Search For the Higgs Boson at the Fermilab Tevatron

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On behalf of the CDF & D0 Collaborations

Outline

- Will present updated CDF and D0 SM Higgs searches.
- Will touch on techniques driving Tevatron search sensitivity.
- Show results of new combinations in searches for :
  - $H \to W^+W^-$
  - $H \to bb$
  - $H \to \gamma\gamma$
  - SM Higgs

Related Presentations	
P. Grannis	S. Desai
E. Pianori	W. Yao
M. Casara	A. Kasmi
A. Patwa	K. Herner

For Additional Details and Latest Results see :

http://tevnphwg.fnal.gov

http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm

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

Constraints on M_H

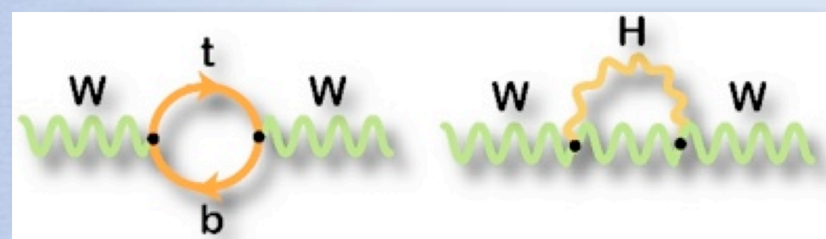
- Direct searches have excluded much of the accessible M_H range.

LEP : M_H > 114.4 GeV/c² @ 95% CL

Tevatron : Exclude M_H ~ 160 GeV/c² @ 95% CL

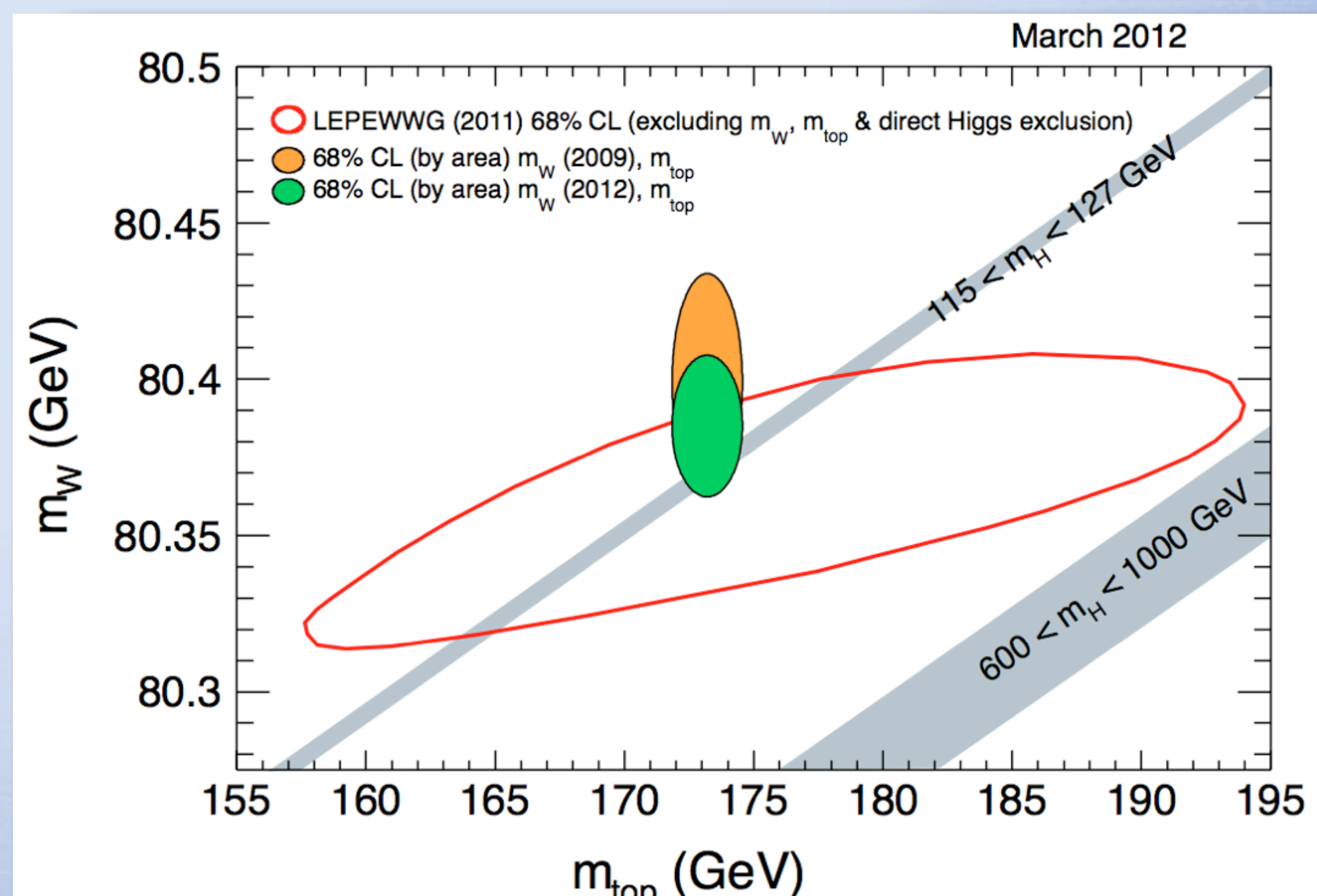
LHC : Exclude most values of M_H up to 600 GeV/c² @ 95% CL

- Indirect constraints point to lower values of M_H



Indirect Constraint from W & top masses + other precision measurements

M_H < 152 GeV/c² @ 95% CL



- Overall picture is consistent with the LHC observation

The Tevatron

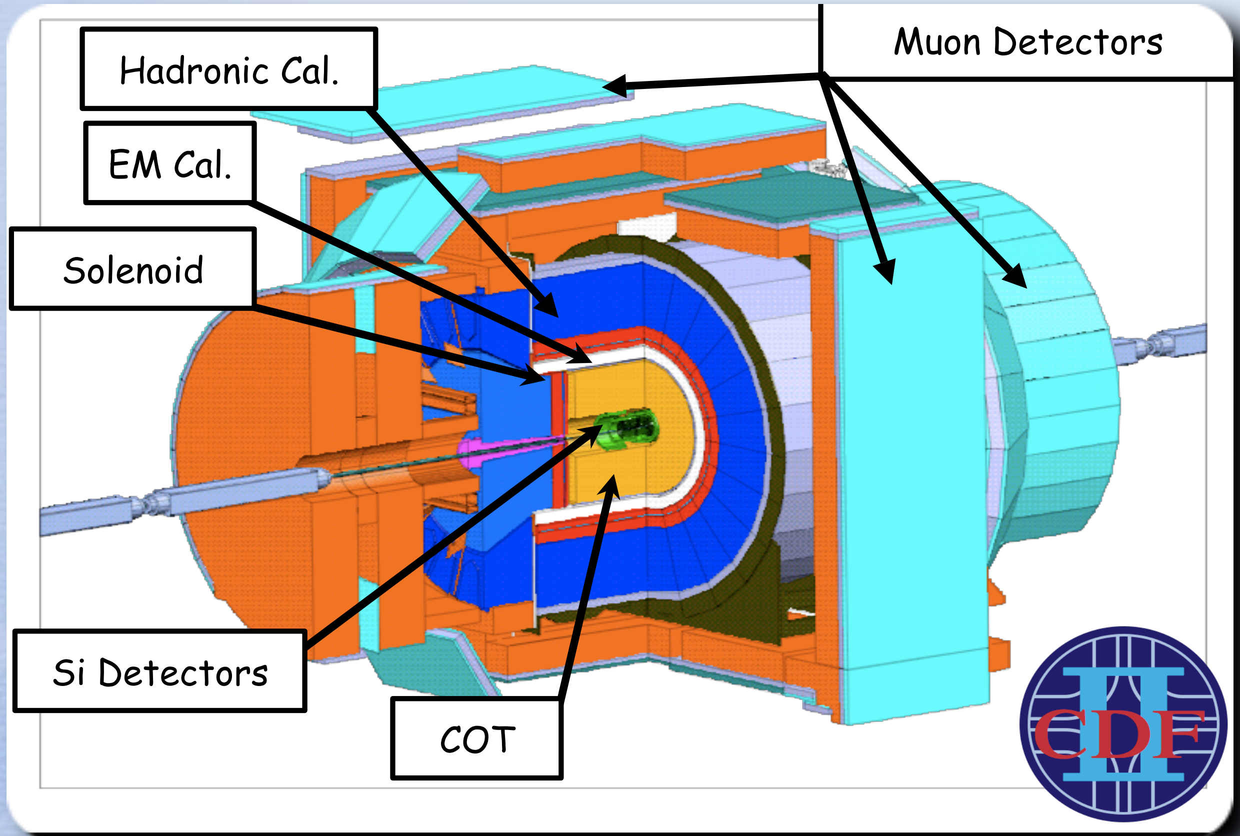
- proton anti-proton collider @ $\sqrt{s}$ = 1.96 TeV
- Delivered ~12/fb per experiment between 2002 & 2011

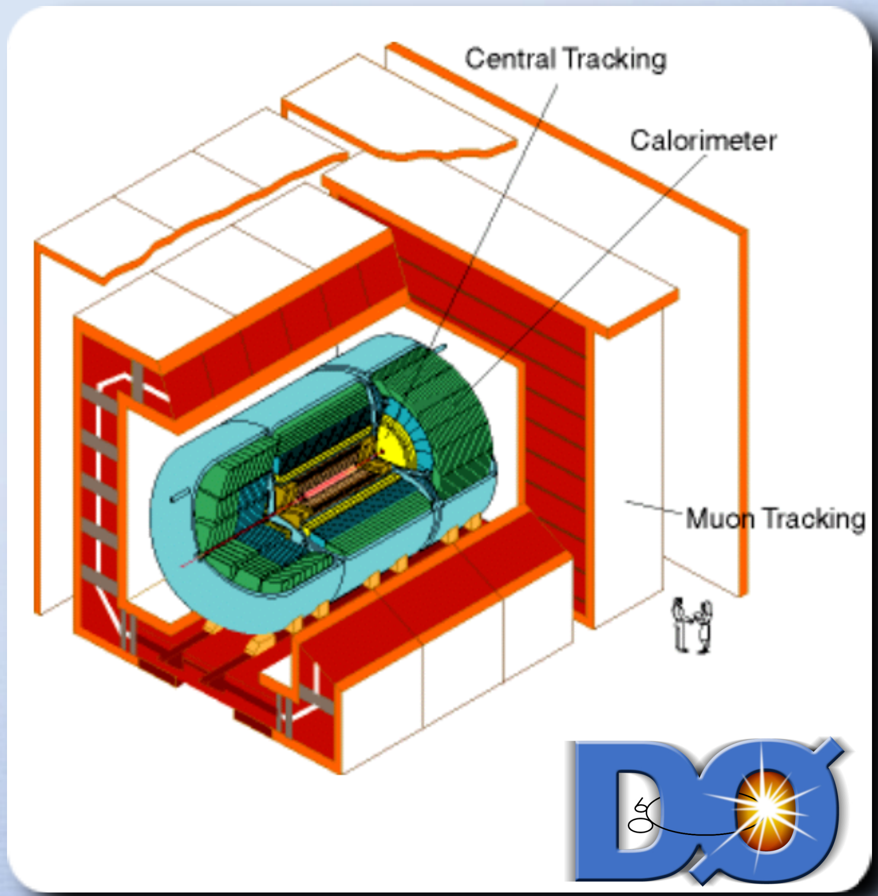
- Energy & initial state differ from LHC → unique environment for Higgs searches

Tevatron sensitivity at $M_H \lesssim 125$ GeV/c^2 driven by **H→bb** searches

CDF & D0

- CDF II and D0 are general purpose detectors
- Silicon Vertex Detectors, Tracking Chambers, Calorimetry, & Muon Systems
- Combined with multi-level 'trigger systems' to select events with topologies of interest (missing transverse energy, energetic jets/leptons)
- Data taking efficiency of ~90%





Production & Decay

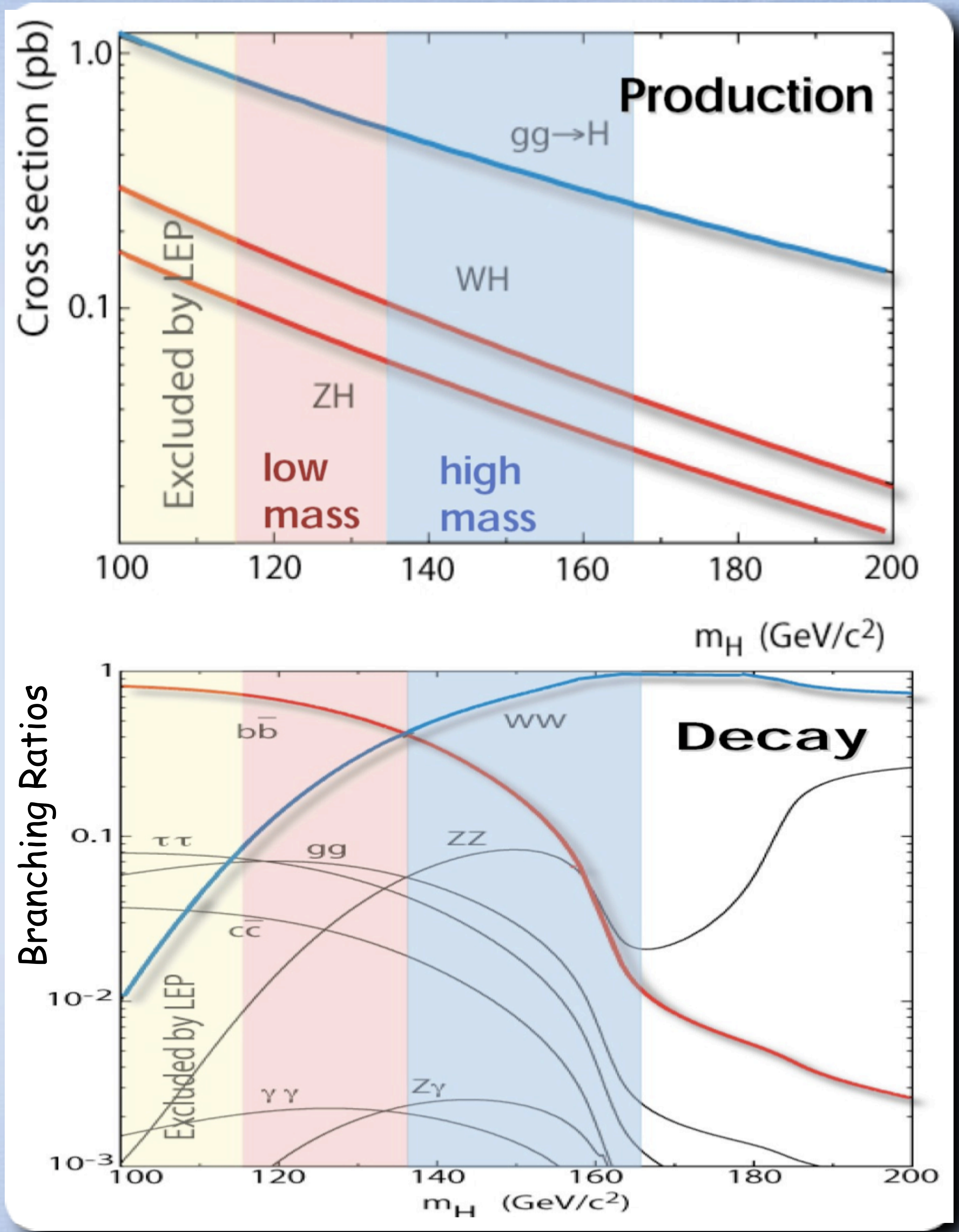
- Main production modes are :

  I. Gluon-gluon fusion ($gg \rightarrow H$)
  II. Associated Production (ZH/WH)

- Decays :

  I. mostly $H \rightarrow WW$ for $M_H > 135$ GeV
  II. mostly $H \rightarrow bb$ for $M_H < 135$ GeV

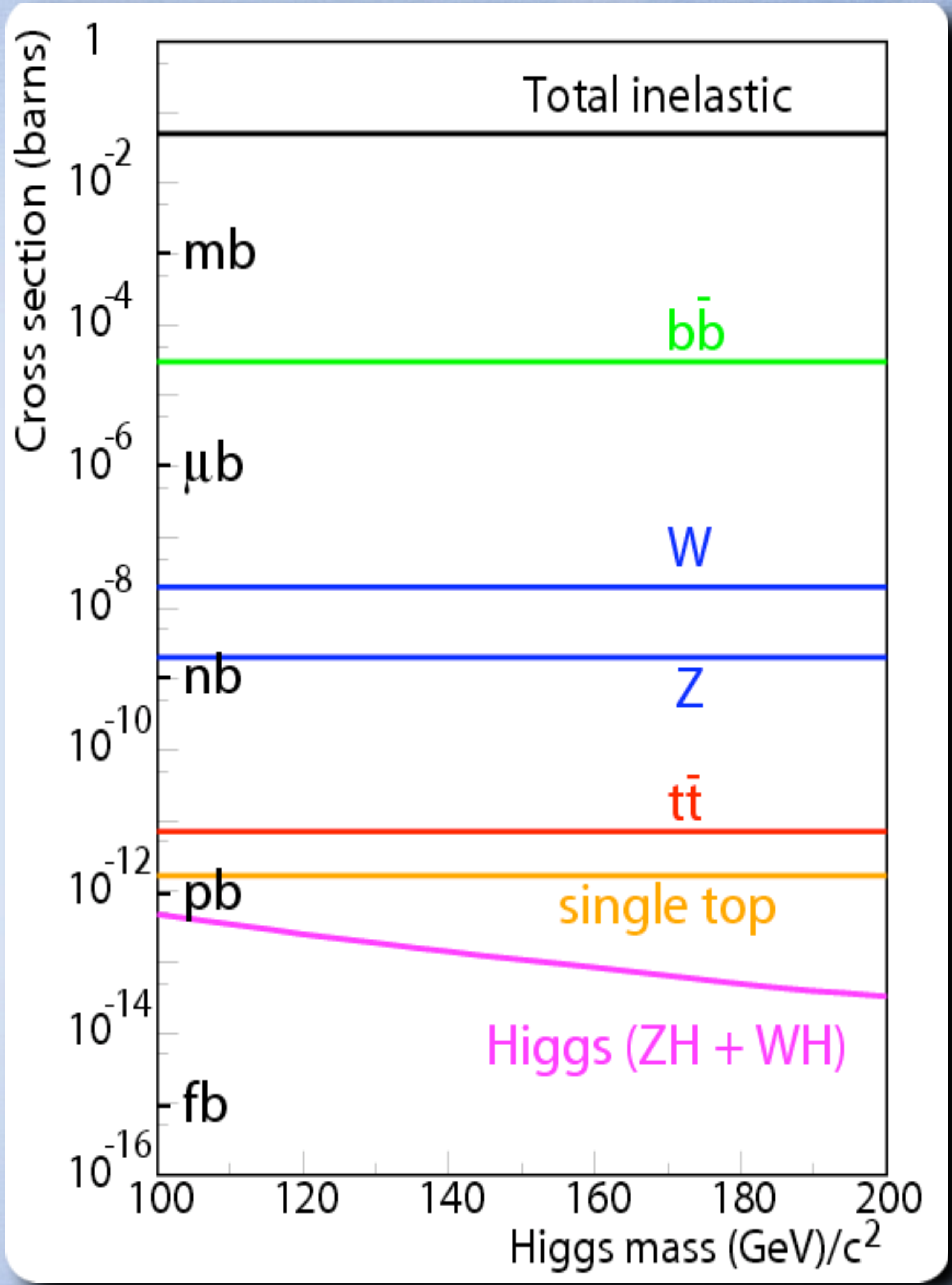
BR($H \rightarrow bb$) ~58% for $M_H = 125$ GeV



The Search Environment

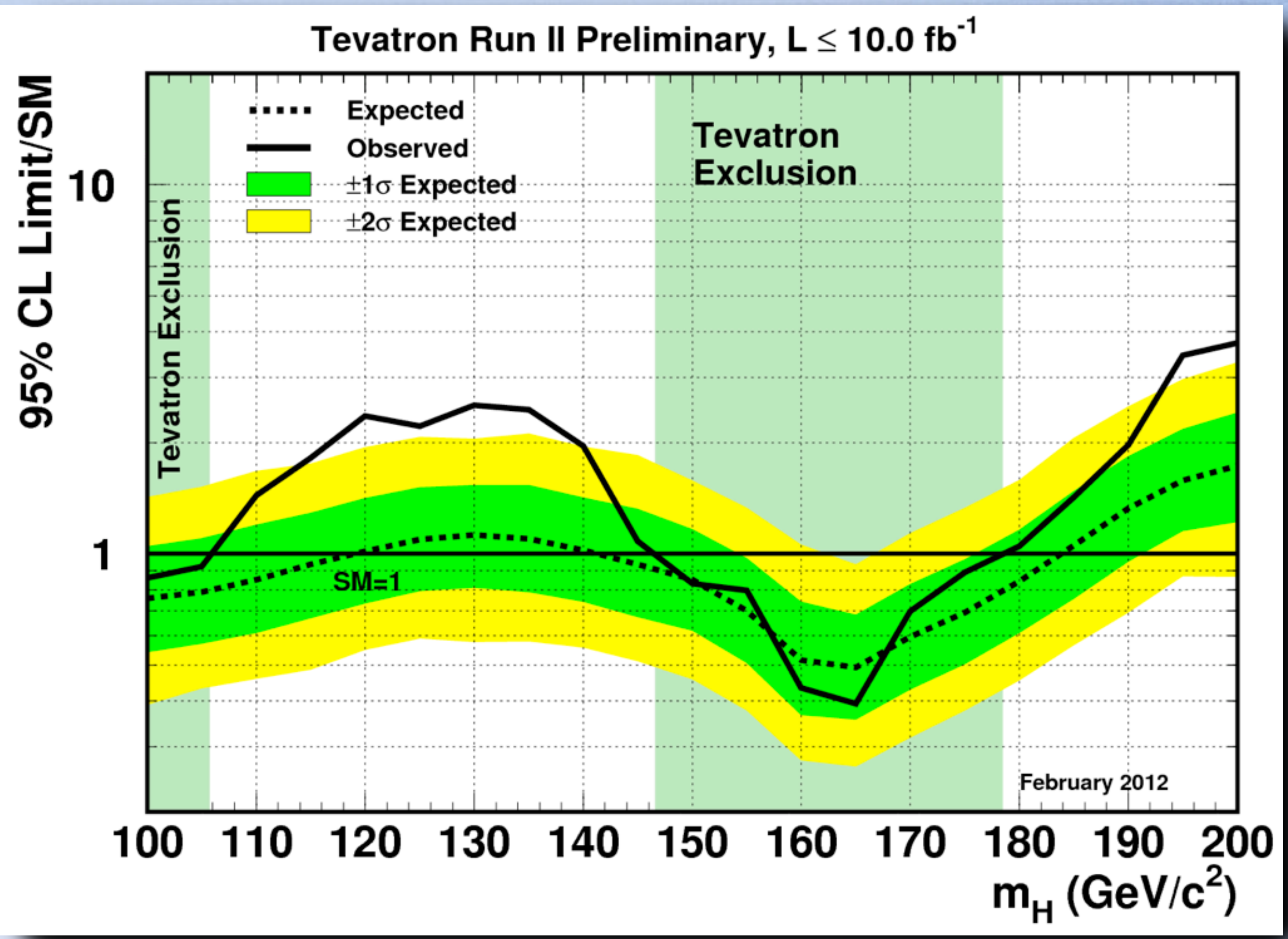
- Background rates many orders of magnitude higher than predicted SM Higgs rates
- Searches target Higgs production/decay modes with 'distinguishing' final states, relying on Z & W boson decays to differentiate signal from background

$e^{\pm}/\mu^{\pm} + \nu + bb$
$e^{-}e^{+}/\mu^{-}\mu^{+} + bb$
$\nu\,\nu + bb$
$e\nu e\nu$ / $\mu\nu\mu\nu$ / $e\nu\mu\nu$



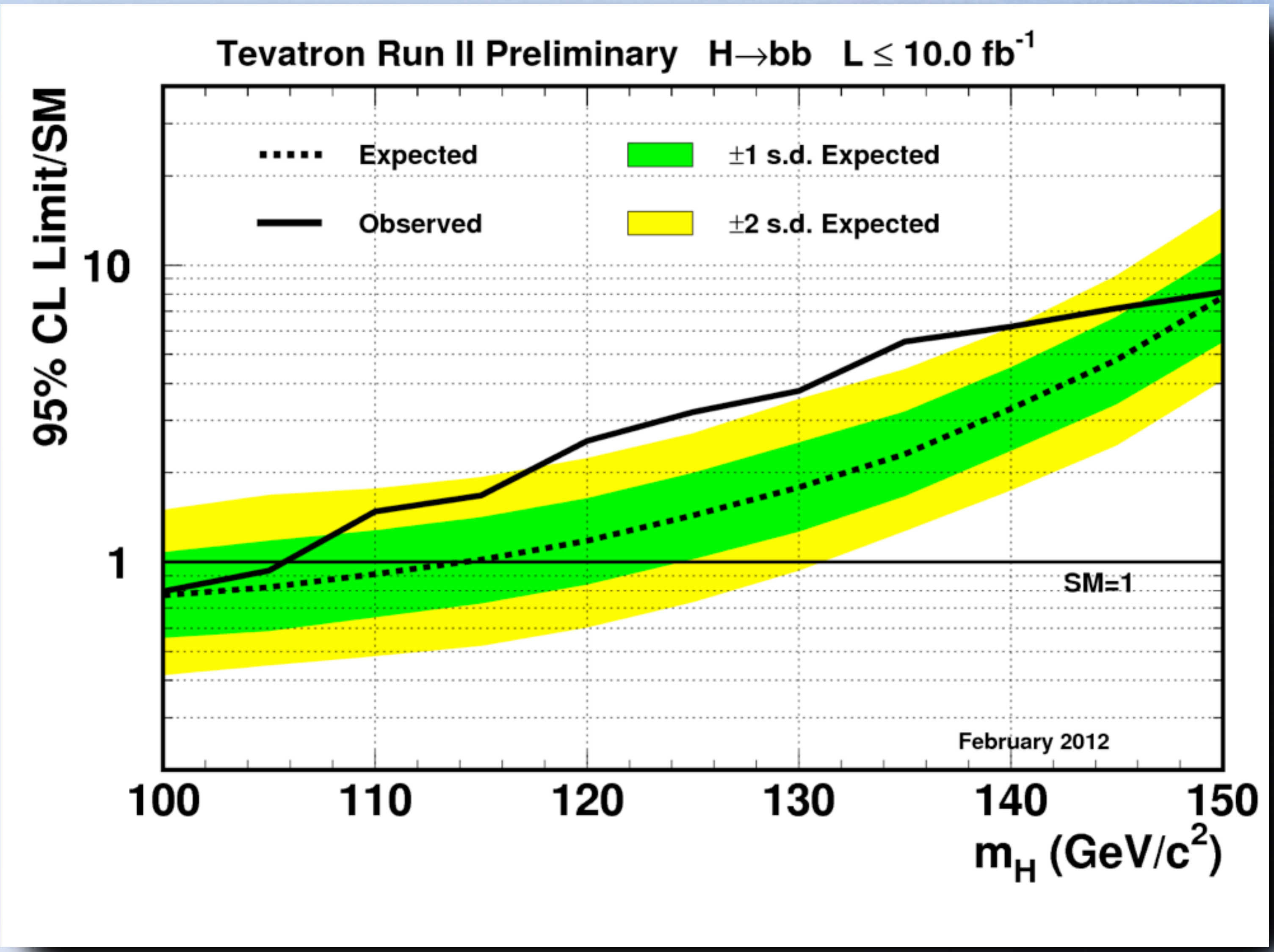
Tevatron Higgs Status (March 2012)

- CDF+D0 as of March 2012
- Combines > 100 exclusive searches
- Exclude 179> M_H > 147 GeV/c^2 @ 95% CL
- Excess in the **~115-135 GeV/c^2** range with **2.2 σ** (global) significance



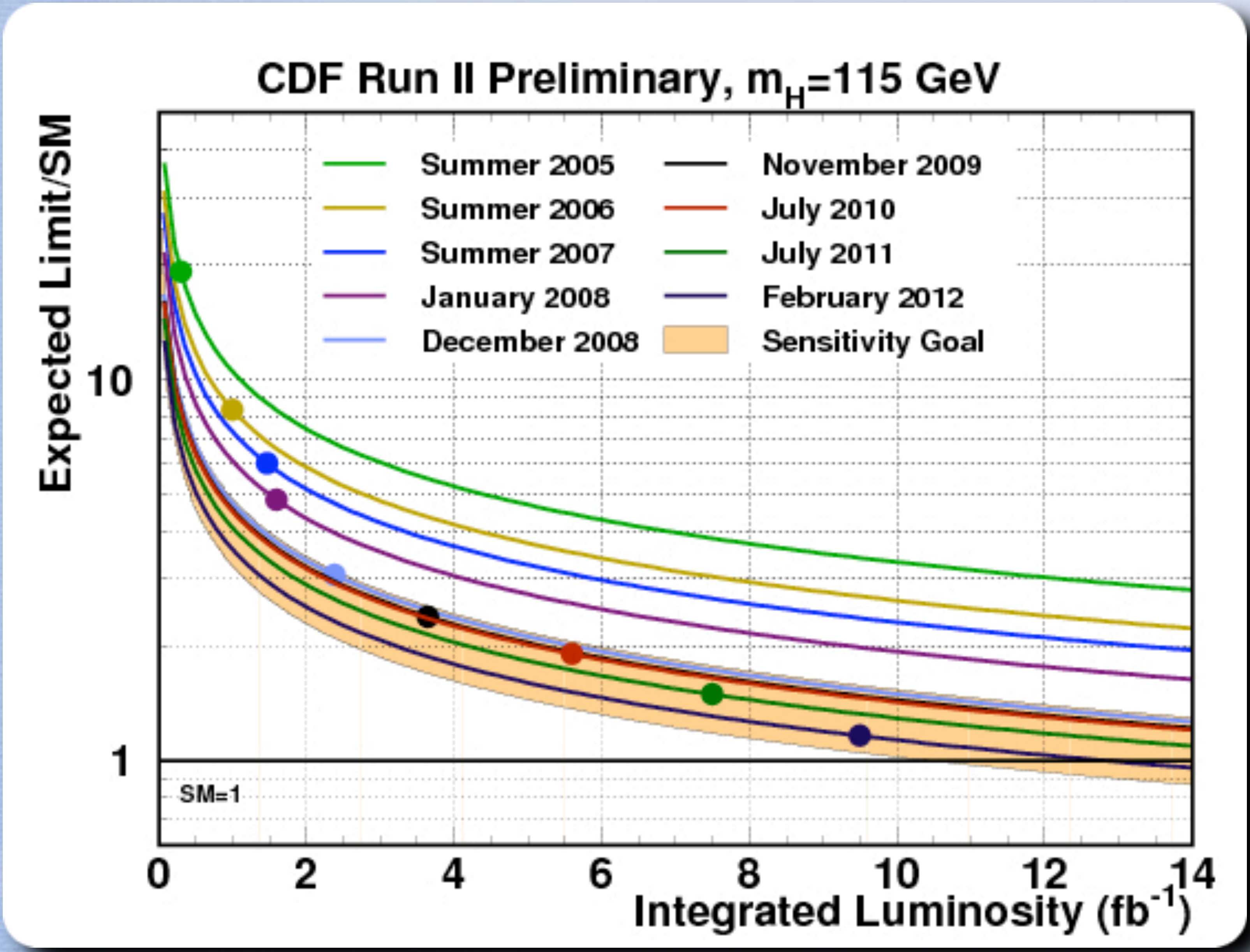
Tevatron Higgs Status (March 2012)

- Restricting to H→bb
  - Broad excess with **2.6 σ** (global) significance



Track Record of Sensitivity Improvements

- In each successive combination have introduced analysis techniques that boost sensitivity beyond expectation from increased data sample alone



- increased lepton acceptance
- better b-tagging
- improved signal discrimination & background rejection

Not finished yet!

Updates for Summer 2012

Search Mode	Changes
$H \rightarrow W^+W^-$	DØ (technique + new data)
$H \rightarrow \gamma\gamma$	DØ (technique)
$ZH \rightarrow l^+l^-bb$	DØ (technique) CDF (minor changes)
$WH \rightarrow l\nu bb$	DØ (technique)
$VH \rightarrow \nu\nu bb$	DØ (technique) CDF (minor changes)
trilepton + X ($H \rightarrow ZZ$ / $H \rightarrow WW$)	DØ (technique)

- ~10% gains in sensitivity for channels with improved technique

Search Overview

- Common features of Tevatron searches :

I. Optimized **selection** (maximize Higgs acceptance, minimize background)
II. **Multivariate** discriminant (Neural Networks, Boosted Decision Trees)
III. Careful treatment of **systematics**, correlated across channels & experiments as appropriate

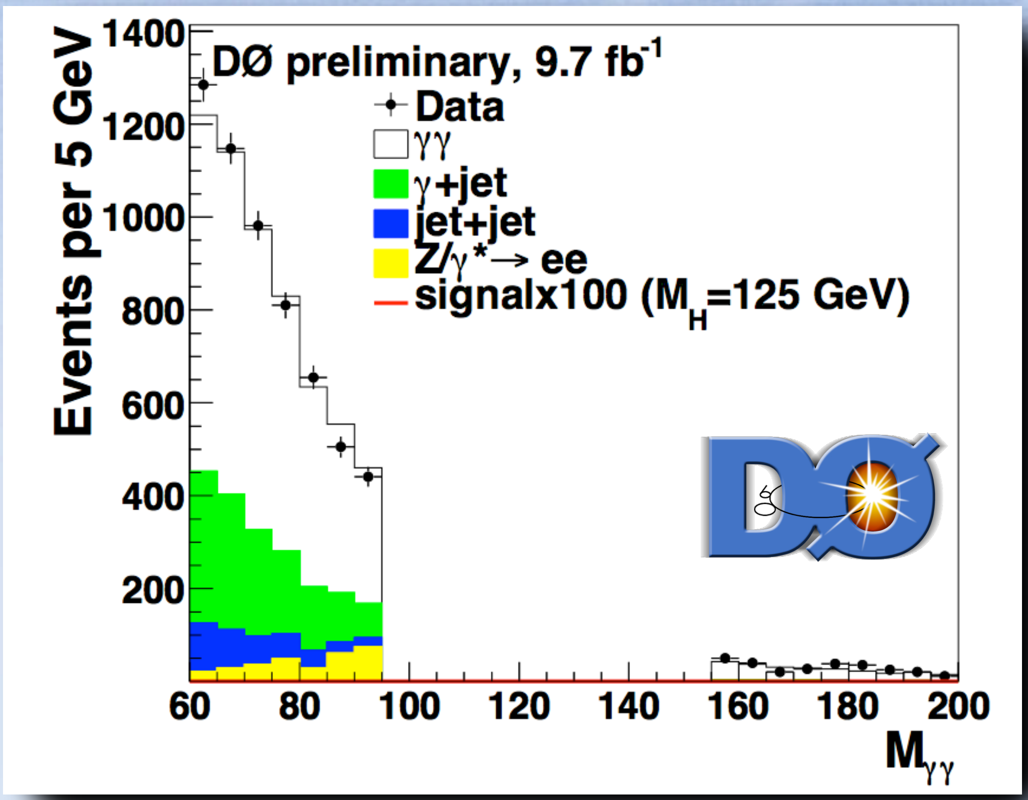
Typical Systematics	Magnitude (+/- σ)
Luminosity	6%
Signal Production Rate	5-30%
background normalization	6-50%
Jet Energy Scale	~7%

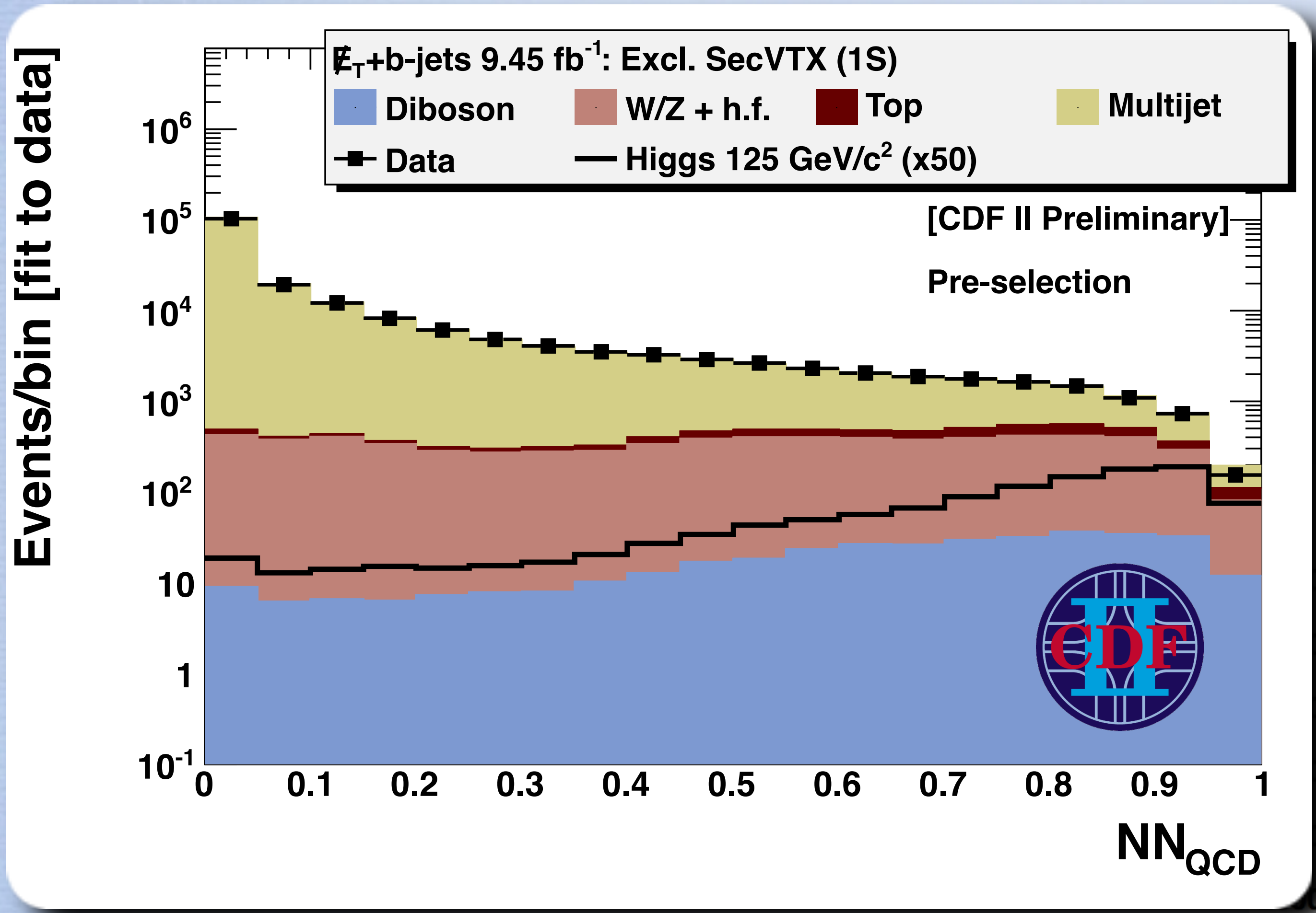
Overall impact ~15-20% degradation in sensitivity

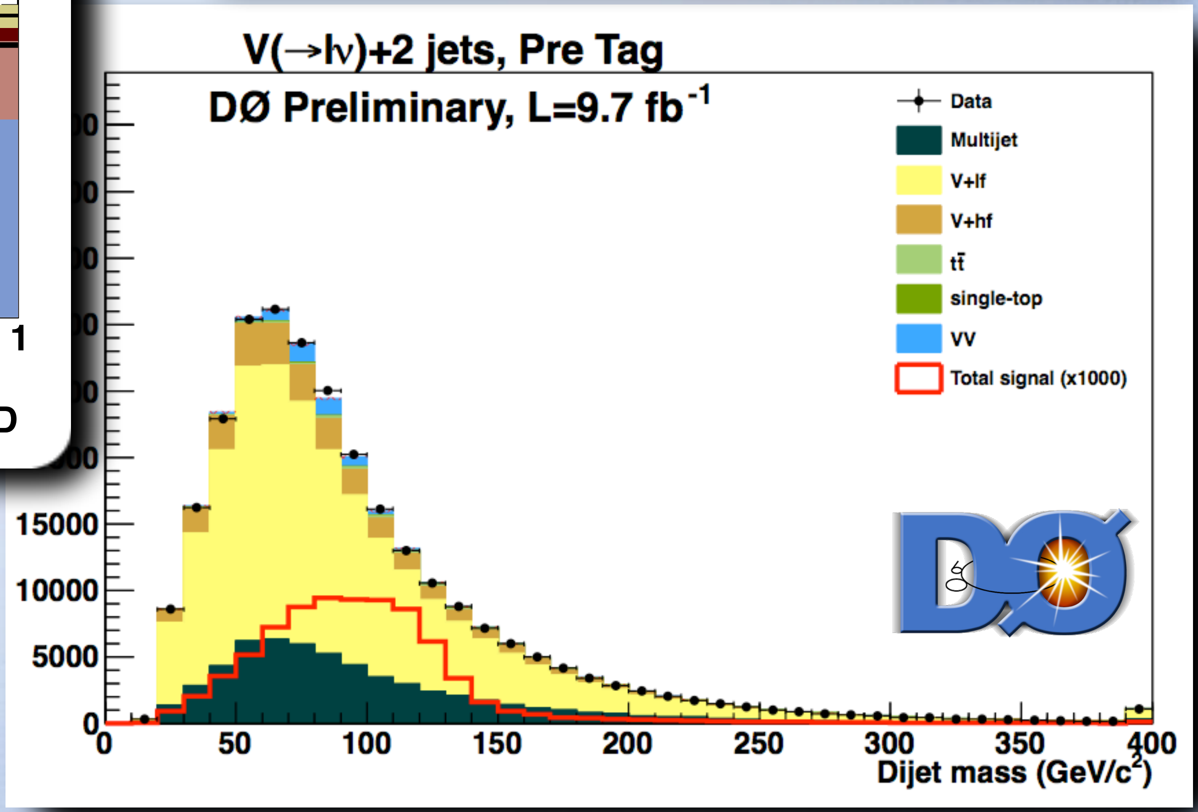
- Extract 95% CL Upper limits on Higgs production rate using both Bayesian & CLs statistical techniques (average ~1% level agreement)

Search Validation

- Understanding of SM backgrounds demonstrated in control regions



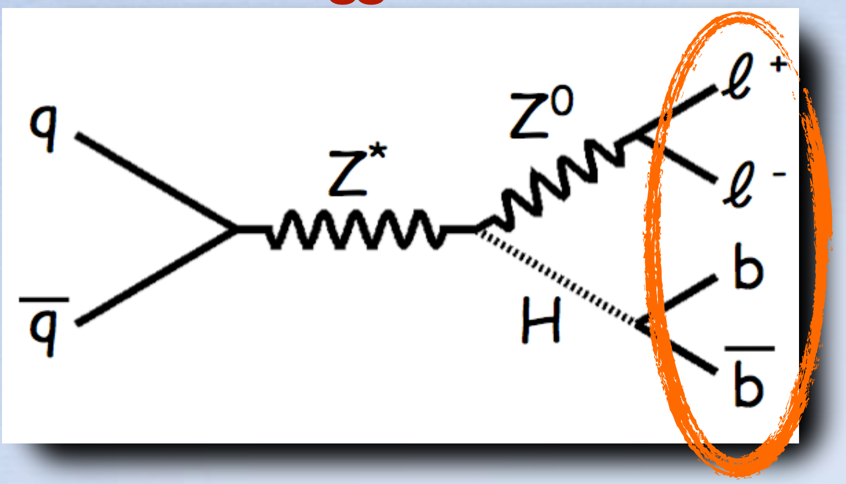




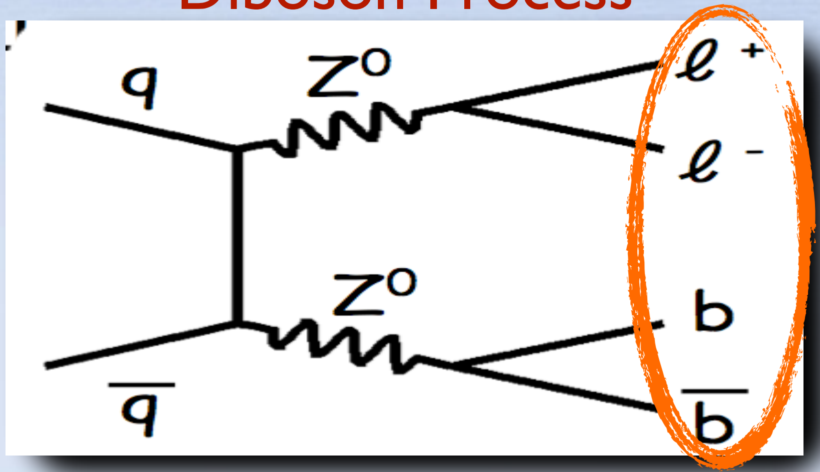
Search Validation

- H→bb search techniques validated with ZZ/WZ diboson extraction

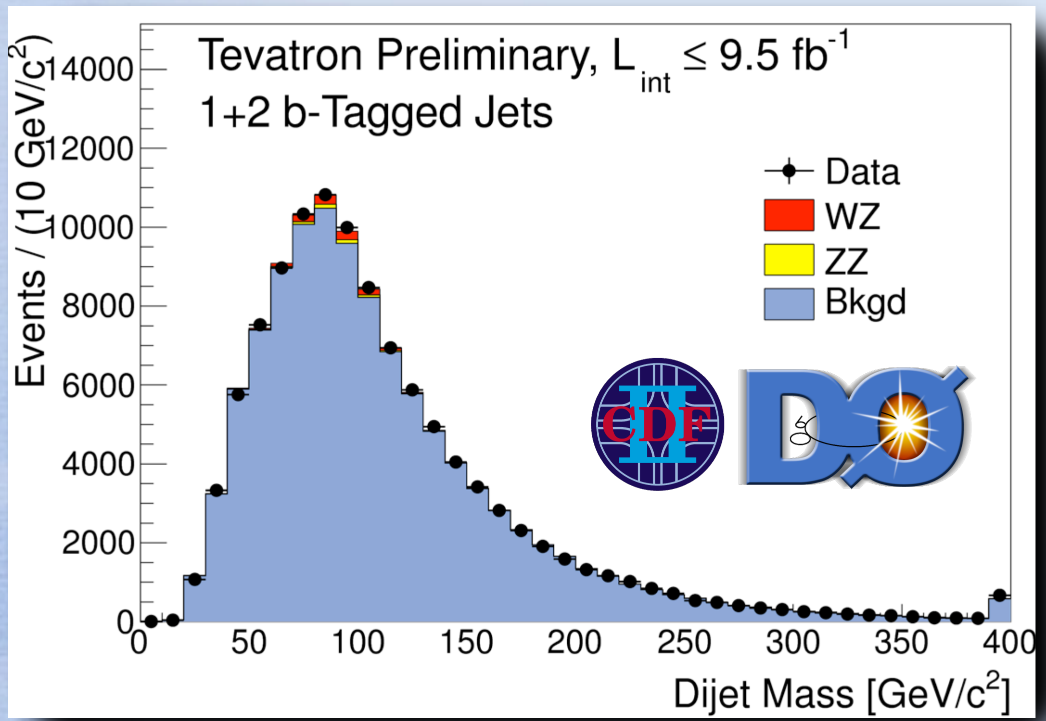
Higgs Process

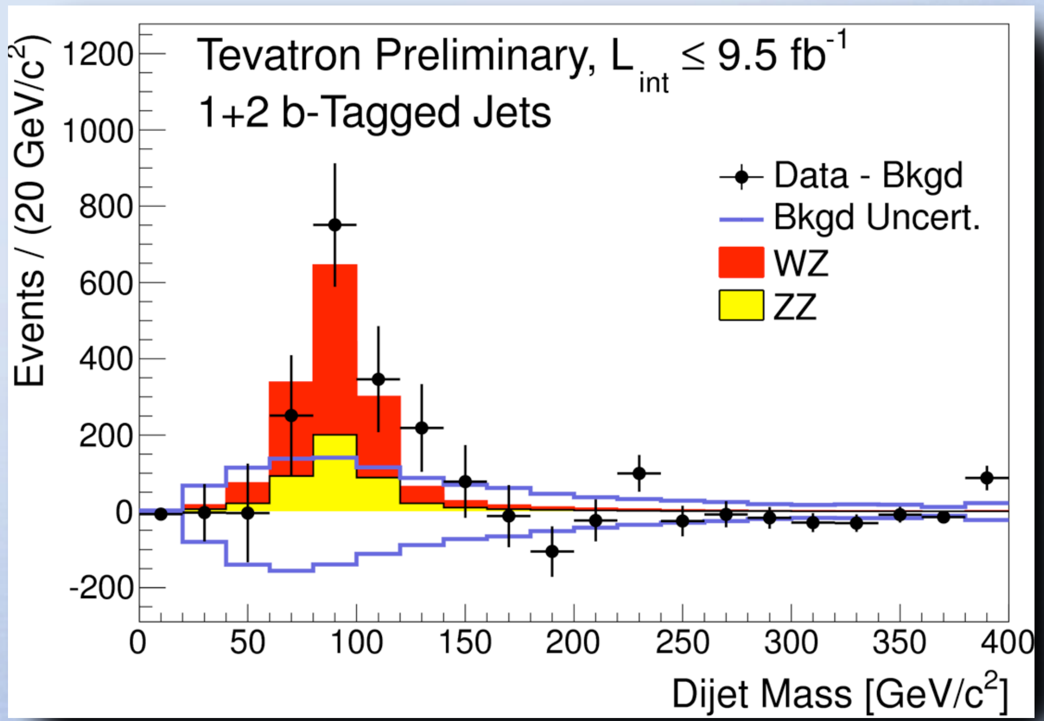


Diboson Process



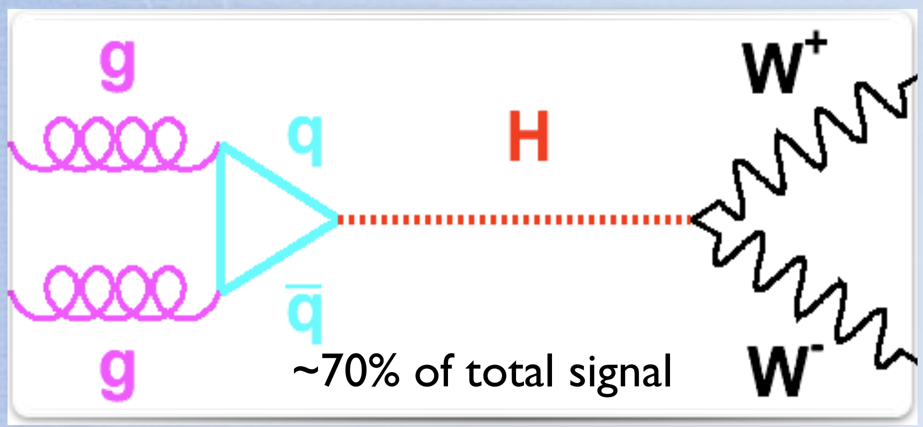
- Validates modeling and ability to extract a Z→bb signal with a production rate ~1 order of magnitude greater than H→bb



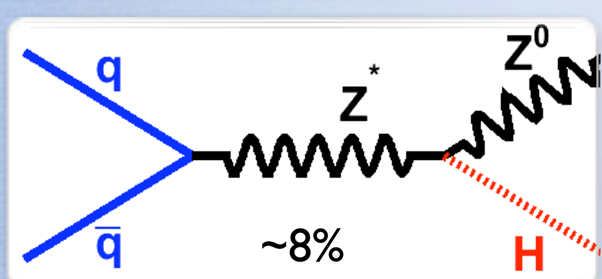


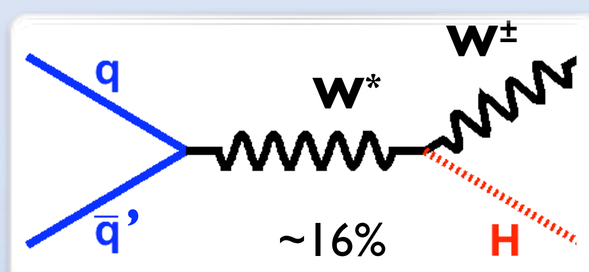
Searches for $H \rightarrow W^+W^-$

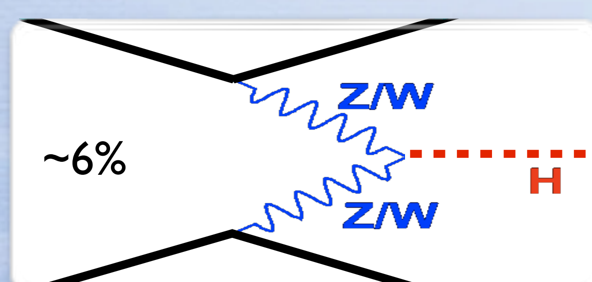
- Primary Signal :



- Additional sensitivity gained by including contributions from :

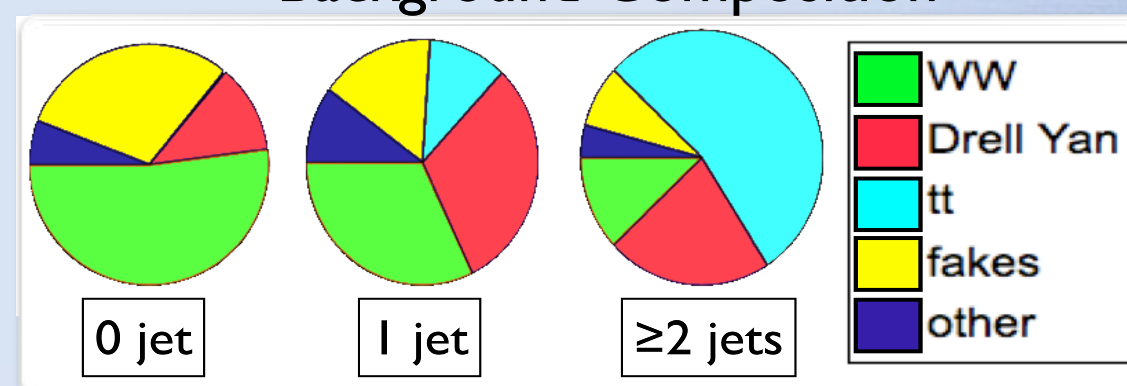




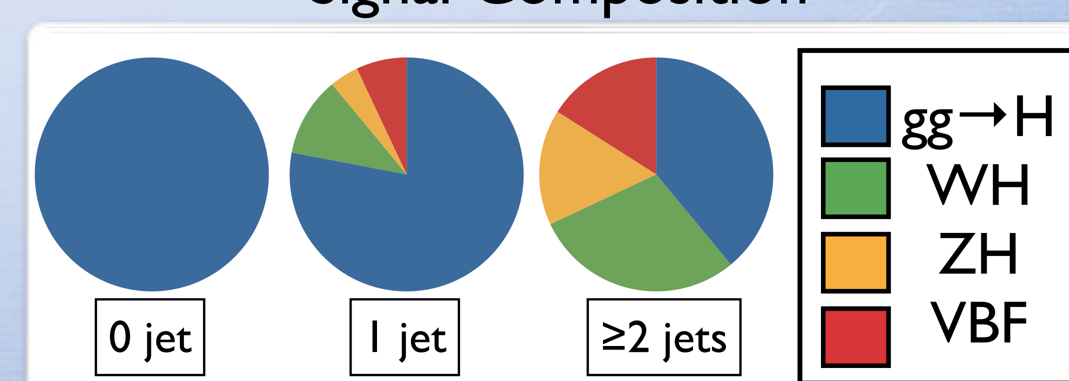


- Selection ($W \rightarrow l^{\pm}\nu$) : high P_T leptons + significant missing E_T
- Separate searches in 0, 1 and ≥2 jet final states
- Background & Signal vary with number of jets

Background Composition

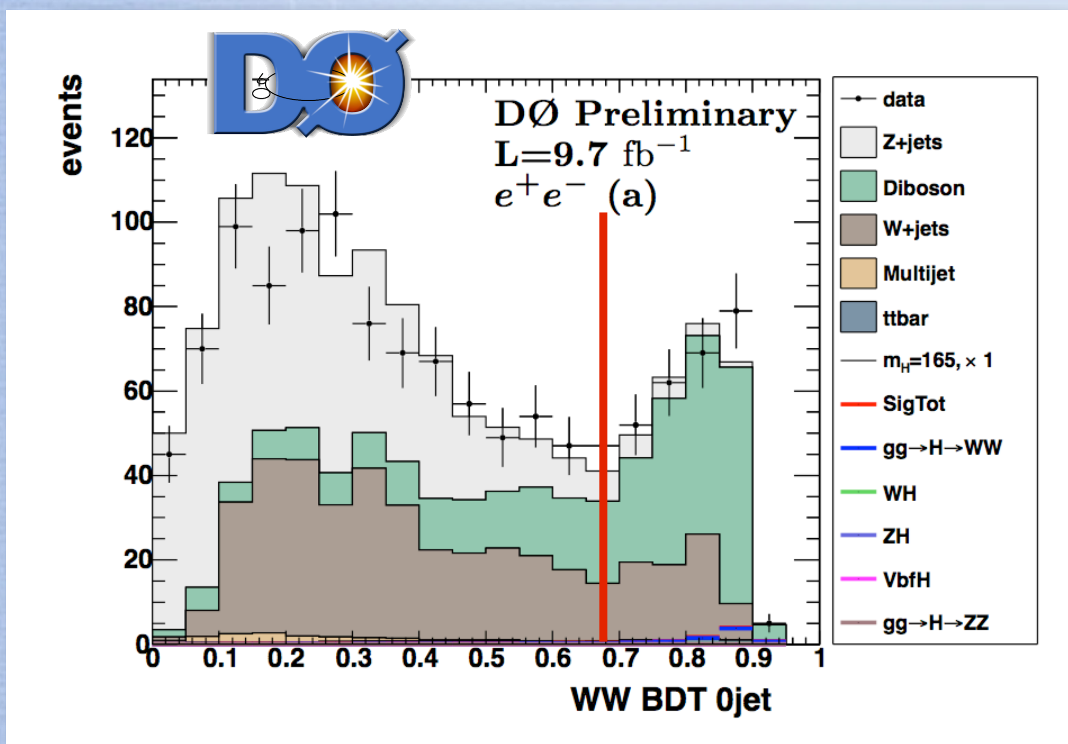


Signal Composition

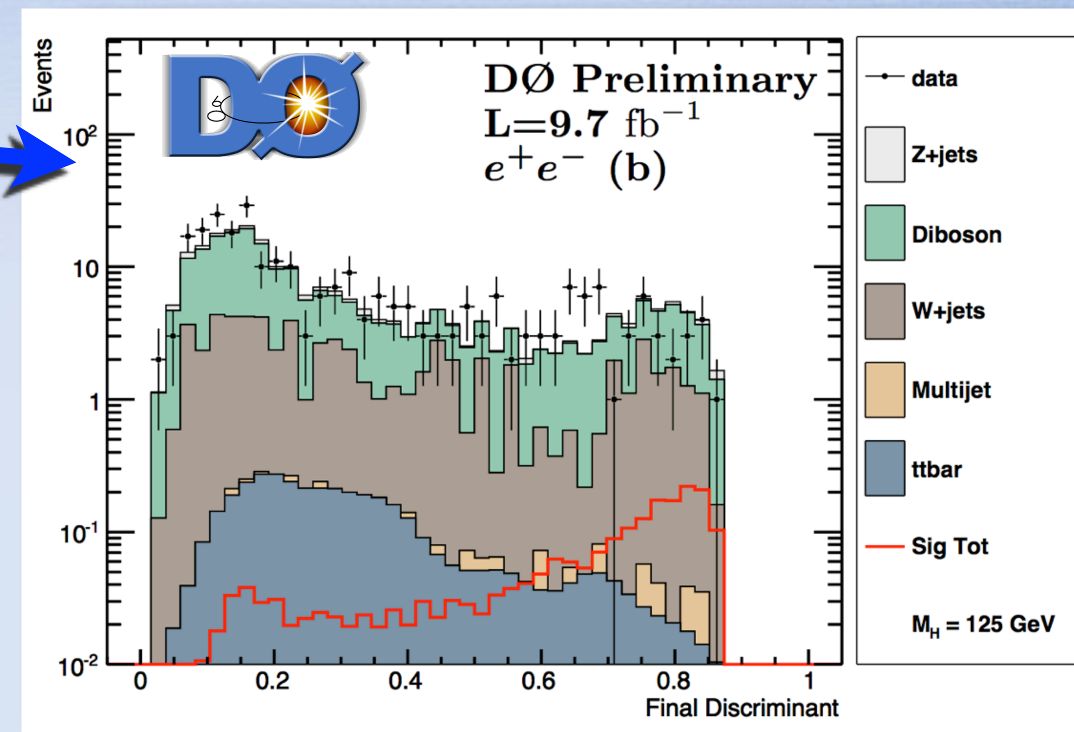


Searches for H→W⁺W⁻

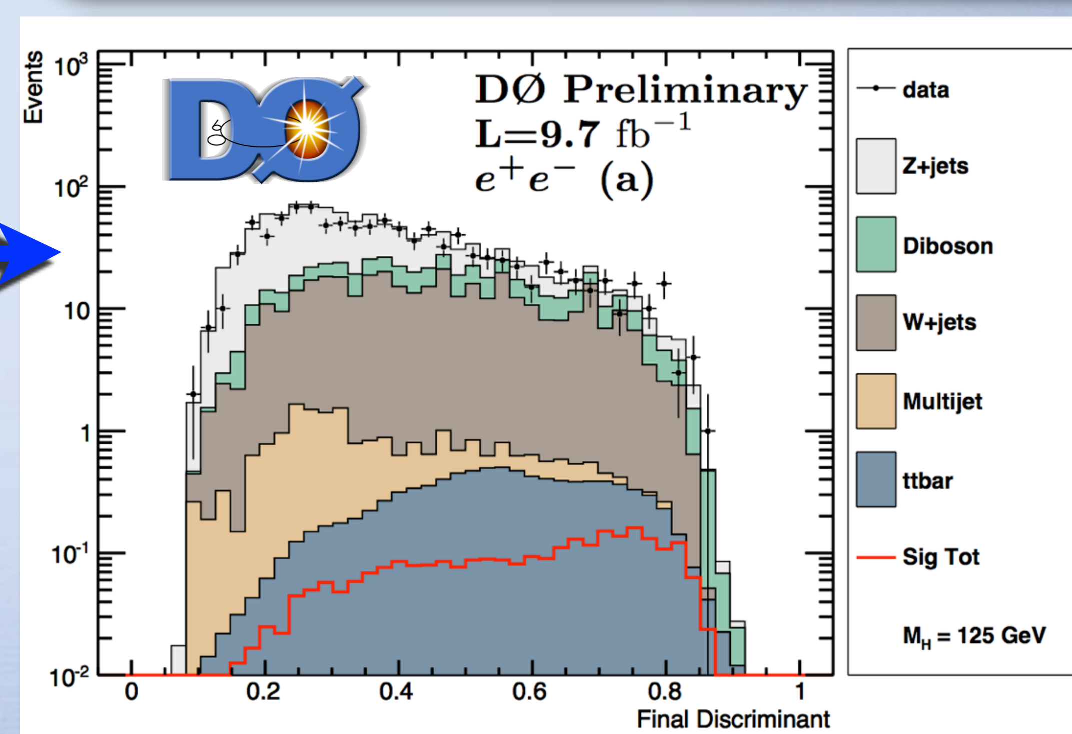
- Advanced use of Multivariate techniques (better isolate high S/B candidates)



WW-rich



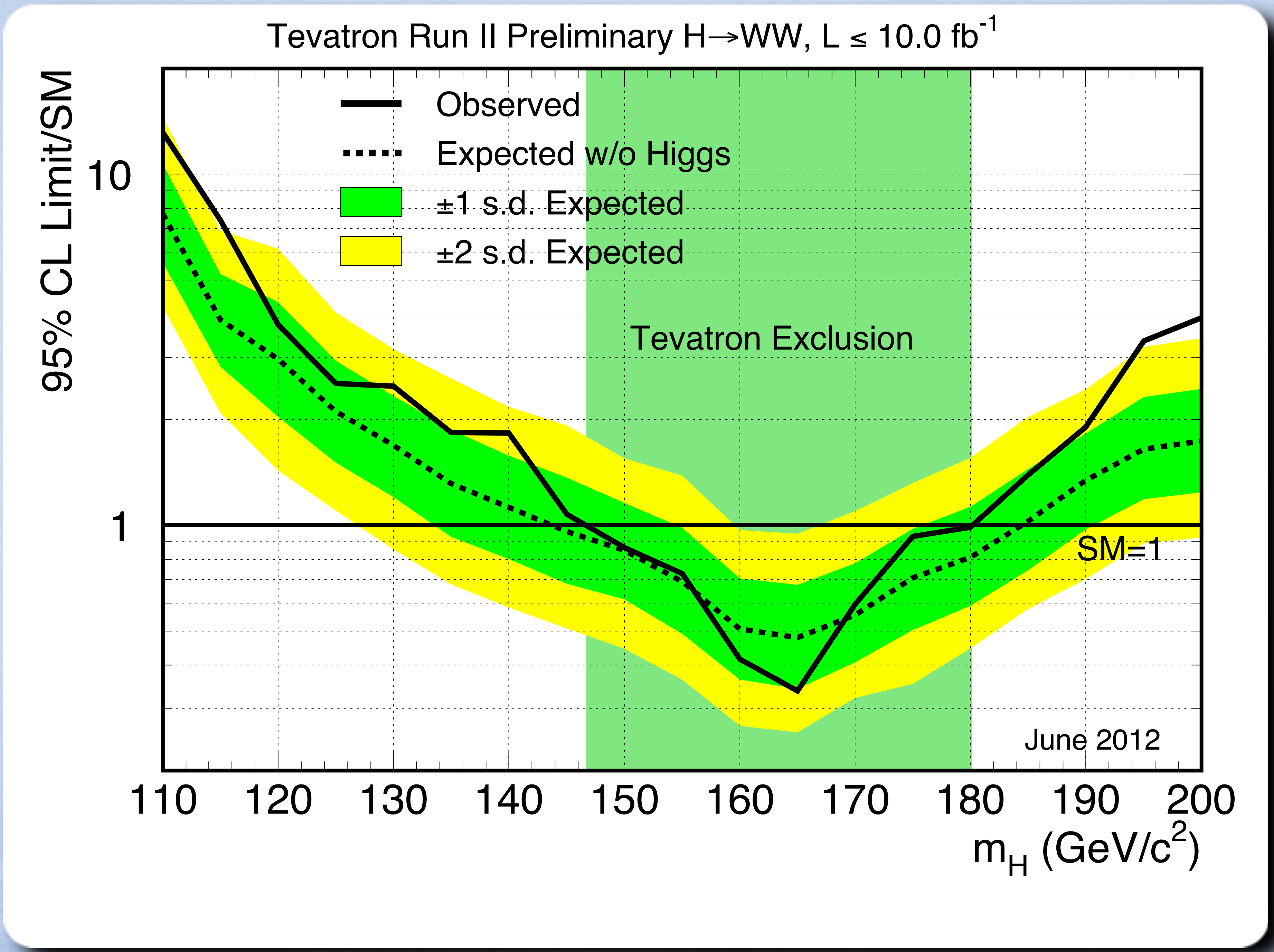
WW-depleted



- 5-10% gain in expected sensitivity
- Similar strategy employed in H→γγ and H→bb

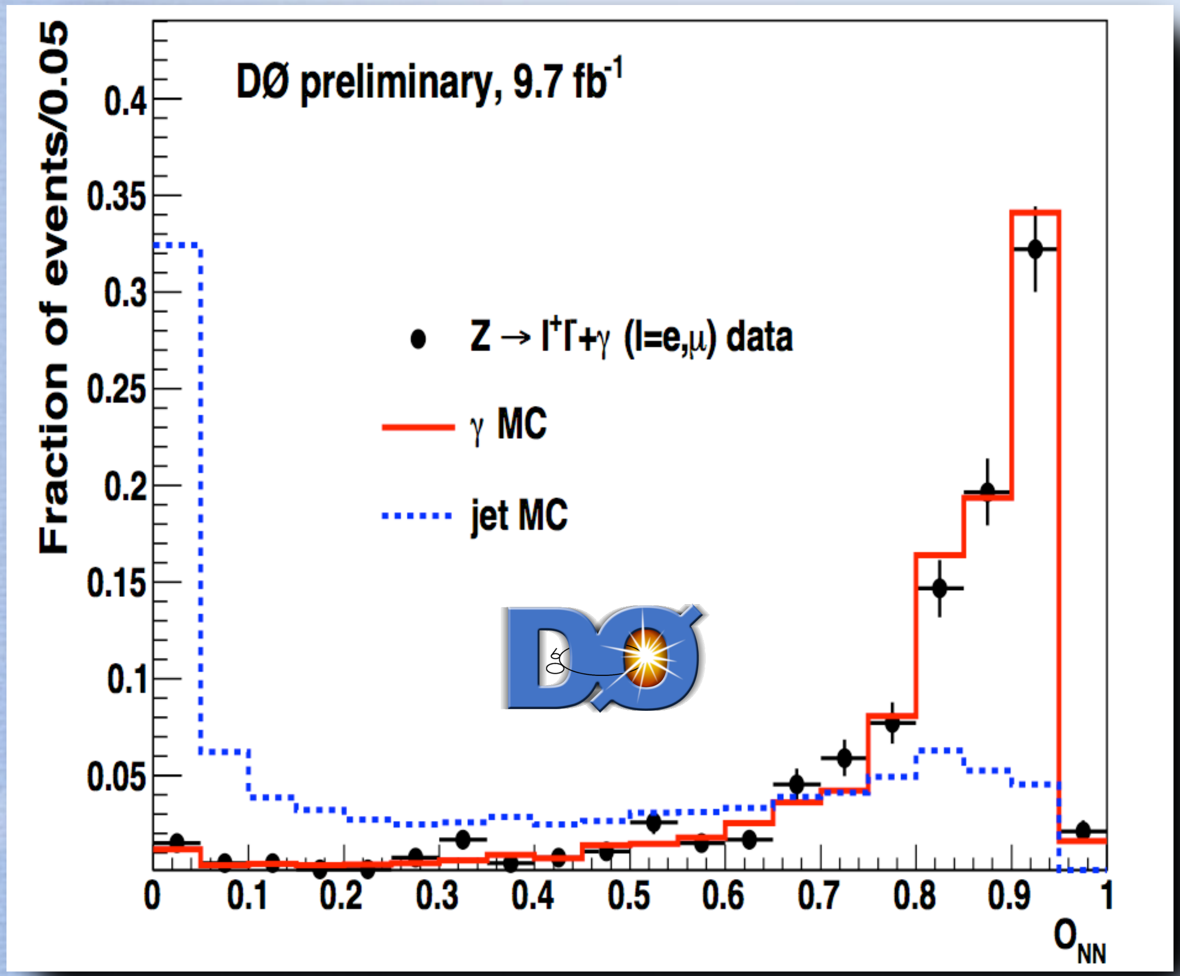
$H \rightarrow W^+W^-$ Combination

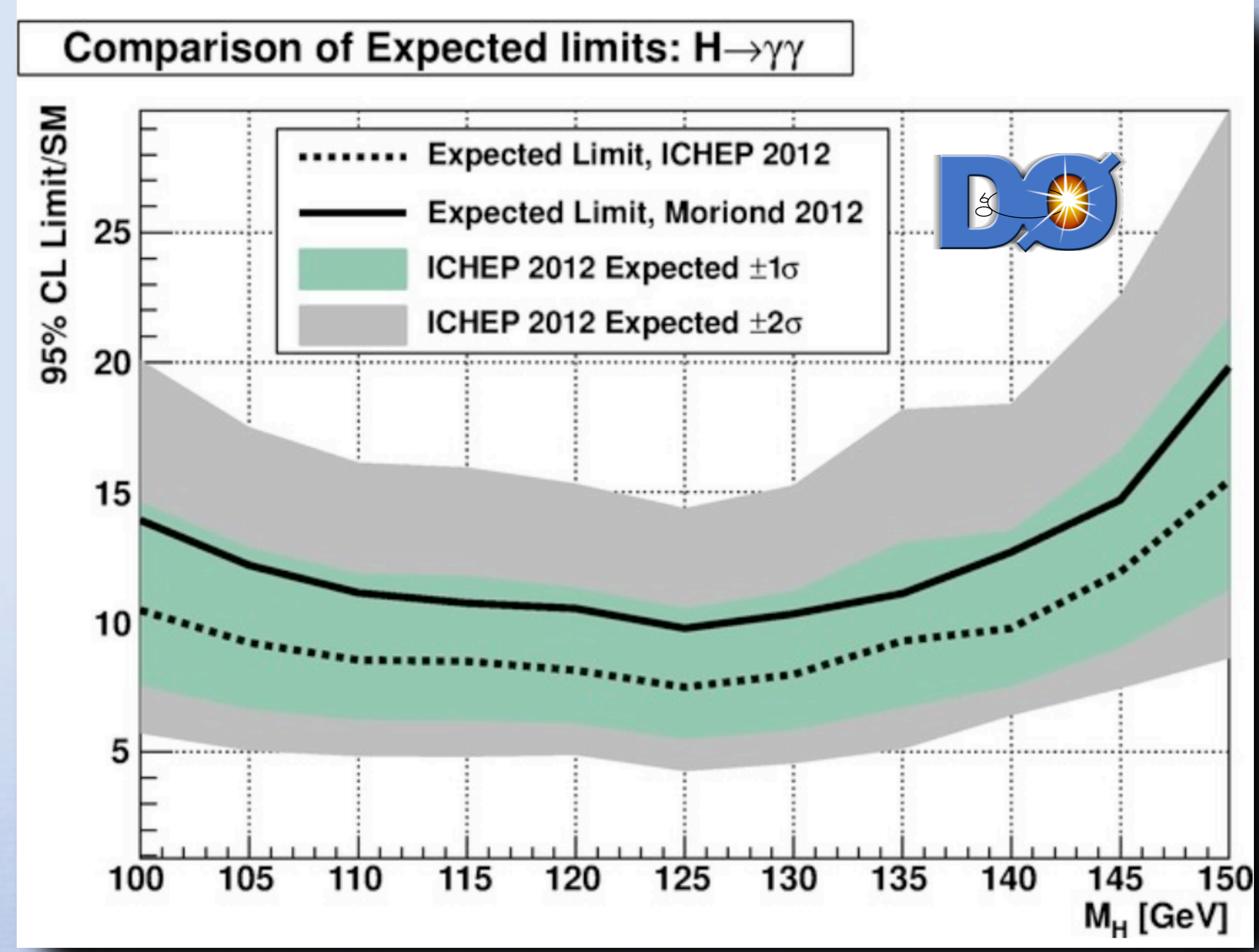
- Exclude 180> M_H > 147 GeV/c^2 @ 95% CL



Searches for H→γγ

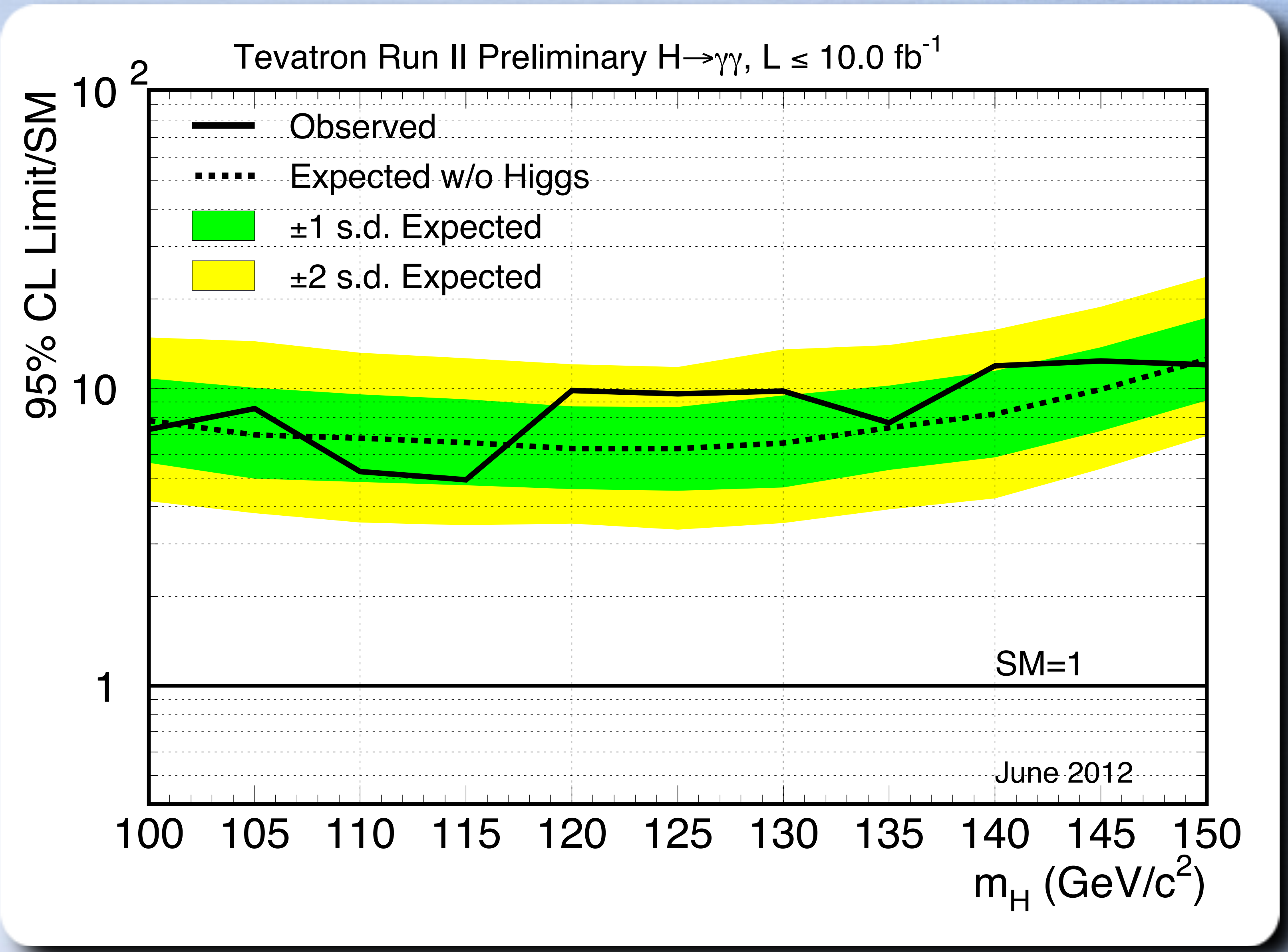
- Select 2 photons using NN
- NN also used to form jet-enriched & jet-depleted samples
- Improved search techniques (including improved MVA)





$H \rightarrow \gamma\gamma$ Combination

- Expected 95% CL Upper limit/SM = 6.3XSM @ 125 GeV/c^2
- ~15% more sensitive than March 2012 search

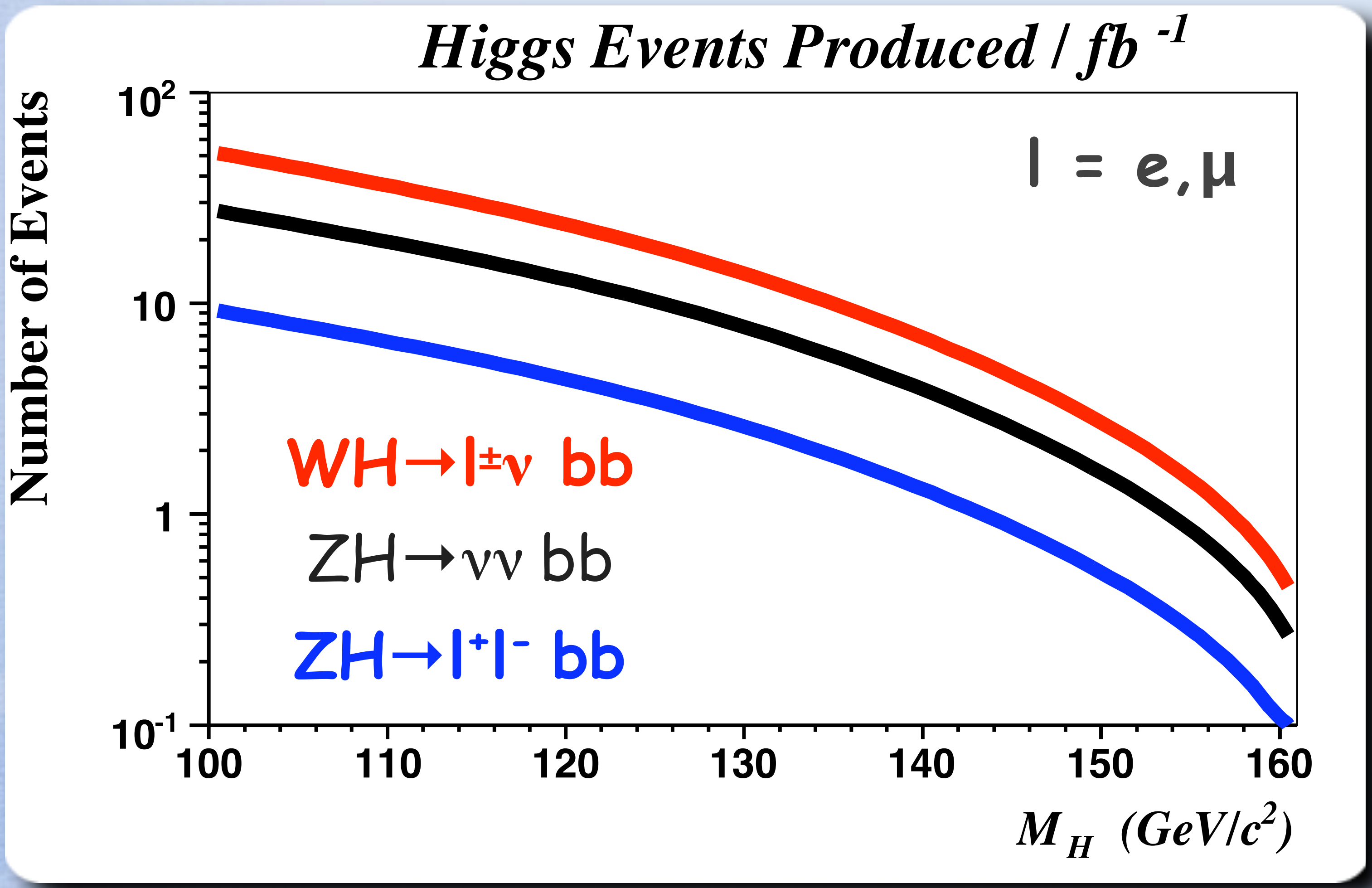


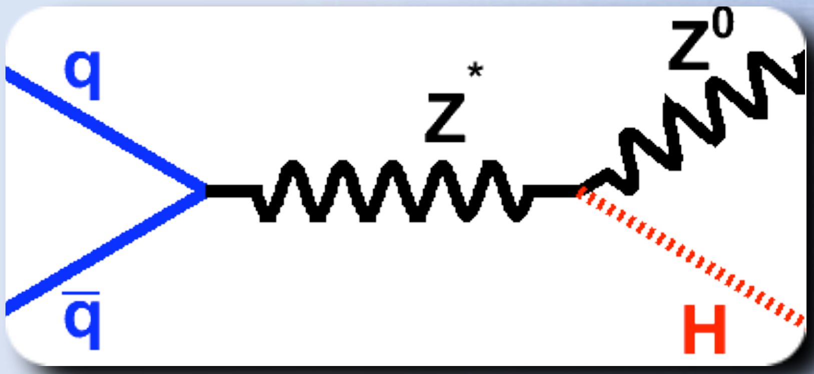
Searches for H→bb

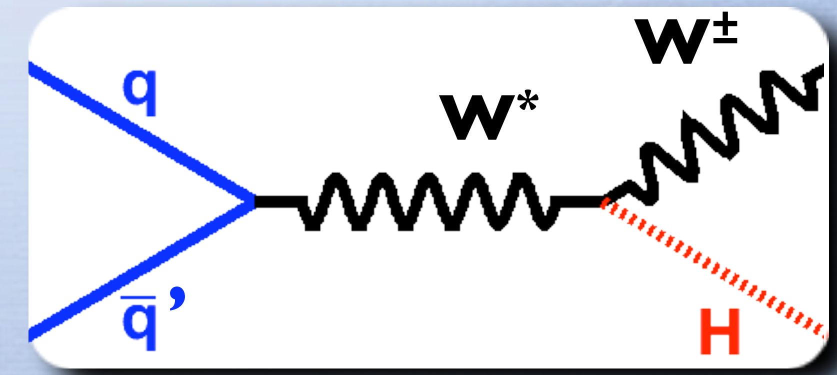
- Searches divided by number of charged leptons in final state

0 leptons	50% ZH→ννbb + 50% WH→l±ν bb
1 lepton	WH→l±ν bb + small contributions from ZH→l+l-bb
2 leptons	mainly ZH→l+l-bb

- Challenging due to low signal rates (~100 events/fb) & large Z/W backgrounds



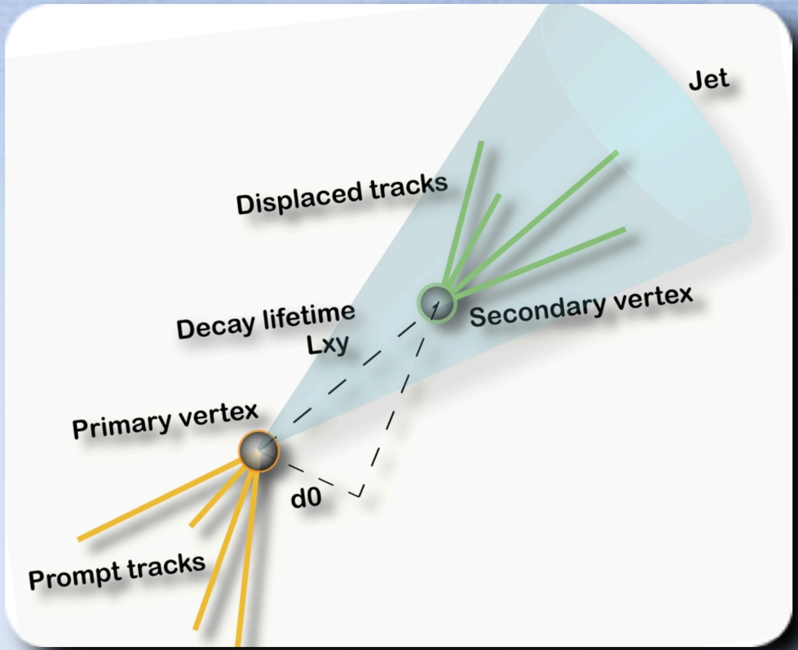




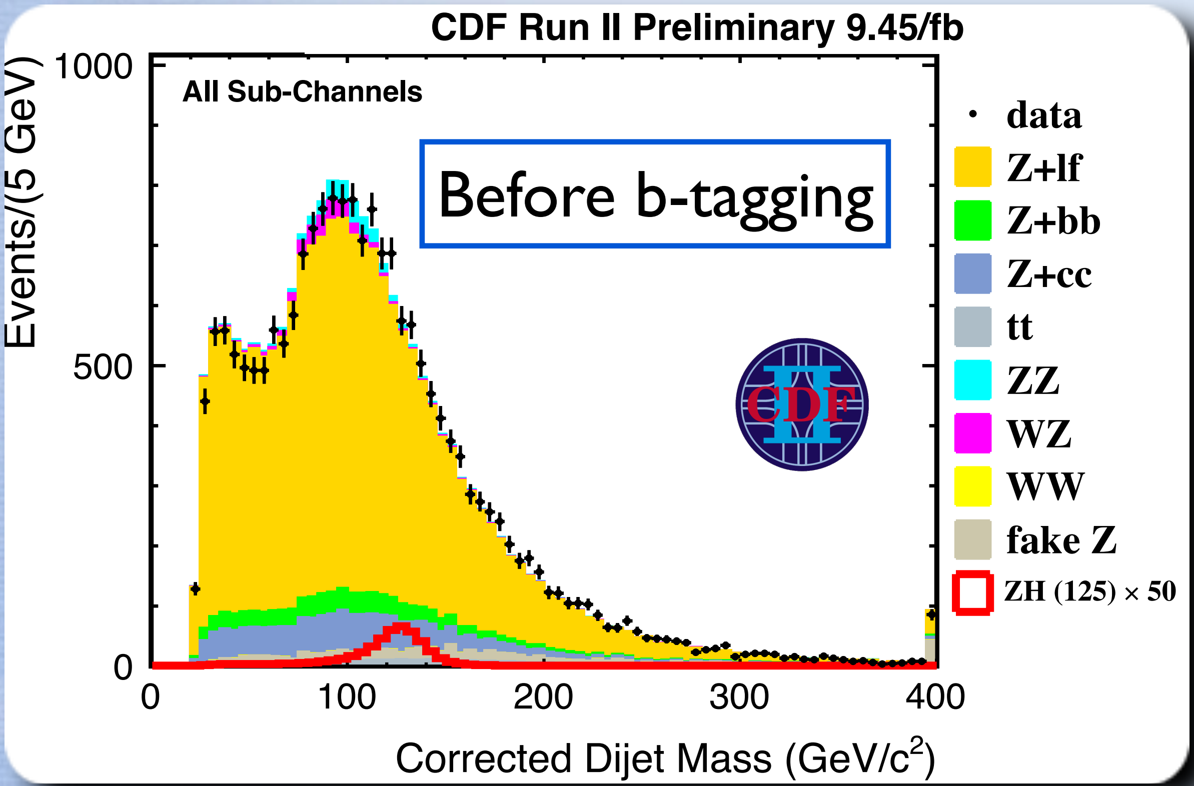
b-jet Tagging is Key

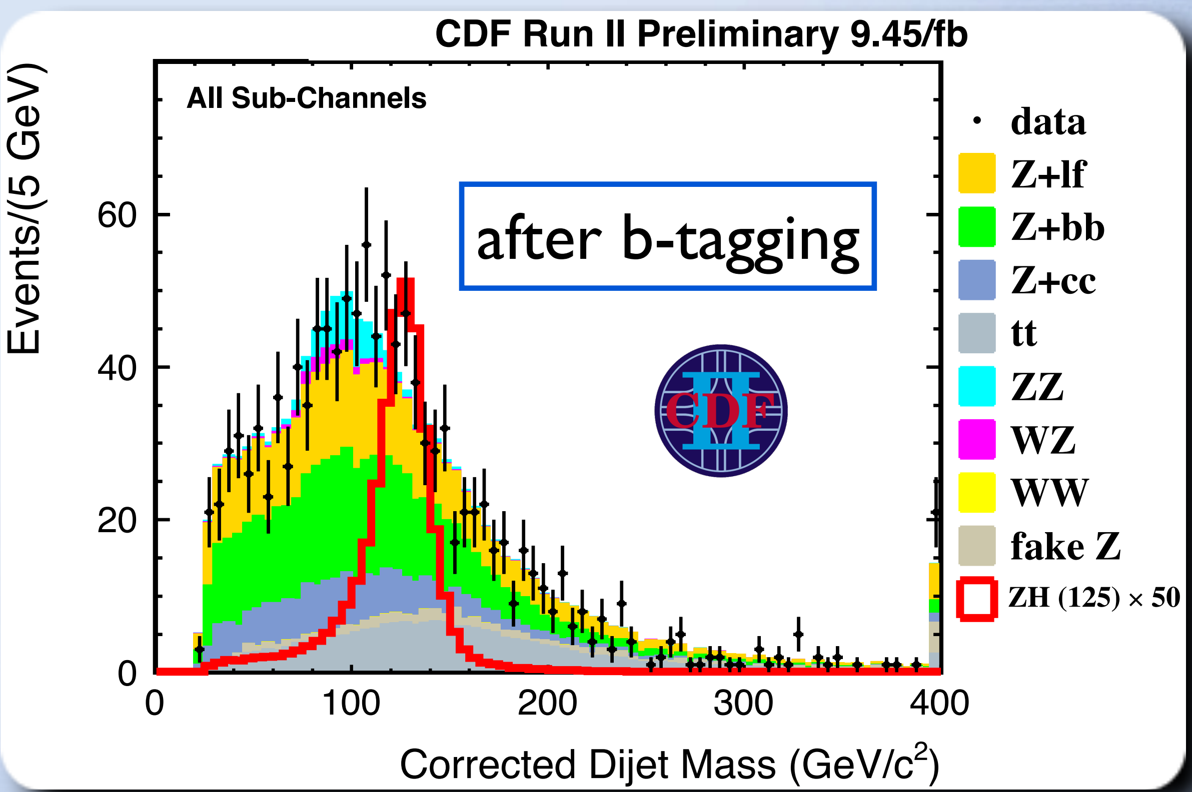
- Little sensitivity to H→bb without efficient b-jet identification capabilities

- CDF & D0 employ advanced ID algorithms (NN/BDT) with b-jet efficiencies of up to 60-80% with low u,d,s,g - jet mis-ID rates (≲1-10%)



Demonstration of b-tagging in ZH→llbb

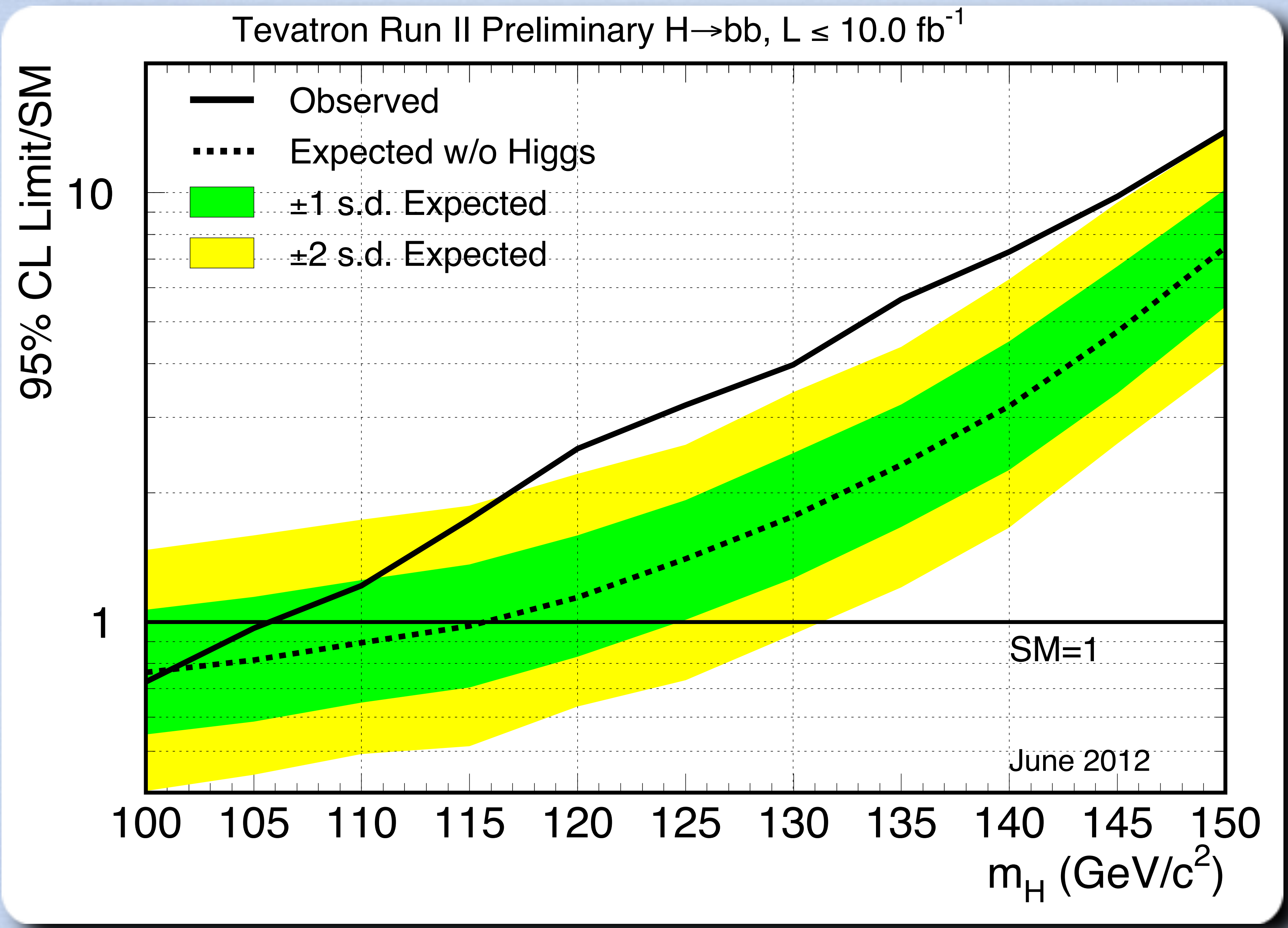




- S/B enhanced by up to a factor of 30

H→bb Combination

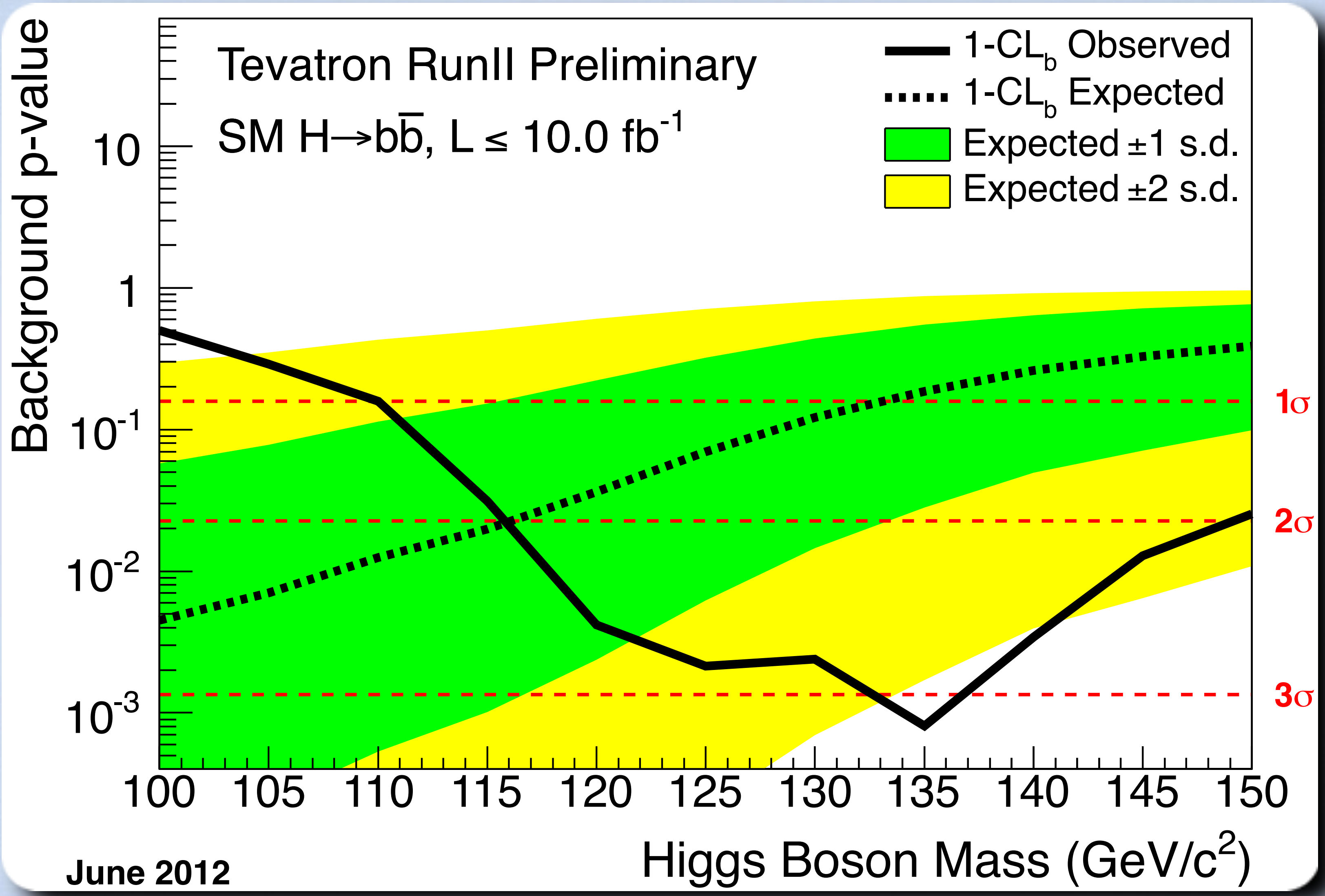
- Broad excess between 110 and 150 GeV/c^2



- ~5% more sensitive than March 2012 result

H→bb p-values

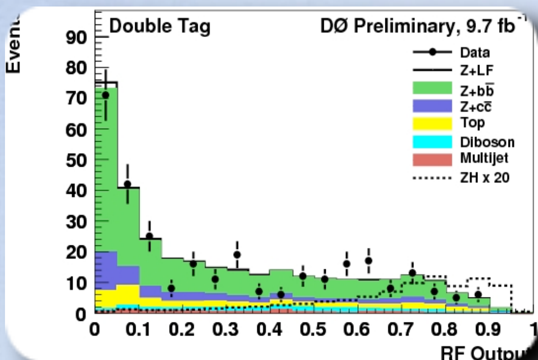
- What is the likelihood of the background producing an excess at least as large as what we see in the data?

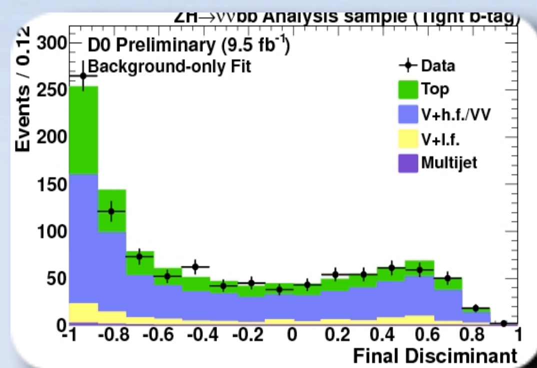


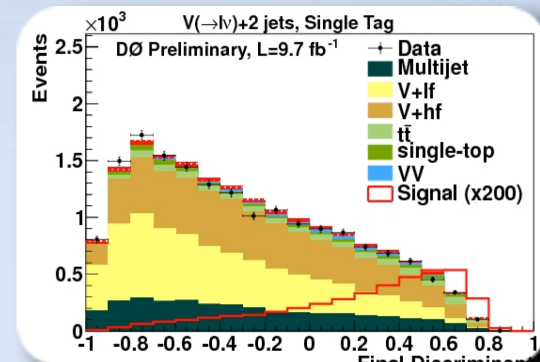
- Max local significance **3.2 σ** at 135 GeV/c^2
- After LEE of 2 the global p-value is **2.9 σ**

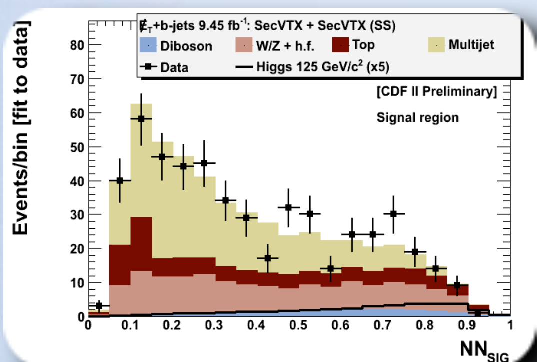
Looking at The Data

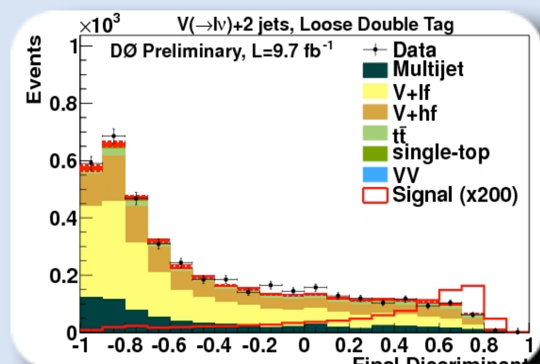
- Challenging due to the large number of H→bb search channels (showing a fraction here!)

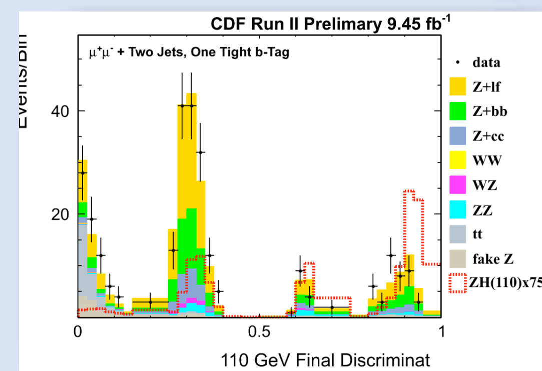


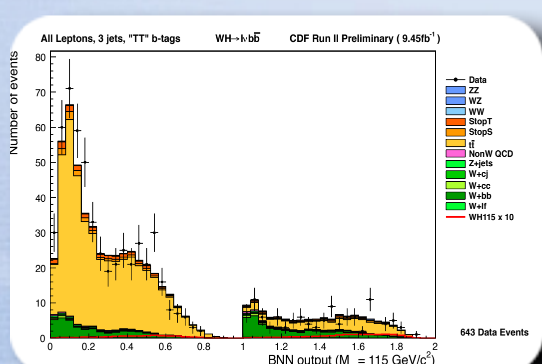


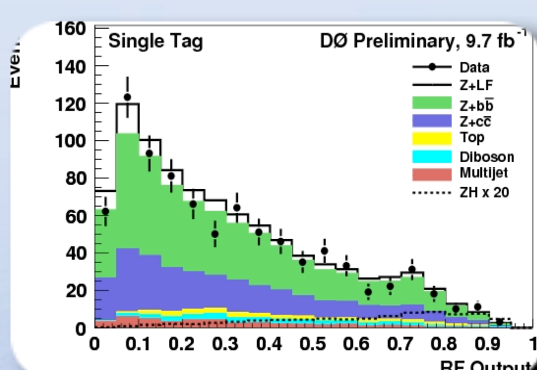


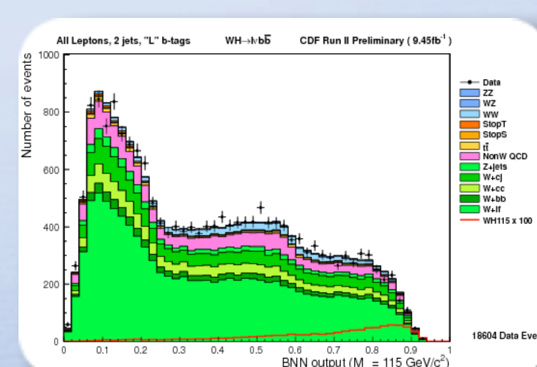






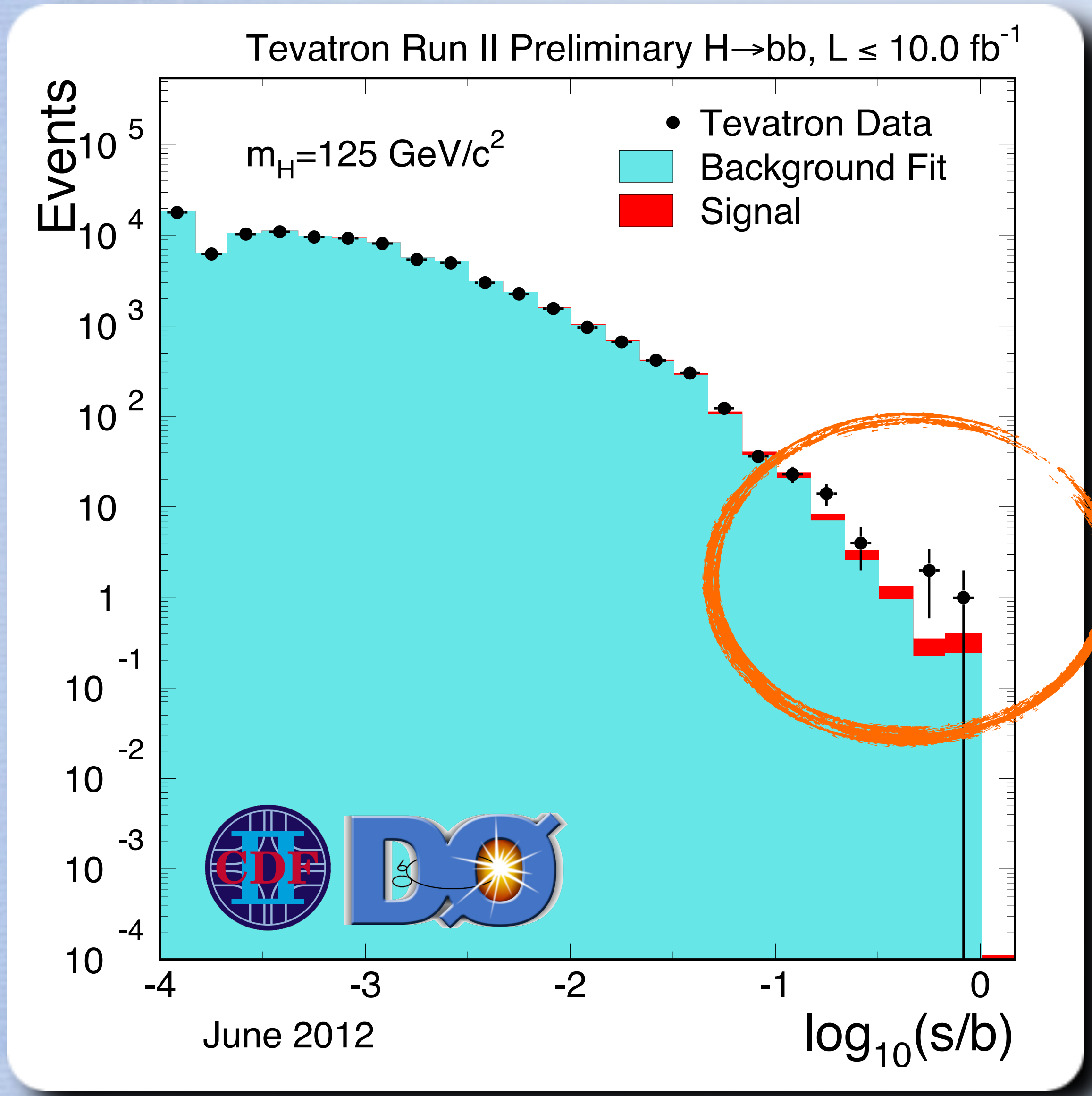


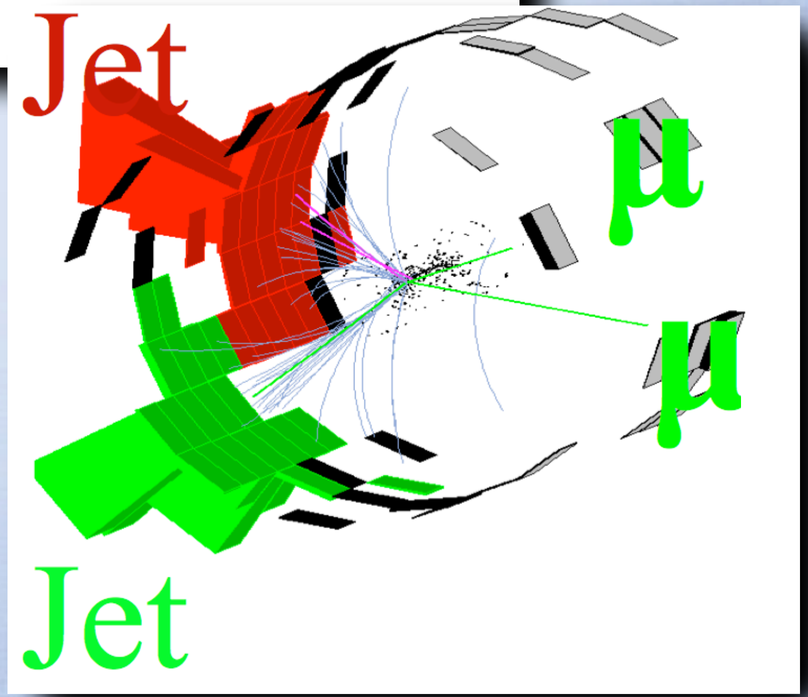




Looking at The Data

- Visualize all candidates at once by combining multiple discriminants
- Order H→bb candidates by $\log_{10}(S/B)$

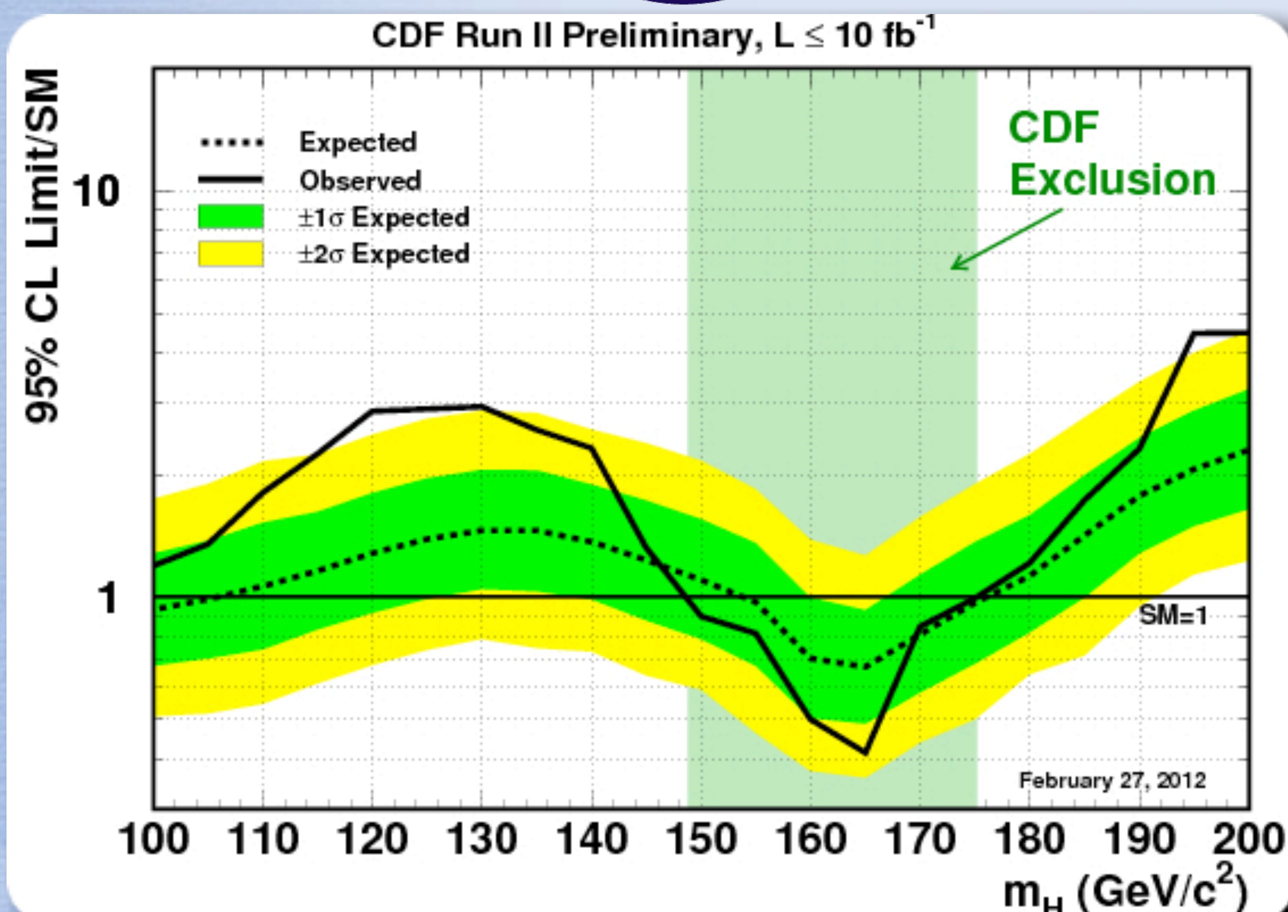


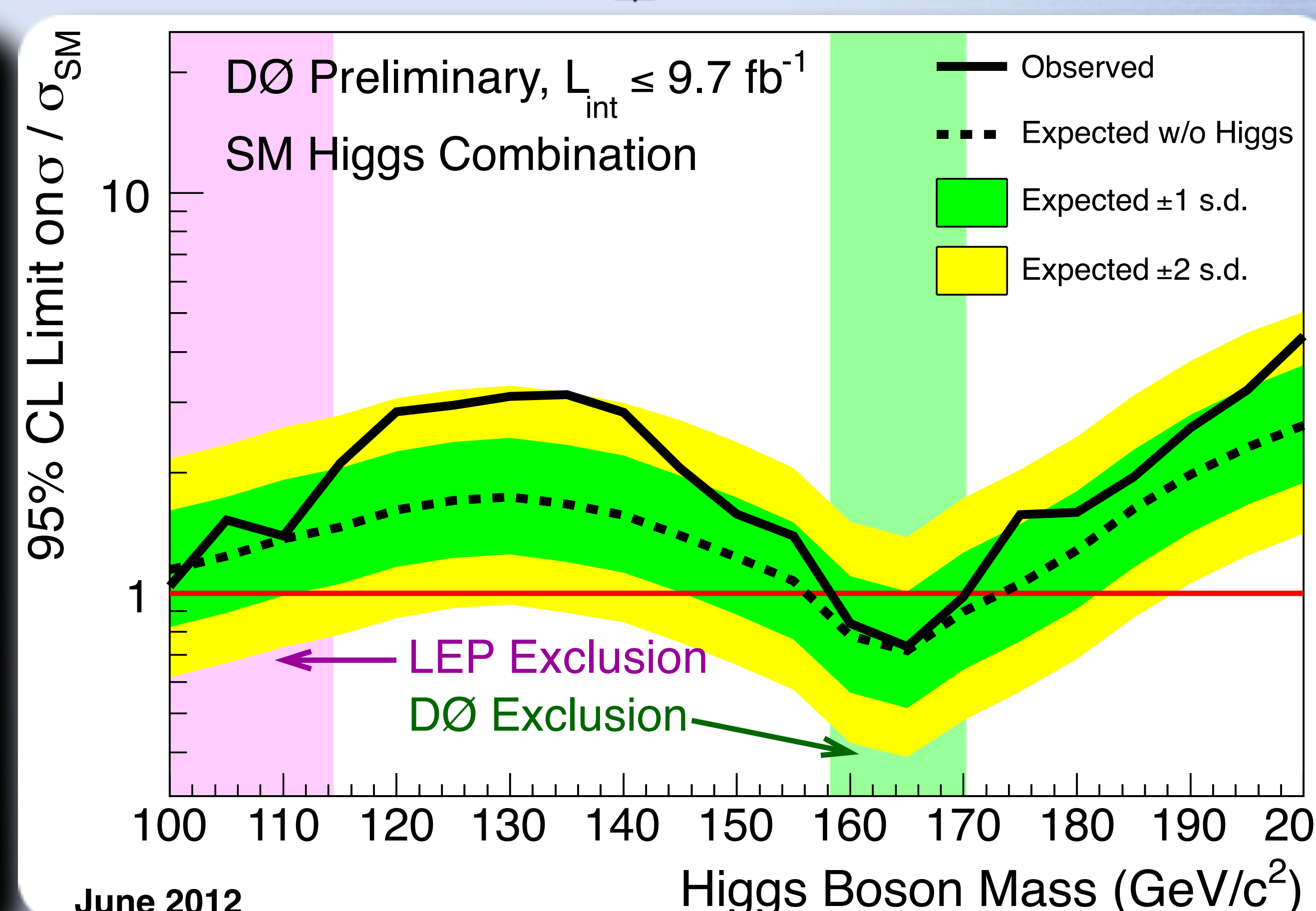


- Events in excess region consistent with expected H→bb topologies

Individual Experiment Results

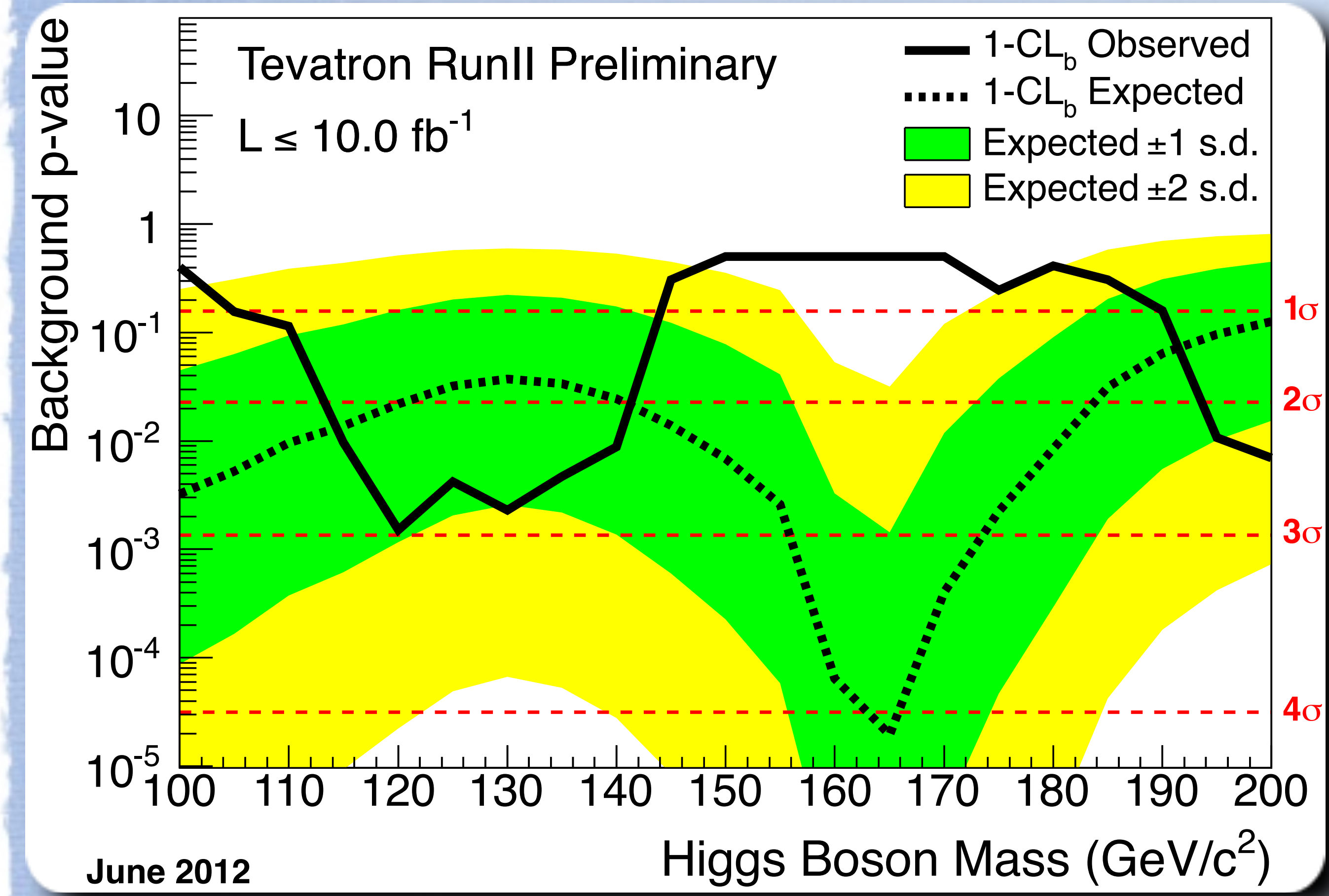
- CDF & D0 single-experiment combinations of all SM Higgs search channels (H→WW, H→bb, H→γγ + other modes)



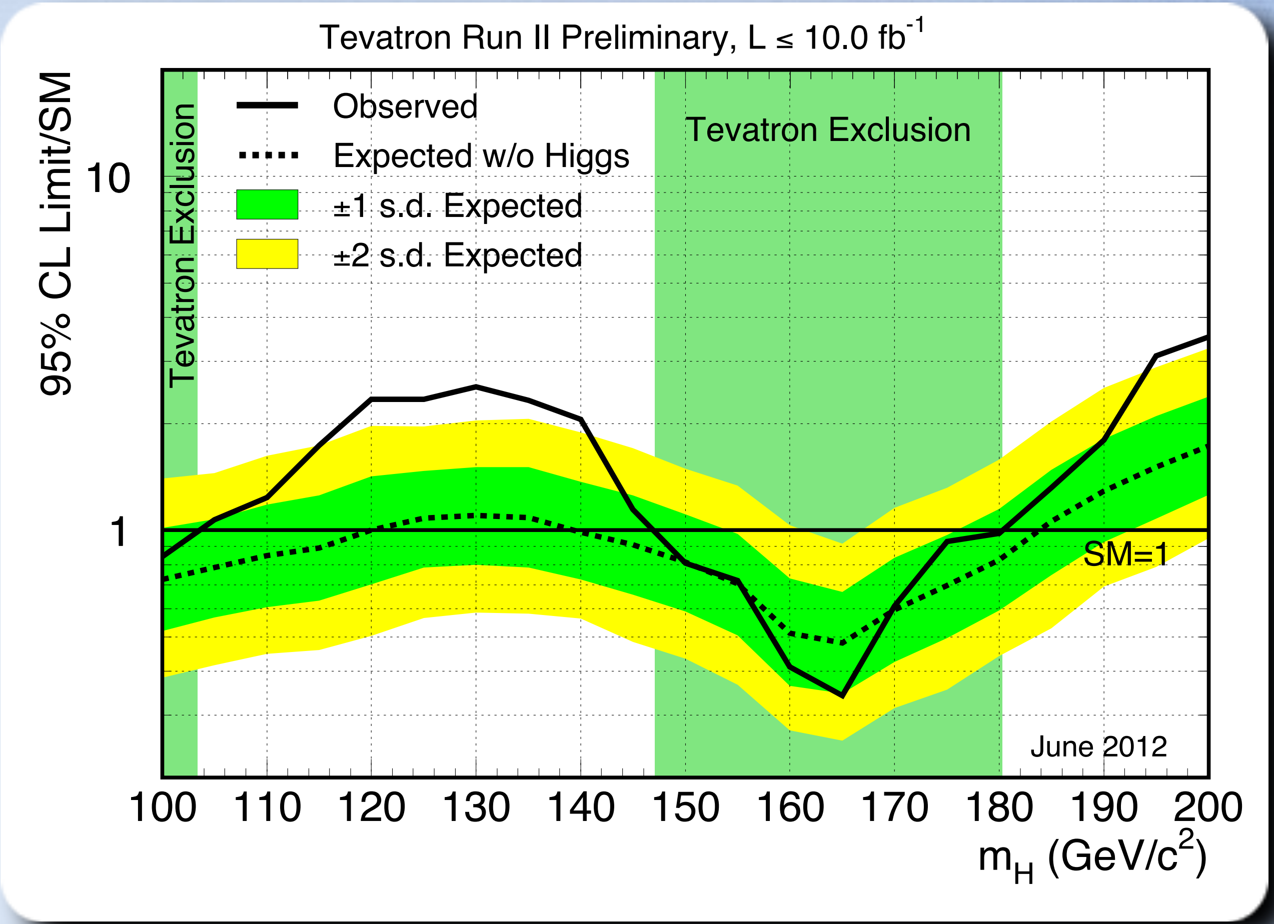


Combined Tevatron Result

Background p-values



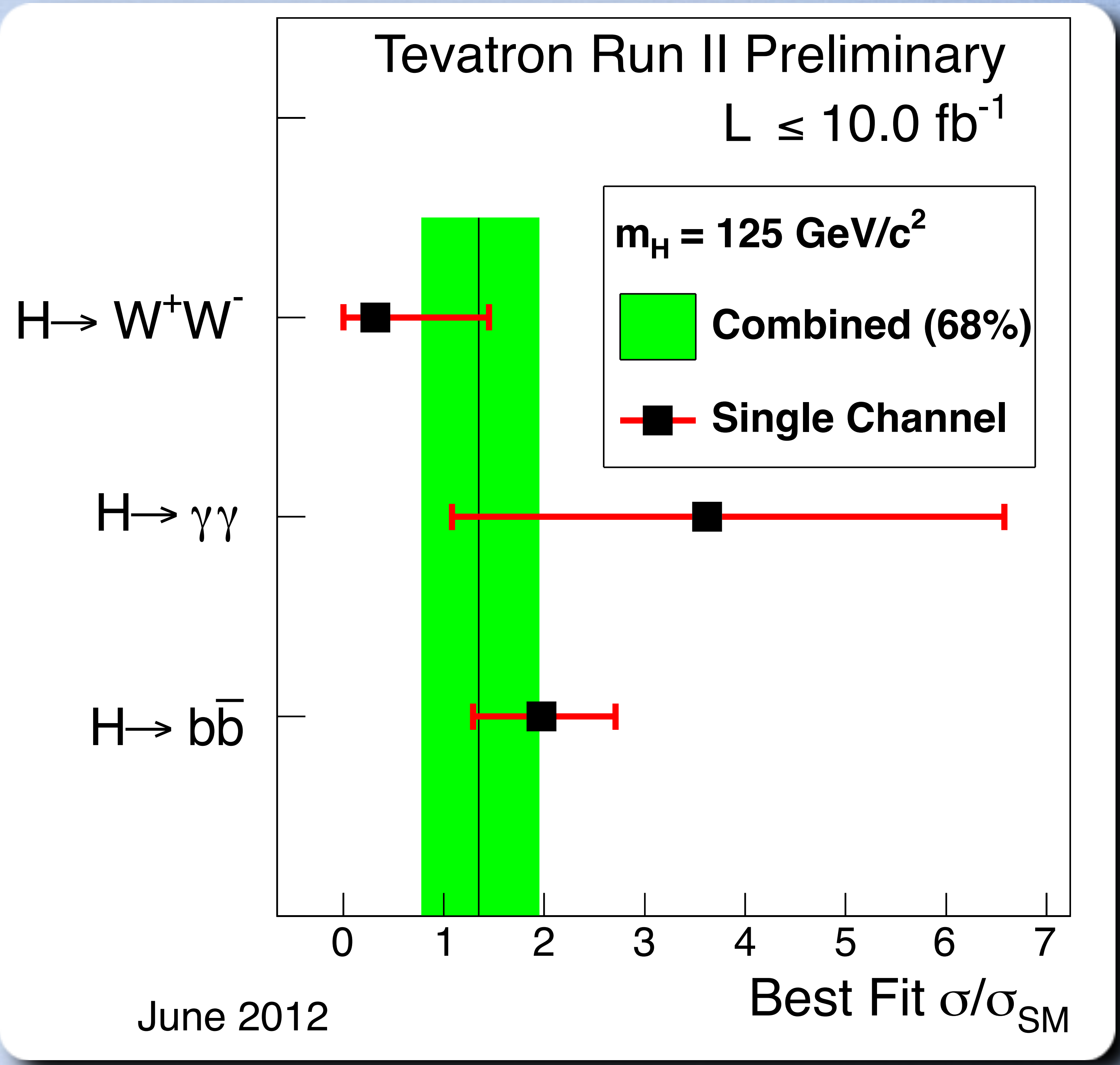
95% CL Upper Limits / SM



- max significance (local) **3 σ**
- max significance (global) **2.5 σ** after LEE of 4

Signal Strength

- Perform fit of S+B model to data
- Compare combined best fit Higgs production cross section to result from individual production modes
- Consistent with SM values within the uncertainties



Summary of SM Higgs Results

- Excluded values of M_H @ 95% CL

Expected	Observed
100-120 GeV	100-103 GeV
139-184 GeV	147-180 GeV

- Significance of observed excess :

Channels	Local	Global
All Tevatron	3 σ	2.5 σ
$H \rightarrow bb$	3.2 σ	2.9 σ

SUSY Neutral Higgs Combination

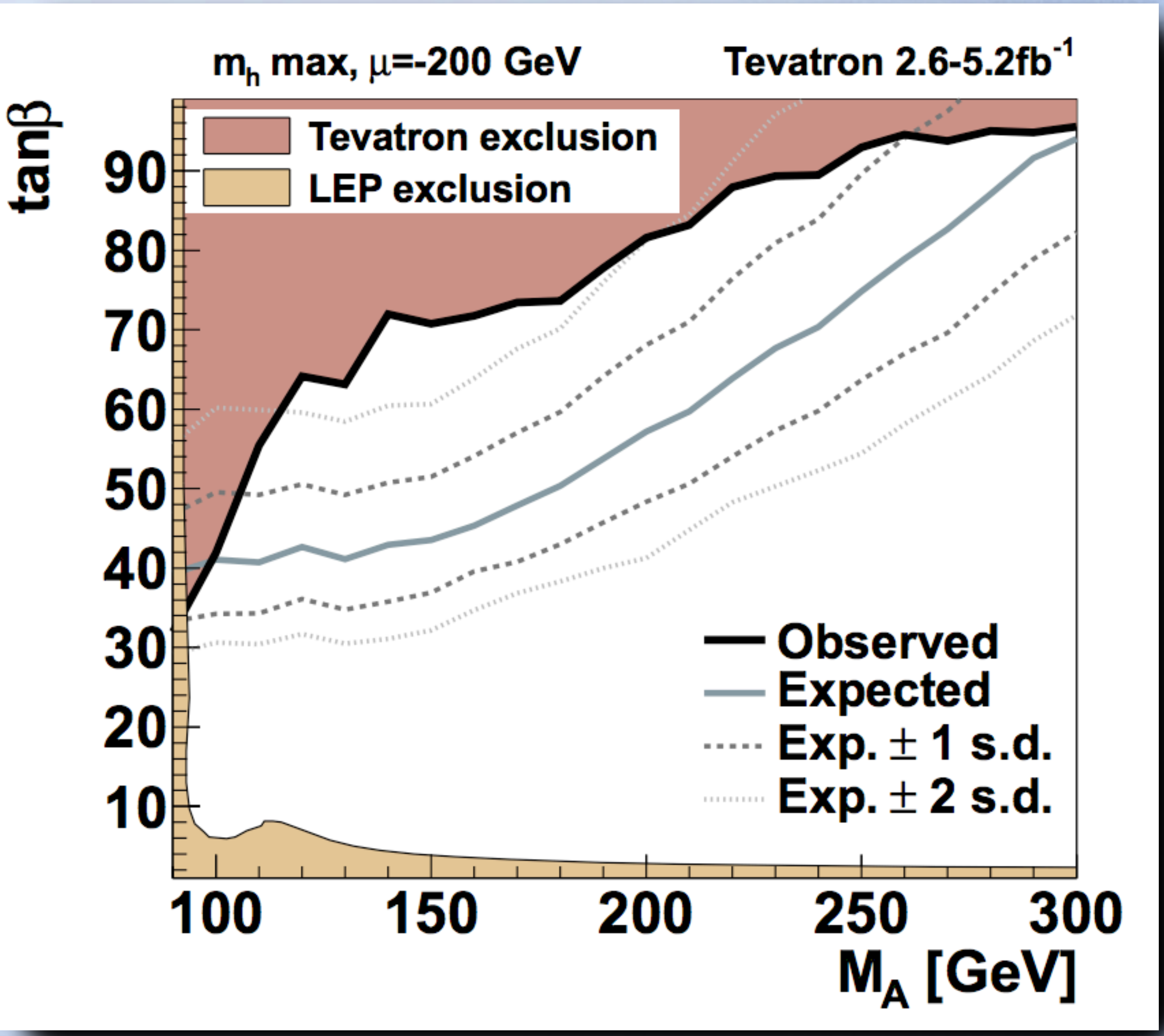
- New **combination** of CDF+D0 searches for neutral SUSY Higgs in **multi-b jet** final states [$bb\Phi \rightarrow bbb(b)$]

- Combines results of :

  I. Phys. Lett. B **689**, 97-103 (2011)
  [see presentation by A. Kharchilava]

  II. Phys. Rev. D **85**, 032005 (2012)

- Paper submitted to PRL, should appear on archives early this week



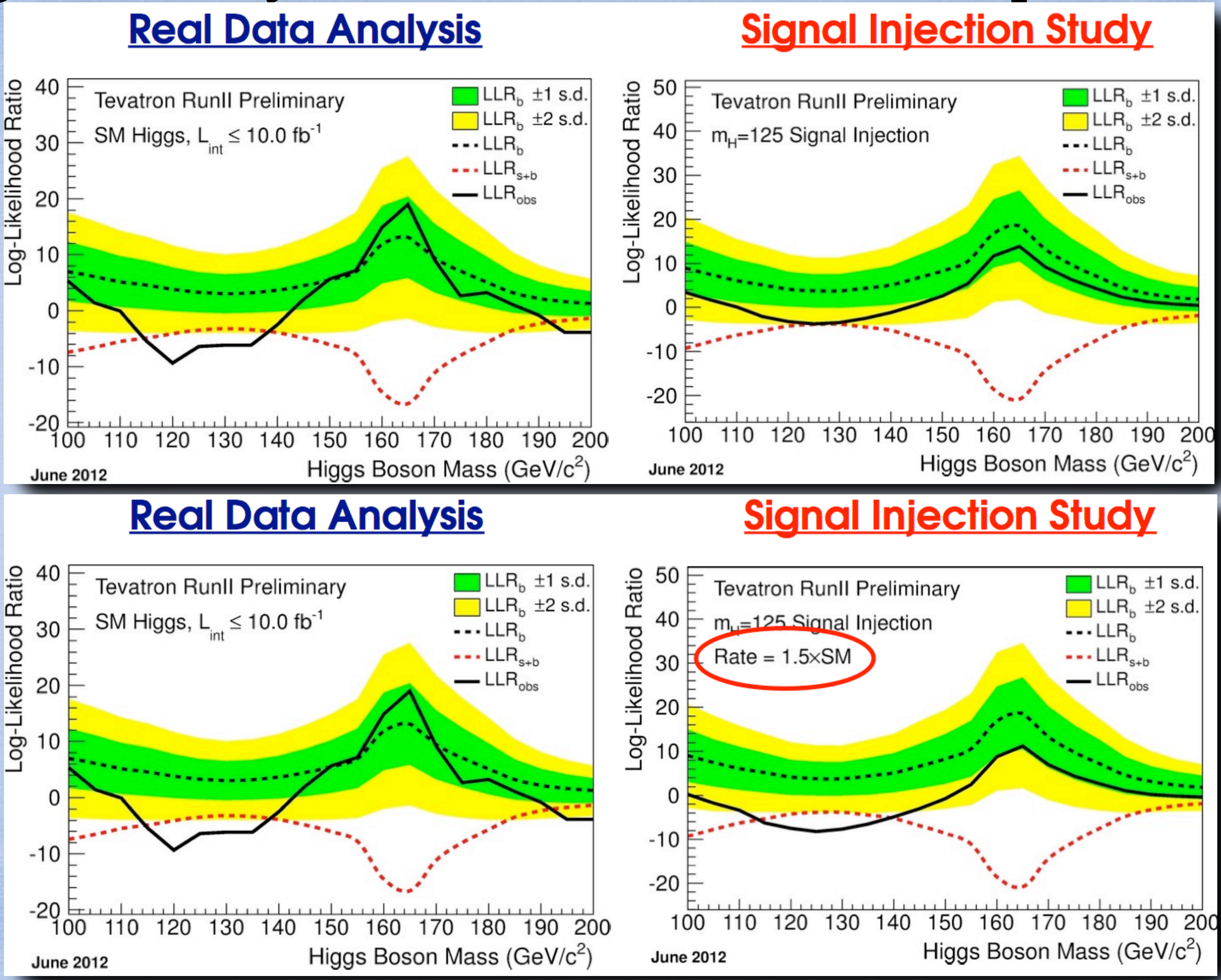
Conclusions

- Presented new SM Higgs combination in full Tevatron dataset
- The data appear to be incompatible with the background-only hypothesis with a global p-value of 2.5 σ (3.0 σ local)
- For combined searches in $H \rightarrow bb$, the global p-value is 2.9 σ (3.2 σ local)
- The Tevatron data are compatible with SM Higgs production for 115-135 GeV

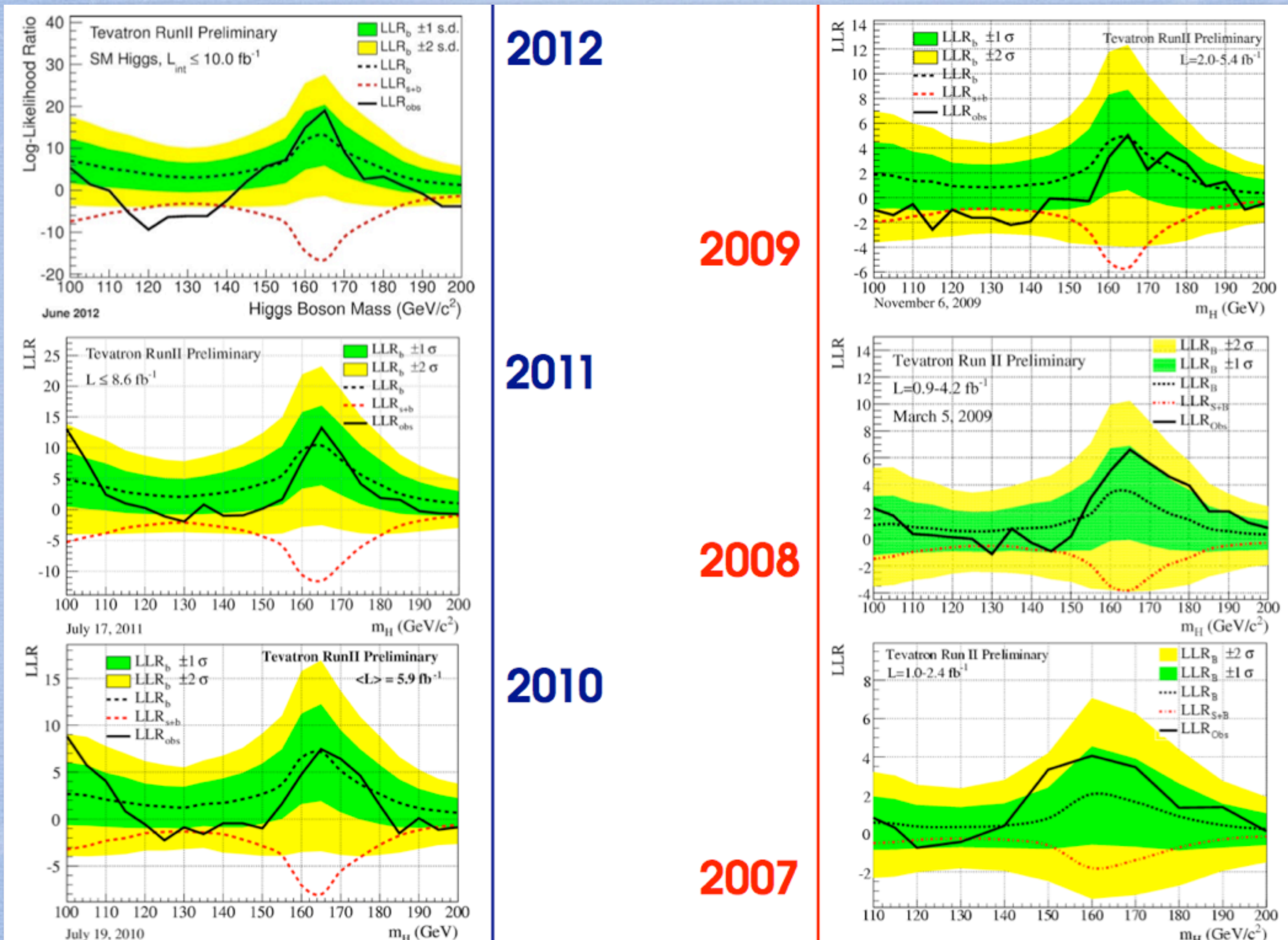
Thanks!

Additional Material

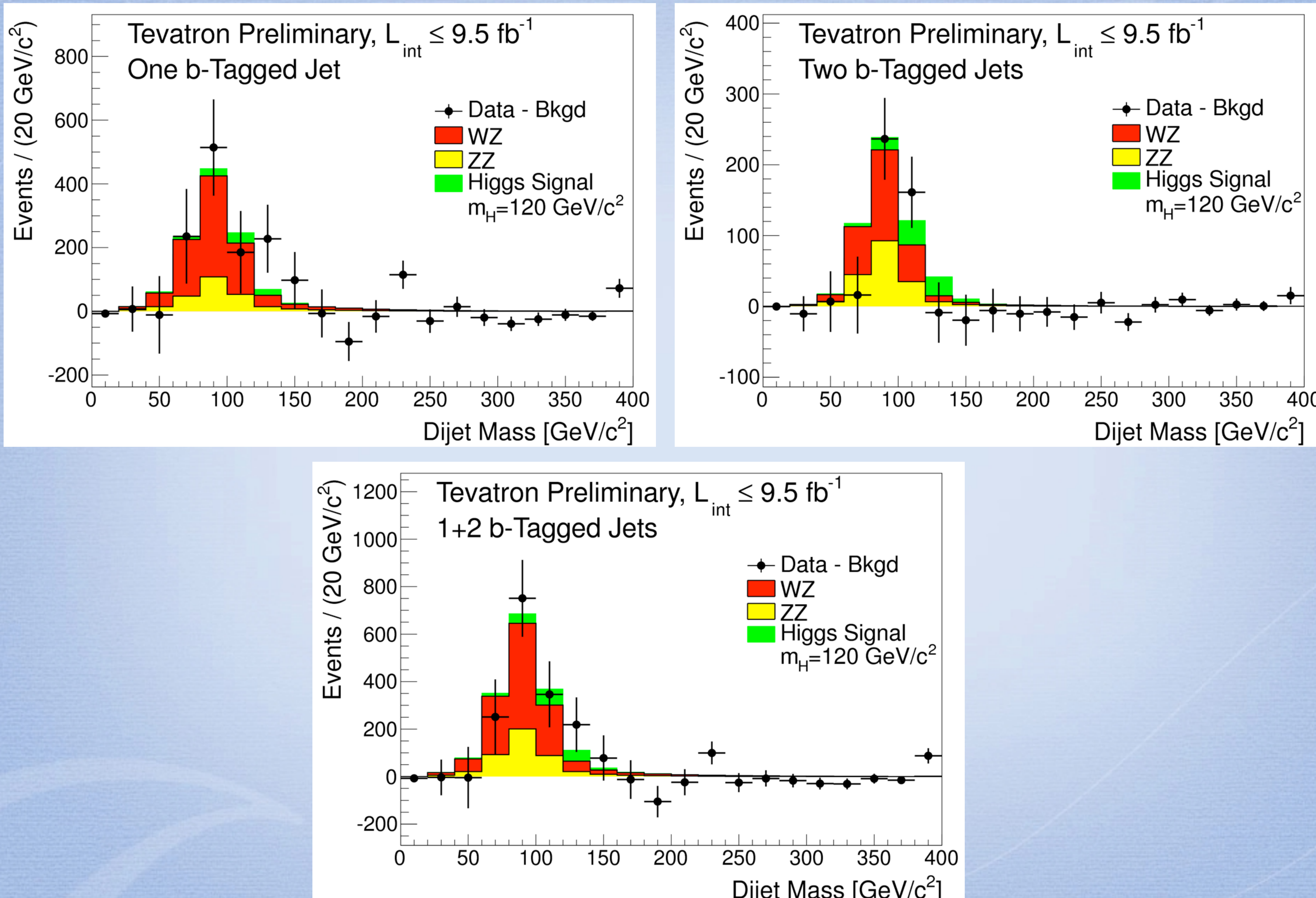
Signal Injection LLR Comparison



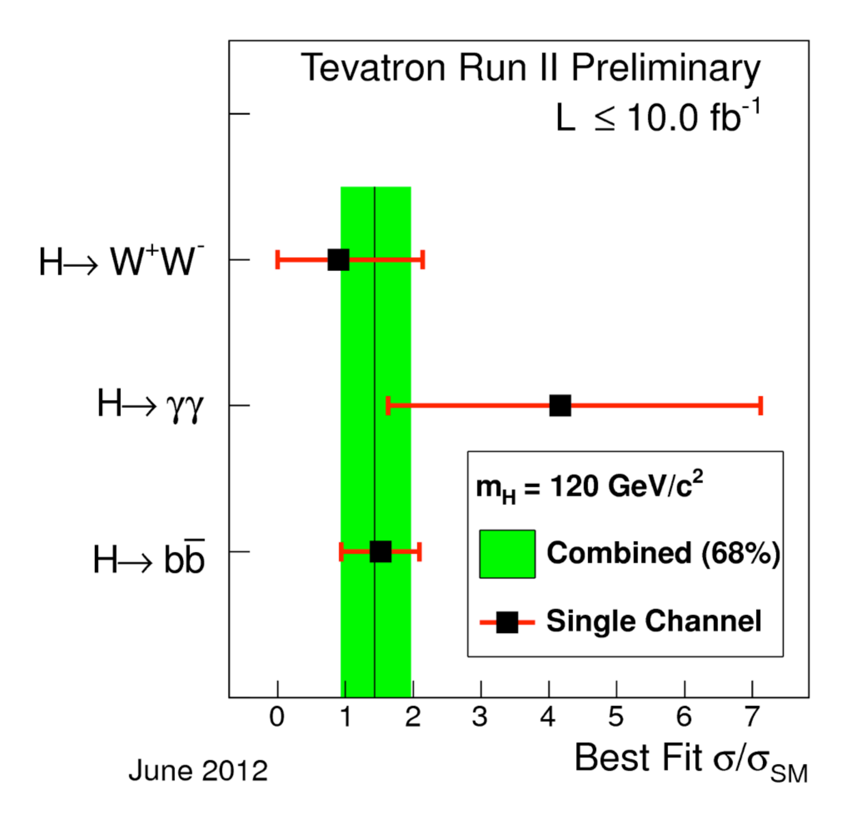
LLR 2007-2012

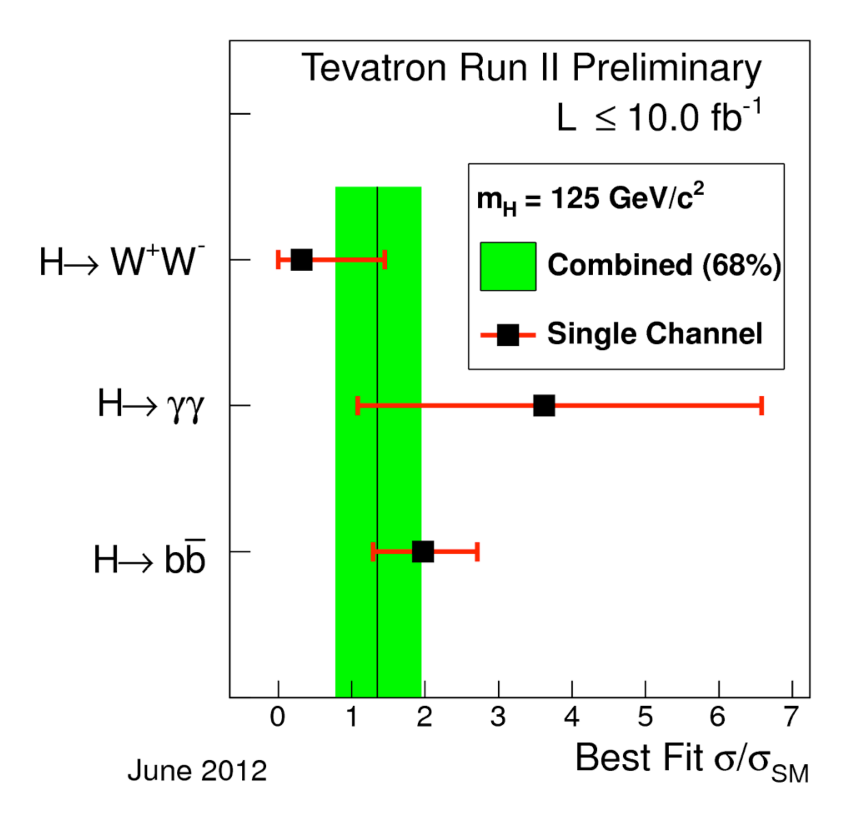


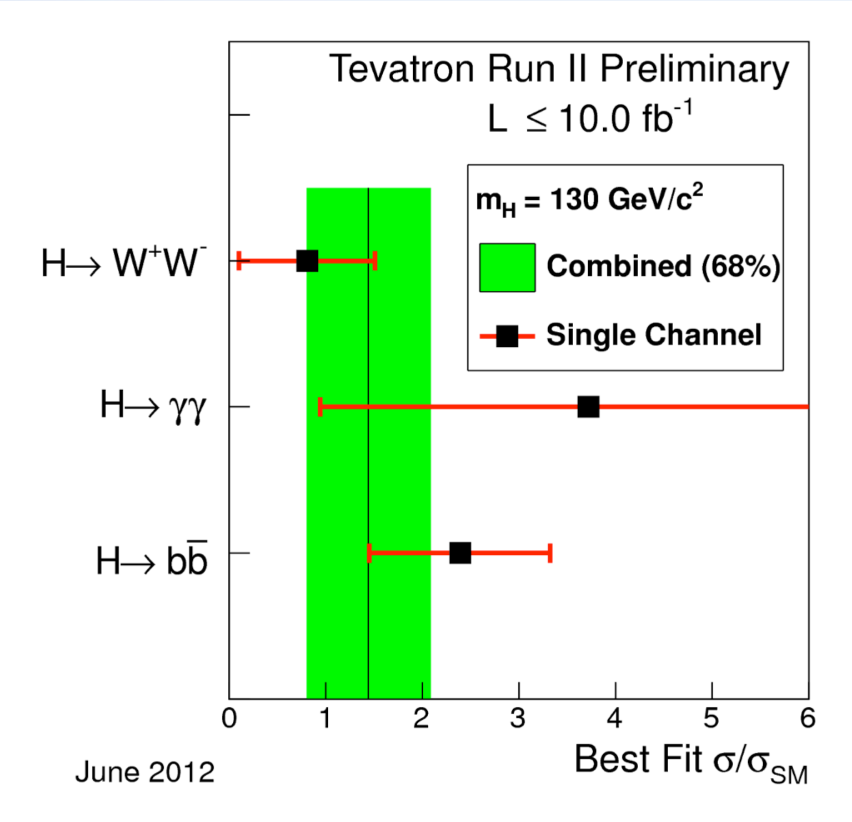
Diboson Extraction

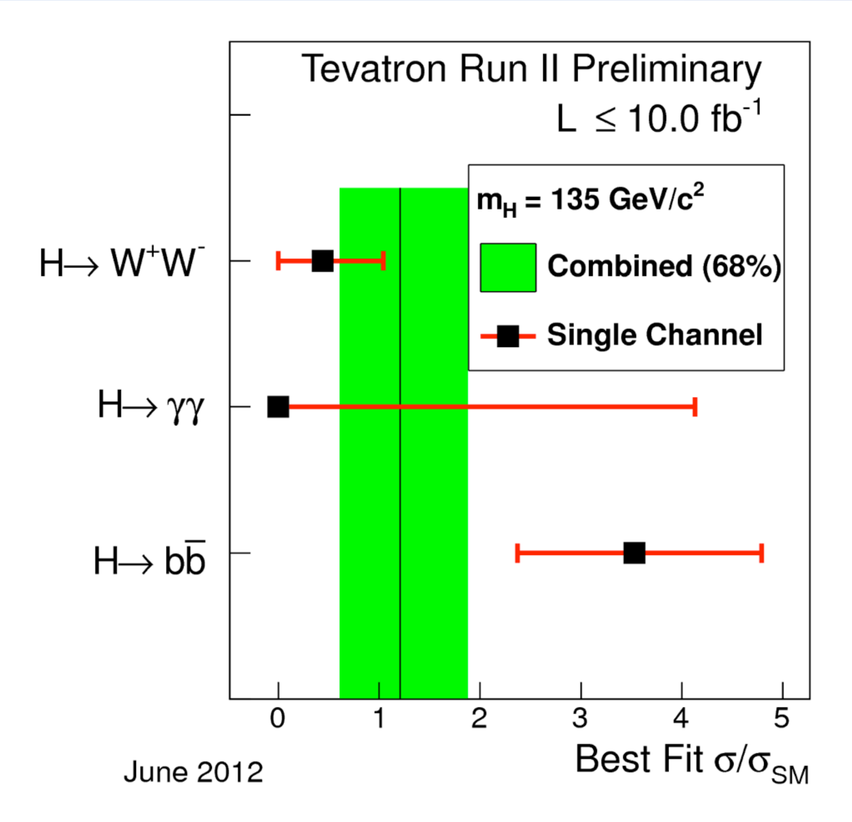


Tevatron Cross Section Fits

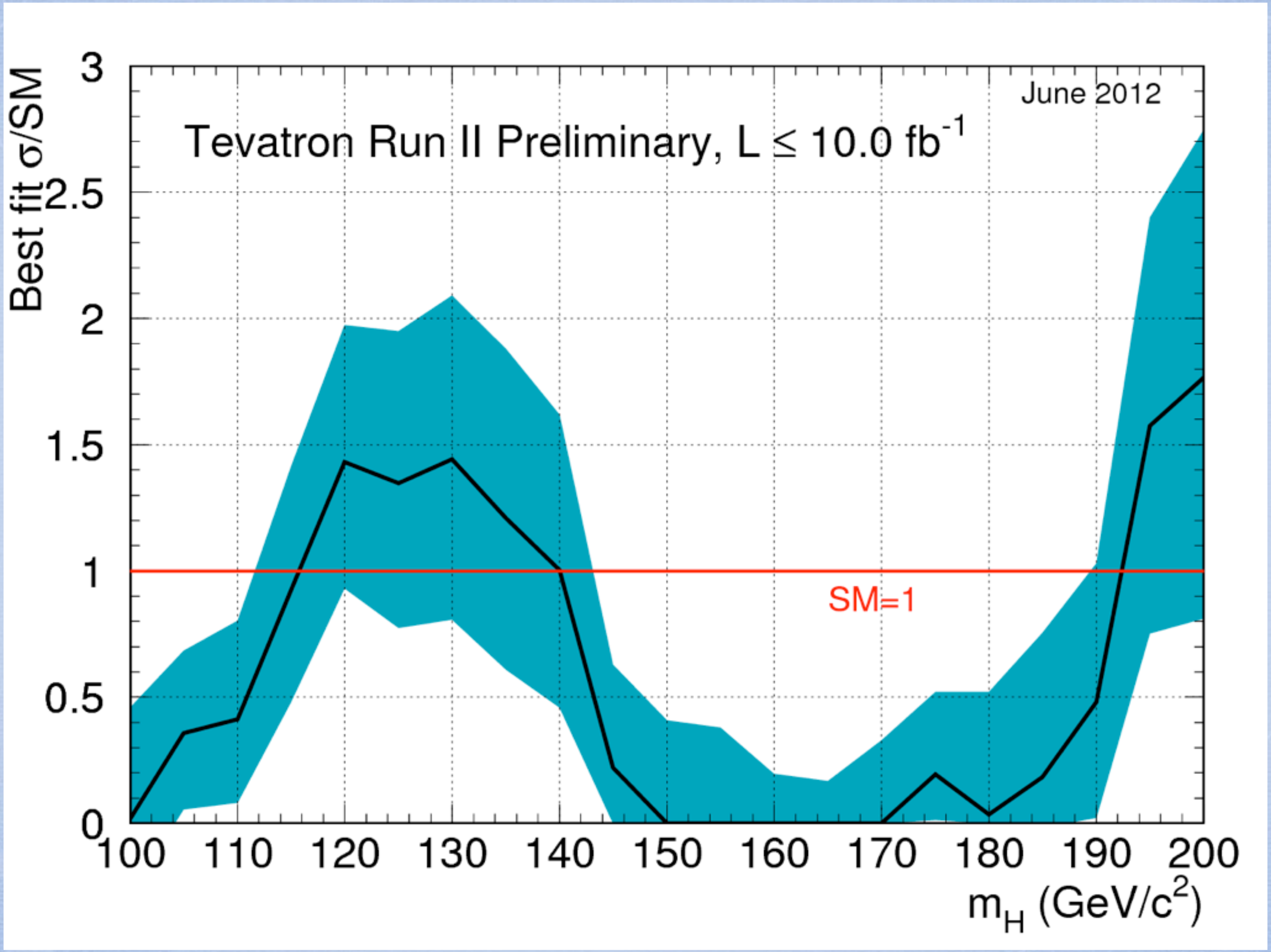




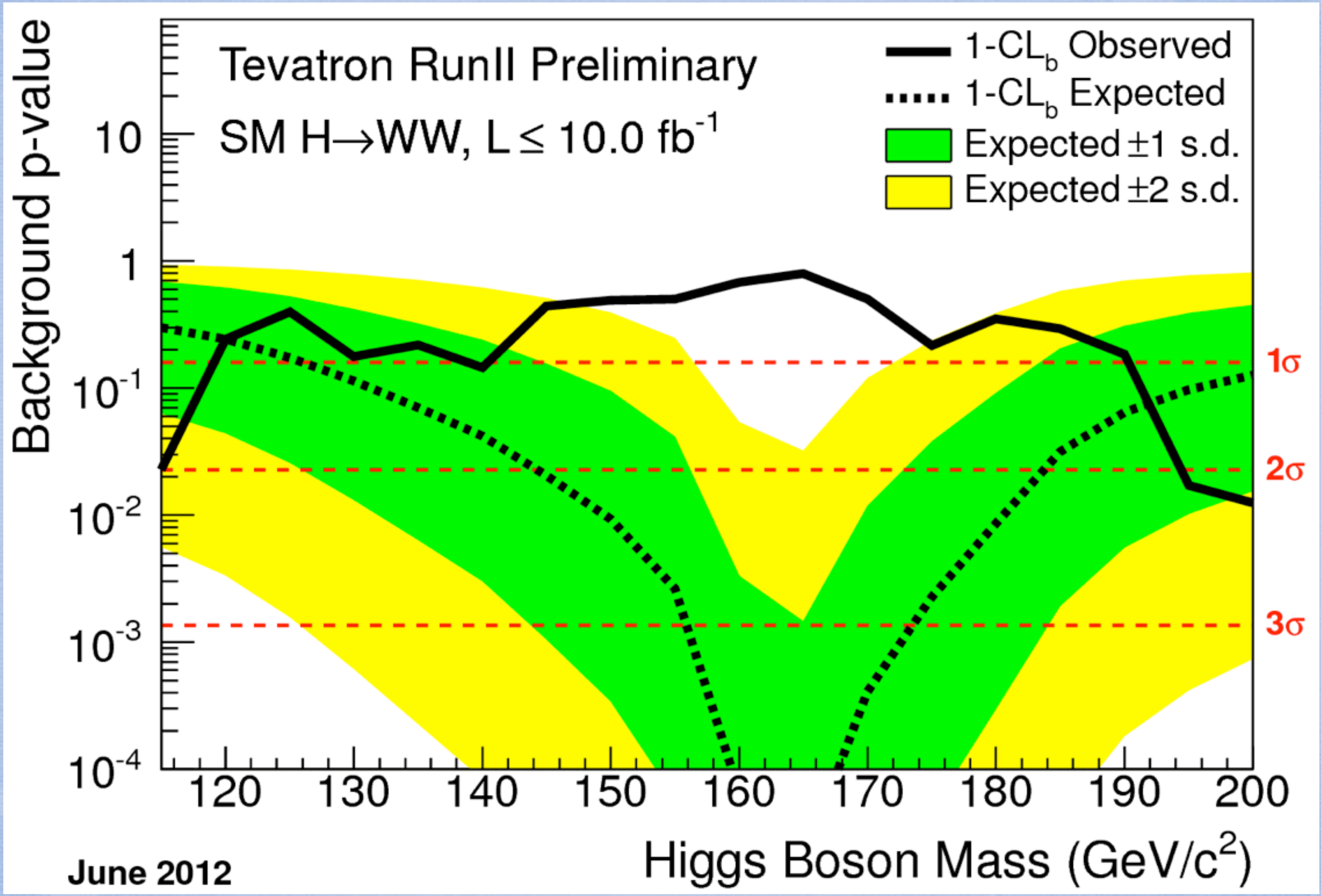




Tevatron Cross Section Fits

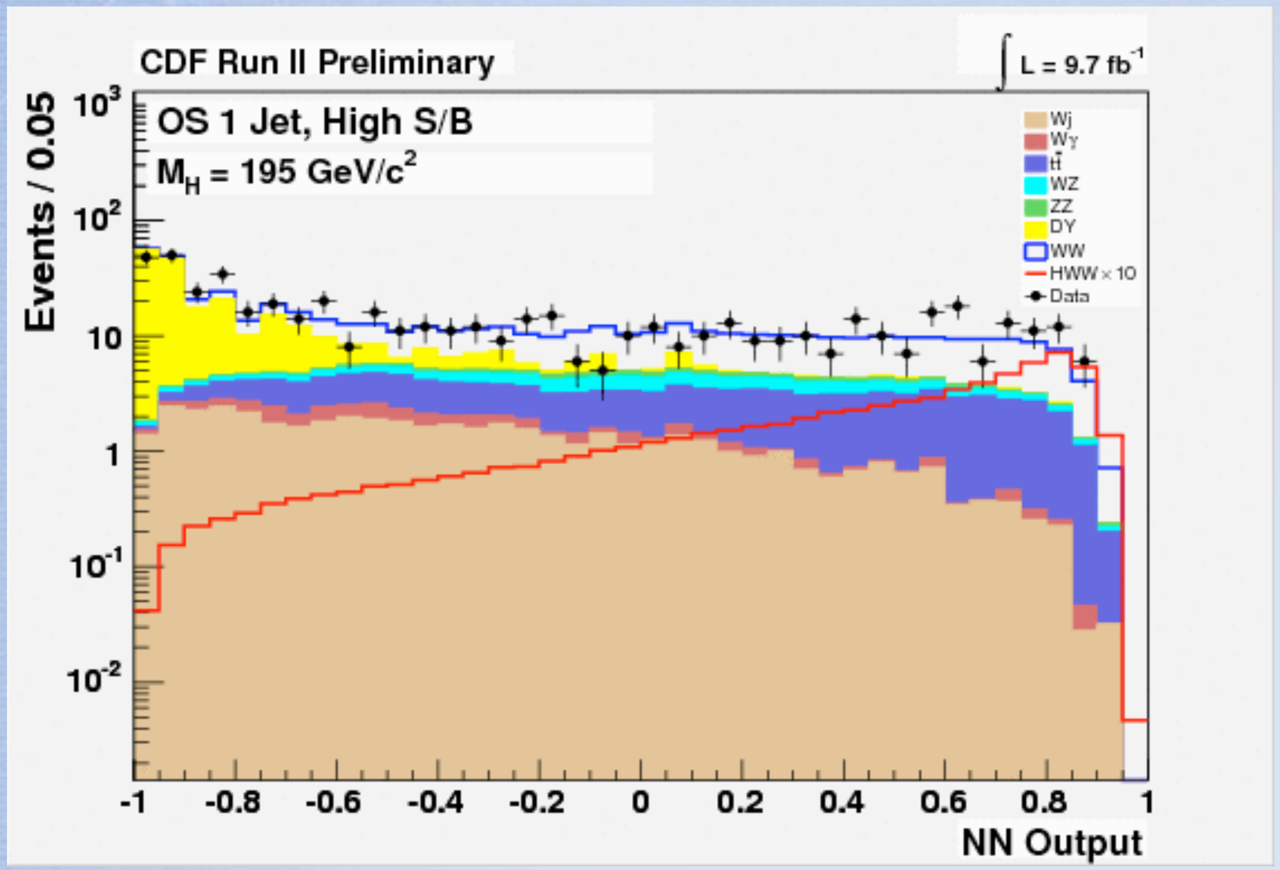


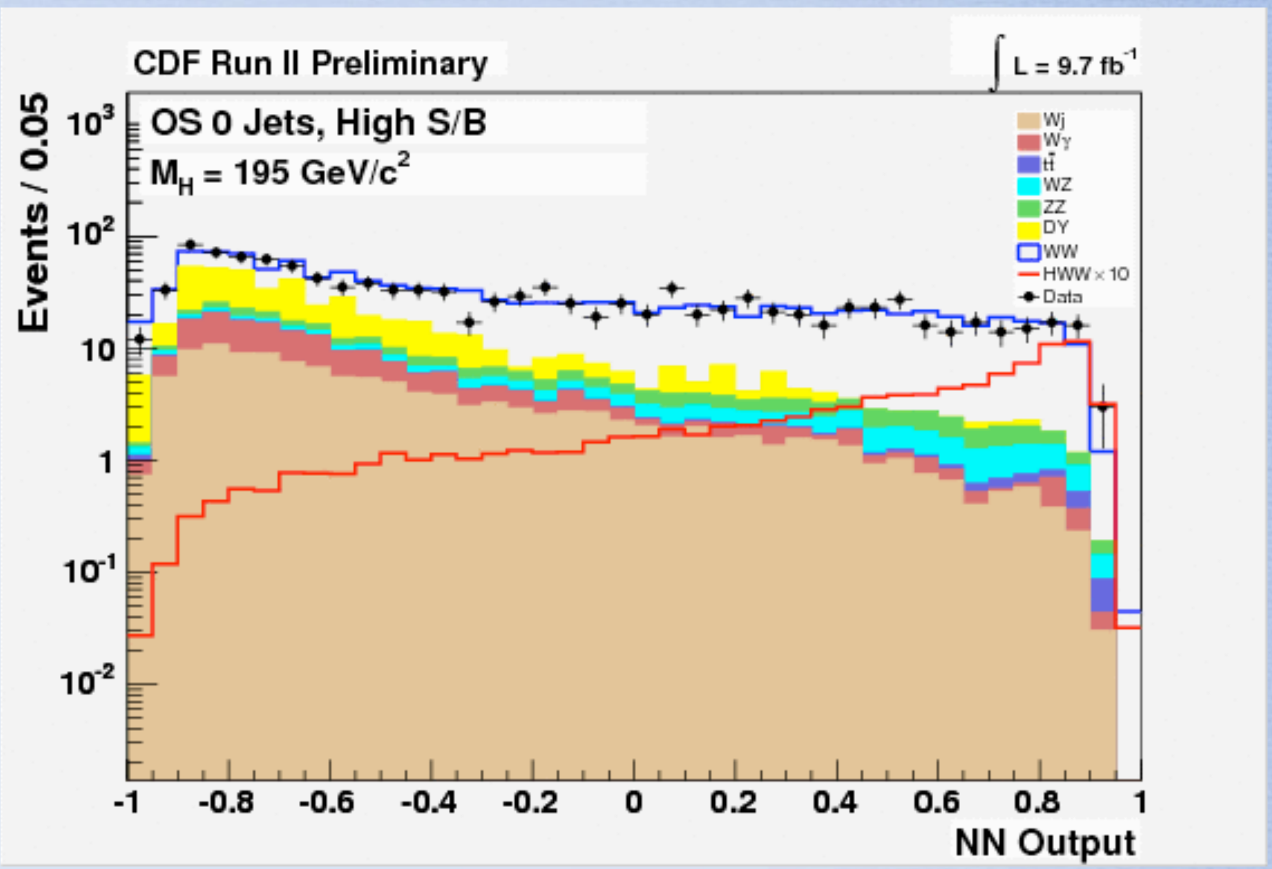
H→WW p-values



Tevatron RunII Preliminary
SM H→WW, L ≤ 10.0 fb^{-1}
1-CL$_b$ Observed
1-CL$_b$ Expected
Expected ±1 s.d.
Expected ±2 s.d.
Background p-value
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
1σ
2σ
3σ
120
130
140
150
160
170
180
190
200
Higgs Boson Mass (GeV/c^2)
June 2012

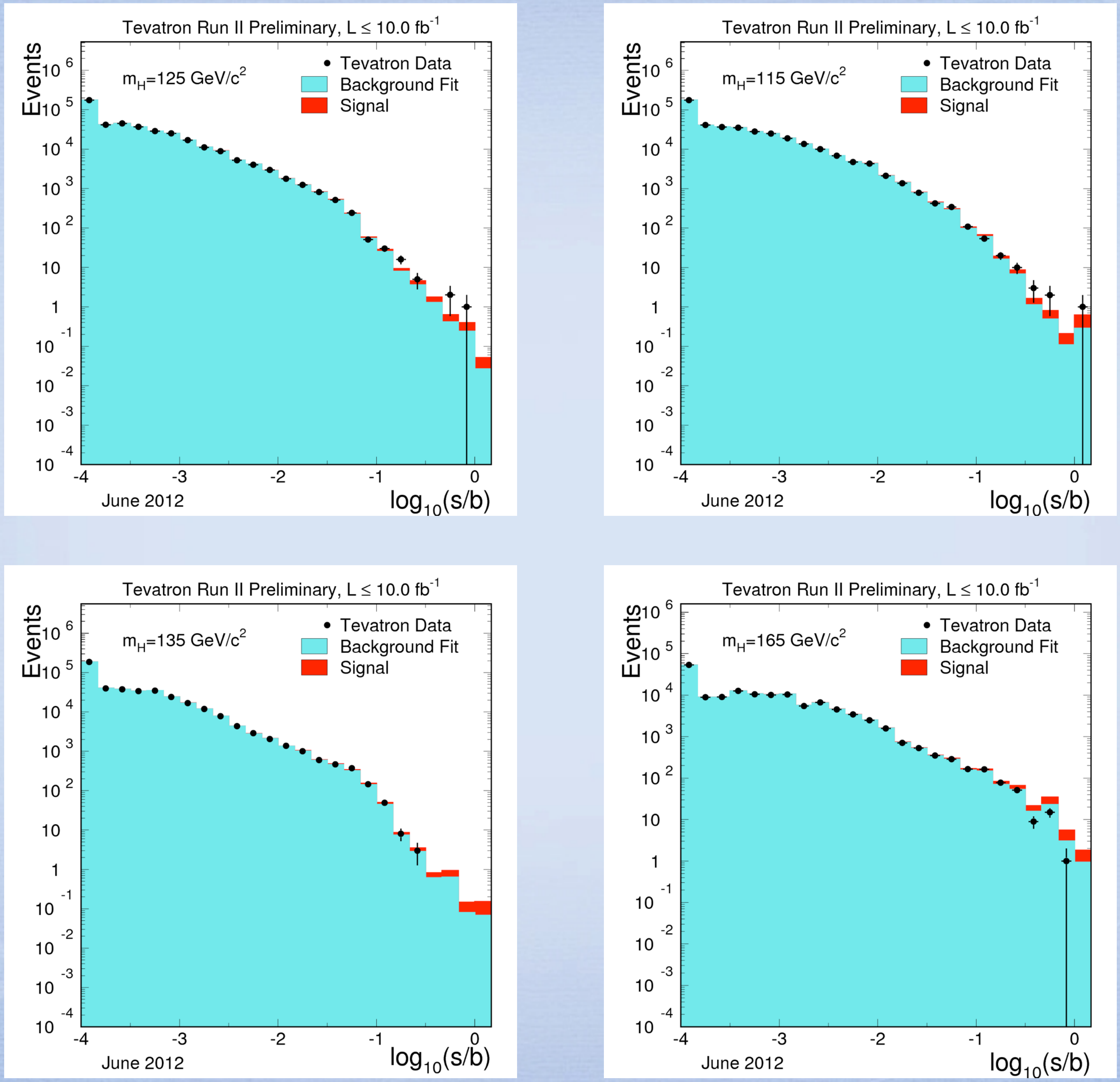
High Mass Excess



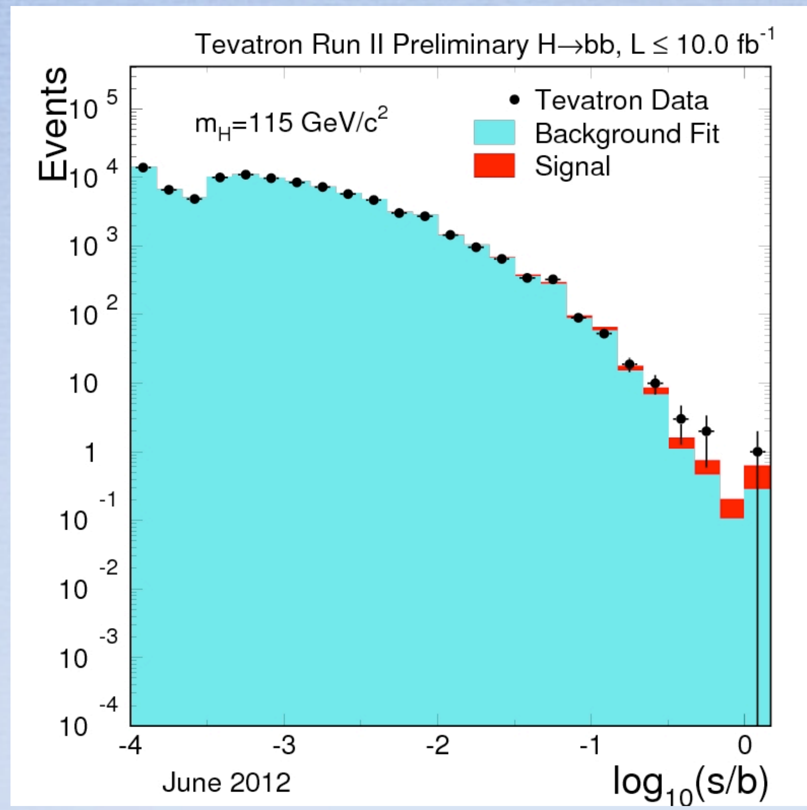


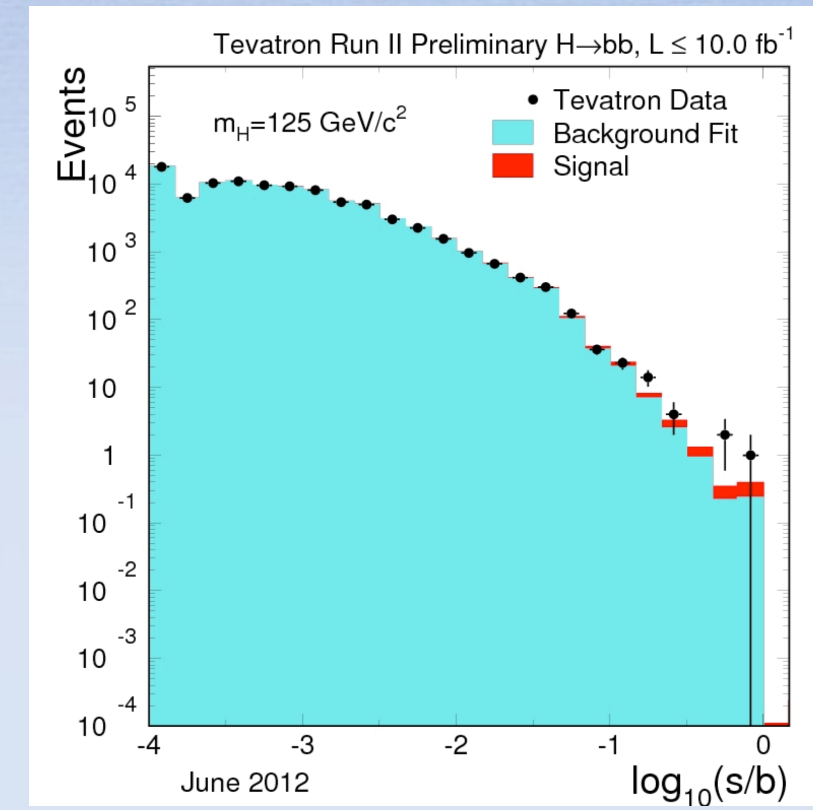
- Behavior of observed limits driven by small event excesses in the high S/B regions of opposite-sign dilepton 0 and 1 jet channels
- Nothing peculiar in the modeling of these distributions

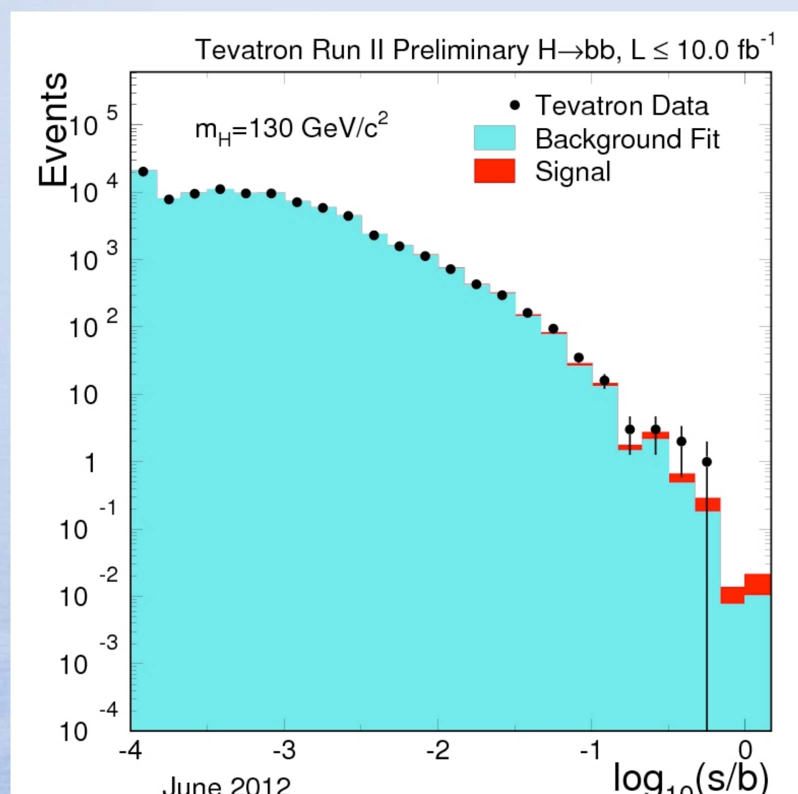
Tevatron log(S/B) plots

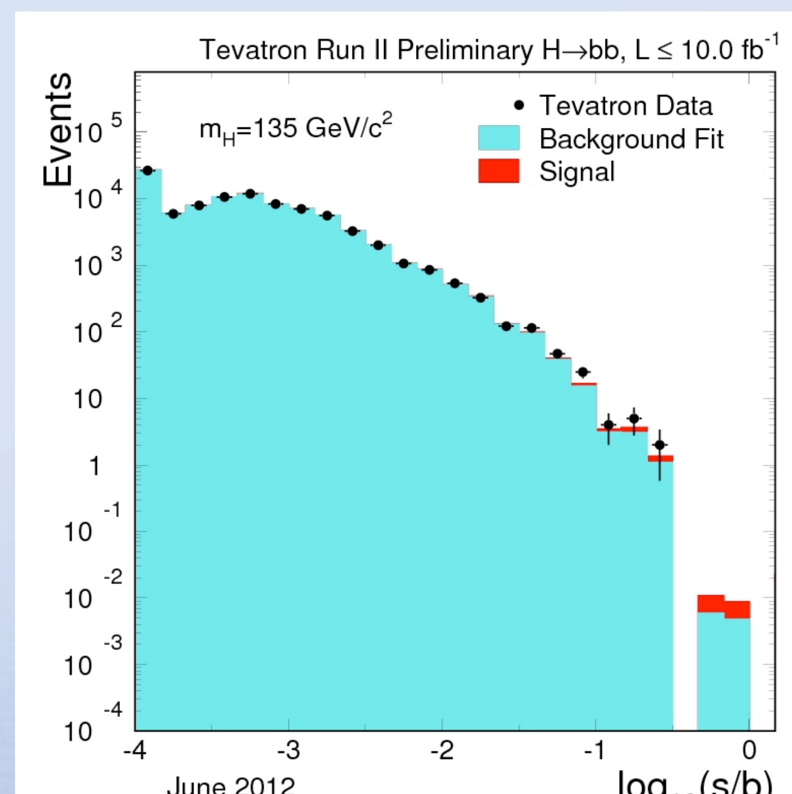


Tevatron (H→bb) log(S/B) plots



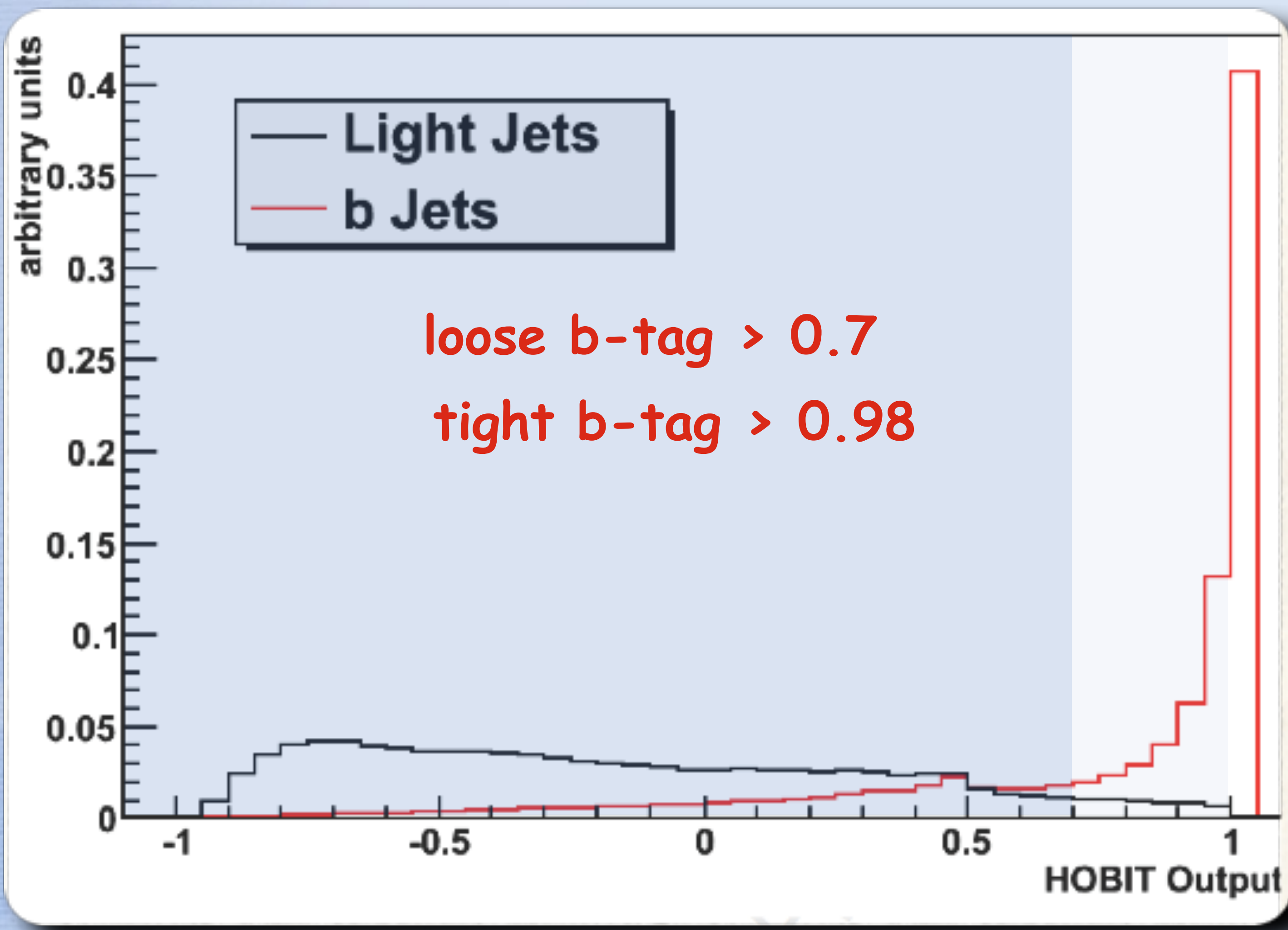






Multivariate b-jet Tagging

- Combine information used by individual b-tag algorithms using a NN (CDF) or BDT (D0)
- Improved b-tag efficiency for similar non-b mis-tag rate
- Direct 10-15% gain in sensitivity for $H \rightarrow bb$ searches
- Performance in MC calibrated to data in control samples

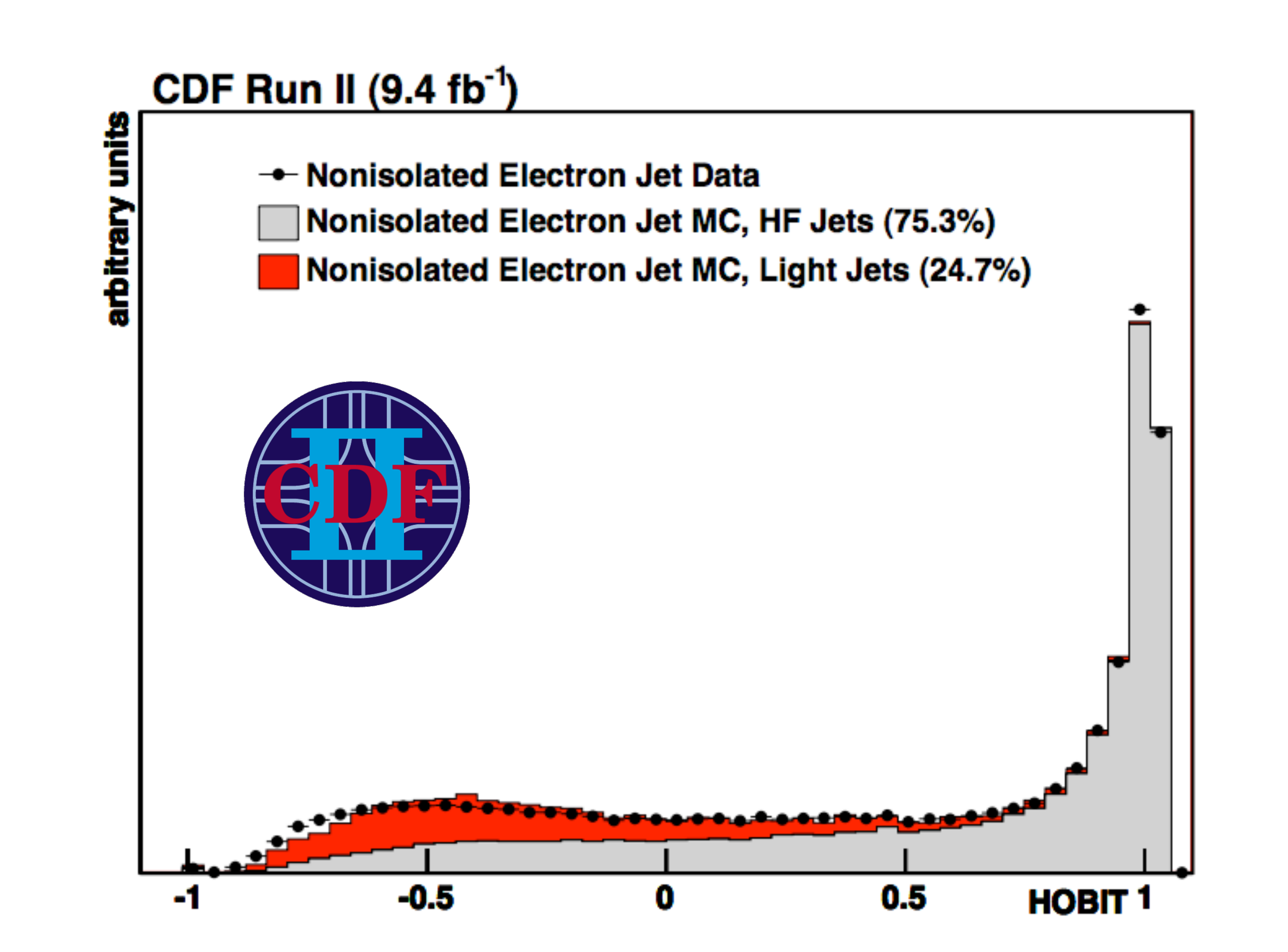


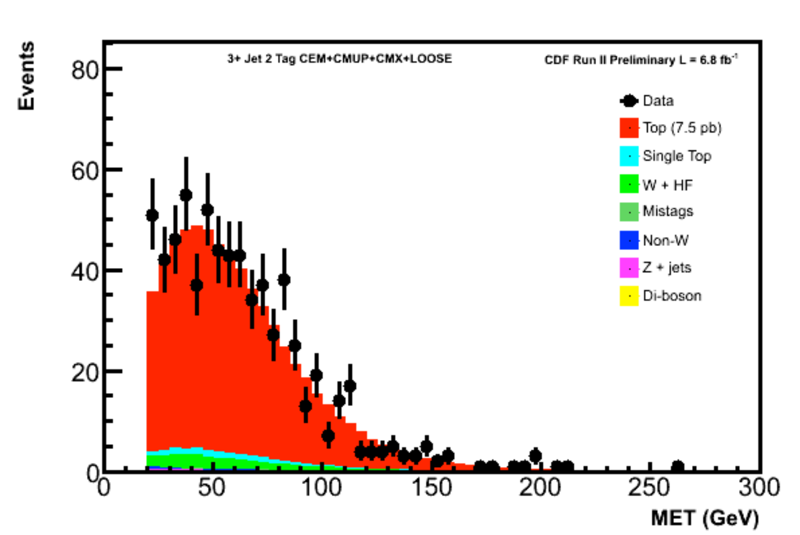
Continuous output allows for multiple exclusive search sub-channels

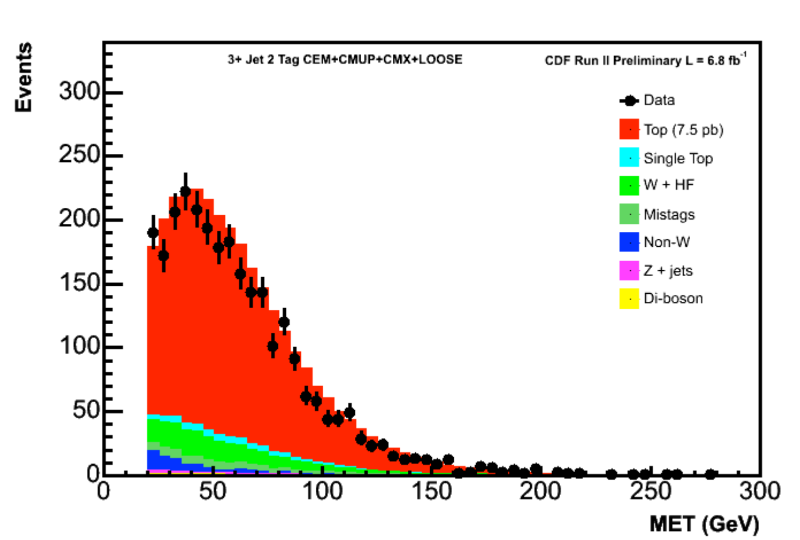
Combination	~S/B (115 GeV)
Tight + Tight	0.017
Tight + Loose	0.009
Single Tight	0.003
Loose + Loose	0.003
Single Loose	0.001

Calibration of b-jet Taggers

- Performance in simulated samples calibrated to data in 2 control regions
  I. tt-enhanced samples (simultaneously extract tt cross section & tagger performance corrections)
  II. Jet pairs with one jet containing an electron (either conversion or from heavy flavor decay)



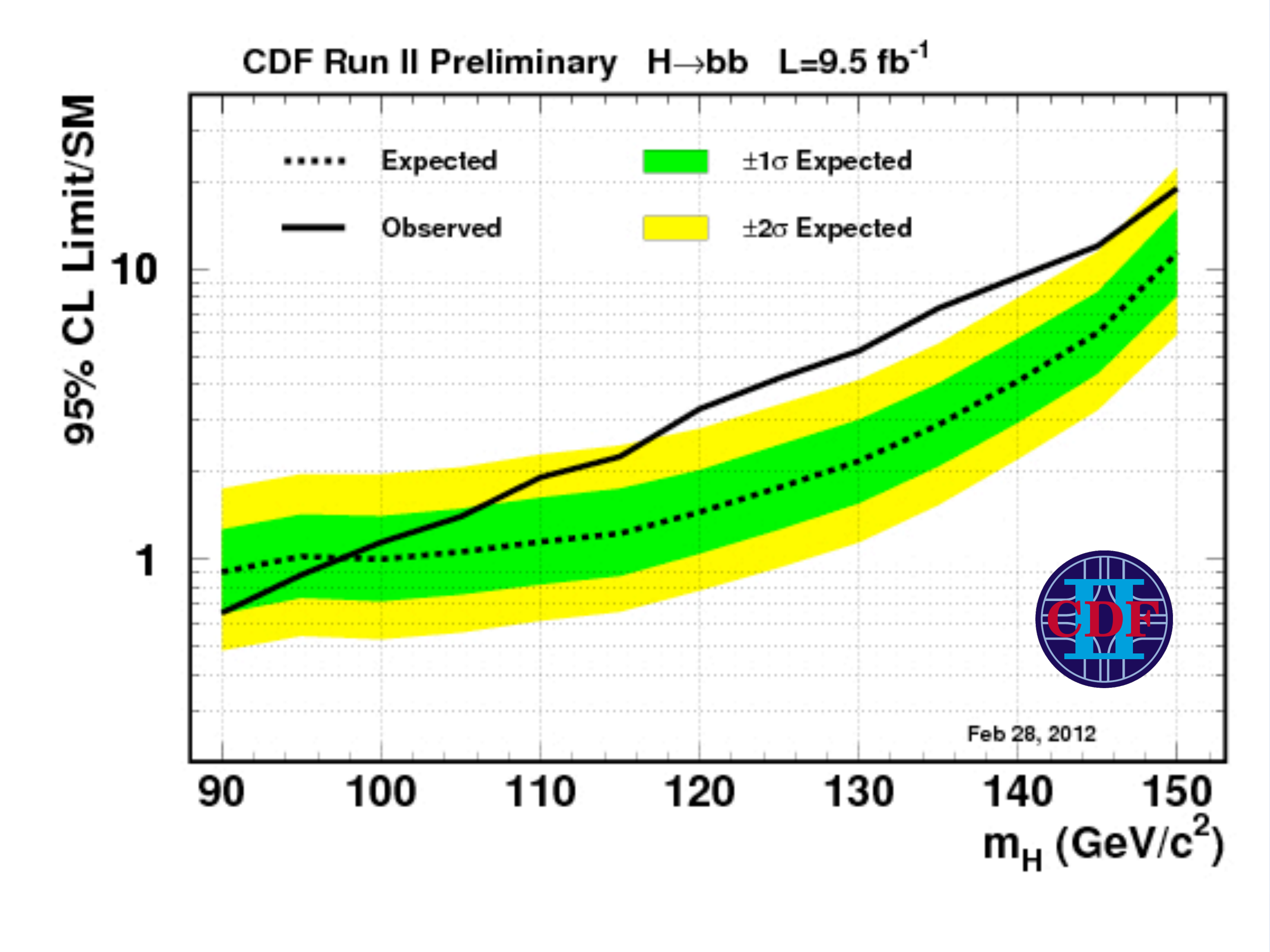


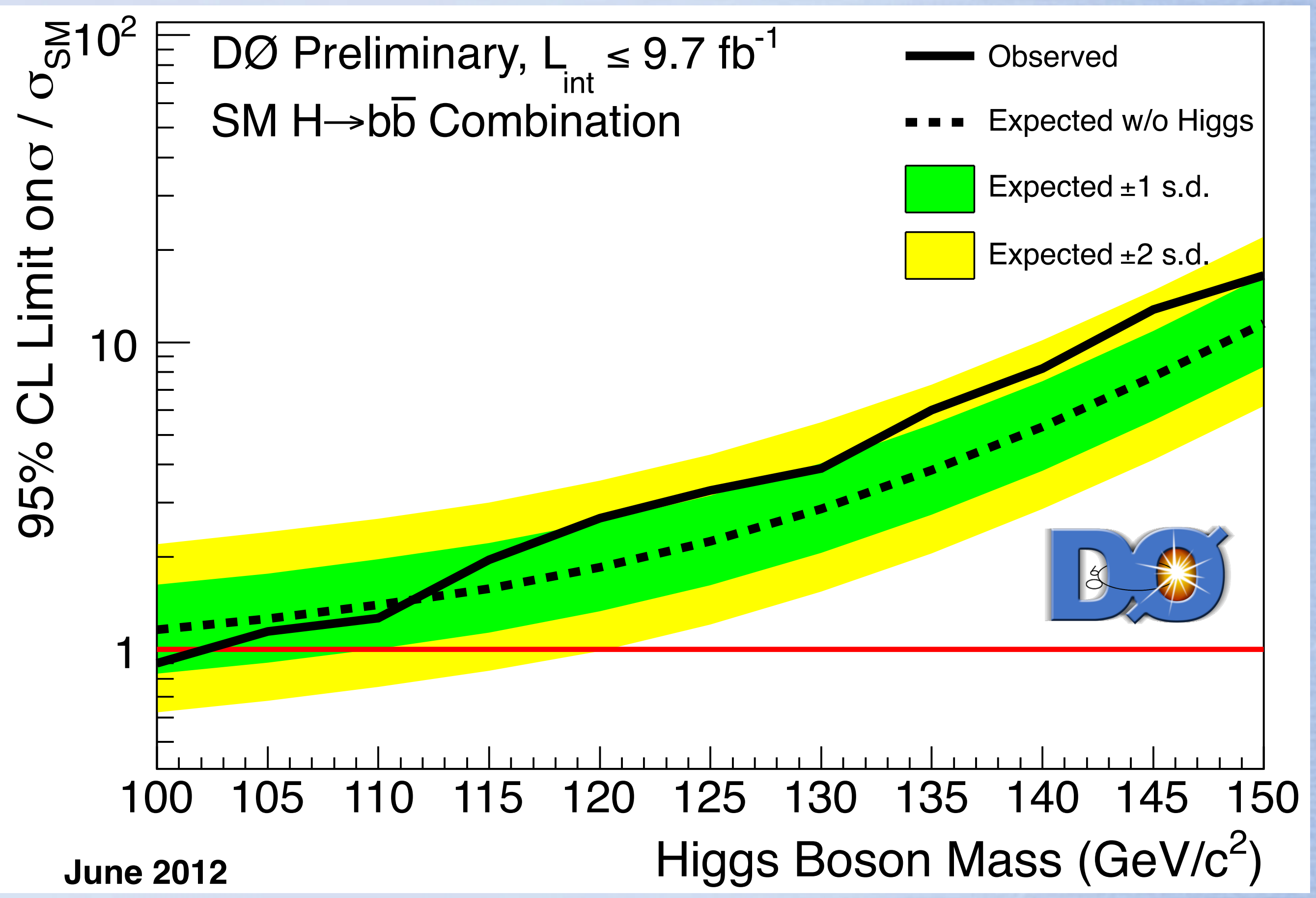


- Include ~10% systematic uncertainty on the b-tagger performance corrections (uncorrelated for both b-jet tags and non-b "mis-tags")

Individual Experiment Results

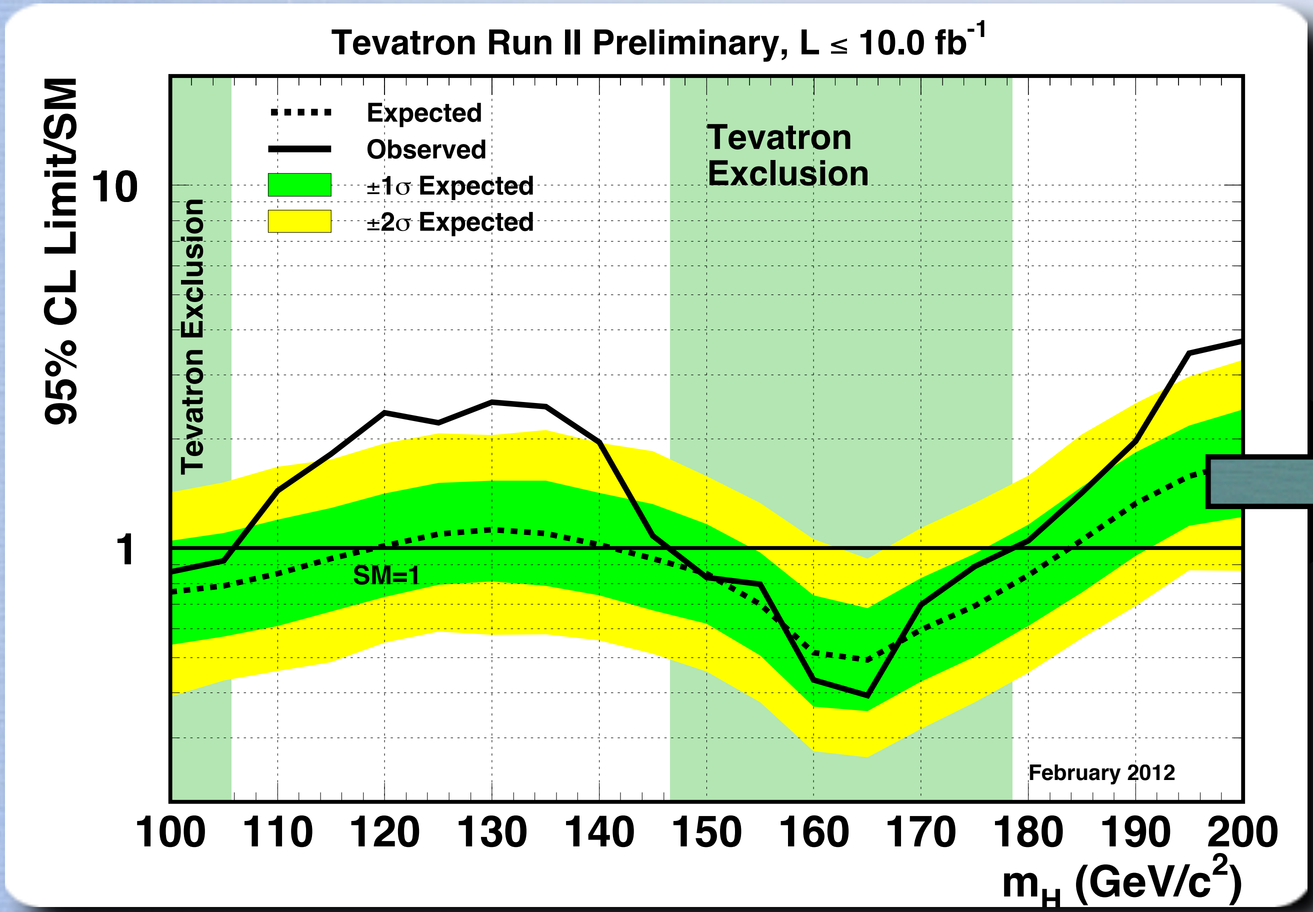
H→bb



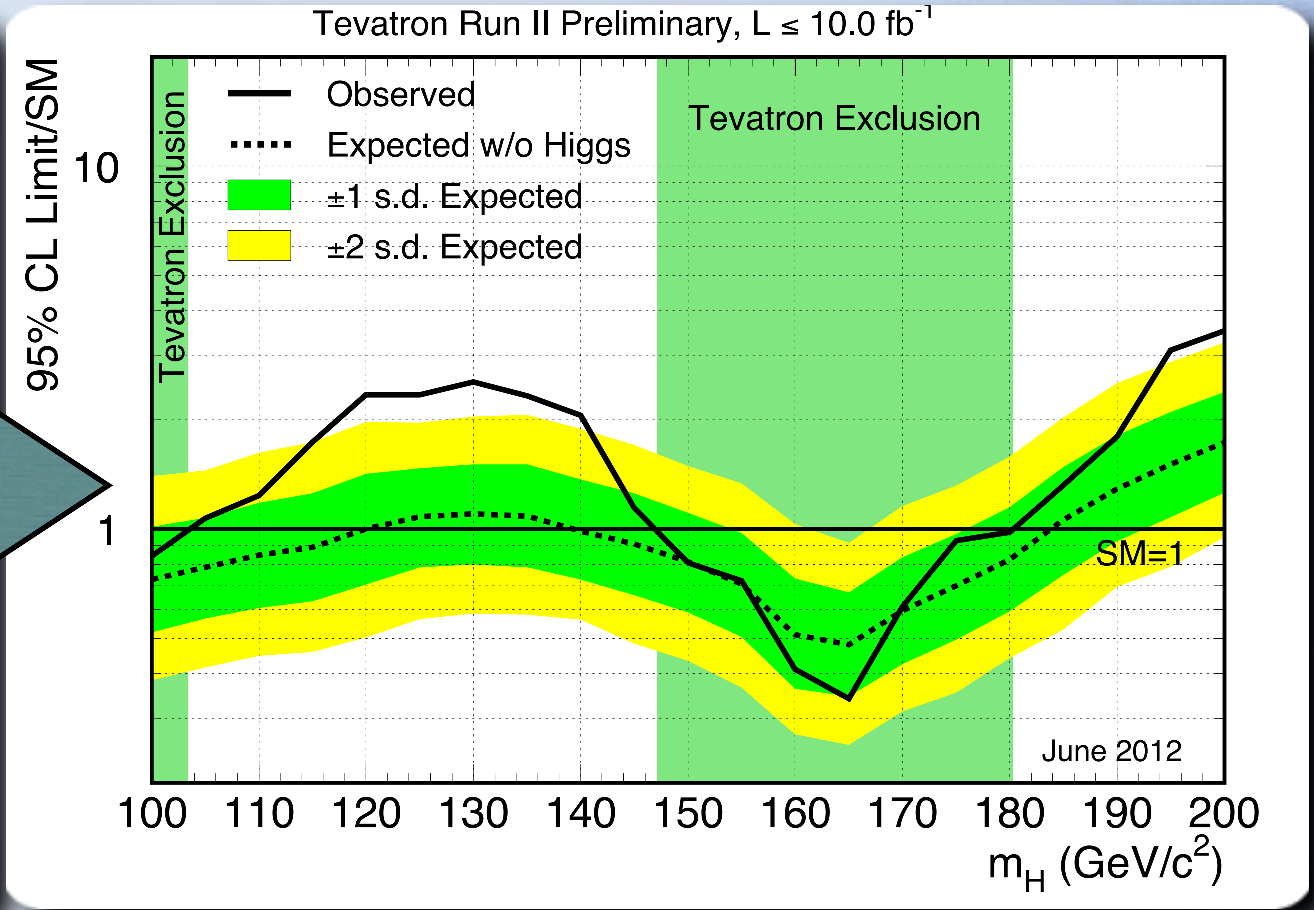


Comparison to March 2012

March 2012 Result

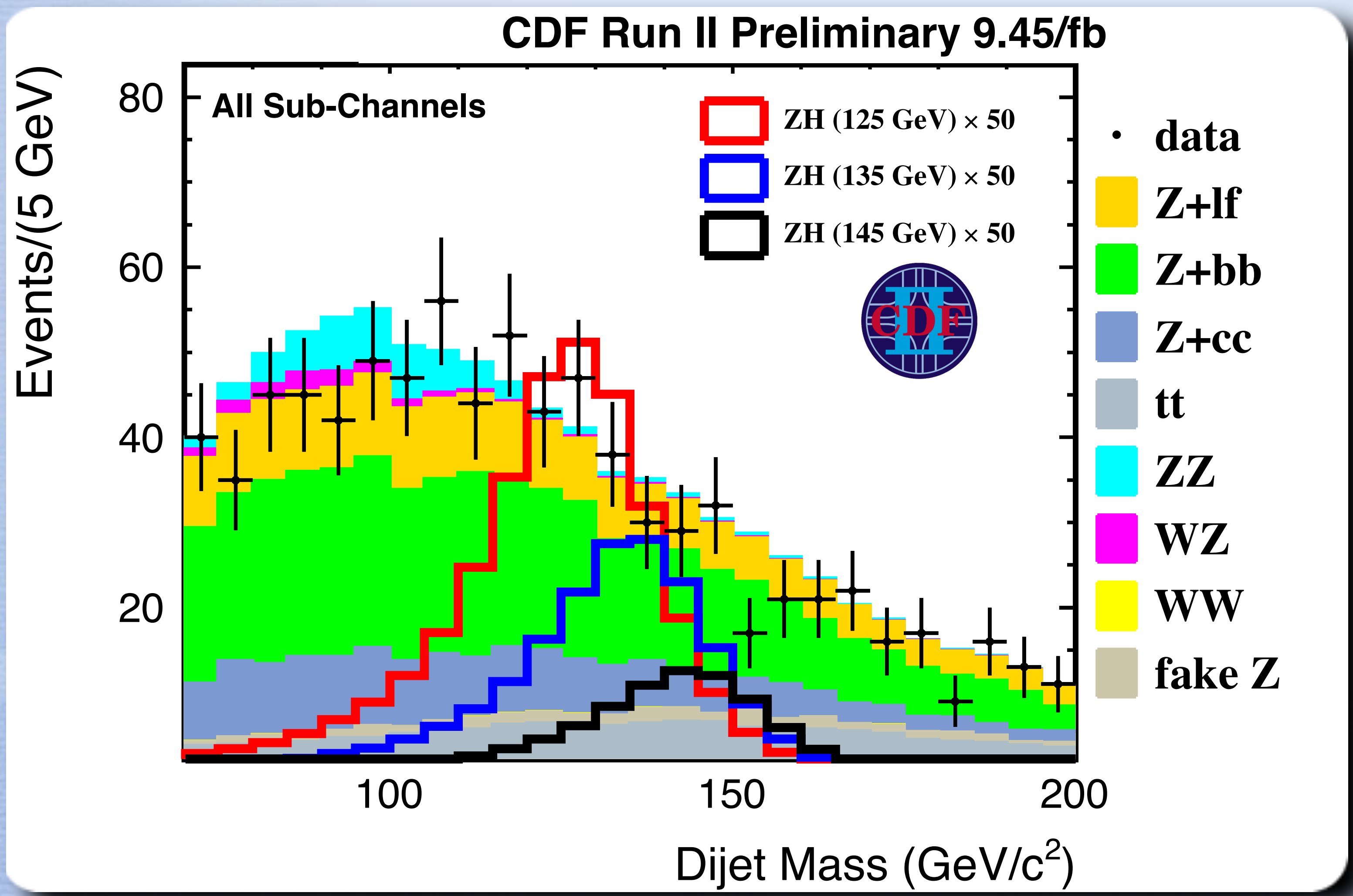


New Result



Look Elsewhere Effect

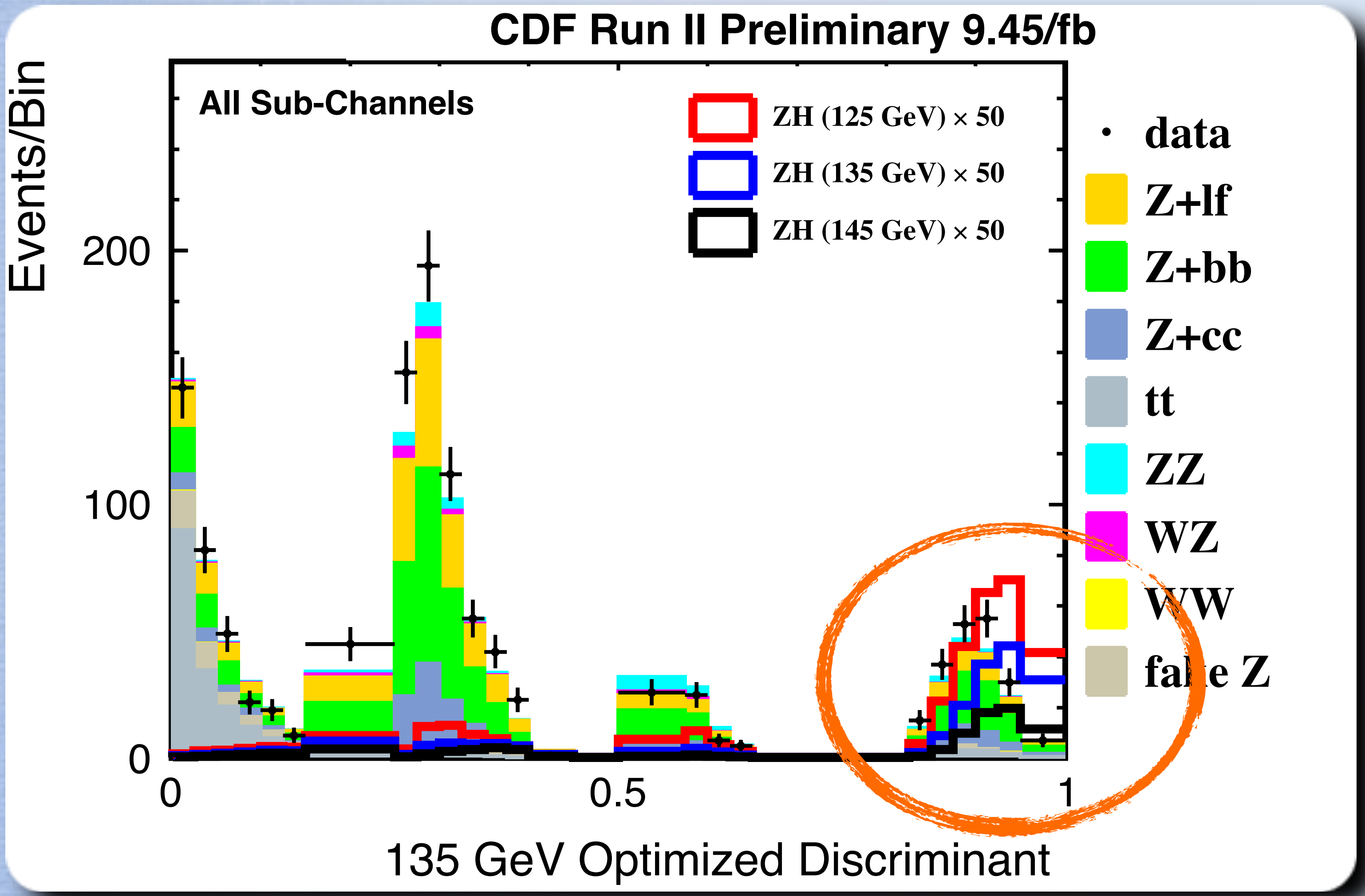
- Adjust significance for probability of a fluctuation anywhere in the search range
- Conservative LEE of 2 determined from MC studies using Dijet Mass
- After LEE the global p-value = **2.9 σ**

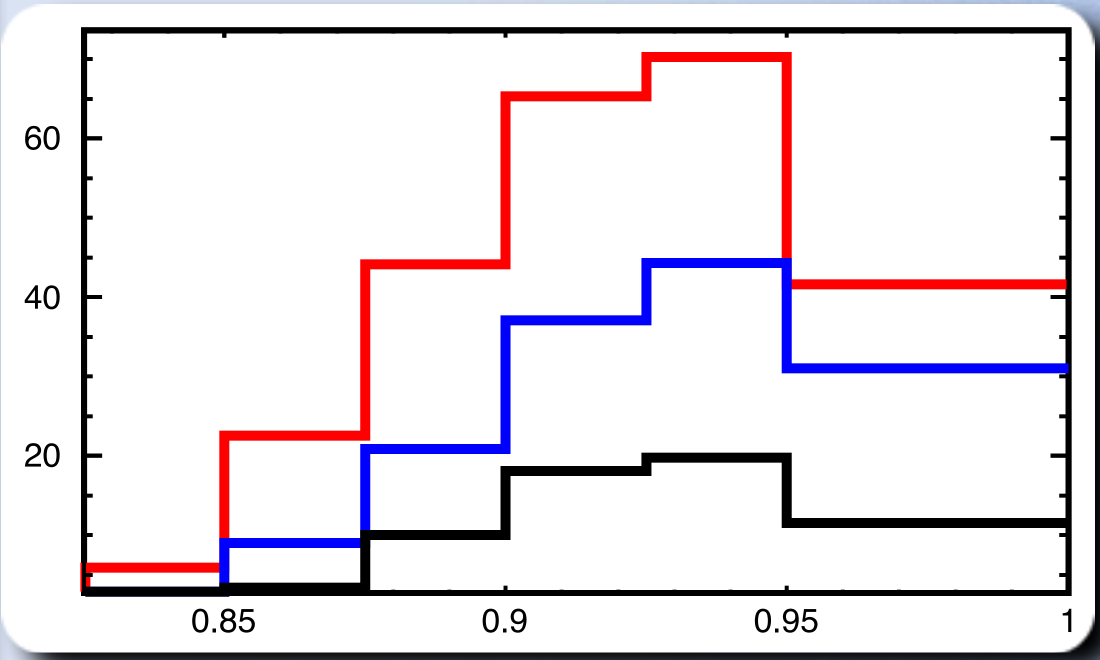


- Due to limited dijet mass resolution, difficult to disentangle signals with different values of M_H

Look Elsewhere Effect

- LEE of 2 generally conservative given limited ability to resolve M_H in multivariate analyses





Cross Sections & BR

m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	$\sigma_{t\bar{t}H}$ (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1821.8	281.1	162.7	97.3	8.000	79.1	3.68	8.36	1.11	0.113	0.159
105	1584.7	238.7	139.5	89.8	7.062	77.3	3.59	8.25	2.43	0.215	0.178
110	1385.0	203.7	120.2	82.8	6.233	74.5	3.46	8.03	4.82	0.439	0.197
115	1215.9	174.5	103.9	76.5	5.502	70.5	3.27	7.65	8.67	0.873	0.213
120	1072.3	150.1	90.2	70.7	4.857	64.9	3.01	7.11	14.3	1.60	0.225
125	949.3	129.5	78.5	65.3	4.279	57.8	2.68	6.37	21.6	2.67	0.230
130	842.9	112.0	68.5	60.5	3.769	49.4	2.29	5.49	30.5	4.02	0.226
135	750.8	97.2	60.0	56.0	3.320	40.4	1.87	4.52	40.3	5.51	0.214
140	670.6	84.6	52.7	51.9	2.925	31.4	1.46	3.54	50.4	6.92	0.194
145	600.6	73.7	46.3	48.0	2.593	23.1	1.07	2.62	60.3	7.96	0.168
150	539.1	64.4	40.8	44.5	2.298	15.7	0.725	1.79	69.9	8.28	0.137
155	484.0	56.2	35.9	41.3	2.037	9.18	0.425	1.06	79.6	7.36	0.100
160	432.3	48.5	31.4	38.2	1.806	3.44	0.159	0.397	90.9	4.16	0.0533
165	383.7	43.6	28.4	36.0	1.607	1.19	0.0549	0.138	96.0	2.22	0.0230
170	344.0	38.5	25.3	33.4	1.430	0.787	0.0364	0.0920	96.5	2.36	0.0158
175	309.7	34.0	22.5	31.0	1.272	0.612	0.0283	0.0719	95.8	3.23	0.0123
180	279.2	30.1	20.0	28.7	1.132	0.497	0.0230	0.0587	93.2	6.02	0.0102
185	252.1	26.9	17.9	26.9	1.004	0.385	0.0178	0.0457	84.4	15.0	0.00809
190	228.0	24.0	16.1	25.1	0.890	0.315	0.0146	0.0376	78.6	20.9	0.00674
195	207.2	21.4	14.4	23.3	0.789	0.270	0.0125	0.0324	75.7	23.9	0.00589
200	189.1	19.1	13.0	21.7	0.700	0.238	0.0110	0.0287	74.1	25.6	0.00526

Cross Sections & BR

We use the following references for our cross sections and branching ratios. The citations below include only those papers which contain numbers that we use. Further citations are available in our conference note.

- The WH and ZH cross sections are from Baglio and Djouadi: arXiv:1003.4266v2, which is published as JHEP 1010:064 (2010). We have obtained from the authors an extension of Table 3 to include test mass range down to 100 GeV and predictions with more digits. The VBF production cross sections were computed with VBF@NNLO, and we multiply these by $(1+\delta_{EW})$ from the HAWK program, which amounts to a roughly 2% to 3% downward correction.
- The $gg \rightarrow H$ production cross section is calculated at NNLL in QCD and also includes two-loop electroweak effects. For details, see C. Anastasiou, R. Boughezal and F. Petriello, "Mixed QCD-electroweak corrections to Higgs boson production in gluon fusion", arXiv:0811.3458 [hep-ph] (2008), which is published as JHEP 0904:003 (2009), and D. de Florian and M. Grazzini, "Higgs production through gluon fusion: updated cross sections at the Tevatron and the LHC", arXiv:0901.2427v1 [hep-ph] (2009), which is published as Phys.Lett.B674:291-294 (2009). These cross were updated with the full m_{top} dependence in the calculation.
- We follow the BNL Accord to assign scale uncertainties separately in the 0, 1, and 2 or more jet bins. Details can be found in arXiv:1107.2117.
- PDF uncertainties follow the prescription of the PDF4LHC working group.
- The Higgs boson decay branching ratios are those reported in the Handbook of LHC Cross Sections: 1. Inclusive observables, arXiv:1101.0593v2.
- Higgs boson decay branching ratio uncertainties from m_b, m_c, and α_s are computed by Baglio and Djouadi in arXiv:1012.0530, which is published as JHEP 1103:055 (2011).