Les Rencontres de Physique de la Vallée d'Aoste

Standard Model Higgs Searches at the Tevatron

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On behalf of the CDF and DØ Collaborations

March 1, 2013

Current Status of the Higgs

- Higgs-like particle already found by CMS and ATLAS at 125 GeV.
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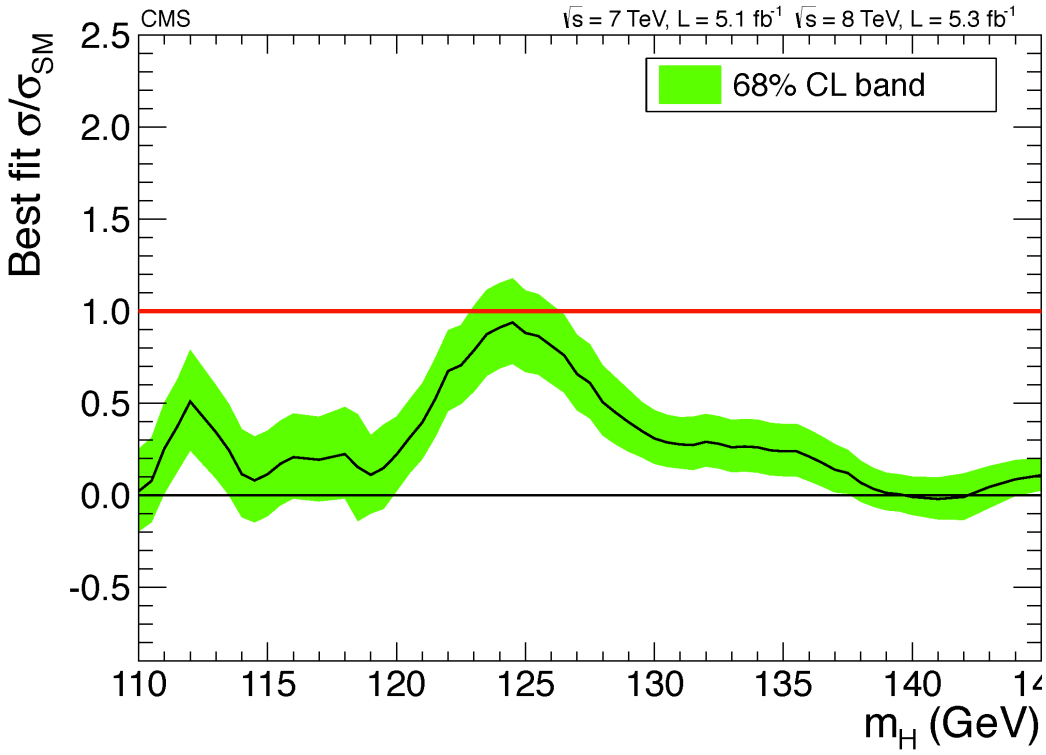

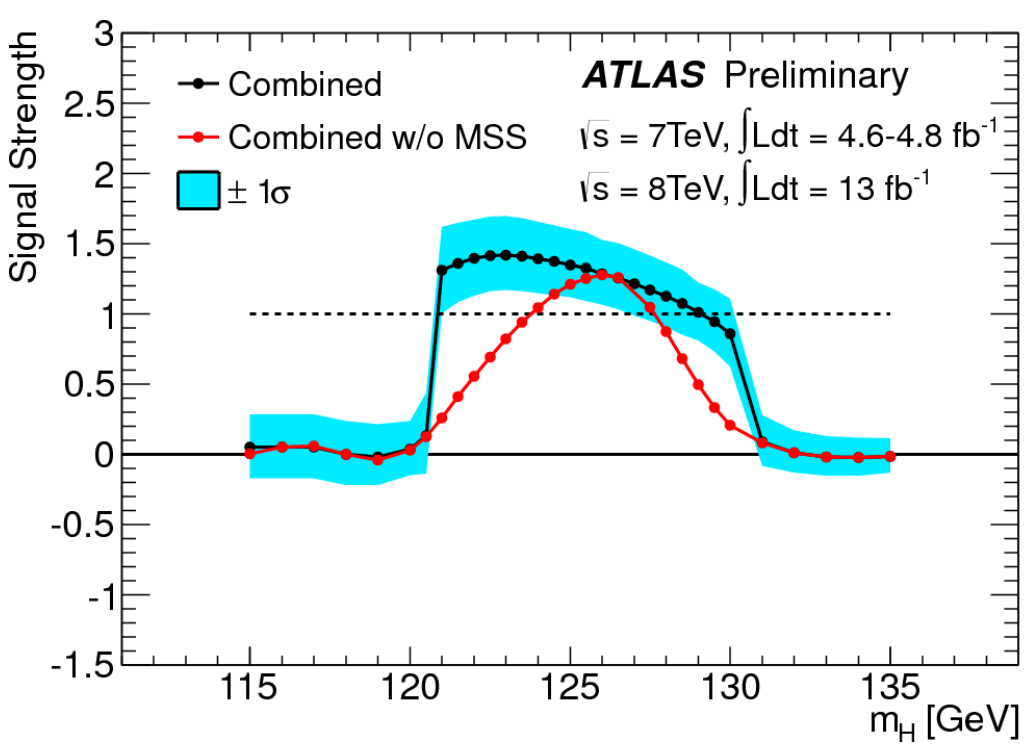

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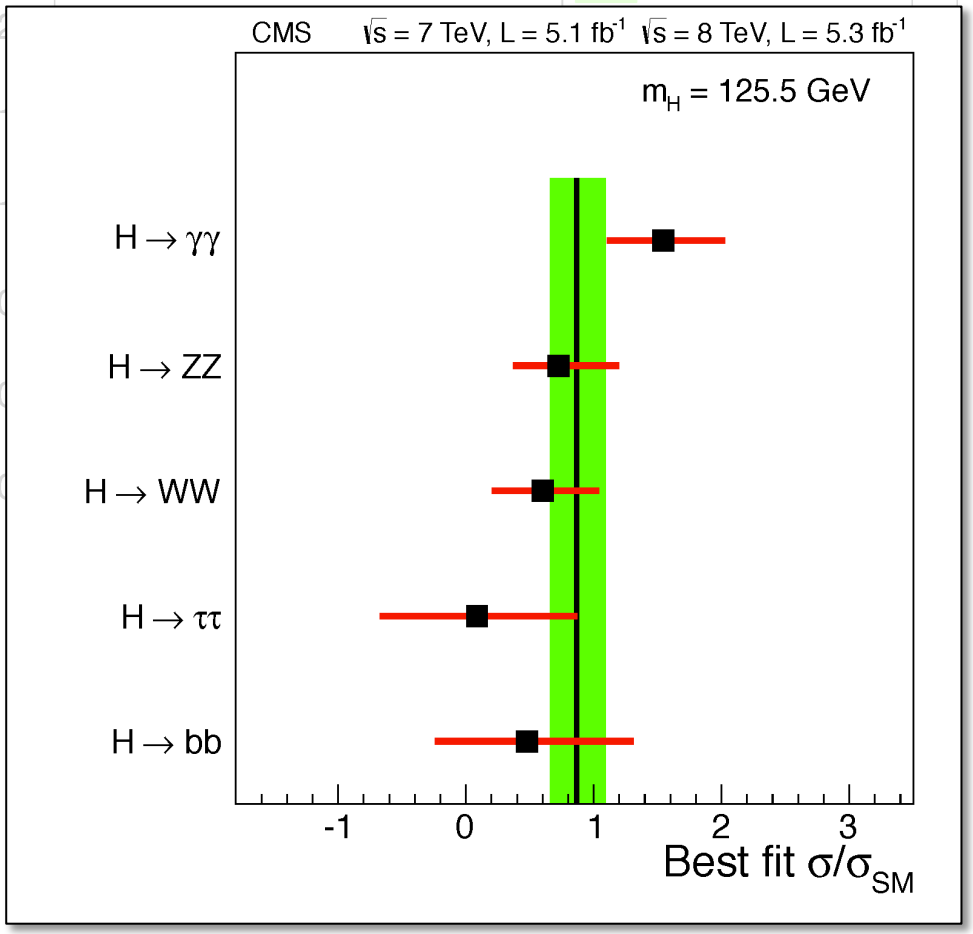

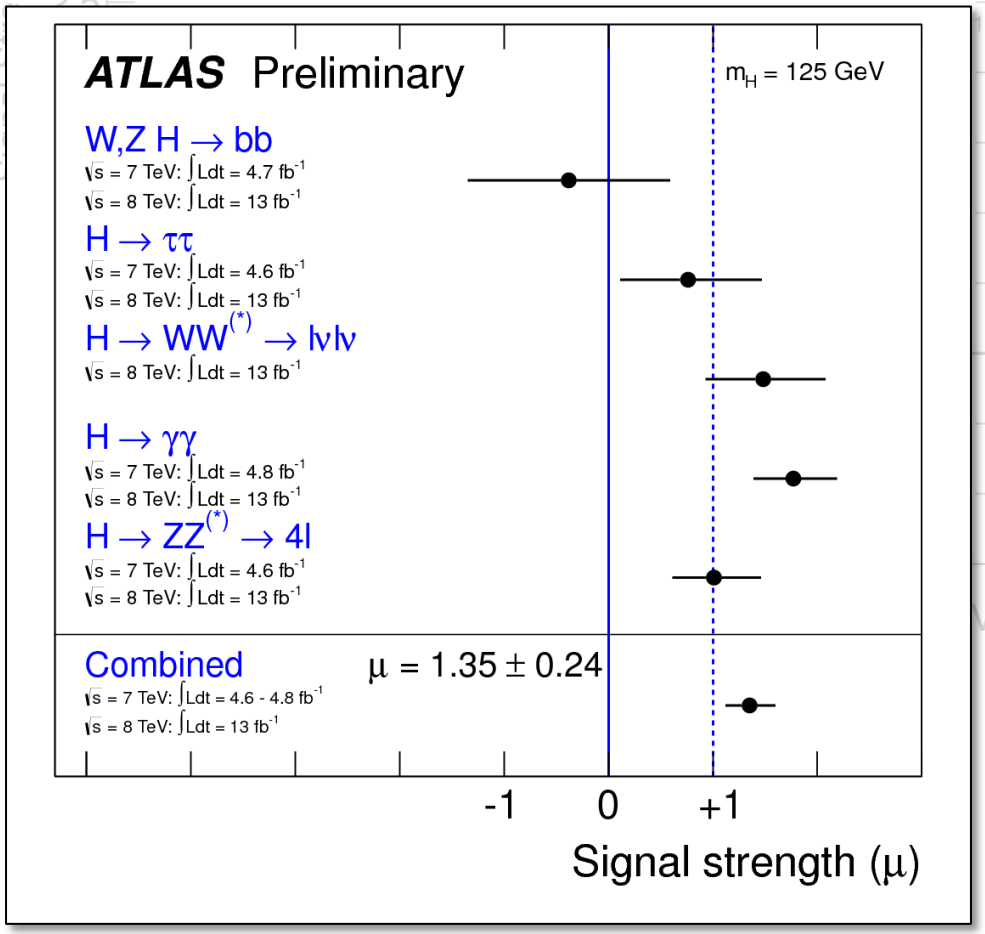

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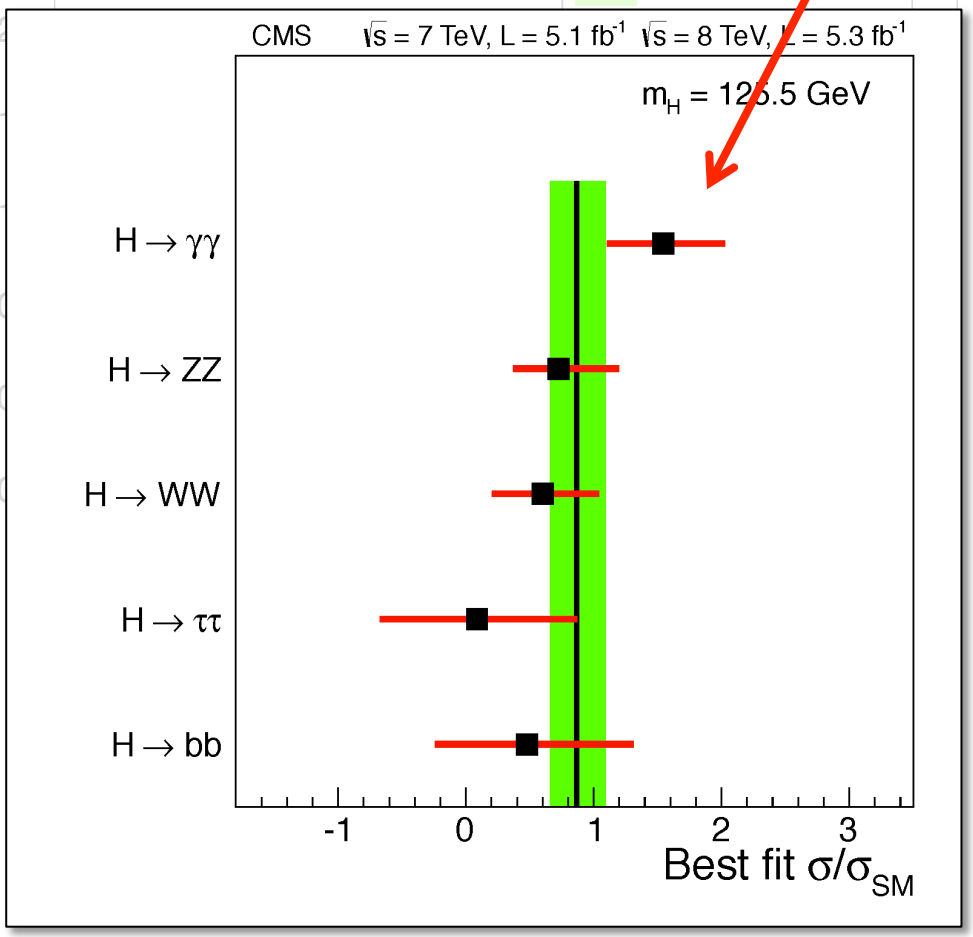
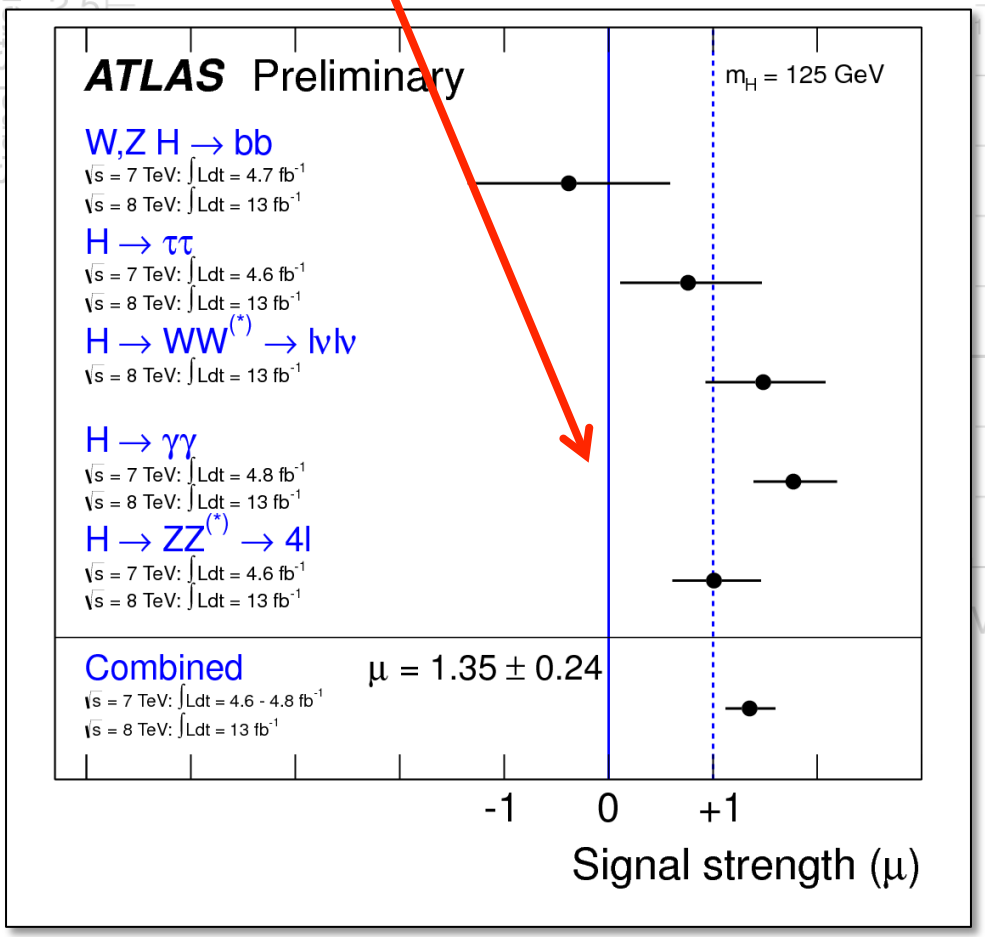
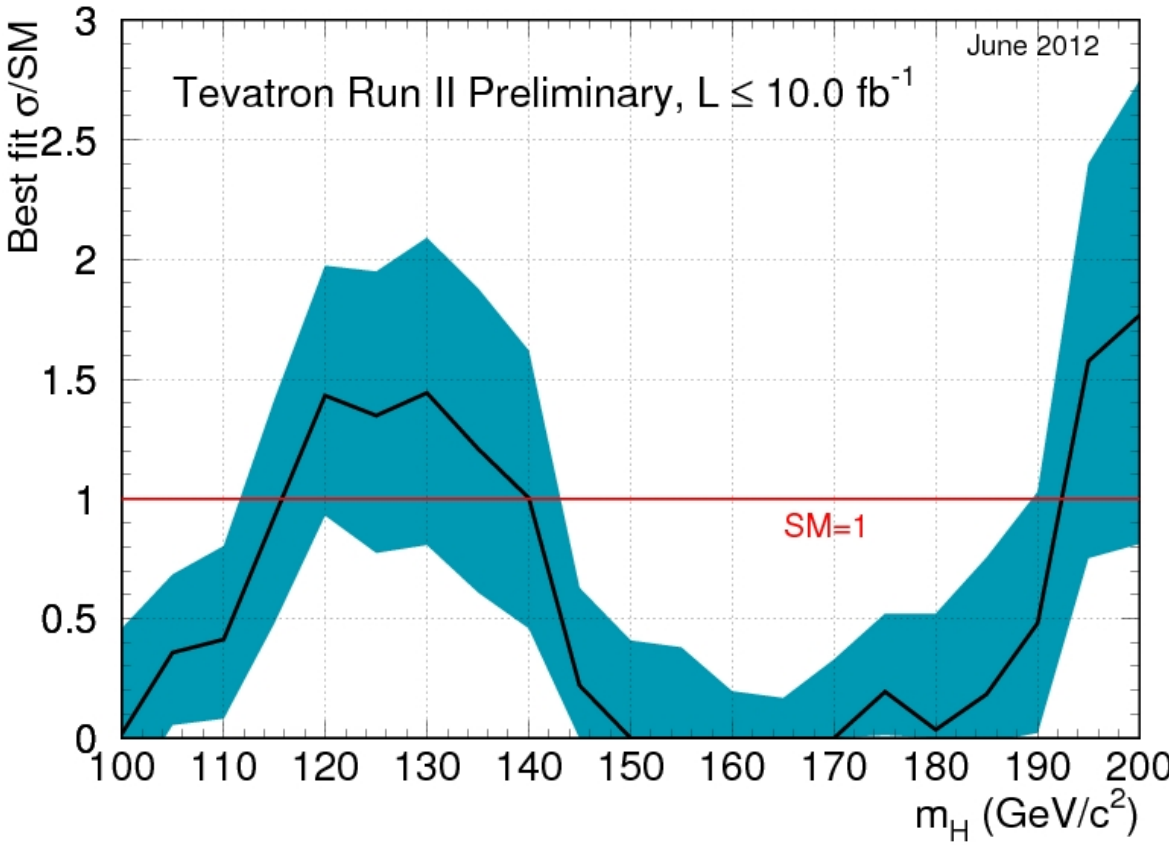
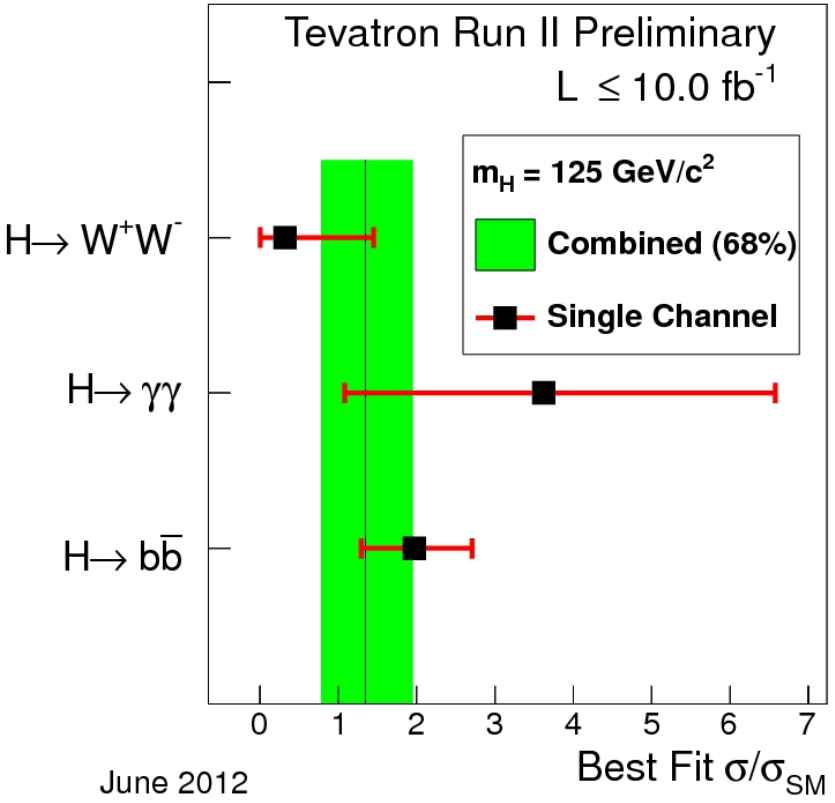
Sensitivity driven mainly by $H \rightarrow \gamma\gamma / VV$ final states





Sensitivity at the Tevatron





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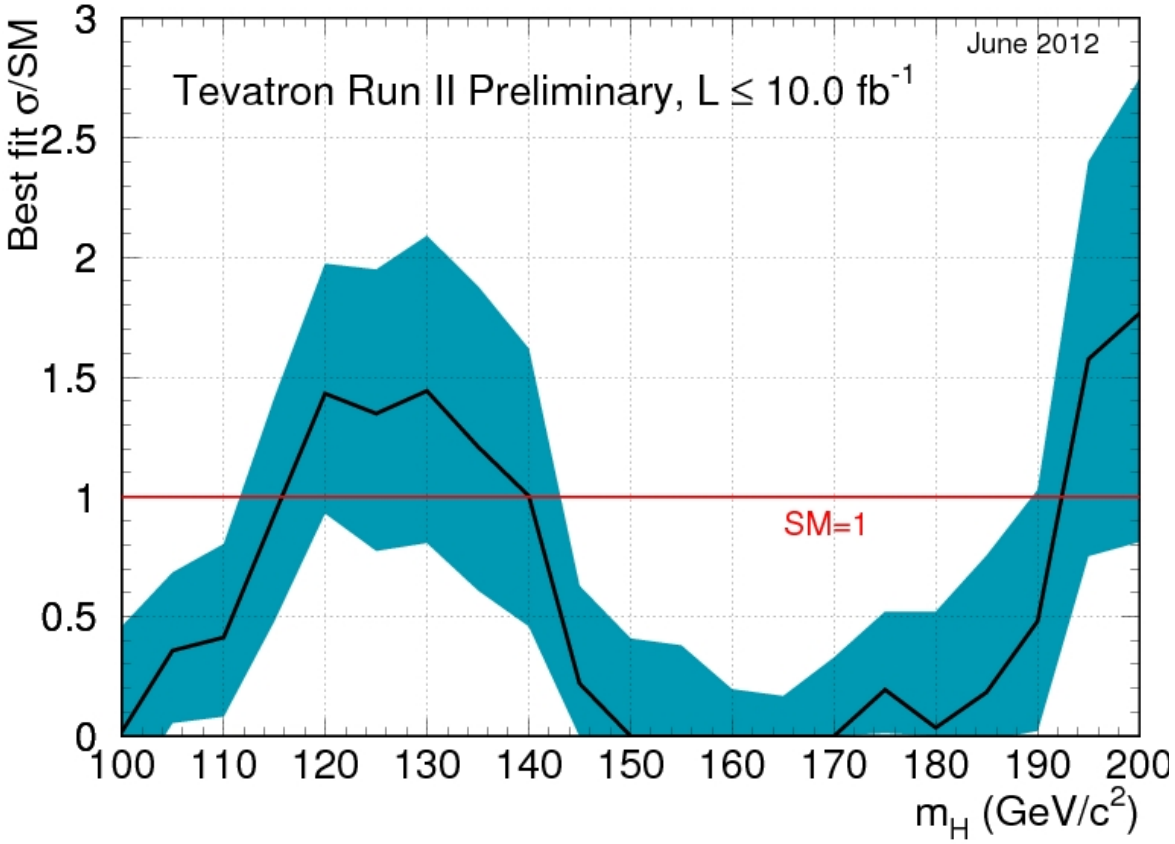
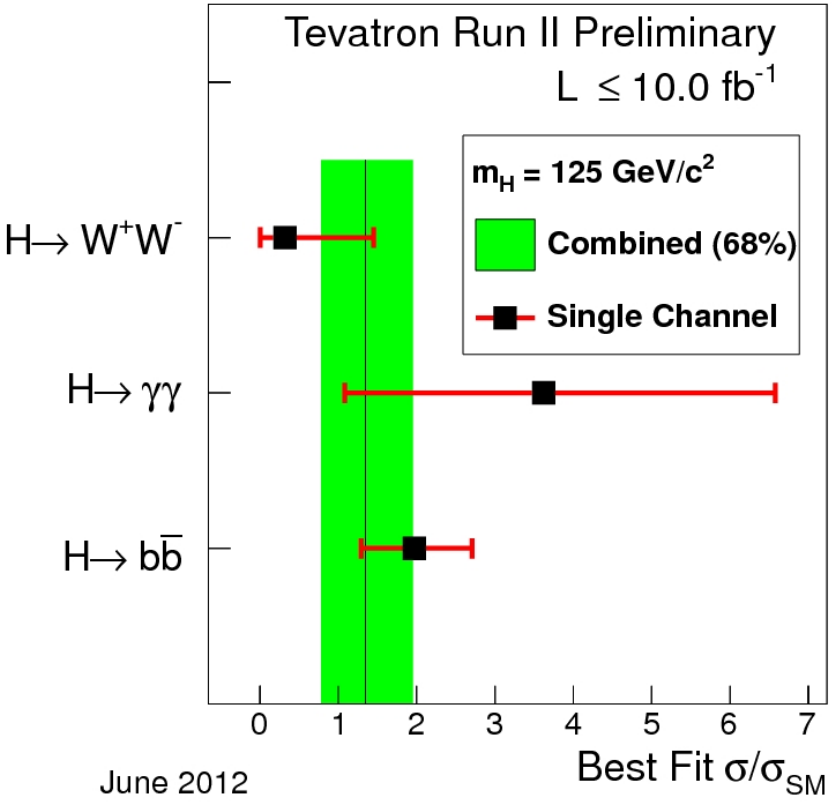
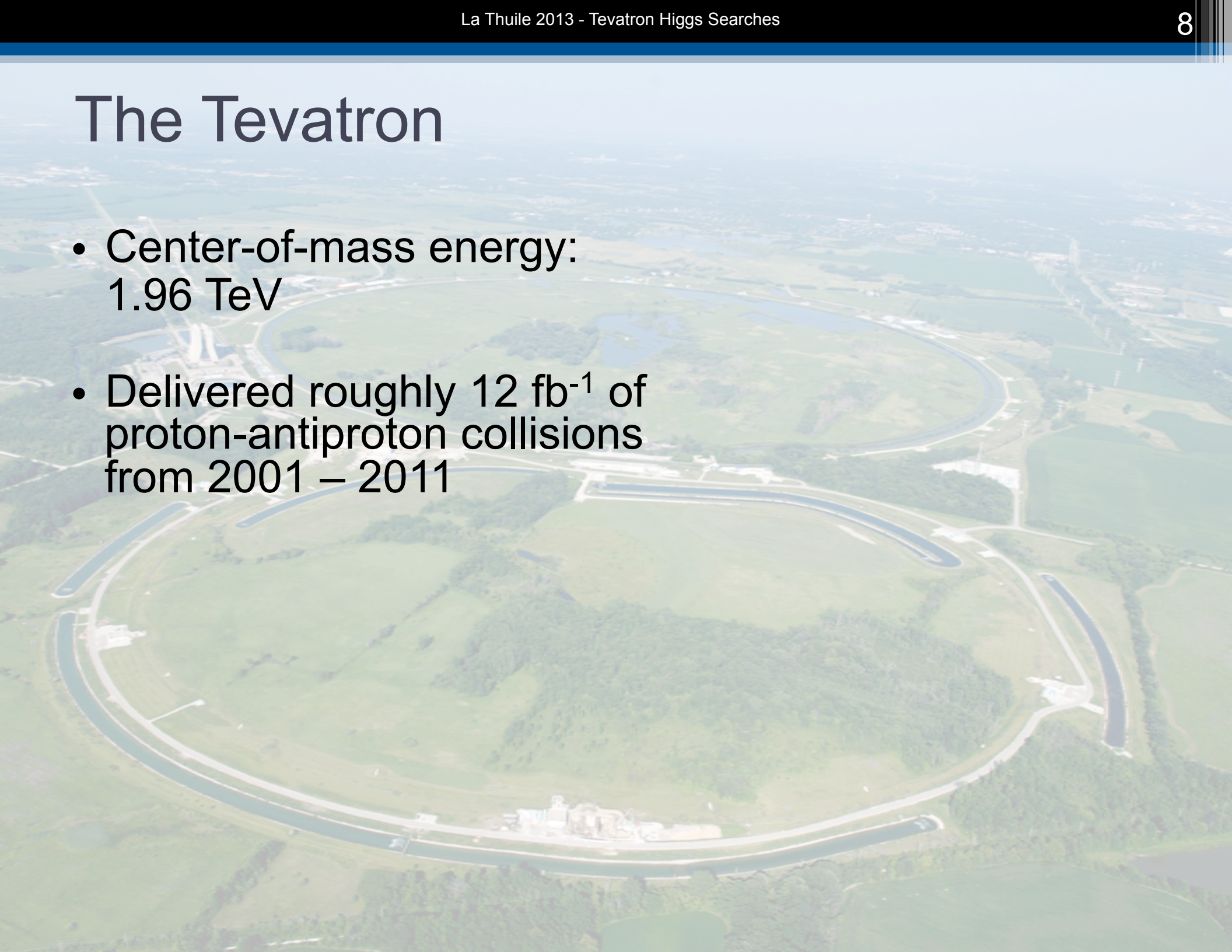




- Primary sensitivities at the LHC and Tevatron *have been* complementary.
- $H \rightarrow bb$ evidence claimed in summer of 2012
  Phys. Rev. Lett. 109, 071804 (2012)

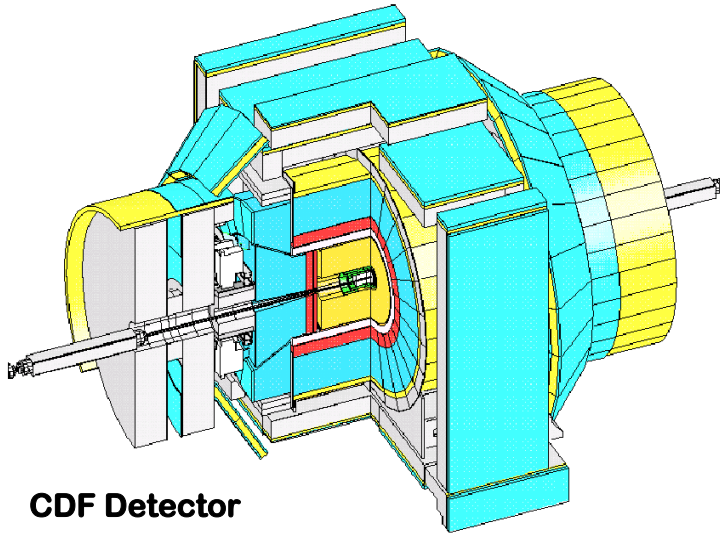
The Tevatron

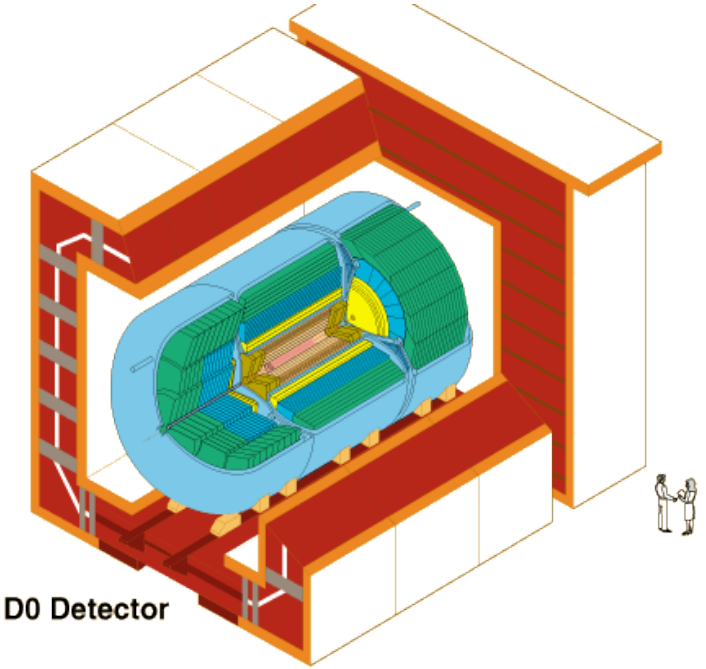
- Center-of-mass energy: 1.96 TeV
- Delivered roughly 12 fb^{-1} of proton-antiproton collisions from 2001 – 2011



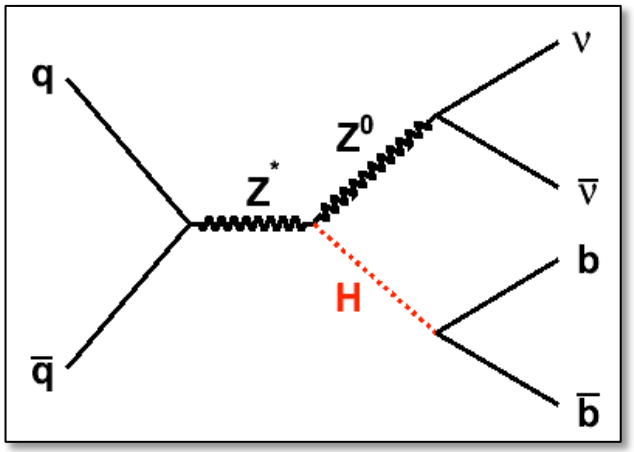
The Tevatron & Experiments

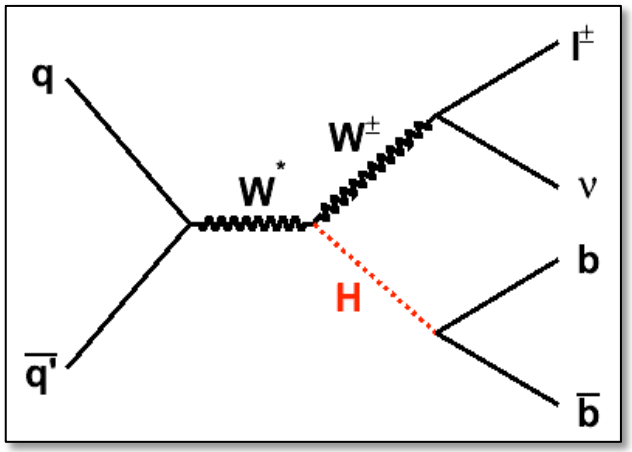
- Center-of-mass energy: 1.96 TeV
- Delivered roughly 12 fb^{-1} of proton-antiproton collisions from 2001 – 2011
- CDF & D0 each recorded over 10 fb^{-1}
- Data samples used in Higgs analyses:
  - D0: Up to ~ 10 fb^{-1}
  - CDF: Up to ~ 10 fb^{-1}

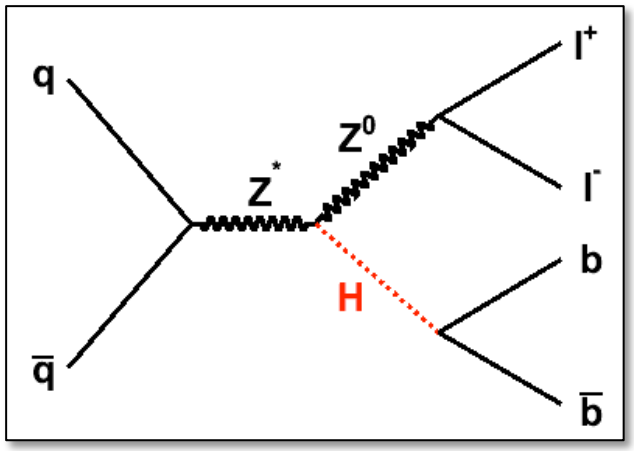

CDF Detector


D0 Detector

H→bb searches





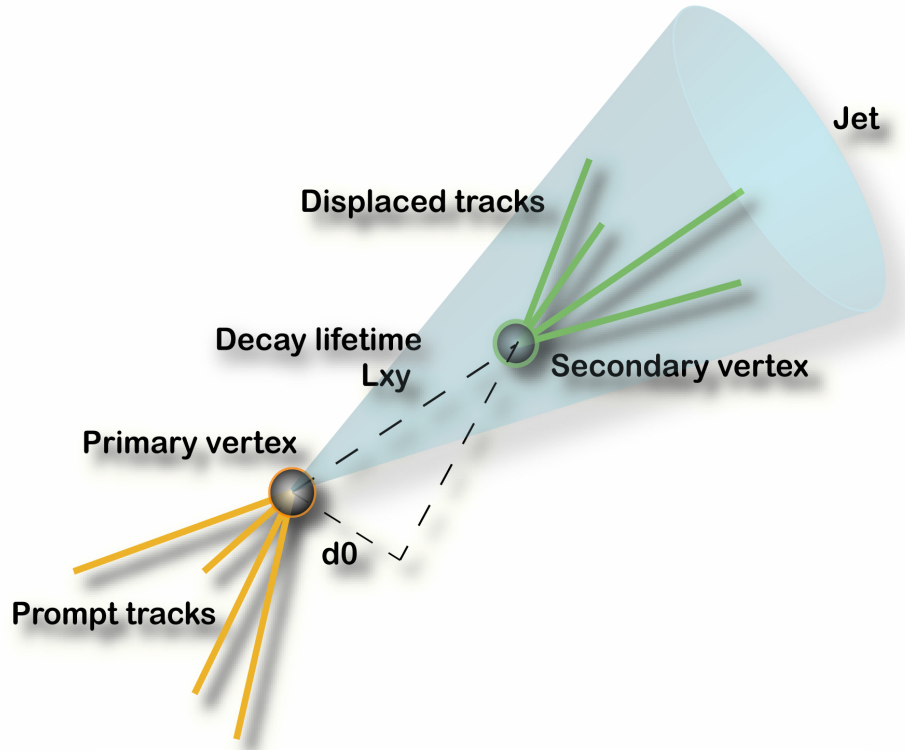


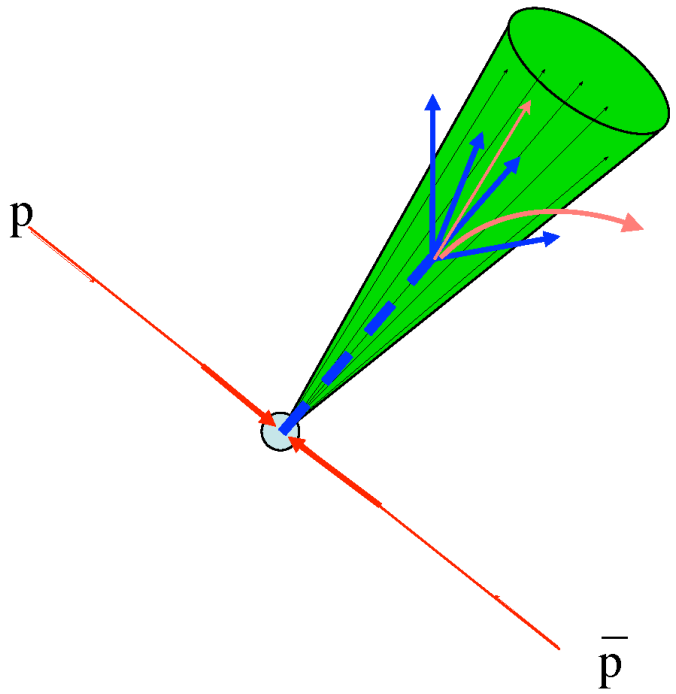
Analysis	No. of Leptons	Missing E_T ?	No. of b-Jets
$ZH \to \nu\bar{\nu} + b\bar{b}$	0	Yes	2
$WH \to \ell\nu + b\bar{b}$	1	Yes	2
$ZH \to \ell^+\ell^- + b\bar{b}$	2	No	2

- To get the most sensitivity:
  - Maximize lepton reconstruction and selection efficiencies
  - Optimize *b*-jet tagging
  - Improve invariant dijet mass resolution

b-tagging improved

- Both collaborations now use MVAs to identify *b(c)*-jets.
  - Neural networks
  - Decision trees
- Use variables which depend on longer lifetimes and heavier masses of *b(c)*-quarks.
  - Displaced vertex (L_{xy}, d_0)
  - Jet mass
  - Distribution of tracks within the jet cone
  - etc.





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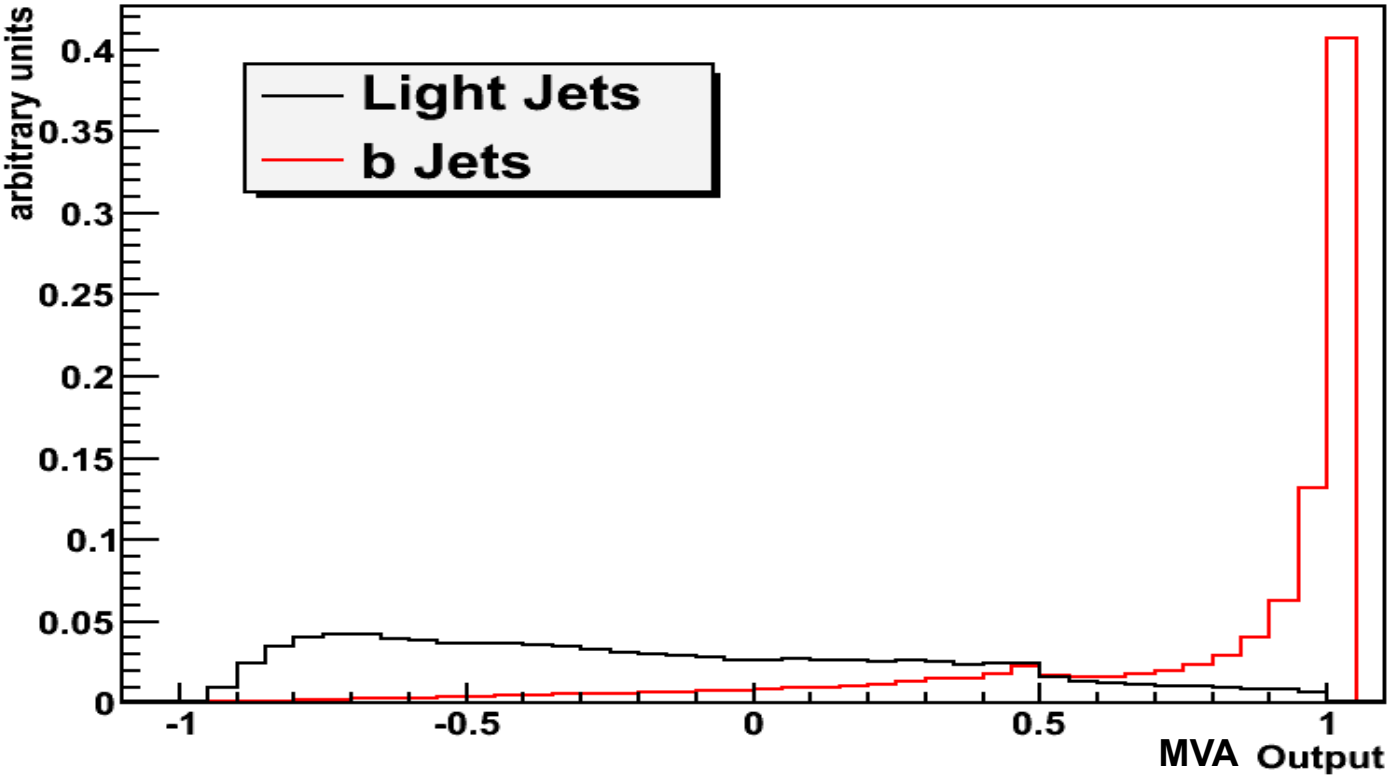

- CDF – HOBIT NN

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

- D0 – L_b BDT

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

Analysis methods improved

- No longer use a single discriminating variable…
  - No longer use one multivariate algorithm…
    - Now use multiple MVAs per analysis, often in series…

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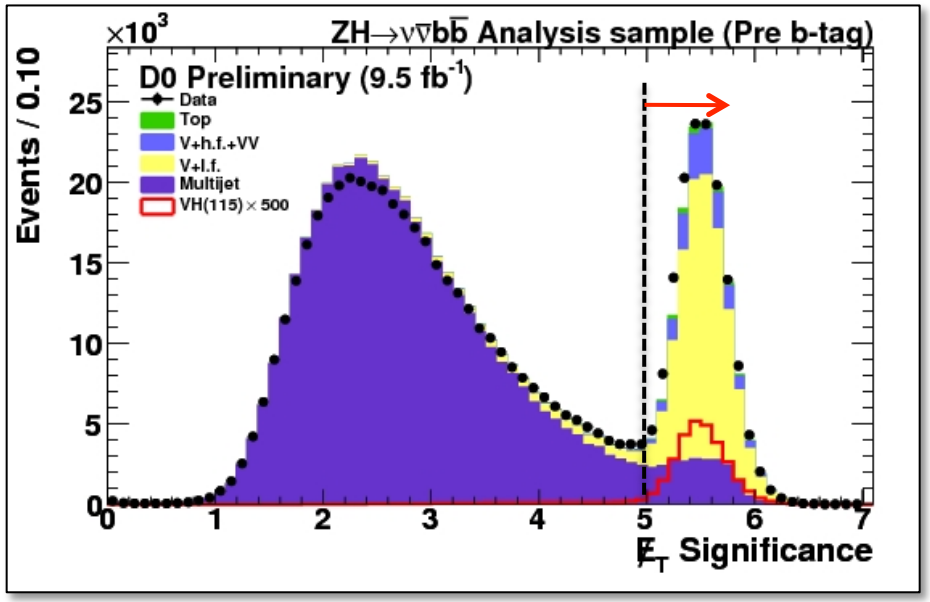

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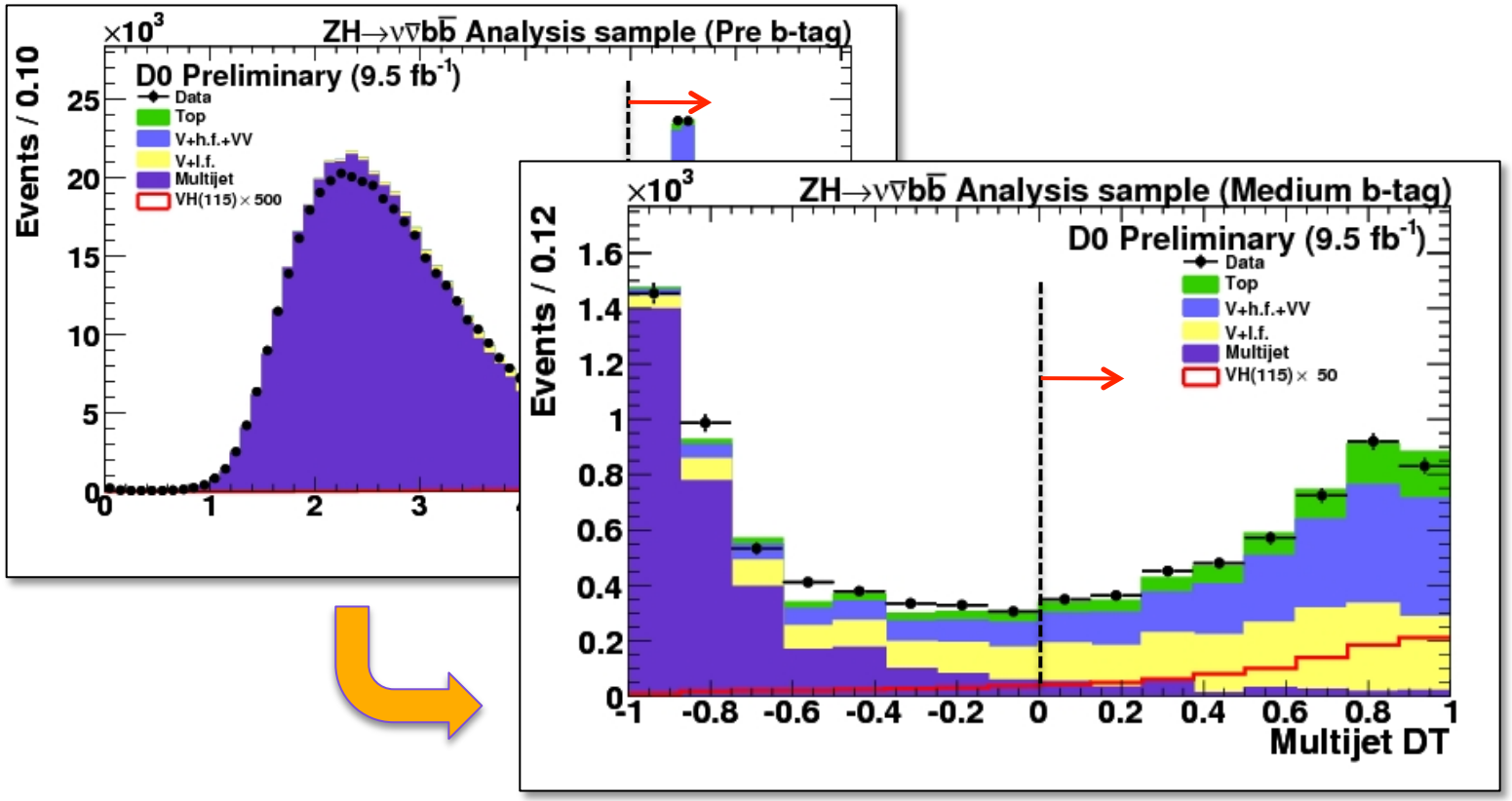

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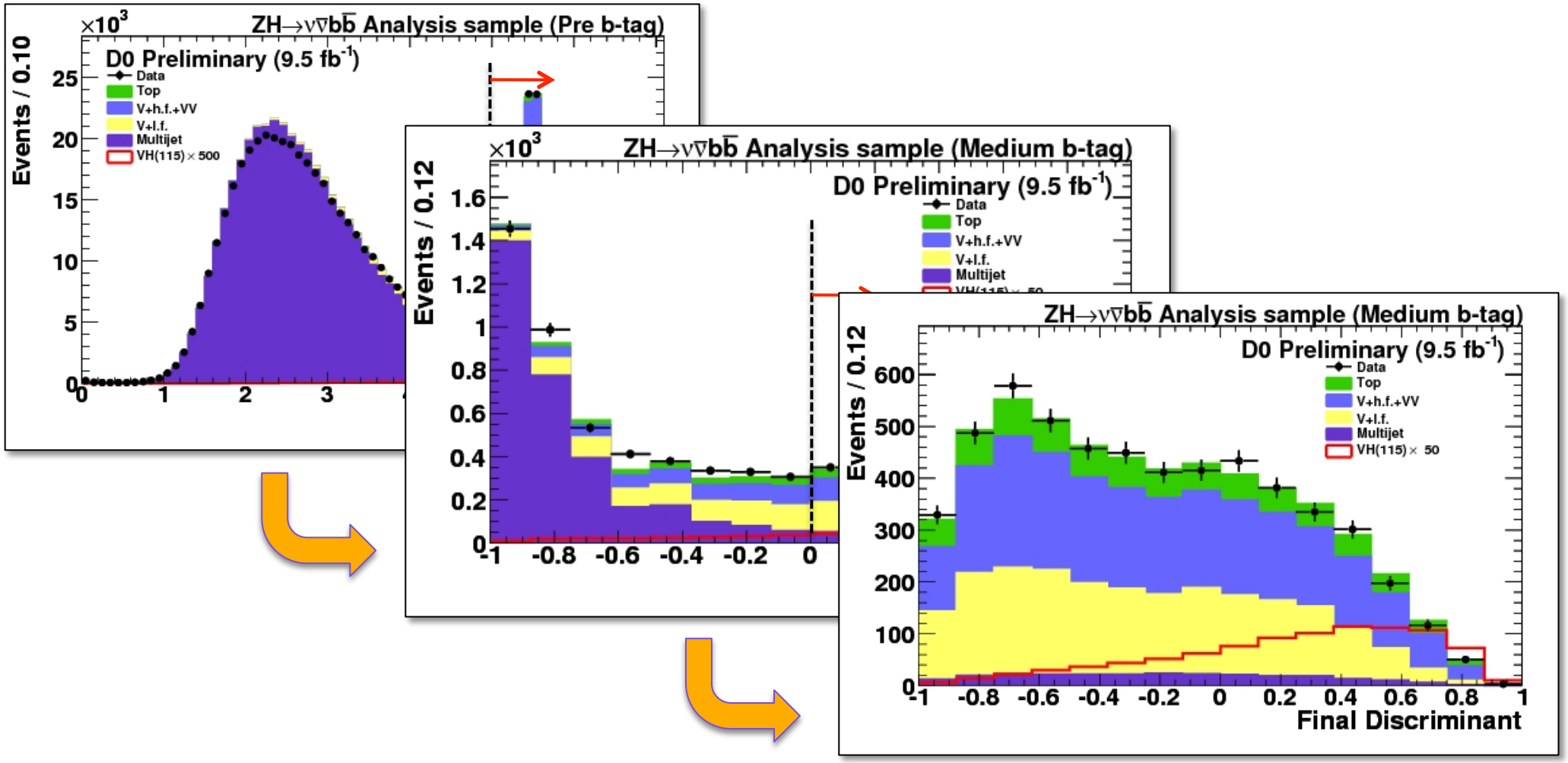

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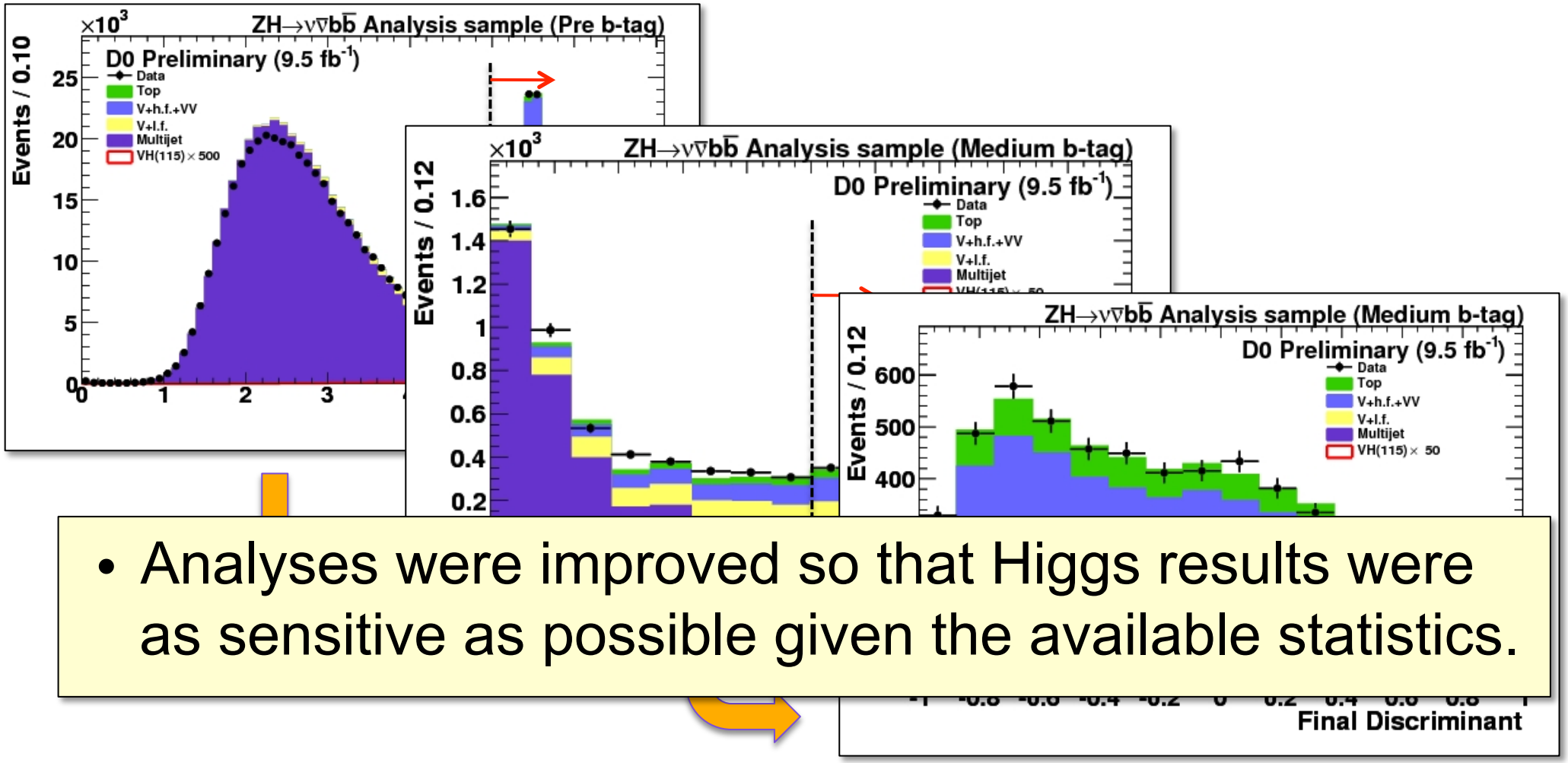


- Analyses were improved so that Higgs results were as sensitive as possible given the available statistics.

Status of the Tevatron Analyses

- Recent focus has been finalizing publications:

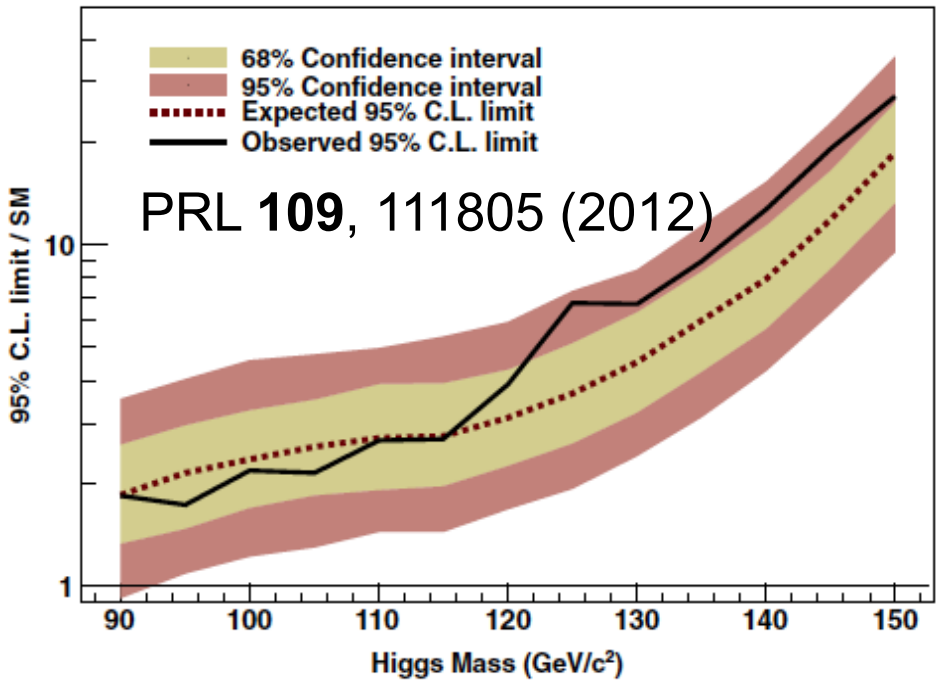
- D0:
  - $WH \rightarrow l\nu + bb$: *Submitted to* Phys. Rev. D (01/13)
  - $H \rightarrow W^+W^-$: *Accepted by* Phys. Rev. D (01/13)
  - $H \rightarrow \gamma\gamma$: *Submitted to* Phys. Rev. D (01/13)
  - $H \rightarrow W^+W^-/\tau^+\tau^-$: *Accepted by* Phys. Rev. D (01/13)
  - Trilepton/SS Lep: Submitted to Phys. Rev. D (02/13)

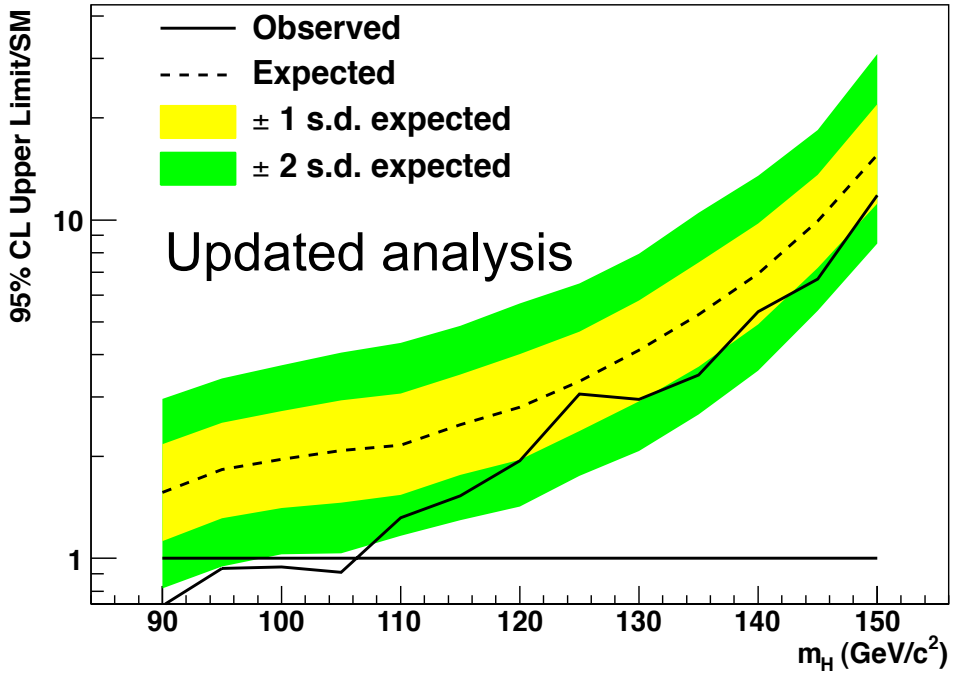
- CDF:
  - $ZH \rightarrow \nu\nu + bb$: *Accepted by* Phys. Rev. D (02/13)
  - $VH \rightarrow qq' + bb$: J. High Energy Phys. 02 (2013) 004

- Most significant effort
  - Suite of cross checks performed on CDF MET+bb analysis (discussed today)

Updated MET+bb Search

- Look for Higgs boson in final state with missing transverse energy and two jets
- Sensitive to following processes:
  - $ZH \rightarrow \nu\nu + bb$
  - $WH \rightarrow l\nu + bb$ (lepton lost in reconstruction)
- Analyze full CDF data set as in summer analysis
  - but *b*-tagging algorithm improved

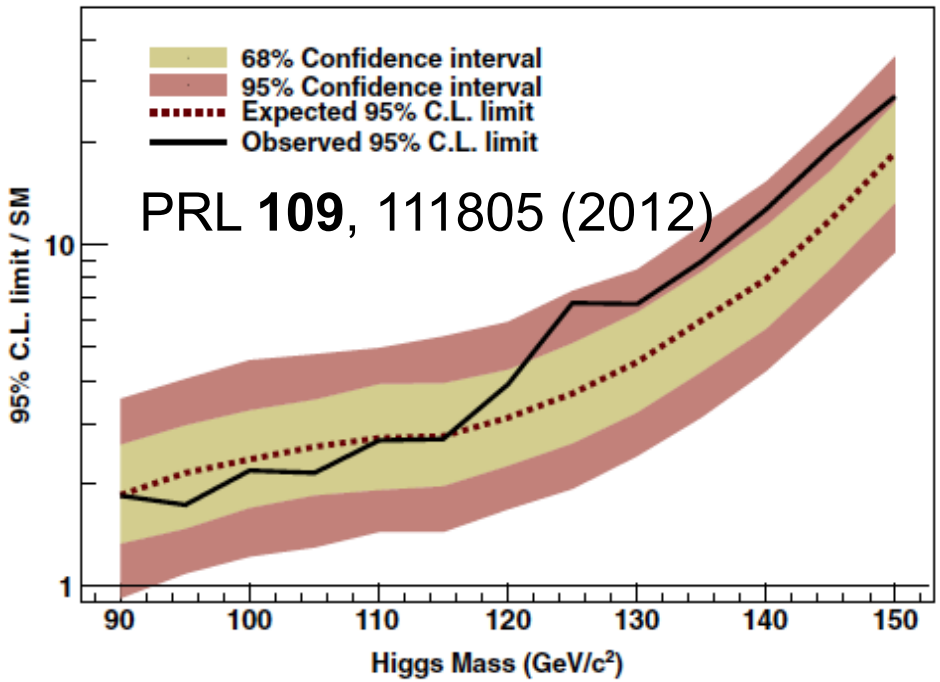


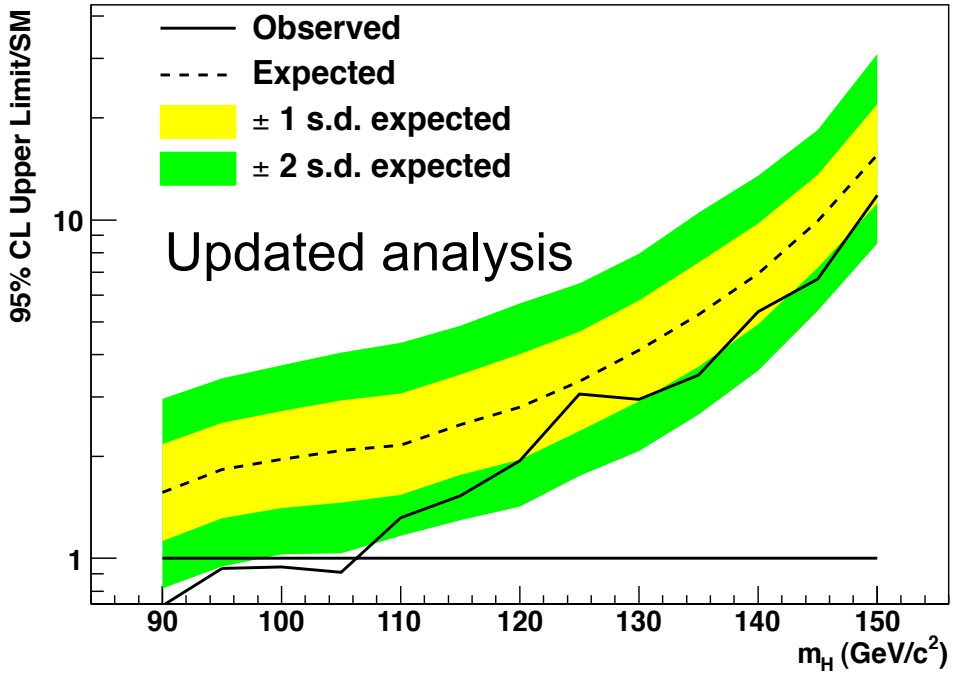


Updated MET+bb Search

- Look for Higgs boson in final state with missing

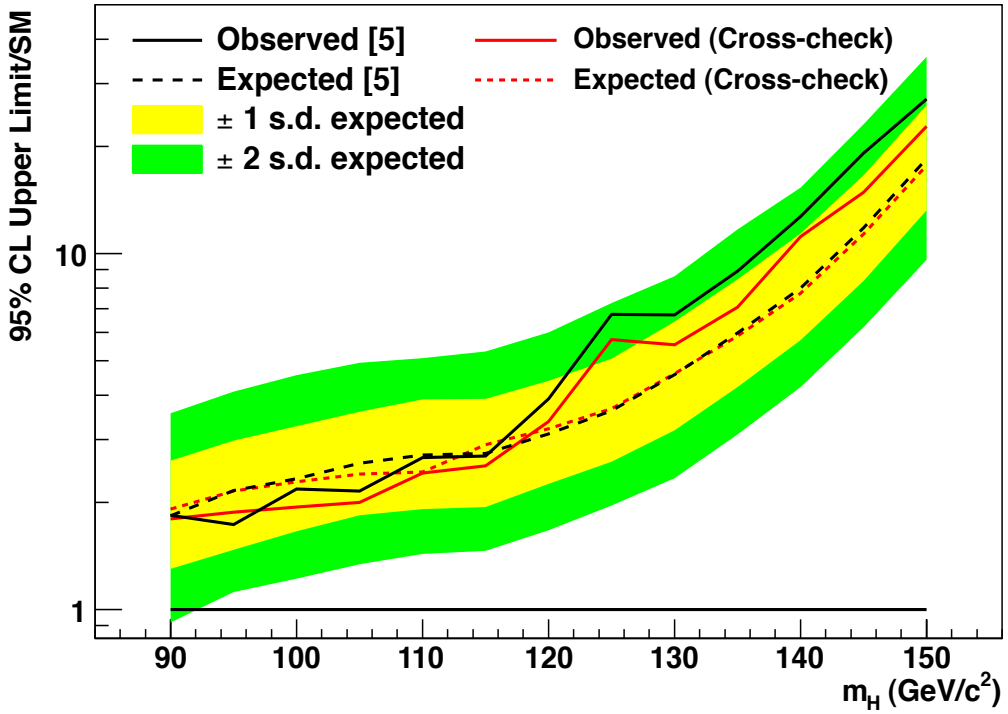
- Expected limits are 14% better on average than those of the previous analysis
- Observed limits are 55% lower on average, fairly independent across Higgs boson mass
- Why such a discrepancy?





Updated MET+bb Search

- Many checks performed in recent months:
  1. Mismodeling of backgrounds? *None seen.*
  2. Mistake in *b*-jet tagging? *None seen.*
  3. Reanalyze data sample using old tagging methods.



- Expected limits in very good agreement with those of summer analysis.
- Observed limits systematically lower than those of summer analysis.
- Non-negligible fraction of discrepancy originates from different (improved) treatment of systematic uncertainties.

Updated MET+bb Search

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  1. Mismodeling of backgrounds? *None seen.*
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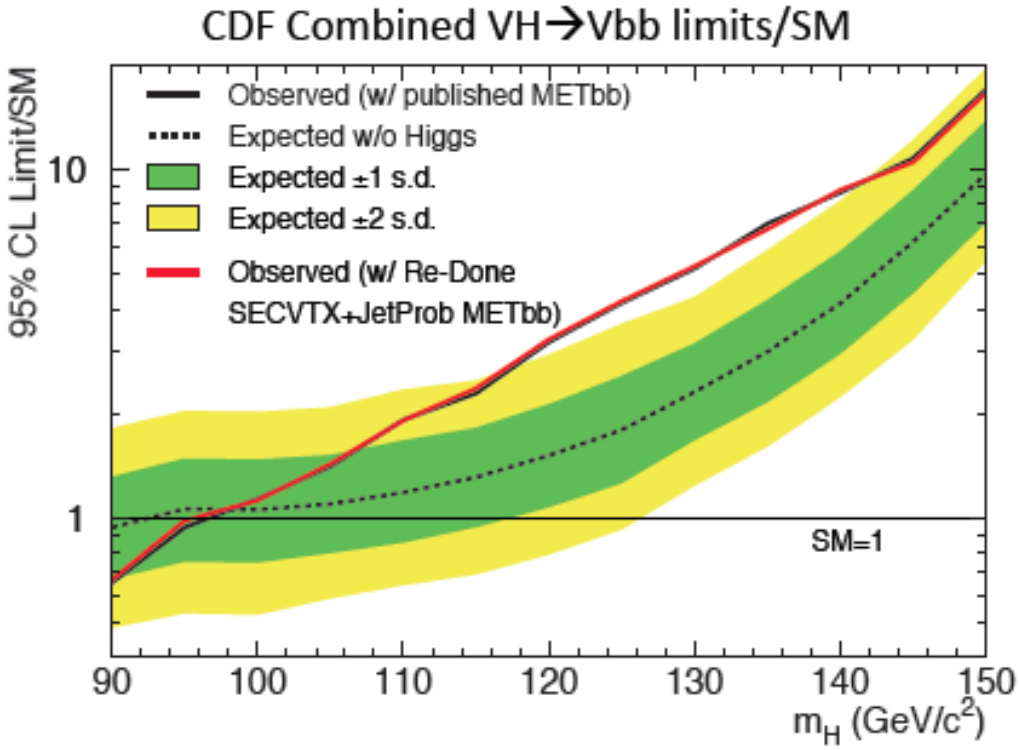
- Effect on H→bb summer combination?
- Limits / *p*-values unchanged wrt to summer combination.
- *Conclusion:* analysis method is robust, and CDF stands behind the H→bb results from last summer.



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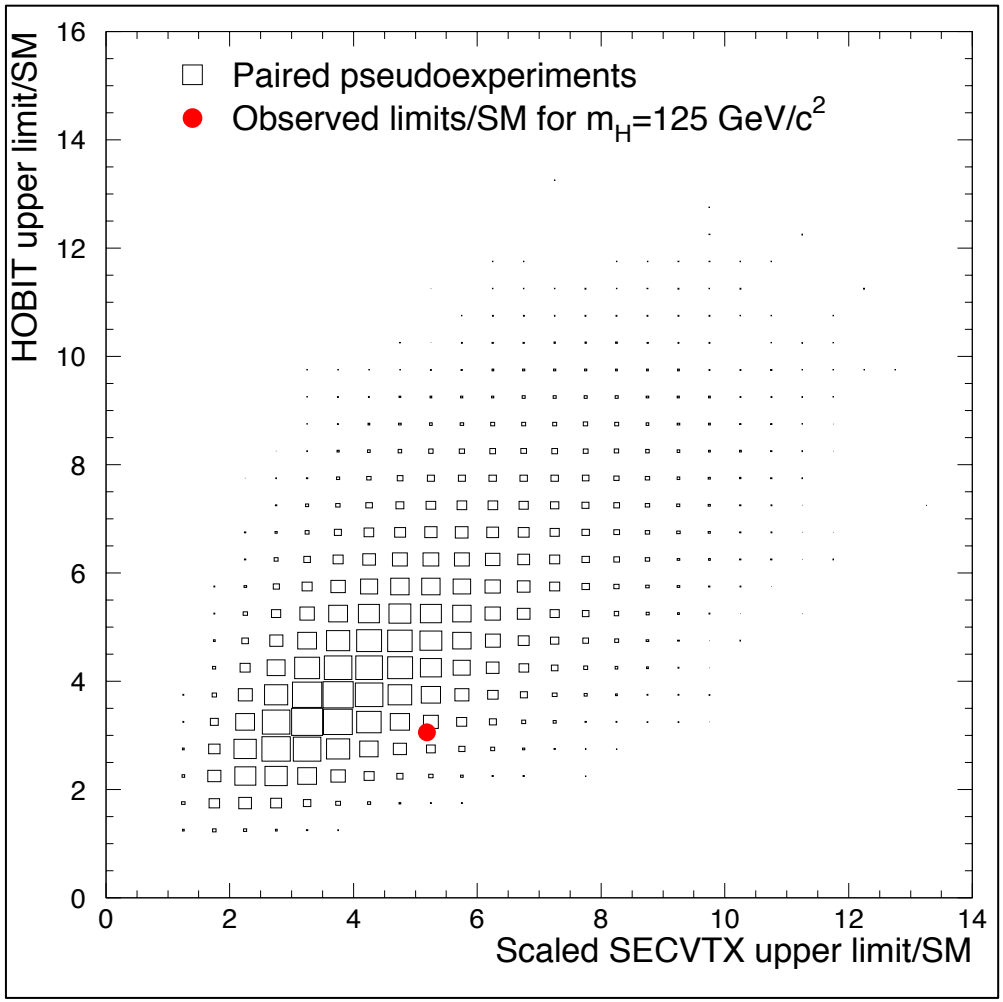
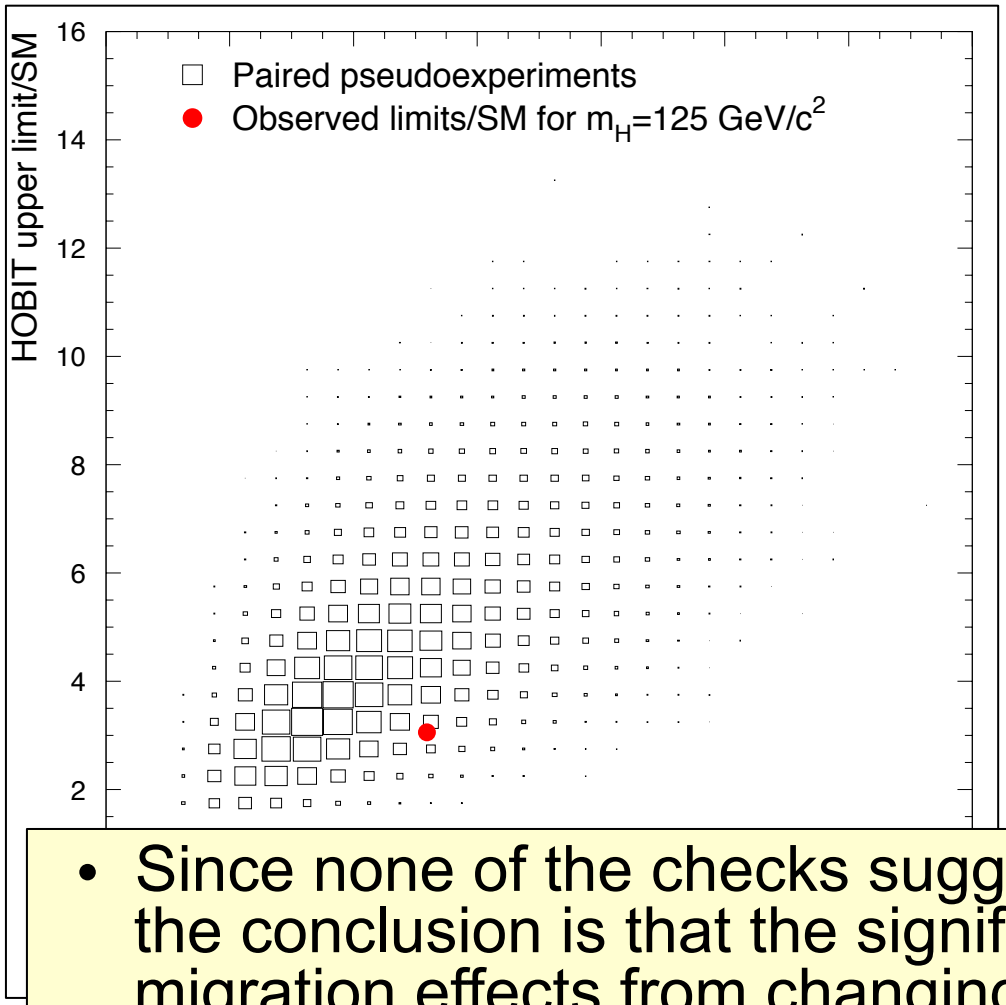


- Remaining check to assess effect of event migration between old and new *b*-tag categories
- Pseudo-experiment study:
  - Use statistical overlap between analyses to produce pairs of limits using the old and new analysis.
  - Calculate *p*-value to determine consistency
- Probability of shift at m_H = 125 GeV:

  7 – 8 %
- Probability of global shift:

  3 – 5 %

Updated MET+bb Search



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  7 – 8 %

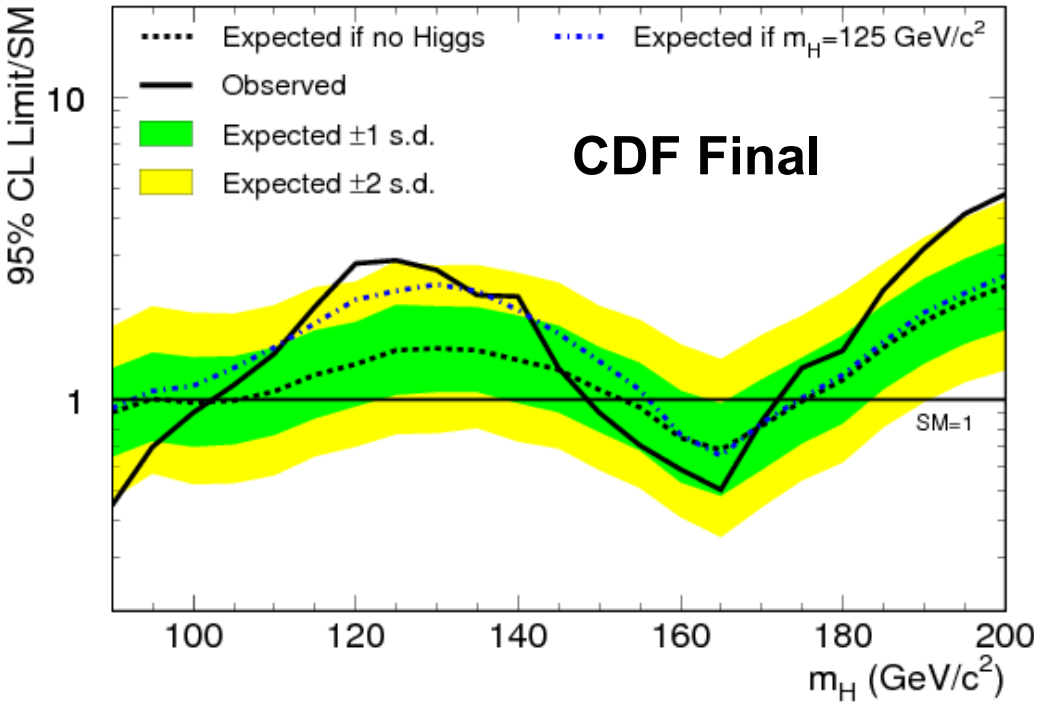
- Since none of the checks suggested any mistakes in analysis, the conclusion is that the significant shift in limits due to event migration effects from changing *b*-tagging algorithms.
- Previous summer publication valid; for final combination, CDF decided to use analysis with most sensitive expected limits.

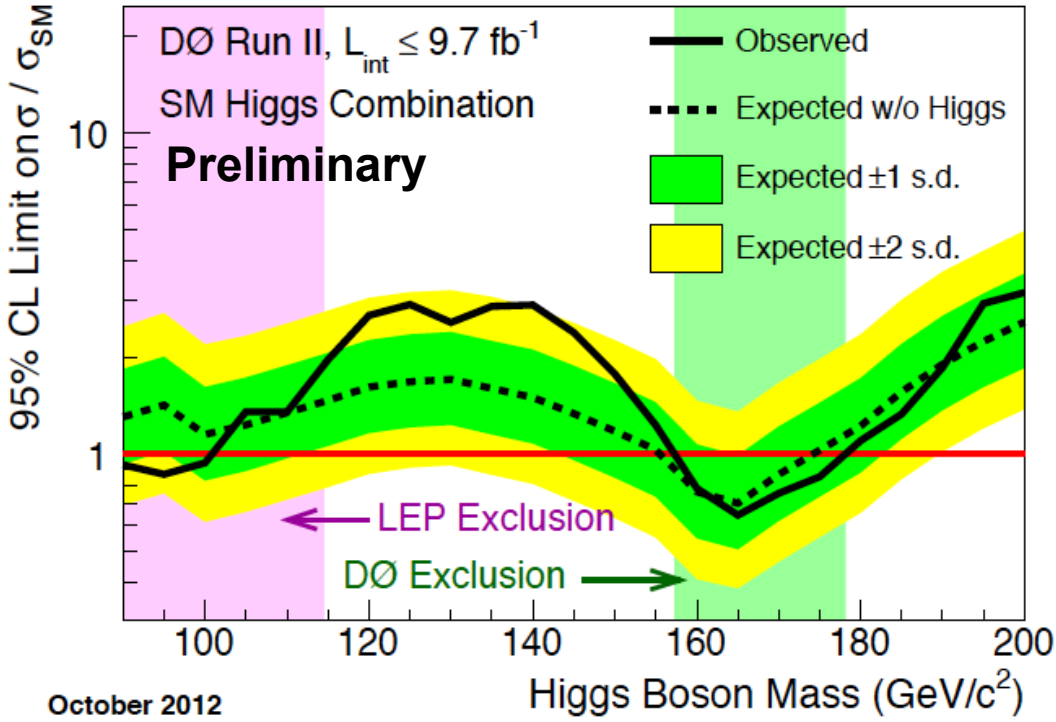
Status of the Combinations

- Today I will present the most recently approved CDF, D0, and Tevatron combinations.
  - A *final* CDF Higgs combination has been performed and submitted to Phys. Rev. D.
  - Preliminary D0 combination from Oct. 2012.
  - Preliminary Tevatron combination from Nov. 2012.

- Final Tevatron combination aiming for release next week.

Higgs limits from all channels



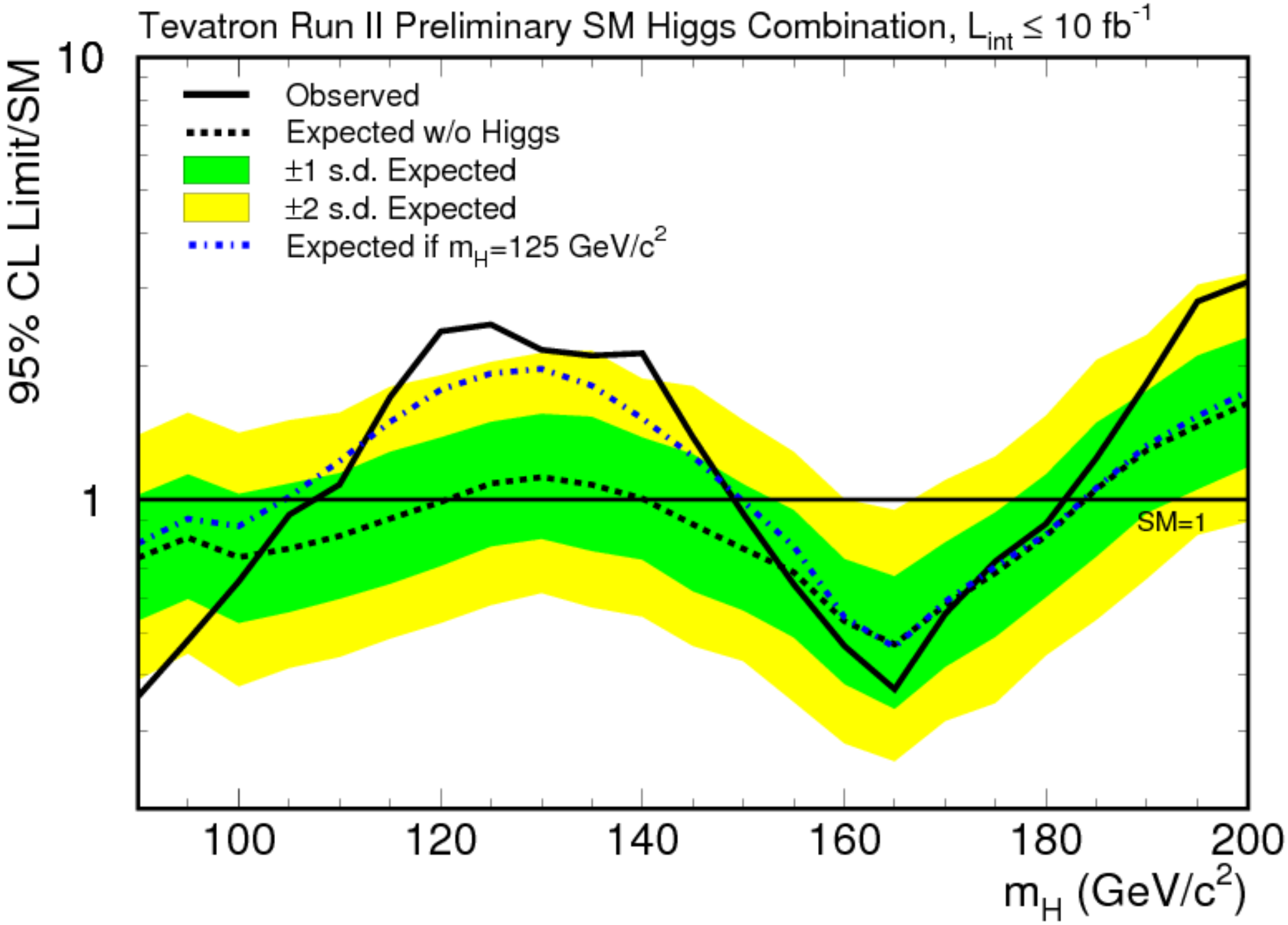


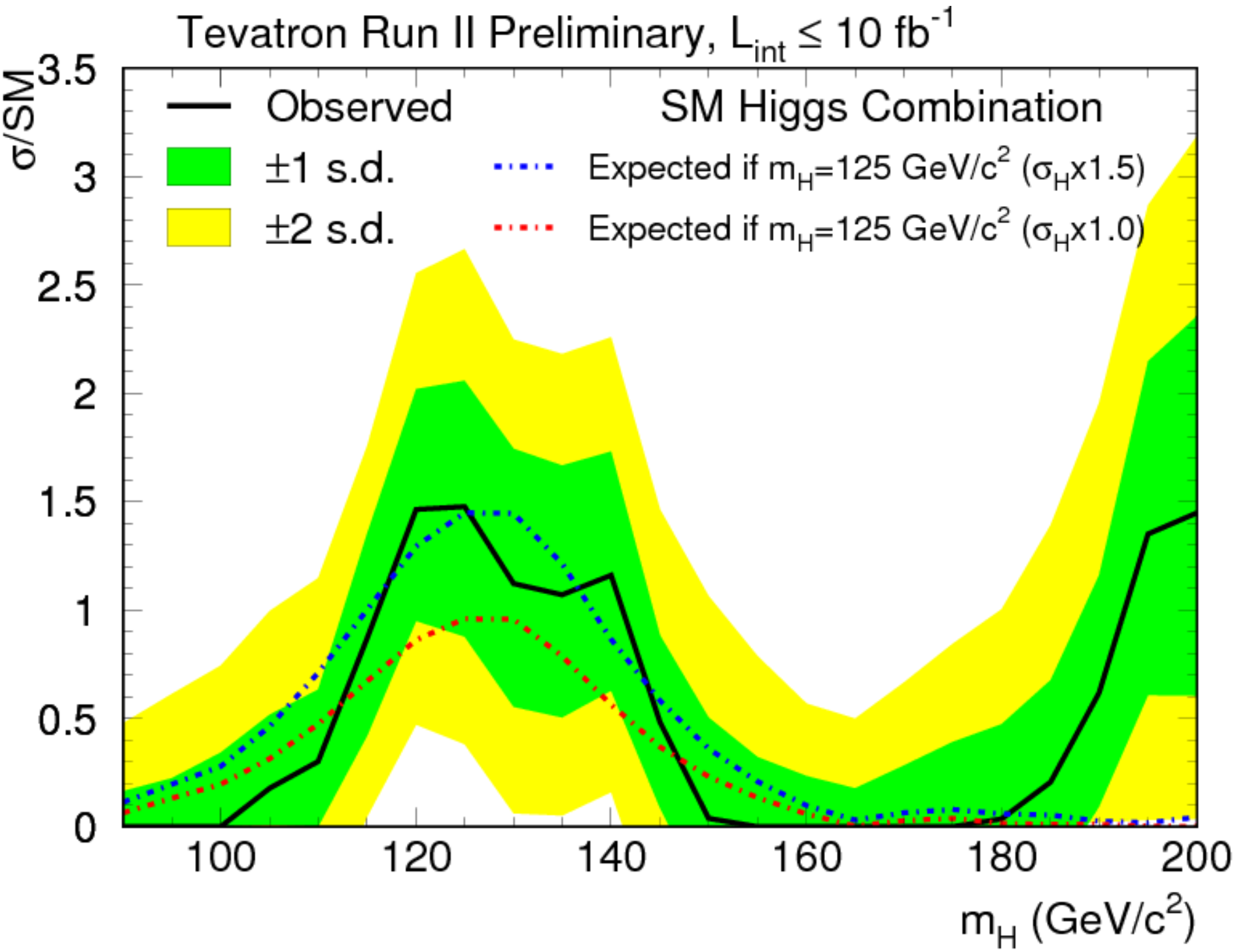
Exp. Exclusion: **90 < m_H < 94 GeV**
96 < m_H < 106 GeV
154 < m_H < 176 GeV

Obs. Exclusion: **90 < m_H < 102 GeV**
149 < m_H < 172 GeV

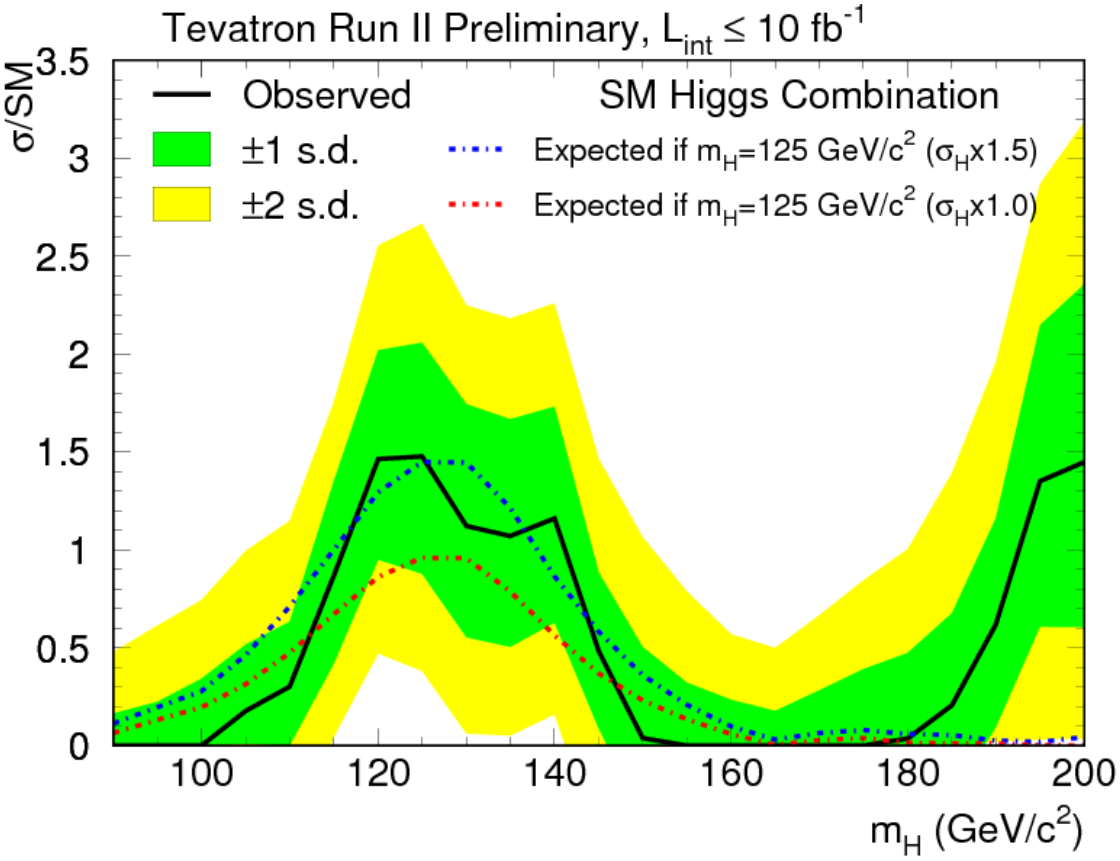
Exp. Exclusion: **156 < m_H < 173 GeV**

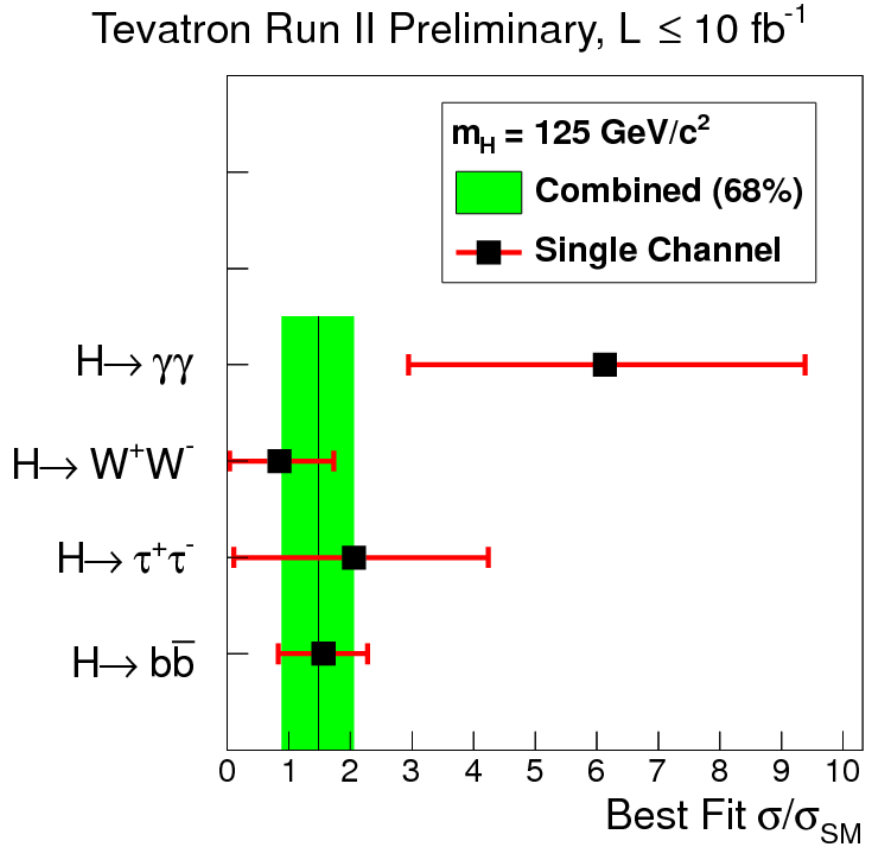
Obs. Exclusion: **90 < m_H < 101 GeV**
157 < m_H < 178 GeV


Tevatron Run II Preliminary SM Higgs Combination, $L_{int} \leq 10$ fb^{-1}
95% CL Limit/SM
10
1
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
Expected if m_H=125 GeV/c^2
SM=1
100
120
140
160
180
200
m_H (GeV/c^2)


Tevatron Run II Preliminary, $L_{int} \leq 10$ fb^{-1}
σ/SM
Observed
±1 s.d.
±2 s.d.
SM Higgs Combination
Expected if m_H=125 GeV/c^2 (σ_Hx1.5)
Expected if m_H=125 GeV/c^2 (σ_Hx1.0)
3.5
3
2.5
2
1.5
1
0.5
0
100
120
140
160
180
200
m_H (GeV/c^2)

Cross-section Measurements: Full





$H \to W^+W^-$	$0.85^{+0.88}_{-0.81} \times$ SM	$H \to \tau^+\tau^-$	$2.12^{+2.25}_{-2.12} \times$ SM
$H \to \gamma\gamma$	$6.13^{+3.25}_{-3.19} \times$ SM	$H \to b\bar{b}$	$1.56^{+0.72}_{-0.73} \times$ SM
		Combined	$1.48^{+0.58}_{-0.60} \times$ SM

Constraining Higgs Couplings

- Window to exotic physics can be parameterized through coupling factors:
  - Hff coupling scaled by: κ_f
  - HWW / HZZ / HVV scaled by: κ_W, κ_Z, κ_V
  - Standard model is obtained when:

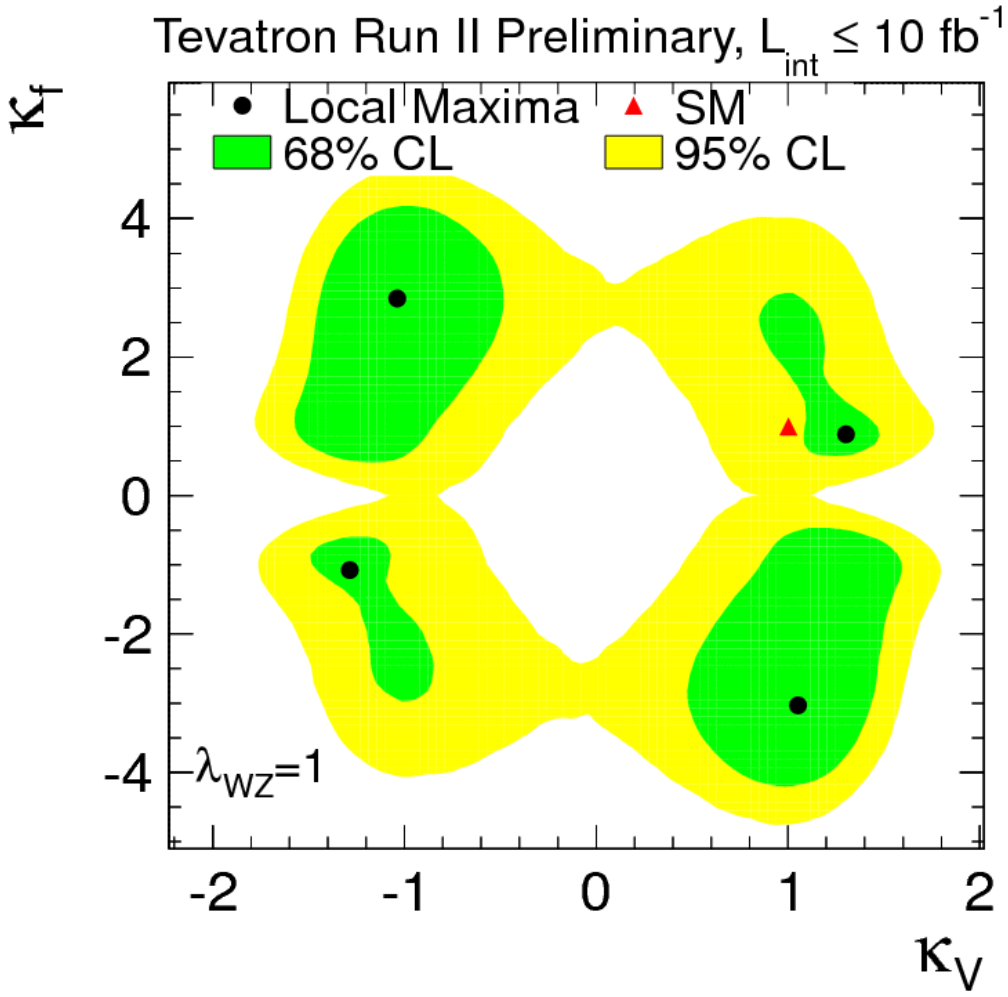
$$\kappa_f = \kappa_W = \kappa_Z = 1 \ .$$

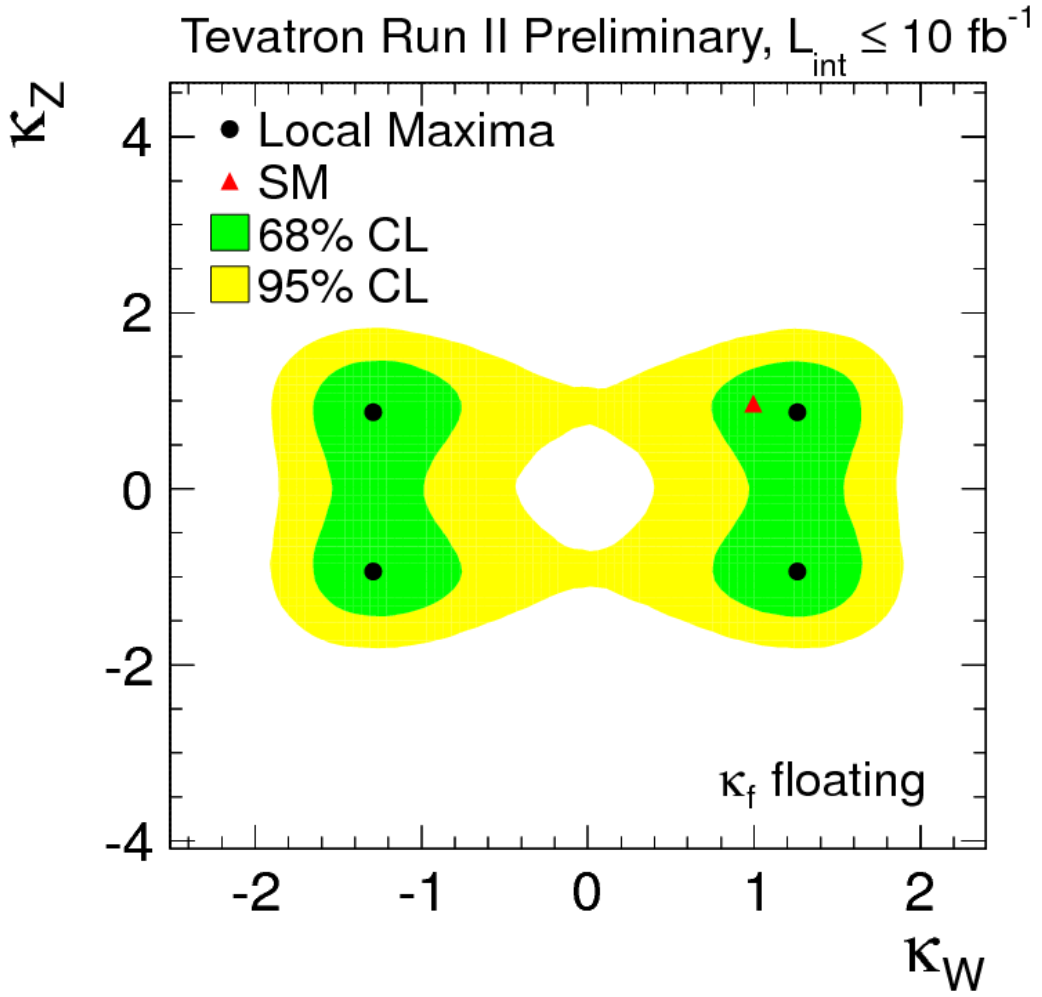
- Expressions for Higgs boson production/decay processes are modified based on production mechanism and decay channel (e.g.):

Process	$\sigma \times \mathcal{B}_H$
$VH \to V + b\bar{b}$	$\propto (\kappa_f \kappa_V)^2$
$t\bar{t}H \to t\bar{t} + b\bar{b}$	$\propto (\kappa_f^2)^2$
$VH \to V + W^+W^-$	$\propto (\kappa_V^2)^2$

- Test coupling factors using Bayesian method:
  - Uniform priors assumed for κ 's

Couplings





- All measured couplings consistent with SM predictions.

Conclusions

- Analysis improvements implemented in CDF and D0 to improve Higgs sensitivity to exclusion to better than
  $1.15\times SM$ for $m_H < 190$ GeV/c^2
  $1.09\times SM$ for $m_H = 125$ GeV/c^2
- Broad excess in observed data relative to background-only hypothesis in $115 < m_H < 150$ GeV/c^2, consistent with LHC observations.
- Measured cross-sections and couplings are constrained and consistent with SM predictions.
- Final Tevatron combination to be released for Moriond
  - Publication to be submitted at same time.

Thank you.

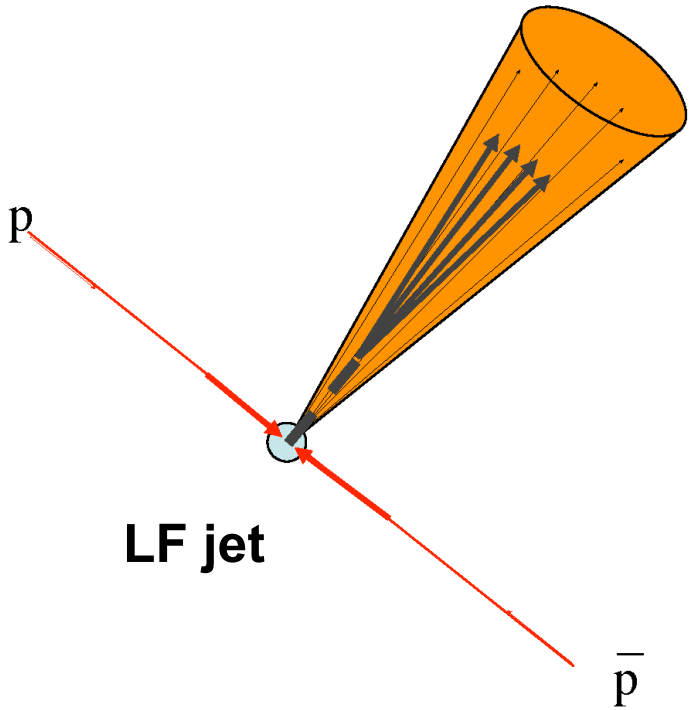
Public Results

- Tevatron Combination
  - http://tevnphwg.fnal.gov/results/
- D0 Results
  - http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#higgs
- CDF Results
  - http://www-cdf.fnal.gov/physics/new/hdg/Results.html

Back-up Slides

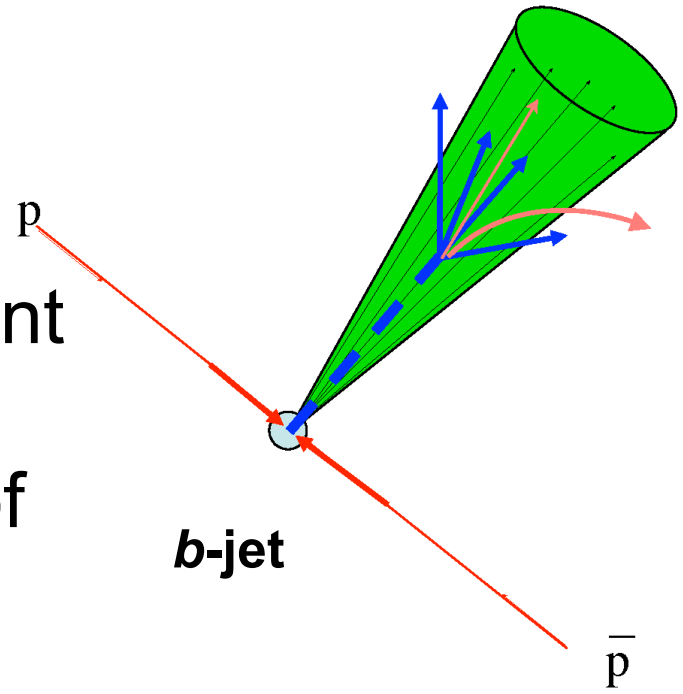
Mass resolution improved

- Shape of invariant mass distribution:
  - Peaking for Higgs signal
  - Peaking for diboson background
  - Falling for other backgrounds

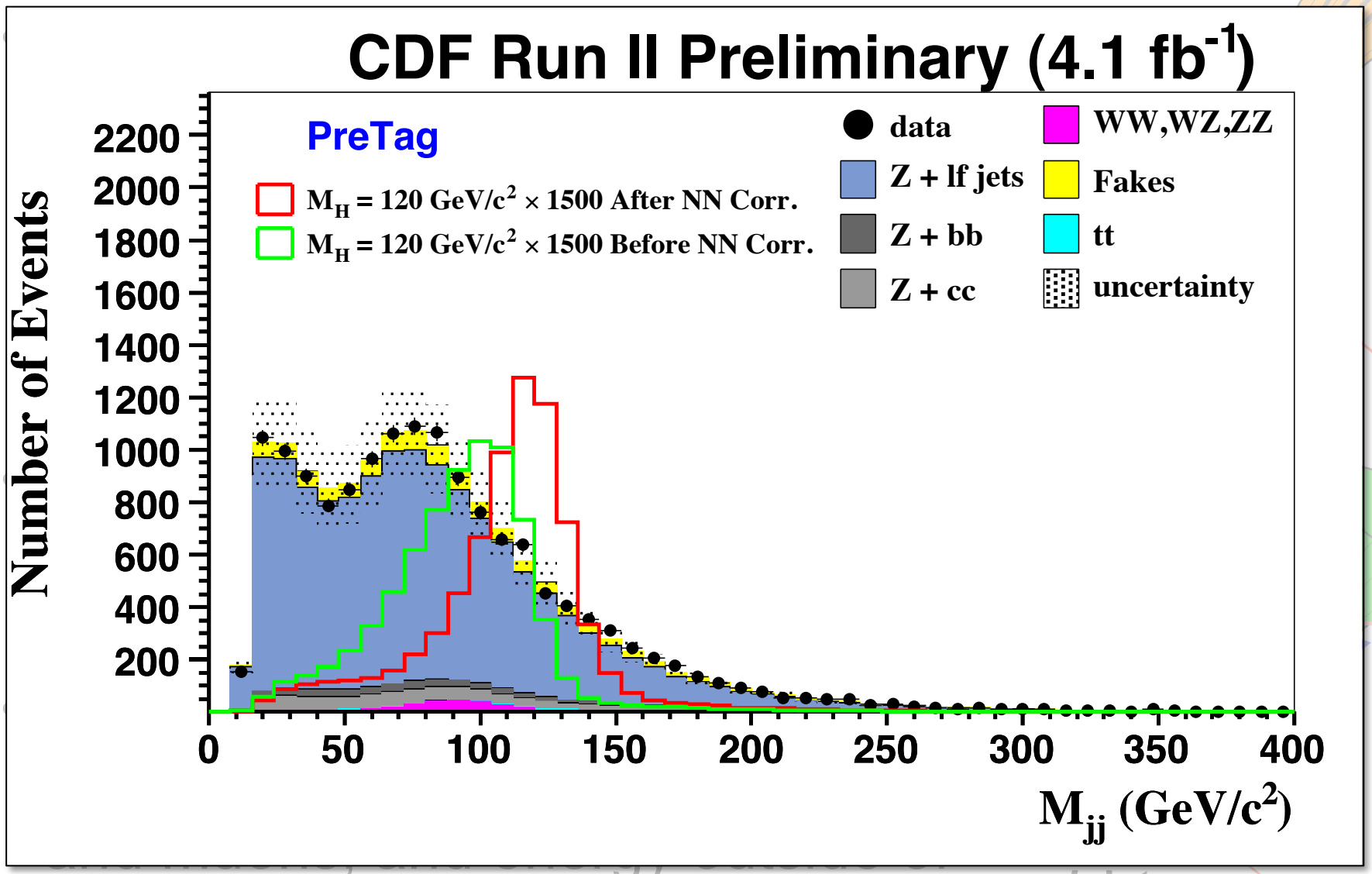


- Jet-energy corrections generally derived from light-quark jets

- Regression algorithms can account for missing energy from neutrinos and muons, and energy outside of the jet-cone for *b*-jets.



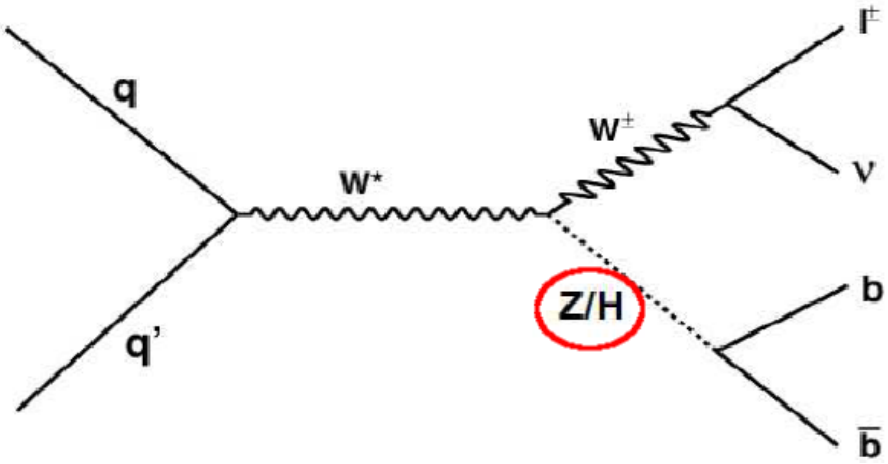
Mass resolution improved



the jet-cone for *b*-jets.

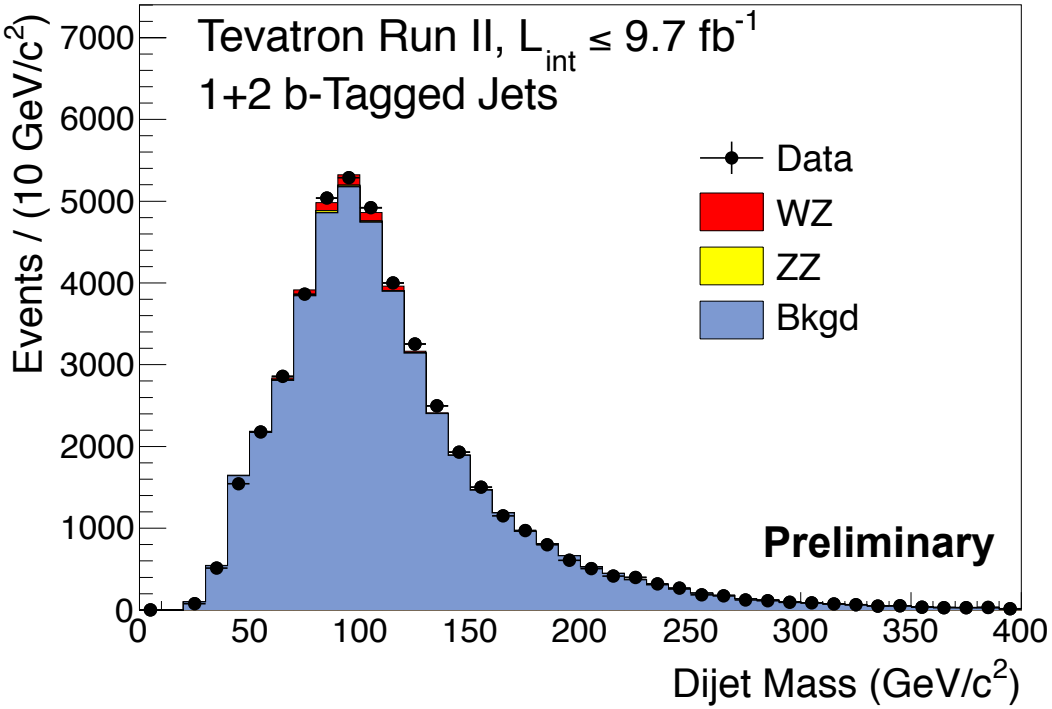
Diboson vs. Higgs Analyses

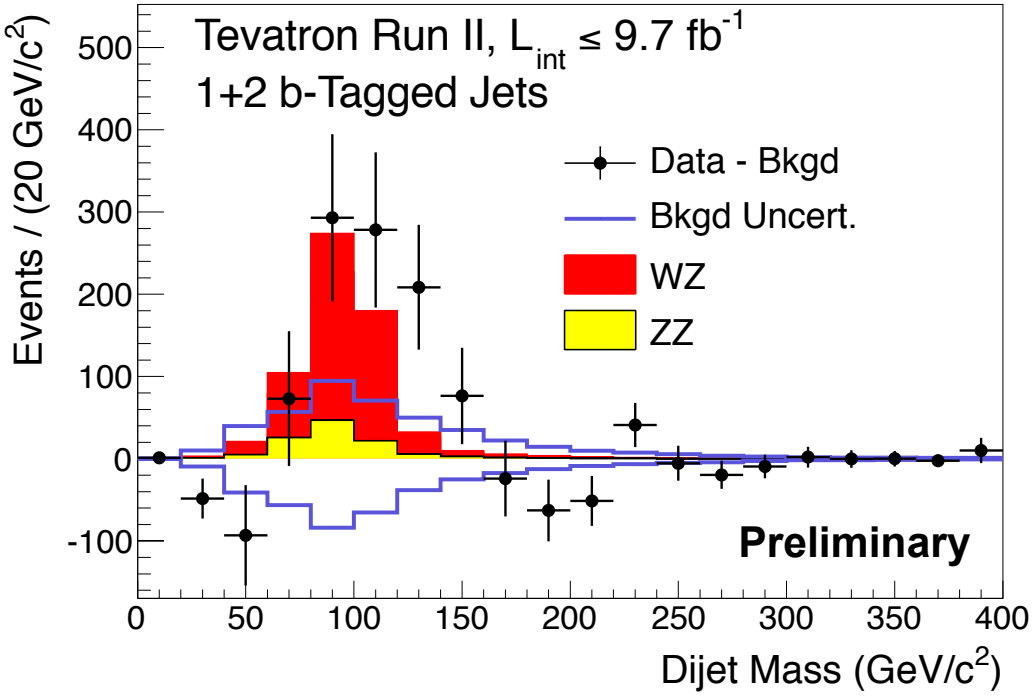
- Feynman diagrams are topologically equivalent



- Same final states, and therefore same analysis strategy, modulo different definitions of signal.
  - Retrained signal/background discriminants

Verify modeling with σ(WZ+ZZ)

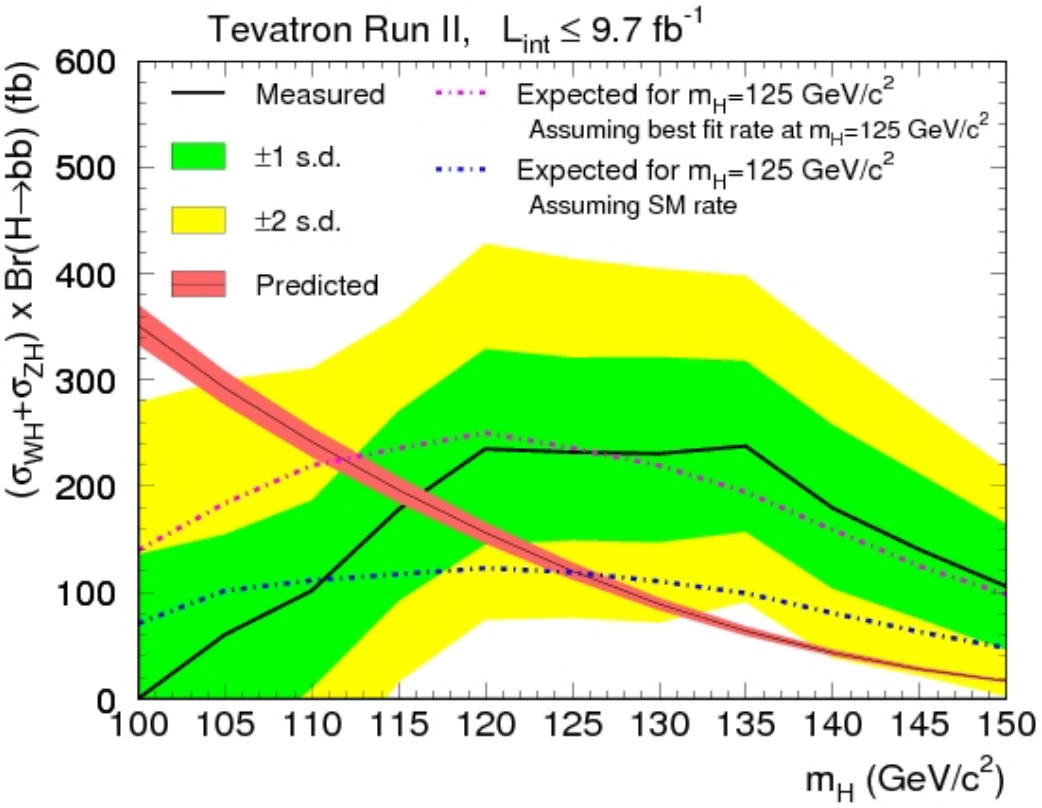


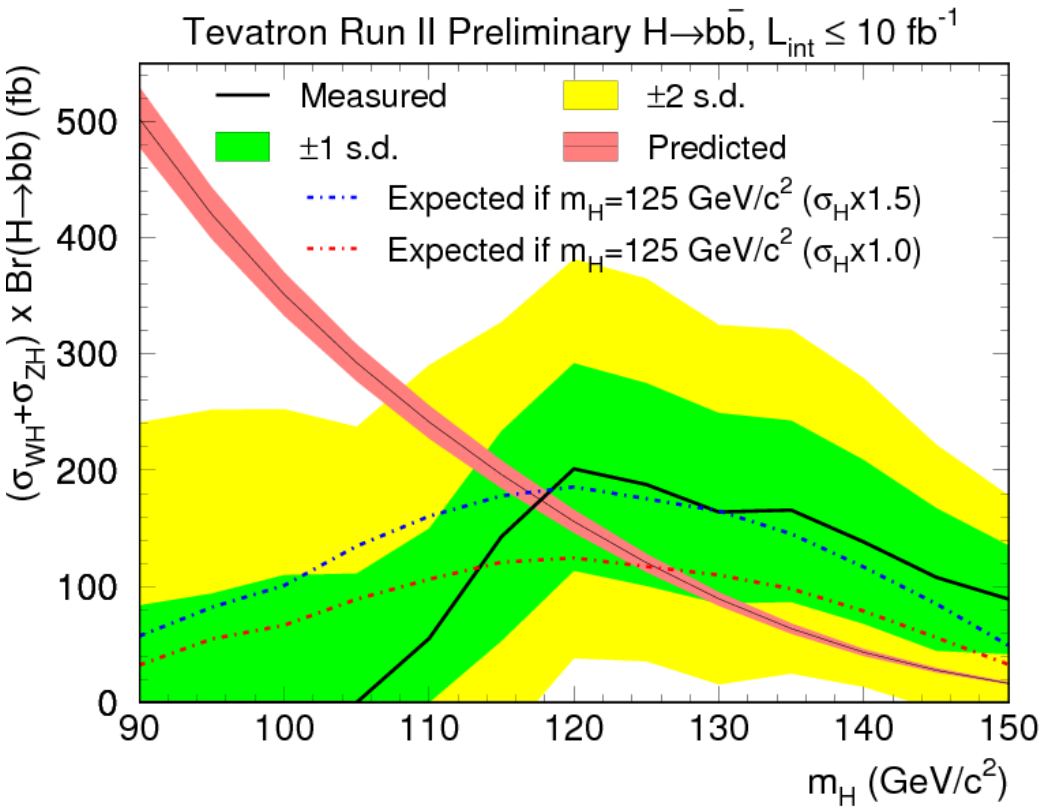


$\sigma(WZ+ZZ)_{meas.} = 3.0 \pm 0.9$ pb

SM Prediction $= 4.4 \pm 0.3$ pb

Cross-section measurements: H→bb





$\sigma(VH)\times Br(H\to bb) = 230\ ^{+90}_{-80}$ fb

$\sigma(VH)\times Br(H\to bb) = 190\ ^{+90}_{-90}$ fb

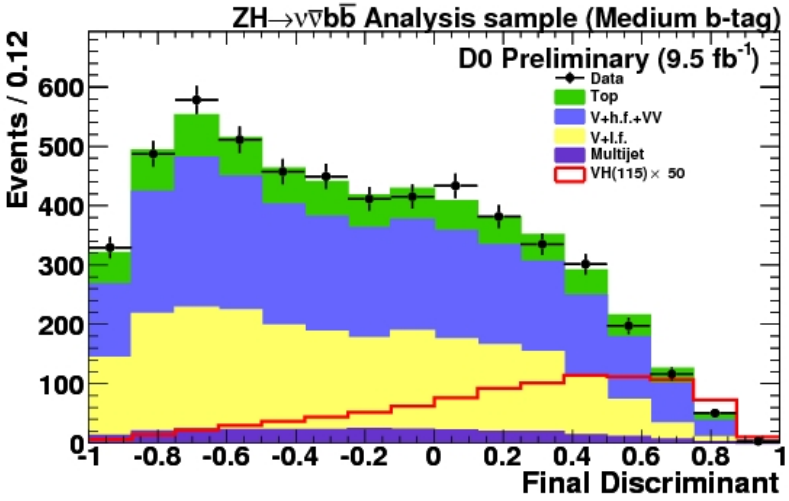
SM Prediction at 125:

$\sigma(VH)\times Br(H\to bb) = 120 \pm 8$ fb

Obtaining Results

- Extracted by starting with a combined likelihood function

$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}}$$



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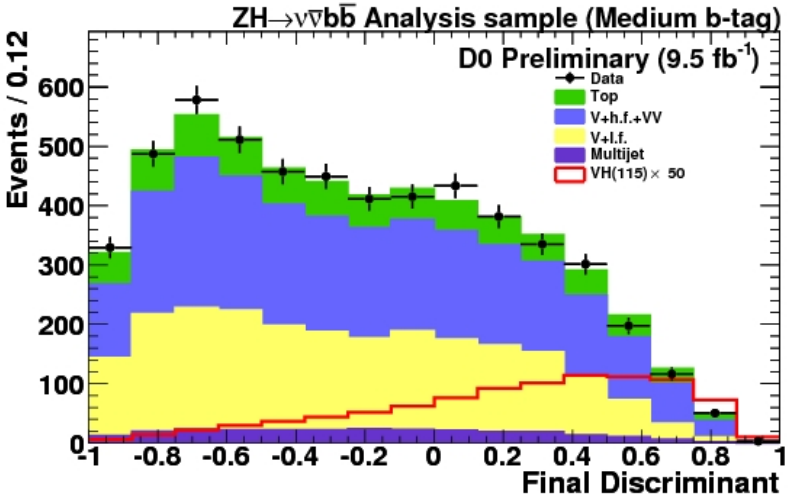
$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}}$$

Expected events

Observed events



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$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{\text{np}}} e^{-\theta_k^2/2}$$

Expected events

Nuisance parameters

Observed events

- Expected signal / background events dependent on systematic uncertainties, included as nuisance parameters

Obtaining Results

- Extracted by starting with a combined likelihood function

$$L = \prod_{i=1}^{N_{\text{channel}}} \prod_{j=1}^{N_{\text{bins}}} \frac{\mu_{ij}^{n_{ij}}}{n_{ij}!} e^{-\mu_{ij}} \times \prod_{k=1}^{N_{\text{np}}} e^{-\theta_k^2/2}$$

Expected events

Nuisance parameters

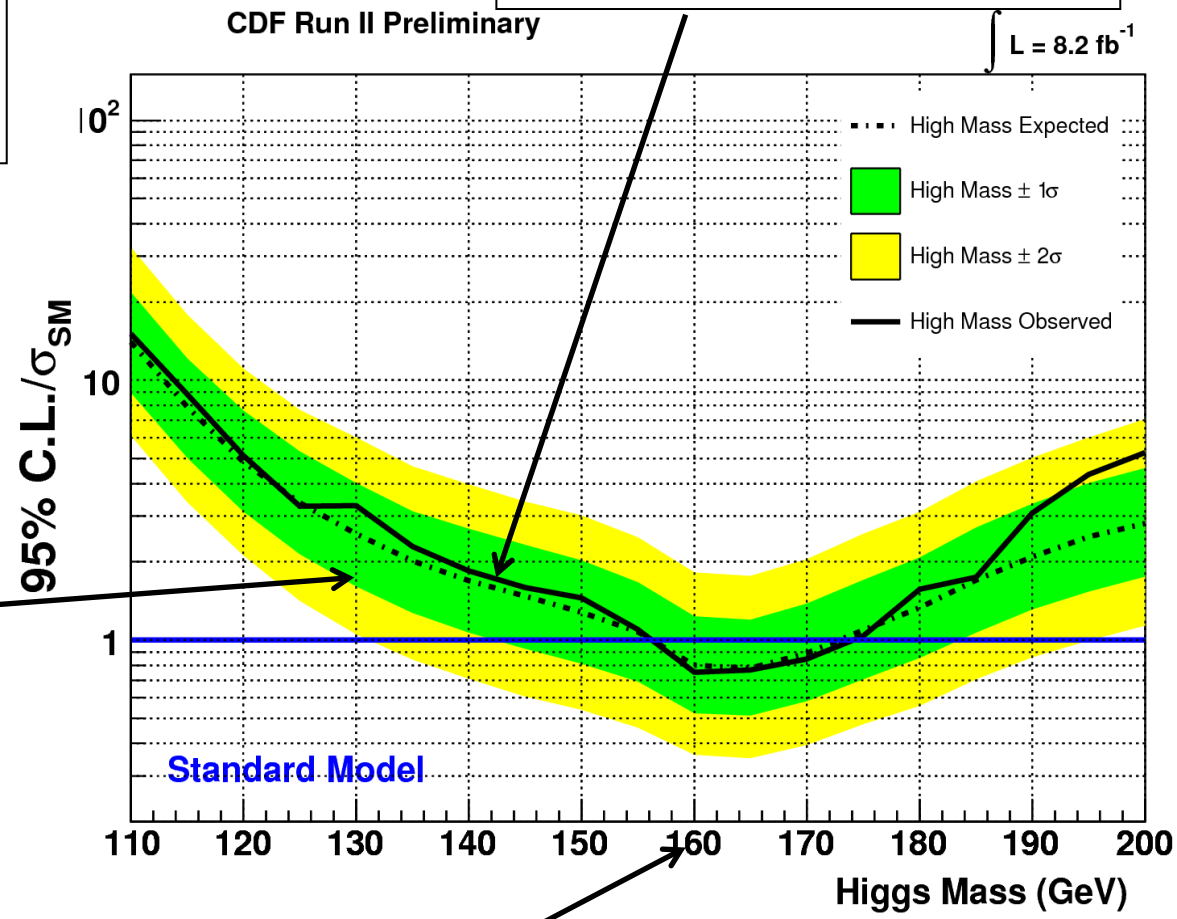
Observed events

- Expected signal / background events dependent on systematic uncertainties, included as nuisance parameters
- Cross-section fits/limits calculated by maximizing likelihood using profiling or marginalizing
  - Good agreement between both
- For Bayesian method (CDF), uniform, non-negative prior assumed for Higgs boson signal.

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 1σ/2σ (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