Rencontres du Vietnam

Higgs Boson Searches at the Tevatron

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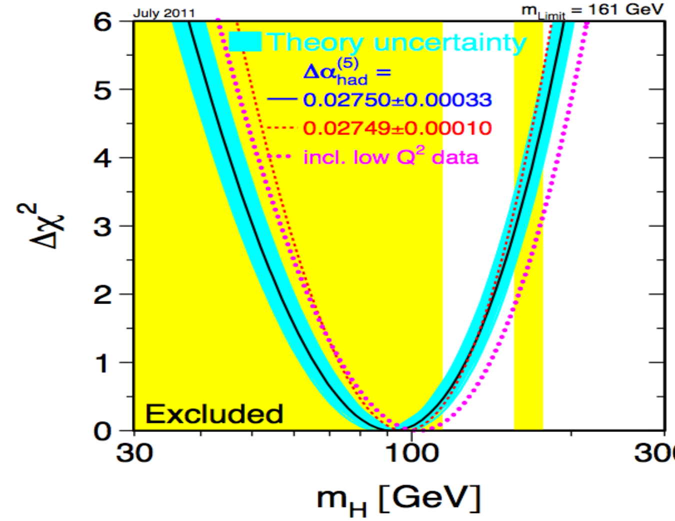
Outline

- Introduction
  - The Tevatron, CDF and DØ detectors
  - Search strategies at the Tevatron
- Standard Model Higgs boson searches
- Constraint on Higgs boson couplings
- Beyond Standard Model Higgs boson interpretations
- Summary

The SM Higgs Boson: Constraints and Evidences

Indirect constraints from EW measurements:

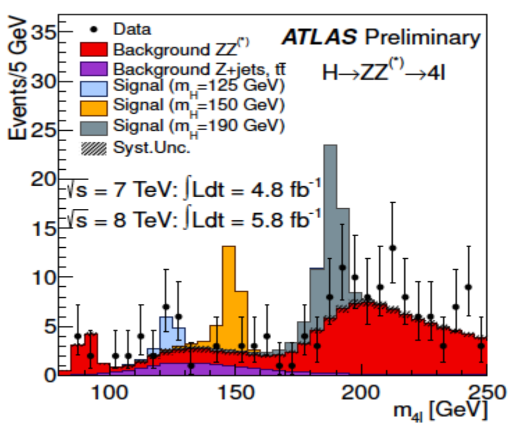
M_H < 152 GeV @95% CL

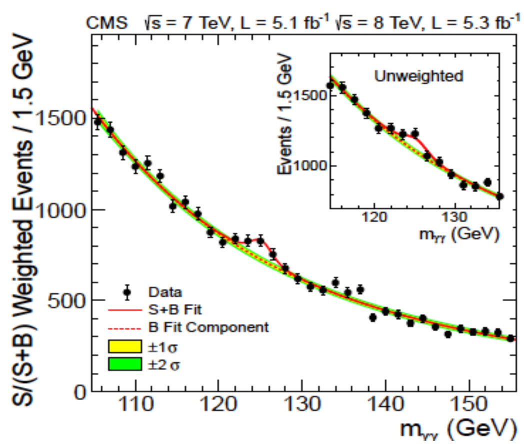


Direct searches at LEP:

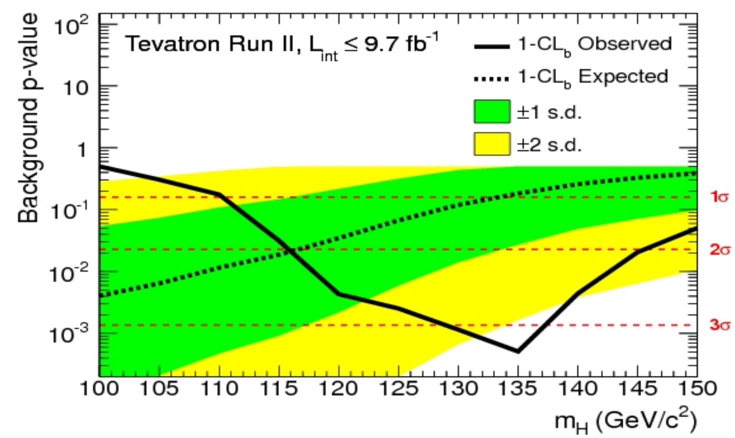
M_H > 114.4 GeV @95% CL

Direct searches at LHC:





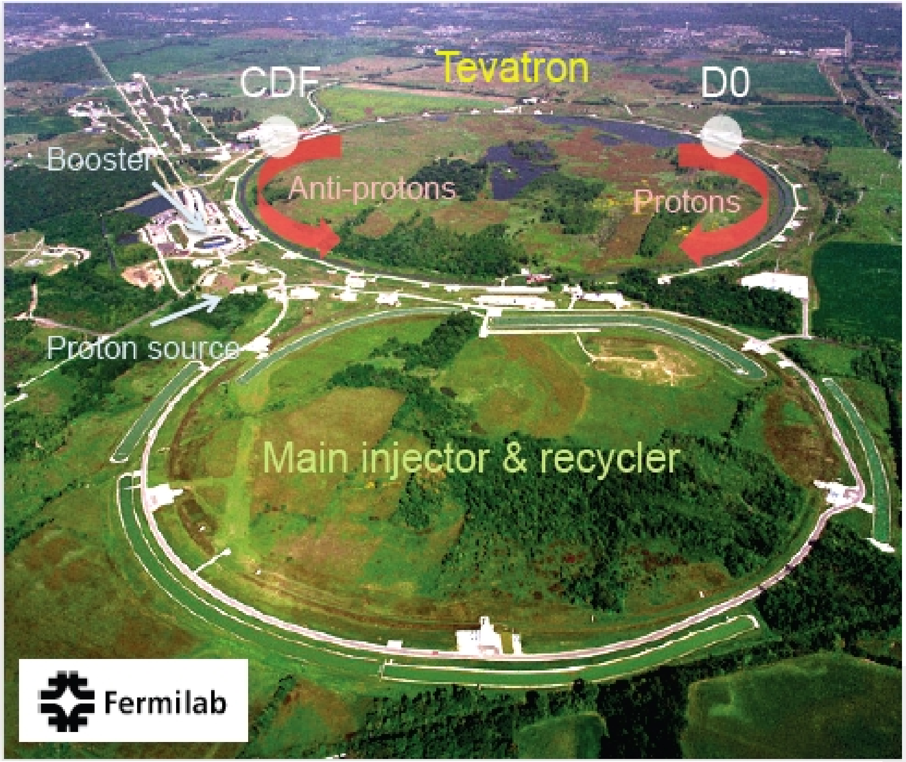
Direct searches at Tevatron:



Observation of a new particle with M_H ~ 125 GeV & properties consistent with the SM Higgs Boson

Evidence for a new particle decayed into bb with compatible mass to that of the new particle at LHC

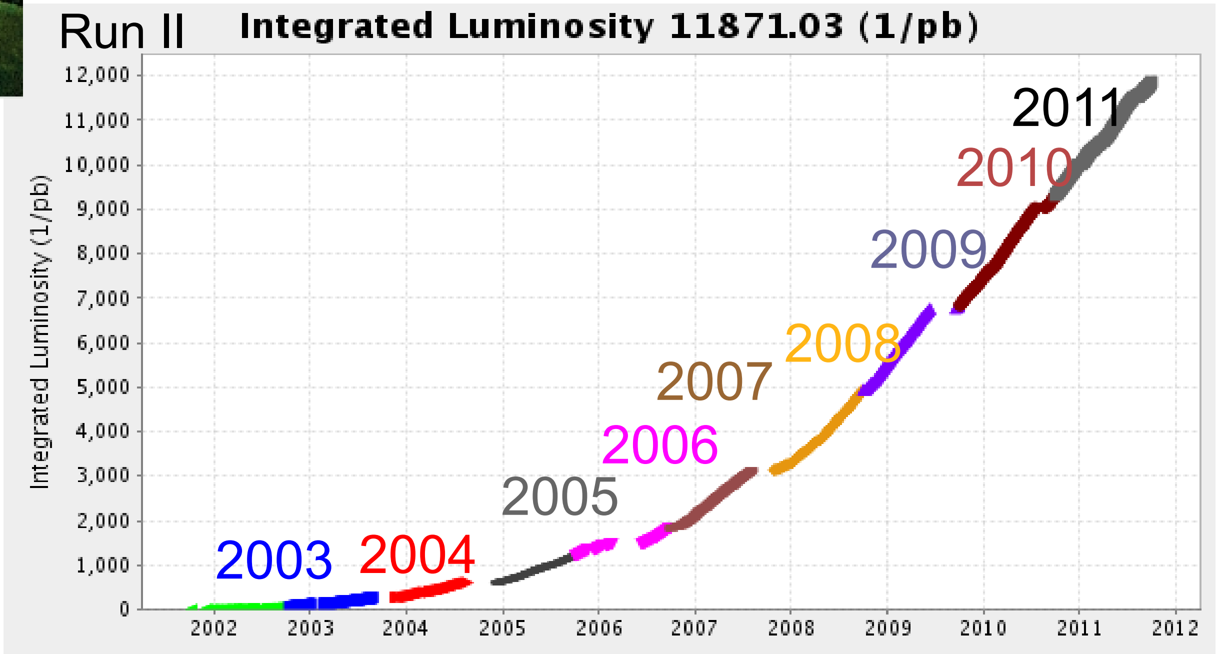
The Tevatron



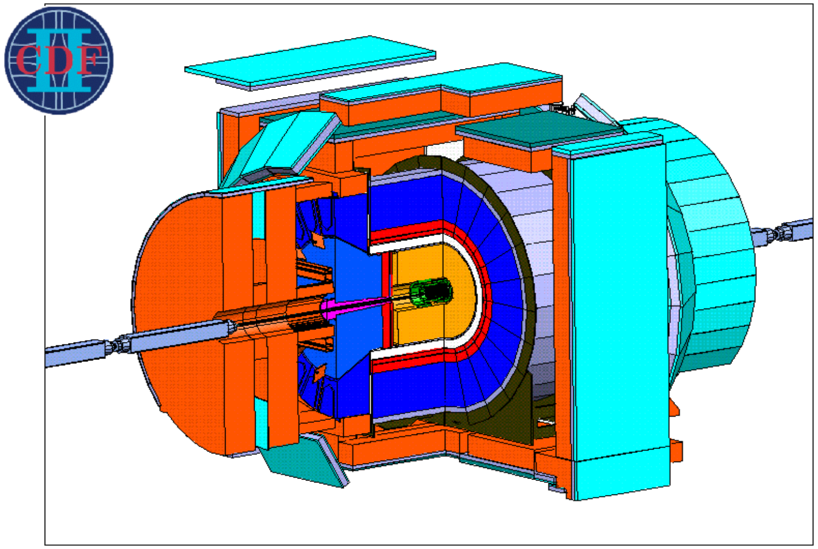
Proton-antiproton collider at $\sqrt{s}$=1.96 TeV

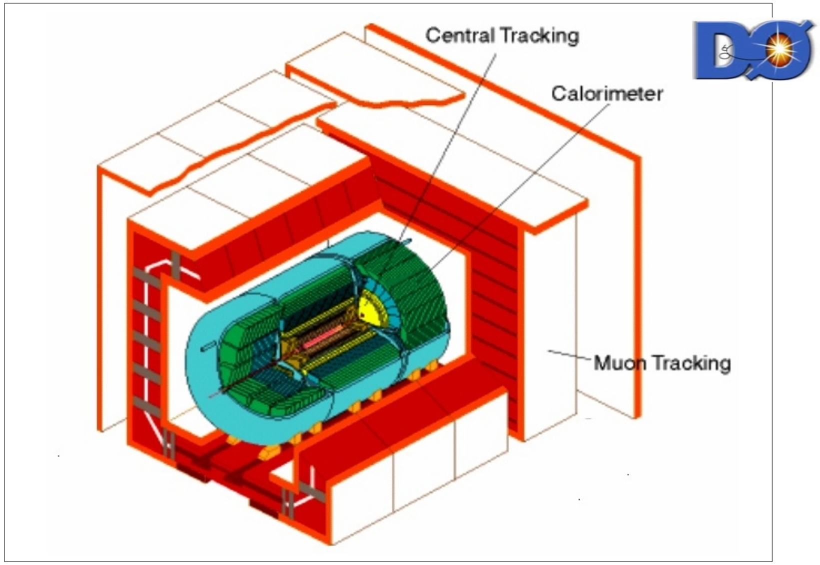
- Tevatron accelerator: 6.5 km circumference
- Two general-purpose experiments: CDF and DØ
- Run II (2002-2011)
  Ended 30 september 2011
  ~12 fb^{-1} delivered per experiment
  ~10 fb^{-1} for physics analysis

The most recent results at the Tevatron discussed today rely on the full RunII data set



CDF and DØ Detectors



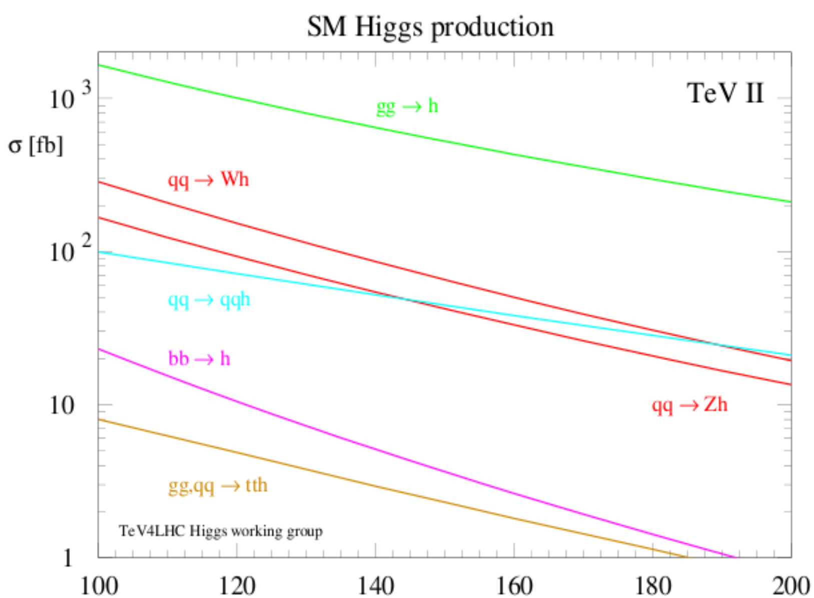


Multipurpose Detectors

- Central tracking system embedded in a solenoidal magnetic field:
- Silicon vertex detector
- Tracking chamber (CDF), Fiber tracker(DØ)
- Calorimeters: EM and Hadronic sections

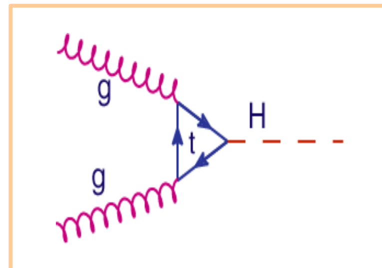
- Muon chambers
- Combined with Multilevel Triggers system to select events of interest
- Data taking efficiency: ~ 90%
- Recorded ~10 fb^{-1} for Run II

SM Higgs Boson at the Tevatron



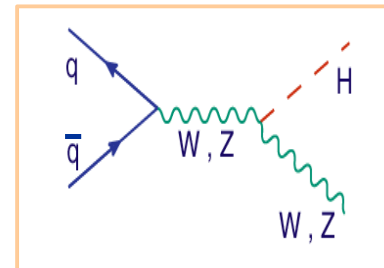
SM Higgs production X-sections at Tevatron

GG Fusion



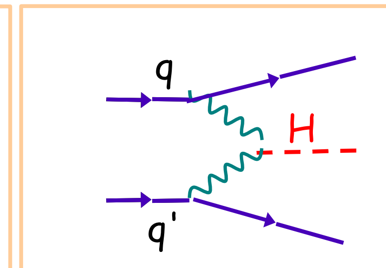
($\sigma \approx 0.2$ -1.0 pb)

W/Z H

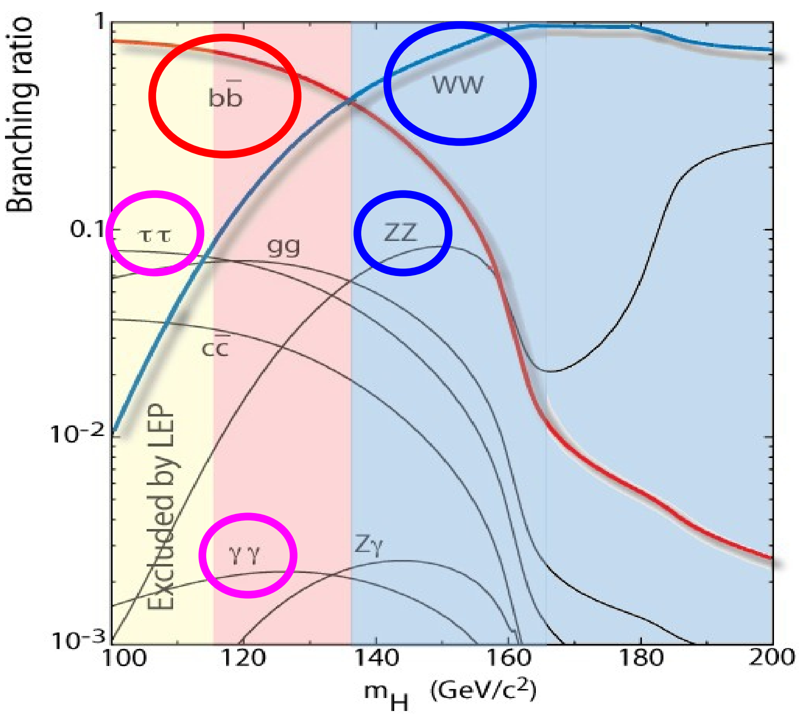


($\sigma \approx 0.01$ - 0.3 pb)

VBF



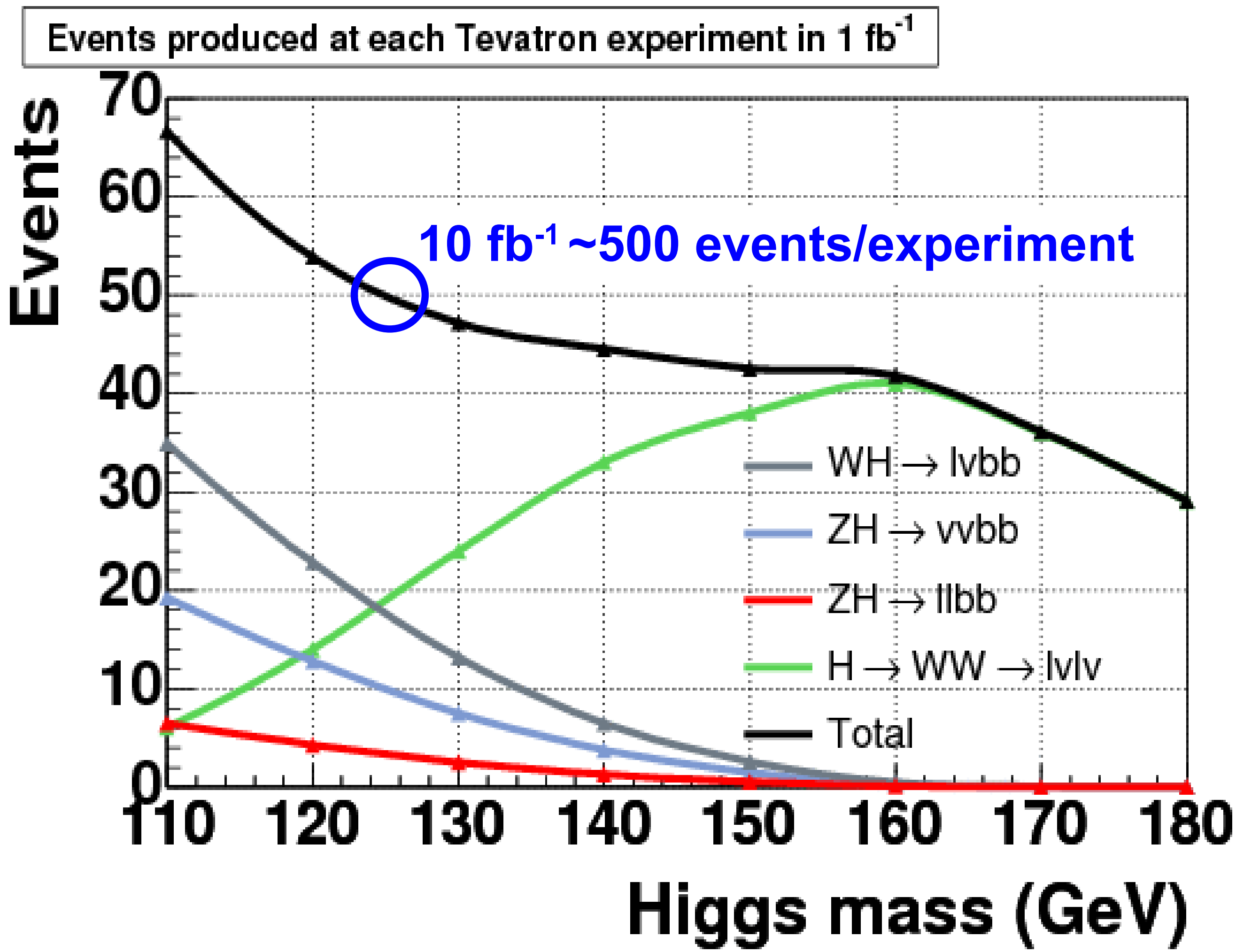
($\sigma \approx 0.01$ - 0.1 pb)

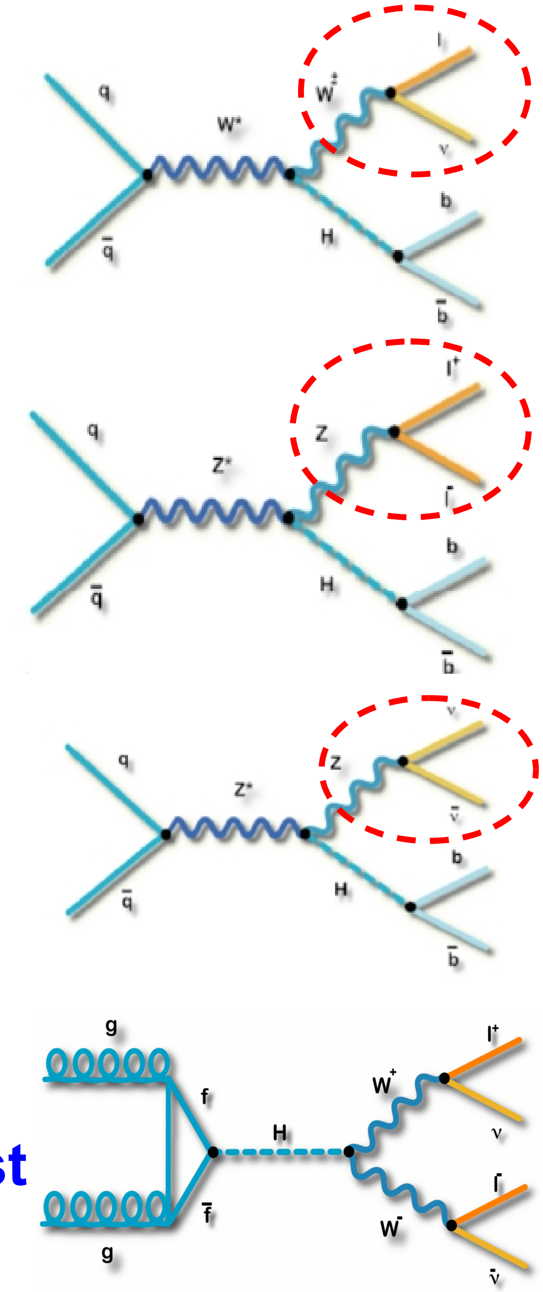


Decay modes depends on the SM Higgs boson mass

- High mass ($m_H > 135$ GeV) dominated by $H \rightarrow WW$
- Low mass ($m_H < 135$ GeV) dominated by $H \rightarrow b\bar{b}$

Leading Contribution to Production Rate





Multiple channels contribute in region of interest

Backgrounds to Higgs

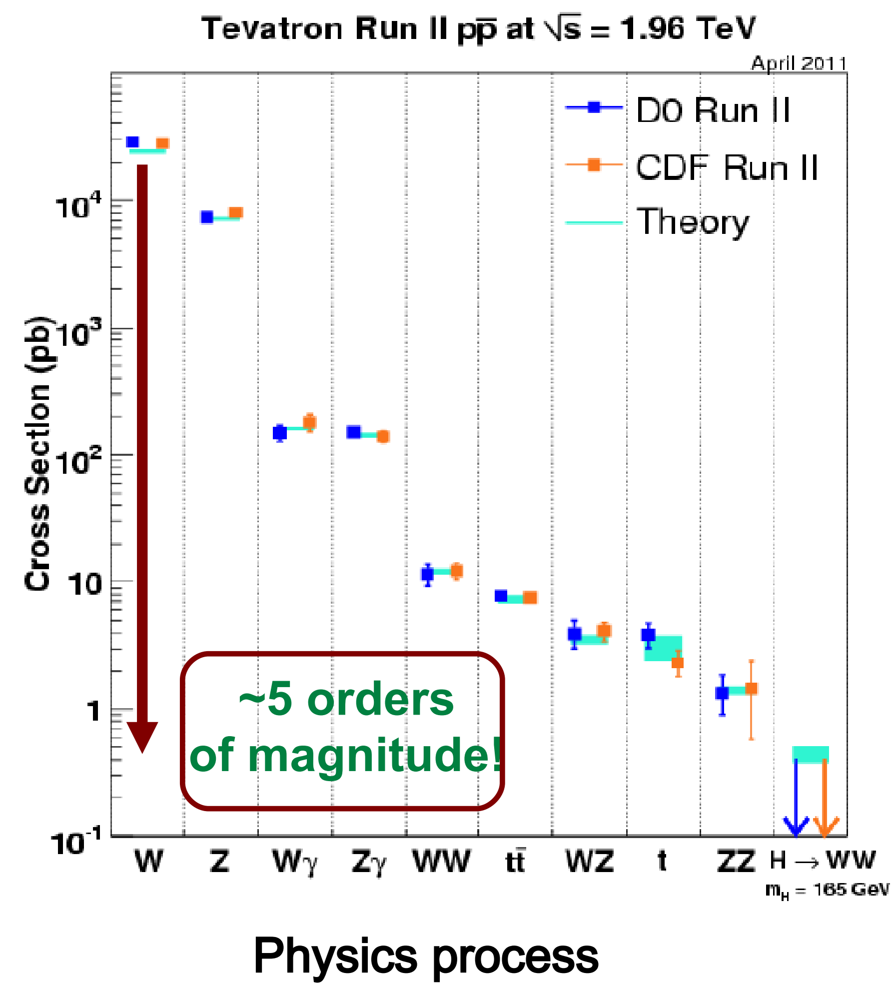
Most Challenge of SM Higgs Searches

Physics backgrounds are estimated by simulation and calibrated to data when possible

- W+jets, W+γ
  - W+jet bkg to semi-hadronic signatures
  - Jet or gamma faking lepton
- Z +jets, Z+γ
  - Mismeasured jets or leptons yielding $\not{E}_T$
  - Jet or gamma faking a 3rd lepton
- Di-boson WW, WZ, ZZ
  - Can yield 1, 2, 3 or 4 real leptons
  - WW, VZ: irreducible bkgs for H →WW, VH
- Double or single Top
  - W, b quark from Top decays

QCD Multijet backgrounds are measured directly from data:

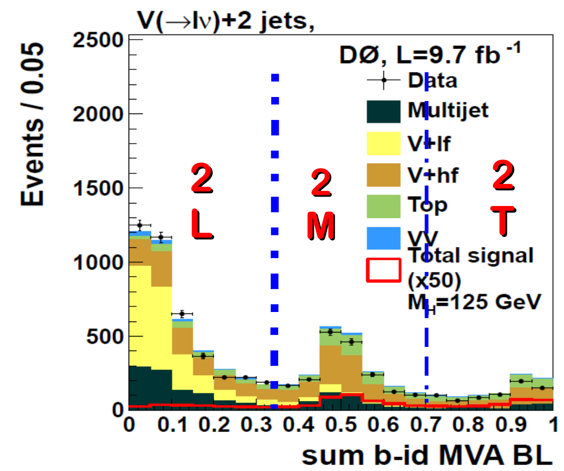
- Jet faking leptons
- Mismeasured jets creating $\not{E}_T$

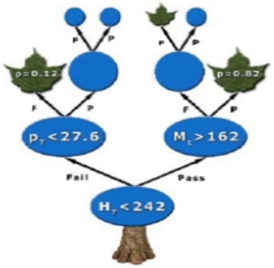


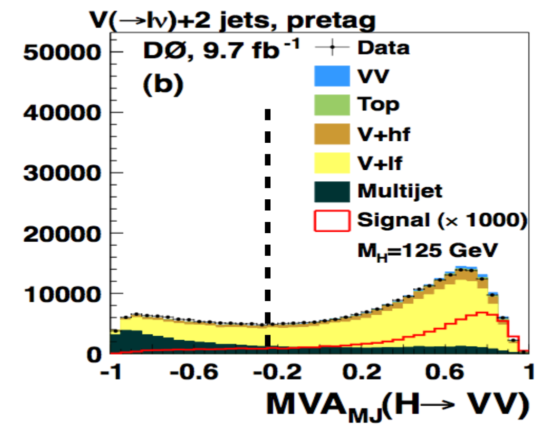
Search Strategy

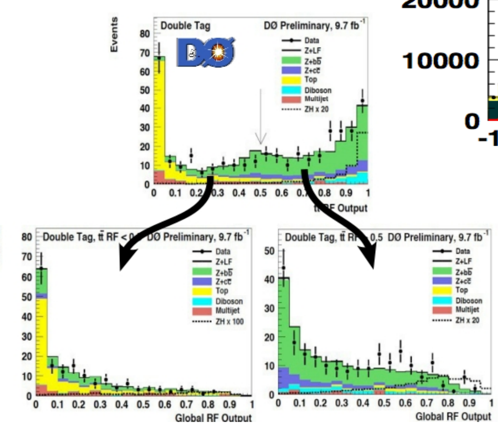
We're not getting any more data! Improving signal sensitivity by:

- **Explore as many final states as possible**
- **Maximize acceptance when possible**
  - Use different lepton reconstruction categories
  - Lower kinematic requirements
  - Inclusive triggers
- **Split analyses into sub-channels**
  - Different background composition
  - Different signal production mode
  - More handles to control systematic uncertainties
- **Use Multivariate techniques (decision trees , neural networks, matrix element)**
  - Maximize the use of available kinematics information
  - Train MVA for specific background to remove/reduce it
  - Best discrimination for measurement





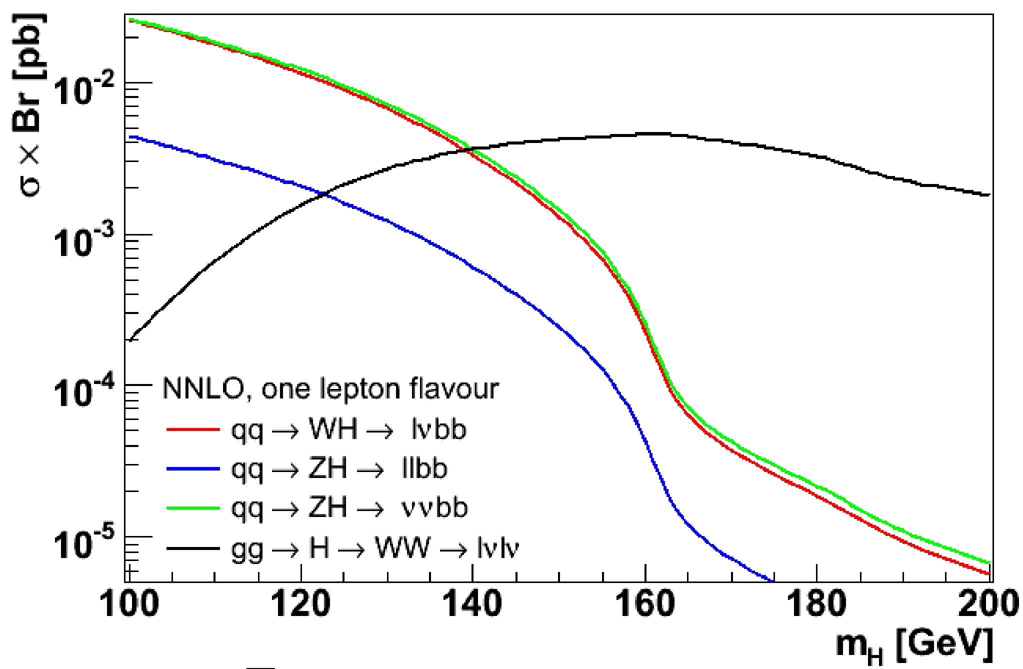


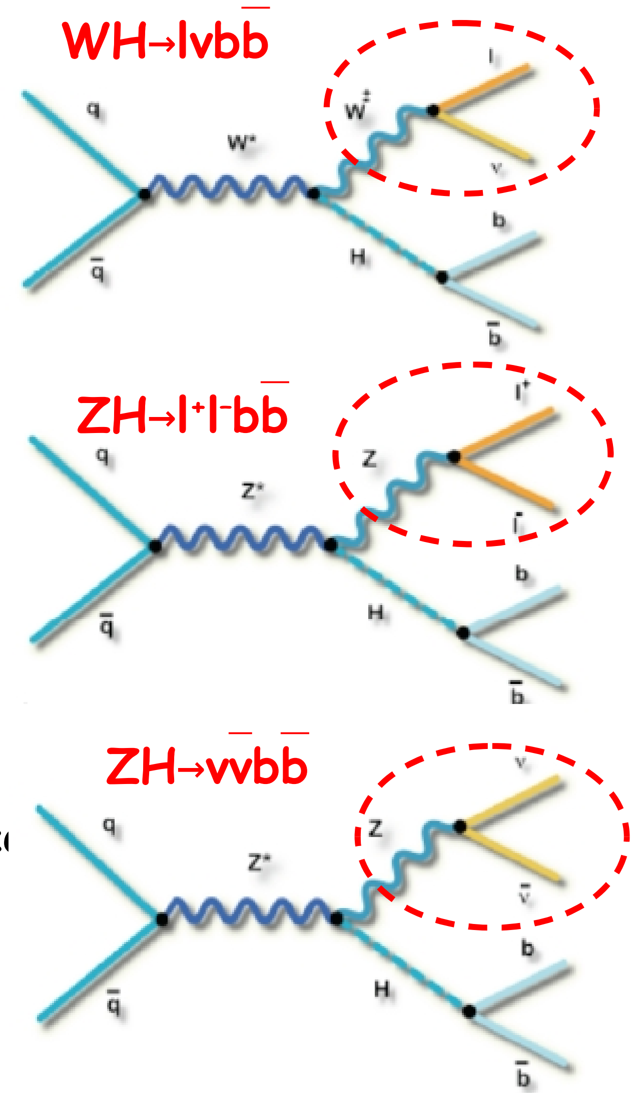


Searching for $VH \rightarrow Vb\bar{b}$

Major Contribution to sensitivity for m_H < 135 GeV

Identify events consistent with leptonic W/Z decays in association with jets





- $WH \rightarrow l\nu b\bar{b}$: e or m and high $\not{E}_T$
- $ZH \rightarrow l^+l^-b\bar{b}$: e^+e^- or m^+m^- consistent with Z resonanc
- $ZH \rightarrow \nu\bar{\nu}b\bar{b}$: No charged leptons,

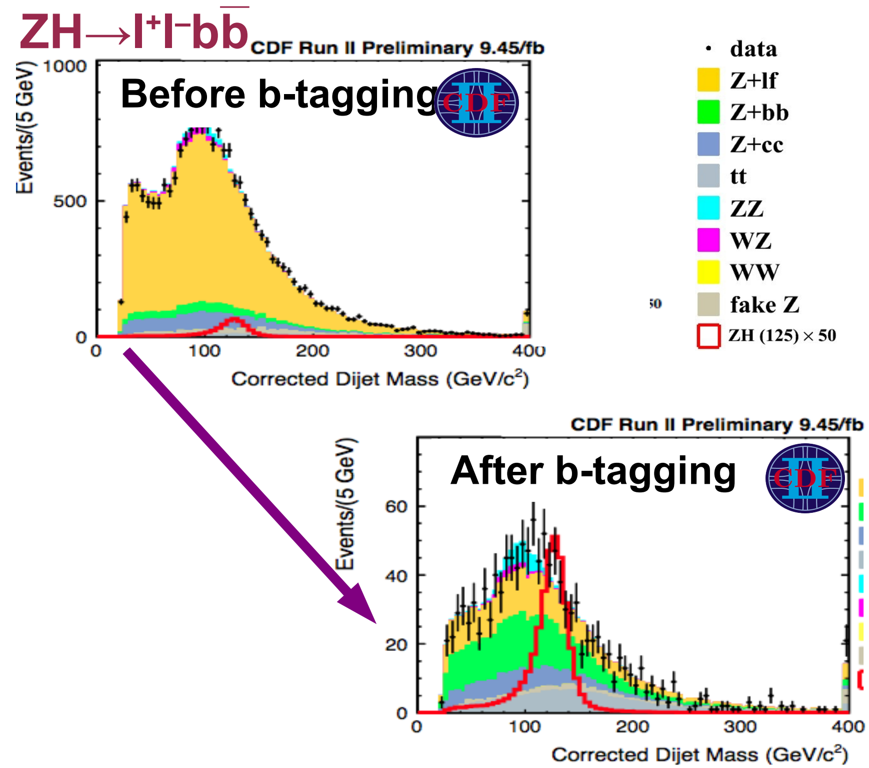
  Two coplanar jets and $\not{E}_T$

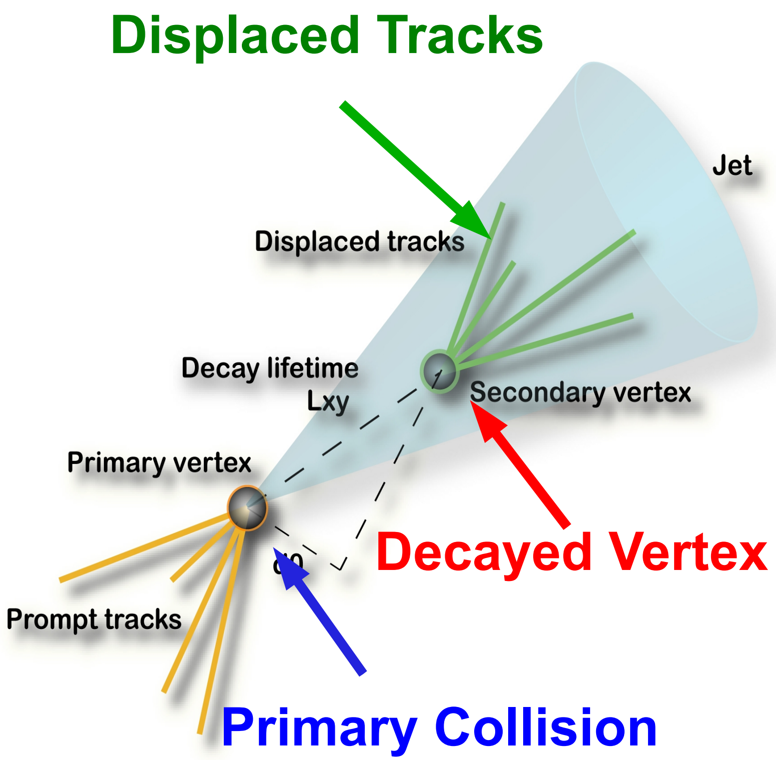
Heavy Flavor Identification

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

Both CDF and DØ use multivariate b-tag classifiers to improve discrimination power

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



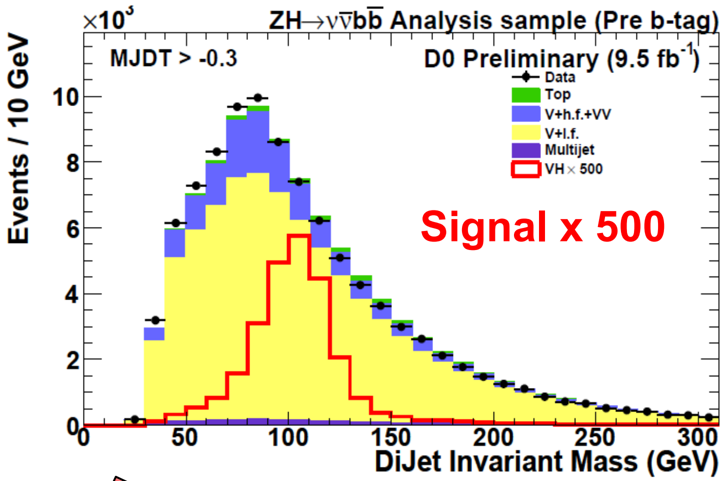


- Most significant improvement for CDF's Winter 2012 update
  ⇒ This alone brought 15 – 30% improvement in H→bb analysis

Dijet Mass with b-taging

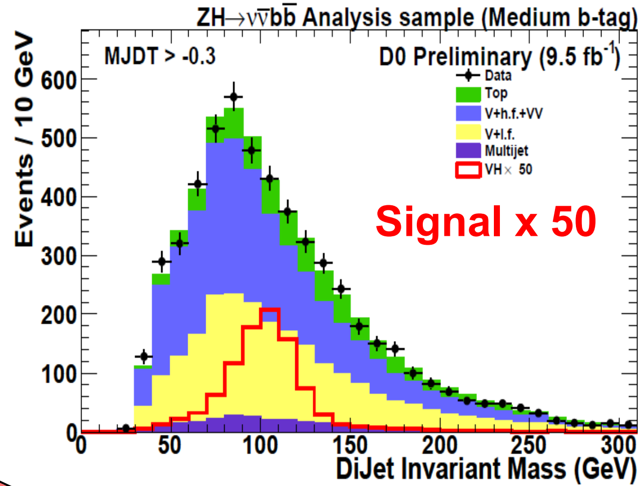
B-tagging brings significant improvement to S:B

Before b-tagging

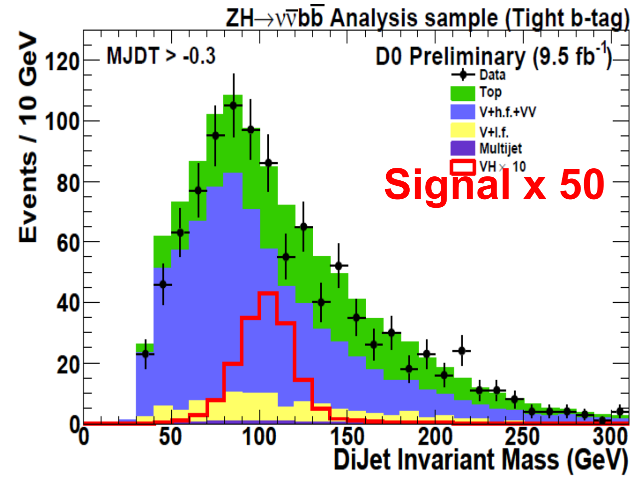


- *Optimize b-tagging point*
- *Optimize number of b-tag categories*

1 b-tag



2 b-tags

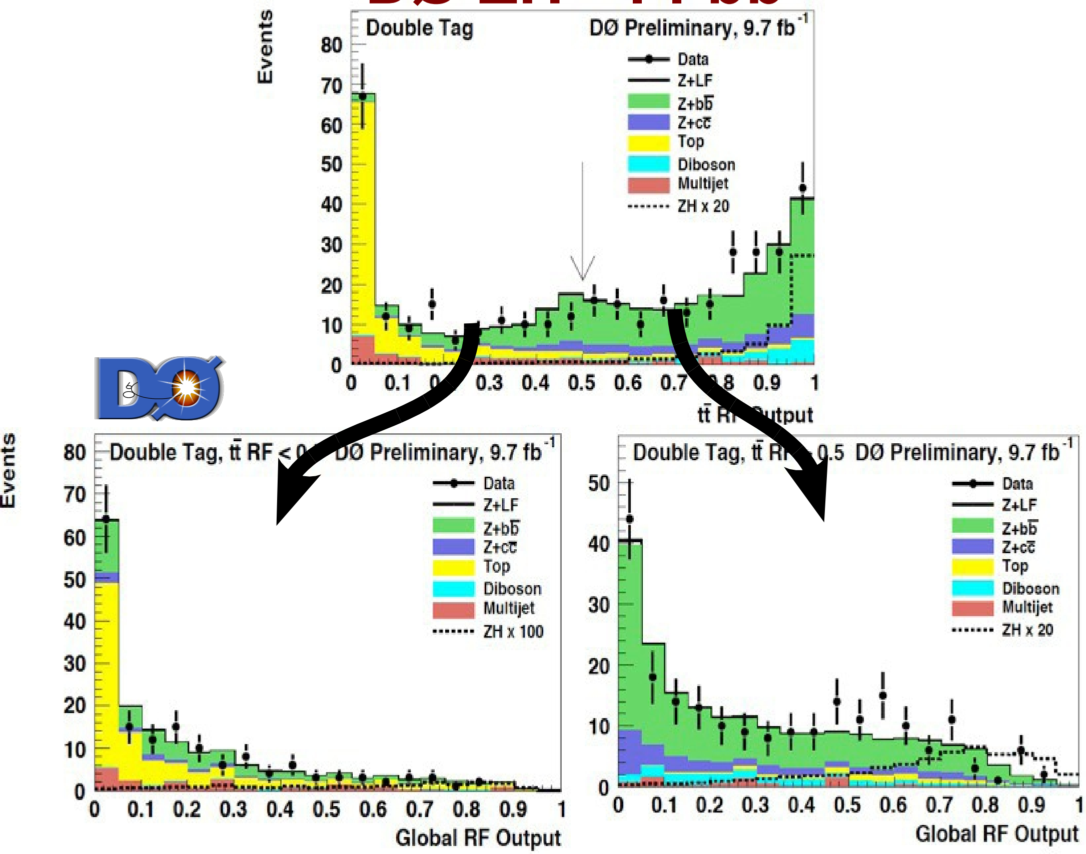


- *Reconstructed Dijet Mass*
  ⇒ The most discriminating variable in H→bb analysis

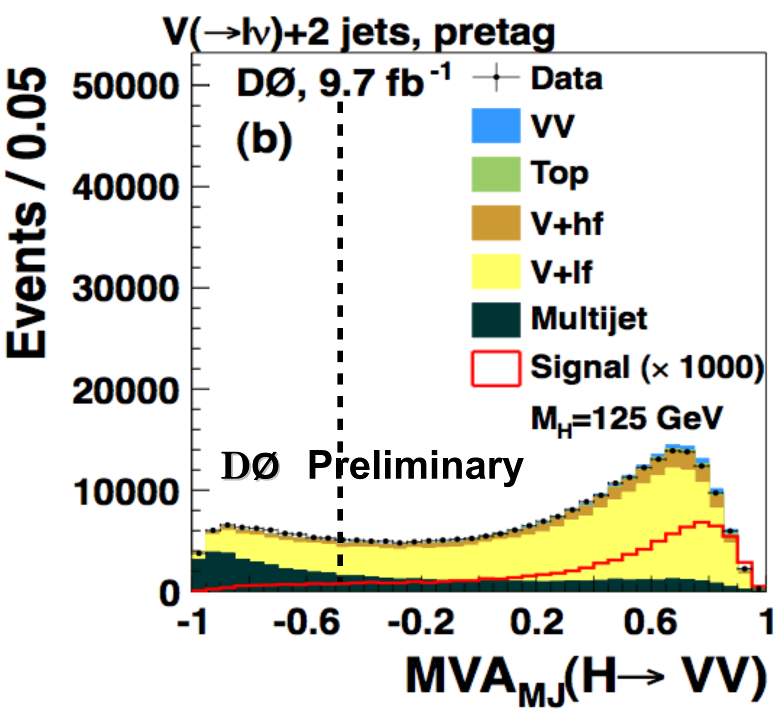
Multivariate analysis in VH → V$b\bar{b}$ search

MVA training against specific background

DØ ZH→l^+l^-bb



DØ WH→lν$b\bar{b}$



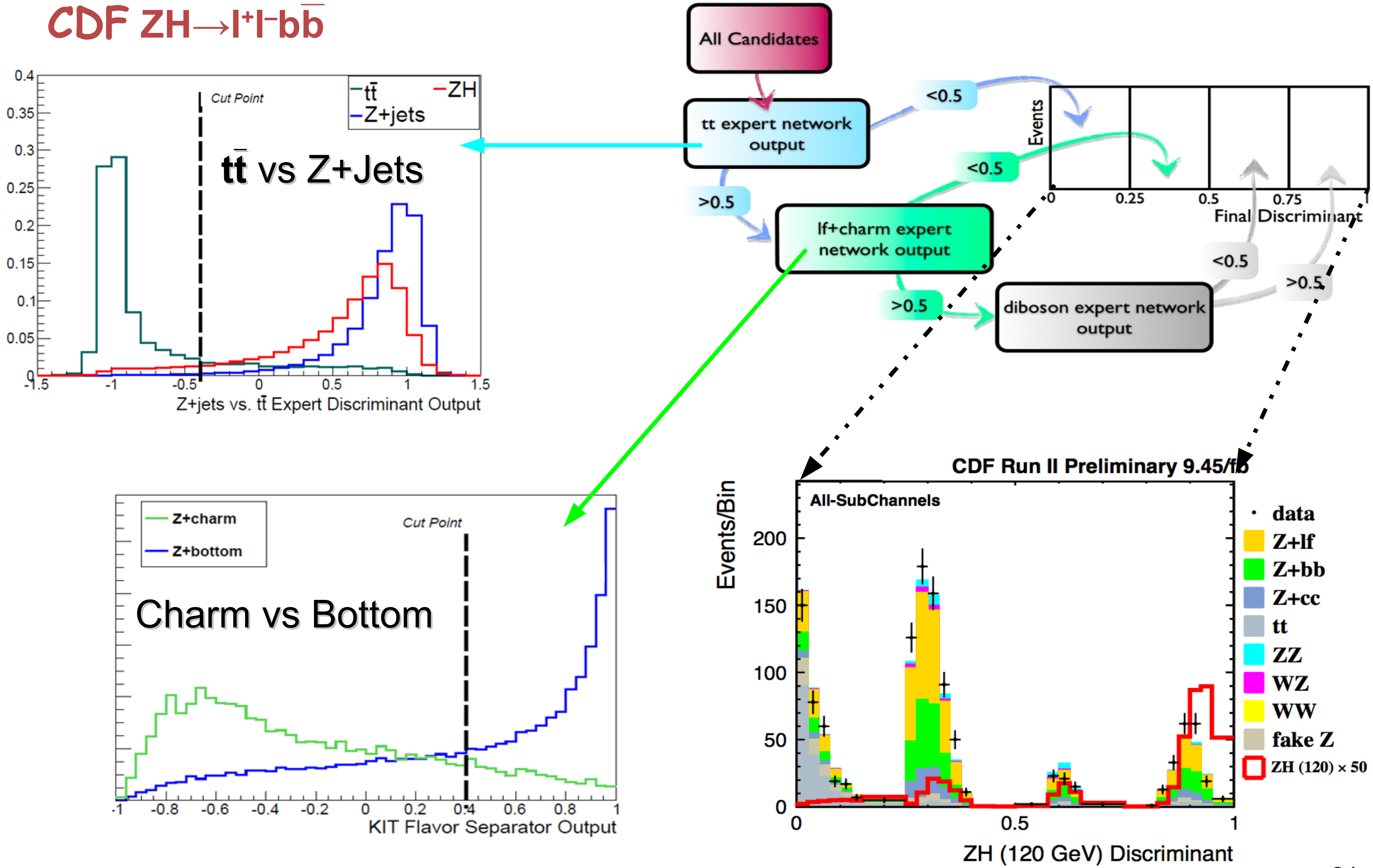
Split channel into $t\bar{t}$ enriched/depleted regions

Suppress Multijets backgrounds

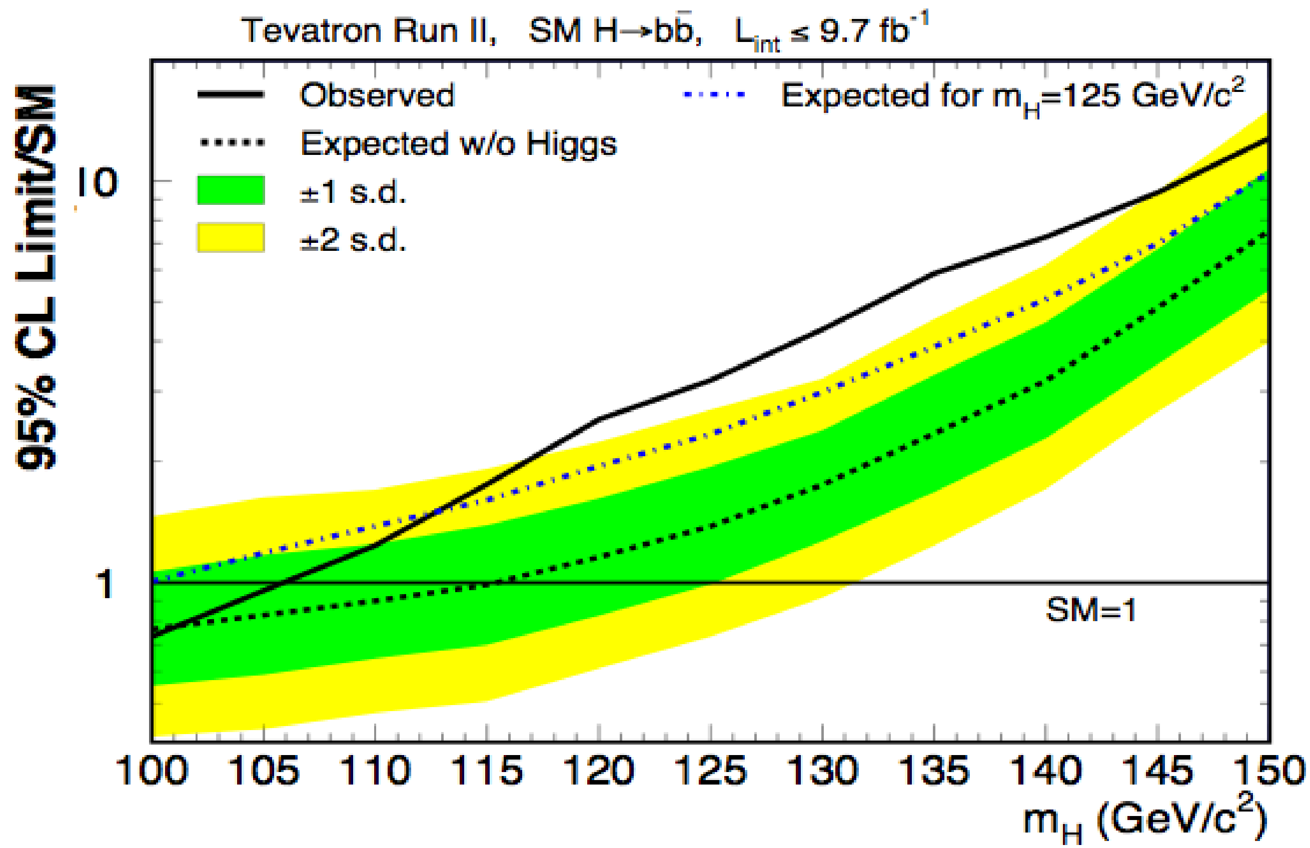
MVA Optimization in VH → $Vb\bar{b}$ search

MVA training against specific background and for the signal

CDF $ZH \to l^+l^-b\bar{b}$



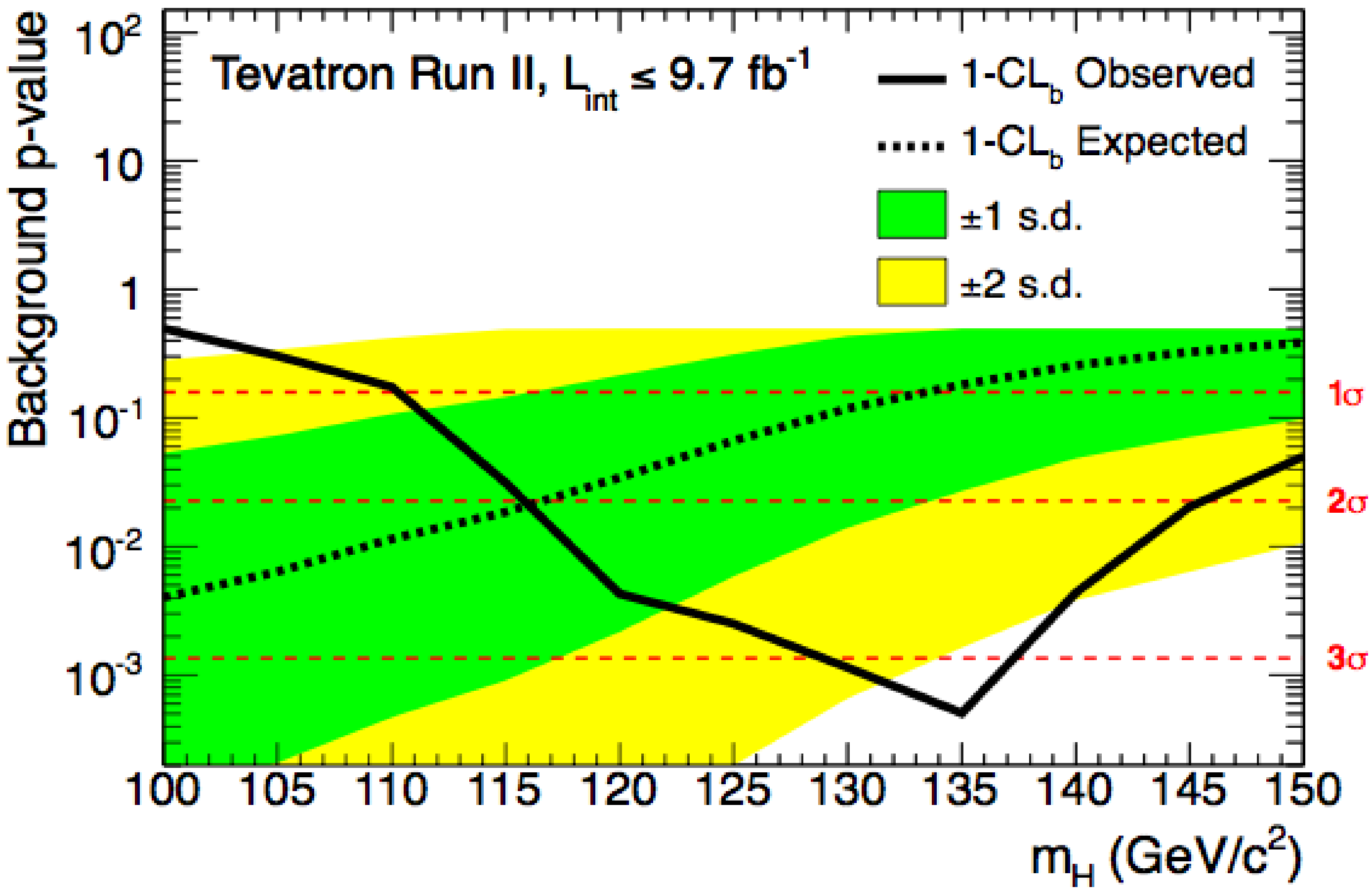
Tevatron H → $b\bar{b}$ Result



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

Significant excess in 120 < M_H < 135 GeV

Quantifying the Excess



Test compatibility with background-only hypothesis

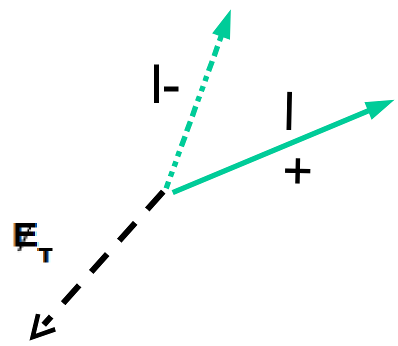
- **Local p-value for H→bb: 3.3 s.d**
- **Global p-value for H→bb: 3.1 s.d**

Searching for H → WW

Final States Driven by H → WW

- **Di-lepton of opposite signs + $\not{E}_T$**

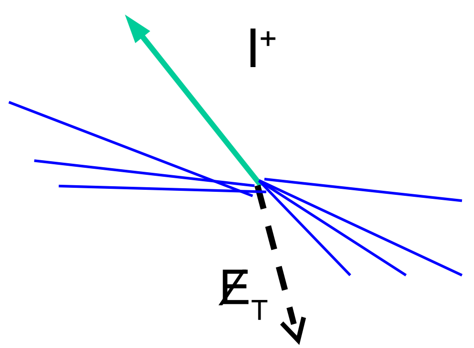
  Clean signal, Small Br~6% (ee +eμ + μμ)



- **Lepton+ tau+ $\not{E}_T$**

  Small Br~4% (et+ mt)

  Difficulty to reconstruct hadronic taus

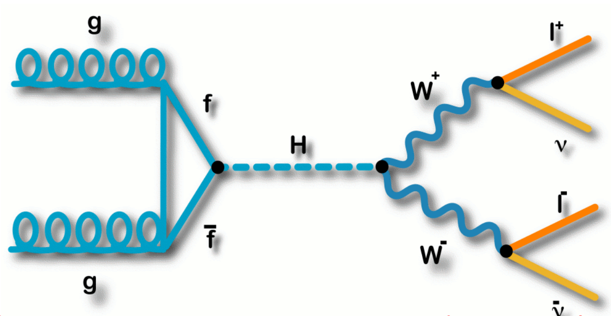


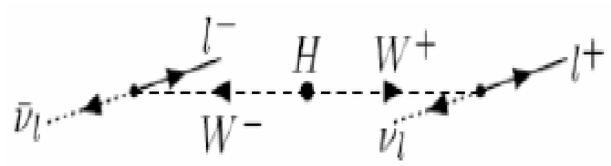
- **Lepton + $\not{E}_T$+ jets**

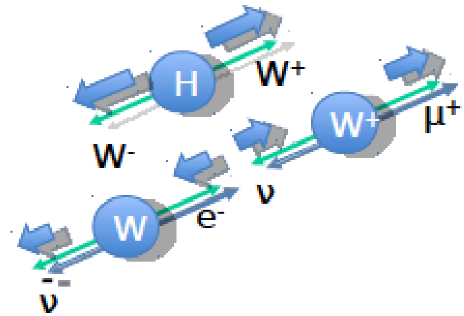
  Larger Br ~ 30% (e+jets, μ+jets)

  Large W+jets background, hard to model

Searching for H → WW → lνlν

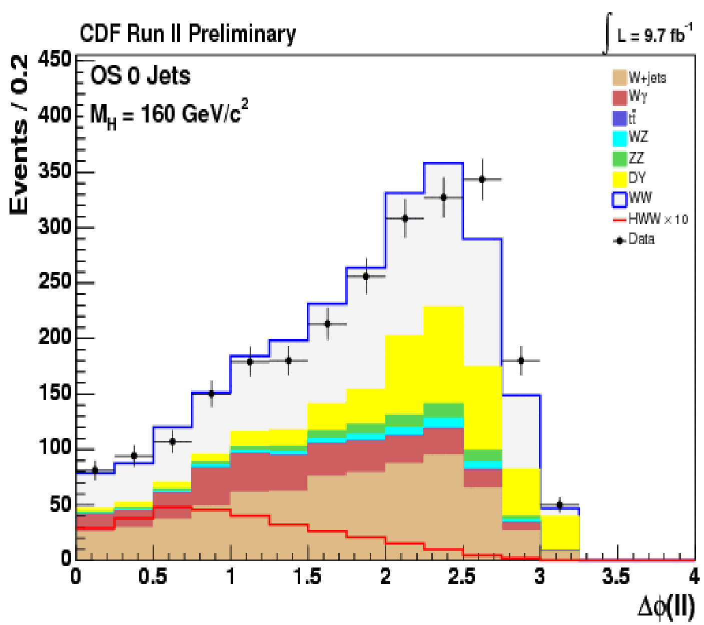




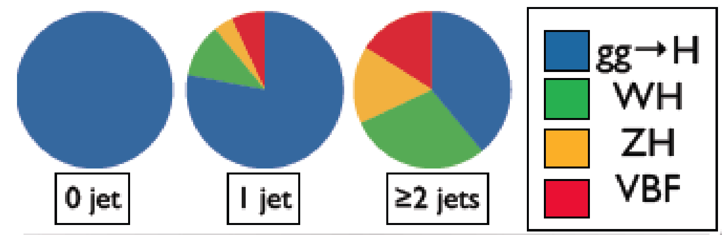


- The most sensitive channel for $130 < m_H < 200$
  - Still one of the most important channels at 125GeV
  - But poor mass information due to neutrinos
- Clean signatures
  - 2 isolated high p_T leptons, opposite signs
  - Large missing E_T
- Spin correlation in $H \rightarrow WW$
  - Spin 0 nature of the Higgs boson
  - Parity violation in W decays

  ⇒ The leptons tend to be collinear



Searching for H → WW → *lνlν*

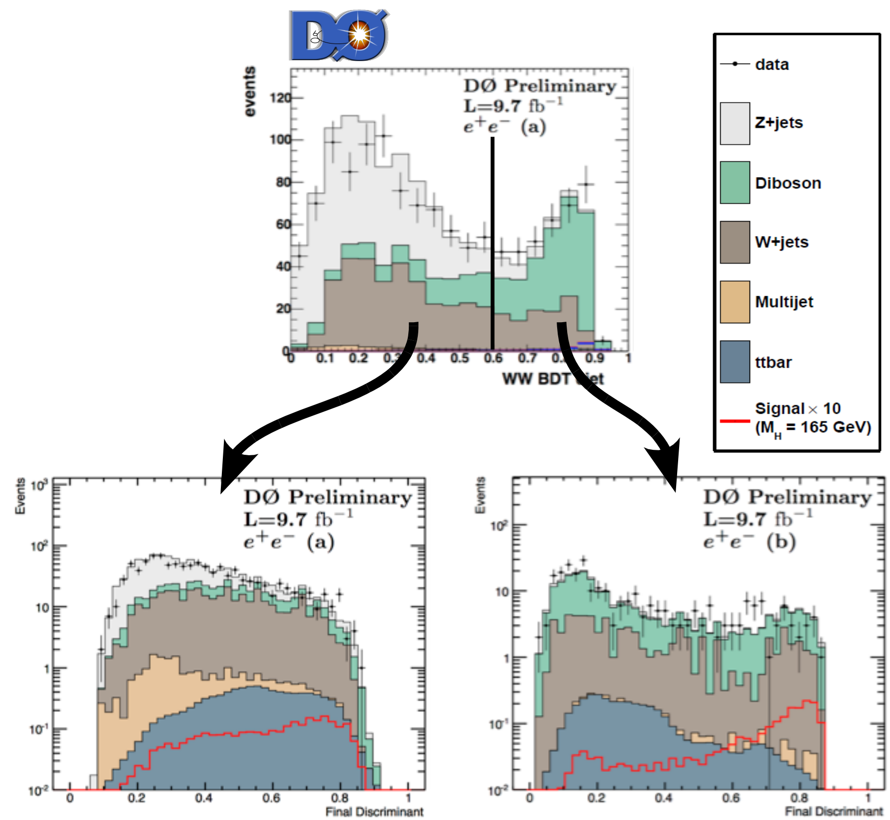


Maximize sensitivity:

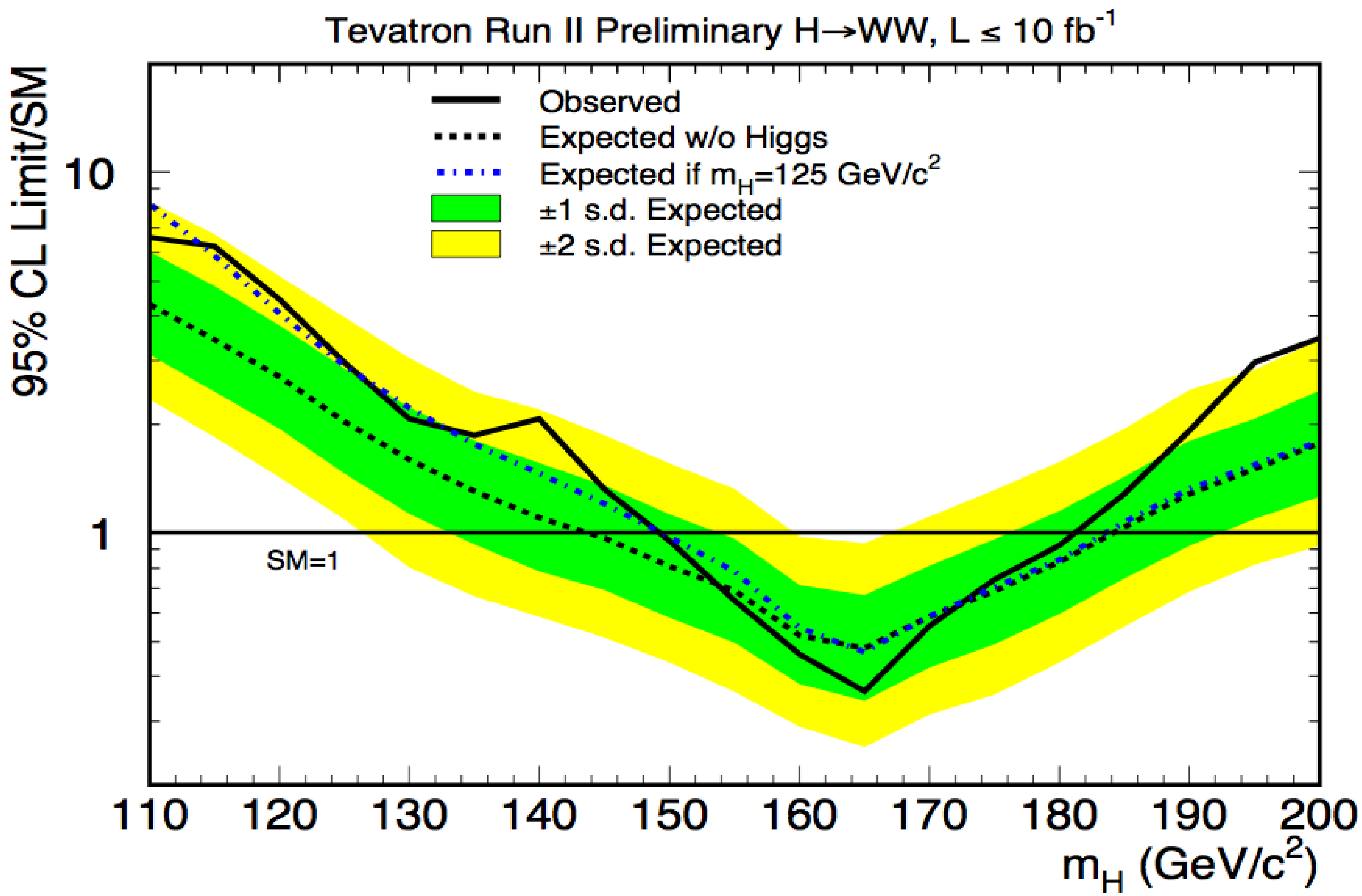
- Consider all signal production modes

  gg→H W/Z H VBF

- Sub-channels optimized for different background compositions:
  - by jet multiplicity
  - by lepton flavor (**DØ**) or quality (**CDF**)
  - by WW-likeness (**DØ**)
- Use MVA techniques
  - Suppress Z/gamma background by cutting on dedicated multivariate discriminant (**DØ**)
  - Suppress top quark pairs by vetoing b-tag (CDF)
  - Define WW enriched / depleted regions (DØ)
  - As a final discriminant to look for signal



Tevatron H → $W\overline{W}$ Result



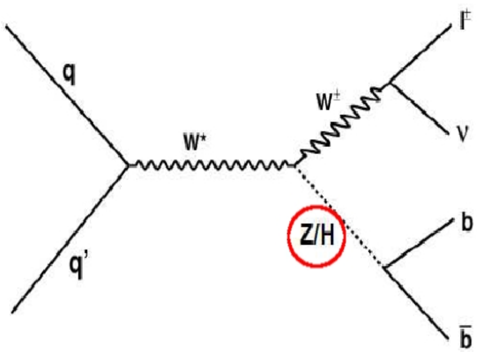
Expected sensitivity of ~2.1 x SM at M_H = 125 GeV

Broad excess consistent with S+B hypothesis at M_H = 125 GeV

Higgs Search Validation

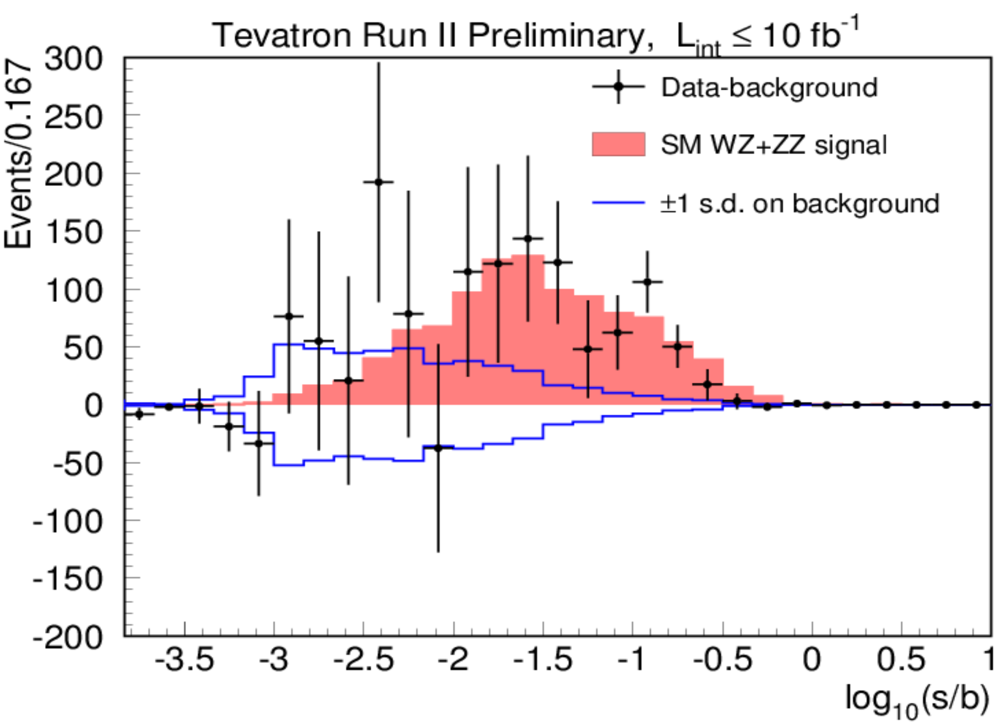
Validate analyses by measuring SM diboson production

- Diboson VZ→Vb$\bar{b}$ and WW→lνlν topologically similar to VH → Vb$\bar{b}$ and H→WW→lνlν Higgs signals
- Employ same final states and analysis strategy as in Higgs searches with different signal definitions



- **Cross check using VZ→Vb$\bar{b}$**

MVA outputs used to extract cross section

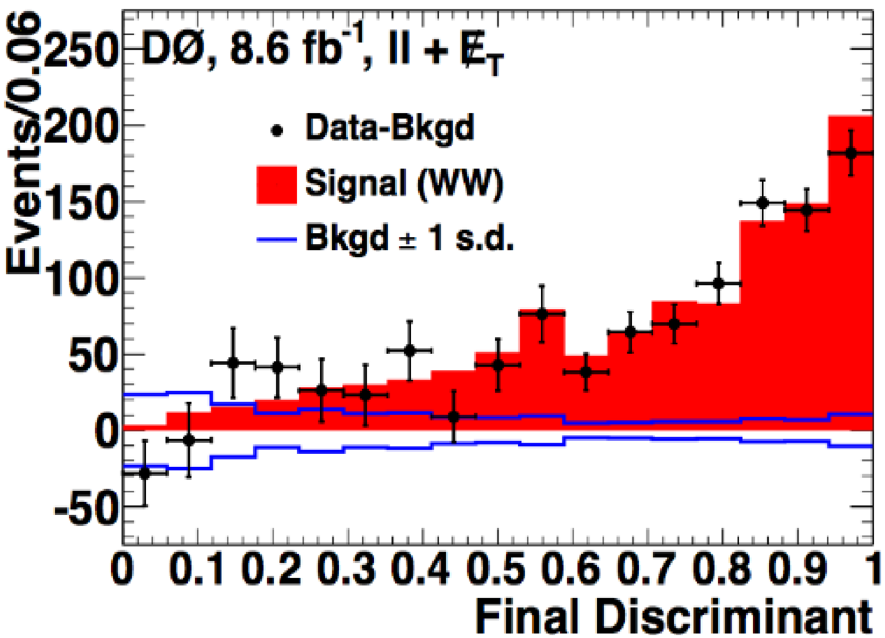


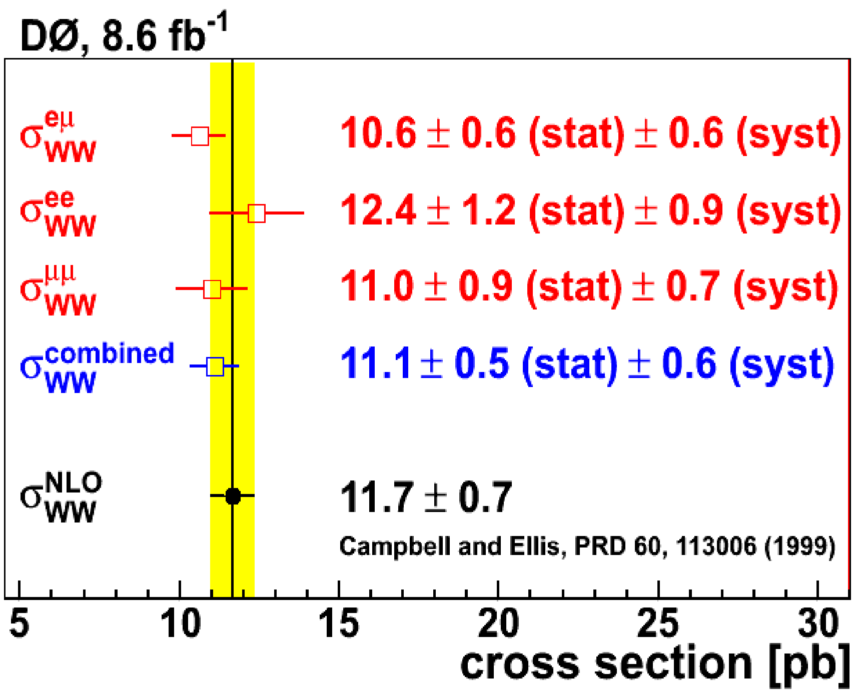
σ_{meas}(WZ+ZZ) = 3.0 ± 0.9 pb

σ_{SM}(WZ+ZZ) = 4.4 ± 0.3 pb

Cross check using WW→lνlν

Validate analyses by measuring SM diboson production

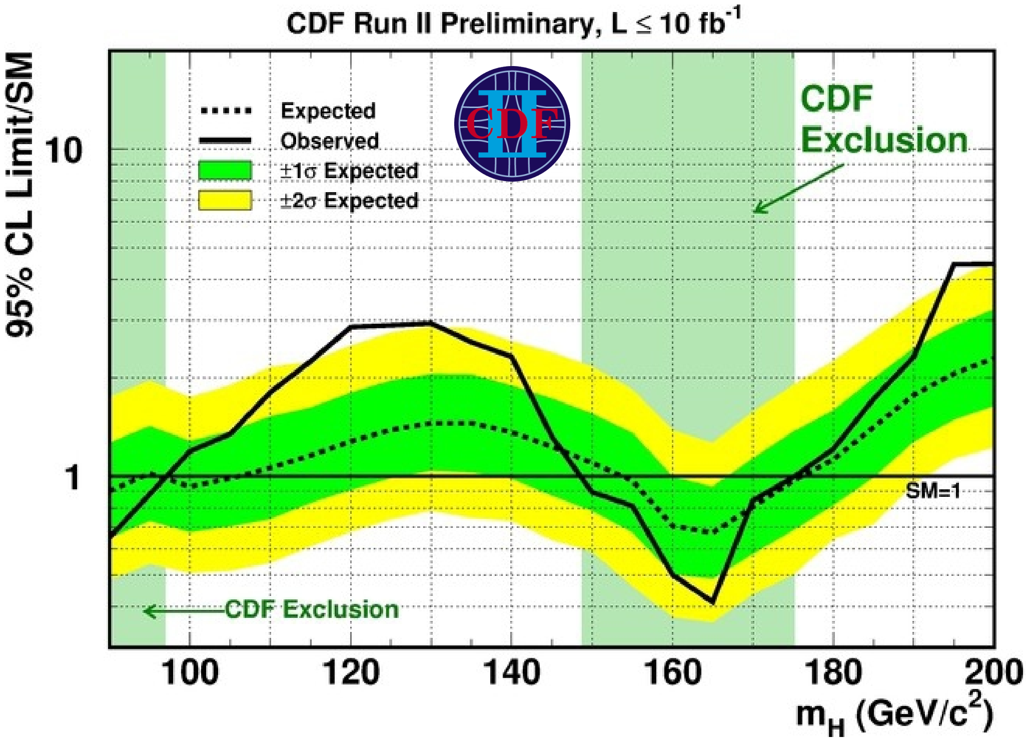


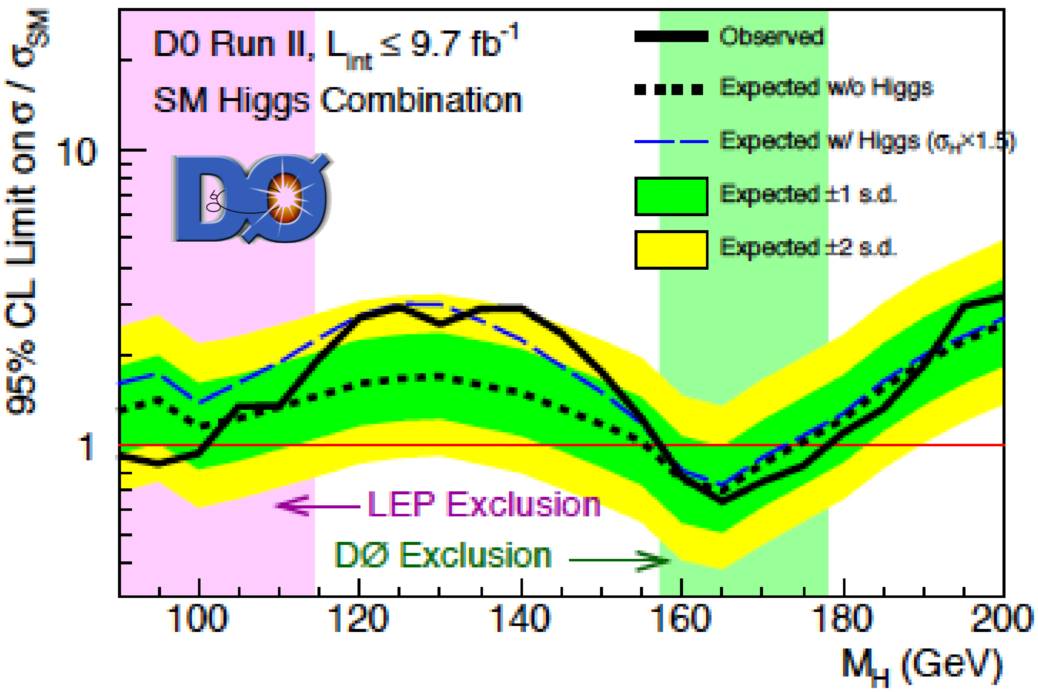


Measured cross-section σ_{mean}(WW) = 11.1 ± 0.5 (stat) +0.6(syst)

In agreement with NNLO prediction

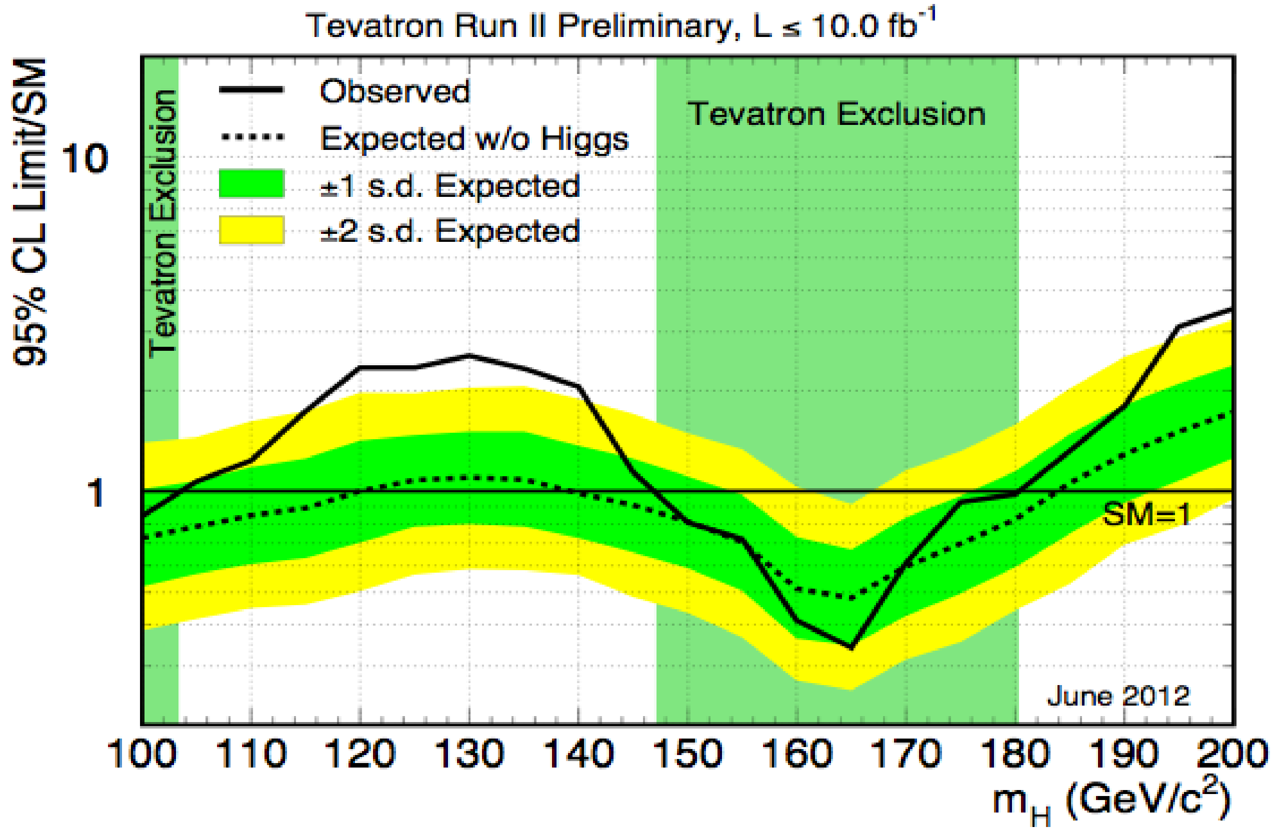
Results from CDF and DØ





- CDF and DØ results show similar sensitivity over entire searched mass range
- At M_H = 125 GeV
  - CDF: Exp. Limit = 1.46 x SM Obs. Limit = 2.89 x SM
  - DØ: Exp. Limit = 1.68 x SM Obs. Limit = 2.92 x SM
- Exclusion at 95% CL
  - CDF: 90 GeV < M_H < 97 GeV & 147 GeV < M_H < 175 GeV
  - DØ: 90 GeV < M_H < 101 GeV & 157 GeV < M_H < 178 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**
- **Significant excess of data events with respect to the background estimation in the mass range 115<M_H<140 GeV**

Probing Higgs Boson Couplings

- Signal contributions from multiple production and decay processes simultaneously accepted by each channel
  ⇒ Direct Interpretation for Higgs couplings is ambiguous
  ⇒ Measure deviation of couplings from the SM prediction
- Assumption
  ⇒ Fix M_H = 125 GeV
  ⇒ The Higgs couplings are varied by scaling with scale factors

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- Signal contributions from multiple production and decay processes simultaneously accepted by each channel
  - ⇒ Direct Interpretation for Higgs couplings is ambiguous
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- Assumption
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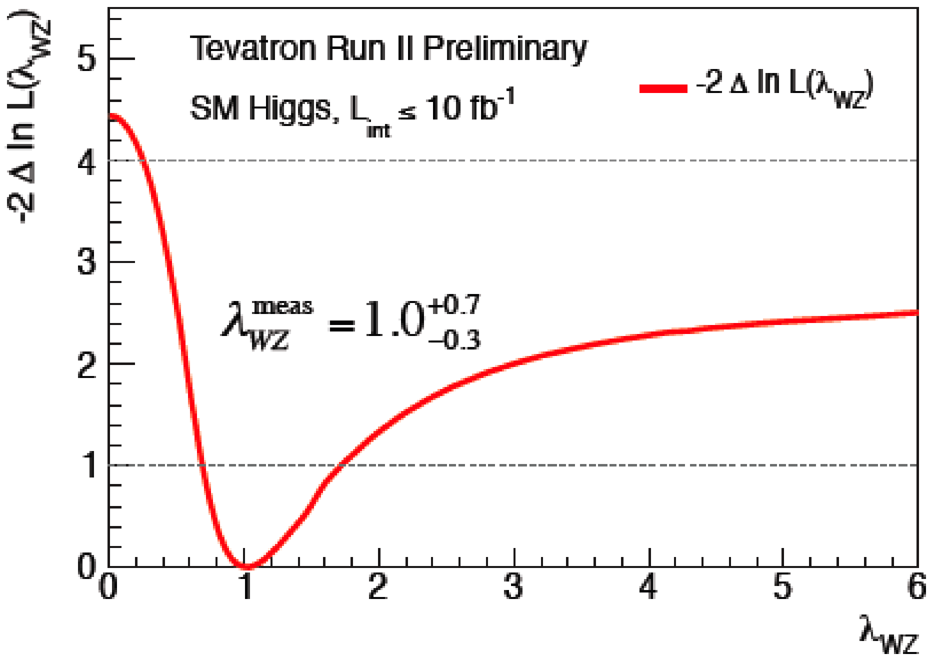
Benchmark 1

- ⇒ Assume couplings to fermion as predicted by SM
- ⇒ Measure the ratio $\lambda_{wz} = k_w/k_z$



Measurements consistent with the SM prediction

Probing Higgs Boson Couplings

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  - ⇒ Fix M_H = 125 GeV
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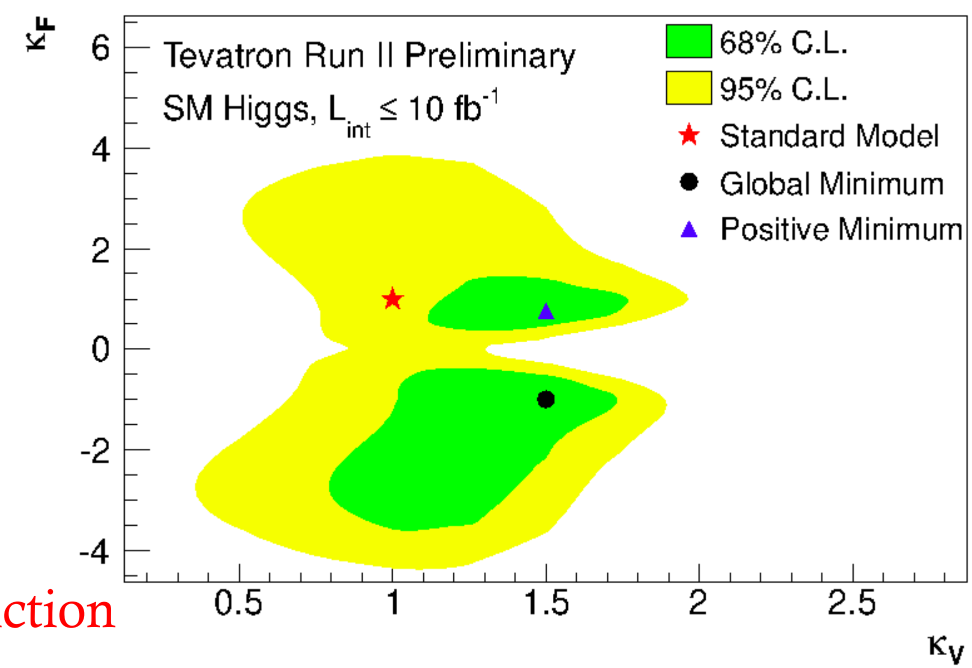
Benchmark 2

⇒ Consider two scaling factors:

k_f applying to couplings to fermions,

k_v applying to couplings to Fermion

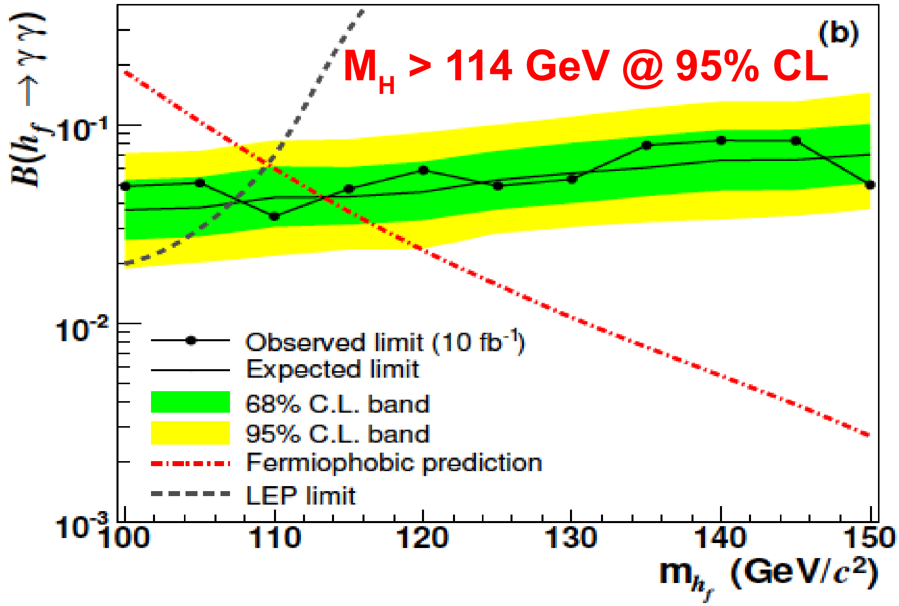
⇒ Measure k_v, k_f simultaneously

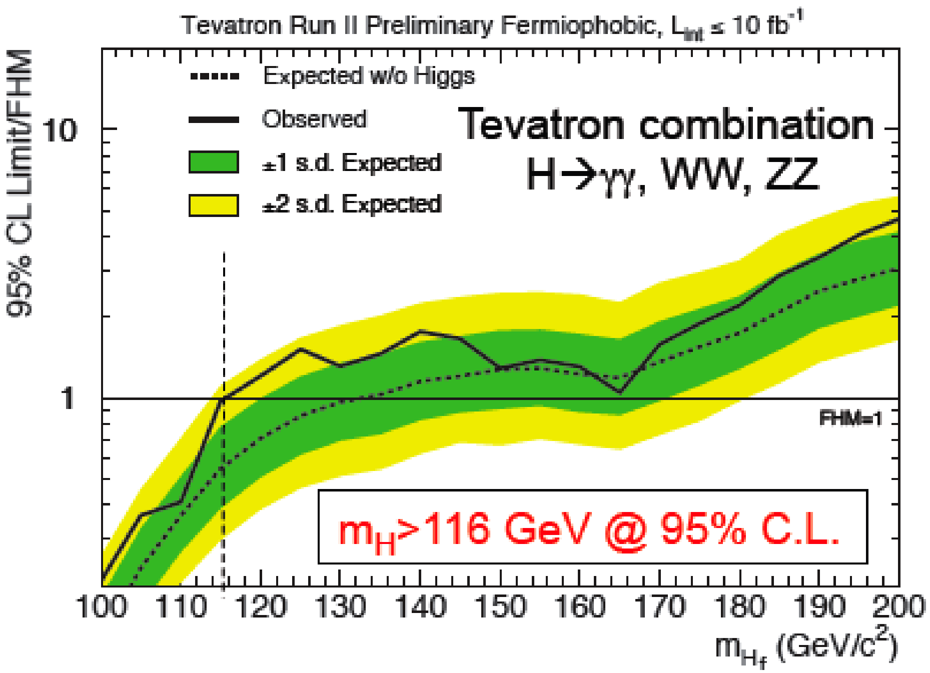


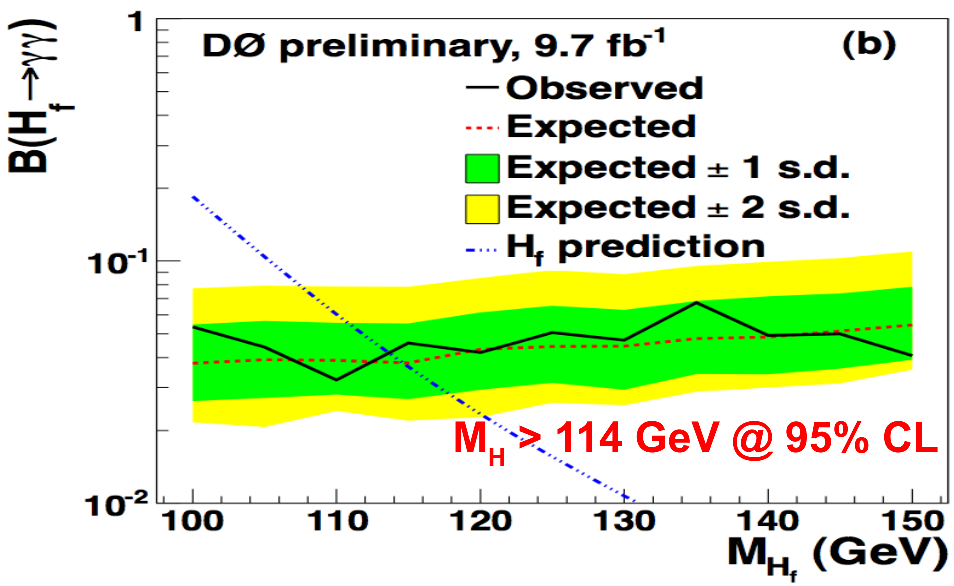
Measurements consistent with the SM prediction

BSM Interpretations: Fermiophobic Higgs

- **Fermiphobic Higgs Mode**
  - Zero couplings to fermion at tree level
  - Couplings to bosons are SM-like
- **Fermiphobic Higgs production & decay**
  - gg→H production is suppressed
  - Only VH & VBF productions are considers
  - Branching ration H→bosons are enhanced
- **Searched channels: H→WW, H→ZZ,H→gg,**

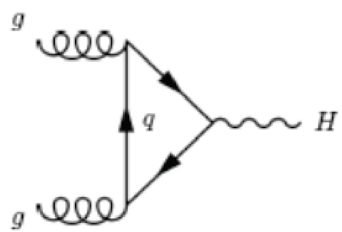


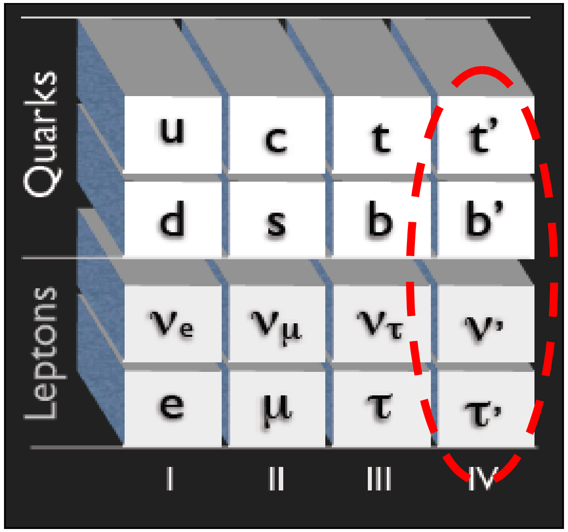




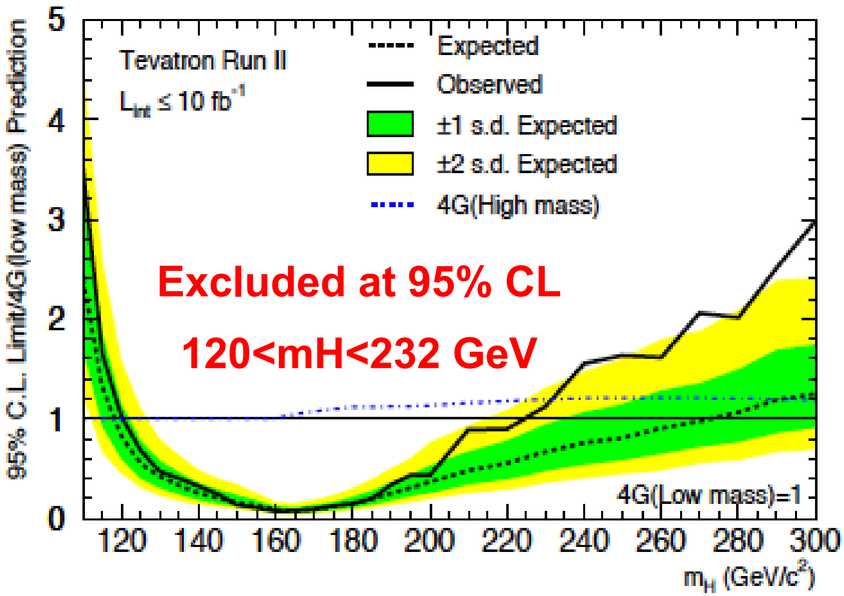
BSM Interpretations: 4th Generation Models

- 4th generation Models
  - Inclusion of a 4th generation of Fermion
  - ggH coupling is enhanced ~ 3 times





- Higgs production cross-sections
  - gg→H→WW production is enhanced by 7-9 times for 100 < M_H < 300 GeV
  - * VH & VBF remain the same at SM rate



- Higgs decay branching ratios
  - H→gg is significantly increased at low mass
  - H→WW dominant mode for high mass
- Searched channels: gg→H→WW, gg→H→ZZ

Summary

- Updated Tevatron results based on full Run II data set in most search channels.

- The H->bb searches at the Tevatron continues to provide valuable information to help unravel the nature of the discovered boson.

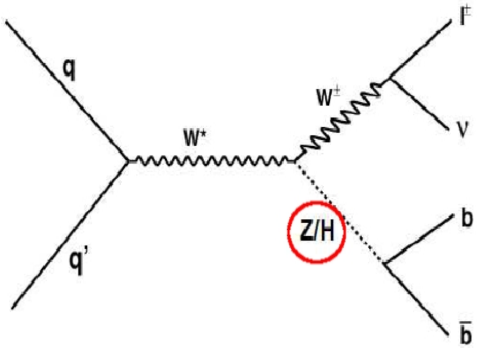
- Excess in 115<mH<140 GeV region with local significance of 3.1 s.d at mH=125 GeV. So far emerging picture consistent with discovered boson at the LHC.

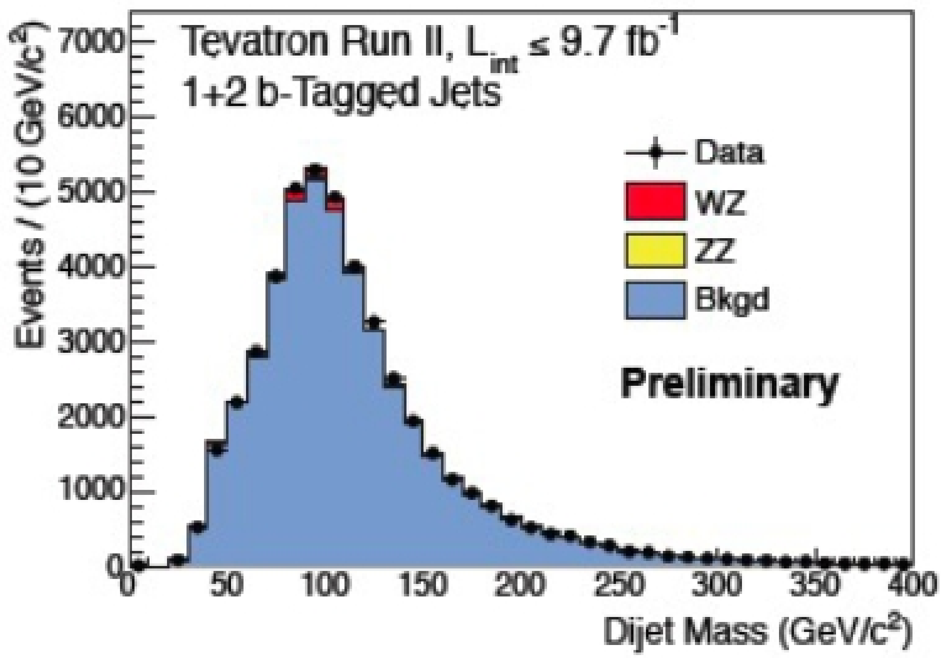
SM Higgs at the Tevatron

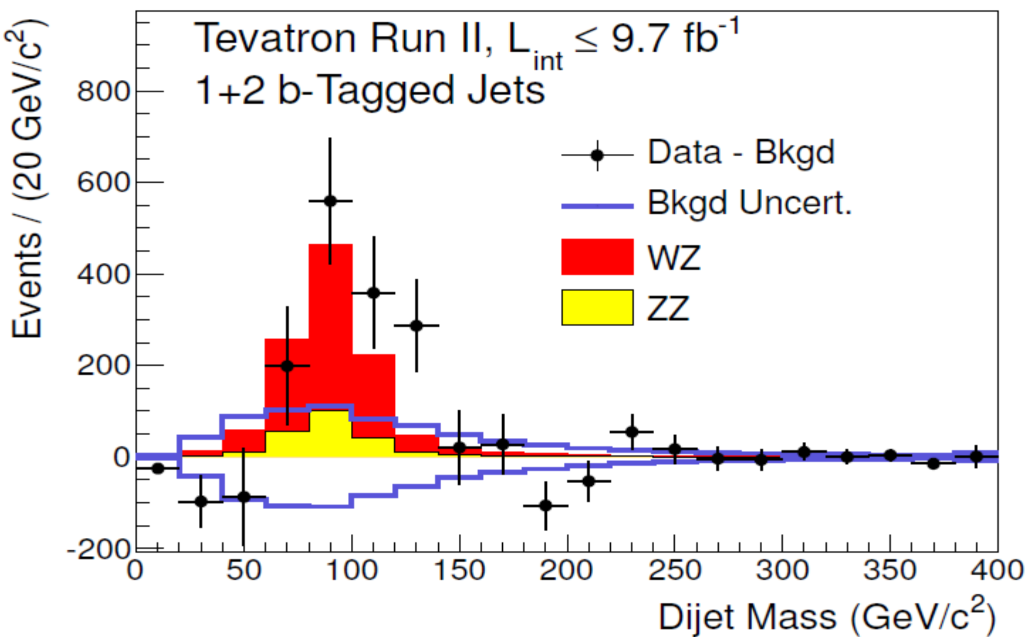
Higgs Search Validation

Validate analyses by measuring SM diboson production

- Diboson VZ→Vb$\bar{b}$ and WW→lνlν topologically similar to VH → Vb$\bar{b}$ and H→WW→lνlν Higgs signals
- Employ same final states and analysis strategy as in Higgs searches with different signal definitions



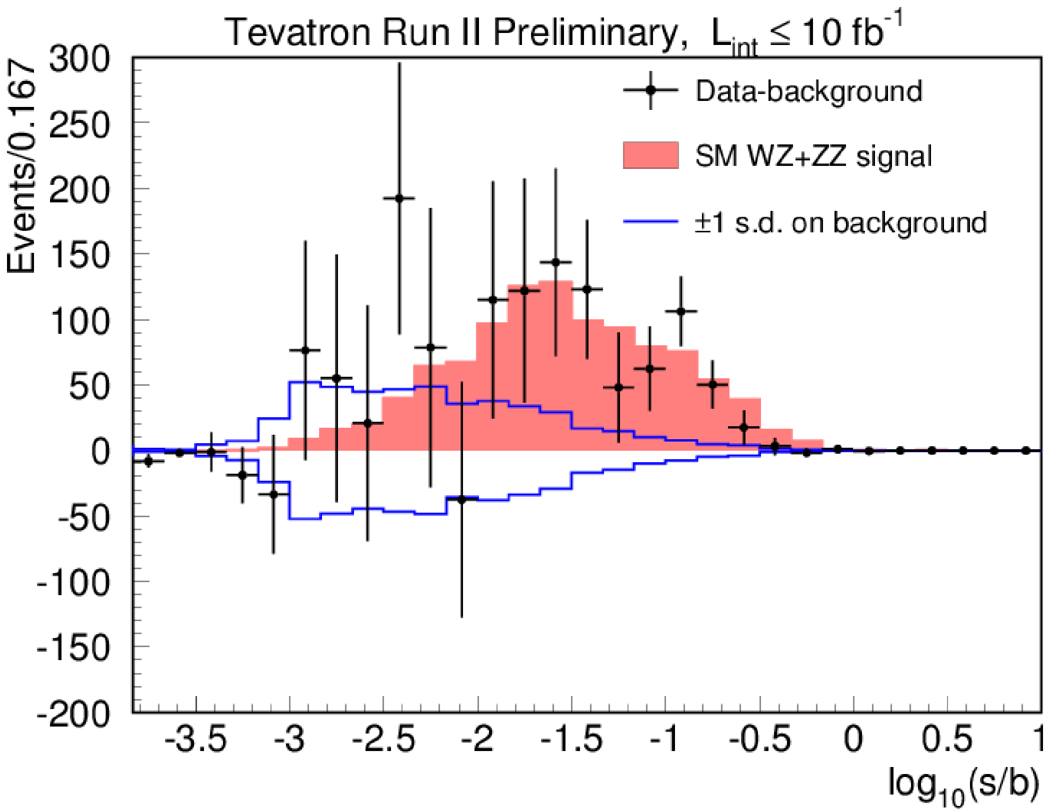




Cross check using VZ→Vb$\bar{b}$

Validate analyses by measuring SM diboson production

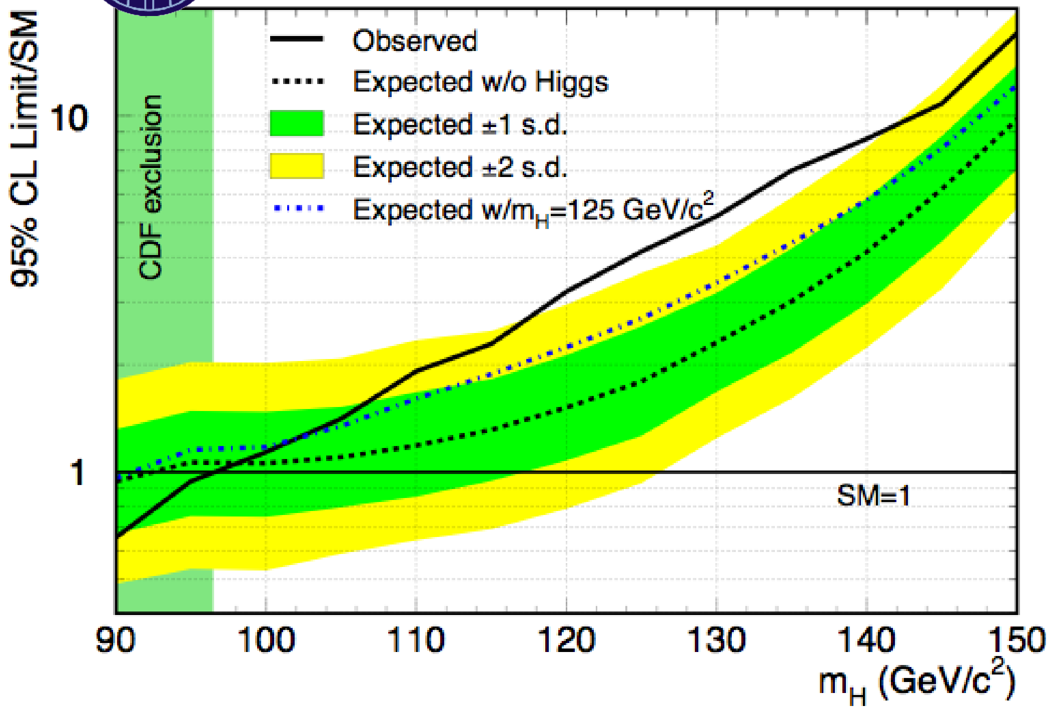
MVA outputs used to extract cross section

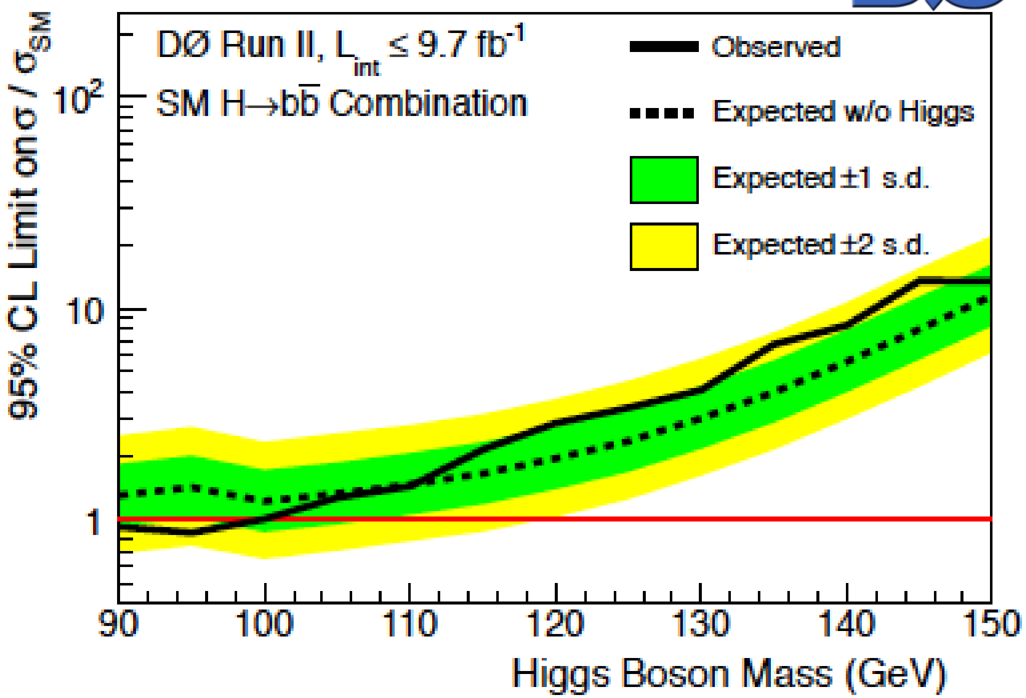


σ_{meas}(WZ+ZZ) = 3.0 ± 0.9 pb

σ_{SM}(WZ+ZZ) = 4.4 ± 0.3 pb

$H \rightarrow b\bar{b}$ Results from CDF and DØ





95% CL SM Higgs limit ratio

@ M_H= 125 GeV

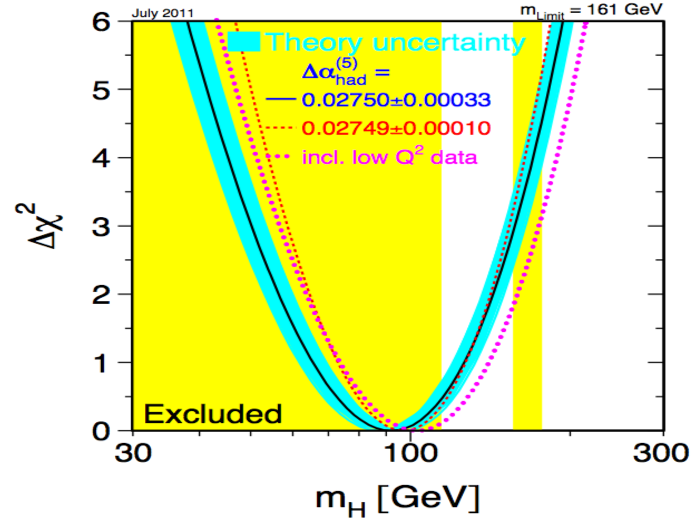
Exp :   Obs :

95% CL SM Higgs limit ratio

@ M_H = 125 GeV

Exp :   2.3   Obs : 3.2

The SM Higgs Boson: Constraints and Evidences



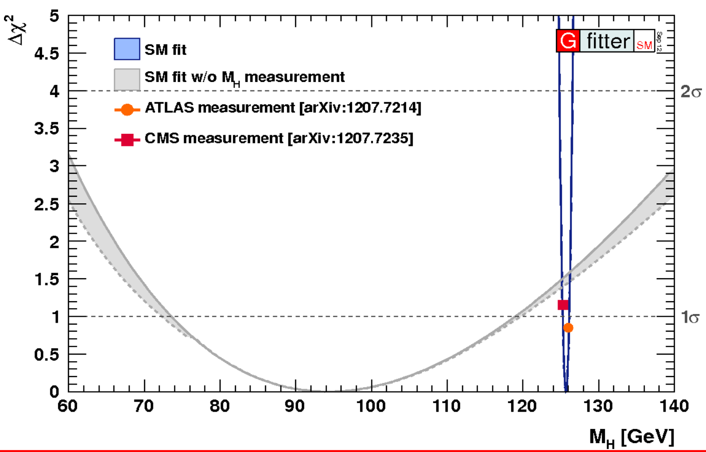
Direct searches at LEP:

M_H > 114.4 GeV @95% CL

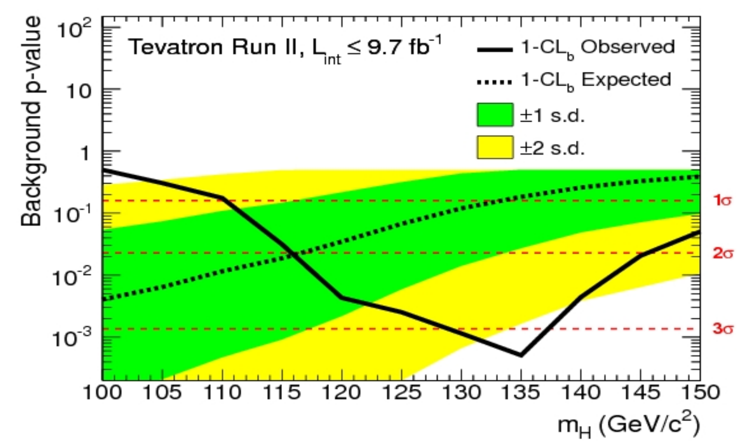
Indirect constraints from EW measurements:

M_H < 152 GeV @95% CL

Direct searches at LHC:



Direct searches at Tevatron:



Observation of a new particle with

M_H ~ 125 GeV & properties consistent

with the SM Higgs Boson

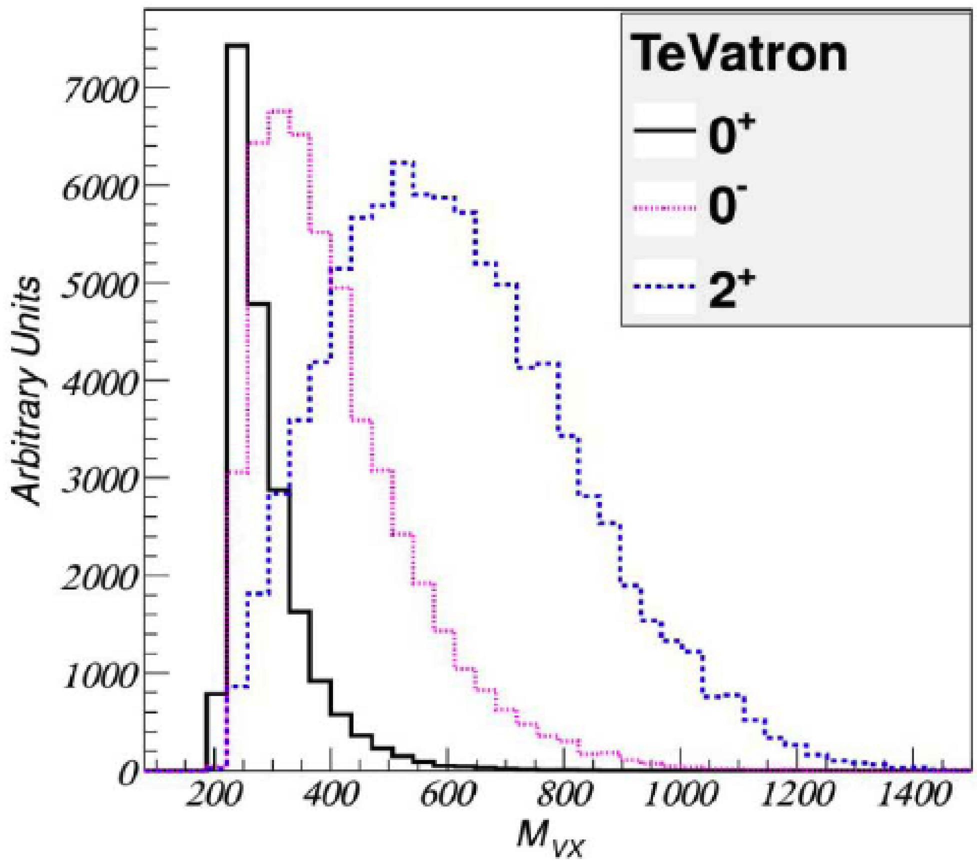
Evidence for a new particle decayed

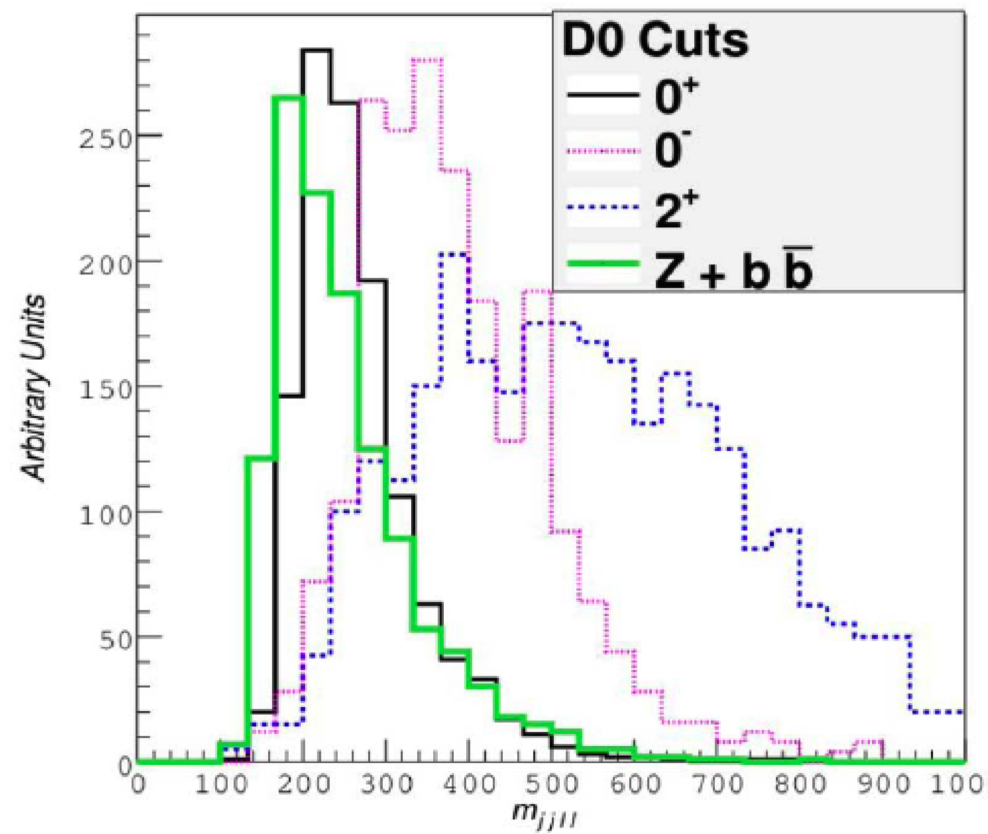
into bb with compatible mass to that

of the new particle at LHC

Spin/Parity Measurement

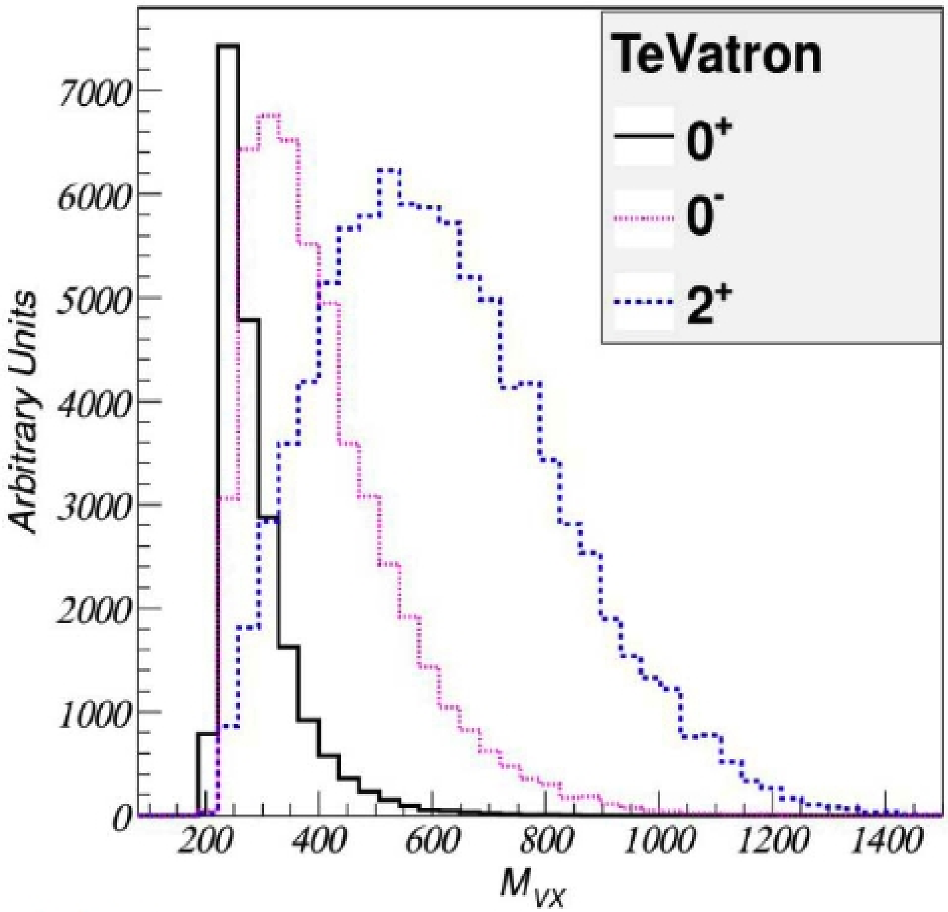
- VH mass good discriminating variable between 0^+, 0^-, 2^+ spin/parity hypotheses (Ellis et al., arxiv:1208.602)
- Planning to do in bb channels (may not be ready for HCP)

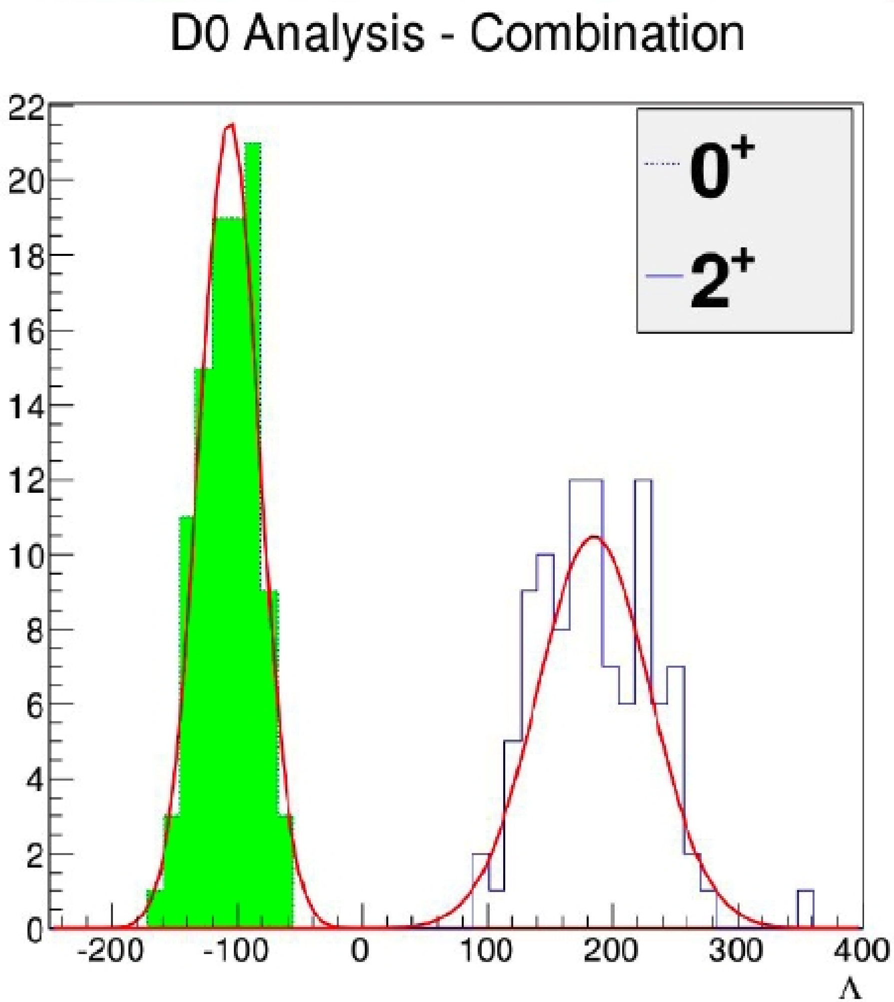




Spin/Parity Measurement

- Expect to (at least) be able to distinguish between 0^+ and 2^+ (assuming backgrounds behave)





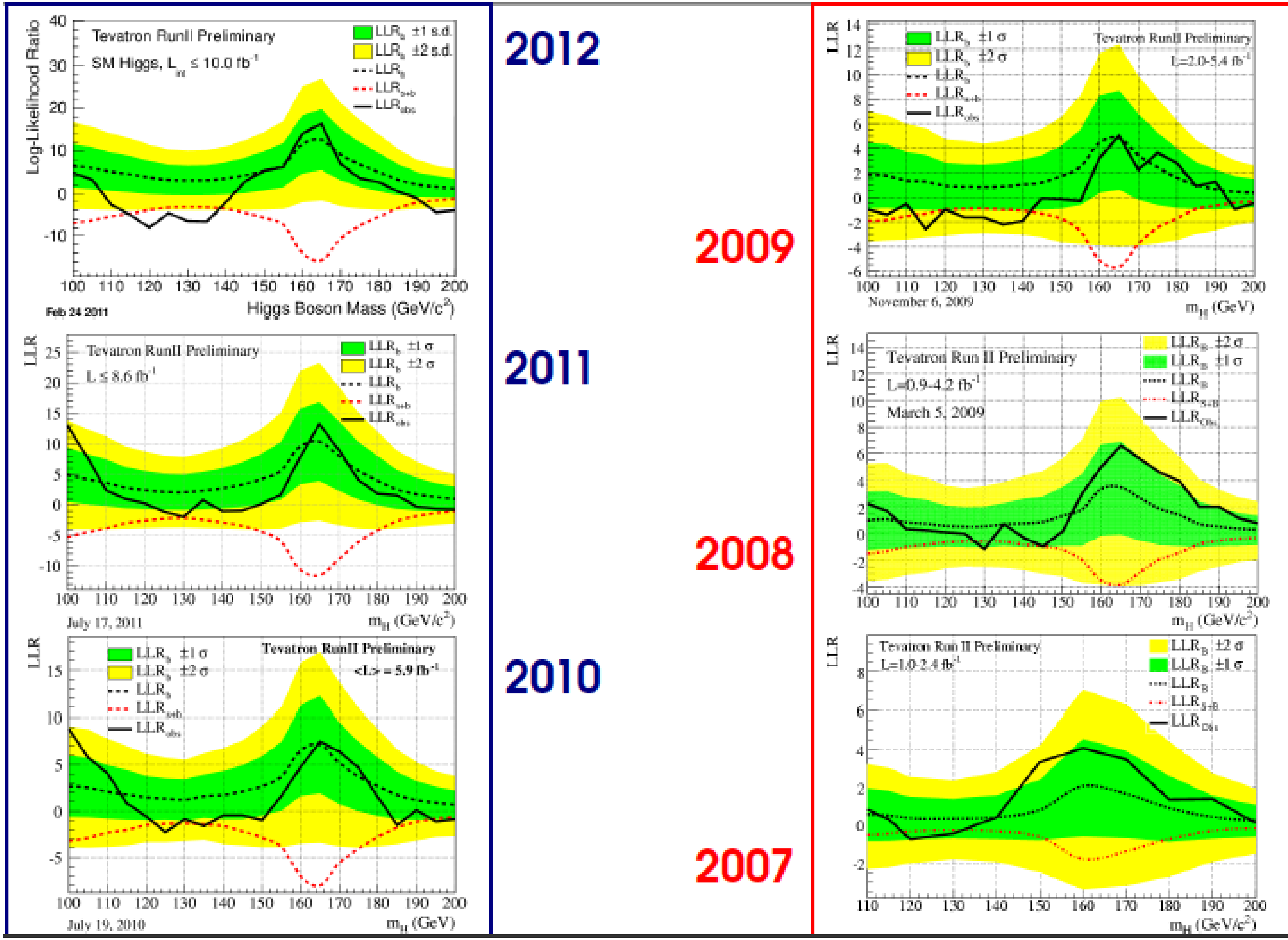
Systematic Uncertainty

Example:

Systematic Uncertainty	Signal (%)	Background (%)
Single Tag		
Jet EC - Jet ER	1.0	2.5
Jet R&T	2.6	2.6
b Tagging	3.2	1.3
Trigger	2	1.9
Lepton Identification	1.1	0.8
Heavy Flavor Fractions	–	4.1
Cross Sections	6	9.8
Luminosity	6.1	5.8
Multijet Normalilzation	–	1.3
Total	9.8	12.3
Double Tag		
Jet EC - Jet ER	0.7	2.3
Jet R&T	3.5	2.6
b Tagging	5.8	3.6
Trigger	2	1.9
Lepton Identification	1.1	1.0
Heavy Flavor Fractions	0	8.0
Cross Sections	6	9.8
Luminosity	6.1	5.8
Multijet Normalilzation	–	1.1
Total	10.9	13.9

Systematic uncertainties can affect both shape and normalization of signal and background.

Historical View



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