Higgs Searches at the Tevatron

Kyle J. Knoepfel
Fermi National Accelerator Laboratory

On behalf of the CDF and D0 Collaborations

July 25, 2012

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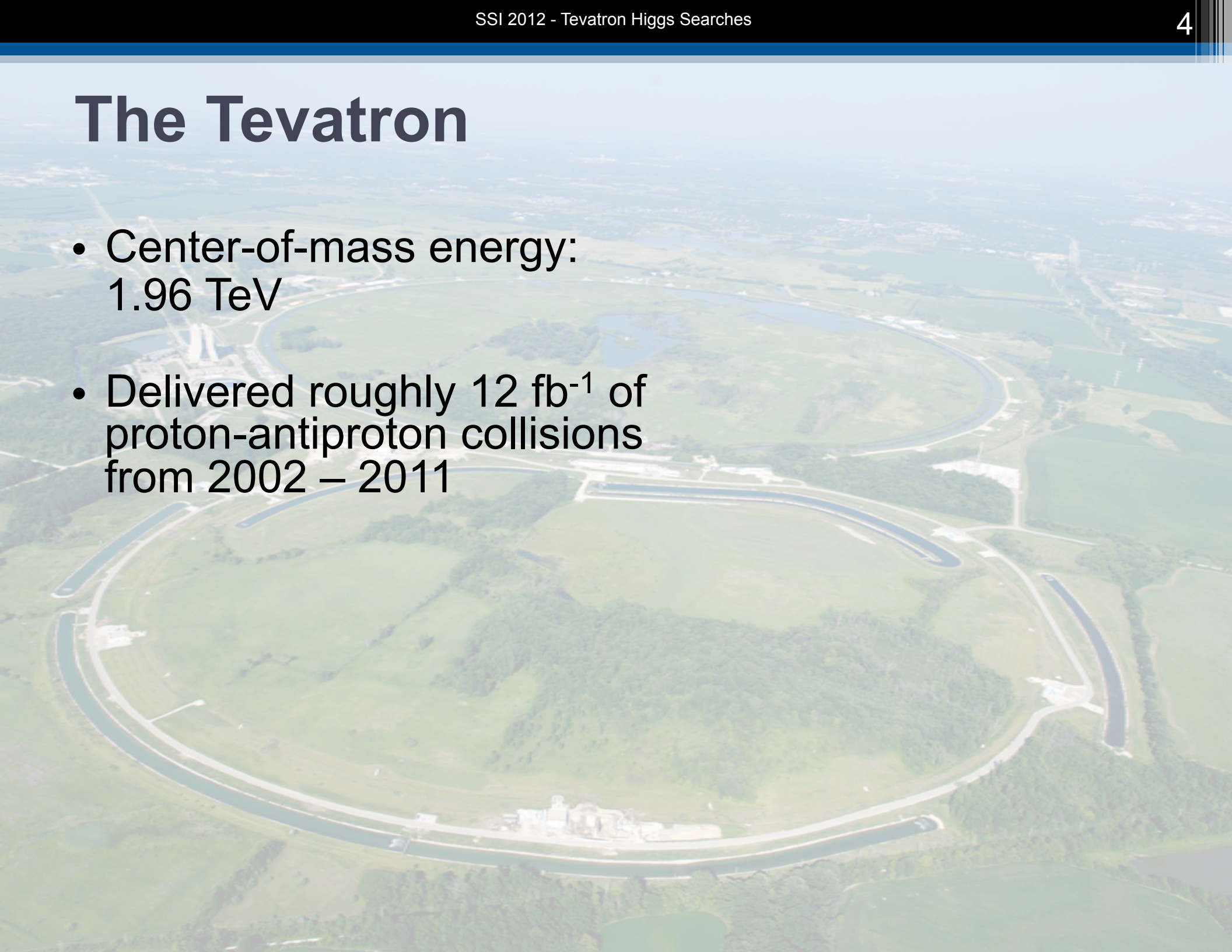
At the Tevatron…

- Nearly 20 yrs. of searching for the Higgs (see back-up slides)
- Cross section for Higgs production is much smaller than at the LHC
- You aren't going to see a beautiful bump in the diphoton mass for $H \rightarrow \gamma\gamma$ searches.
  - Not enough events
- You aren't going to see a beautiful bump in the *dijet* mass for $H \rightarrow bb$ searches.
  - Not enough events
  - Jet-energy resolution ~15%,
  - Final-state radiation
- You *will* see extensive use of multivariate statistical techniques
  - Necessary because we don't have a lot of Higgs events
  - i.e. "Cut-and-count" is not sufficient to get to SM Higgs sensitivity;

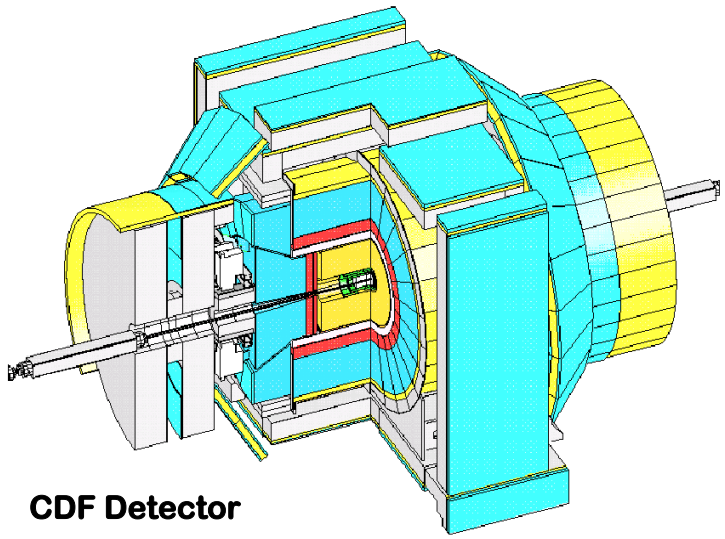
The Tevatron

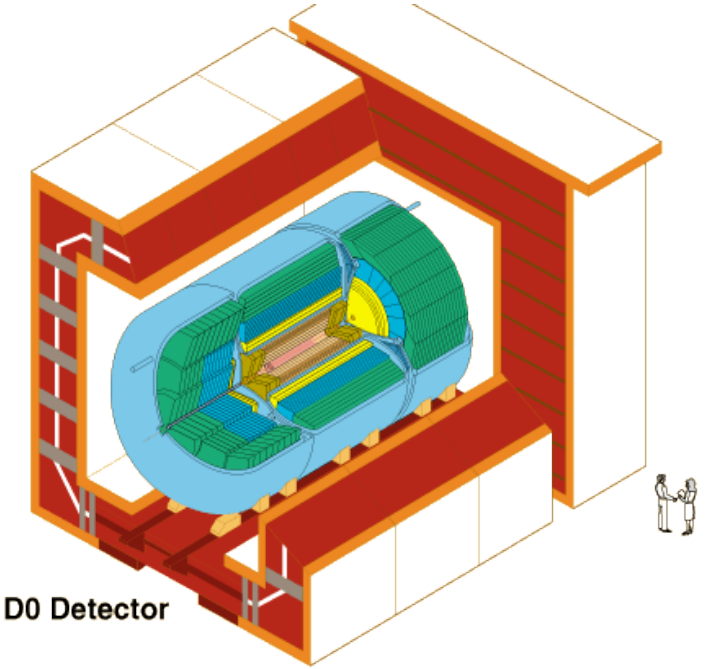
- Center-of-mass energy: 1.96 TeV
- Delivered roughly 12 fb^{-1} of proton-antiproton collisions from 2002 – 2011



The Tevatron & Experiments

- Center-of-mass energy: 1.96 TeV
- Delivered roughly 12 fb^{-1} of proton-antiproton collisions from 2002 – 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}

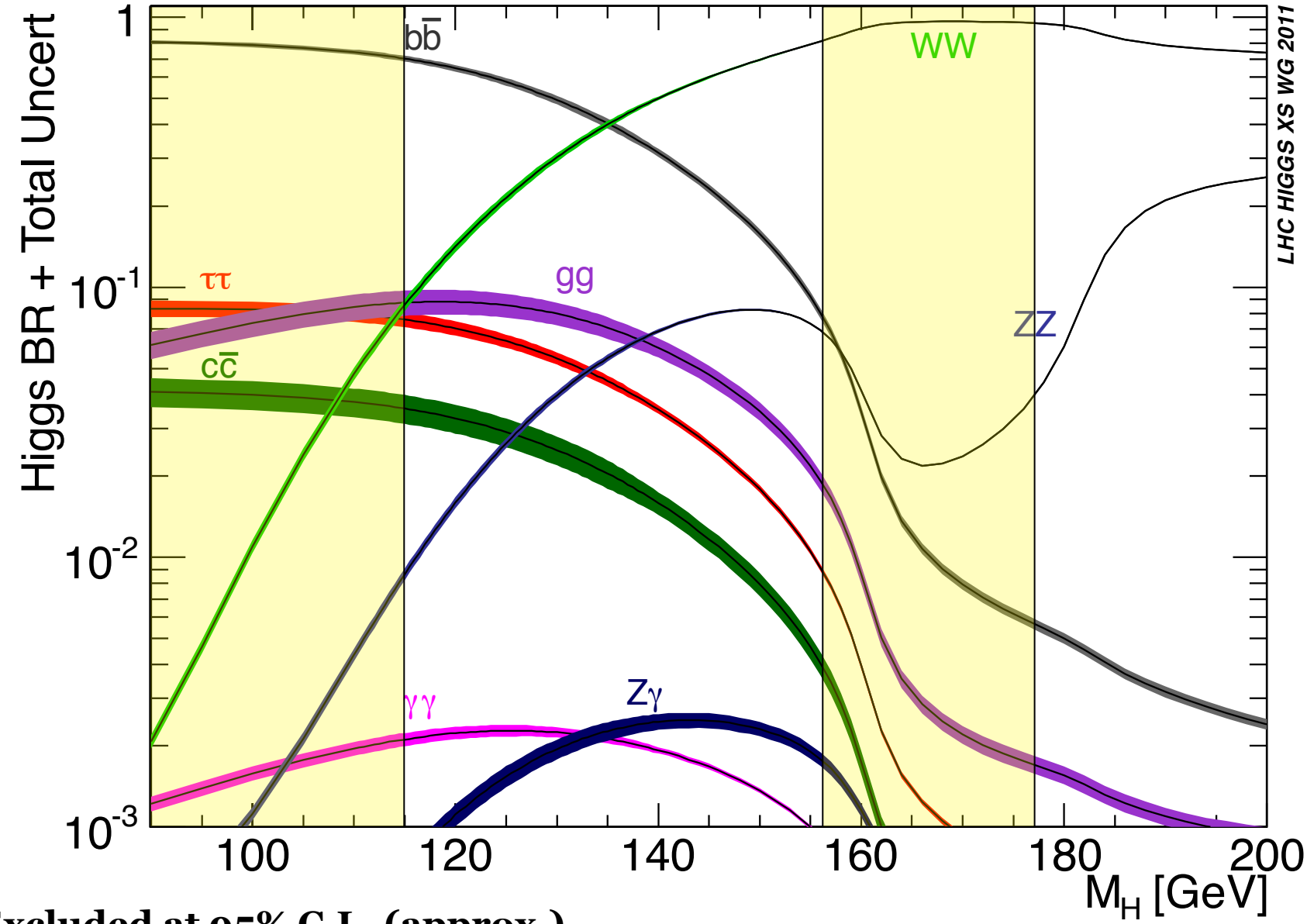

CDF Detector


D0 Detector

Higgs Branching Ratios

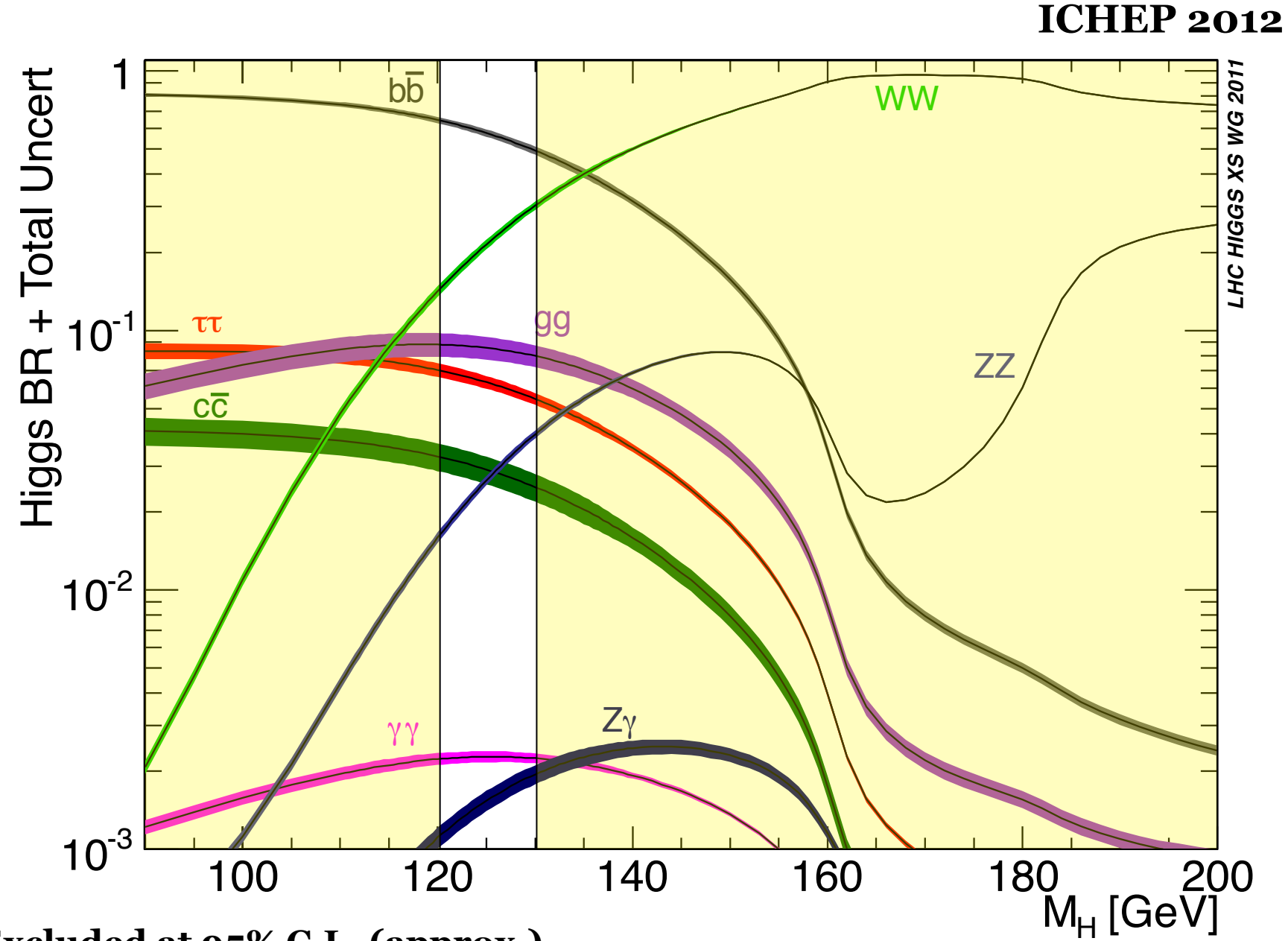
(See Frank's talk from this morning.)

~1.5 yrs. ago

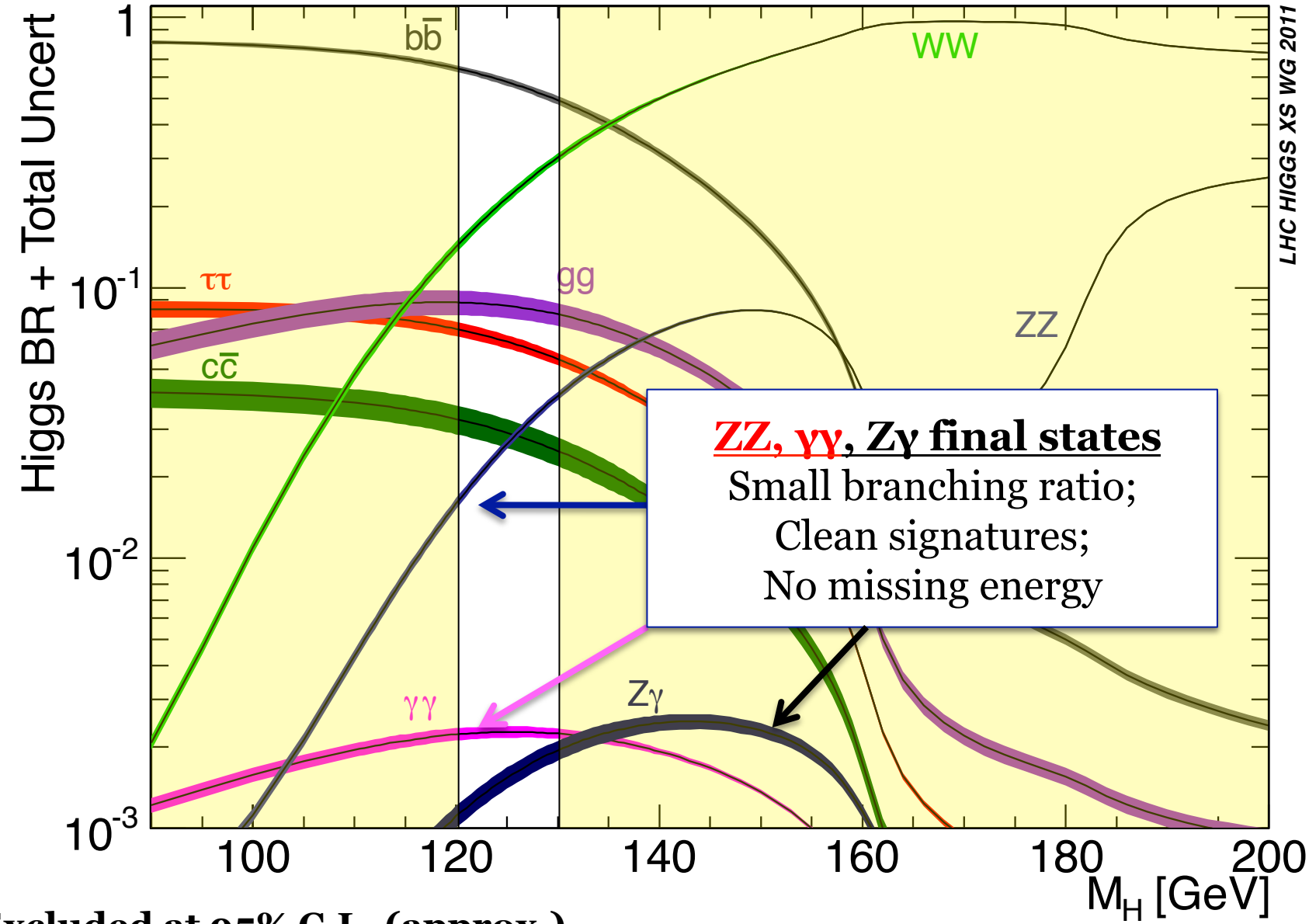


Excluded at 95% C.L. (approx.)

Higgs Branching Ratios



Higgs Branching Ratios



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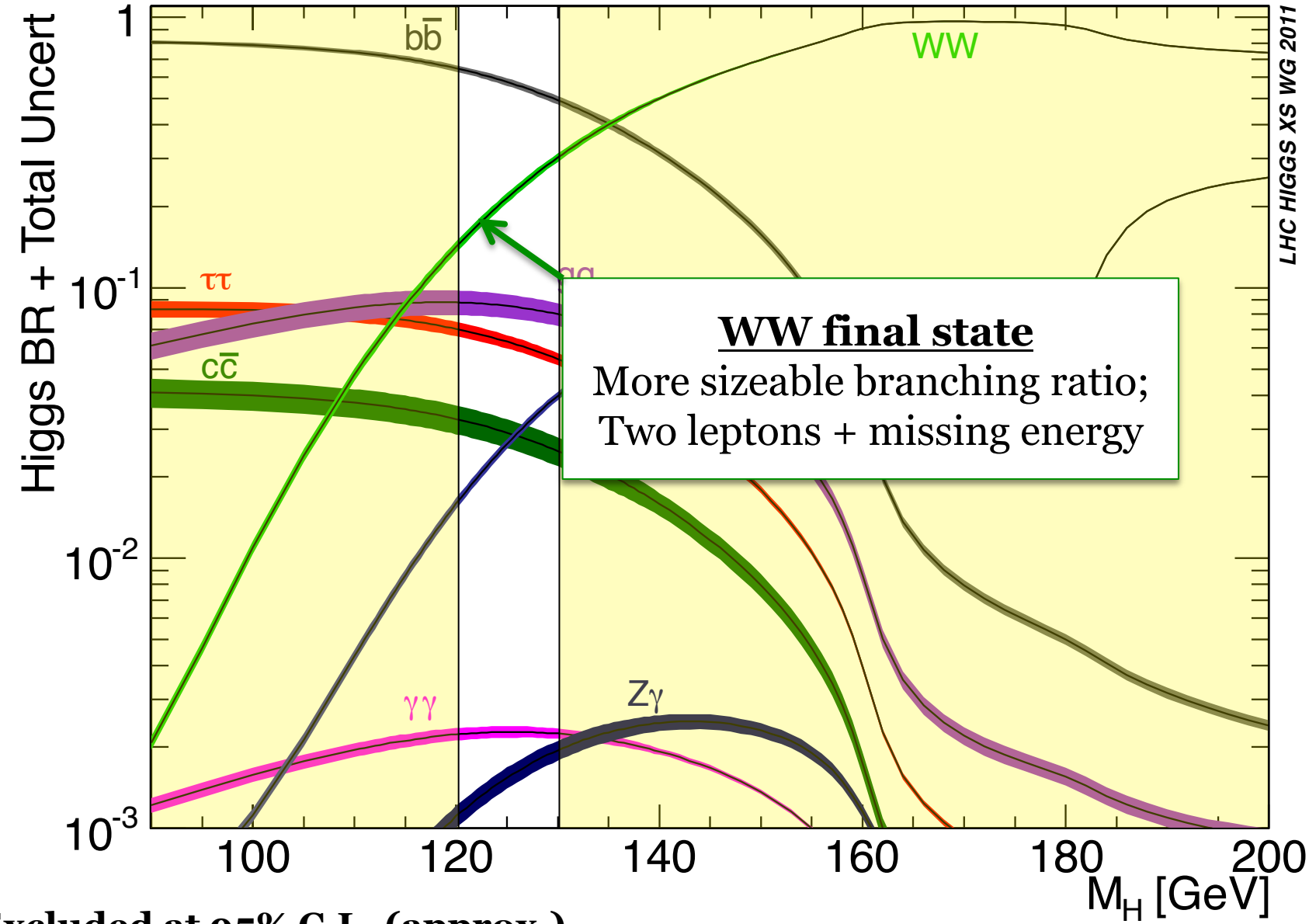

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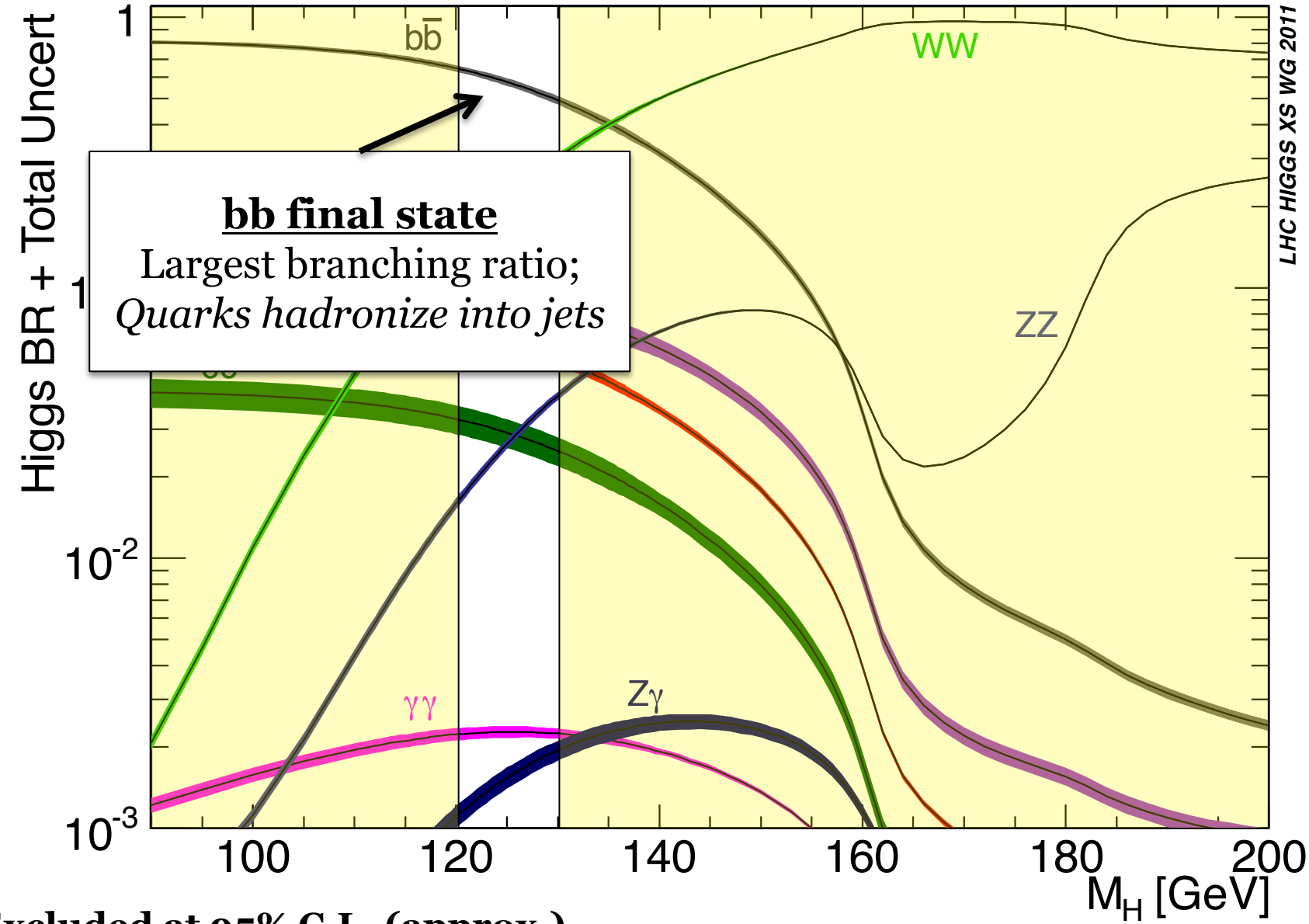

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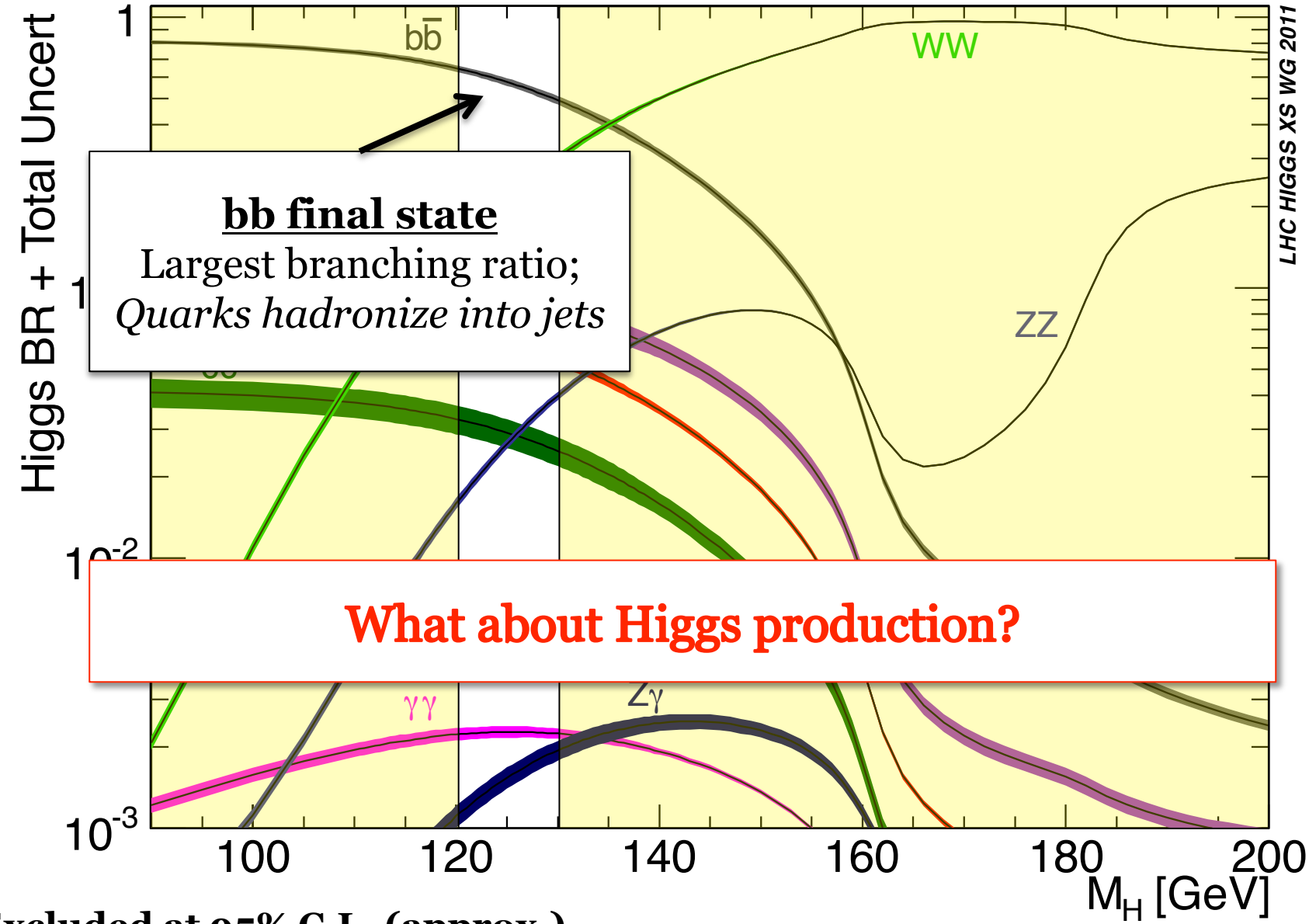
Higgs Branching Ratios

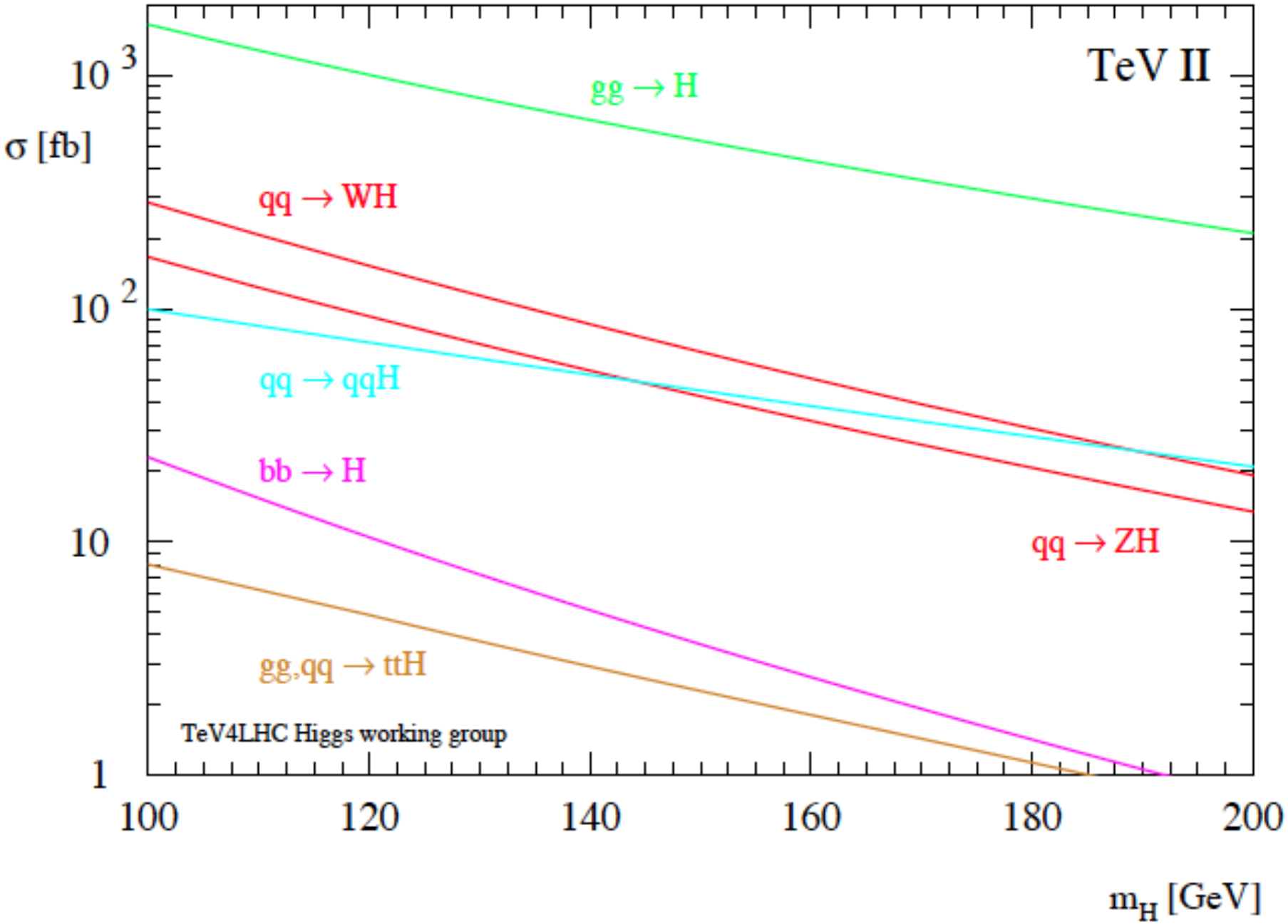


bb final state
Largest branching ratio;
Quarks hadronize into jets

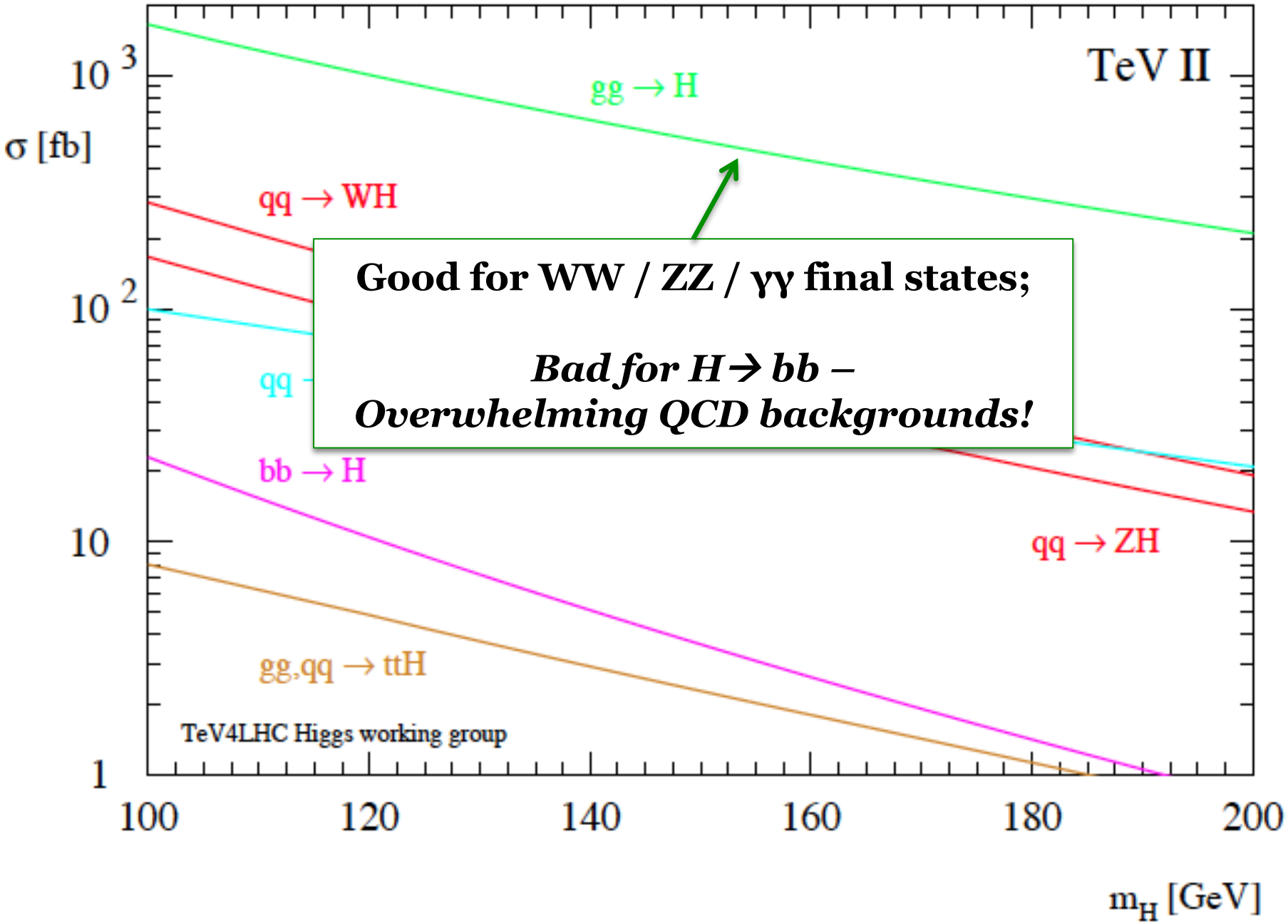
What about Higgs production?

Excluded at 95% C.L. (approx.)

Higgs Production



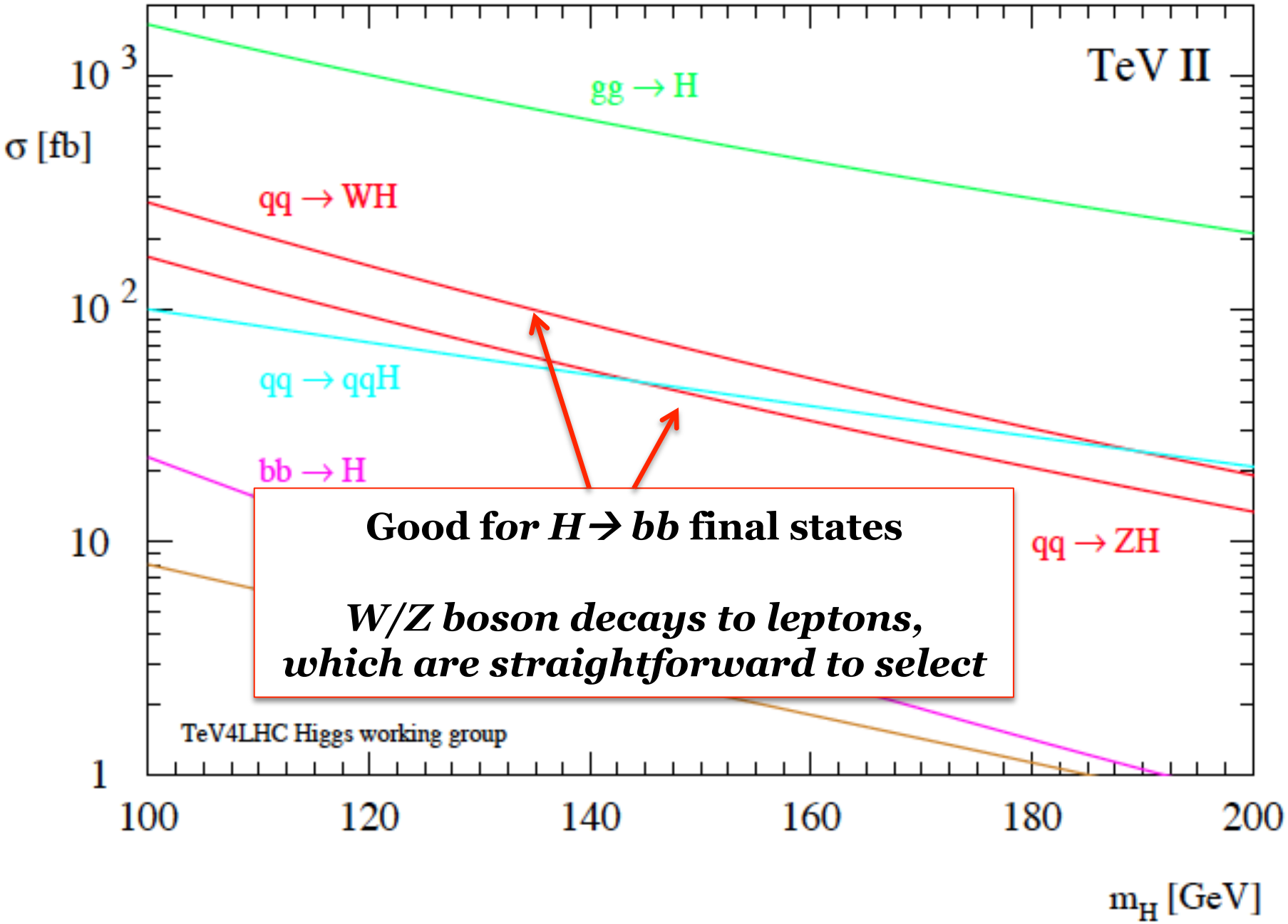
Higgs Production



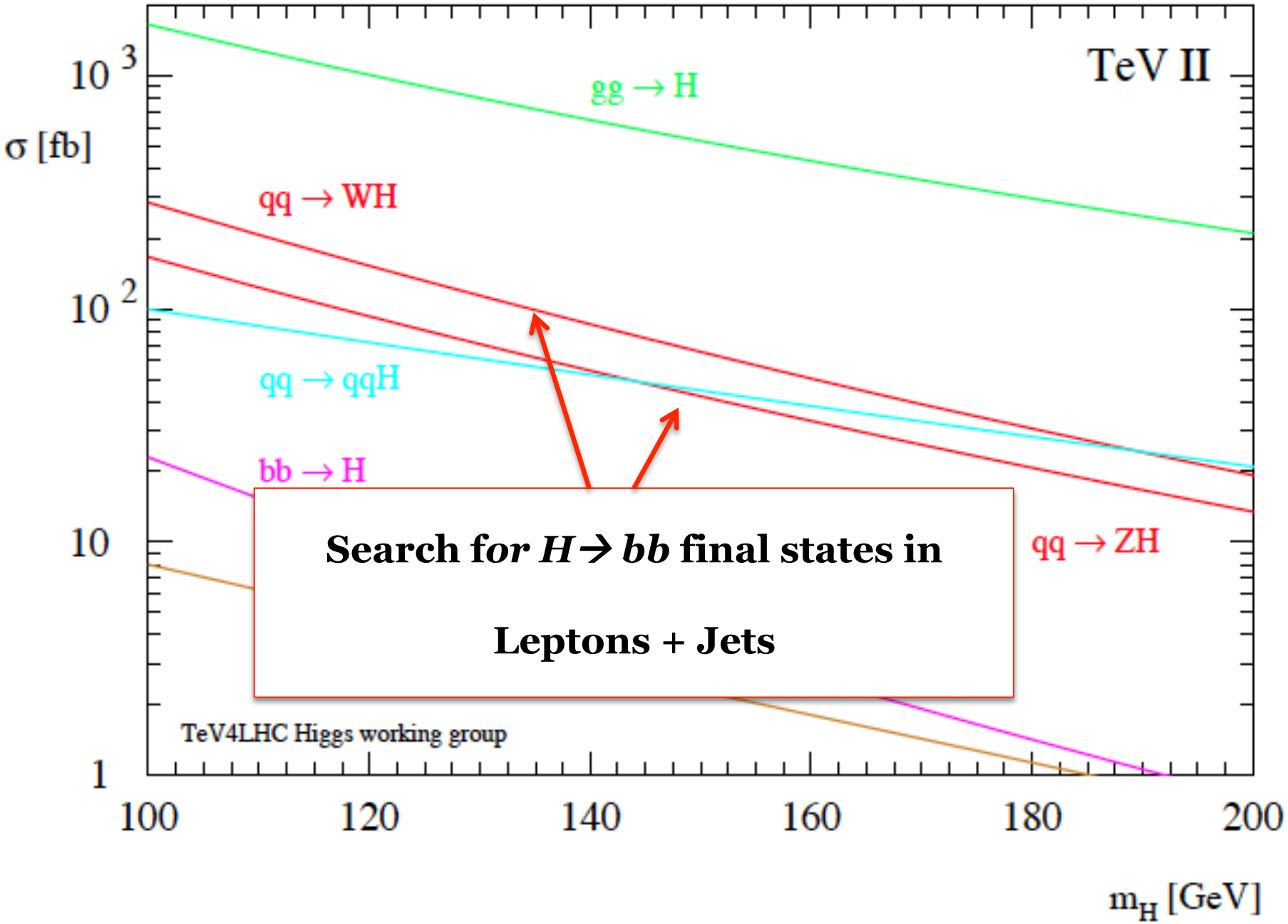
Good for WW / ZZ / γγ final states;

Bad for H→ bb –
Overwhelming QCD backgrounds!

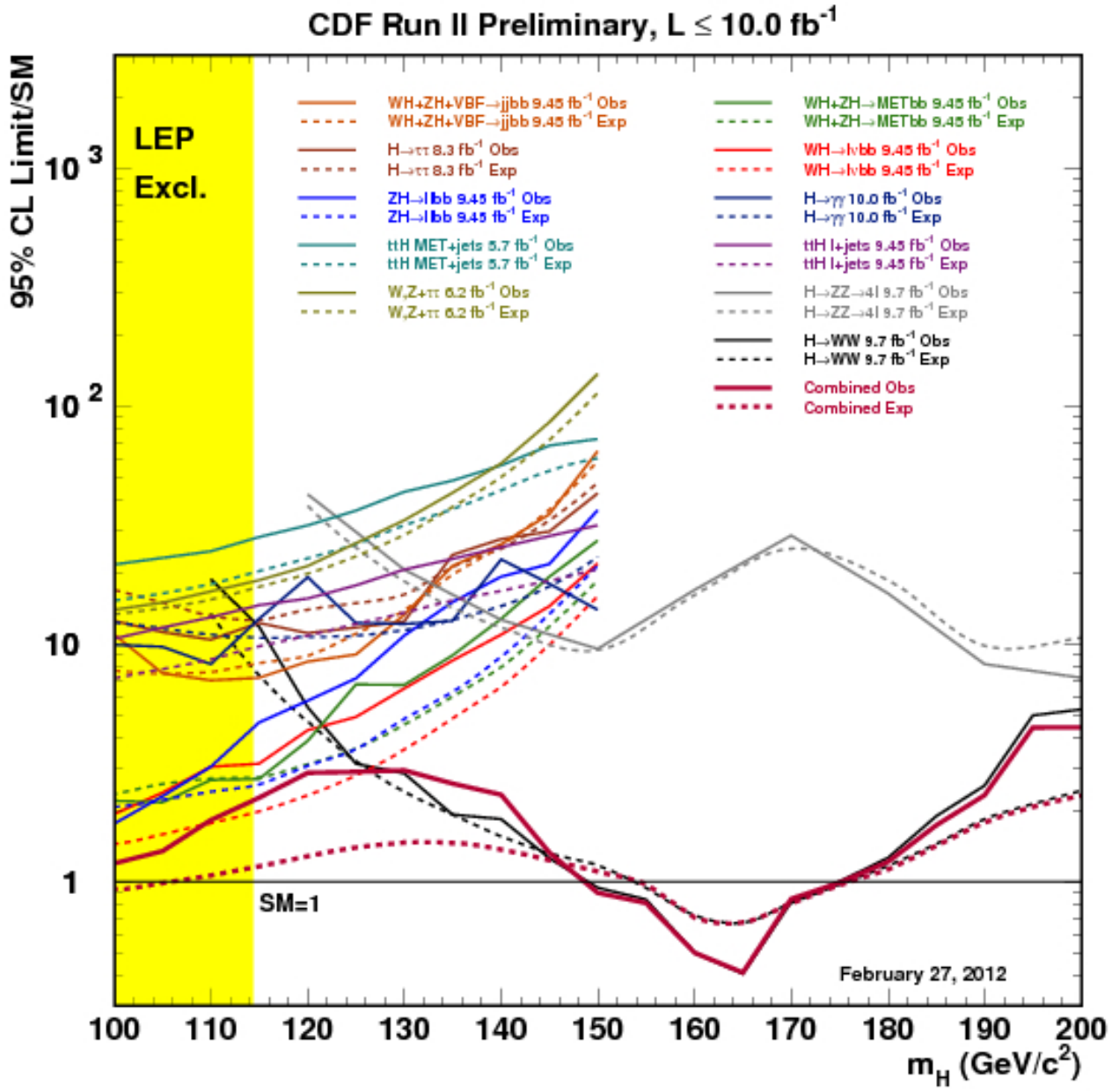
Higgs Production



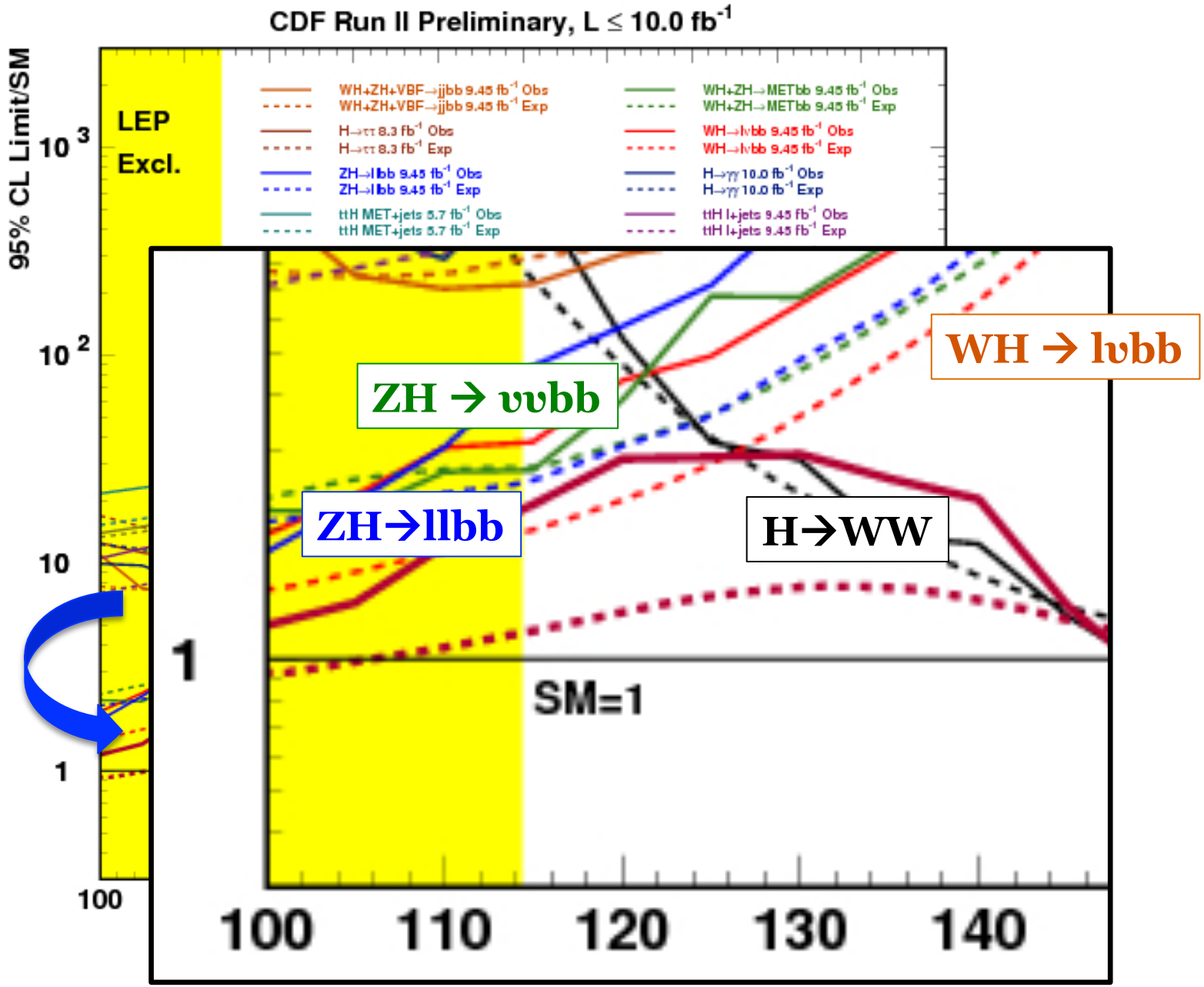
Higgs Production



Tevatron Sensitivities



Tevatron Sensitivities



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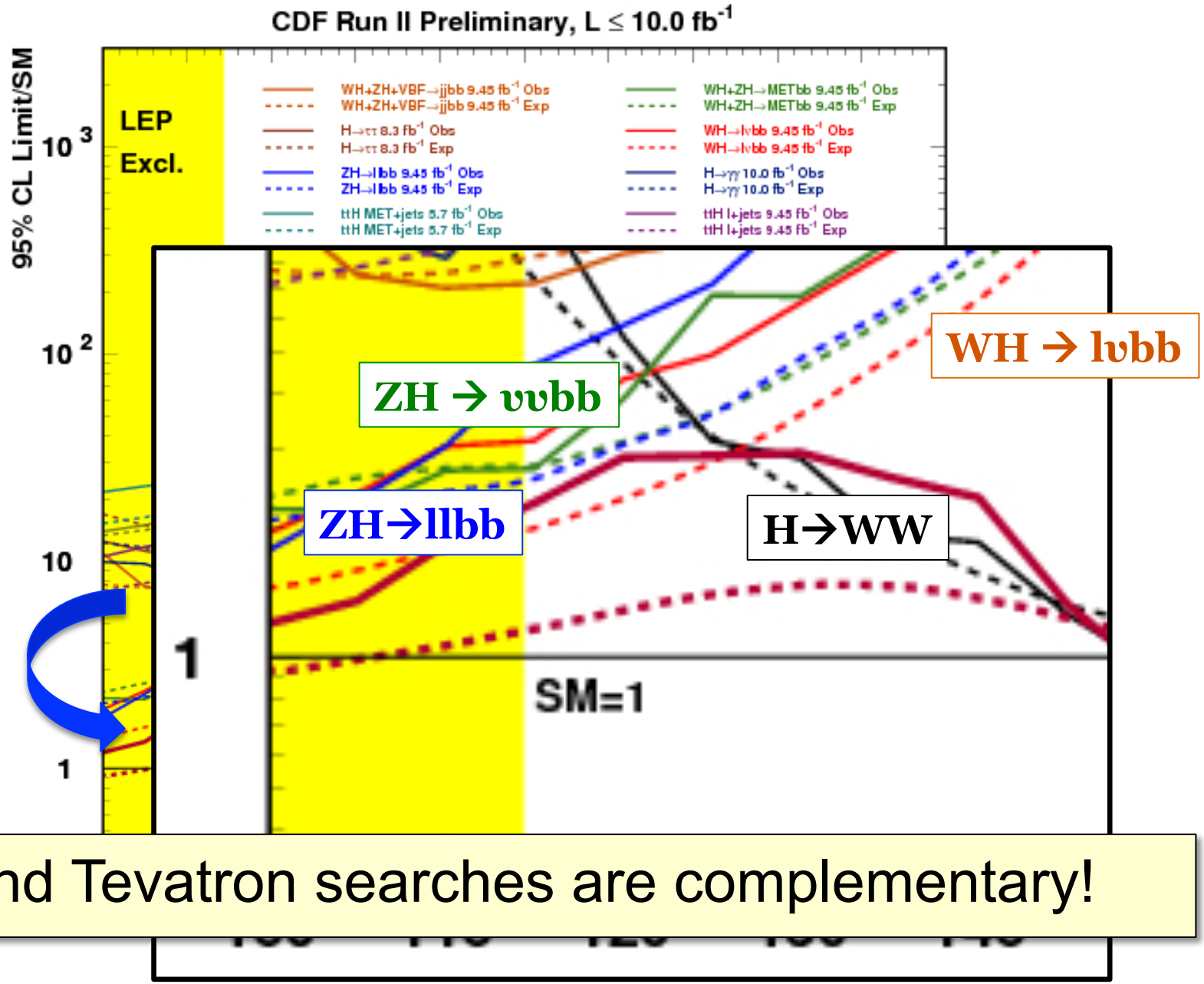
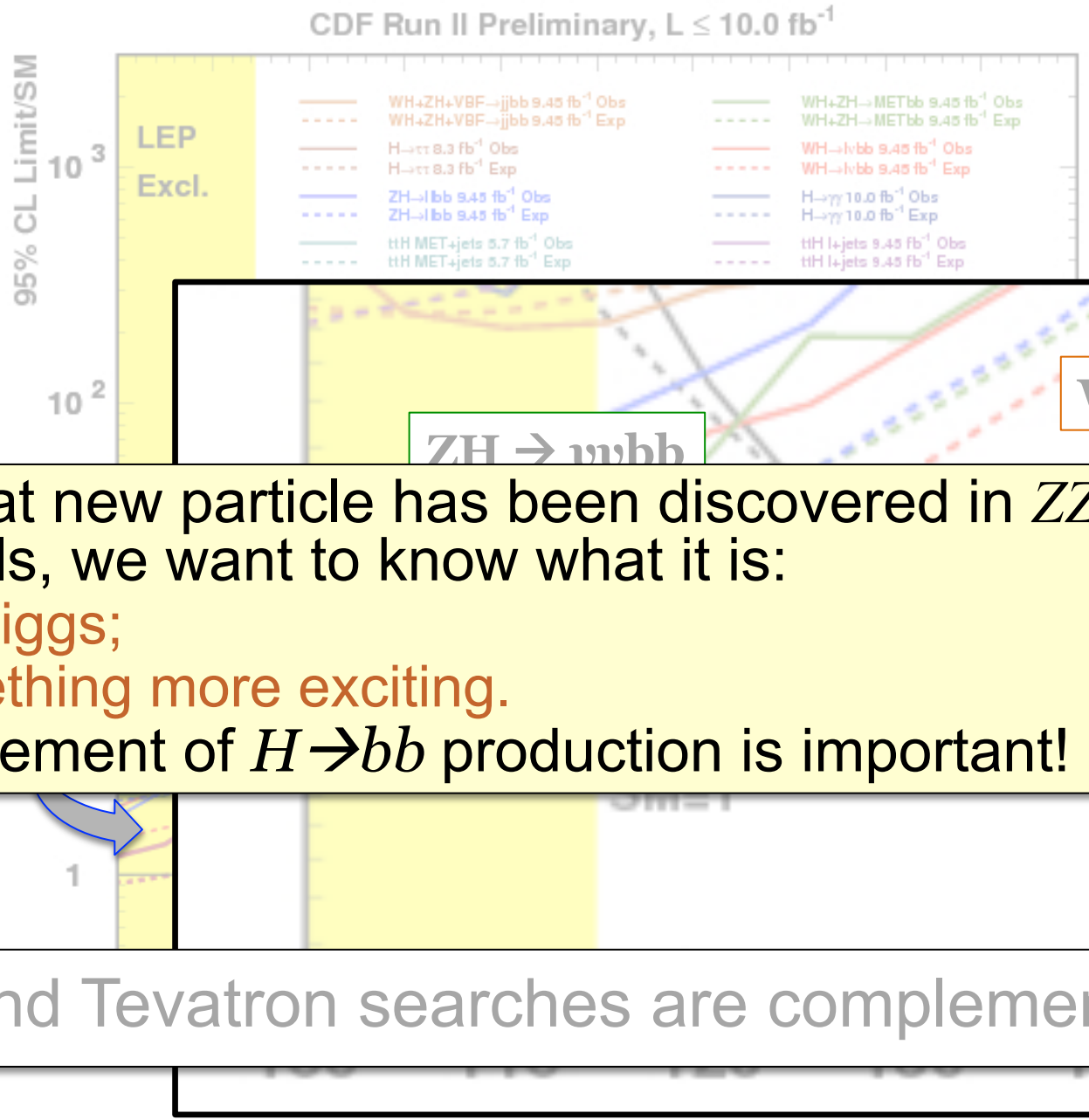


- LHC and Tevatron searches are complementary!

Tevatron Sensitivities

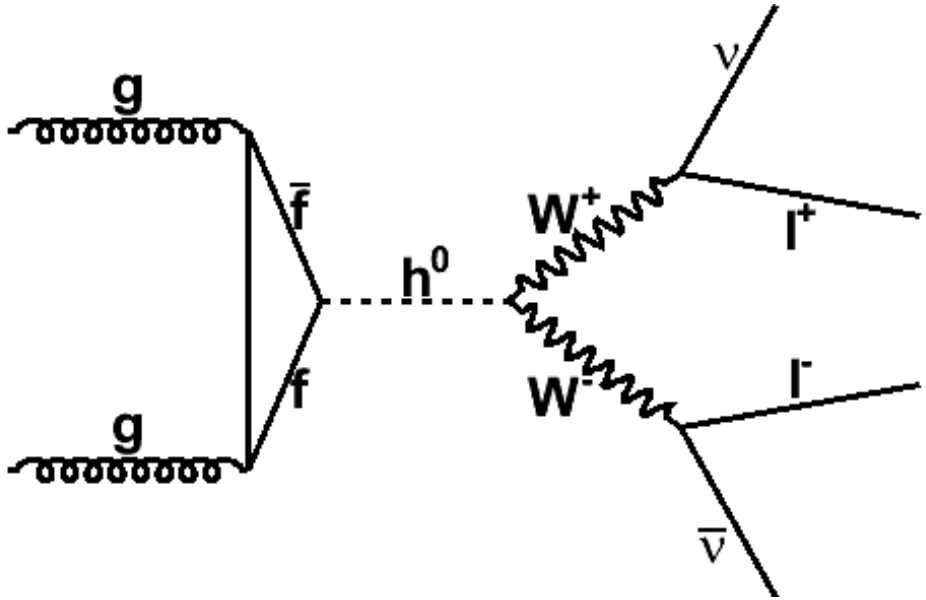


- Now that new particle has been discovered in ZZ / $\gamma\gamma$ channels, we want to know what it is:
  - SM Higgs;
  - Something more exciting.
- Measurement of $H \rightarrow bb$ production is important!

- LHC and Tevatron searches are complementary!

$H \rightarrow WW$ Searches

- Basic requirements:
  - Two oppositely-charged leptons
  - Significant amount of missing energy from associated with neutrinos
  - Samples split into subsamples based on number of accompanying jets (*increases sensitivity*)



- Neural network incorporates variables that give some discrimination between signal and background

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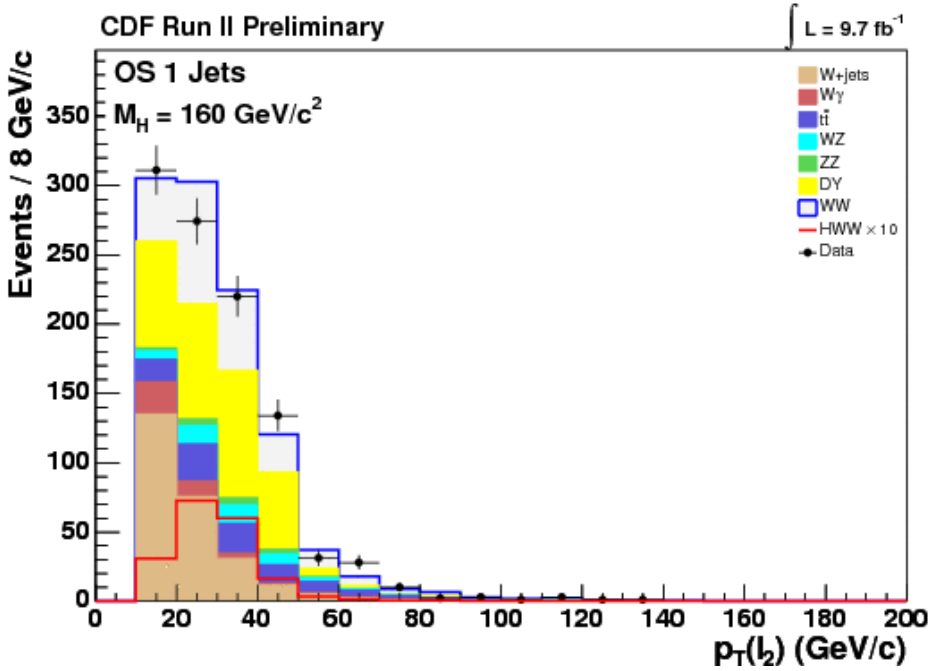

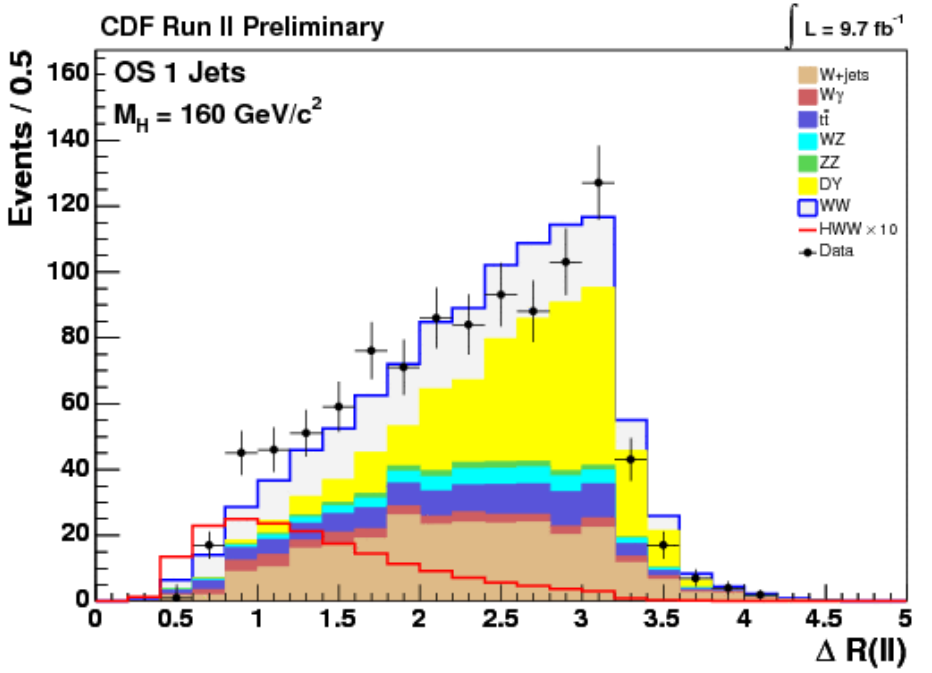

$H \rightarrow WW$ Searches

- Basic requirements:
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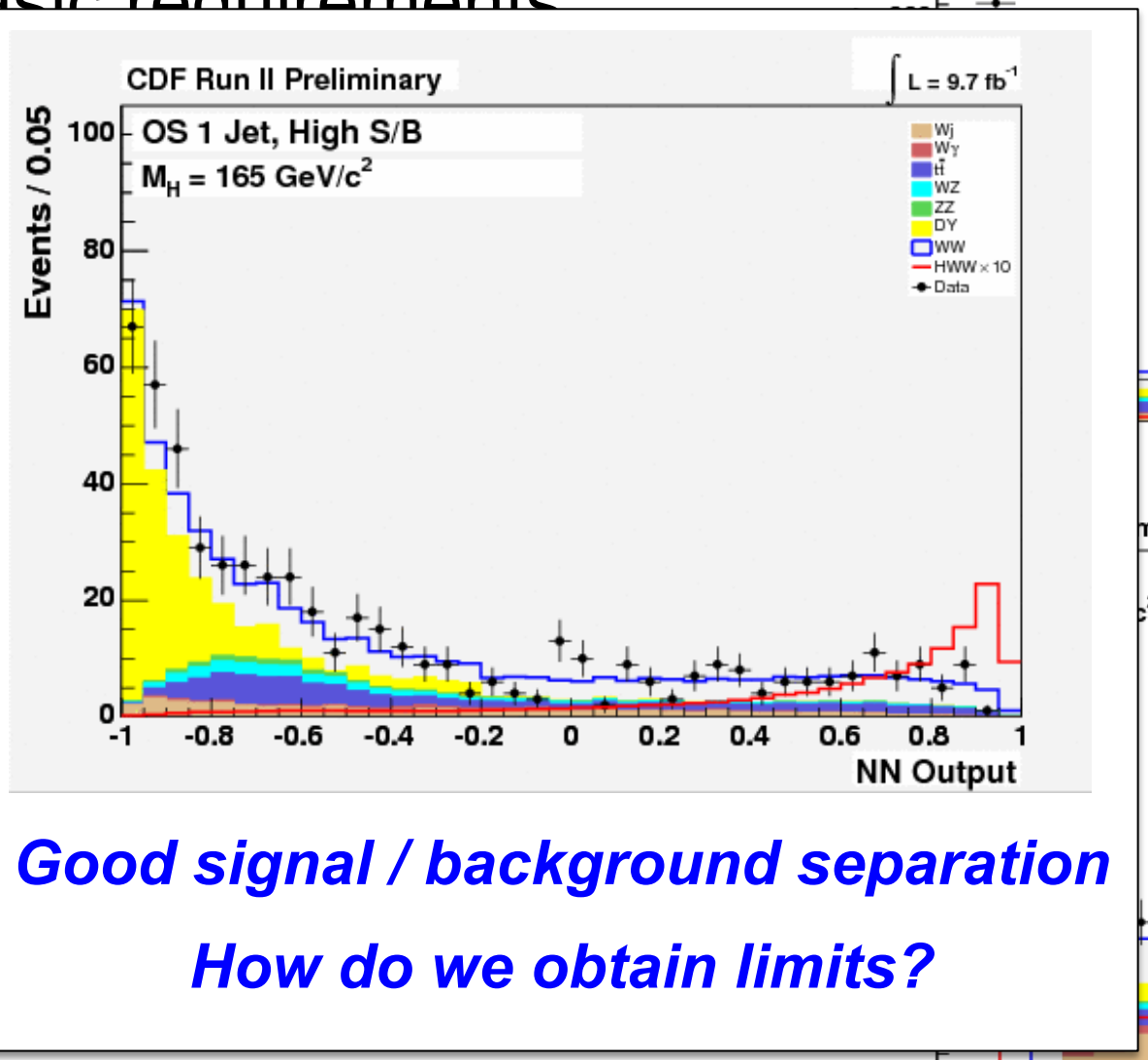
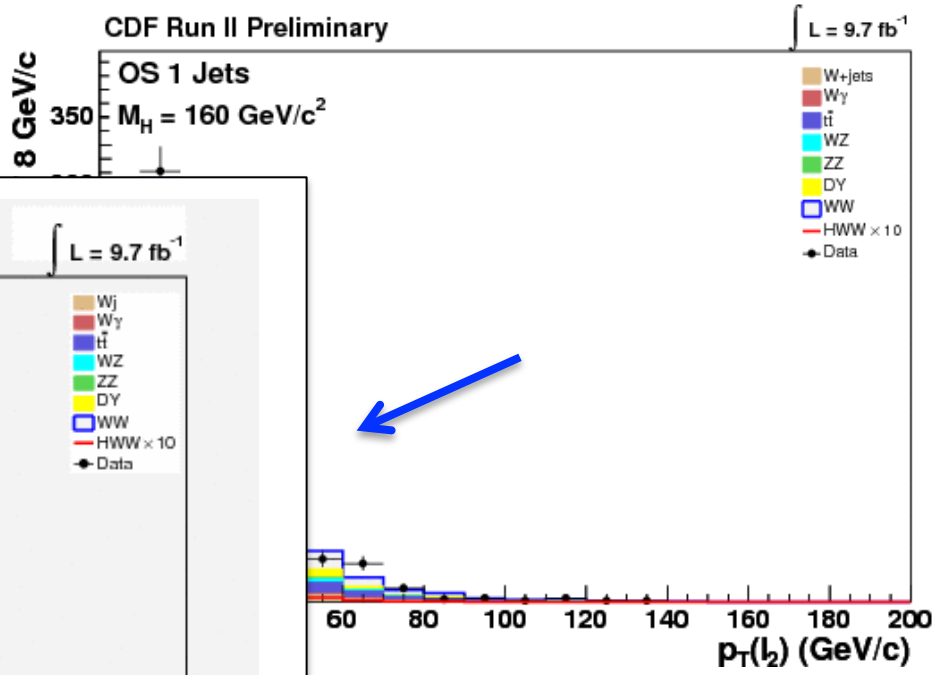
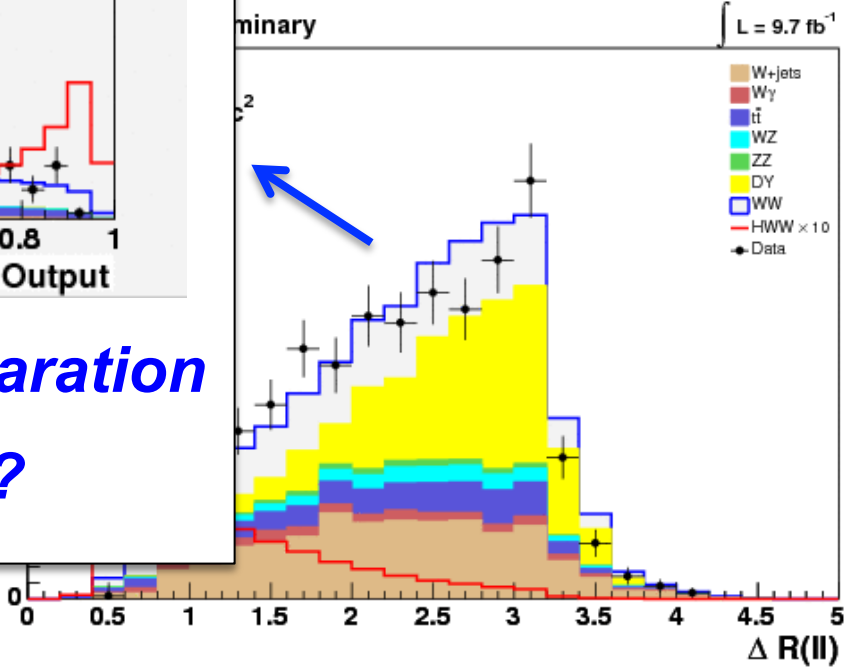


Good signal / background separation

How do we obtain limits?

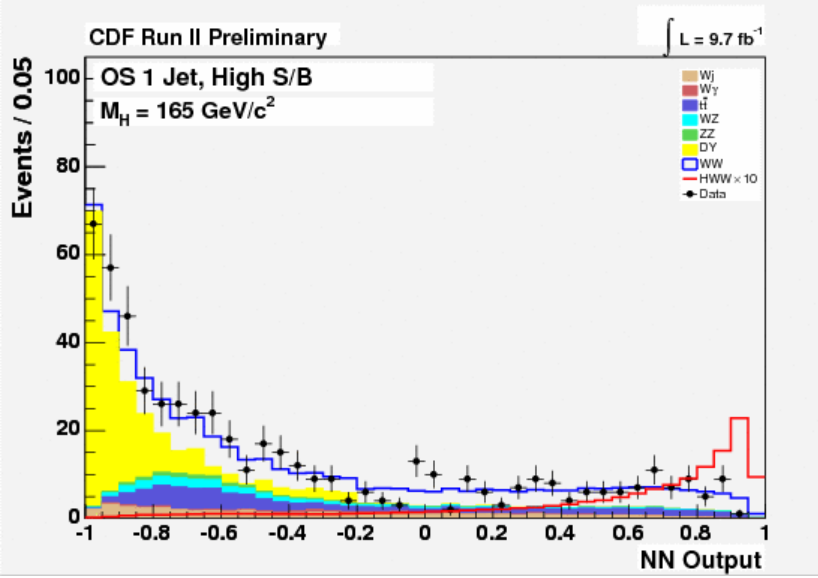




Extracting Limits on SM Higgs Production

- Limits 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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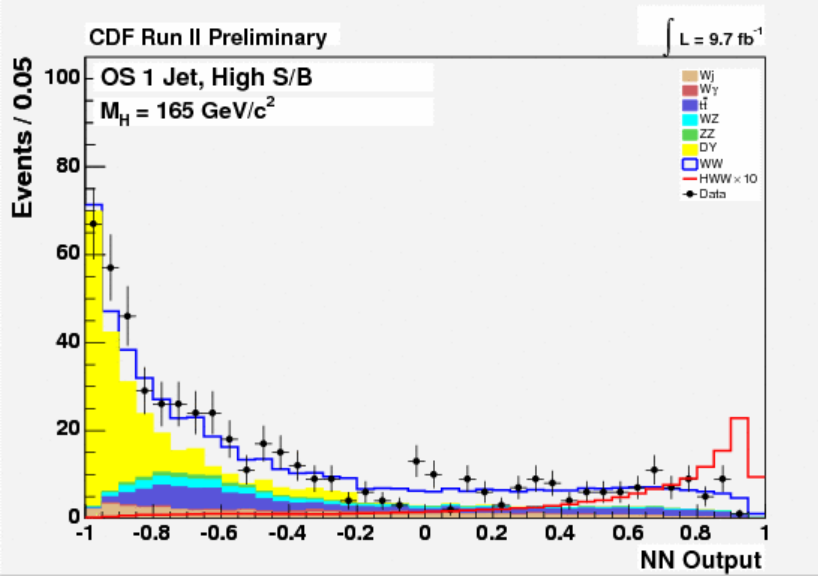
Expected events

Observed events



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Expected events

Nuisance parameters

Observed events

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

Extracting Limits on SM Higgs Production

- Limits extracted by starting with a combined likelihood function

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

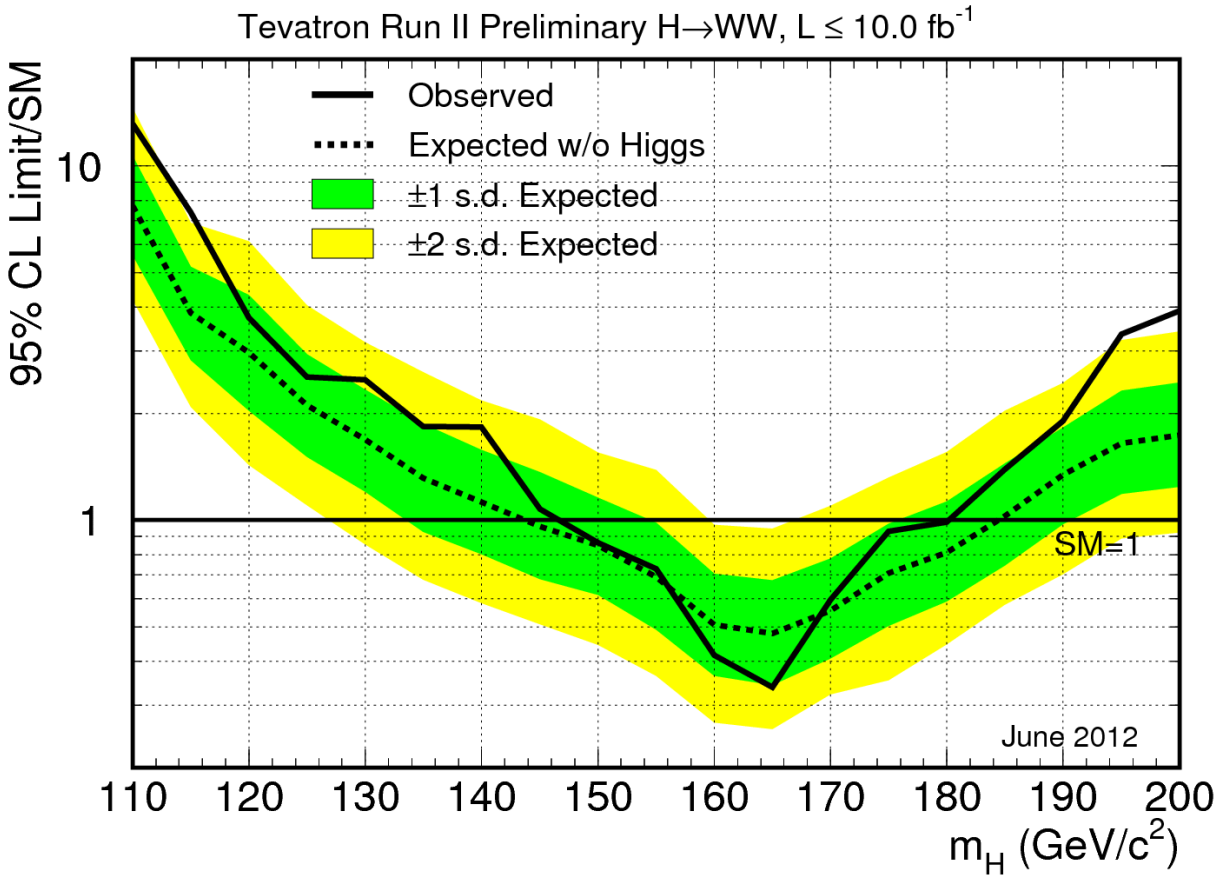
Expected events

Nuisance parameters

Observed events

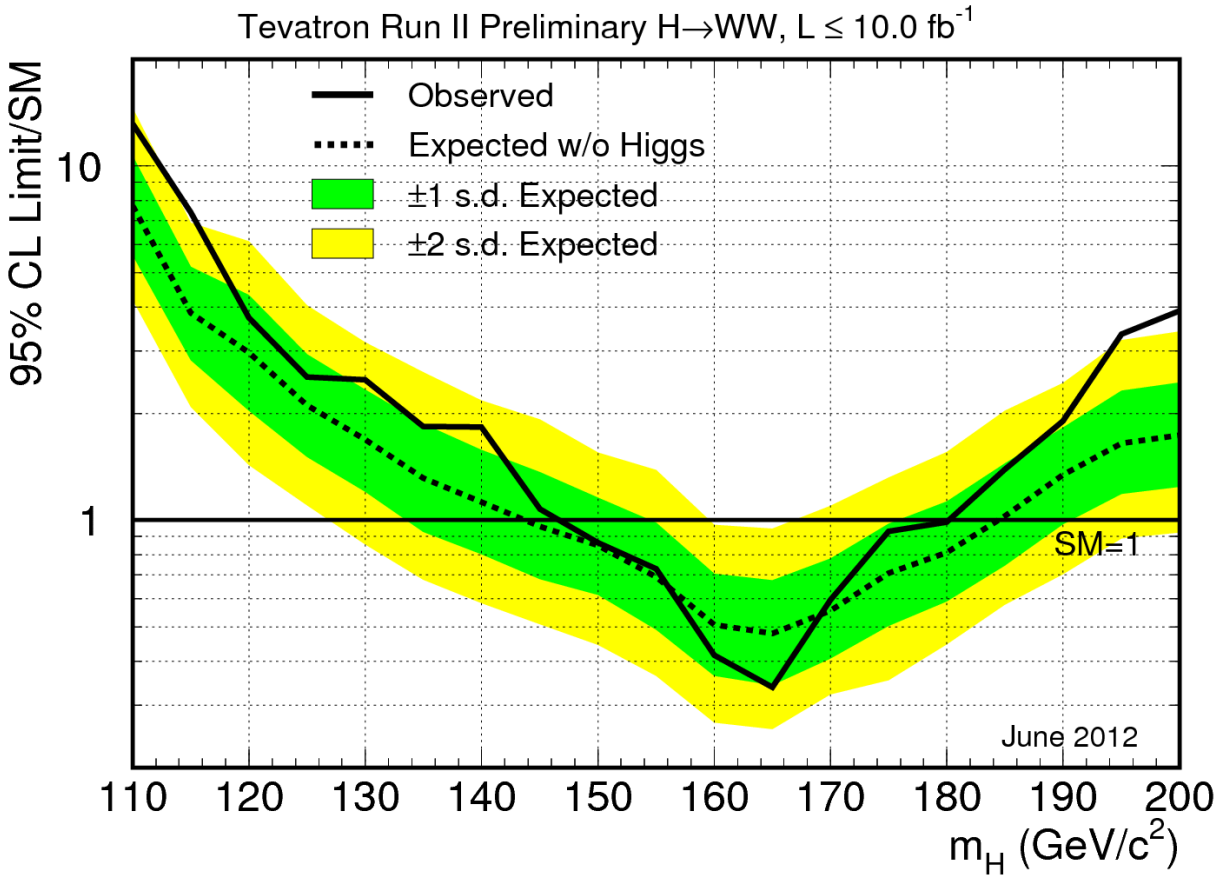
- Expected signal / background events dependent on systematic uncertainties, included as nuisance parameters
- Determine best-fit nuisance-parameters by maximizing likelihood
- Higgs limits derived using both Bayesian (marginalization) / Frequentist (profile) methods
  - Good agreement between both

H → WW Tevatron Limits



H → WW Tevatron Limits

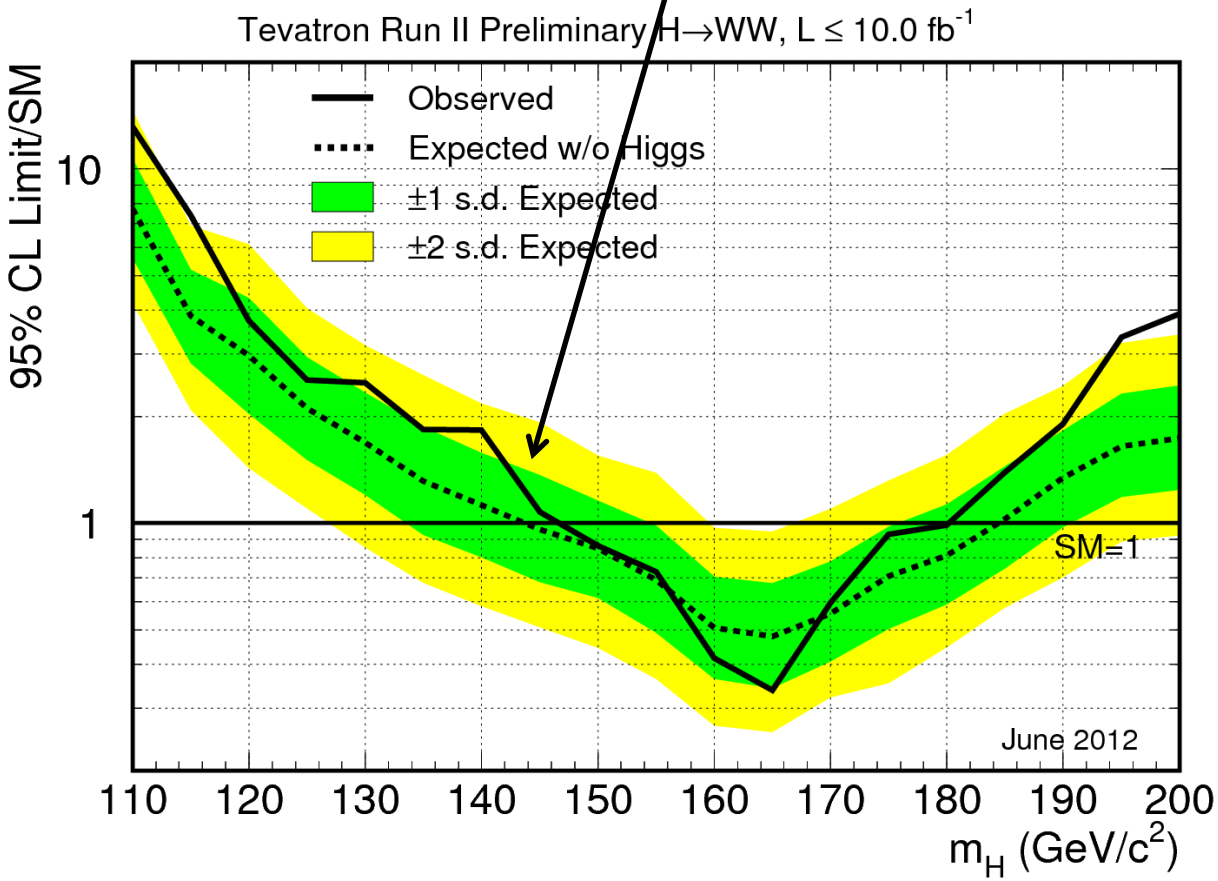
1. Upper cross section limit for Higgs production relative to SM prediction



H → WW Tevatron Limits

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

2. Observed limit (solid line) from data



H → WW Tevatron Limits

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

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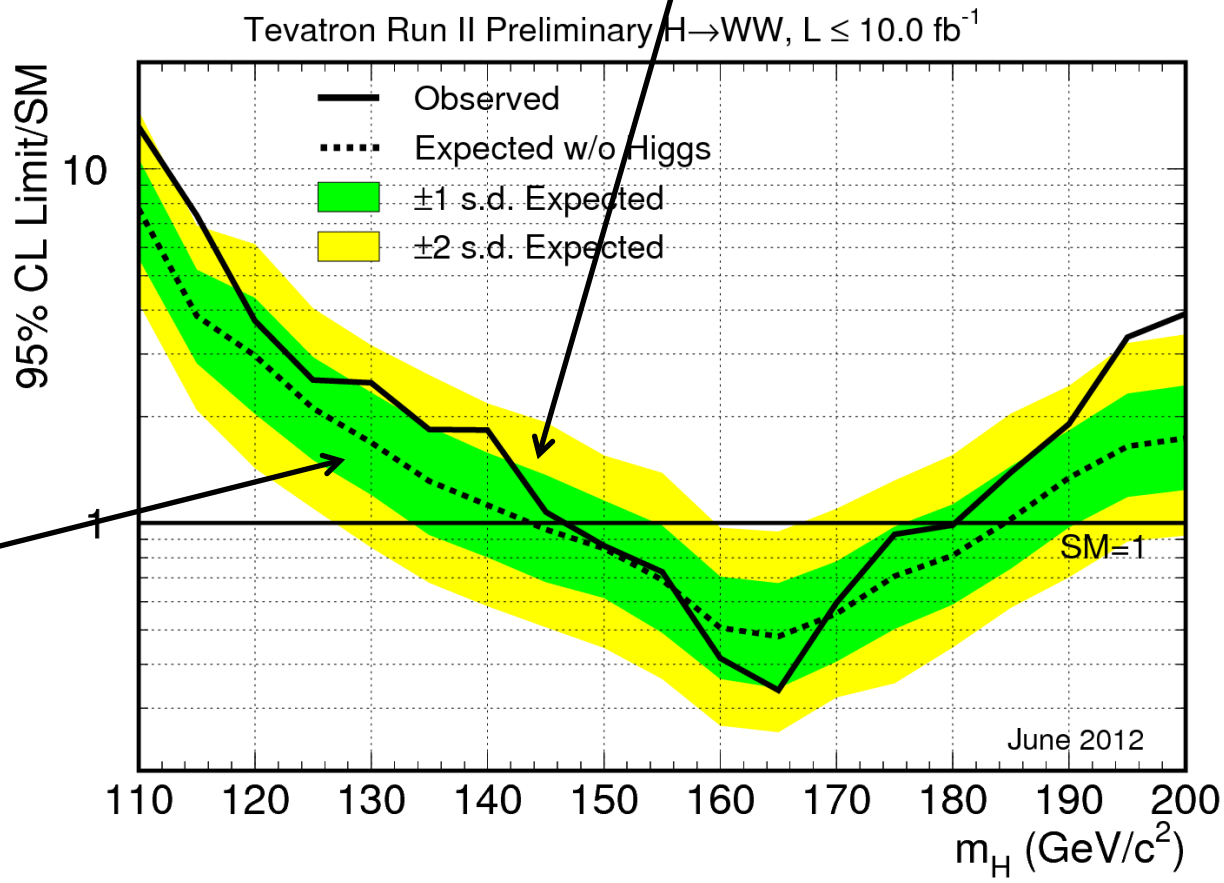
3. Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments



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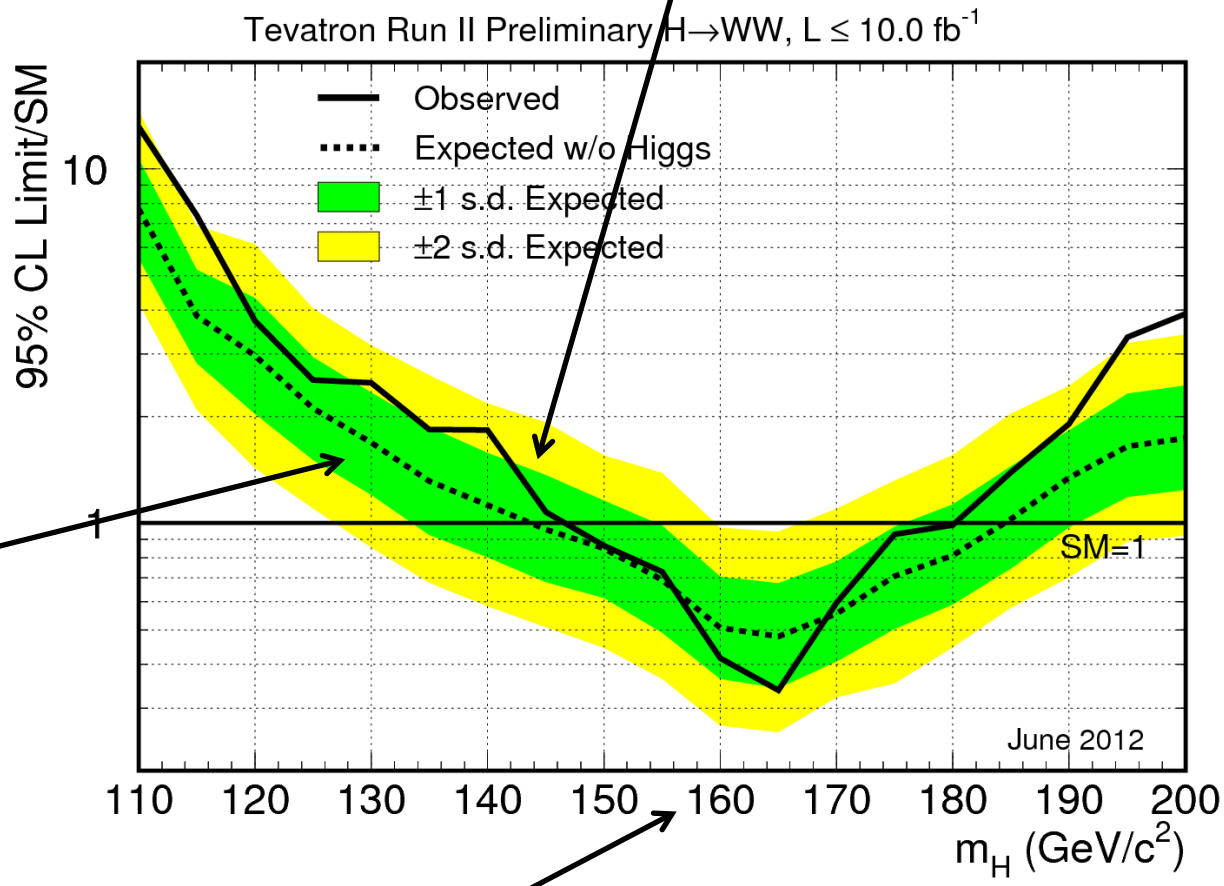
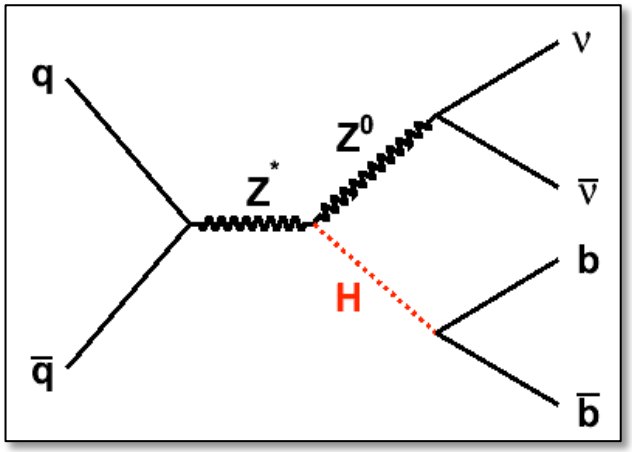
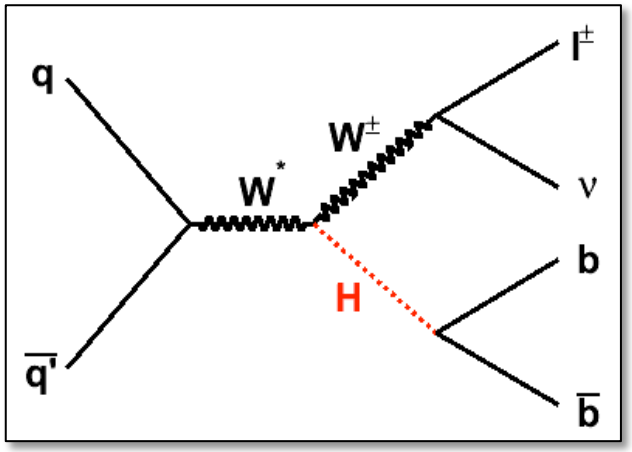


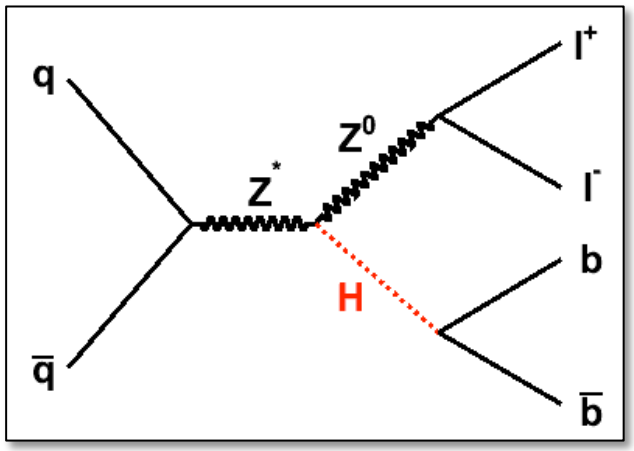
3. Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

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

Searching for an $H \rightarrow b\bar{b}$ Signal





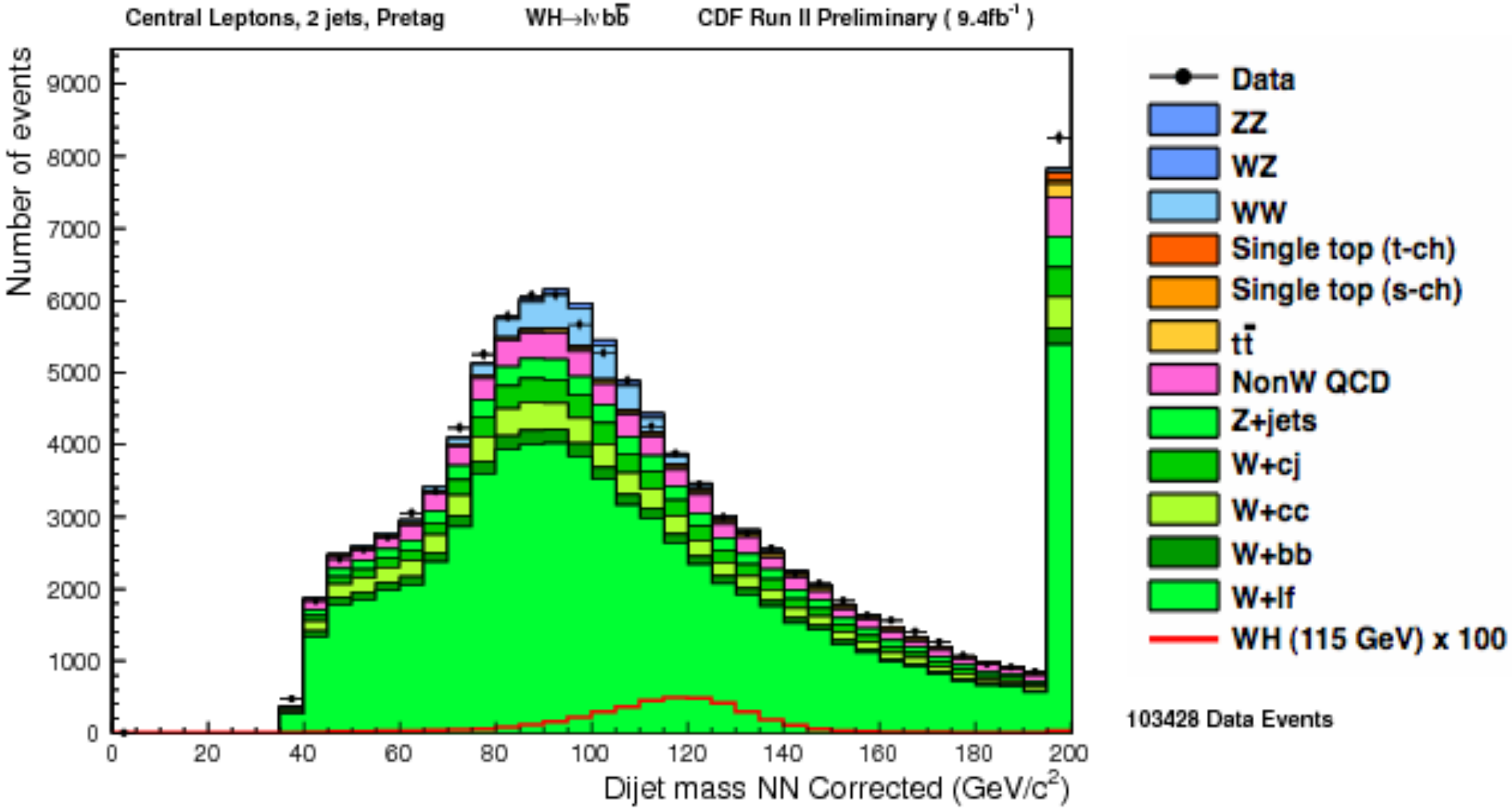


Analysis	No. of Leptons	Missing E_T ?	No. of b-Jets
$ZH \rightarrow \nu\bar{\nu} + b\bar{b}$	0	Yes	2
$WH \rightarrow \ell\nu + b\bar{b}$	1	Yes	2
$ZH \rightarrow \ell^+\ell^- + b\bar{b}$	2	No	2

- To get the most sensitivity:
  - Maximize lepton reconstruction and selection efficiencies
  - Maximize *b*-jet tagging – *discussed today*
  - Improve invariant dijet mass (m_{jj}) resolution
  - Suppress / separate background from signal – *discussed today*

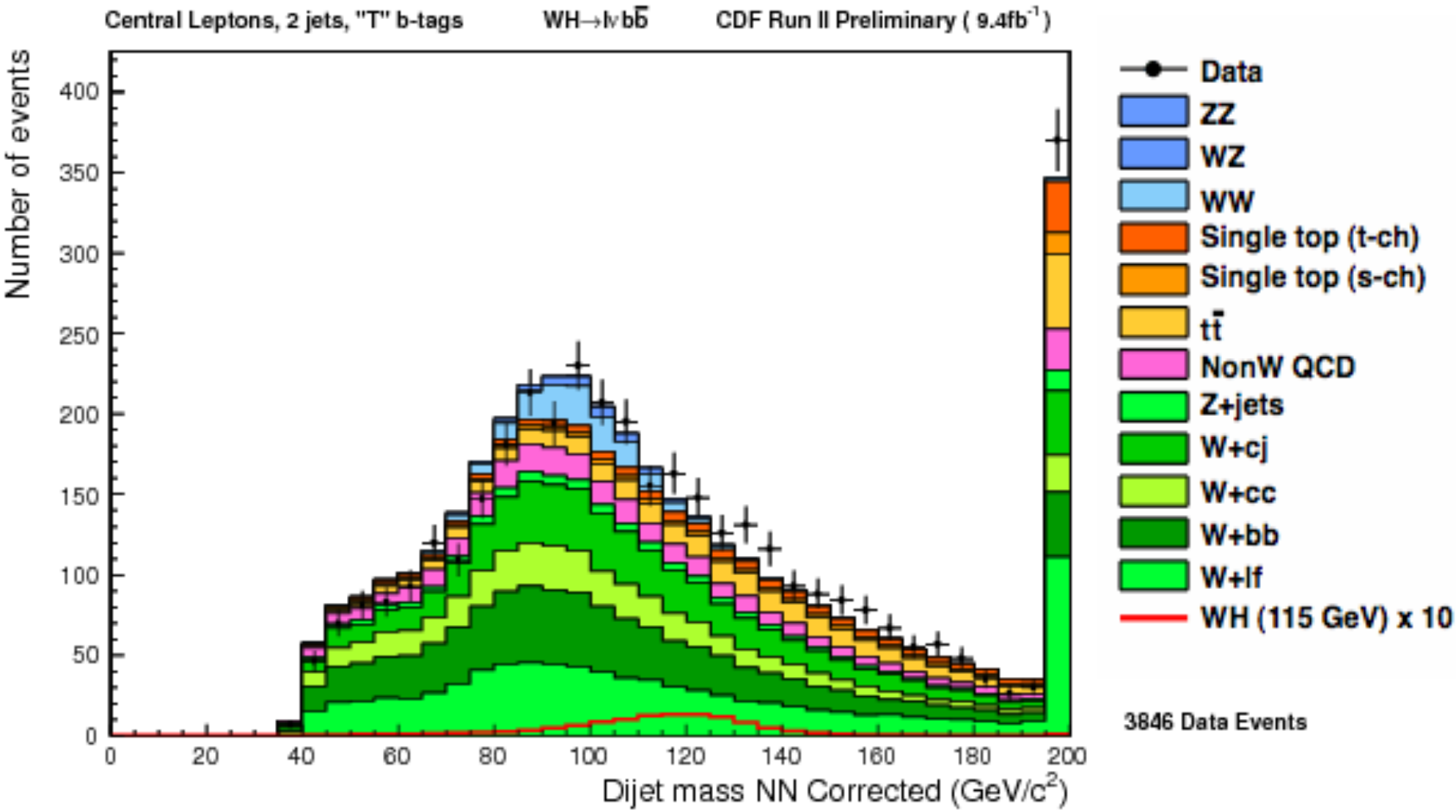
Why *b*-tagging?

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



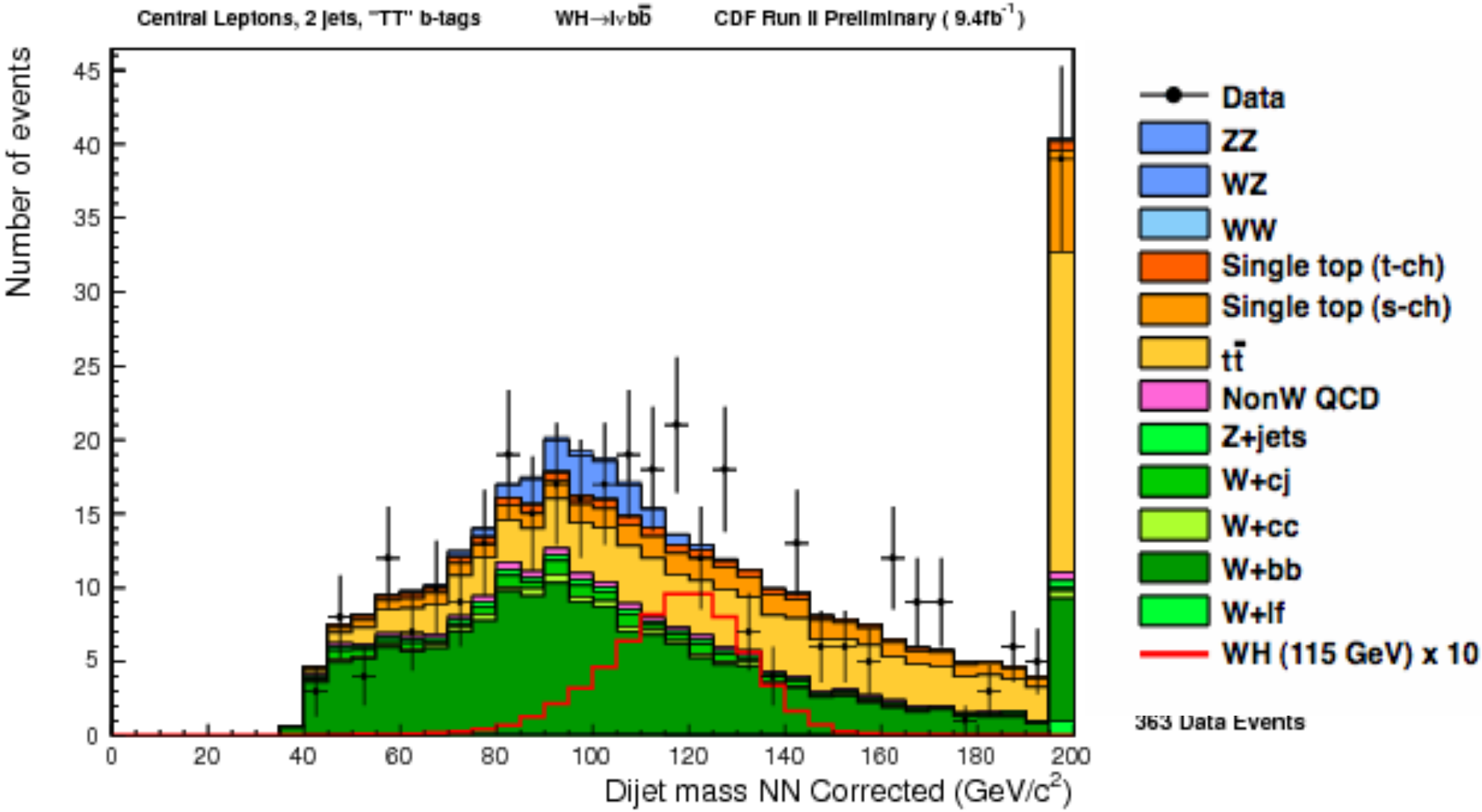
Why *b*-tagging?

- Loose event selection + 1 tightly tagged b-quark jet



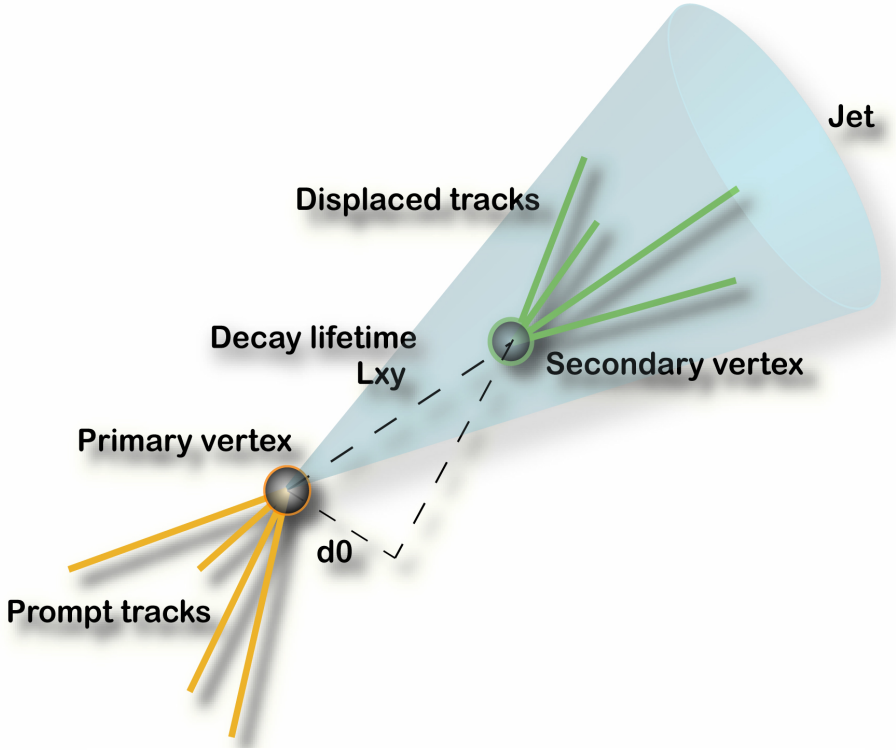
Why *b*-tagging?

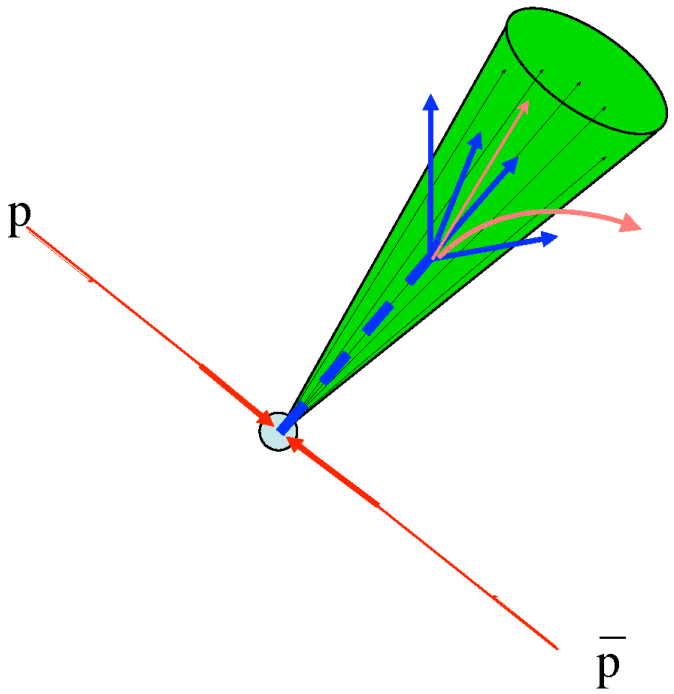
- Loose event selection + 2 tightly tagged b-quark jets



Improved *b*-tagging

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





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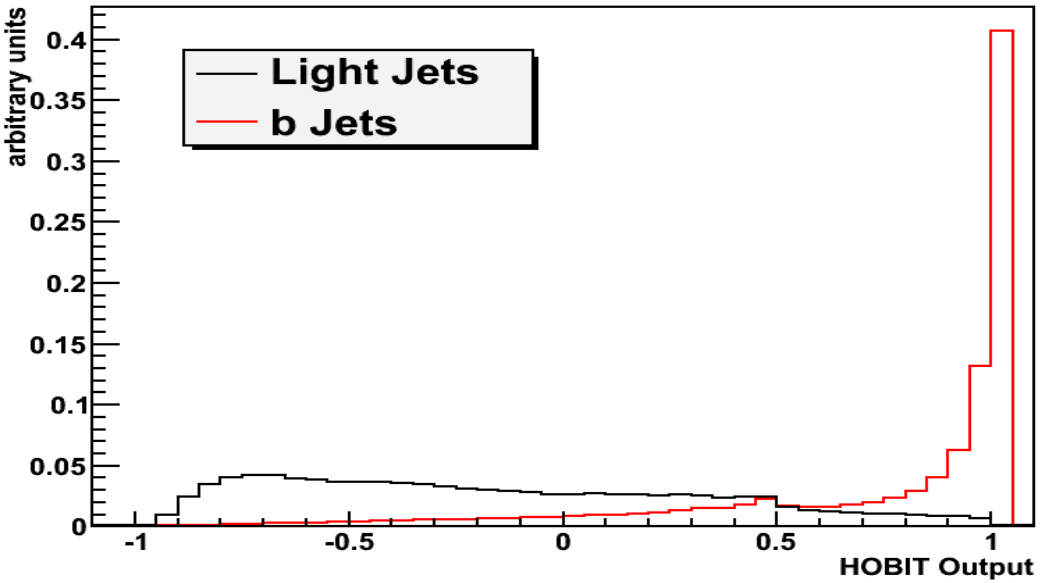
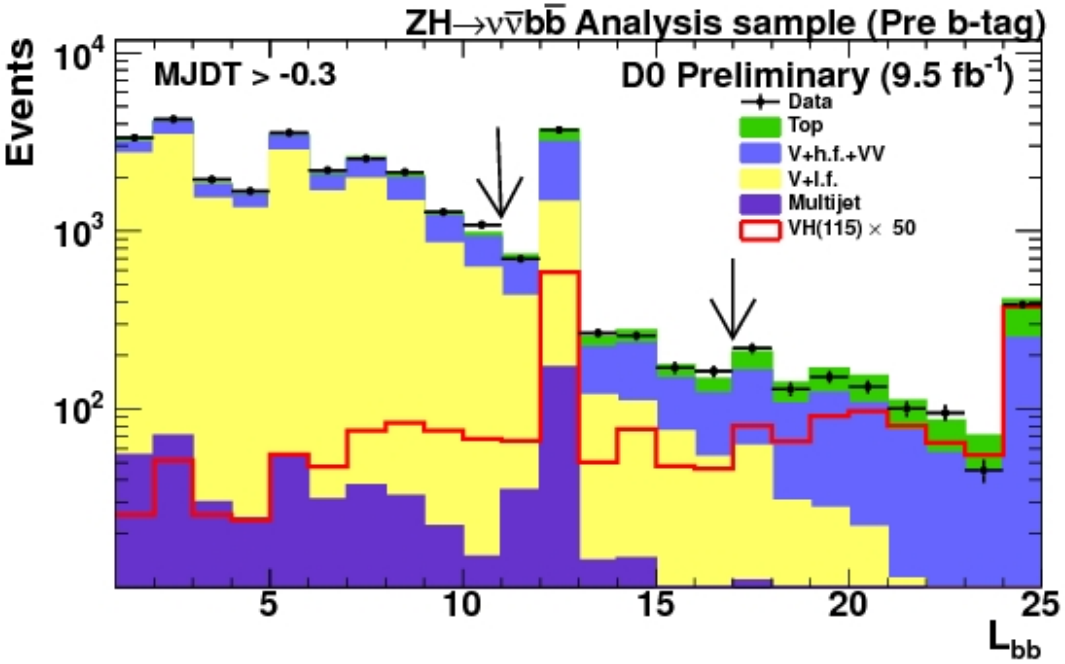


- CDF – HOBIT NN
  - NN discriminant trained using properties of H→ bb decays

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



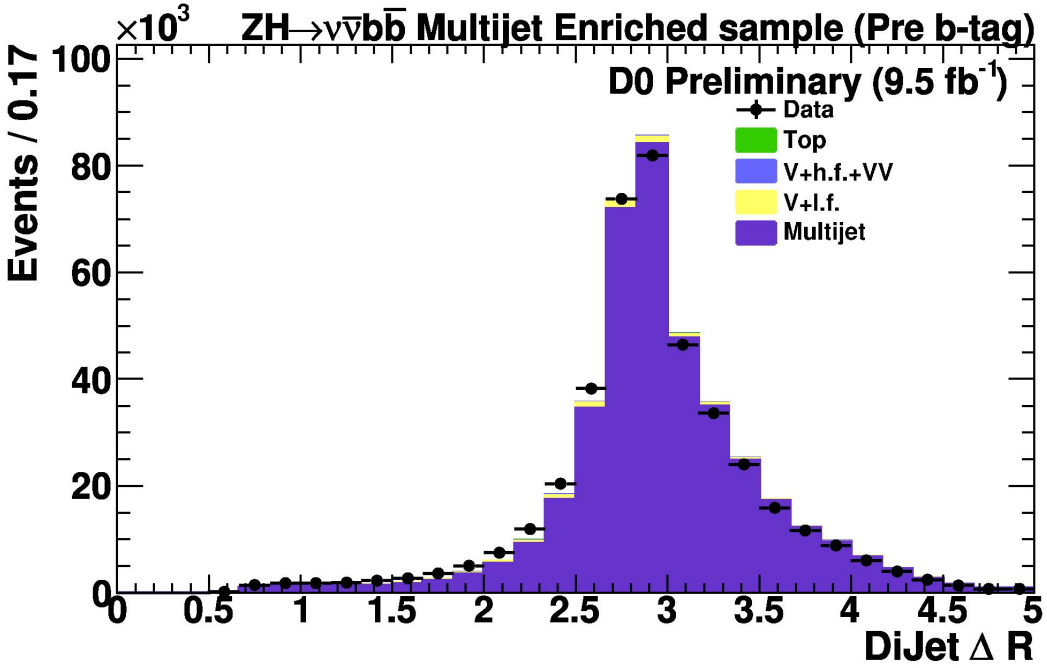
- D0 – L_b BDT
  - Continuous output ranked into 12 operating points, based on purity

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

Multivariate Analysis Techniques

- **How do you beat down QCD backgrounds in $ZH \rightarrow \nu\nu + b\bar{b}$?**

- QCD backgrounds suppressed with selection criteria:
  - Large MET
  - MET should not align with jet
  - Jets should not be back-to-back



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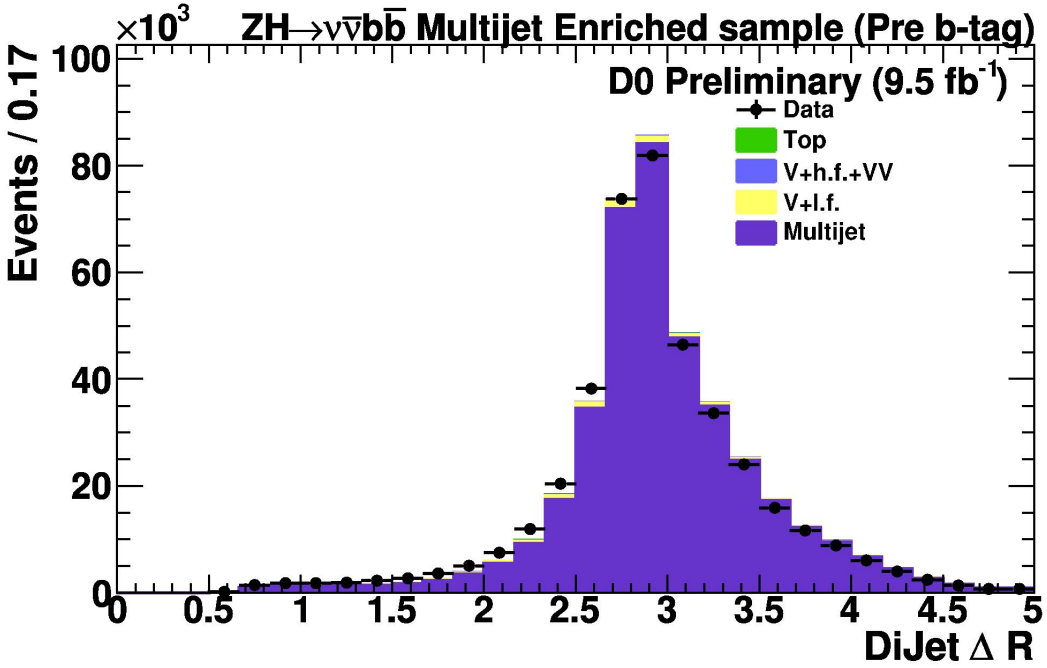
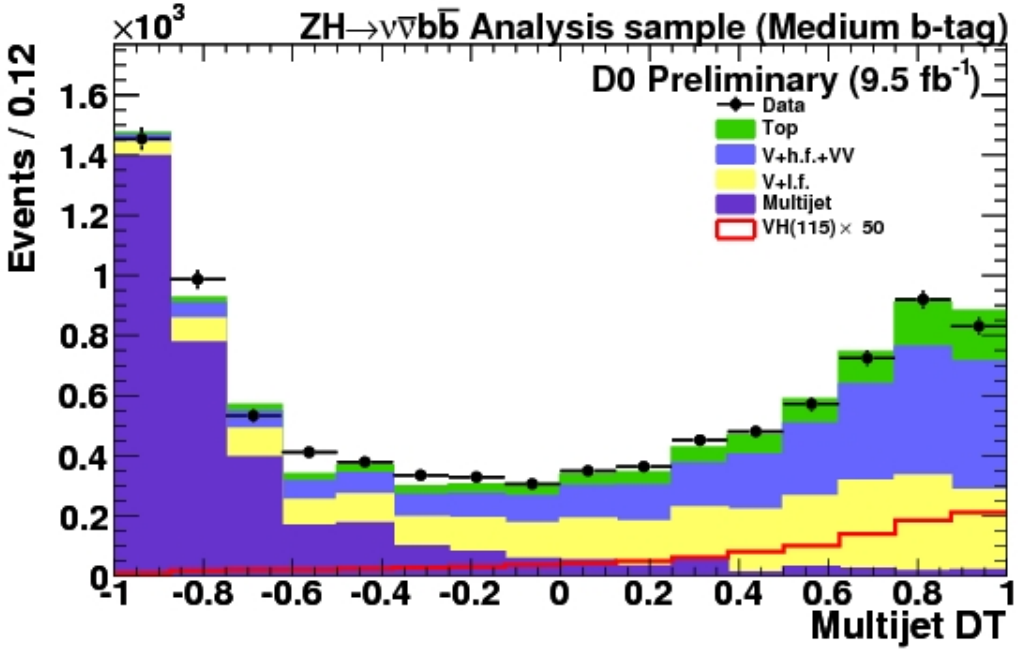


- After selection:
  - QCD ~ 90% of background
  - S/B ~ 10^{-4}

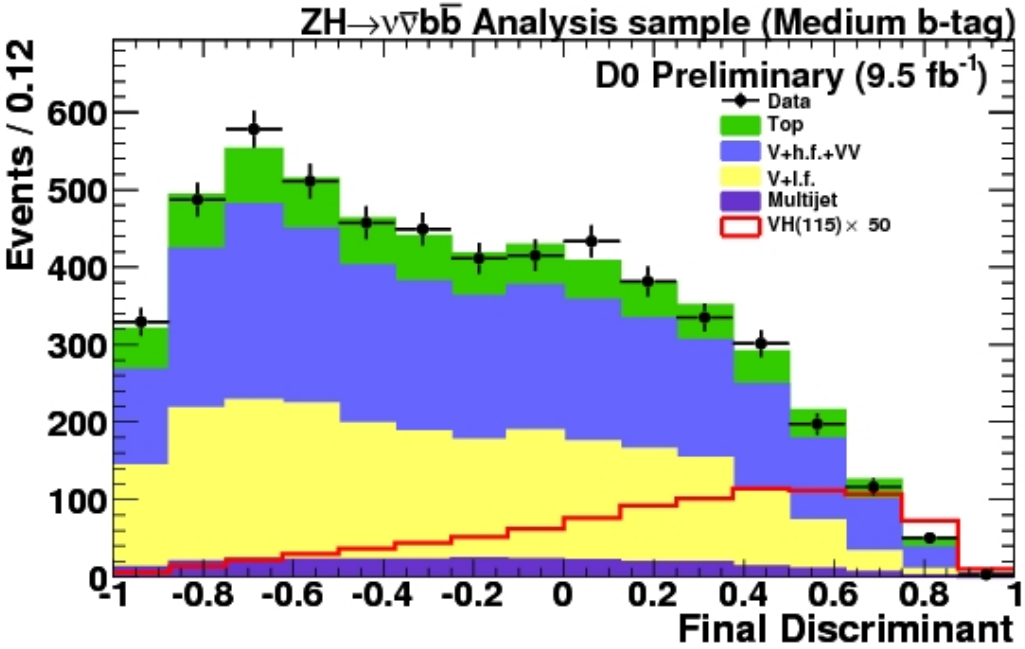
Multivariate Analysis Techniques

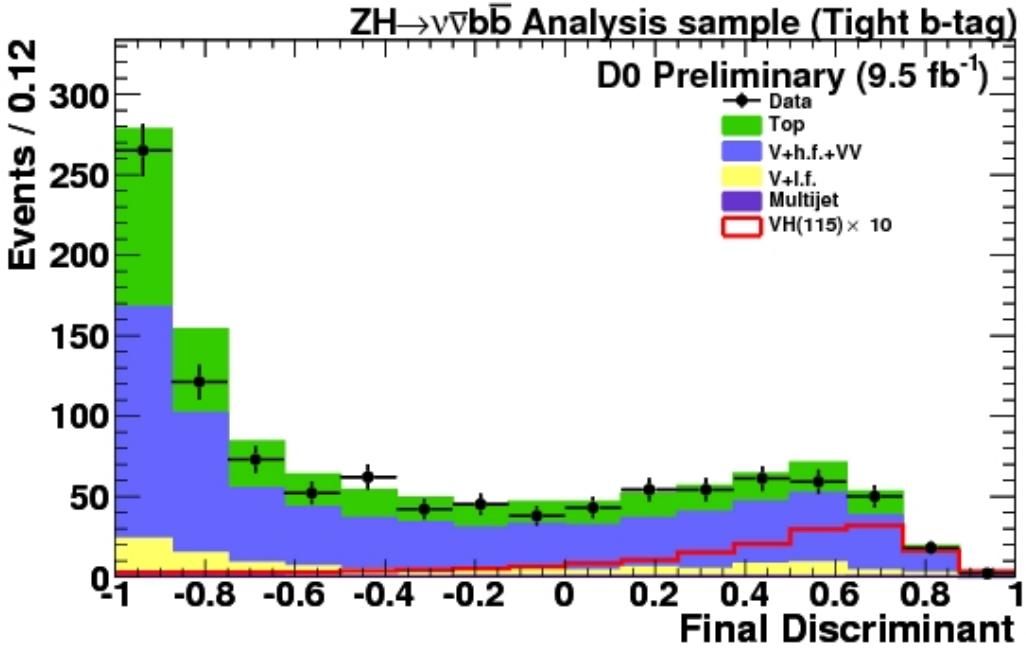
- **How do you beat down QCD backgrounds in $ZH \rightarrow \nu\nu + b\bar{b}$?**
- QCD backgrounds suppressed with selection criteria:
  - Large MET
  - MET should not align with jet
  - Jets should not be back-to-back
- After selection:
  - QCD ~ 90% of background
  - S/B ~ 10^{-4}
- Remaining QCD background suppressed with BDT, including variables:
  - MET
  - MET significance
  - Track Missing p_T
  - Angular Variables
  - Etc.



Multivariate Analysis Techniques

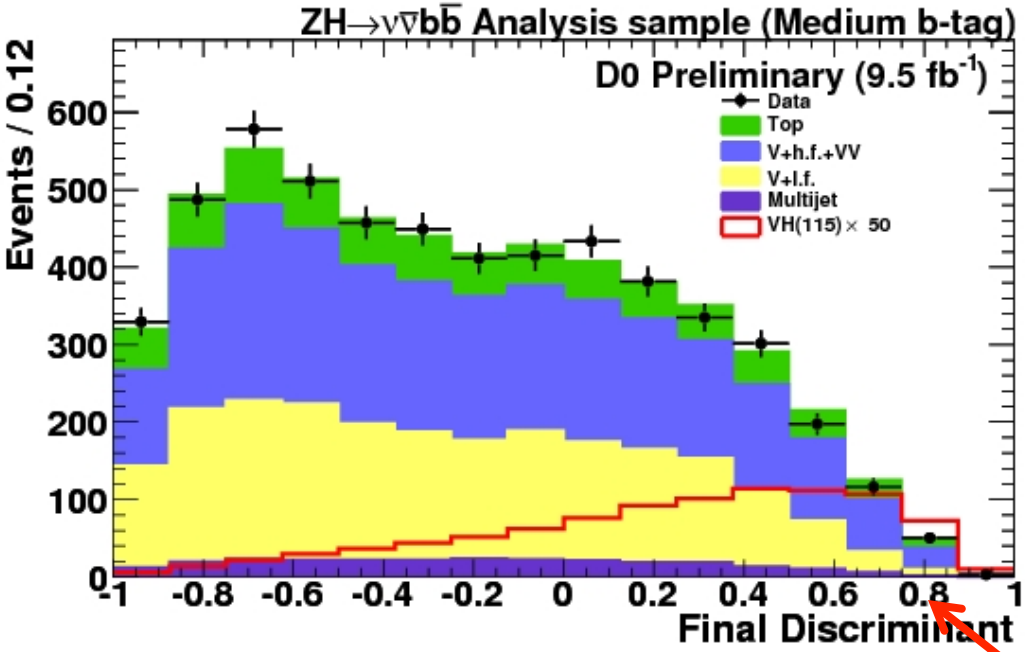
- One final discriminant to separate signal and the remaining background.

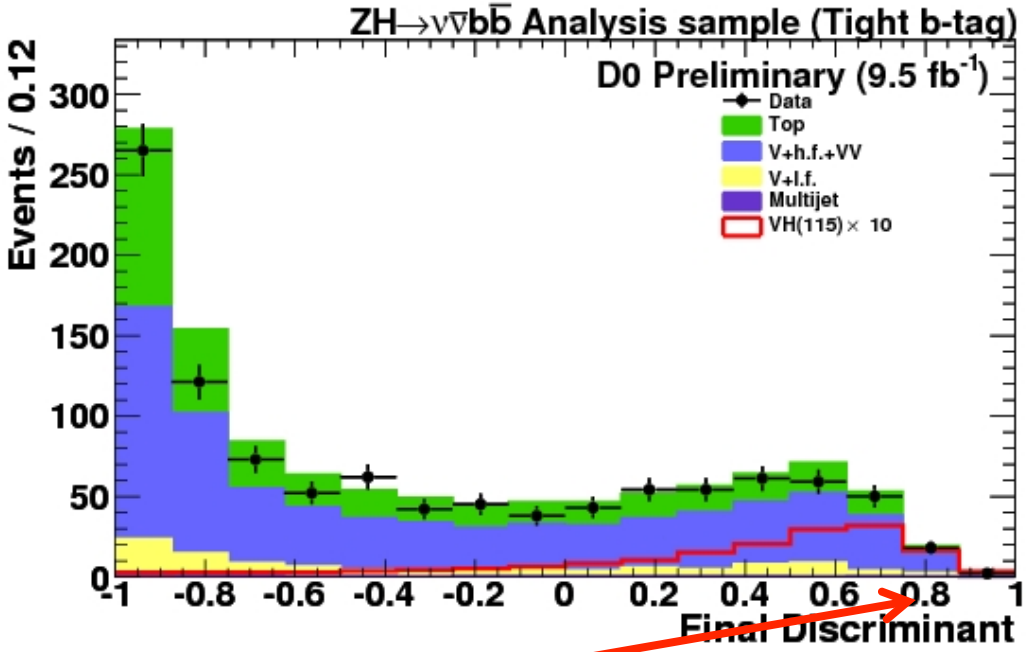




Multivariate Analysis Techniques

- One final discriminant to separate signal and the remaining background.

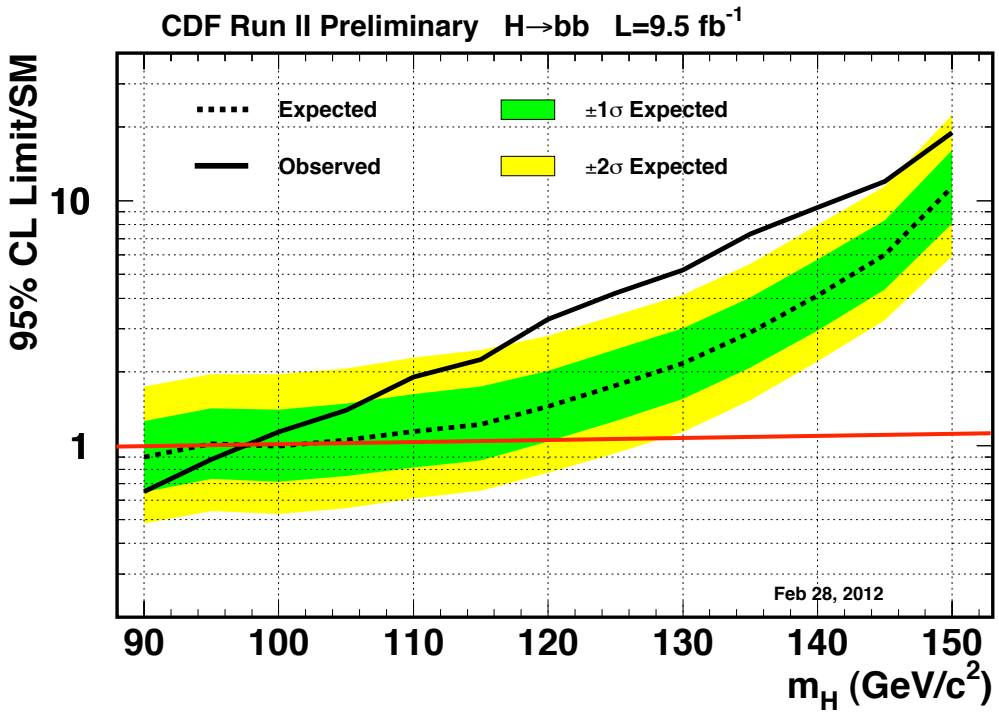


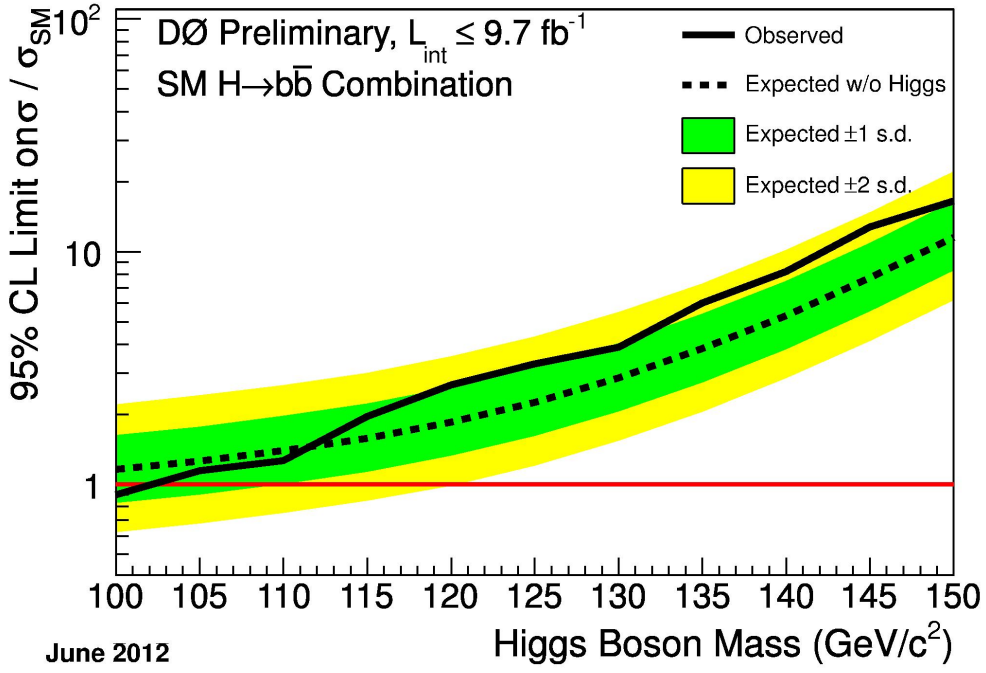


Good signal / background separation.

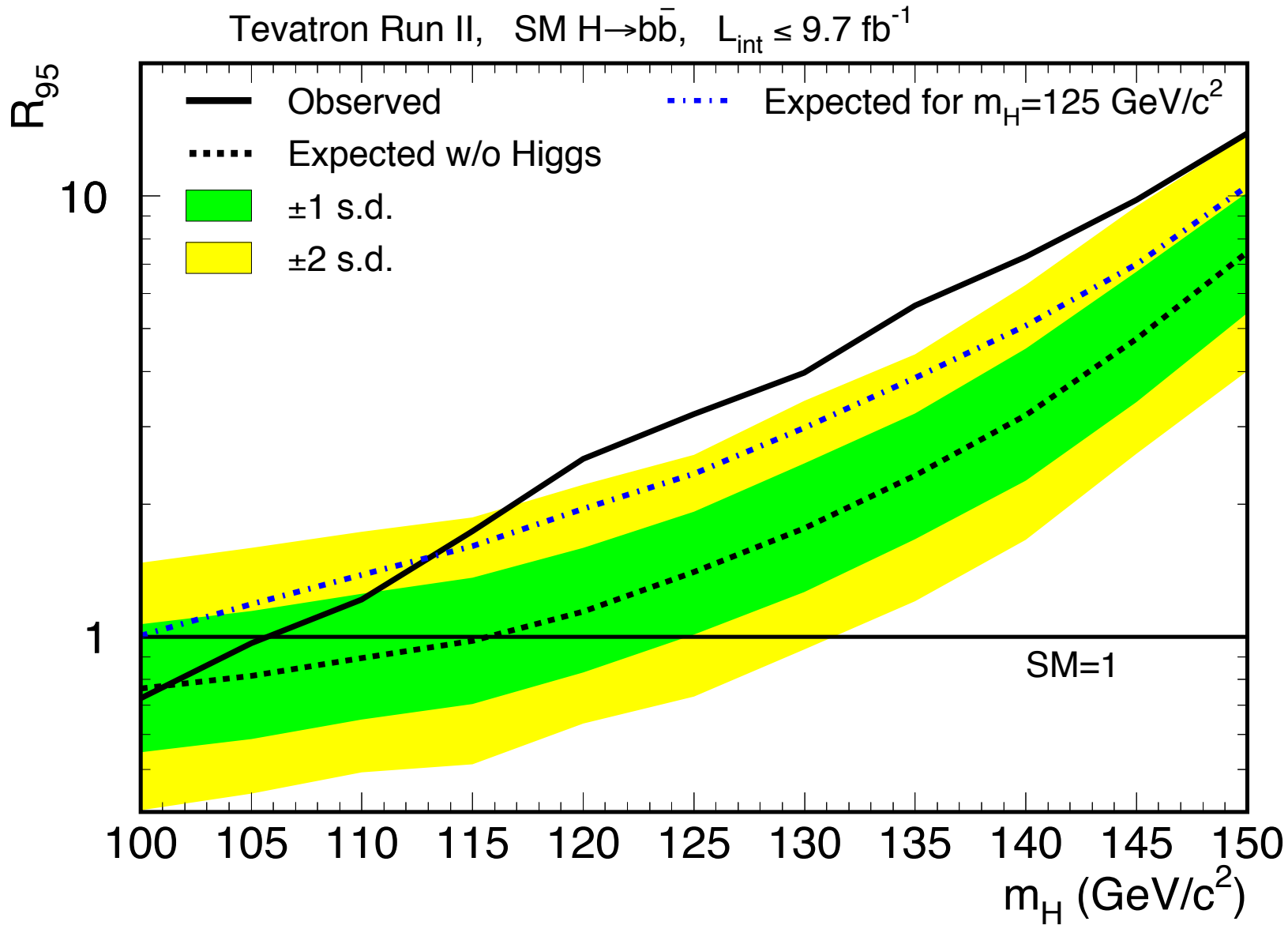
Limits on H → bb

Low-Mass States	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
WH → lν bb	2.8	4.1
VH → MET + bb	3.6	3.9
ZH → ll + bb	3.6	5.1

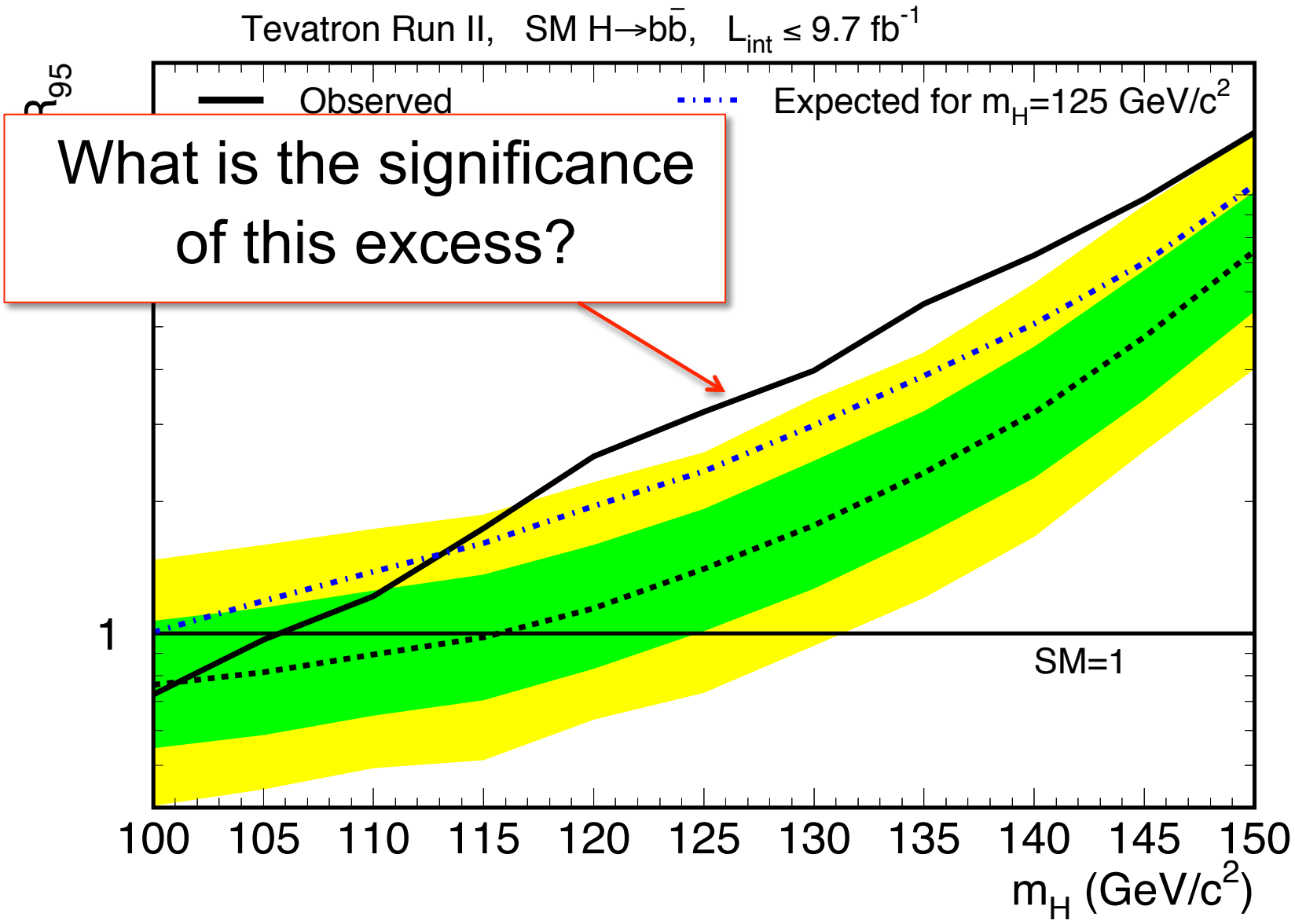




H→bb Limits for Tevatron Combination

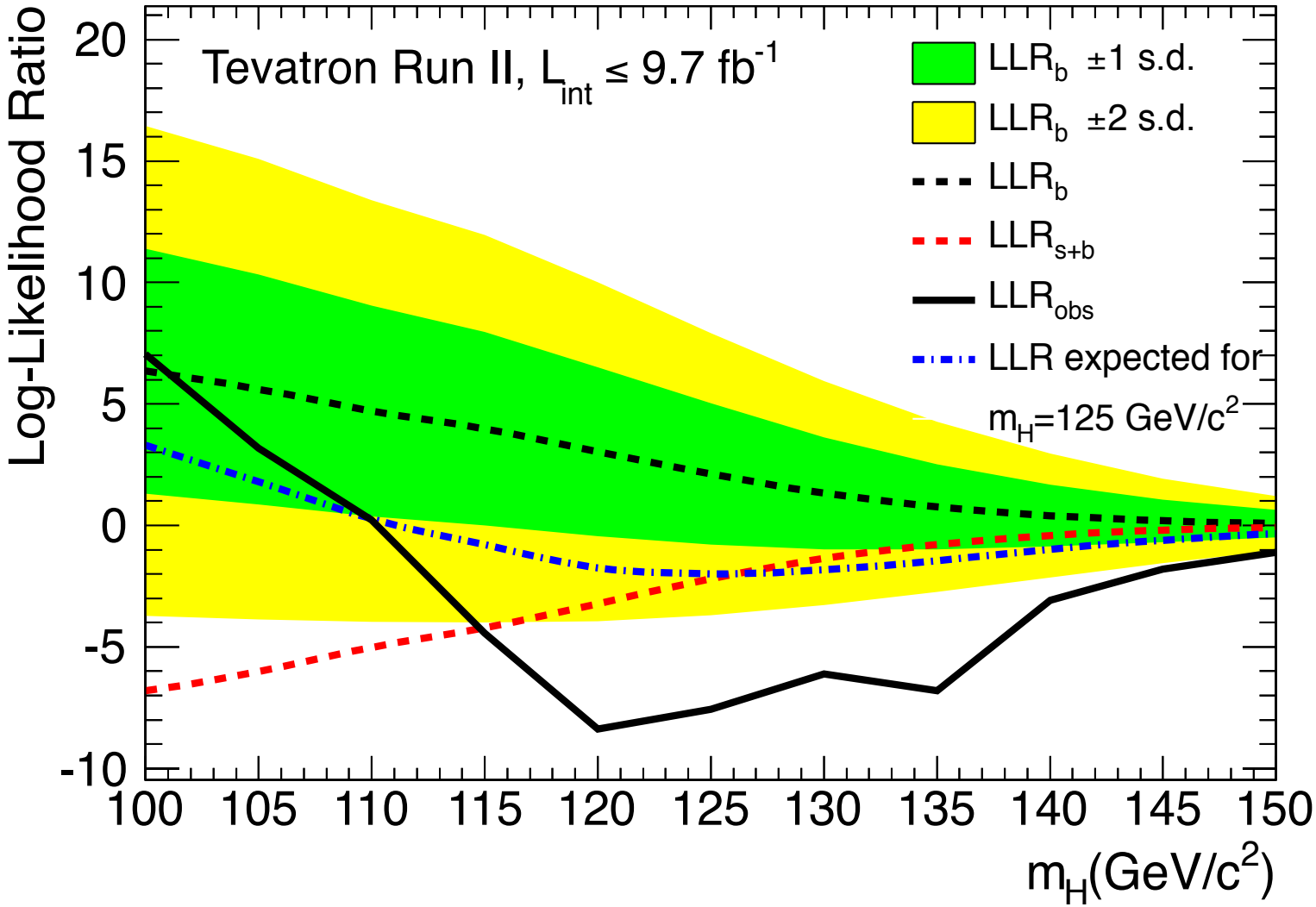


H→bb Limits for Tevatron Combination

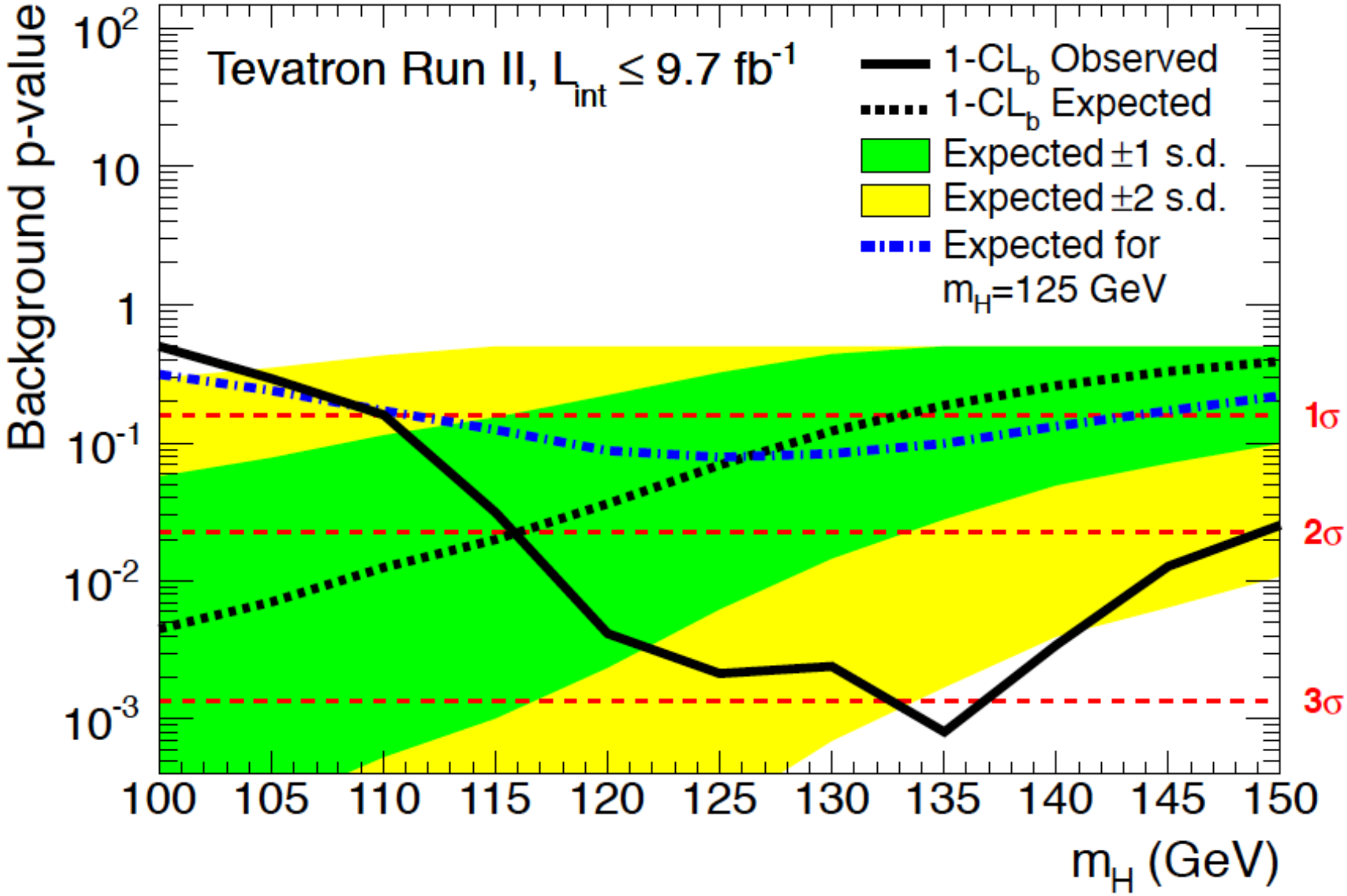


H→ bb LLR of Tevatron Combination

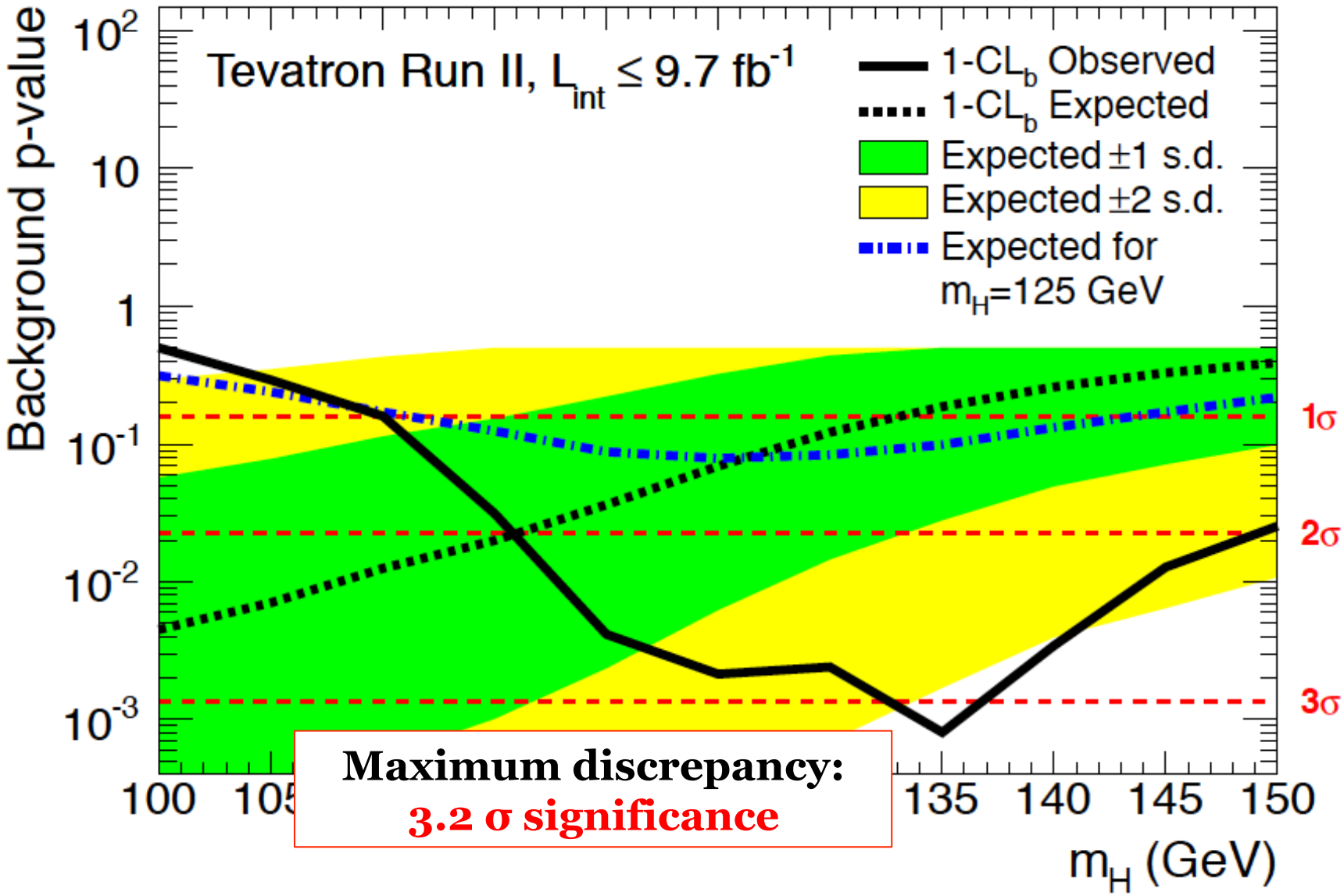
$$Q = -2\ln\frac{p(\text{data}|s+b)}{p(\text{data}|\ \ b\ \ )}$$



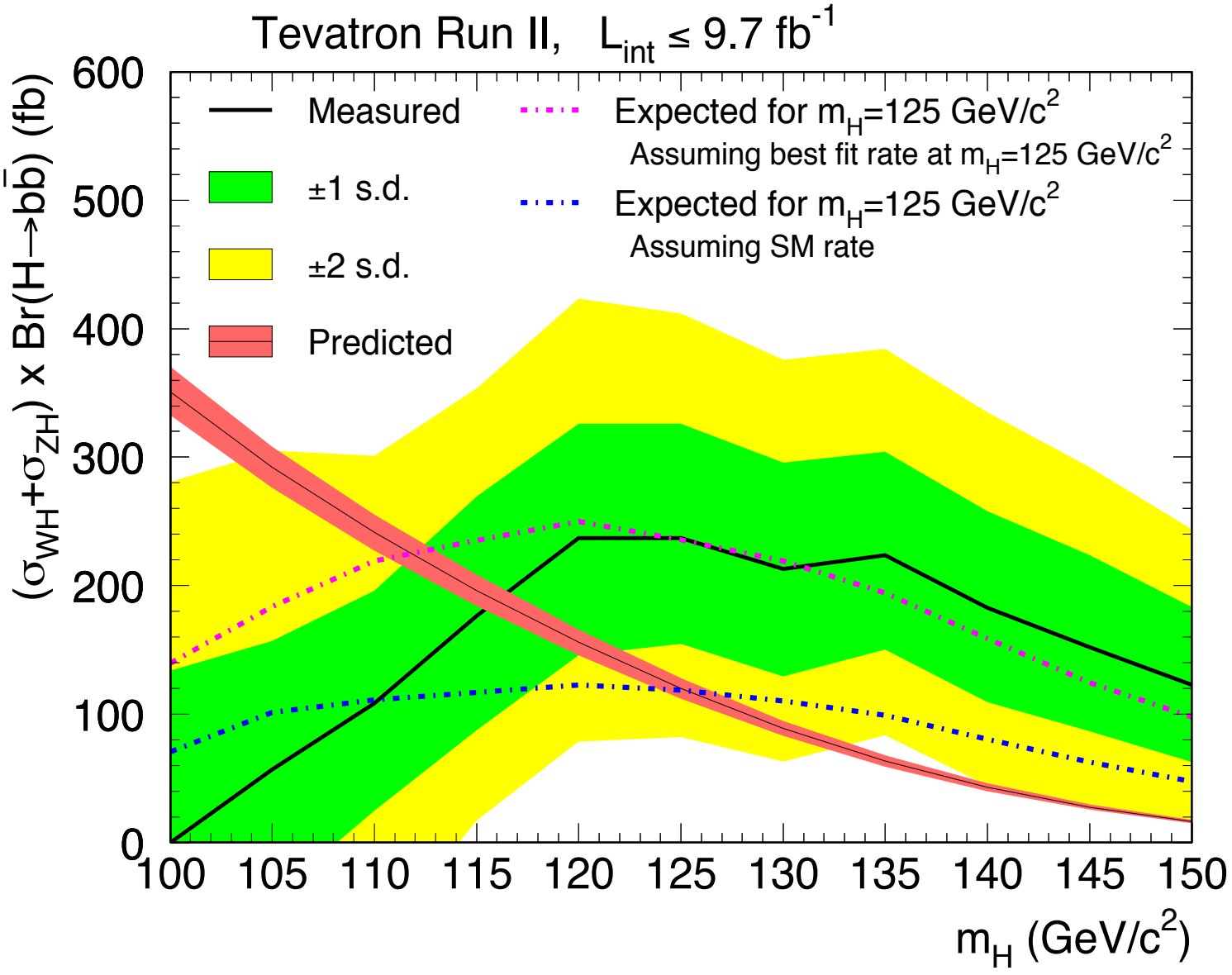
H→bb *p*-value of Tevatron Combination



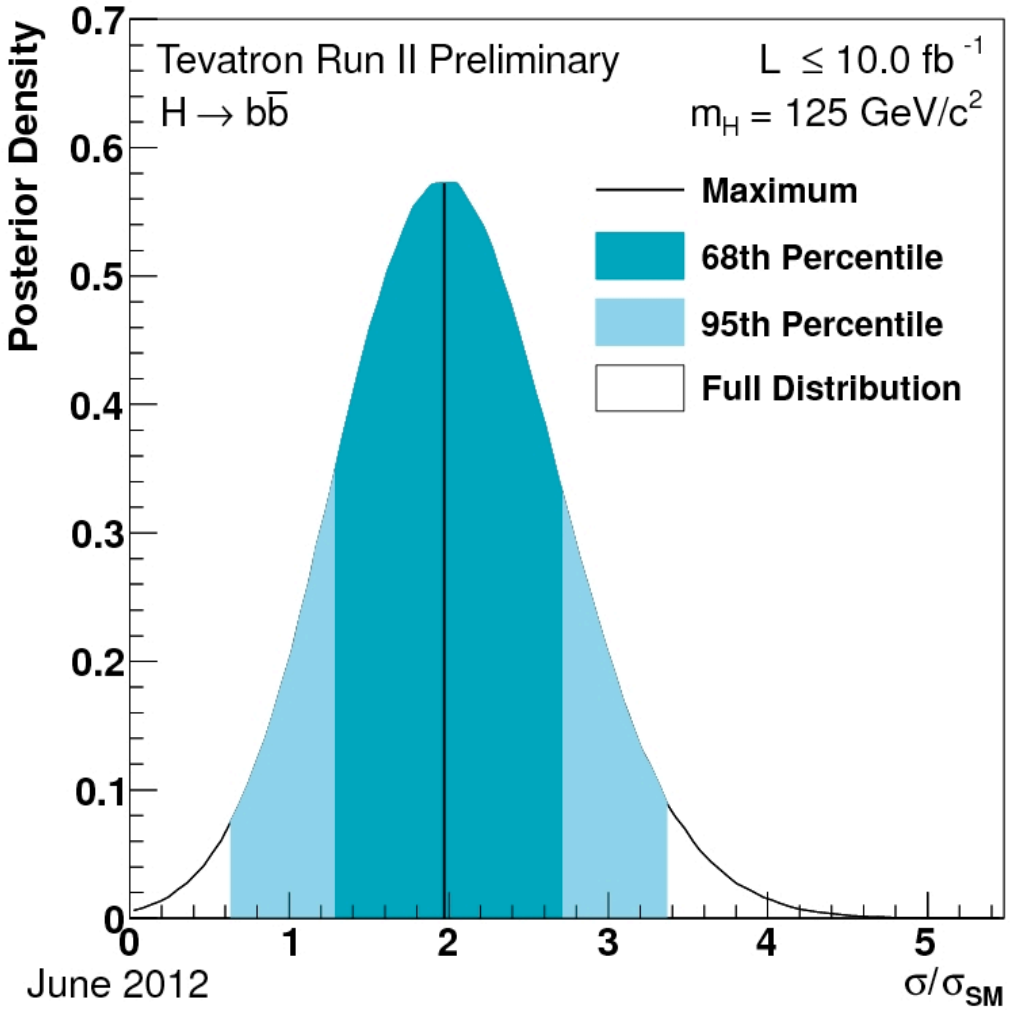
H→bb *p*-value of Tevatron Combination

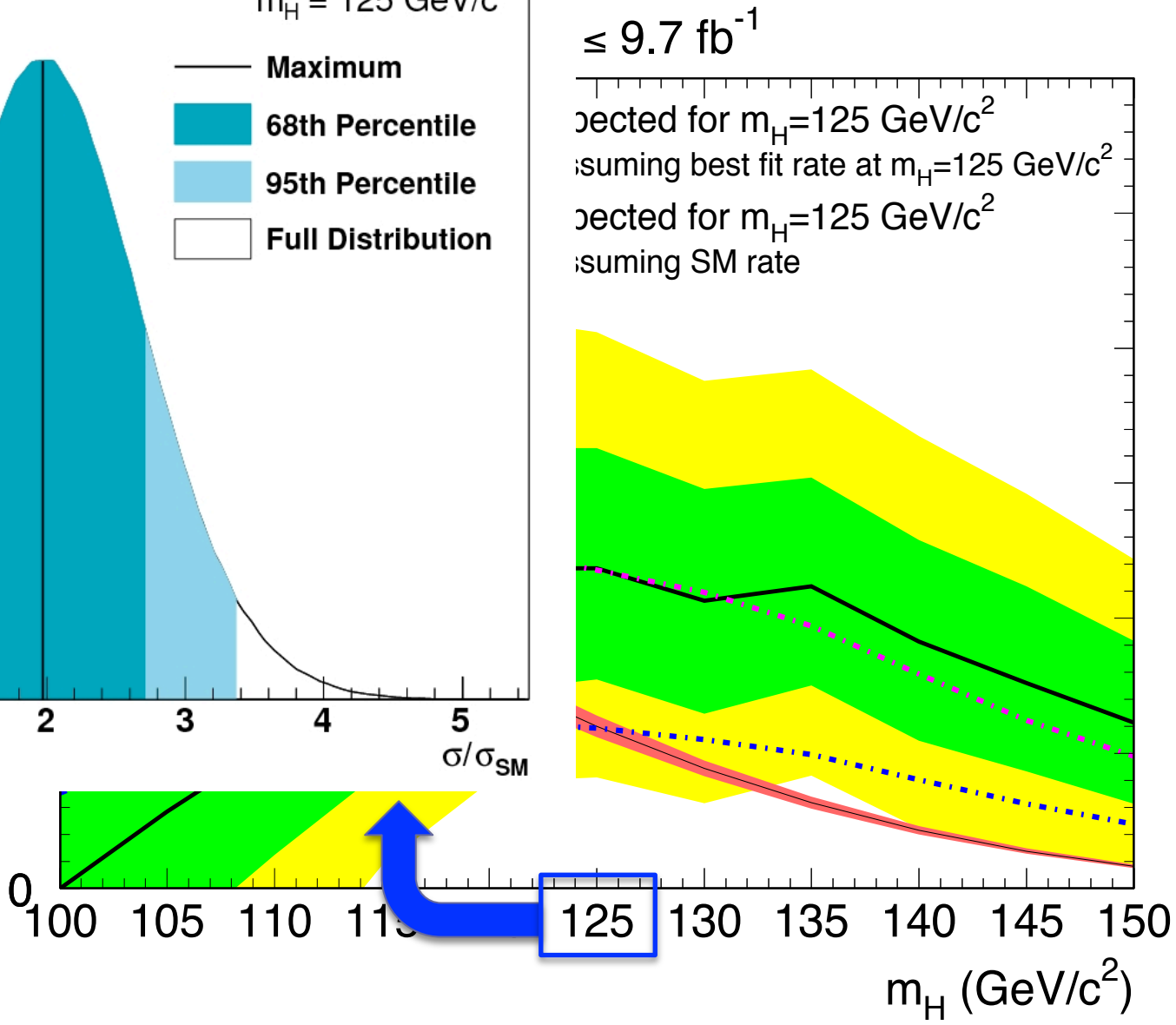


Best $\sigma_H \times \mathcal{B}(H \rightarrow b\bar{b})$ Fit Value



Best $\sigma \times \mathcal{B}(H \to b\bar{b})$ Fit Value





Combining All Channels

Low-Mass Channels	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
WH → lν bb	2.8	4.1
VH → MET + bb	3.6	3.9
ZH → ll + bb	3.6	5.1

High-Mass Channels	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
gg → H → WW → lνlν	3.1	3.6

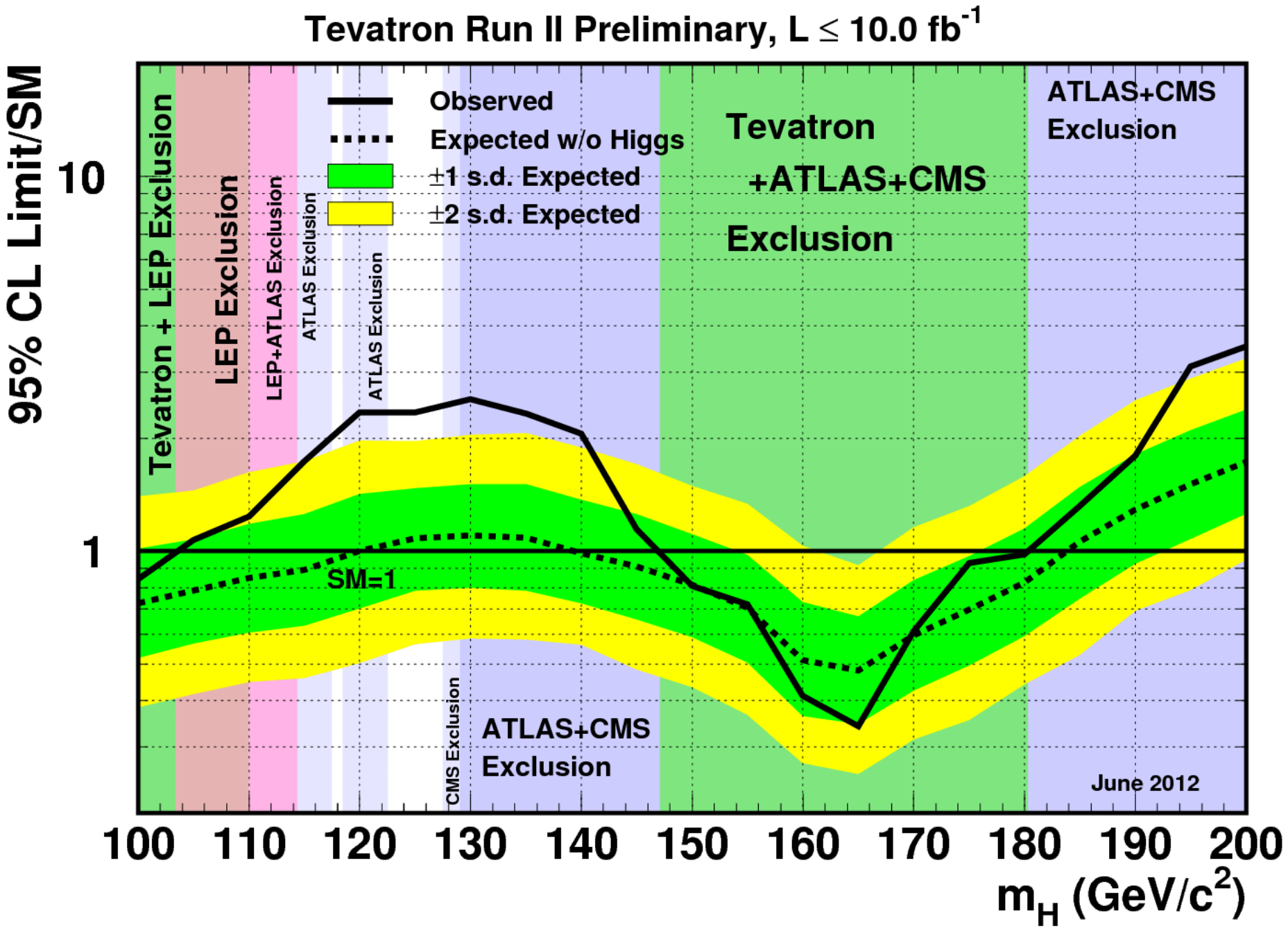
Combining All Channels

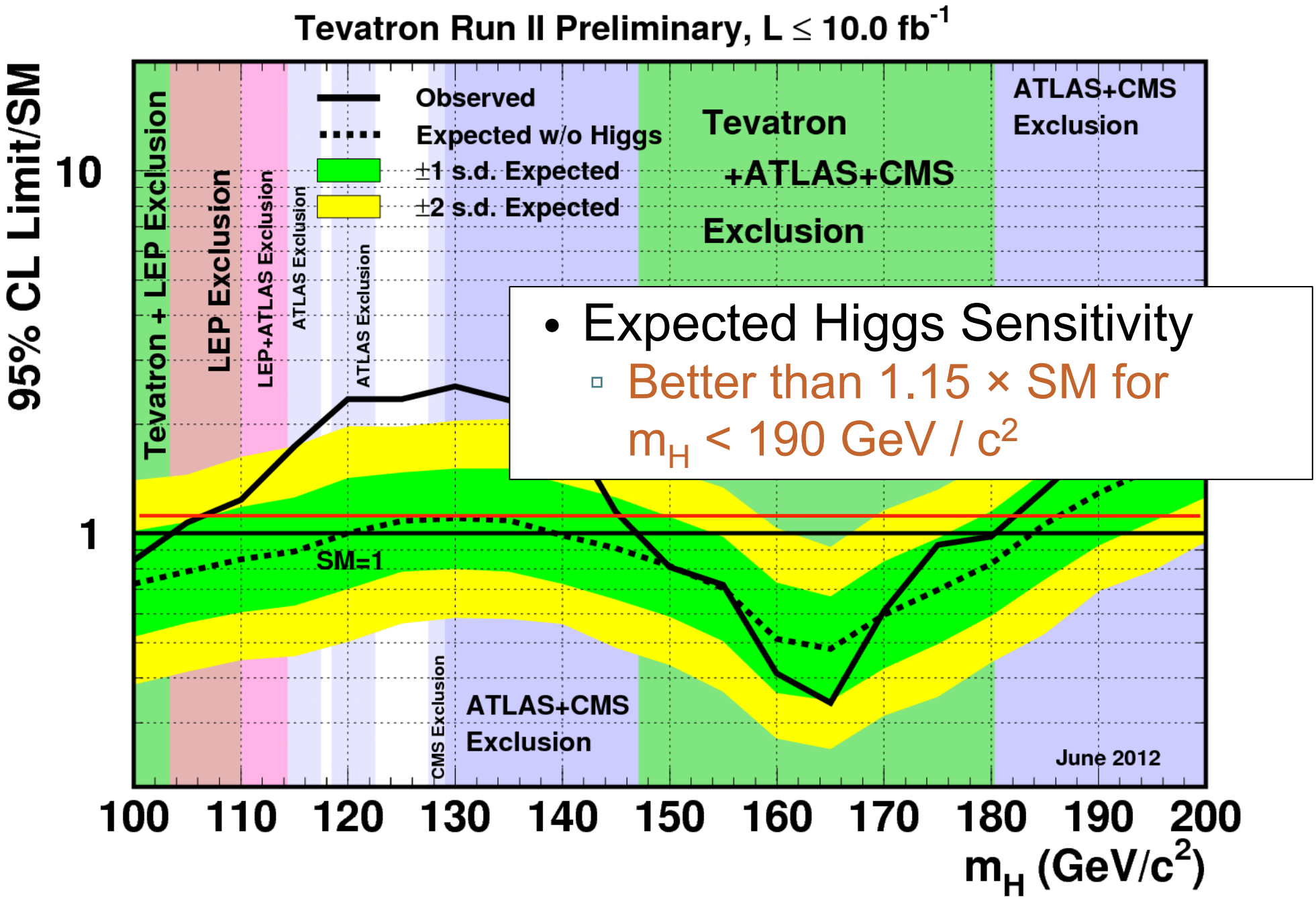
Low-Mass Channels	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
WH → lν bb	2.8	4.1
VH → MET + bb	3.6	3.9
ZH → ll + bb	3.6	5.1
H → γγ	11	8.2
VH→eμ + X	-	11.6
VH→ eeμ/μμe + X	-	11.1
VH → 4 jets	11	-

etc.

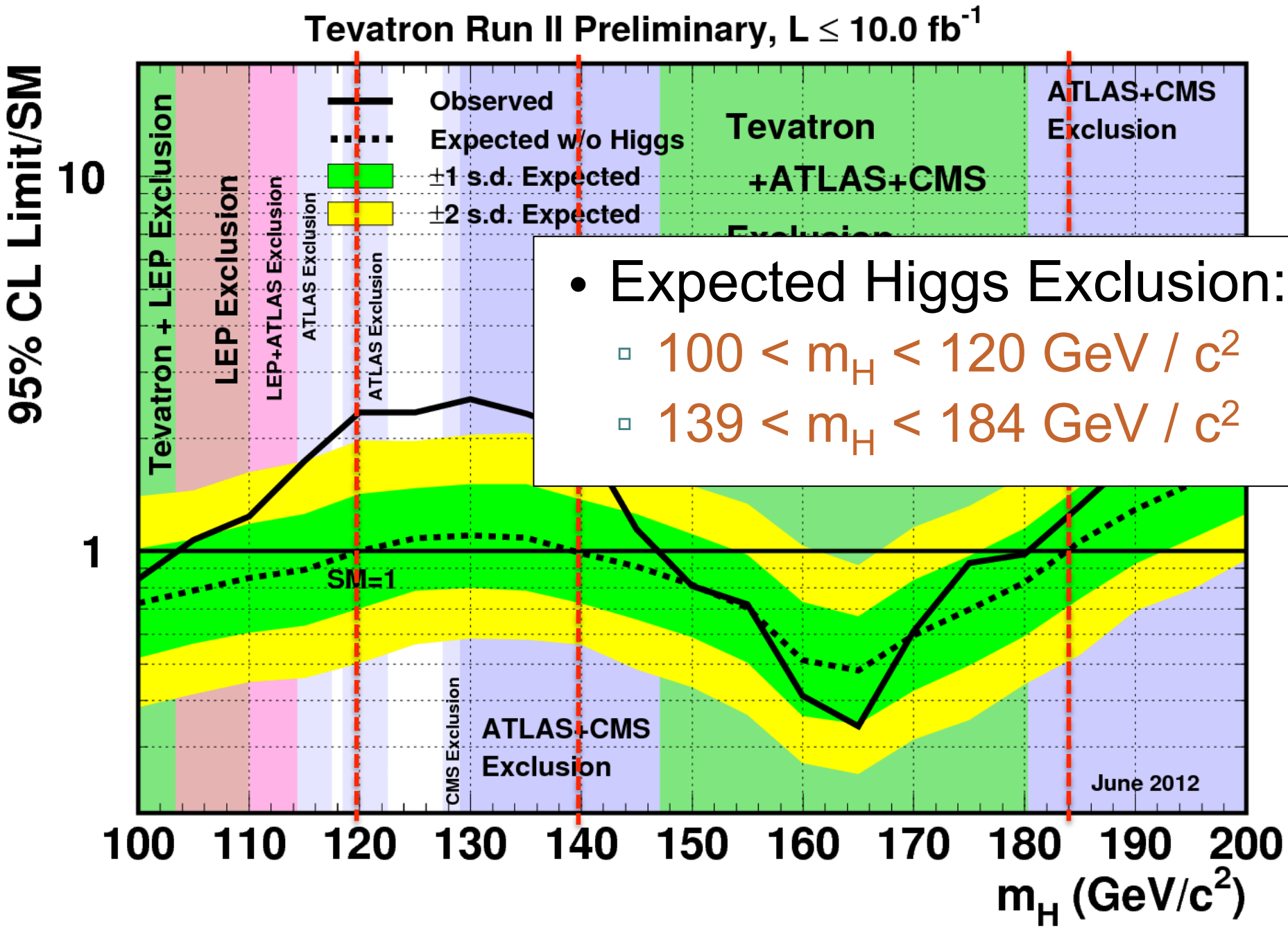
High-Mass Channels	Sensitivity (m_H = 125 GeV)	
	CDF [SM]	D0 [SM]
gg → H → WW → lνlν	3.1	3.6
H→WW→lνqq'	-	4.1
H→ZZ→ llll	28	-

etc.

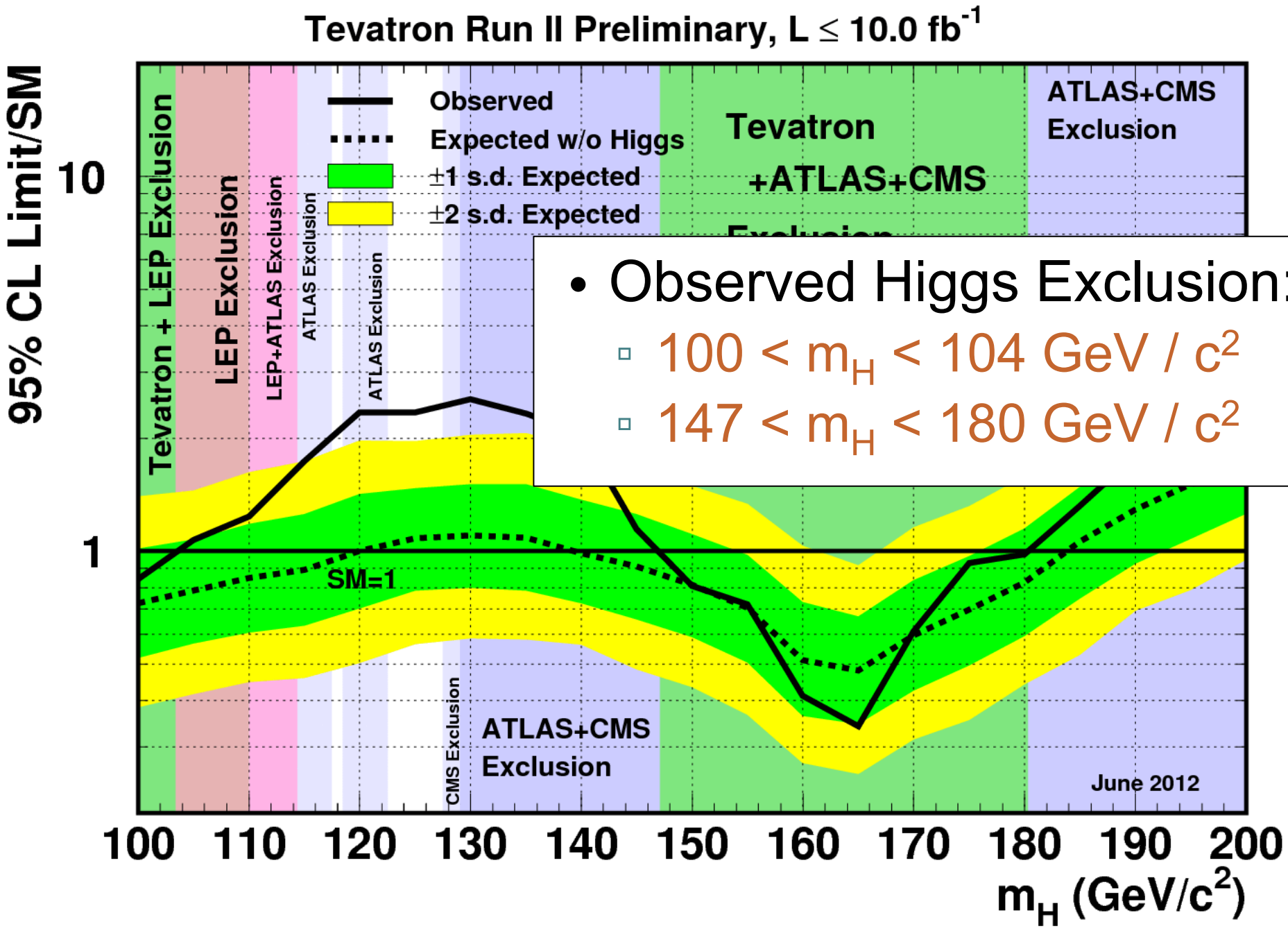

Tevatron Run II Preliminary, L ≤ 10.0 fb-1
95% CL Limit/SM
10
1
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expected
Tevatron +ATLAS+CMS Exclusion
ATLAS+CMS Exclusion
Tevatron + LEP Exclusion
LEP Exclusion
LEP+ATLAS Exclusion
ATLAS Exclusion
ATLAS Exclusion
CMS Exclusion
ATLAS+CMS Exclusion
SM=1
June 2012
100 110 120 130 140 150 160 170 180 190 200
mH (GeV/c2)



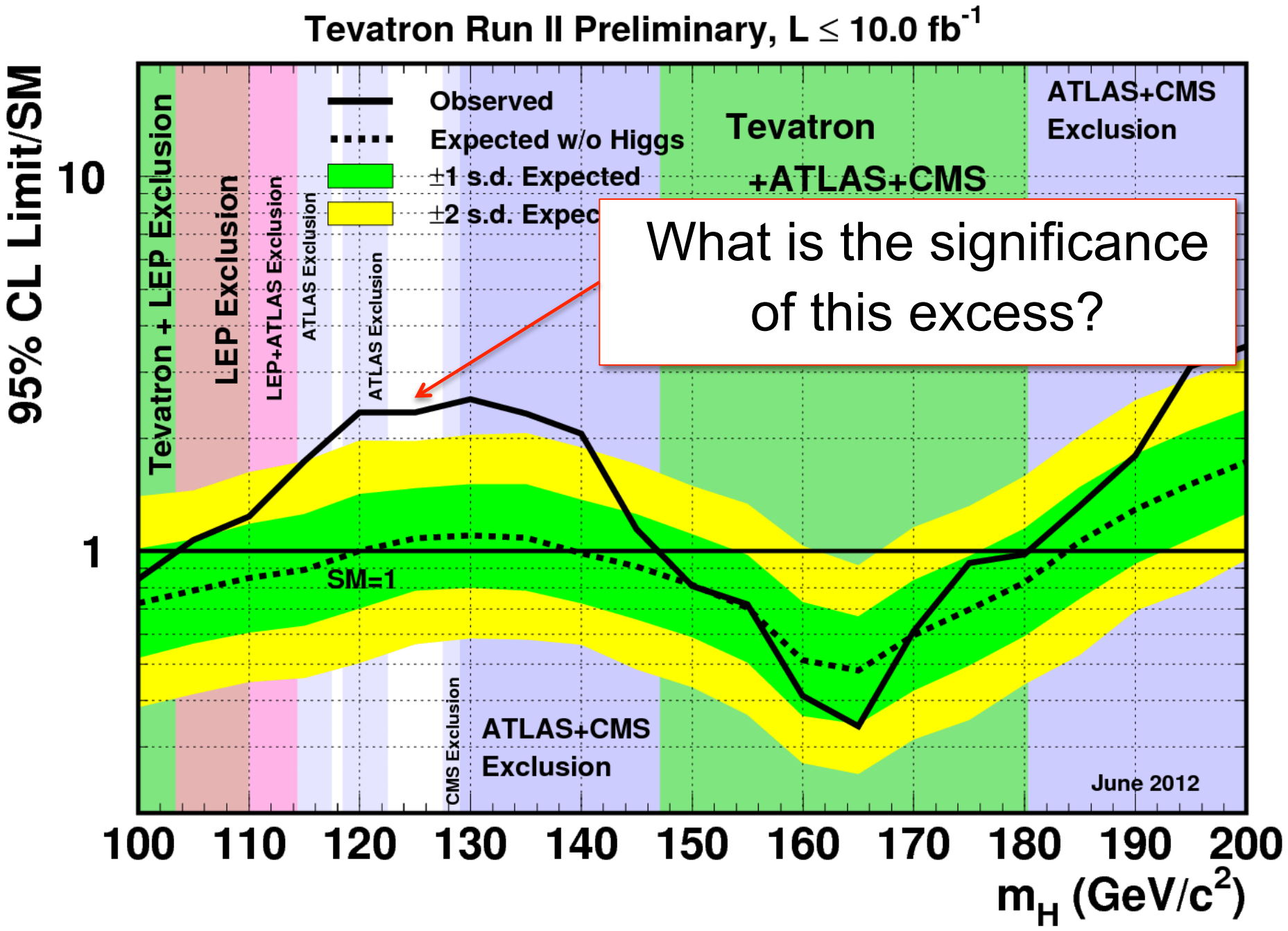
- Expected Higgs Sensitivity
  - Better than 1.15 × SM for $m_H < 190$ GeV / c^2



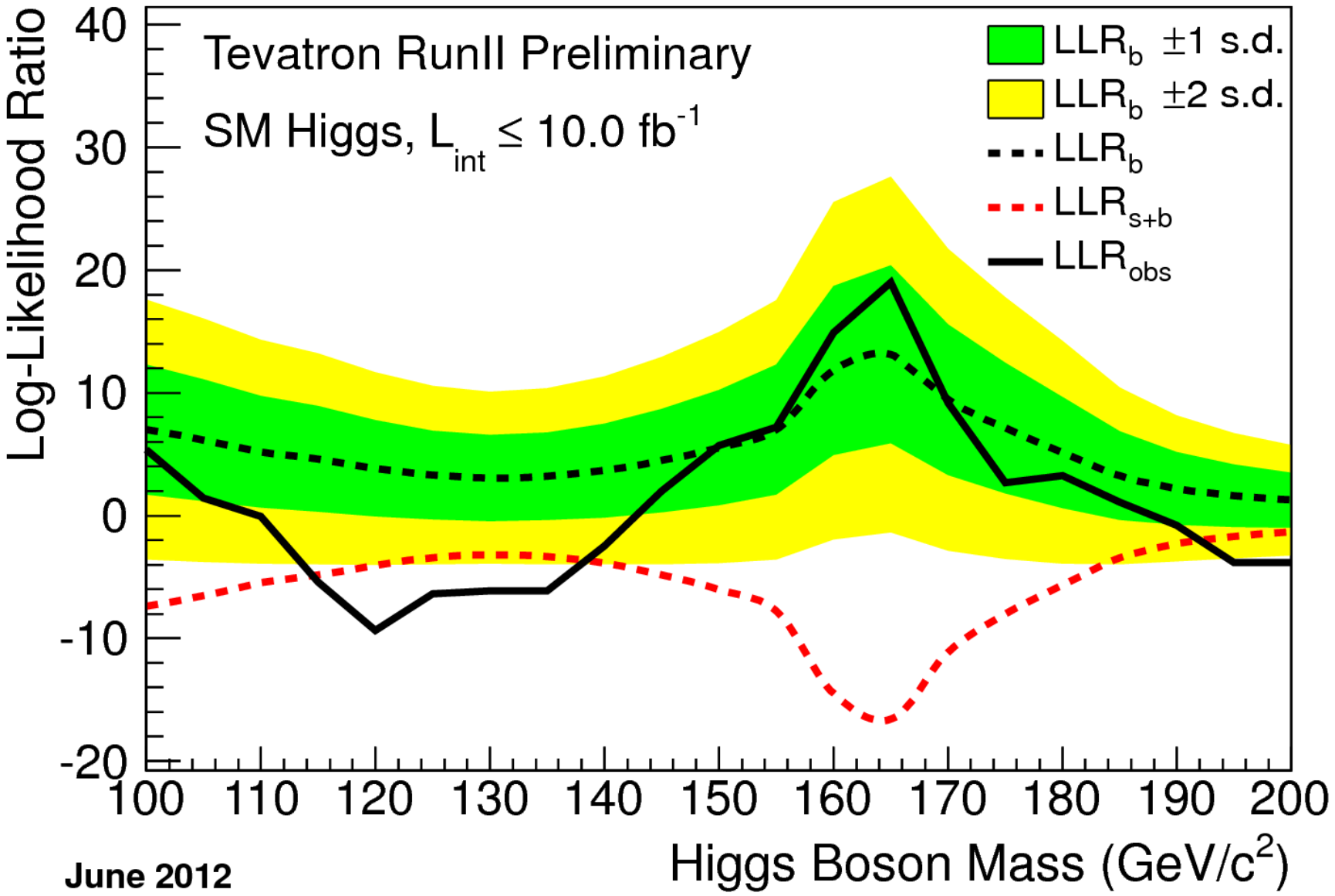
- Expected Higgs Exclusion:
  - $100 < m_H < 120$ GeV / c^2
  - $139 < m_H < 184$ GeV / c^2



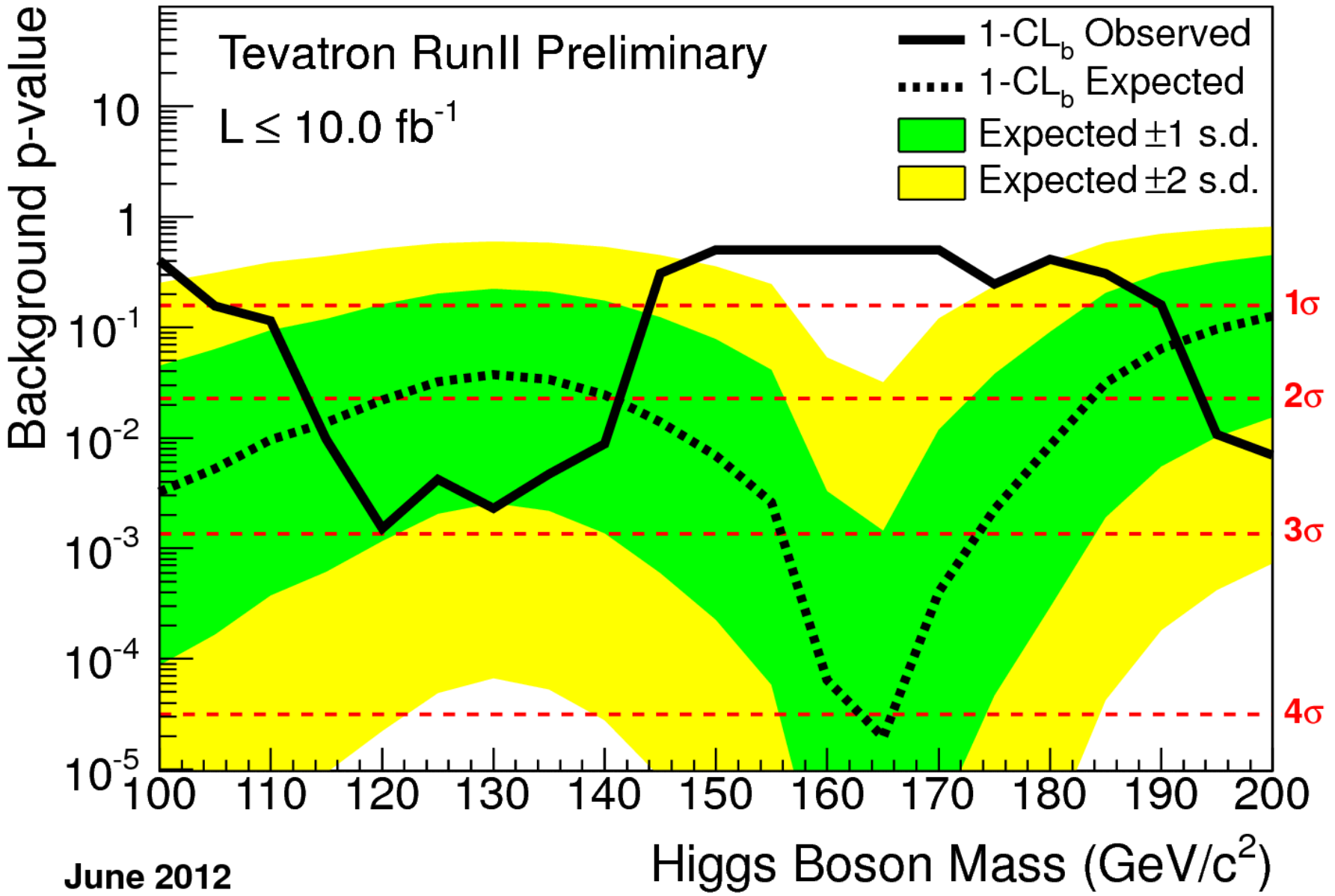
- Observed Higgs Exclusion:
  - $100 < m_H < 104$ GeV / c^2
  - $147 < m_H < 180$ GeV / c^2


Tevatron Run II Preliminary, L ≤ 10.0 fb-1
95% CL Limit/SM
10
1
Observed
Expected w/o Higgs
±1 s.d. Expected
±2 s.d. Expec
Tevatron
+ATLAS+CMS
ATLAS+CMS
Exclusion
What is the significance of this excess?
Tevatron + LEP Exclusion
LEP Exclusion
LEP+ATLAS Exclusion
ATLAS Exclusion
ATLAS Exclusion
SM=1
CMS Exclusion
ATLAS+CMS
Exclusion
June 2012
100 110 120 130 140 150 160 170 180 190 200
mH (GeV/c2)

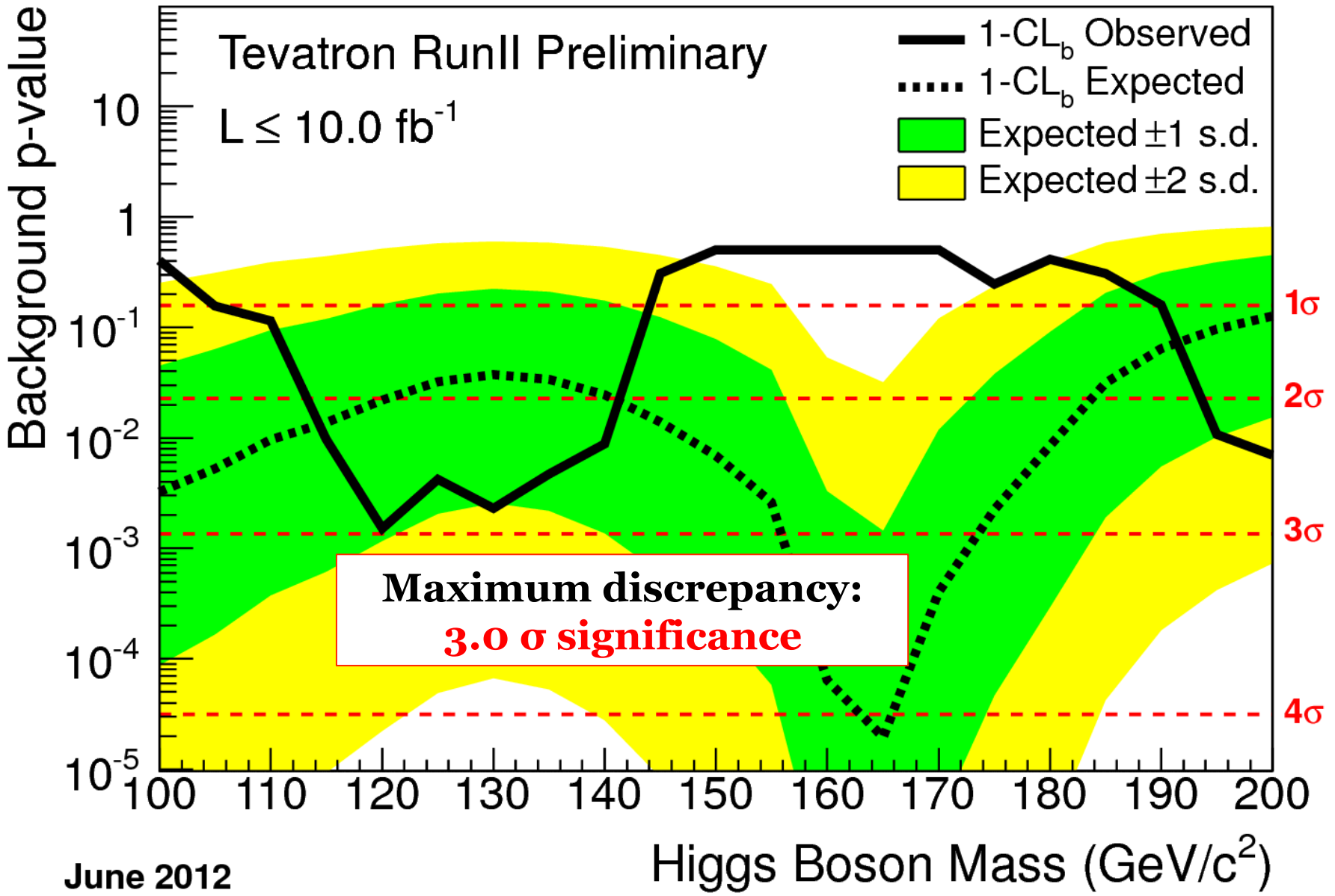
LLR of Tevatron Combination



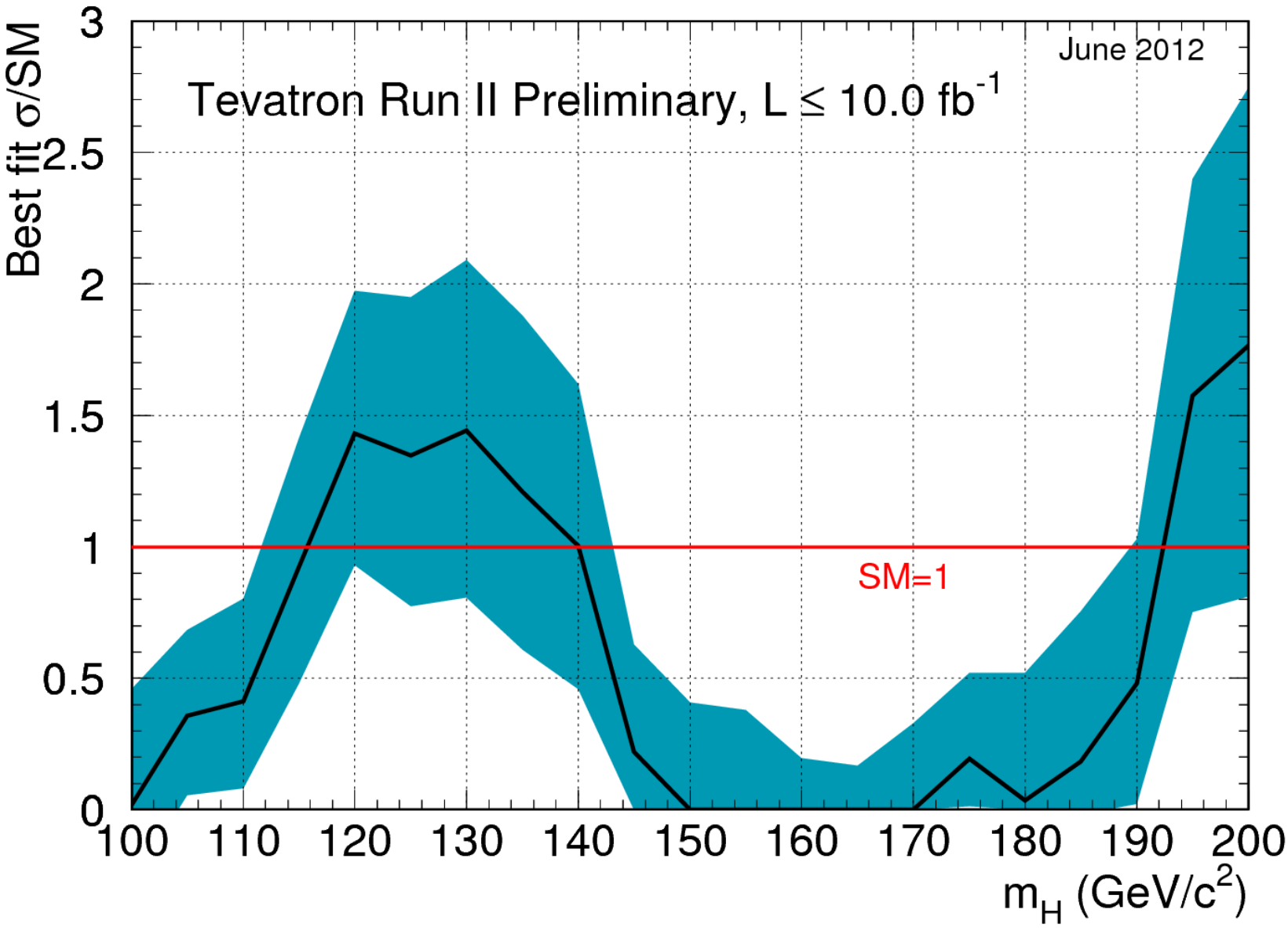
p-value of Tevatron Combination



p-value of Tevatron Combination



Best $\sigma_H \times \mathcal{B}(H \rightarrow X)$ Fit Value



Significance of Excesses

- Significance of local excesses diluted by look-elsewhere effect (LEE).

- H→bb final state (with LEE)
  - Assume 2 independent searches within $100 < m_H < 150$ GeV/c^2.
  - Global p-value ≈ 2 × min. local p-value
- H→bb final state (without LEE)
  - Assume Higgs has mass of $m_H = 125$ GeV – i.e. no LEE.
  - Use p-value at $m_H = 125$ GeV

Final States	Local Significance	Global Significance
H → bb (at $m_H = 135$)	**3.2 σ**	**2.9 σ**
H → bb (at $m_H = 125$, no LEE)	**2.9 σ**	**2.9 σ**

Significance of Excesses (cont.)

- Full SM Higgs combination
  - Assume 4 independent searches within $100 < m_H < 200$ GeV/c^2.
  - Global p-value ≈ 4 × min. local p-value

	Local Significance	Global Significance
SM Higgs (m_H = 120 GeV)	**3.0 σ**	**2.5 σ**
SM Higgs (m_H = 125 GeV, no LEE)	**2.6 σ**	**2.6 σ**

- Results complement those of the LHC, and are consistent with a signal near $m_H \sim 125$ GeV/c^2.

Conclusions

- Analysis improvements implemented in CDF and D0 to improve Higgs sensitivity to better than
  $1.15 \times SM$ for $m_H < 190$ GeV/c^2
- Broad excess in observed data relative to background-only hypothesis in $105 < m_H < 145$ GeV/c^2.
- Global significance of excesses
  - H→bb channel: 2.9 σ significance
  - All higgs channels: 2.5 σ significance
- Current Tevatron Higgs plans:
  - A few updates from various analyses
  - *Mostly time to wrap things up*

Thank you.

Public Results

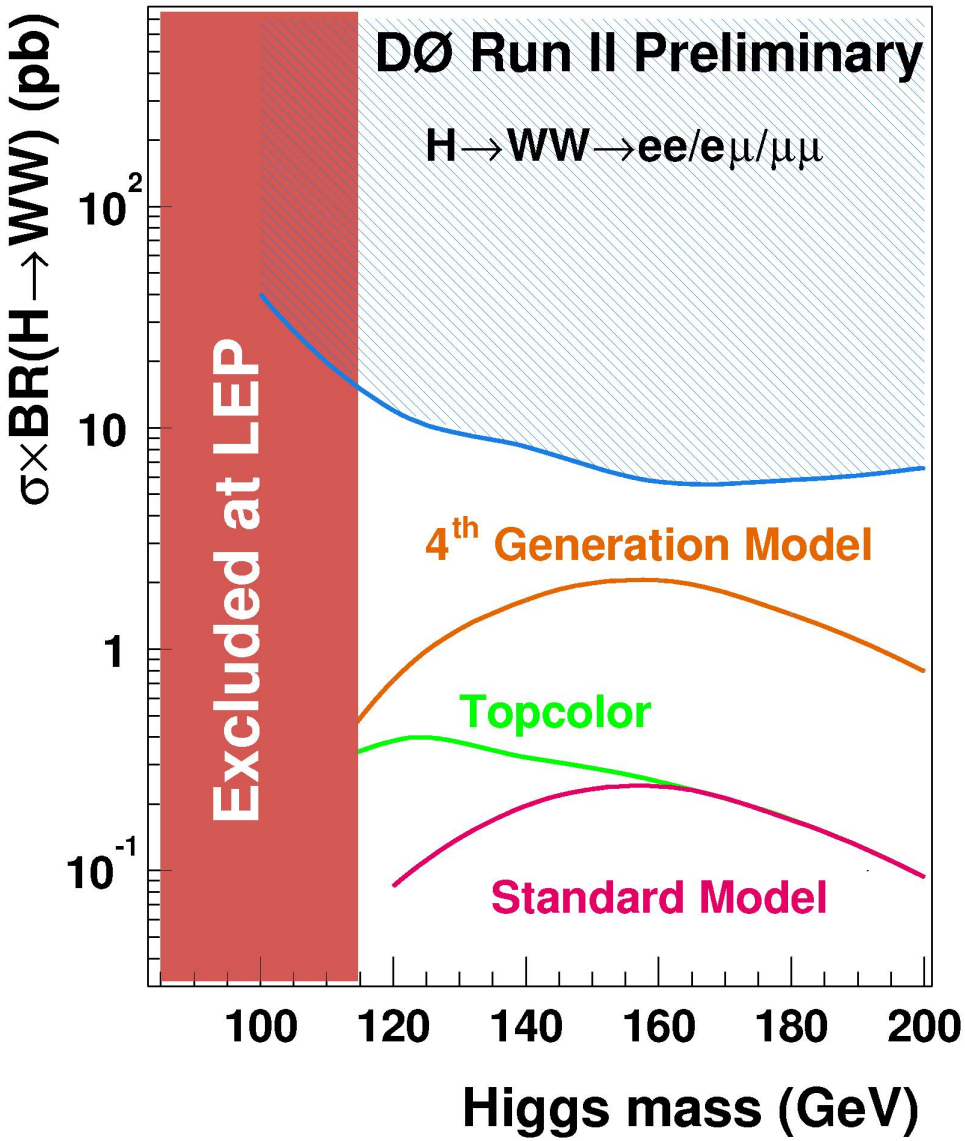
- Tevatron Combination
  - http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_12/index.html
  - http://arxiv.org/abs/1207.0449
- D0 Results
  - http://www-d0.fnal.gov/Run2Physics/WWW/results/final/EW/E08H/
- CDF Results
  - http://www-cdf.fnal.gov/physics/new/hdg/Results.html

Back-up Slides

History of Run II Tevatron Higgs Searches

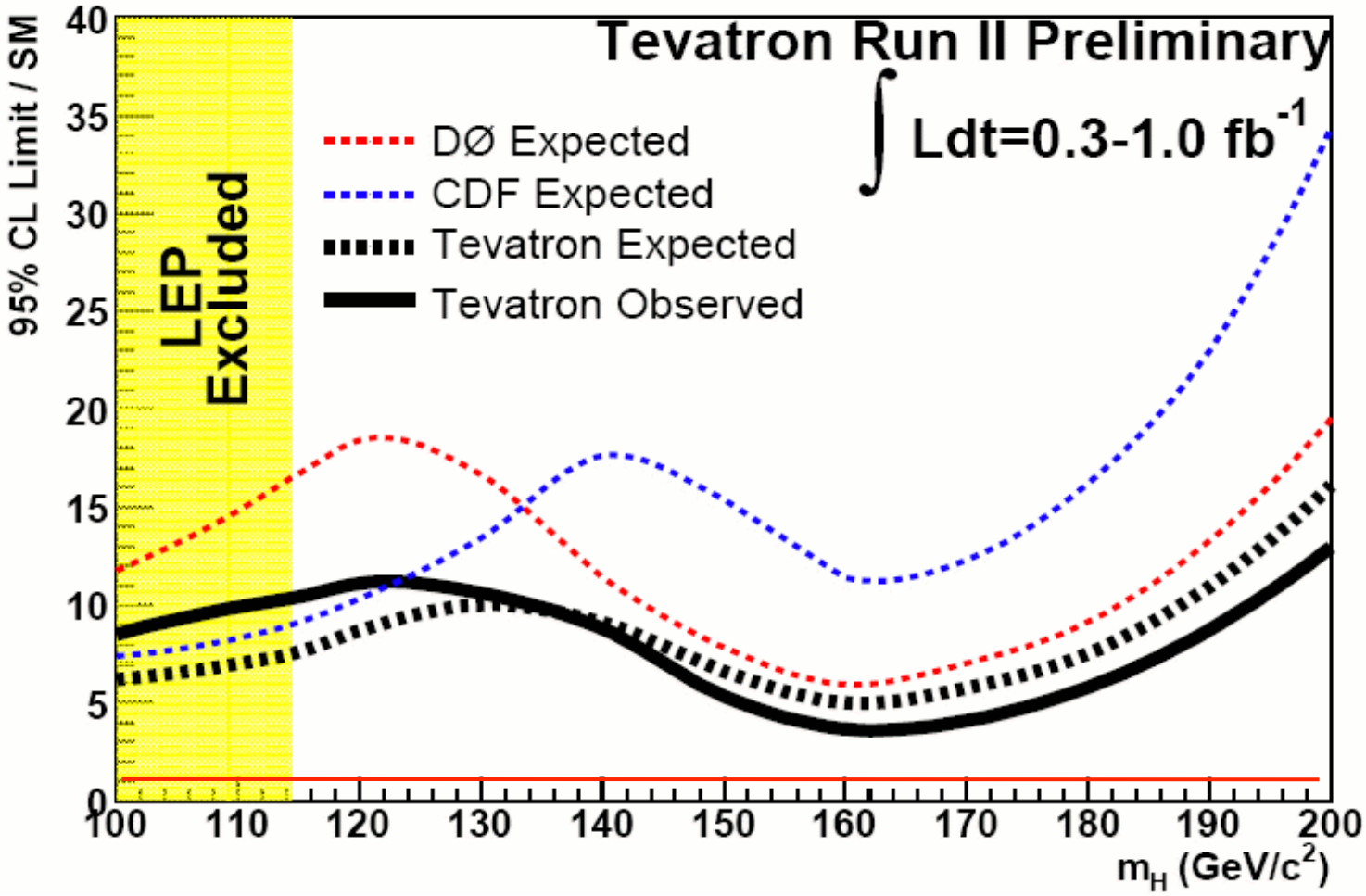
History of Run II Tevatron Higgs Searches

- 2004 – First Preliminary Higgs Result (~175 pb^{-1})



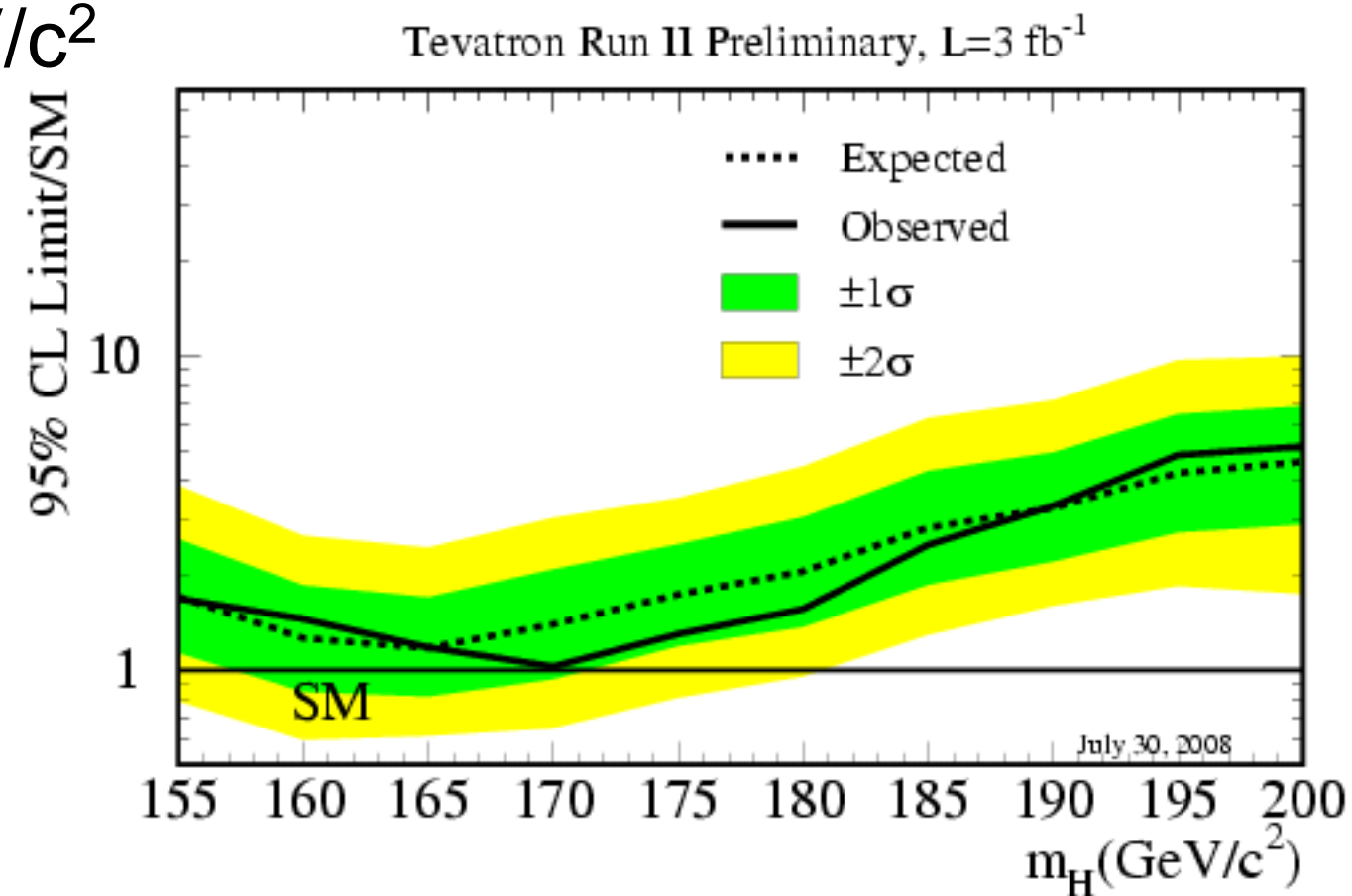
History of Run II Tevatron Higgs Searches

- 2004 – First Preliminary Higgs Result (~175 pb^{-1})
- 2006 – First CDF-D0 Combination plot



History of Run II Tevatron Higgs Searches

- 2004 – First Preliminary Higgs Result (~175 pb^{-1})
- 2006 – First CDF-D0 Combination plot
- 2008 – First Tevatron Higgs Exclusion at m_H = 170 GeV/c^2



History of Run II Tevatron Higgs Searches

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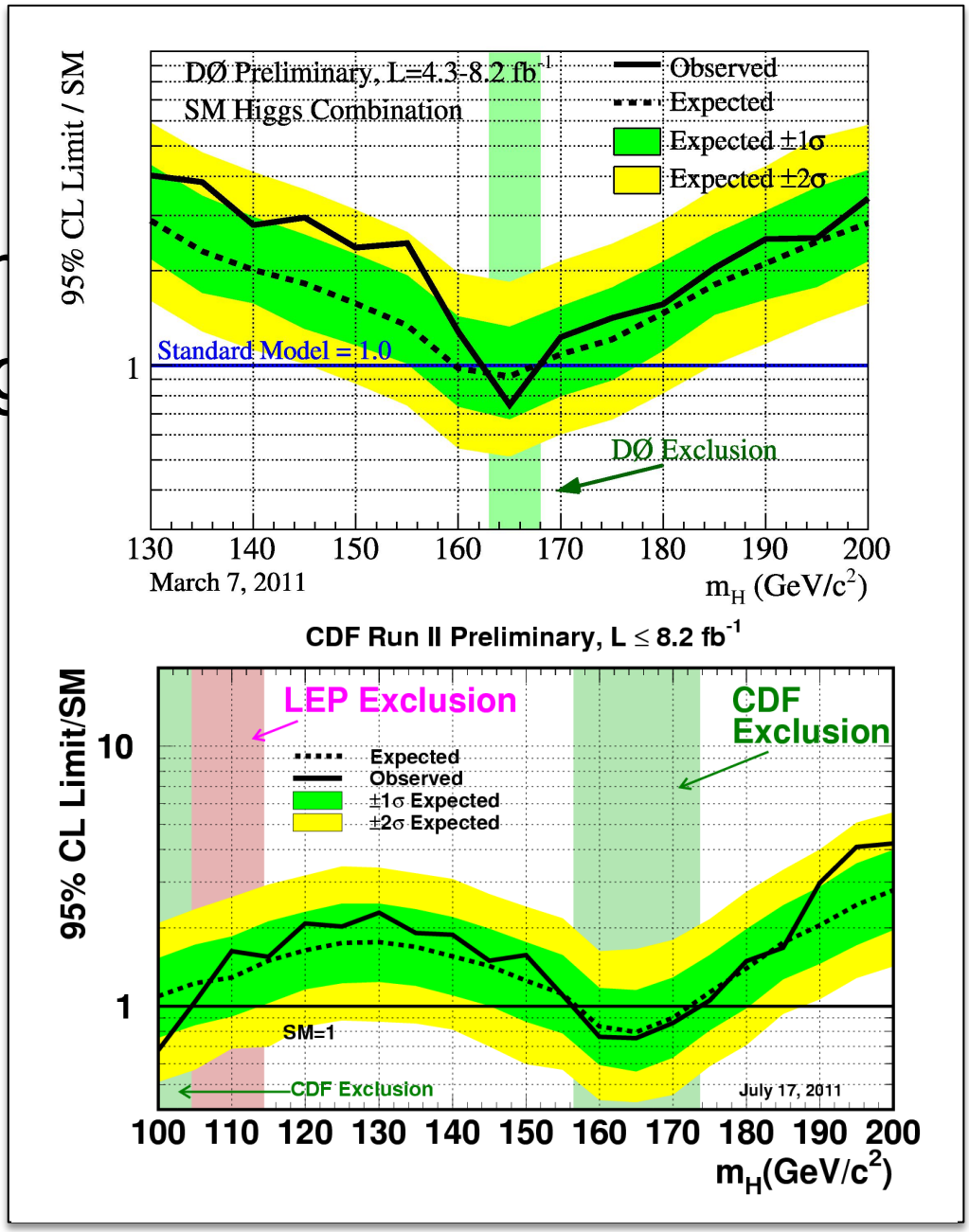
- 2008 – First Tevatron Higg m_H = 170 GeV/c^2
- 2011 – First single-exp. exclusions



History of Run II Tevatron Higgs Searches

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- 2012 – Excess seen
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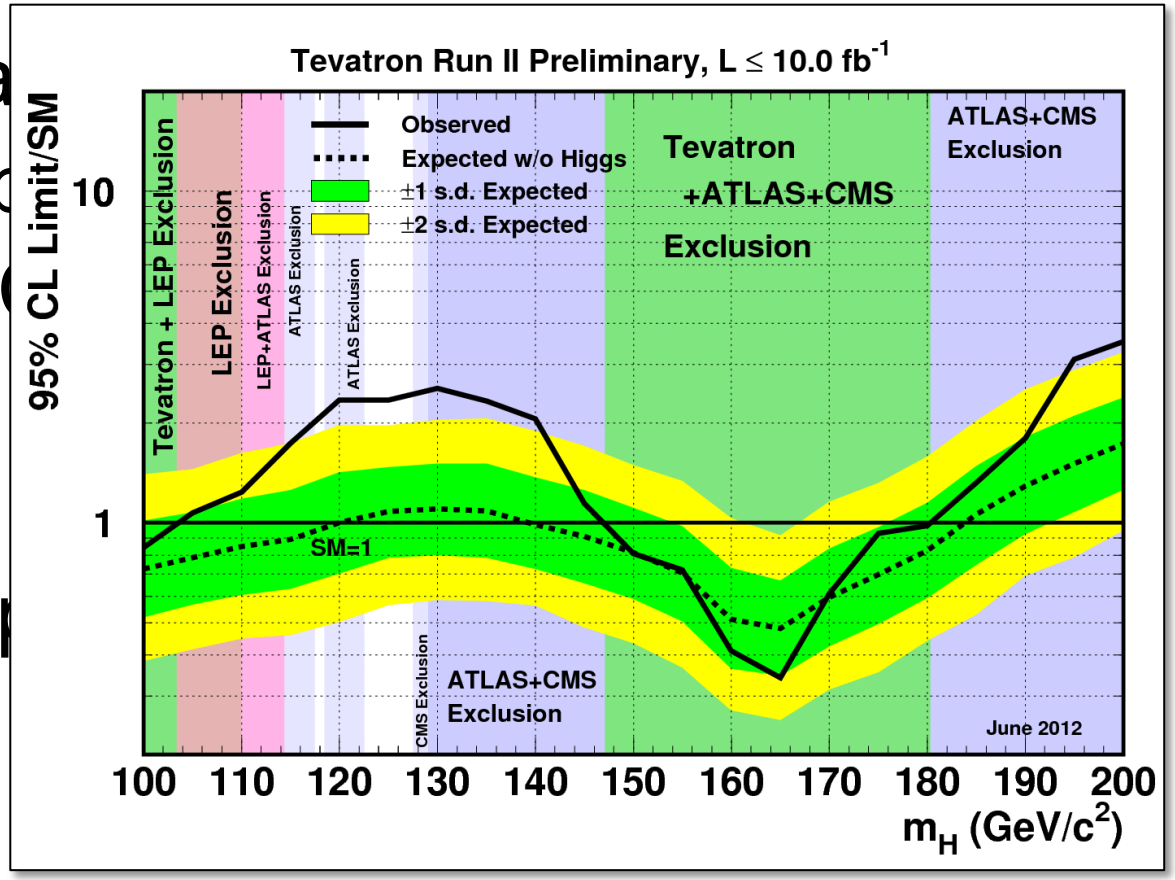

History of Run II Tevatron Higgs Searches

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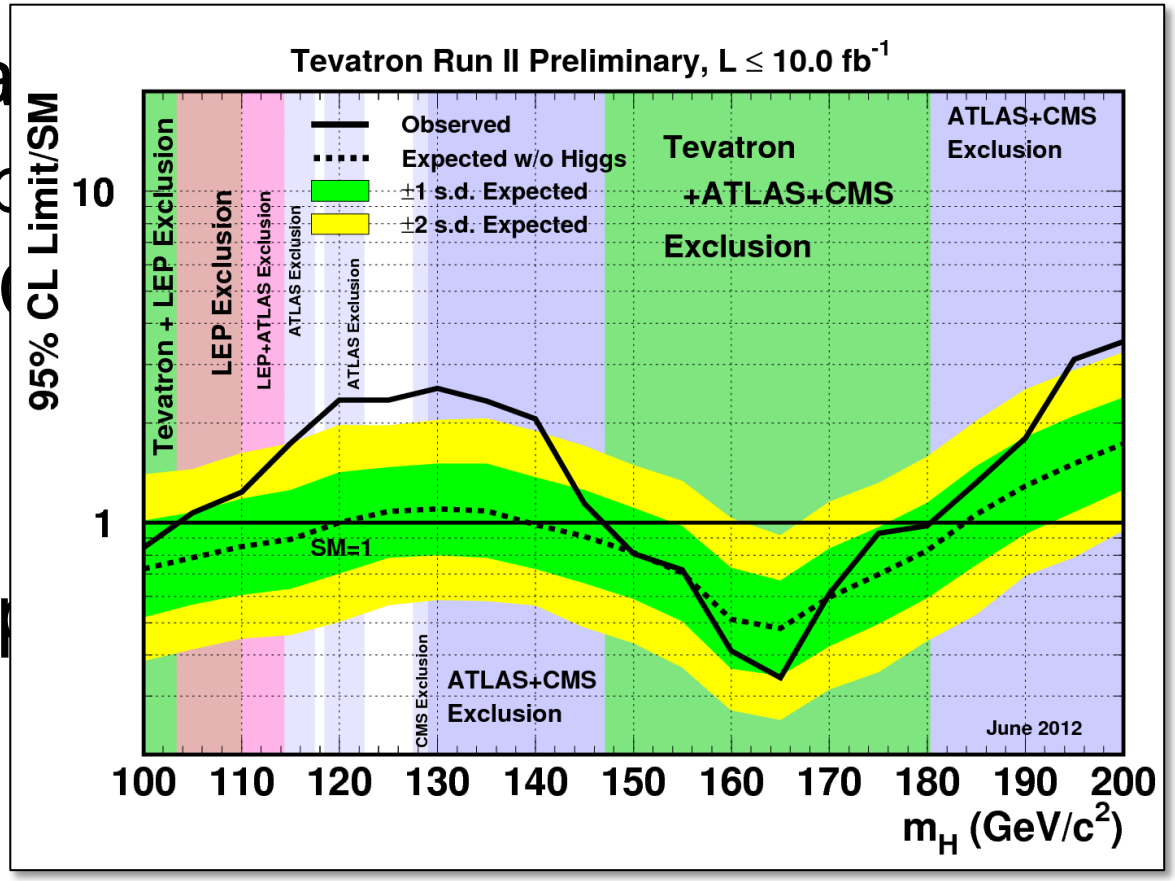
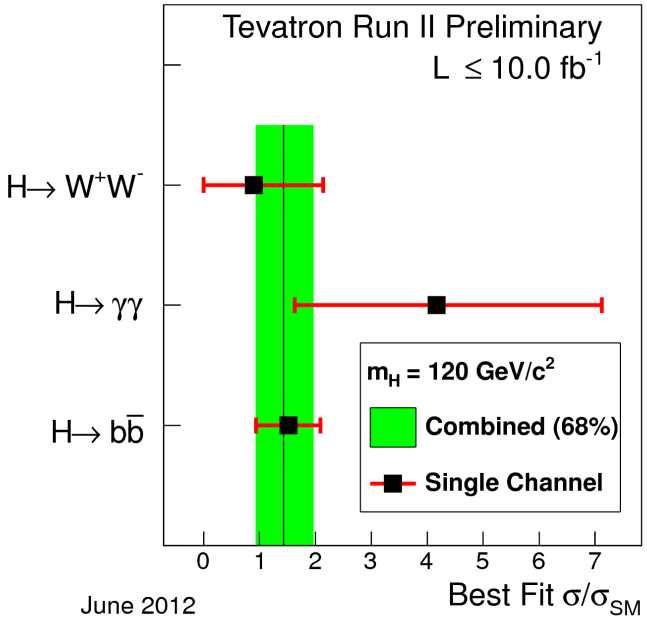
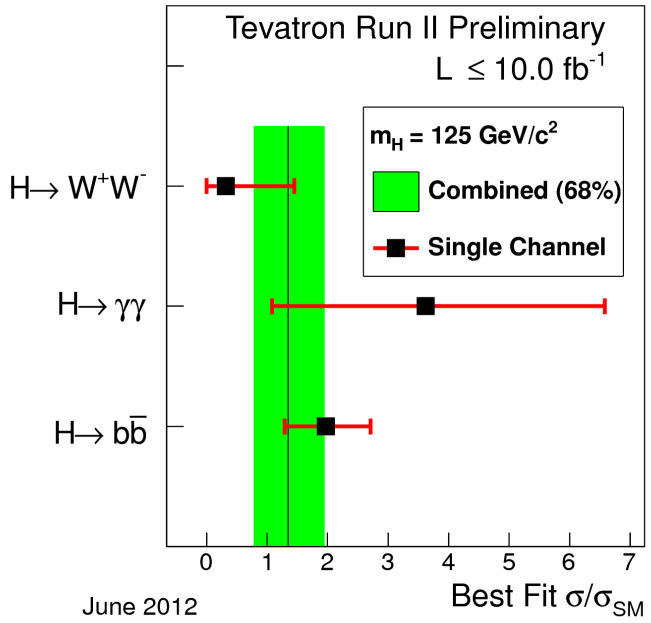
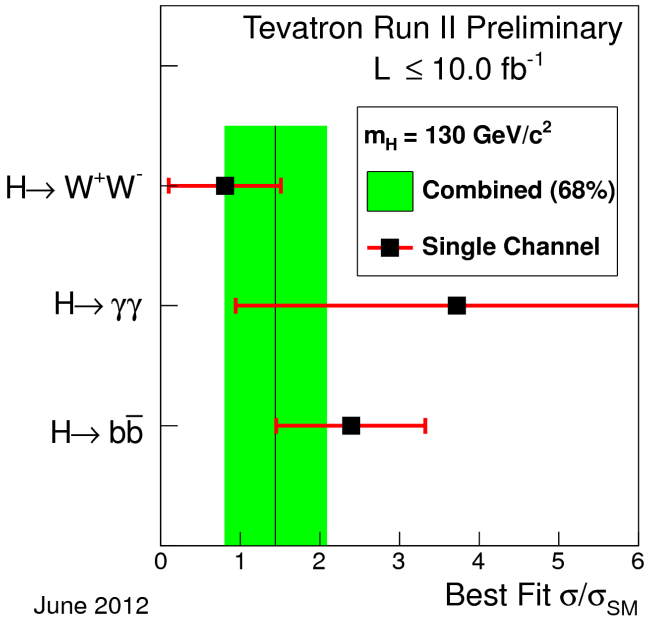


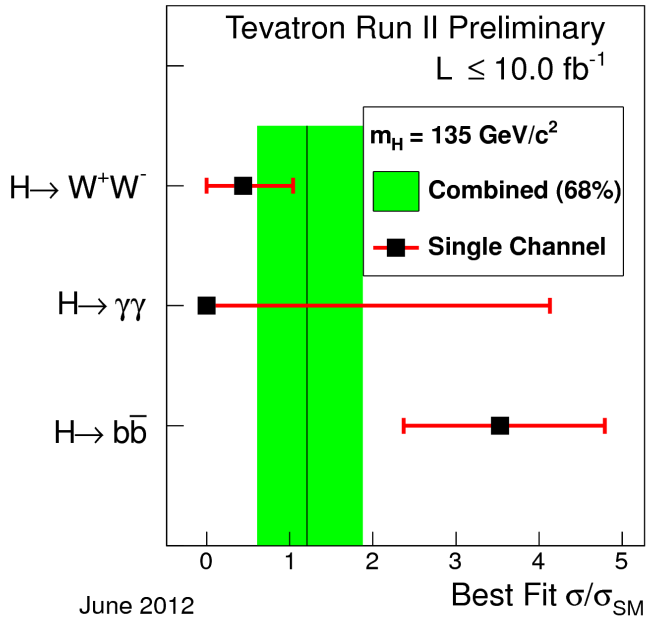
Today's talk: a description of above results

Best $\sigma_H \times \mathcal{B}(H \to X)$ Fit Values



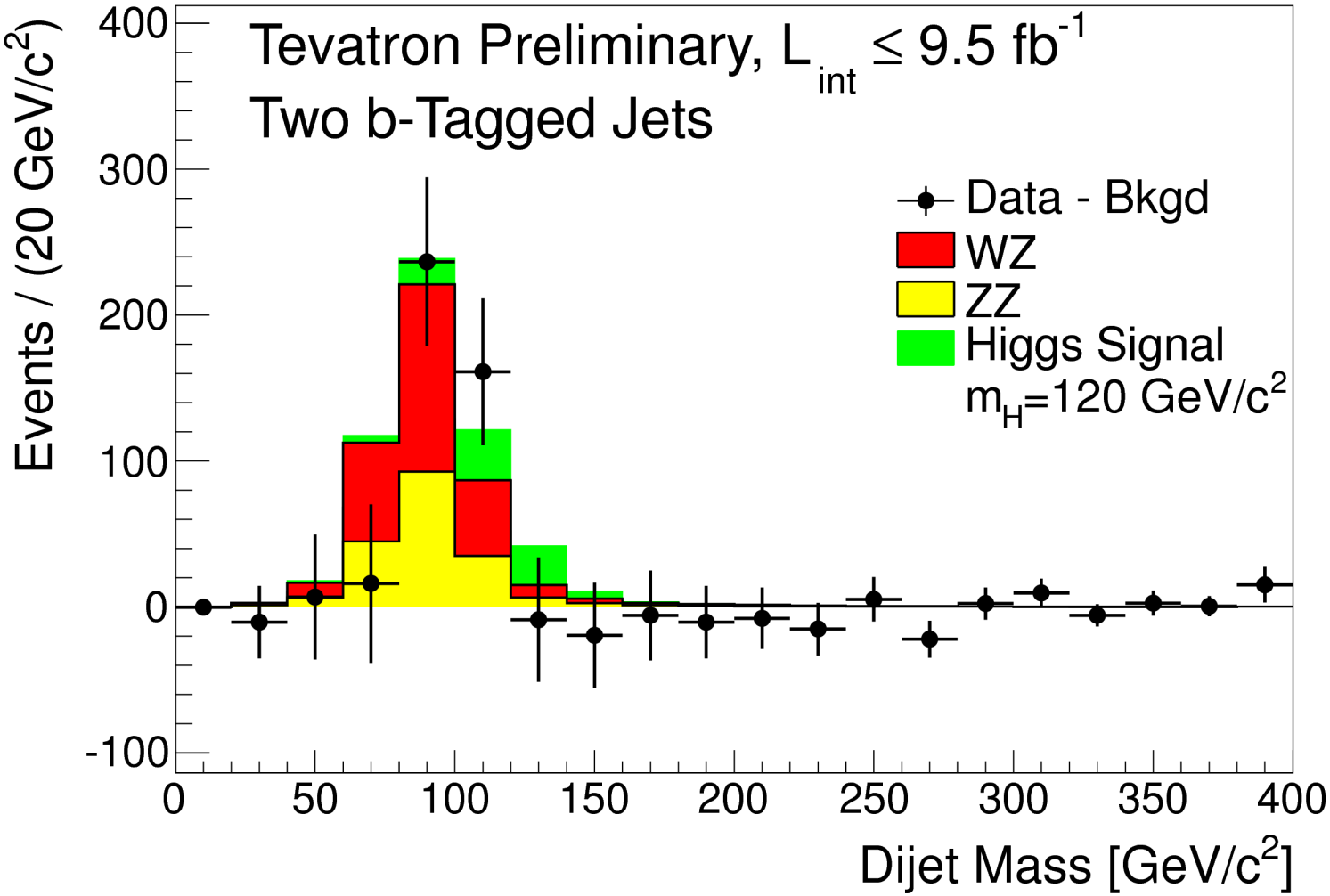




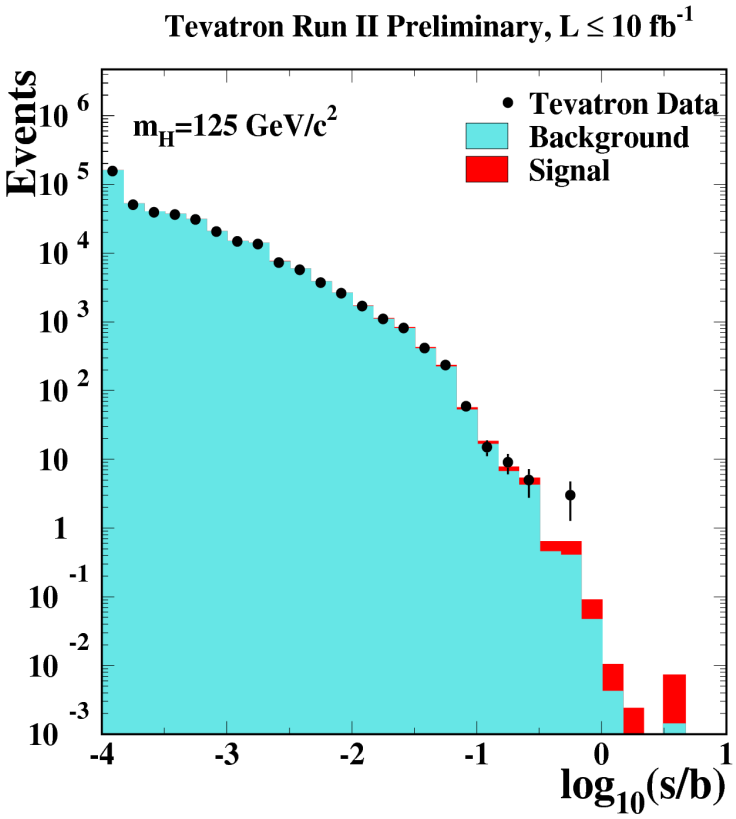


What does Dijet Invariant Mass Look Like

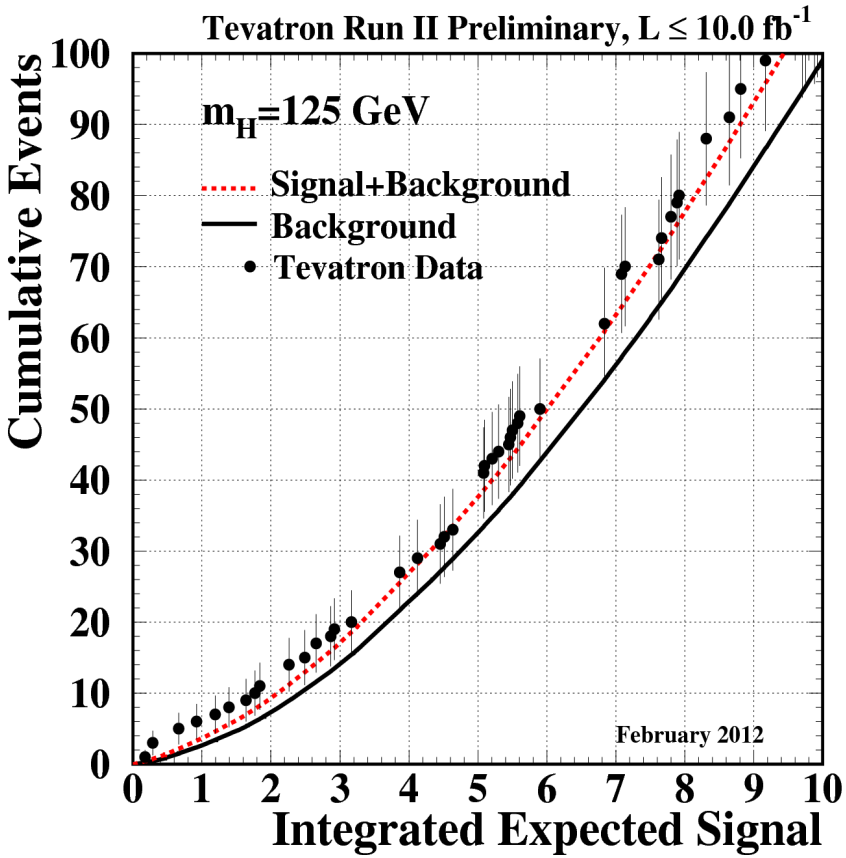
- Assuming best $\sigma_H \times \mathcal{B}$ (H → X) rate, can combine all H→bb channels and plot dijet mass



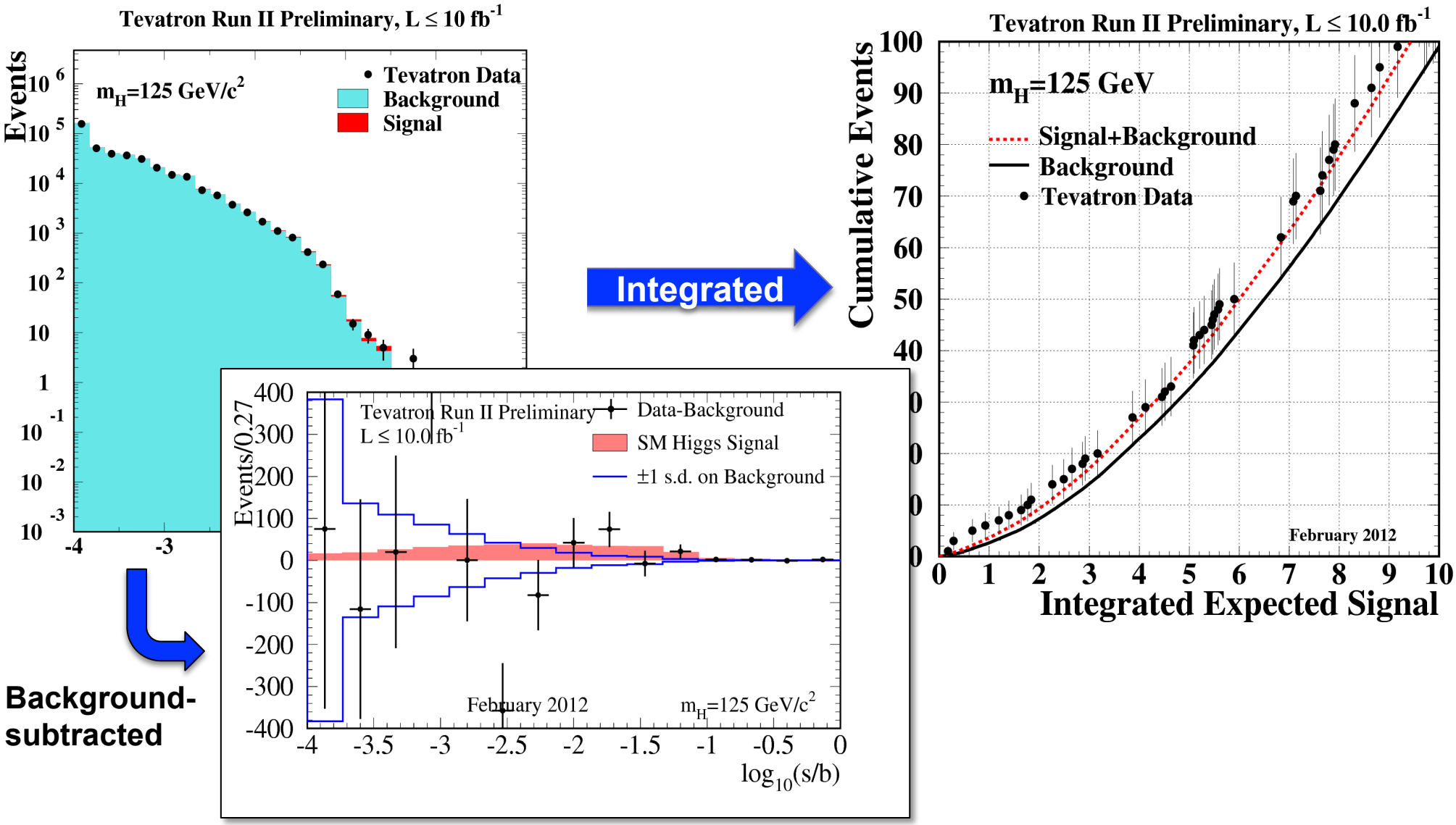
Combined discriminants – rebinned in ***s/b***



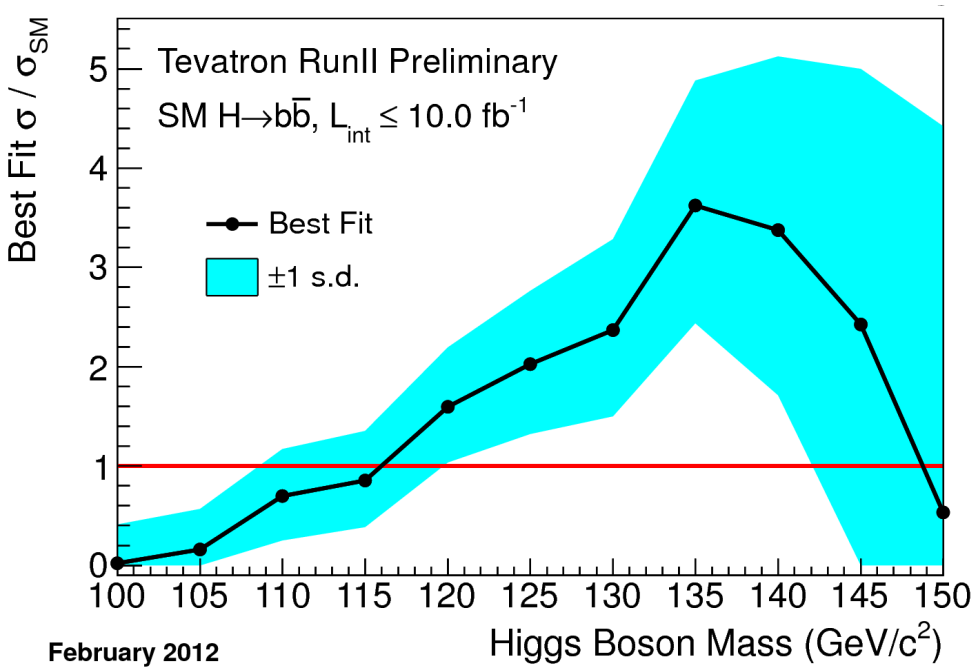
Integrated

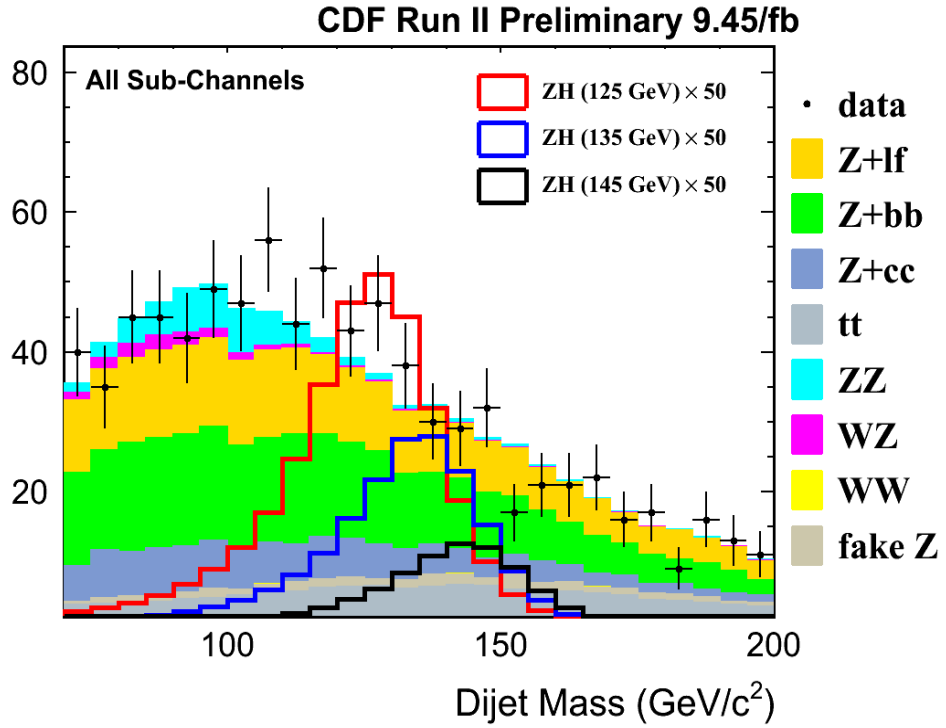


Combined discriminants – rebinned in *s/b*



Increase of $\sigma_H \times \mathcal{B}(H \rightarrow bb)$ vs. m_H

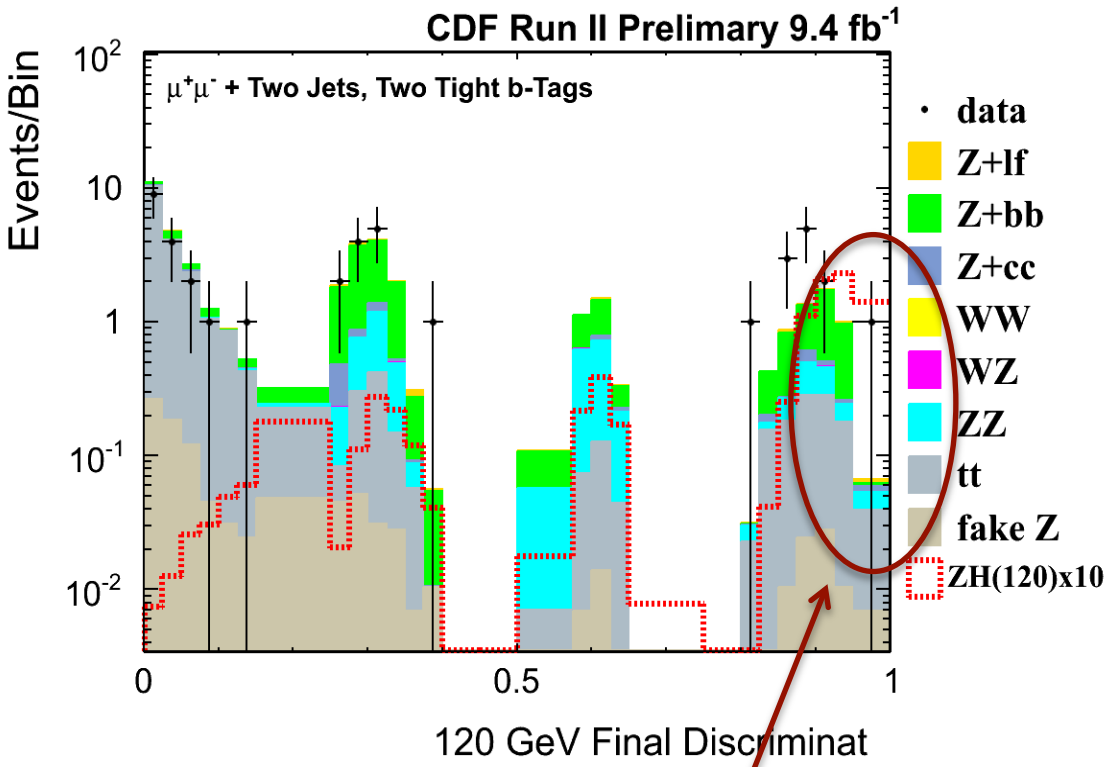




- Data are most consistent with SM in mass range from $110 < m_H < 120$ GeV/c^2
- Behavior at higher m_H values is consistent with the expectation from a lower mass Higgs due to sizeable m_{jj} tail at low mass

ZH→ll bb Analysis

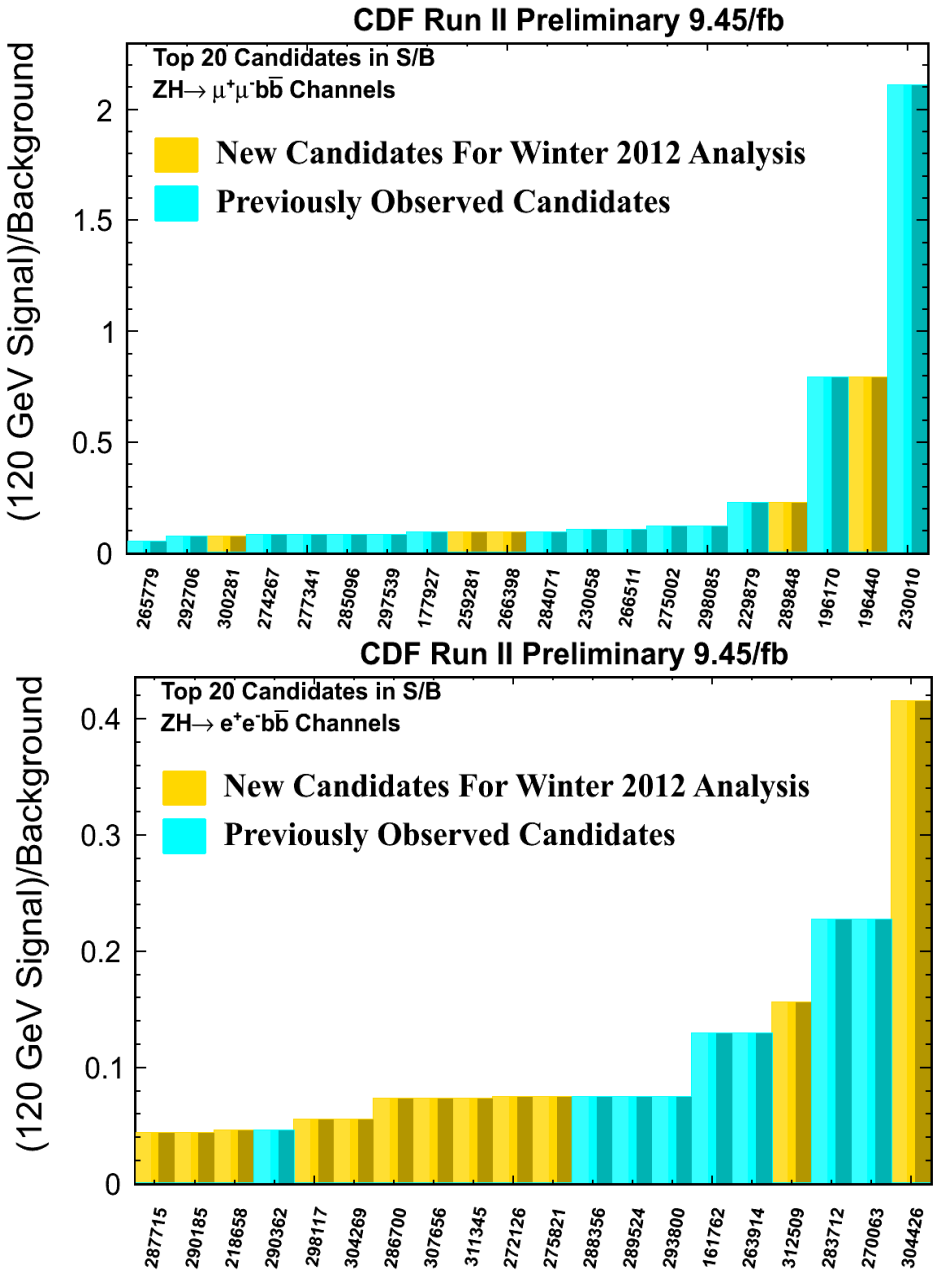
- ZH→llbb channel has . . .
  - lowest backgrounds
  - smallest expected signal yields (9 events for m_H=120 GeV/c^2)
- Some discriminant bins with large S/B
  - Low probability for observing events in these bins
  - A few such events can have substantial effects on observed limits



S = 0.16 events,
B = 0.06 events

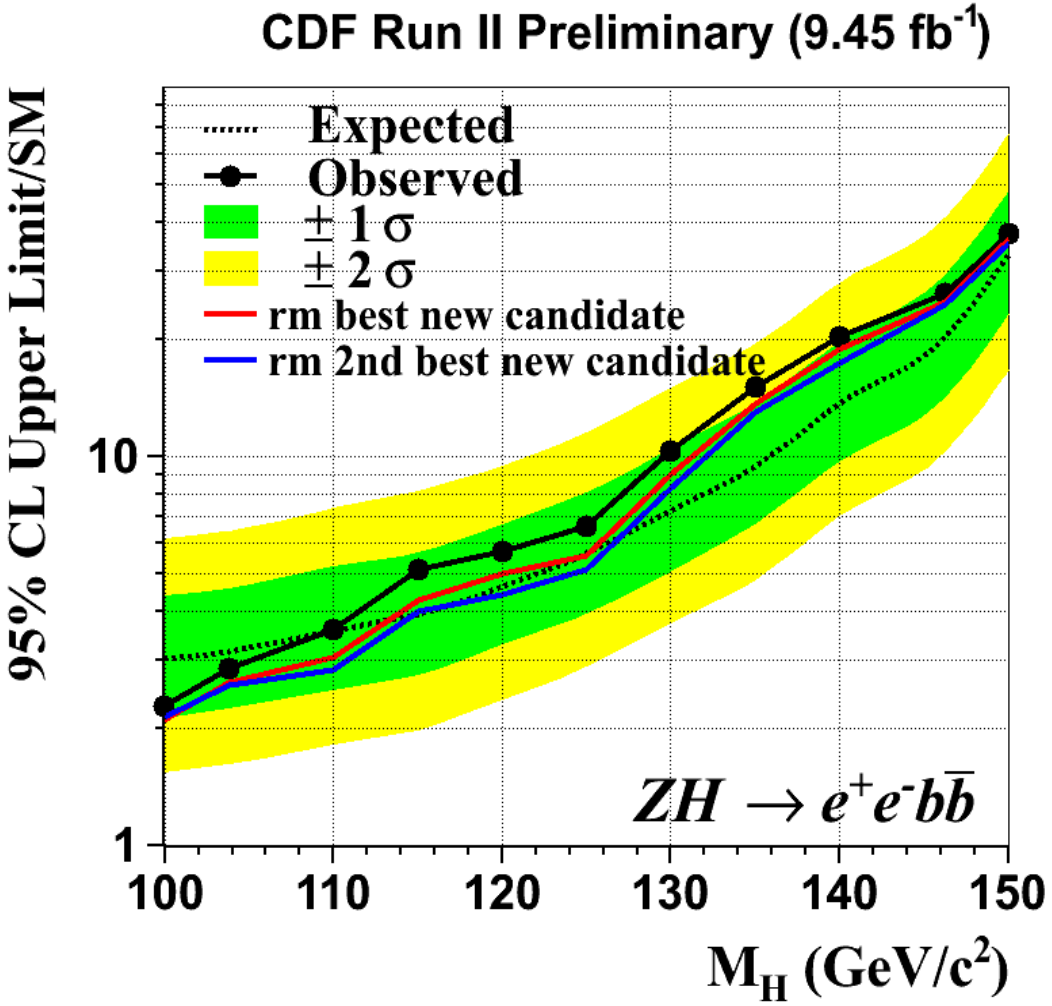
ZH→ll bb Analysis

- 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



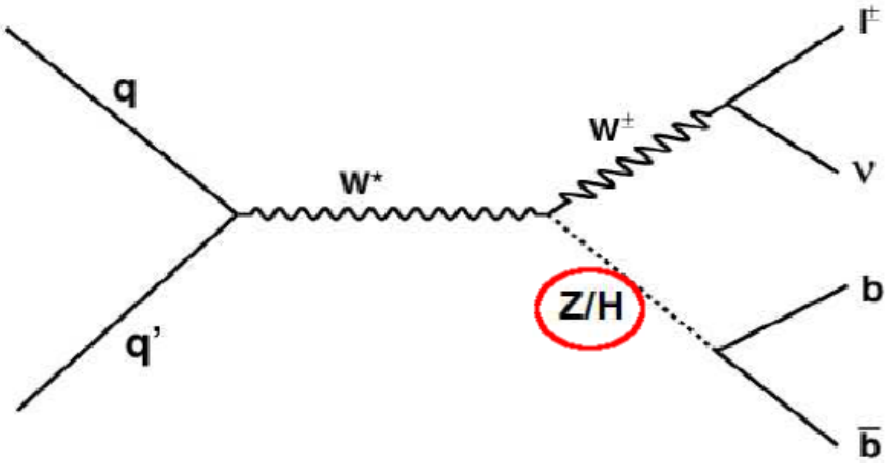
ZH→ll bb Analysis

- To study the effect of high S/B events on CDF's observed limits, the 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



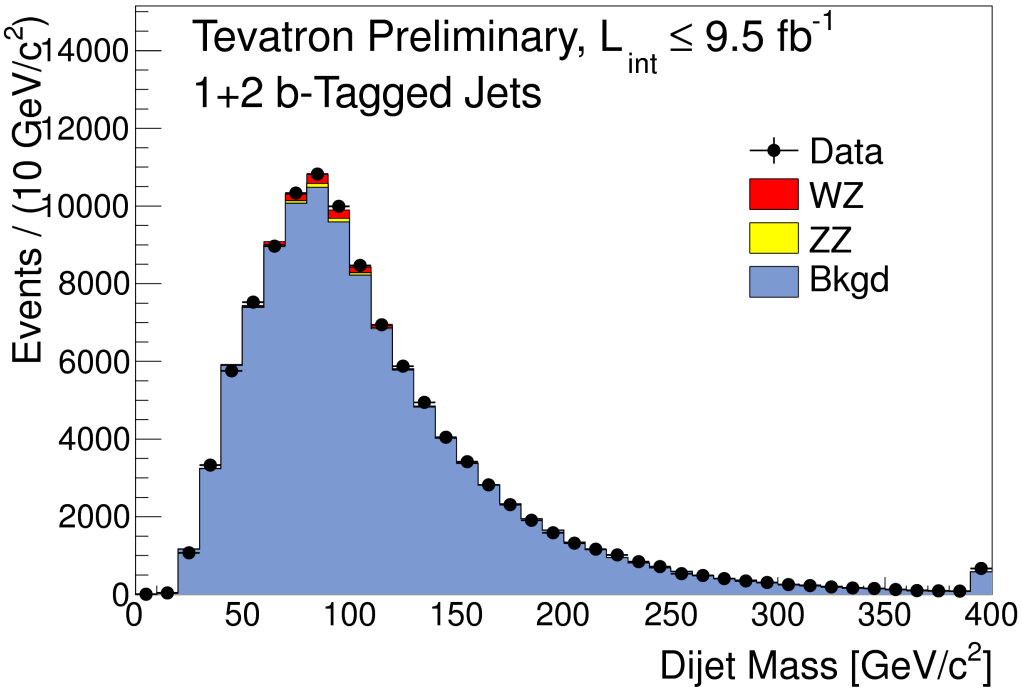
Diboson vs. Higgs Analyses

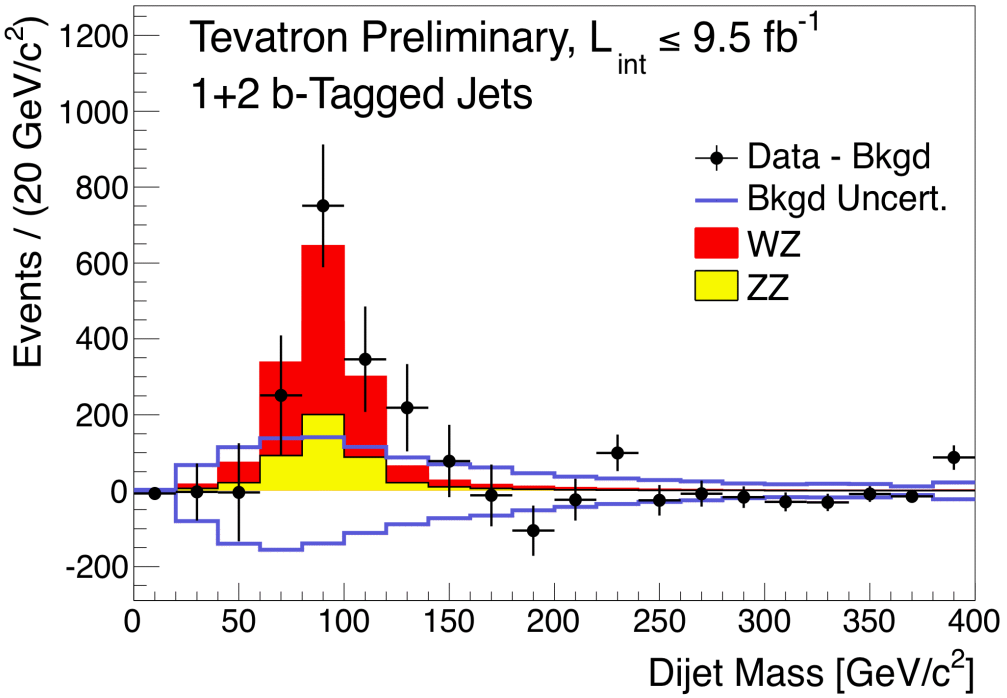
- Feynman diagrams are topologically equivalent



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

Verify modeling with σ(WZ+ZZ)

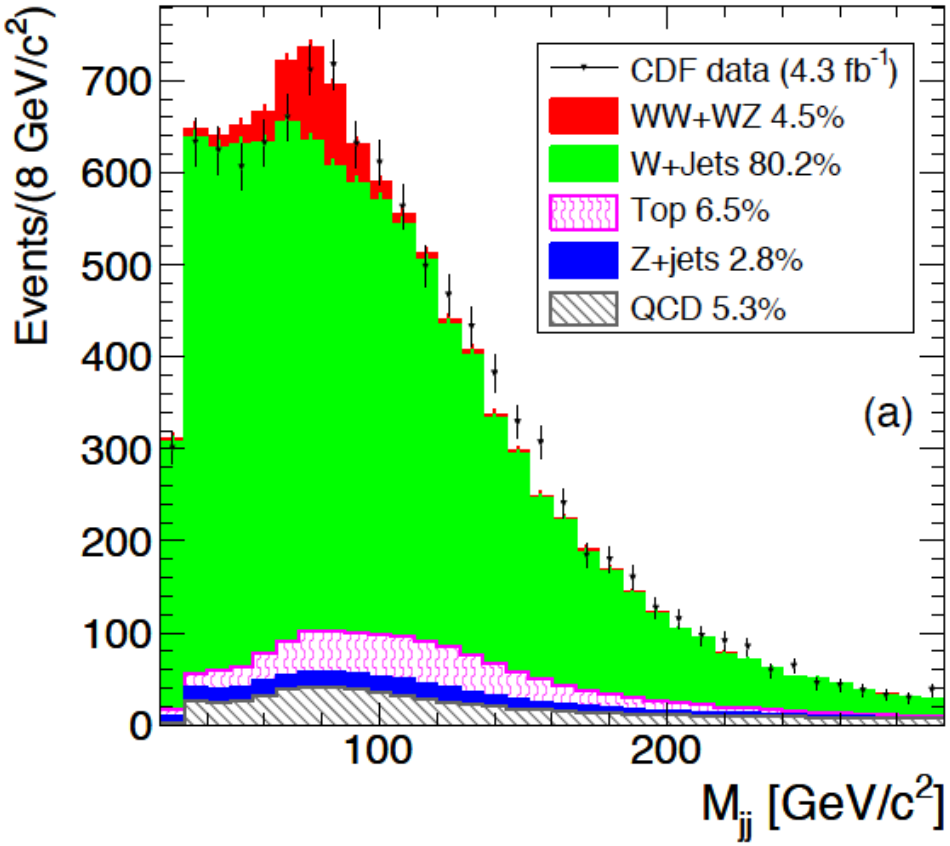


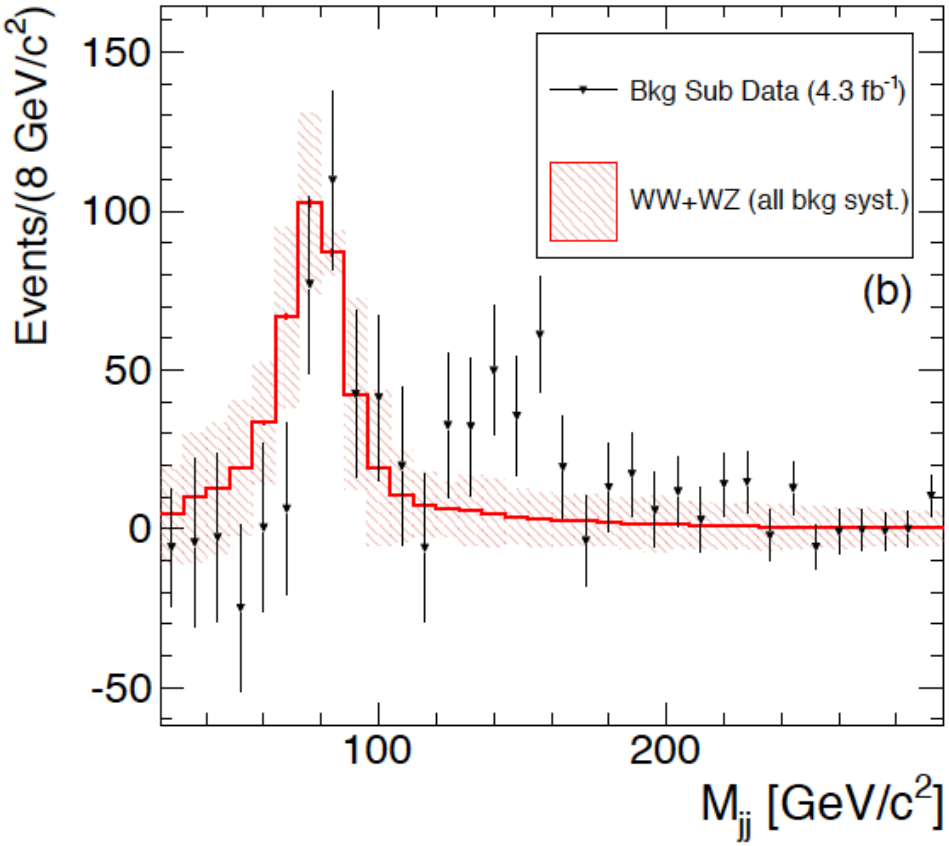


σ(WZ+ZZ) = 4.47 ± 0.64 (stat) ± 0.73 (syst) pb

SM Prediction = 4.4 ± 0.3 pb

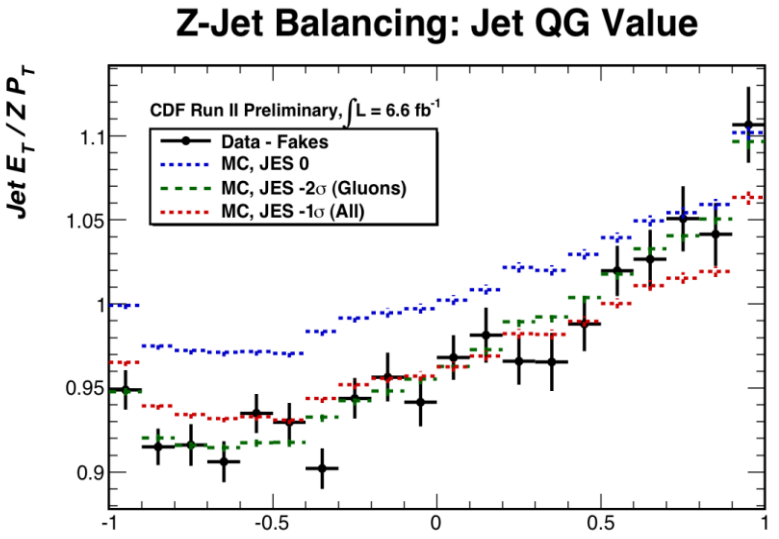
What about the CDF W + jets bump?

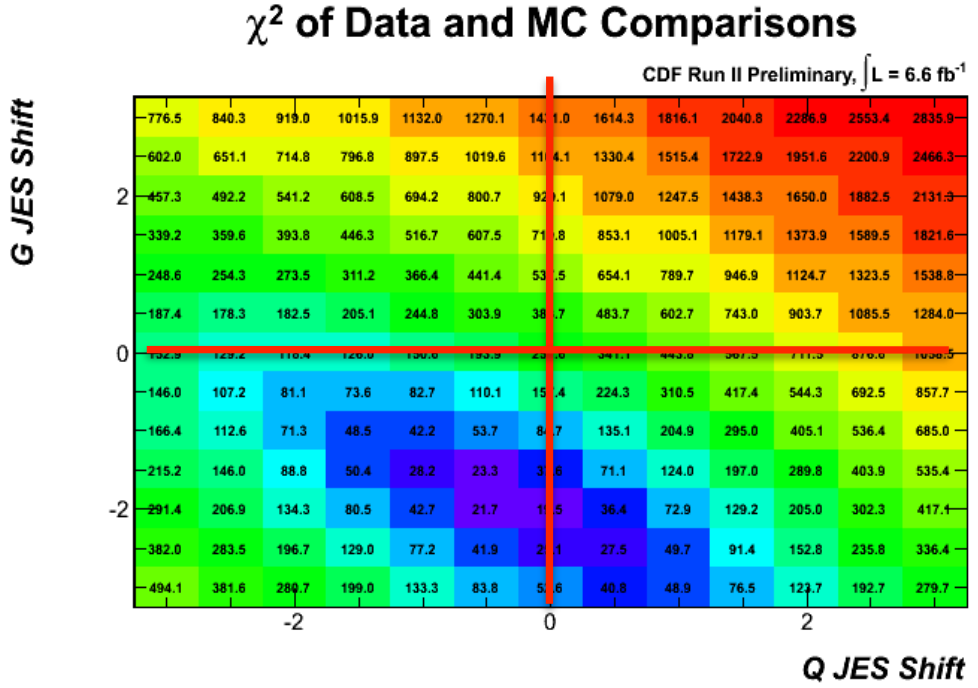




What about the CDF W + jets bump?

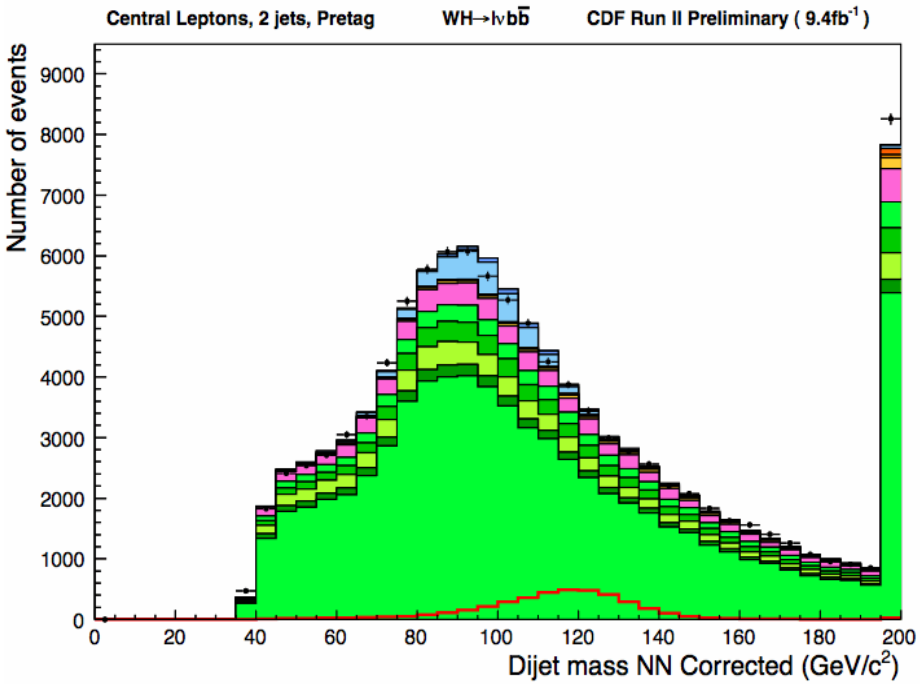
- Z+ jet balancing study done indicating that JES for gluon jets needs to be shifted by 2σ in MC to match with data
- The JES for quark jets is good – not surprising since well constrained by top mass measurements





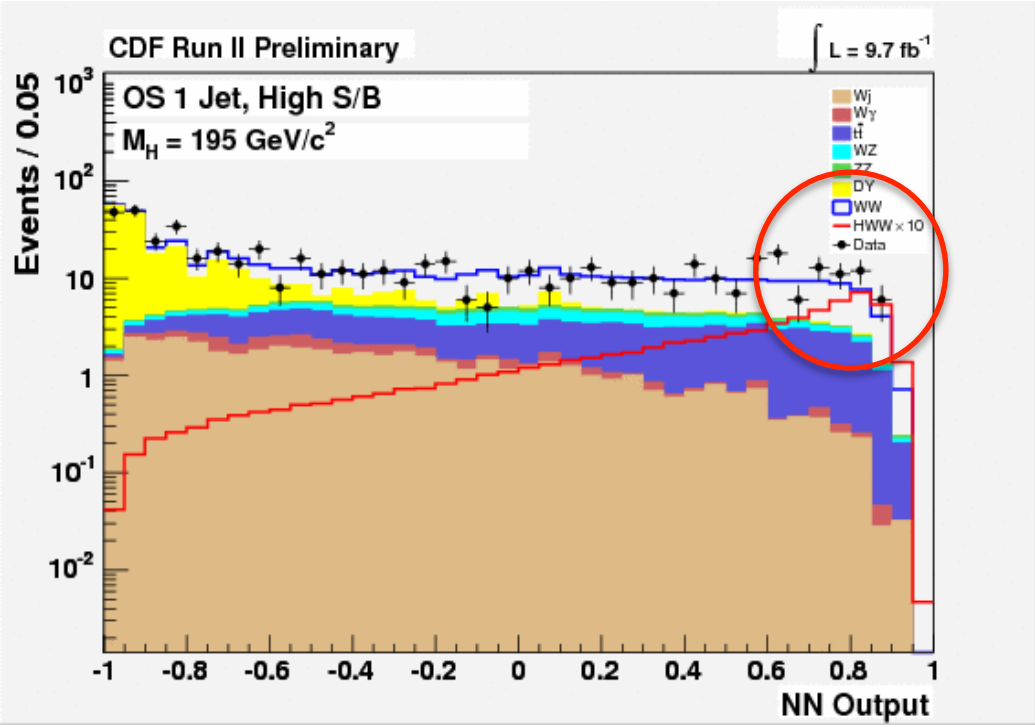
What about the CDF W + jets bump?

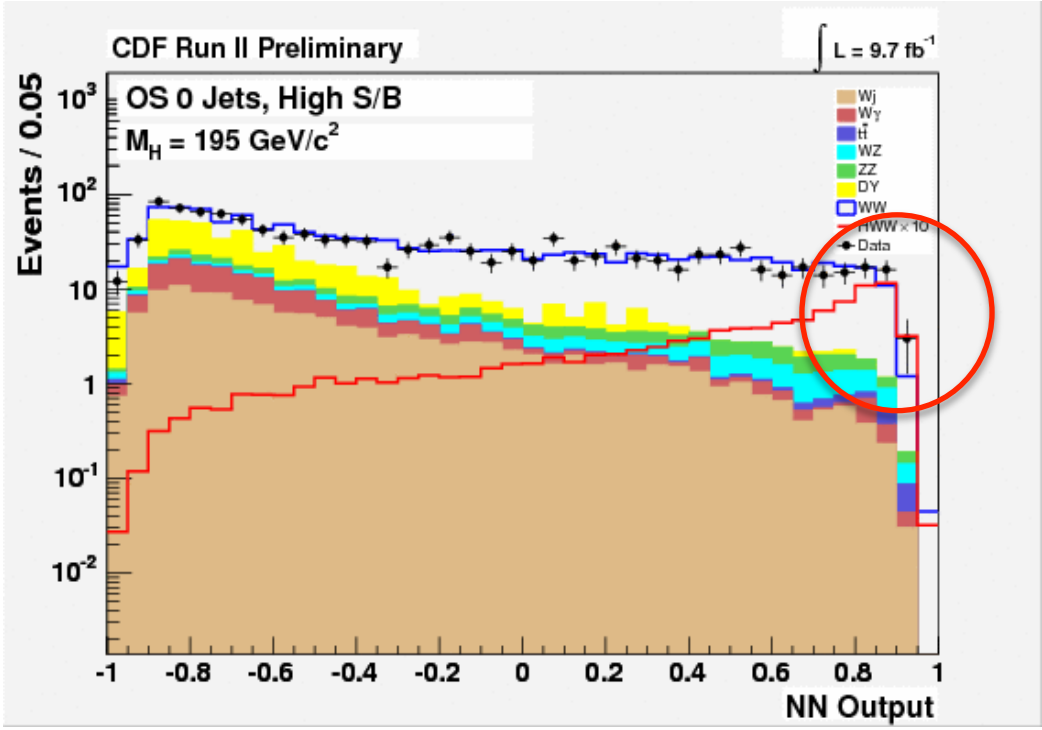
- In CDF Higgs, -2σ JES corrections are applied to the gluon jets in the MC samples
- In the end, since there are so few gluon jets in tagged samples, the effect is small



- With these corrections in place no mis-modeling observed in the pre-tag region of the WH Higgs search

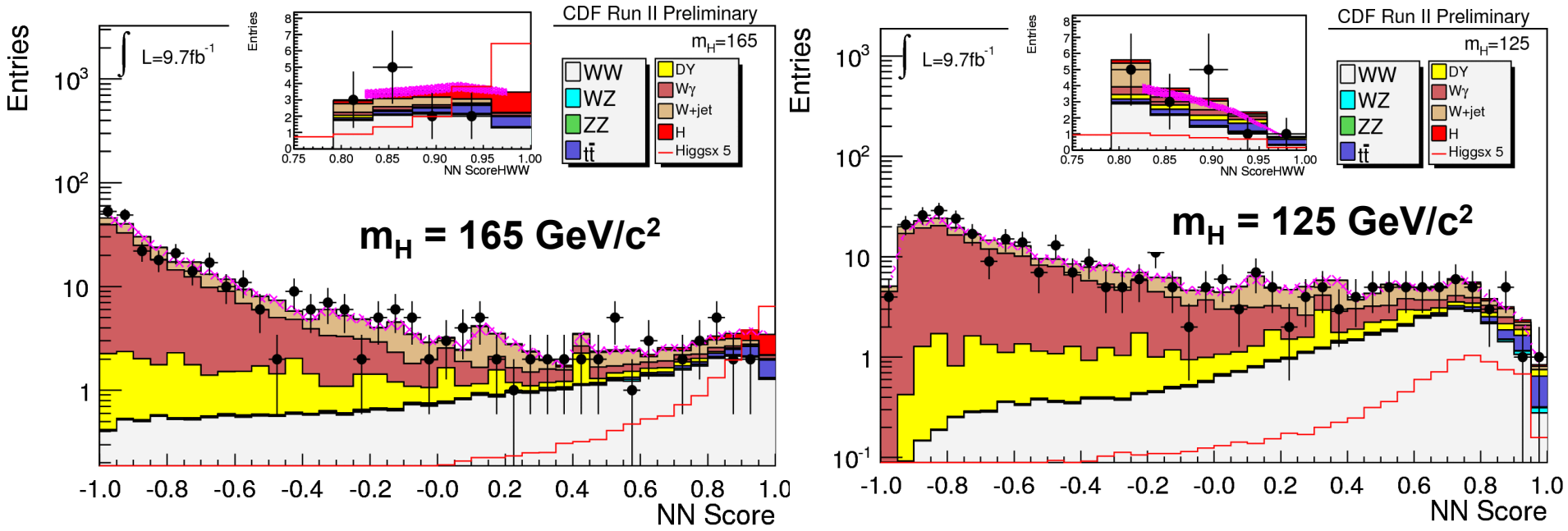
Excess at m_H = 195 GeV/c^2





- 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

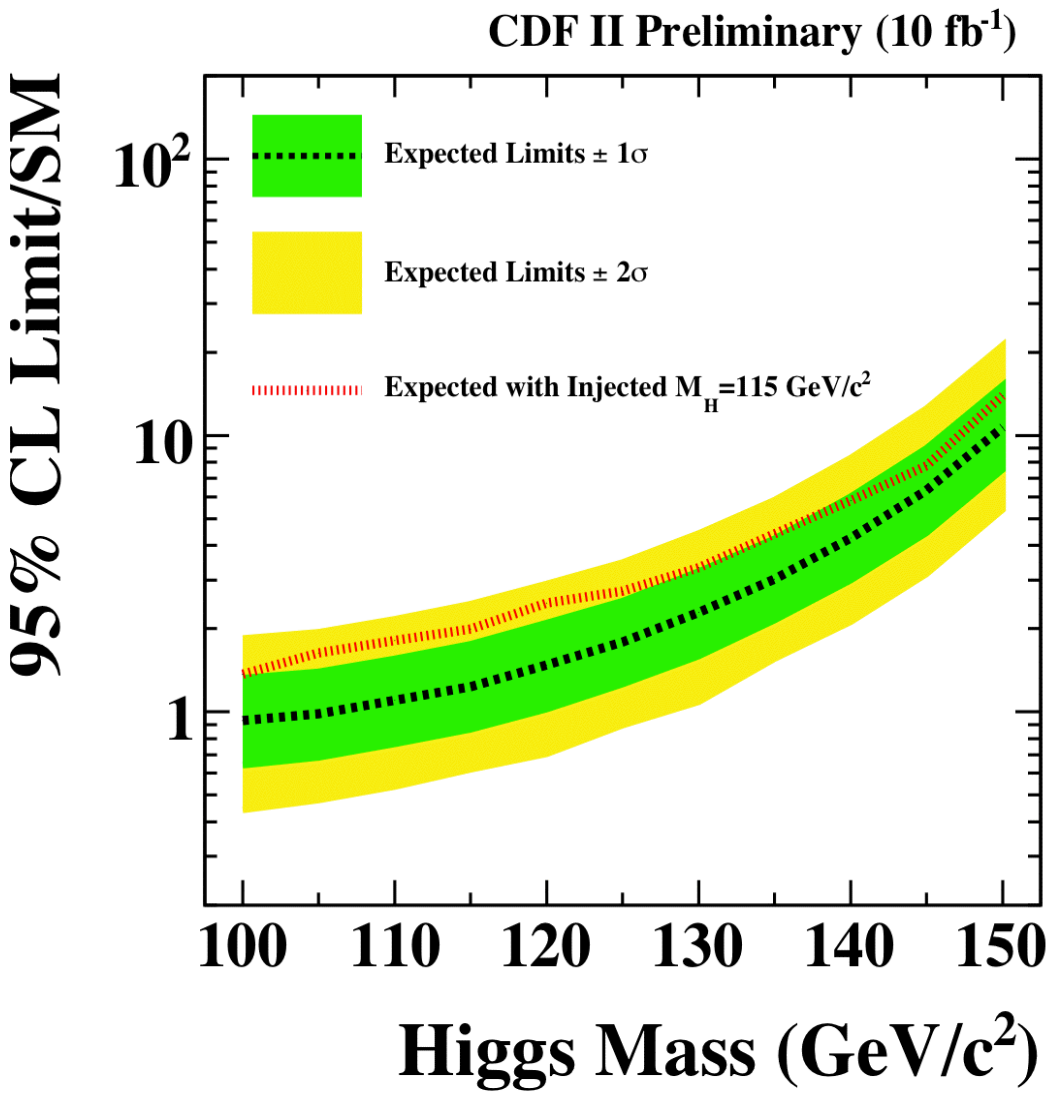


- Driven by deficit of events in high S/B region of our opposite-sign, low invariant mass dilepton channel
- This is the channel in which we obtain increased acceptance from low ΔR_{ll} events
- Nothing peculiar in the overall modeling of this distribution and deficit is not spread over a wide mass range

Signal Injection study

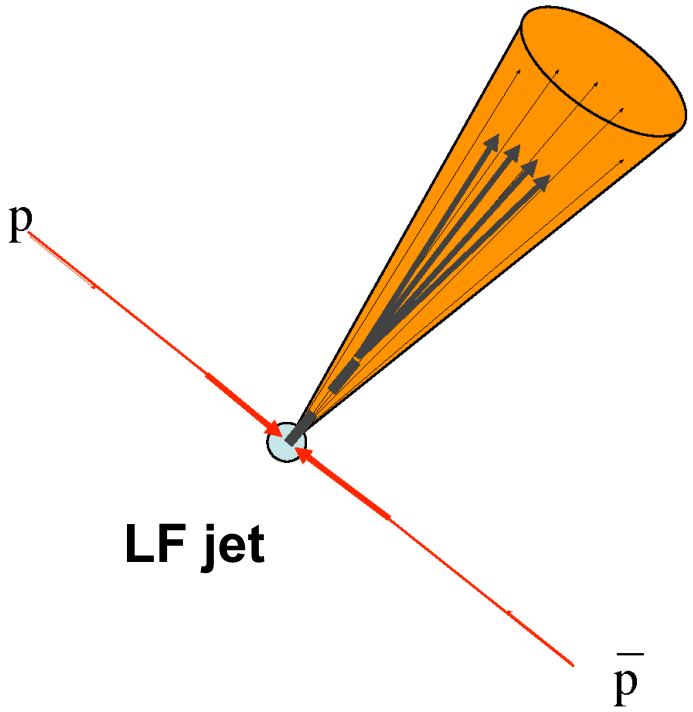
The figure on right shows the results of a previous study where CDF injected a m_H = 115 GeV/c^2 Higgs signal into background-only pseudo-experiments to study the potential effect on our observed limits

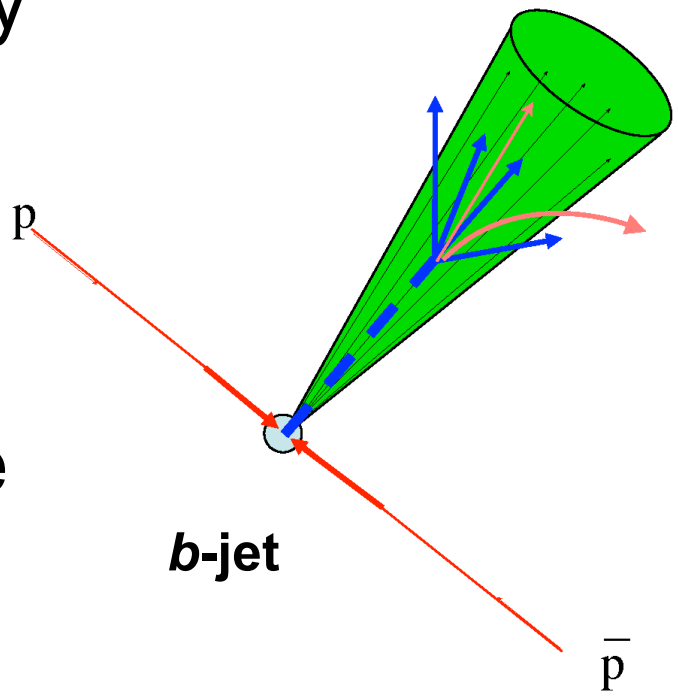
Because neural network discriminants are optimized for separation of signal and background rather than mass reconstruction, we expect to observe (in the presence signal) higher than expected observed limits over a broad mass range



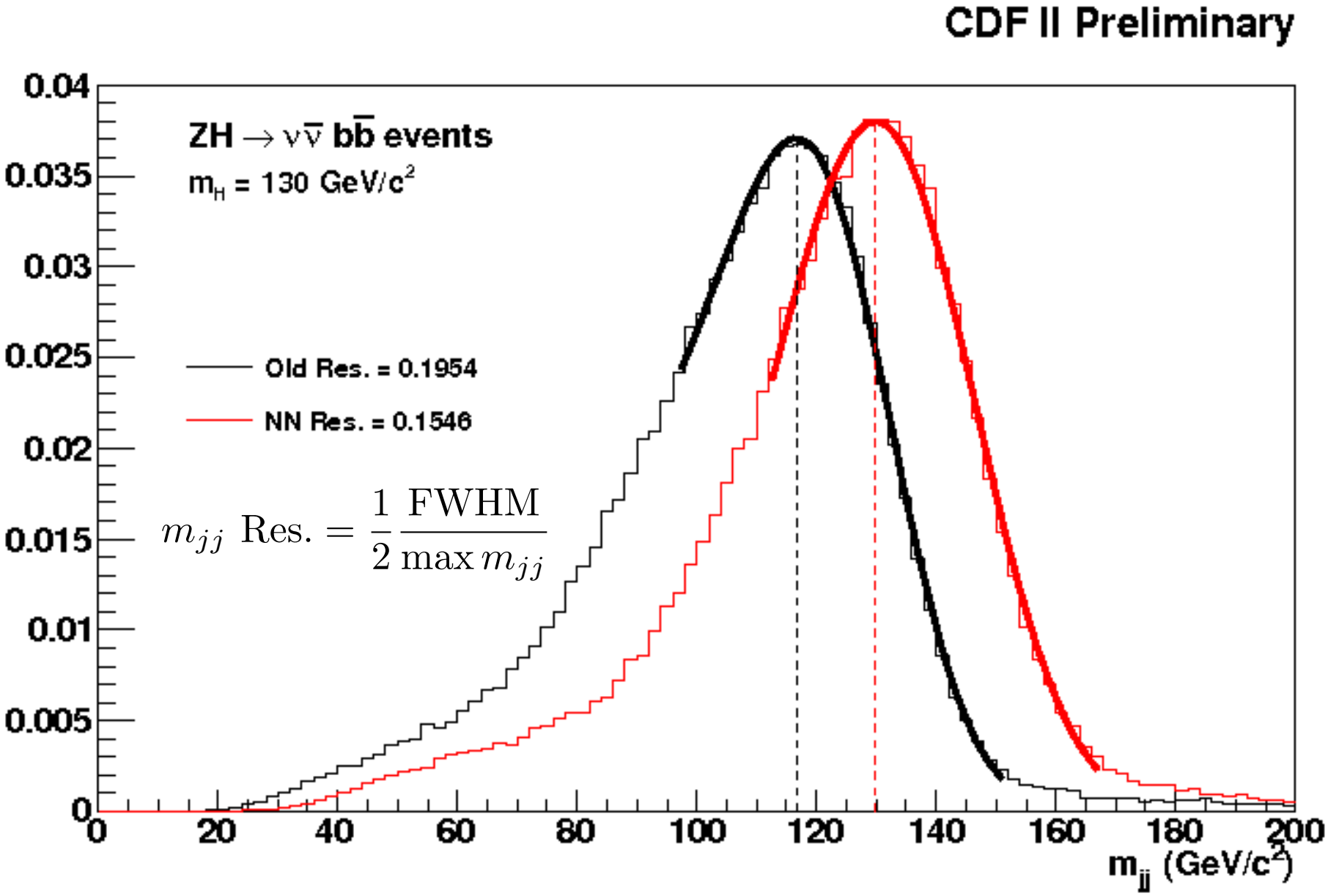
Improved Mass Resolution

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





Improved Mass Resolution



Jet-energy NN can improve resolution by ~20% (relative)