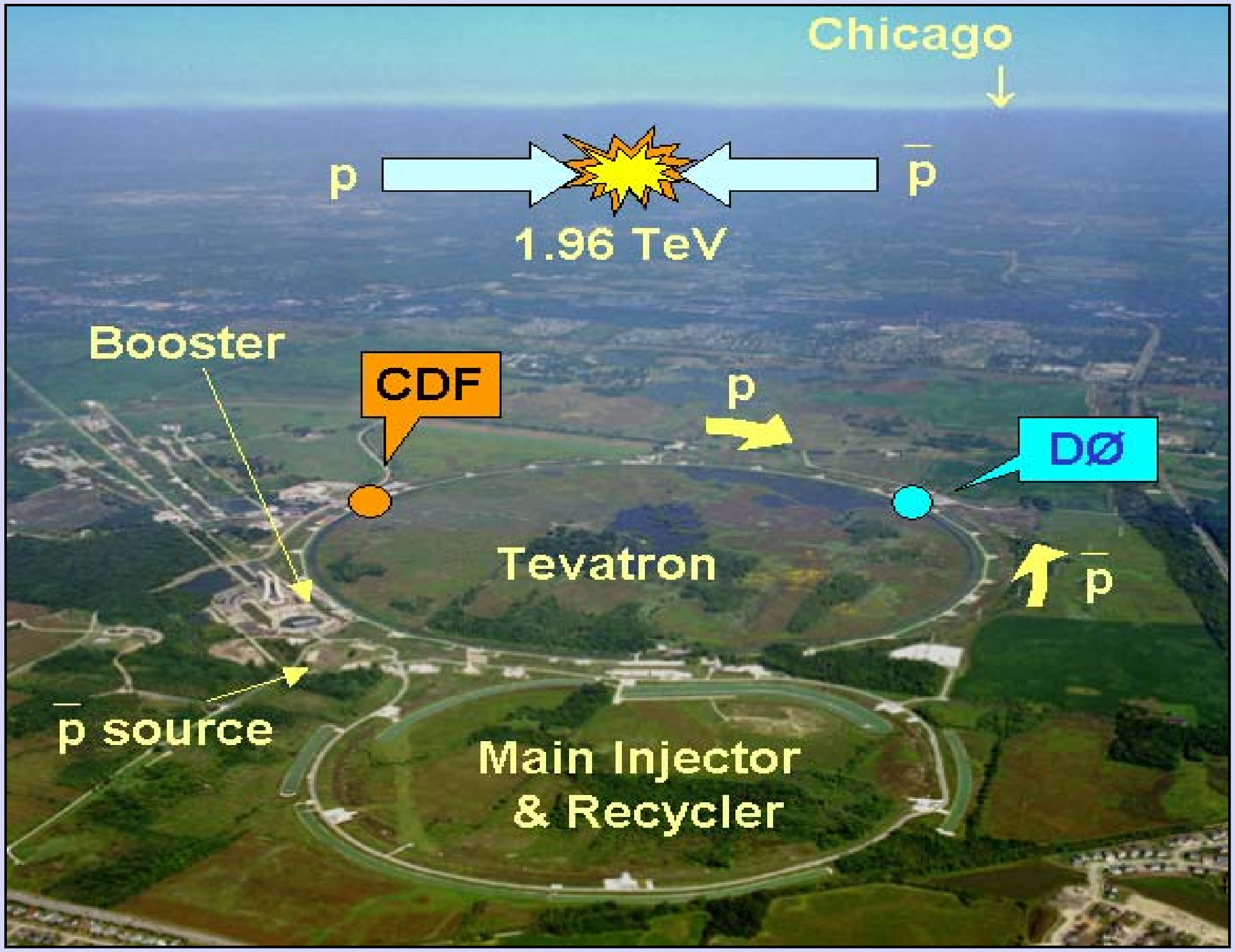
Evidence for the Standard Model Higgs Boson Production at the Tevatron



JLab Seminar

October 3, 2012

Dmitri Denisov, Fermilab

Talk Outline

Tevatron program

The Tevatron

Standard Model Higgs searches

Evidence for Higgs production and decay to b-quarks

Cross checks based on di-boson production

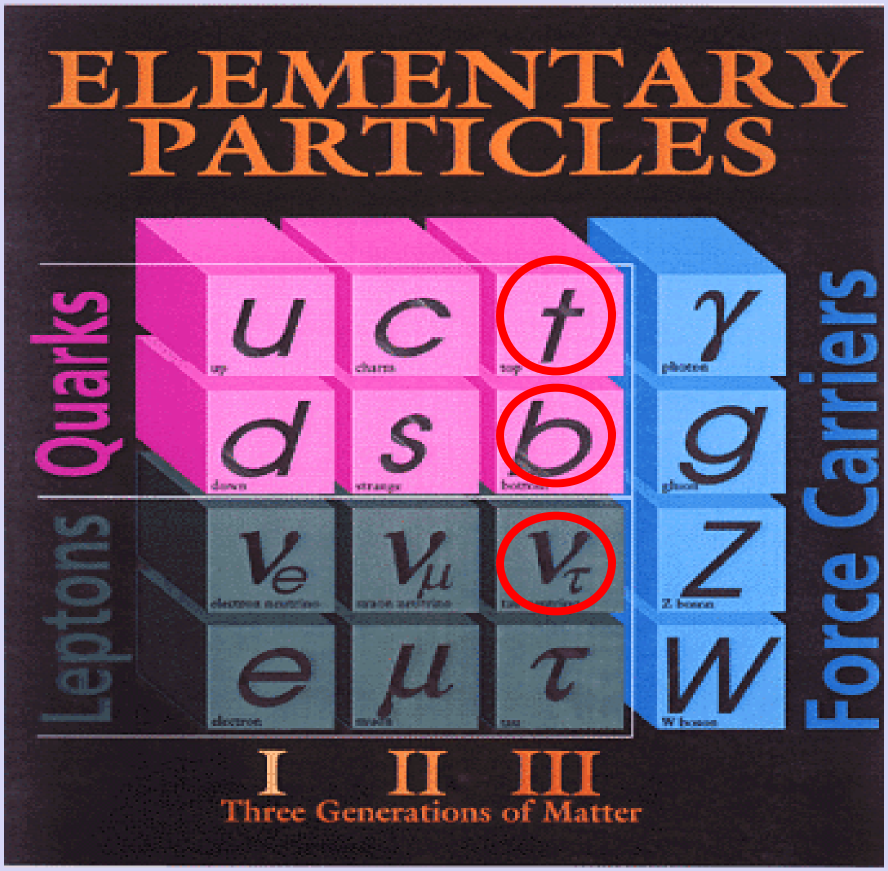
What we know about the Higgs today

Summary

Tevatron Physics Program

Precision tests of the Standard Model
- **Weak bosons, top quark, QCD, B-physics…**

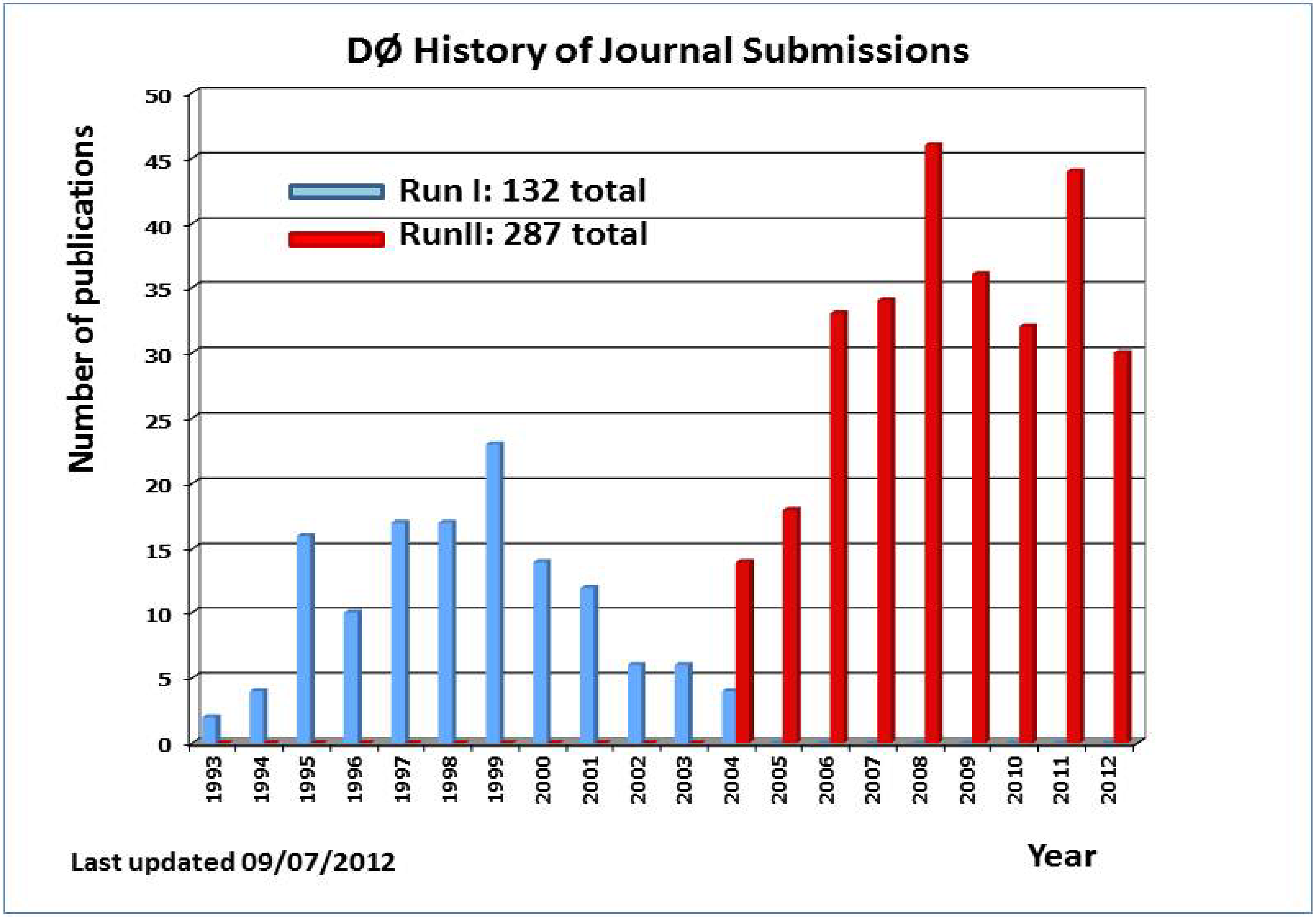
Search for particles and forces beyond those known
- **Higgs, supersymmetry, extra dimensions…**



Fundamental Questions

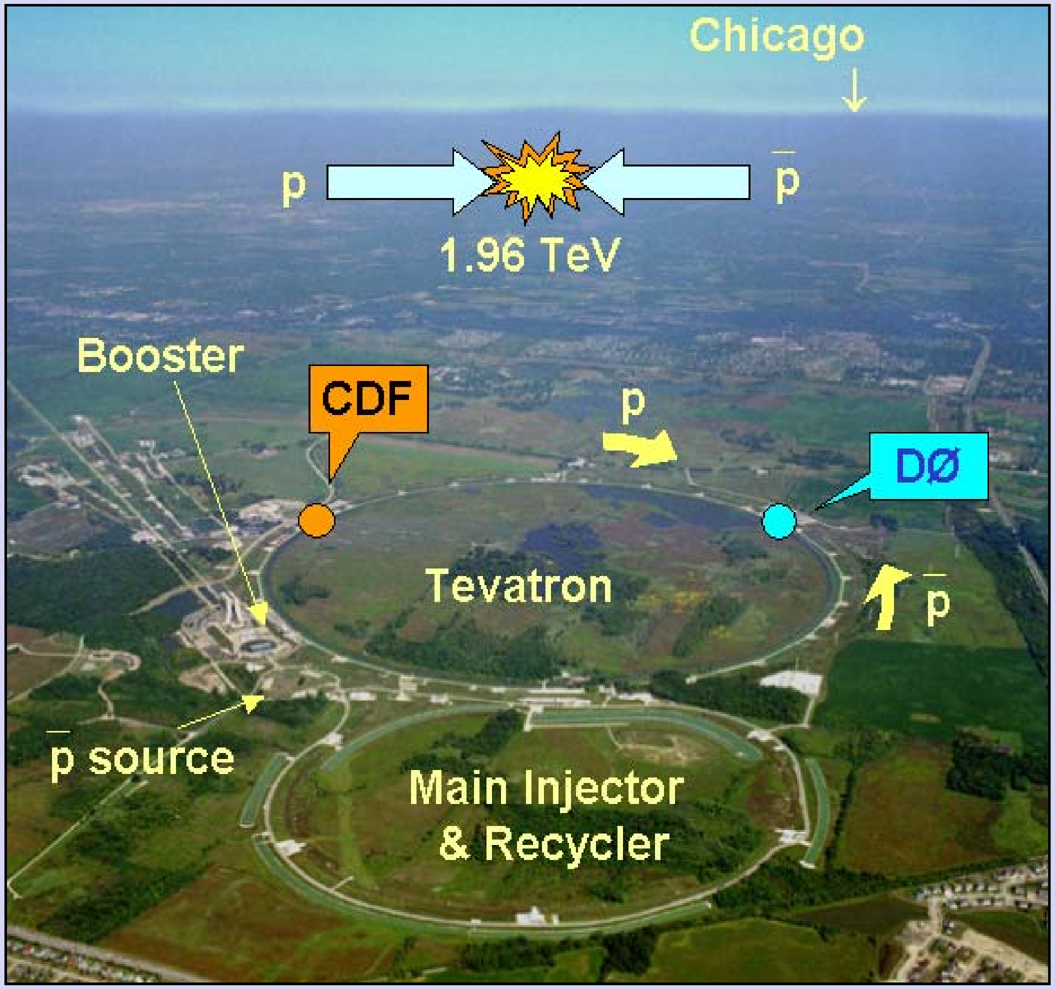
- ✓ **Quark sub-structure?**
- ✓ **Origin of mass? Higgs?**
- ✓ **Matter-antimatter asymmetry?**
- ✓ **What is cosmic dark matter?**
  SUSY?
- ✓ **What is space-time structure?**
  Extra dimensions?…

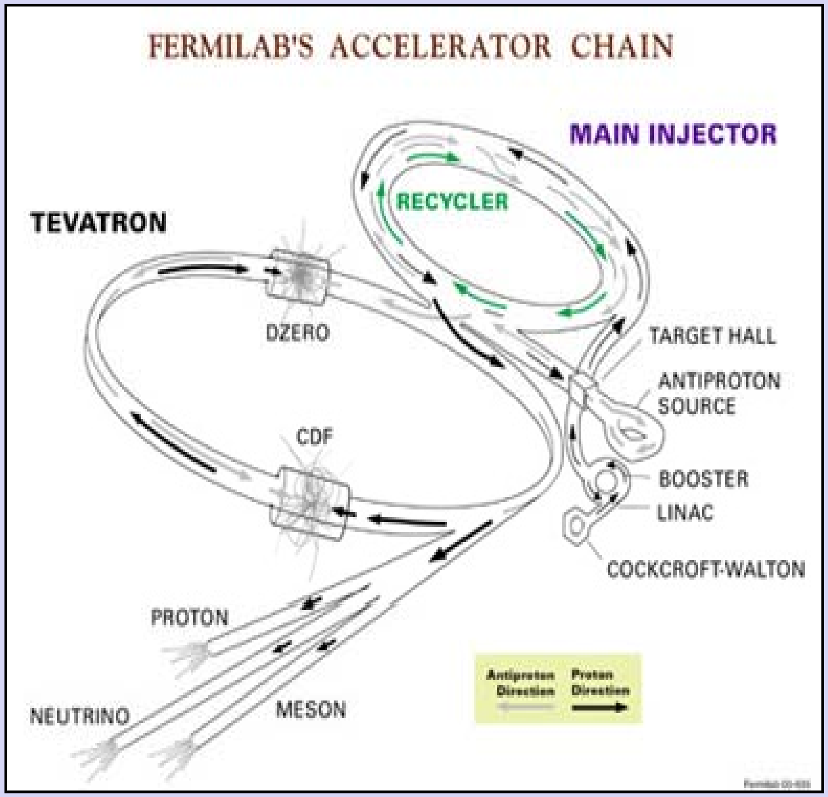
Tevatron Results



- **Over 1000 publications in referenced journals from CDF and DØ**
- **From discoveries of top quark, new mesons and baryons to precision measurements and searches for new phenomena**

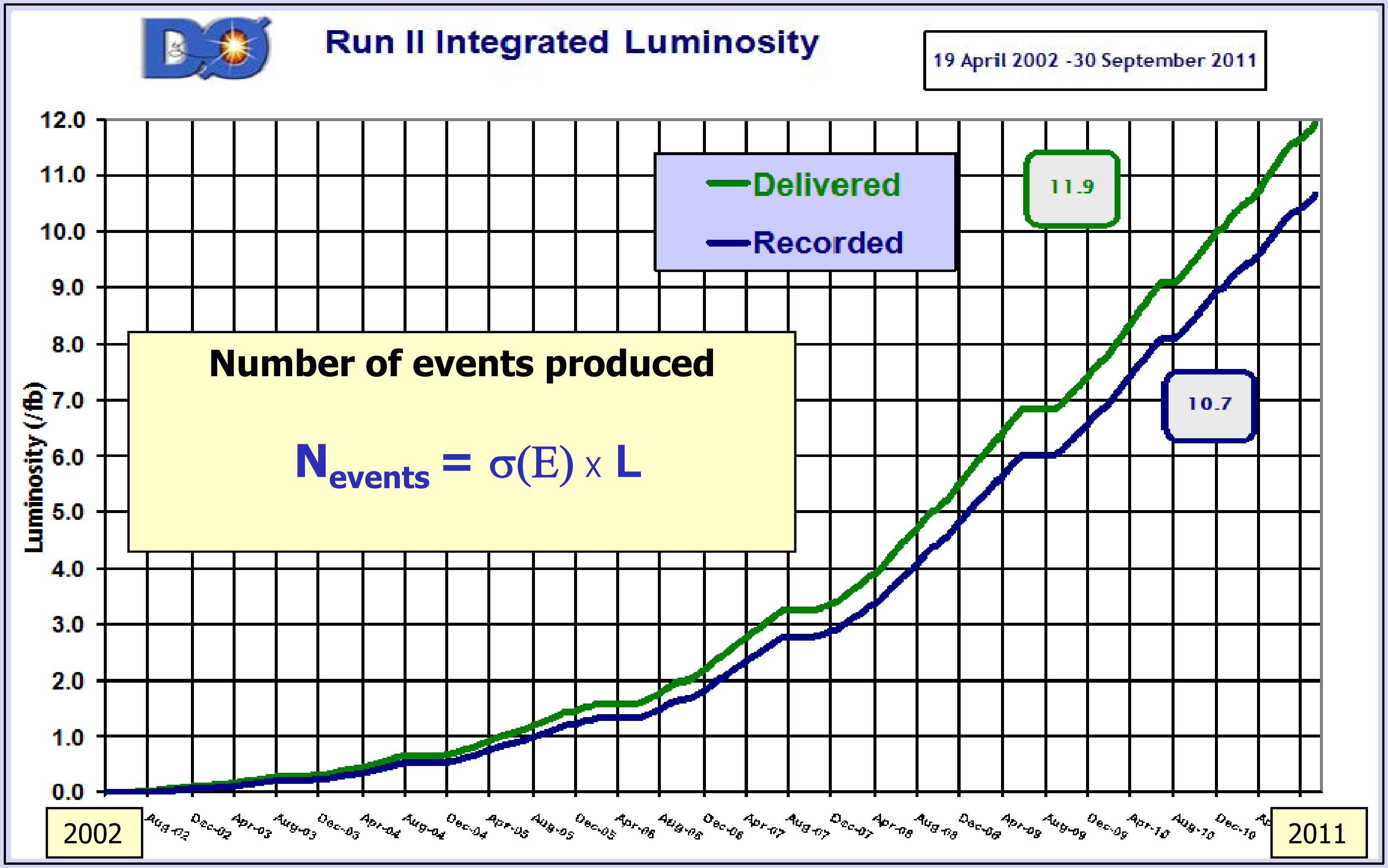
Tevatron: Proton-antiproton Collider





- Chain of six accelerators to get to 1 TeV per beam energy
- Single magnet ring – protons and antiprotons circulate in the opposite directions
- Beam particles wavelength of ~10^{-16} cm
- Objects with mass up to ~2 TeV could be created

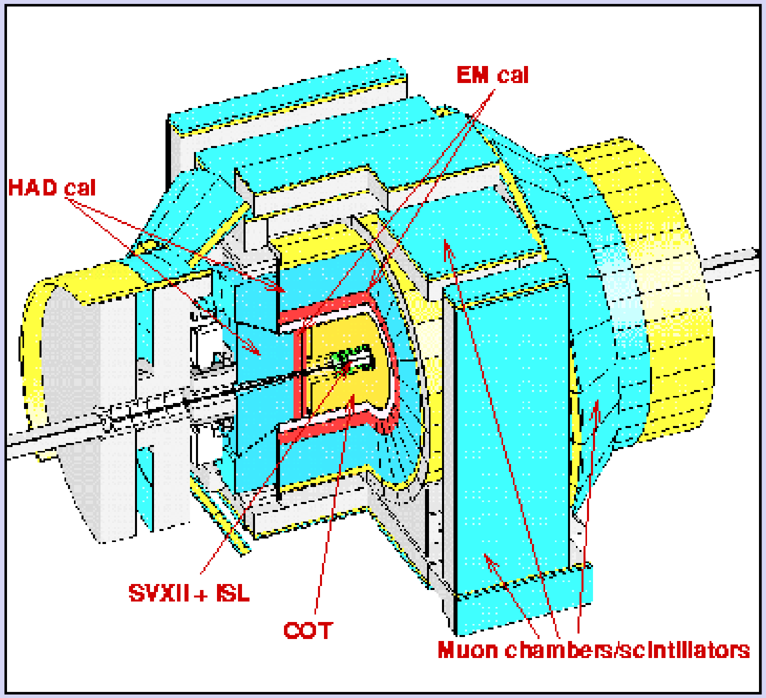
Tevatron Performance



- **Steady increase in luminosity reaching ~12 fb^{-1} per experiment**
  - **~12,000 events for a process with 1 pb cross section**
- **Total number of proton-antiproton collisions is 500 trillions**
- **Tevatron was shut down on September 30, 2011**

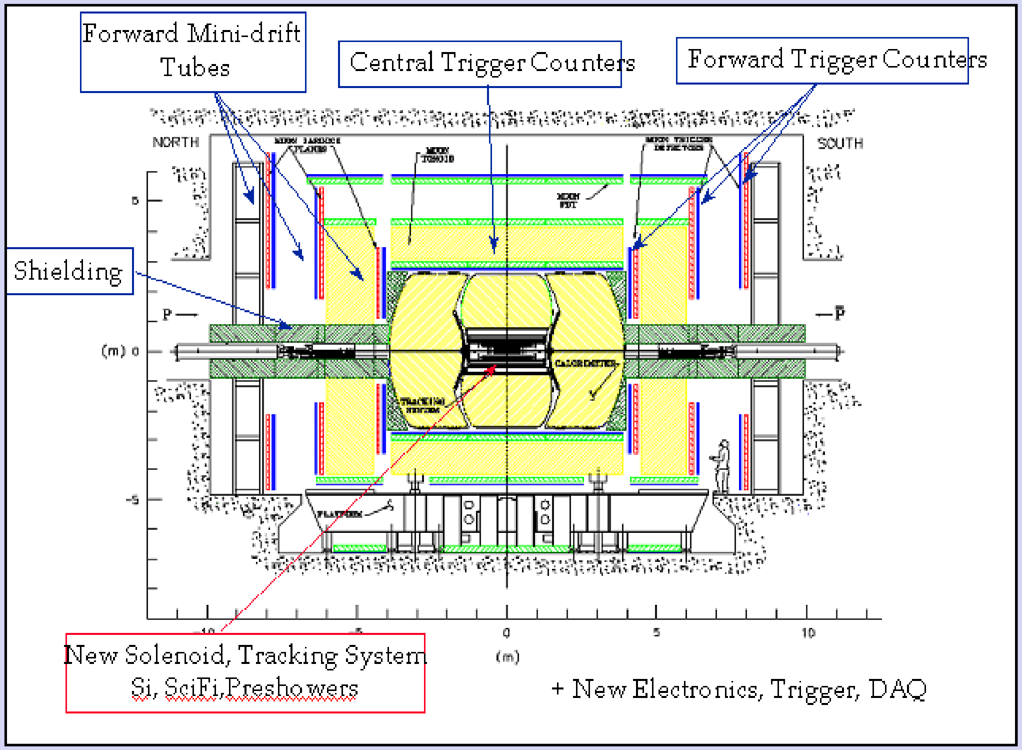
CDF and DØ Detectors

CDF



- Silicon Detector
- Central Drift Chamber
- Calorimetry
- Extended muon coverage
- Fast electronics

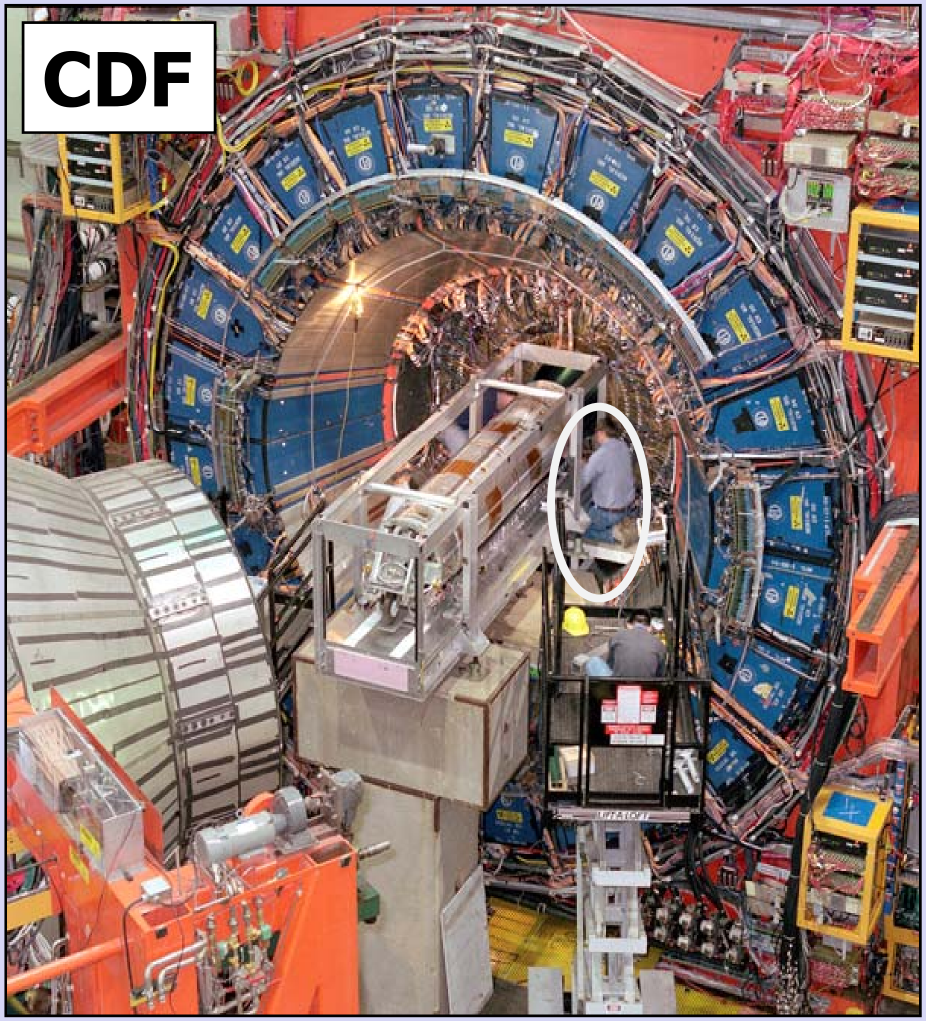
DØ

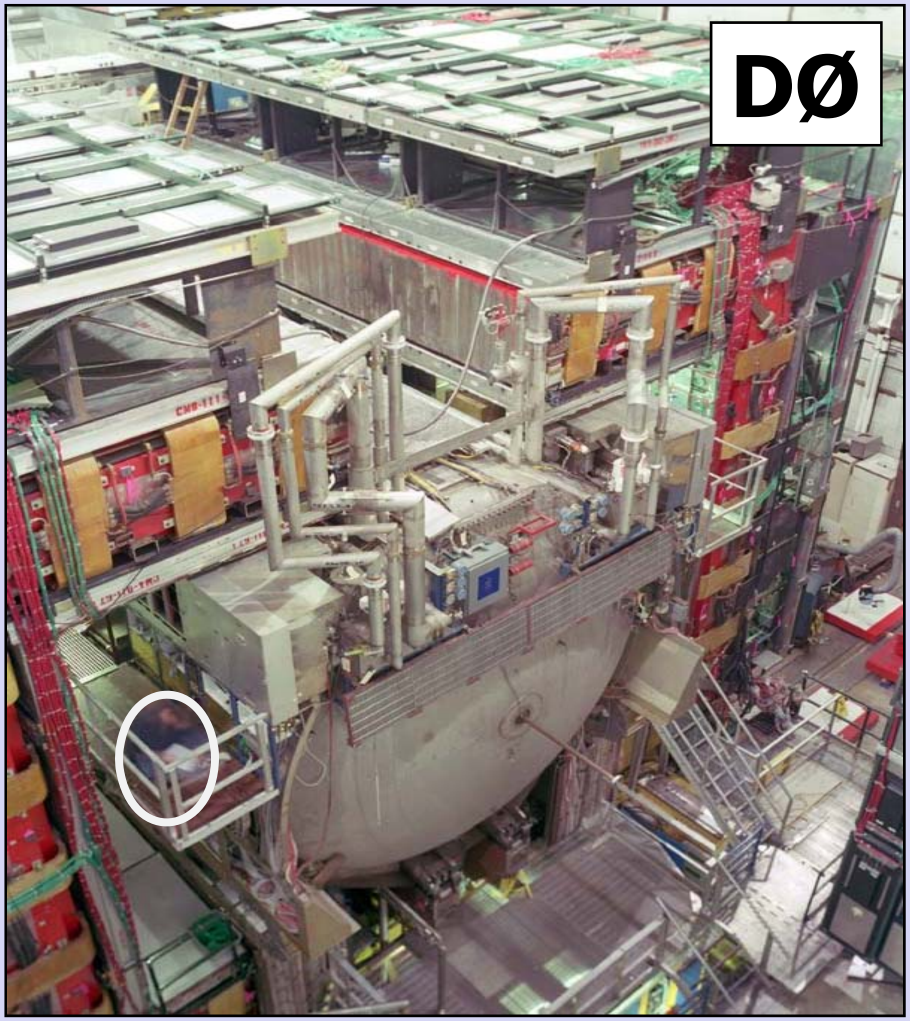


- Silicon Detector
- 2 T solenoid and central fiber tracker
- Large coverage muon system
- Fast electronics

Driven by physics goals detectors are rather "similar":
silicon, central magnetic field, hermetic calorimetry and muon systems

CDF and DØ Detectors

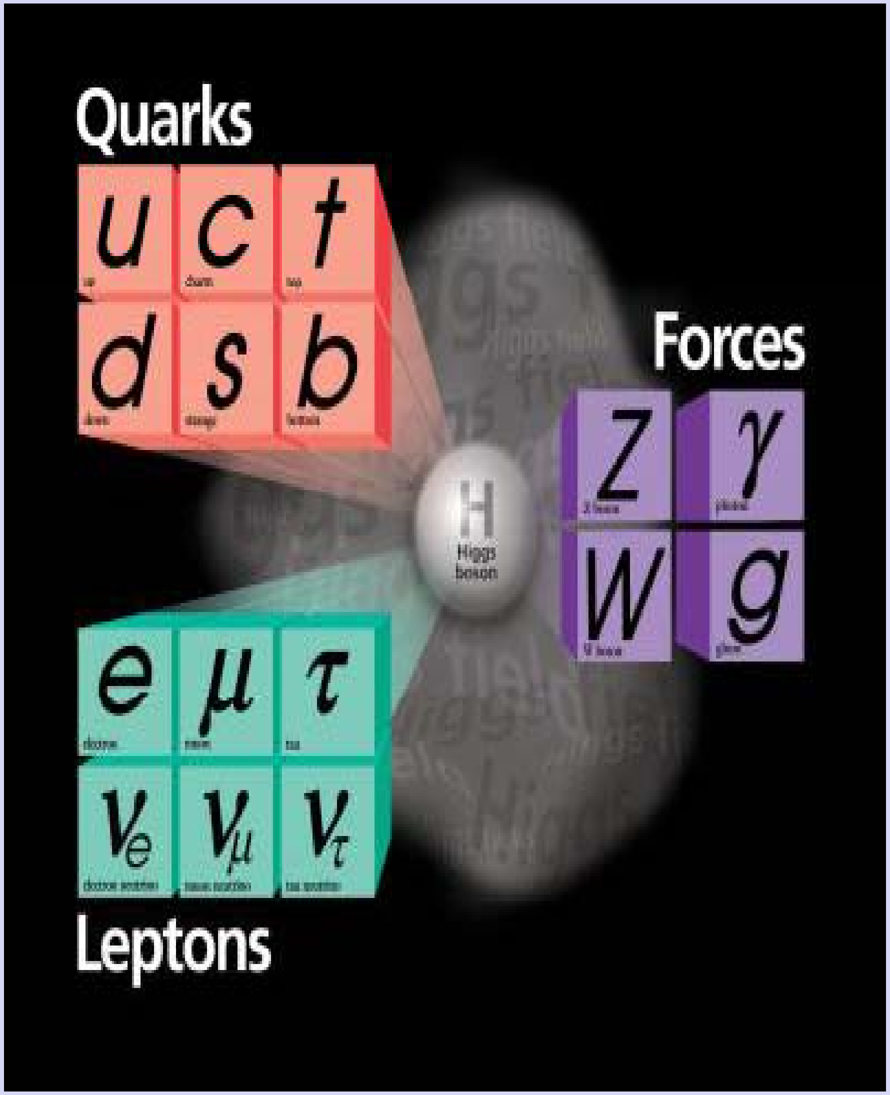




Sizes and complexity of the collider detectors are enormous

Introducing the Higgs

- Mass is a fundamental parameter of any object
  - Inertia, gravitational force, energy
- The fundamental forces of the Standard Model are symmetric (do not depend) upon mass
  - In order to provide particles with masses the symmetry breaking mechanism has been developed
- The "Higgs mechanism" provides mathematical description of mass via "Higgs field"
  - The whole Universe is filled with "Higgs Field"
  - Particles acquire mass by interacting with this field
- The Higgs mechanism predicts existence of new fundamental particle
  - The Higgs particle



It is challenge for experimental physicists to find Higgs particle – the last particle of the Standard Model

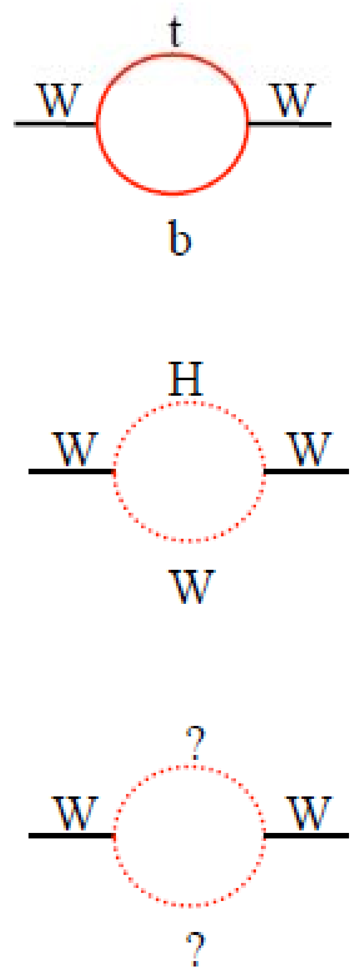
Constrains on the Higgs Mass

- SM Higgs boson mass is a free parameter of the theory
- Constrained indirectly through precision measurements
- In particular, self-energy corrections to the W mass depend on the mass of the top quark and Higgs boson

$\Delta M_W \propto M^2_{top}$

$\Delta M_W \propto \ln M_H$

New Physics

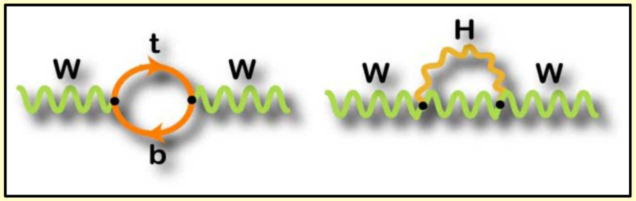


What is the Higgs Mass?

Experimental limits

→ **Direct searches at LEP: M_H >114 GeV at 95% C.L.**

→ **Precision theory fits**

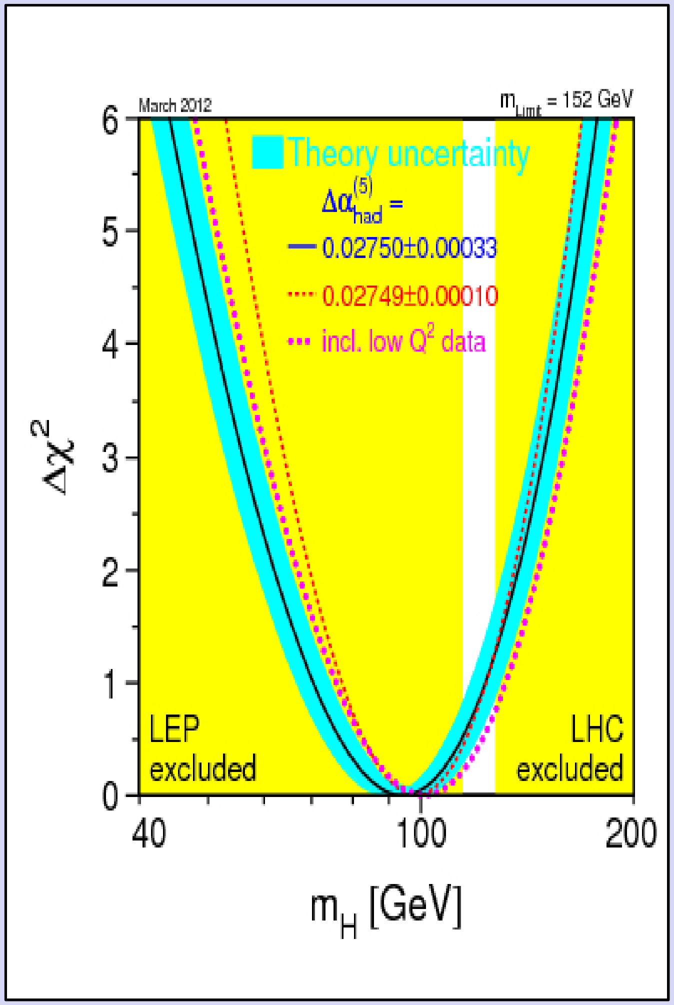


M_H<152 GeV

Light Higgs favored –> in the Tevatron accessible mass range!

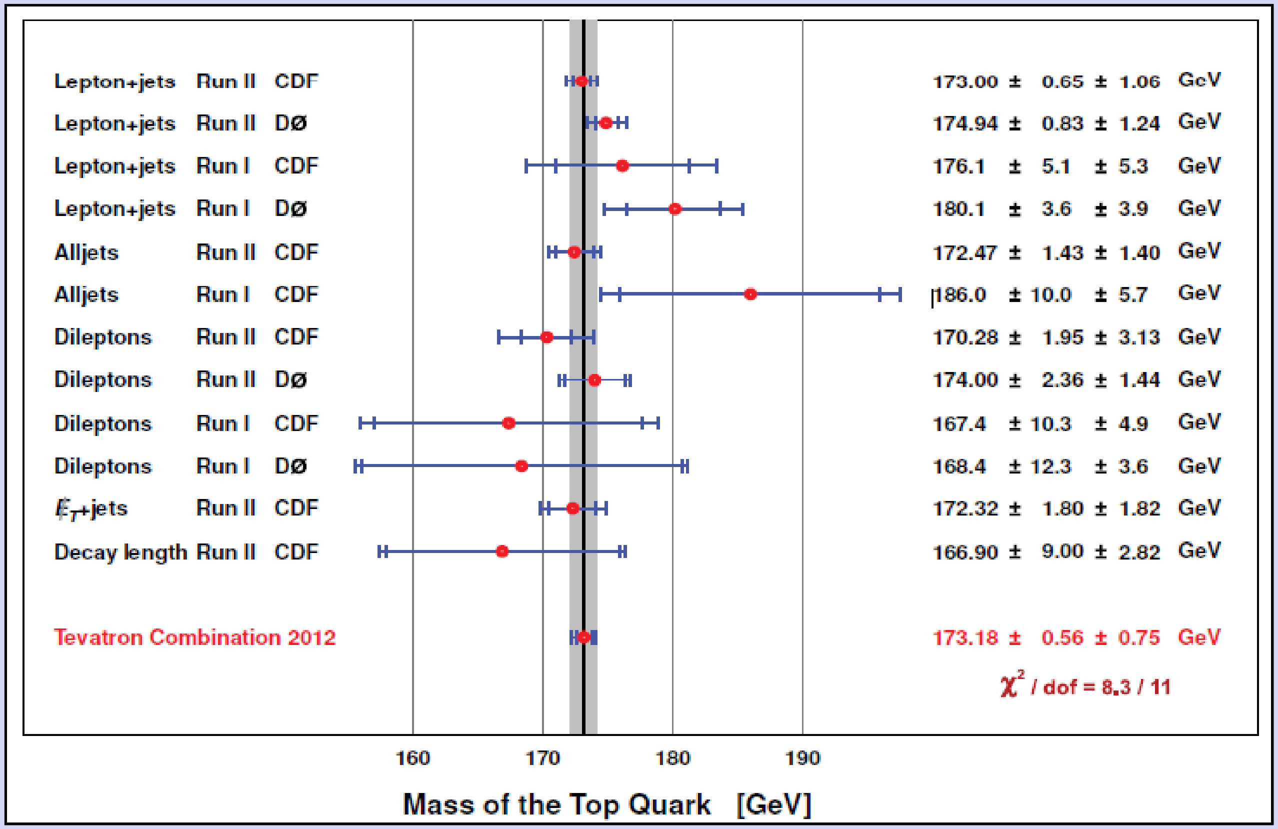
Tevatron provides:

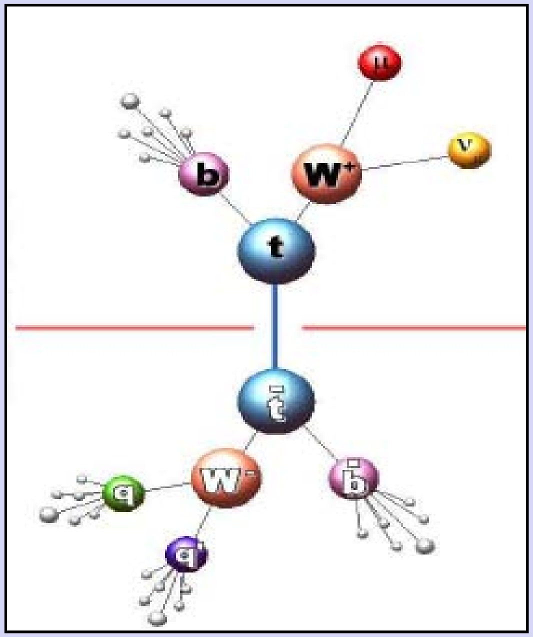
Precision m_{top} and M_w measurements



Top Quark Mass Measurement

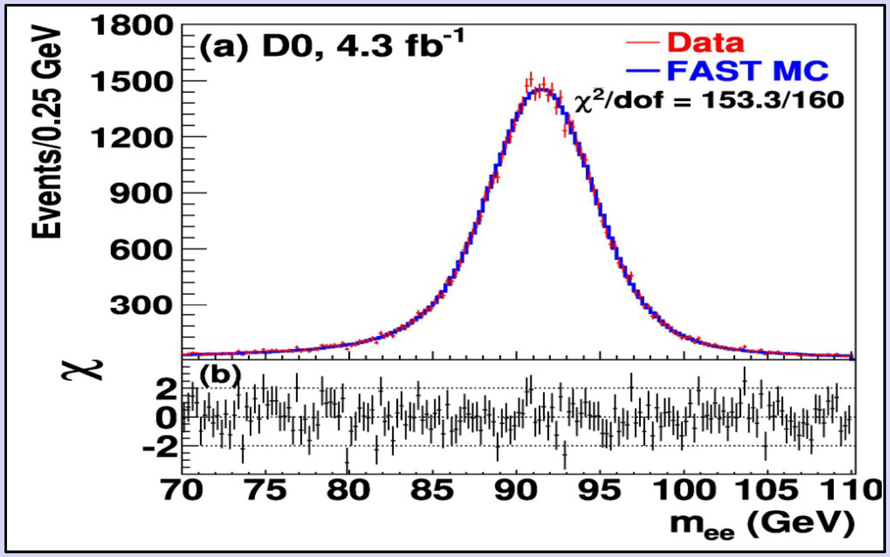
- **Top quark mass is measured using decay products in many different channels**
  - **Thousands of top quark events available for analysis**
- **Lepton+jets channel with two jets coming from W boson is the most precise**

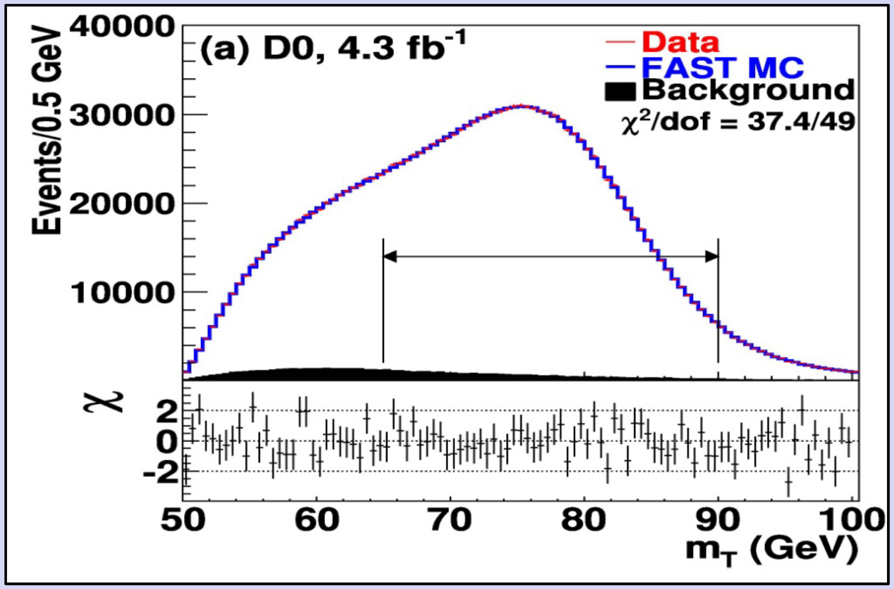


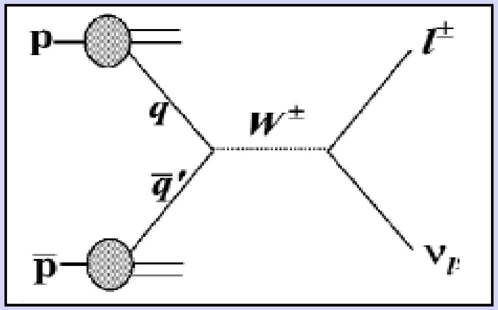


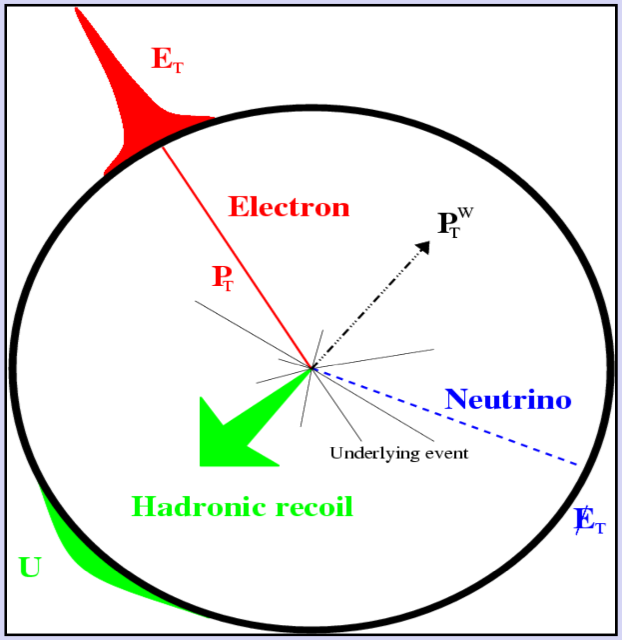
DØ and CDF combined top mass result
m_t = 173.2±0.9 GeV
0.5% accuracy
Best (of any) quark mass measurement!

W Boson Mass Measurement





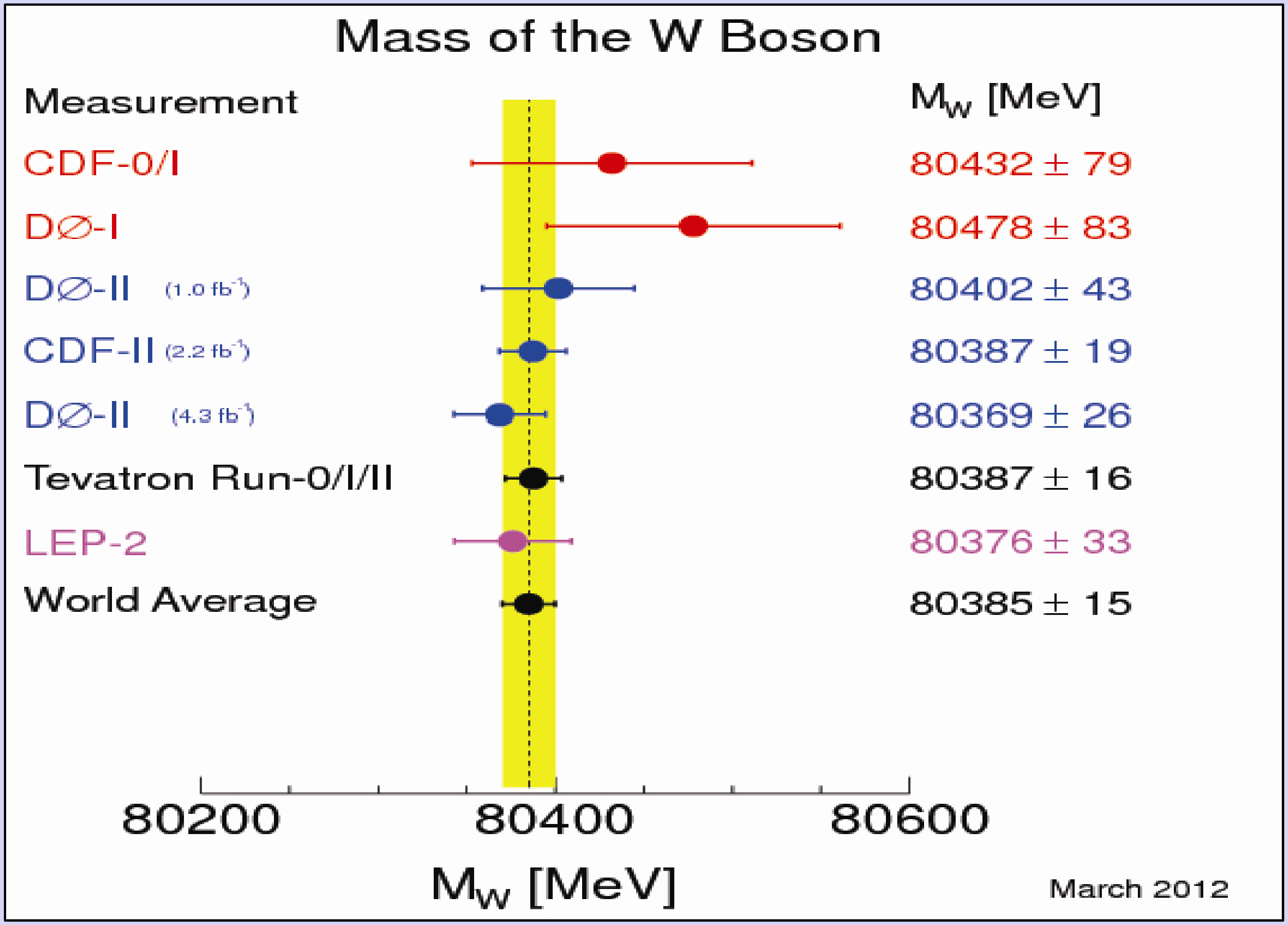




M_W = 80,375 ± 23MeV
0.03% accuracy

- **W boson mass is measured using decay products: electron and neutrino**
- **Calibration of energy scale is performed using Z boson mass**

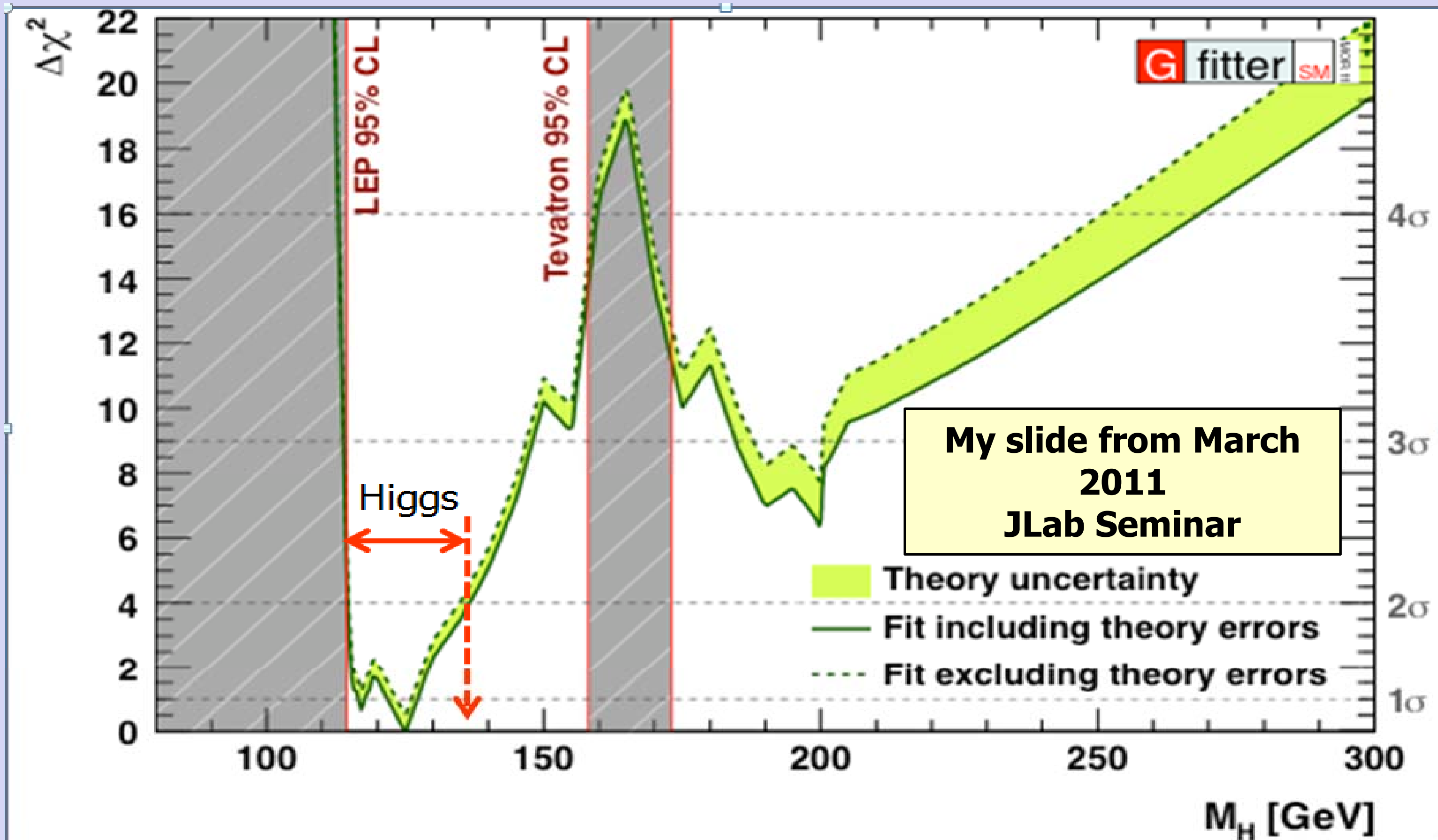
World Average W boson Mass



W mass world average is now
80,385 ± 15 MeV (0.02%)

Higgs Searches Status: 1.5 Years Ago

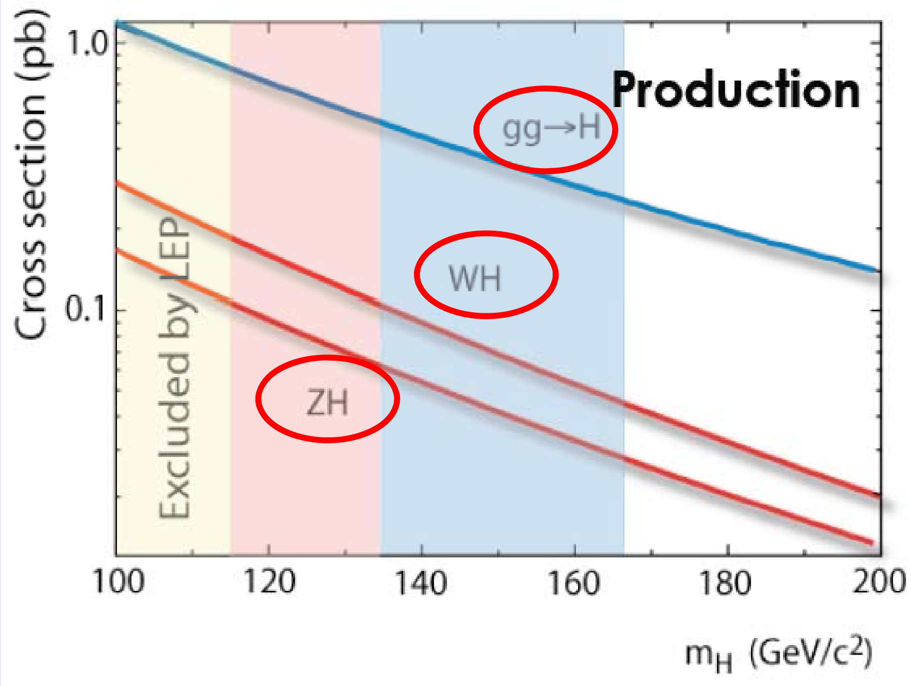
- **Higgs masses ~160-175 GeV are excluded by the Tevatron**
- **Precision measurements point to Higgs masses below ~150 GeV**
- **LEP results indicate Higgs mass is above ~114 GeV**
- **LHC just starting Higgs searches**

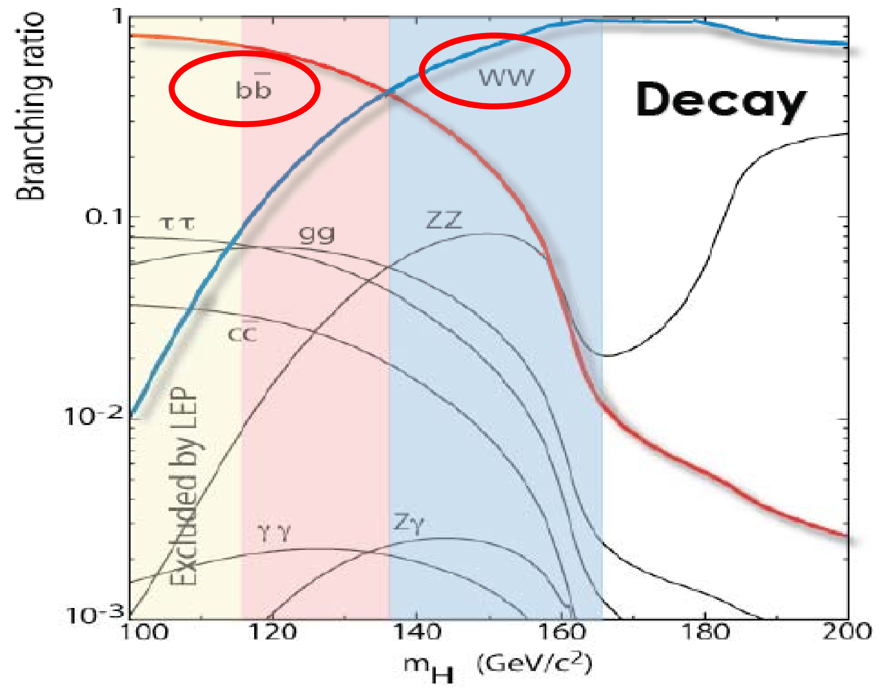


My slide from March 2011 JLab Seminar

- **Higgs mass was limited to 114 to 137 GeV window at 95% CL**
- **Most probable value was… 125 GeV**
- **The mass was known with high precision, but not if the Higgs exists**

Higgs Production and Decays at the Tevatron





Production cross sections
→ in the 1 pb range for gg → H
→ in the 0.1 pb range for associated vector boson production

Decays
→ bb for M_H < 135 GeV
→ WW for M_H > 135 GeV

Search strategy:
M_H <135 GeV associated production and bb decay W(Z)H → $l\nu(ll/\nu\nu)$ bb
Main backgrounds: top, Wbb, Zbb
M_H >135 GeV gg → H production with decay to WW
Main background: electroweak WW production

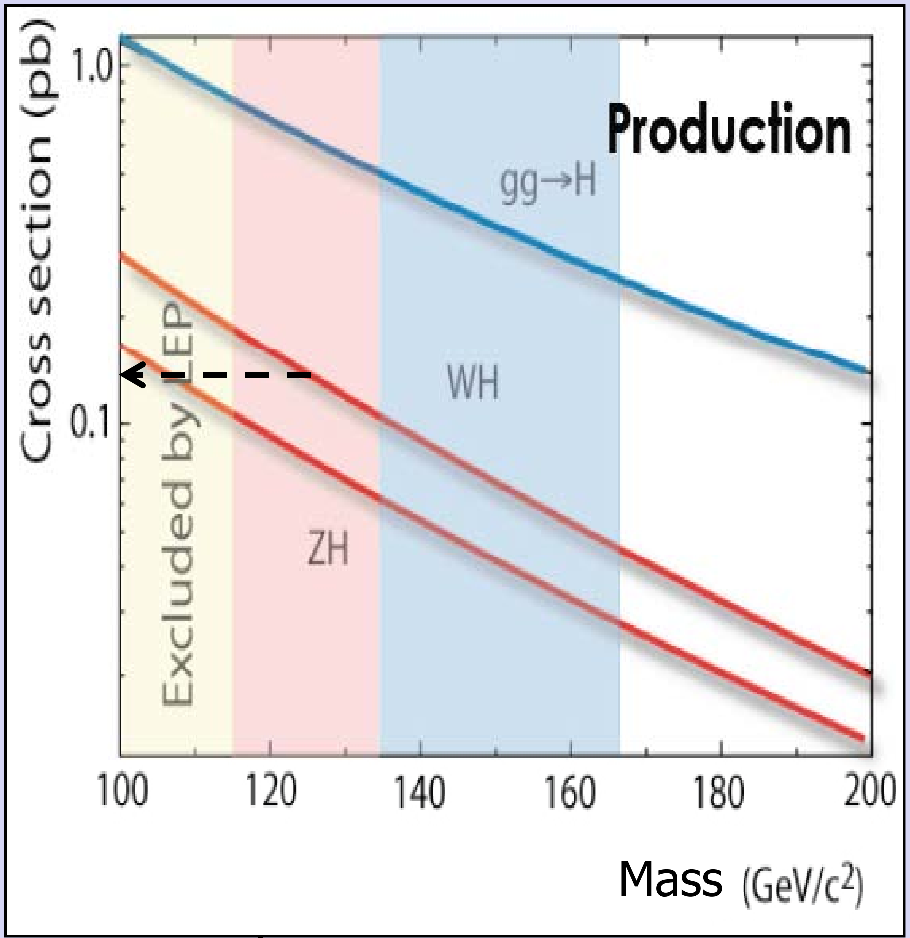
Experimental Challenges

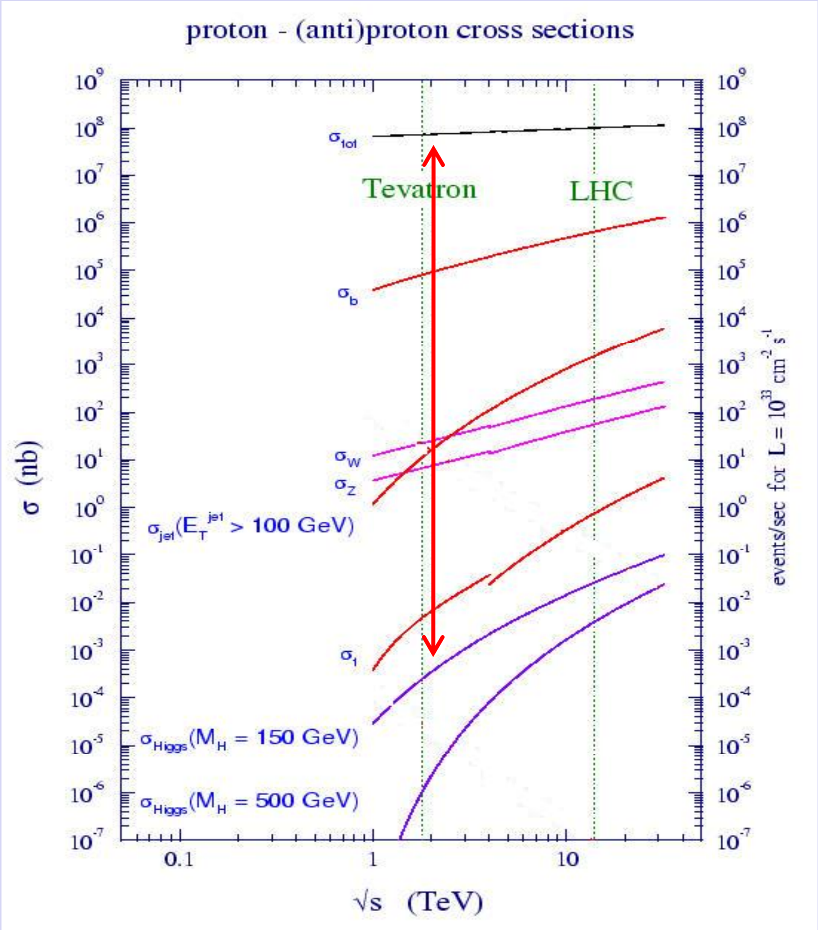
- Probability of producing Higgs is low

$$N_{events} = L \times \sigma$$

- To increase number of produced Higgs bosons we need high luminosity

- Backgrounds from Standard Model processes are high
  - Only one out of ~10^{12} collisions might contain Higgs particle
- Separation of backgrounds is one of the main challenges in hunt for the Higgs

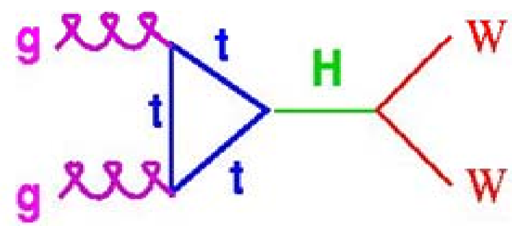




Higgs Searches at the Tevatron

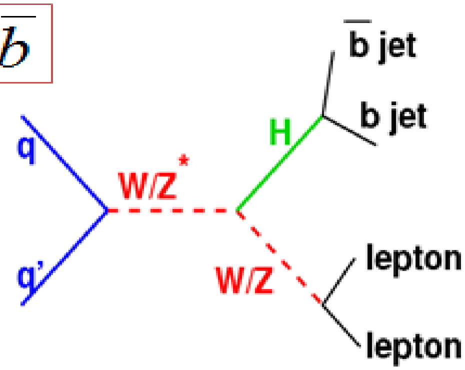
"High" mass (m_H > 135 GeV) dominant decay:

$H \to WW^{(*)}$ $\quad gg \to H \to WW \to \ell\nu\ell'\nu'$



Low mass (m_H < 135 GeV) dominant decay:

$H \to b\bar{b}$



$WH \to \ell\nu b\bar{b}$

$ZH \to \ell^+\ell^- b\bar{b}$

$ZH \to \nu\bar{\nu} b\bar{b}$

use associated production modes to get better S/B

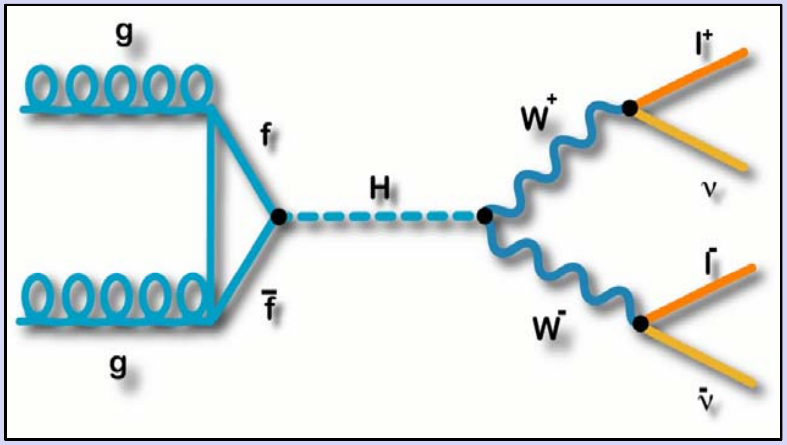
These are the main search channels, but there is an extensive program of measurements in other channels to extend the Higgs sensitivity

Number of Events

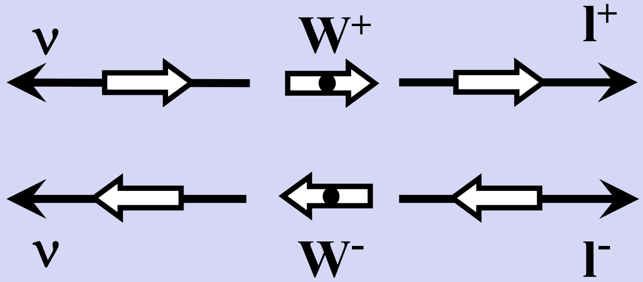
Higgs Mass	WH→lνbb	ZH→ννbb	ZH→llbb	H→WW→lνlν
120 GeV	~500	~240	~80	~260
135 GeV	~200	~100	~40	~520
150 GeV	~60	~40	~20	~640

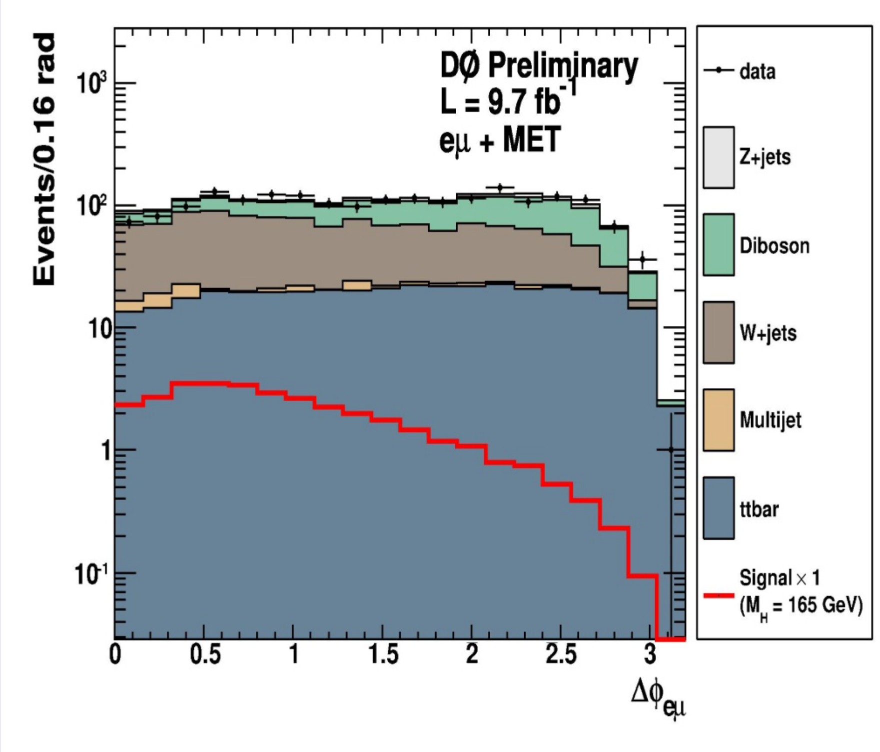
- **Expected number of events available for selection to CDF+DØ with the full Tevatron Run II data set of 10 fb^{-1}**
- **Reconstruction/selection/tagging efficiencies**
  - **~ 10% in H→bb channels**
  - **~ 25% in H→WW channels**

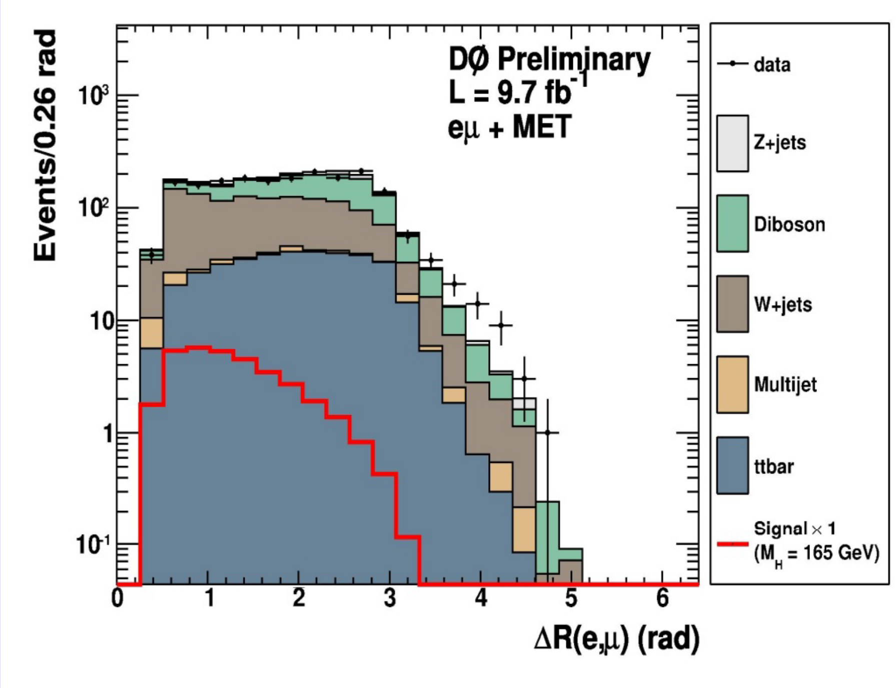
Higgs Search: H → WW → lνlν (M_H >130 GeV)



Search strategy:
→ 2 high P_t leptons and missing E_t
→ WW pair comes from spin 0 Higgs: leptons prefer to point in the same direction



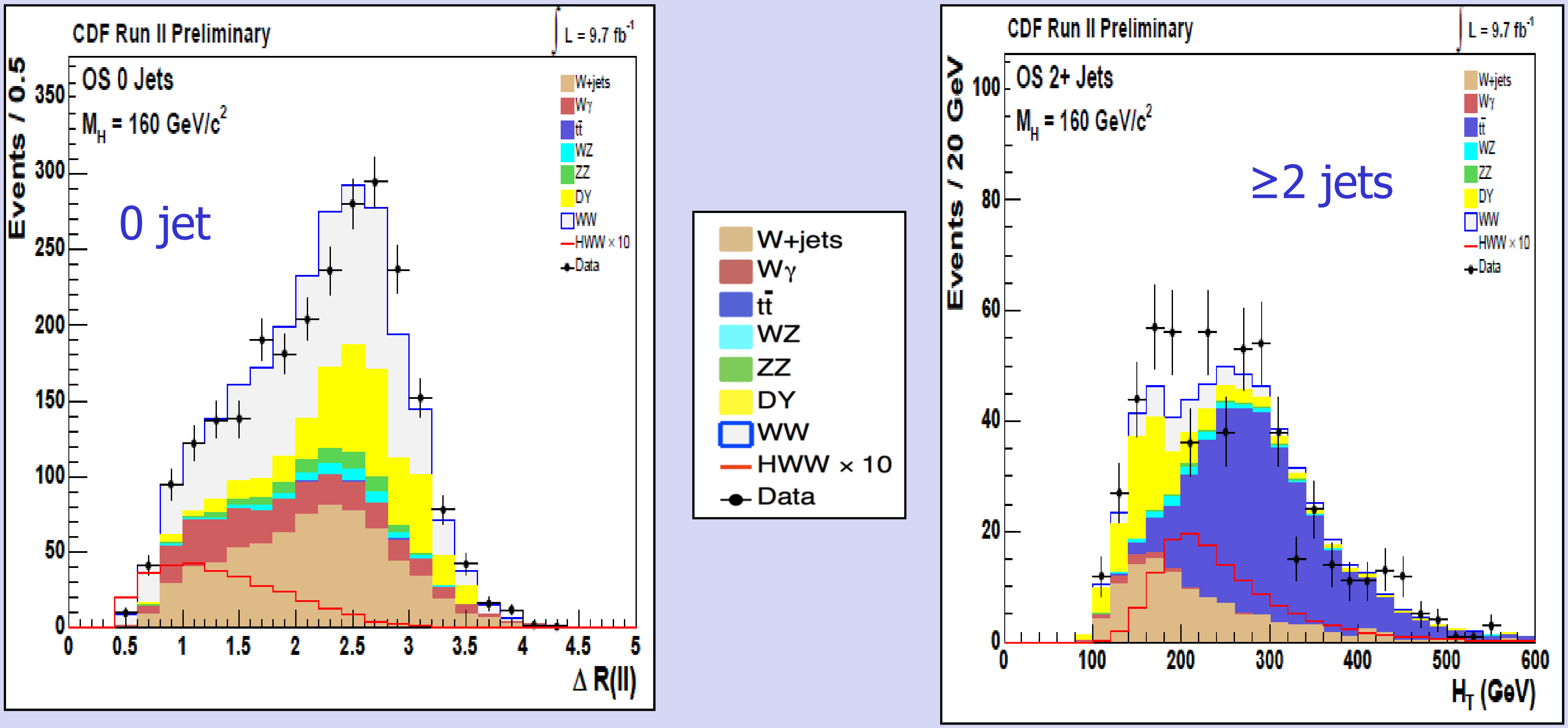




Separating Signal from Backgrounds

Separate events using different final states to improve signal to background ratio

Depending upon number of jets different backgrounds could be estimated from data



Final Discriminants

Multivariate Analyses (neural networks, boosted decision trees, etc.) are used to provide a gain sensitivity beyond that obtained from optimized, cut-based analysis

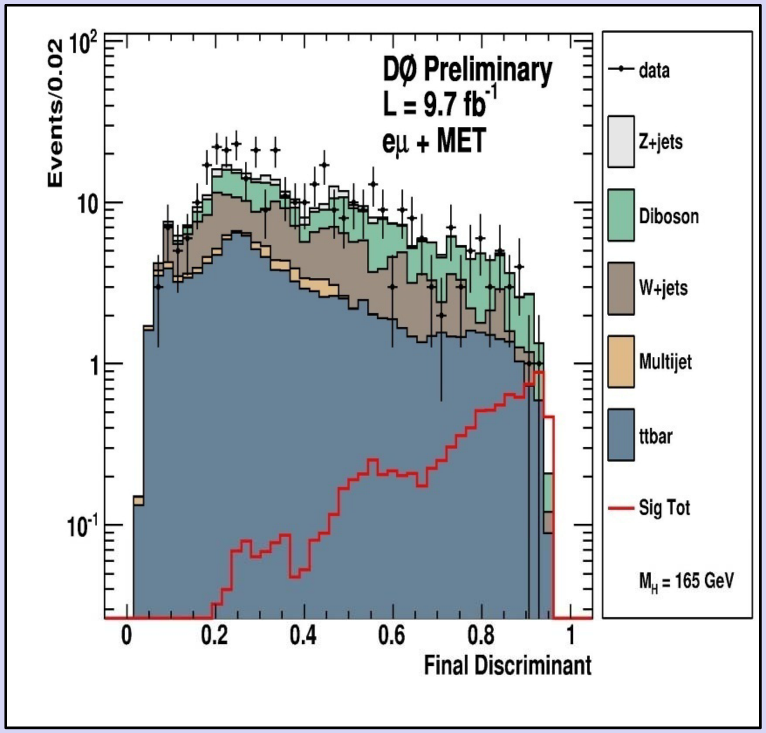
Backgrounds

Signal

Training

Event Kinematics → **MVA (NN, BDT…)** → Final Discriminant

Training ➔correlate multiple input variables



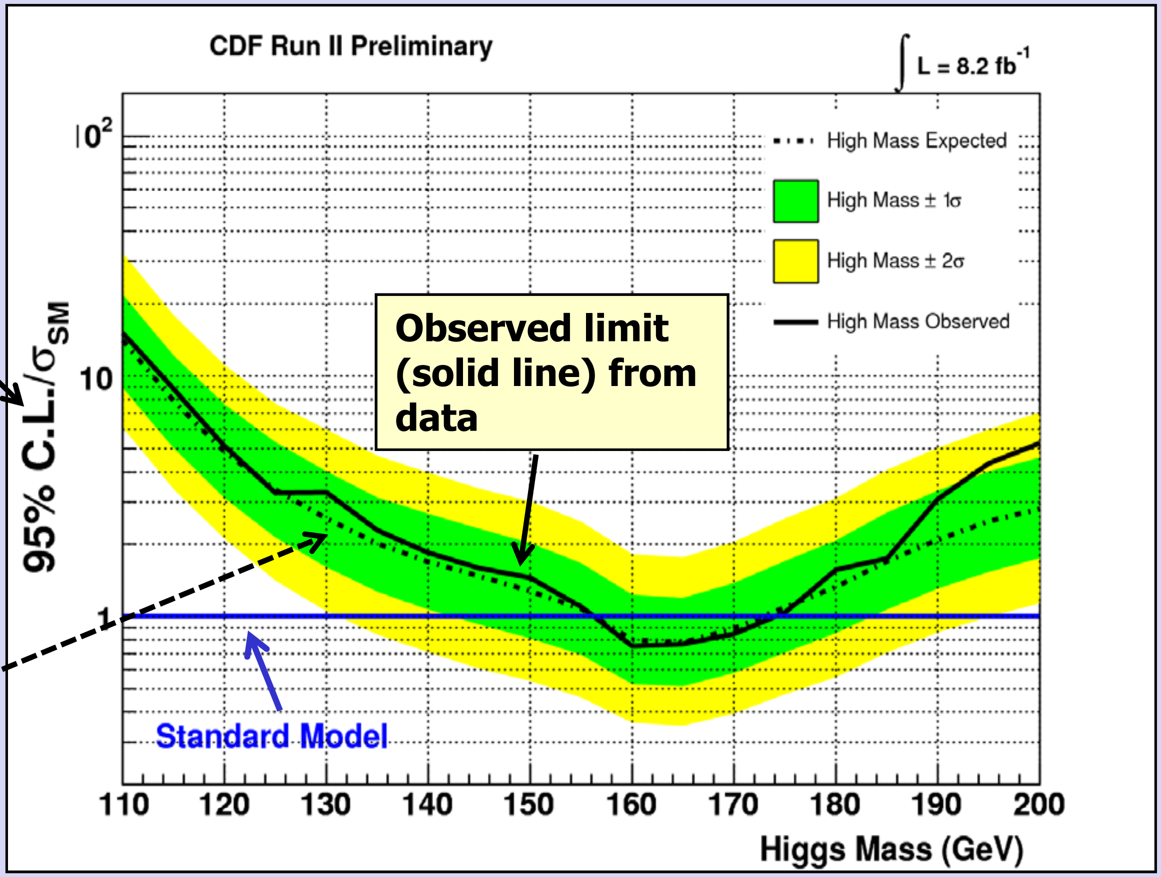
Even for a single channel reach S/B ~1 in high discriminant region!

Limits Settings

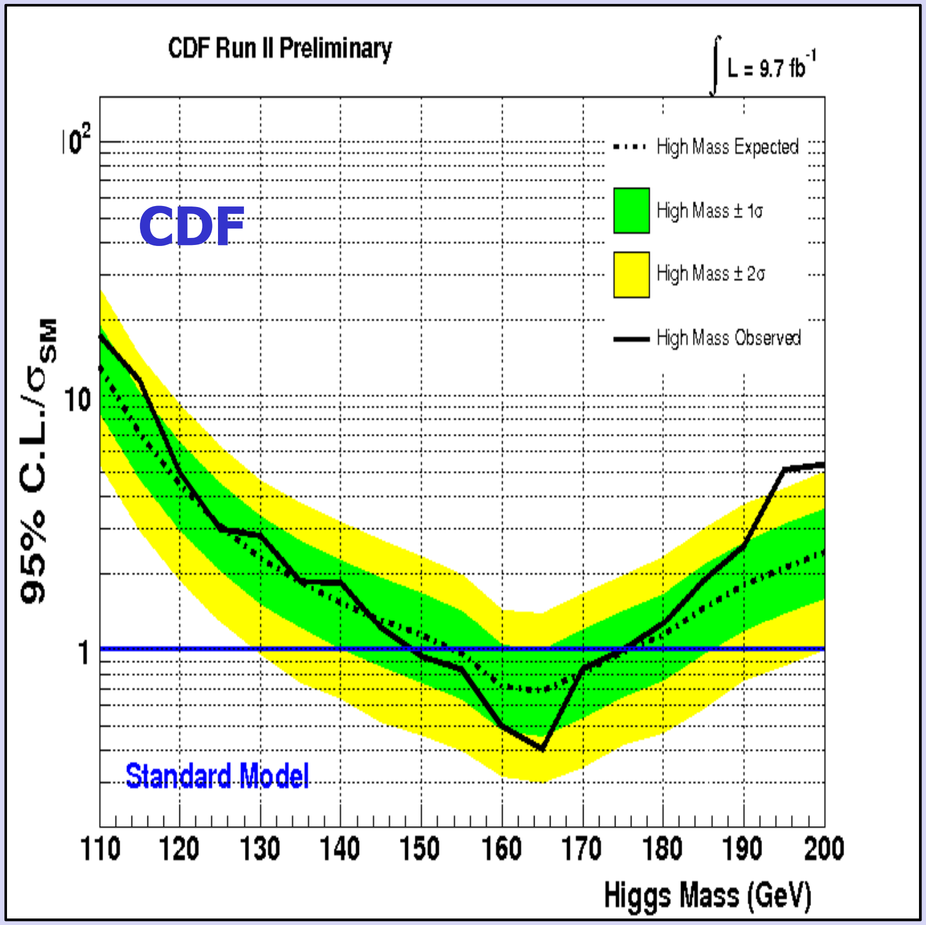
- We combine searches in multiple channels of different Higgs production and decay modes, cross section limits are given as a ratio to Standard Model predictions
- Limits are derived using Bayesian and CLs methods
  - Both produce the same results

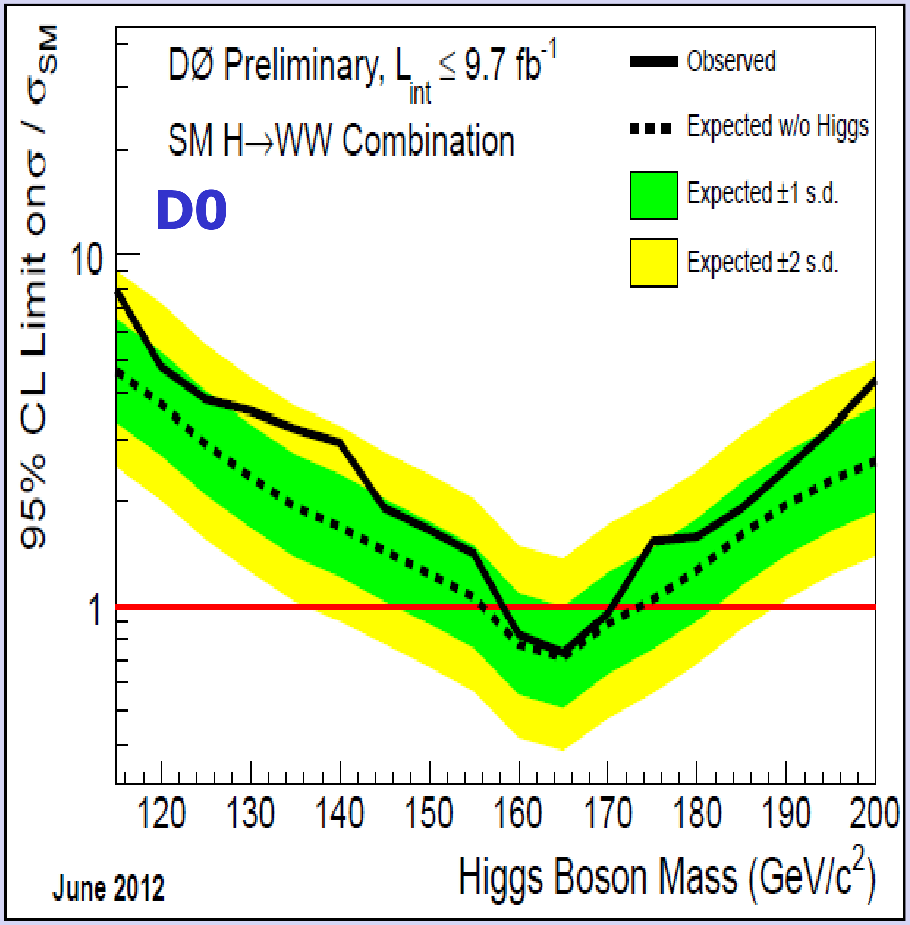
Upper cross section limit for Higgs production relative to SM prediction

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



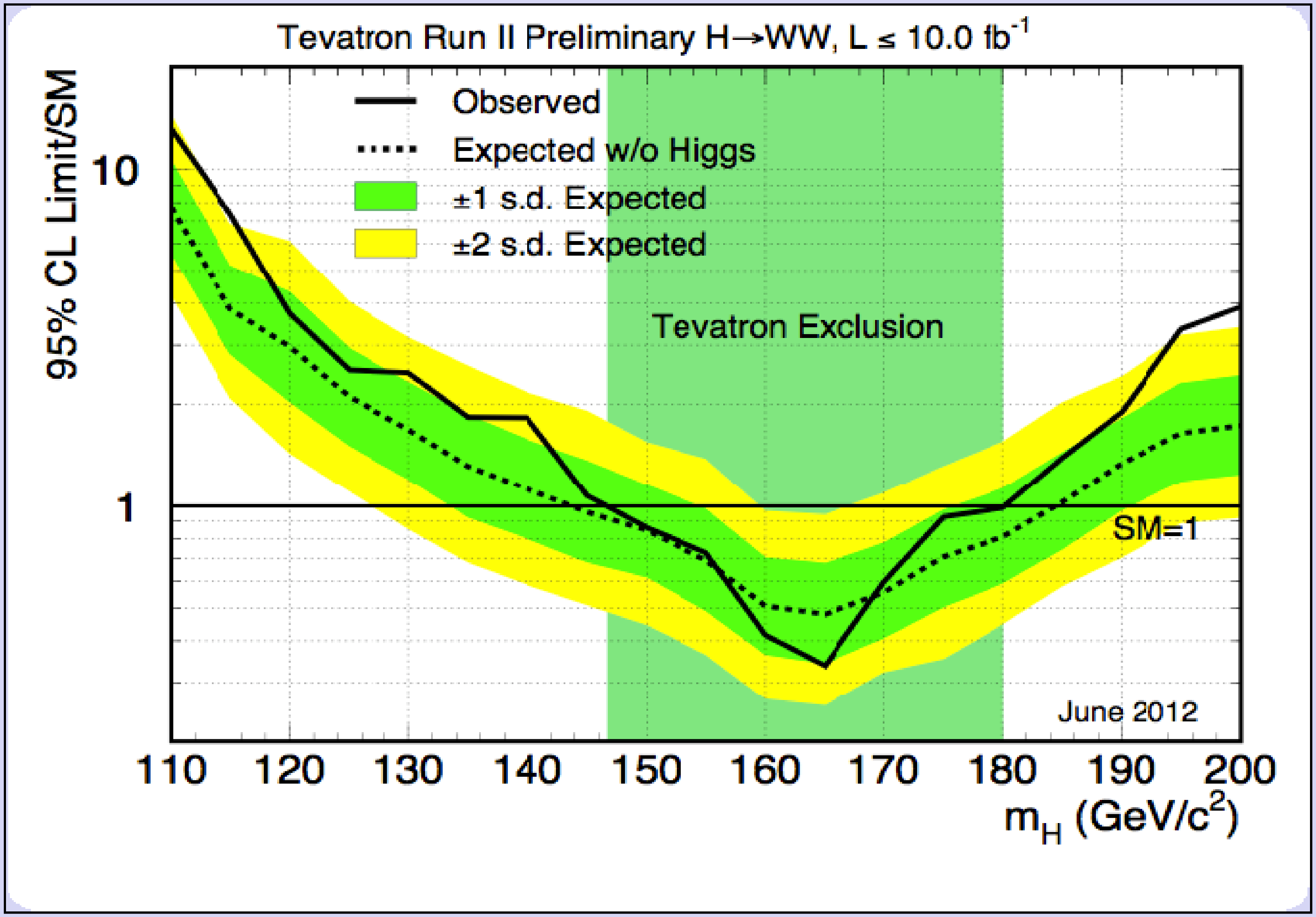
CDF/D0 H→WW→lνlν Limits





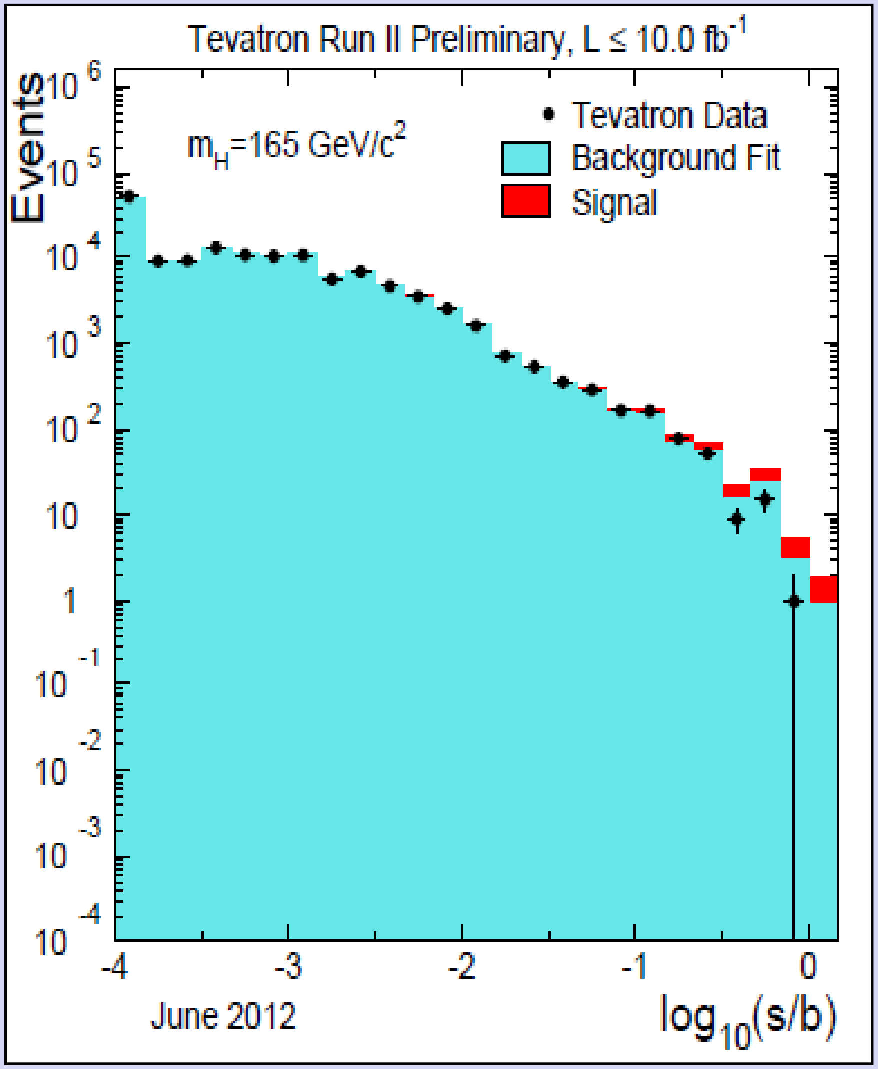
Both experiments exclude SM Higgs boson around 165 GeV

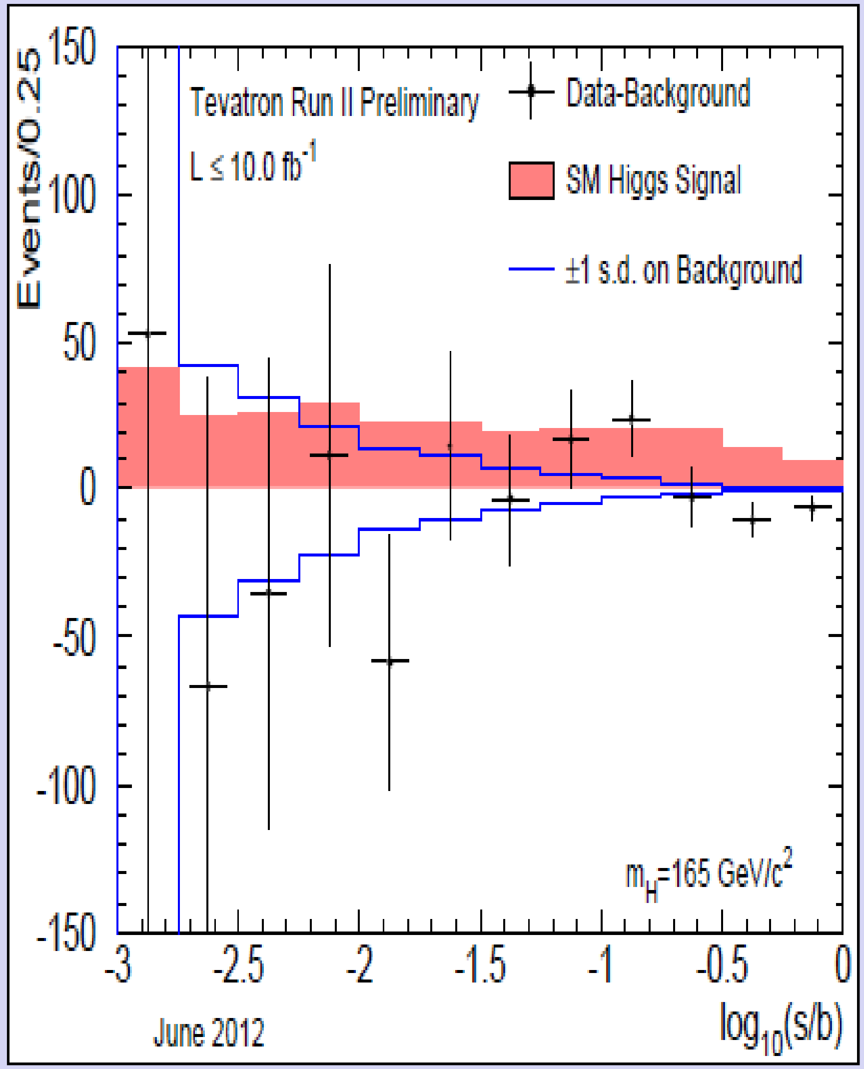
$H \rightarrow W^+W^-$ Tevatron Combination



Exclude 147< M_H < 180 GeV at 95% CL

H→WW Number of Events





Events in all channels are sorted based on signal/background
No excess observed

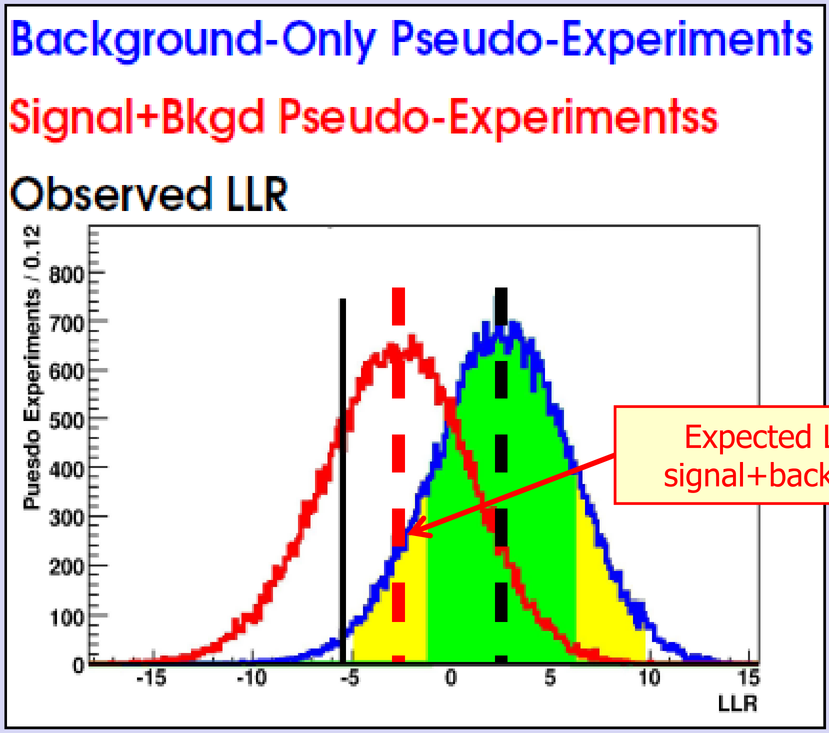
LLR – Log Likelihood Ratio

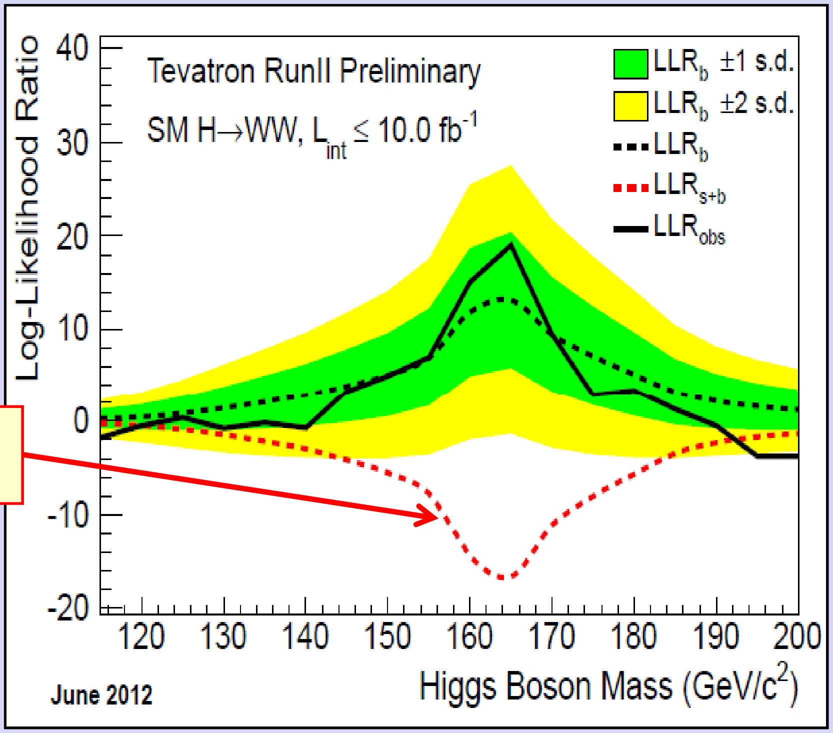
The Log-Likelihood Ratio (LLR) allows to check the data/expectation agreement on background or signal + background hypothesis

H_1 is test hypothesis in our case "background+signal"

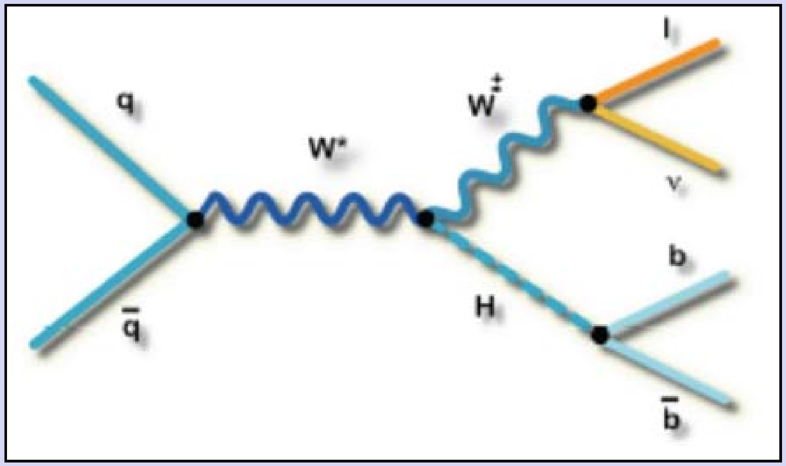
H_0 is "null" hypothesis in our case "background only"

$$LLR = -2\ln\frac{p(\mathrm{data}|H_1)}{p(\mathrm{data}|H_0)}$$

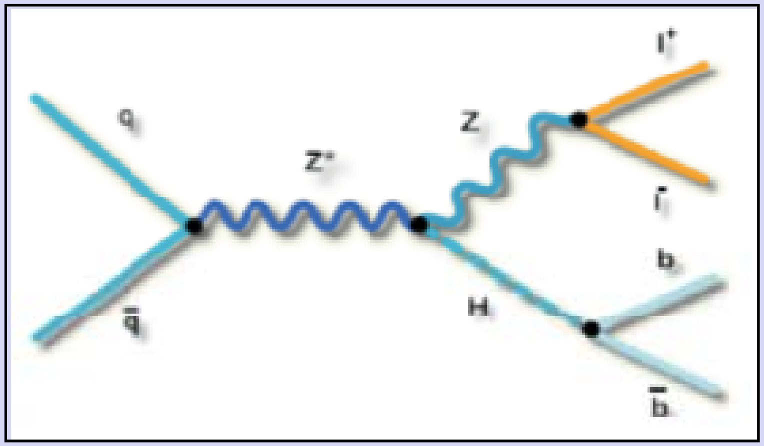




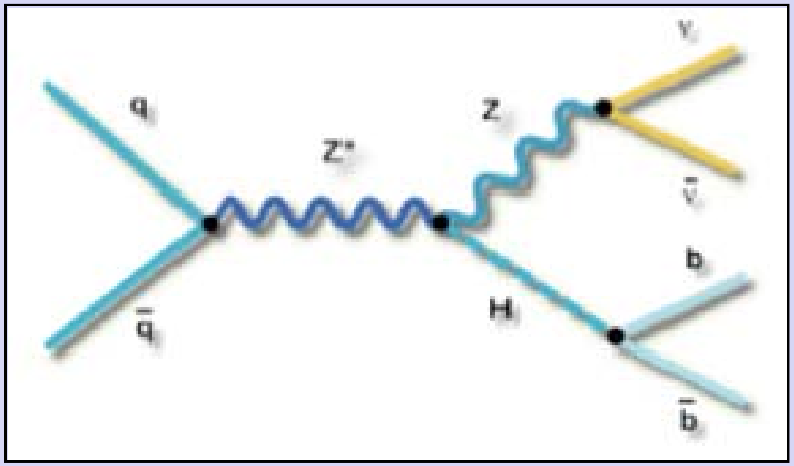
Low Mass Higgs Channels



WH→lνbb:
Large production cross section
Higher backgrounds than in ZH→llbb

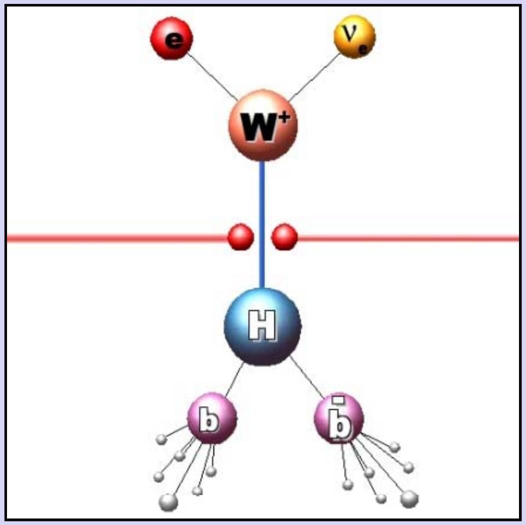


ZH→llbb:
Low background
Fully constrained
Small Signal

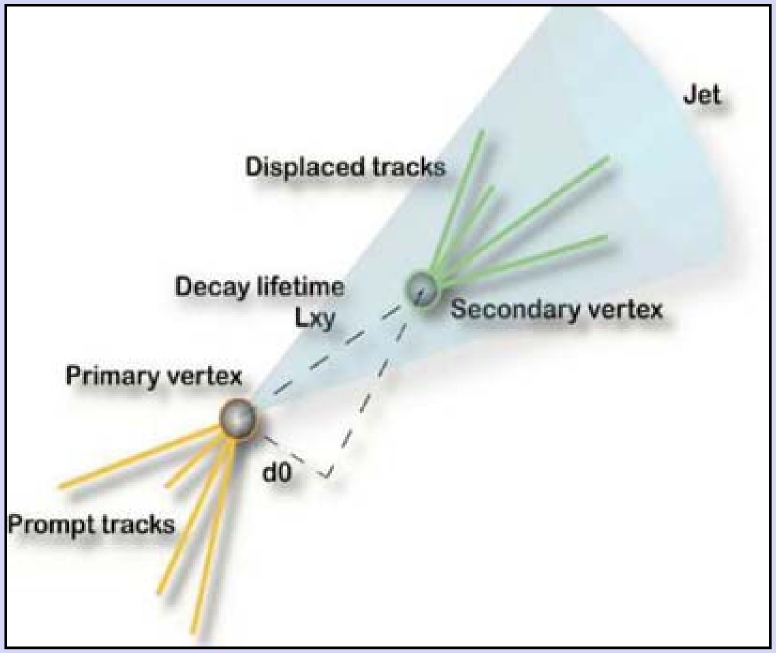


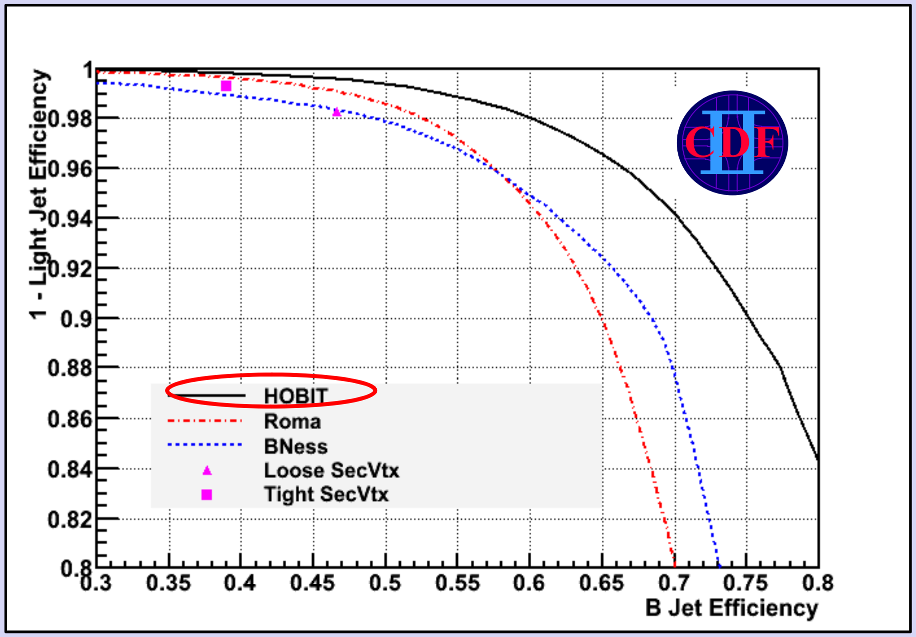
ZH→ννbb:
Signal 3x larger than ZH→llbb
High backgrounds

b-quark Jets Identification



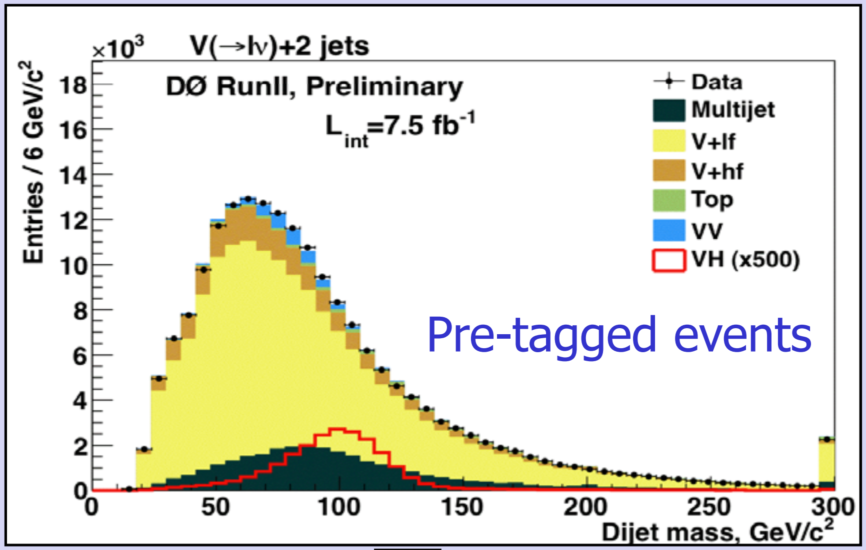
- Higgs searches below 135 GeV are based on most probable Higgs decay channel to a pair of b-quarks
- Selection of jets coming from b-quarks is called b-tagging
- Critical to reduce backgrounds from light quarks/jets
- Use lifetime of ~1 ps for b mesons and baryons to tag b-quark jets



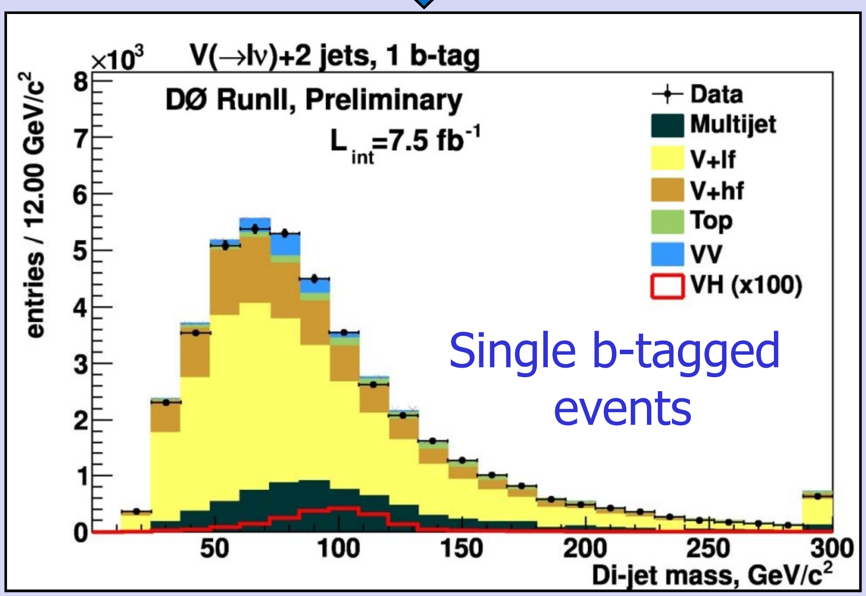


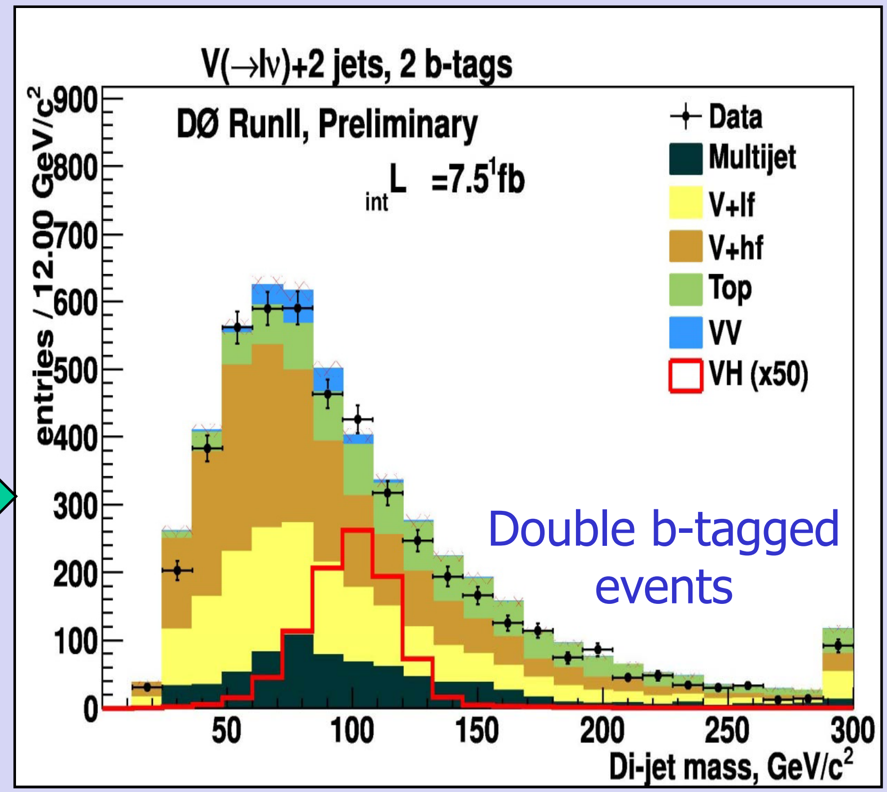
75% eff. for 10% mistag rate of light quarks jets
42% eff. for 0.9% mistag rate of light quarks jets

Low Mass Higgs Searches

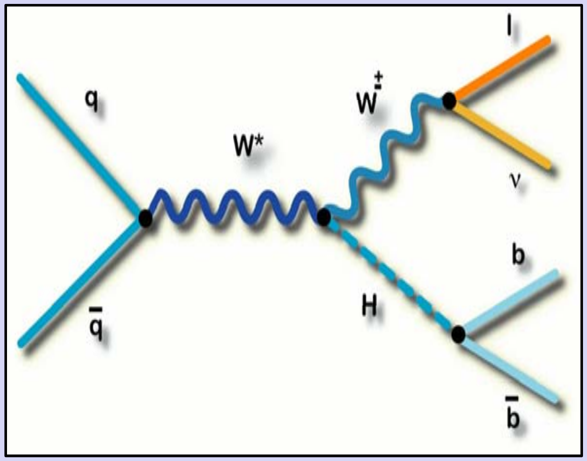


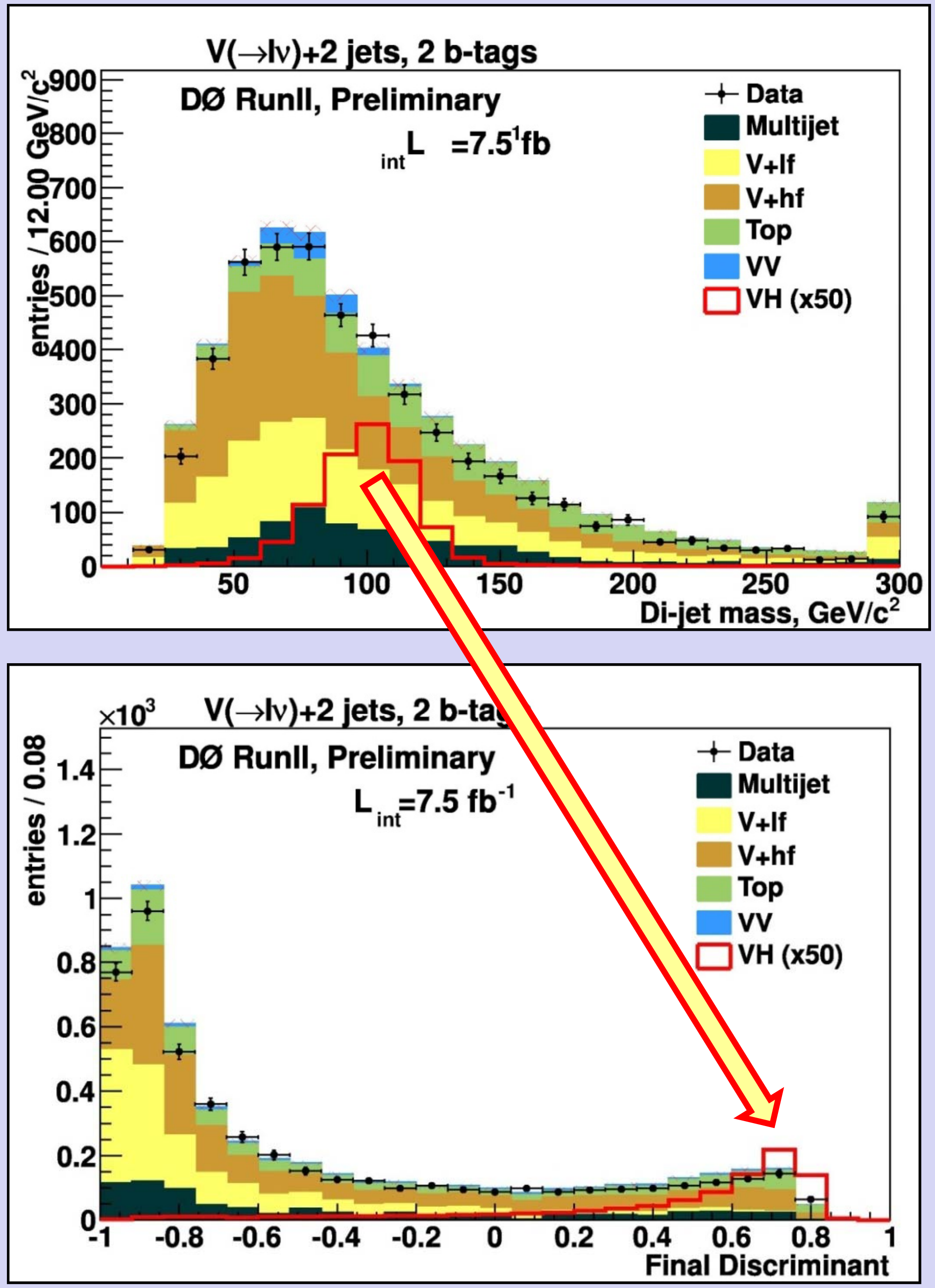
- **Substantial improvement in S/B with increase in number of b-tagged jets**
- **Can further use multivariate analyses to improve signal and background separation**





Multivariate Analysis

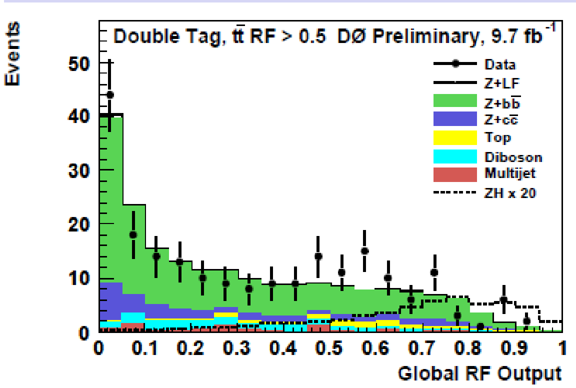


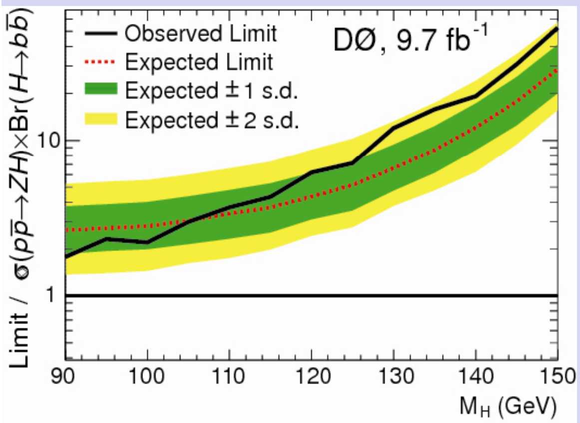


- **To improve S/B ➔ utilize full kinematic event information**
- **Multivariate Analyses**
  - **Neural Networks**
  - **Boosted Decision Trees**
- **Approach validated in single top quark observation**
- **Substantial S/B gain obtained**

Results from DØ

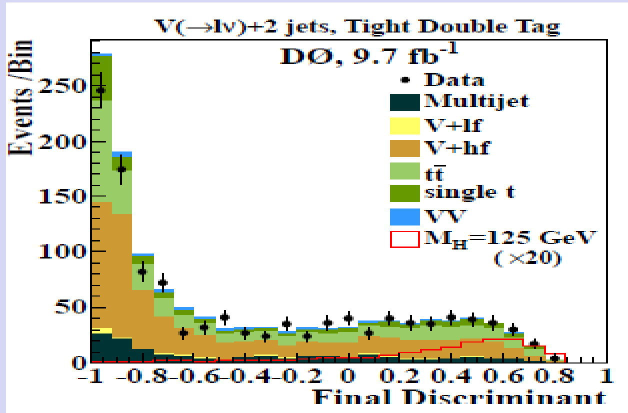
ZH→llbb ∫Ldt=**9.7**fb^{-1}

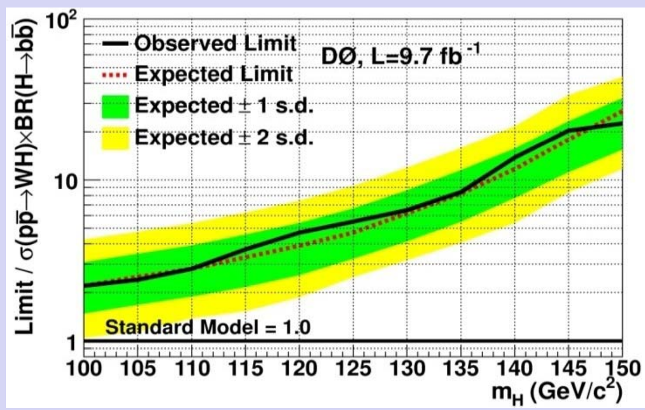




95% CL Exp (obs)
Limit **3.7** (**4.3**) x SM
@ MH=115 GeV

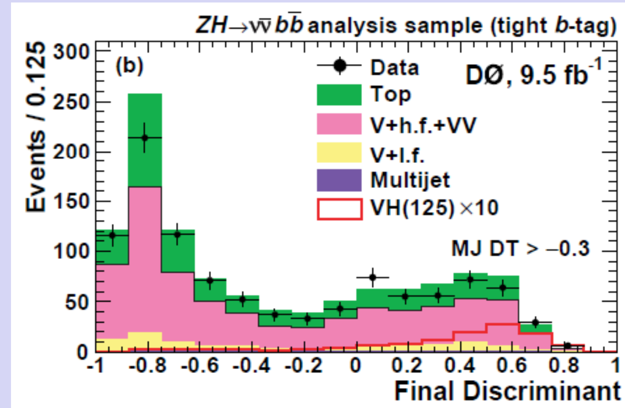
WH→lvbb ∫Ldt=**9.7** fb^{-1}

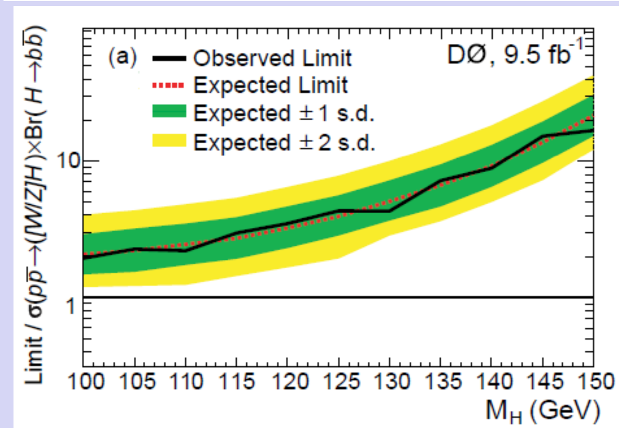




95% CL Exp (obs)
Limit **3.2** (**3.7**) x SM
@ MH=115 GeV

ZH→vvbb ∫Ldt=**9.5** fb^{-1}



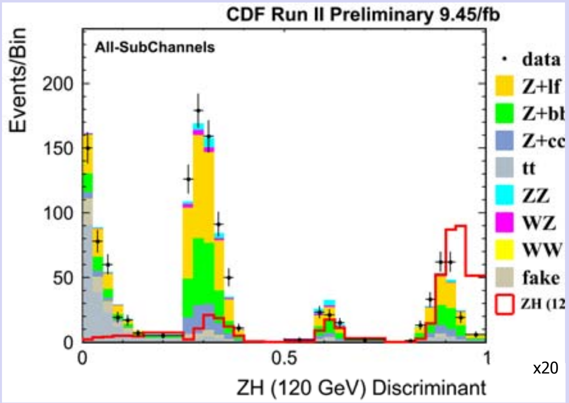


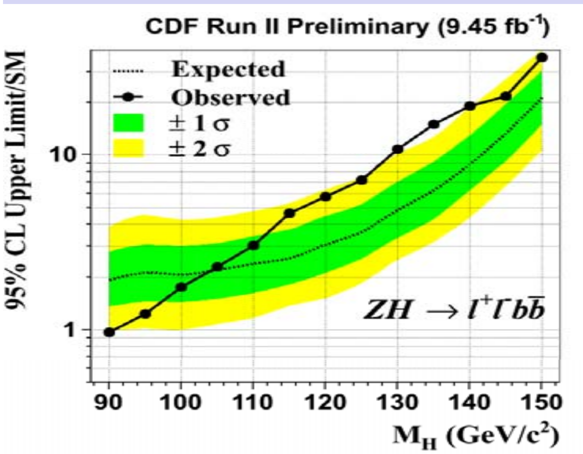
95% CL Exp (obs)
Limit **3.0** (**2.7**) x SM
@ MH=115 GeV

All channels are consistent and demonstrate sensitivity to the Higgs

Results from CDF

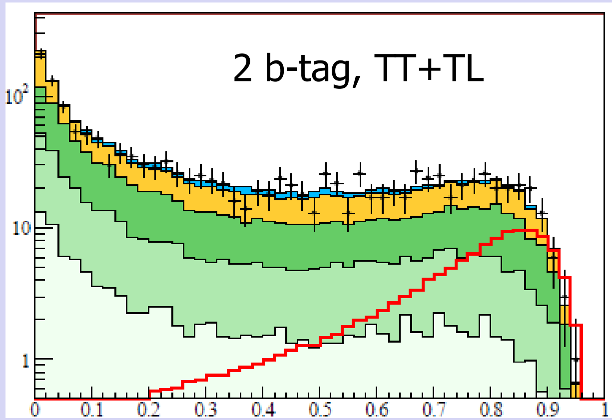
ZH→llbb̄ ∫Ldt=**9.5** fb^{-1}

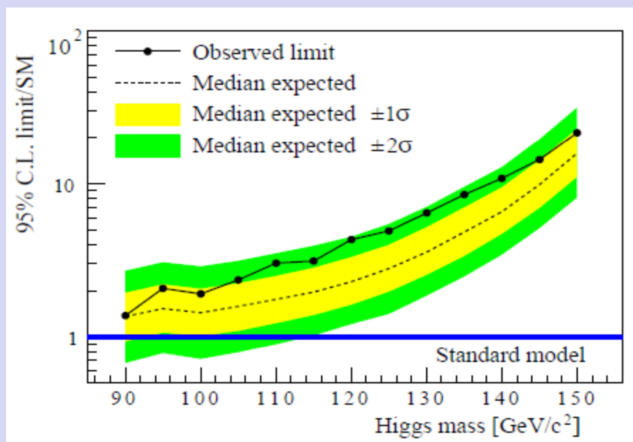




95% CL Exp (obs)
Limit **2.6** (**4.7**) x SM
@ MH=115 GeV

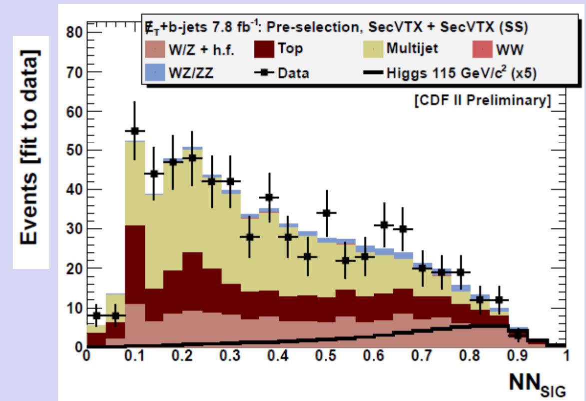
WH→lvbb̄ ∫Ldt=**9.5** fb^{-1}

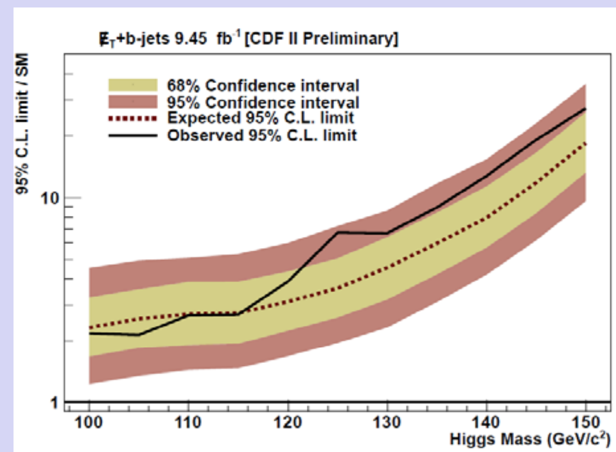




95% CL Exp (obs)
Limit **2.0** (**3.1**) x SM
@ MH=115 GeV

ZH→vvbb̄ ∫Ldt=**9.5** fb^{-1}





95% CL Exp (obs)
Limit **2.7** (**2.7**) x SM
@ MH=115 GeV

Pattern of an excess is starting to appear while combination is ahead

Cross Check on Diboson Processes

Benchmark for H→bb searches using well known process

WZ, ZZ with W or Z decaying to leptons and Z decaying to heavy flavor jets

For m_H=115 GeV

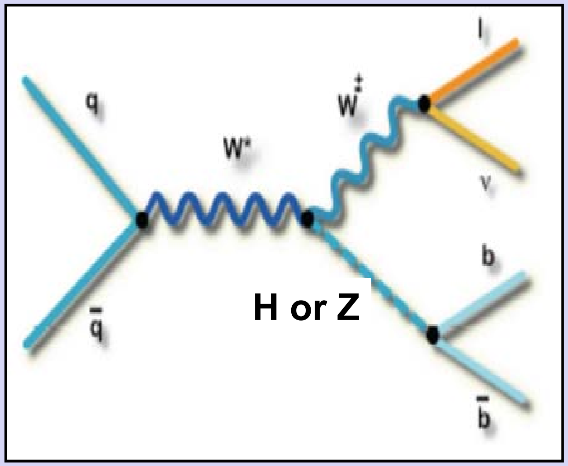
WH→lνbb: σ = 26 fb
ZH→ ννbb:σ = 15 fb
ZH→ llbb: σ = 5 fb

Total Z/W+H: σ = 46 fb

Replace H with Z

WZ→lνbb: σ = 105 fb
ZZ →ννbb: σ = 81 fb
ZZ → llbb: σ = 27 fb

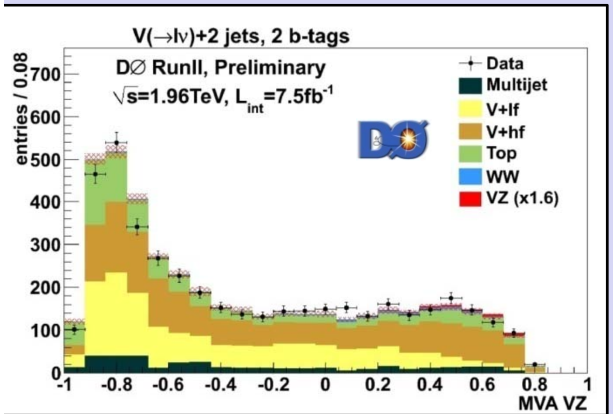
Total Z/W+Z: σ = 213 fb



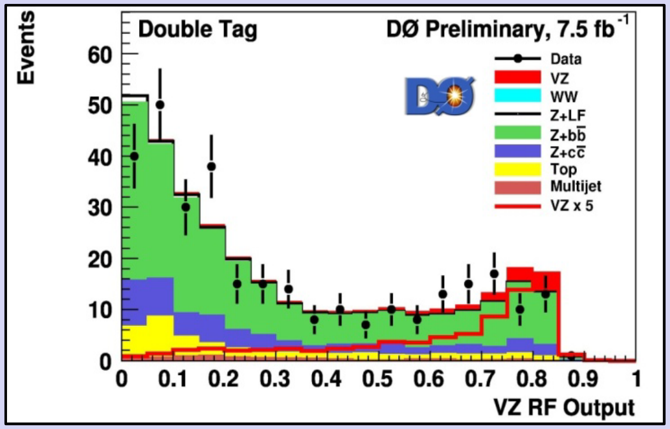
Apply exactly the same selection and multivariate analysis as for W boson with Higgs or Z boson with Higgs production (optimized for Z mass), detect access of events and measure WZ/ZZ cross section

Diboson Cross Check

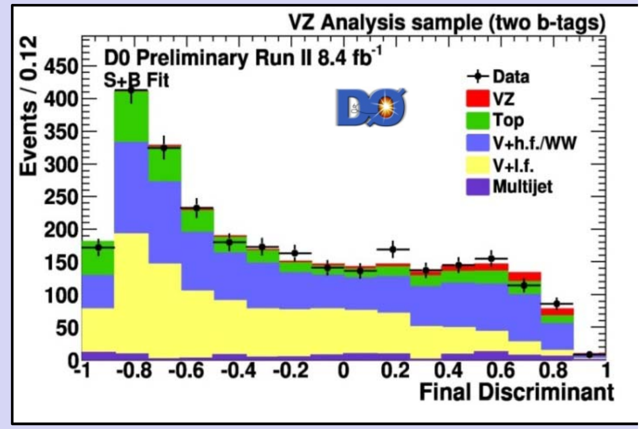
Diboson lvbb



Diboson llbb

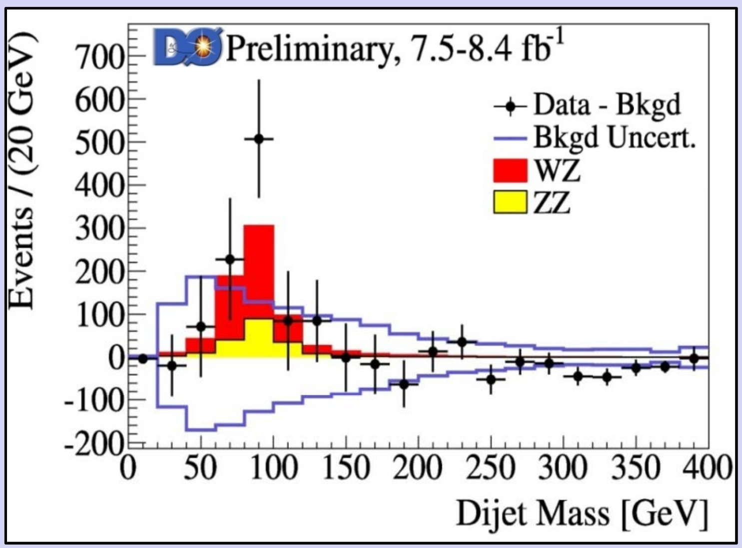


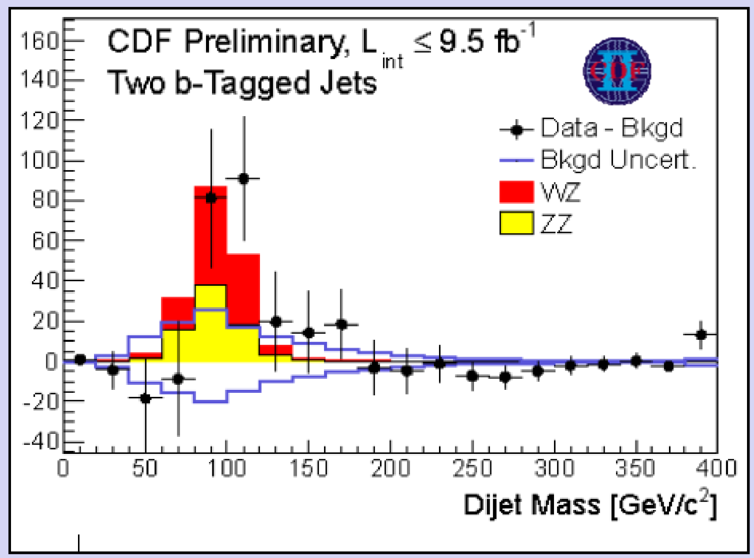
Diboson ννbb



Combining all channels and keeping WW as background

Evidence of >3 sigma/experiment for WZ/ZZ detection with Z decaying to b-quarks



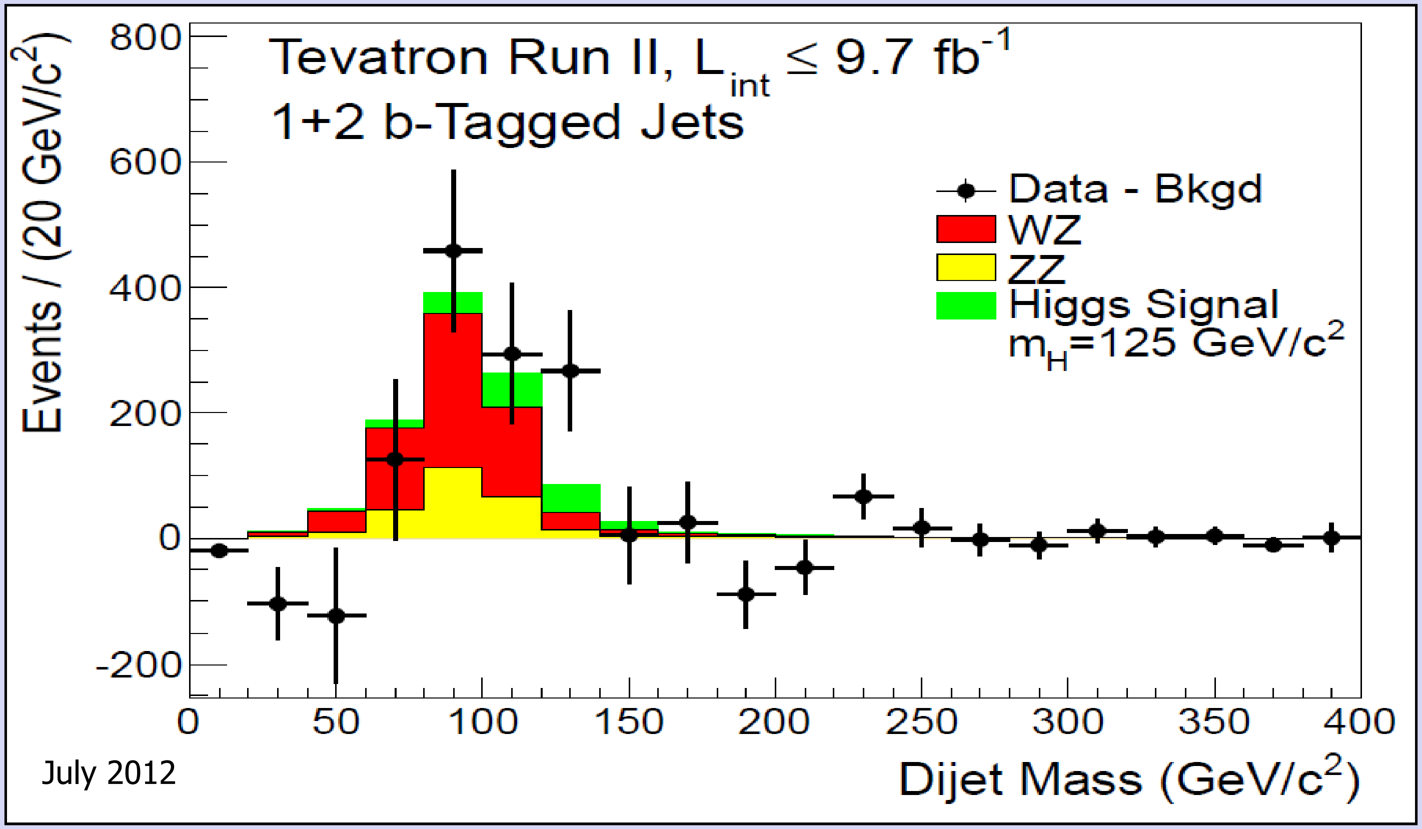


CDF+DØ Diboson Combination

CDF-DØ combination cross-section: 3.9 +/- 0.9 pb

Next to leading order prediction: 4.4 +/- 0.3 pb

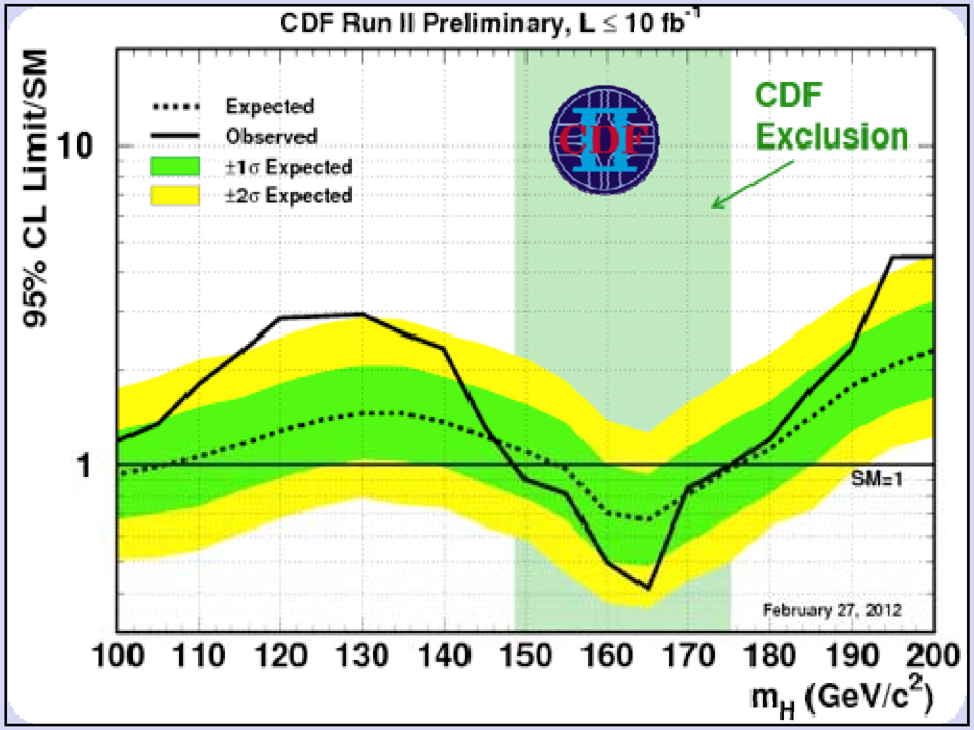
4.5 σ significance!

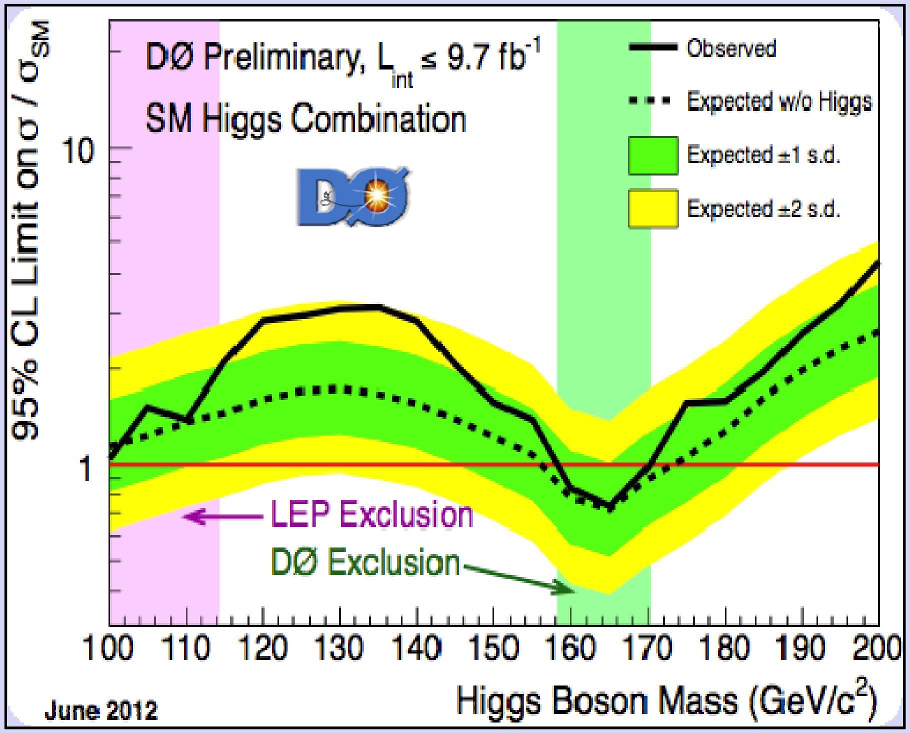


Higgs signal is becoming a background to low cross section Standard Model processes…

CDF and DØ Higgs Search Results

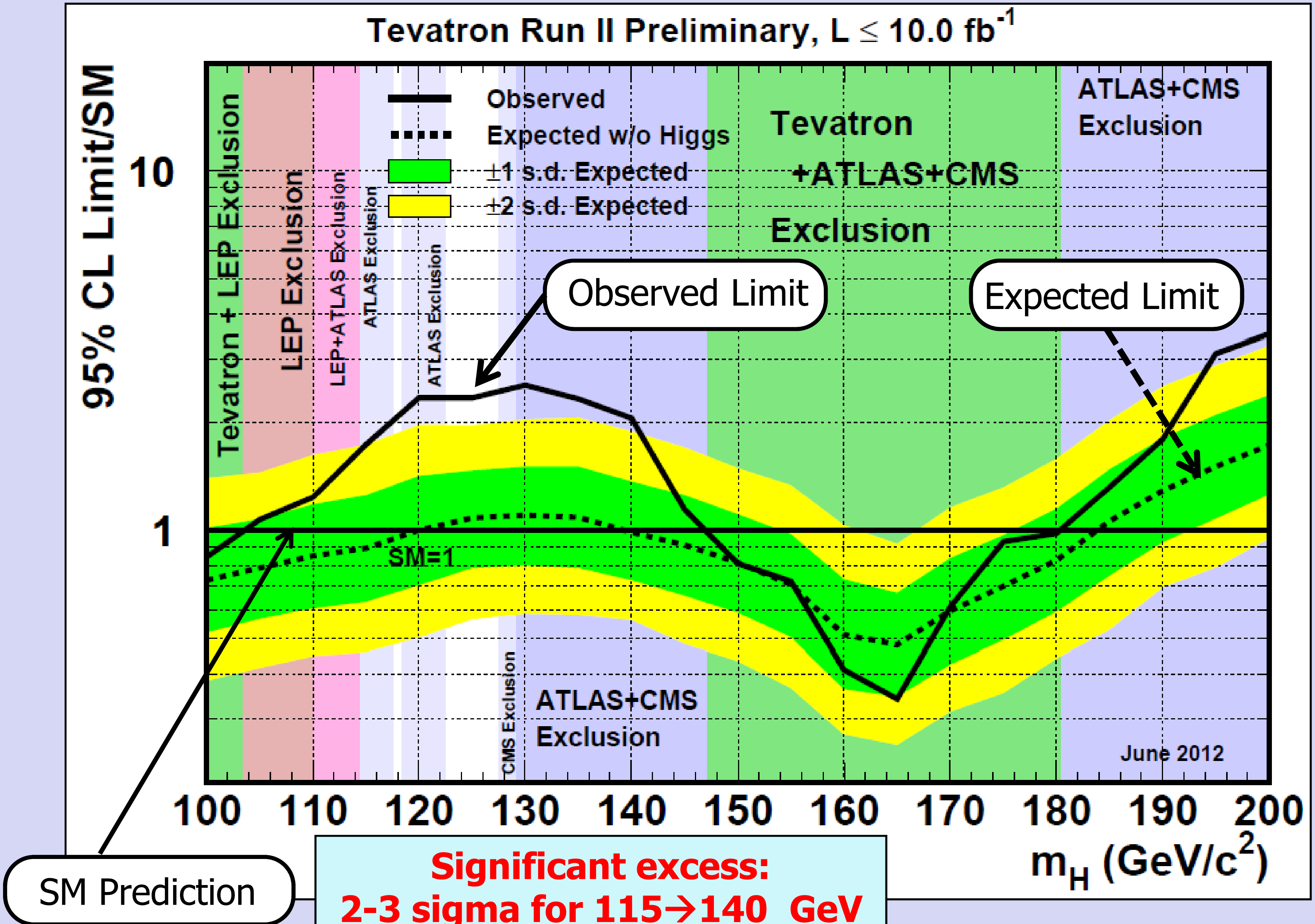
CDF and DØ single-experiment combinations of all Higgs search channels: H→WW, H→bb, H→γγ + other modes





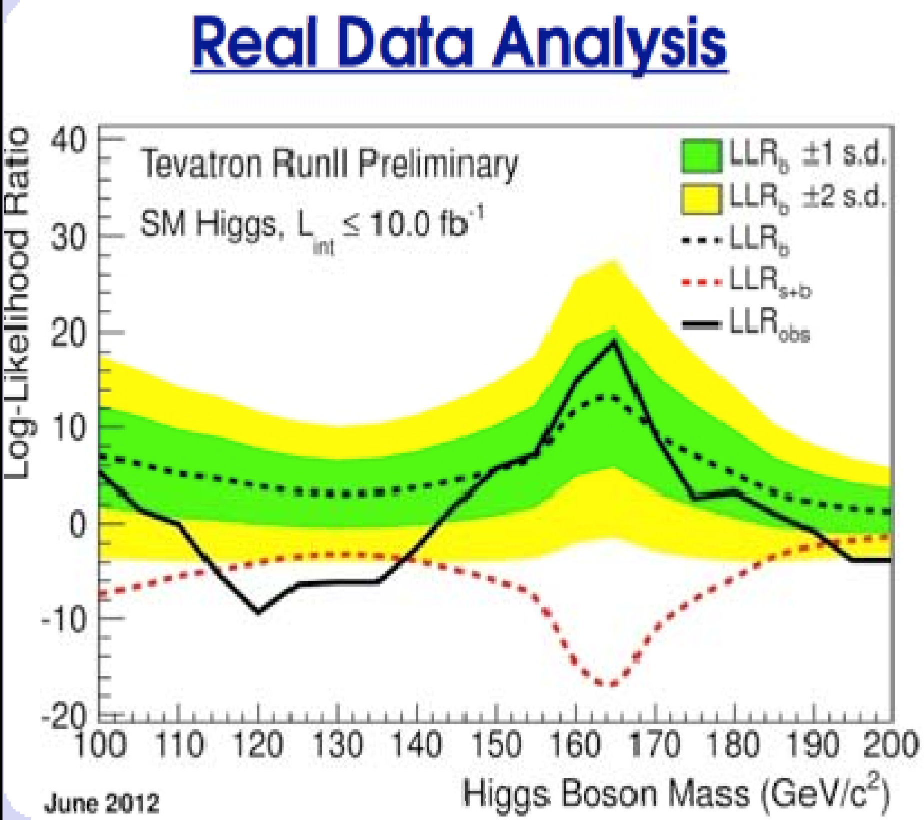
Remarkably similar shapes: no excess below ~110 GeV
broad excess around ~120-140 GeV
exclusion around ~165 GeV

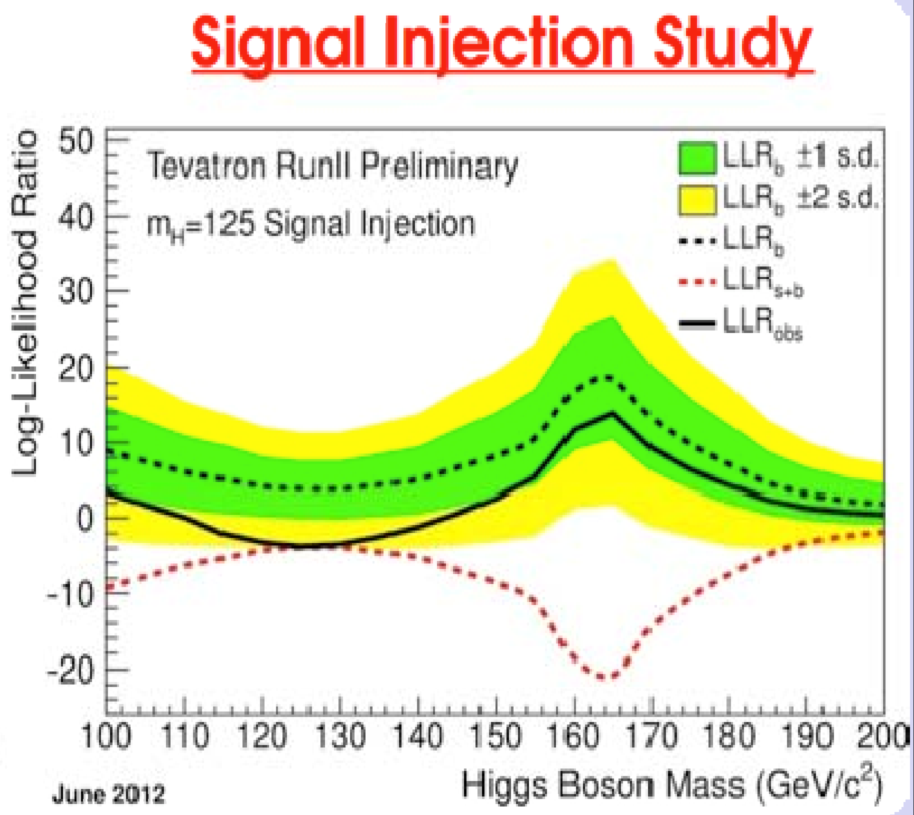
Summer 2012 Tevatron Combination



Significant excess:
2-3 sigma for 115→140 GeV

LLR test: Excess Shape Comparable with Higgs?



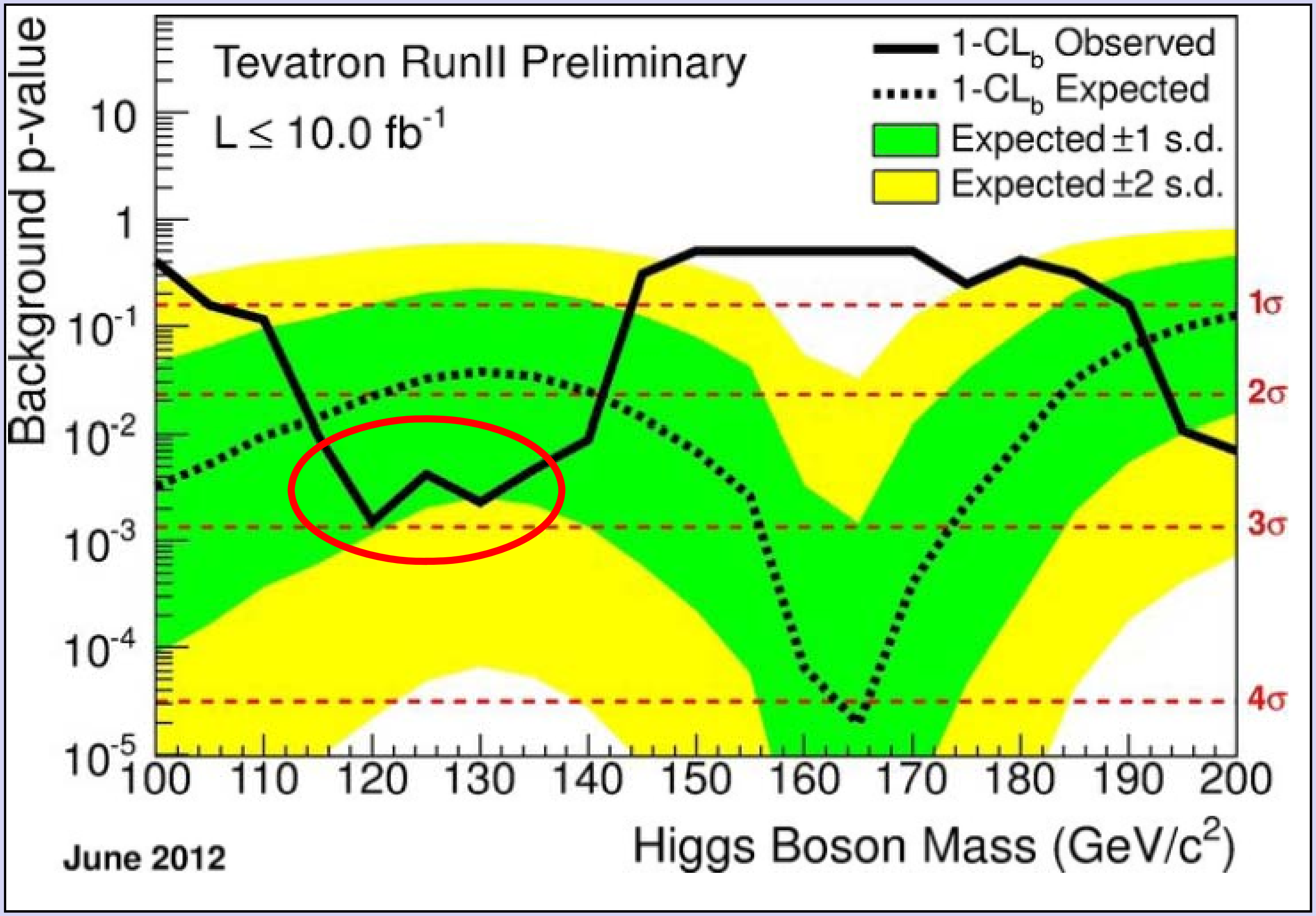


Injection of Standard Model Higgs signal at 125 GeV provides very similar to the observed behavior

"background like" shape above ~140 GeV
"signal like" shape in 115-140 GeV region

Width of the excess is defined by the effective mass resolution for a pair of b-quark jets and is ~15%

Probability of Background to Mimic Signal

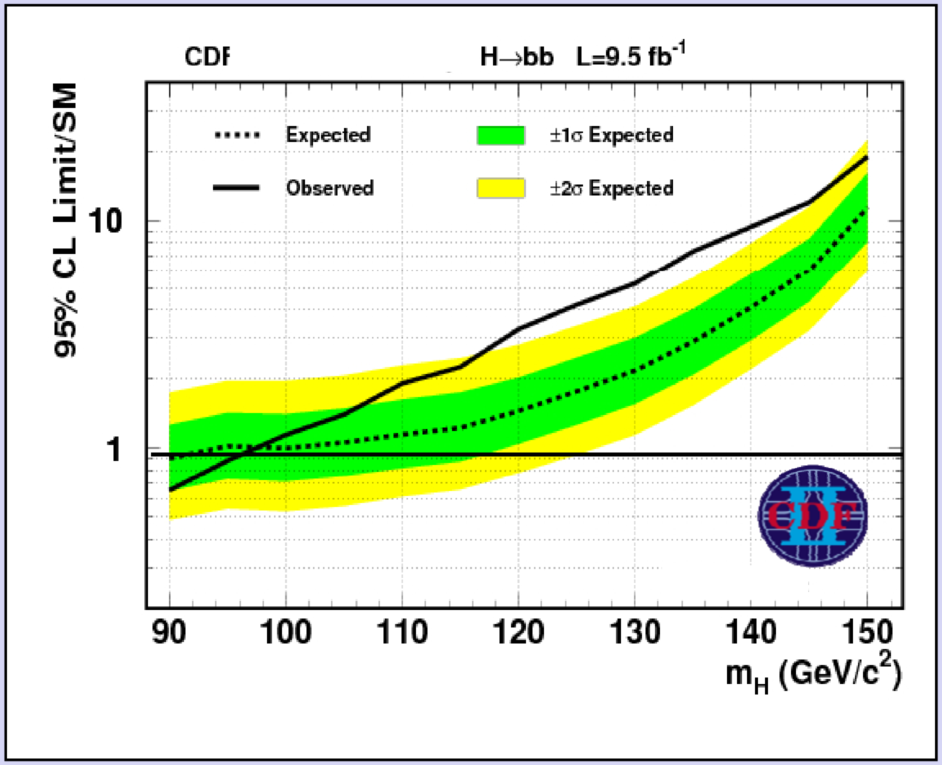


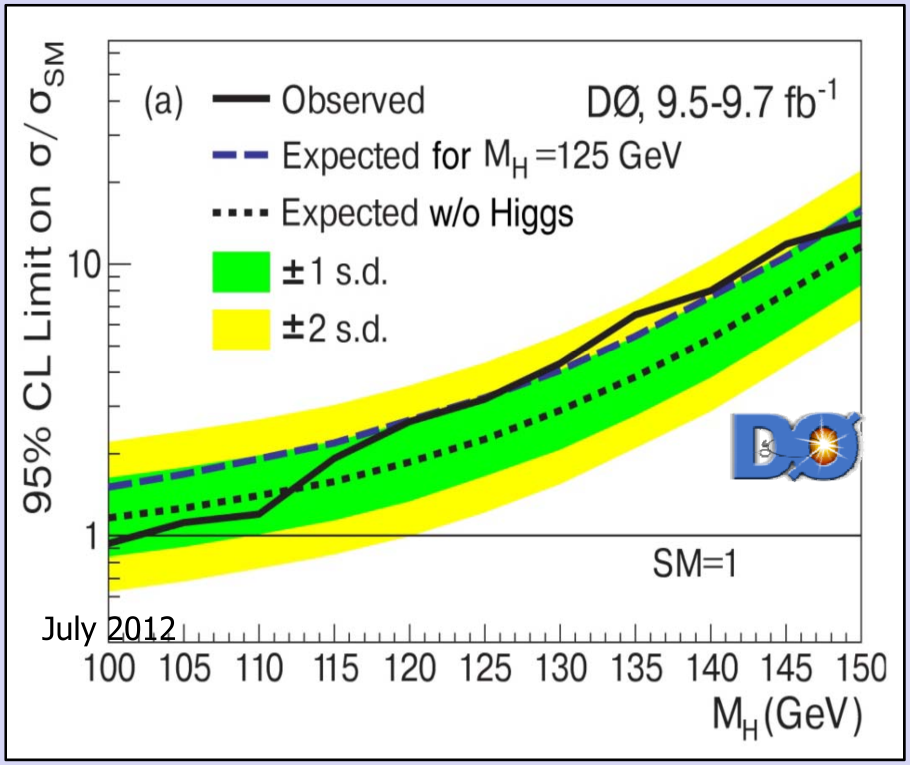
3.0σ local excess at 120 GeV

2.5σ global excess taking into account "look elsewhere effect" as we perform studies at many data points

H→bb Individual Experiments Results

Similar broad excesses due to limited b-jets energy resolution

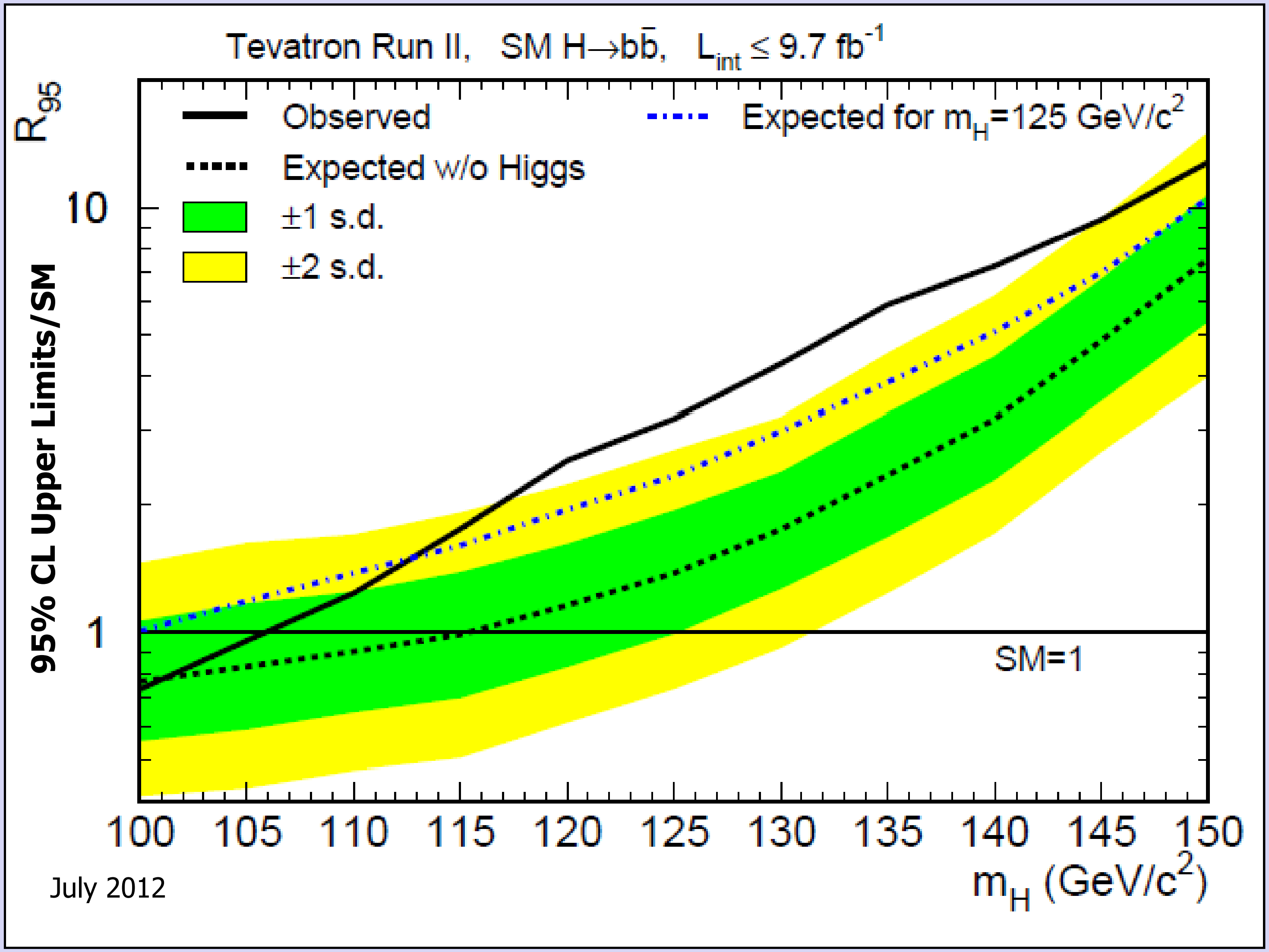




> 2 σ excess in 120-145 GeV
Global significance **2.5 σ**

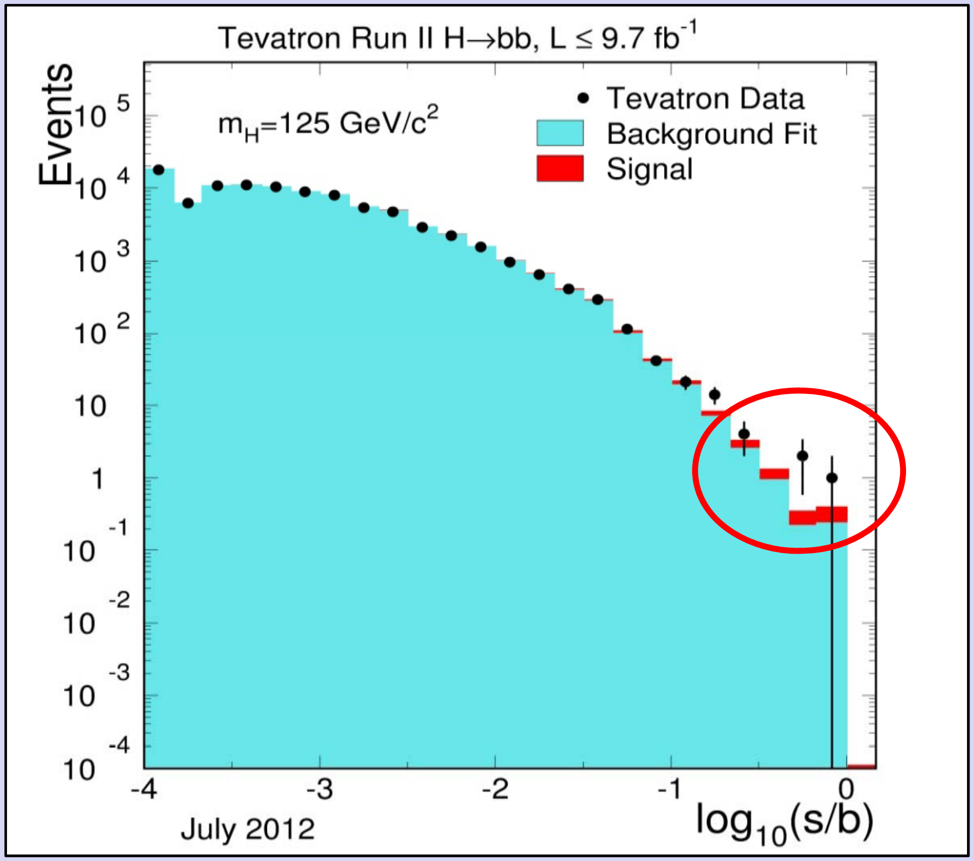
~2 σ excess in 120-145 GeV
Global significance **1.5 σ**

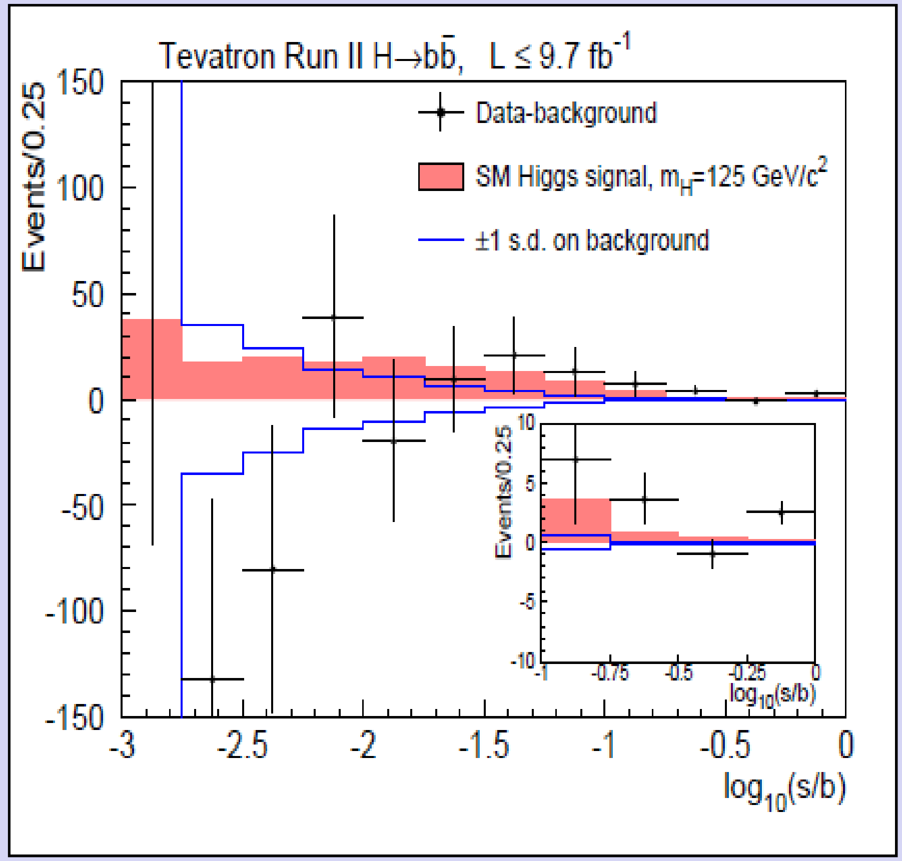
Tevatron H→bb Combination



Broad excess, maximum between 120 and 140 GeV

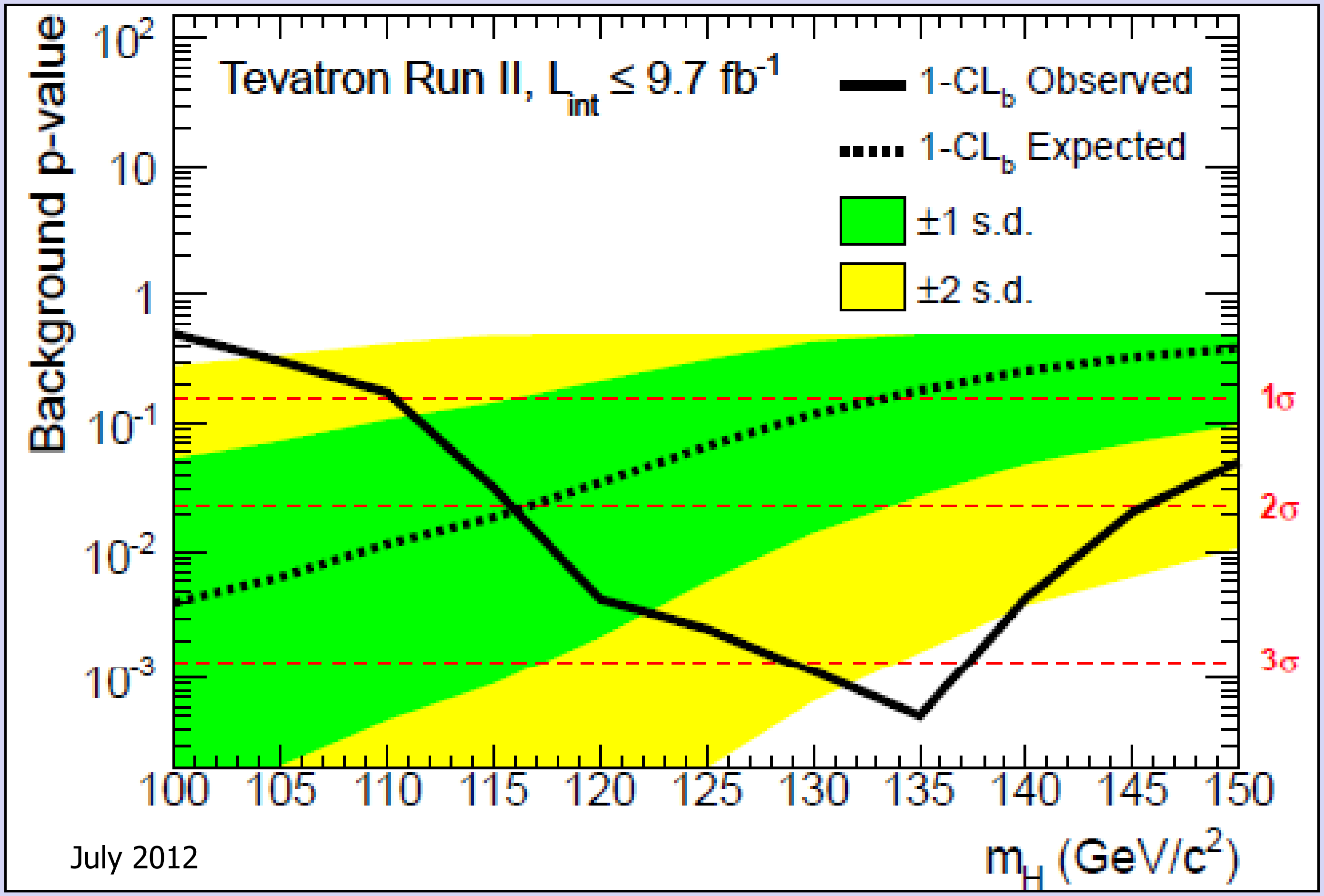
Events Count for 125 GeV Higgs Search





Clear excess in the high Signal/Background region

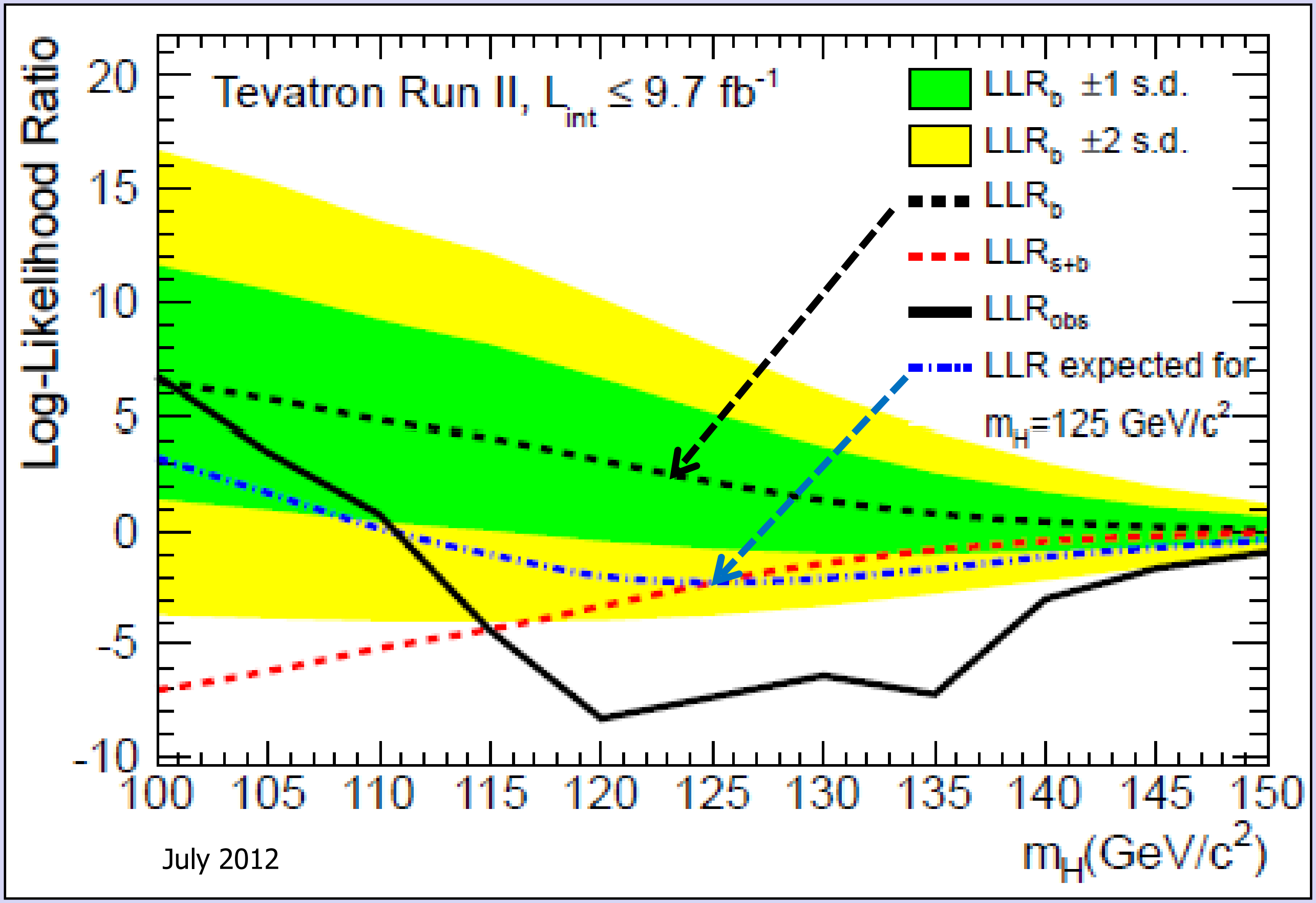
H→bb, Probability of Background to Mimic Signal



Significance of observed excess

Channels	Local	Global
All Tevatron	3.0 σ	2.5 σ
H→bb	3.3 σ	3.1 σ - Evidence!

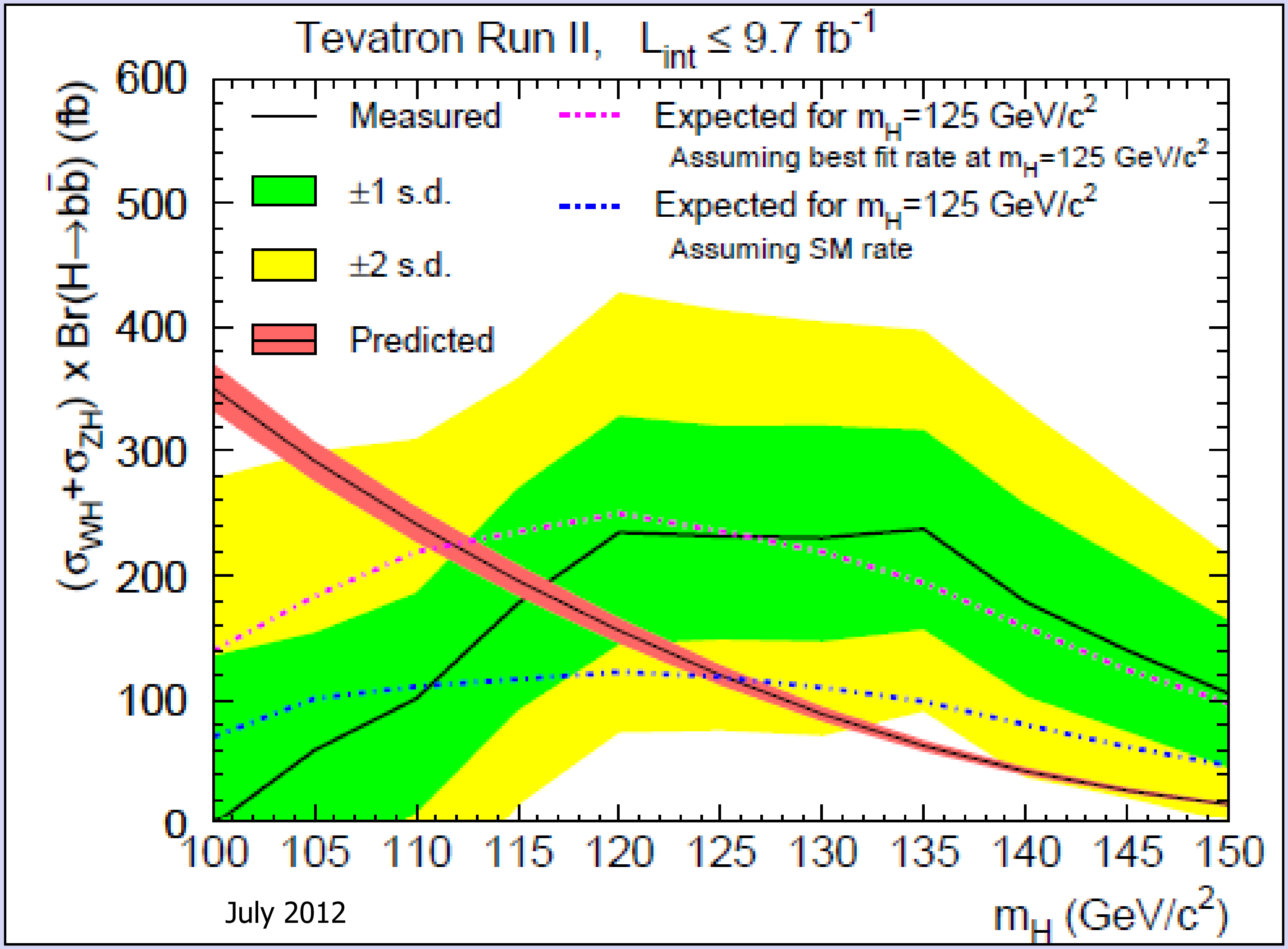
LLR for H→ bb and Signal Injection



Excess more pronounced than expected with a 120-135 GeV Higgs

Data prefer higher x-section*BR than Standard Model with 125 GeV Higgs – but within errors compatible

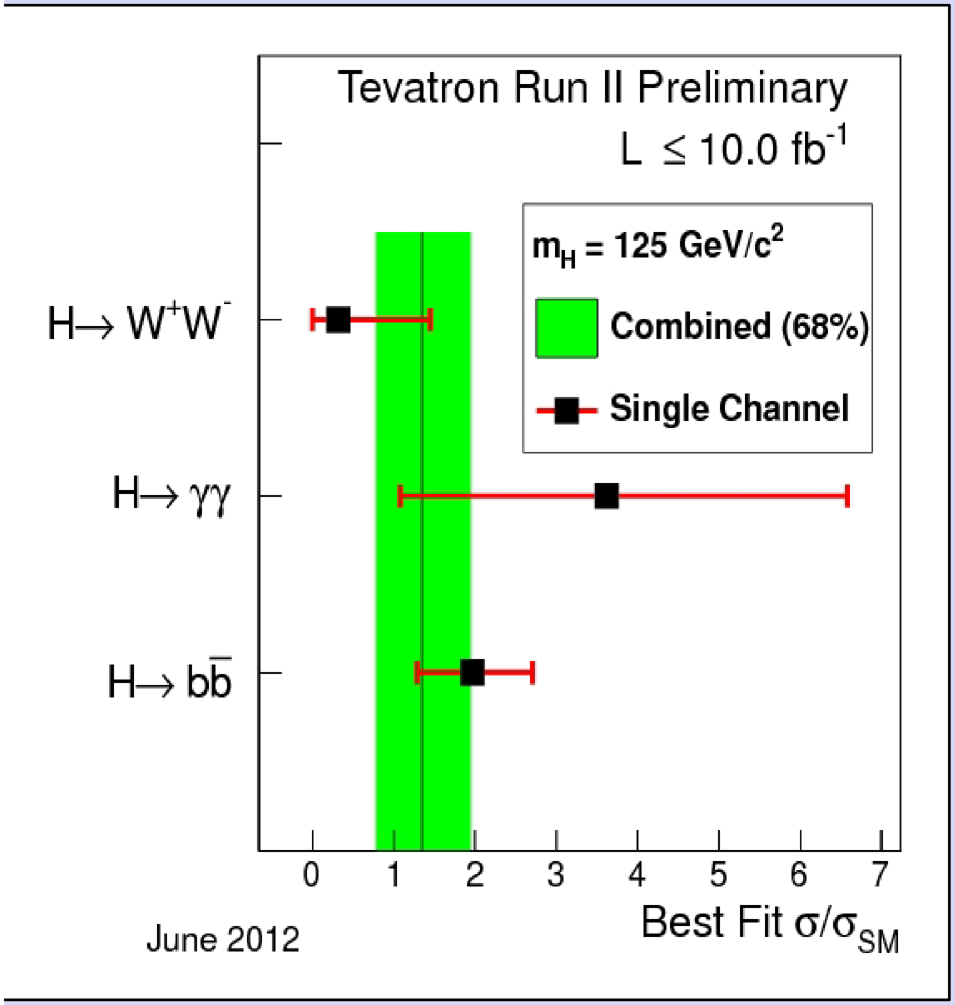
Cross Section * BR Measurement

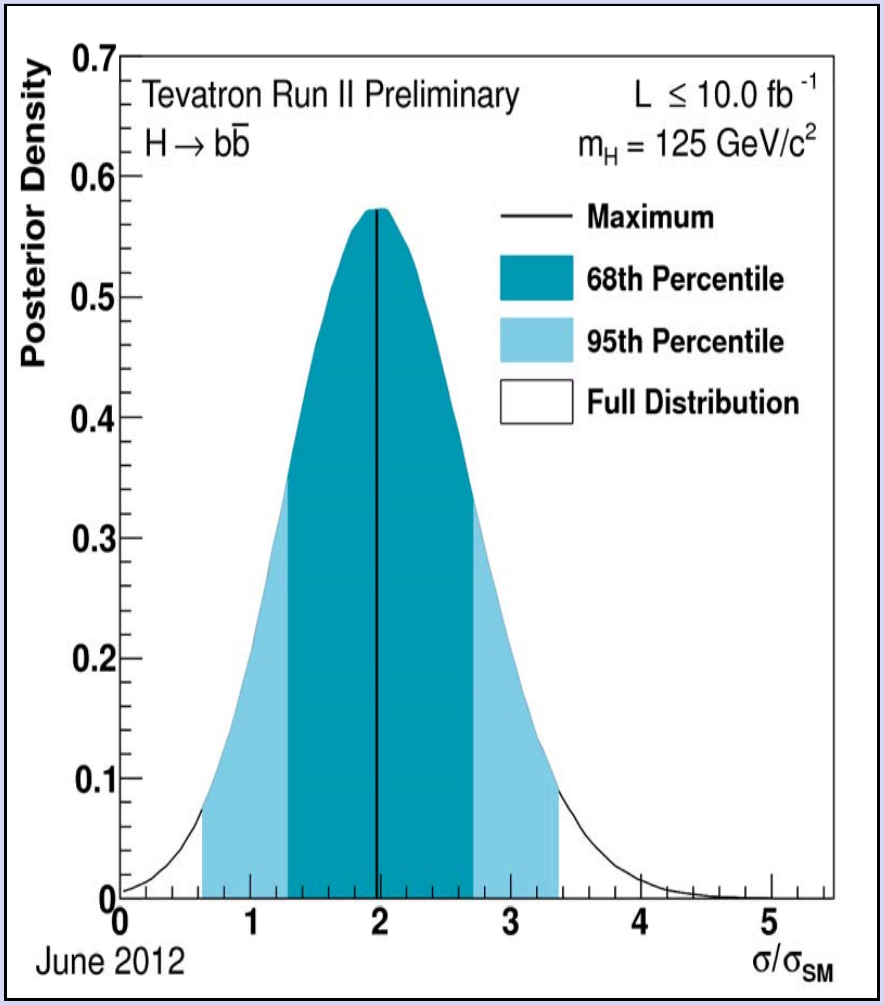


$$(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08}\ (\text{stat} + \text{syst})\ \text{pb}$$

SM Higgs @ 125 GeV: 0.12 ± 0.01 pb

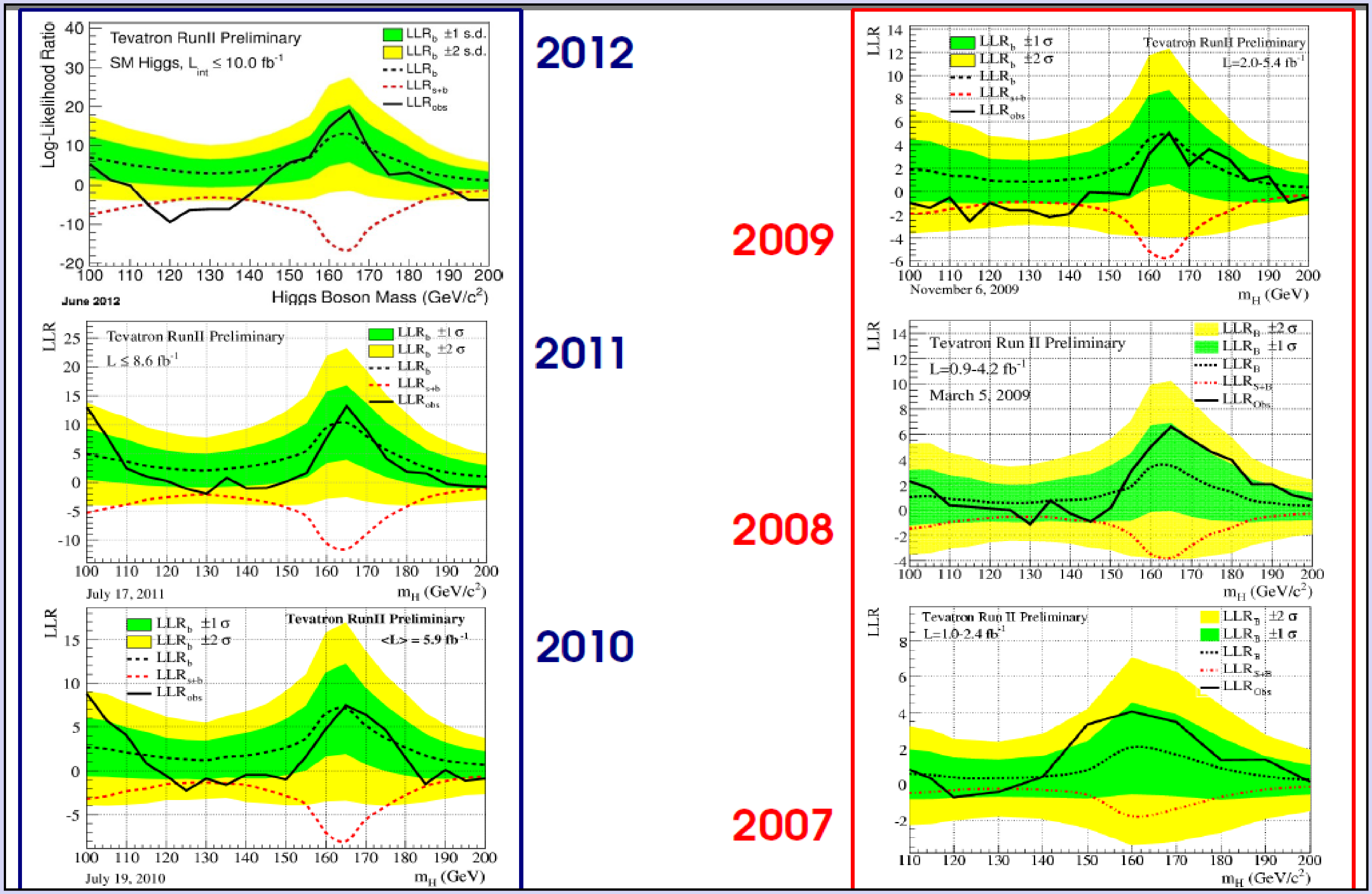
Best Fit Cross Sections





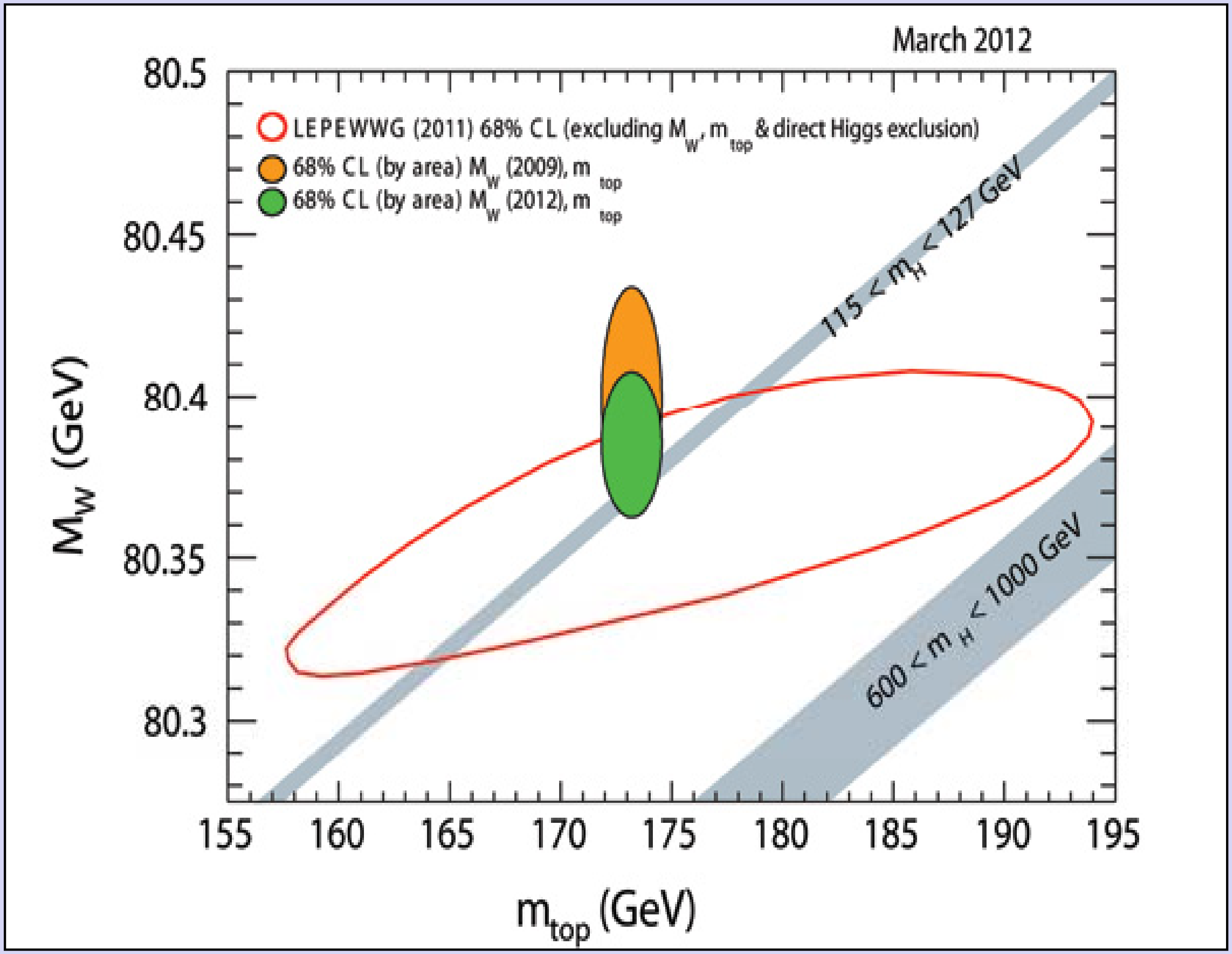
- Using method similar to extraction of σ x Br for H → bb we extract from the data H → WW and H → γγ values normalized by Standard Model predictions
- Within errors all data are compatible with predictions for Standard Model Higgs boson

Log-Likelihood Distributions



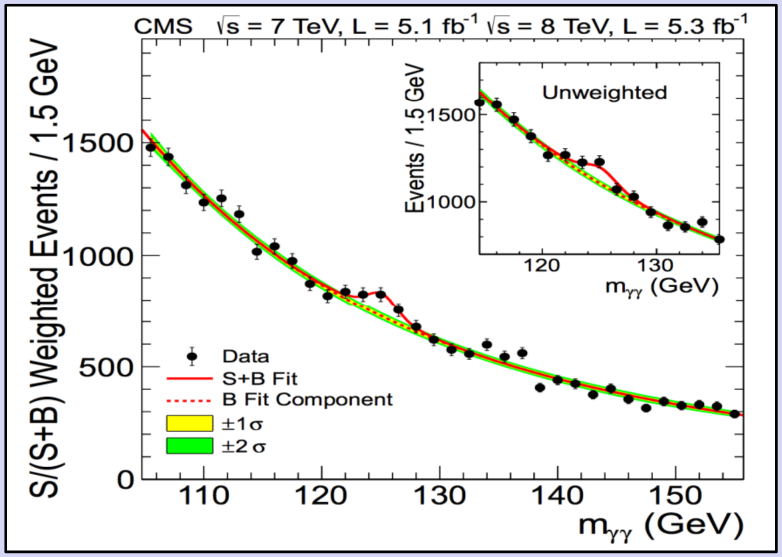
- **Over years with more data and analysis improvements steady increase in ability to separate signal from background**
- **Excess at low mass and deficit at high mass were pretty stable over years while significance increased**

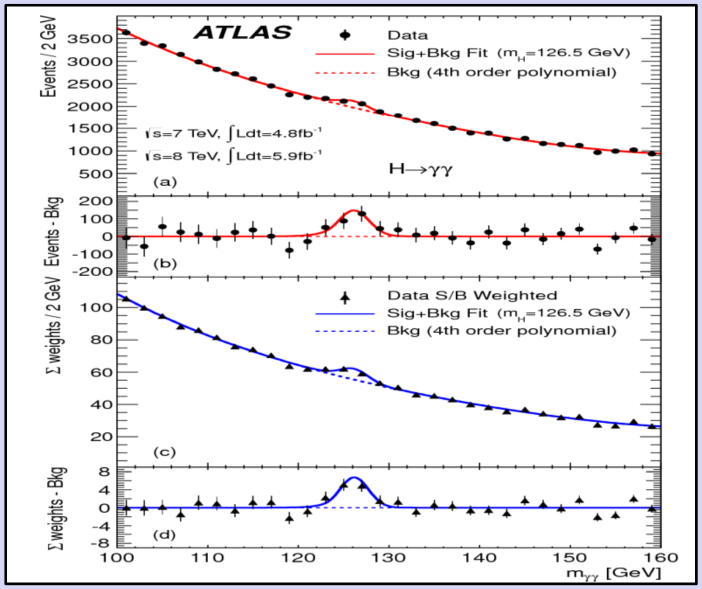
Self-consistency of the Standard Model

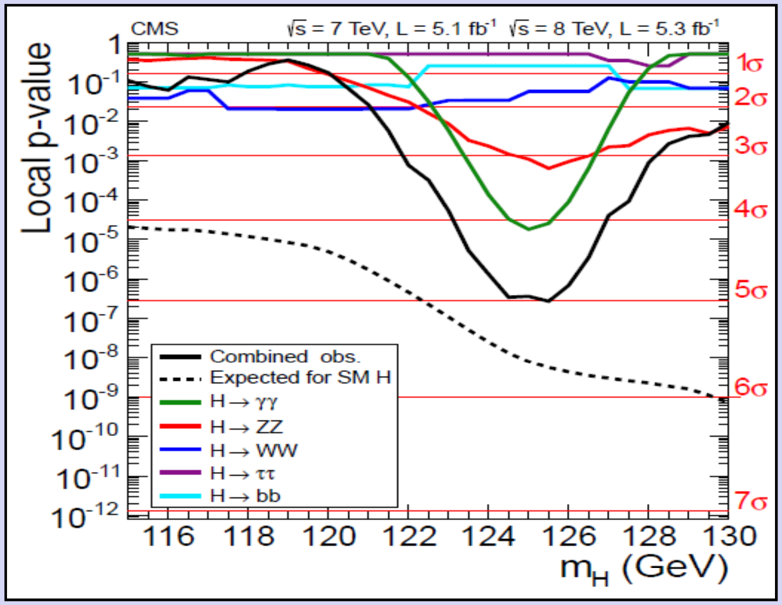


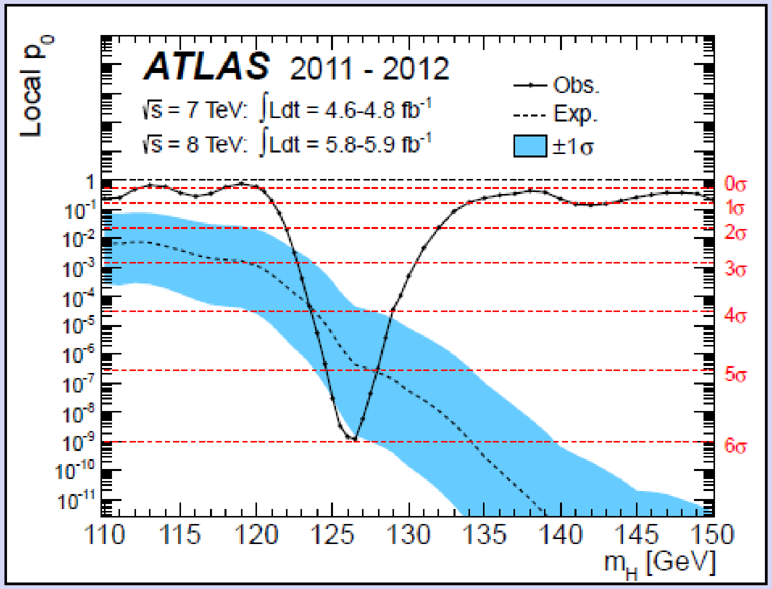
Precision measurements of Standard Model parameters and Higgs mass of 125 GeV are in perfect agreement!

LHC Discovery





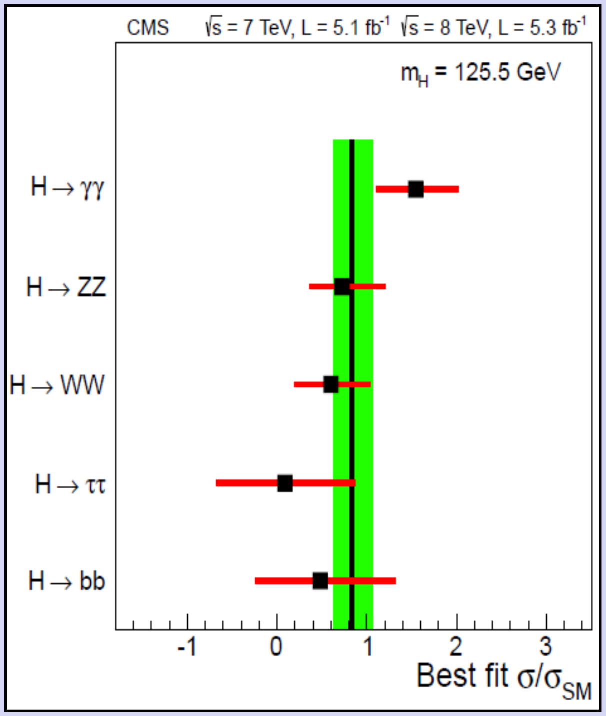


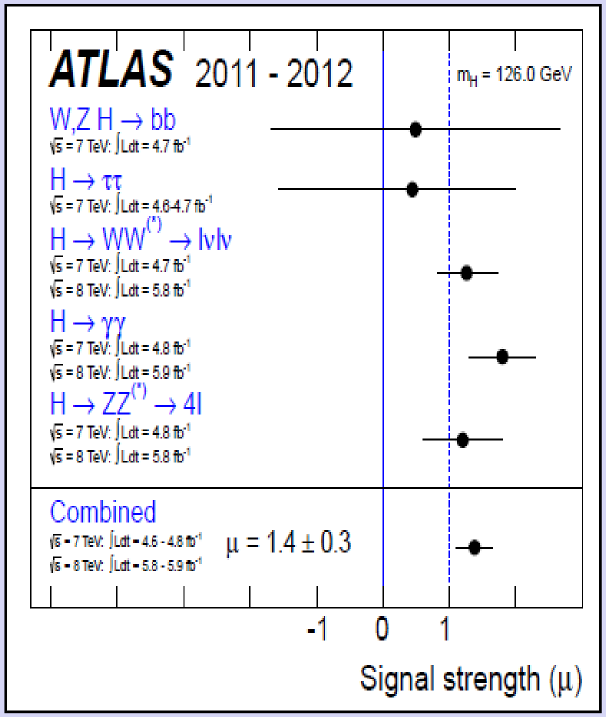


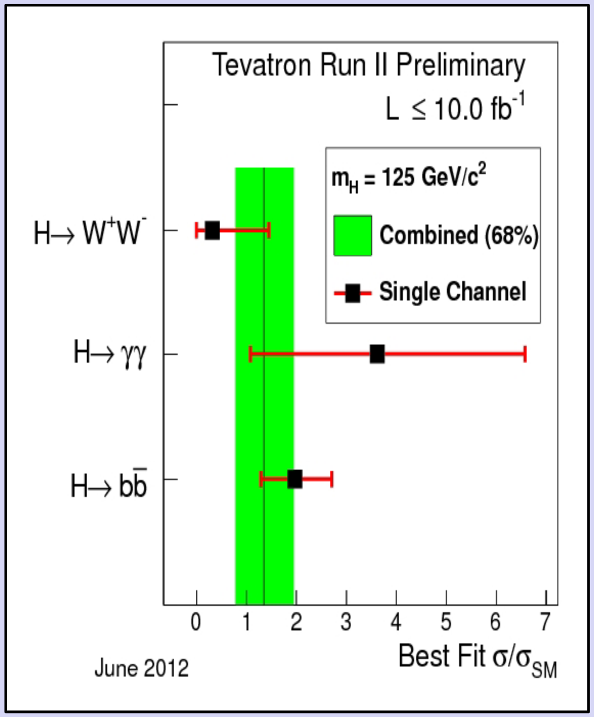
- **Both ATLAS and CMS see over 5σ significance for Higgs-like particle**
- **Sensitivity comes mainly from ZZ and γγ decay channels**

Current Status of Higgs Searches

- **LHC provides very large samples of Higgs bosons (x100 Tevatron cross section)**
  - **Rare and clean decay modes, like gg can be used**
- **Tevatron, due to proton-antiproton collisions, provides unique opportunity to study most probable at 125 GeV decay mode: pair of b quarks and indicates coupling to fermions**







- **Careful analysis of all available data, including cross sections at vastly different collision energies, demonstrates good agreement between properties of the observed particle and predicted in Standard Model Higgs boson**
- **Together with precision W boson and top quark mass measurements all indications that the particle we see is indeed the Higgs boson**

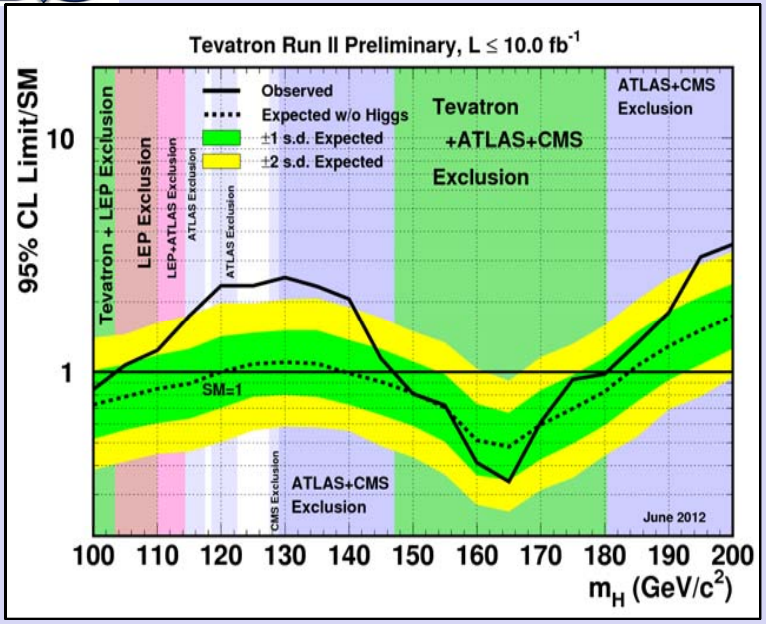
Looking Ahead

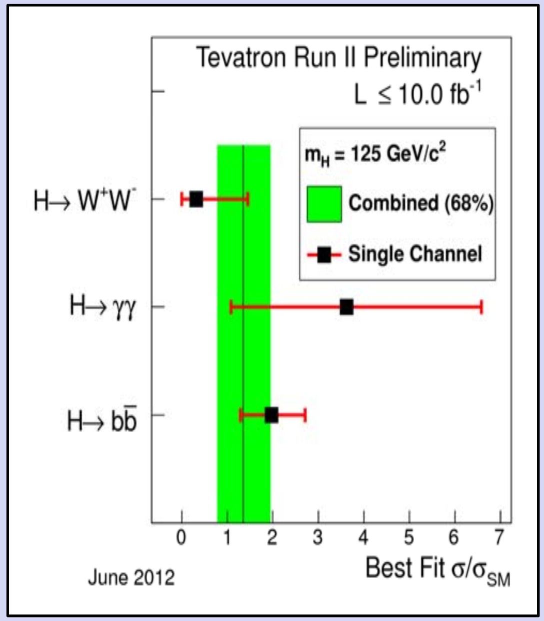
- **Tevatron**
  - **Improved analysis will gain another ~10% in sensitivity**
  - **Using mass constrain of 125 GeV will improve measurements of branching fraction to a pair of b-quarks**
  - **Publications of ~20 papers to document vast experience obtained in searches for Higgs boson**

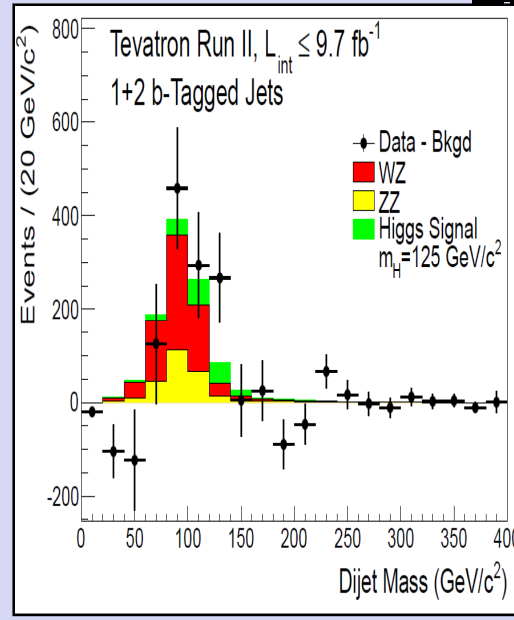
- **LHC**
  - **More data coming: ~30 fb^{-1} by later this year before ~2 years shutdown**
  - **Sensitivity over 3 σ for majority decay modes, including fermions**
  - **Measurement of Higgs spin using large data sets**
  - **Measurement of Higgs couplings**

- **Higgs factory!?**
  - **As mass is relatively low, medium energy lepton collider**
  - **High luminosity is required for reasonable number of Higgses**
  - **Exciting option widely discussed**

Evidence for Higgs Boson with Full Tevatron Data Set







- **Tevatron Higgs search data are incompatible with background only hypothesis**
  - **For Higgs to bb channel p-value is 3.1σ**
- **Tevatron data are compatible with Standard Model Higgs boson production in the mass range**
  - **115 GeV < M_H < 135 GeV in all studied channels including H → bb, H → WW and H → $\gamma\gamma$**
  - $(\sigma_{WH} + \sigma_{ZH}) \times \mathcal{B}(H \to b\bar{b}) = 0.23^{+0.09}_{-0.08}\ (\mathrm{stat} + \mathrm{syst})\ \mathrm{pb}$
- **Based on Tevatron results, including precision W boson and top quark mass measurements, new particle has properties predicted for the Higgs in the Standard Model and couples to fermions**

- **All of the above is interpreted as**
  - **Evidence for Higgs boson production at the Tevatron**