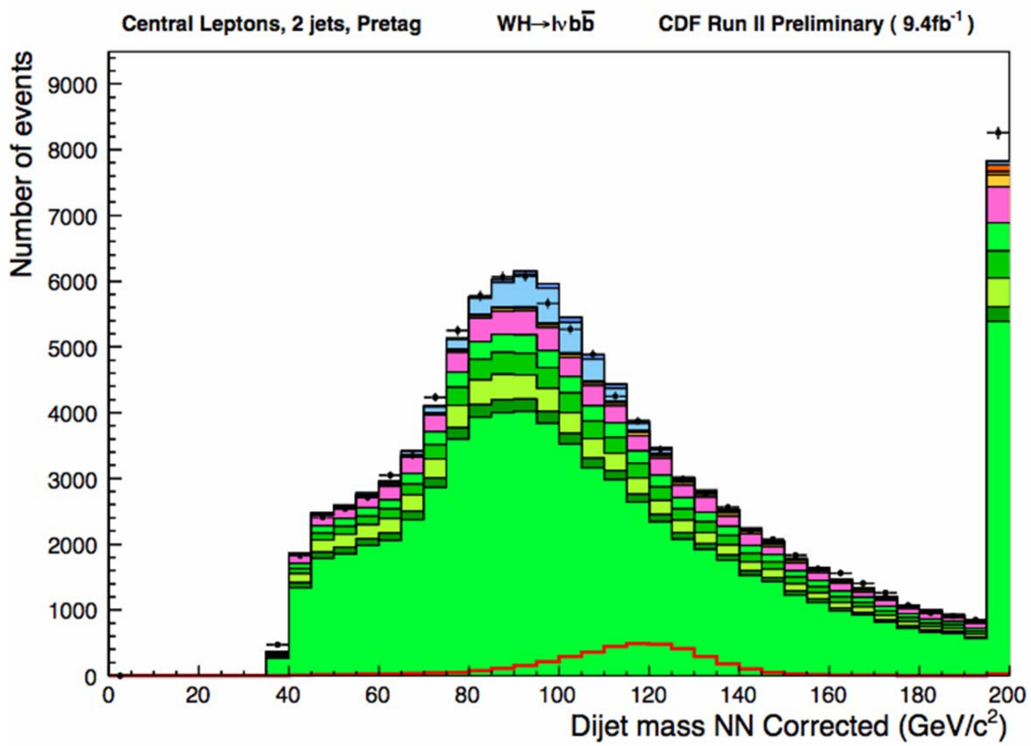
- Bottom line of these studies is that the JES for gluon jets needs to be shifted by 2σ in MC to match with data
- The JES for quark jets is good – not surprising since well constrained by top mass measurements





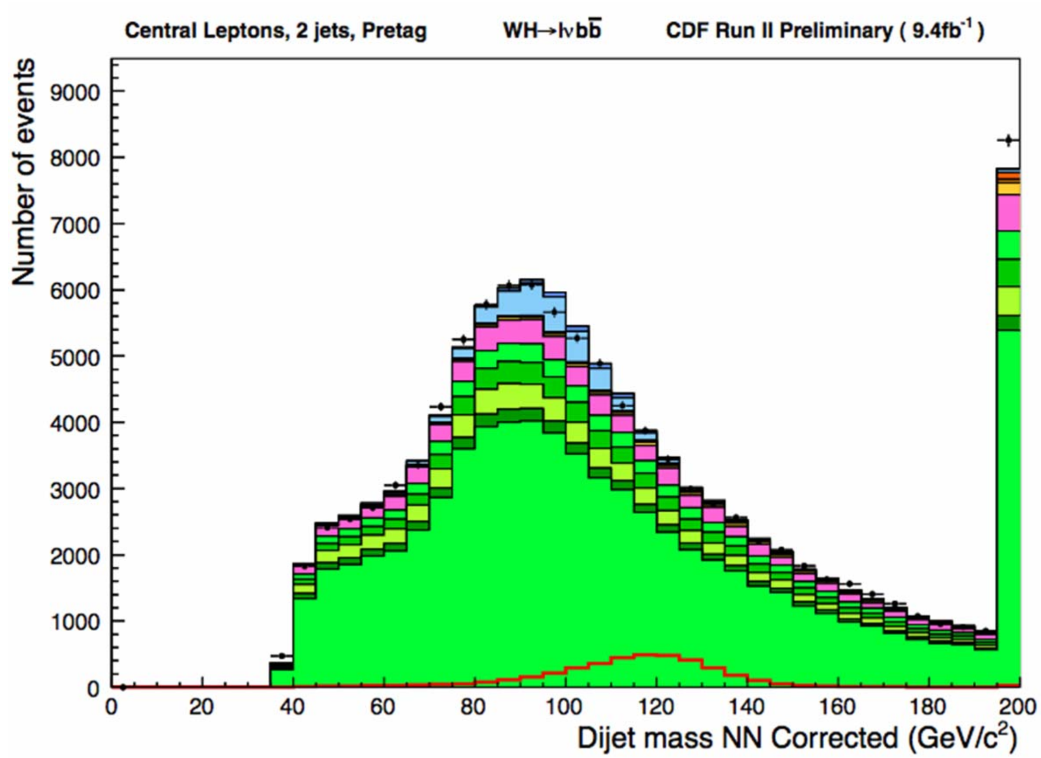
CDF Wjj

- In CDF Higgs searches we apply -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



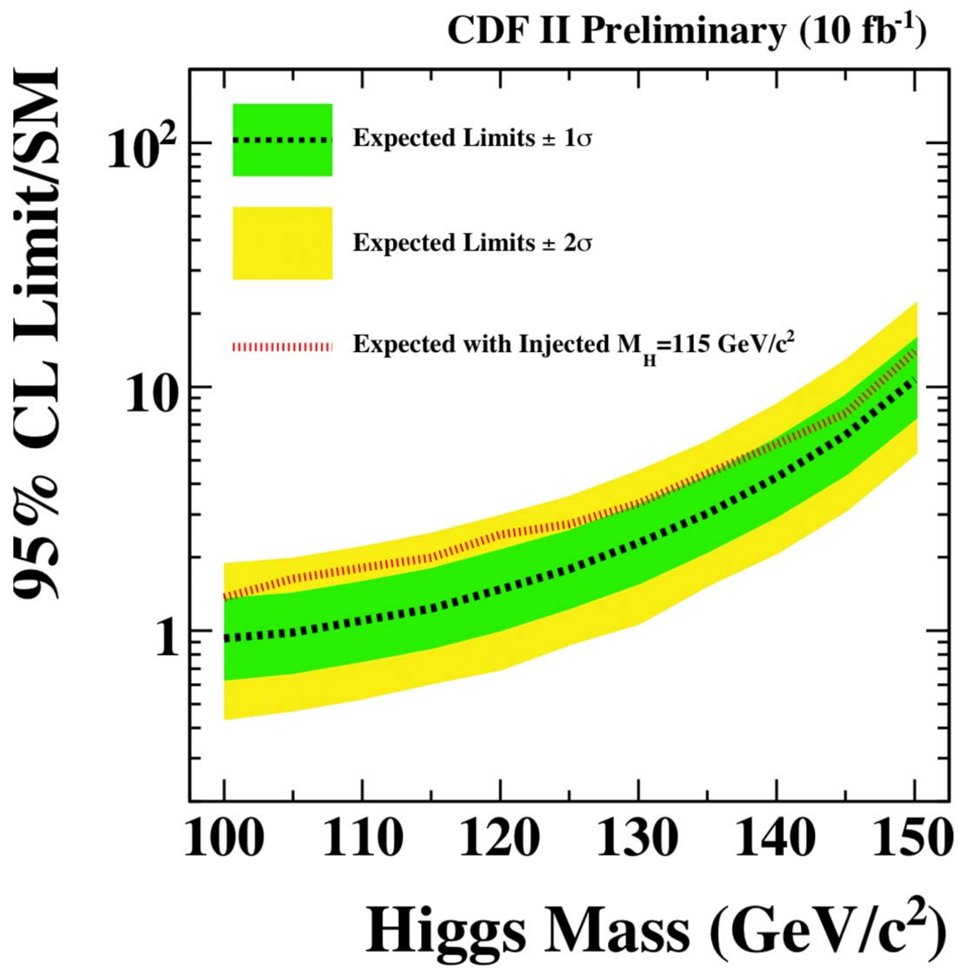
CDF Wjj

- 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



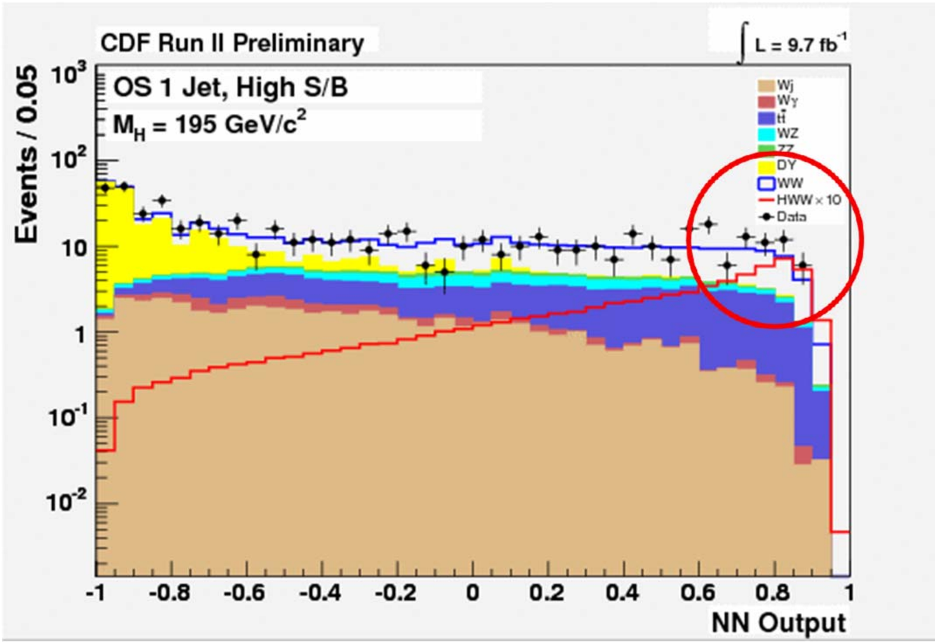
Signal Injection study

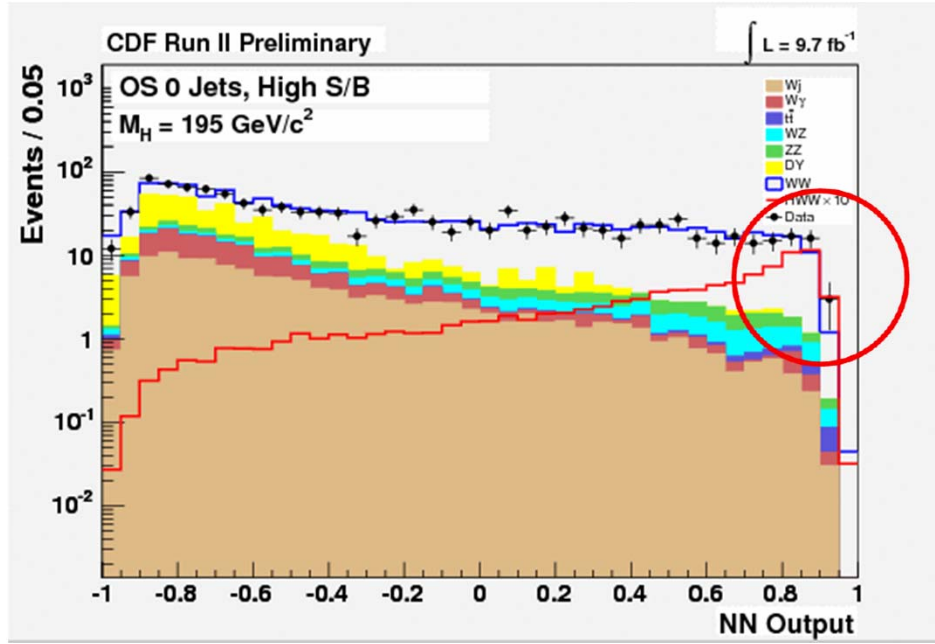
The figure on right shows the results of a previous study where we injected a m_H = 115 GeV/c^2 Higgs signal into background-only pseudo-experiments to study the potential effect on our observed limits



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

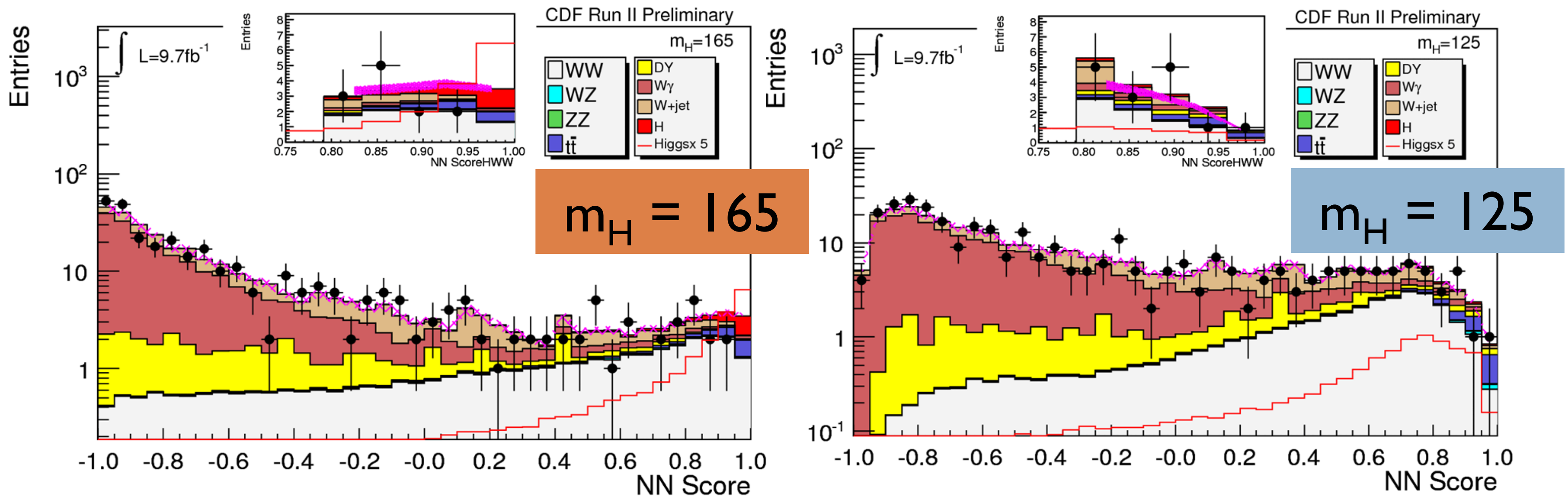
Excess at m_H = 195 GeV/c^2





- 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

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 →bb jets
  - ~20% more acceptance
- Additional triggers and leptons

More events

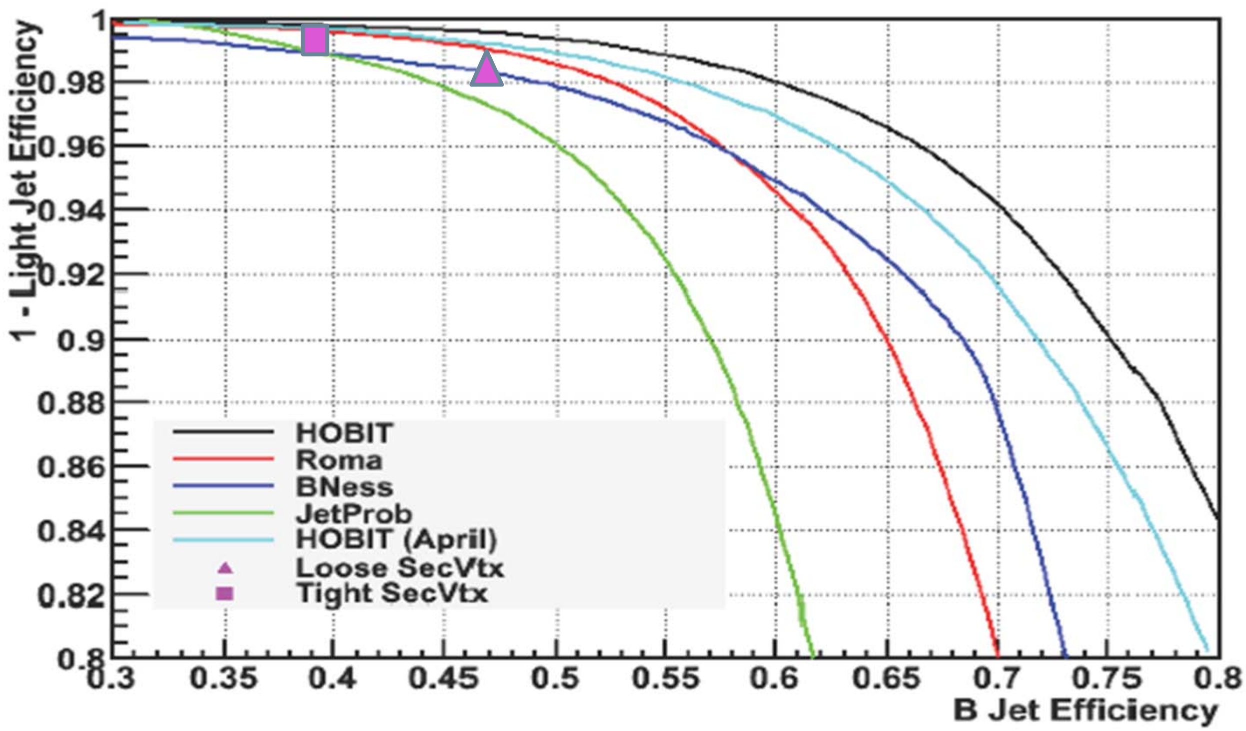
- Improved dijet invariant mass resolution
- Improved MVA
- Improved modeling

Signal vs. background separation

HOBIT performance

Higgs Optimized b Identification Tagger (2011)

- 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



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