2013 FNAL Users Meeting

Higgs Boson Studies at the Tevatron

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On behalf of the CDF and DØ Collaborations

June 12, 2013

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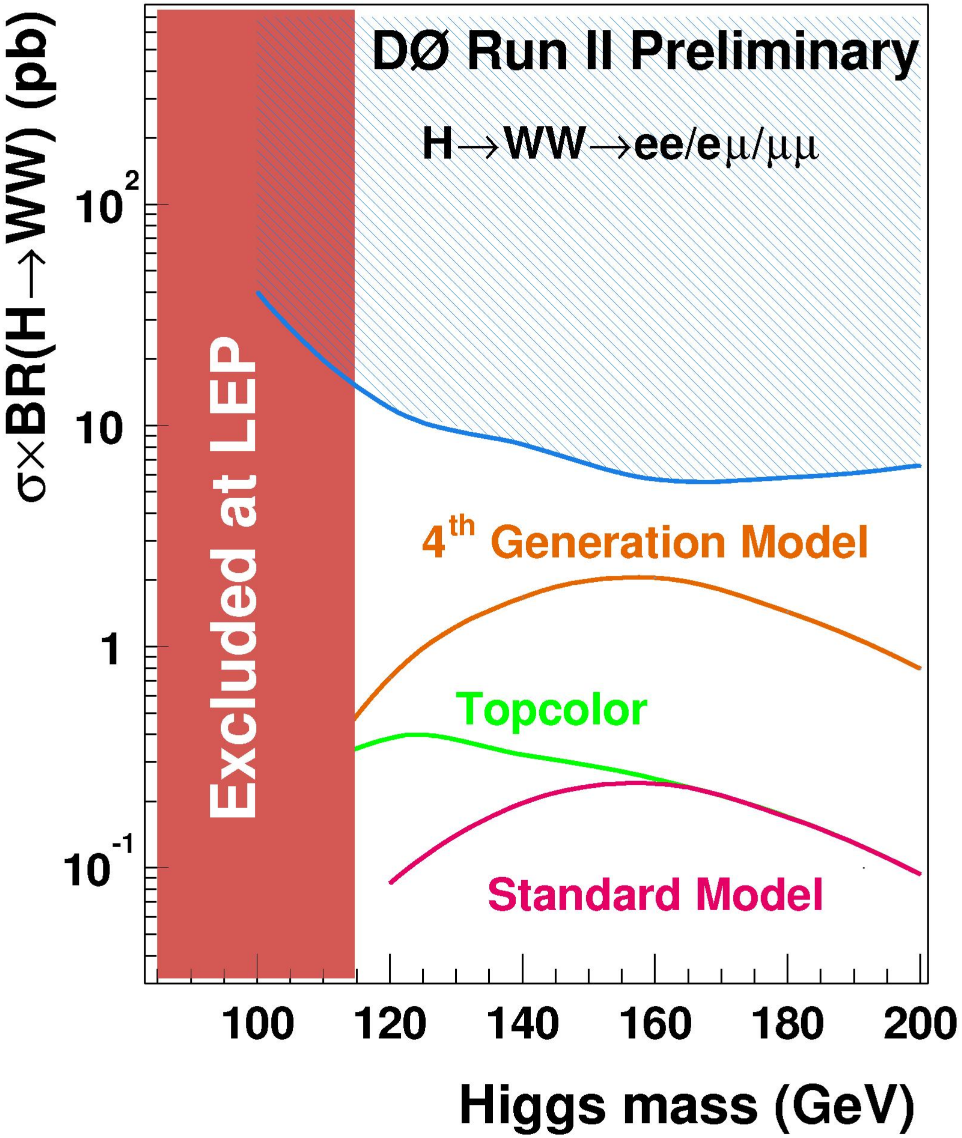

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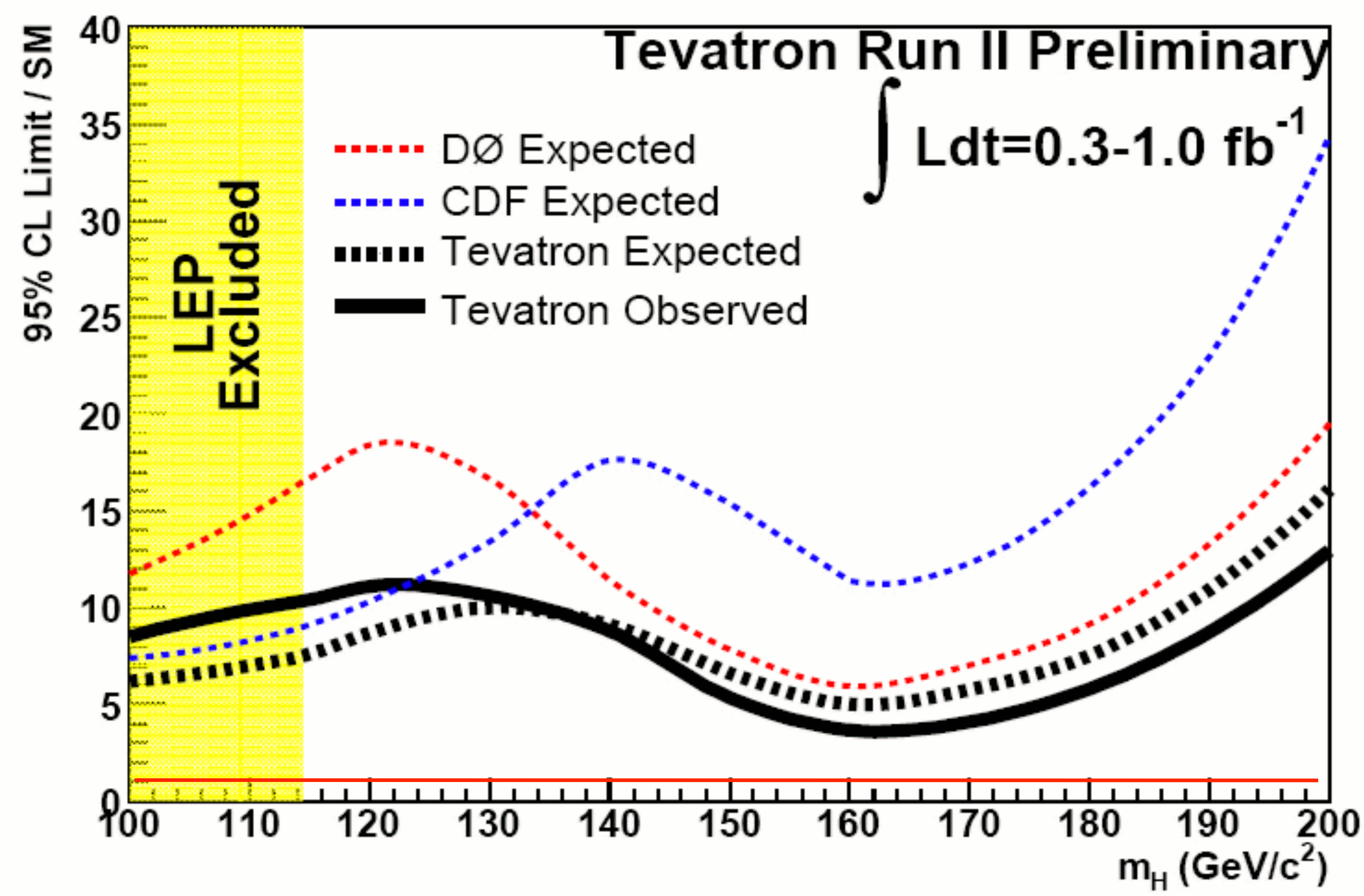

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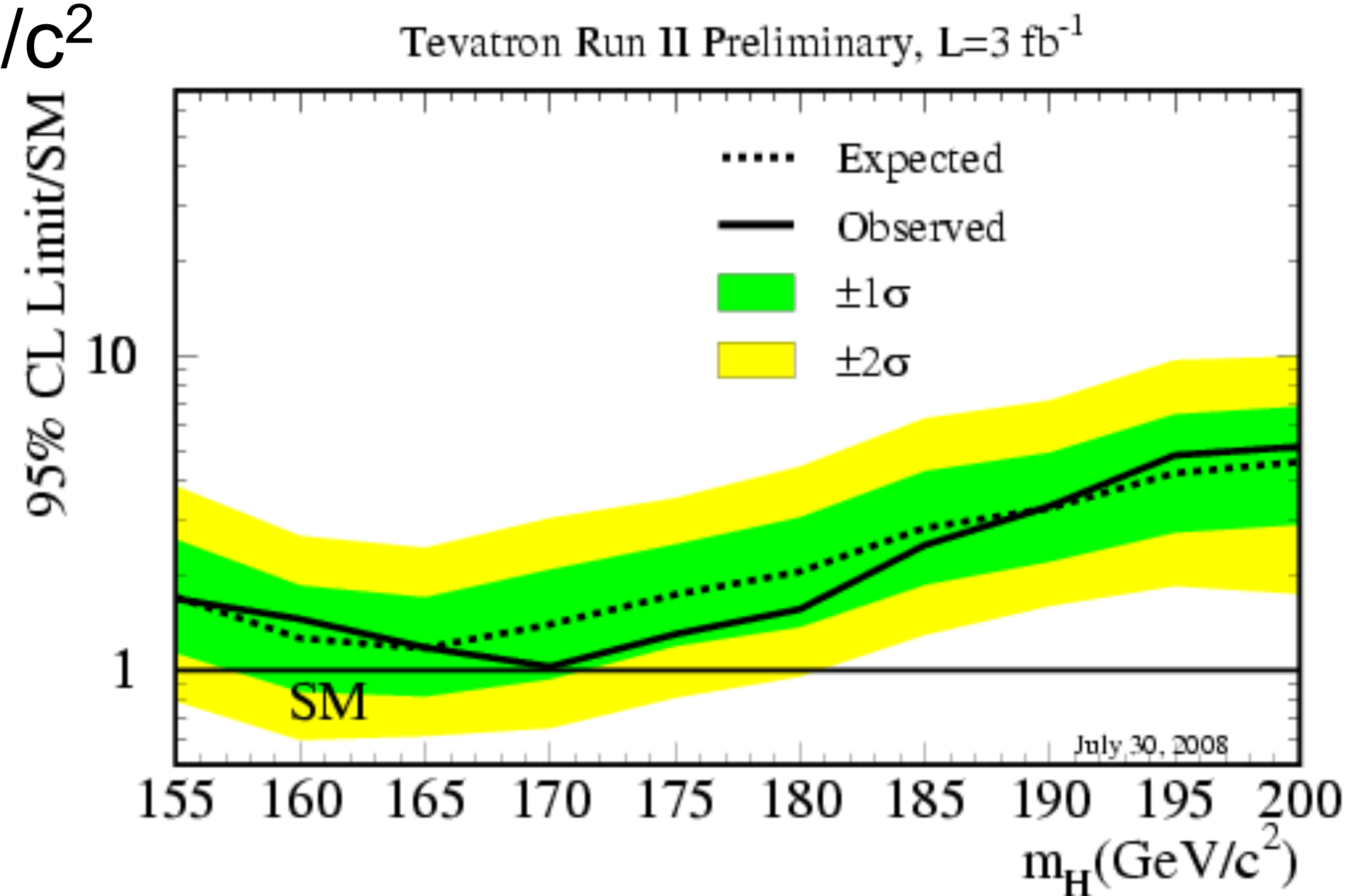
- **2008** – First Tevatron Higgs Exclusion at $m_H = 170\ GeV/c^2$



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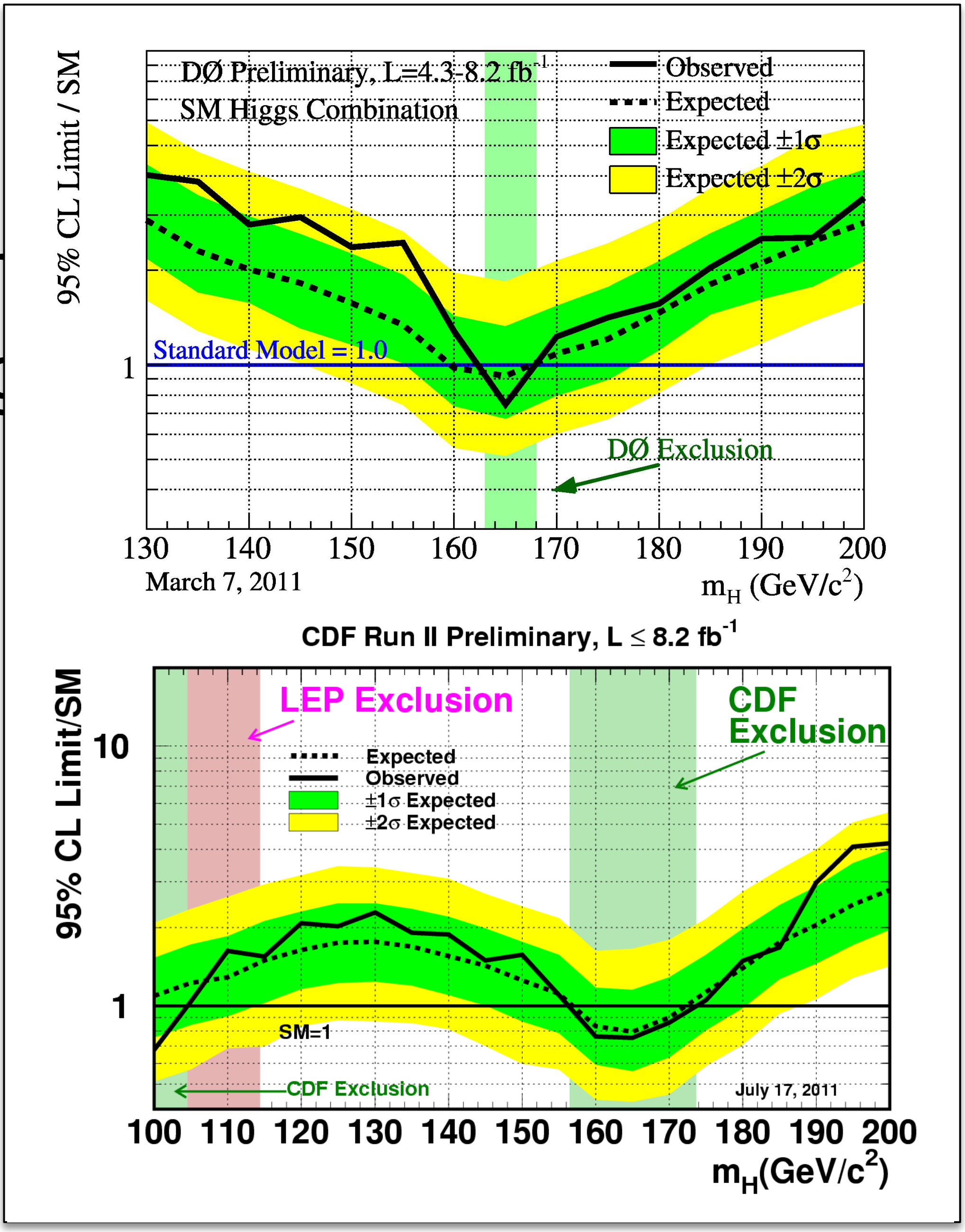

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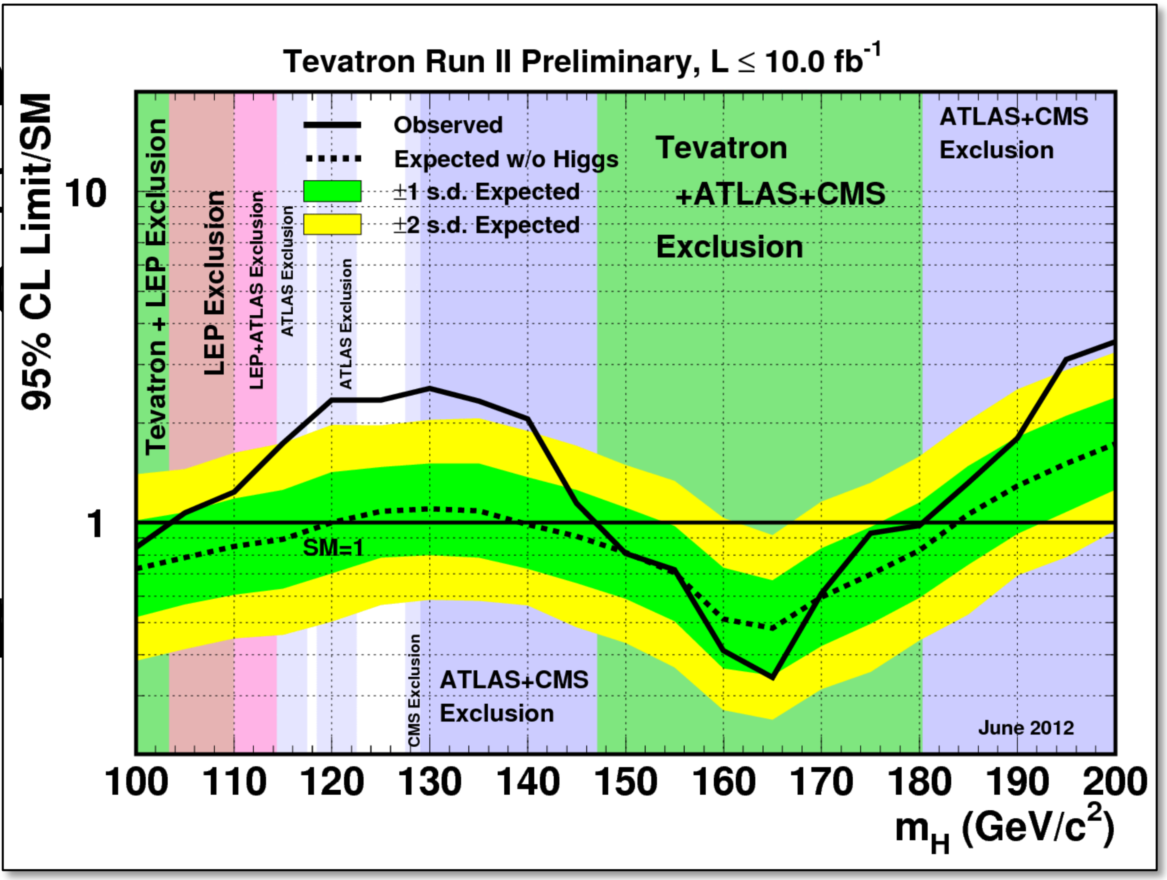

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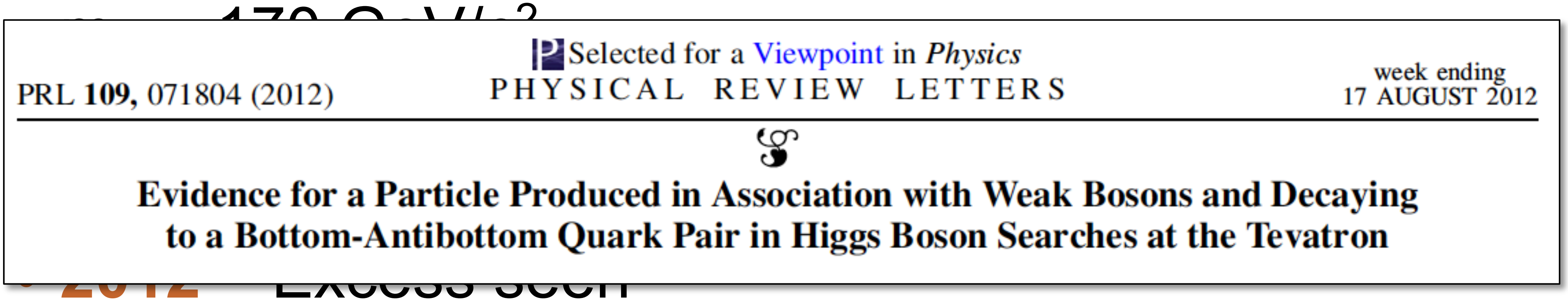

Selected for a Viewpoint in *Physics*

PRL **109,** 071804 (2012) PHYSICAL REVIEW LETTERS week ending 17 AUGUST 2012

Evidence for a Particle Produced in Association with Weak Bosons and Decaying to a Bottom-Antibottom Quark Pair in Higgs Boson Searches at the Tevatron

- **2012** Excess seen
  at low mass in Tevatron combination
- **2012** – $H \rightarrow b\bar{b}$ evidence (3.1σ).

Current Status of the Higgs

- Higgs boson found by CMS and ATLAS at 125 GeV.
- Measuring properties (not limits) are the “name of the game.”

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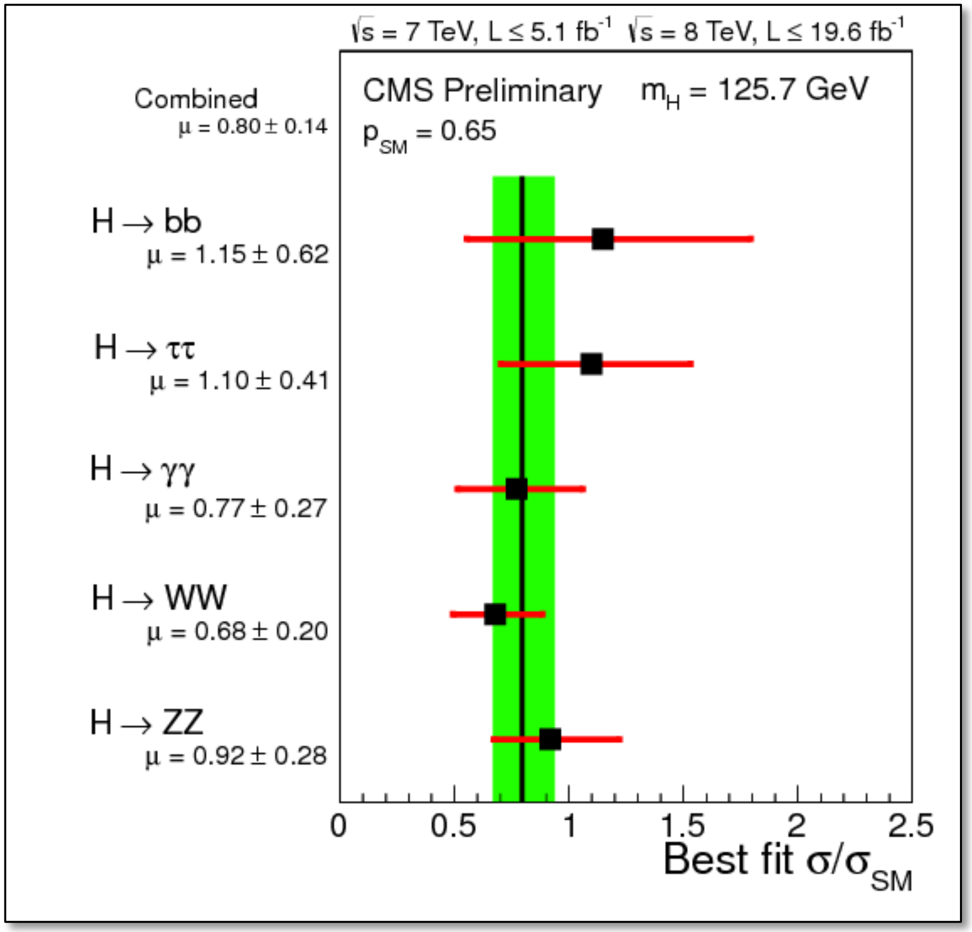

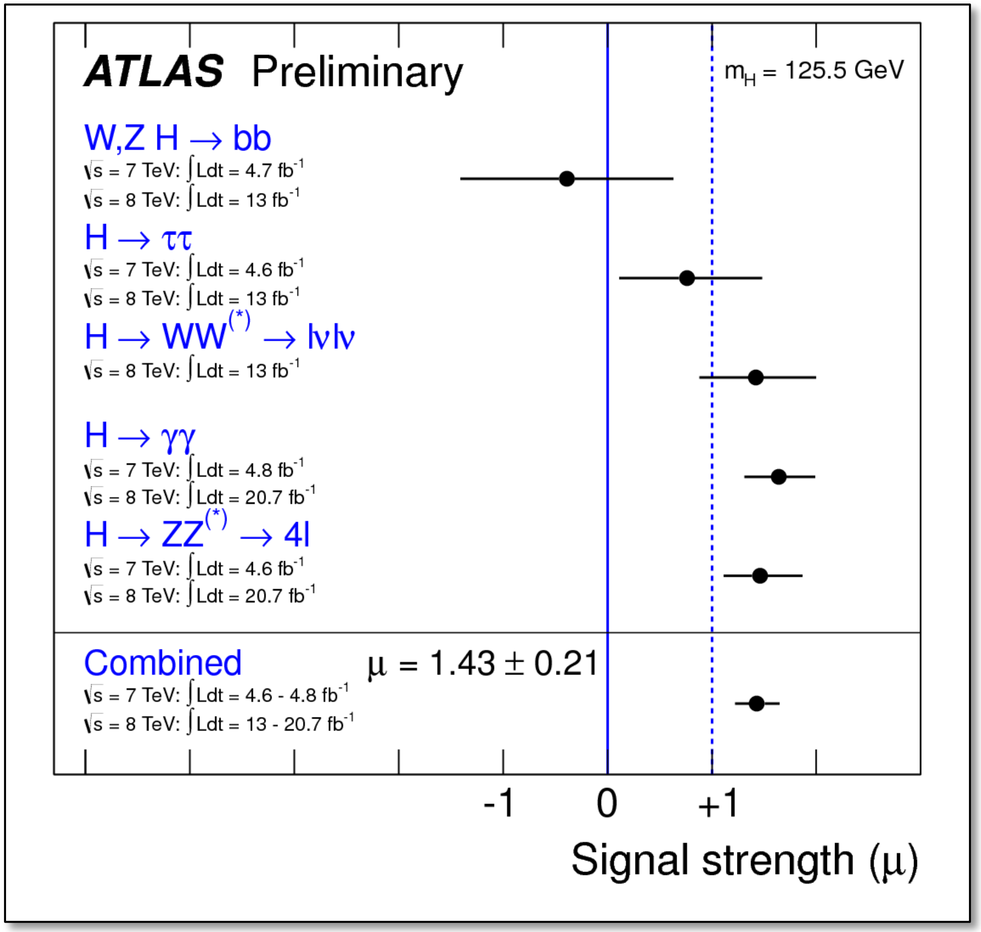

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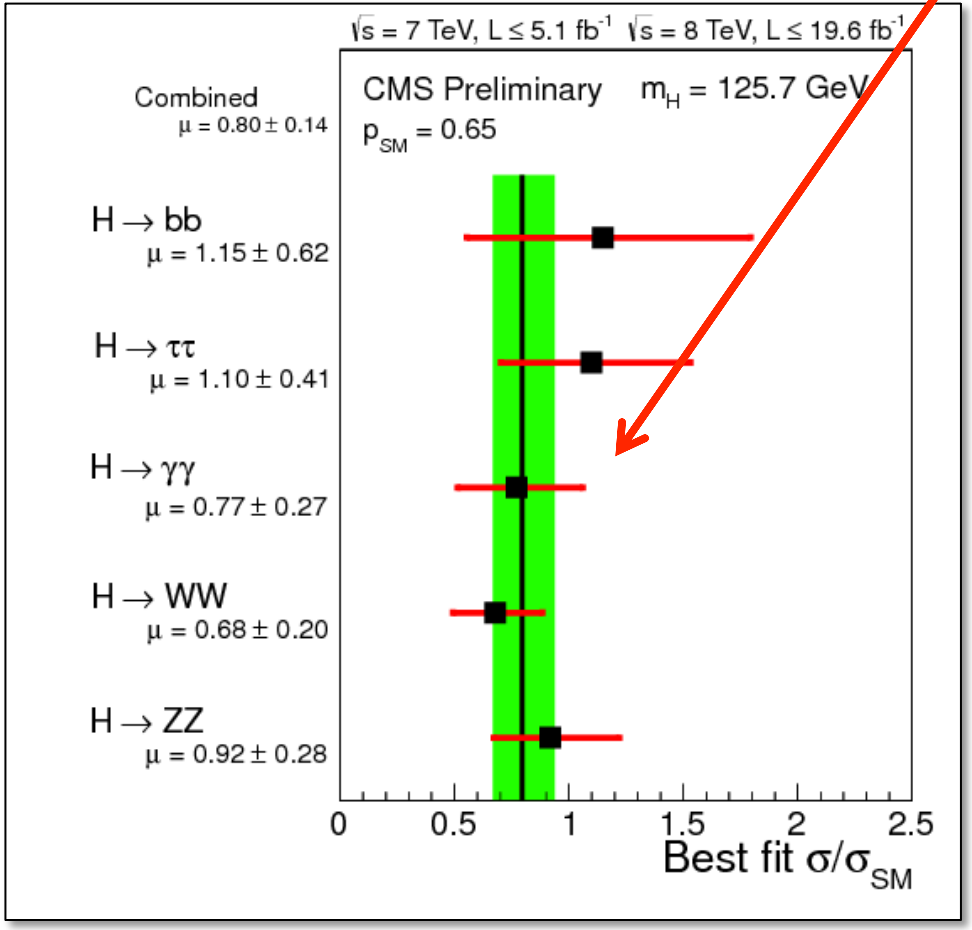
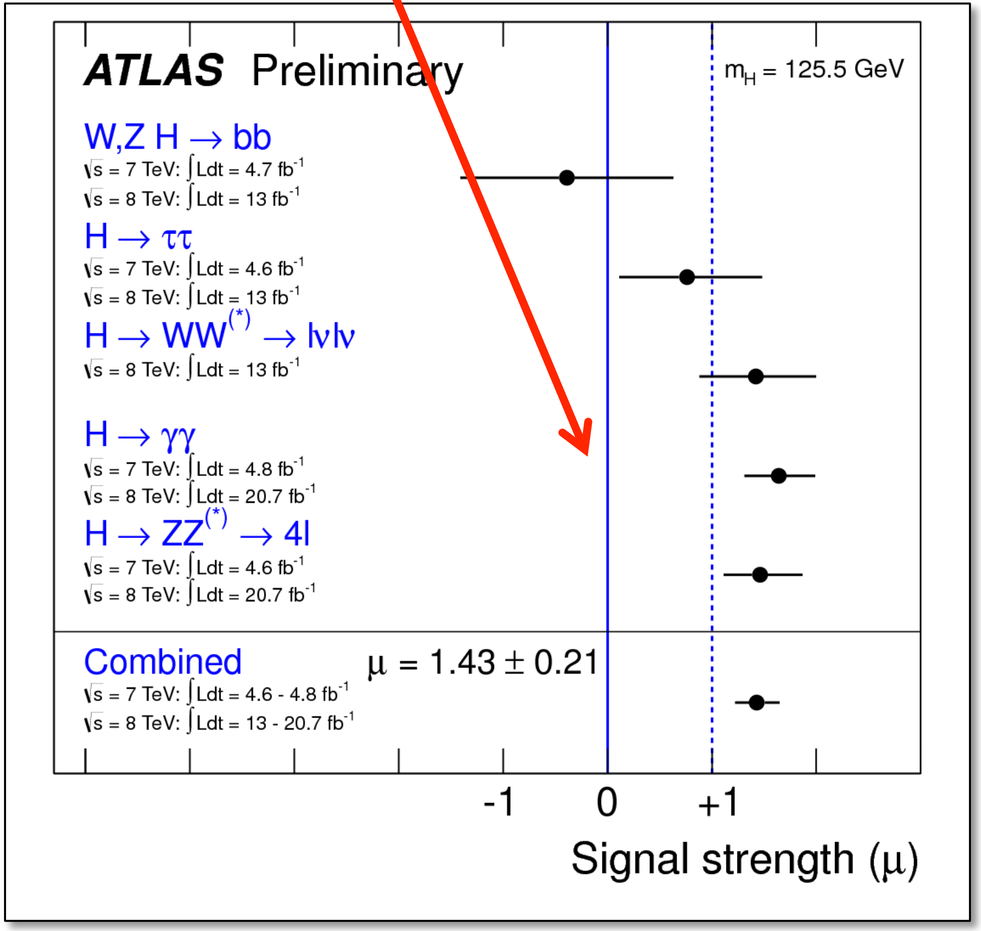
LHC sensitivity driven mainly by $H \rightarrow \gamma\gamma/VV$ final states





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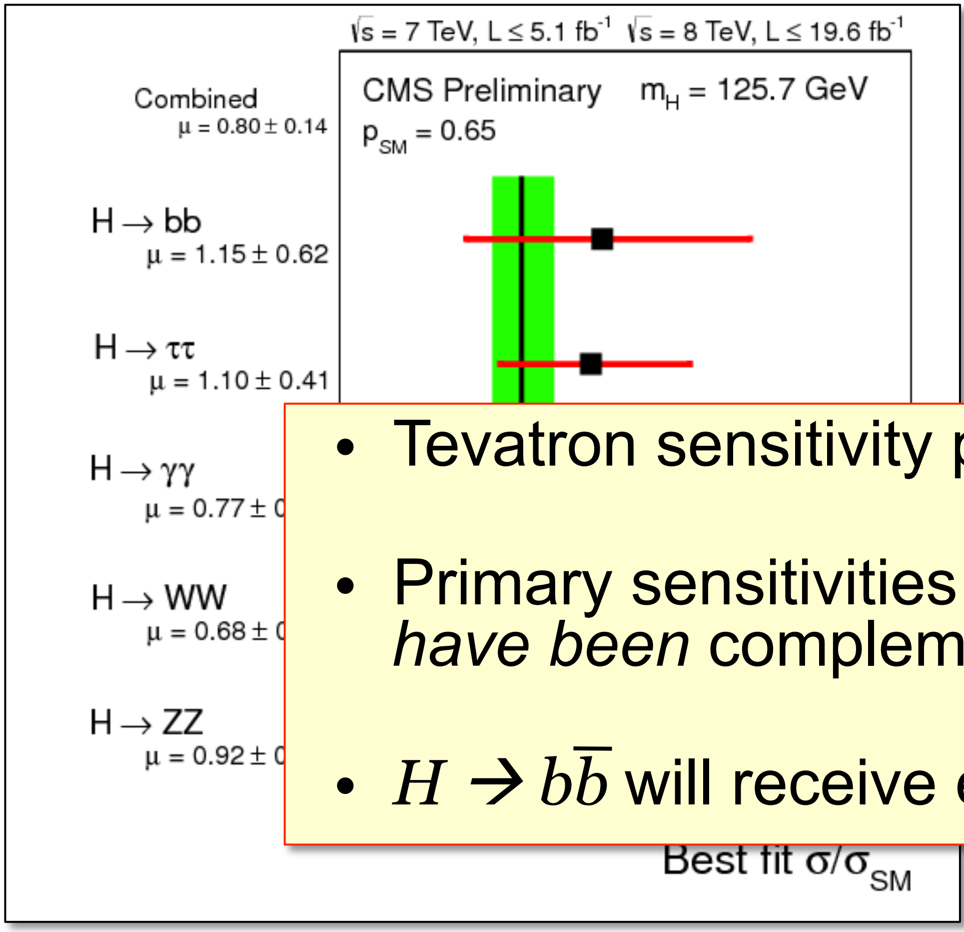
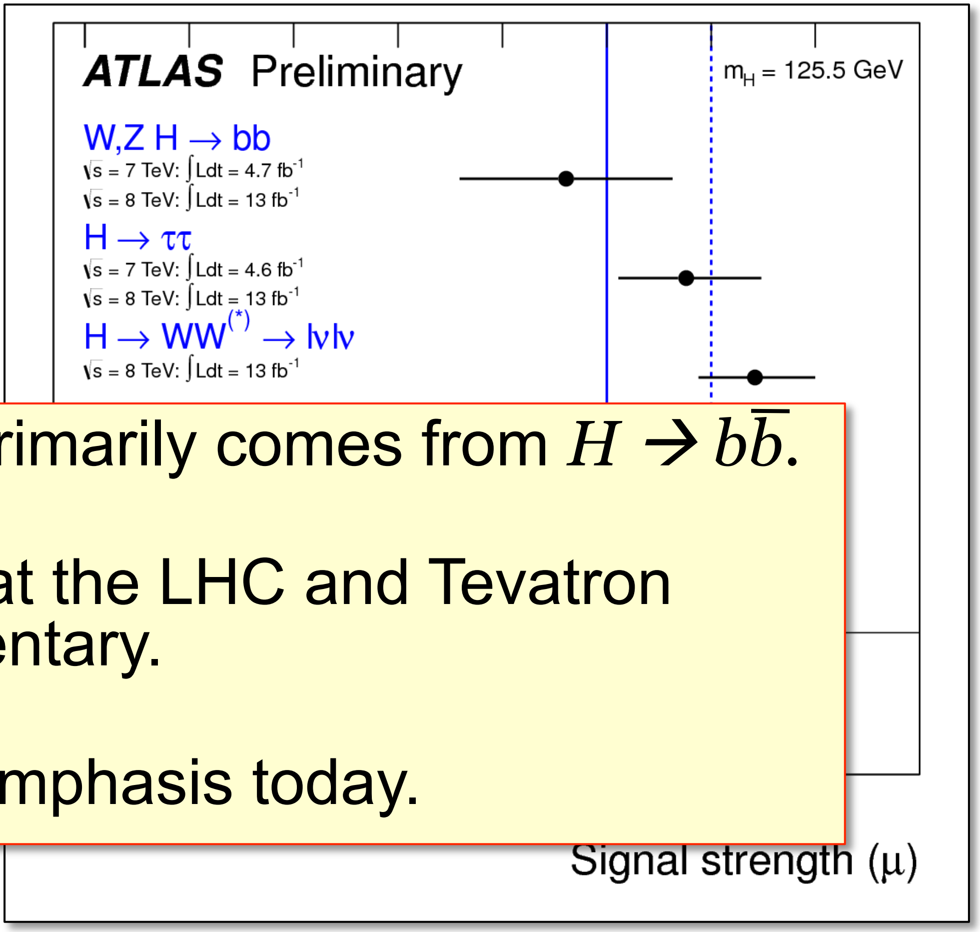
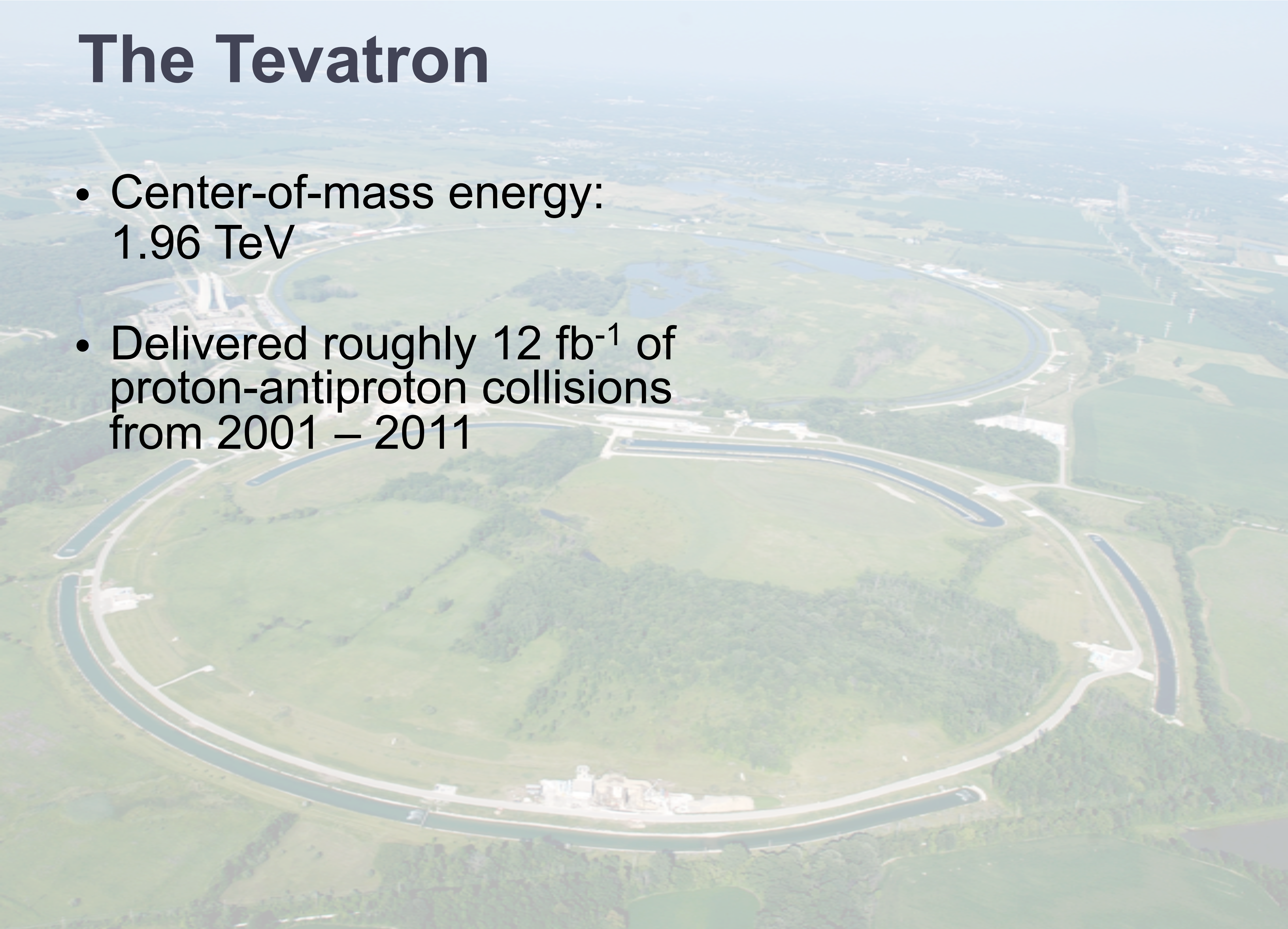




- Tevatron sensitivity primarily comes from $H \rightarrow b\bar{b}$.
- Primary sensitivities at the LHC and Tevatron *have been* complementary.
- $H \rightarrow b\bar{b}$ will receive emphasis today.

The Tevatron



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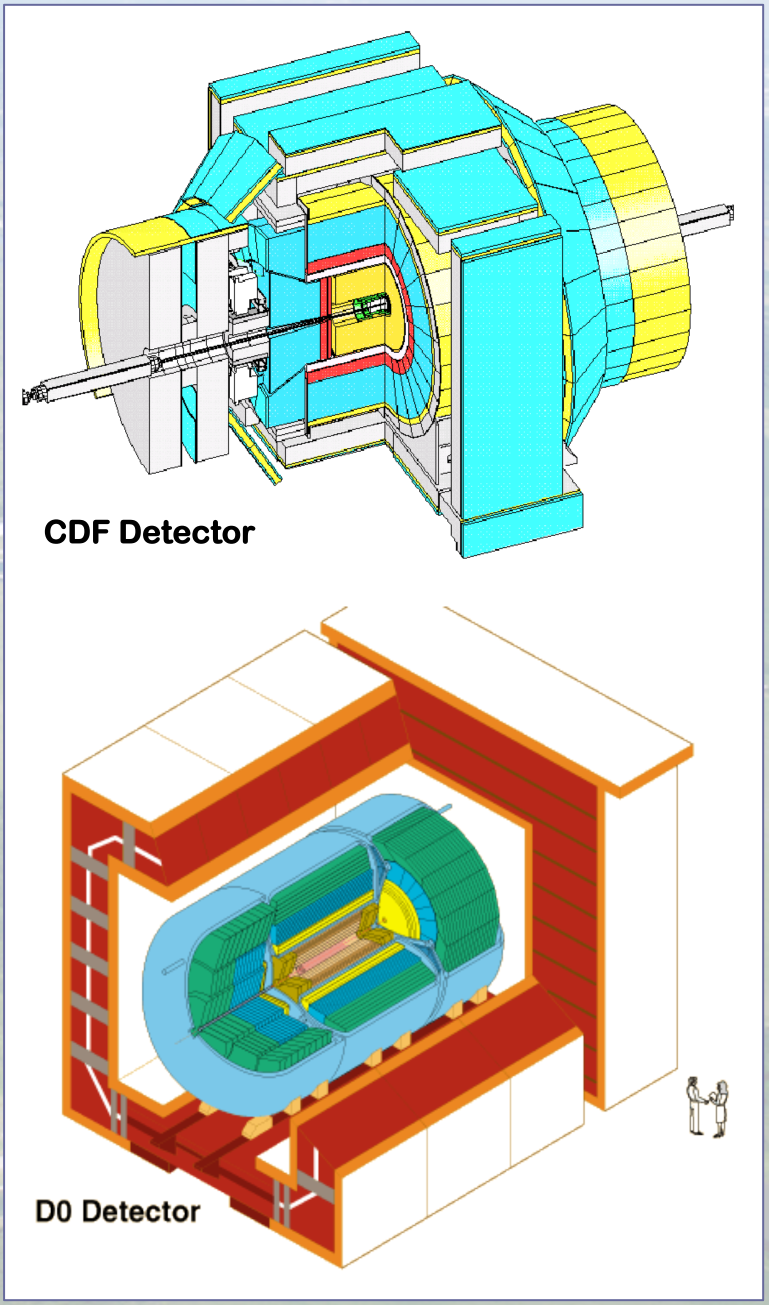
The Tevatron & Experiments

- 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}**



Searching for the Higgs

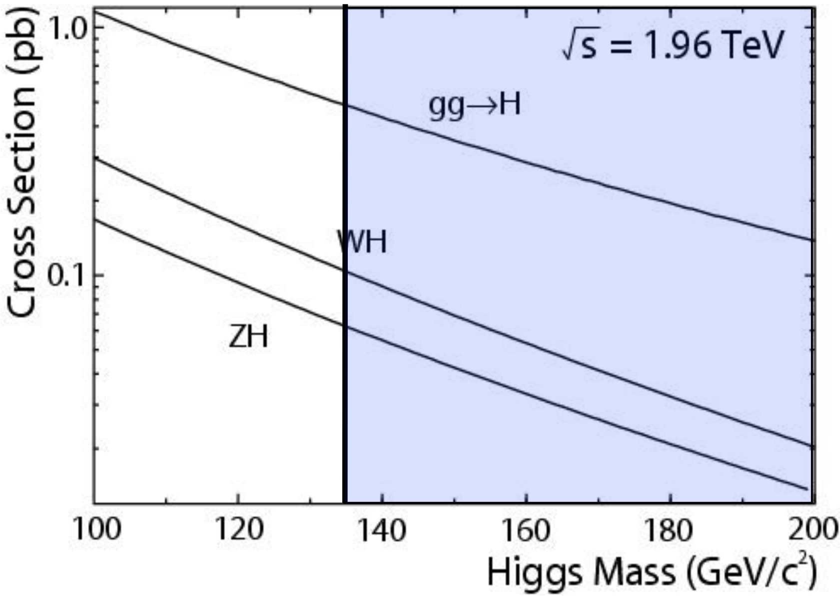
- Higgs production cross-sections are *very* small
  - (0.01 to 1) pb
- Look in production modes/decay channels with:
  - High statistics: $\sigma_H \times \mathcal{B}(H \rightarrow X)$
  - Low background: Clean Events
- Search Channels at the Tevatron:
  - High-mass Higgs (m_H > 135 GeV)

    $$gg \rightarrow H \rightarrow W^+W^-$$

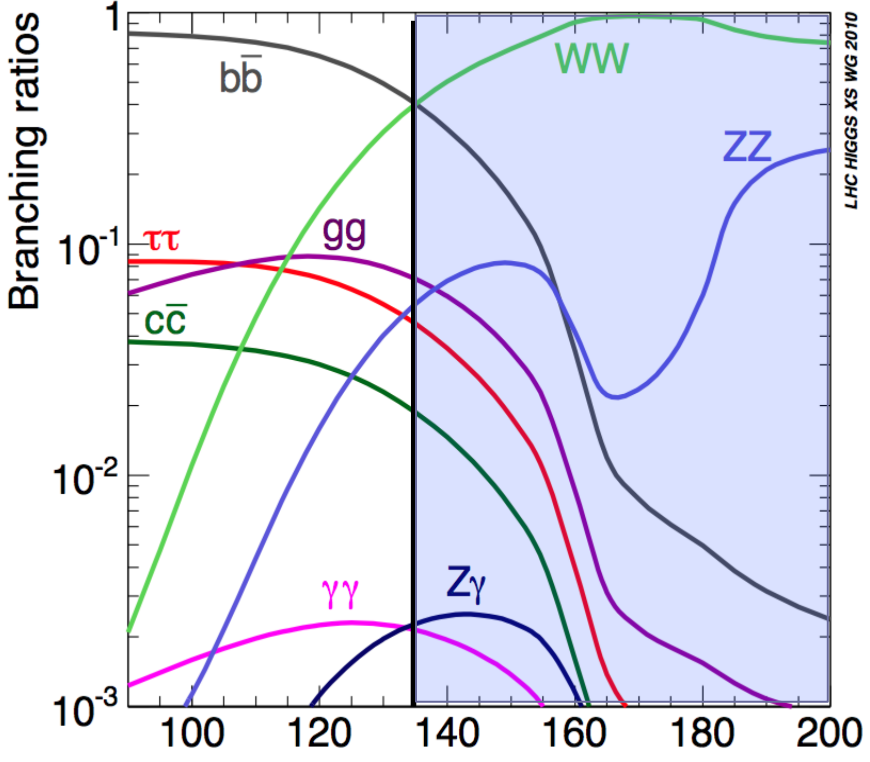
  - Low-mass Higgs (m_H < 135 GeV)

    $$VH \rightarrow \text{Leptons} + b\bar{b}$$

Higgs Production

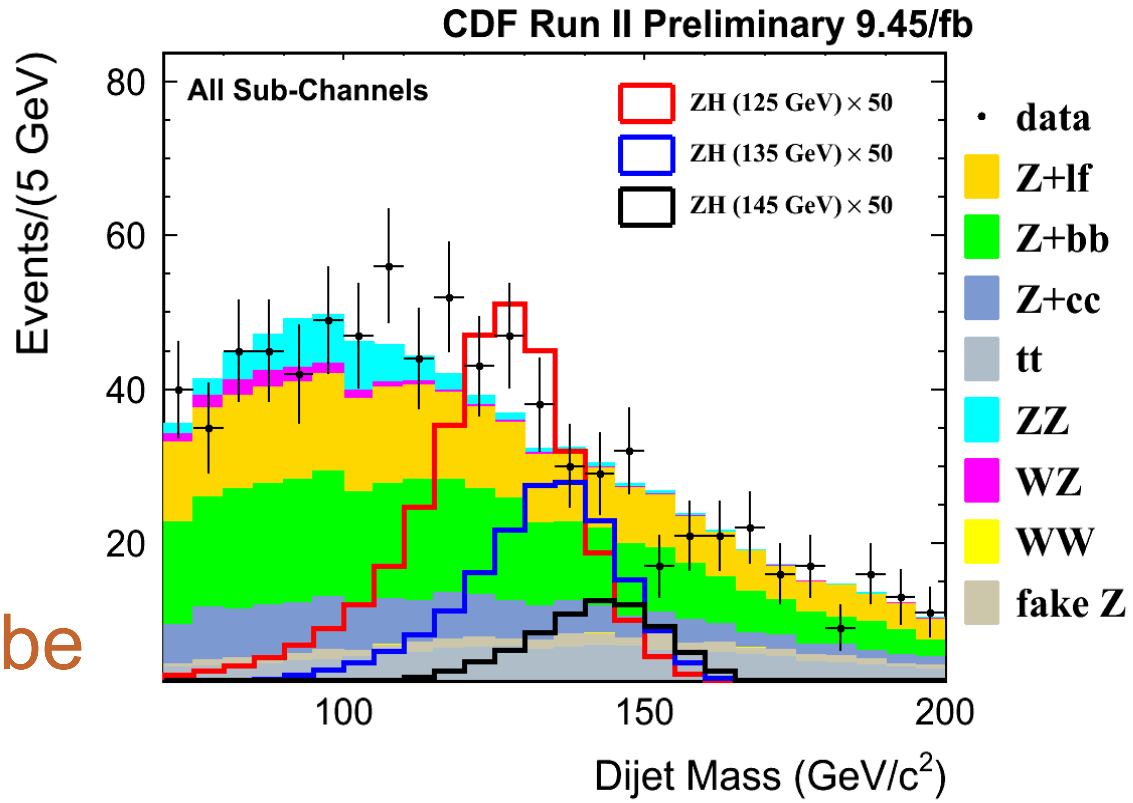


Higgs Decay

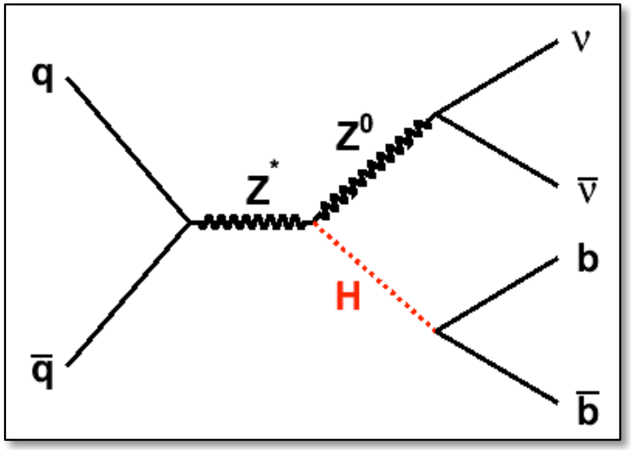


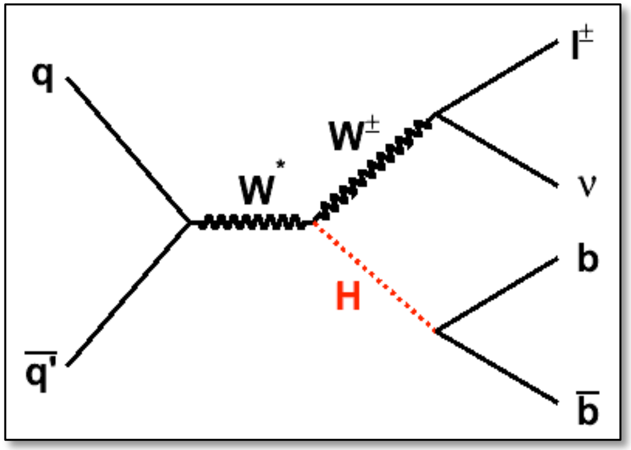
At the Tevatron…

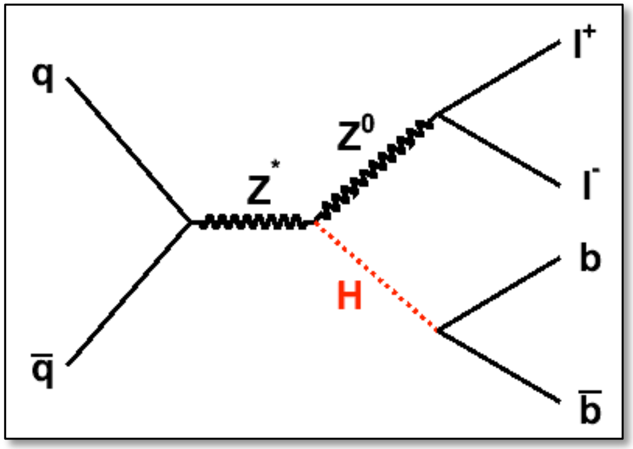
- Cross section for Higgs production is much smaller than at the LHC
- You aren't going to see a beautiful bump in the *dijet* mass for $H \rightarrow b\bar{b}$ searches.
    - Not enough events
    - Jet-energy resolution
    - Final-state radiation
- Significant overlap between Higgs mass hypotheses
    - Any $H \rightarrow b\bar{b}$ signal will be very broad



$H \rightarrow b\bar{b}$ searches





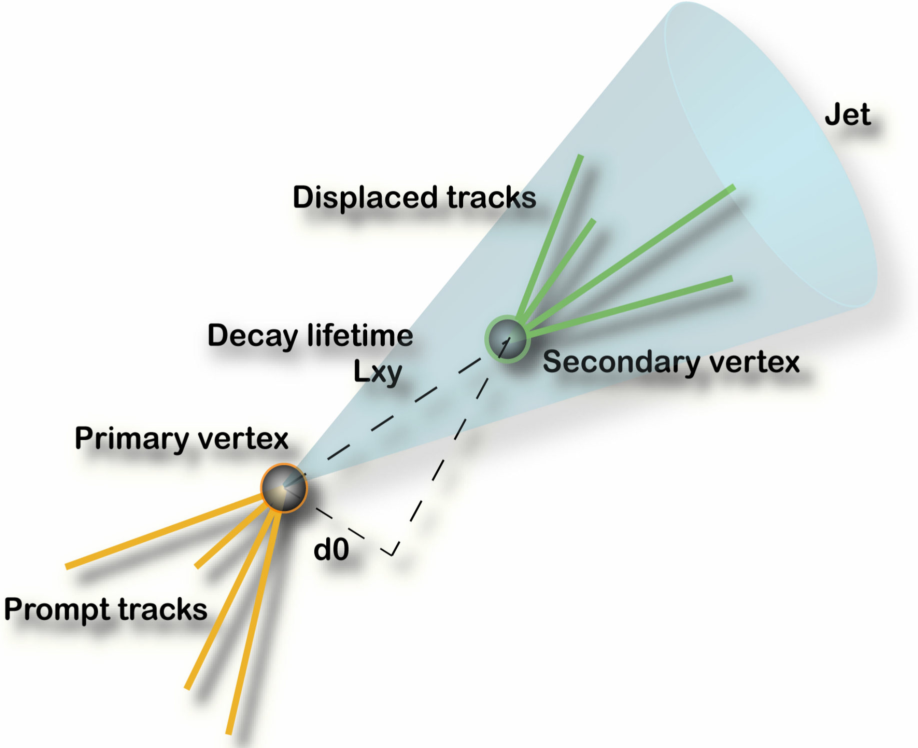


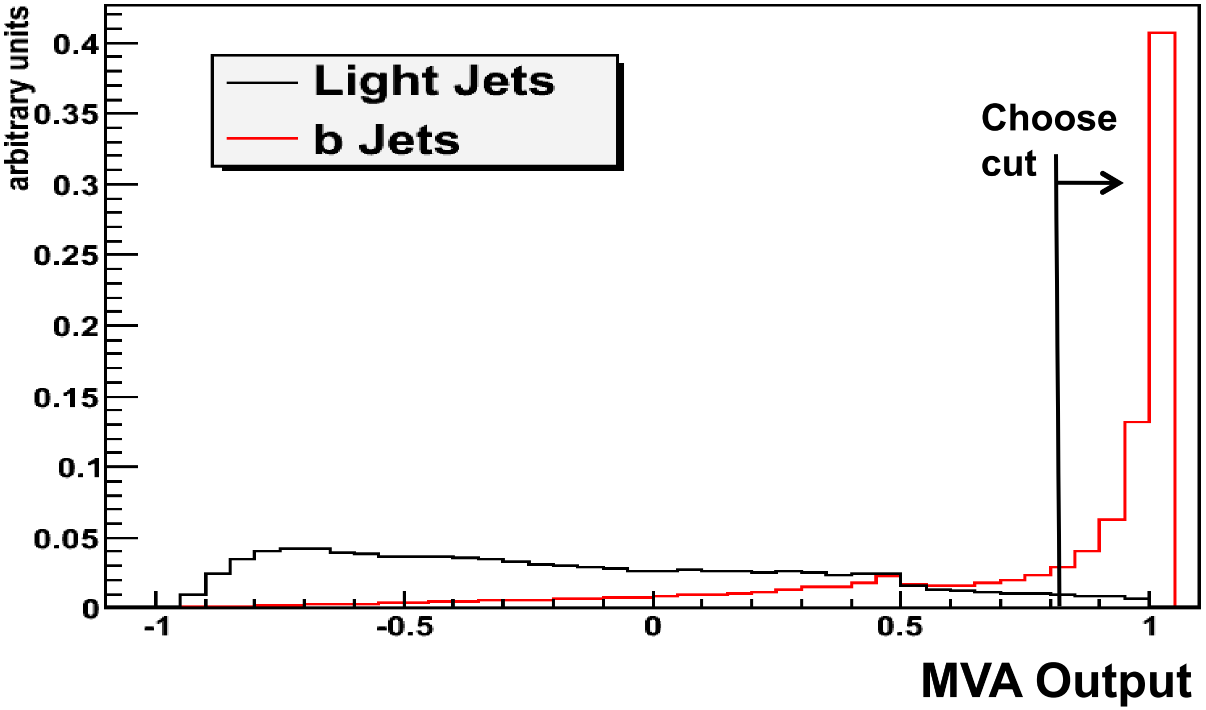
Analysis	No. of Leptons	Missing E_T ?	No. of b-Jets
$ZH \rightarrow \nu\bar{\nu} + b\bar{b}$	0	Yes	2
$WH \rightarrow \ell\nu + b\bar{b}$	1	Yes	2
$ZH \rightarrow \ell^+\ell^- + b\bar{b}$	2	No	2

- 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 heavy-flavor jets, using discriminating variables (e.g.) :
  - Displaced vertex (L_{xy}, d_0)
  - Jet mass
  - Distribution of tracks within the jet cone





	New Taggers	Old Taggers
B-tag eff.	60 %	50 %
Fake rate	1 %	1 %

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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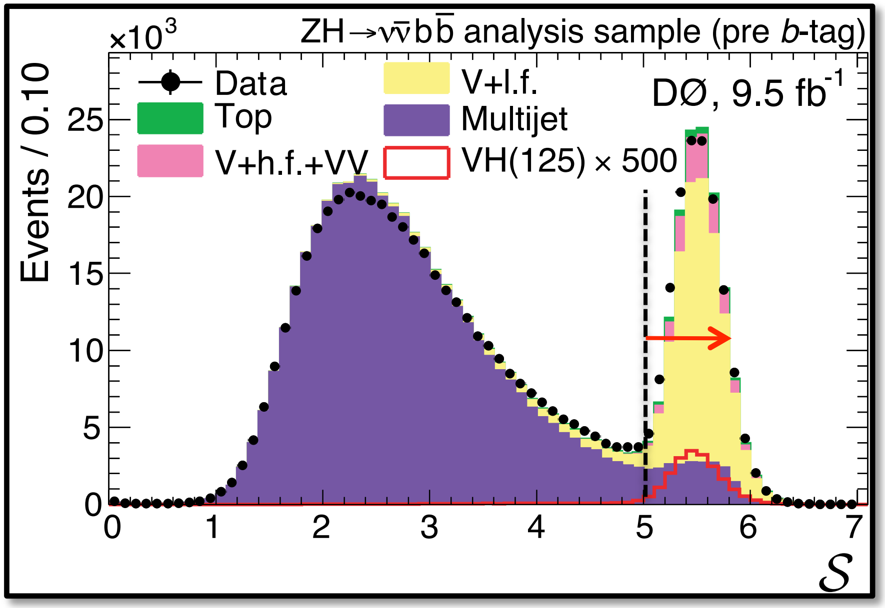

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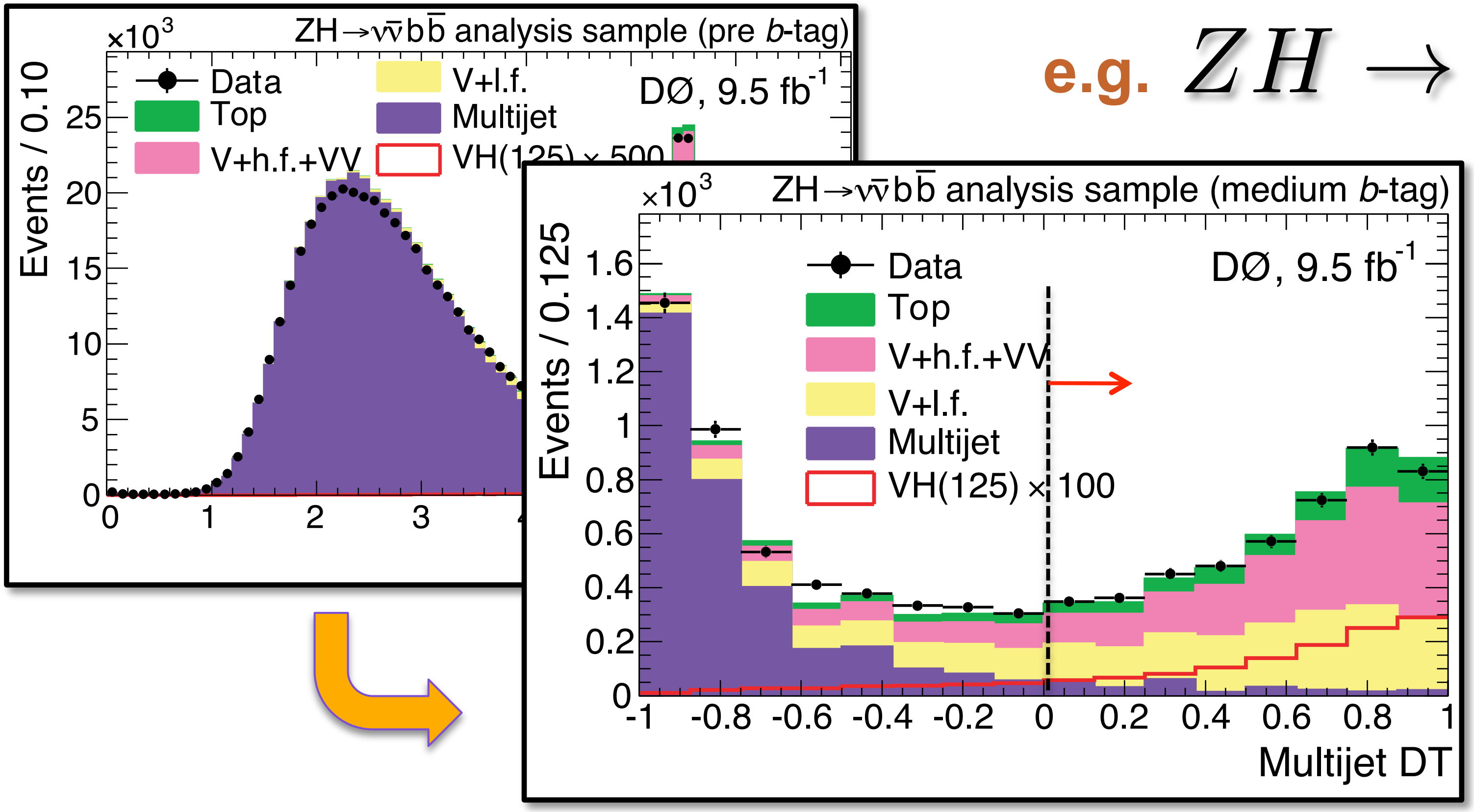

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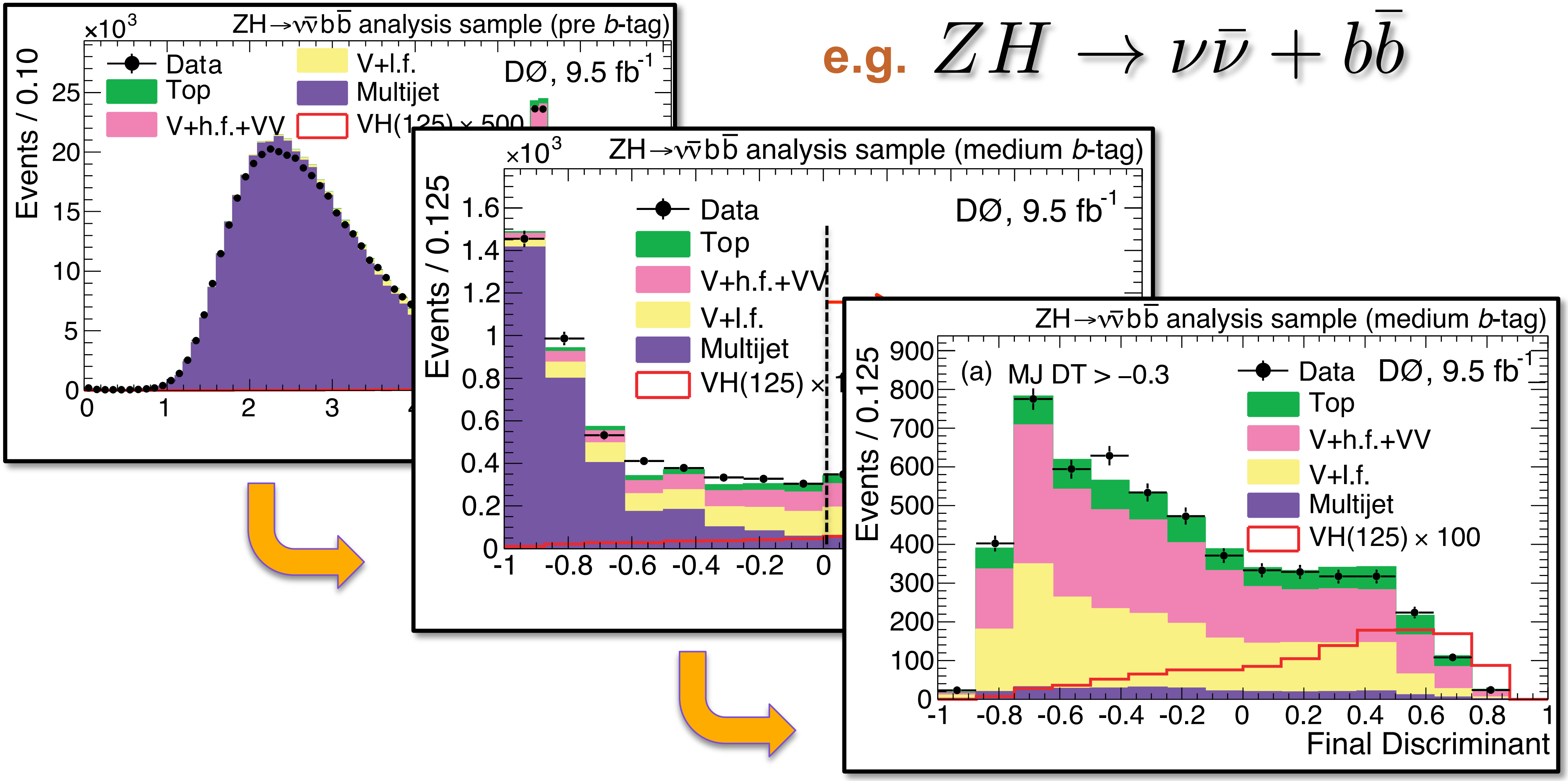

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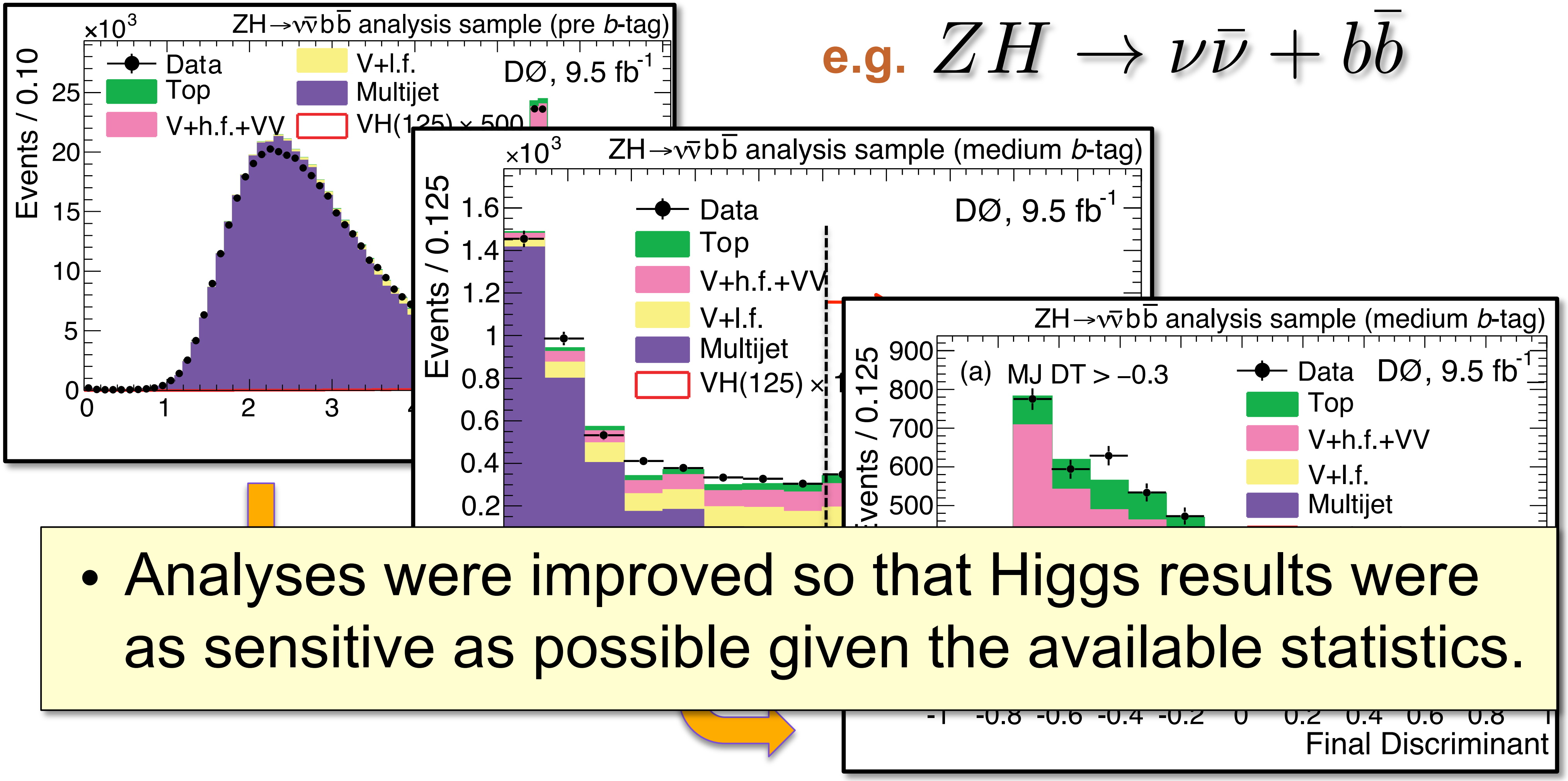
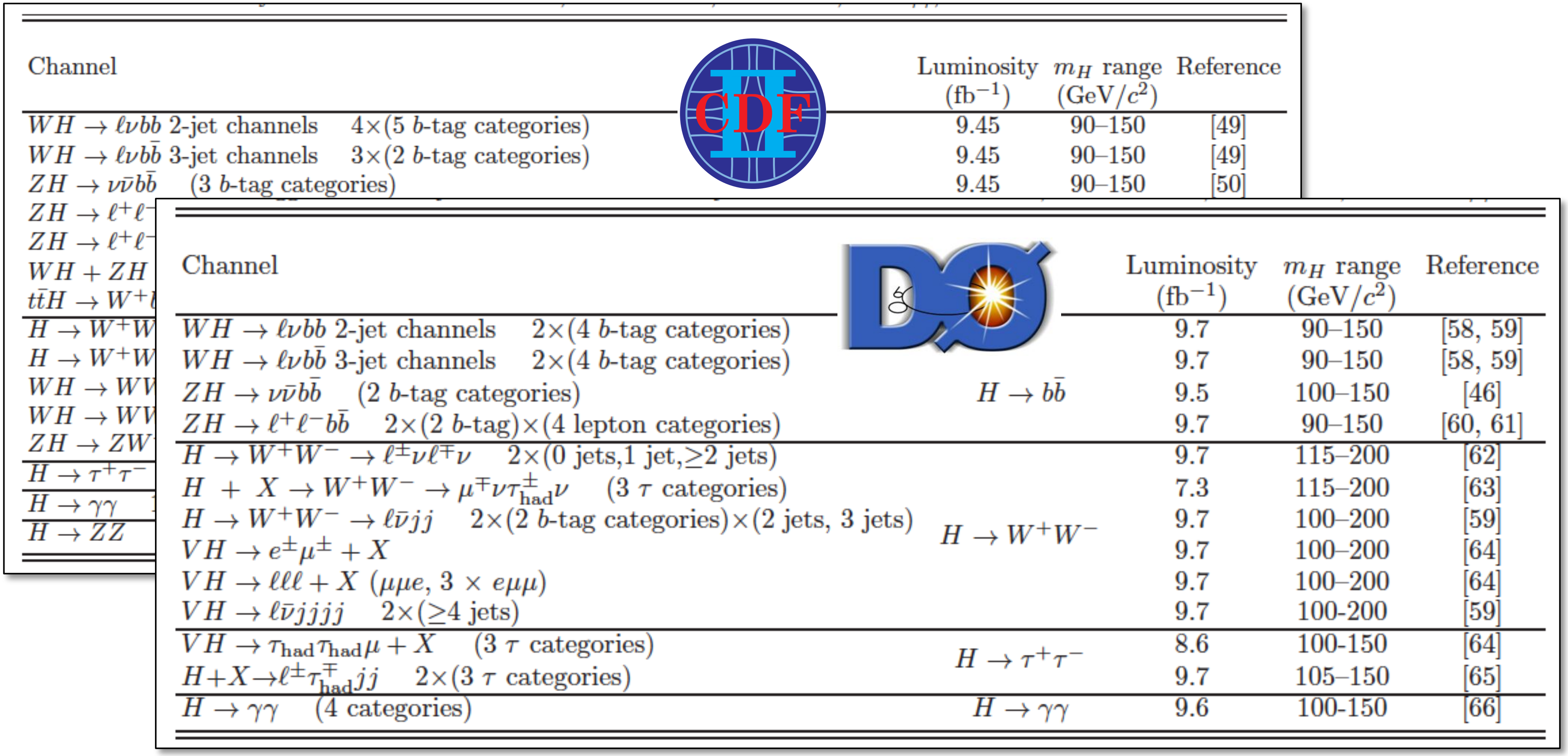


- Analyses were improved so that Higgs results were as sensitive as possible given the available statistics.

Analyses Included in the Combinations



Channel	Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 2-jet channels 4×(5 b-tag categories)	9.45	90–150	[49]
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)	9.45	90–150	[49]
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)	9.45	90–150	[50]
$ZH \to \ell^+\ell^-$			
$ZH \to \ell^+\ell^-$			
$WH + ZH$			
$t\bar{t}H \to W^+$			
$H \to W^+W$			
$H \to W^+W$			
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$ZH \to ZW$			
$H \to \tau^+\tau^-$			
$H \to \gamma\gamma$			
$H \to ZZ$			

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)	Reference
$WH \to \ell\nu bb$ 2-jet channels 2×(4 b-tag categories)		9.7	90–150	[58, 59]
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$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)	$H \to b\bar{b}$	9.5	100–150	[46]
$ZH \to \ell^+\ell^-b\bar{b}$ 2×(2 b-tag)×(4 lepton categories)		9.7	90–150	[60, 61]
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ 2×(0 jets,1 jet,≥2 jets)		9.7	115–200	[62]
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{\mathrm{had}}\nu$ (3 τ categories)		7.3	115–200	[63]
$H \to W^+W^- \to \ell\bar{\nu}jj$ 2×(2 b-tag categories)×(2 jets, 3 jets)	$H \to W^+W^-$	9.7	100–200	[59]
$VH \to e^\pm\mu^\pm + X$		9.7	100–200	[64]
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$VH \to \tau_{\mathrm{had}}\tau_{\mathrm{had}}\mu + X$ (3 τ categories)	$H \to \tau^+\tau^-$	8.6	100-150	[64]
$H{+}X{\to}\ell^\pm\tau^\mp_{\mathrm{had}}jj$ 2×(3 τ categories)		9.7	105–150	[65]
$H \to \gamma\gamma$ (4 categories)	$H \to \gamma\gamma$	9.6	100-150	[66]

Roughly 30 independent analysis channels included in Tevatron combination

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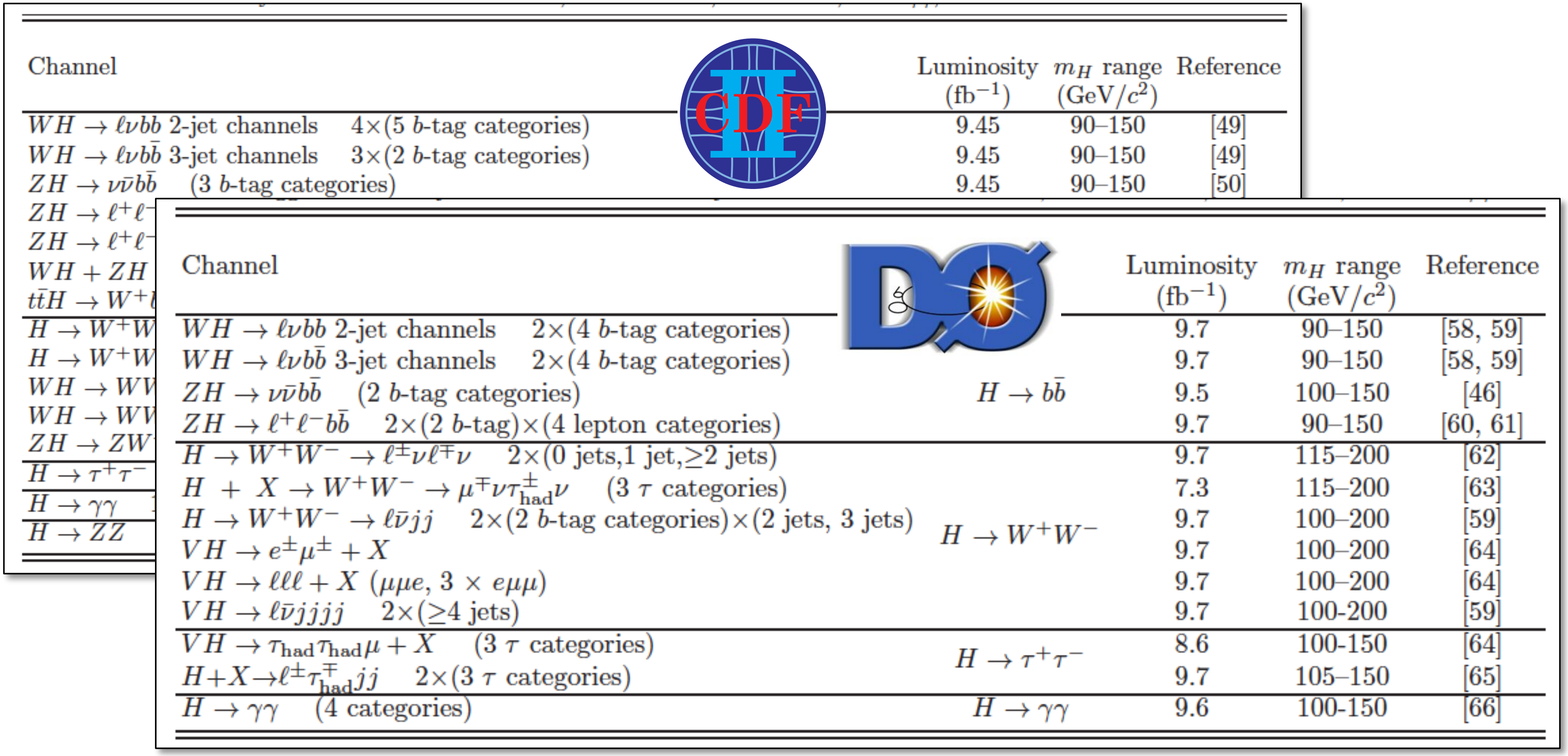

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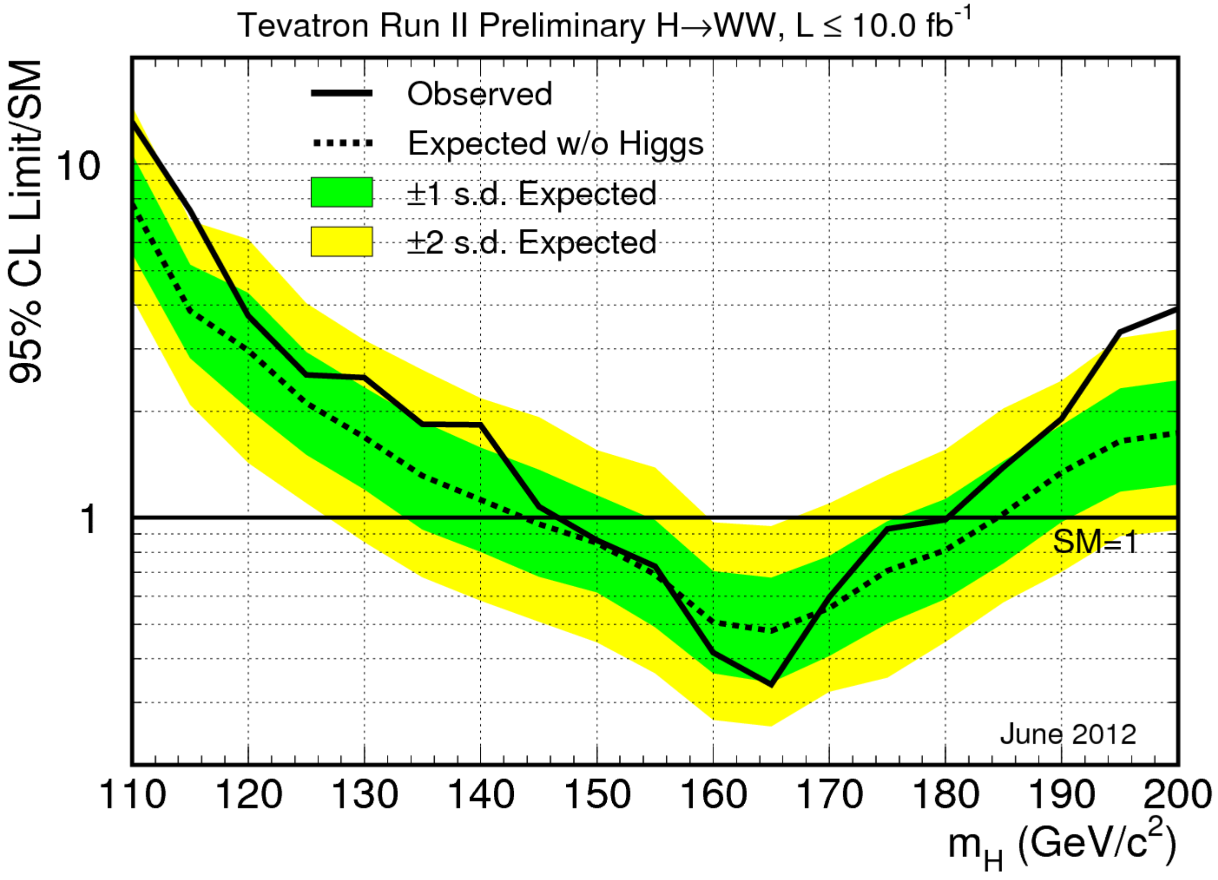
Almost all analyses published with full Tevatron data set!

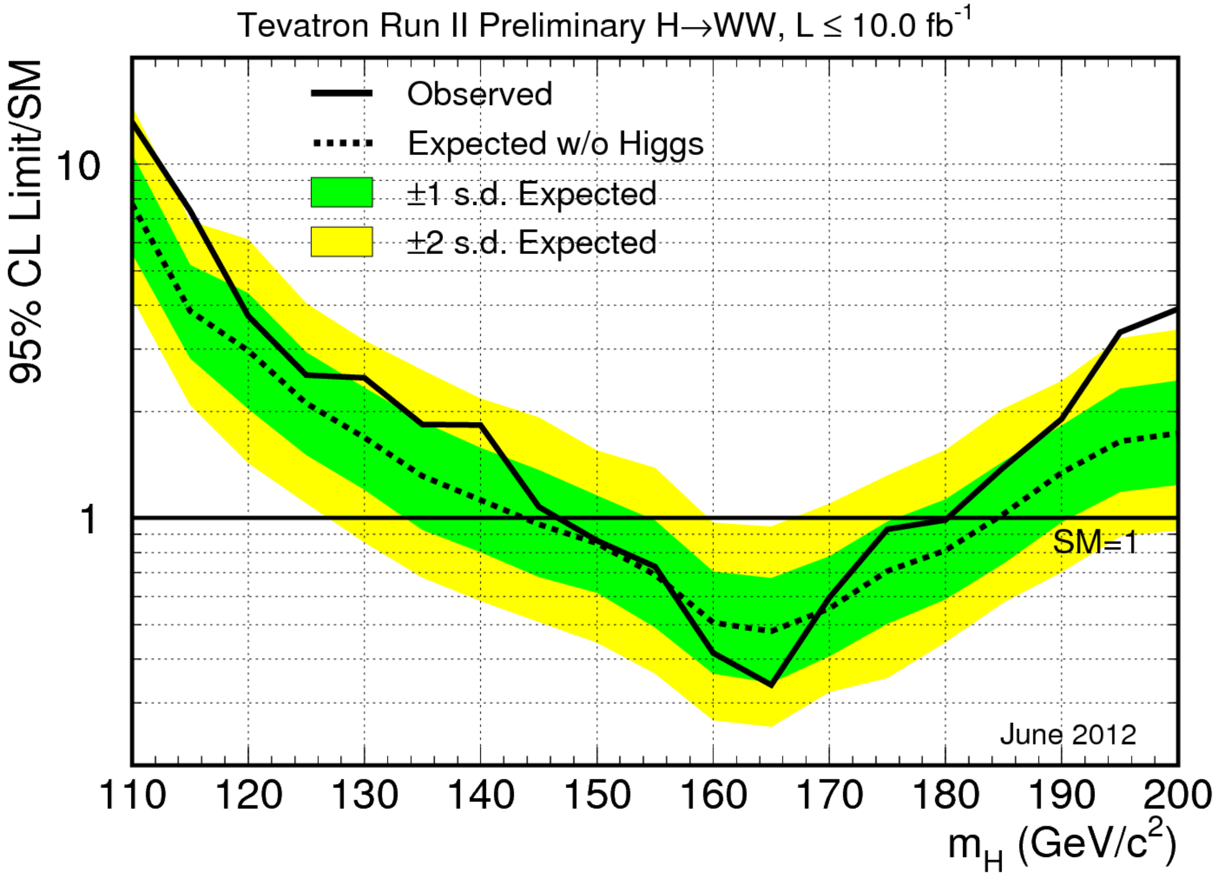
Tevatron Final Combinations

A Limit Plot


Tevatron Run II Preliminary H→WW, L ≤ 10.0 fb^{-1}
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
95% CL Limit/SM
10
1
SM=1
June 2012
110
120
130
140
150
160
170
180
190
200
m$_H$ (GeV/c^2)

A Limit Plot

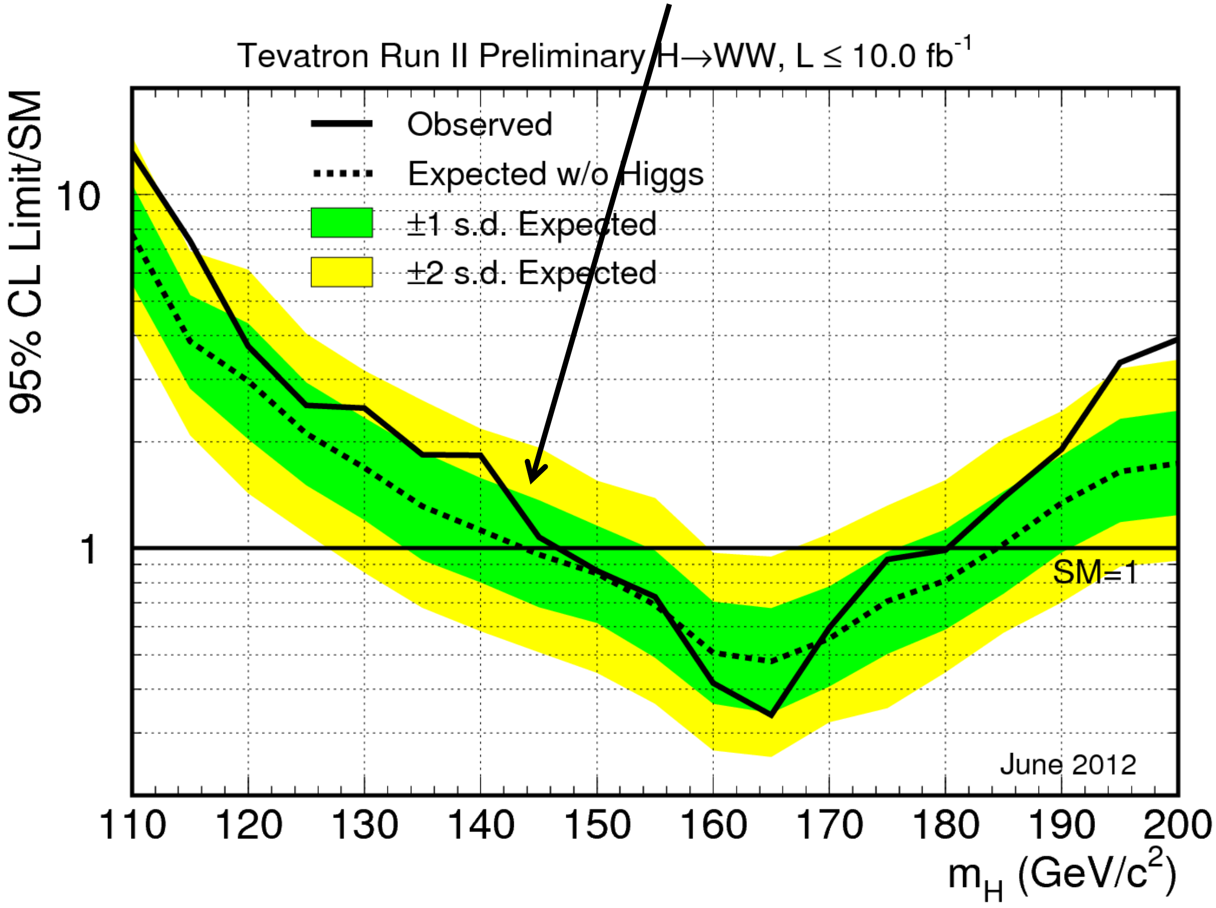
1. Upper cross section limit for Higgs production relative to SM prediction



A Limit Plot

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

2. Observed limit (solid line) from data



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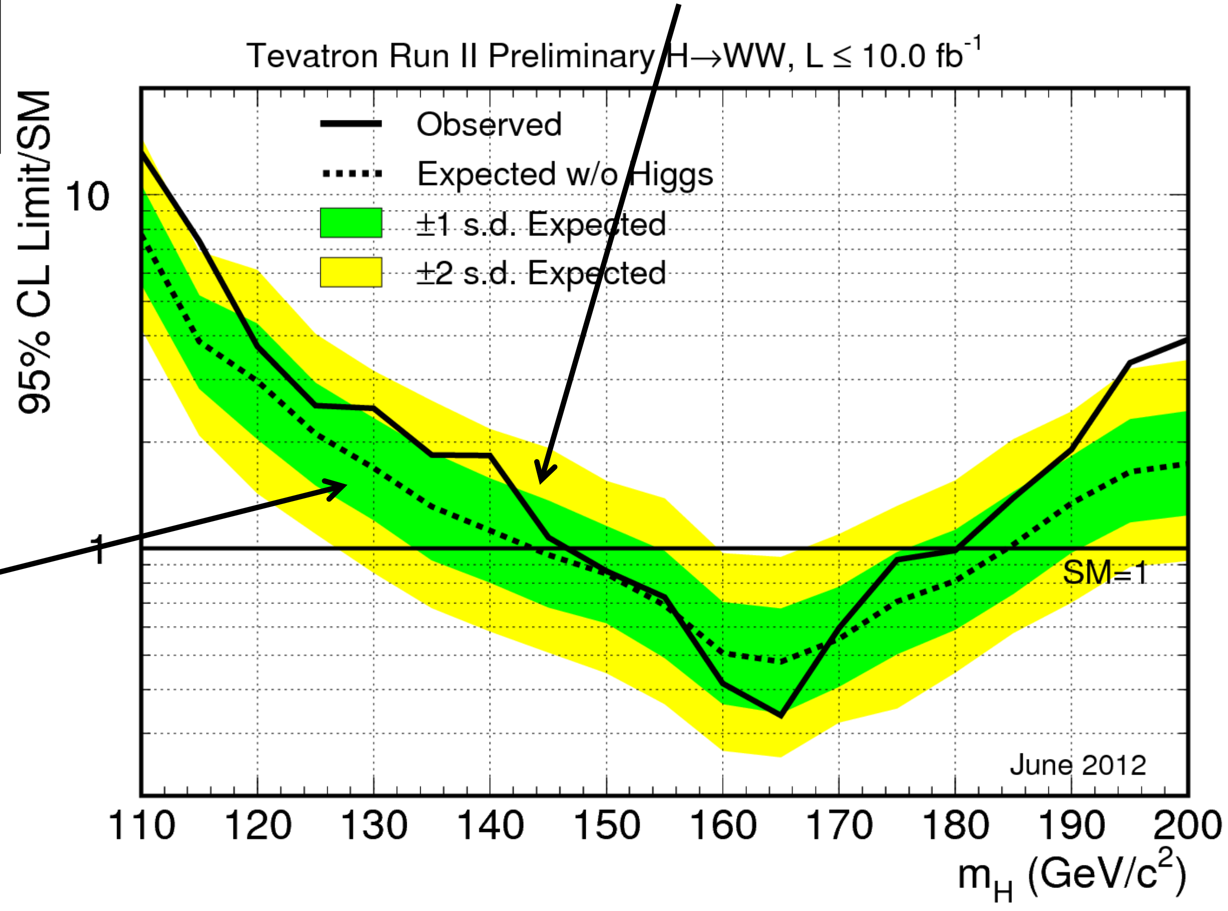

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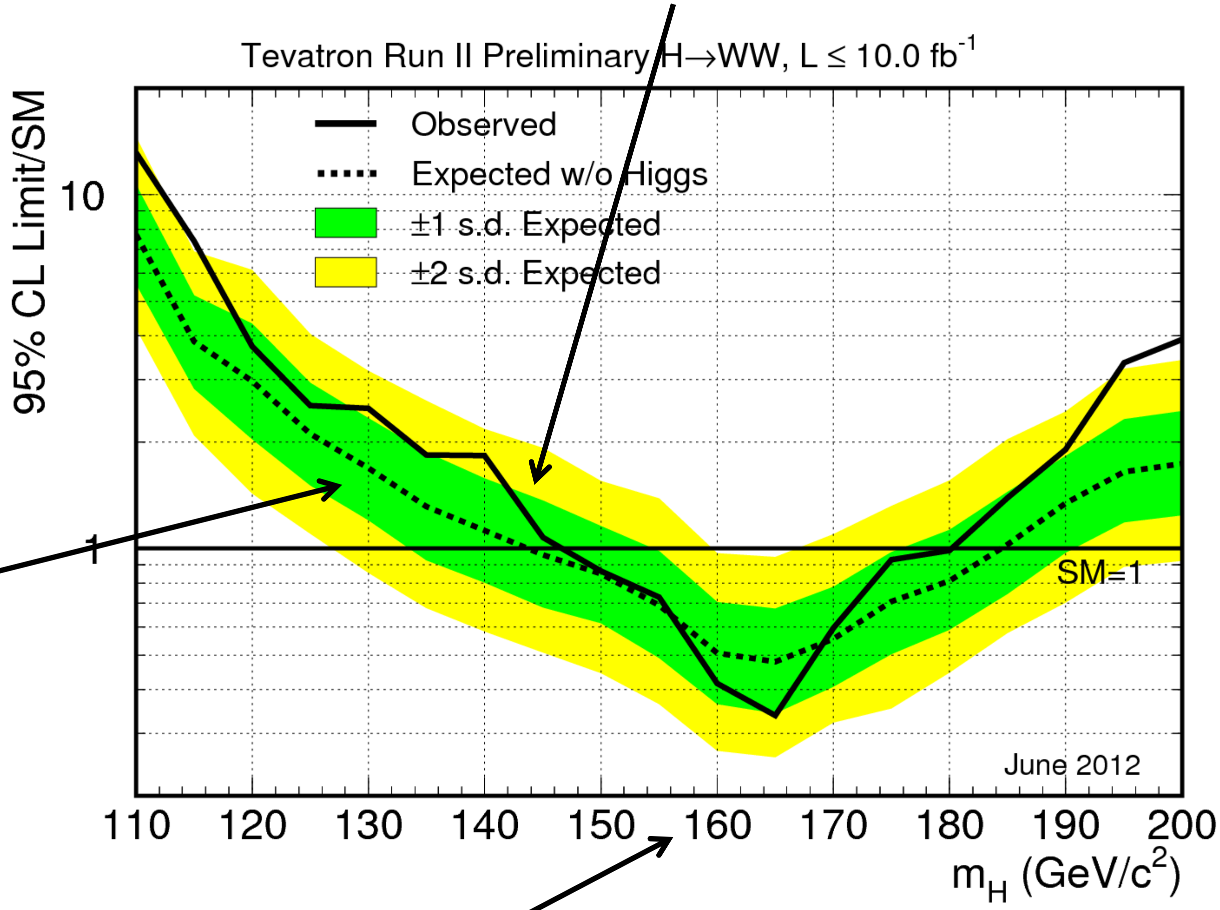
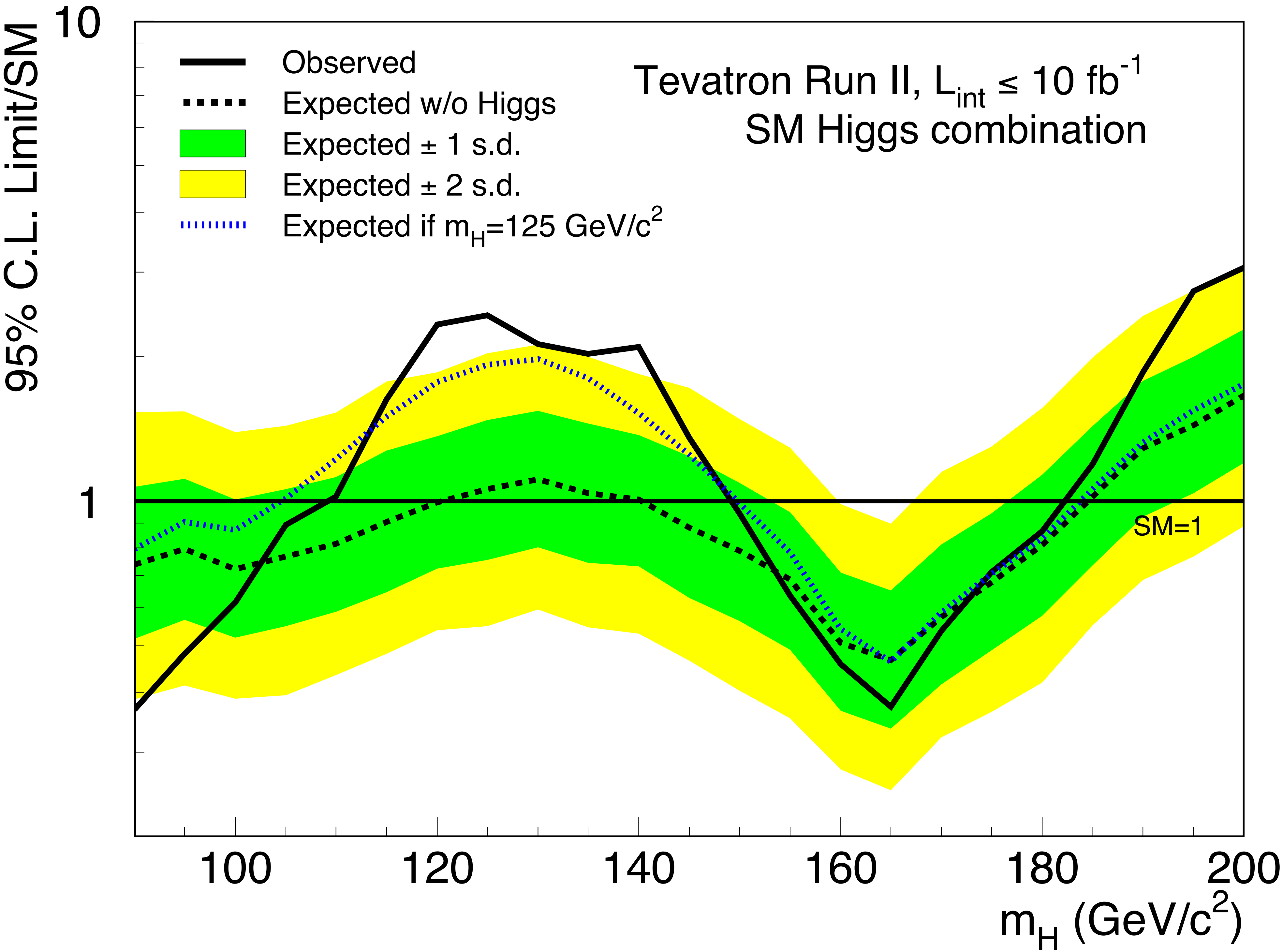
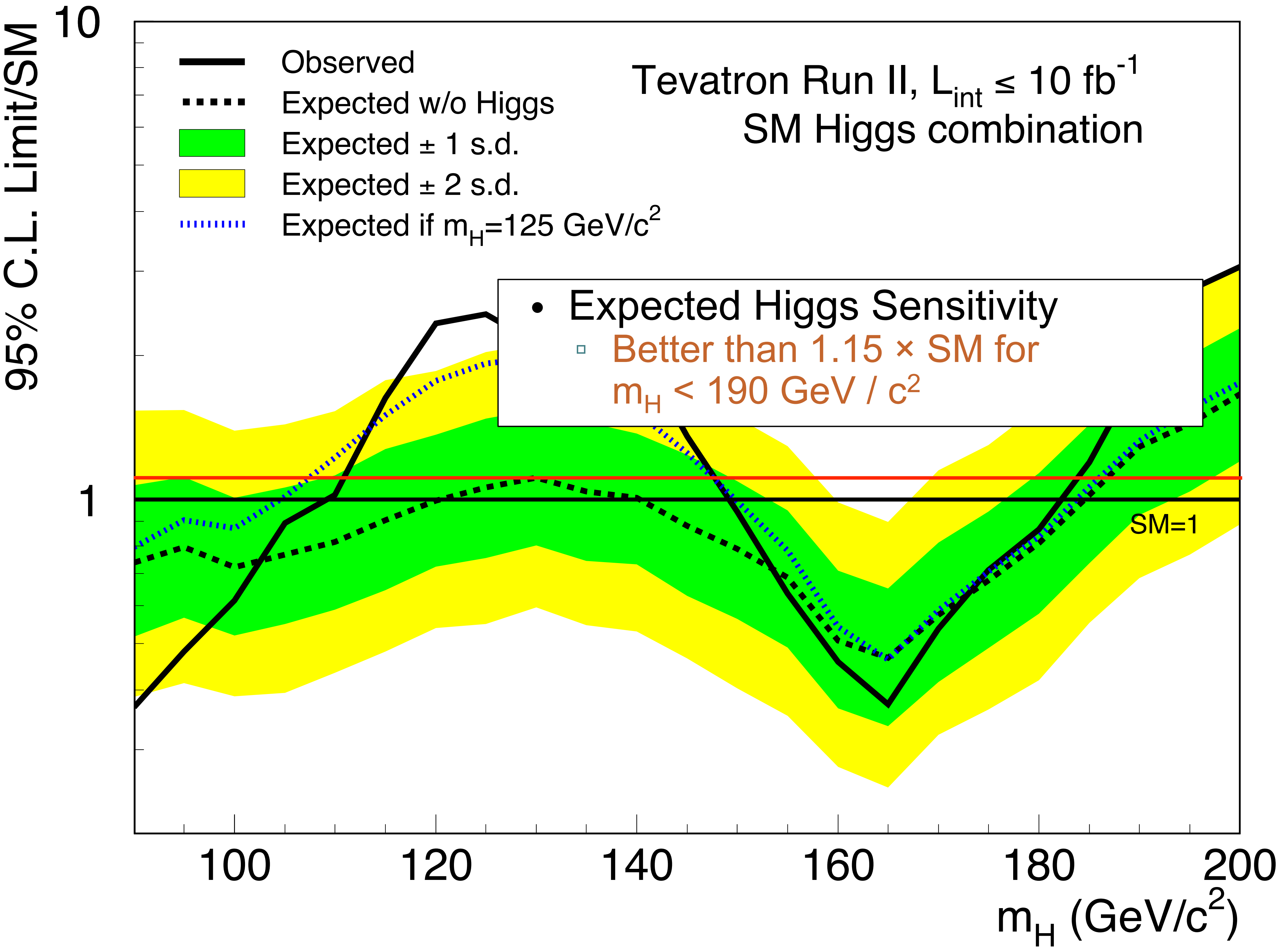


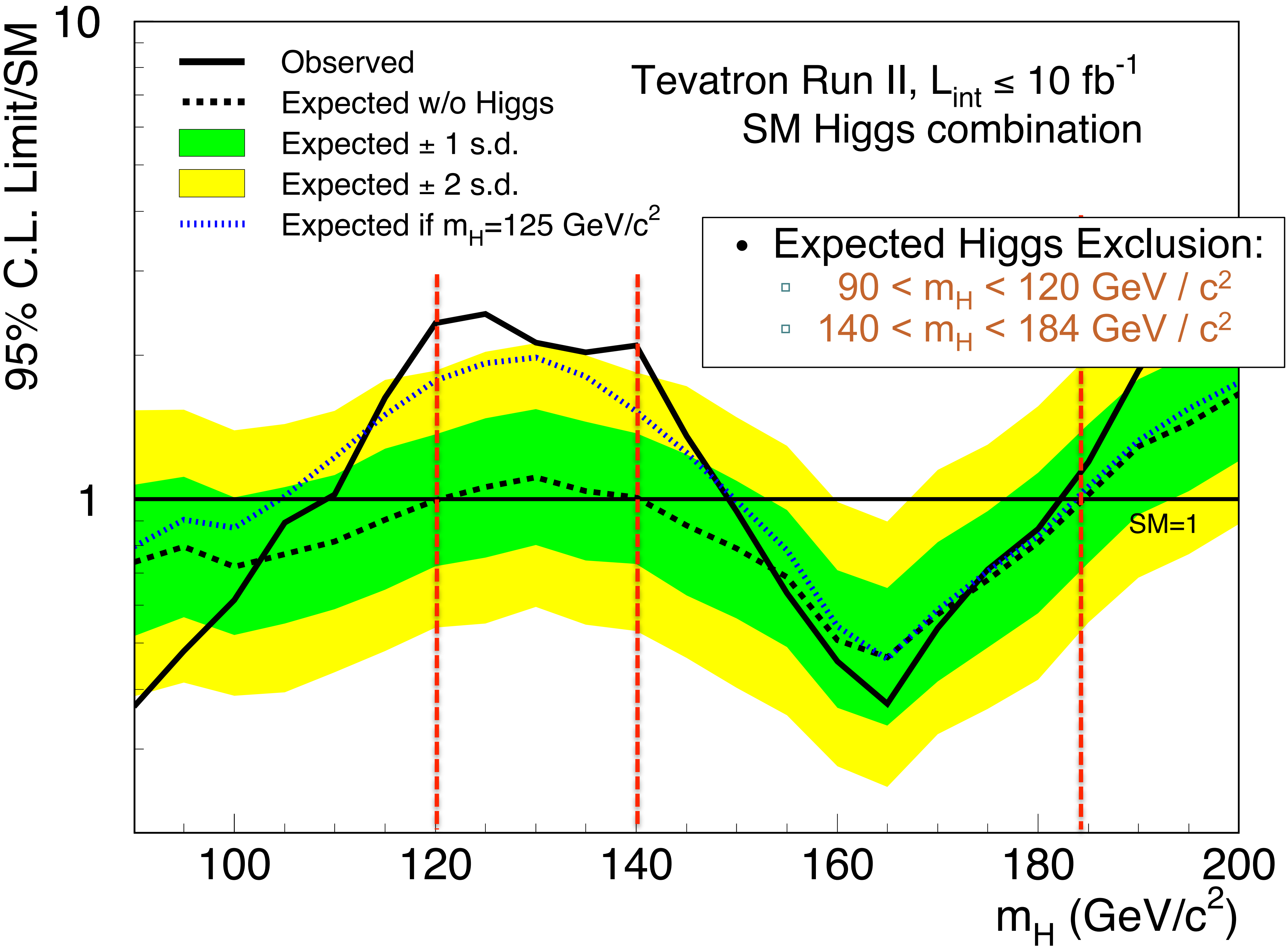
3. Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

4. Analysis repeated using *<u>different signal discriminants</u>* for each m_H in 5 GeV steps

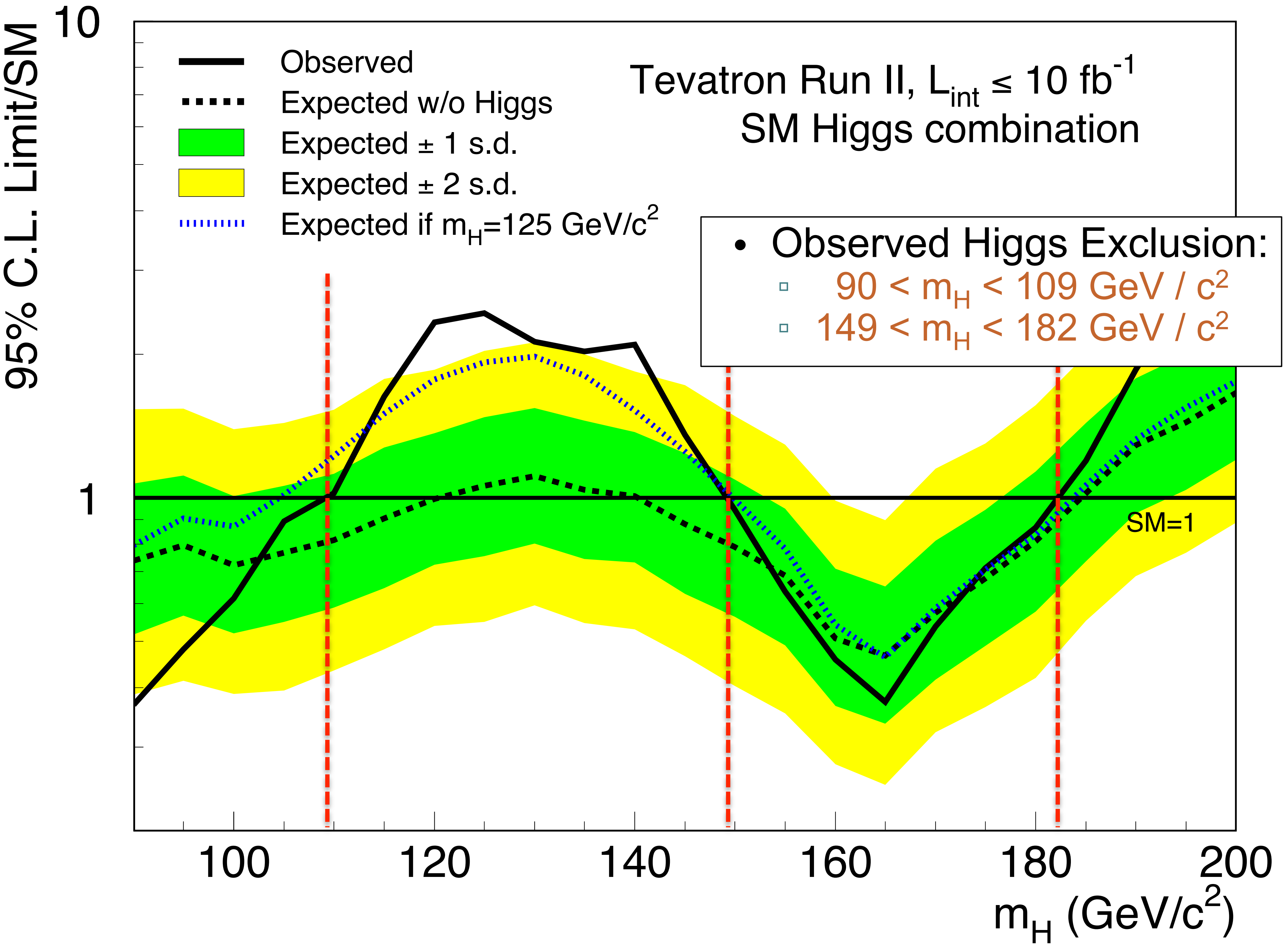

Observed
Expected w/o Higgs
Expected ± 1 s.d.
Expected ± 2 s.d.
Expected if m_H=125 GeV/c^2
Tevatron Run II, $L_{int} \leq 10$ fb^{-1}
SM Higgs combination
SM=1
95% C.L. Limit/SM
10
1
100
120
140
160
180
200
m_H (GeV/c^2)



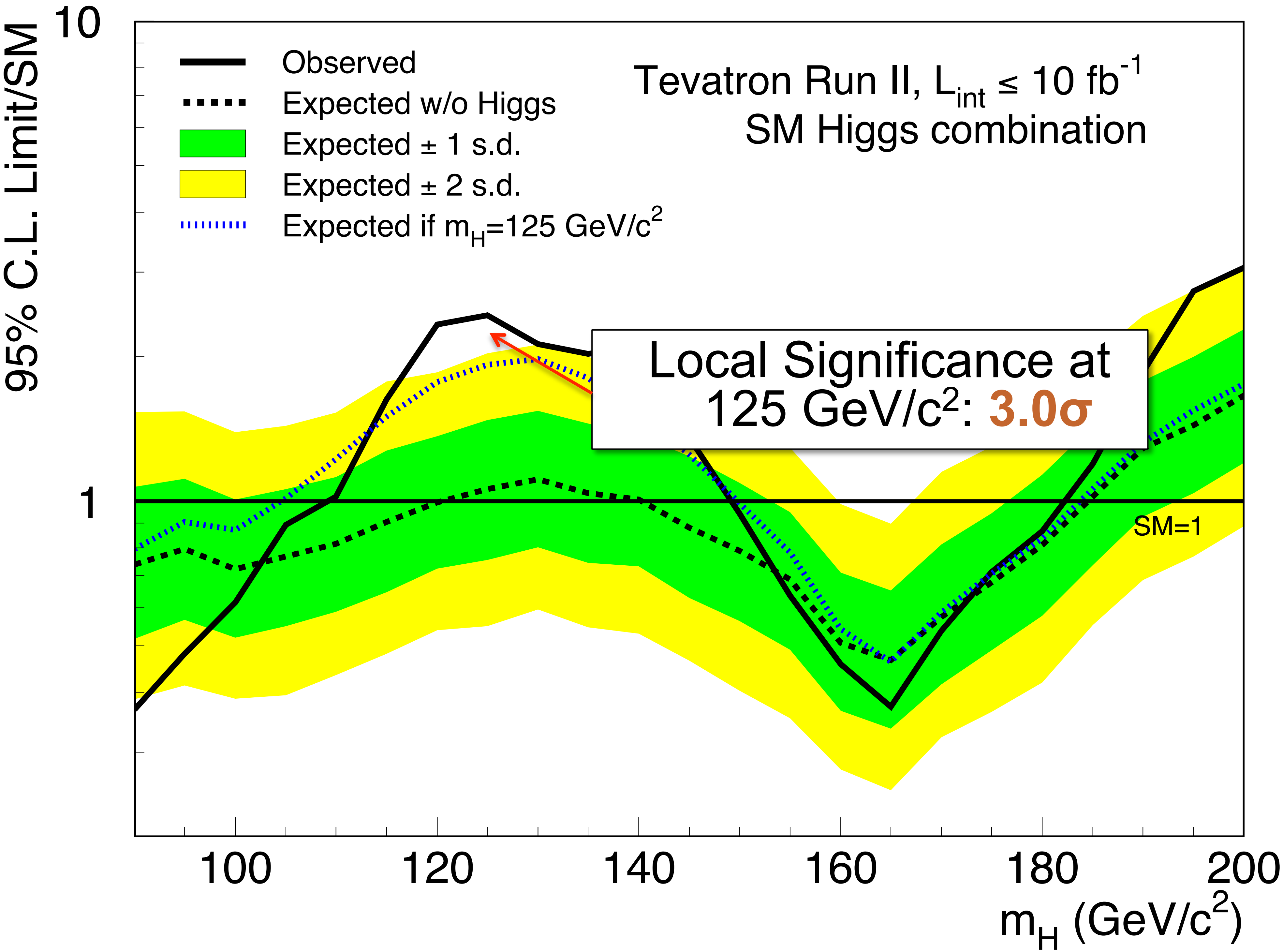
- Expected Higgs Sensitivity
  - Better than 1.15 × SM for m_H < 190 GeV / c^2



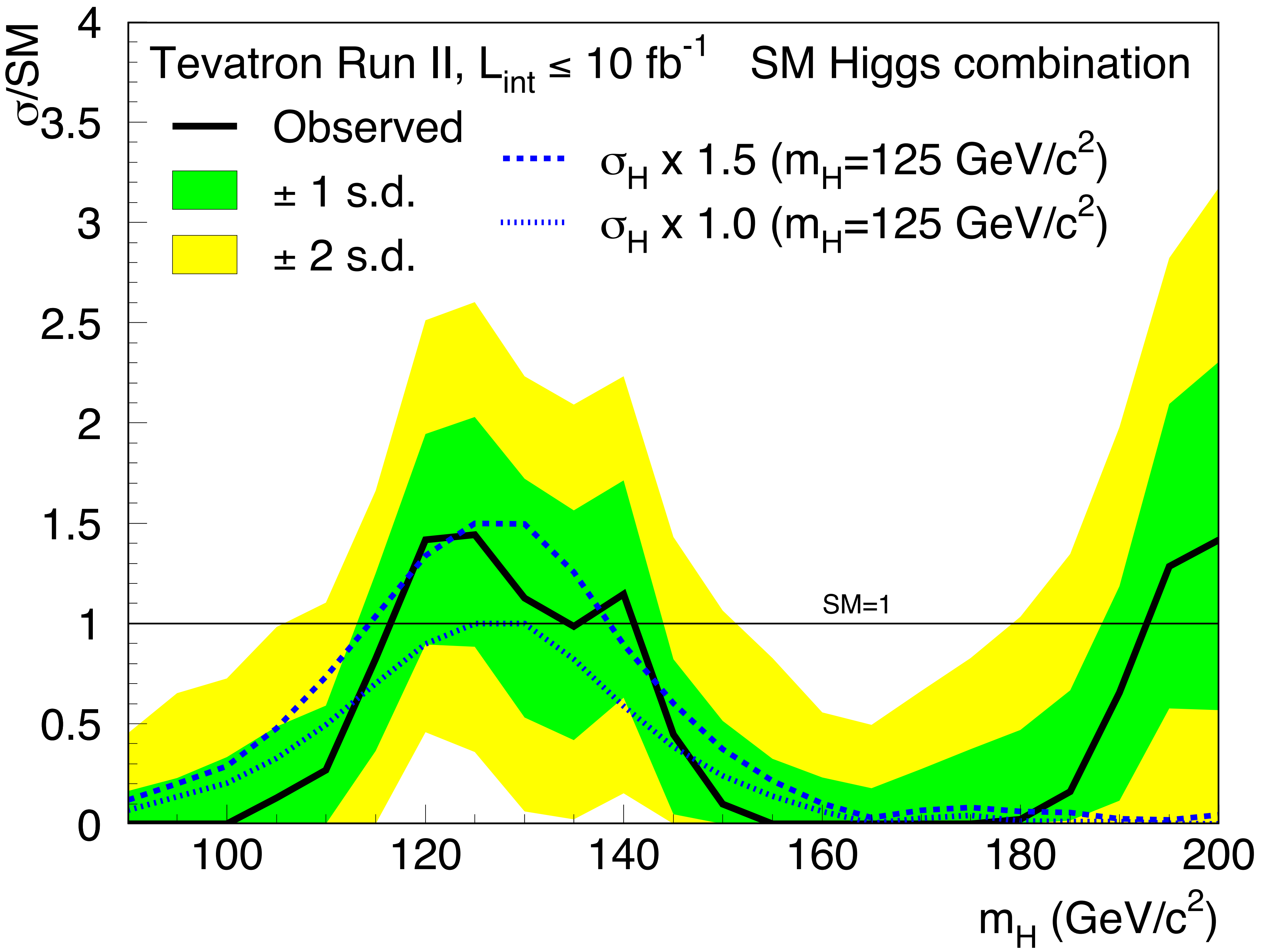
- Expected Higgs Exclusion:
  - $90 < m_H < 120$ GeV / c^2
  - $140 < m_H < 184$ GeV / c^2



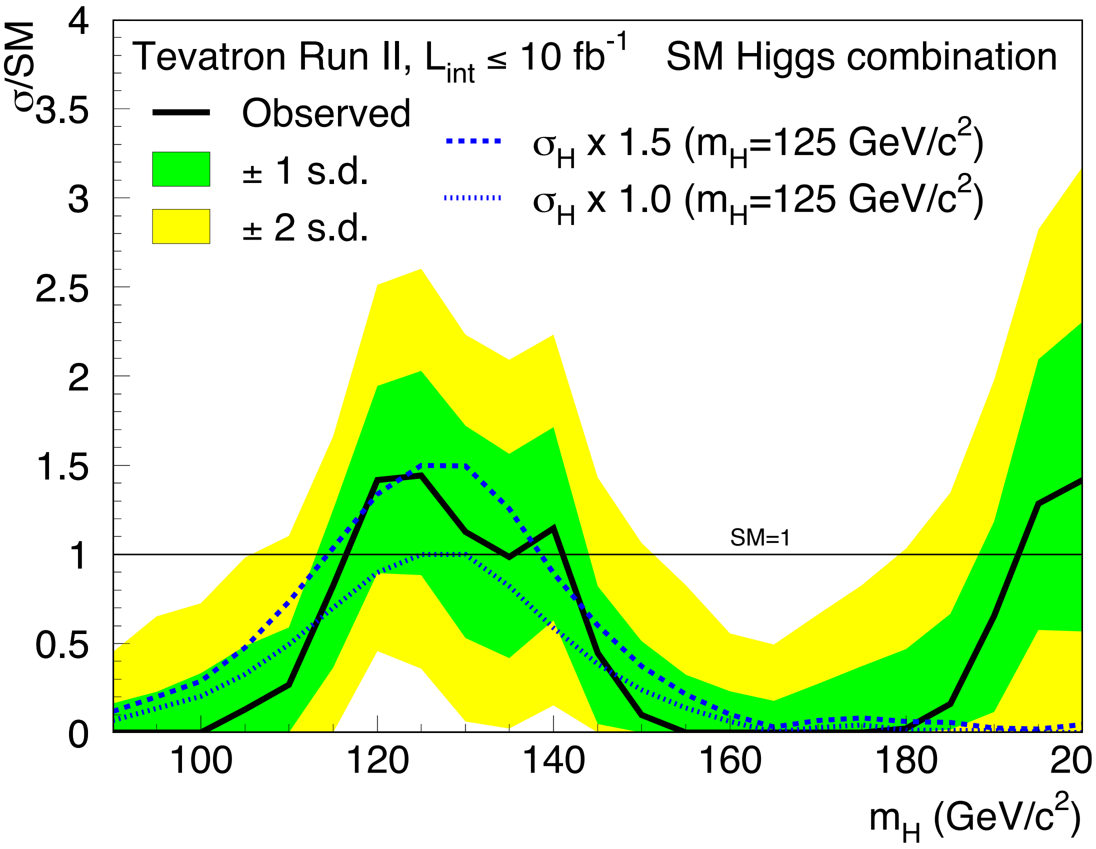
- Observed Higgs Exclusion:
  - $90 < m_H < 109$ GeV / c^2
  - $149 < m_H < 182$ GeV / c^2

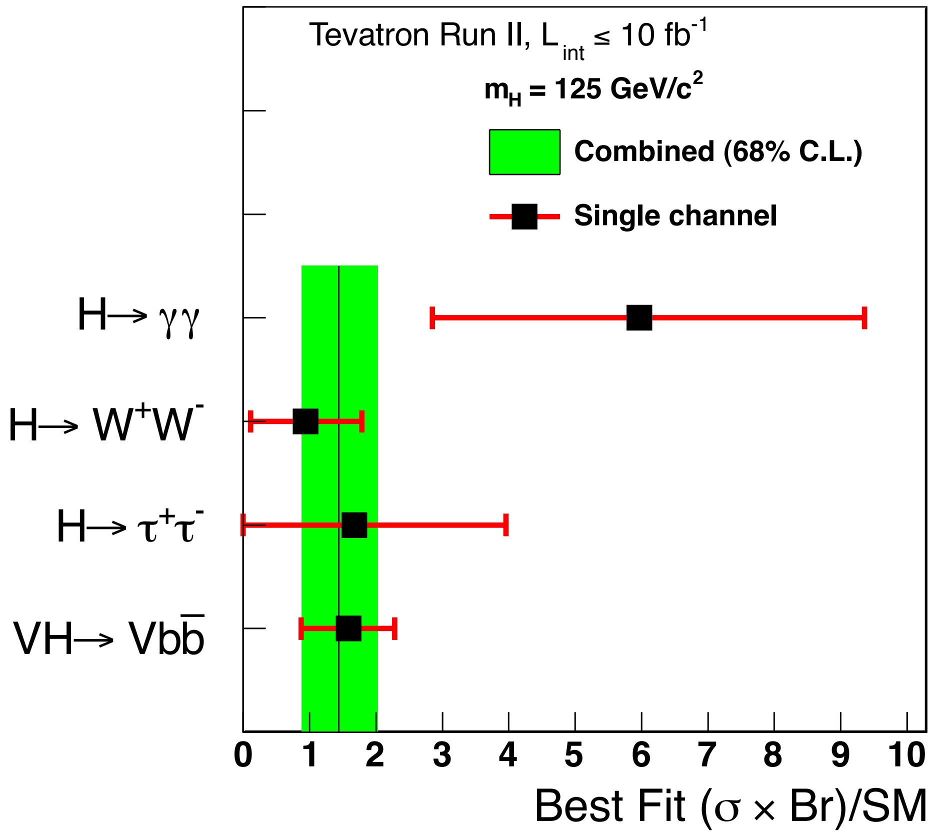


Local Significance at 125 GeV/c^2: **3.0σ**


Tevatron Run II, $L_{int} \leq 10$ fb^{-1} SM Higgs combination
Observed
± 1 s.d.
± 2 s.d.
σ_H x 1.5 (m_H=125 GeV/c^2)
σ_H x 1.0 (m_H=125 GeV/c^2)
SM=1
σ/SM
0
0.5
1
1.5
2
2.5
3
3.5
4
100
120
140
160
180
200
m_H (GeV/c^2)

Cross-section Measurements: Full





$H \to W^+W^- \quad 0.94^{+0.85}_{-0.83} \times \text{SM}$

$H \to \gamma\gamma \quad 5.97^{+3.39}_{-3.12} \times \text{SM}$

$H \to \tau^+\tau^- \quad 1.68^{+2.28}_{-1.68} \times \text{SM}$

$H \to b\bar{b} \quad 1.59^{+0.69}_{-0.72} \times \text{SM}$

$\text{Combined} \quad 1.44^{+0.59}_{-0.56} \times \text{SM}$

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:

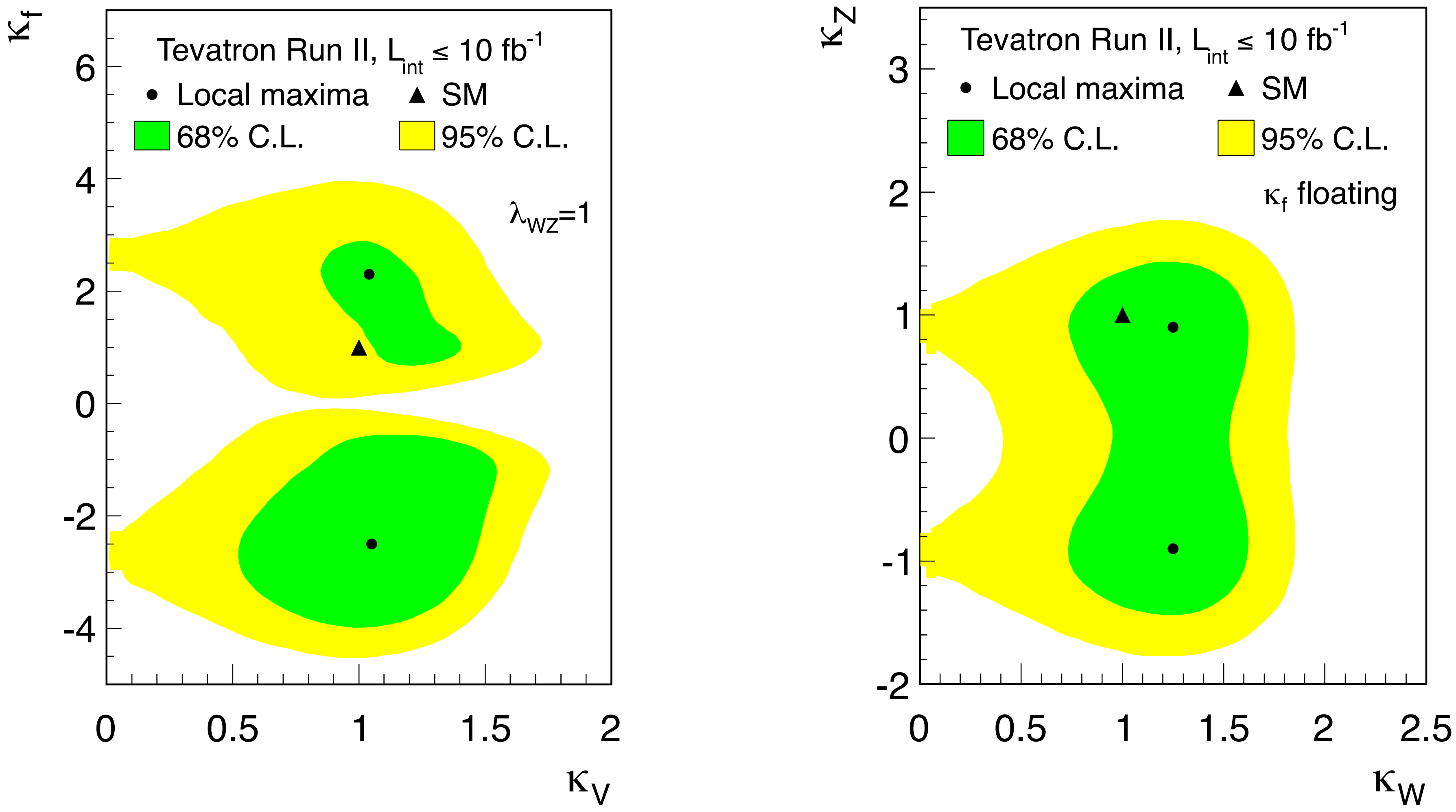
$$\kappa_f = \kappa_W = \kappa_Z = 1 \, .$$

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

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

- 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 $90 \leq m_H \leq 185$ GeV/c^2 .
- Final combinations also included for BSM interpretations.
- 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.
- All Higgs analyses published/submitted at CDF and D0.
- Final Tevatron Higgs combination submitted to PRD.

Thank you.

Public Results

- Tevatron Combination
    - ▫ http://tevnphwg.fnal.gov/results/

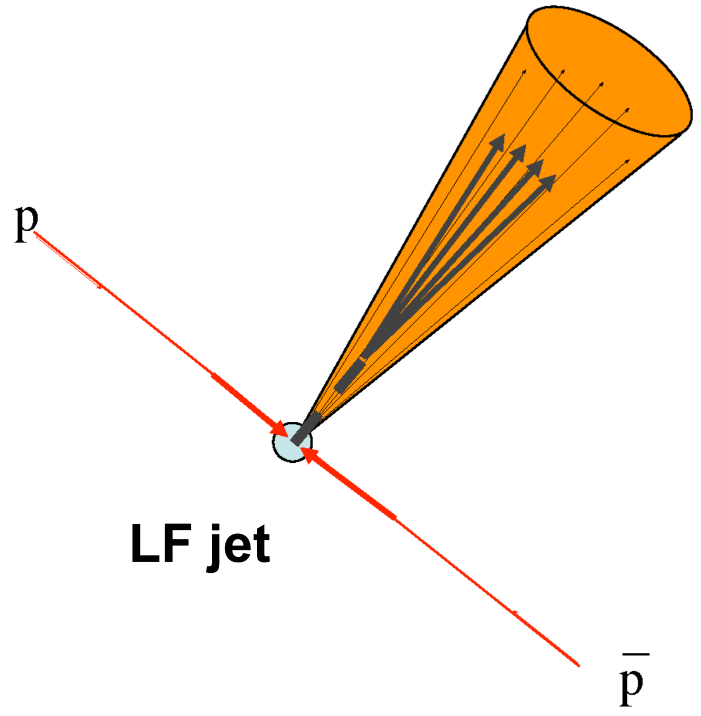
- D0 Results
    - ▫ http://www-d0.fnal.gov/d0_publications/d0_pubs_list_runII_bytopic.html#higgs

- CDF Results
    - ▫ http://www-cdf.fnal.gov/physics/new/hdg/Results.html

Back-up Slides

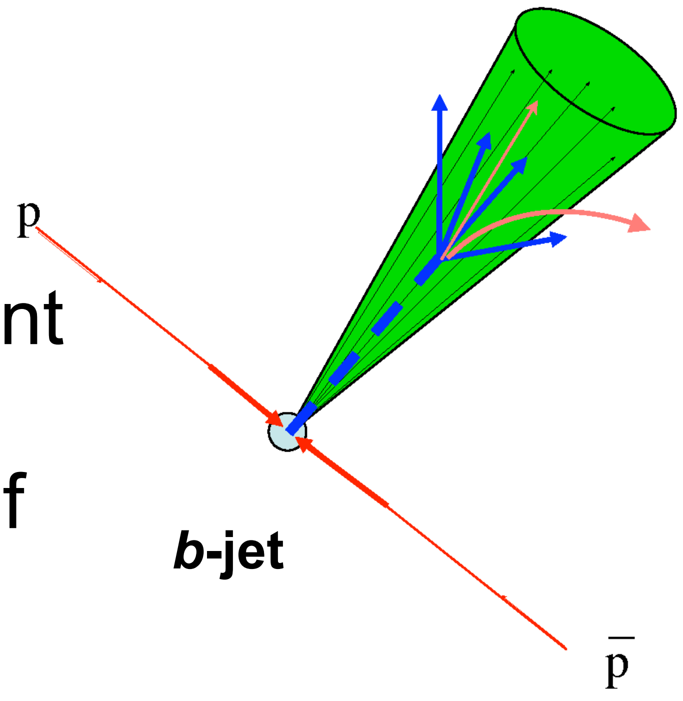
Mass resolution improved

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

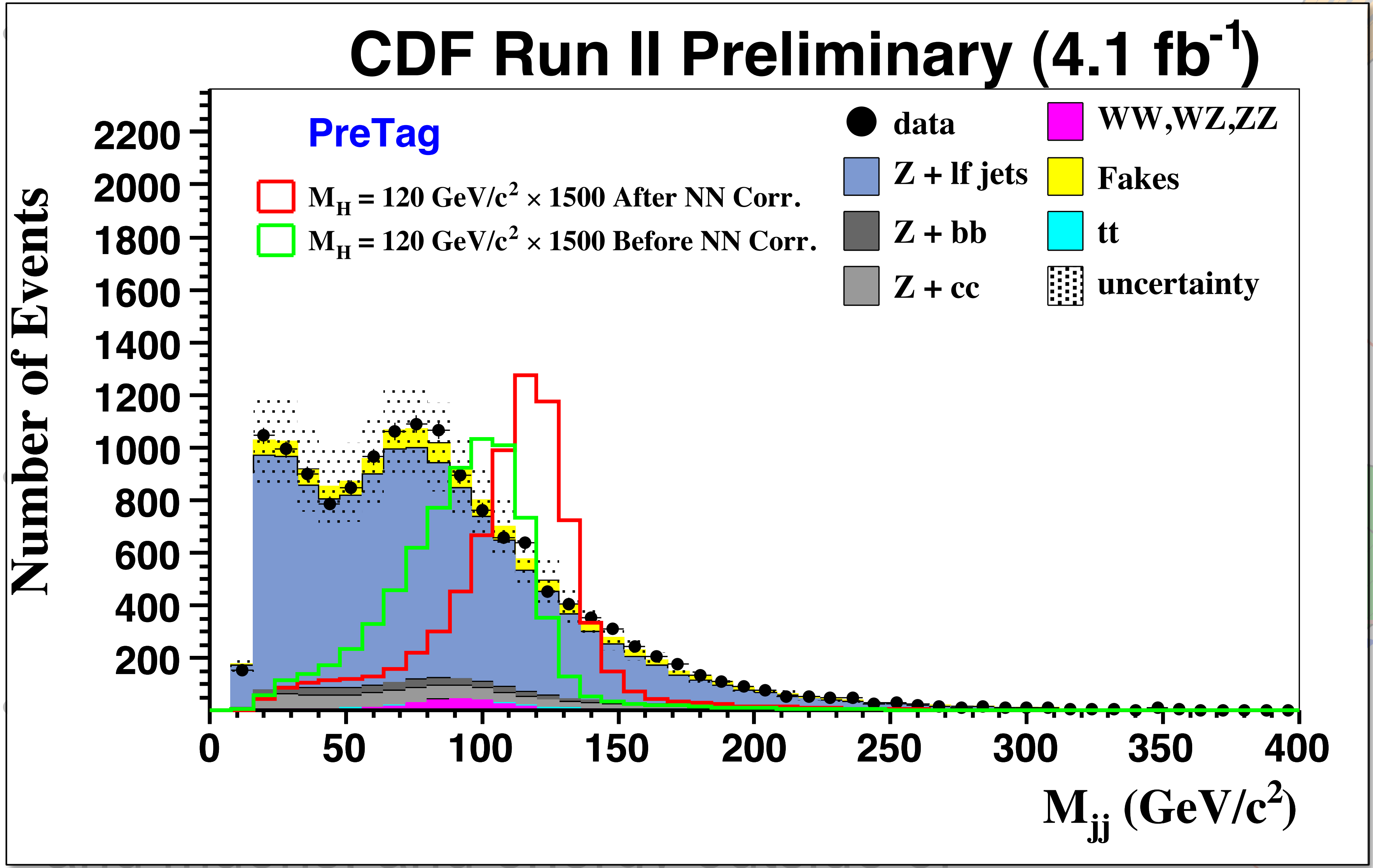


- Jet-energy corrections generally derived from light-quark jets

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



Mass resolution improved

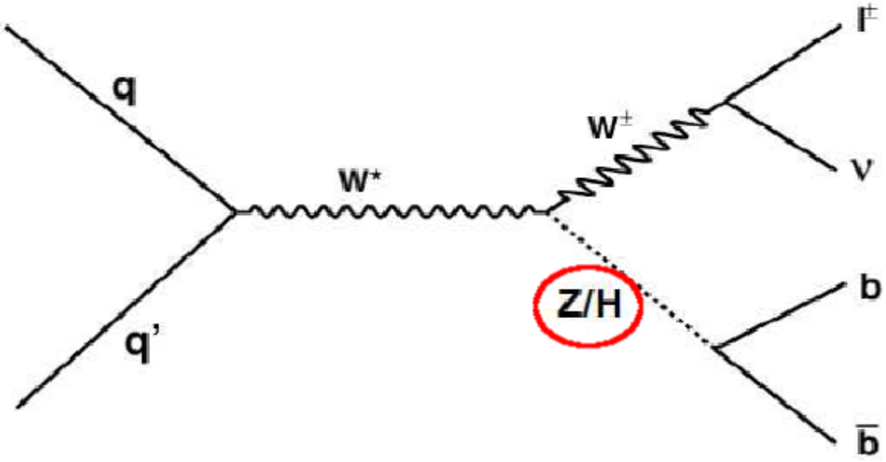


the jet-cone for *b*-jets.

b-jet

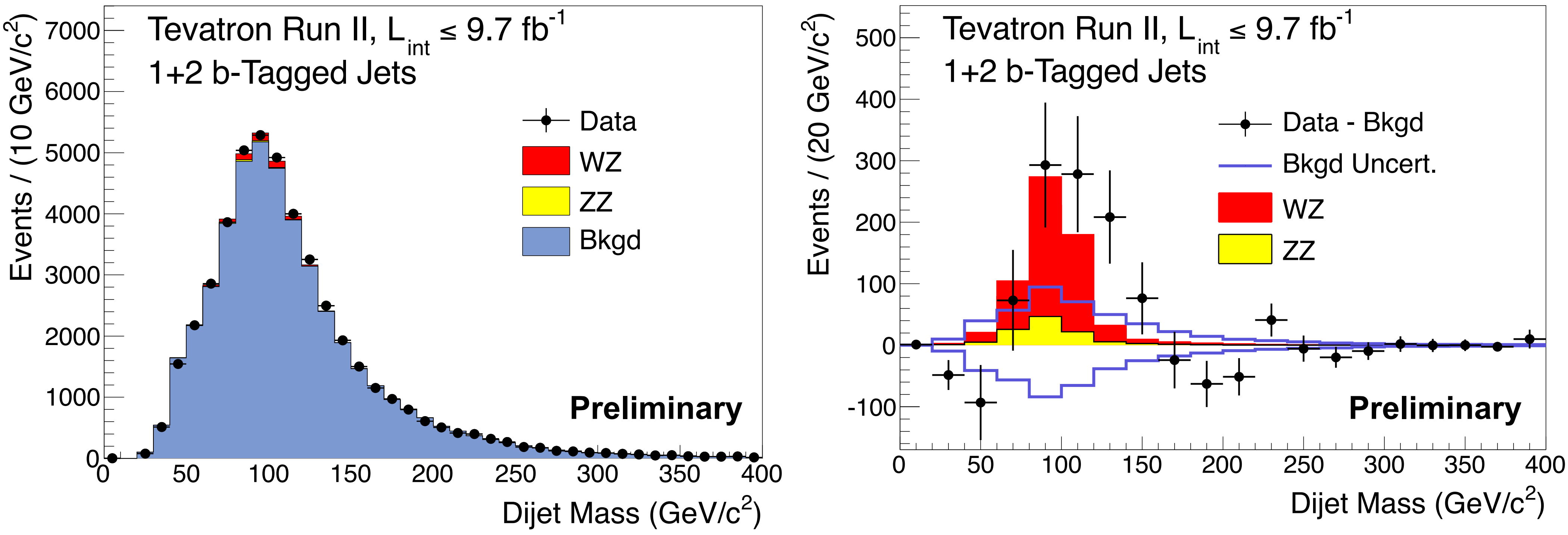
Diboson vs. Higgs Analyses

- Feynman diagrams are topologically equivalent



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

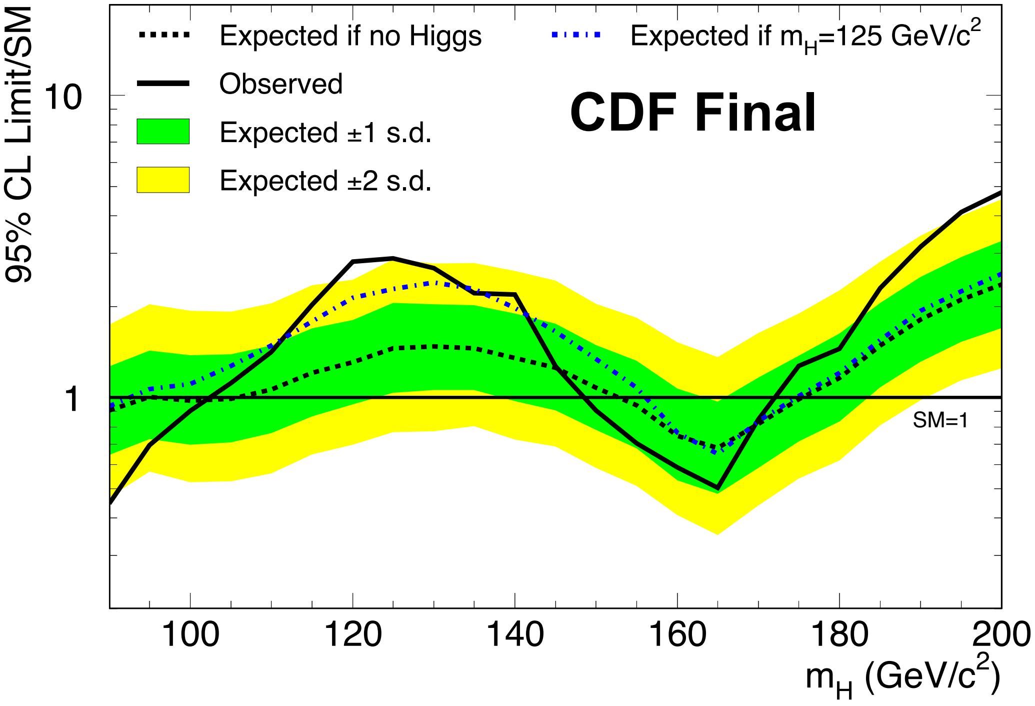
Verify modeling with σ(WZ+ZZ)

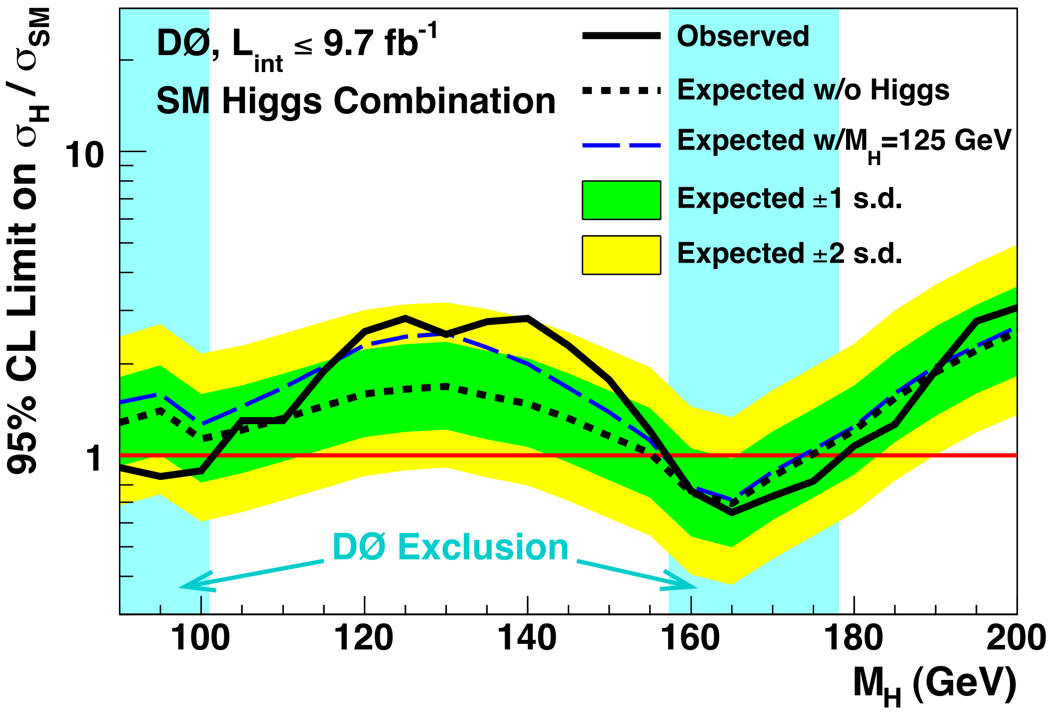


$\sigma(WZ+ZZ)_{meas.}$ = 3.0 ± 0.9 pb

SM Prediction = 4.4 ± 0.3 pb

SM Higgs limits from all channels





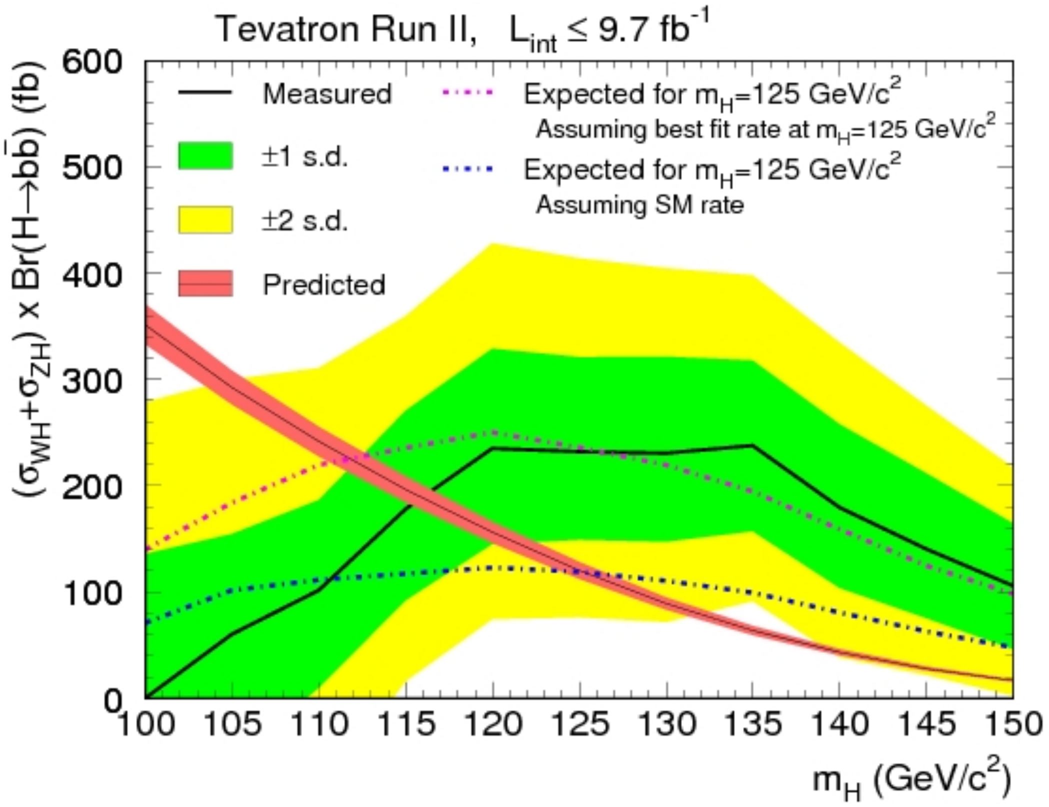
Exp. Exclusion: $90 < m_H < 94$ GeV
$96 < m_H < 106$ GeV
$154 < m_H < 176$ GeV

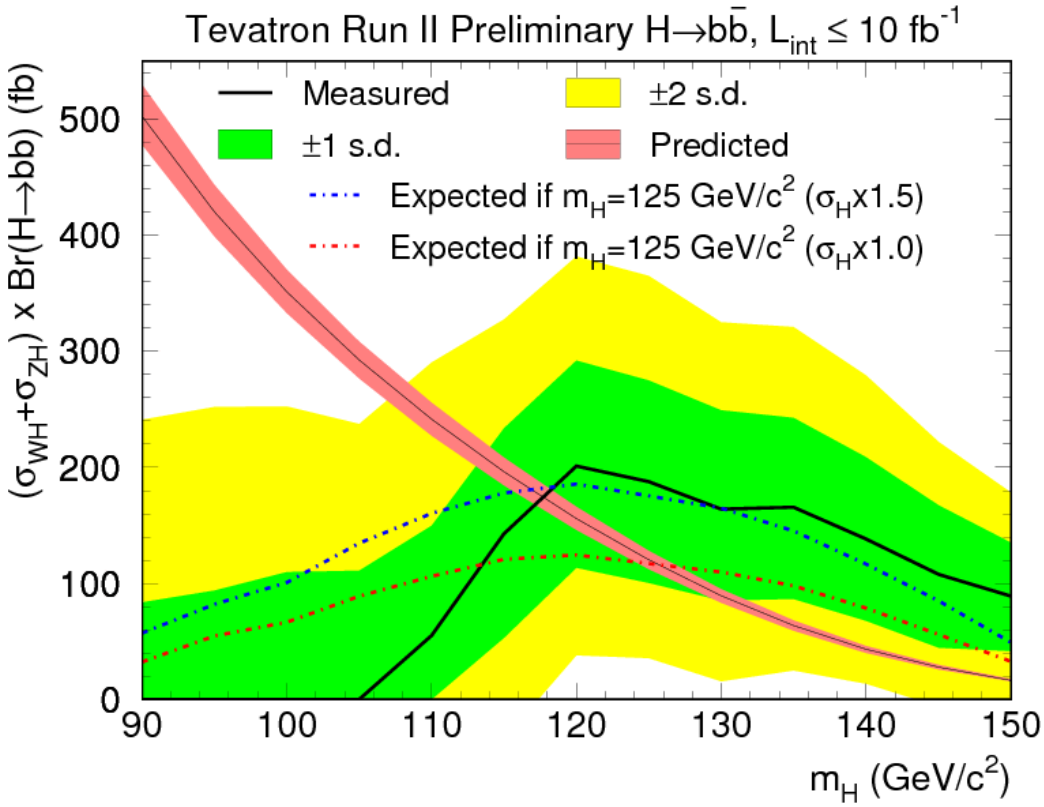
Obs. Exclusion: $90 < m_H < 102$ GeV
$149 < m_H < 172$ GeV

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

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

Cross-section measurements: H→bb





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

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

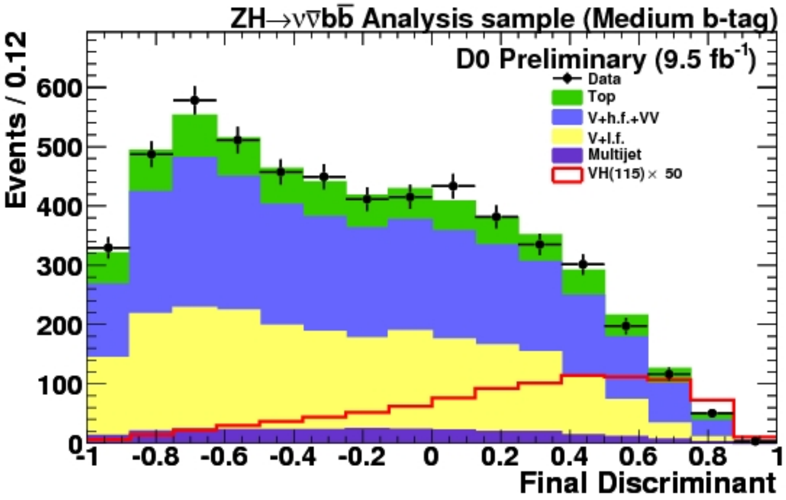
SM Prediction at 125:

$\sigma(VH)\times Br(H\rightarrow bb)$ = **120 ± 8 fb**

Obtaining Results

- Extracted by starting with a combined likelihood function

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



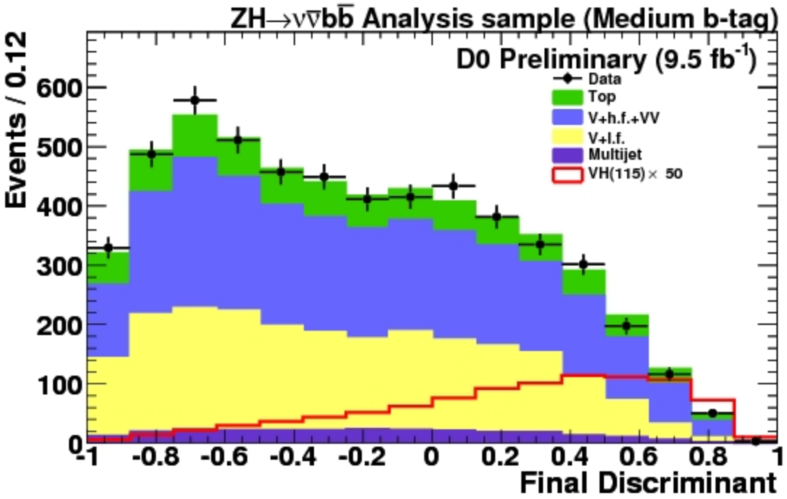
Obtaining Results

- Extracted by starting with a combined likelihood function

Expected events

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

Observed events



Obtaining Results

- Extracted by starting with a combined likelihood function

Expected events

Nuisance parameters

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

Observed events

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

Obtaining Results

- Extracted by starting with a combined likelihood function

Expected events

Nuisance parameters

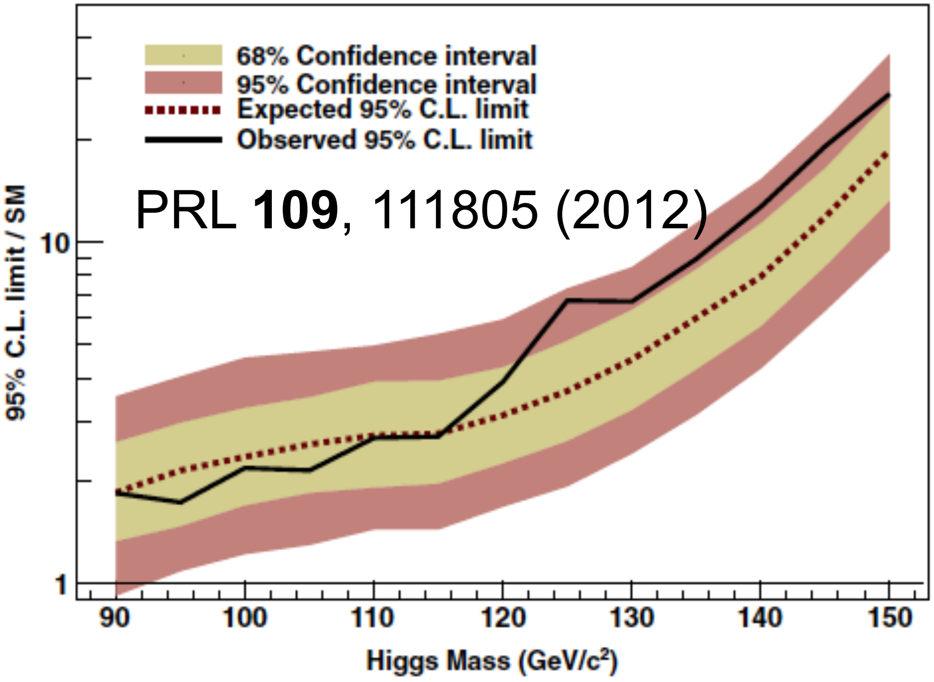
$$L = \prod_{i=1}^{N_{\mathrm{channel}}} \prod_{j=1}^{N_{\mathrm{bins}}} \frac{\mu_{ij}^{n_{ij}}}{\boxed{n_{ij}!}} e^{-\boxed{\mu_{ij}}} \times \prod_{k=1}^{N_{\mathrm{np}}} e^{-\boxed{\theta_k^2/2}}$$

Observed events

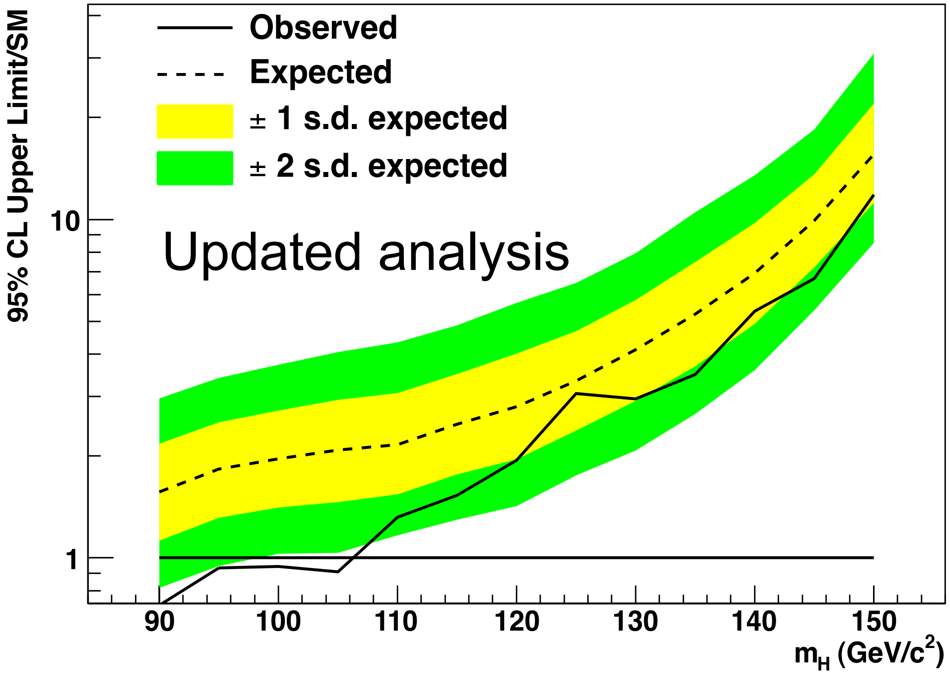
- Expected signal / background events dependent on systematic uncertainties, included as nuisance parameters
- Cross-section fits/limits calculated by maximizing likelihood using profiling or marginalizing
    - Good agreement between both
- For Bayesian method (CDF), uniform, non-negative prior assumed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

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



PRL **109**, 111805 (2012)



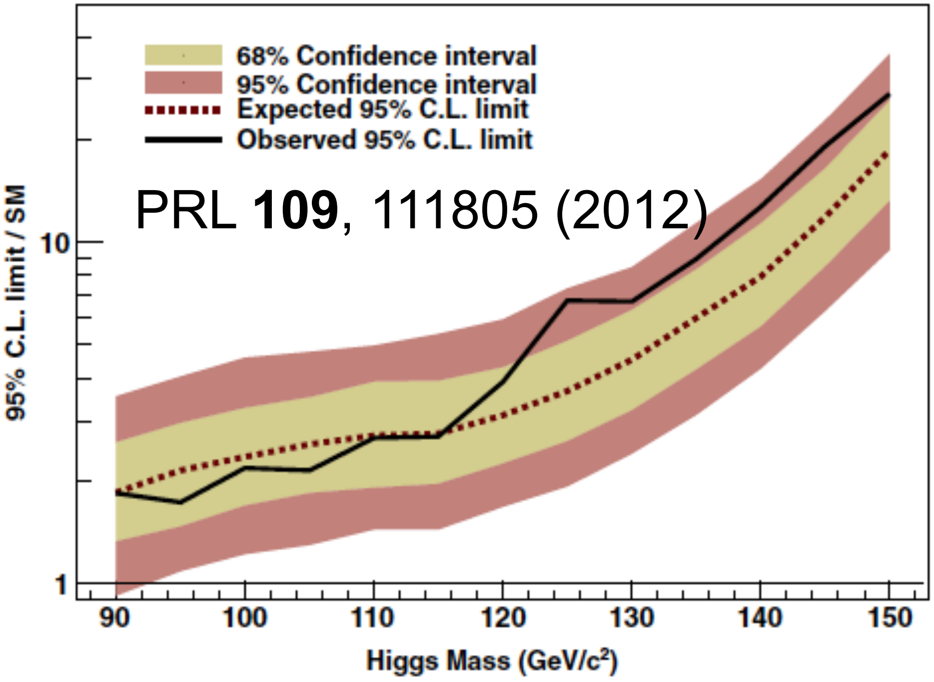
Updated analysis

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?

– but b-tagging algorithm improved



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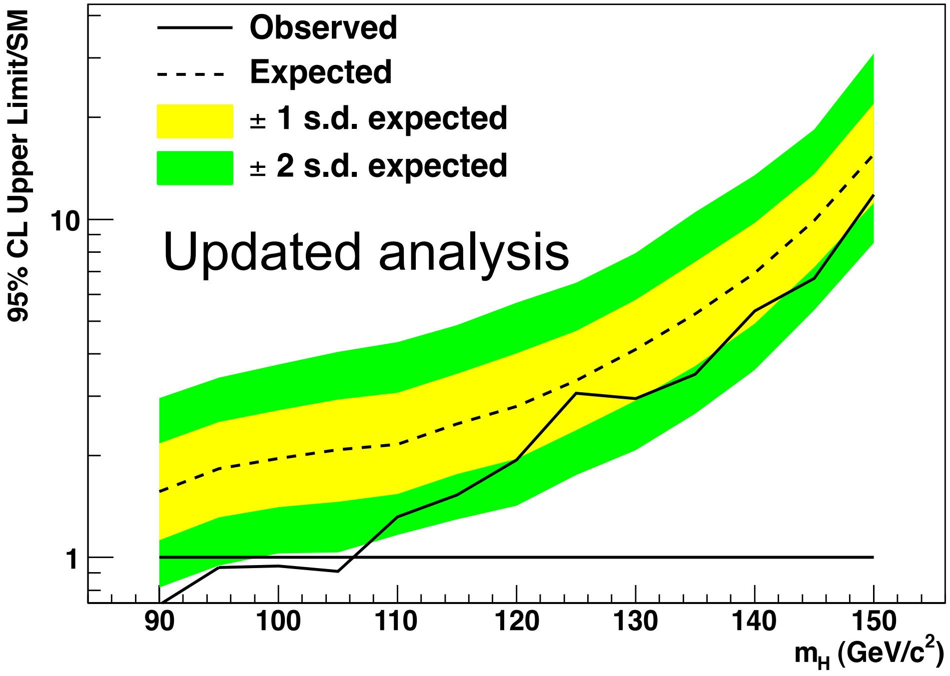
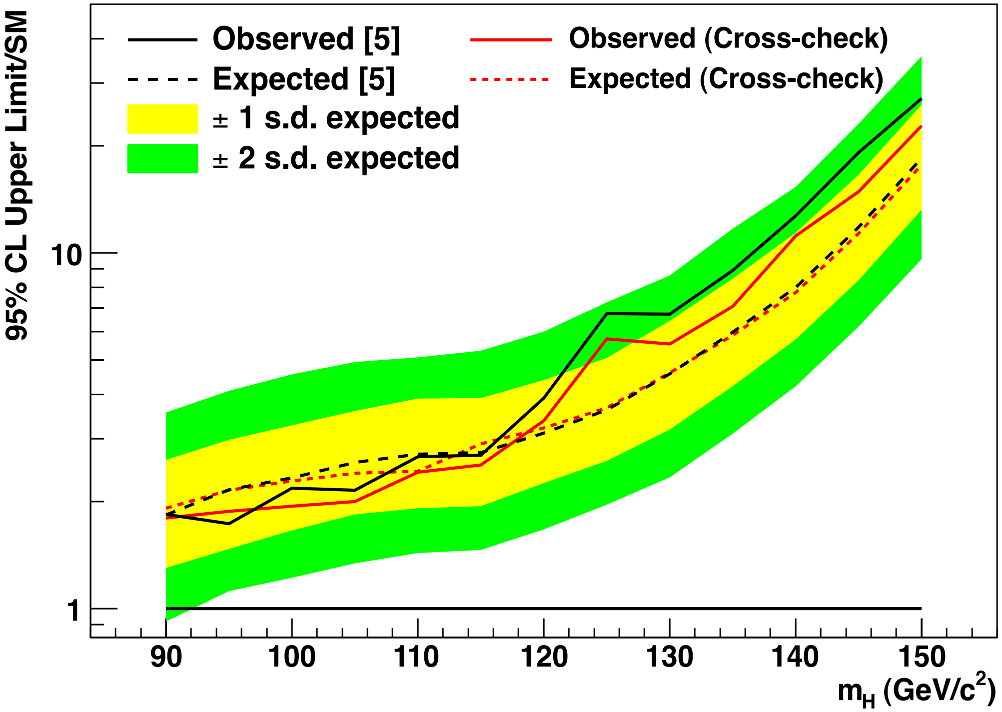


Updated analysis

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.

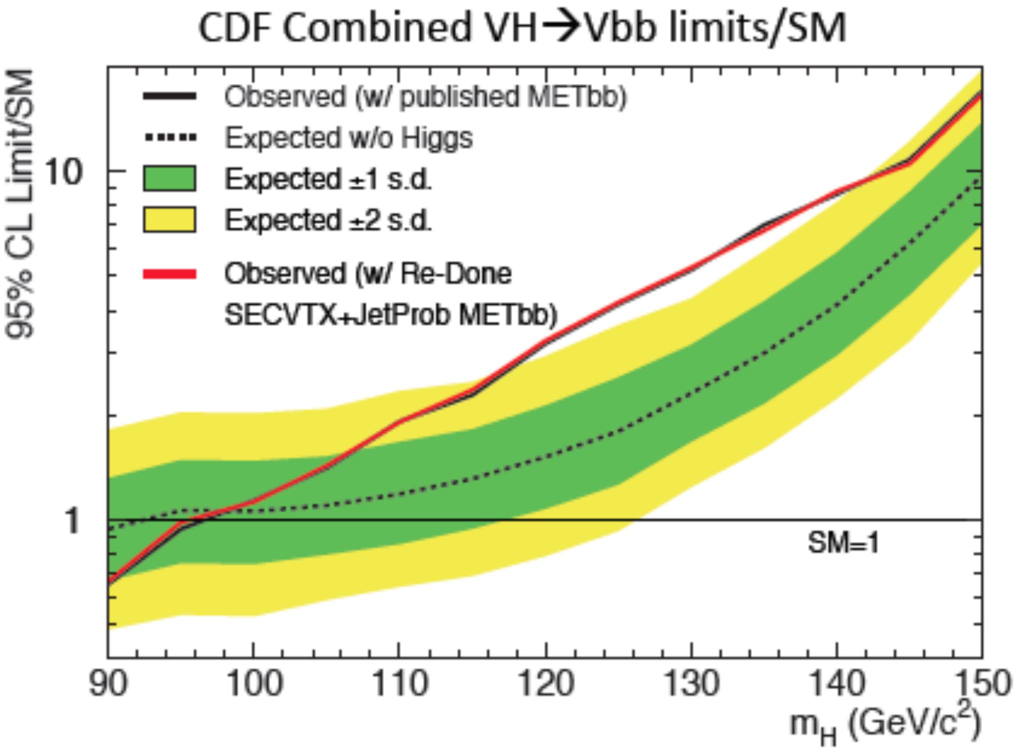


- Expected limits in very good agreement with those of summer analysis.
- Observed limits systematically lower than those of summer analysis.
- Non-negligible fraction of discrepancy originates from different (improved) treatment of systematic uncertainties.

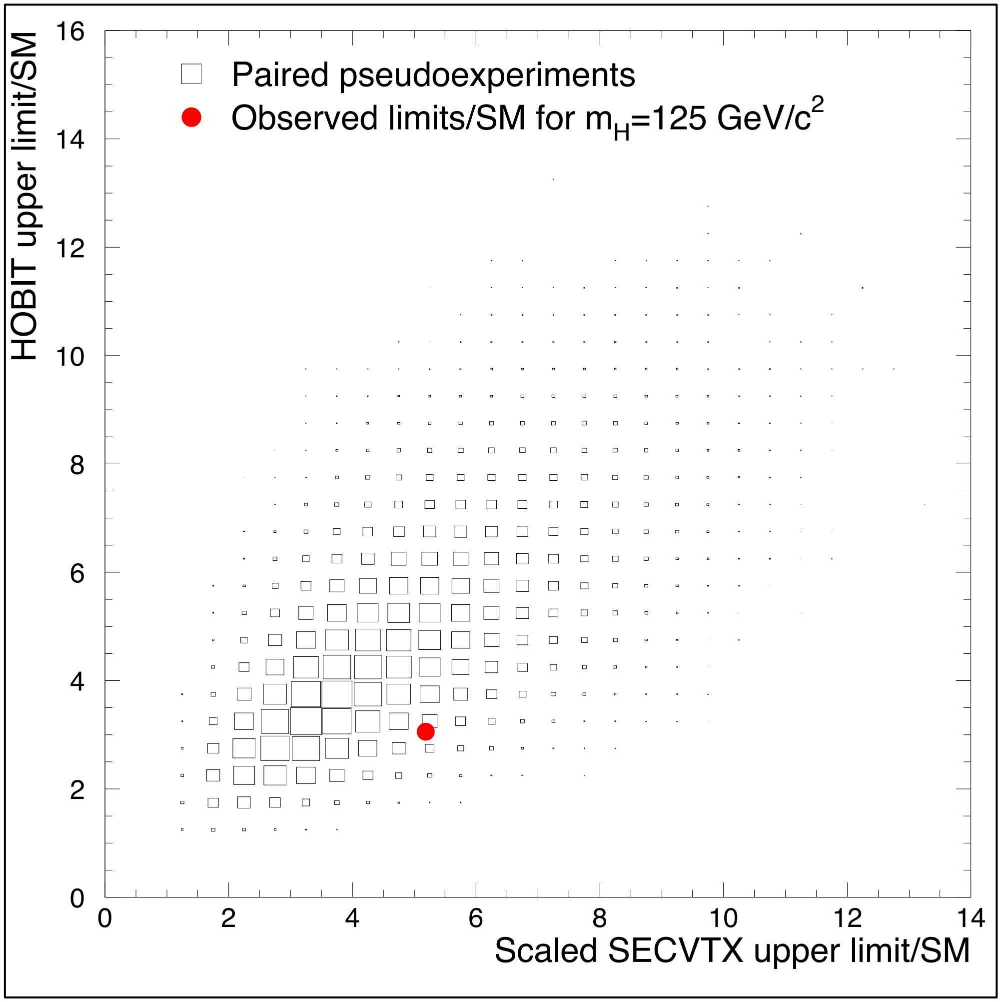
Updated MET+bb Search

- 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.

- 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.



Updated MET+bb Search



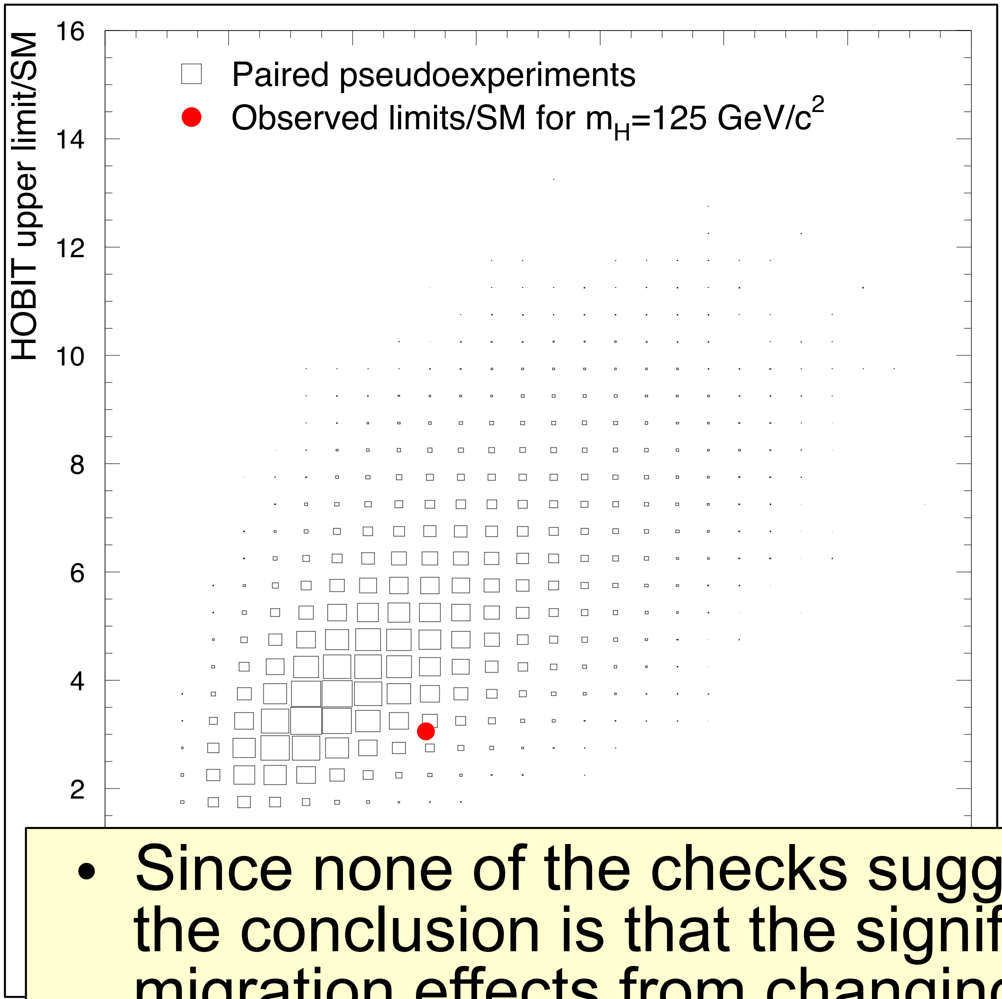
- Remaining check to assess effect of event migration between old and new *b*-tag categories
- Pseudo-experiment study:
    - Use statistical overlap between analyses to produce pairs of limits using the old and new analysis.
    - Calculate *p*-value to determine consistency
- Probability of shift at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

7 – 8 %

- Probability of global shift:

3 – 5 %

Updated MET+bb Search



- 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:

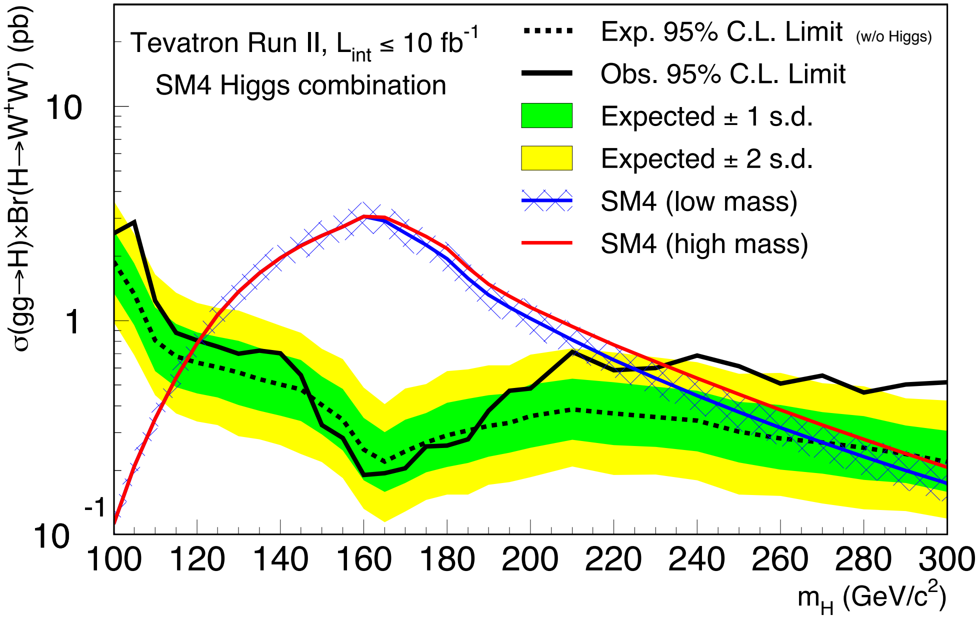
  7 – 8 %

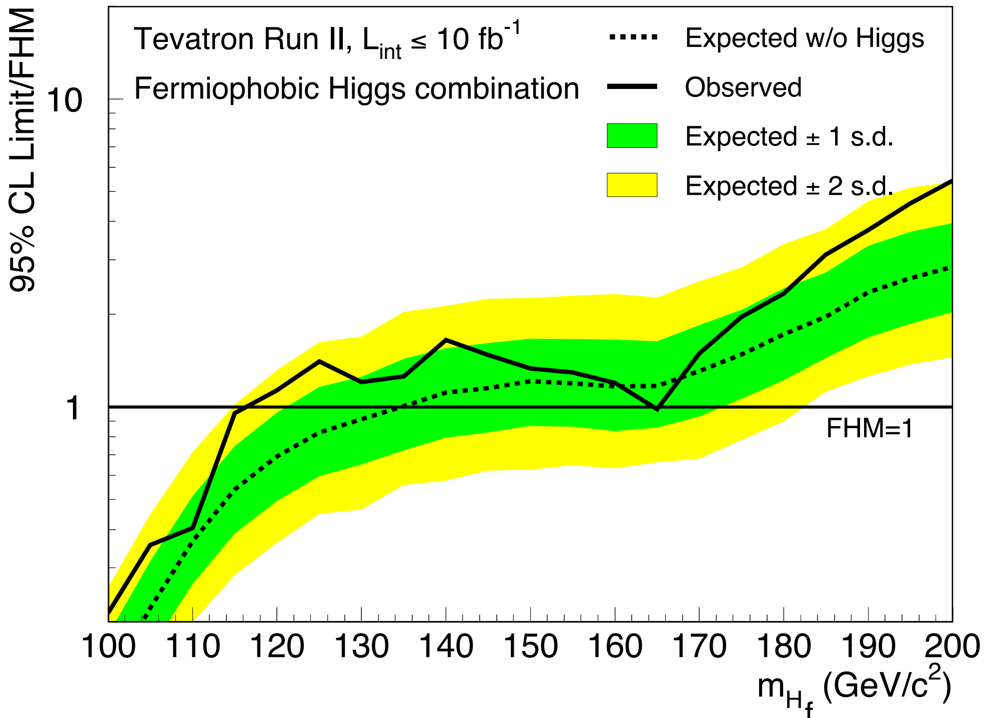
- Since none of the checks suggested any mistakes in analysis, the conclusion is that the significant shift in limits due to event migration effects from changing *b*-tagging algorithms.
- Previous summer publication valid; for final combination, CDF decided to use analysis with most sensitive expected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

Beyond the SM Models

- 4th generation model
  - Additional generation of quarks/leptons added
  - Two types of models depending on 4th-gen. lepton masses
  - Exclude SM4 Higgs masses in region: $121 < m_H < \sim 230$ GeV/c^2

- Fermiophobic model
  - Higgs couplings to fermions set to 0.
  - Exclude H_f mass below 116 GeV/c^2.





Improvements in Sensitivity

Example from CDF