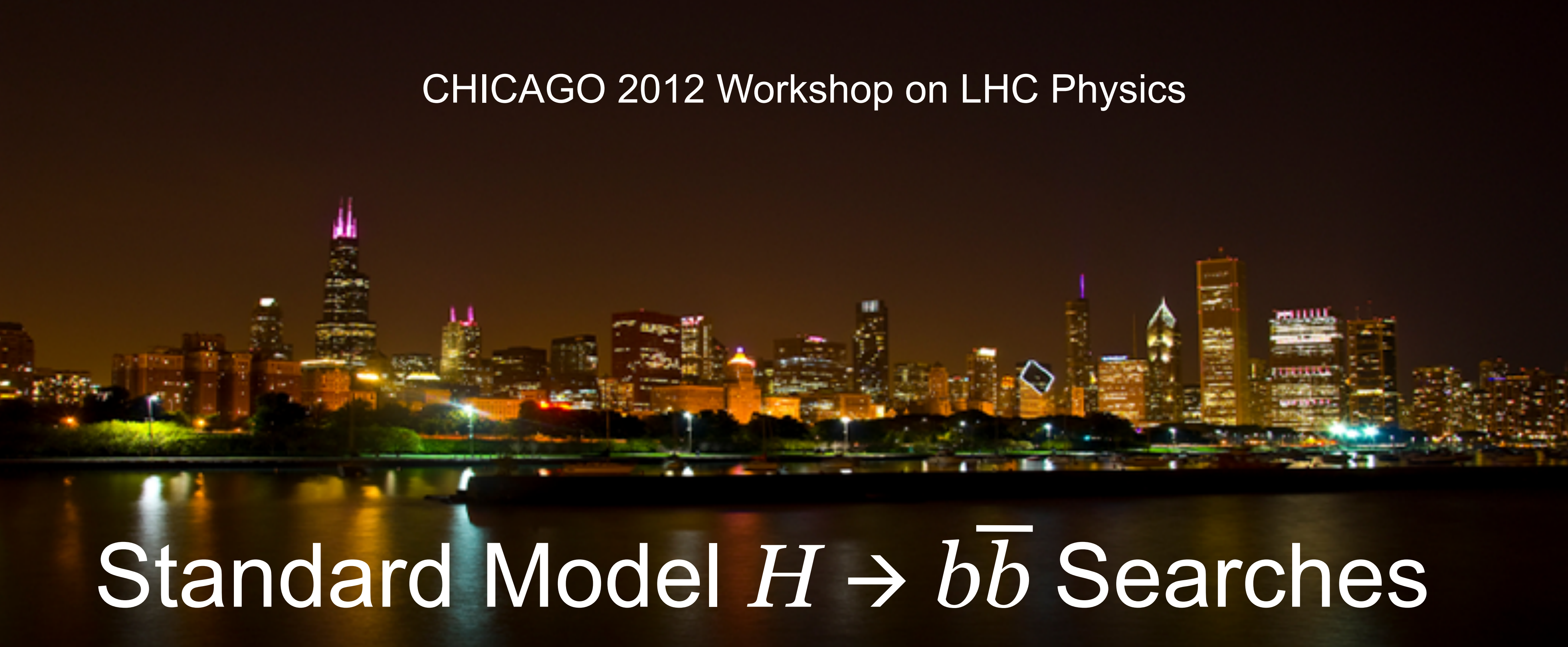
CHICAGO 2012 Workshop on LHC Physics



Standard Model $H \rightarrow b\bar{b}$ Searches

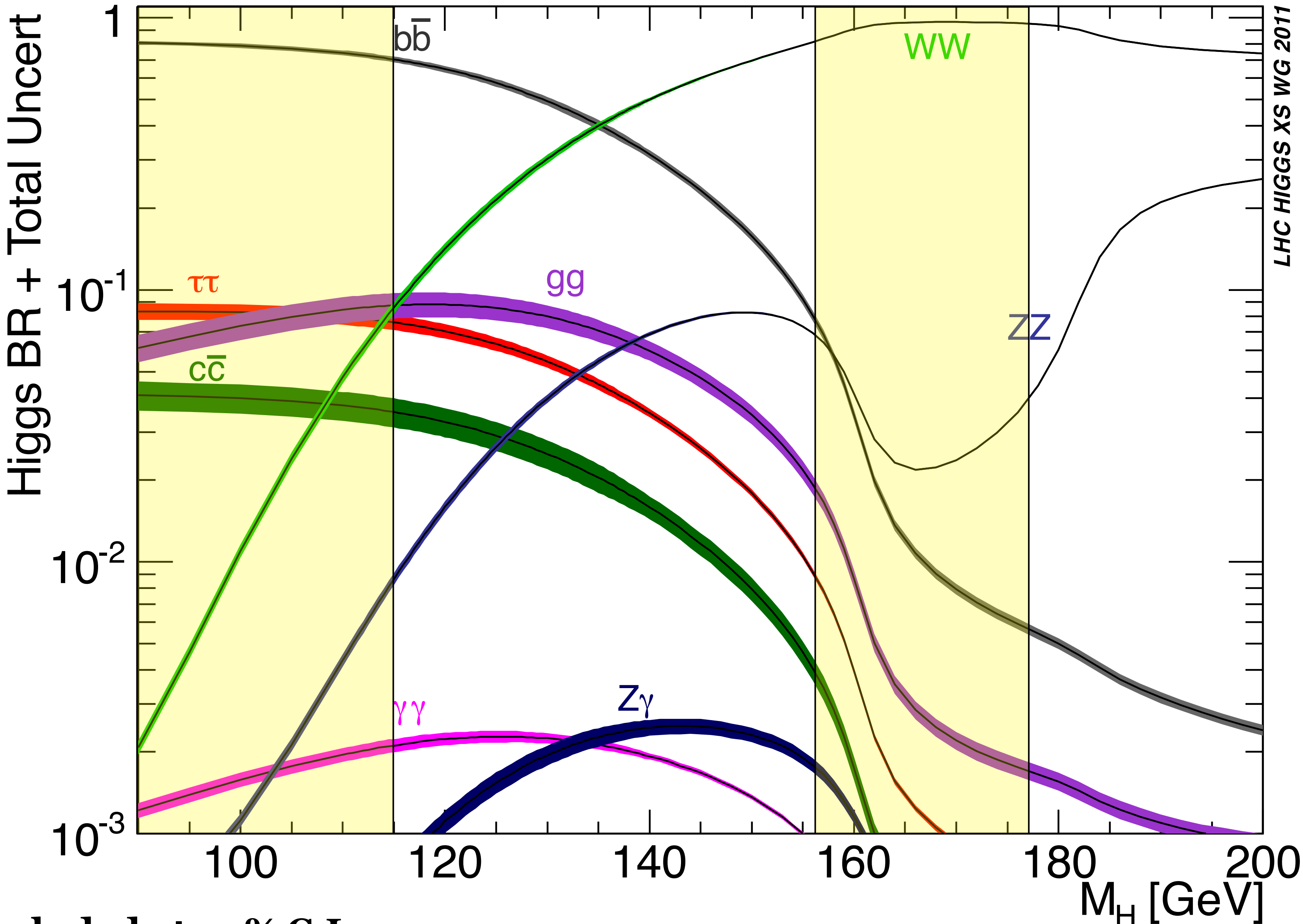
Kyle J. Knoepfel

Fermi National Accelerator Laboratory

May 4, 2012

Higgs Branching Ratios

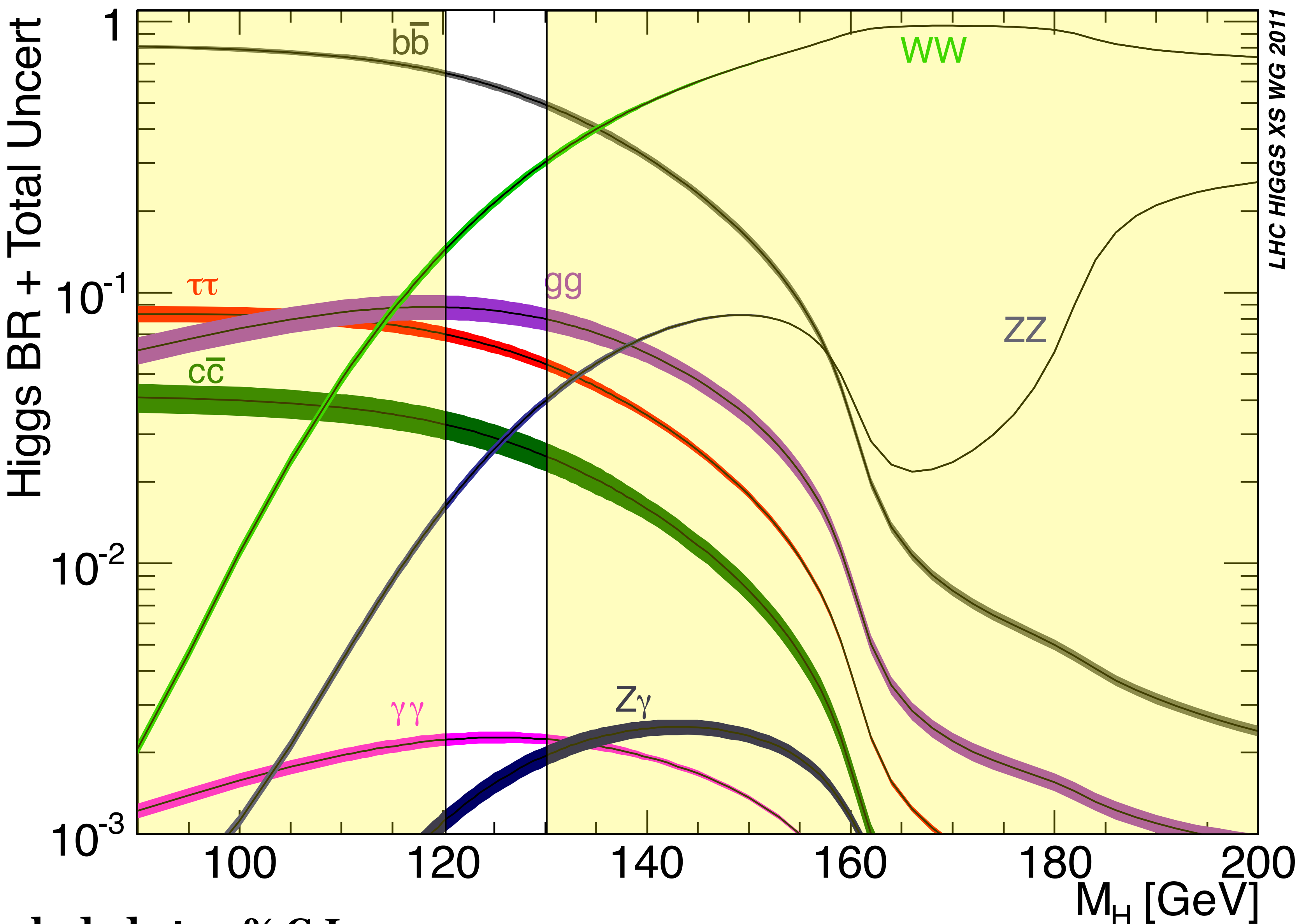
Last Year



Excluded at 95% C.L.

Higgs Branching Ratios

Moriond 2012



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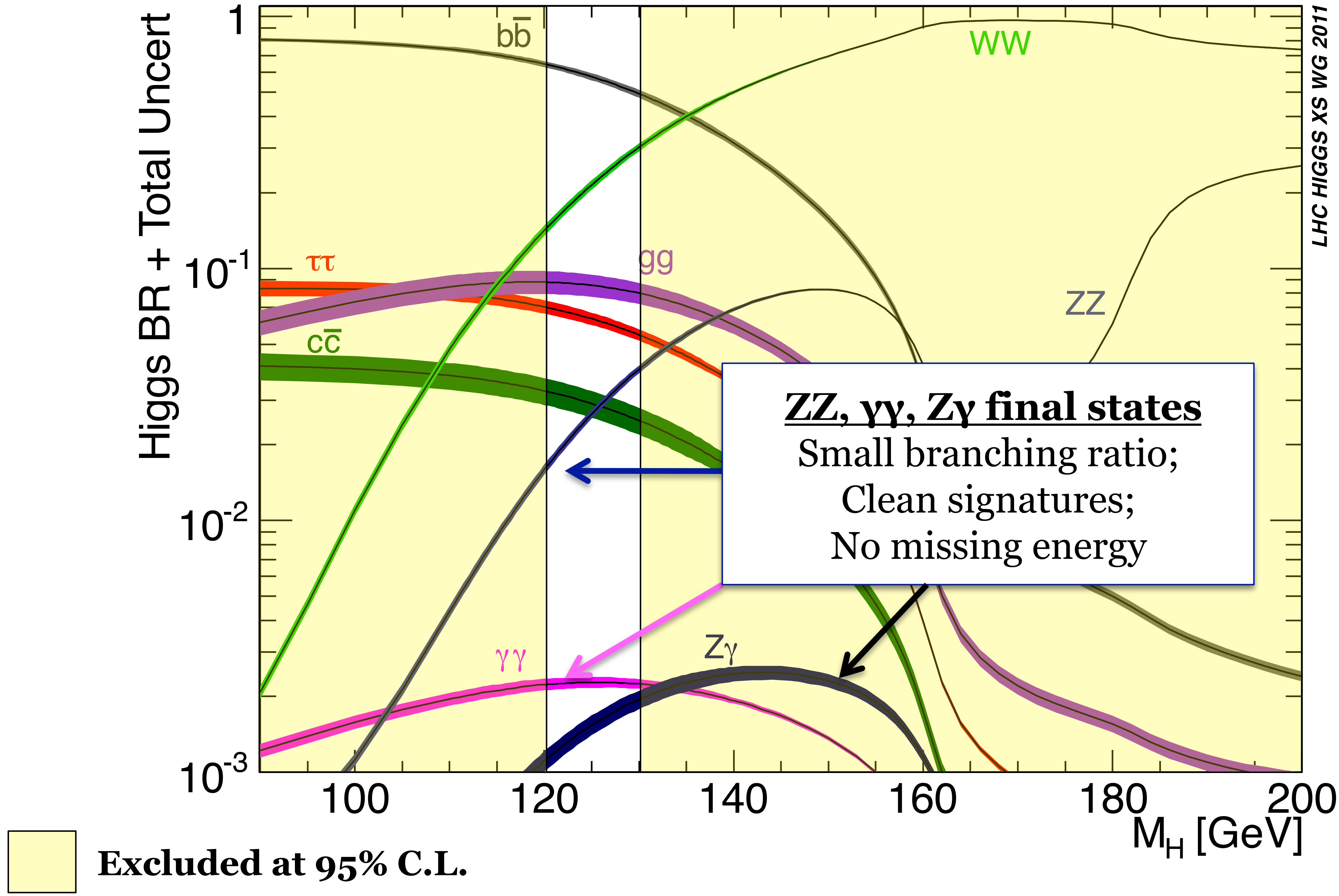
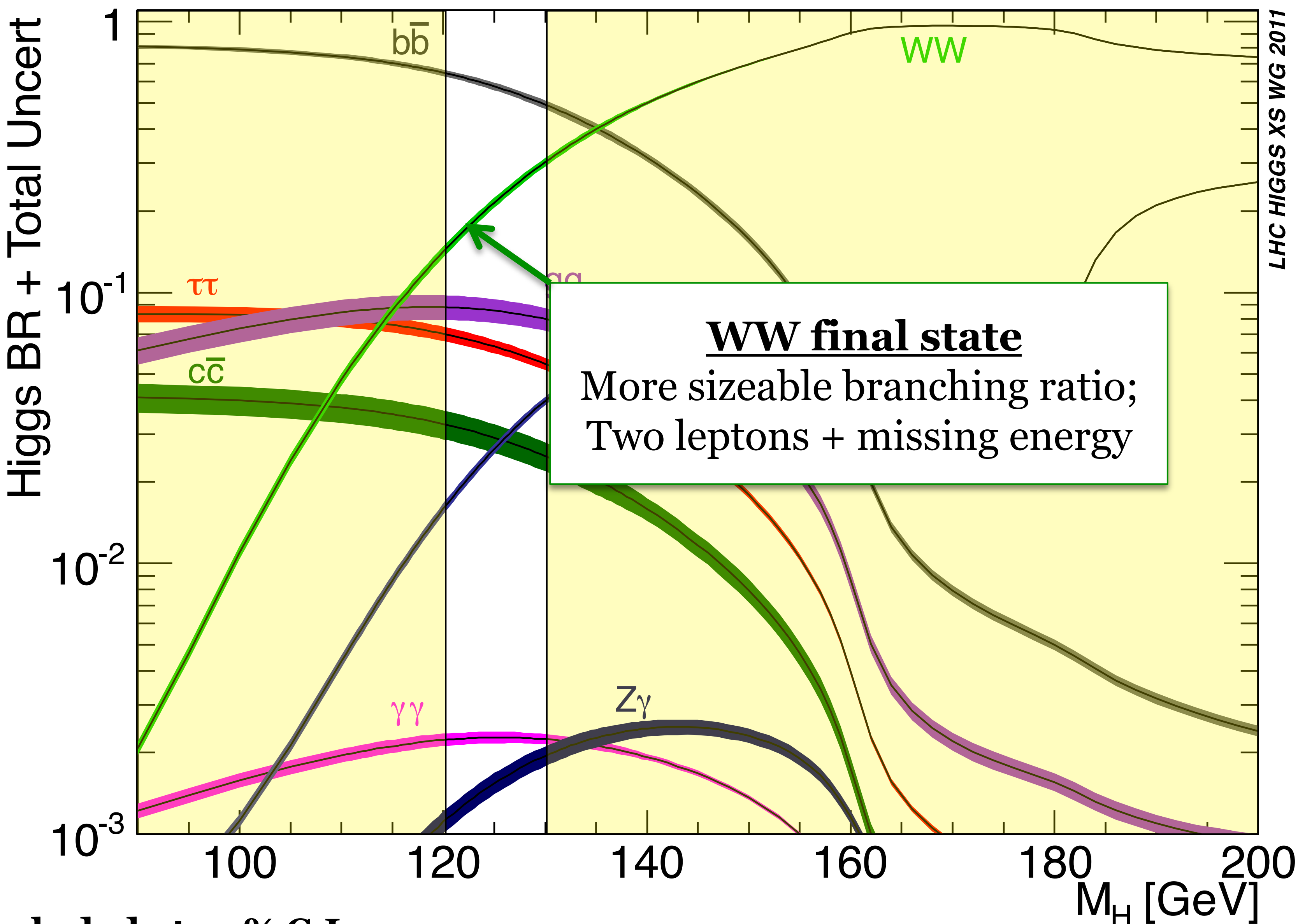
Higgs Branching Ratios



Higgs Branching Ratios



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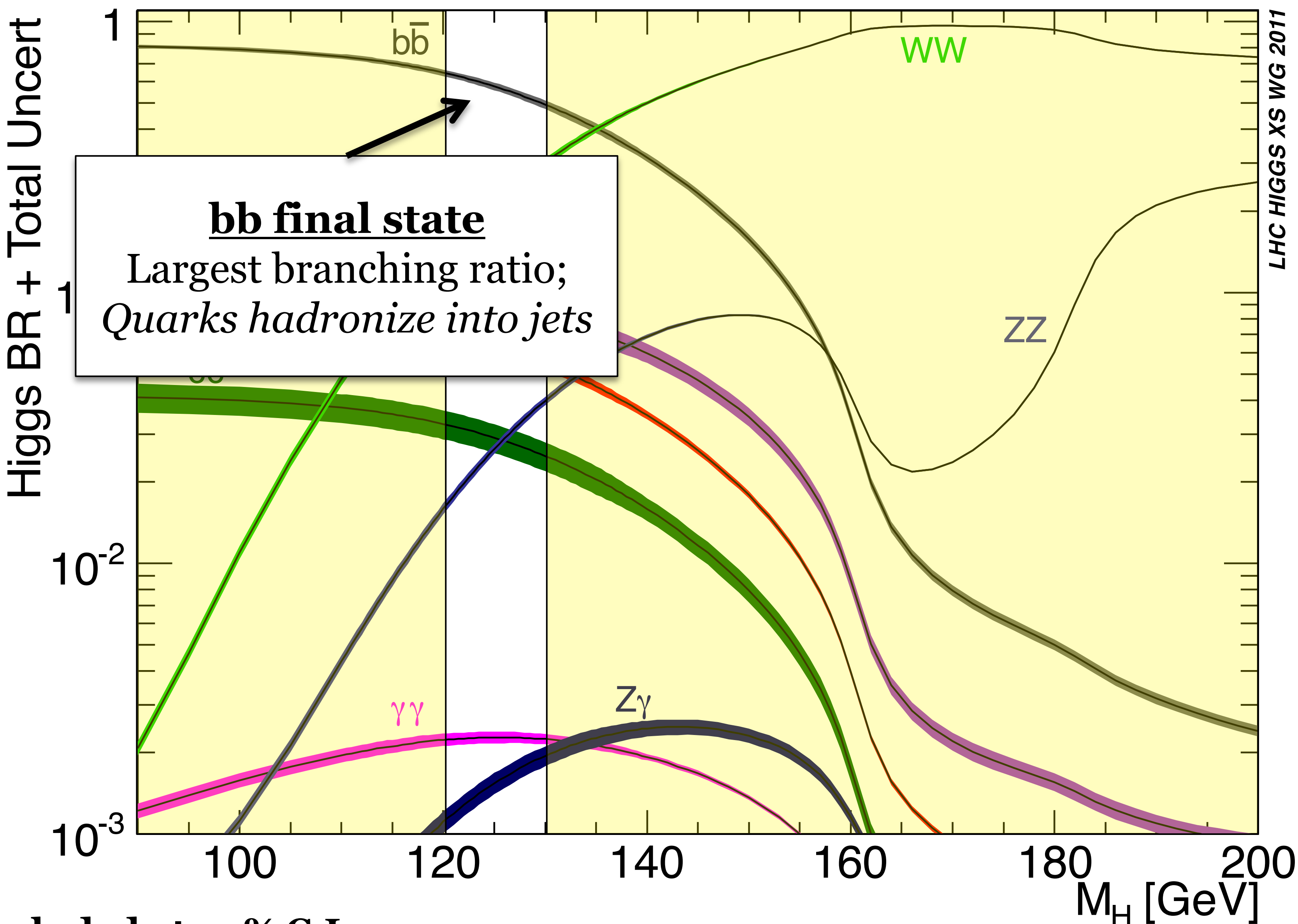

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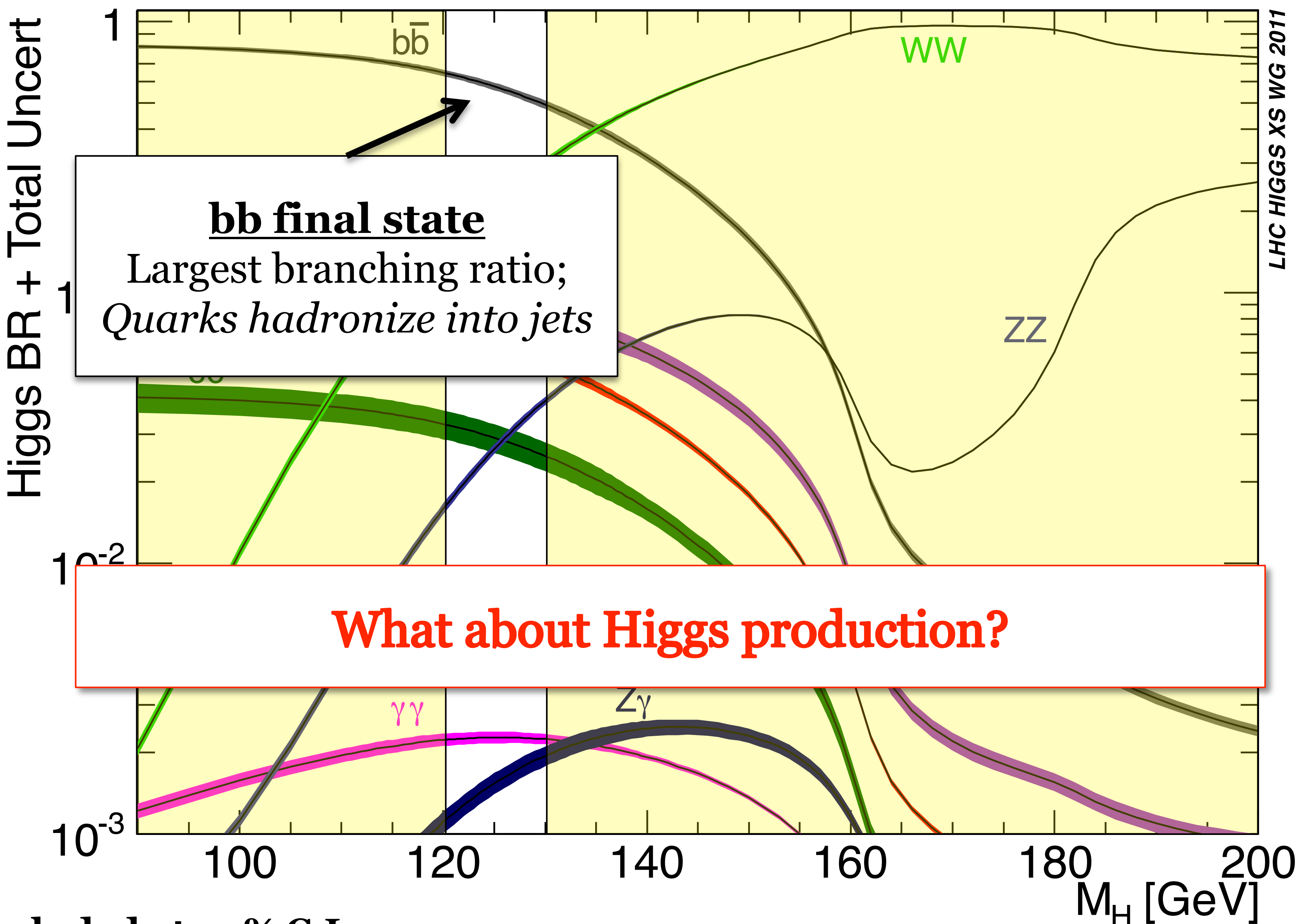
Higgs Branching Ratios

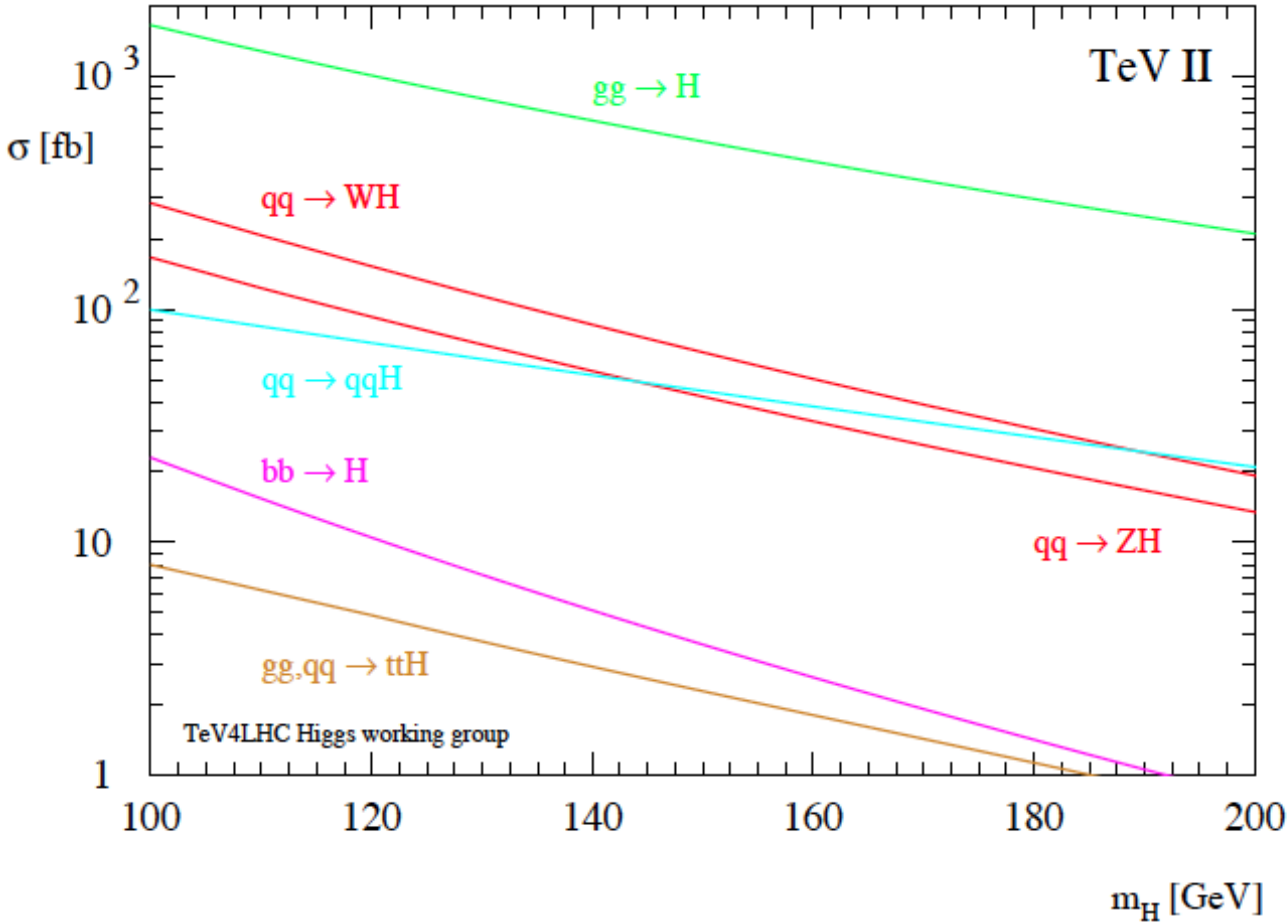


<u>bb final state</u>
Largest branching ratio;
Quarks hadronize into jets

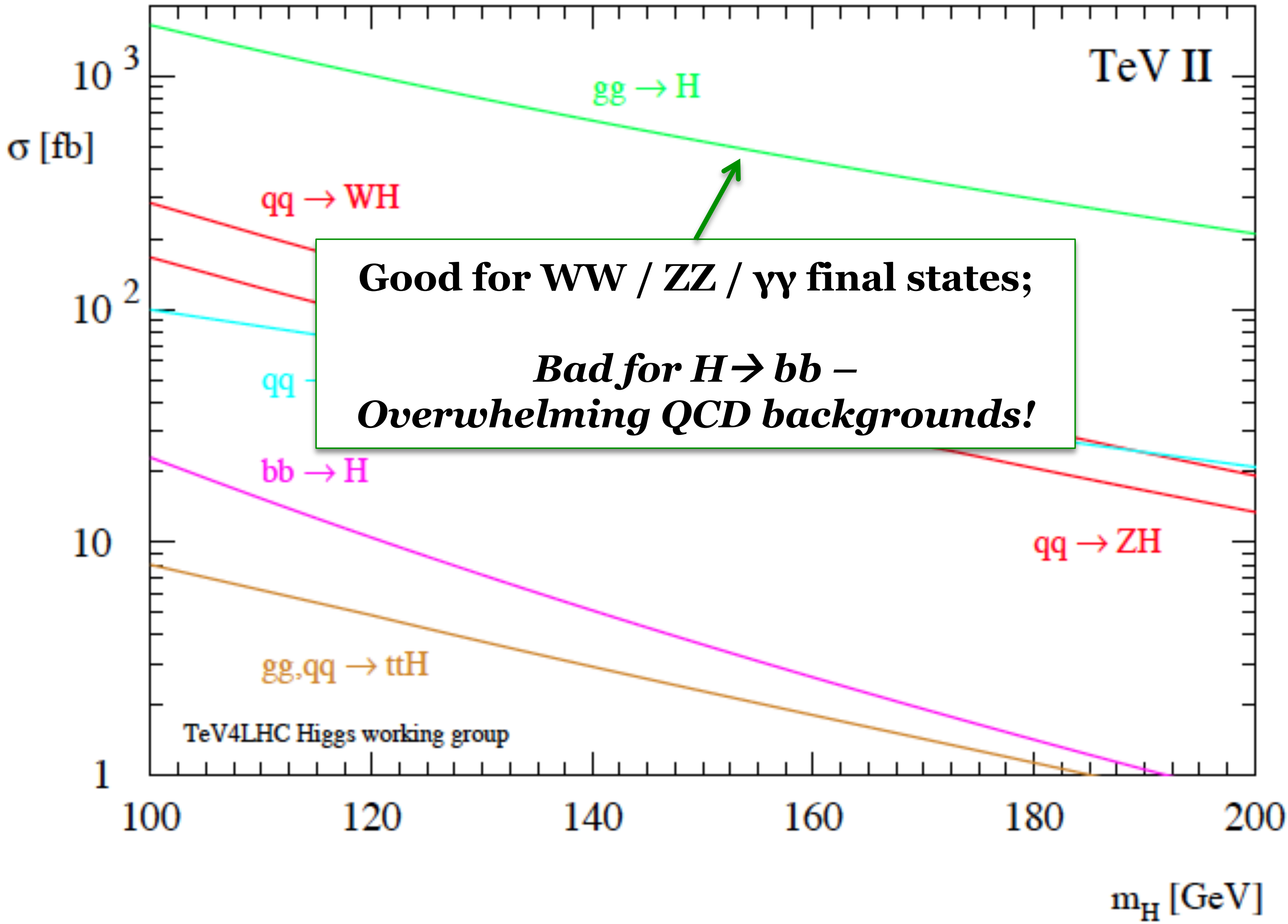
What about Higgs production?

Excluded at 95% C.L.

Higgs Production



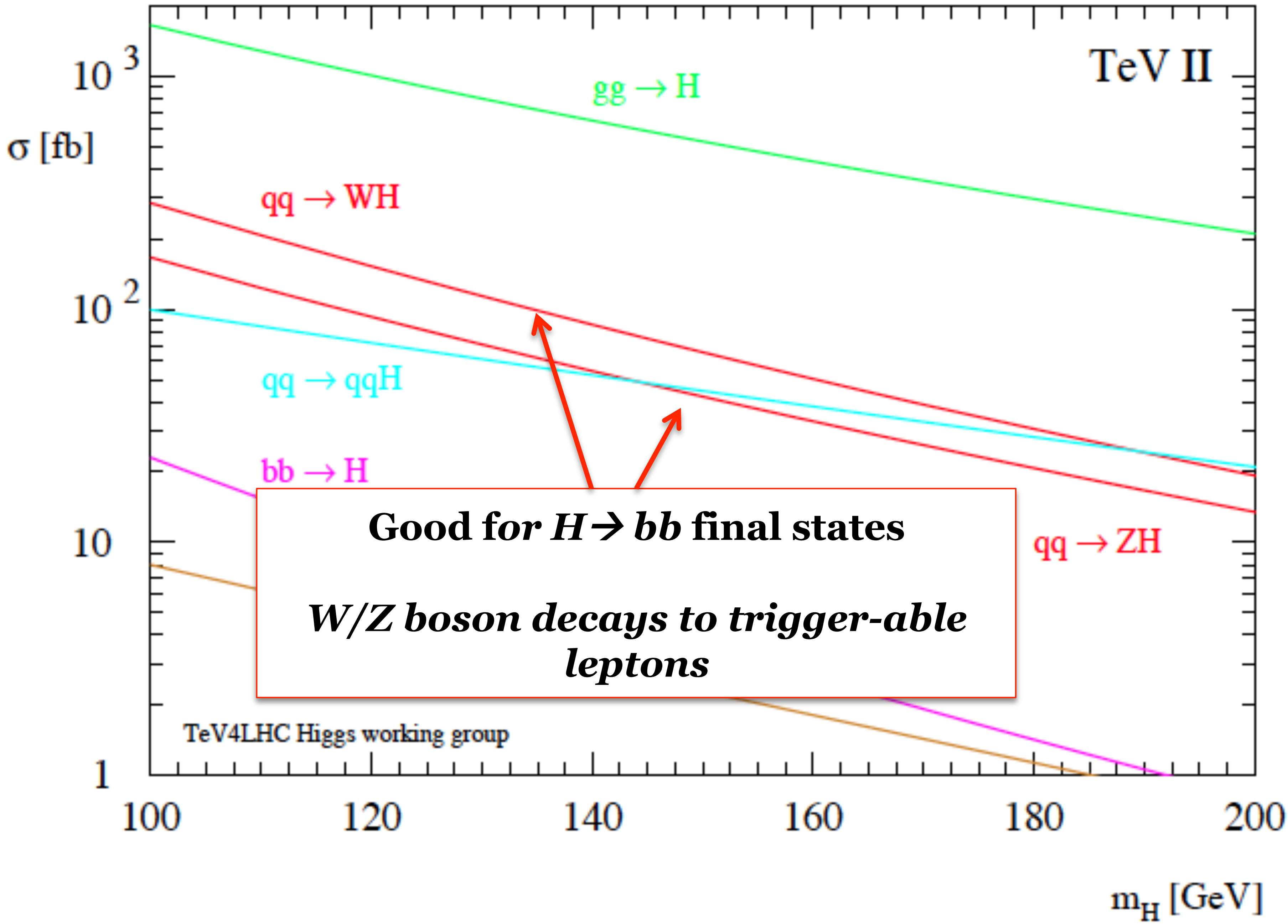
Higgs Production



Good for WW / ZZ / γγ final states;

Bad for H→ bb –
Overwhelming QCD backgrounds!

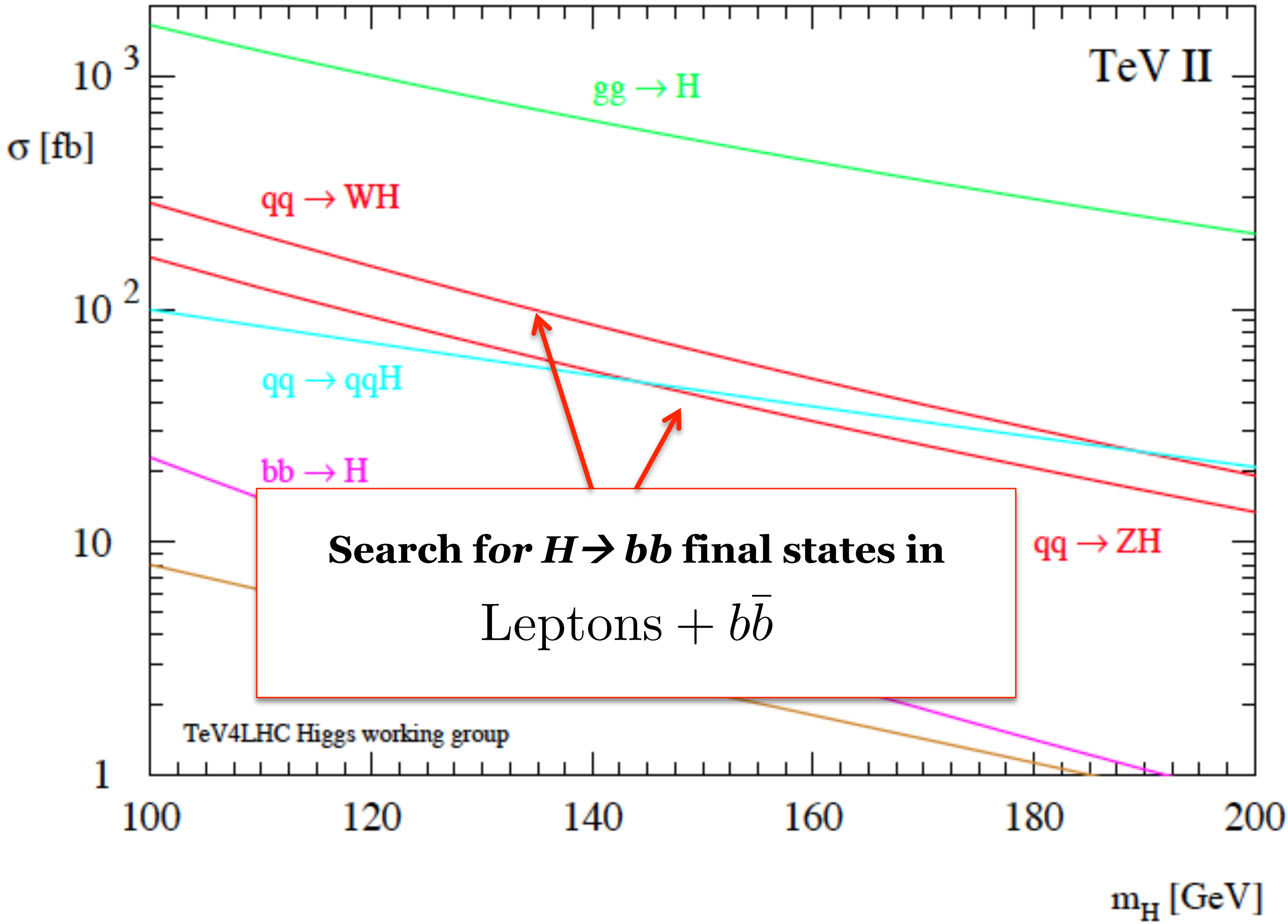
Higgs Production



Good for *H→ bb* final states

W/Z boson decays to trigger-able leptons

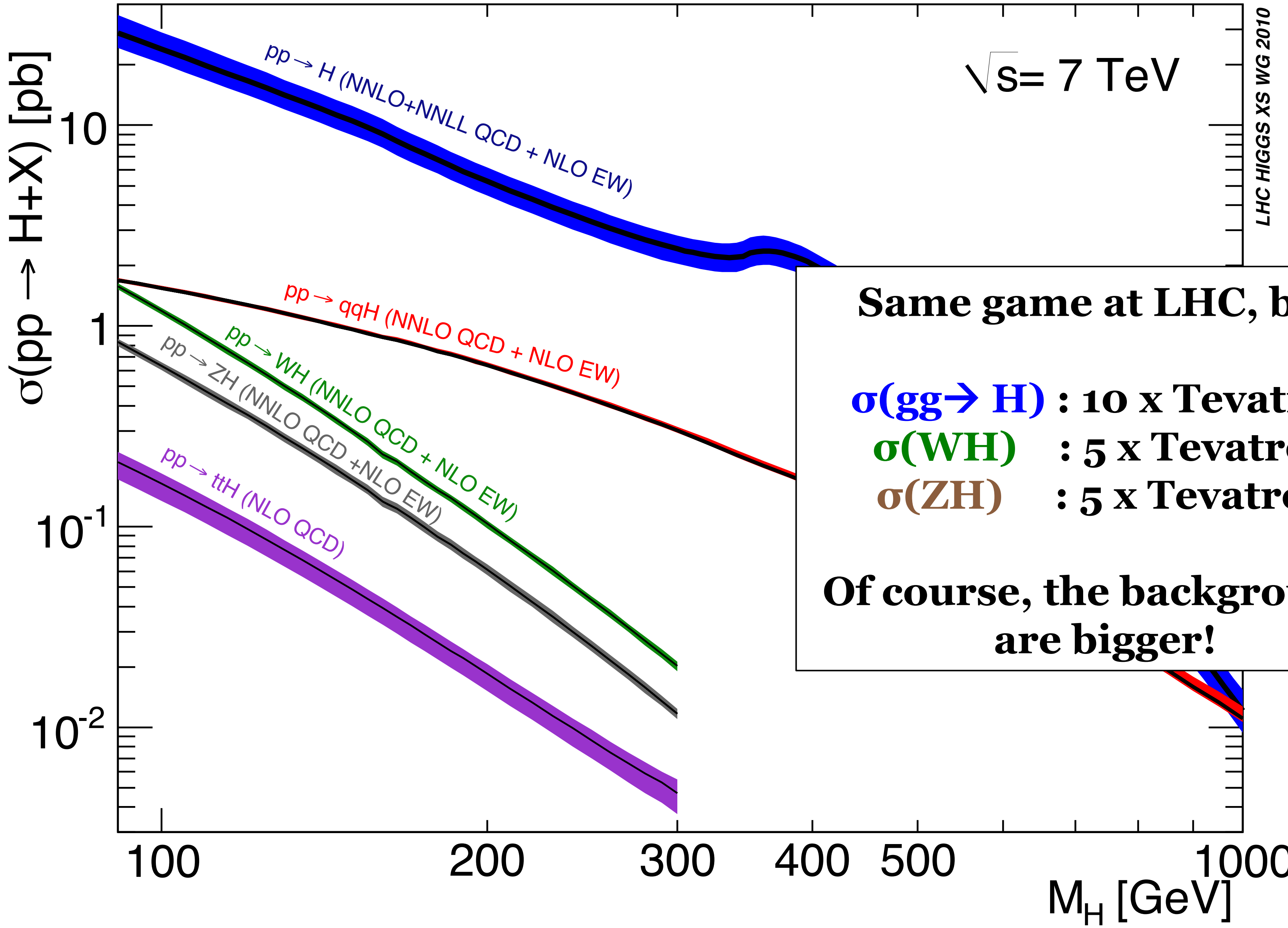
Higgs Production



Search for *H*→ *bb* final states in

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

Higgs Production

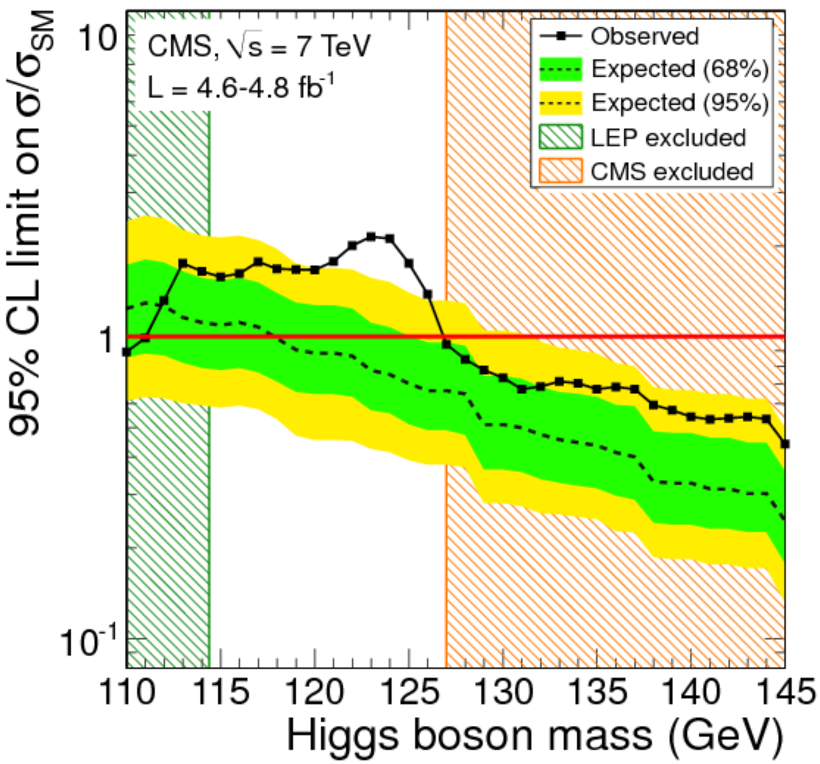


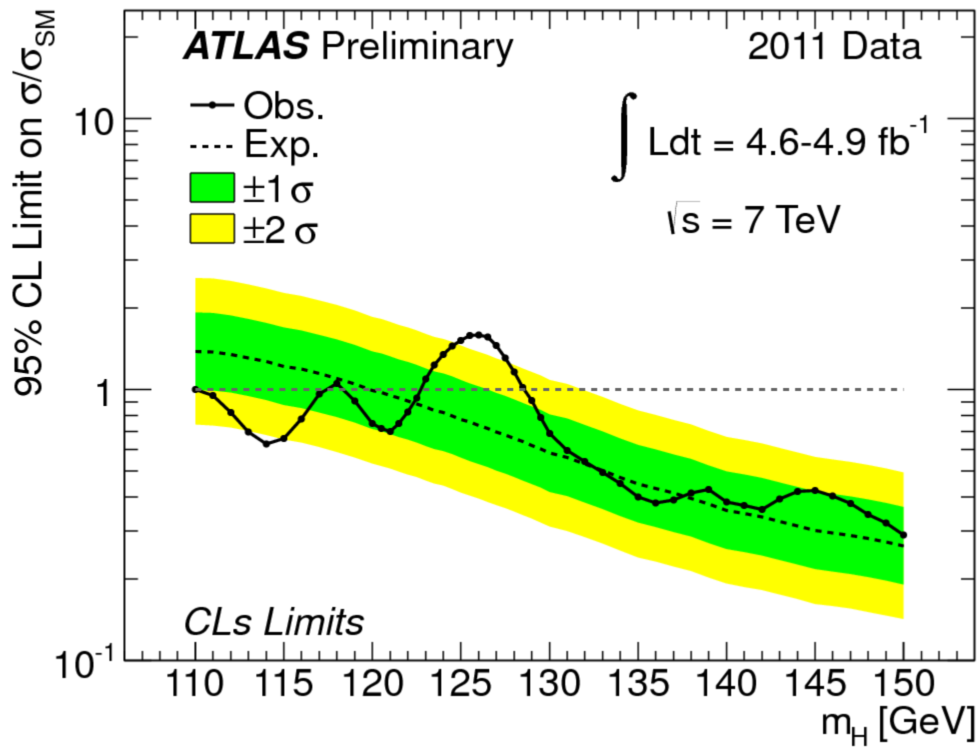
Same game at LHC, but:

σ(gg→ H) : 10 x Tevatron
σ(WH) : 5 x Tevatron
σ(ZH) : 5 x Tevatron

Of course, the backgrounds are bigger!

Current LHC Limits





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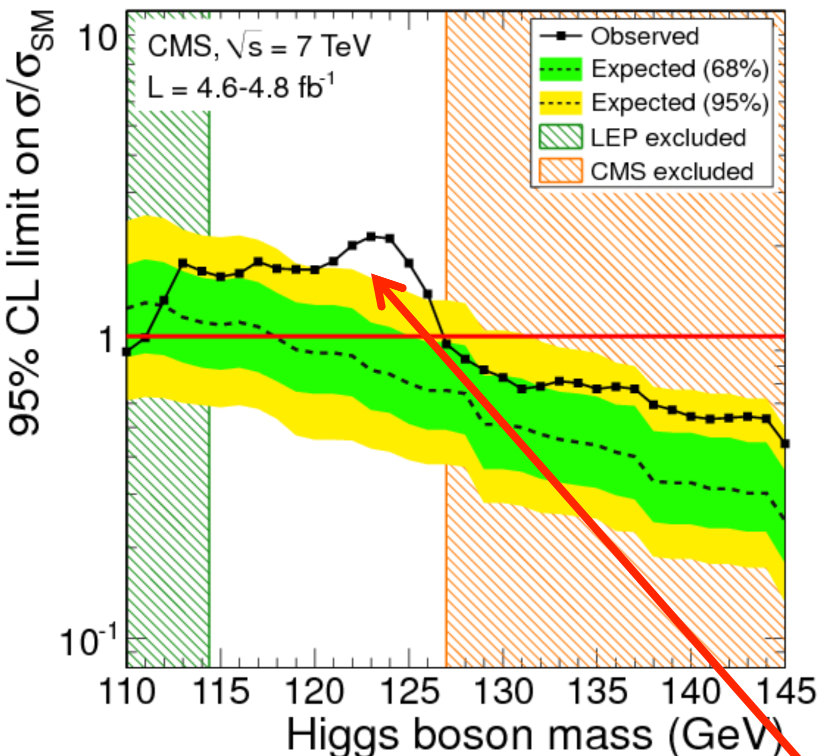
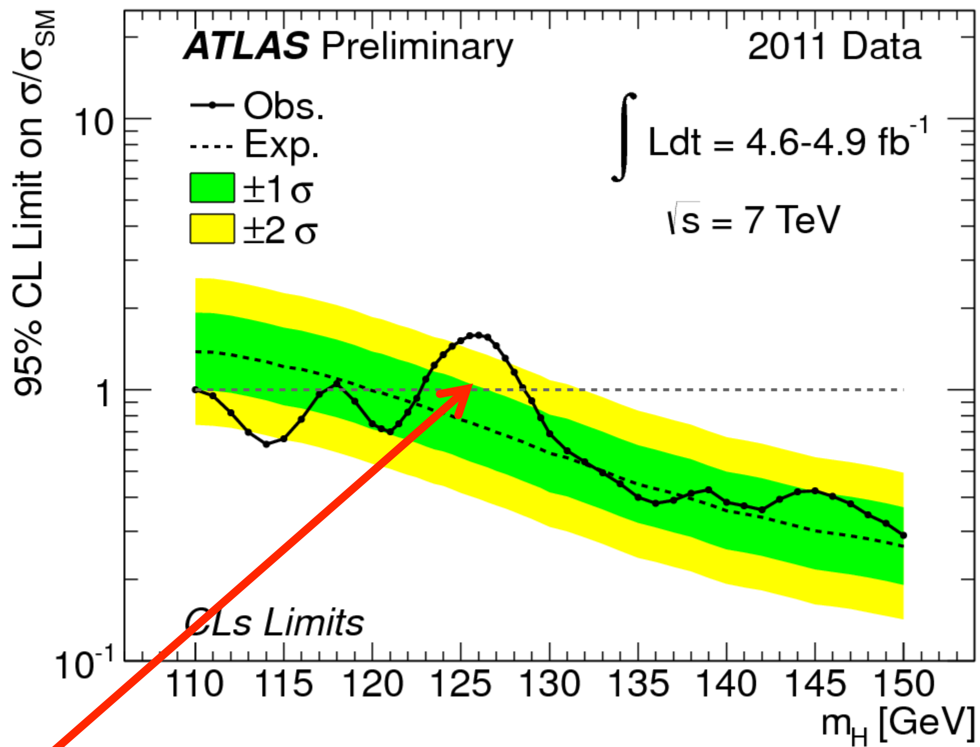
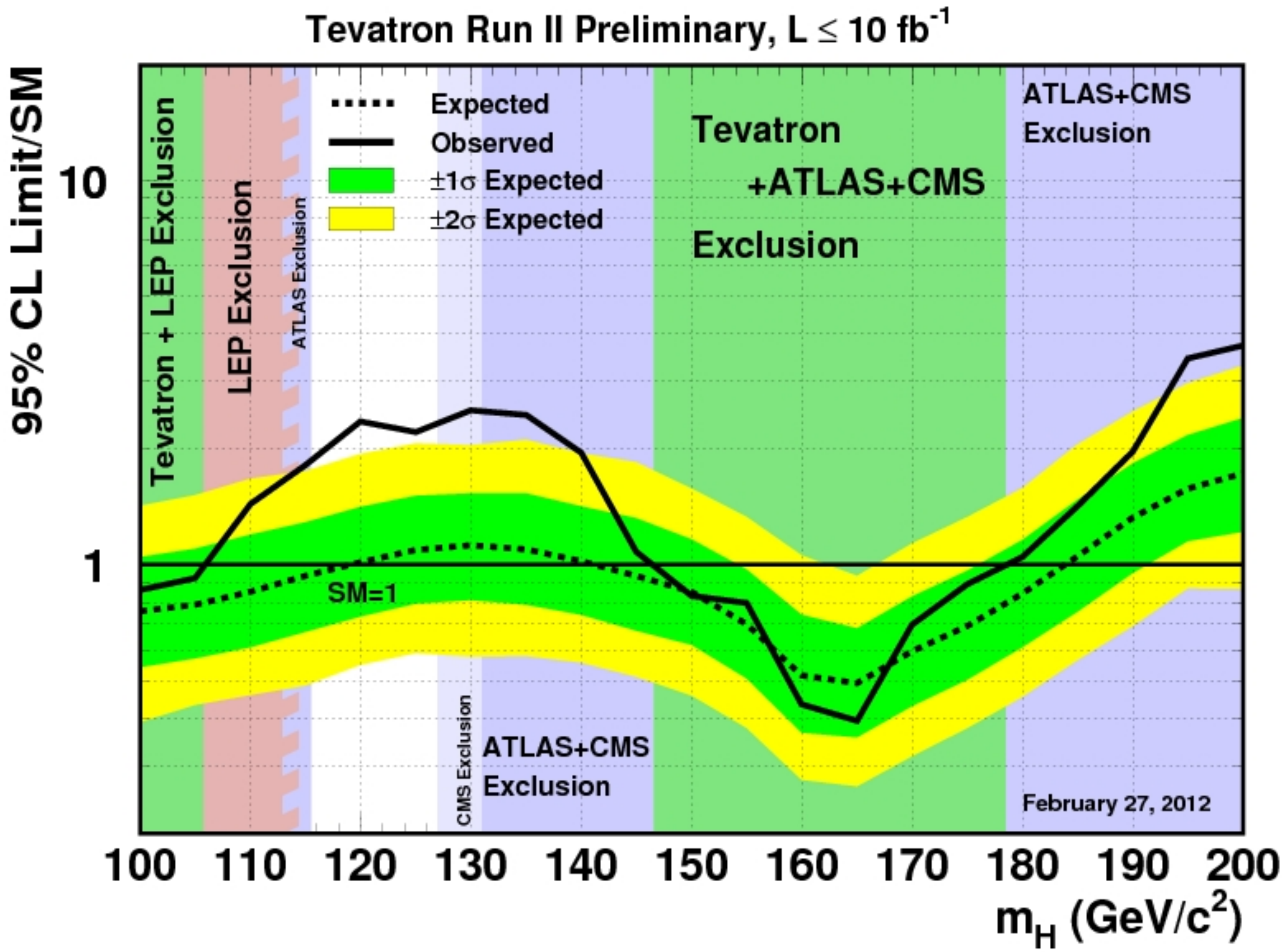




Excesses driven mainly by $H \rightarrow \gamma\gamma$ final state

Current Tevatron Limits



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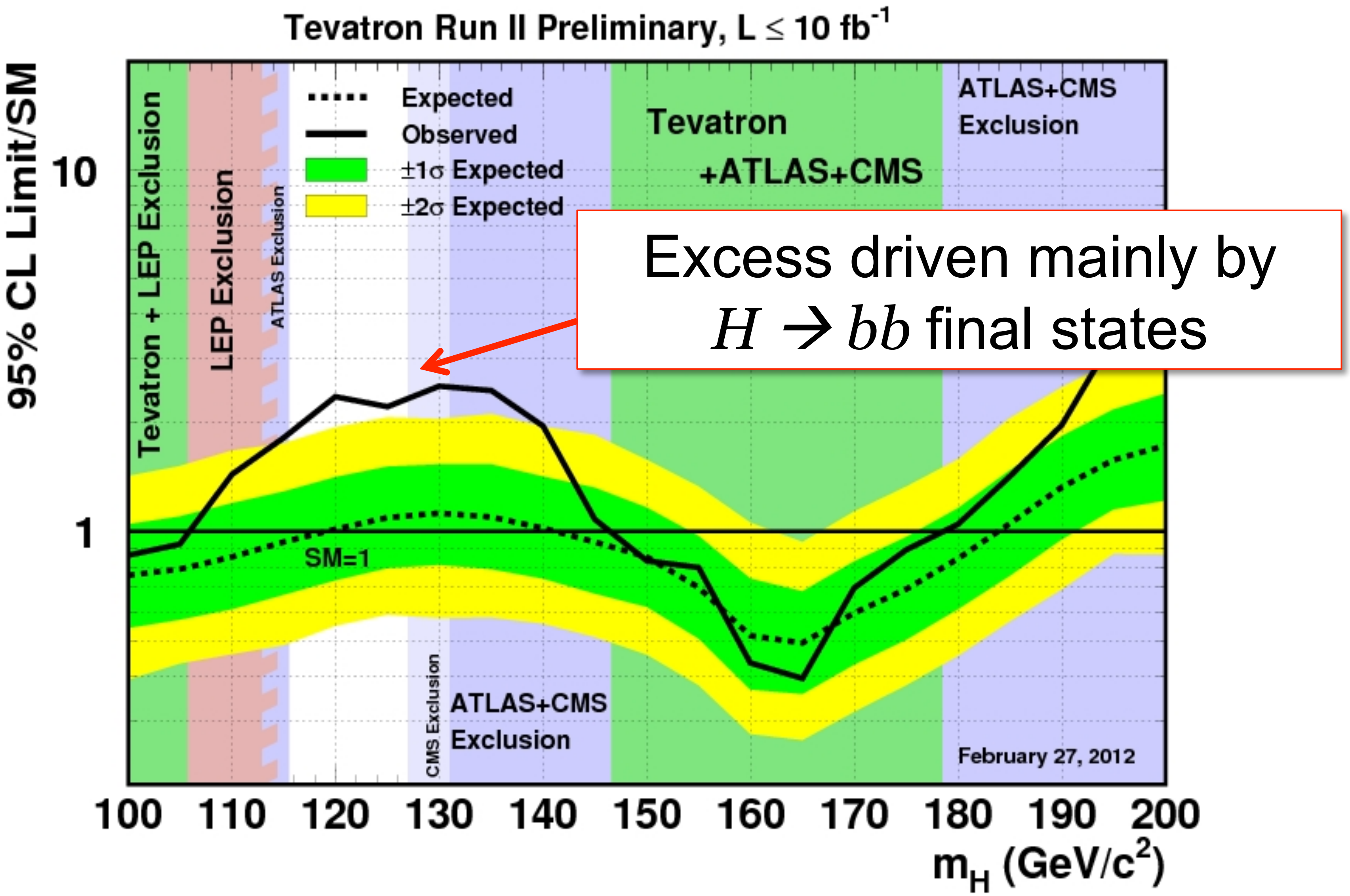
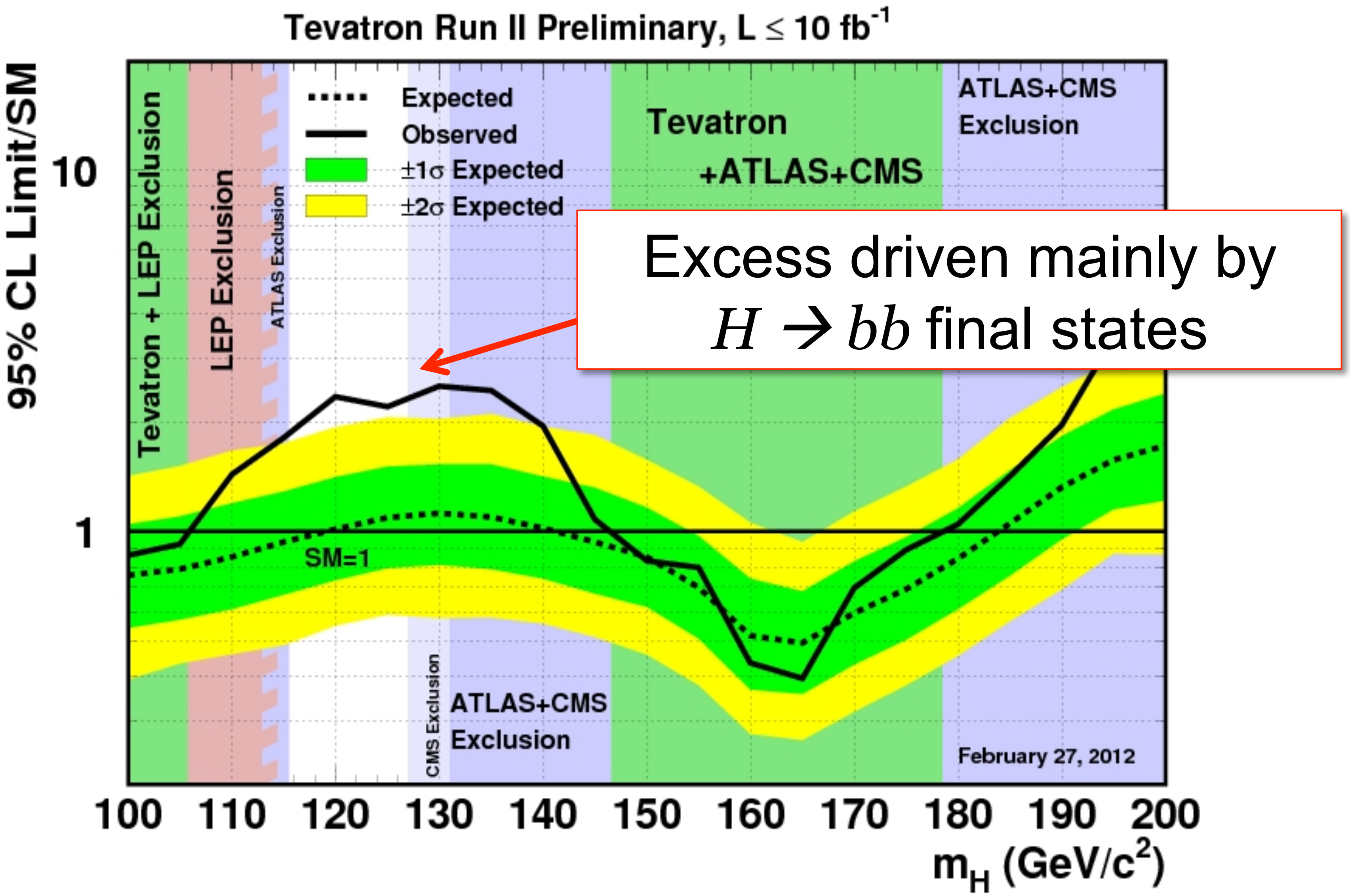
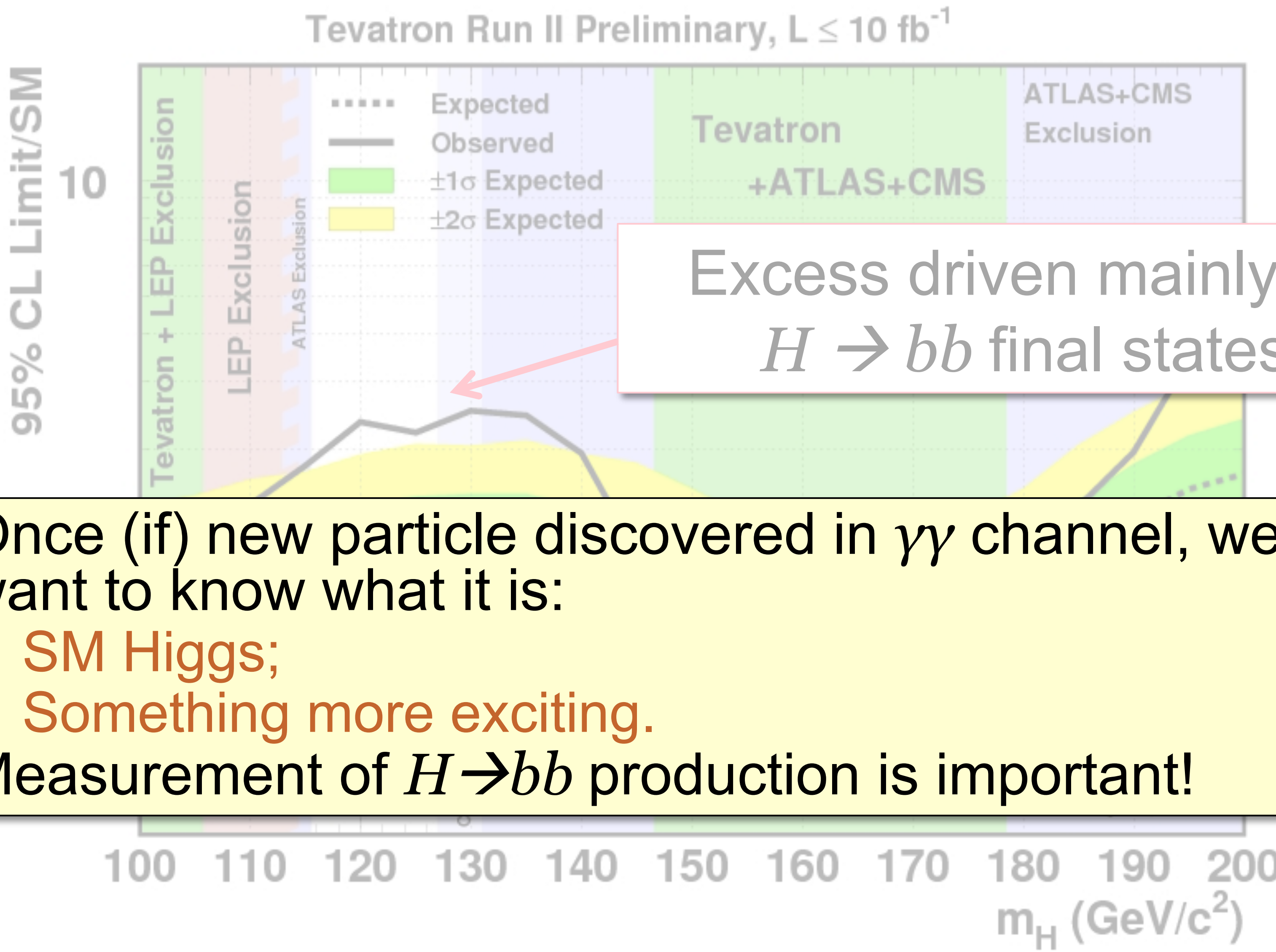


Current Tevatron Limits



- LHC and Tevatron searches are complementary!

Current Tevatron Limits

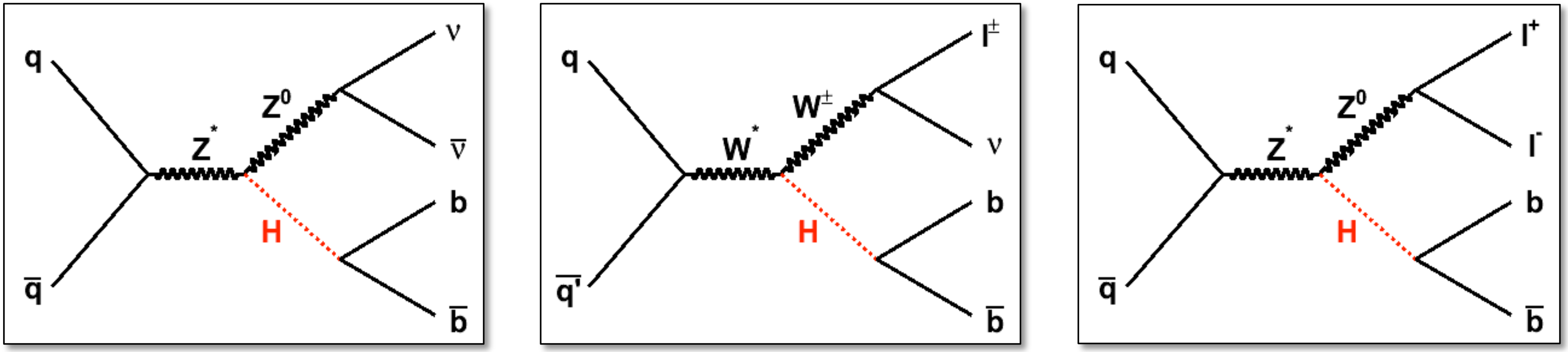


Excess driven mainly by $H \to bb$ final states

- Once (if) new particle discovered in $\gamma\gamma$ channel, we will want to know what it is:
  - SM Higgs;
  - Something more exciting.
- Measurement of $H \to bb$ production is important!

- LHC and Tevatron searches are complementary!

Searching for an $H \rightarrow bb$ Signal

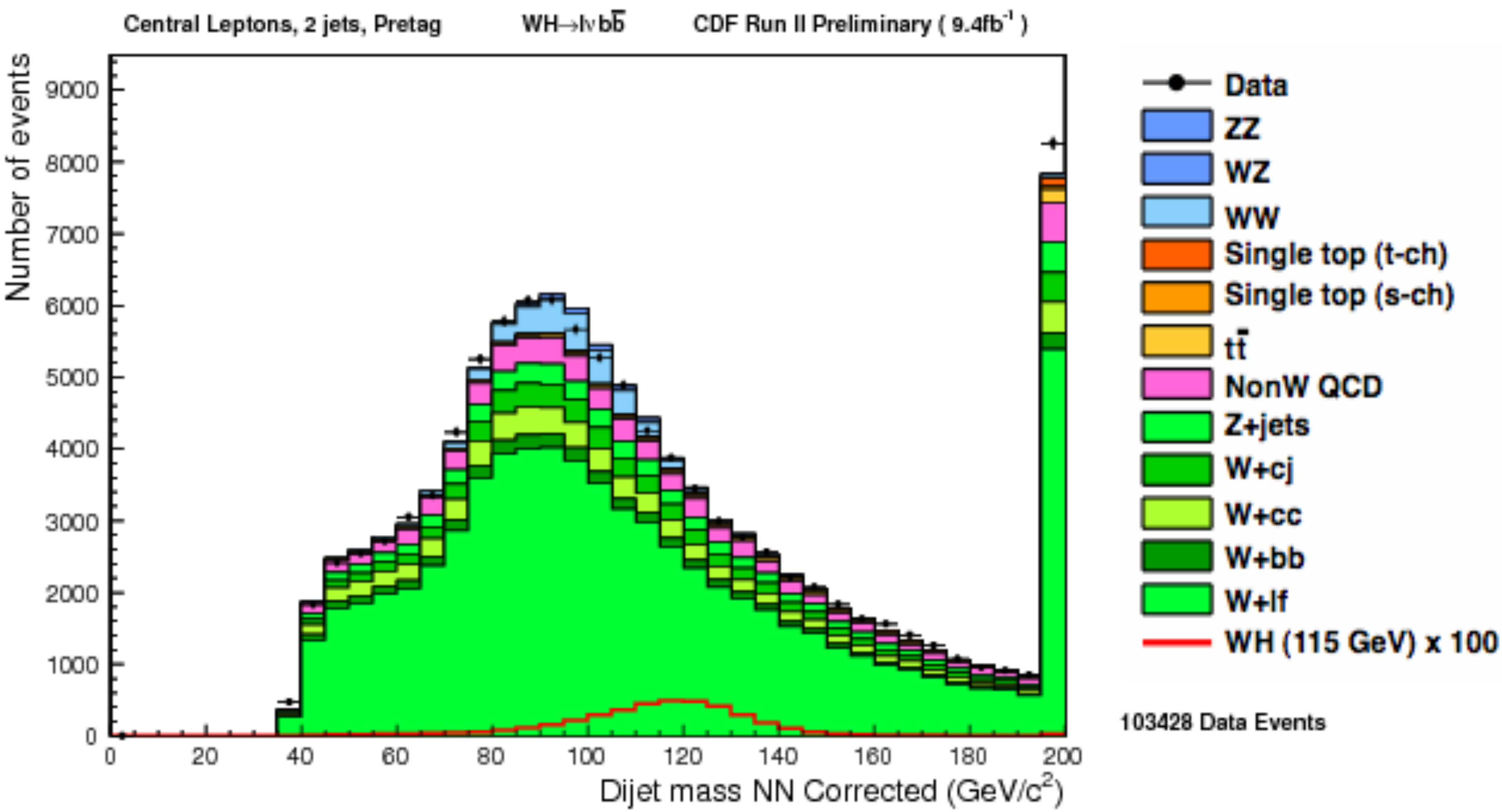


Analysis	No. of Leptons	Missing E_T ?	No. of b-Jets
$ZH \rightarrow \nu\bar{\nu} + b\bar{b}$	0	Yes	2
$WH \rightarrow \ell\nu + b\bar{b}$	1	Yes	2
$ZH \rightarrow \ell^+\ell^- + b\bar{b}$	2	No	2

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

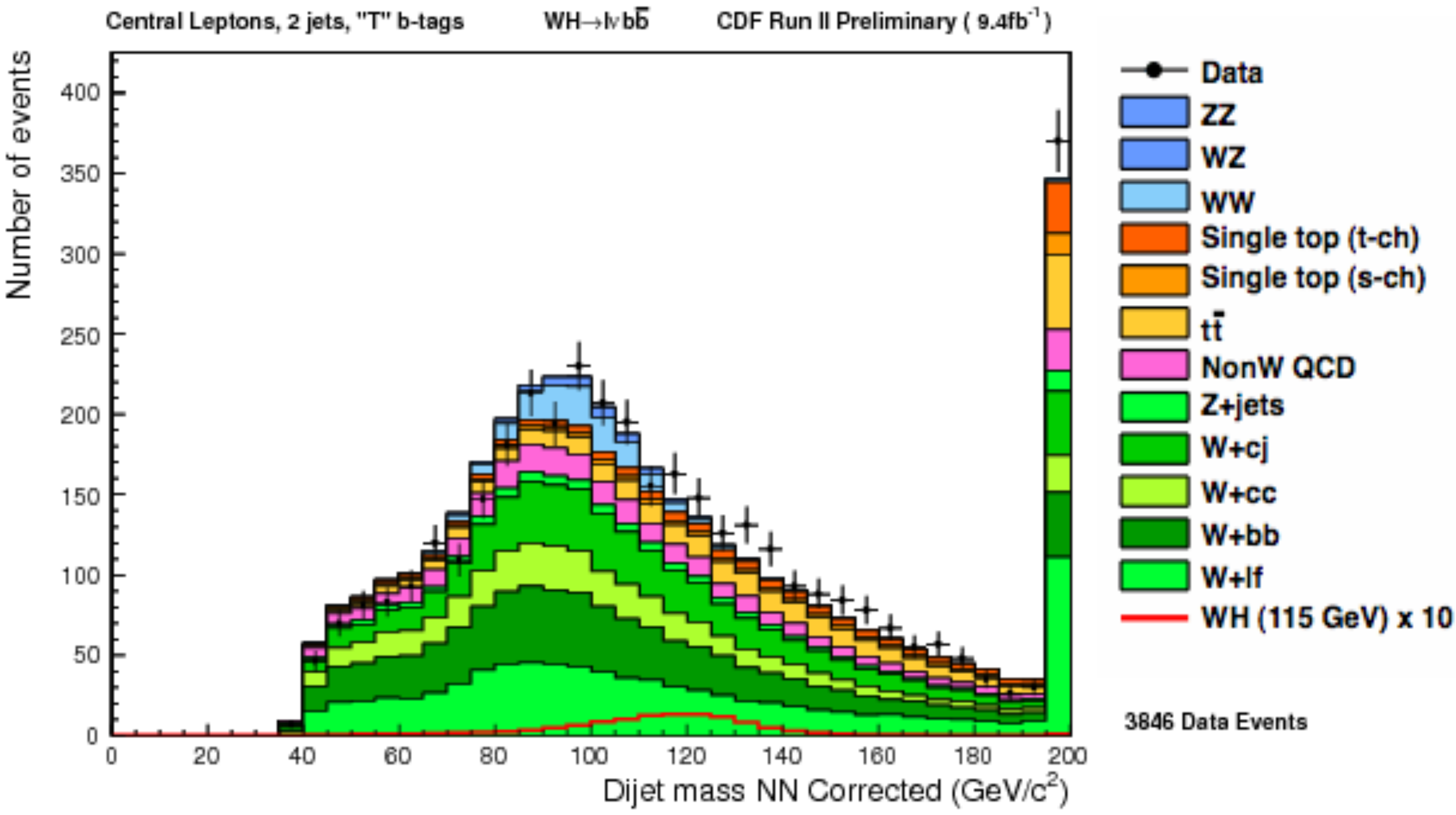
Why *b*-tagging?

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



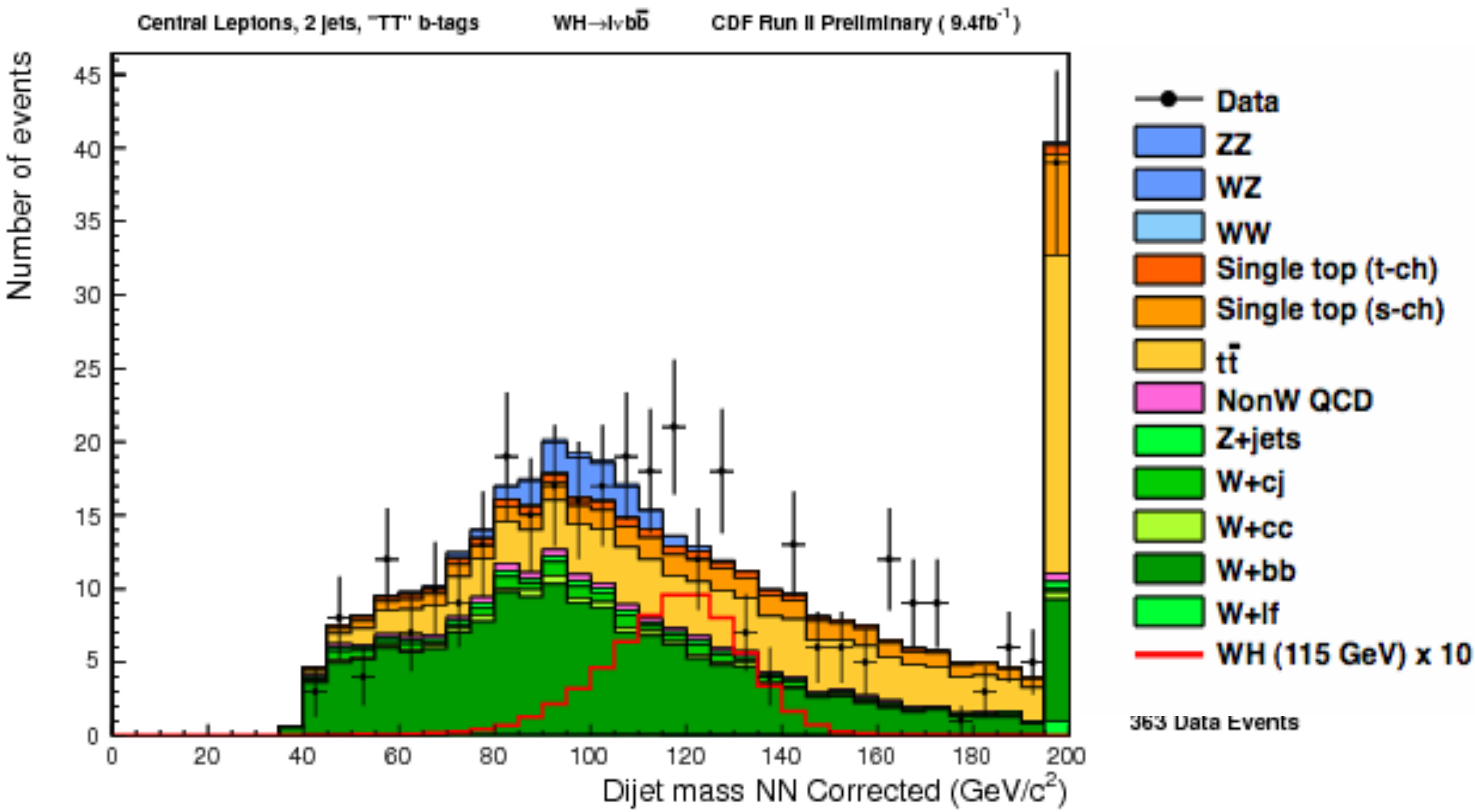
Why *b*-tagging?

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



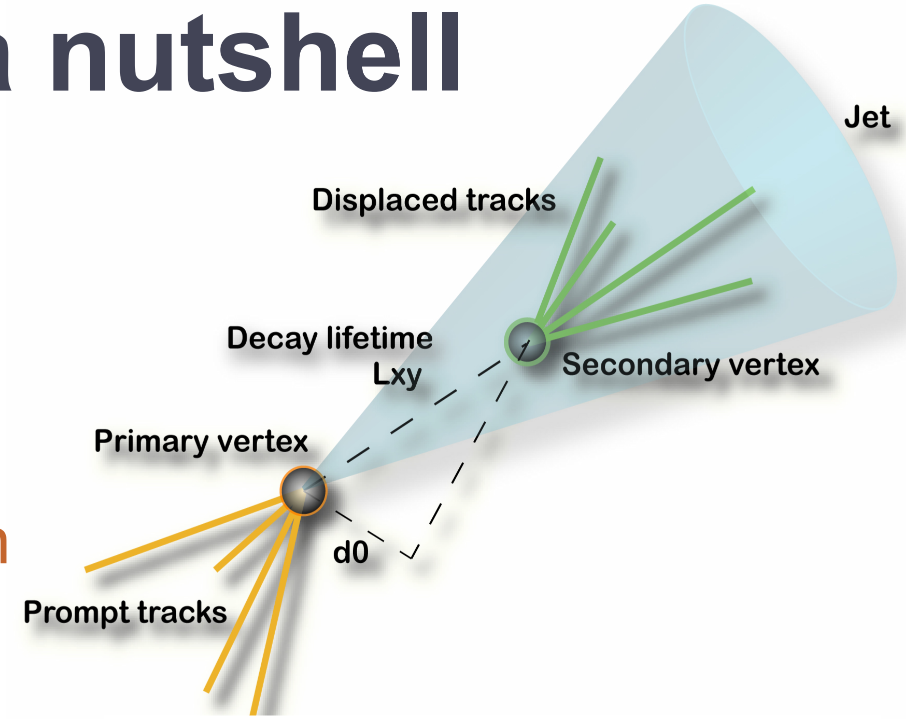
Why *b*-tagging?

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

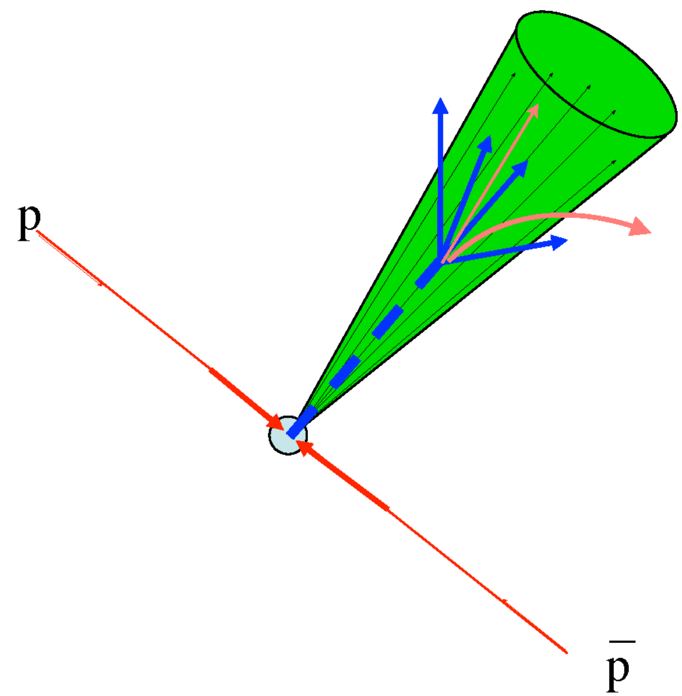


b-tagging in a nutshell

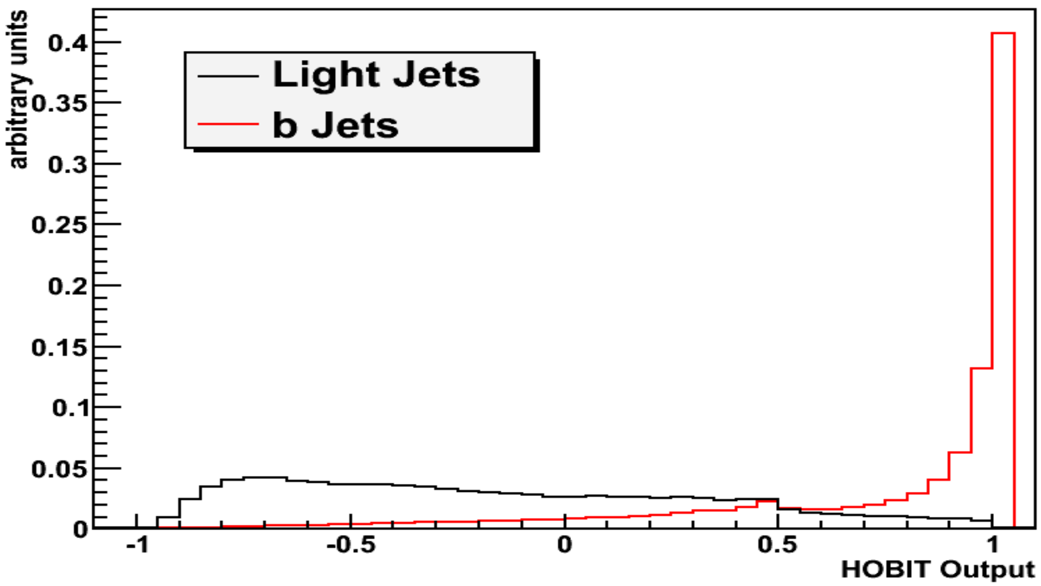
- *b*-quarks are heavy and long-lived!
  - Displaced vertex (L_{xy}, d_0)
  - Large jet mass
  - Wide distribution of tracks within the jet
  - etc.



- Various methods using these features to identify *b*-jets.
  - Using impact parameters of jet tracks (JetProb)
  - Reconstructing secondary vertices (SV)
  - Multivariate techniques (many!)

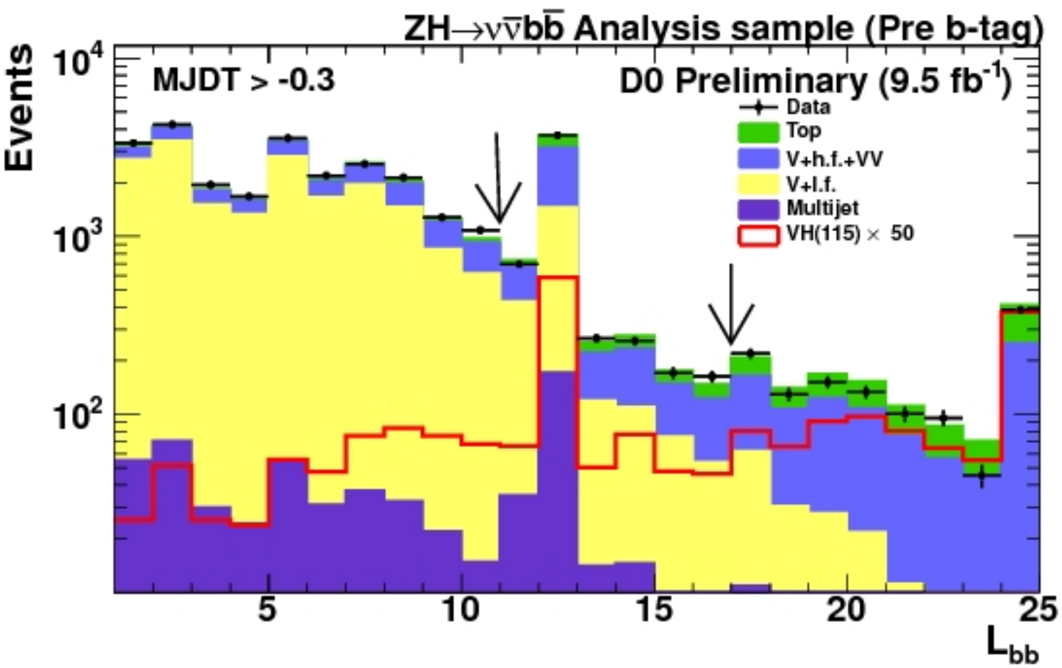


b-tagging at the Tevatron



- CDF – HOBIT NN

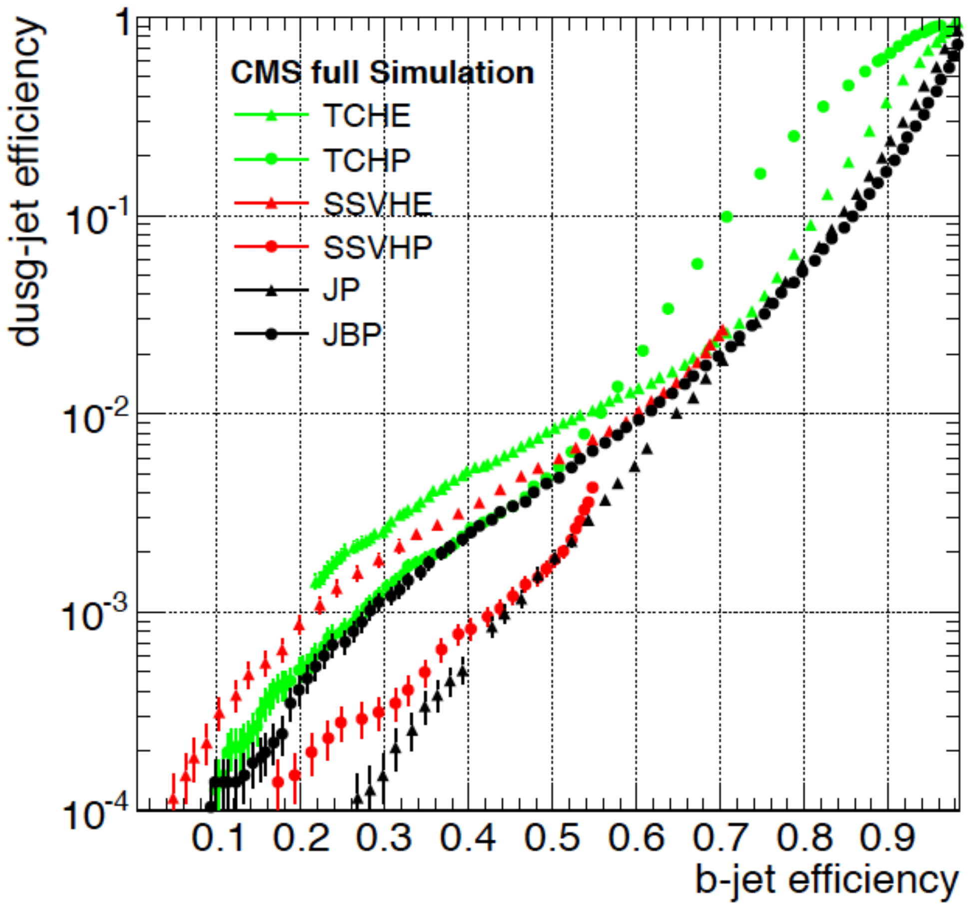
	Tag Efficiency
B-jets	54 – 59%
LF jets	1 – 2%

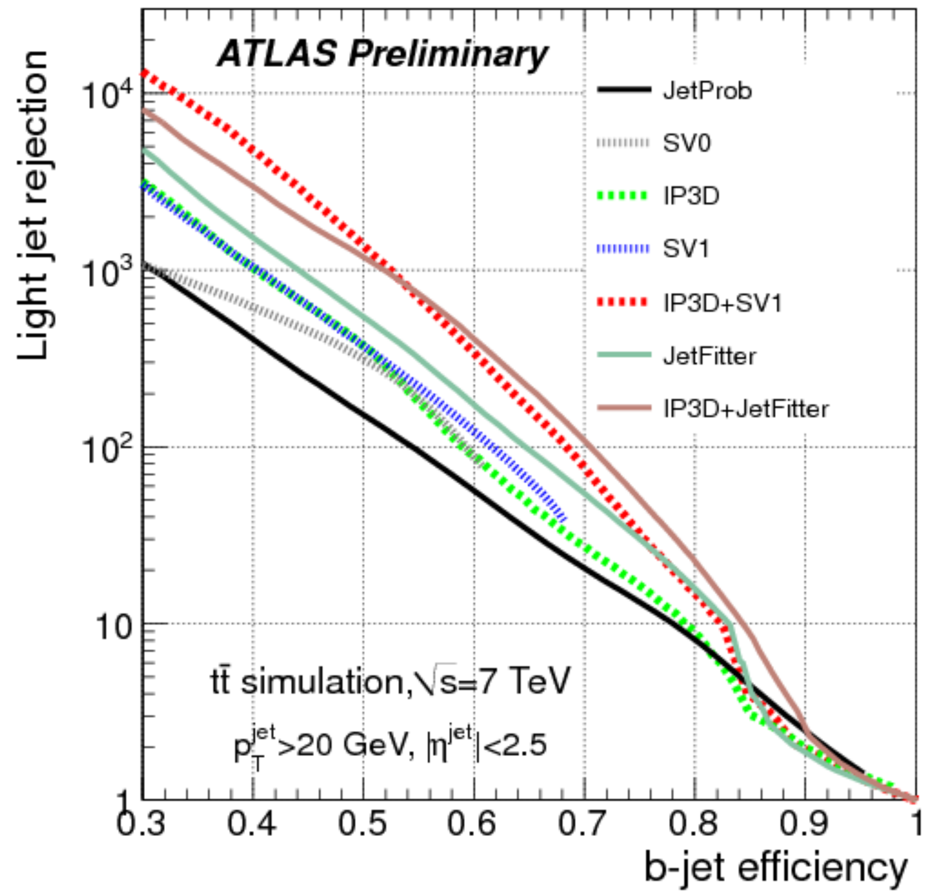


- D0 – L_b BDT

	Tag Efficiency
B-jets	50 – 70%
LF jets	0.5 – 4.5%

b-tagging at the LHC



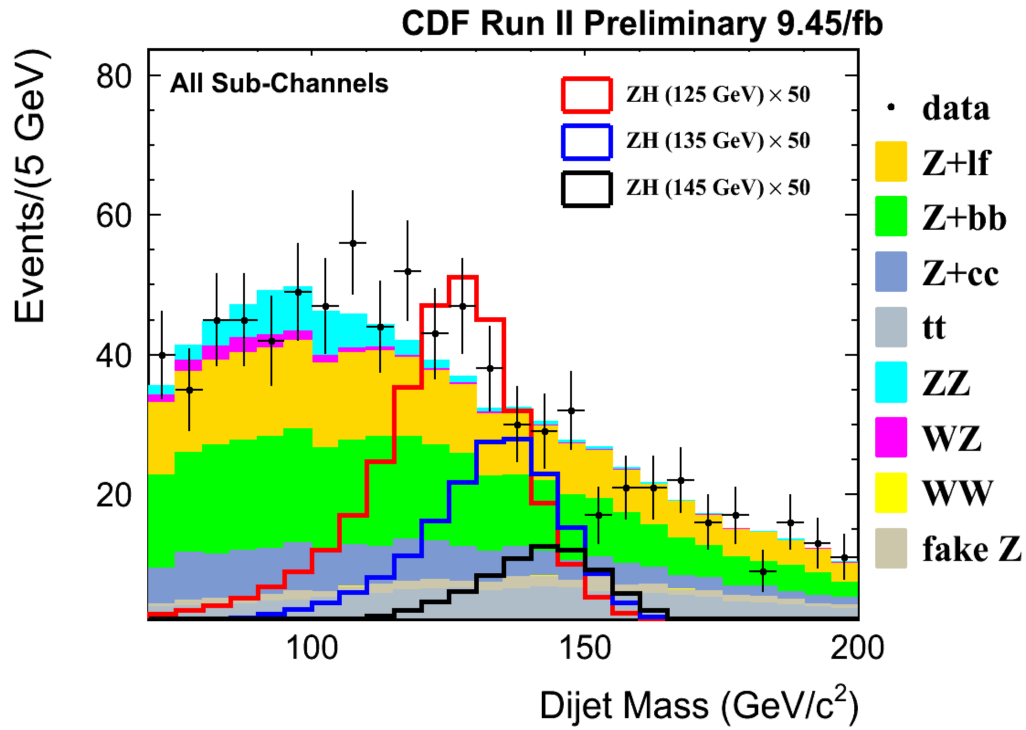


CMS	Tag Efficiency
B-jets	**50%**
LF jets	**0.2 – 0.8 %**

ATLAS	Tag Efficiency
B-jets	**50%**
LF jets	**0.1 – 0.9 %**

Improved Mass Resolution

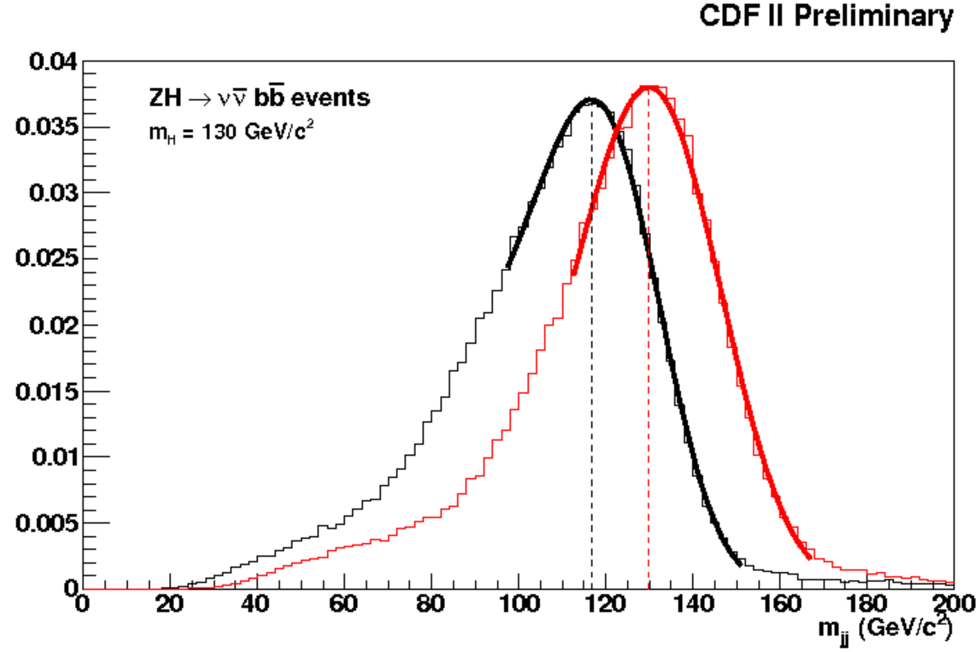
- Shape of m_{jj}
  - Higgs signal: *peaking*
  - Dibosons: *peaking*
  - Others: *falling*

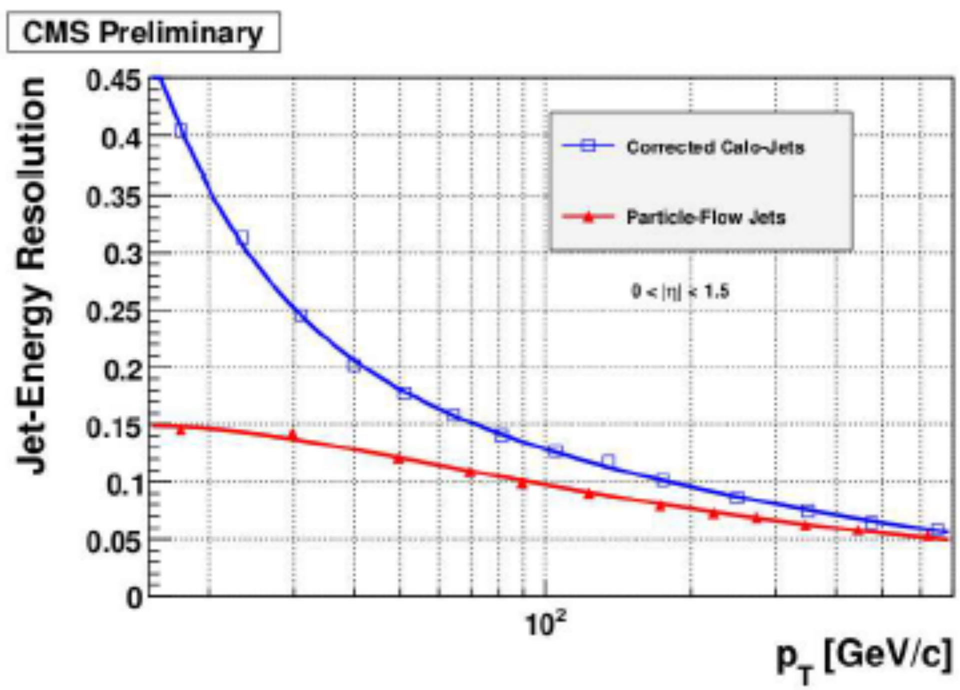


- Mis-measured energy means smeared out m_{jj}:
  - Missed detectable particles (lost through cracks)
  - Splash-in / Splash-out effects
  - Muons (minimum-ionizing)
  - Neutrinos (undetectable but possibly inferrable)

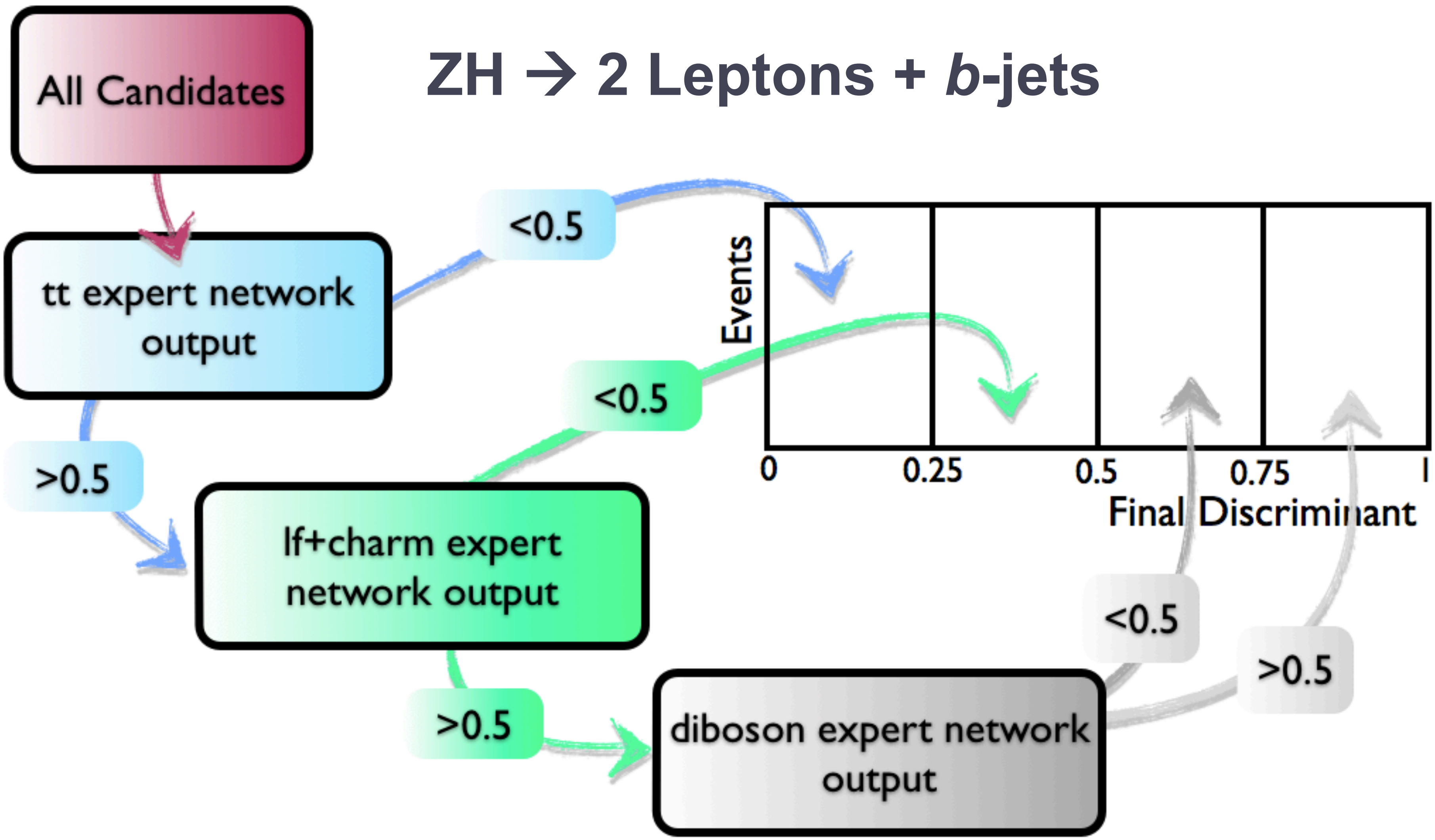
Improved Mass Resolution

- Various methods to correct for this:
  - Correct calorimeter energies based on track momenta
  - Neural-network based approaches (Tevatron)
  - Particle Flow Algorithm (Richard Cavanaugh):
    - Reconstruct every particle, but avoid double-counting
    - Can improve JER to 10% or better
- Improved JER also means improves MET.





Separation of Signal and Background



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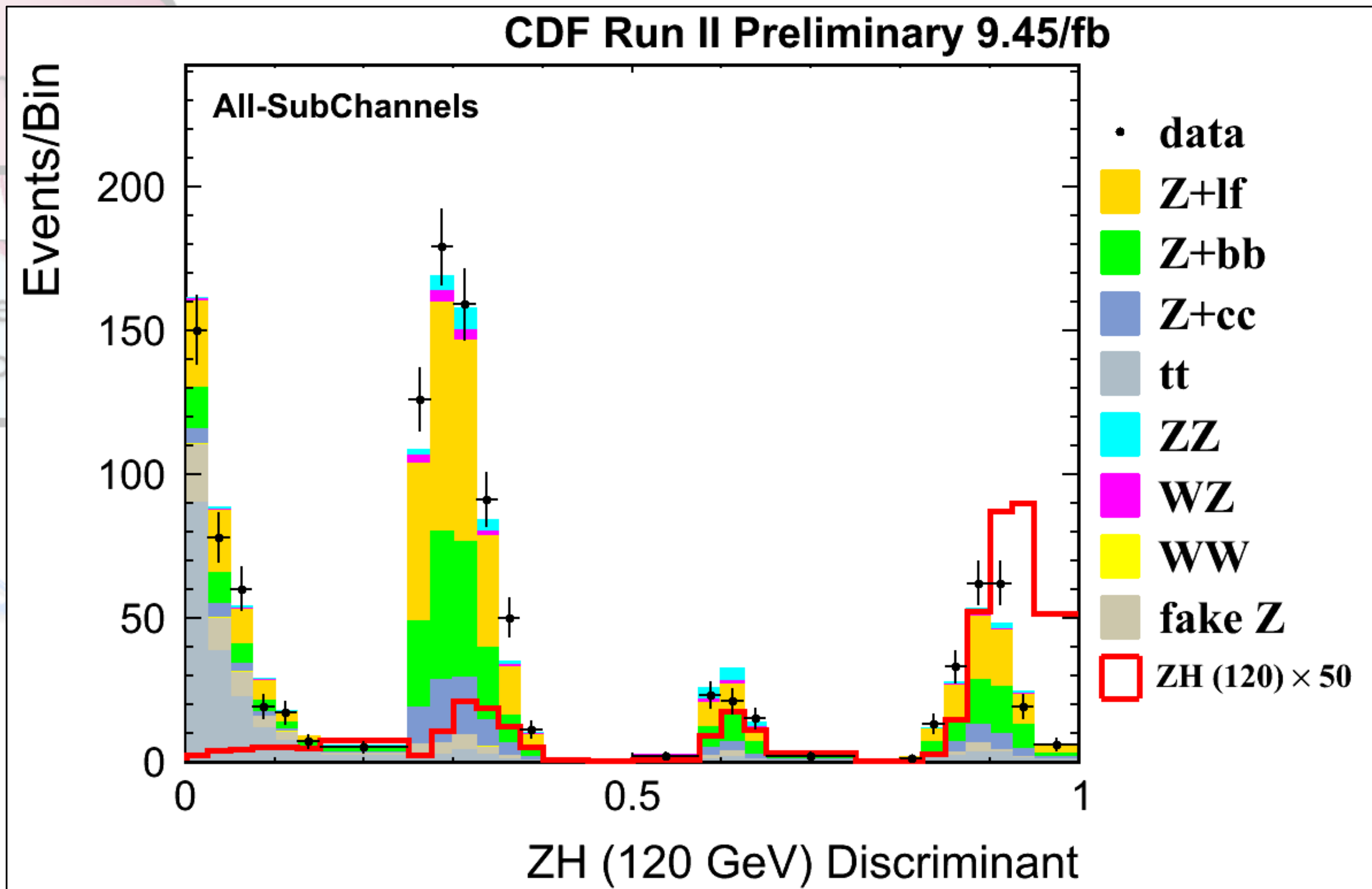

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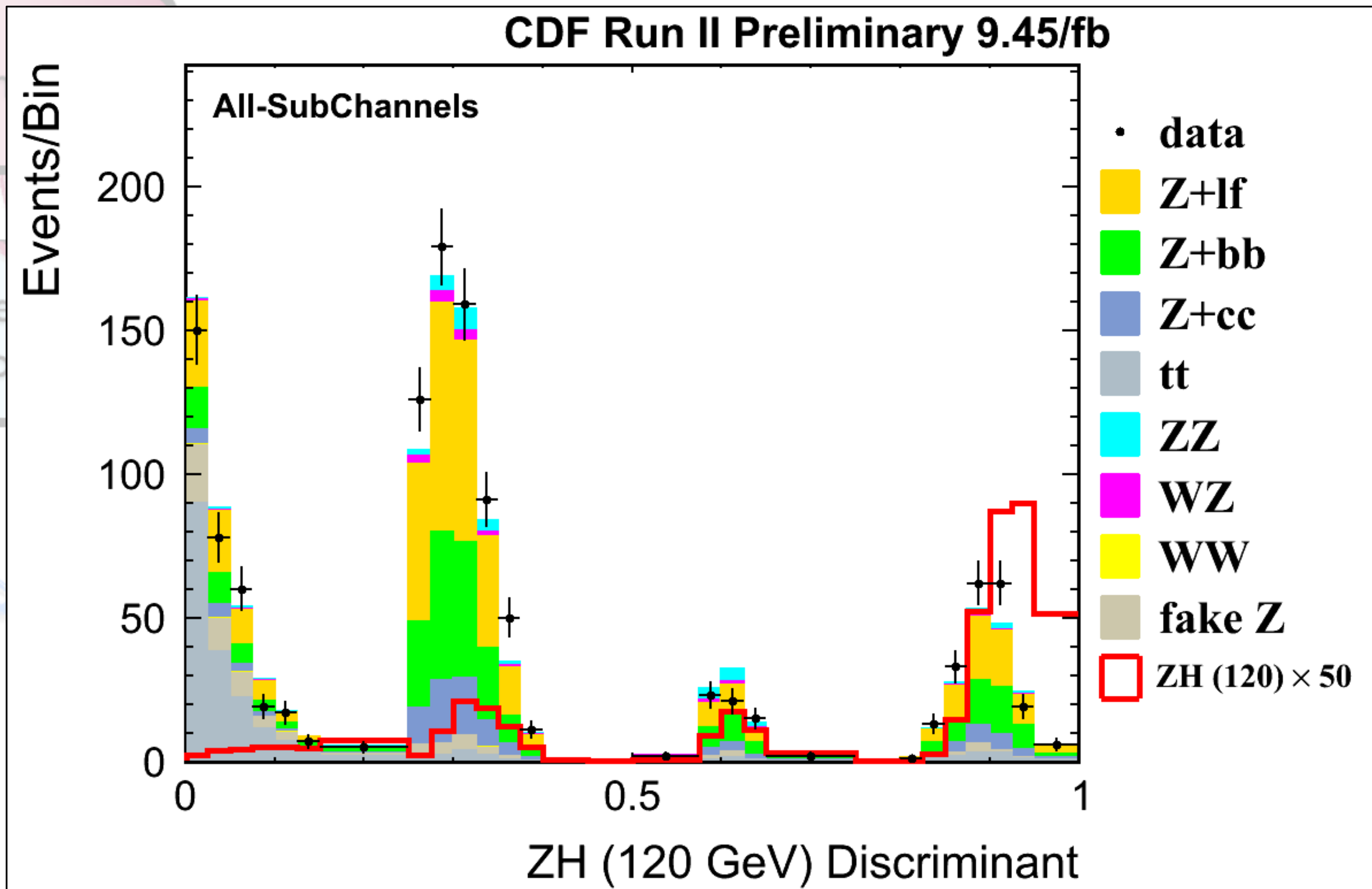
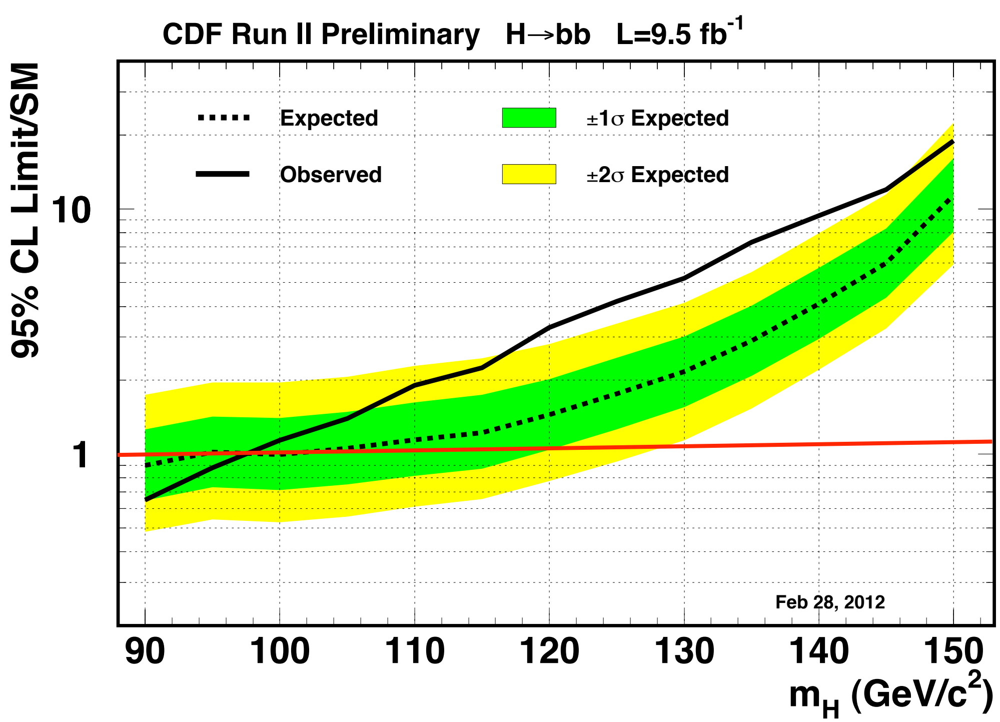
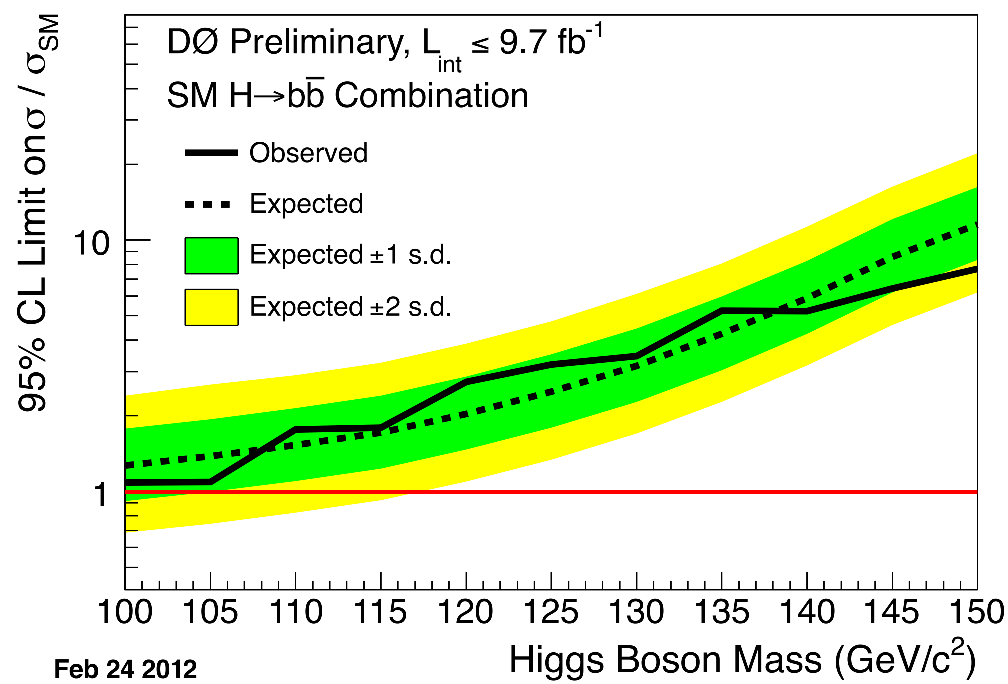


Combine final discriminants from all bb channels.

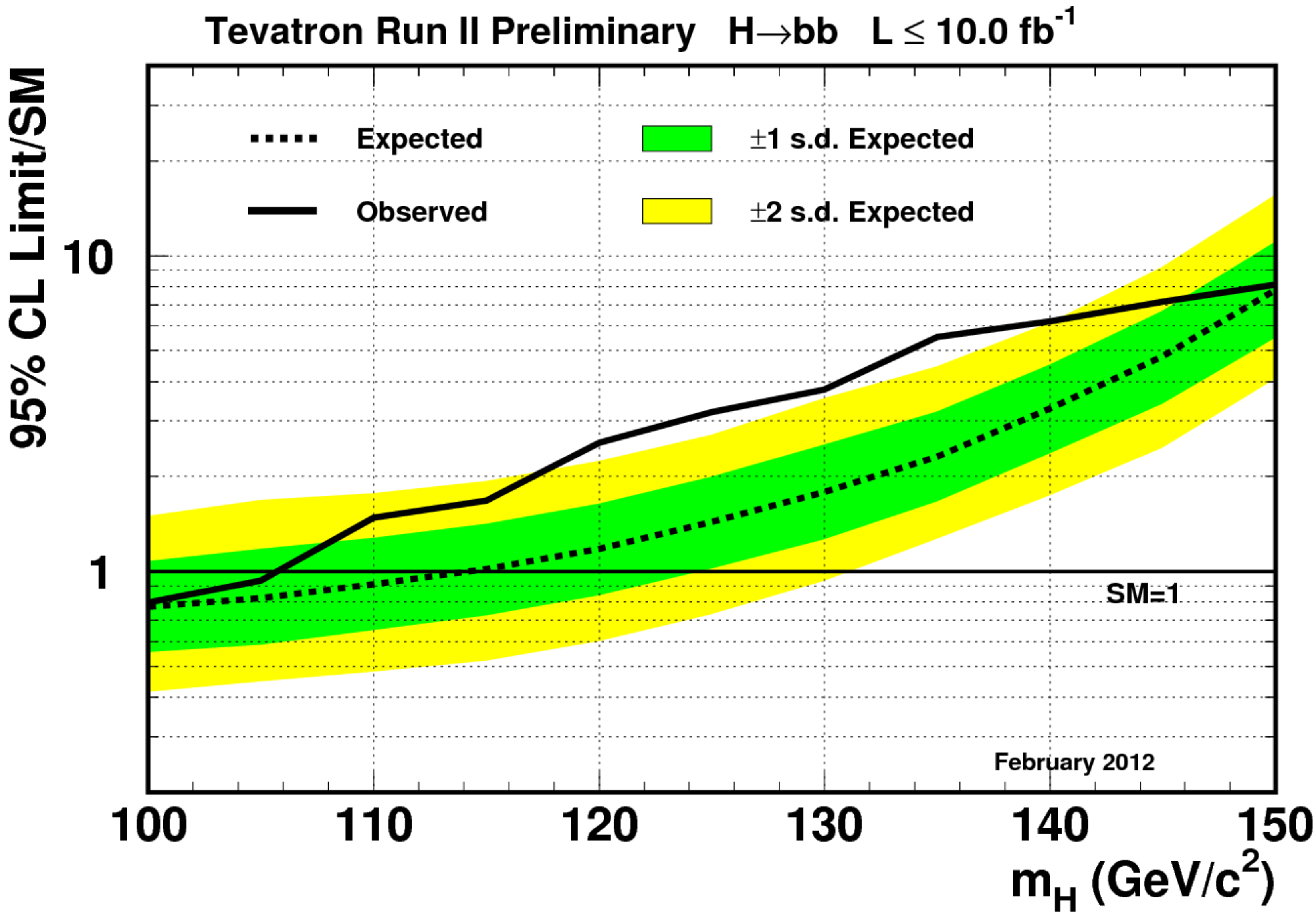
Limits on $H \rightarrow bb$

Low-Mass Analyses	Sensitivity (m_H = 120 GeV)	
	CDF [SM]	D0 [SM]
$WH \rightarrow \ell\nu + b\bar{b}$	2.0	3.2
$ZH \rightarrow \nu\bar{\nu} + b\bar{b}$	2.7	3.0
$ZH \rightarrow \ell^+\ell^- + b\bar{b}$	2.6	4.2

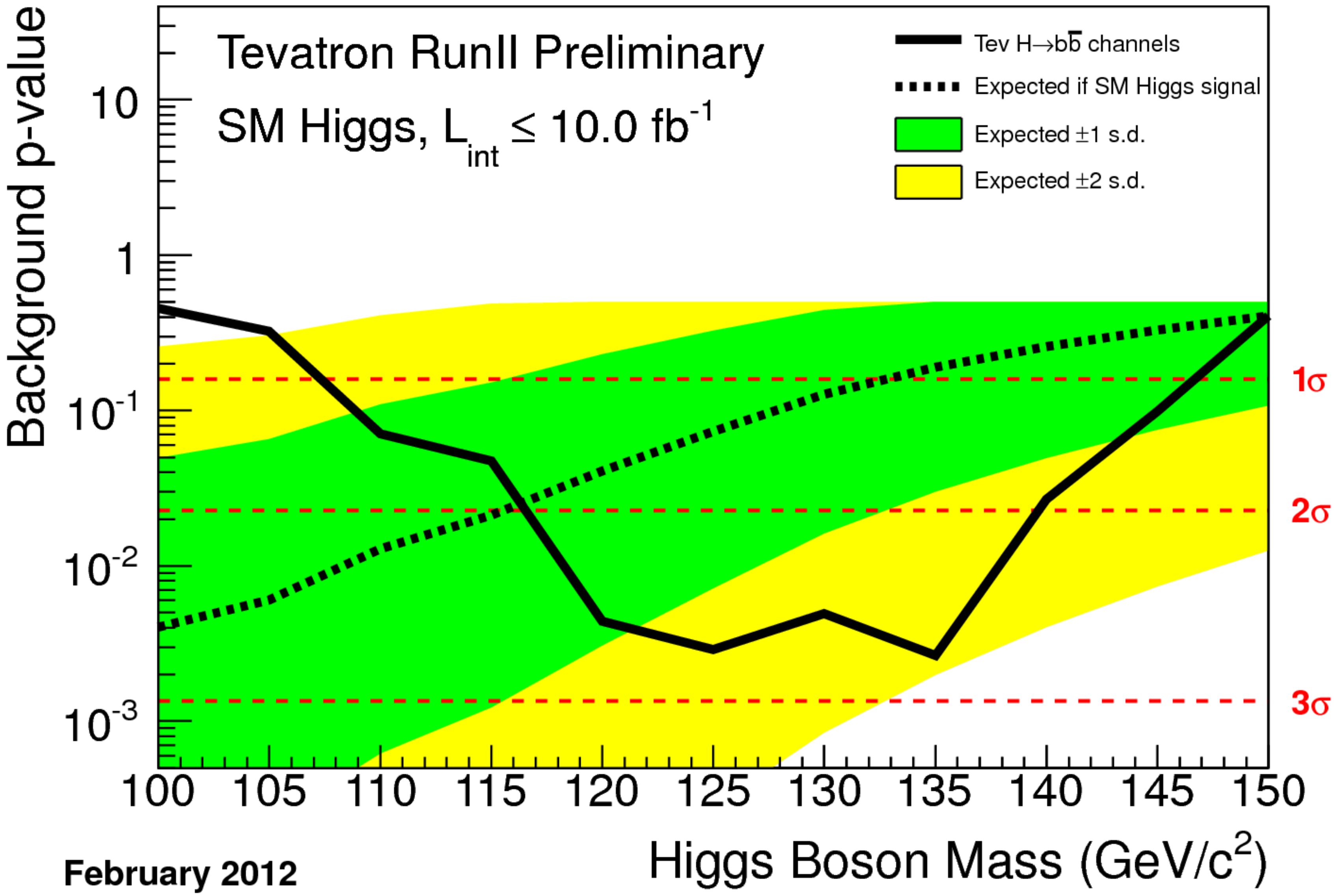




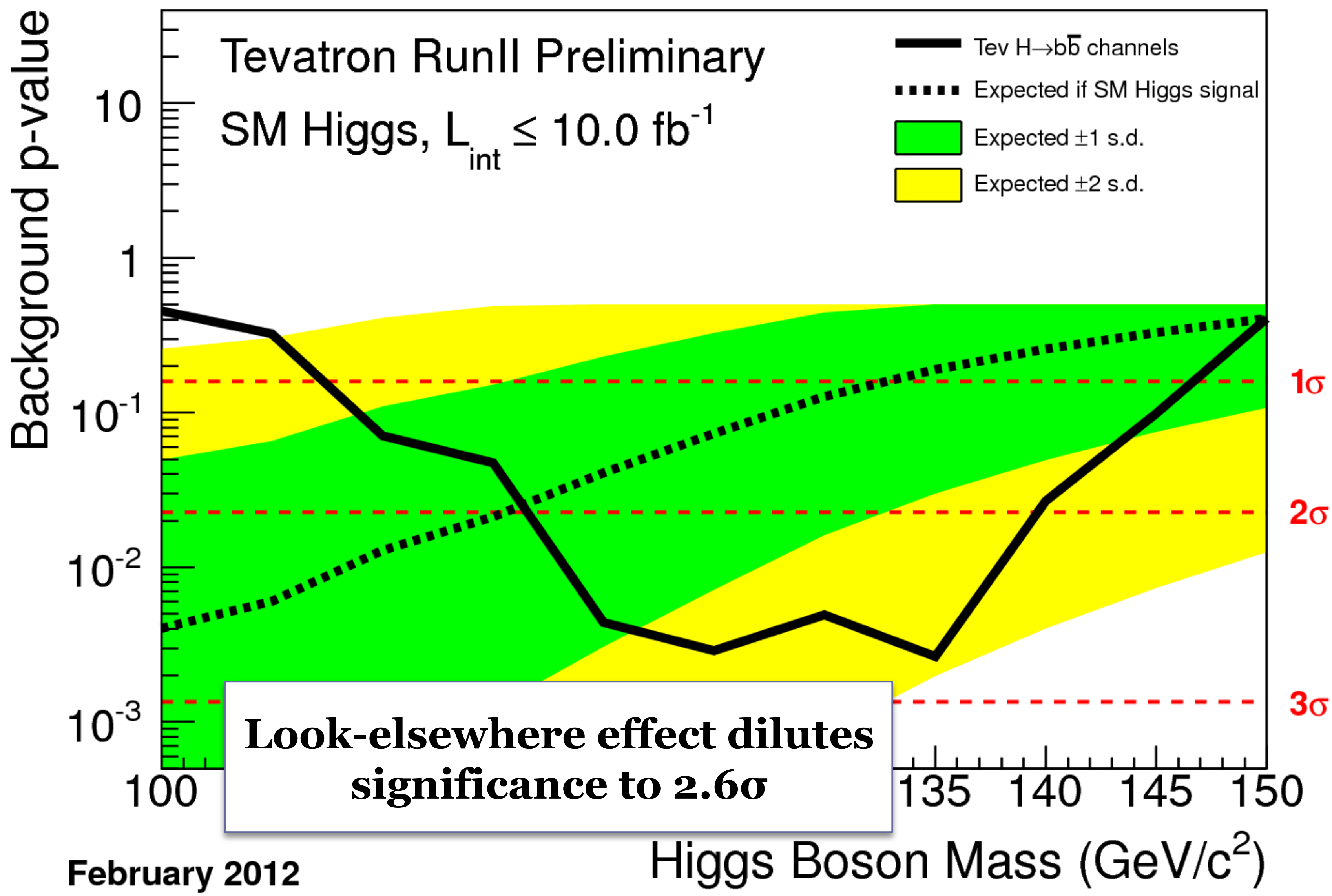
$H \rightarrow bb$ Limits for Tevatron Combination



H→ *bb* *p*-value of Tevatron Combination

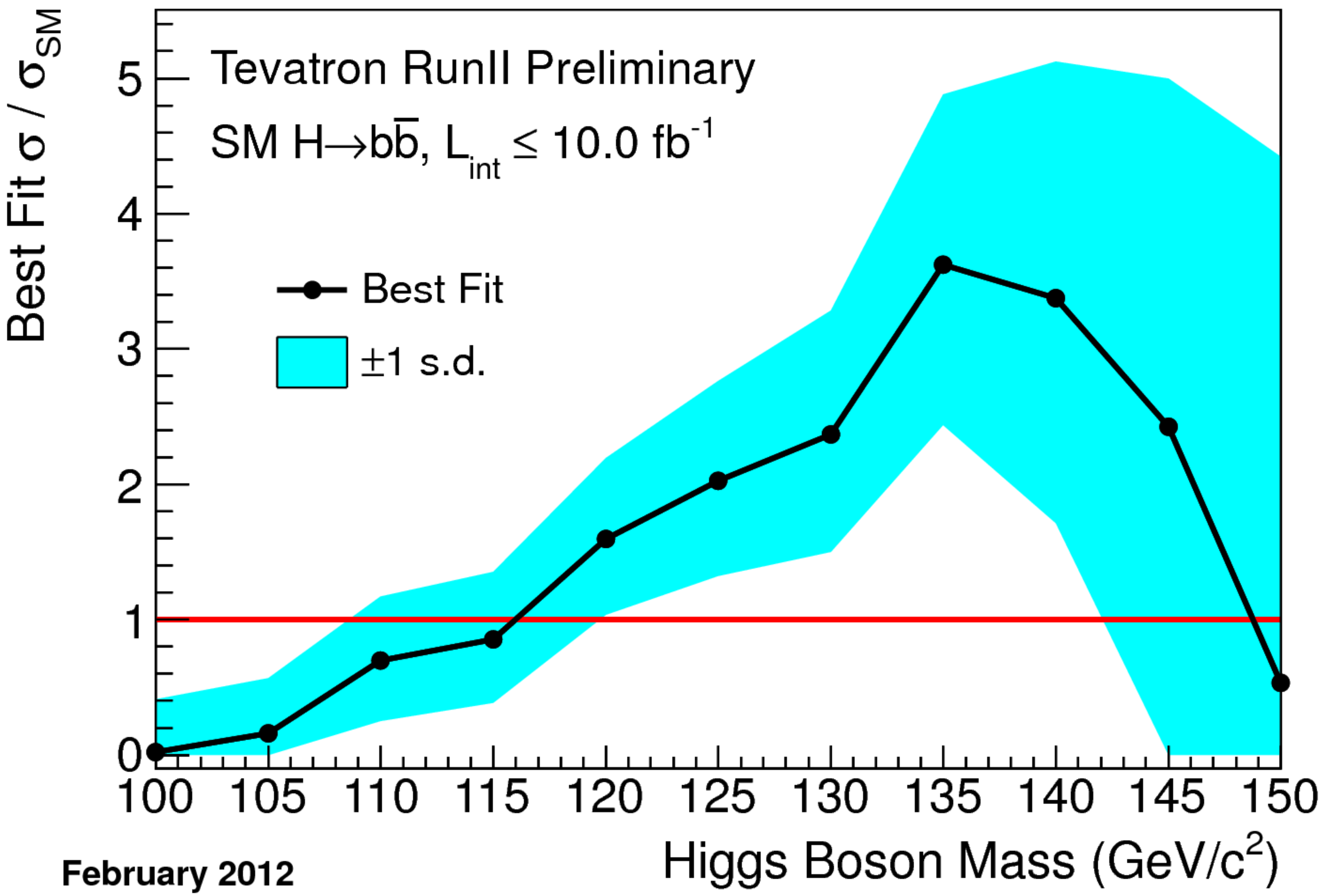


$H \rightarrow bb$ *p*-value of Tevatron Combination



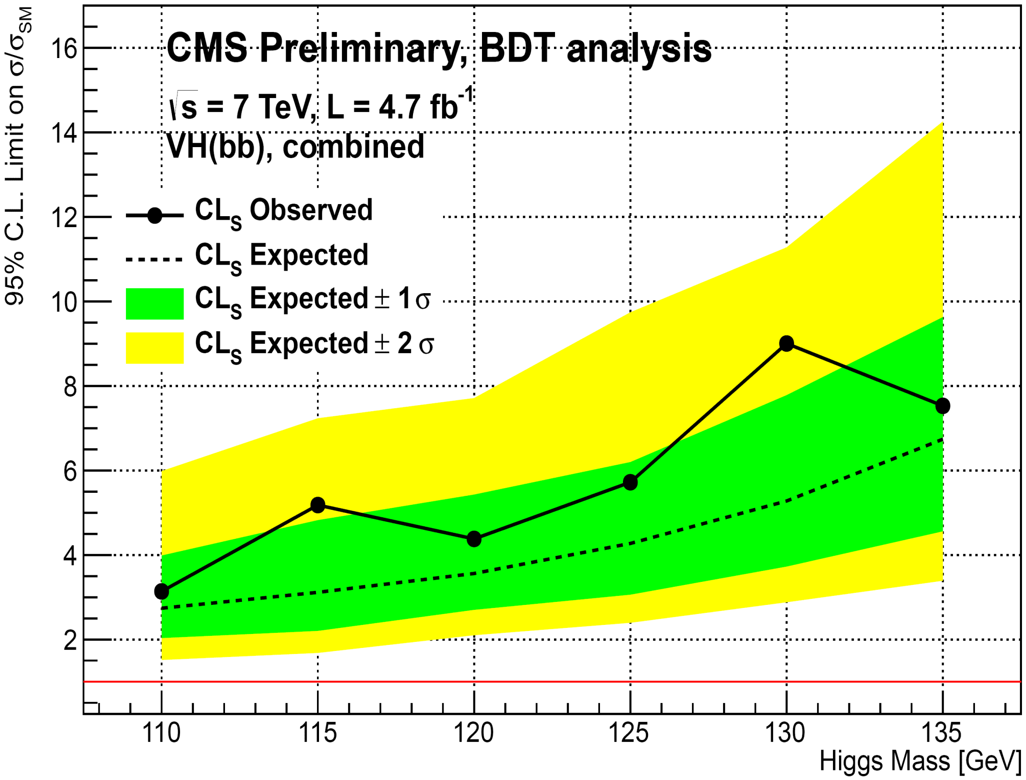
February 2012

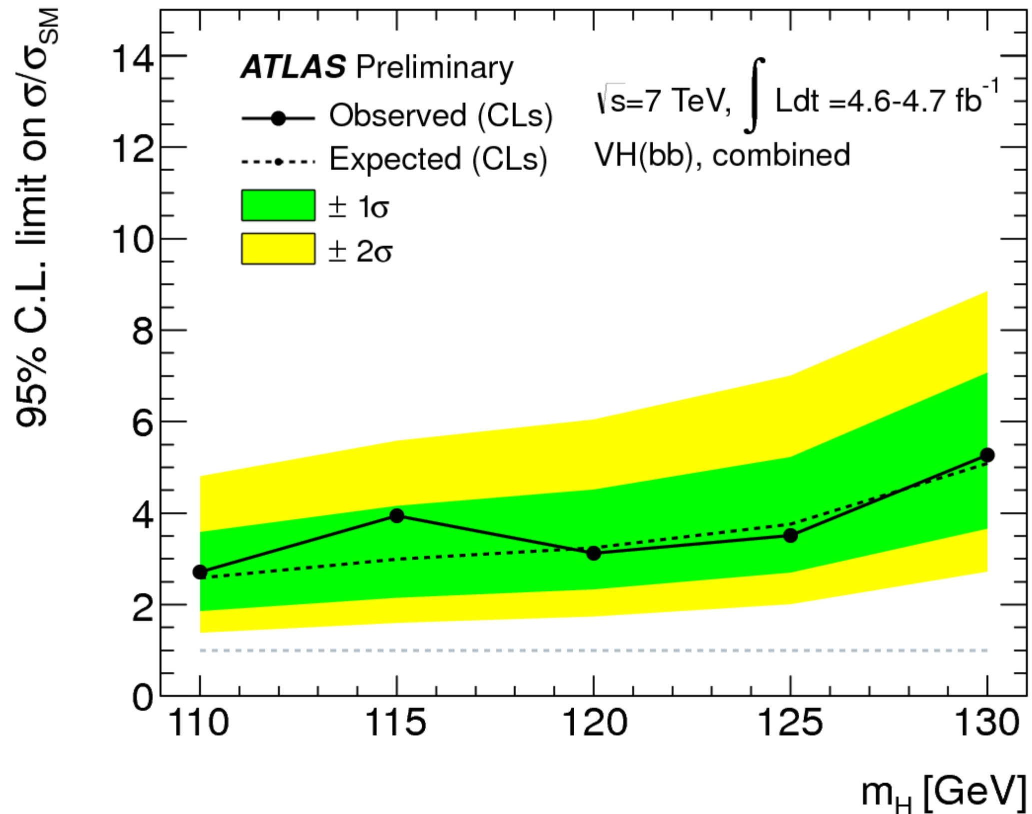
Best $\sigma_H \times \mathcal{B}(H \to bb)$ Fit Value



February 2012

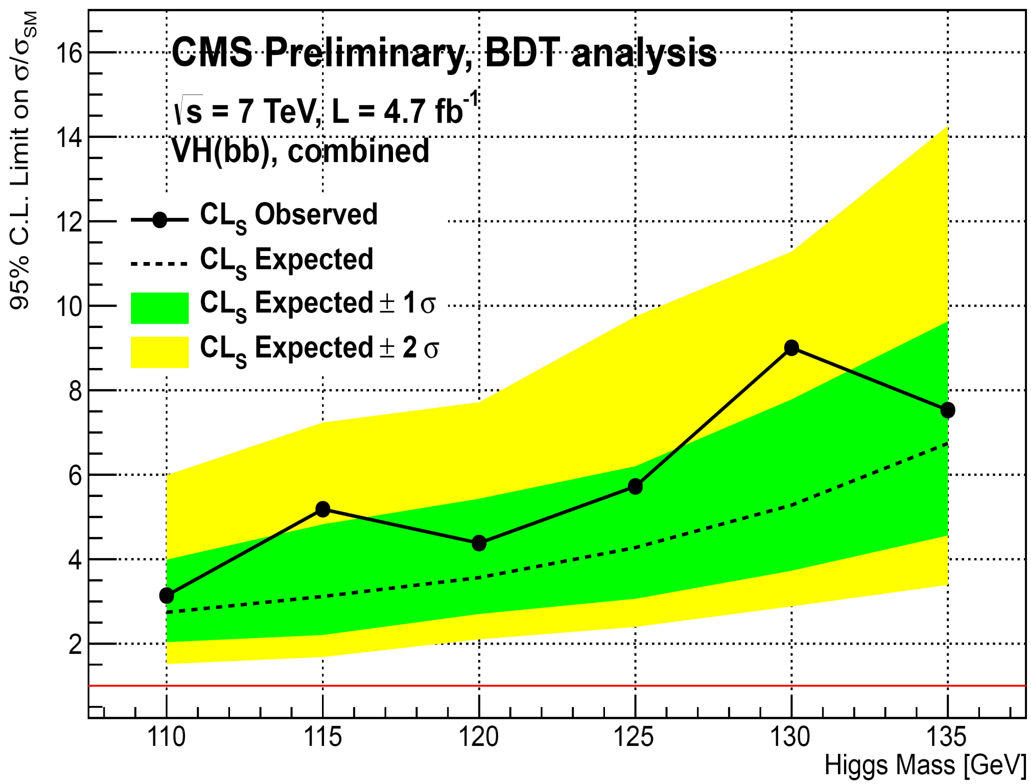
LHC $H \rightarrow bb$ Results

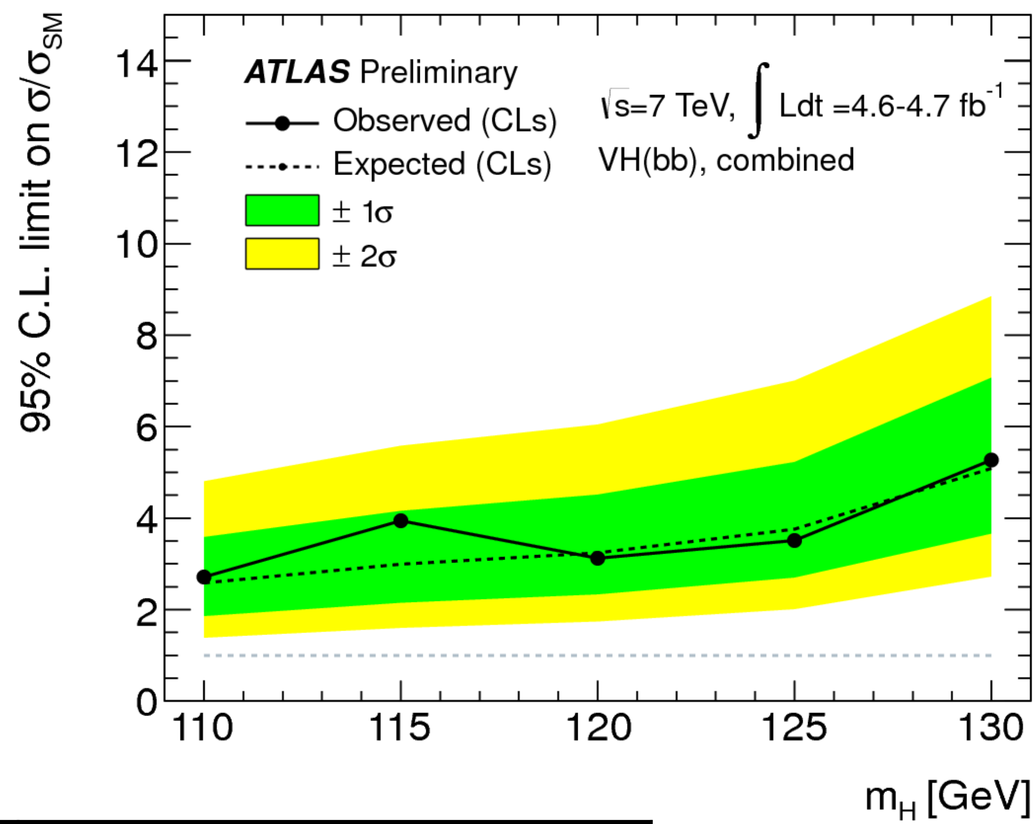




Sensitivites	Expected Sensitivity m_H = 120 GeV / c^2
Tevatron Experiments	1.5 x SM
LHC Experiments	3.0 x SM

LHC $H \rightarrow bb$ Results





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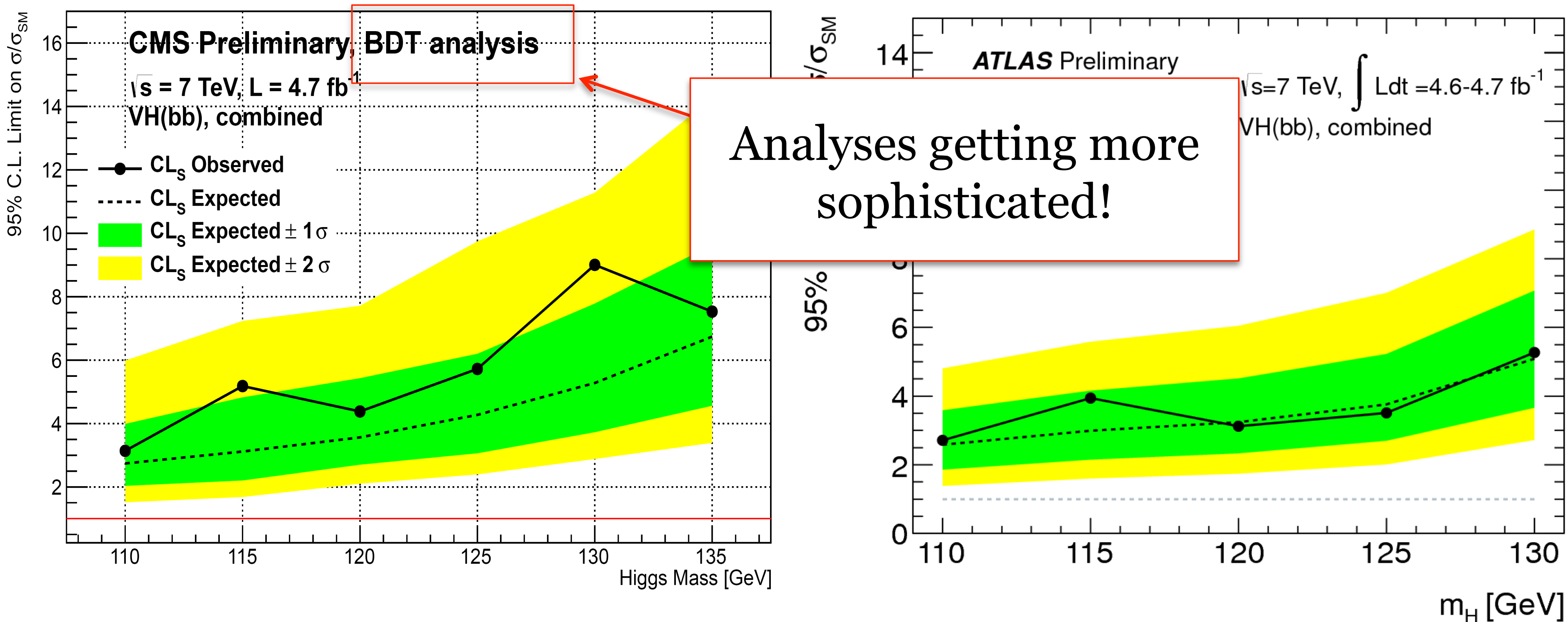

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LHC Experiments	**3.0 x SM**

- LHC results will be competitive with Tevatron after an ***equivalent*** increase in luminosity of 4 x Moriond dataset

New Analysis Techniques at the LHC

- Moving to MVA discriminant-based analyses

- Jet substructure techniques
  - To overcome sizeable backgrounds from many multiple interactions, high P_T requirements made on $H \rightarrow bb$ candidate dijet system
  - Can result in highly-boosted dijet reference frames—i.e. difficult to resolve both *b*-jets
  - New jet substructure techniques introduced to address this issue

(See Monday's "Jet Substructure" session)

Outlook and Summary of $H \rightarrow bb$

- Tevatron
  - Combinations update / publication planned for summer
  - CDF: MET + bb analysis improvements
  - D0: Updates expected across the board
- LHC
  - Jet substructure techniques to increase Higgs acceptance
  - Improved analysis techniques – MVAs
  - *A lot* more data by the end of the year
- Why H→ bb?
  - Orthogonal search channel to $H \rightarrow WW / ZZ / \gamma\gamma$ final states
  - Once (if) Higgs-like particle is discovered, important to find out what it is – measurement of $H \rightarrow bb$ production is important

Thank you

Links / References

- Tevatron Higgs Results:
  - http://tevnphwg.fnal.gov/results/SM_Higgs_Winter_12/index.html
- LHC Higgs Results:
  - https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIG
  - https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HiggsPublicResults
- B-tagging at the LHC:
  - CMS – arXiv:1205.5292
  - ATLAS – ATLAS-CONF-2011-102
- Particle Flow Algorithm at CMS:
  - CMS CR -2010/276

Back-up Slides

The Higgs…

- Only standard model (SM) particle yet to be discovered.
- Within SM, generation of masses depends on existence of Higgs
- Mass of Higgs is a parameter, can be constrained by M_W and M_{top}

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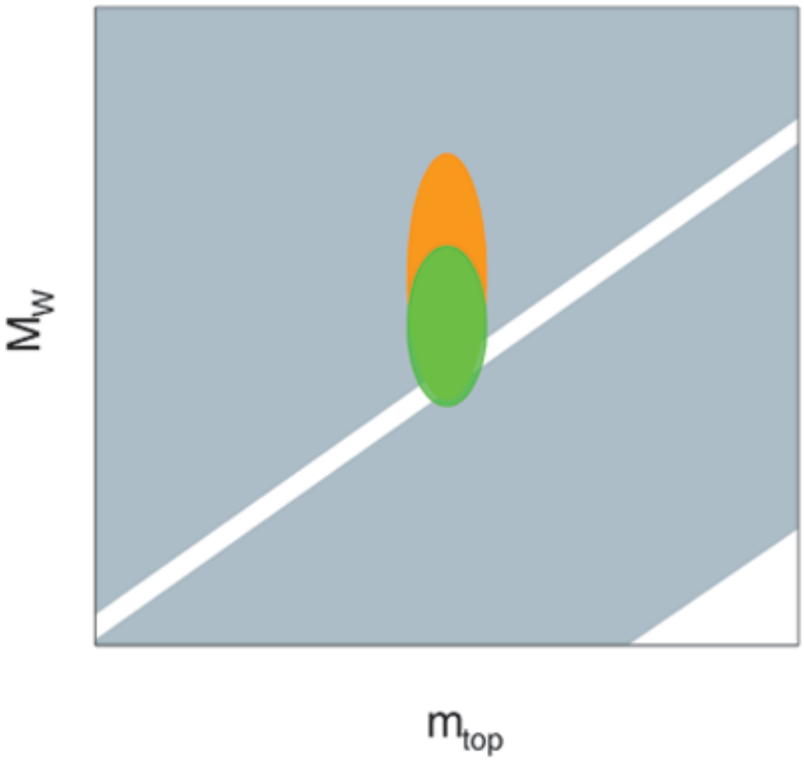

Cover of PRL
Vol. 108, Iss. 15

Combined measurements of the *W* boson mass from the CDF and D0 collaborations at Fermilab yield a smaller ellipse (green) in top-*W* mass space than the one from previous data (orange). The white stripe is the band allowed for the Higgs boson mass by data from direct searches. Both Letters selected for an Editors' Suggestion and a Synopsis in *Physics*. [T. Aaltonen et al. (CDF Collaboration), Phys. Rev. Lett. **108**, 151803 (2012)]

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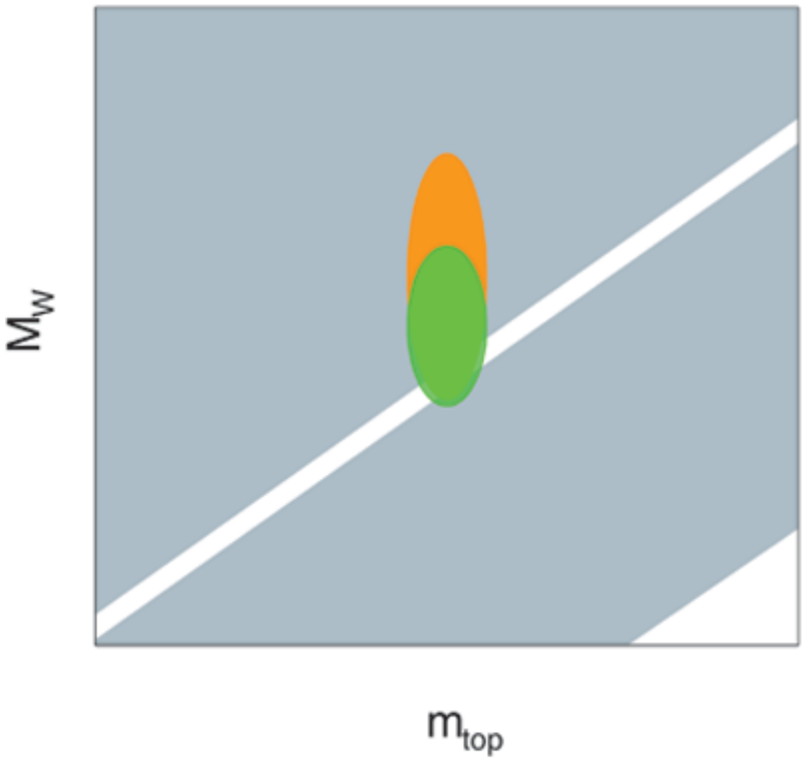

Cover of PRL Vol.

Electroweak constraints:
$m_H < 145$ GeV/c² at 95% C.L.

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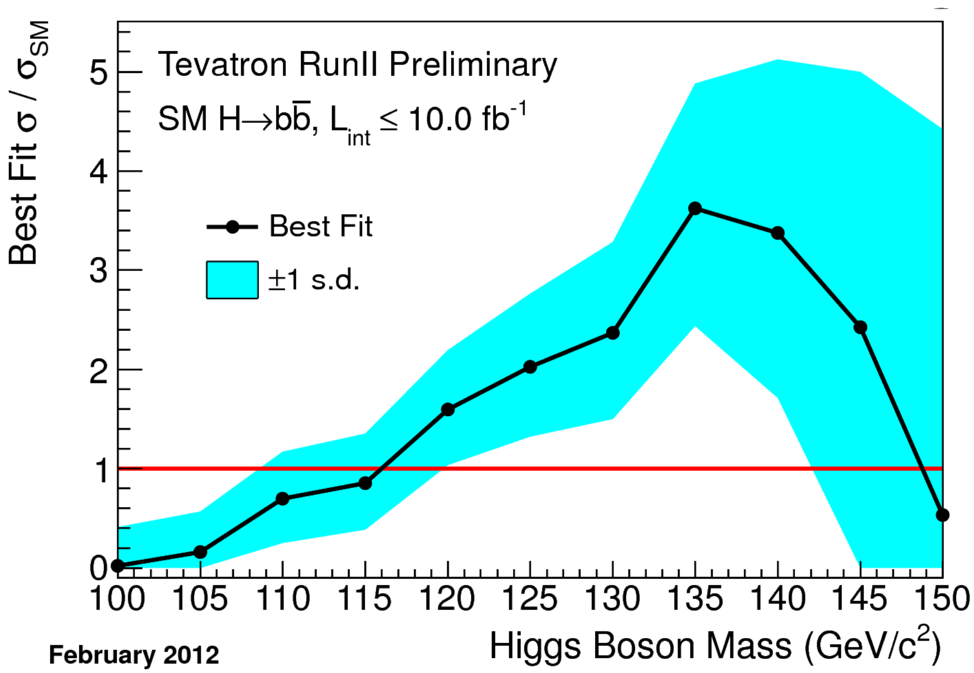
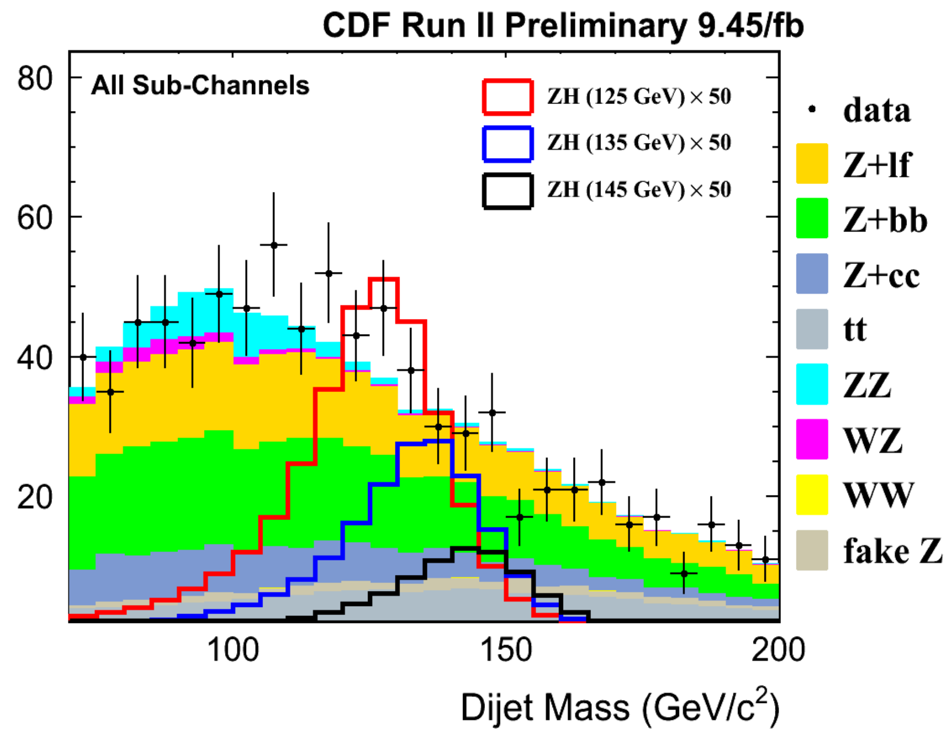
Increase of $\sigma_H \times \mathcal{B}(H \to bb)$ vs. m_H

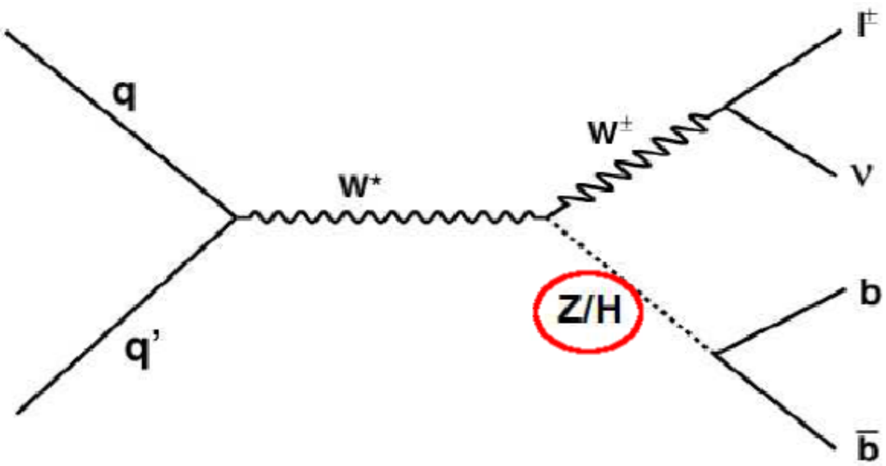




- Data are most consistent with SM in mass range from $110 < m_H < 120$ GeV/c^2
- Behavior at higher m_H values is consistent with the expectation from a lower mass Higgs due to sizeable m_{jj} tail at low mass

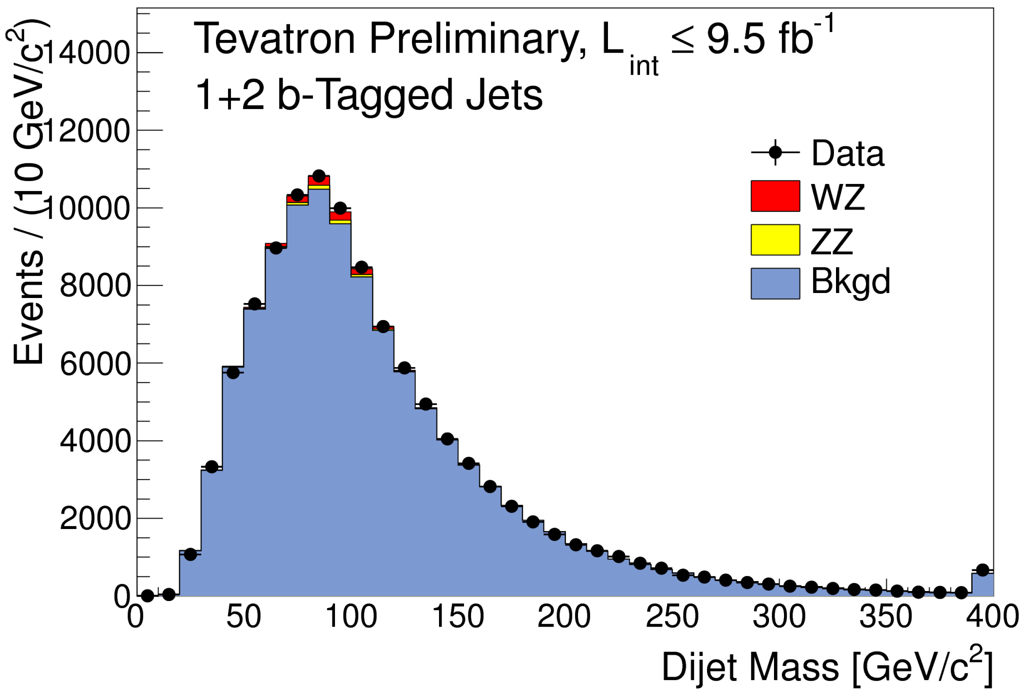
Diboson vs. Higgs Analyses

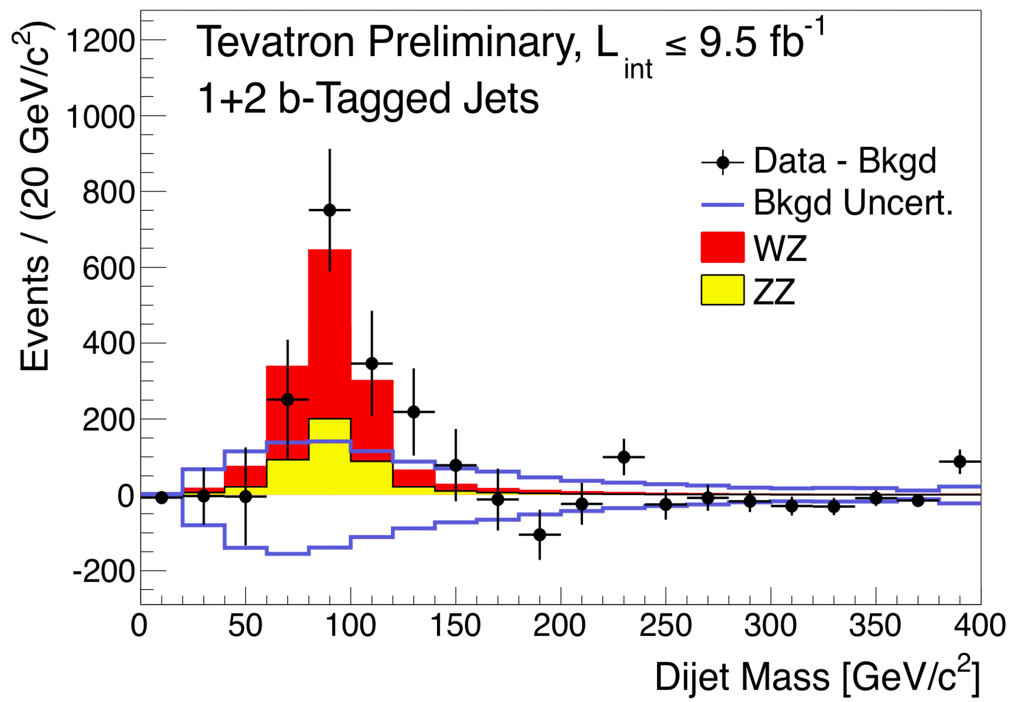
- Feynman diagrams are topologically equivalent



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

Verify modeling with σ(WZ+ZZ)



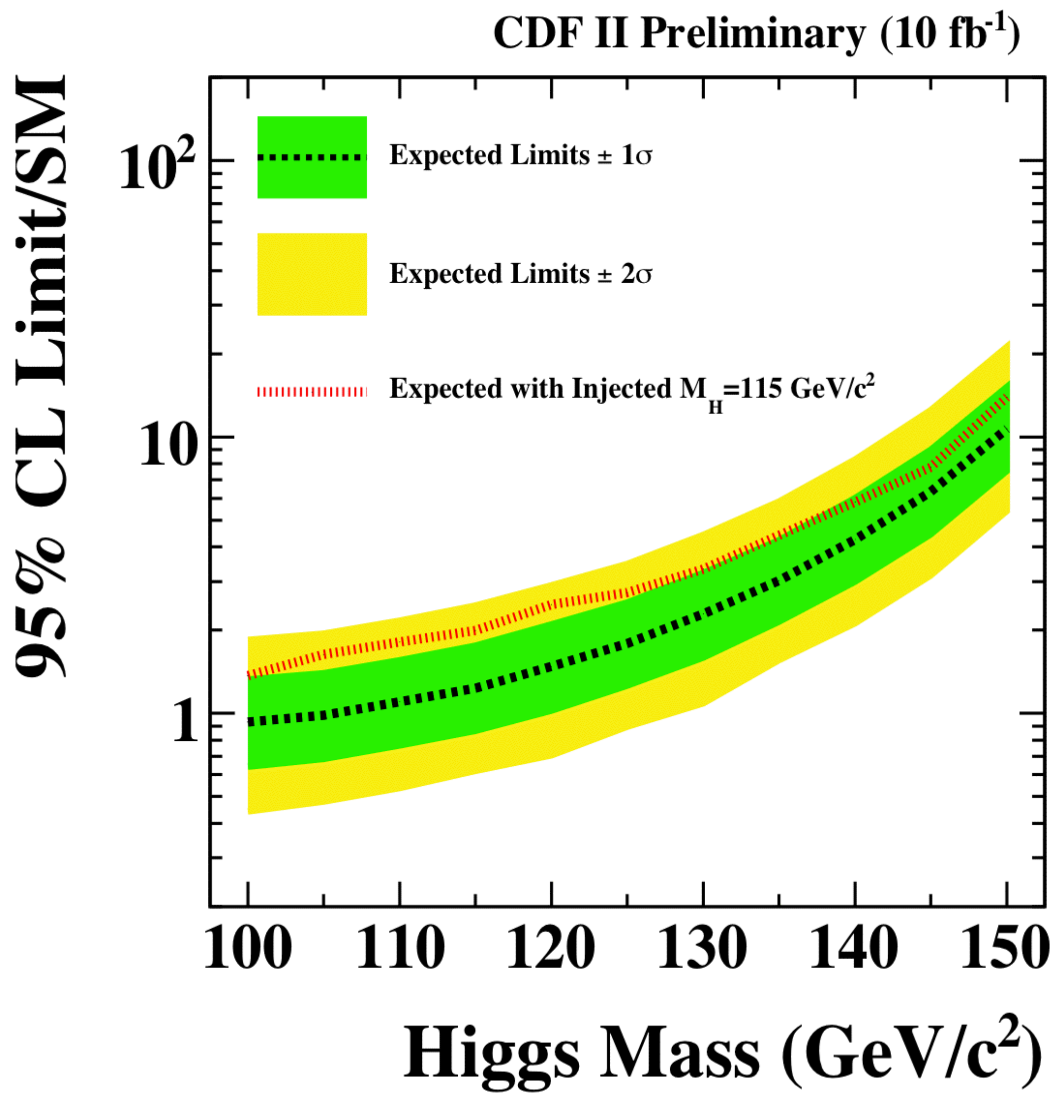


σ(WZ+ZZ) = 4.47 ± 0.64 (stat) ± 0.73 (syst) pb

SM Prediction = 4.4 ± 0.3 pb

Signal Injection study

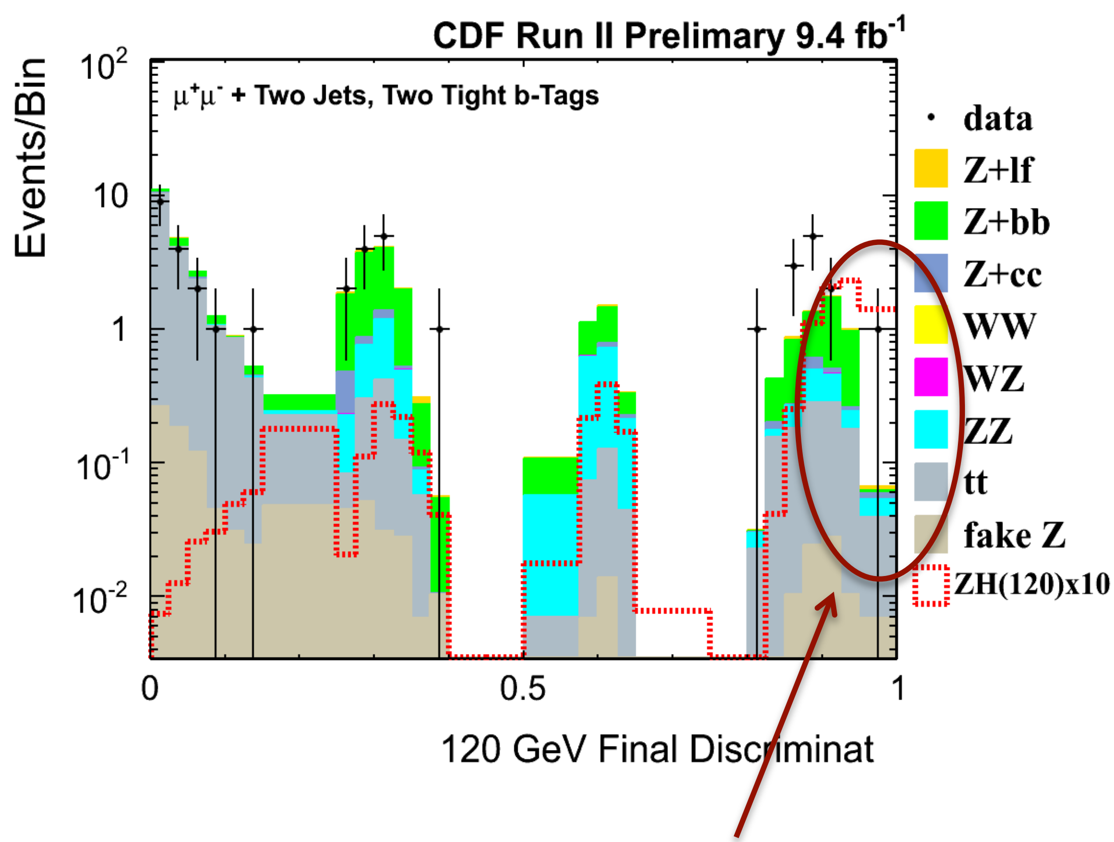
The figure on right shows the results of a previous study where CDF injected a m_H = 115 GeV/c^2 Higgs signal into background-only pseudo-experiments to study the potential effect on our observed limits



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

ZH→ll bb Analysis

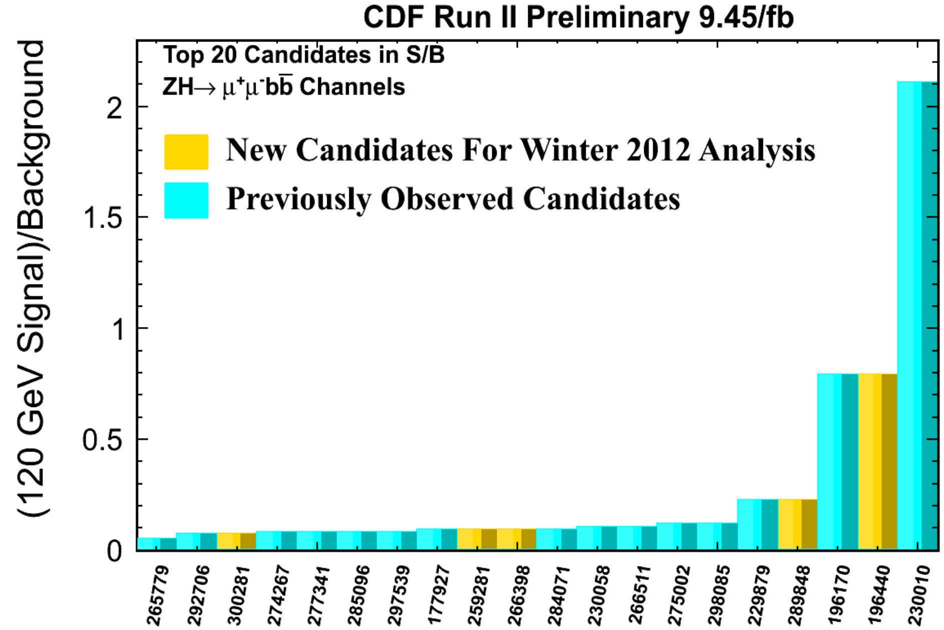
- ZH→llbb channel has . . .
  - lowest backgrounds
  - smallest expected signal yields (9 events for m_H=120 GeV/c^2)
- Some discriminant bins with large S/B
  - Low probability for observing events in these bins
  - A few such events can have substantial effects on observed limits

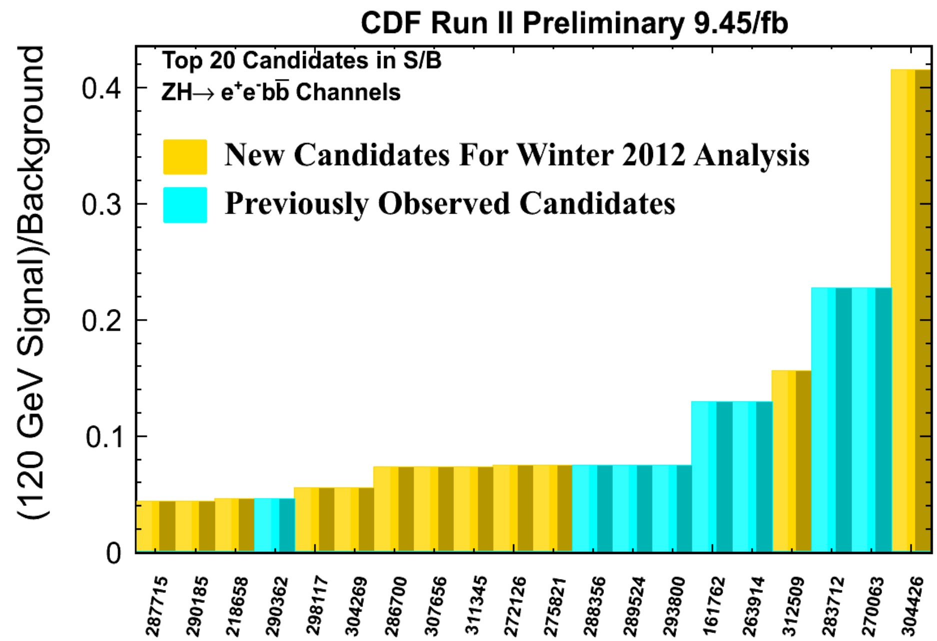


S = 0.16 events,
B = 0.06 events

ZH→ll bb Analysis

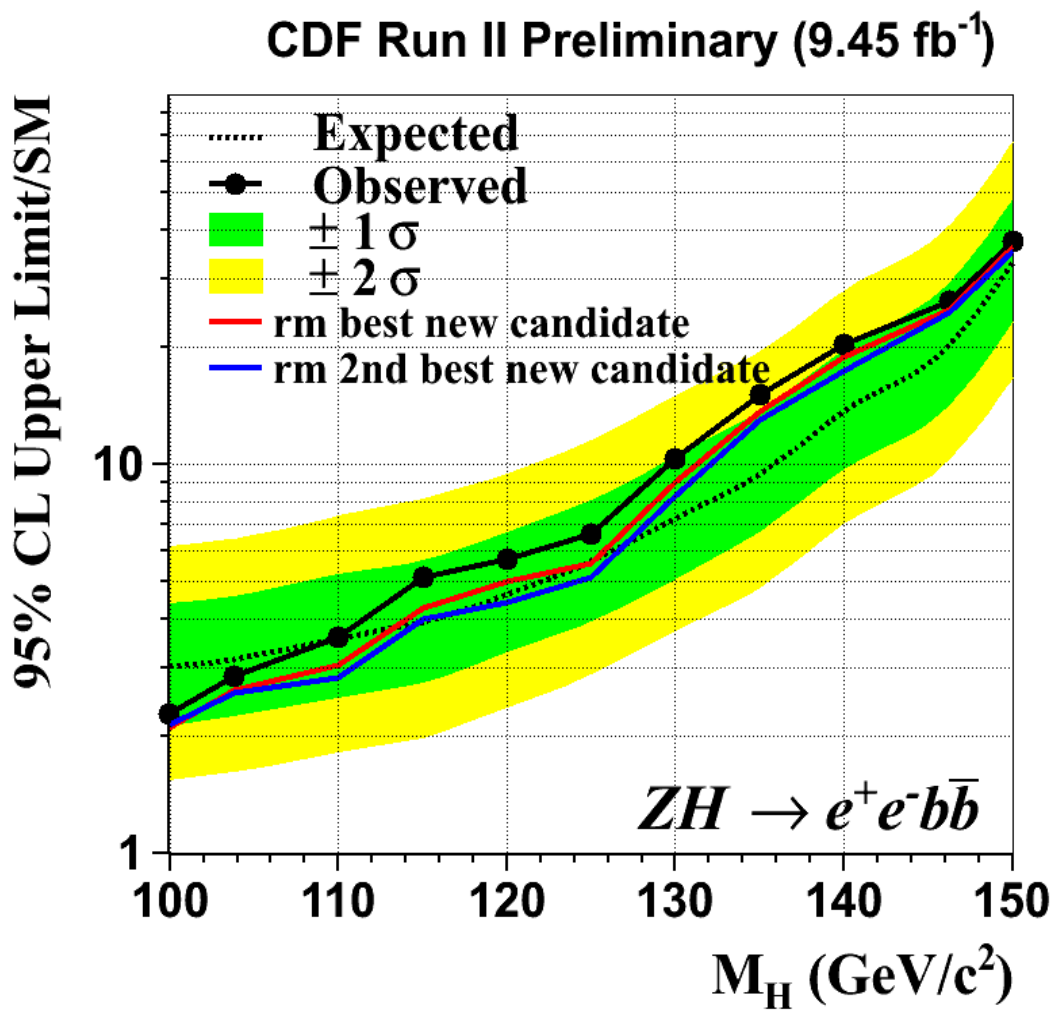
- Examine top 20 events in both channels based on S/B of the discriminant bin in which it's located
- The electron channel contains 12 new candidates within this high score region, while muon channel has 5



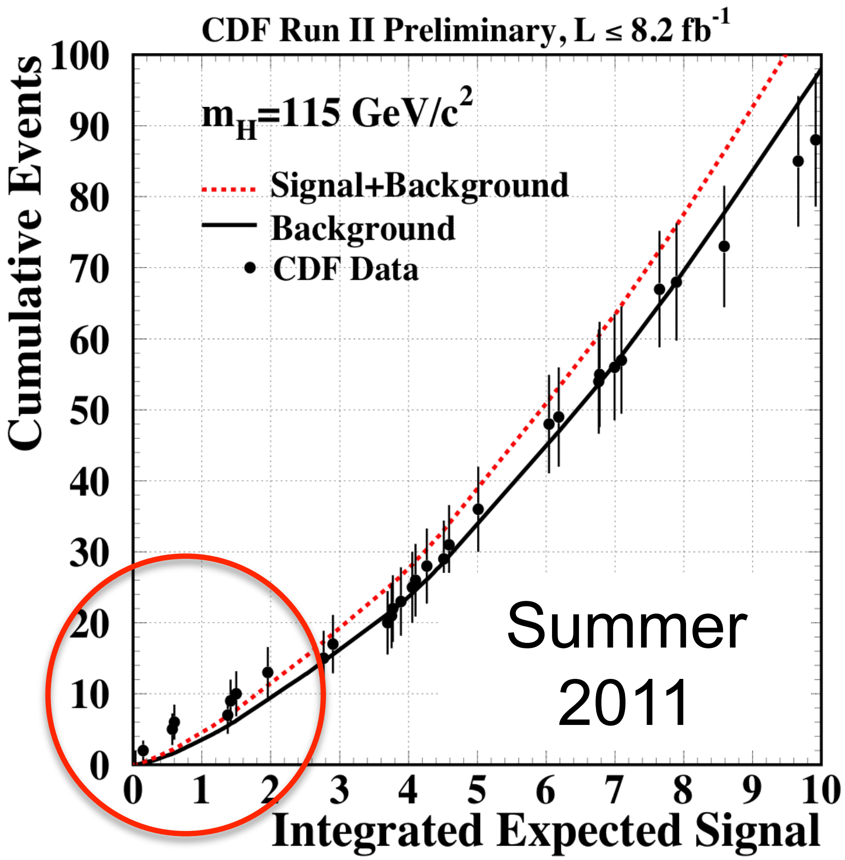


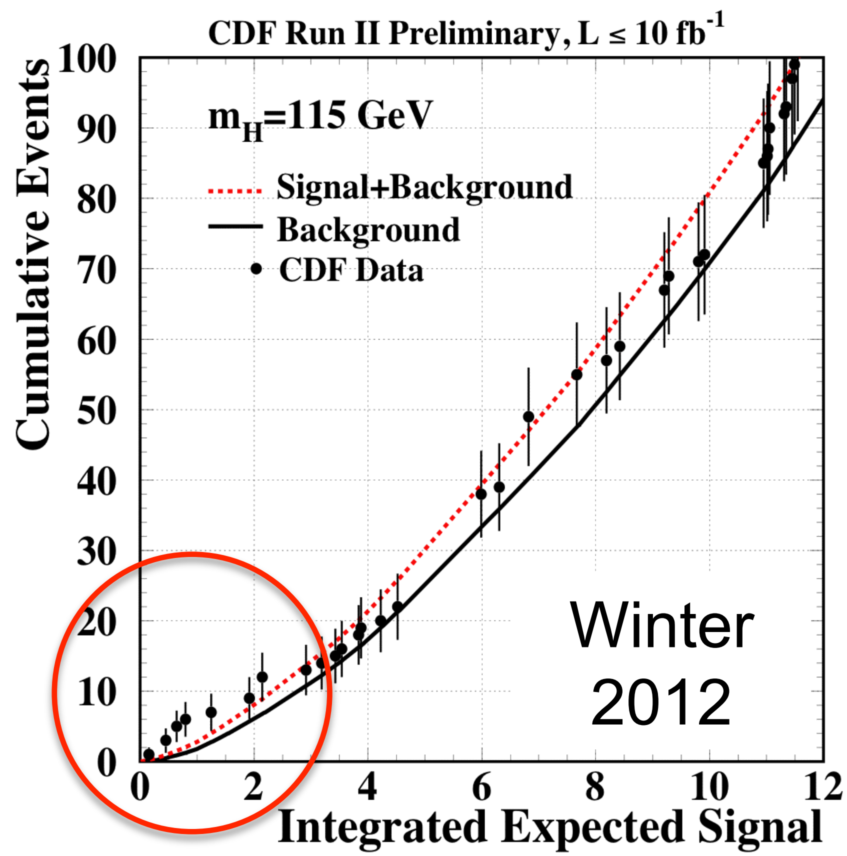
ZH→ll bb Analysis

- 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



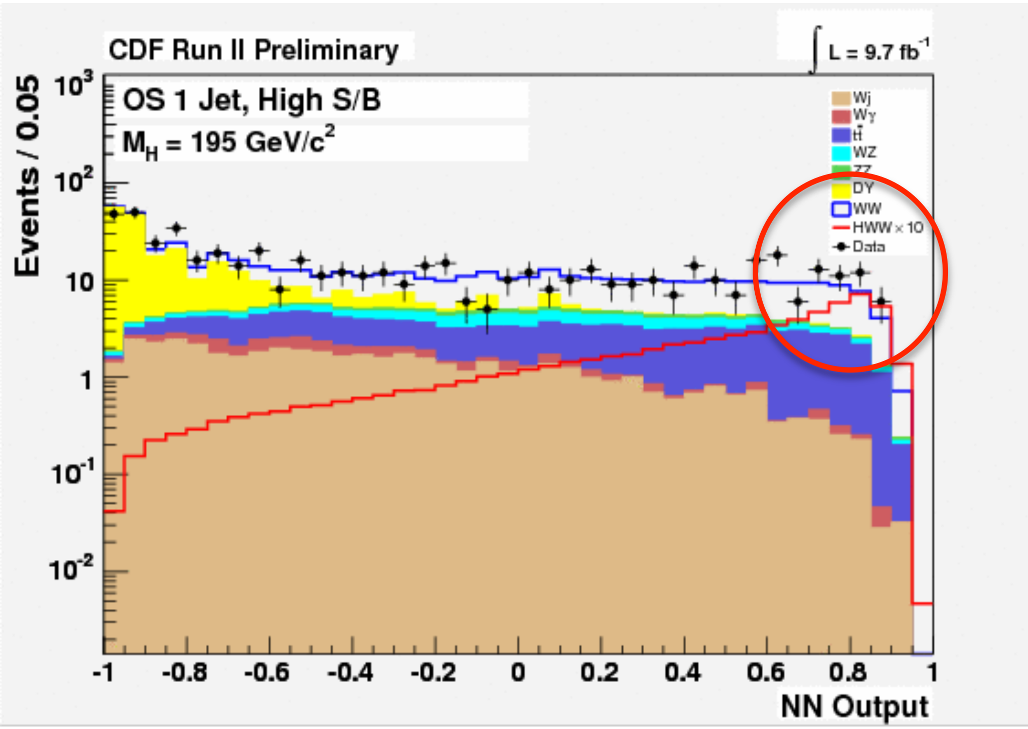
Change in Limits at m_H = 115 GeV/c^2

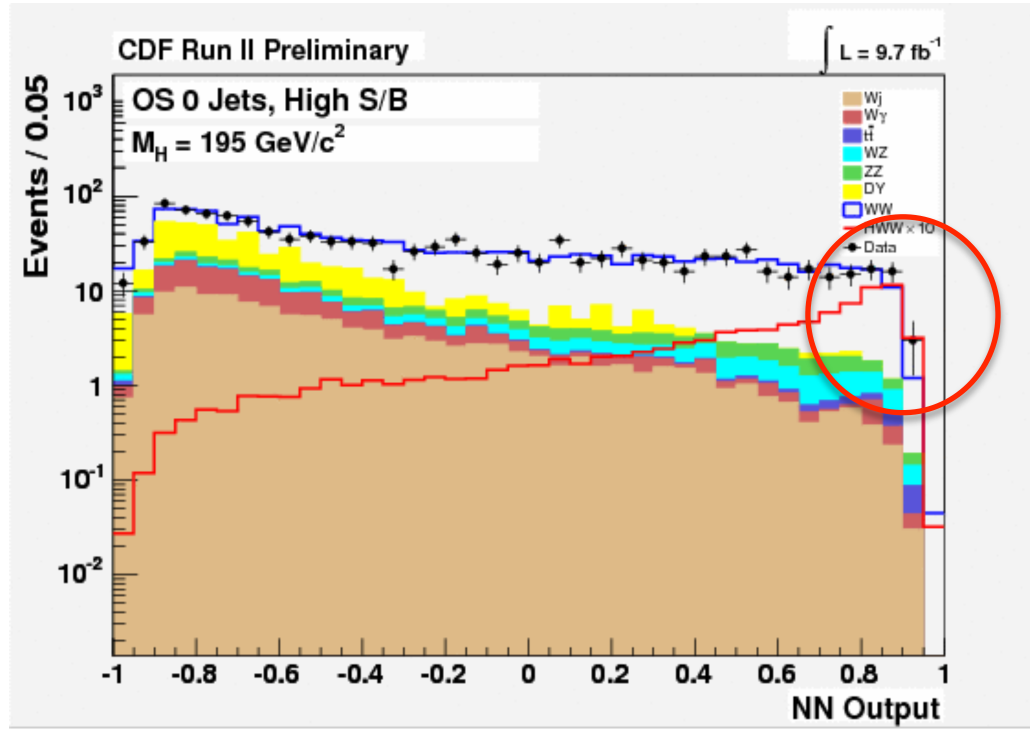




- Excess of high S/B events was present in previous analysis
- Change is that the lower S/B event region has become more consistent with S+B hypothesis

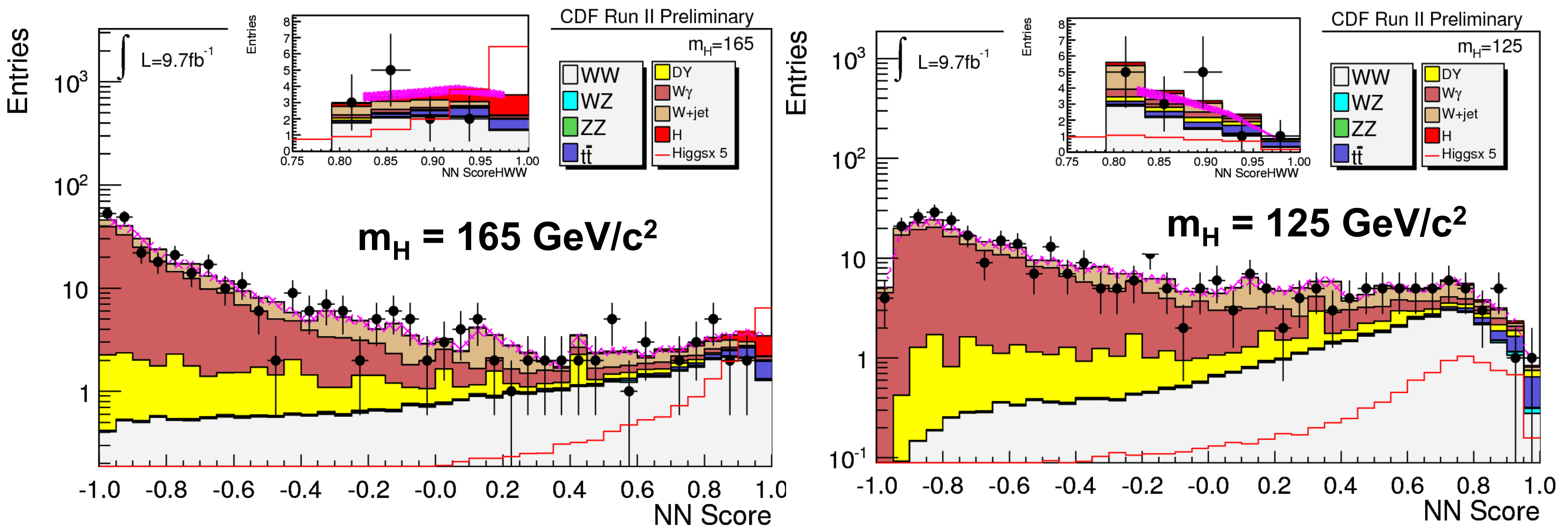
Excess at $m_H = 195\ GeV/c^2$





- Behavior of observed limits driven by small event excesses in the high S/B regions of opposite-sign dilepton 0 and 1 jet channels
- Nothing peculiar in the modeling of these distributions
- Of course, ATLAS and CMS have ruled out a $m_H = 195\ GeV/c^2$ SM Higgs based primarily on equivalent searches in $H \rightarrow WW$

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

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

Nuisance parameters

Observed events

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

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Expected events

Nuisance parameters

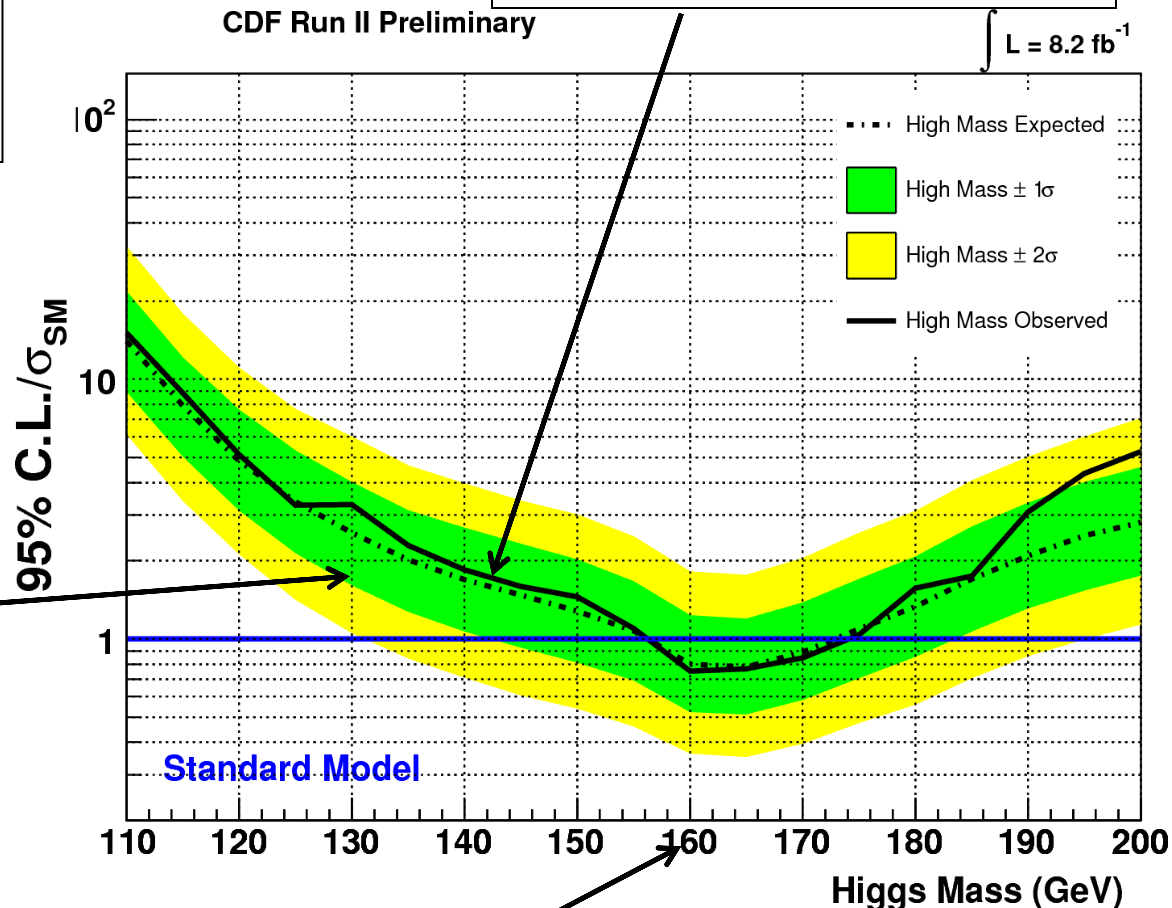
Observed events

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

Anatomy of a Limit Plot

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

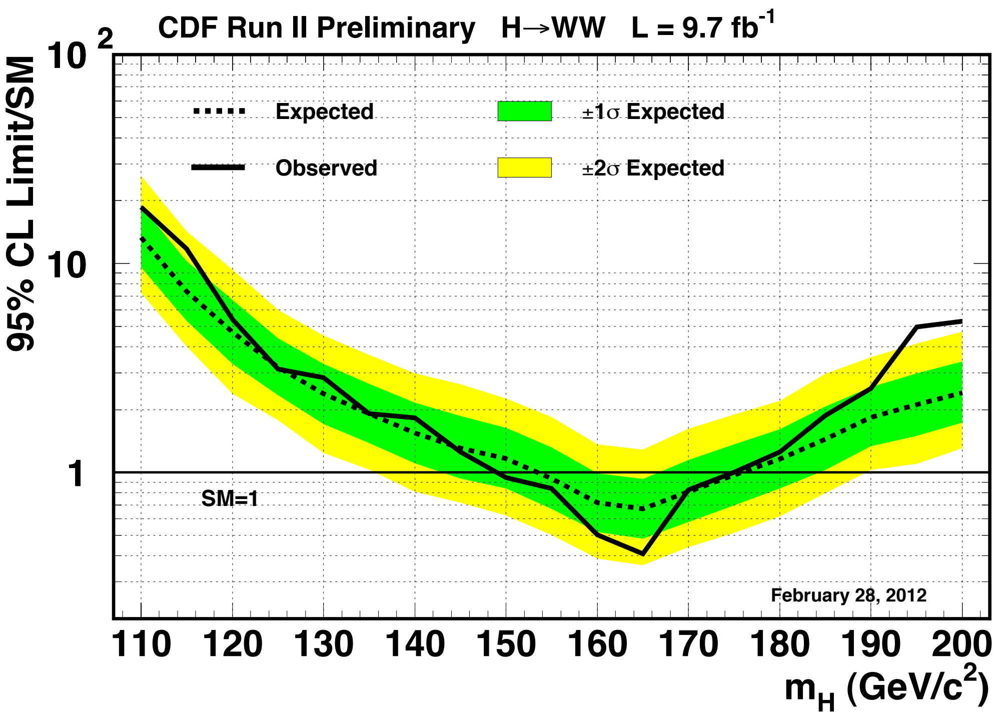
2. Observed limit (solid line) from data

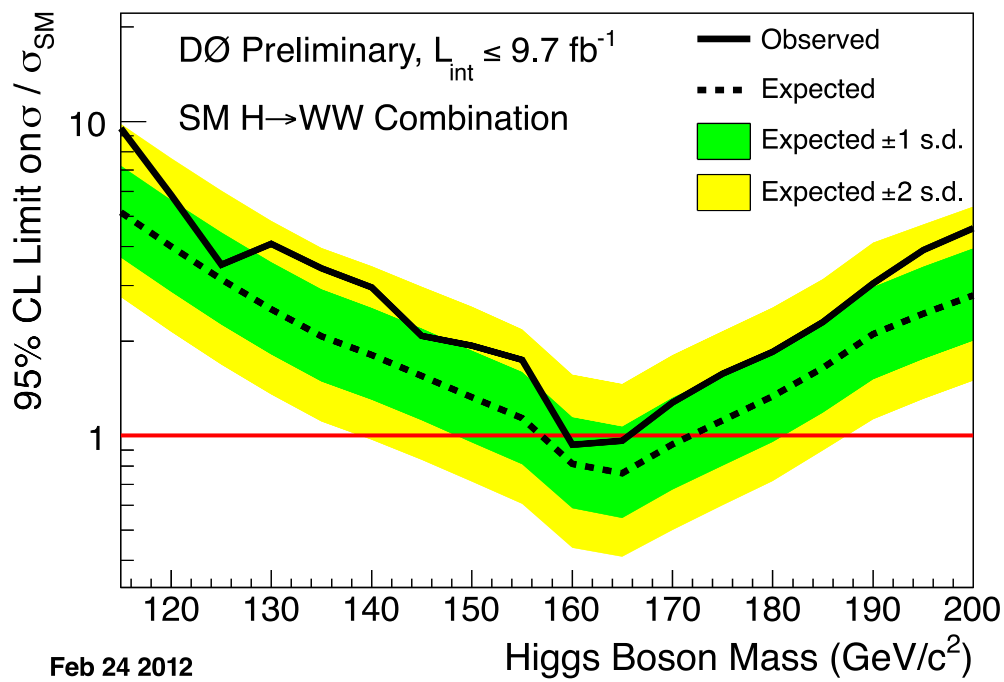


3. Median expected limit (dot-dashed line) and predicted 1σ/2σ (green/yellow bands) excursions from background only pseudo-experiments

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

Limits on H → W⁺W⁻

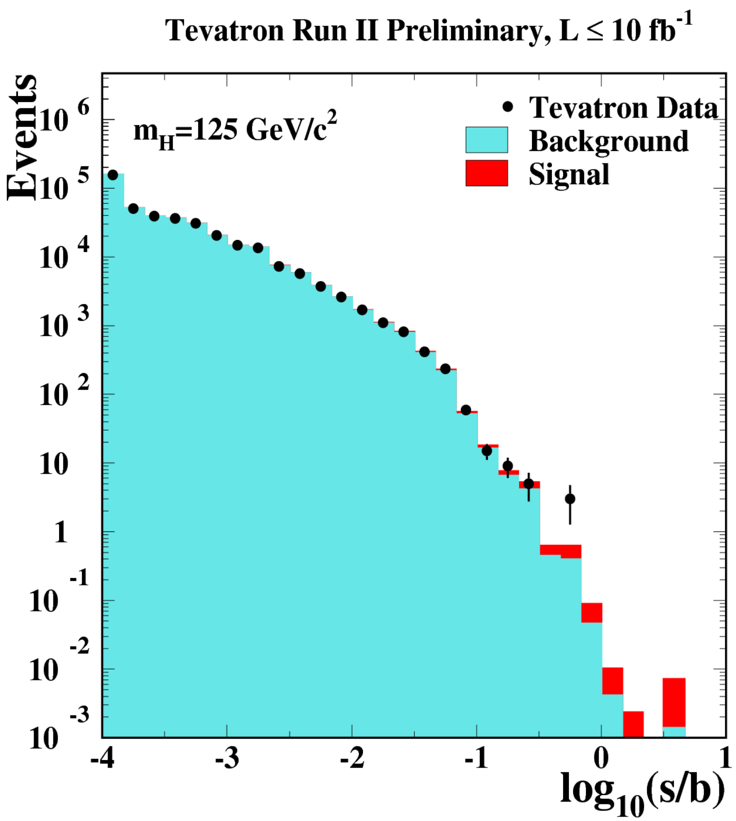


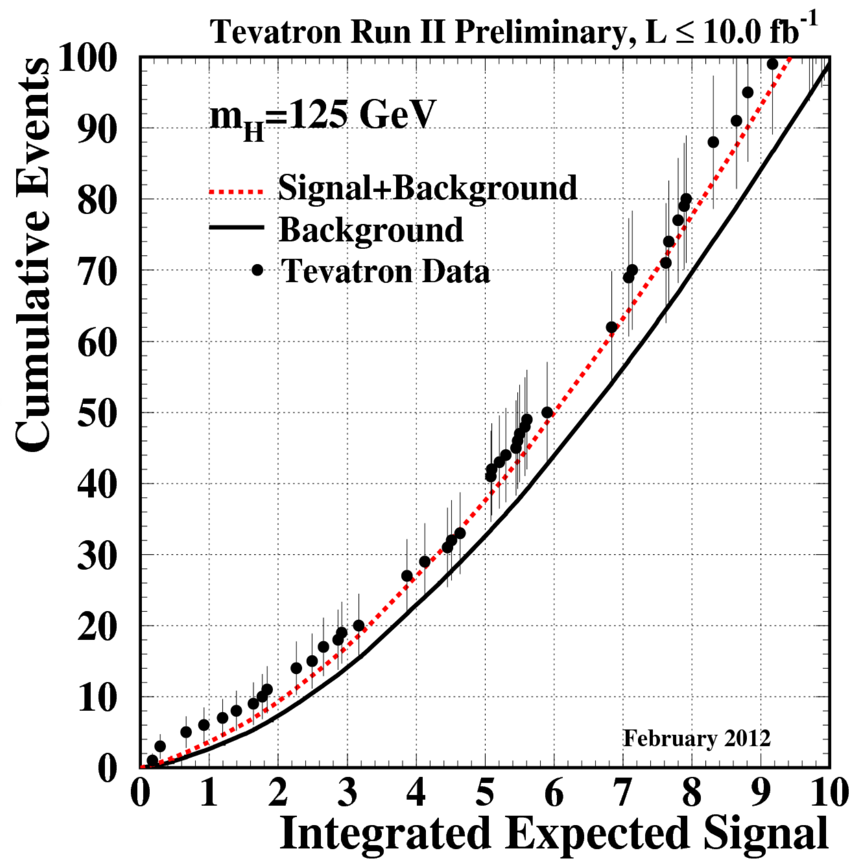


Exp. Exclusion: **154 < m_H < 176 GeV**
Obs. Exclusion: **149 < m_H < 175 GeV**

Exp. Exclusion: **157 < m_H < 172 GeV**
Obs. Exclusion: **159 < m_H < 166 GeV**

Combined discriminants – rebinned in *s/b*





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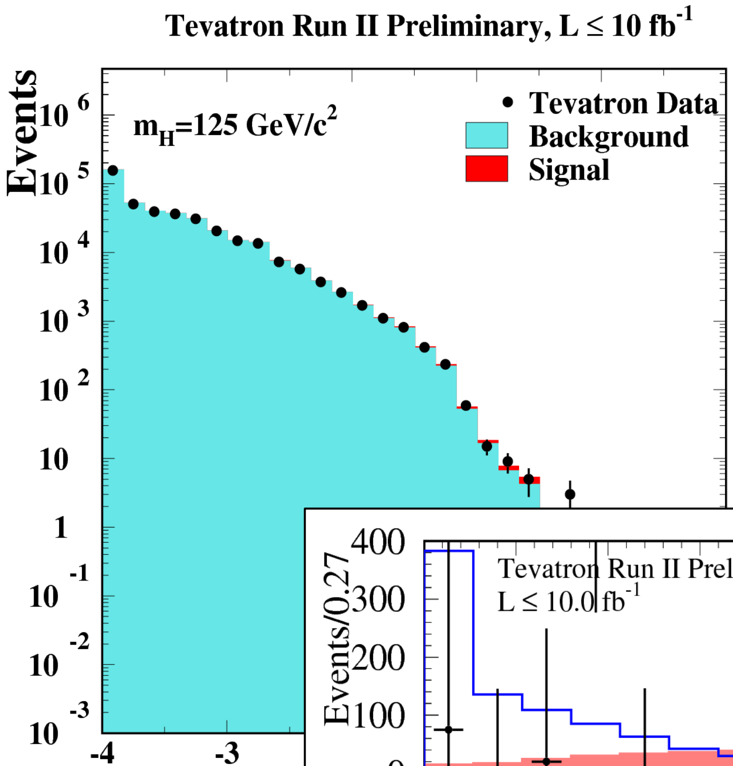
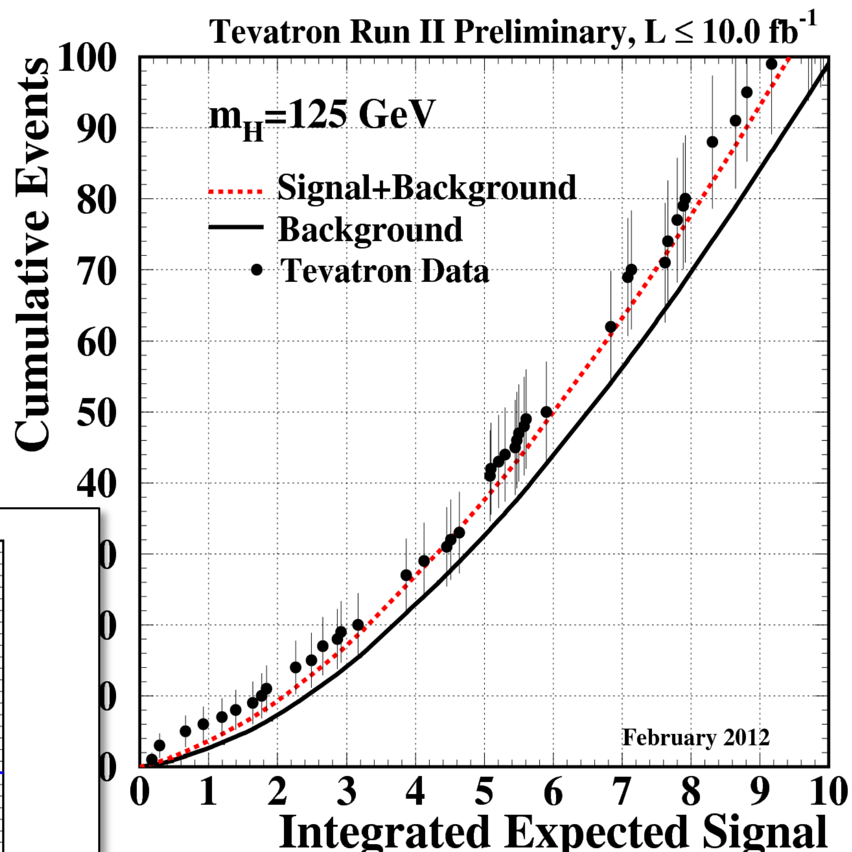
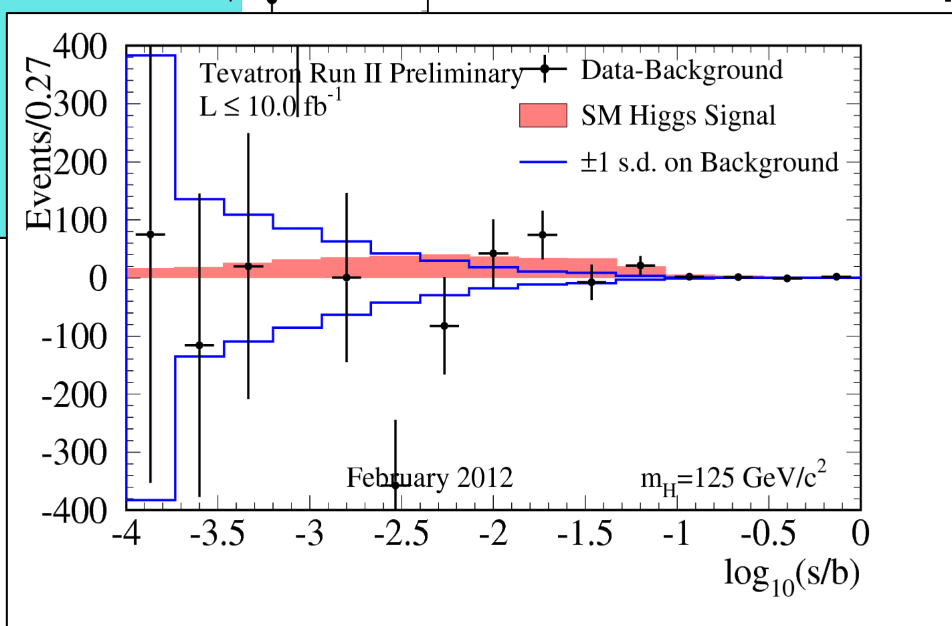


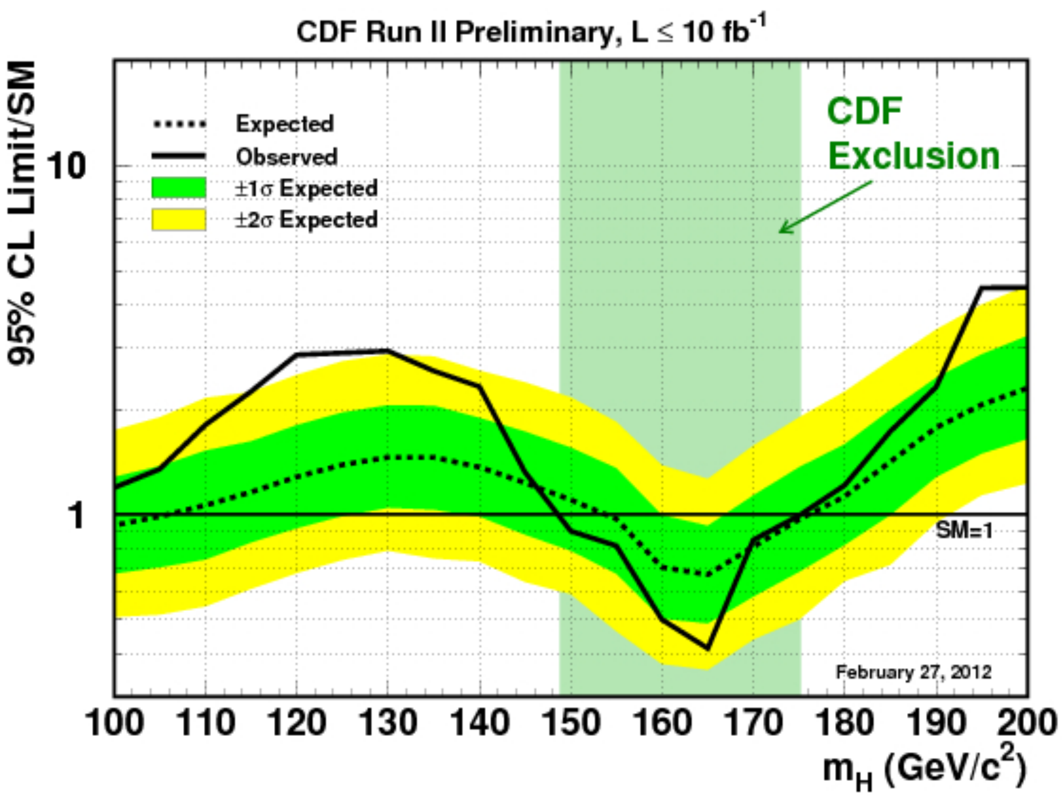
Integrated

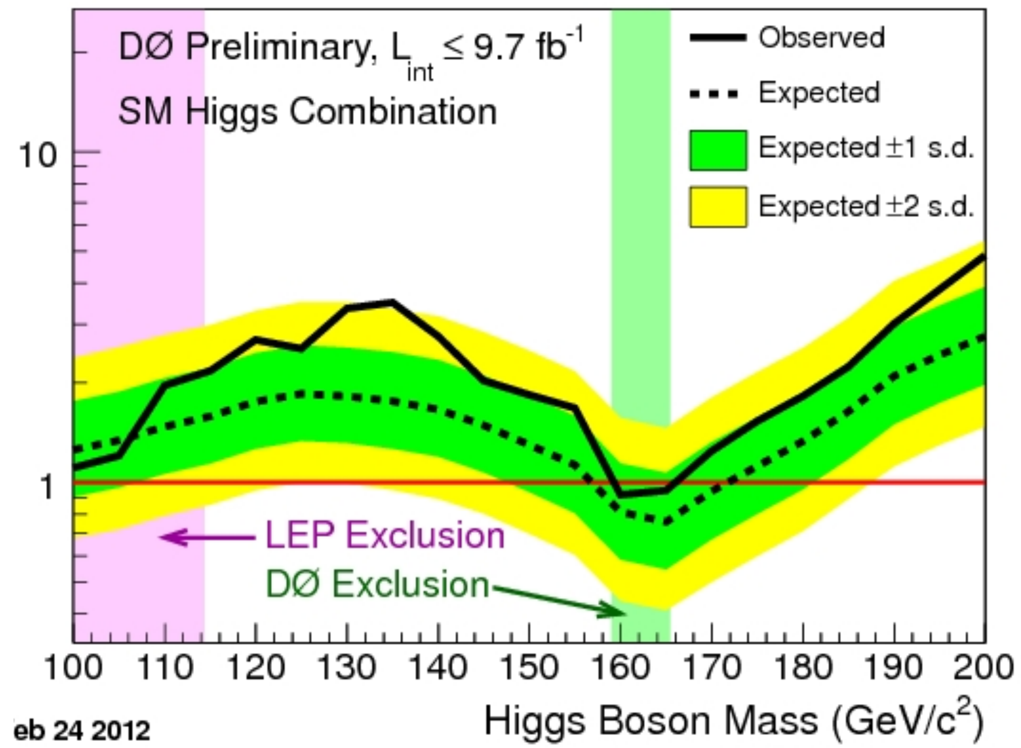




Background-subtracted

Higgs limits from all channels





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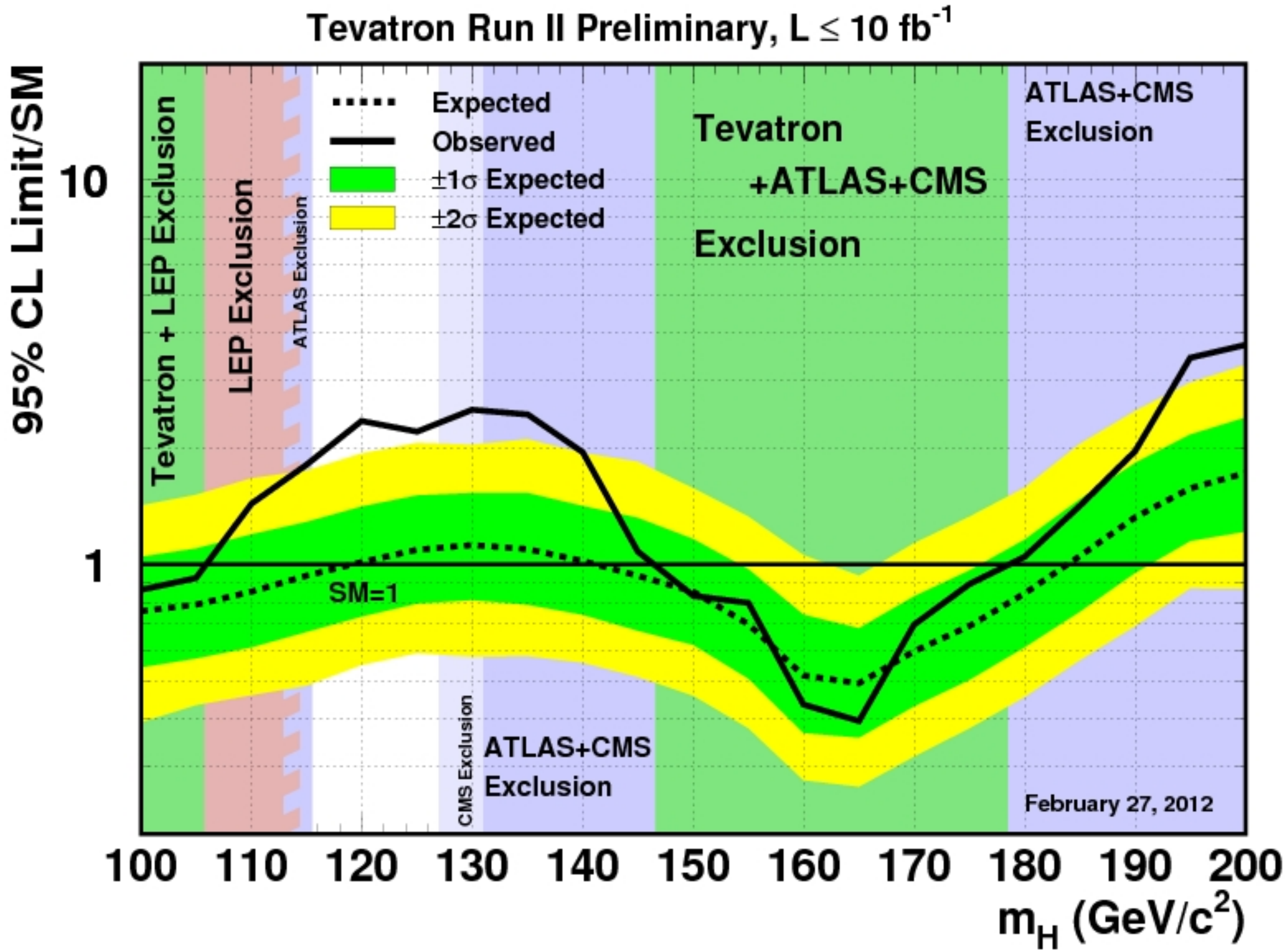
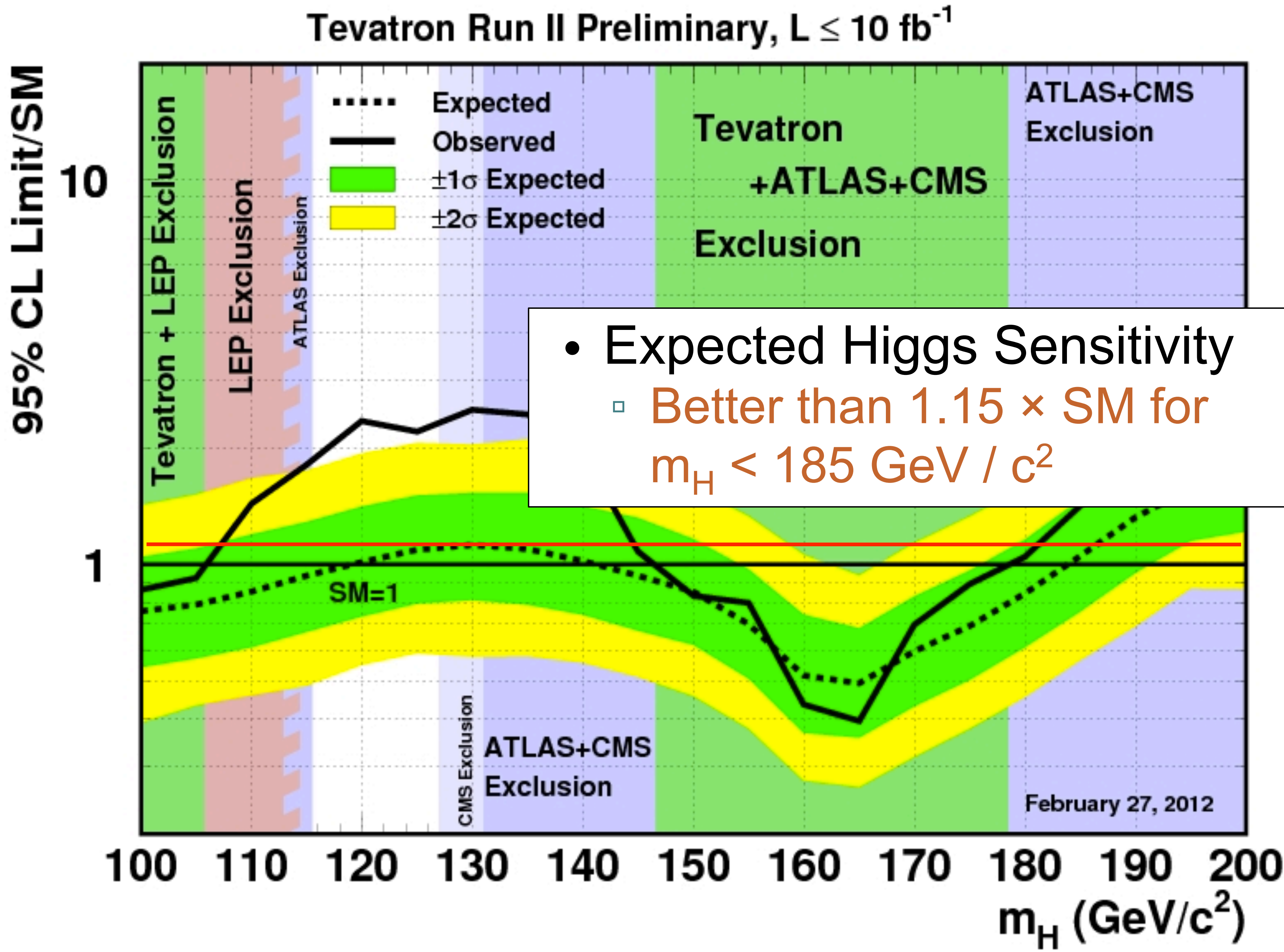
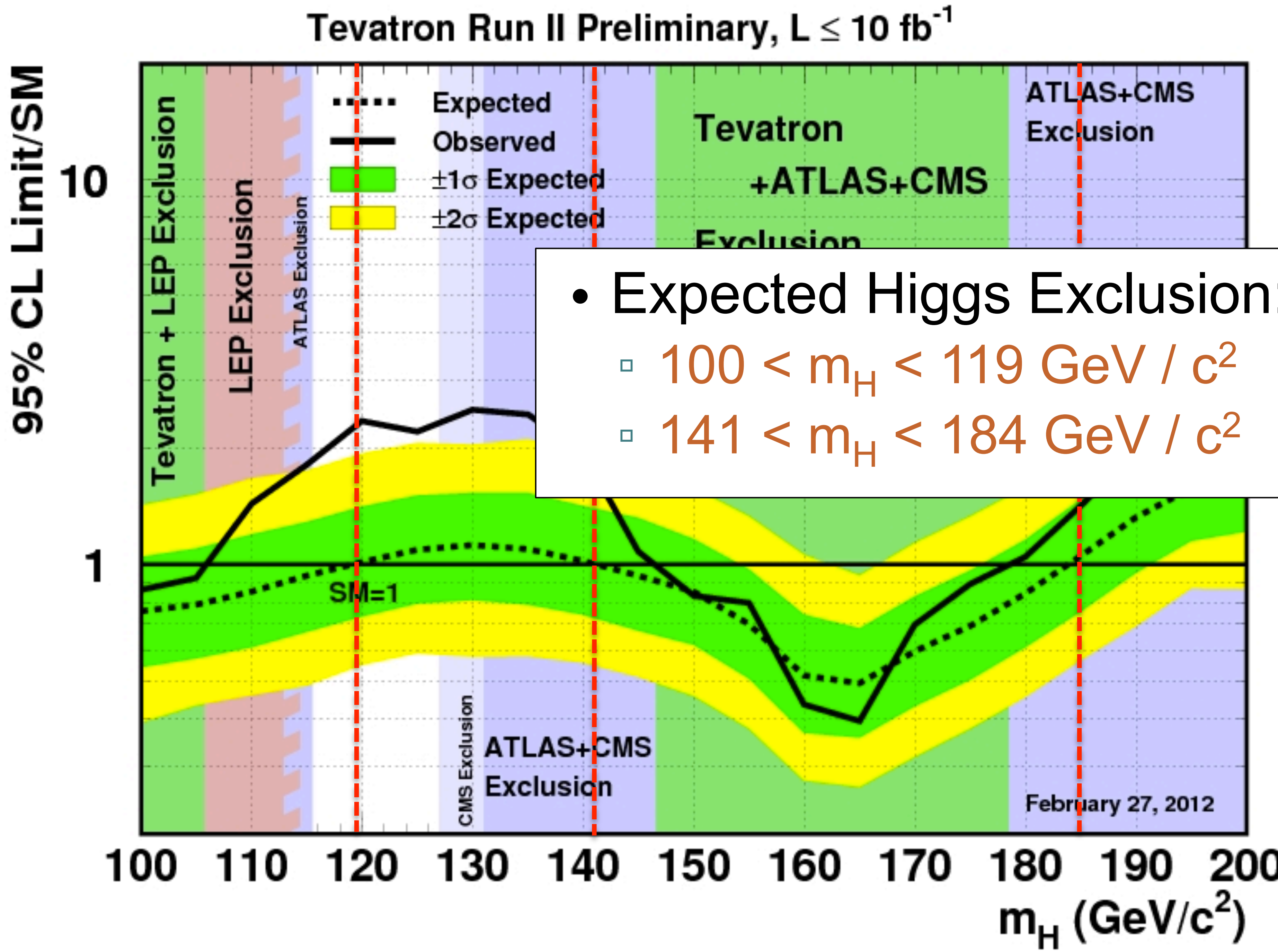
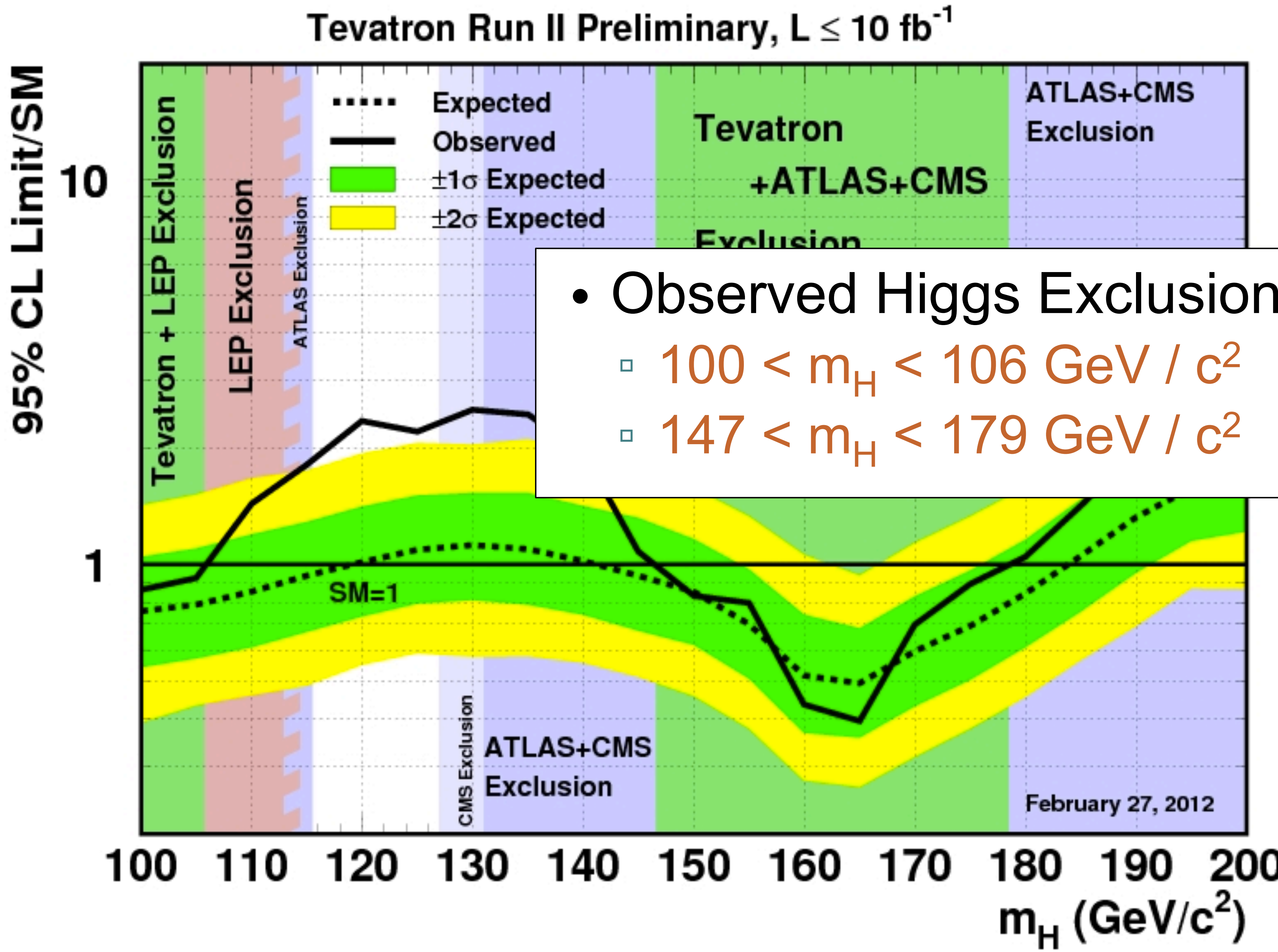

Tevatron Run II Preliminary, L ≤ 10 fb-1
95% CL Limit/SM
10
1
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron + LEP Exclusion
LEP Exclusion
ATLAS Exclusion
CMS Exclusion
ATLAS+CMS
Exclusion
Tevatron
+ATLAS+CMS
Exclusion
ATLAS+CMS
Exclusion
SM=1
February 27, 2012
100
110
120
130
140
150
160
170
180
190
200
mH (GeV/c2)



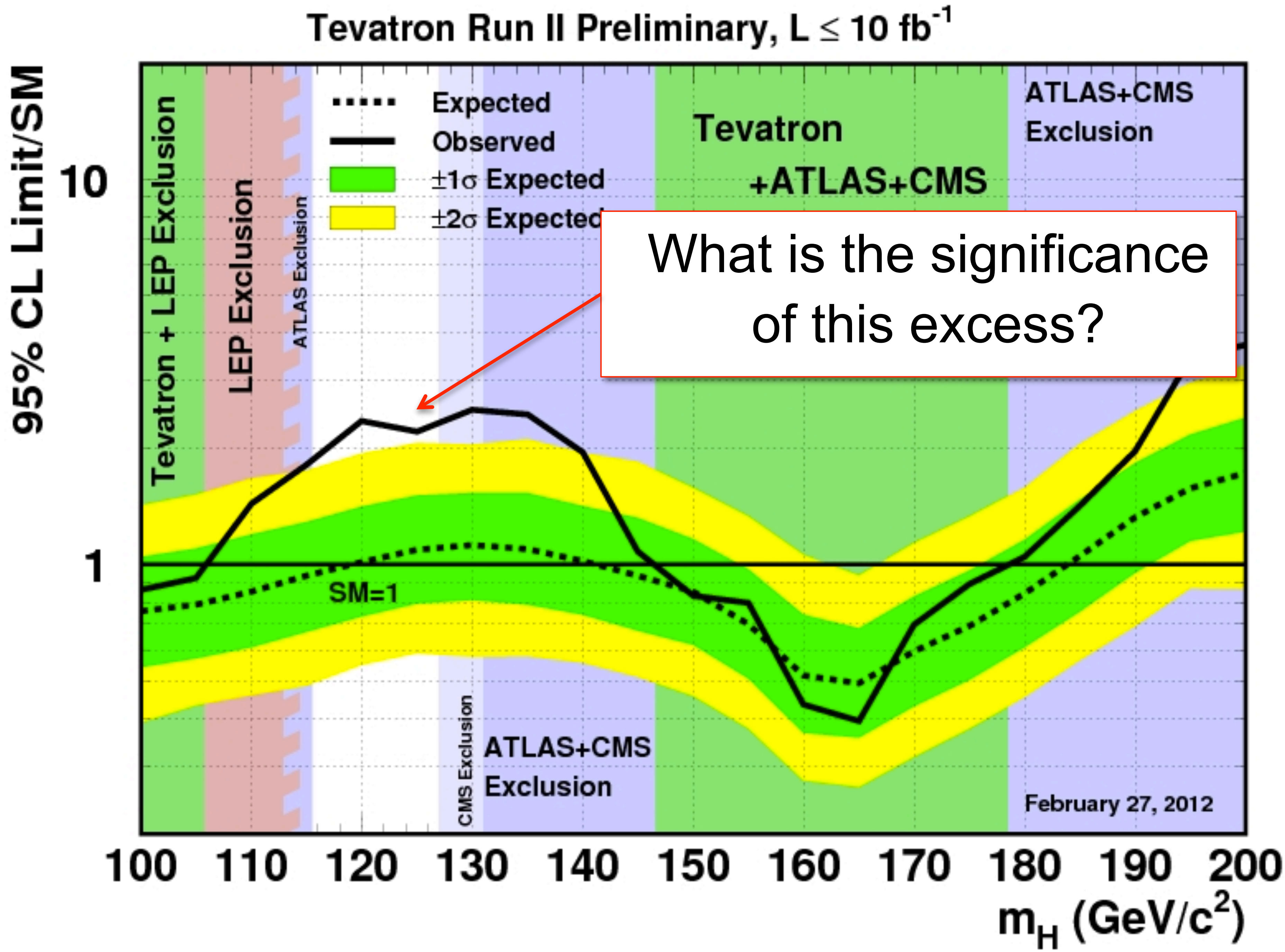
- Expected Higgs Sensitivity
  - Better than 1.15 × SM for m_H < 185 GeV / c^2



- Expected Higgs Exclusion:
  - $100 < m_H < 119$ GeV / c^2
  - $141 < m_H < 184$ GeV / c^2

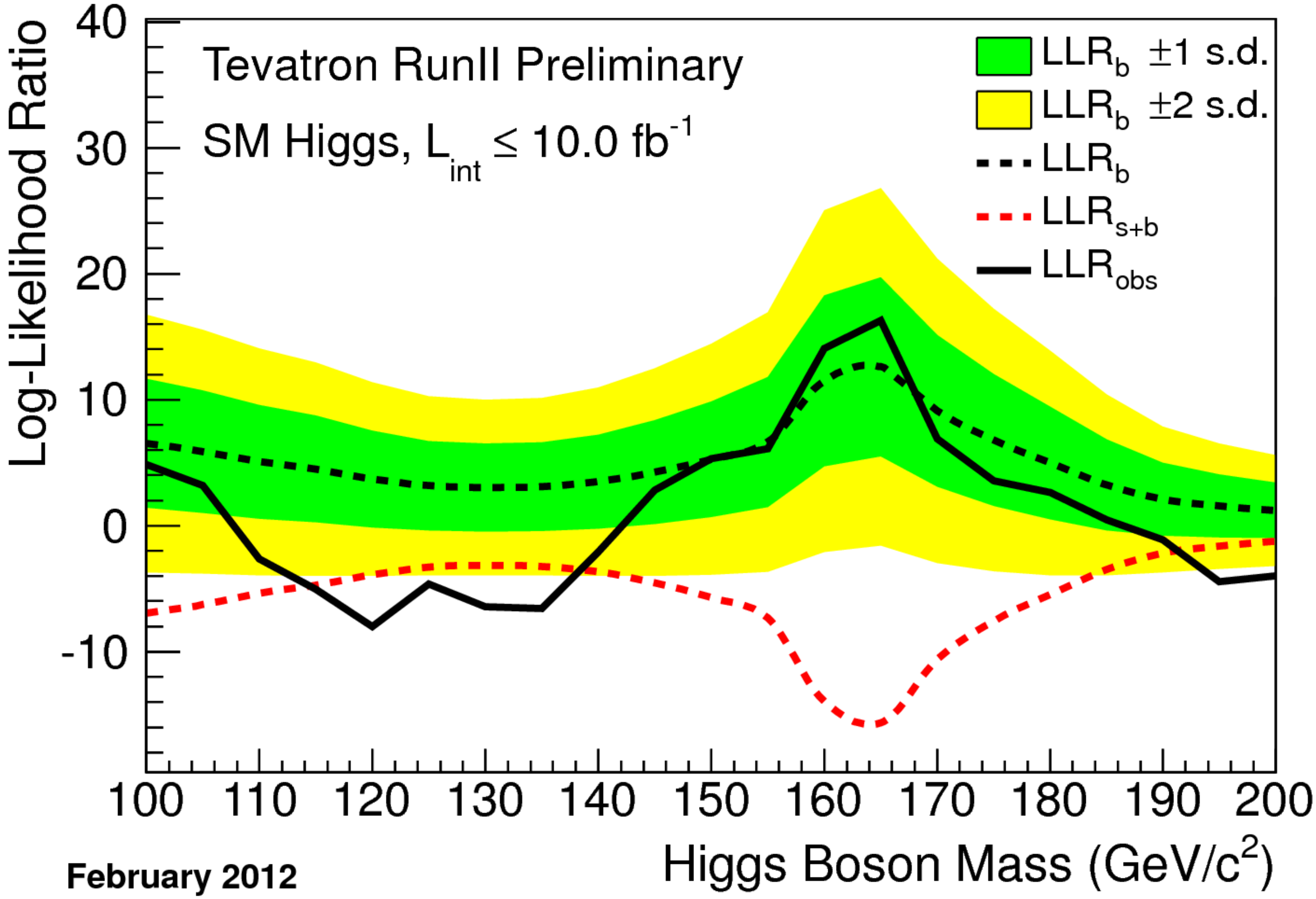


- Observed Higgs Exclusion:
  - $100 < m_H < 106$ GeV / c^2
  - $147 < m_H < 179$ GeV / c^2


Tevatron Run II Preliminary, L ≤ 10 fb-1
95% CL Limit/SM
10
1
Tevatron + LEP Exclusion
LEP Exclusion
ATLAS Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
Tevatron
+ATLAS+CMS
ATLAS+CMS
Exclusion
What is the significance of this excess?
SM=1
CMS Exclusion
ATLAS+CMS
Exclusion
February 27, 2012
100
110
120
130
140
150
160
170
180
190
200
mH (GeV/c2)

LLR of Tevatron Combination

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



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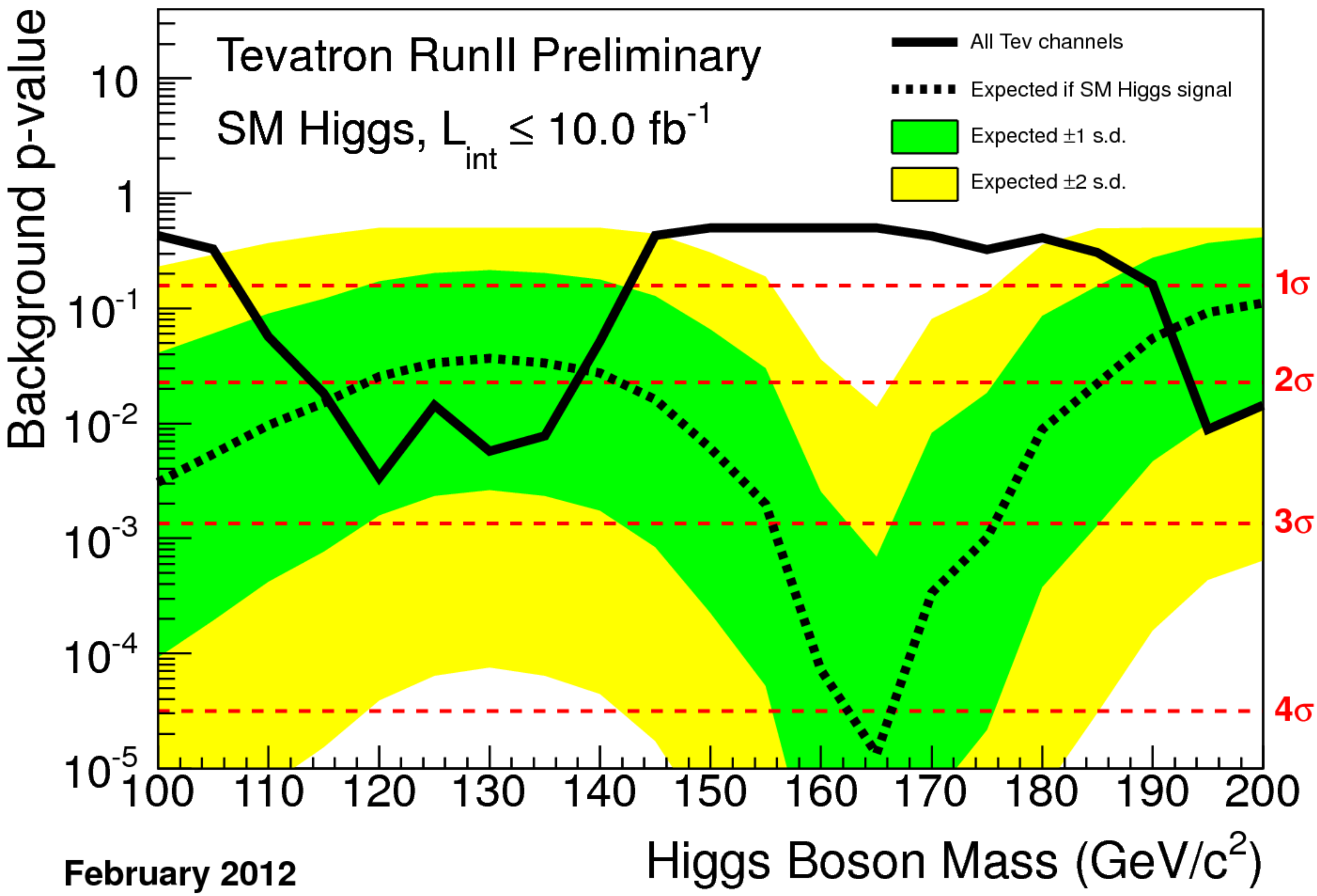
p-value of Tevatron Combination



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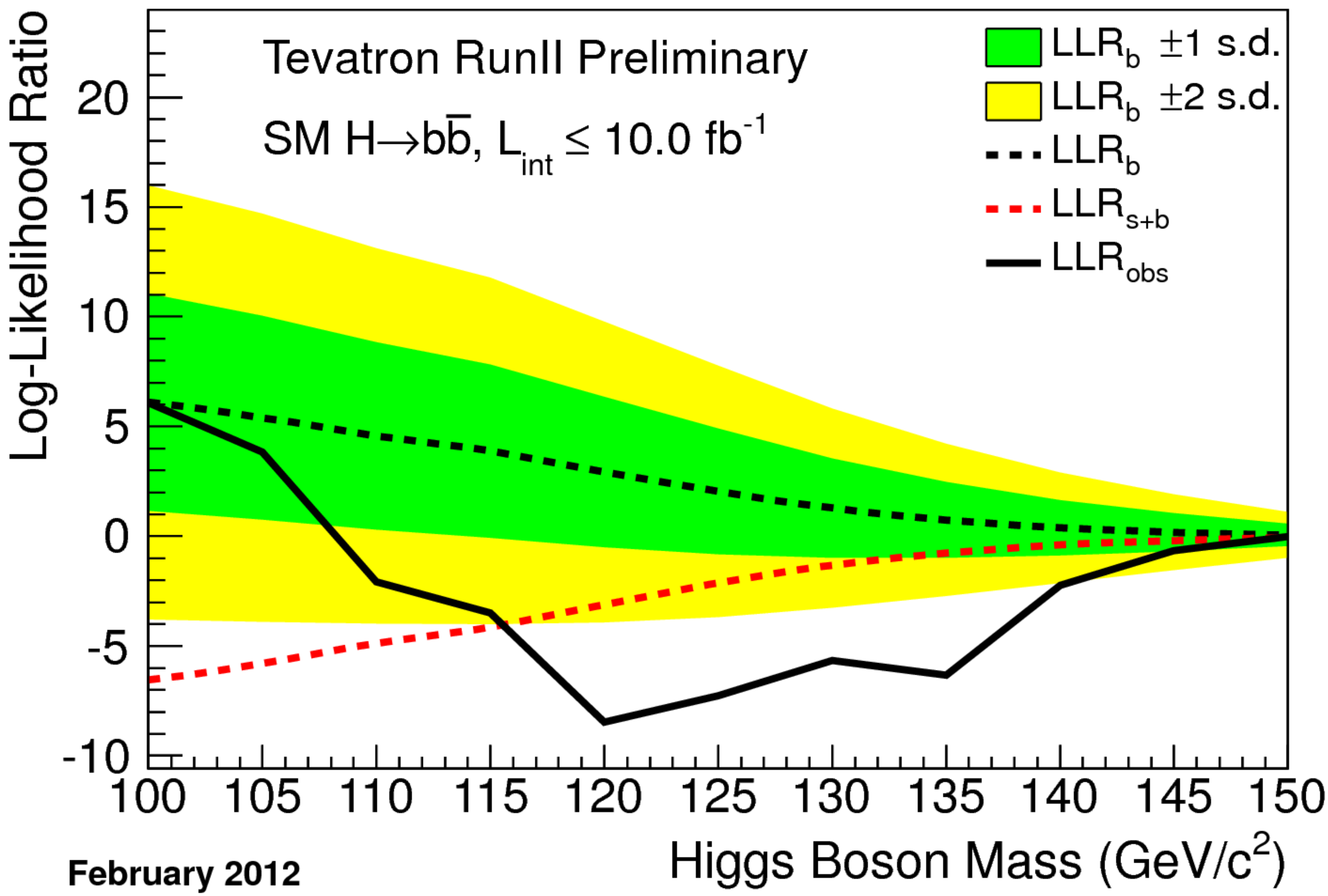
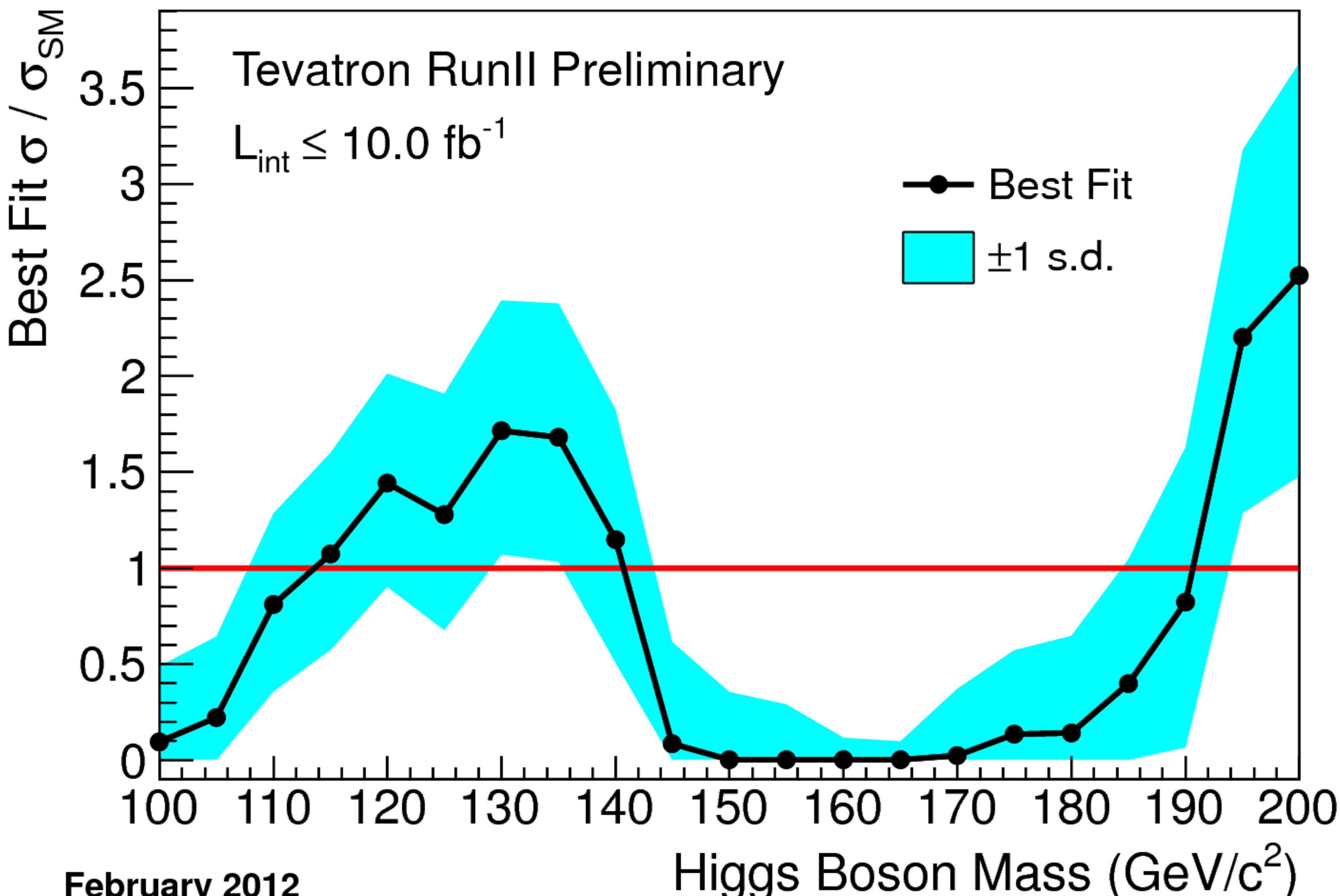
H→ bb LLR of Tevatron Combination



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



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Significance of Excesses

- Both LHC and Tevatron experiments see excesses in data relative to the null hypothesis at the low-mass Higgs region

	Local Significance	Global Significance
CDF	**2.6 σ**	**2.1 σ**
D0	**2.2 σ**	**1.5 σ**
Tevatron	**2.7 σ**	**2.2 σ**
ATLAS	**3.5 σ**	**2.2 σ**
CMS	**2.8 σ**	**2.1 σ**

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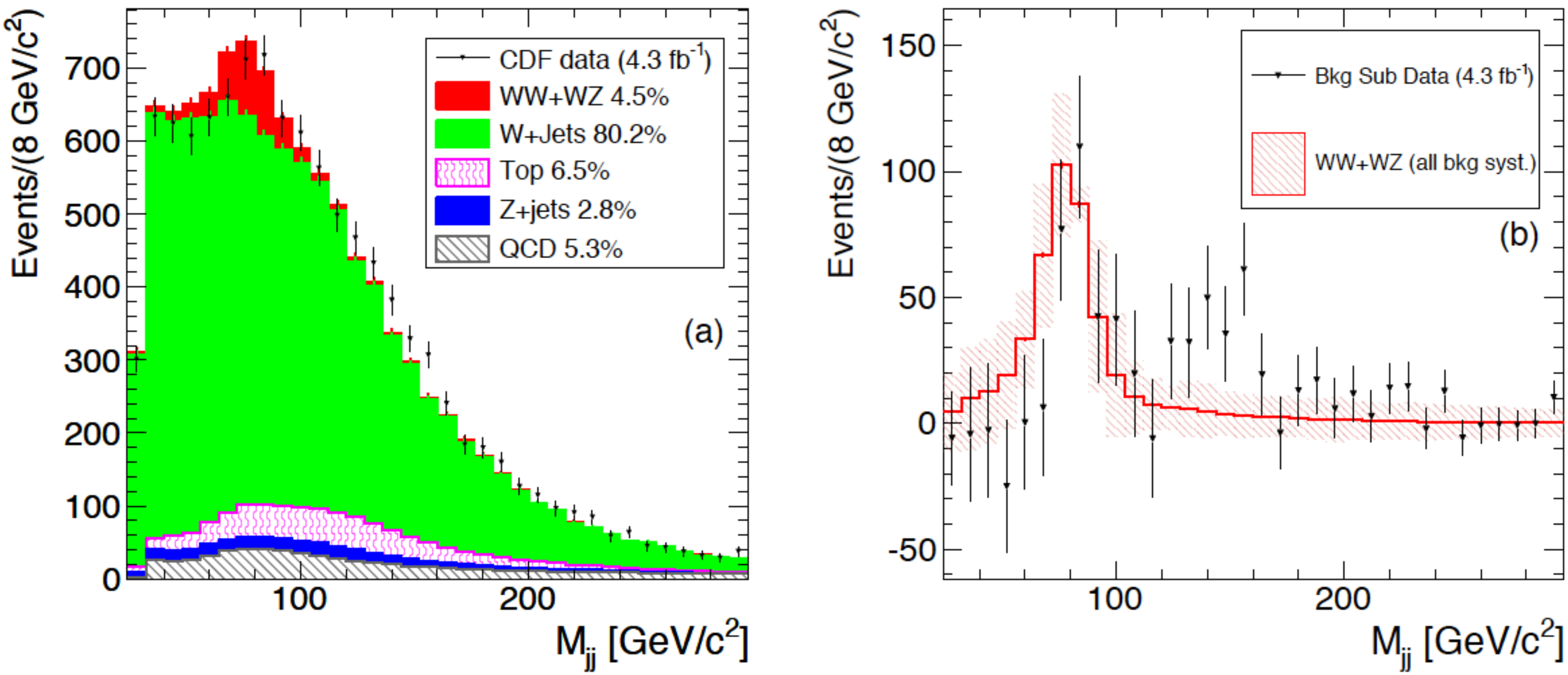
- Similar-sized excesses in complementary searches at the LHC and Tevatron.

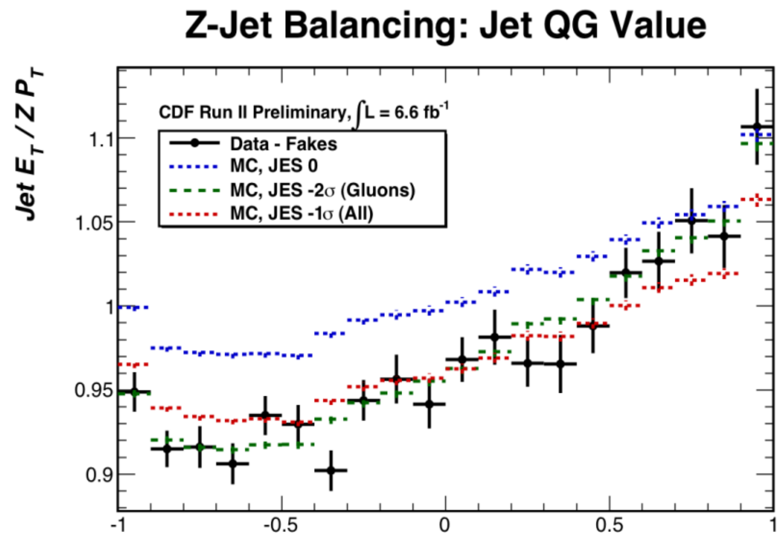
What about the CDF W + jets bump?

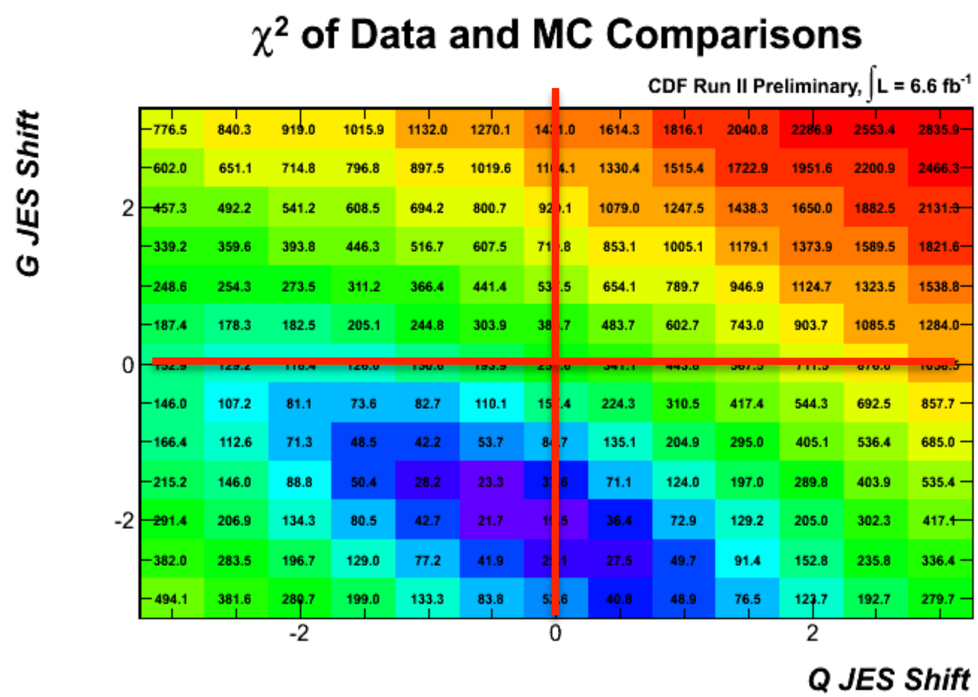


What about the CDF W + jets bump?

- Z+ jet balancing study done indicating that JES for gluon jets needs to be shifted by 2σ in MC to match with data

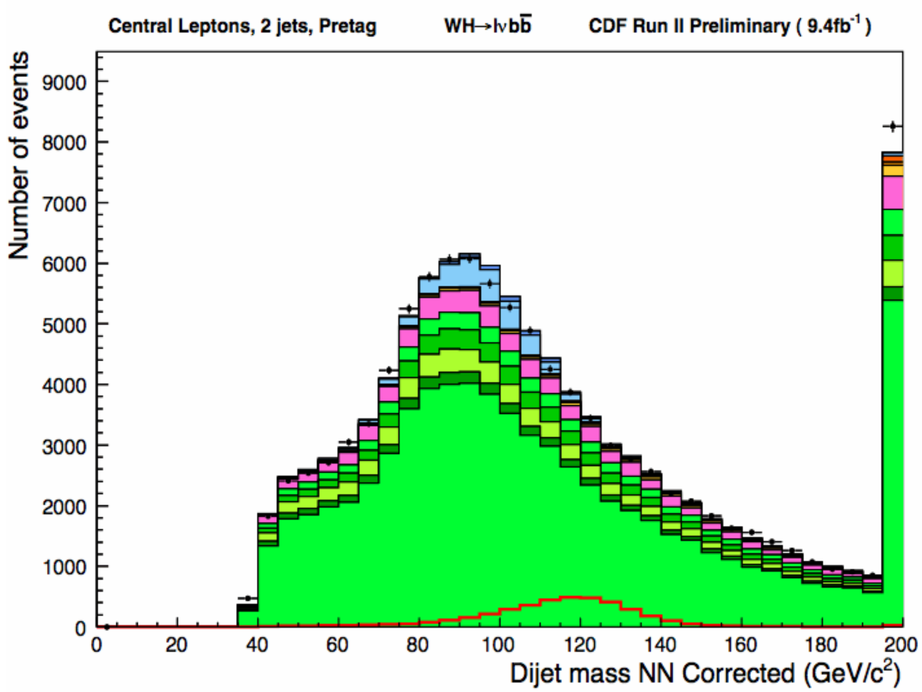
- The JES for quark jets is good – not surprising since well constrained by top mass measurements





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