Tevatron SM Higgs Combination

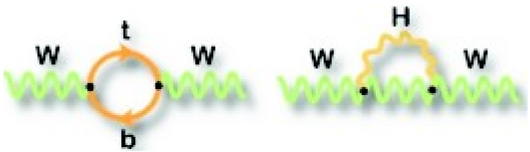
Joseph Haley on behalf of CDF and DØ

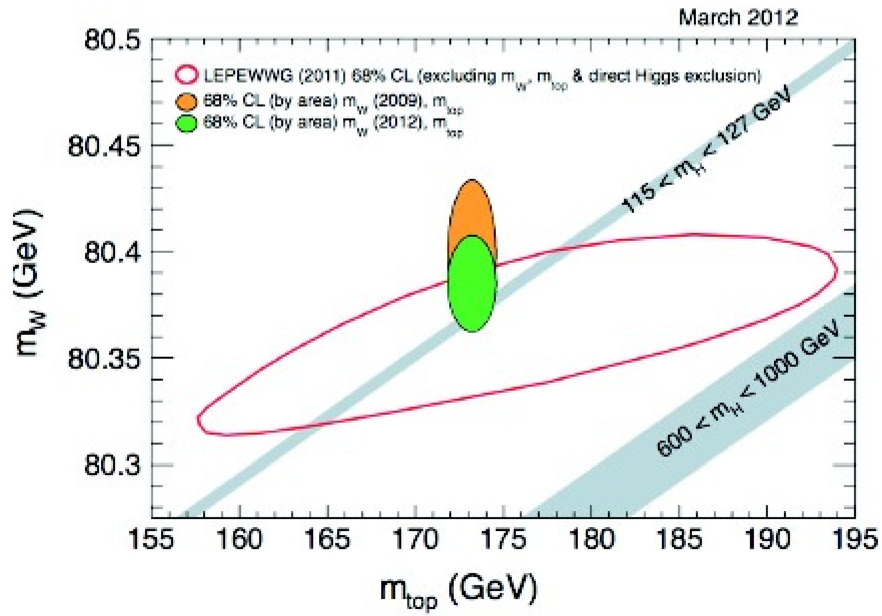
Northeastern University

Higgs Hunting 2012, Orsay-France

What We Already Know

Indirect constraints from precision EW measurements prefer lower Higgs boson masses





- M_H < 152 GeV @ 95% CL

Direct searches have excluded much of the accessible mass range

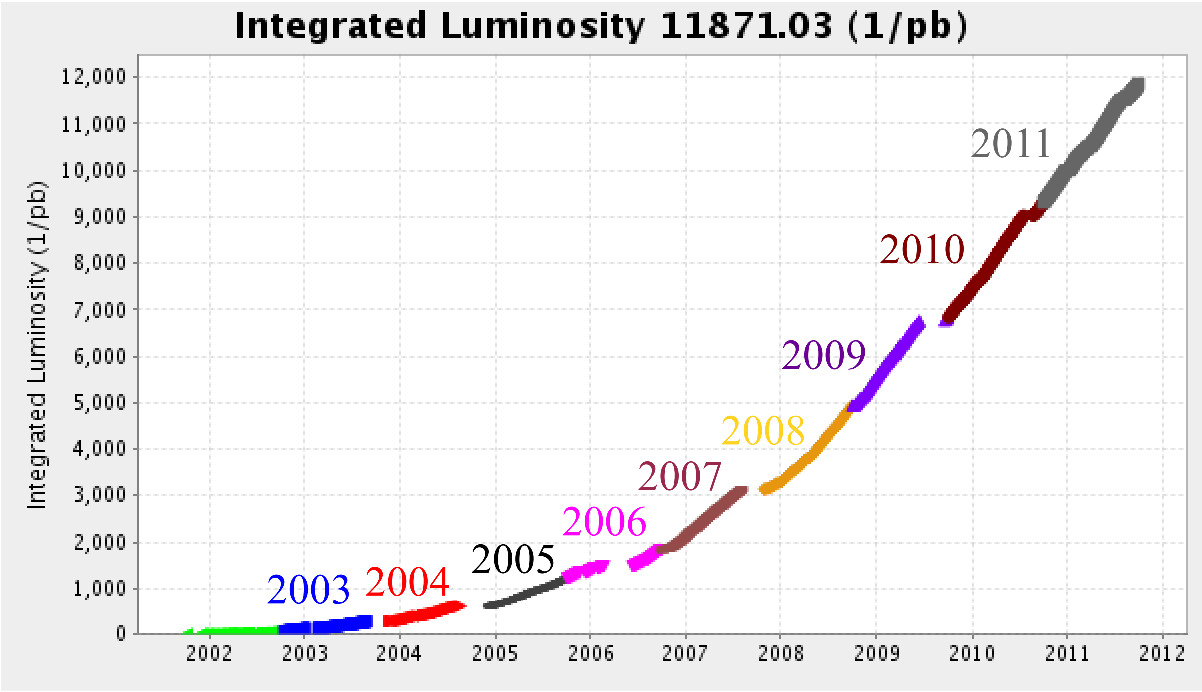
- LEP: M_H > 114.4 GeV @ 95% CL
- Tevatron: Exclude $M_H \sim$ 160 GeV @ 95% CL
- LHC: Exclude most values of M_H up to 600 GeV @ 95% CL

Most recently from LHC: Observation of Higgs (like) boson at 125 GeV

Tevatron

$p\bar{p}$ collider with $\sqrt{s}$ = 1.96 TeV

- Shutdown September 30, 2011 after 26 years of outstanding operation
- ~12 fb^{-1} delivered, ~11 fb^{-1} recorded, ~10 fb^{-1} after data quality / experiment



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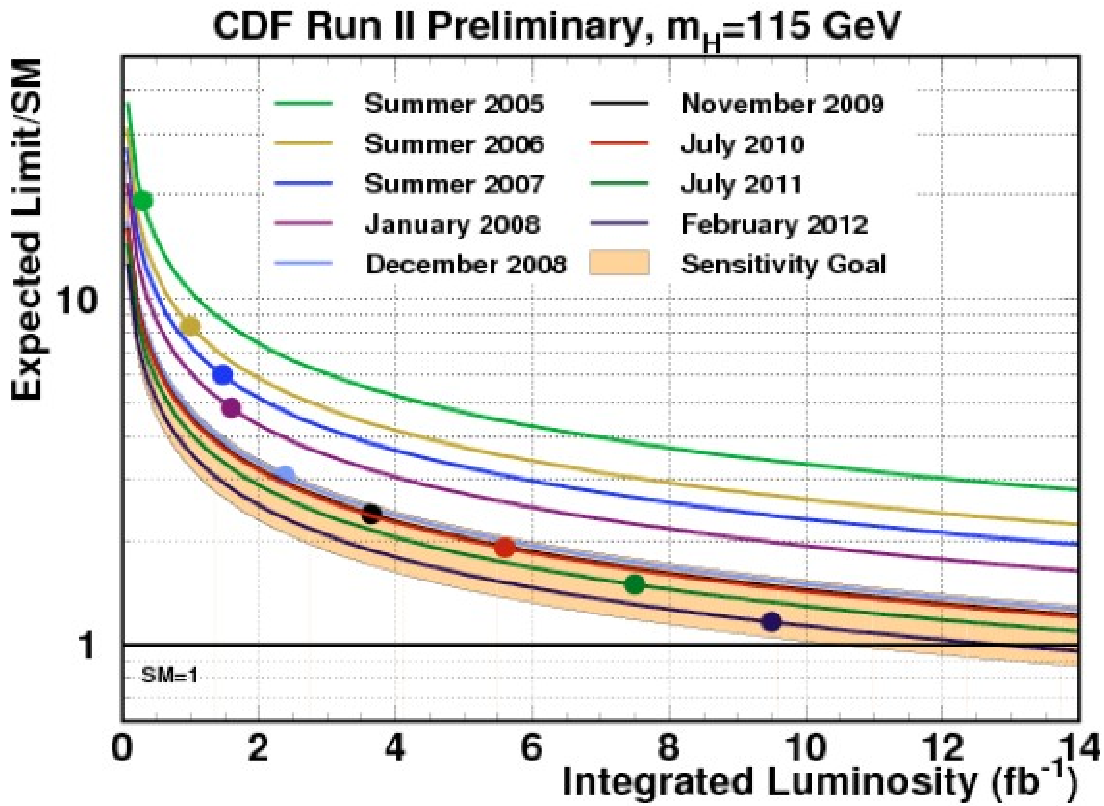
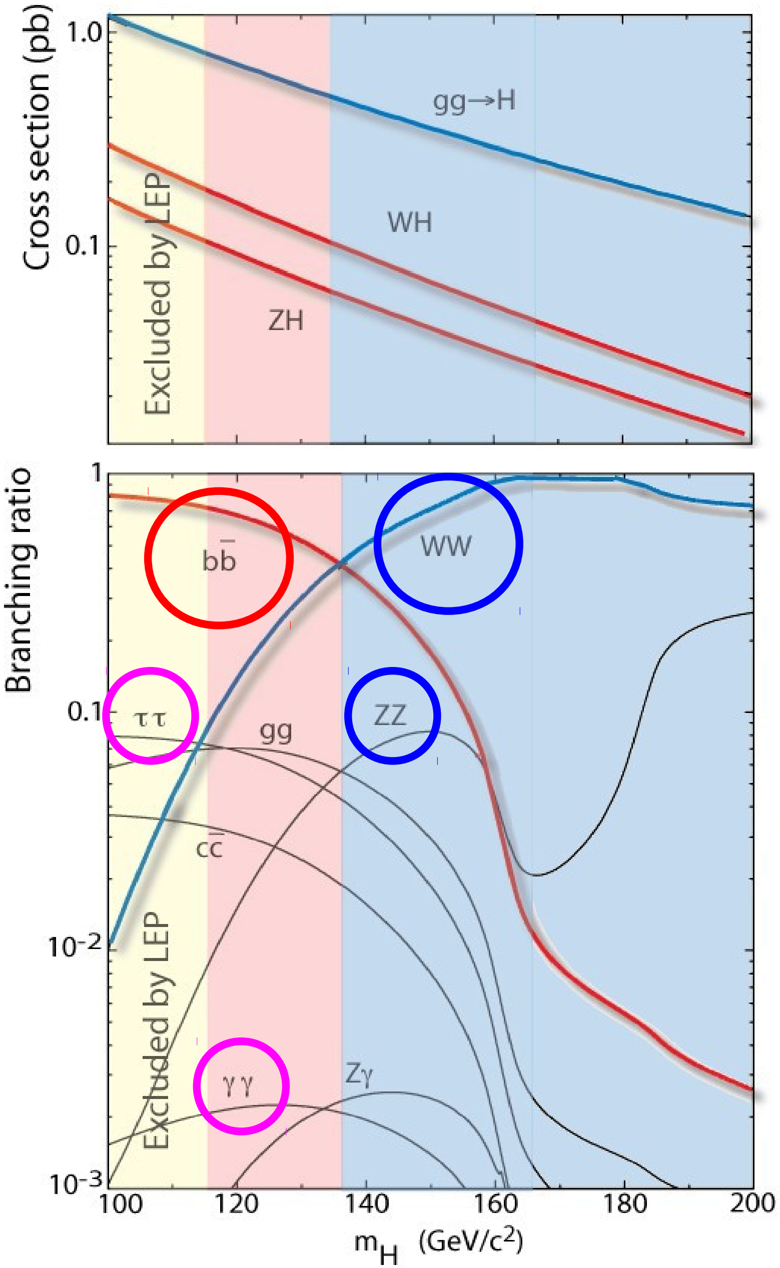
We aren't getting any more data!

- But we have a track record of improving sensitivity beyond simply adding more data



Analyses

- High mass sensitivity dominated by H→WW→lνlν
  - Talk by B. Tuchming
- Low mass sensitivity dominated by H→bb in association with W or Z
  - Talk by A. Buzatu
- Less sensitive channels add overall sensitivity of combination
  - Talk by N. Osman
- Also, BSM Higgs searches
  - Talk by R. Madar



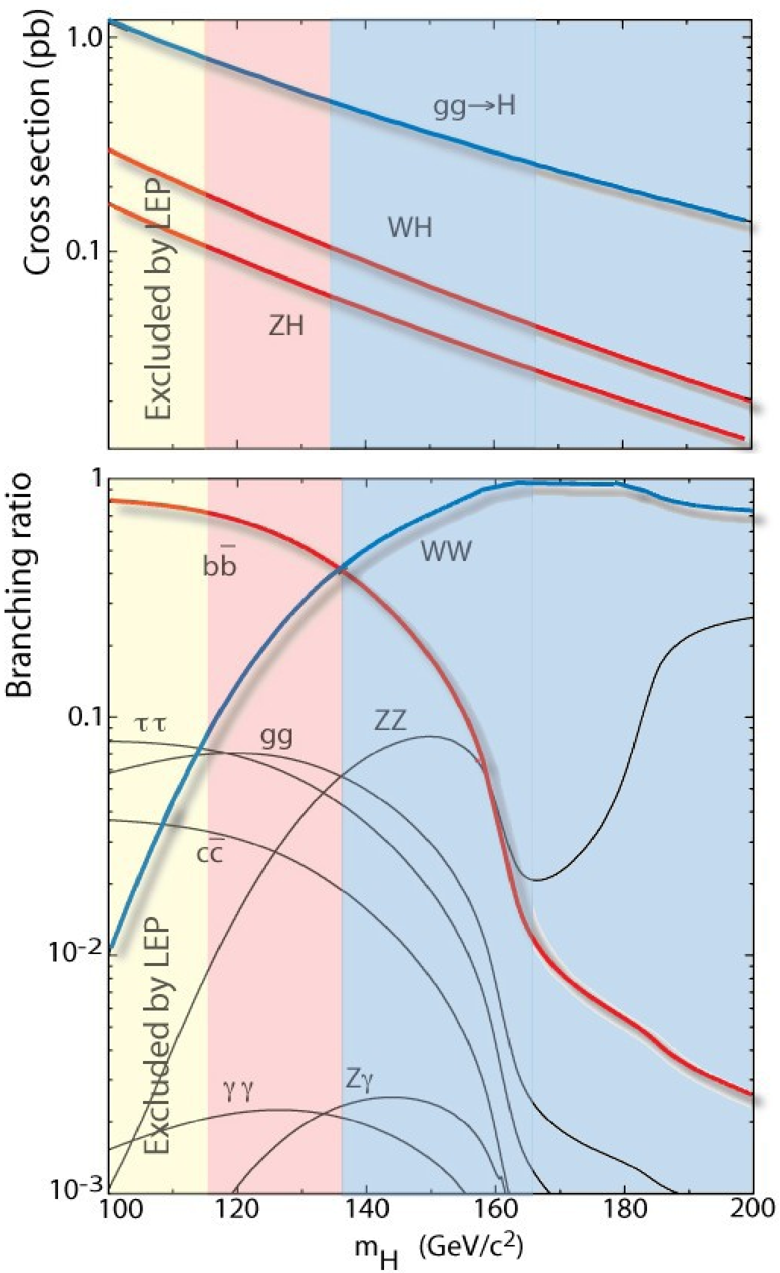
Search Strategy

No single channel has enough sensitivity
⇒ Divide and conquer

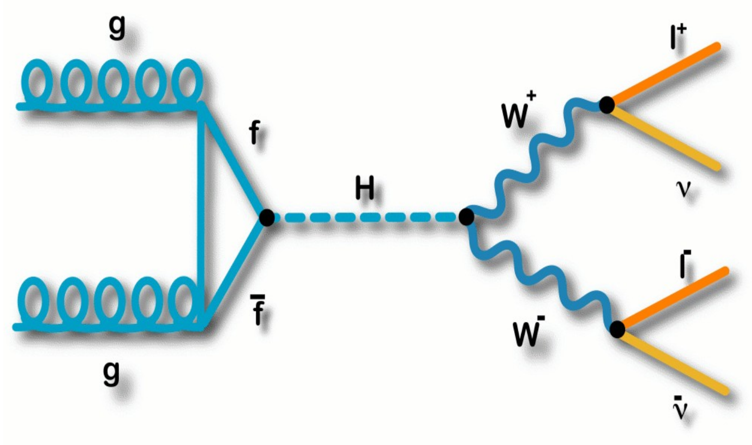
- Explore as many final states as possible
- Maximize acceptance
- Separate into sub-channels
  - Different signal purity
  - Different background composition
- Use multivariate techniques
  - Reduce/remove backgrounds
  - Best discrimination for measurement

Put it all back together

- Account for correlations between channels
- Perform statistical tests to see if the data are compatible with SM Higgs signal



$\mathcal{H} \rightarrow WW \rightarrow l\nu l\nu$



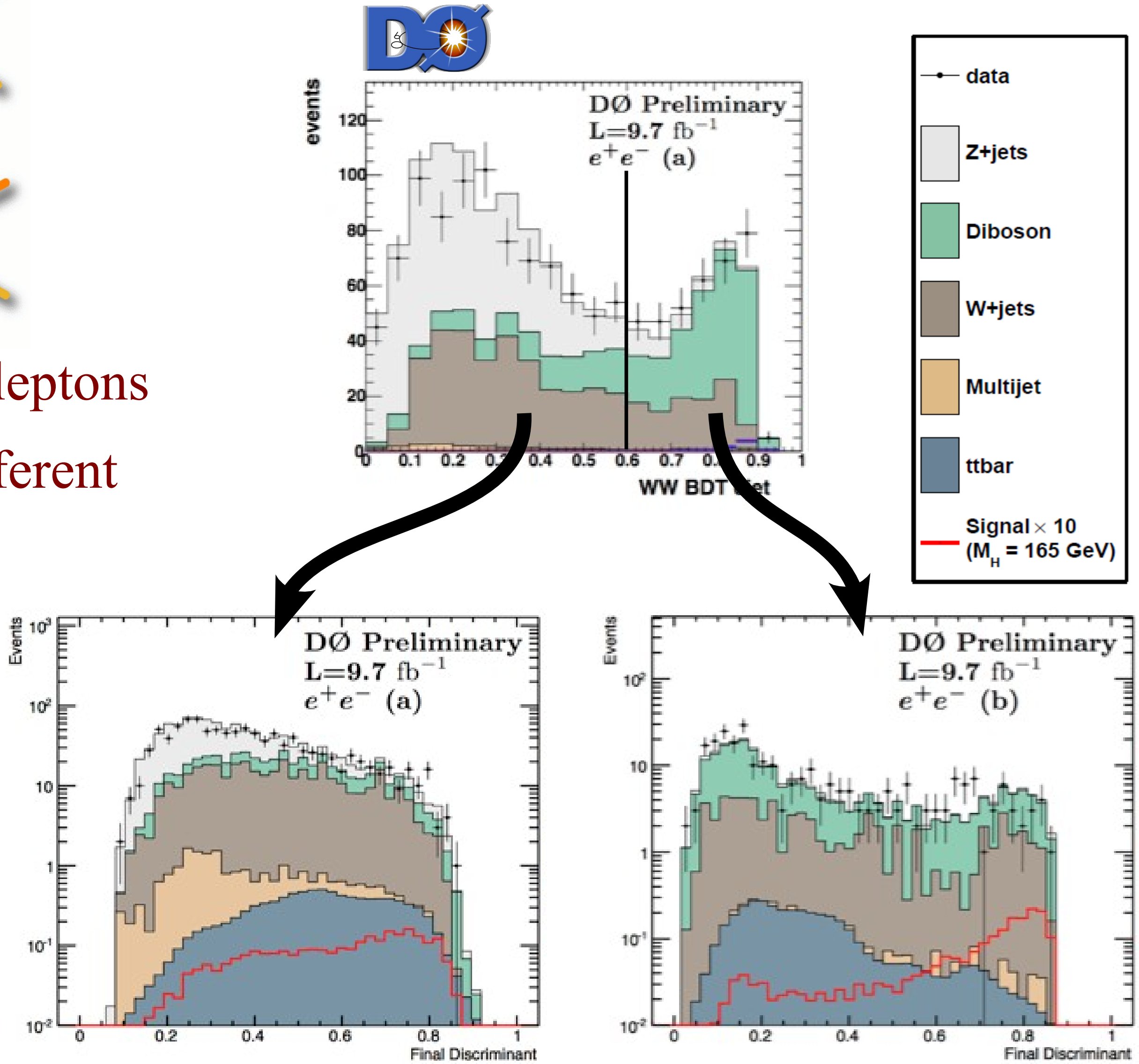
Two oppositely charge high-p_T leptons

Sub-channels optimized for different background compositions

- Lepton flavor
- Jet multiplicity

New for DØ analyses:

- WW depleted / enriched



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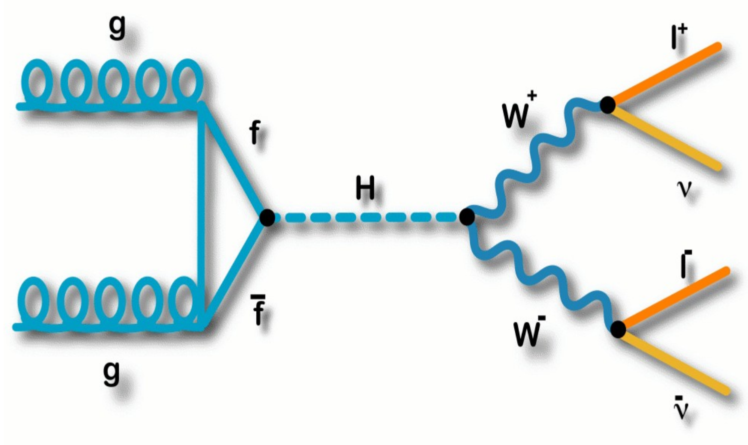

Two oppositely charge high-p_T leptons

Sub-channels optimized for different background compositions

- Lepton flavor
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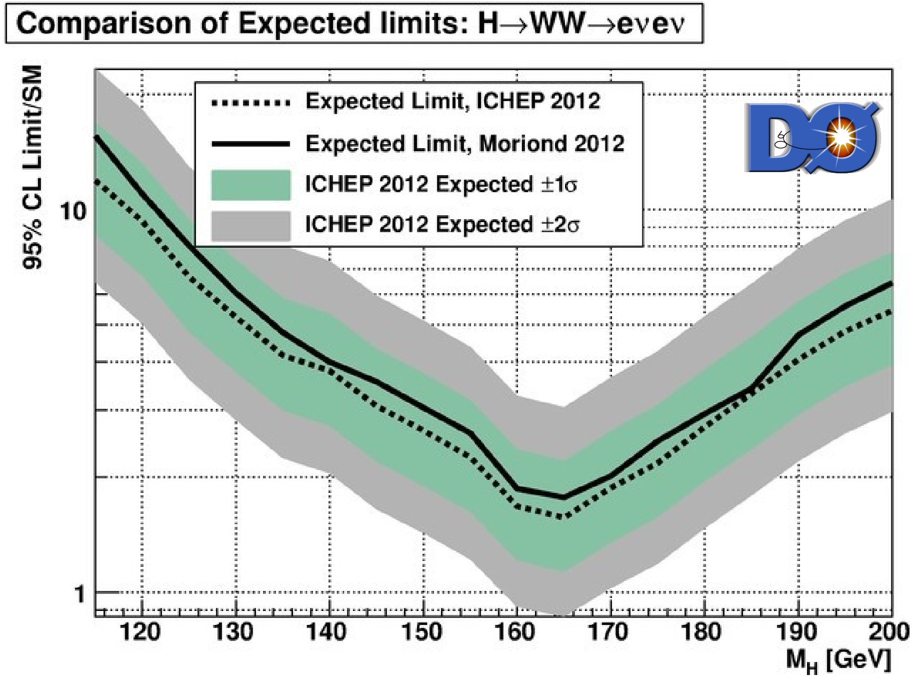
New for DØ analyses:

- WW depleted / enriched

⇒ ~10% improvement in sensitivity

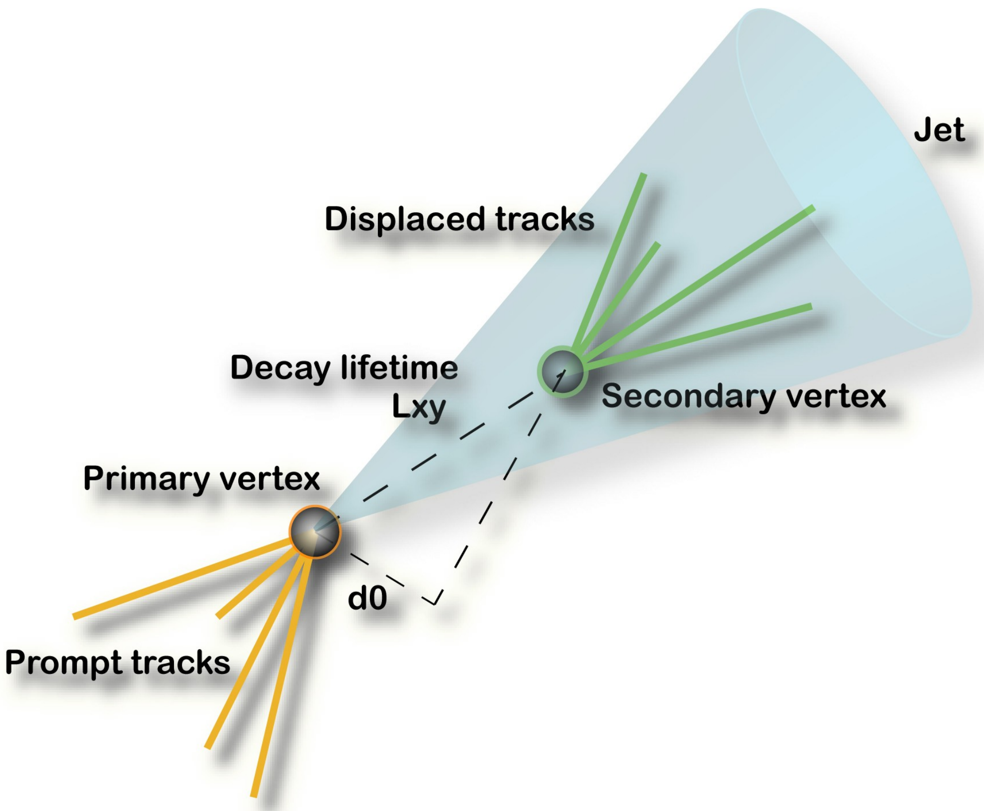


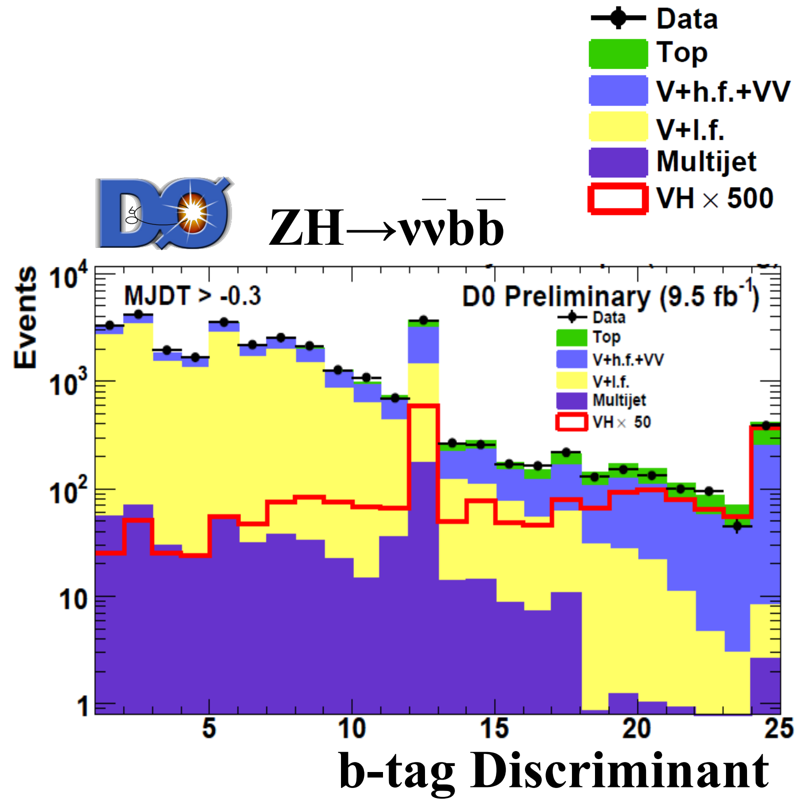
$VH \to Vb\bar{b}$

Enhance H→bb by requiring jets to be "b-tagged"

Use **multivariate** b-tag classifiers to improve discrimination power

- 50 – 80% efficiency to tag b-jet
- 0.5 – 10% chance to tag light jet





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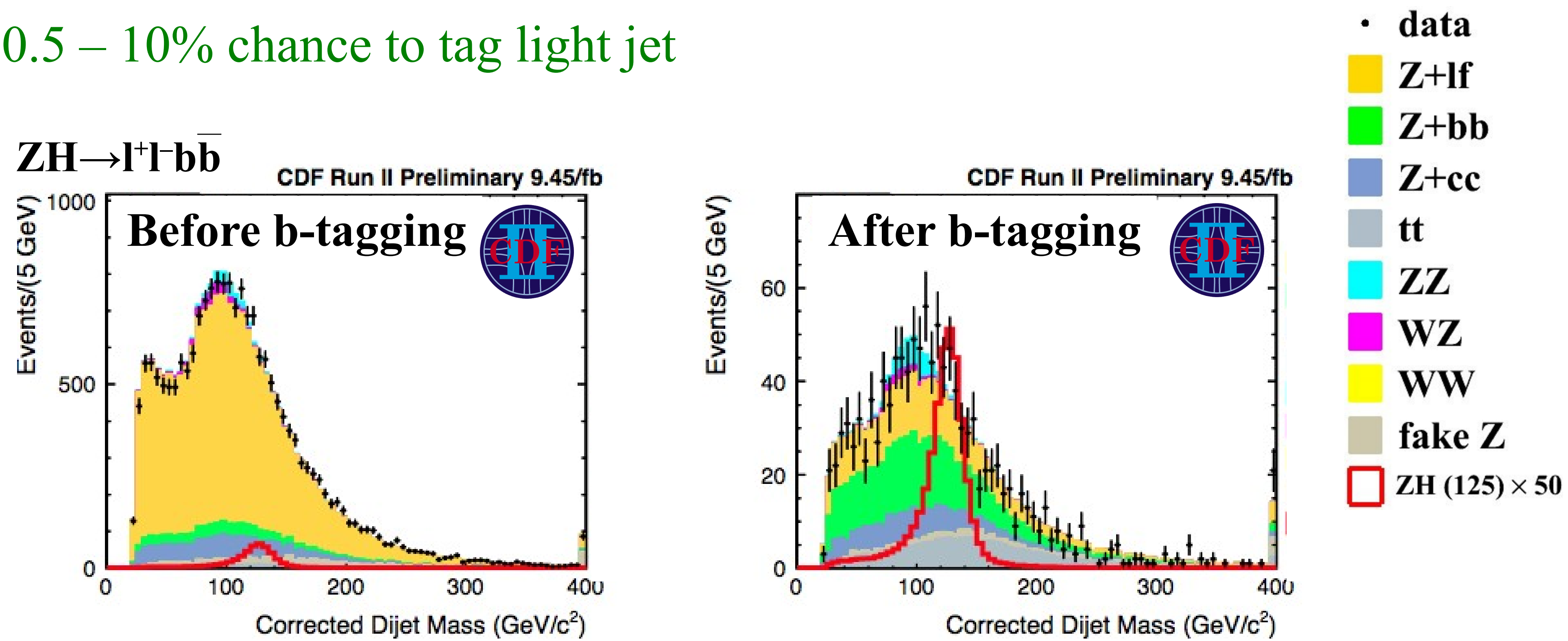

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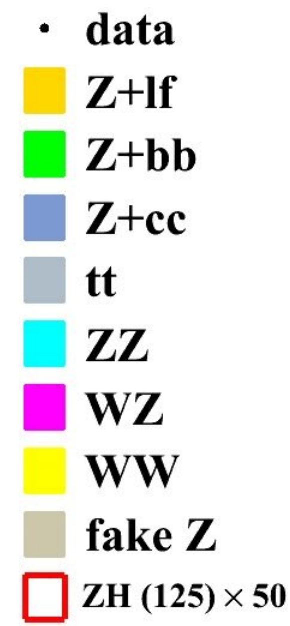
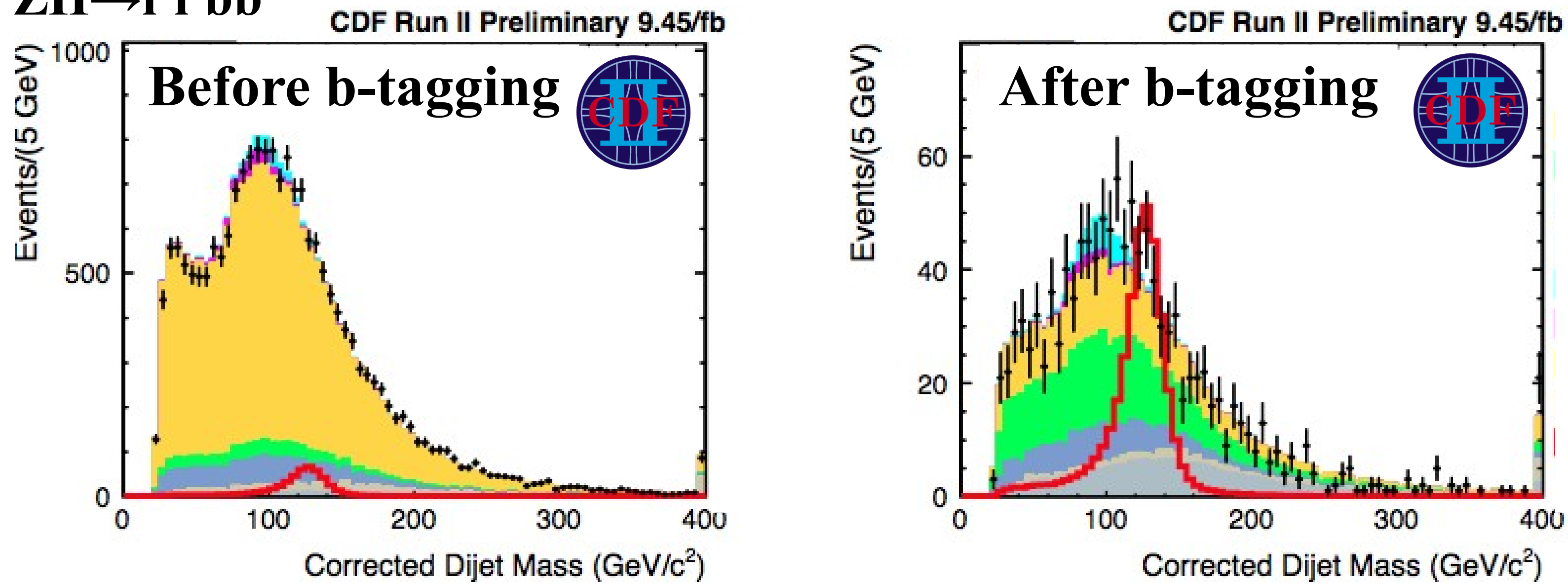


$ZH \rightarrow l^+l^-b\bar{b}$



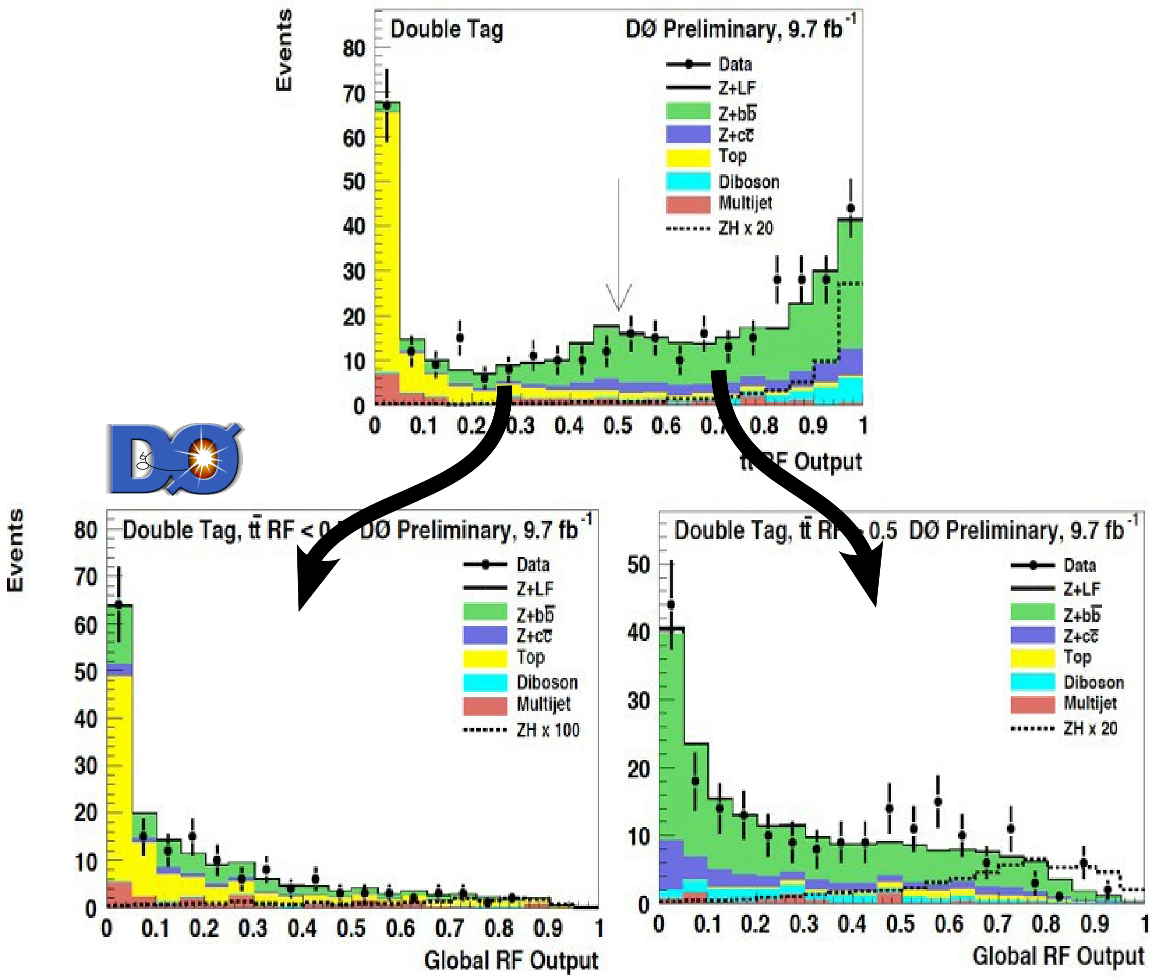
Most significant improvement for CDF's Winter 2012 update

⇒ This alone brought 15 – 30% improvement in each H→bb analysis

$VH \rightarrow Vb\bar{b}$

DØ $ZH \rightarrow l^+l^-bb$

- Increased acceptance
- tt depleted / enriched



DØ $WH \rightarrow l\nu b\bar{b}$

- Additional muon trigger
- Better multijet rejection
- Additional b-tag category

DØ $ZH \rightarrow \nu\bar{\nu}b\bar{b}$

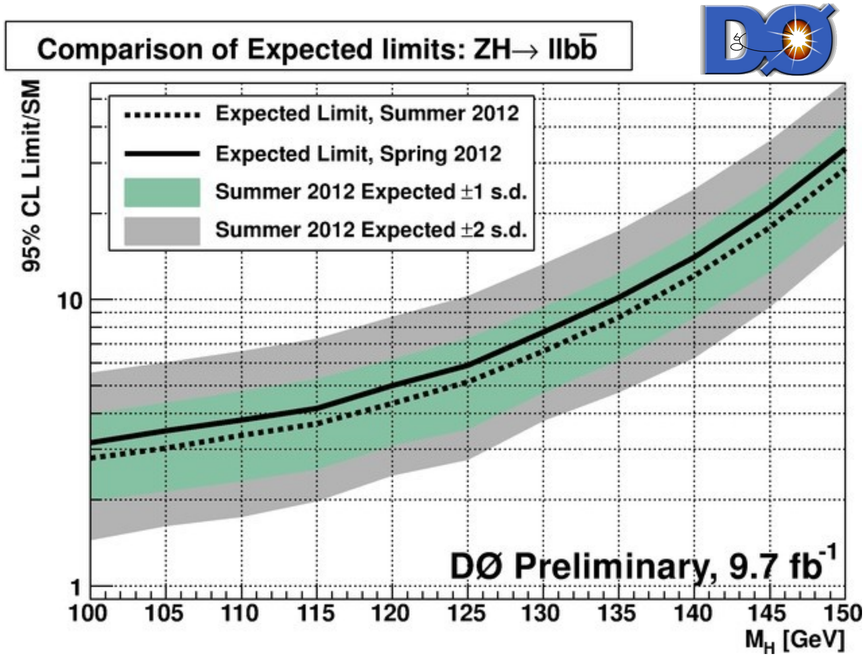
- Improved multivariate training

$VH \rightarrow V b\bar{b}$

DØ ZH→l^+l^-bb

- Increased acceptance
- tt depleted / enriched

⇒ 10 – 15% improvement



DØ WH→lνb$\bar{b}$

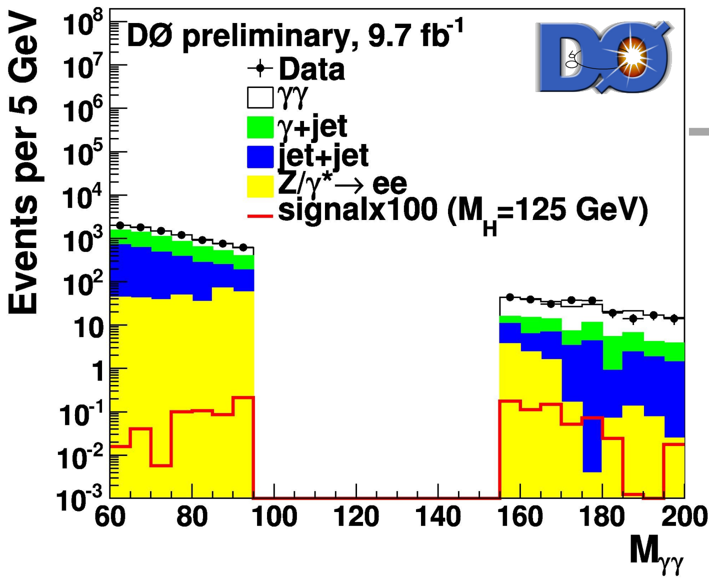
- Additional muon trigger
- Better multijet rejection
- Additional b-tag category
- ⇒ 10 – 15% improvement

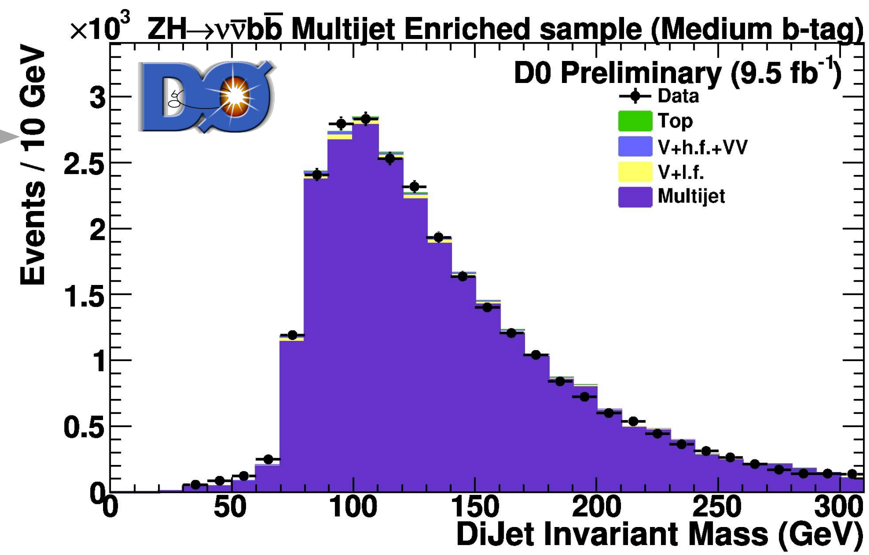
DØ ZH→ν$\bar{\nu}$b$\bar{b}$

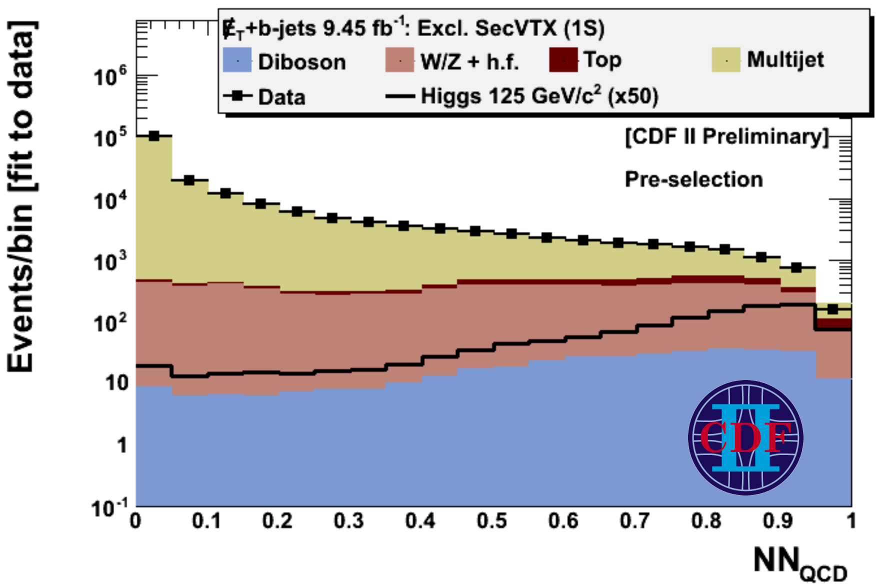
- Improved multivariate training
- ⇒ 5 – 10% improvement

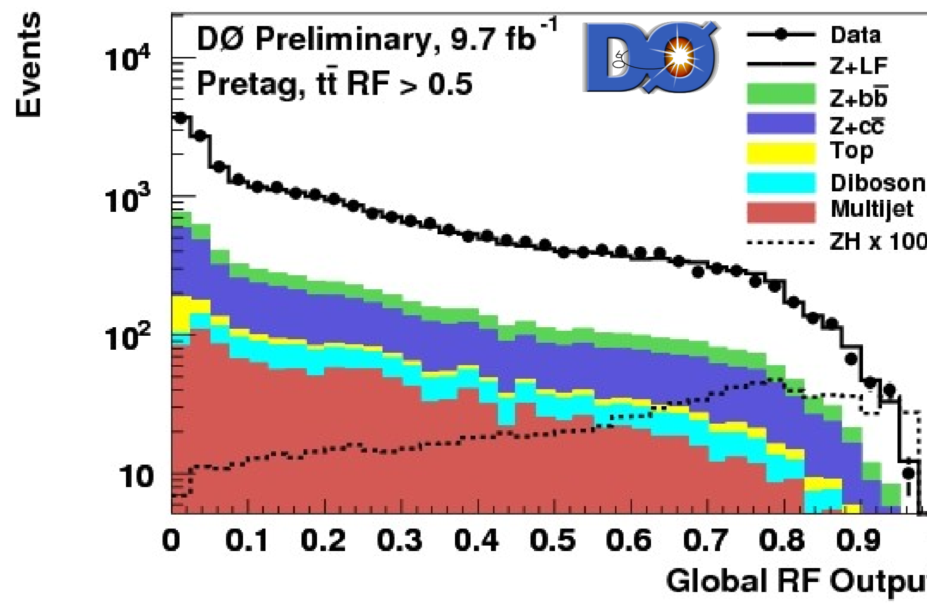
Higgs Search Validation

Use sideband and control regions to check background modeling









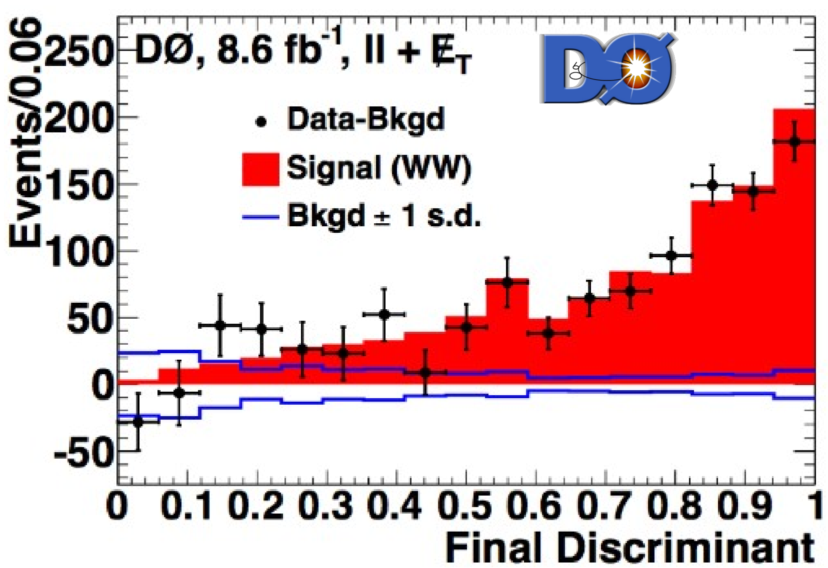
Higgs Search Validation

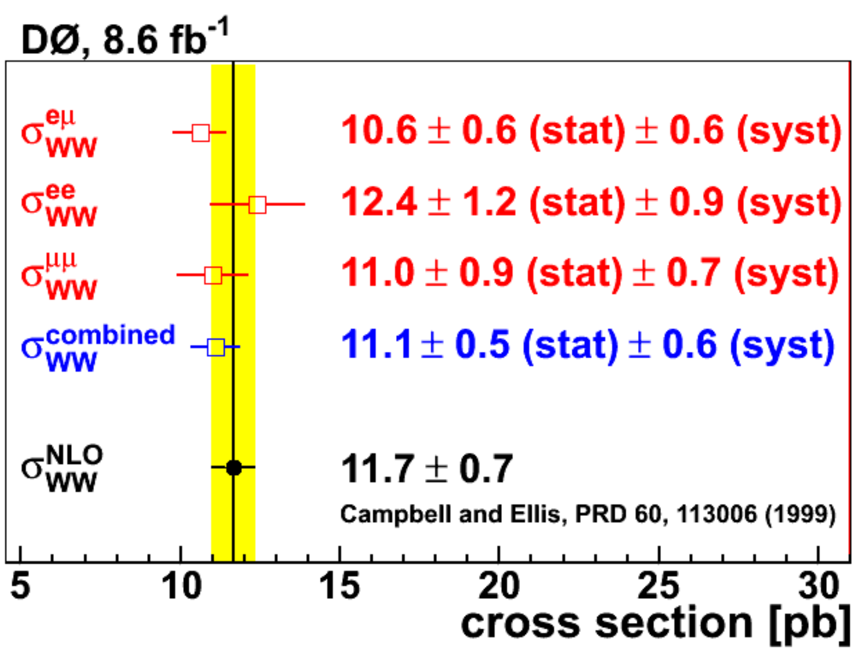
Use sideband and control regions to check background modeling

Validate analyses by measuring SM diboson production

- Replace the Higgs signal with diboson signal in the final discriminants

➢ H→WW→lνlν analyses measure WW→lνlν production





Higgs Search Validation

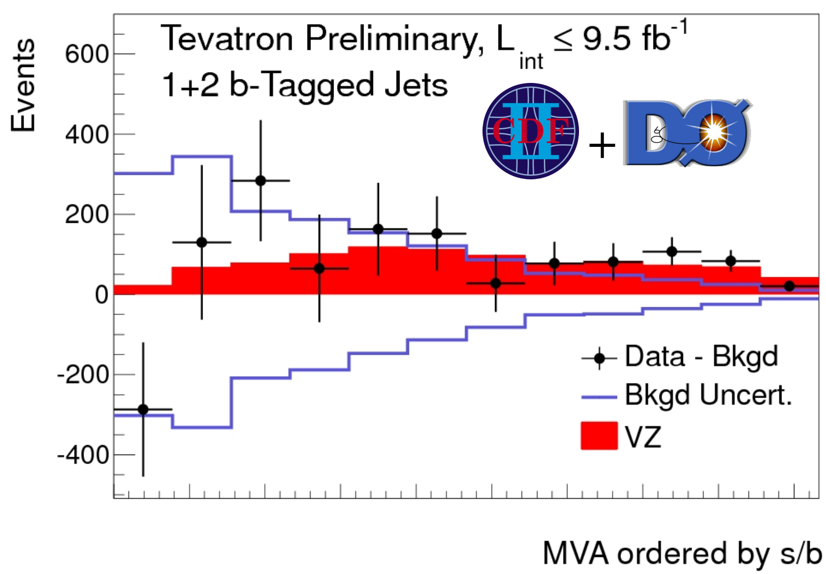
Use sideband and control regions to check background modeling

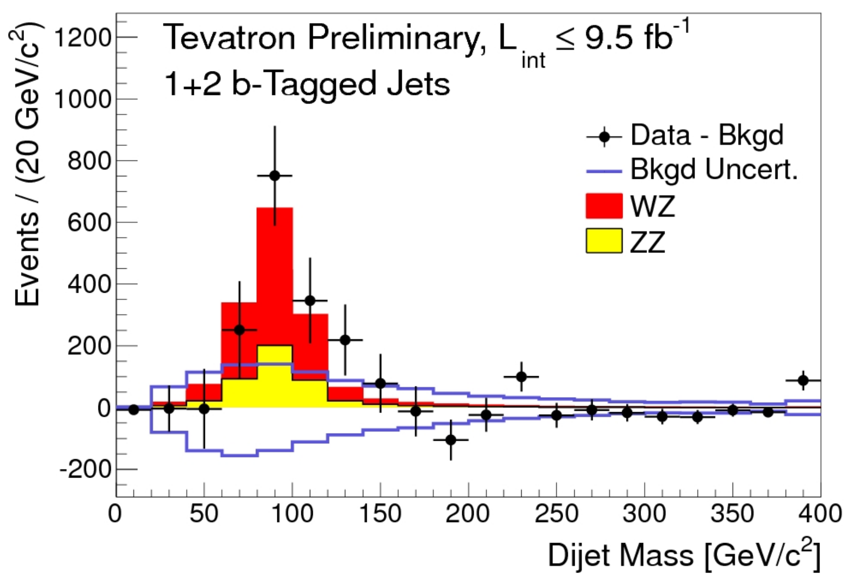
Validate analyses by measuring SM diboson production

- Replace the Higgs signal with diboson signal in the final discriminants

➢ $H \rightarrow WW \rightarrow l\nu l\nu$ analyses measure $WW \rightarrow l\nu l\nu$ production

➢ $VH \rightarrow Vbb$ analyses measure WZ and ZZ (WW still as a background)



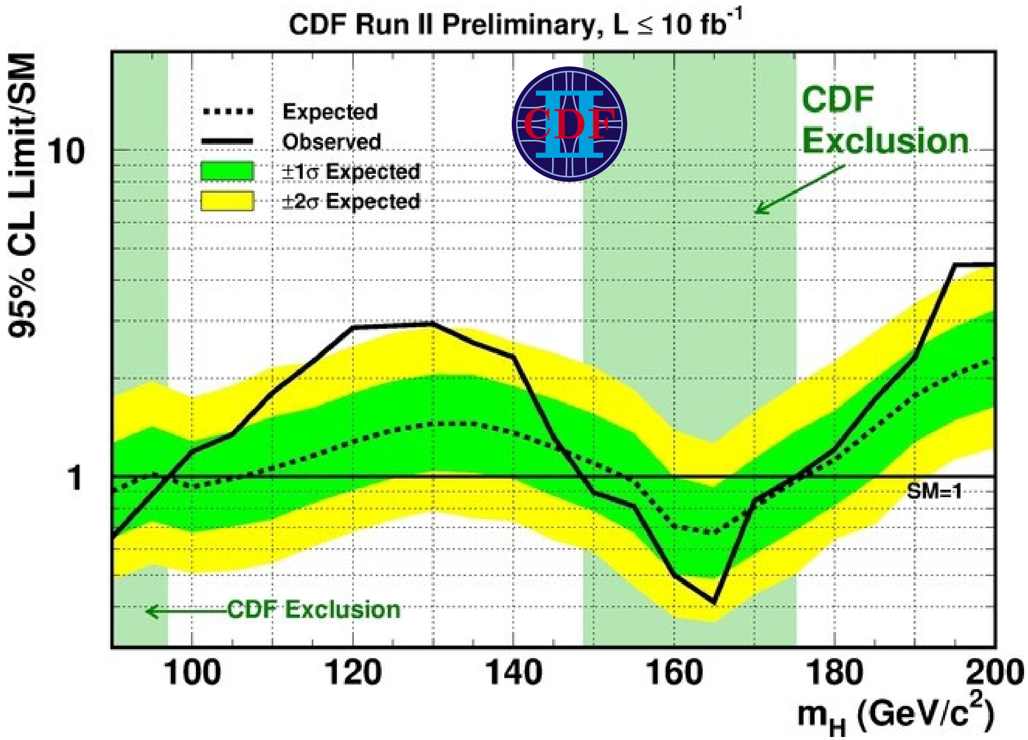


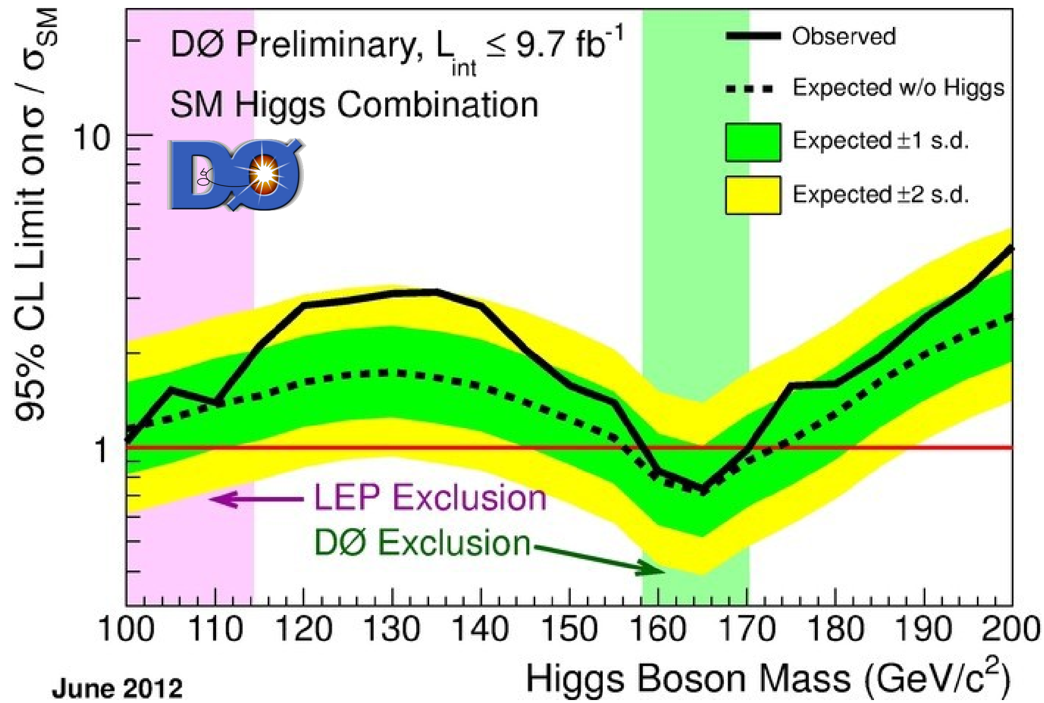
- $\sigma(WZ+ZZ) = 4.5 \pm 1.0$ pb
- Significance : 4.6 standard deviations

$\sigma_{SM}(WZ+ZZ) = 4.4 \pm 0.3$ pb

Individual Experiment Results

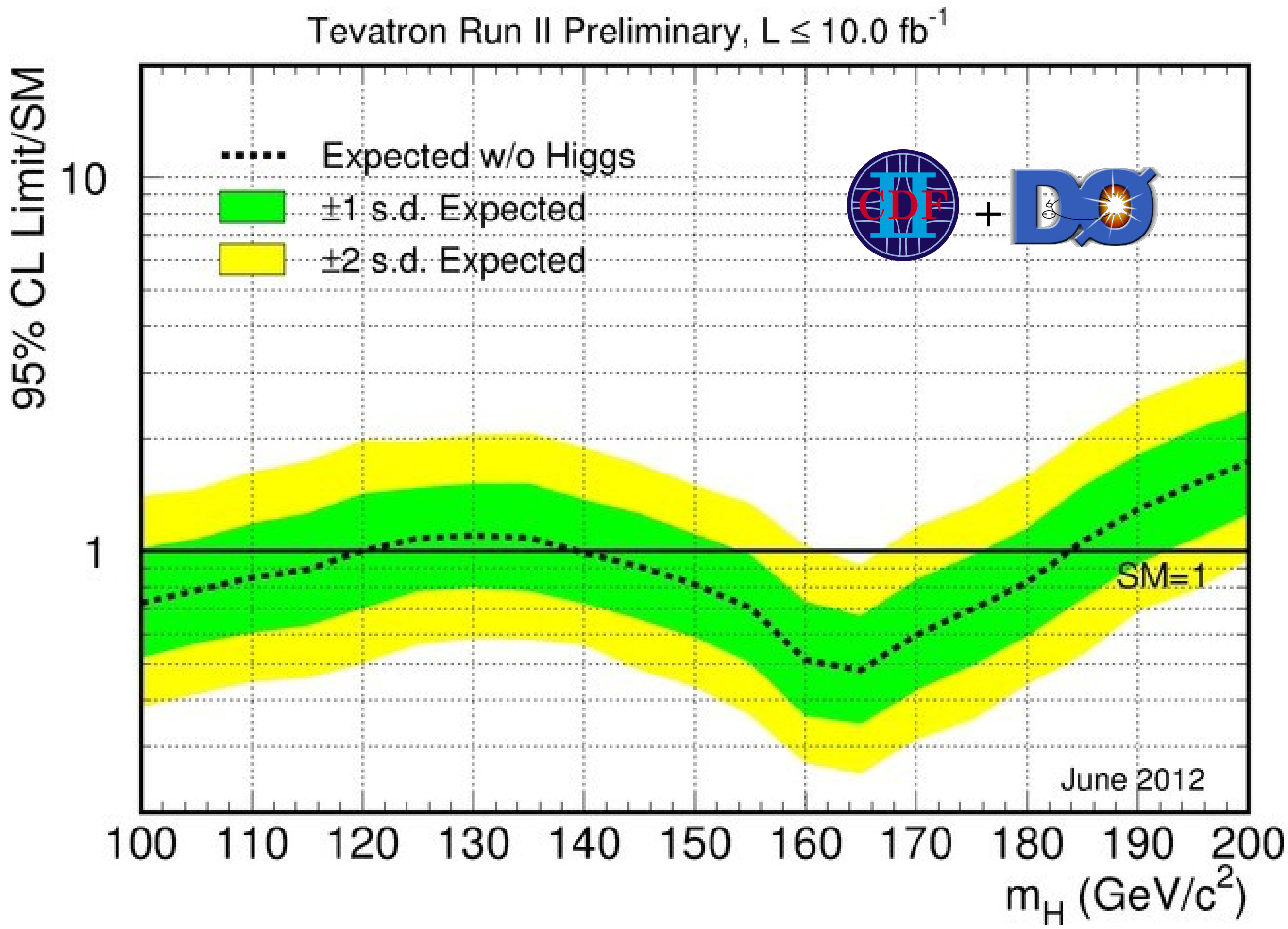
- Individual results from CDF and DØ





- Similar search sensitivity over entire probed mass range
  - Exclusions at 95% CL
    - CDF: 90 GeV < M_H < 97 GeV & 147 GeV < M_H < 175 GeV
    - DØ: 159 GeV < M_H < 170 GeV

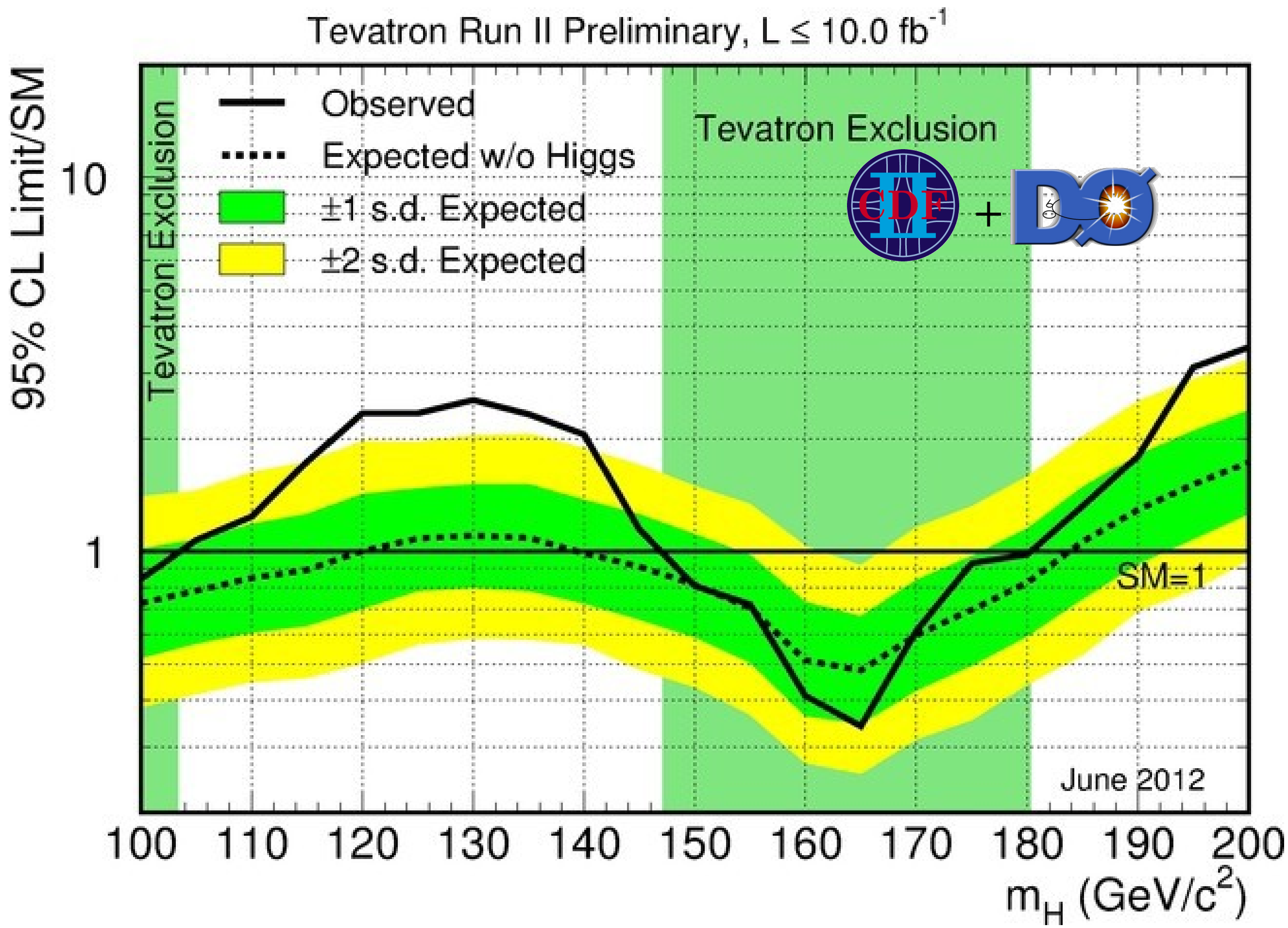
Tevatron Combination



95% CL upper limits on SM Higgs production at the Tevatron

- Expected exclusion: $100 < M_H < 120$ GeV and $139 < M_H < 184$ GeV

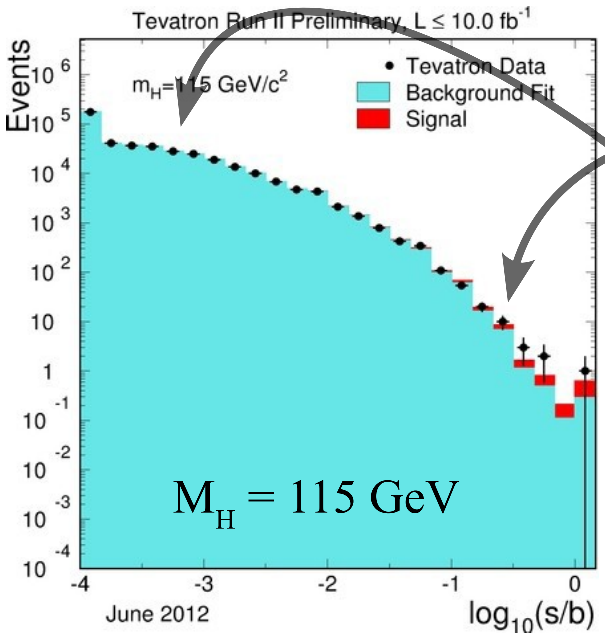
Tevatron Combination



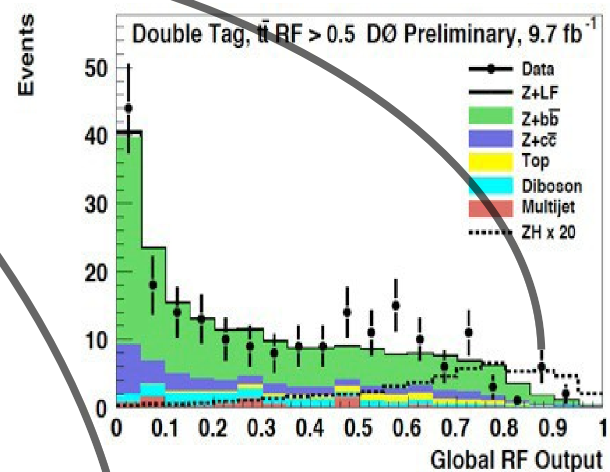
95% CL upper limits on SM Higgs production at the Tevatron

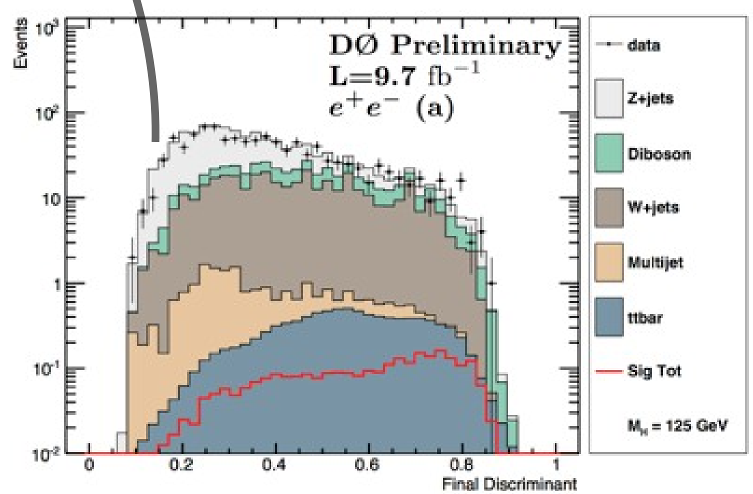
- Expected exclusion: $100 < M_H < 120$ GeV and $139 < M_H < 184$ GeV
- Observed exclusion: **$100 < M_H < 103$ GeV** and $147 < M_H < 180$ GeV

Looking At The Data



Sort bins from all input distributions by s/b





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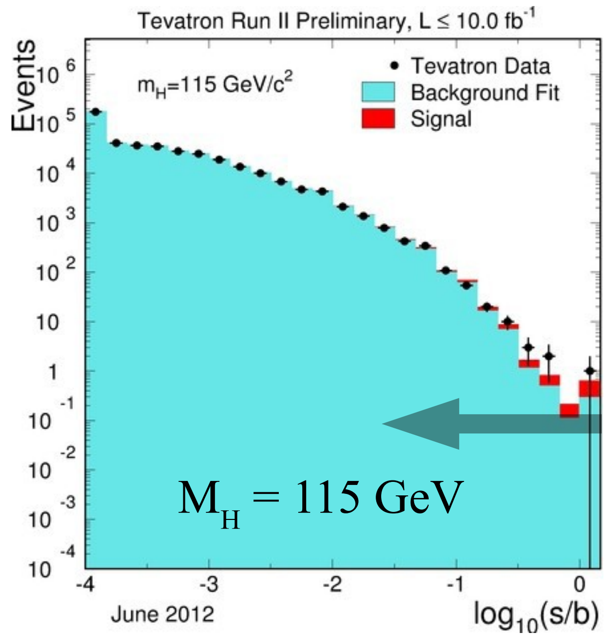
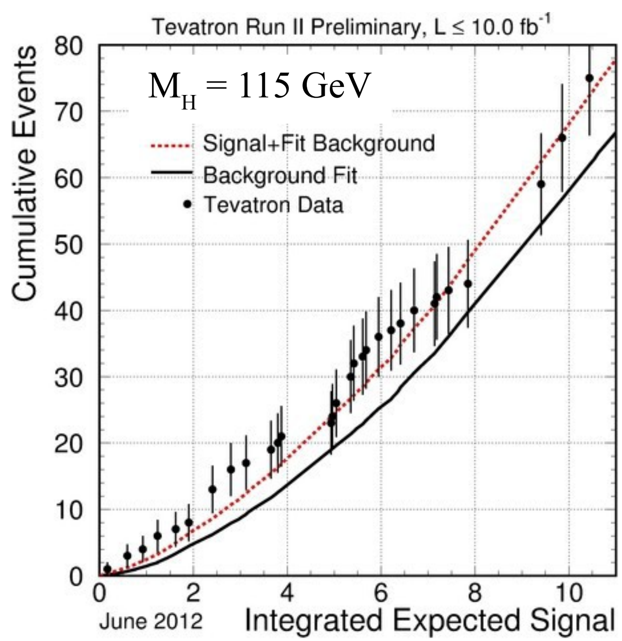


Integrate highest s/b bins



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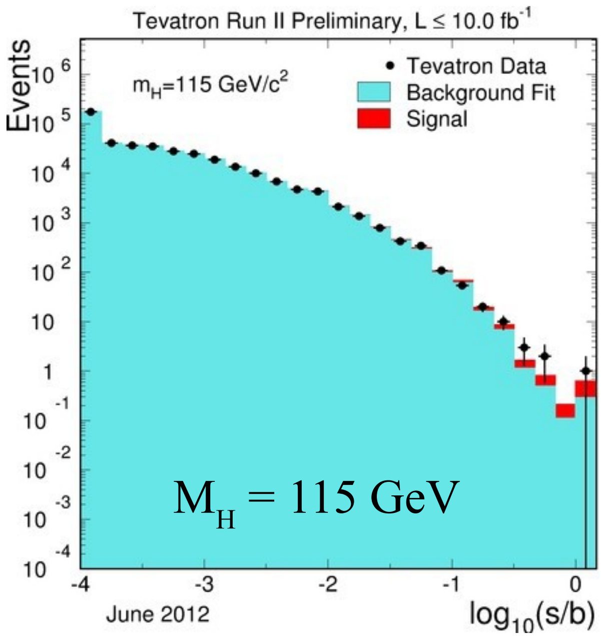
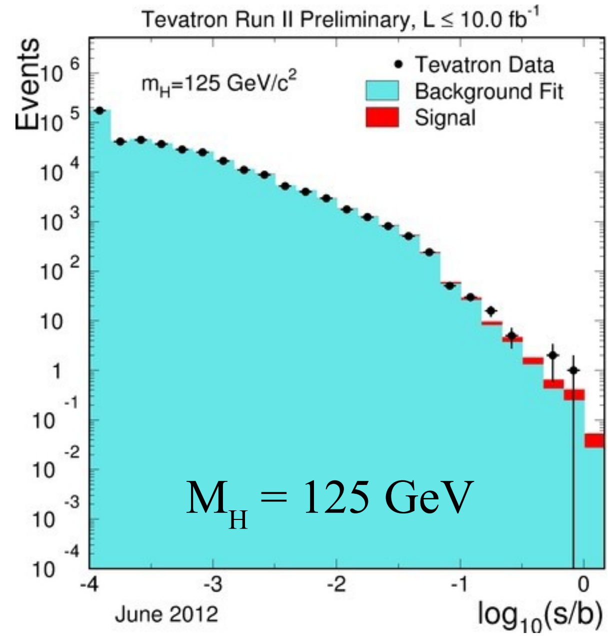
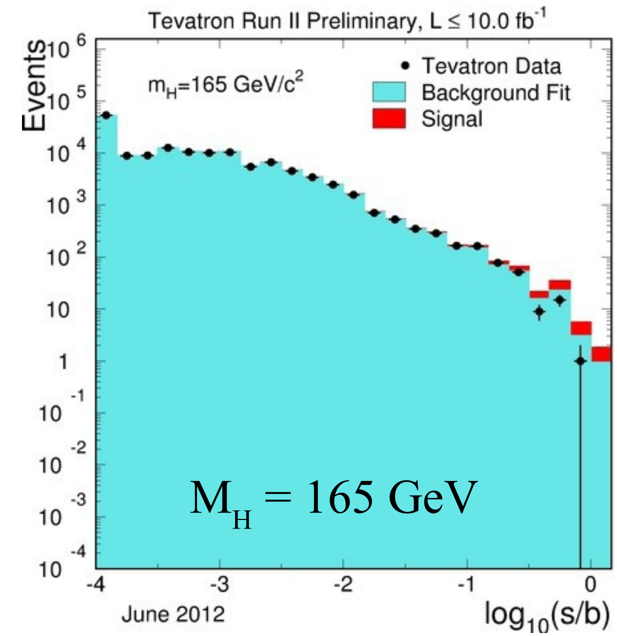
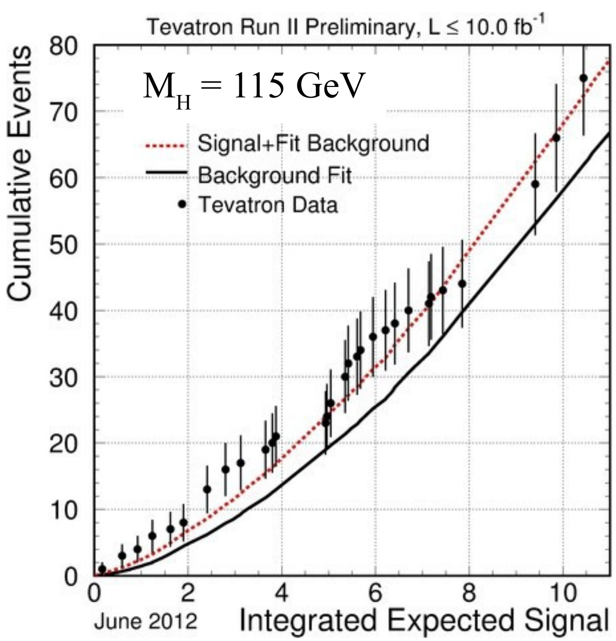
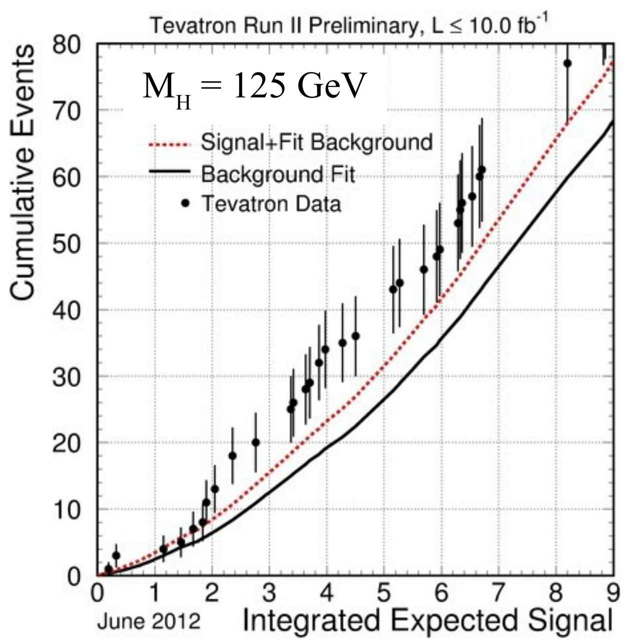
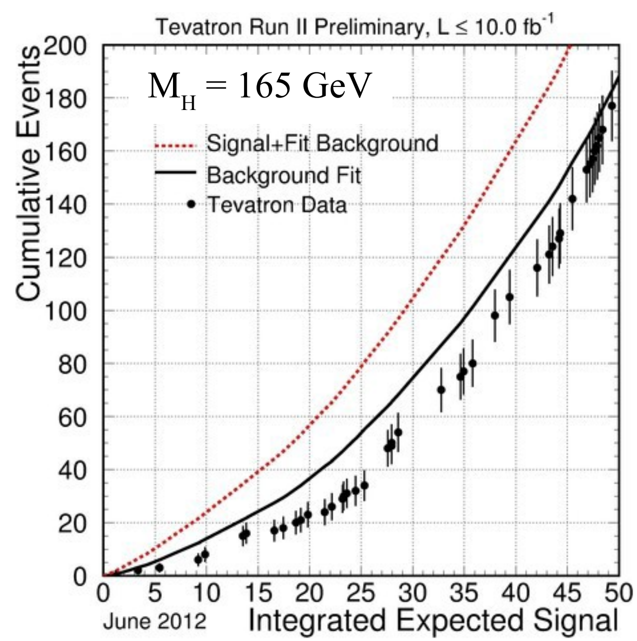




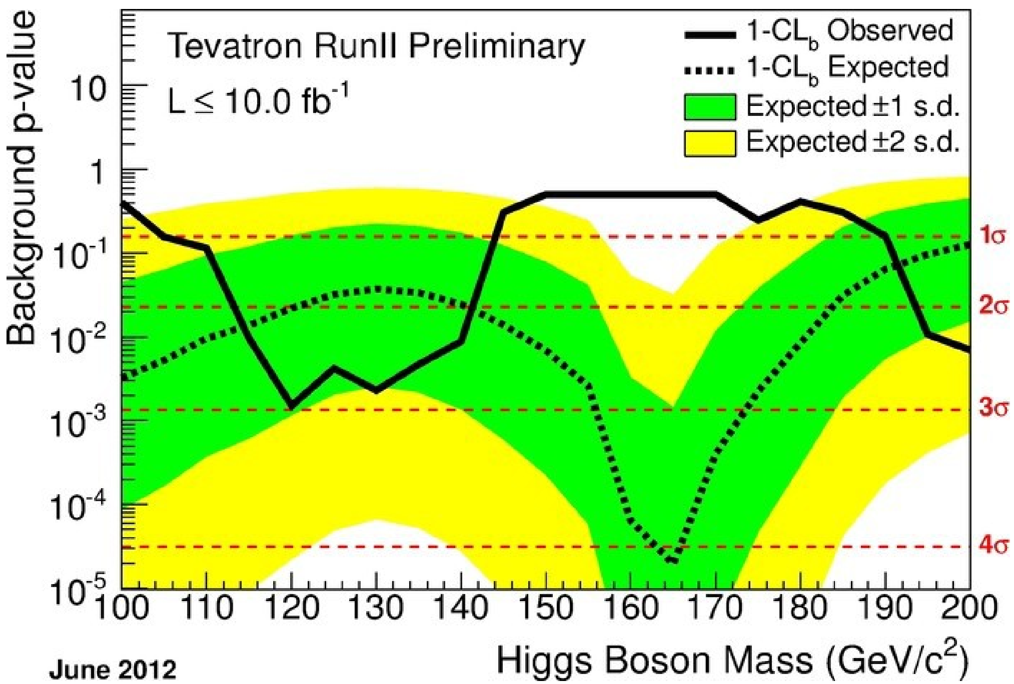


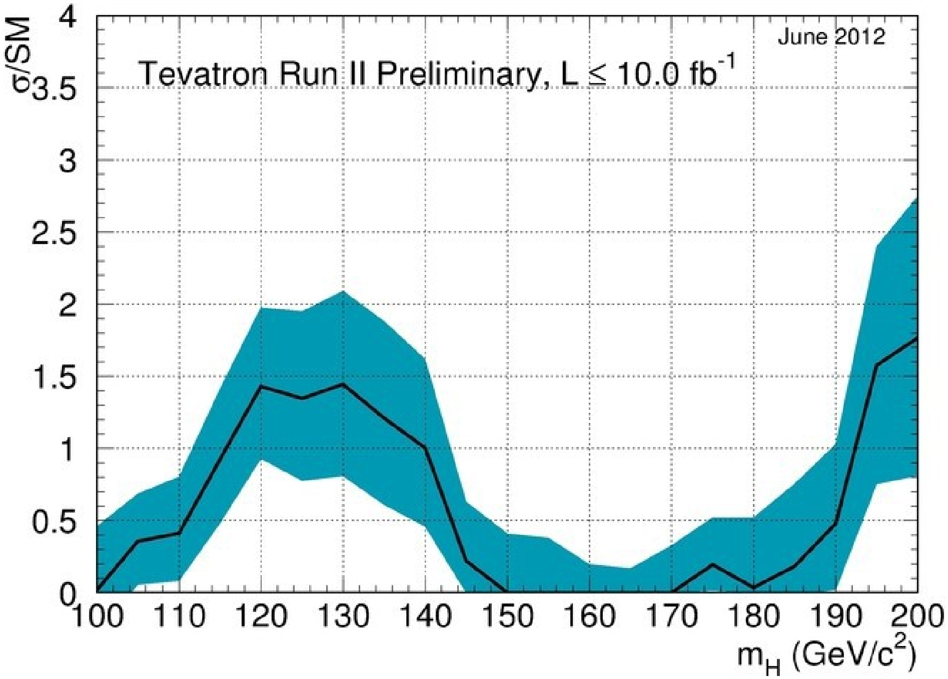






Quantifying the Excess





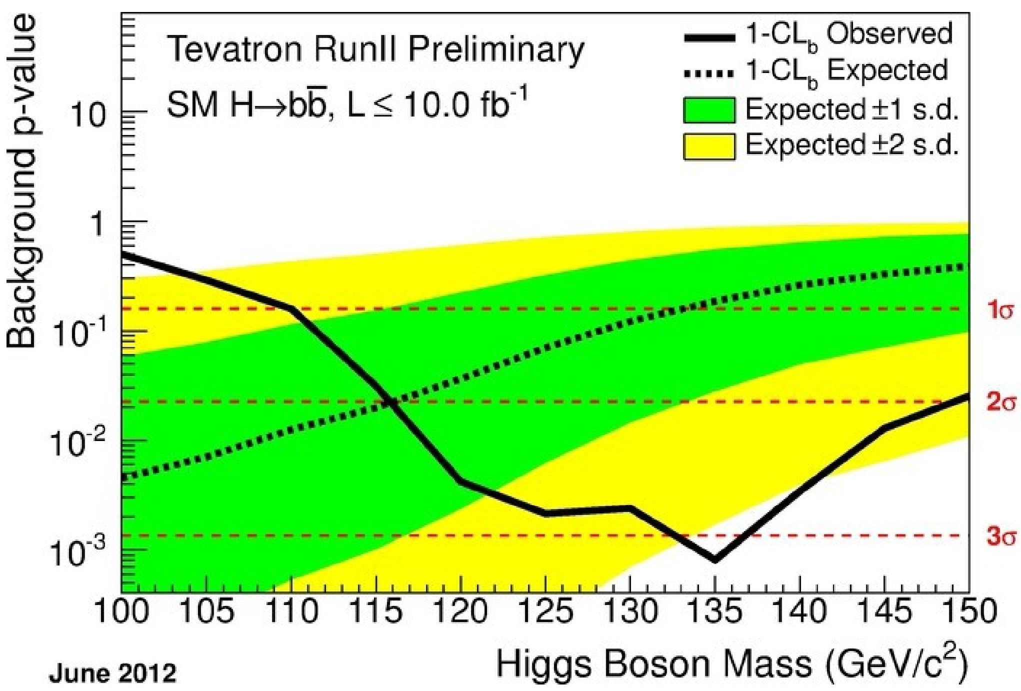
Test compatibility with background-only hypothesis (left)

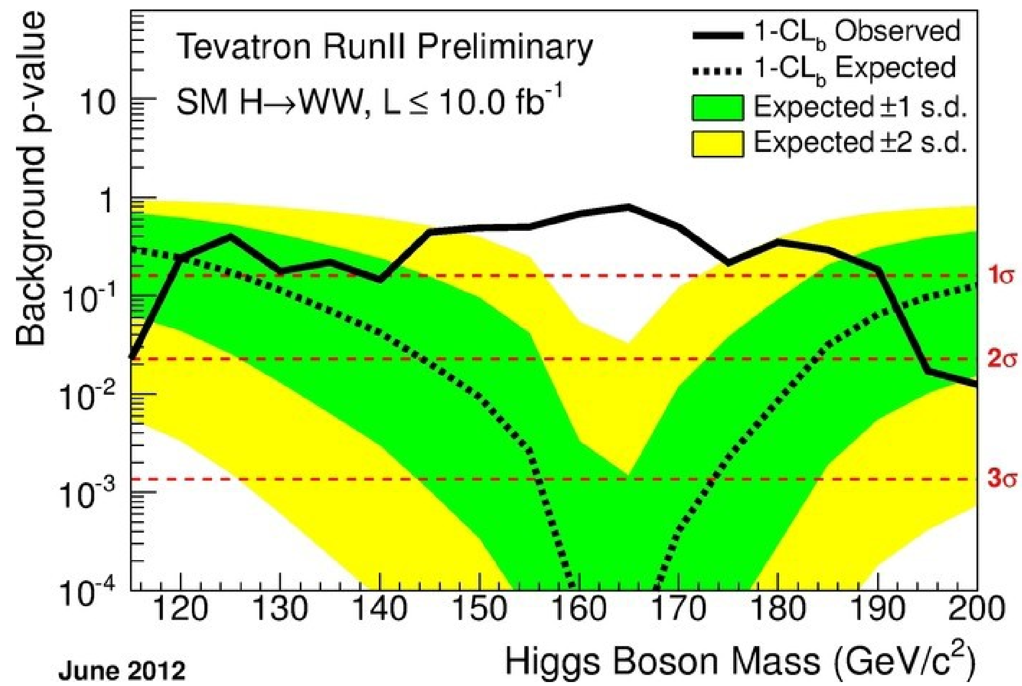
- Minimum local p-value: 3.0 standard deviations
- Global p-value with LEE factor of 4: 2.5 standard deviations

Test compatibility with signal+background hypothesis (right)

- Maximum likelihood fit with Higgs cross section as a free parameter

Quantifying the Excess

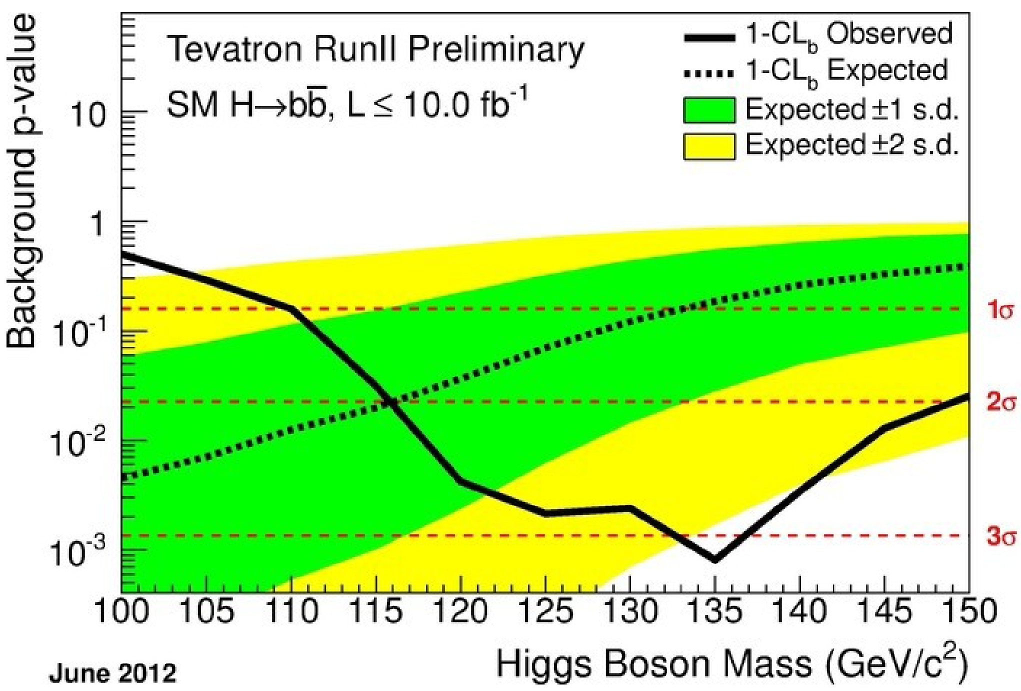


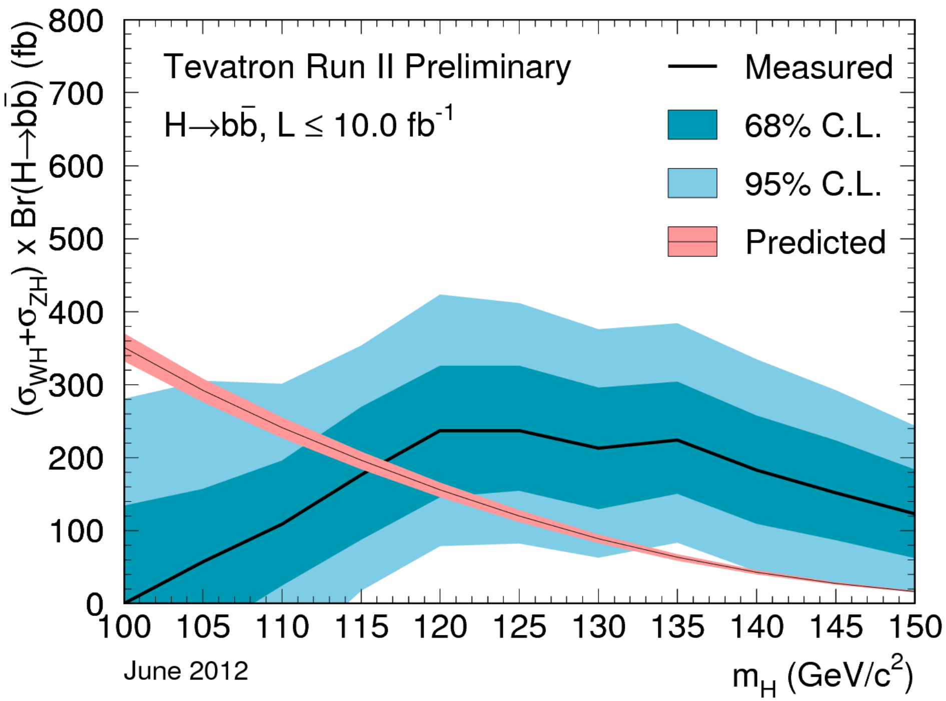


Test compatibility with background-only hypothesis

- Look separately at **H→bb** and **H→WW**
  - Minimum local p-value for H→bb: 3.2 standard deviations
  - Global p-value with LEE factor of 2: 2.9 standard deviations

Quantifying the Excess





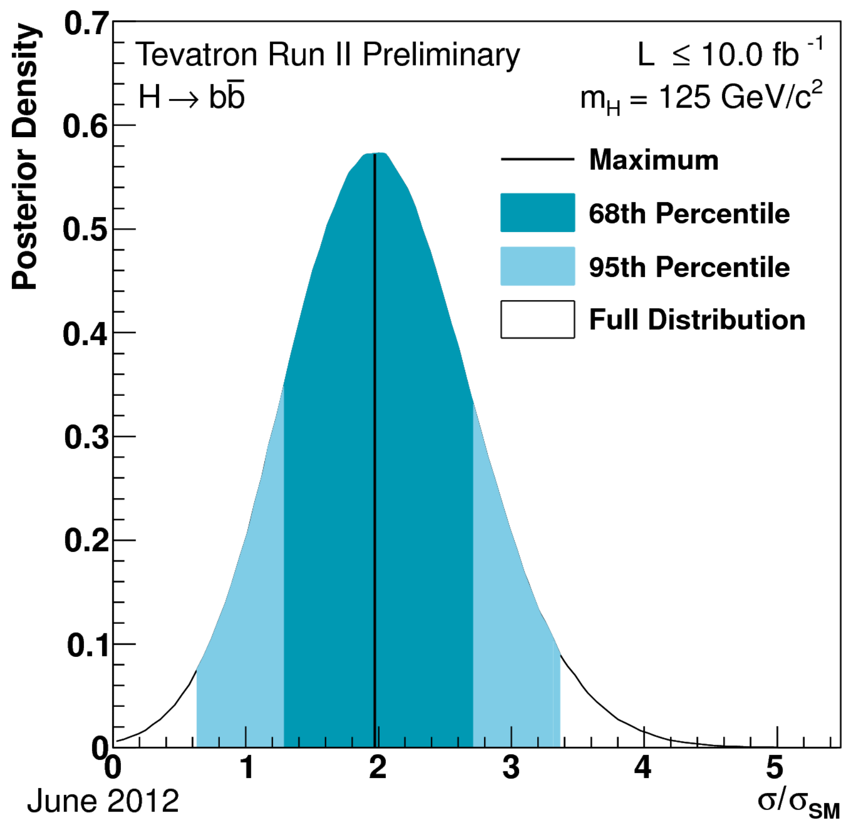
Test compatibility with background-only hypothesis

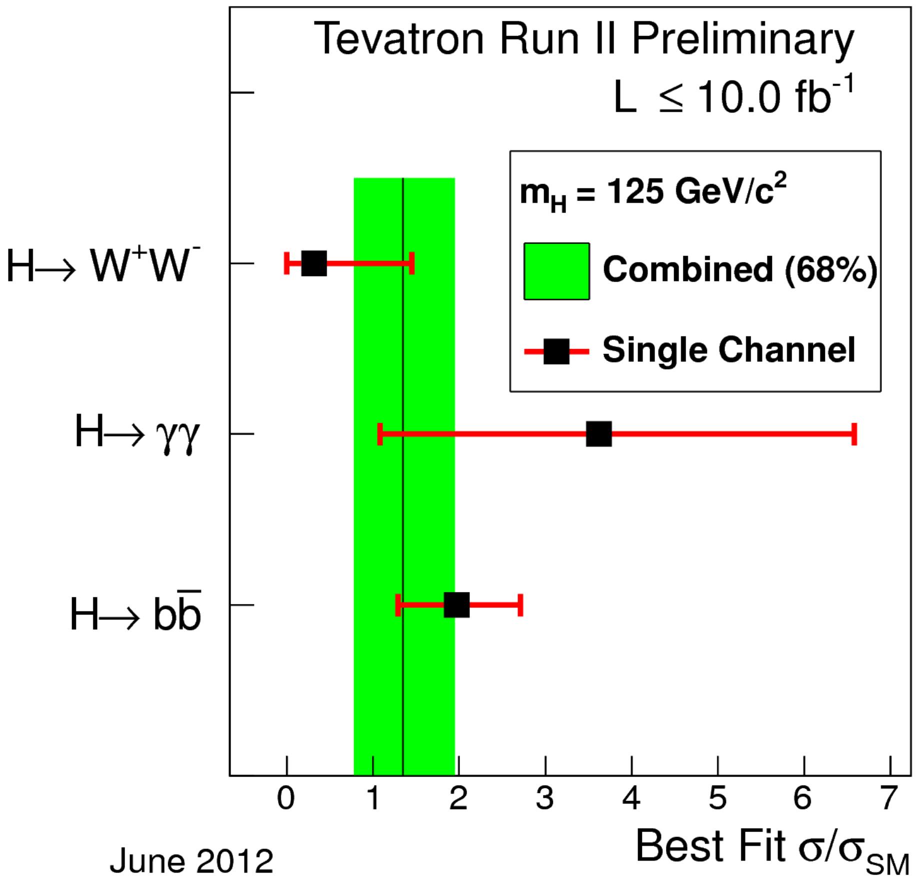
- Look separately at H→bb and H→WW
  - Minimum local p-value for H→bb: 3.2 standard deviations
  - Global p-value with LEE factor of 2: 2.9 standard deviations

Fit cross section × BR(H→bb) : ~1.4 s.d. from SM for M_H = 125 GeV

Quantifying the Excess

Looking at M_H = 125 GeV

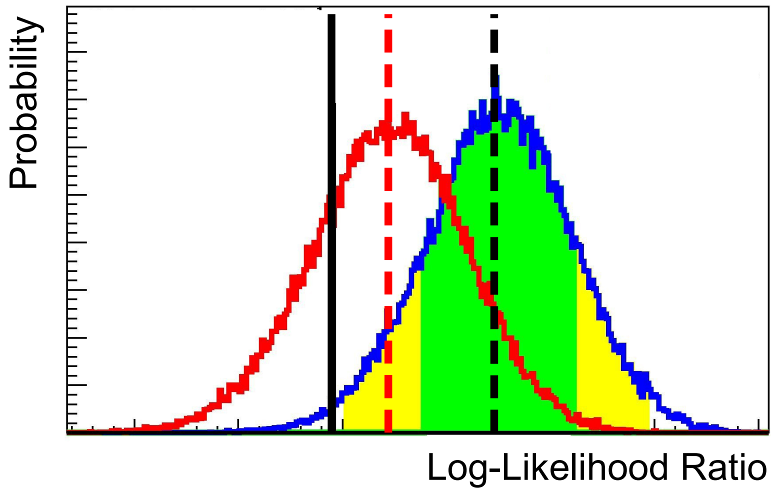




Log-Likelihood Ratio

Log-likelihood gauges the relative agreement of the data with the background-only or signal+background models

- Throw pseudo-experiments to populate LLR distributions for background-only and signal+background models
- Compare to observed LLR



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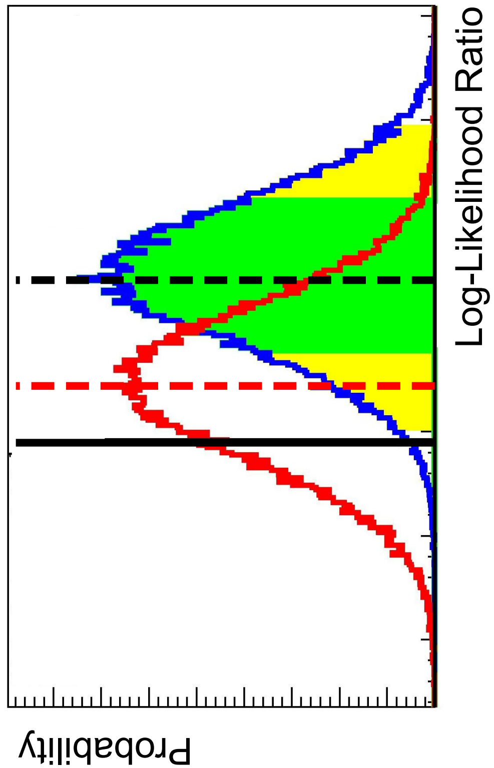
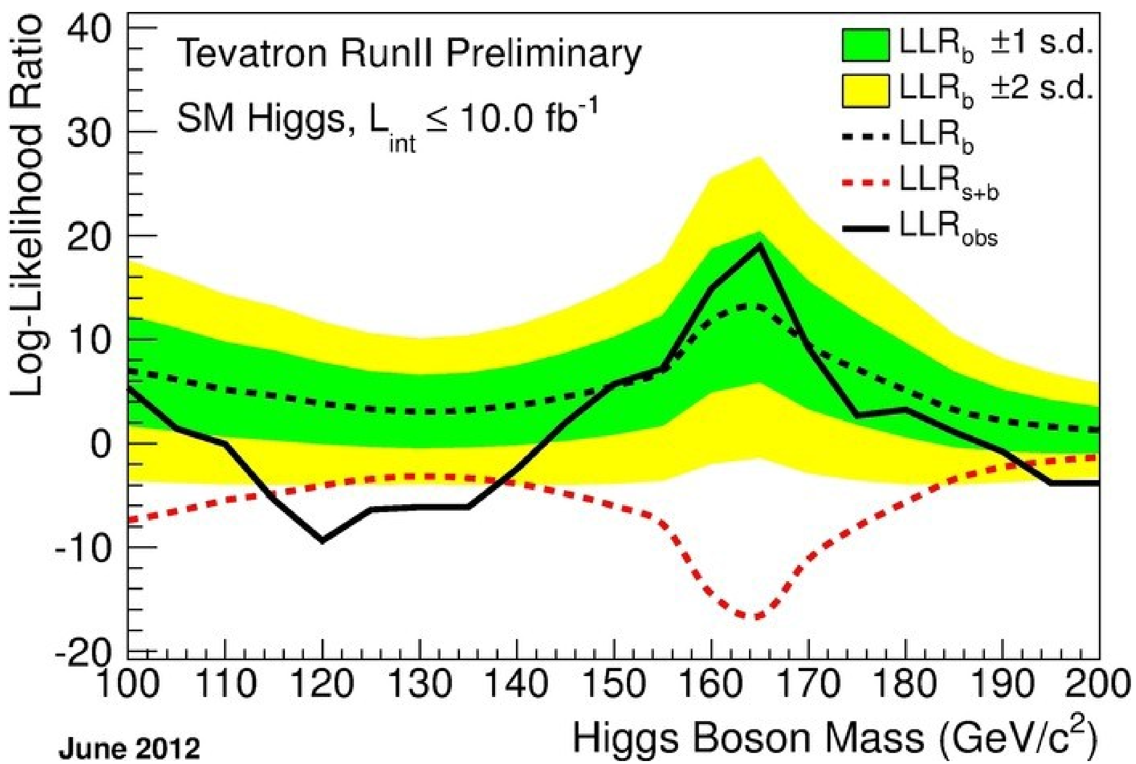
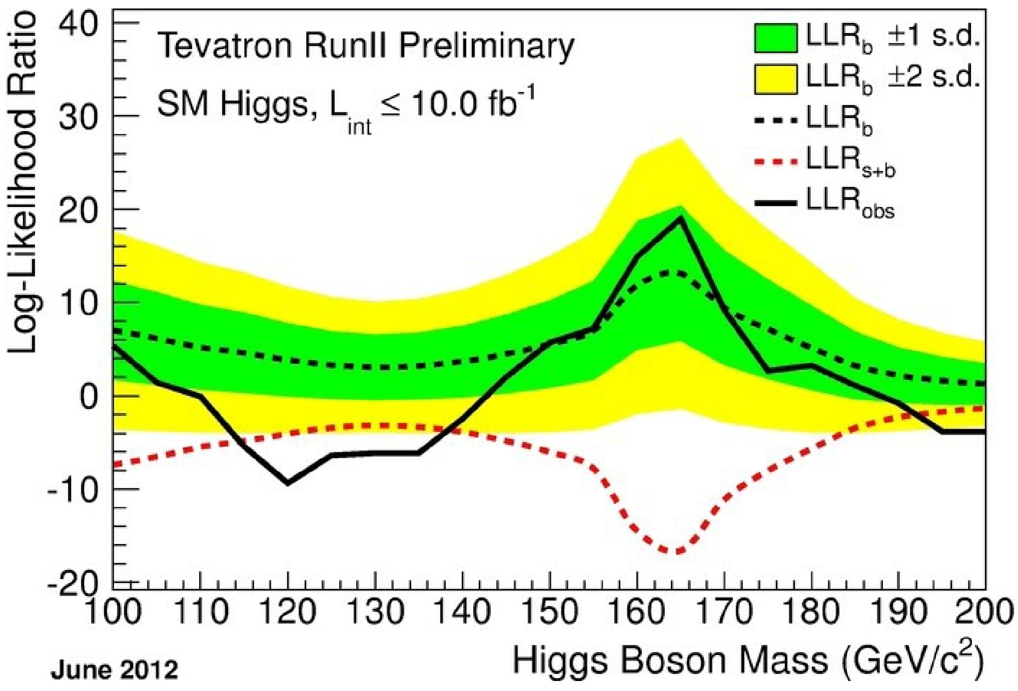
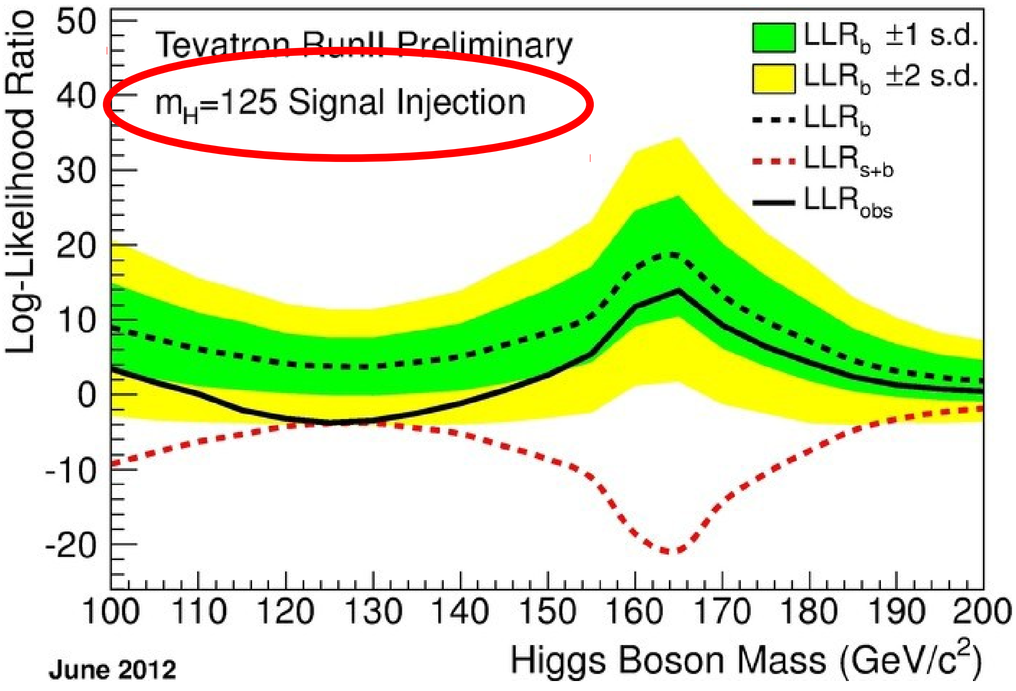




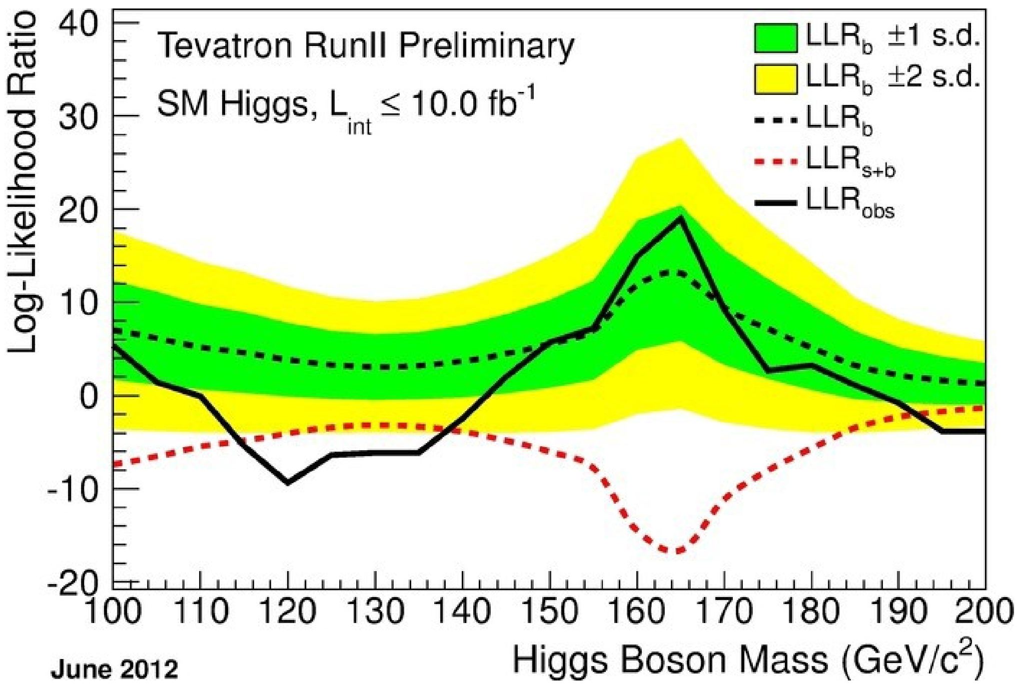
Signal Injection

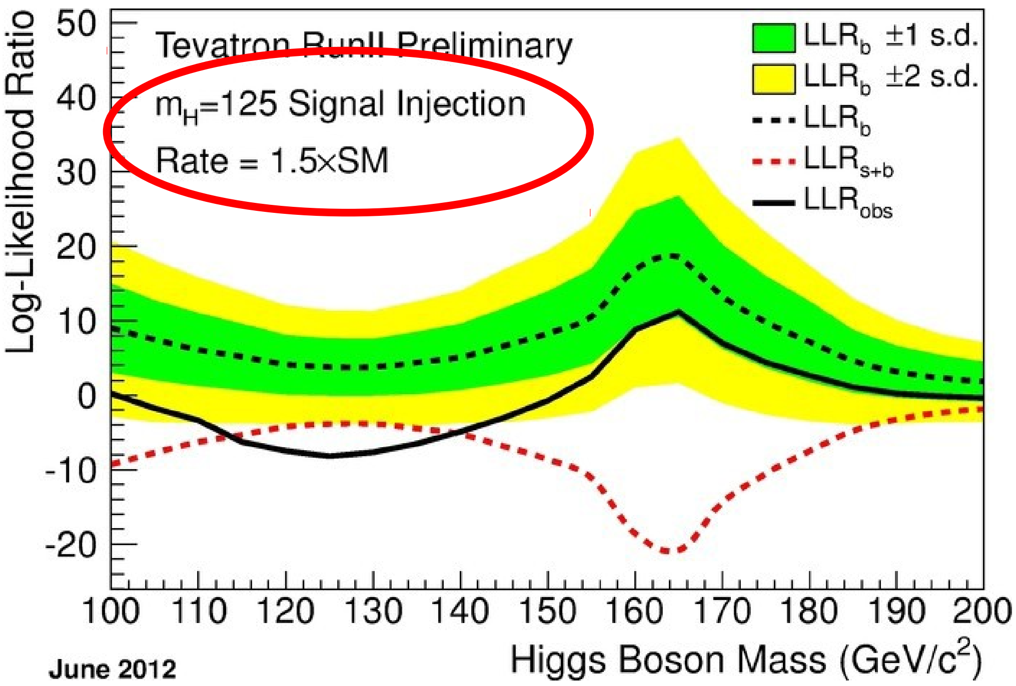




Compare observed results with expectation from injecting a signal with a mass of 125 GeV

Signal Injection

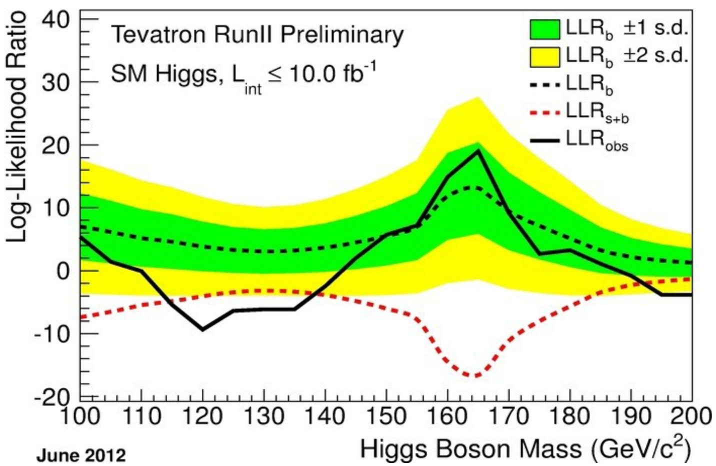




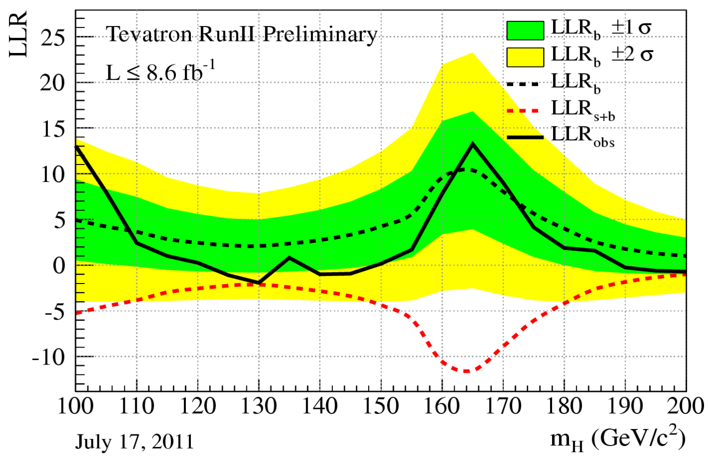
Compare observed results with expectation from injecting a signal with a mass of 125 GeV

- With injected signal scaled to 1.5 × SM

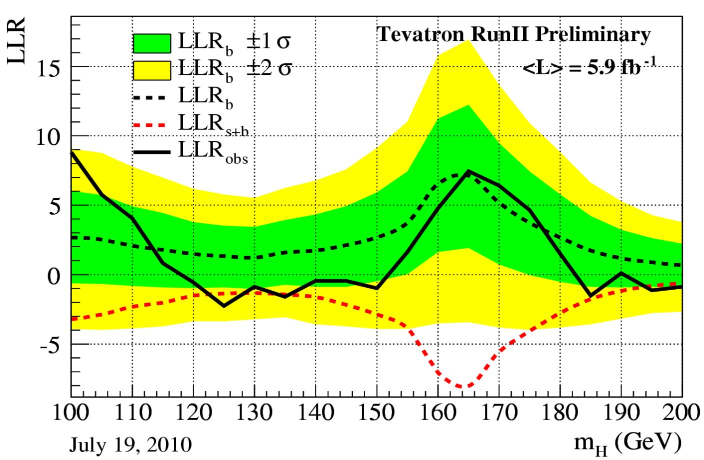
Historical View



2012

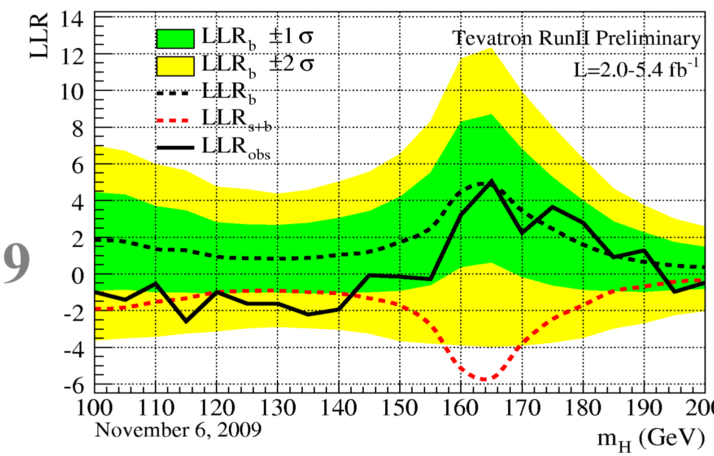


2011

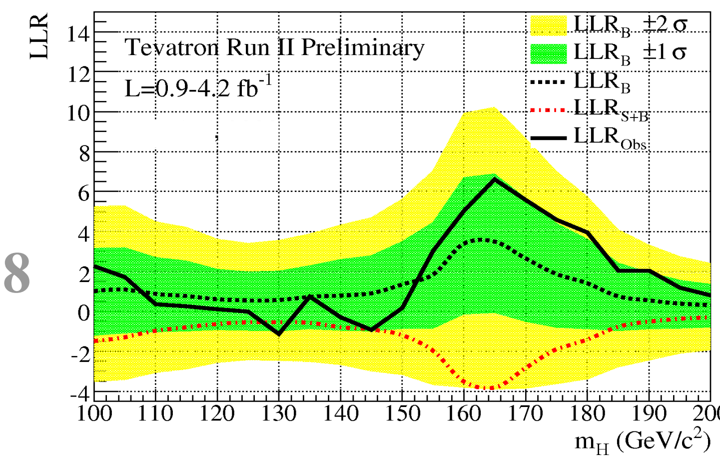


2010

2009



2008



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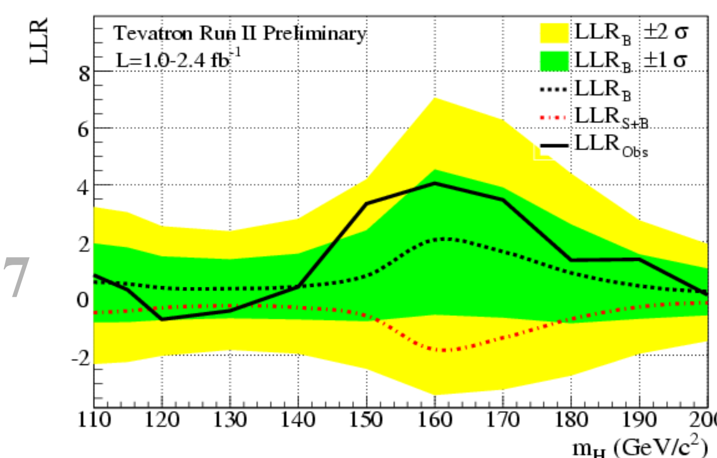
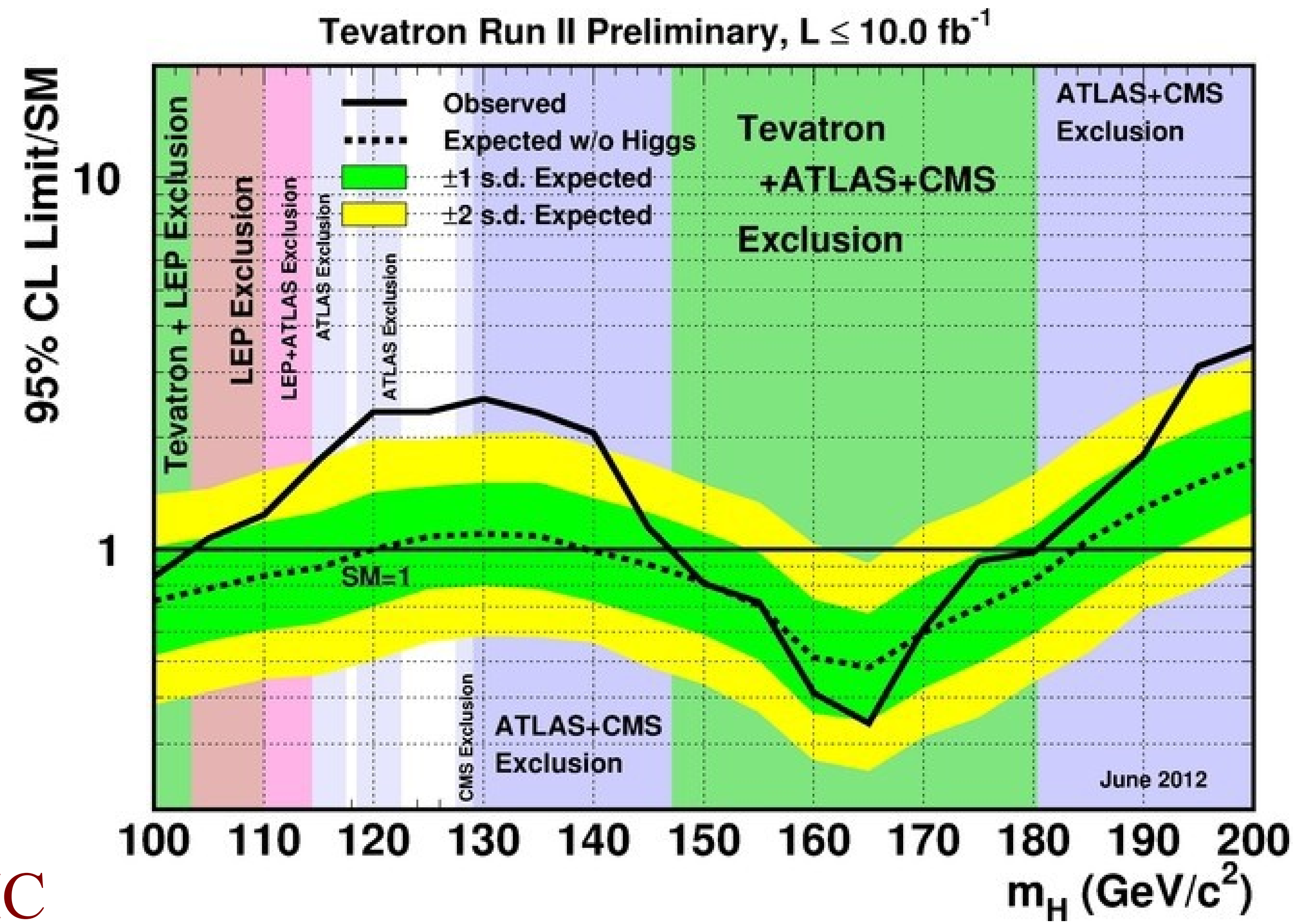


Conclusions

Tevatron Higgs searches analyzing the full data set

The background-only model is being rejected

- Full search
  - 3.0 s.d. local excess
  - 2.5 s.d. with LEE
- H → bb only
  - 3.2 s.d. local excess
  - 2.9 with LEE



Compatible with a 125 GeV Higgs (like) signal as seen at the LHC

- Tevatron's sensitivity to H→bb will help determine the nature of Higgs (like) boson discovered at the LHC

Thank You

- For additional details see
  - Tevatron: http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_12/
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.html

- Thanks to everyone who contributed to these results!
- Bigger thanks to everyone who designed, built, or operated the experiments!
- FNAL Computing Division: Thanks for all the computing power and software!
- FNAL Beams Division: Thanks for all the collisions!

CDF and DØ Collaborations

Signal Strength Fits

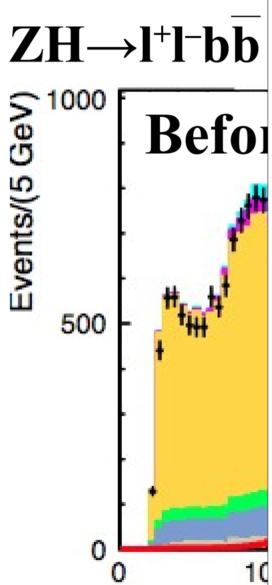
m_H (GeV/c^2)	R_{fit} (SM)	R_{fit} ($H \to W^+W^-$)	R_{fit} ($H \to bb$)	R_{fit} ($H \to \gamma\gamma$)
100	$0.00^{+0.44}_{-0.00}$		$0.00^{+0.38}_{-0.00}$	$0.00^{+3.73}_{-0.00}$
105	$0.36^{+0.33}_{-0.30}$		$0.19^{+0.34}_{-0.19}$	$1.69^{+3.04}_{-1.69}$
110	$0.41^{+0.39}_{-0.33}$	$5.38^{+3.96}_{-3.51}$	$0.45^{+0.36}_{-0.35}$	$0.00^{+2.68}_{-0.00}$
115	$0.92^{+0.49}_{-0.44}$	$3.50^{+2.08}_{-2.13}$	$0.90^{+0.47}_{-0.45}$	$0.00^{+2.47}_{-0.00}$
120	$1.43^{+0.54}_{-0.50}$	$0.90^{+1.24}_{-0.90}$	$1.52^{+0.57}_{-0.58}$	$4.17^{+2.95}_{-2.54}$
125	$1.35^{+0.60}_{-0.57}$	$0.32^{+1.13}_{-0.32}$	$1.97^{+0.74}_{-0.68}$	$3.62^{+2.96}_{-2.54}$
130	$1.44^{+0.65}_{-0.64}$	$0.81^{+0.70}_{-0.71}$	$2.39^{+0.93}_{-0.94}$	$3.72^{+2.91}_{-2.78}$
135	$1.21^{+0.67}_{-0.60}$	$0.44^{+0.60}_{-0.44}$	$3.53^{+1.26}_{-1.16}$	$0.00^{+4.13}_{-0.00}$
140	$1.00^{+0.62}_{-0.54}$	$0.69^{+0.54}_{-0.52}$	$4.24^{+1.74}_{-1.70}$	$3.85^{+3.52}_{-3.31}$
145	$0.22^{+0.41}_{-0.22}$	$0.10^{+0.50}_{-0.10}$	$5.49^{+2.59}_{-2.35}$	$2.09^{+4.68}_{-2.09}$
150	$0.00^{+0.41}_{-0.00}$	$0.00^{+0.45}_{-0.00}$	$7.44^{+3.66}_{-3.65}$	$0.00^{+6.05}_{-0.00}$
155	$0.00^{+0.38}_{-0.00}$	$0.00^{+0.38}_{-0.00}$		
160	$0.00^{+0.20}_{-0.00}$	$0.00^{+0.20}_{-0.00}$		
165	$0.00^{+0.17}_{-0.00}$	$0.00^{+0.17}_{-0.00}$		
170	$0.00^{+0.33}_{-0.00}$	$0.00^{+0.32}_{-0.00}$		
175	$0.19^{+0.33}_{-0.18}$	$0.19^{+0.34}_{-0.19}$		
180	$0.03^{+0.49}_{-0.03}$	$0.05^{+0.48}_{-0.05}$		
185	$0.18^{+0.57}_{-0.18}$	$0.26^{+0.50}_{-0.26}$		
190	$0.48^{+0.55}_{-0.48}$	$0.57^{+0.54}_{-0.57}$		
195	$1.57^{+0.82}_{-0.82}$	$1.76^{+0.87}_{-0.86}$		
200	$1.77^{+0.98}_{-0.95}$	$2.12^{+1.07}_{-0.94}$		

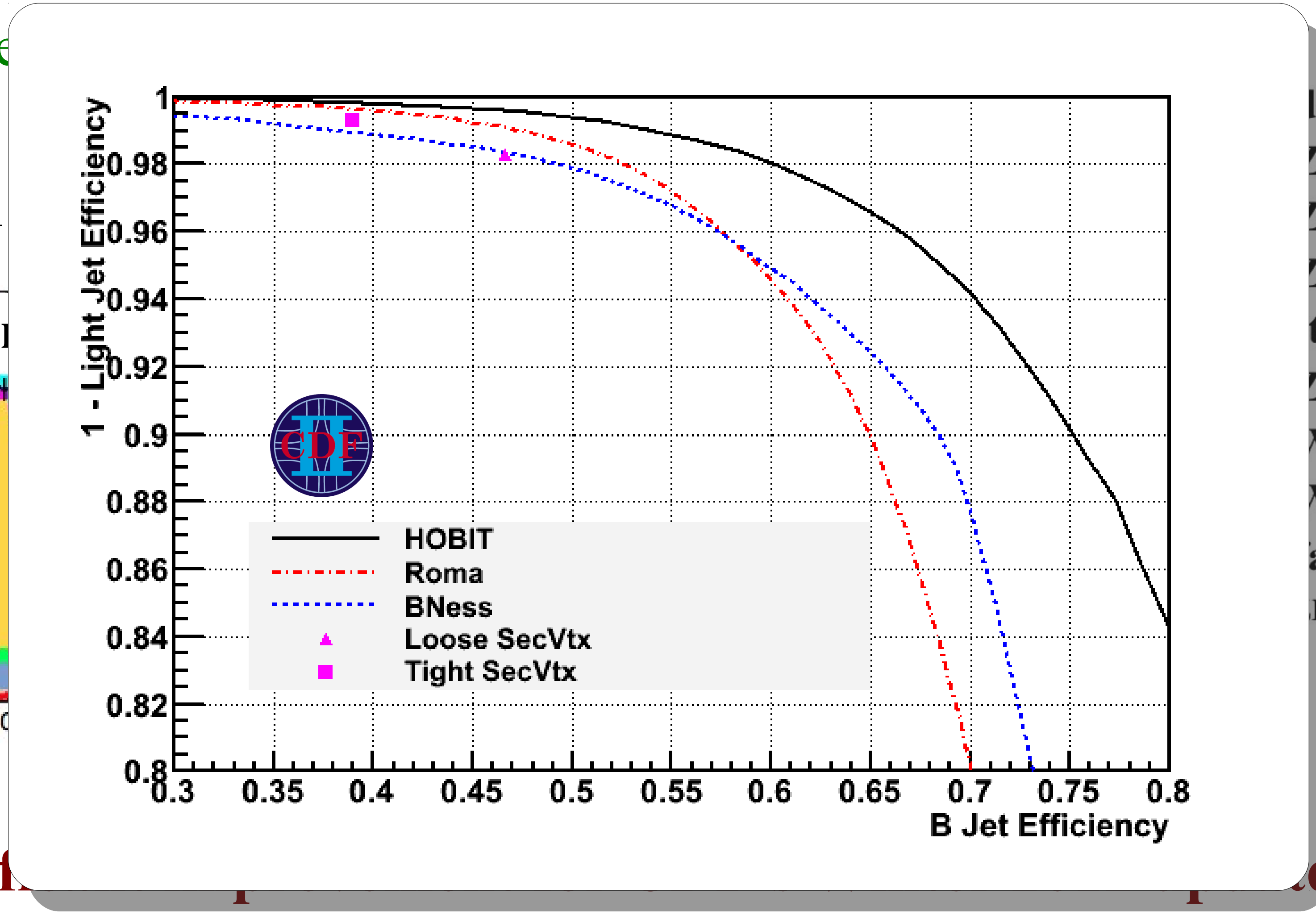
$VH \rightarrow Vb\bar{b}$

Enhance H→bb by requiring jets to be "b-tagged"

Use **multivariate** b-tag classifiers to improve discrimination power

- 50 – 80% e
- 0.5 – 10%





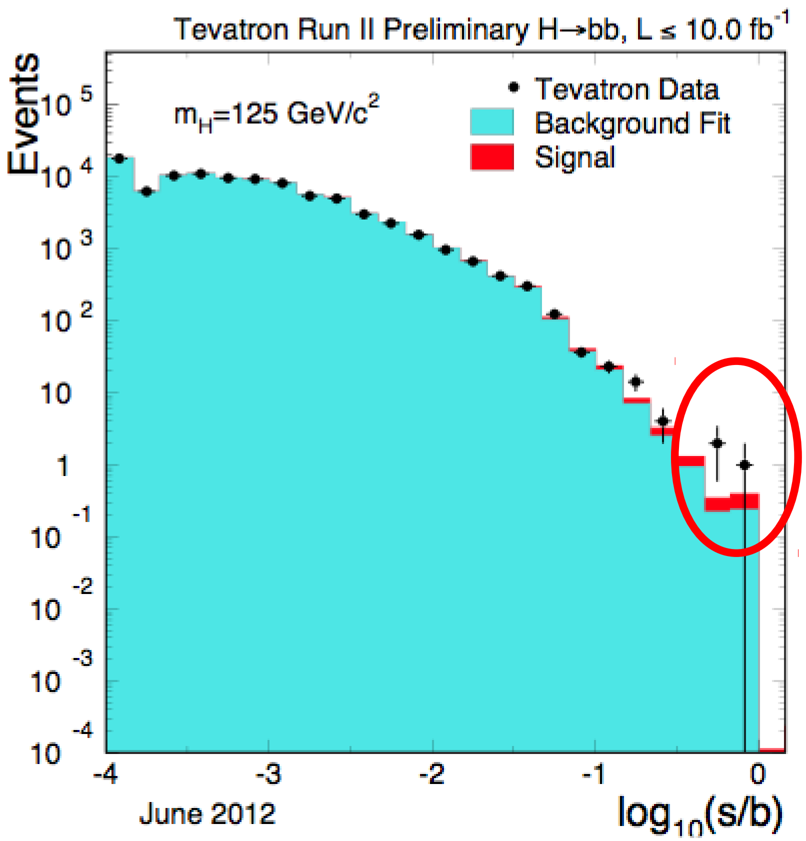
Most signif e

⇒ This alone brought 15 – 30% improvement in each H→bb analysis

$H \rightarrow bb$ Events

Revisit s/b ordered events for H→bb

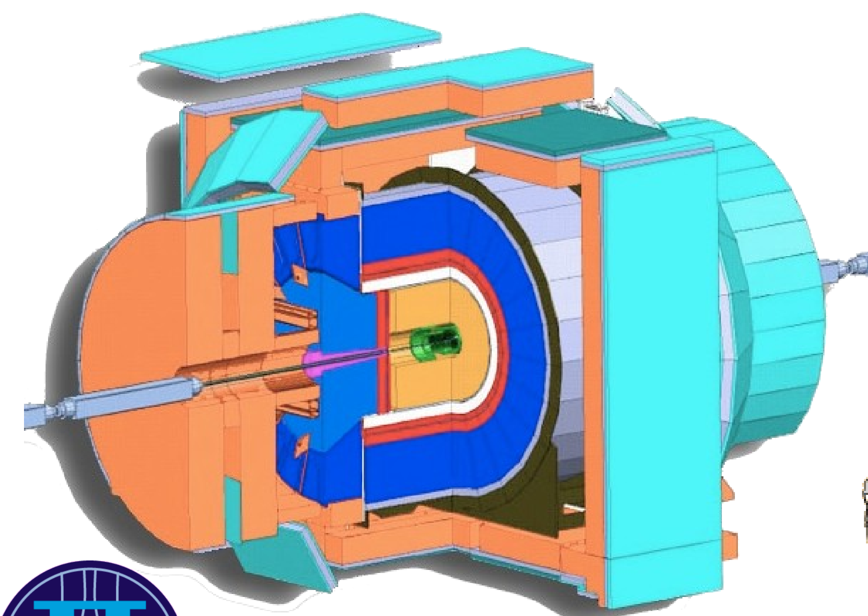
- Pick out the most signal-like events
- Topologies consistent with Higgs signal

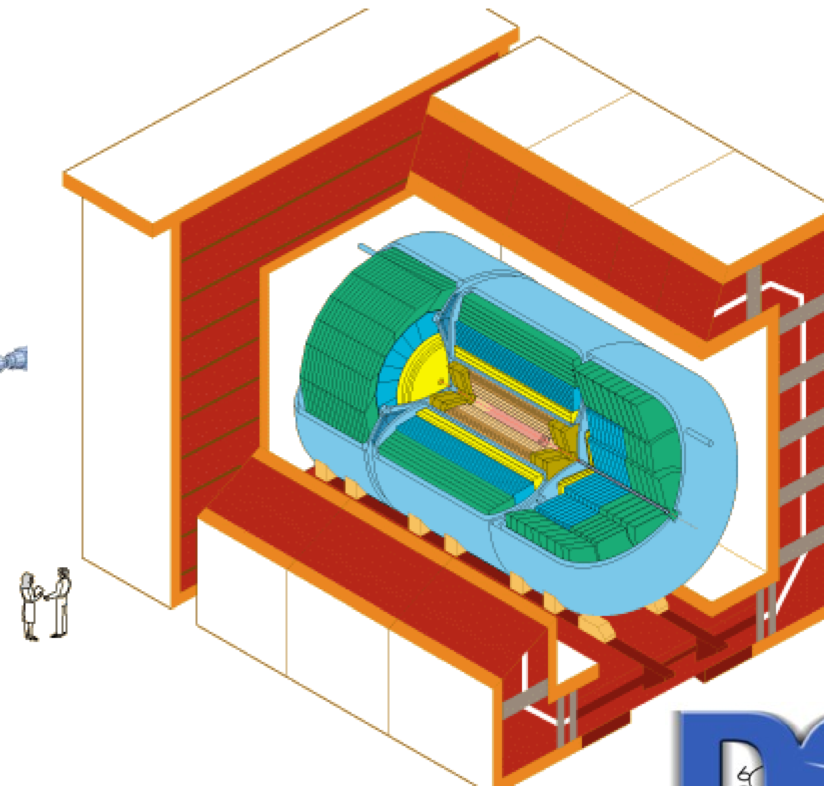


CDF and DØ Detectors

CDF II and DØ 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%





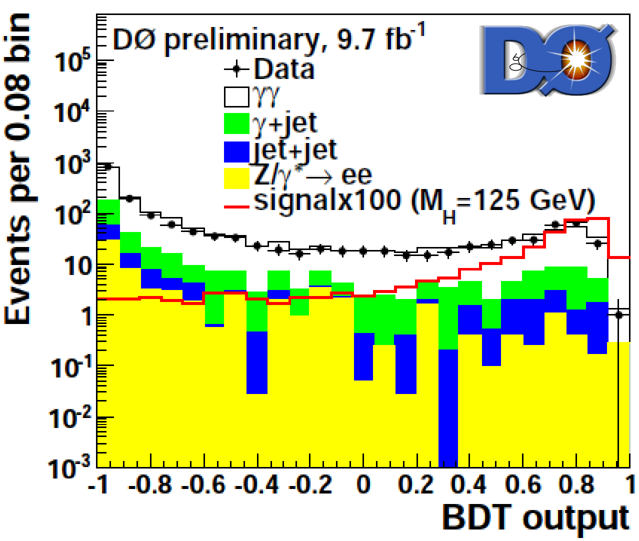
$\mathcal{H} \rightarrow \gamma\gamma$

Significant improvements in DØ H→γγ

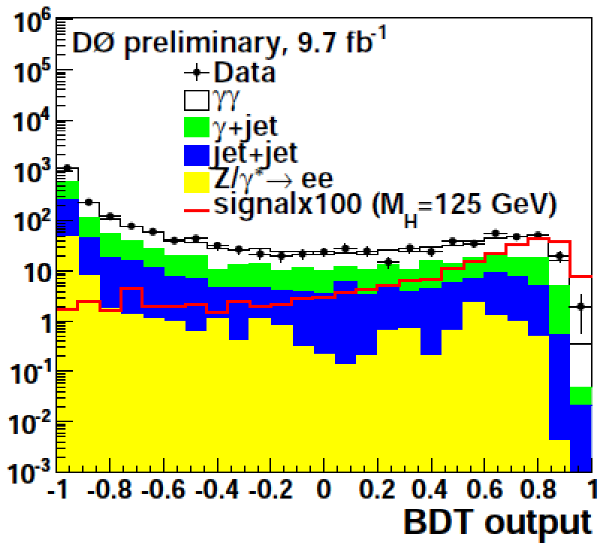
- Improved MC/data statistics for background modeling
- Combat systematic uncertainties by splitting events into jet-dominated or photon-dominated region

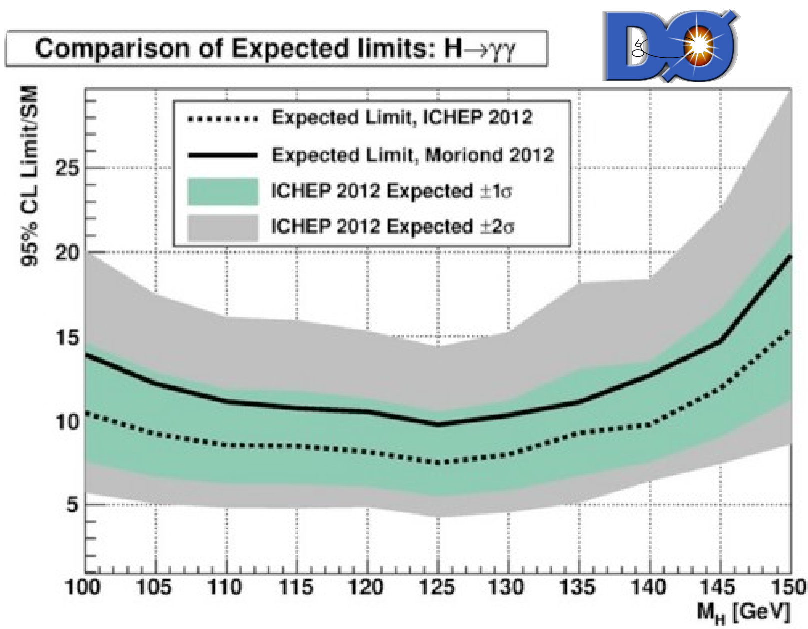
  ⇒ 20 – 30% more sensitivity

Photon-dominated



Jet-dominated

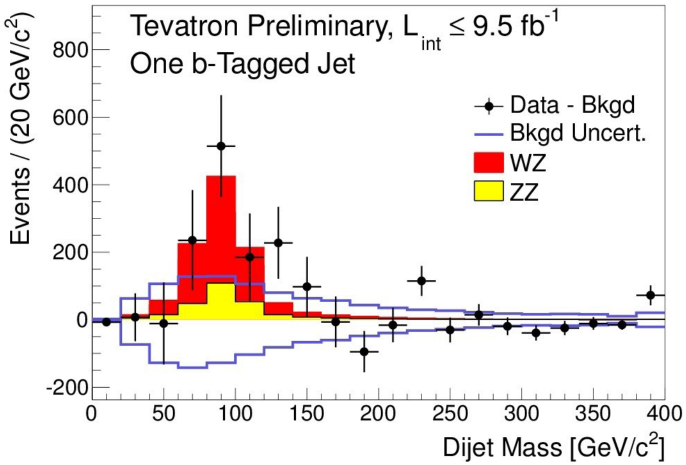




Further Investigation

Revisit diboson measurement

- Tevatron measurement of WZ+ZZ using H→bb analyses



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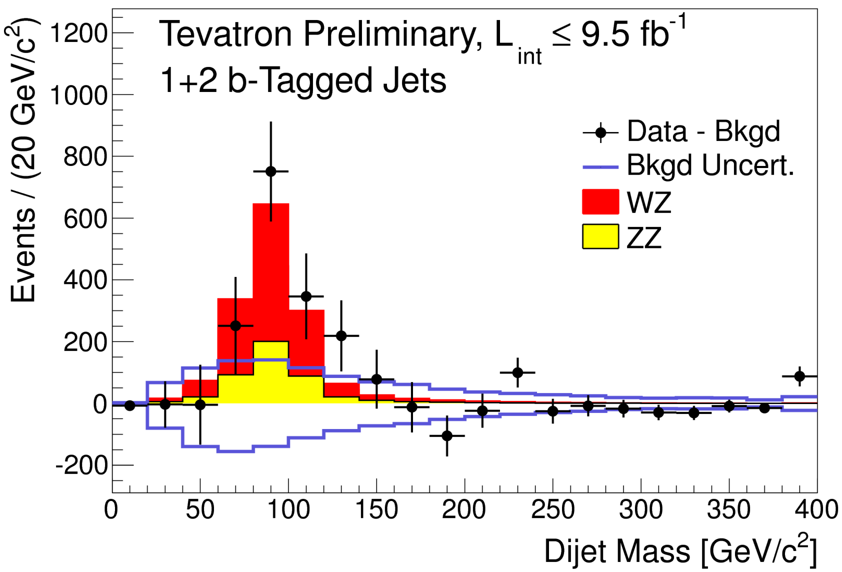
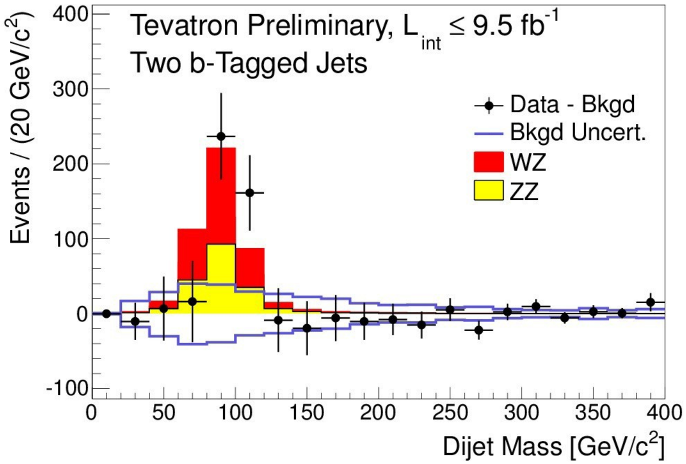
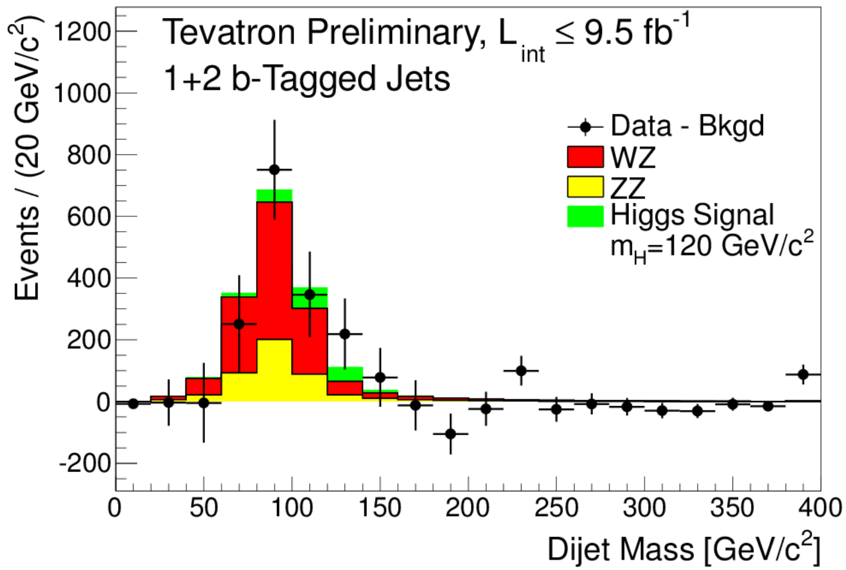


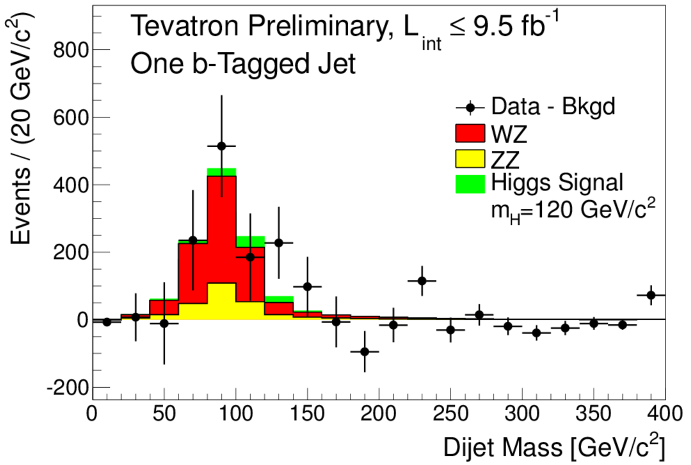


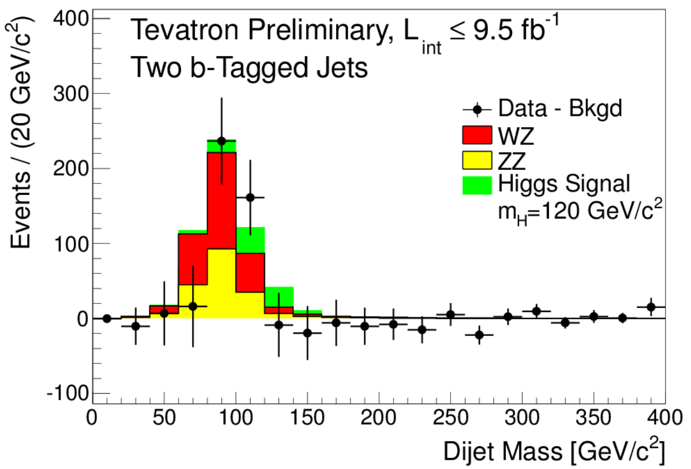
$H \rightarrow bb$ Events

Revisit diboson measurement

- Tevatron measurement of WZ+ZZ using H→bb analyses
- Add simple overlay of SM H→bb signal with a mass of 120 GeV







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).