The Tevatron's Search for the Standard Model Higgs Boson

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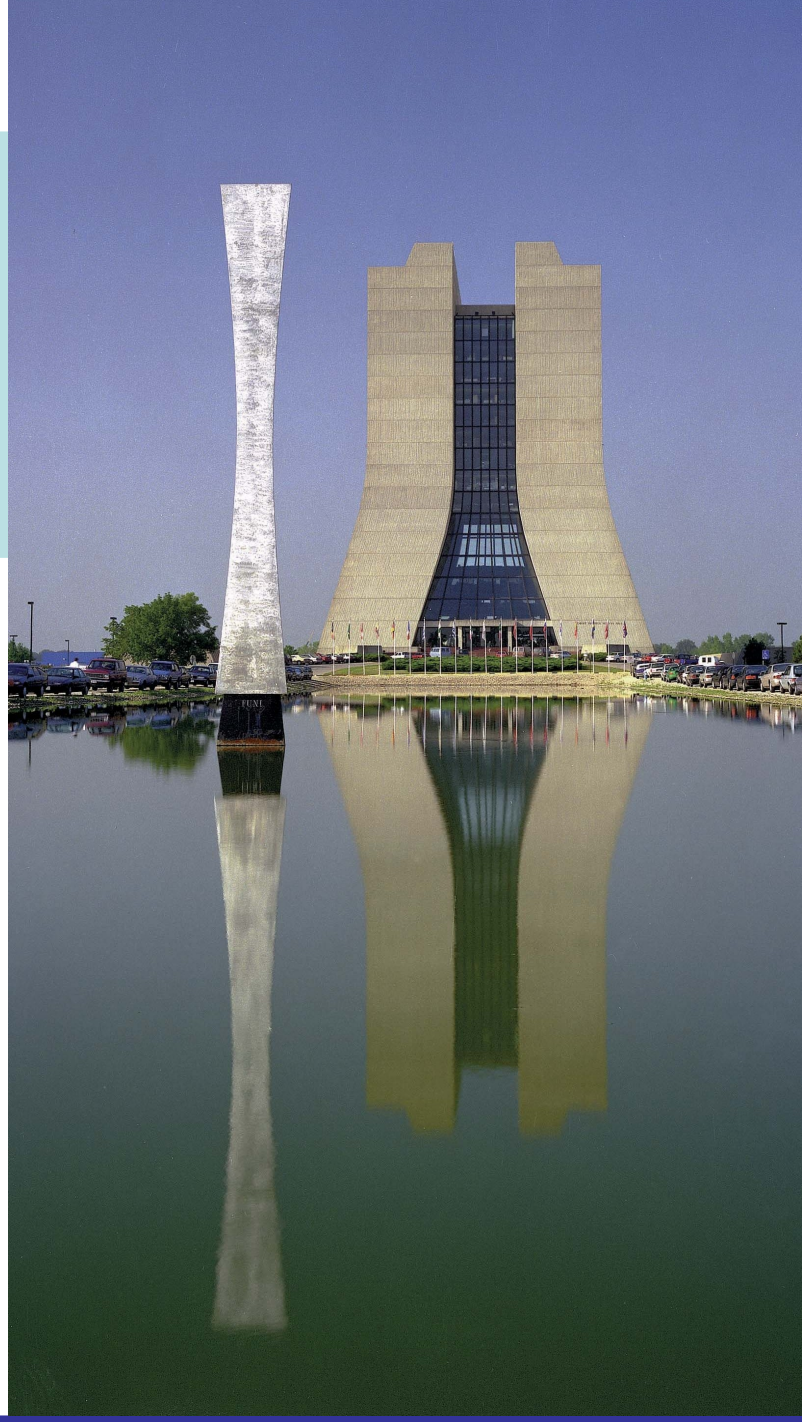
Michigan State University

On behalf of the CDF & DØ Collaborations



Outline

- The Tevatron's Higgs Search
  - Theory & existing evidence
  - Higgs production & decay at the Tevatron
  - Low mass search strategies
  - High mass search strategies
- Results & Outlook
  - New limits on Higgs production
  - Impact to global fits
  - Prospects for the future

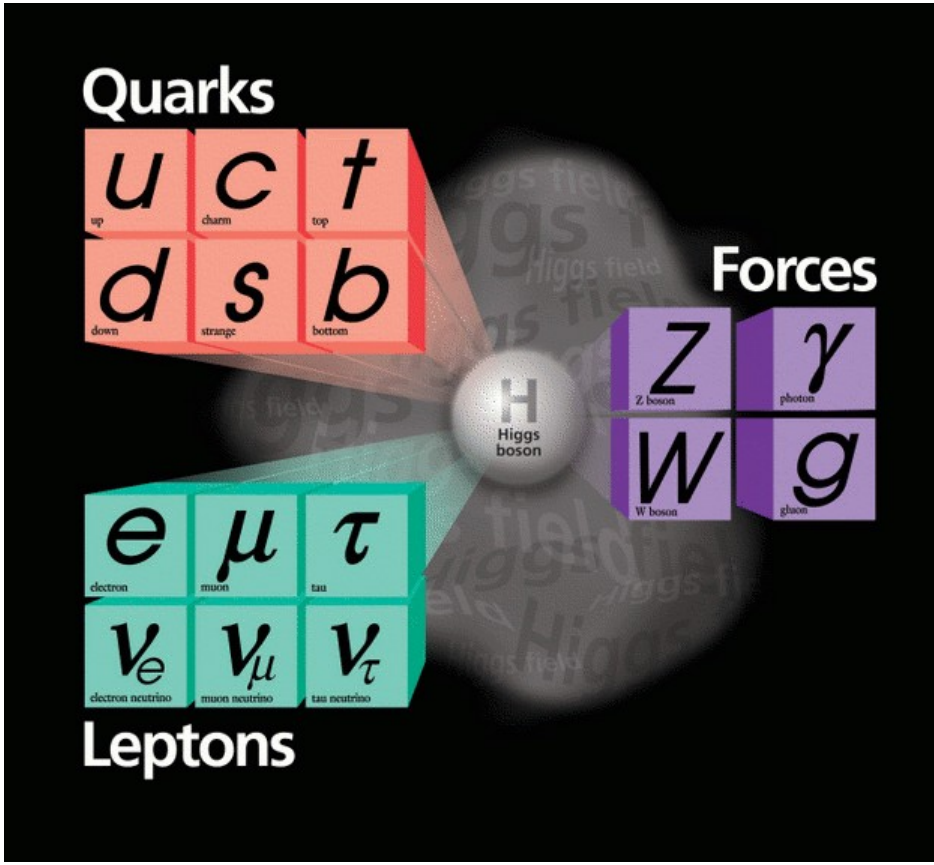
The Case for the Higgs

The Standard Model of particle physics

- Describes known particles & interactions
- Does ***not*** describe mass generation
- The BEGHHK* mechanism may be a solution

The theory predicts a new particle, but not its mass

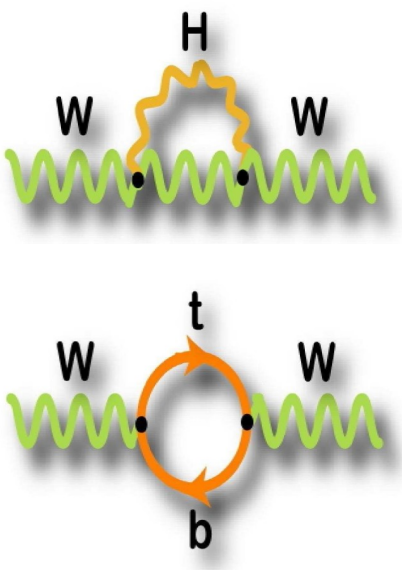
- If it exists, the mass must be determined experimentally

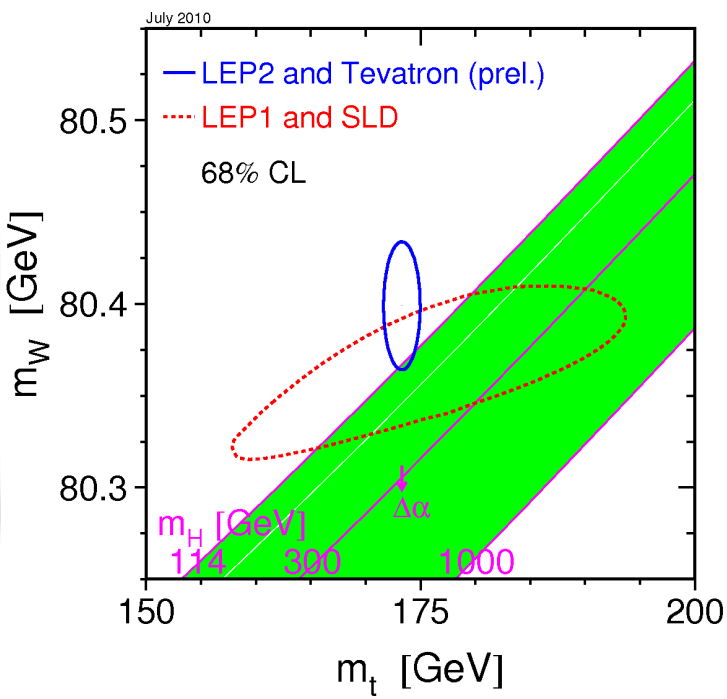


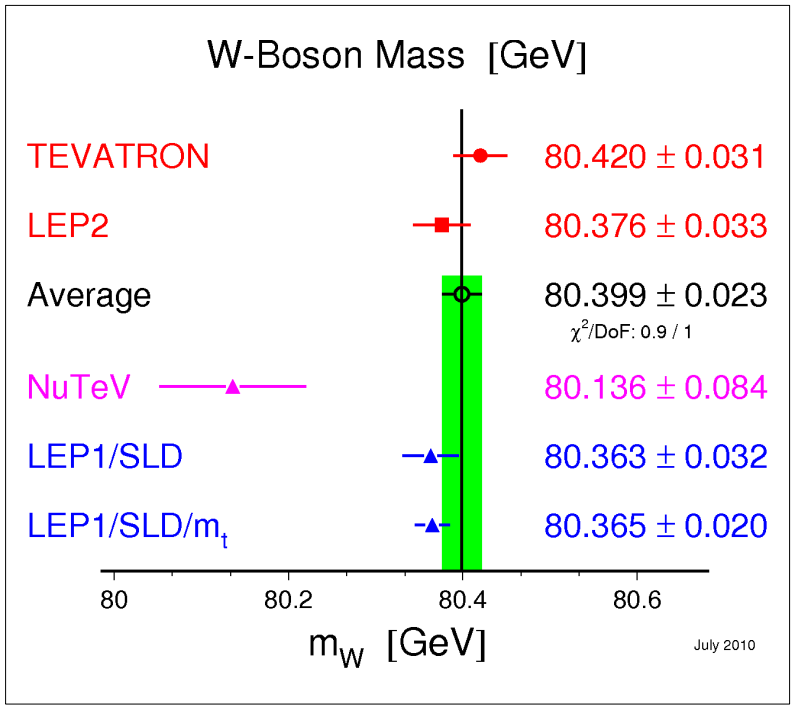
* F. Englert and R. Brout, Phys. Rev. Lett. 13: 321-323 (1964);
P.W. Higgs, Phys. Rev. Lett. 13: 508-509 (1964);
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble, Phys. Rev. Lett. 13: 585-587 (1964).

Experimental Constraints

- Existing experimental results can point us in the right direction
  - Direct search at LEPII resulted in lower mass bound: **M_H>114.4 GeV**
  - Refinements of top-quark and W-boson masses can indicate Higgs mass
  - **Top Mass: CDF+DØ: 173.1 ± 0.6 *(stat)* ± 1.1 *(syst)* GeV**
  - **W Mass: Tevatron measurements on track to dominate world average**







Indirect Experimental Evidence

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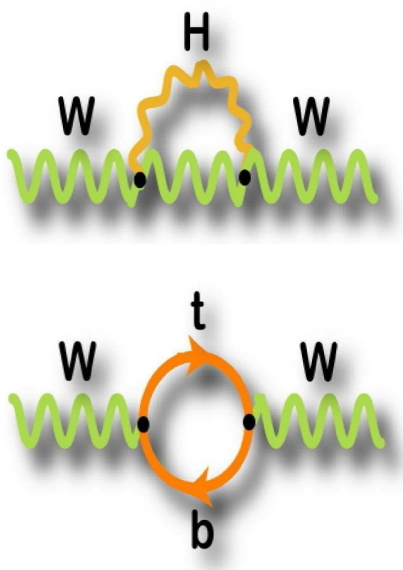
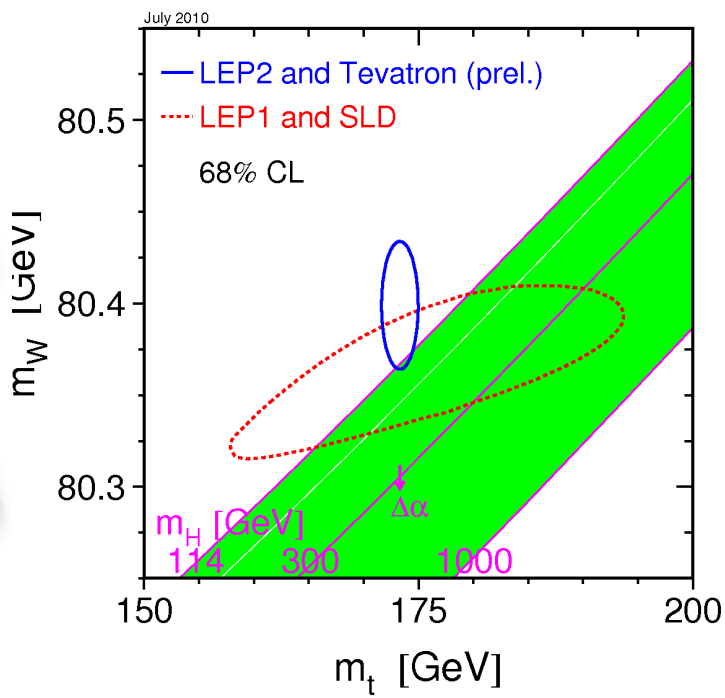
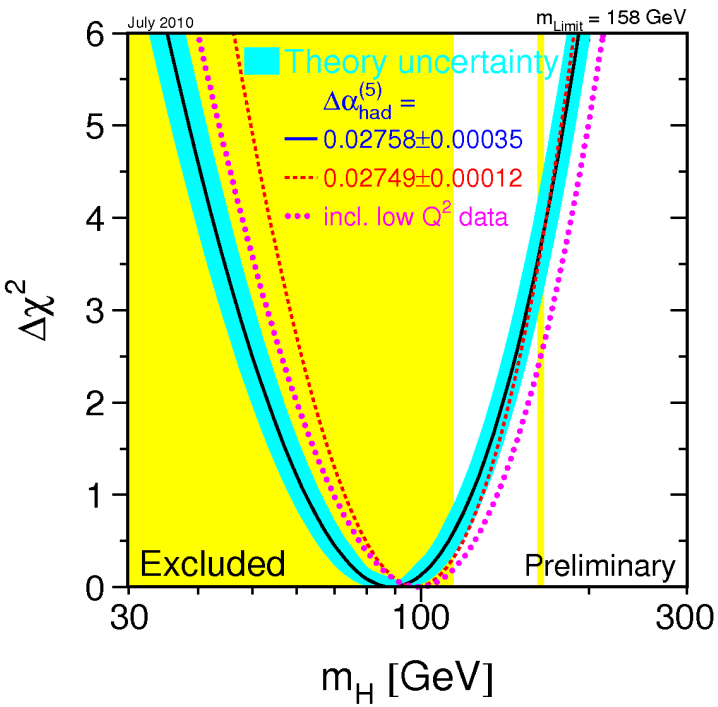
  - Refinements of top-quark and W-boson masses can indicate Higgs mass
  - **A fit of precision electroweak data yields: M_H < 185 GeV at 95% C.L.**
  - ***(M_H < 158 GeV not including the LEP II limit)***







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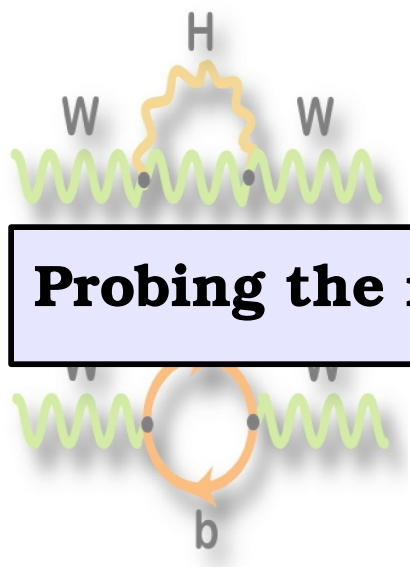
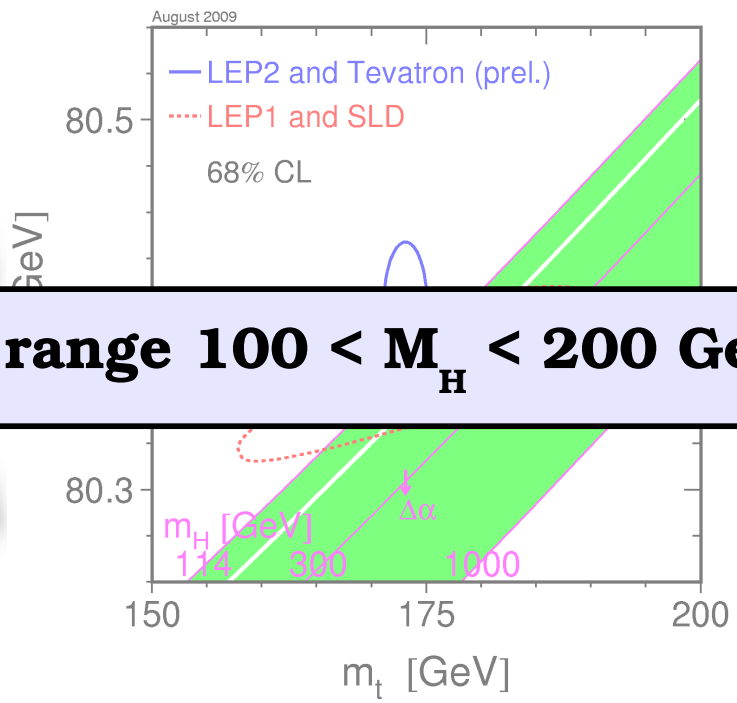
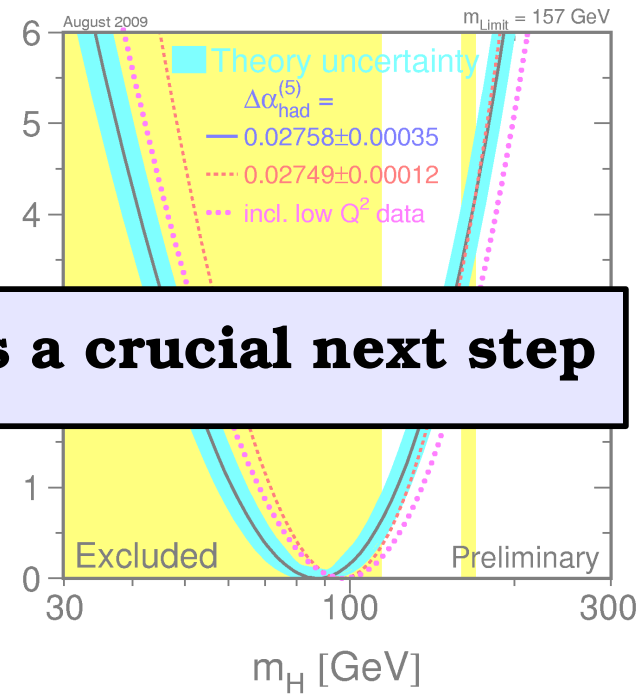




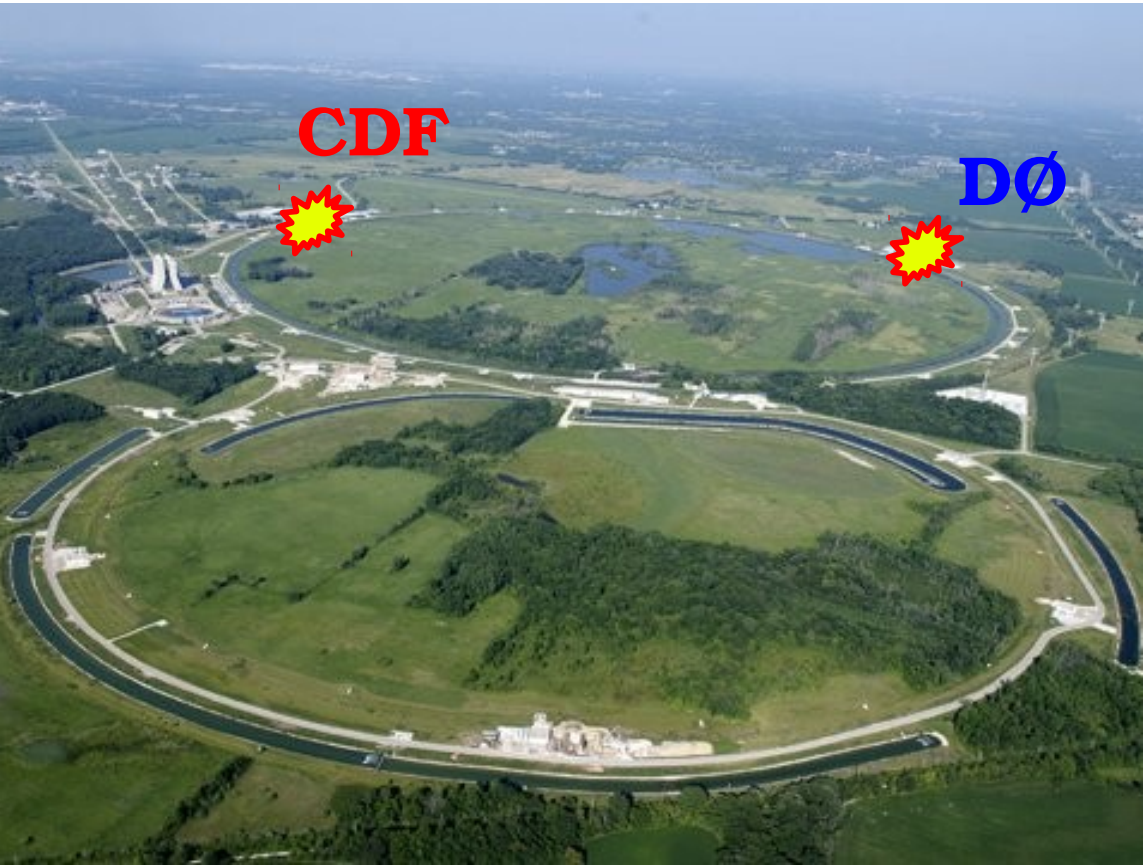


Probing the range 100 < M_H < 200 GeV is a crucial next step

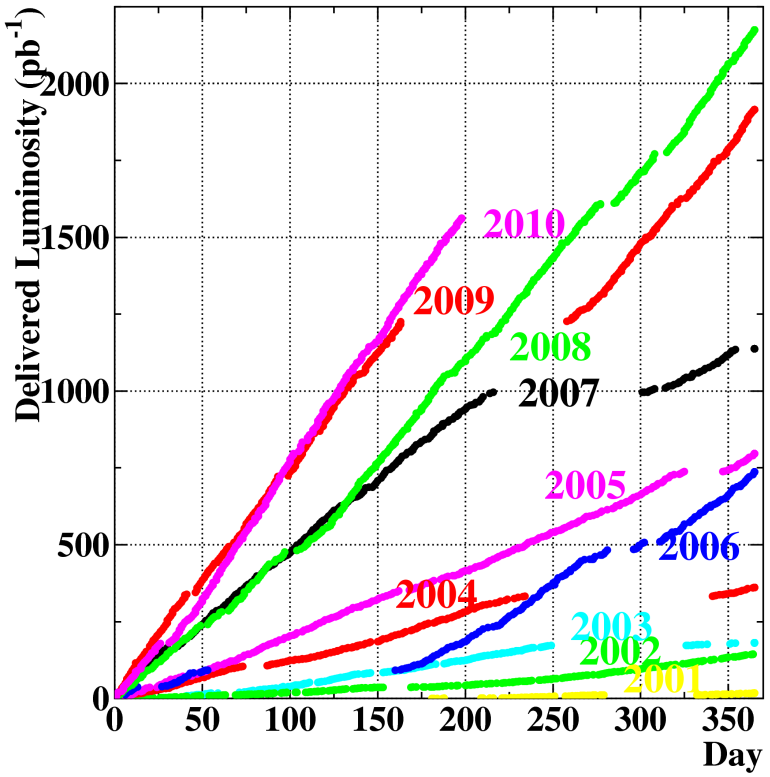
The Continued Higgs Search

- Generations of physicists are eagerly awaiting the next chapter
  - The Tevatron collider provides an excellent hunting ground
  - Both experiments (CDF & DØ) have been delivered **>9 fb^{-1}** as of July 2010!
  - At least one more year of running planned beyond 2010

Tevatron Accelerator Complex

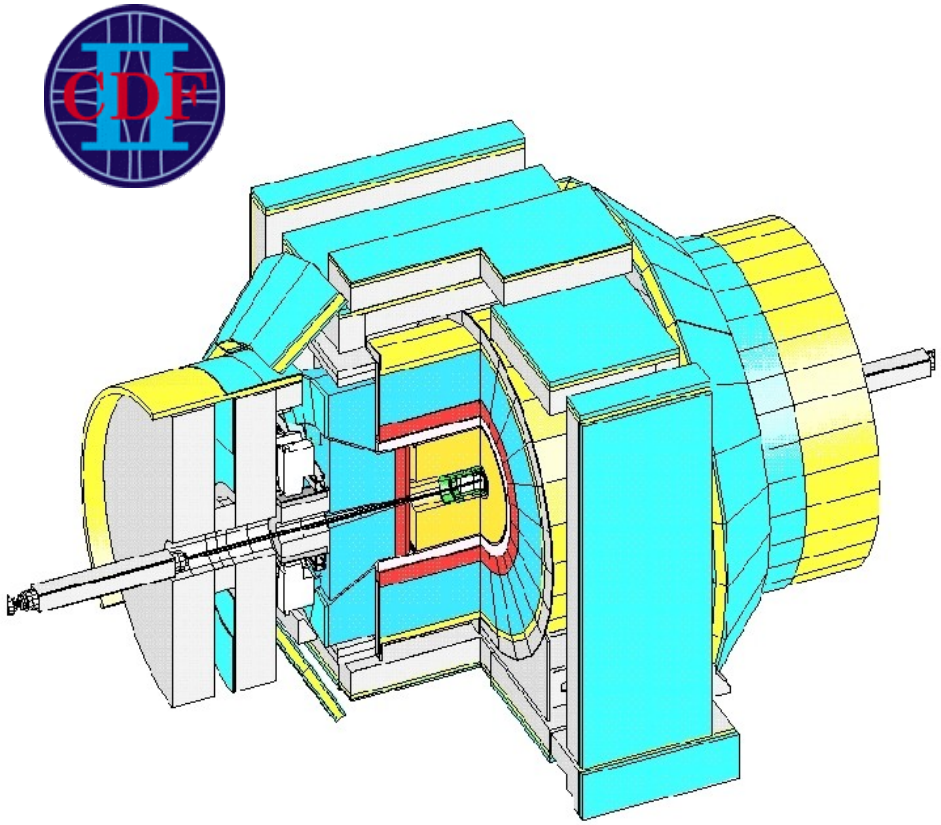


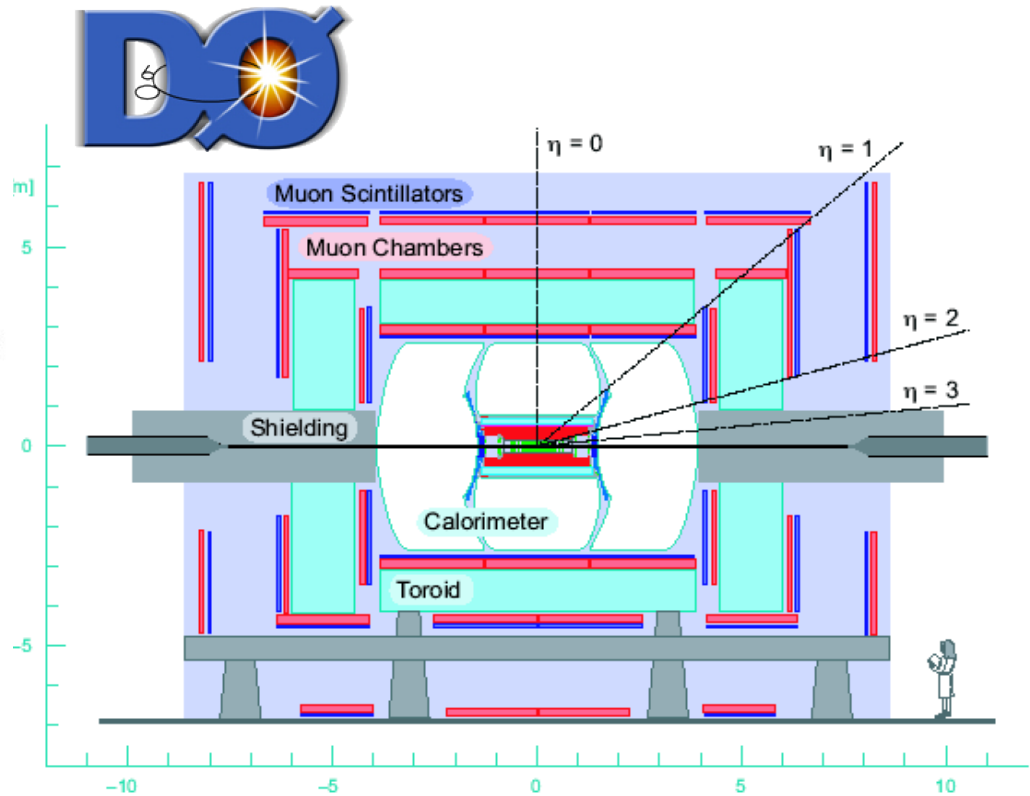
Luminosity Delivered to CDF per Calendar Year



Tevatron Experiments

- Tevatron experiments: multipurpose detectors with broad particle-ID capability
  - Stable detectors and trigger. No further upgrades planned.
  - Efficient data taking through the highest instantaneous luminosities





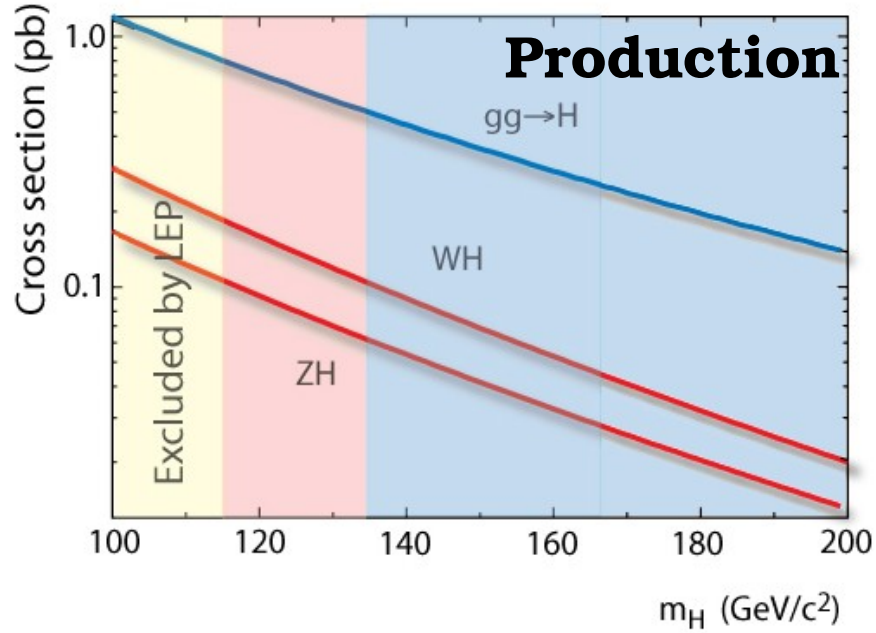
Tevatron Higgs Search Strategy

Higgs production via gluon fusion dominates at the Tevatron

- Large multijet background makes fully hadronic searches difficult

Next largest rate is associated production of W/Z bosons + Higgs

- Leptonic decays of W/Z bosons provide a tag for triggering and analysis

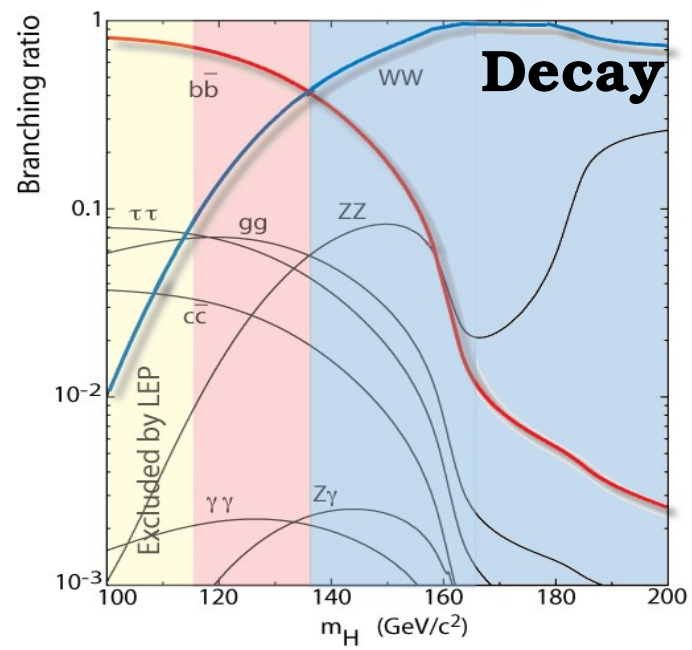


A low-mass Higgs (M_H < 135 GeV) prefers to decay to bottom-quark pairs

- Need efficient identification of bottom quarks to reduce backgrounds

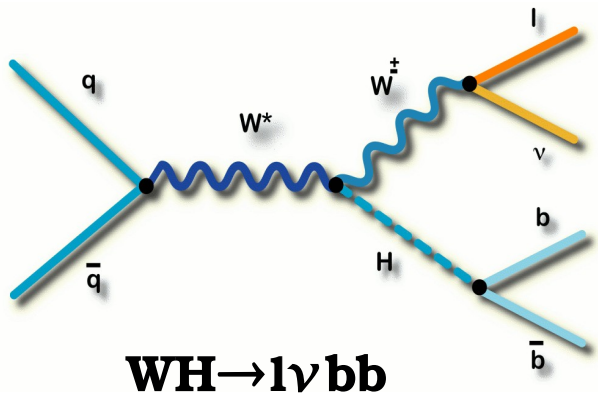
At high mass (M_H > 135 GeV), search for $H \rightarrow WW^*$

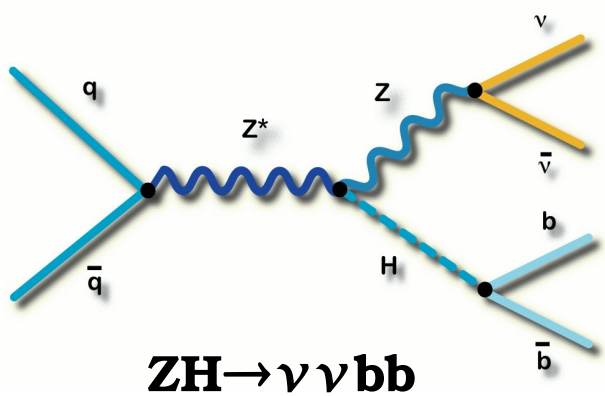
- Potential for an off-shell W boson allows non-resonant production

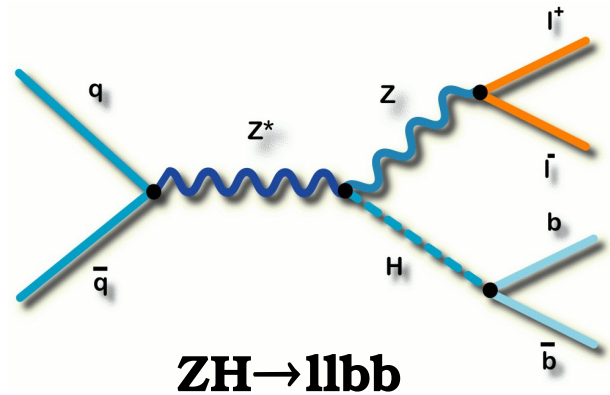


Higgs Search Channels

Associated Production: 3 dominant final states. Up to M_H=150 GeV



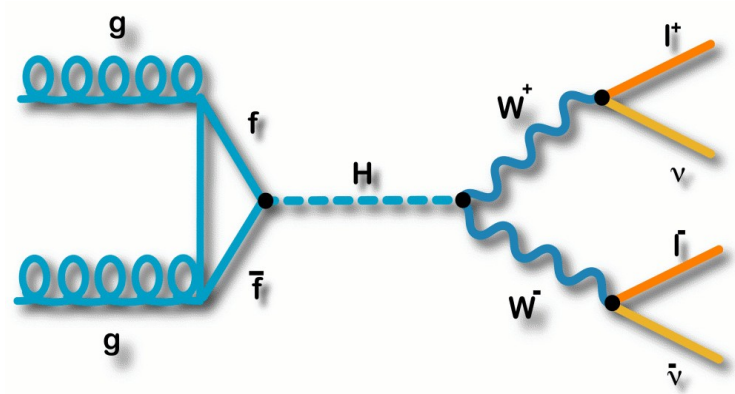




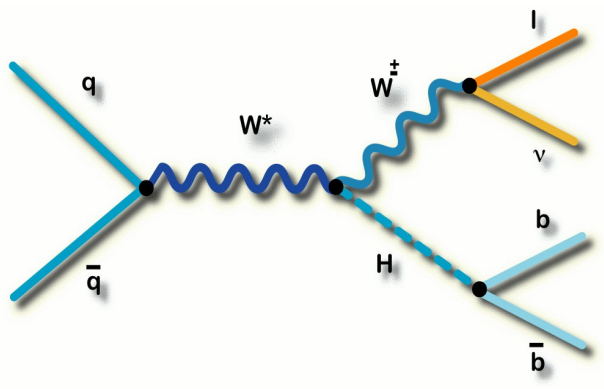
Gluon Fusion Production:

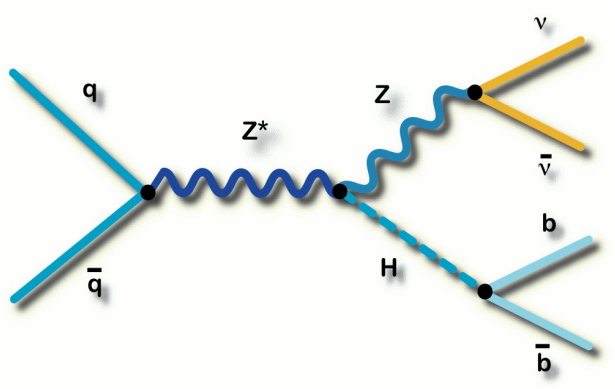
Search from 110 < M_H < 200 GeV

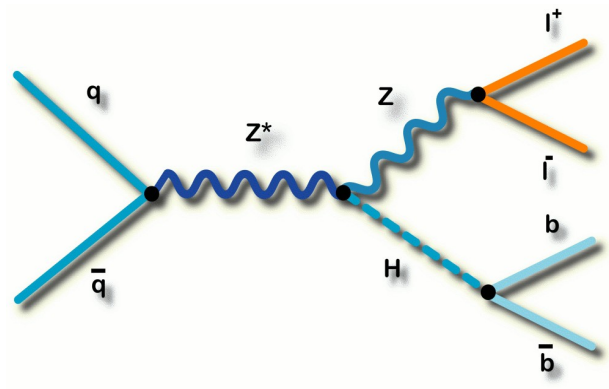
Maximum sensitivity near M_H=165 GeV

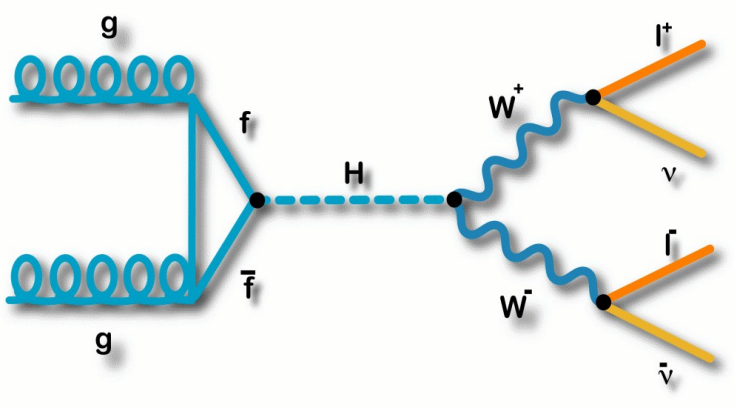


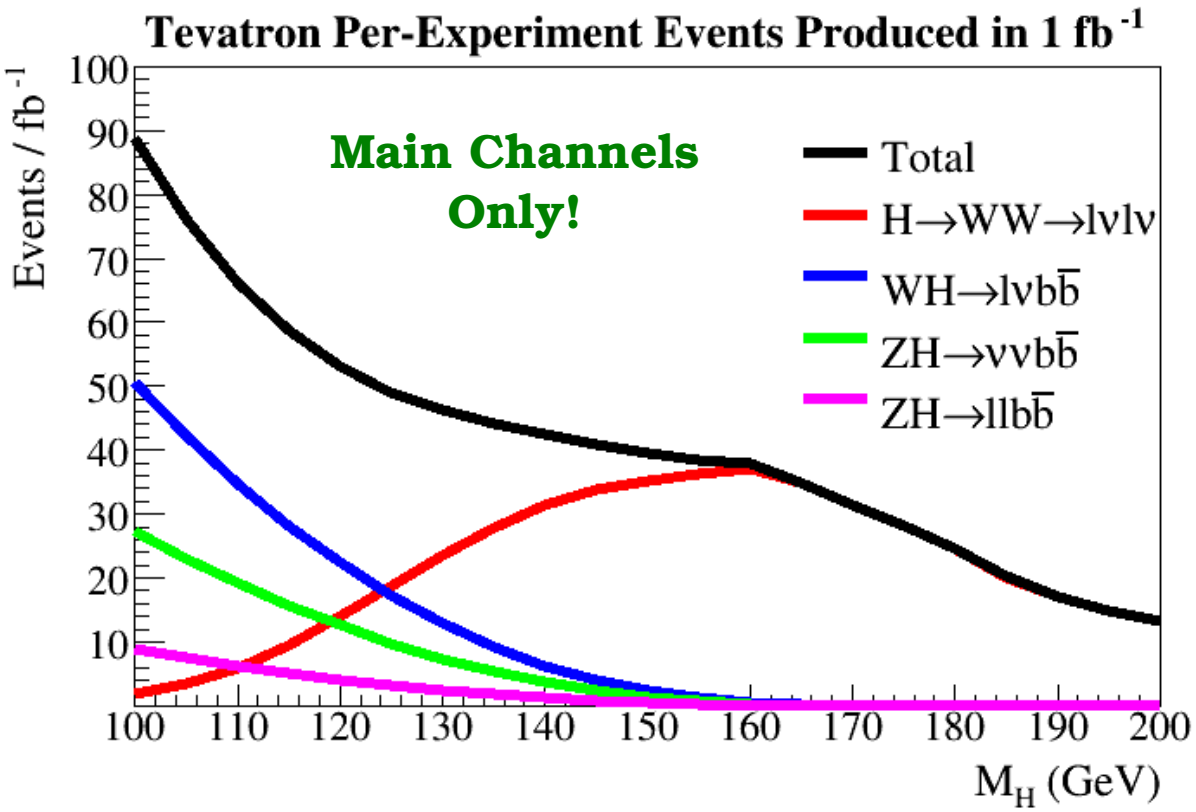
Higgs Search Channels











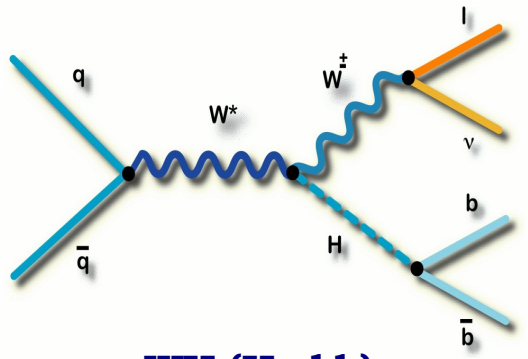
Higgs Search Channels

A broad search program!

TABLE I: The production cross sections and decay branching fractions for the SM Higgs boson assumed for the combination.

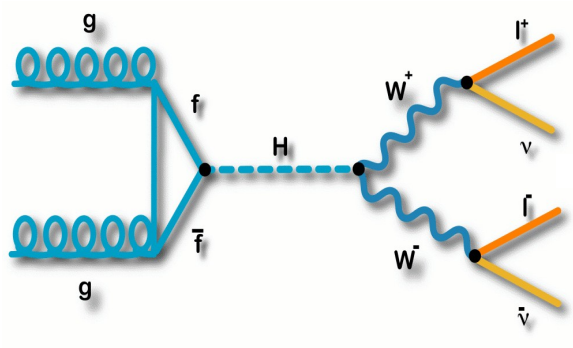
m_H (GeV/c^2)	$\sigma_{gg\to H}$ (fb)	σ_{WH} (fb)	σ_{ZH} (fb)	σ_{VBF} (fb)	σ_{ttH} (fb)	$B(H\to b\bar{b})$ (%)	$B(H\to c\bar{c})$ (%)	$B(H\to\tau^+\tau^-)$ (%)	$B(H\to W^+W^-)$ (%)	$B(H\to ZZ)$ (%)	$B(H\to\gamma\gamma)$ (%)
100	1861	291.9	169.8	99.5	8.000	80.33	3.542	7.920	1.052	0.1071	0.1505
105	1618	248.4	145.9	93.3	7.062	78.57	3.463	7.821	2.307	0.2035	0.1689
110	1413	212.0	125.7	87.1	6.233	75.90	3.343	7.622	4.585	0.4160	0.1870
115	1240	181.9	108.9	79.07	5.502	71.95	3.169	7.288	8.268	0.8298	0.2029
120	1093	156.4	94.4	71.65	4.857	66.49	2.927	6.789	13.64	1.527	0.2148
125	967	135.1	82.3	67.37	4.279	59.48	2.617	6.120	20.78	2.549	0.2204
130	858	116.9	71.9	62.5	3.769	51.18	2.252	5.305	29.43	3.858	0.2182
135	764	101.5	63.0	57.65	3.320	42.15	1.854	4.400	39.10	5.319	0.2077
140	682	88.3	55.3	52.59	2.925	33.04	1.453	3.472	49.16	6.715	0.1897
145	611	77.0	48.7	49.15	2.593	24.45	1.075	2.585	59.15	7.771	0.1653
150	548	67.3	42.9	45.67	2.298	16.71	0.7345	1.778	68.91	8.143	0.1357
155	492	58.9	37.9	42.19	2.037	9.88	0.4341	1.057	78.92	7.297	0.09997
160	439	50.8	33.1	38.59	1.806	3.74	0.1646	0.403	90.48	4.185	0.05365
165	389	44.6	30.0	36.09	1.607	1.29	0.05667	0.140	95.91	2.216	0.02330
170	349	40.2	26.6	33.58	1.430	0.854	0.03753	0.093	96.39	2.351	0.01598
175	314	35.6	23.7	31.11	1.272	0.663	0.02910	0.073	95.81	3.204	0.01236
180	283	31.4	21.1	28.57	1.132	0.535	0.02349	0.059	93.25	5.937	0.01024
185	255	28.2	18.9	26.81	1.004	0.415	0.01823	0.046	84.50	14.86	0.008128
190	231	25.1	17.0	24.88	0.890	0.340	0.01490	0.038	78.70	20.77	0.006774
195	210	22.4	15.3	23	0.789	0.292	0.01281	0.033	75.88	23.66	0.005919
200	192	20.0	13.7	21.19	0.700	0.257	0.01128	0.029	74.26	25.33	0.005285

Backgrounds & Rates



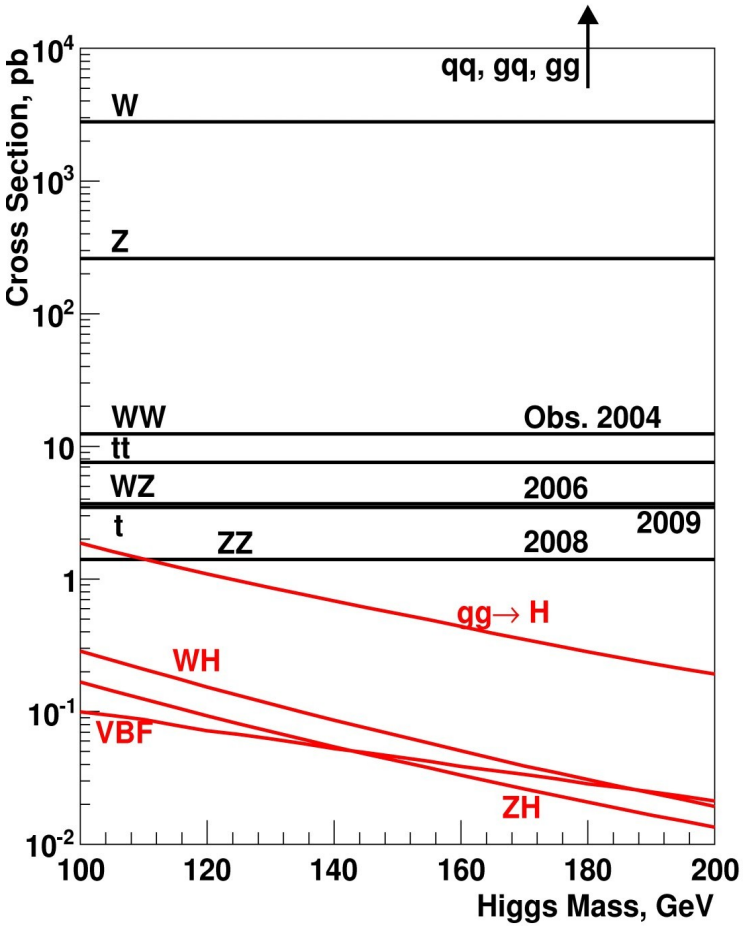
WH (H→bb)

$\sigma\times$BR = 130 fb @ M_H=115



gg→H→WW

$\sigma\times$BR = 373 fb @ M_H=160



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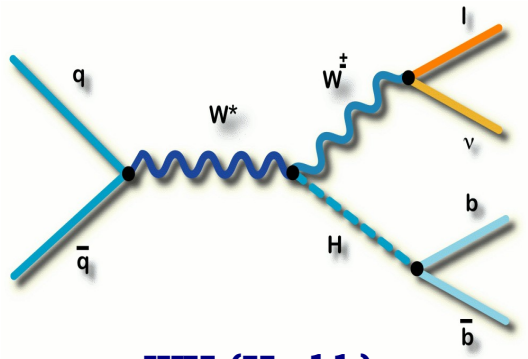

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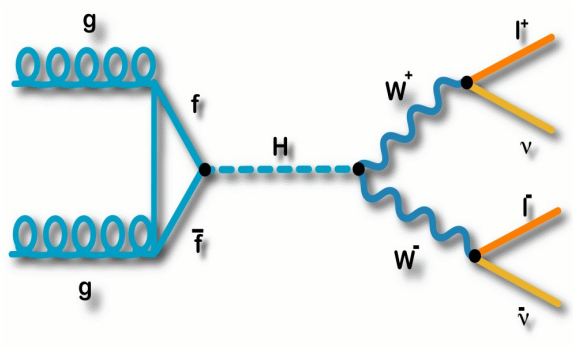

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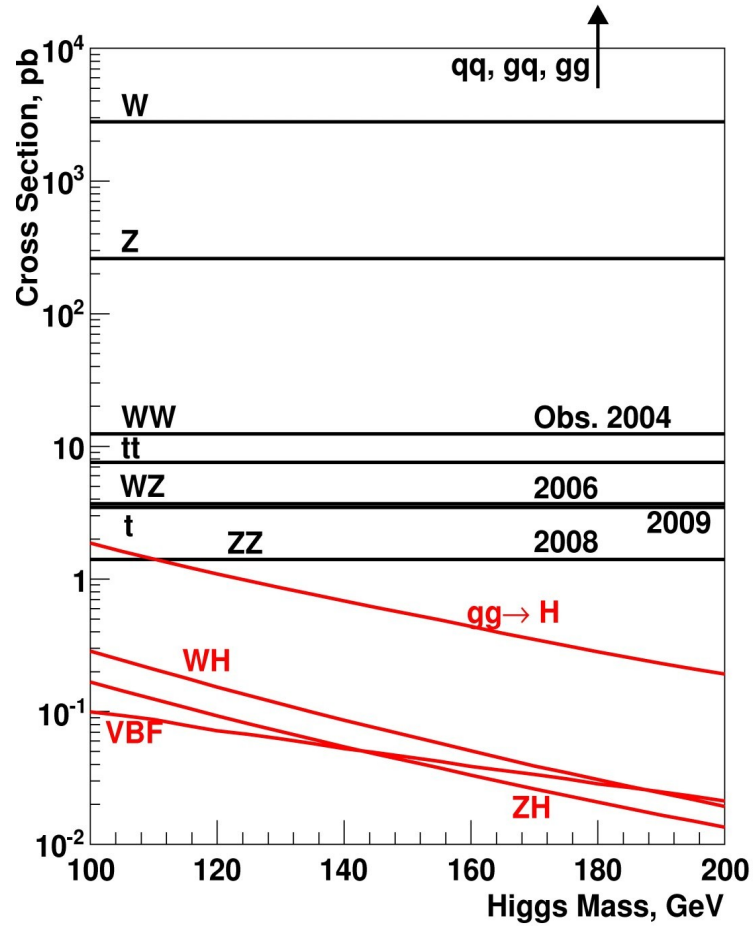
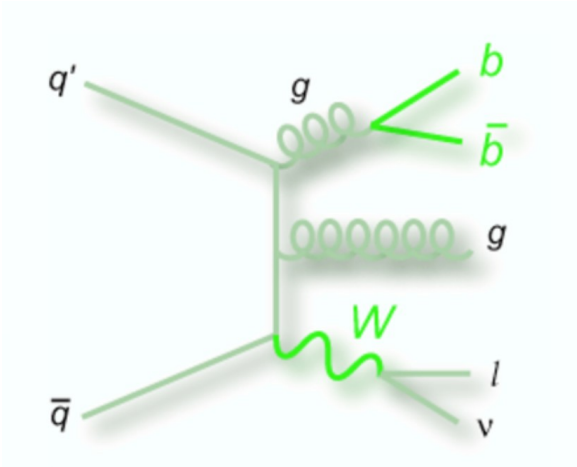
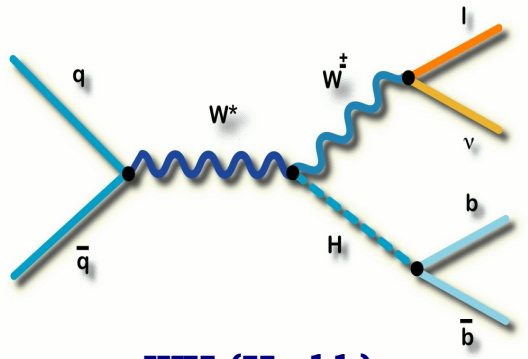




W/Z+jets or "Gluon Splitting"

$\sigma\times$BR > 3,000,000 fb

Backgrounds & Rates



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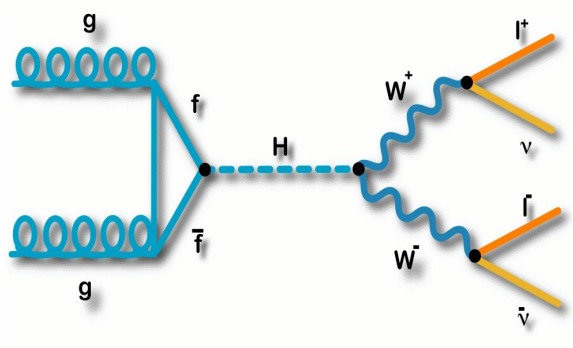

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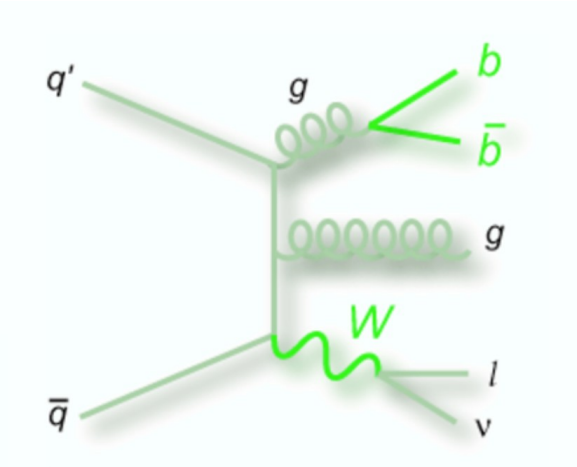

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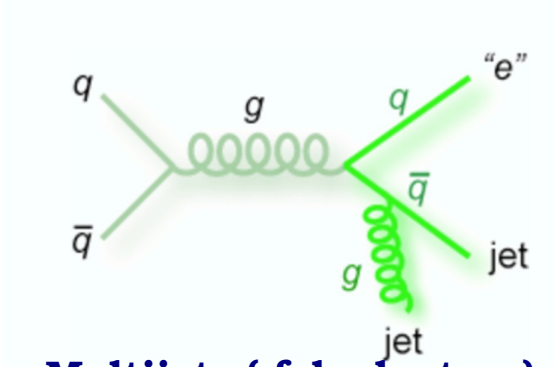
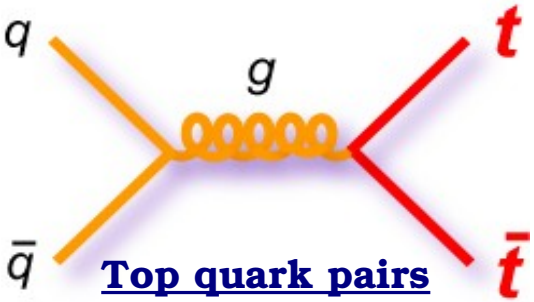
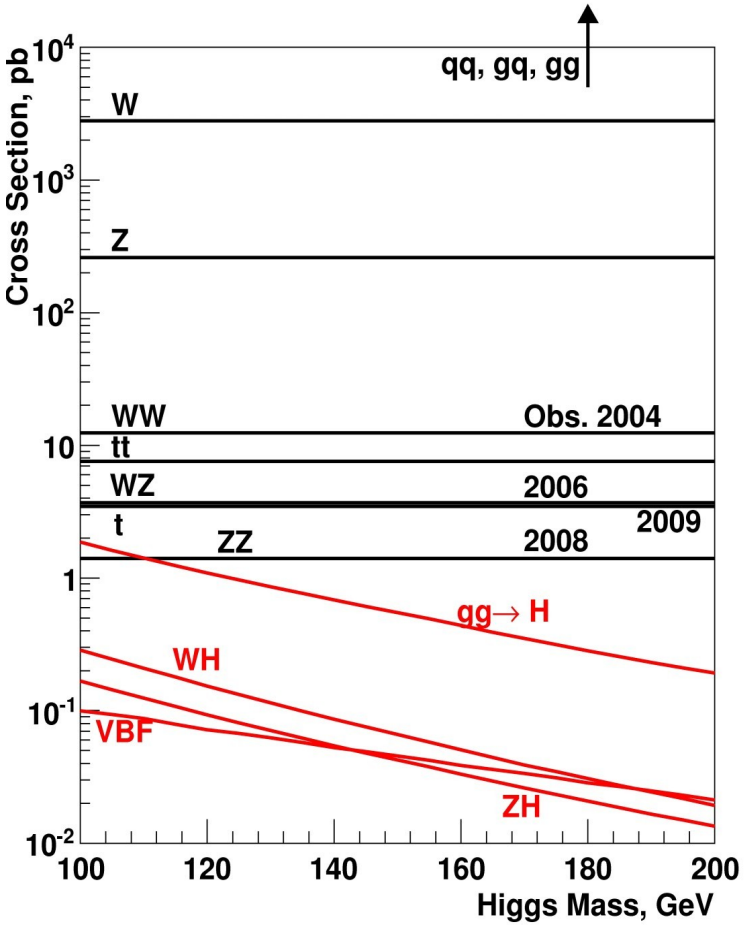


Multijets (fake lepton)
Measured in data

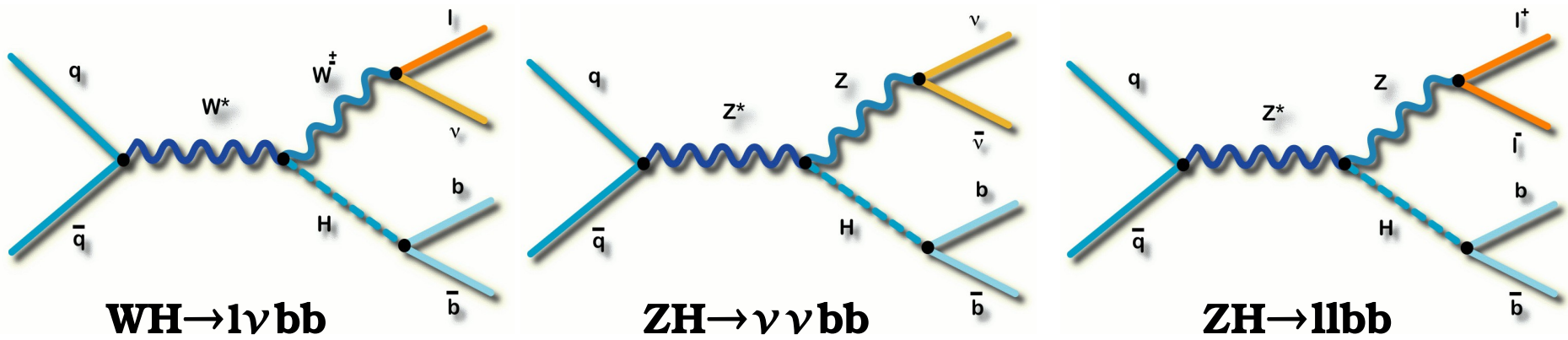


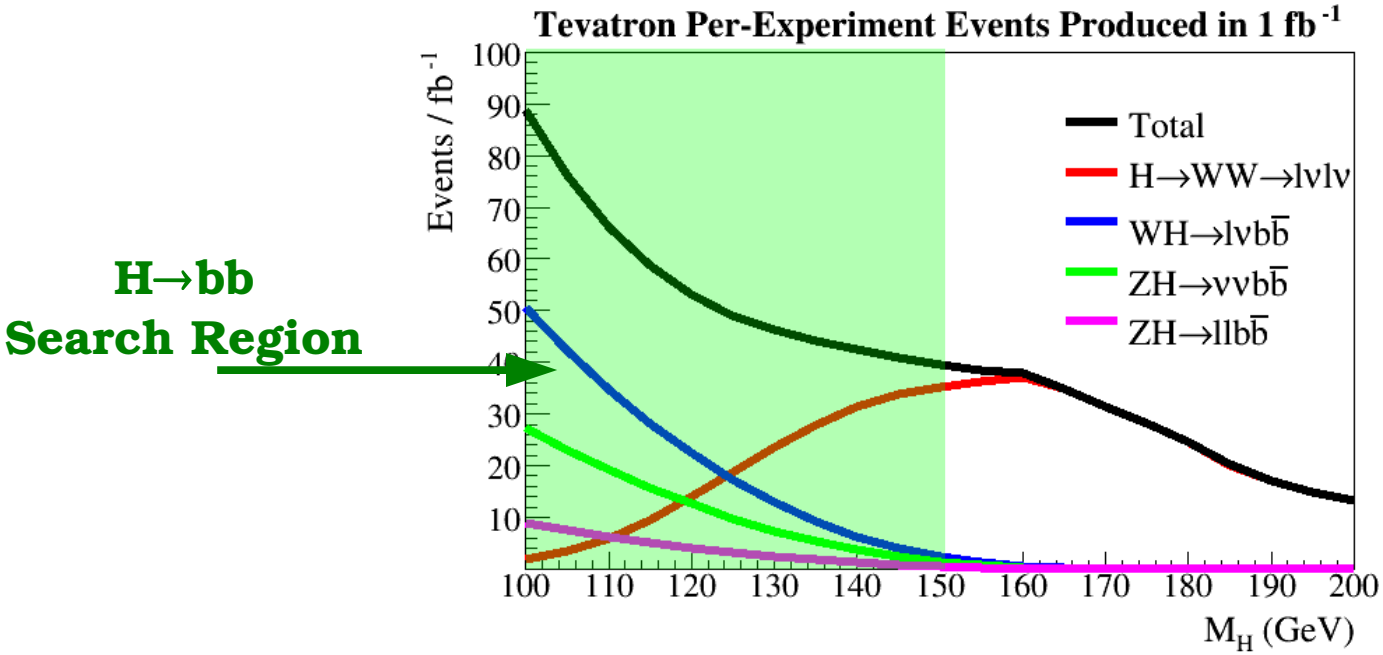
Top quark pairs
$\sigma\times$BR = 7,040 fb



Searching for a Low Mass Higgs

Associated Production: 3 dominant final states. Up to M_H=150 GeV





Selecting Vector Bosons

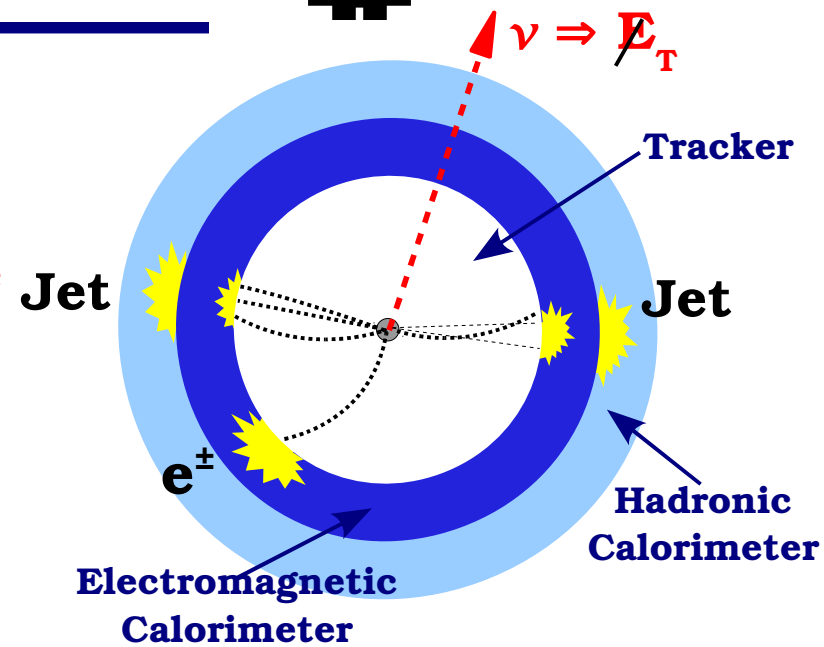
- Identify events consistent with W/Z decays

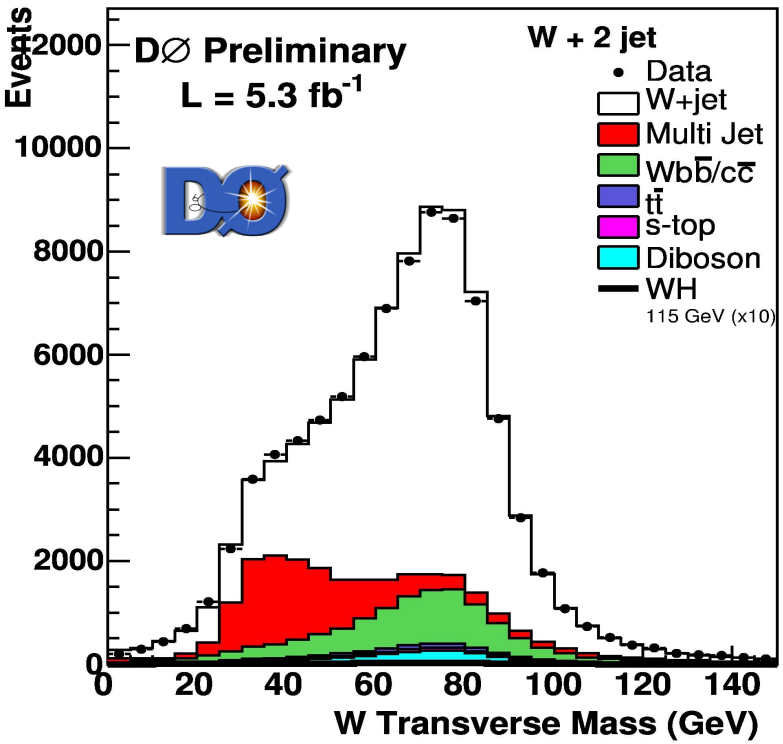
  Trigger on **electrons**, **muons, or MET**

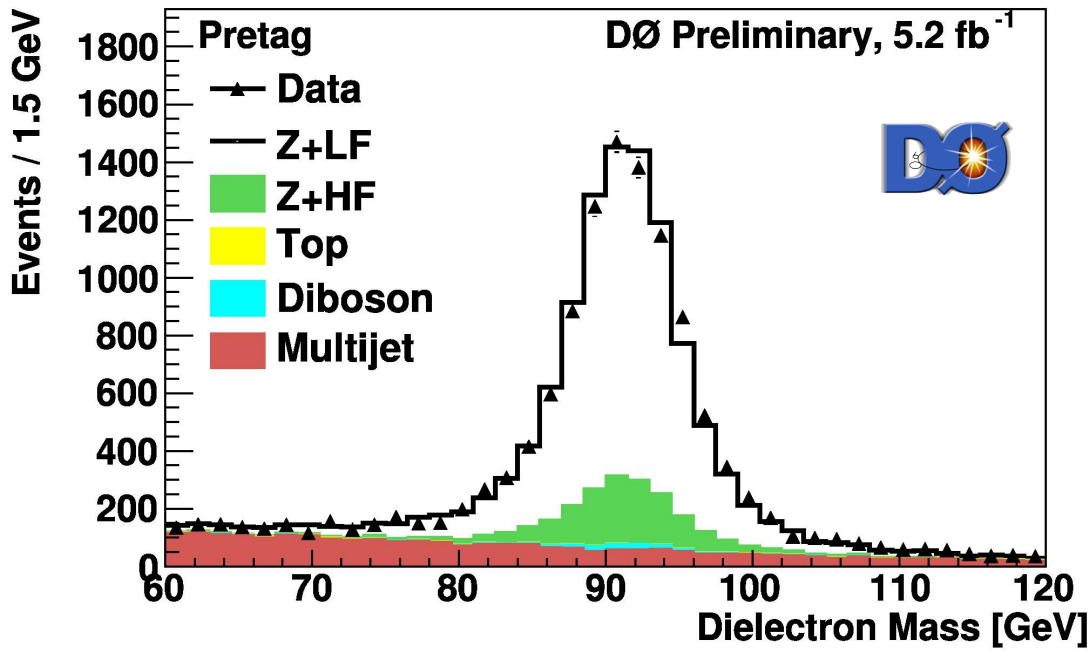
  W bosons: Select significant missing transverse energy (MET) as a signature for neutrinos

  Z bosons: Charged lepton signature very clean and have highly-efficient triggers.

  Z bosons: "Invisible" decays can be a challenge.



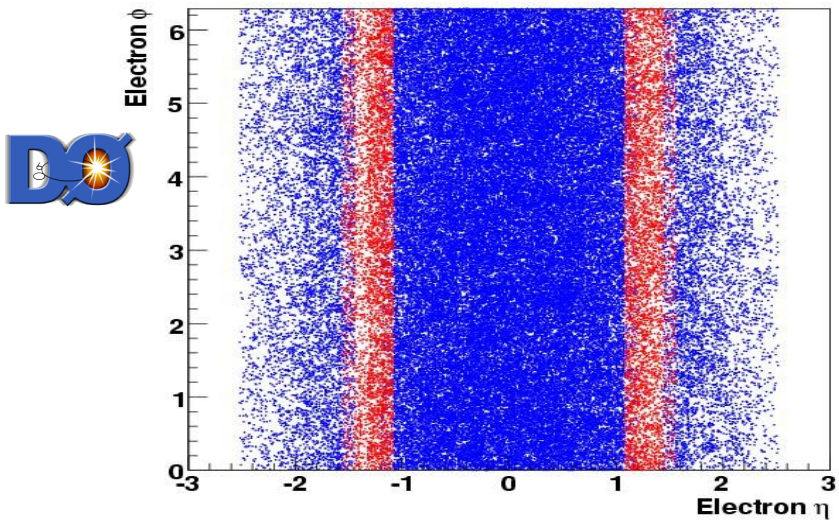


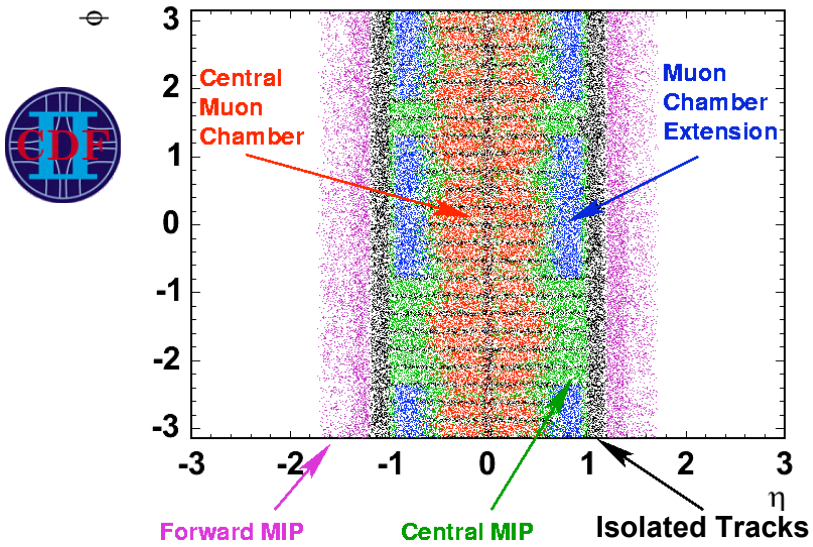


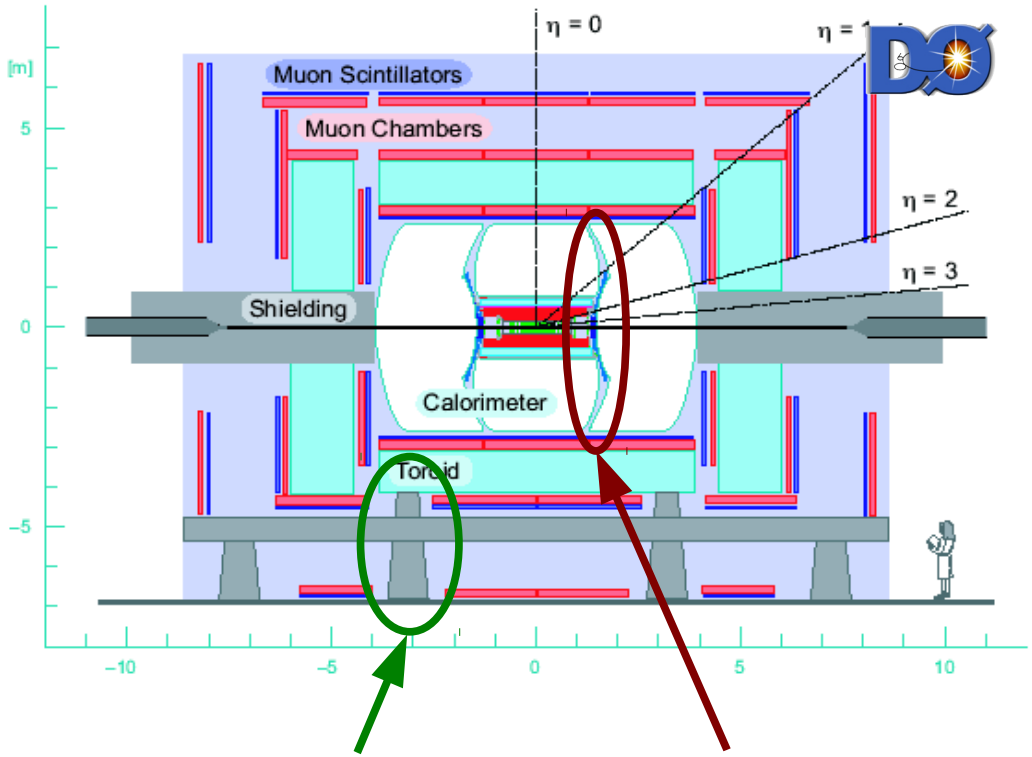
Recovering Leptons

- For finding weak bosons, charged leptons are Higgs-search gold

  Much effort has been poured into lepton recovery efforts to great success







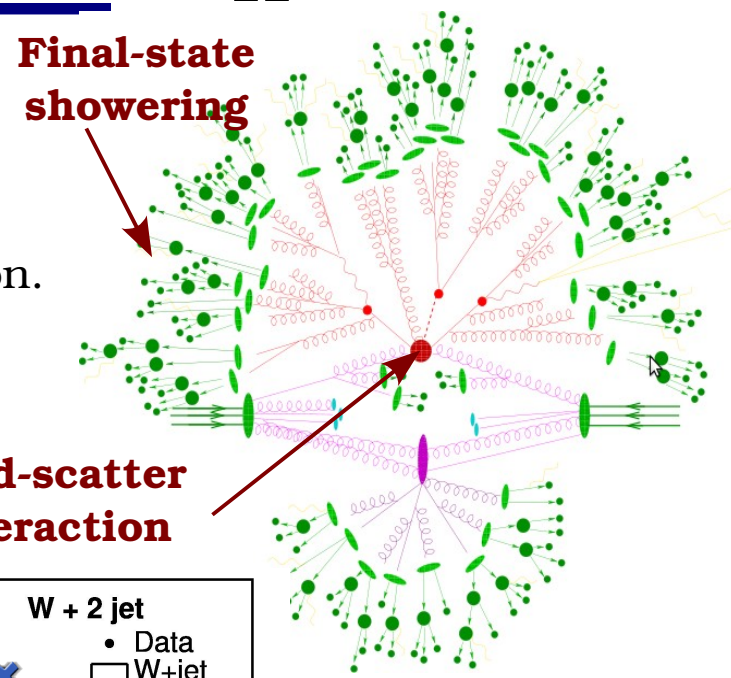
Tracks in detector support regions

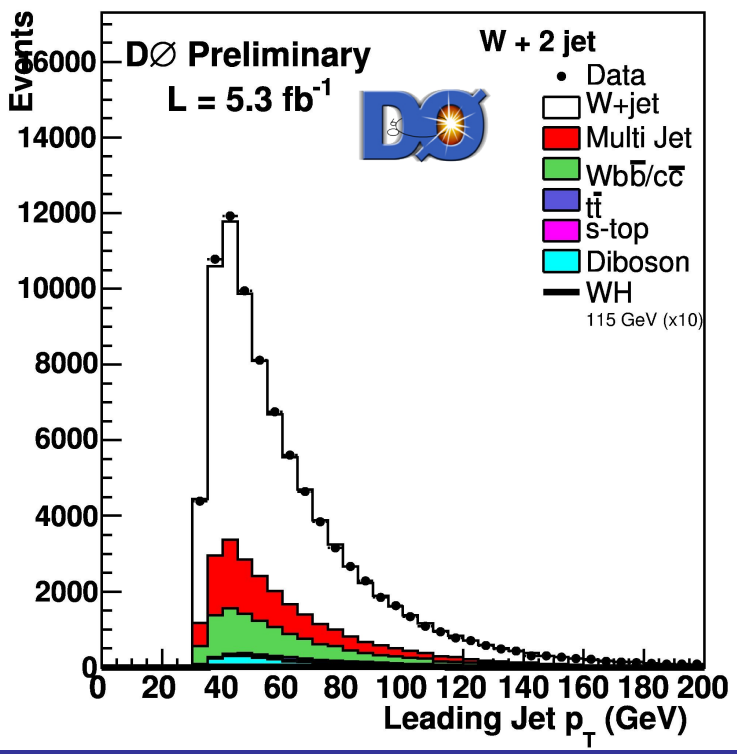
Electrons between cryostats

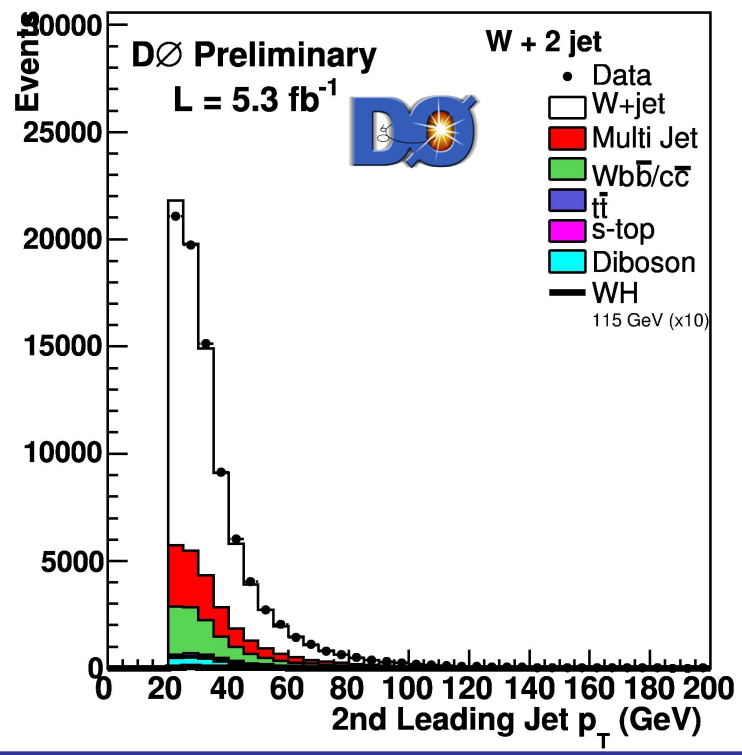
- MET + Jet triggers found to help boost muon triggering efficiency

Jet Selections

- Finding H→bb decays requires two hard jets
  - But hadron colliders are jet factories!
  - Predictions and simulations are notoriously difficult
    - A lot happens between hard-scatter and detection.
    - Both rates and distributions are uncertain
  - A lot of work goes into getting this right.







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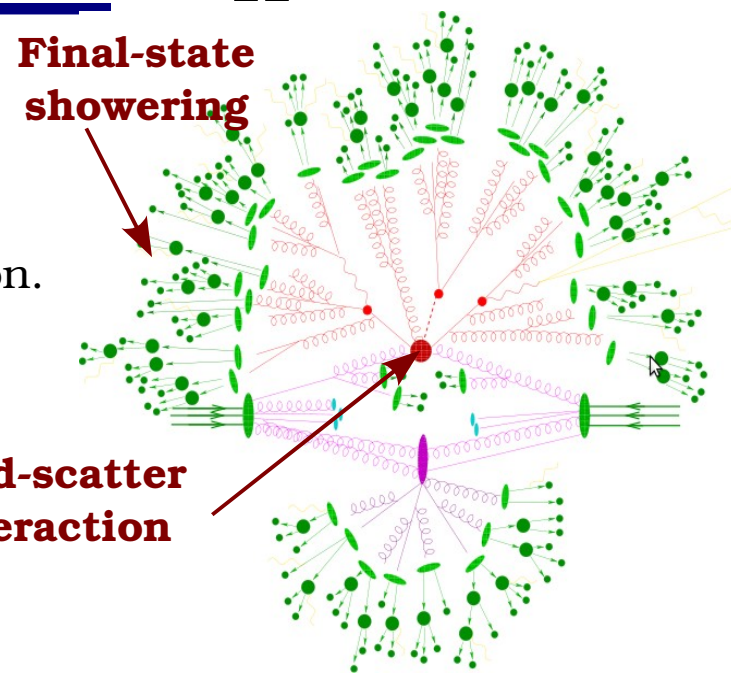
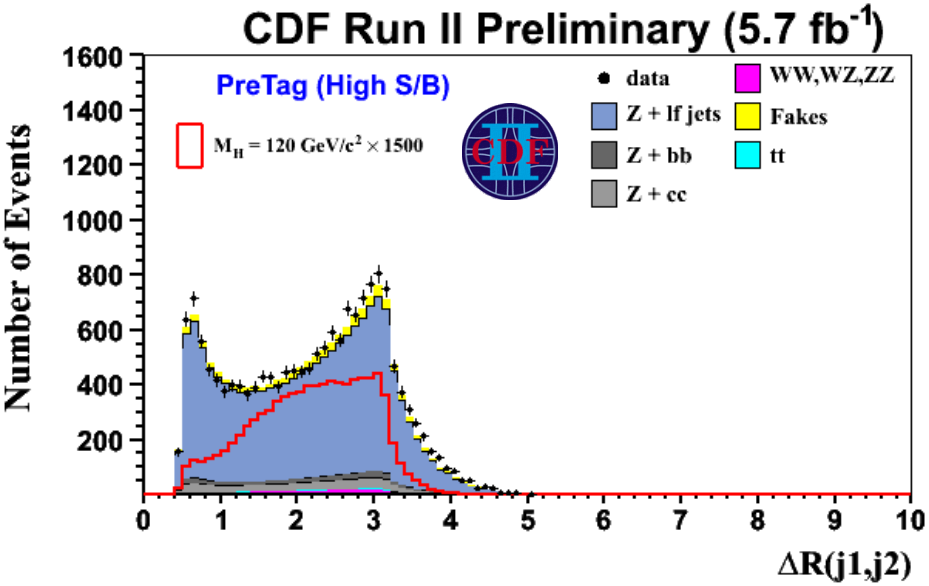
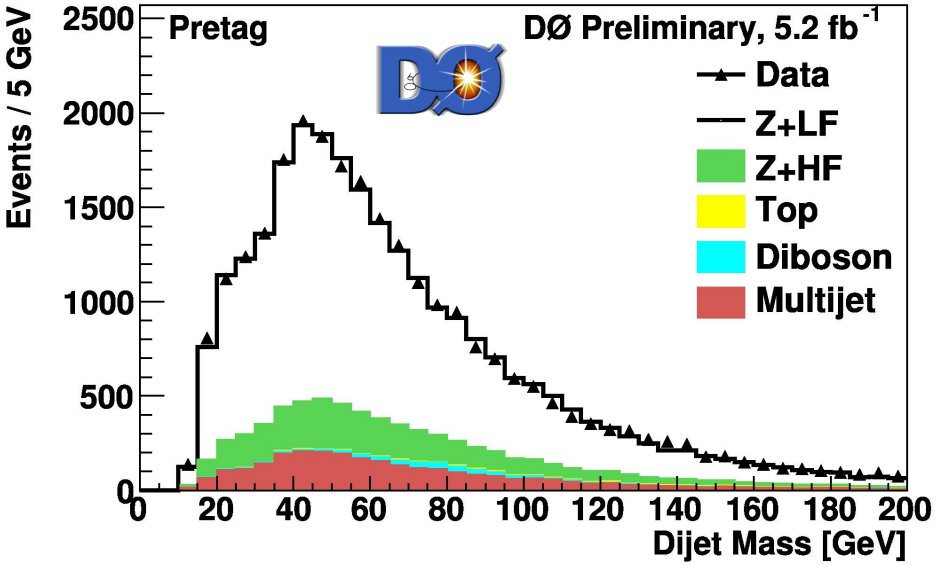
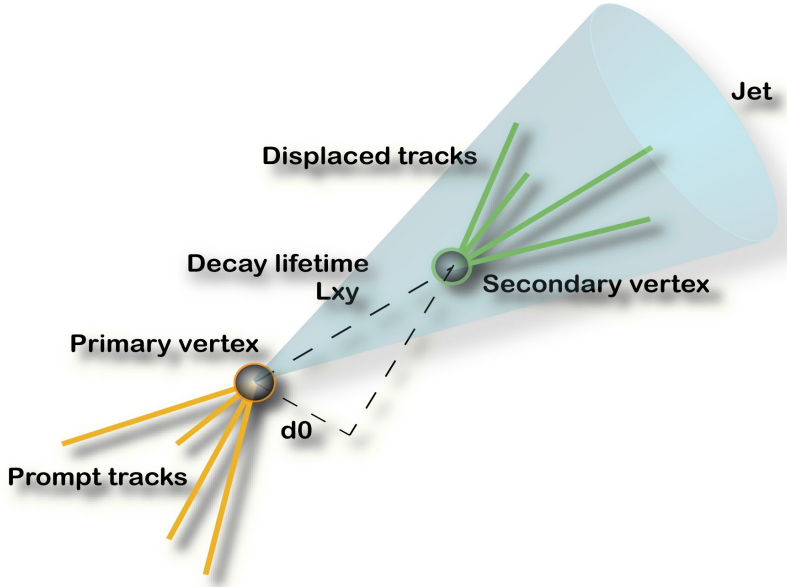






Identifying b Quarks



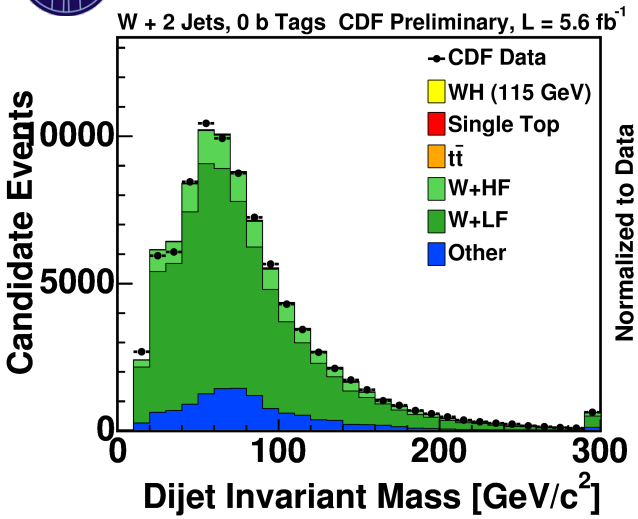
Background reduction via the identification of displaced jet decay vertices (b-Tagging)

Typical tag efficiency:

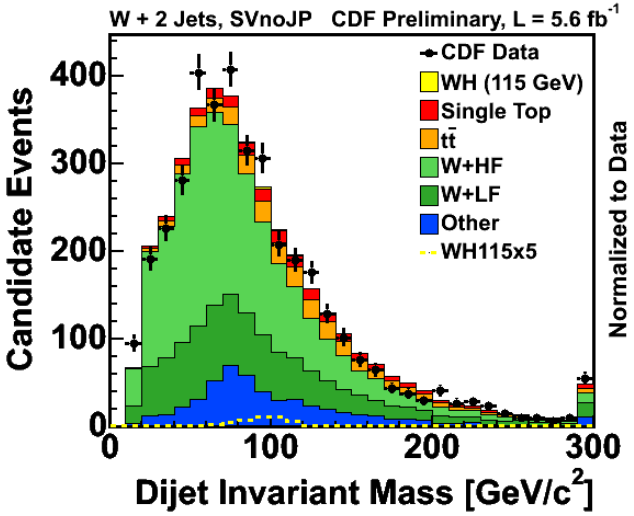
50-70% real b quarks

0.5-5% light quarks

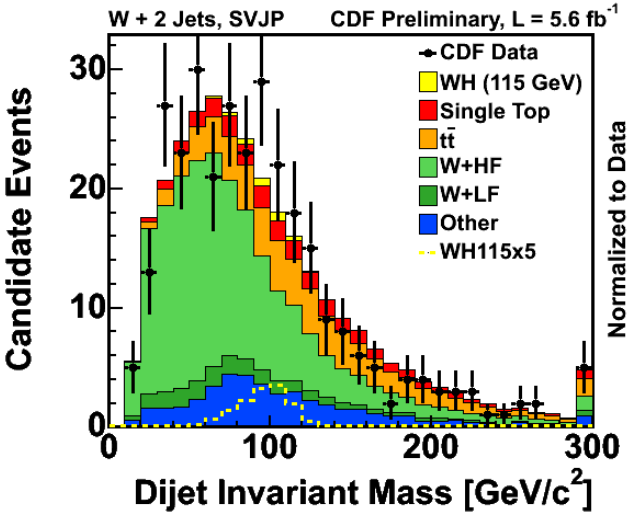
0 Tagged Jets



1 Tagged Jet

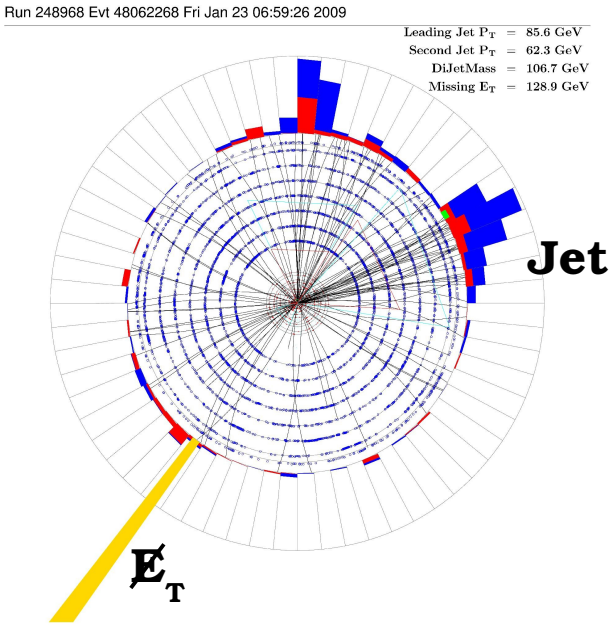


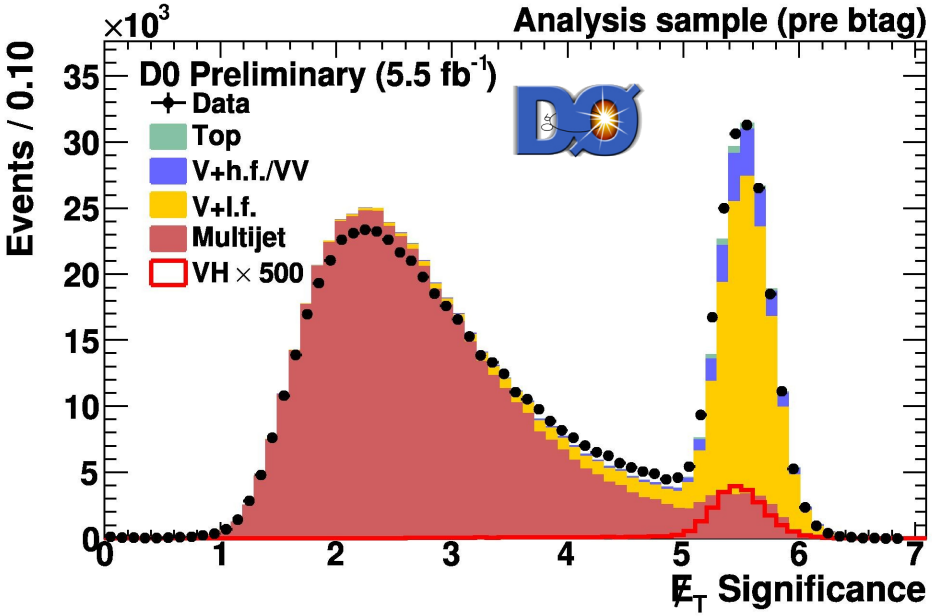
2 Tagged Jets

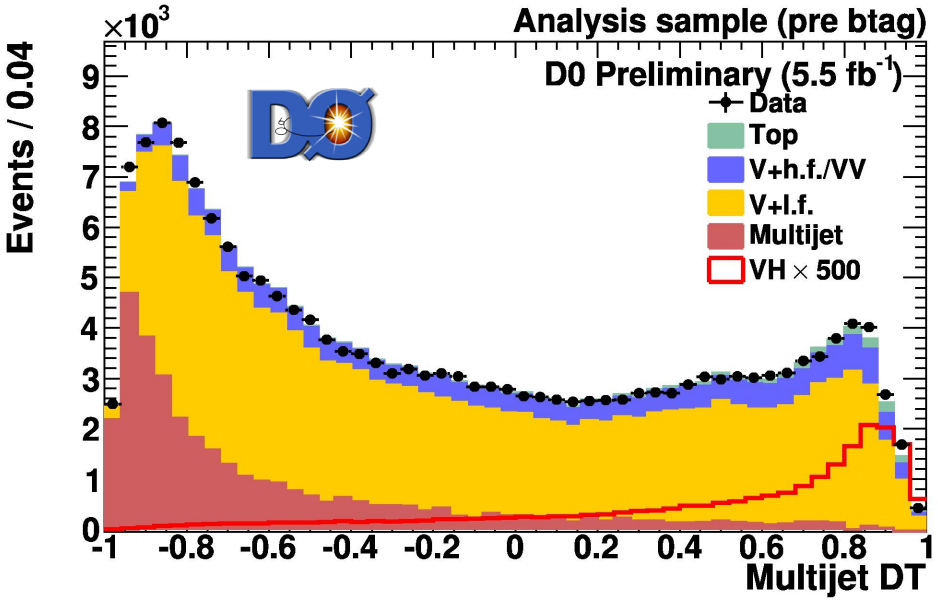


Tough Backgrounds

- For ZH→$\nu\nu$bb the search is more difficult: no charged leptons!
  - Rely on large MET (neutrinos!)
  - Large "instrumental" background from mismeasured jets
- MET significance and correlation of calorimeter & tracker MET measurements helps identify background
- Multivariate analysis techniques ultimately control multijet background



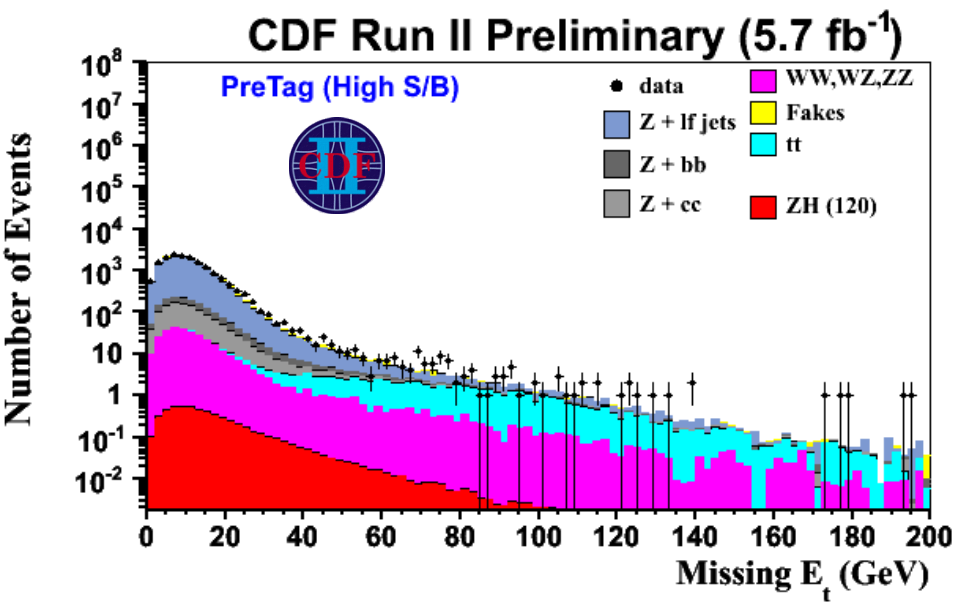


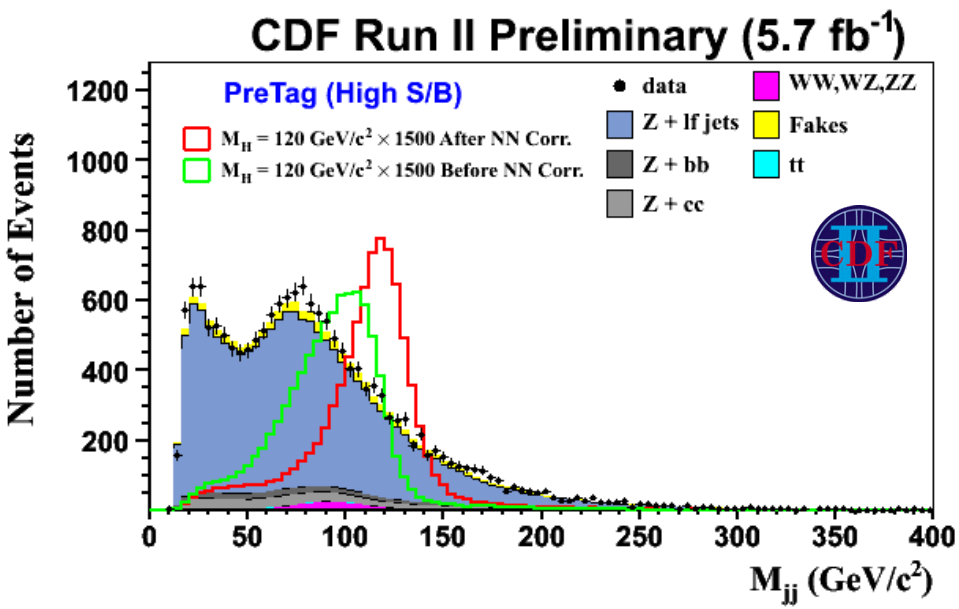


Dijet Mass Resolution

- The H→bb mass resonance is the key to the low mass Higgs search
  - Narrow mass resonance is the primary background discriminating variable
  - Intrinsic calorimeter resolution can be improved using clever techniques

- For ZH→llbb candidates, there should be little or no MET
  - Any missing energy likely comes from jet mis-measurement
  - Algorithms to recalibrate *in situ* have shown to be successful.
  - **Ongoing work with a lot of promise!**



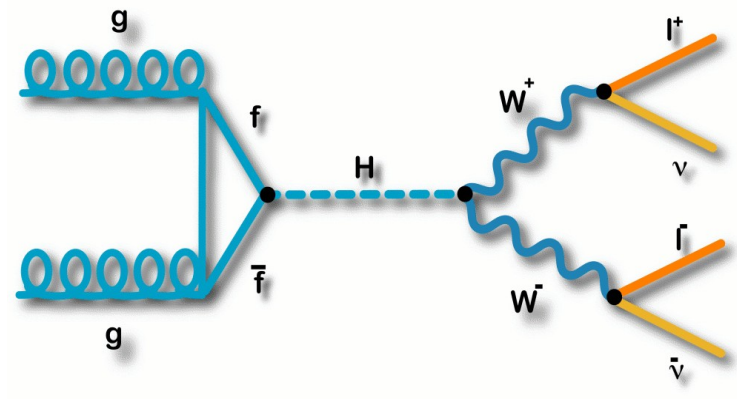


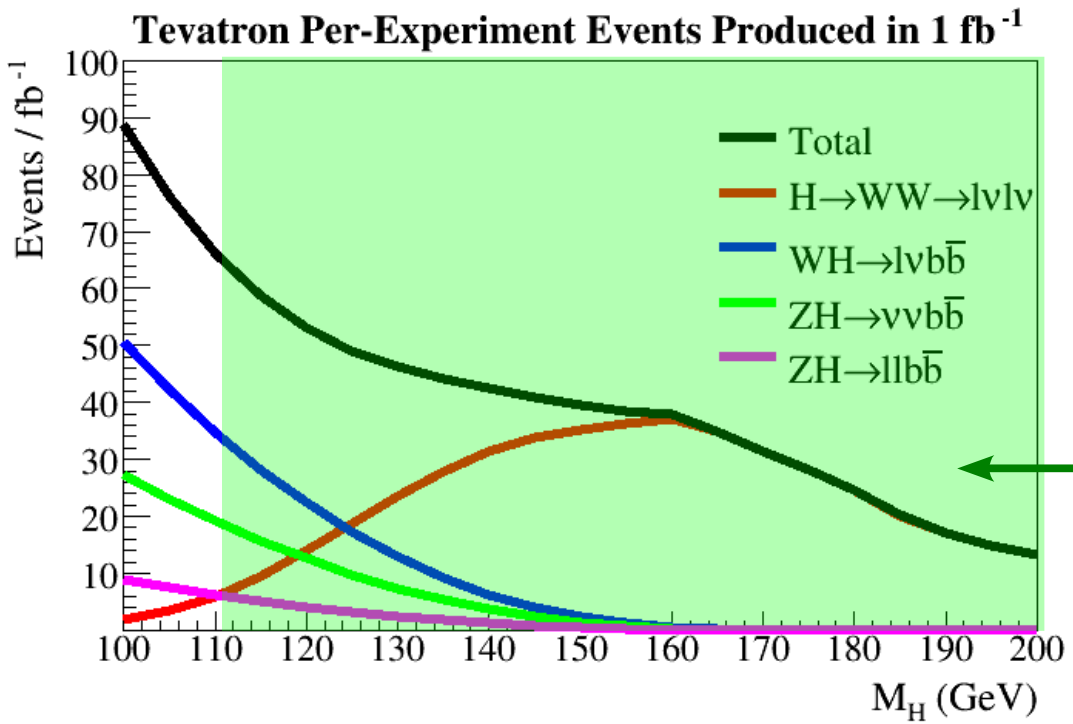
High Mass Searches

Gluon Fusion Production:

Search from $110 < M_H < 200$ GeV

Maximum sensitivity near M_H=165 GeV



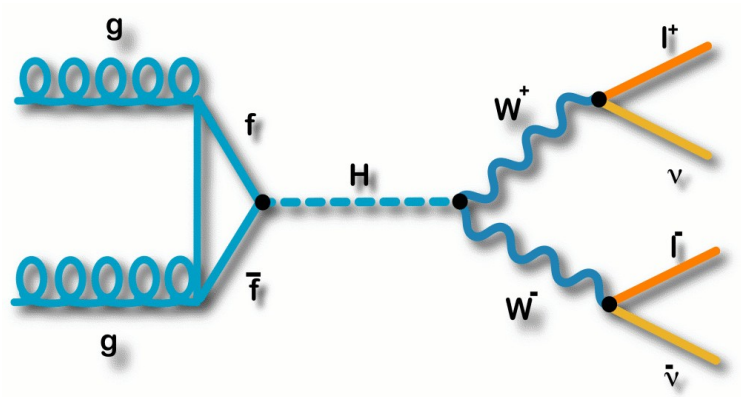


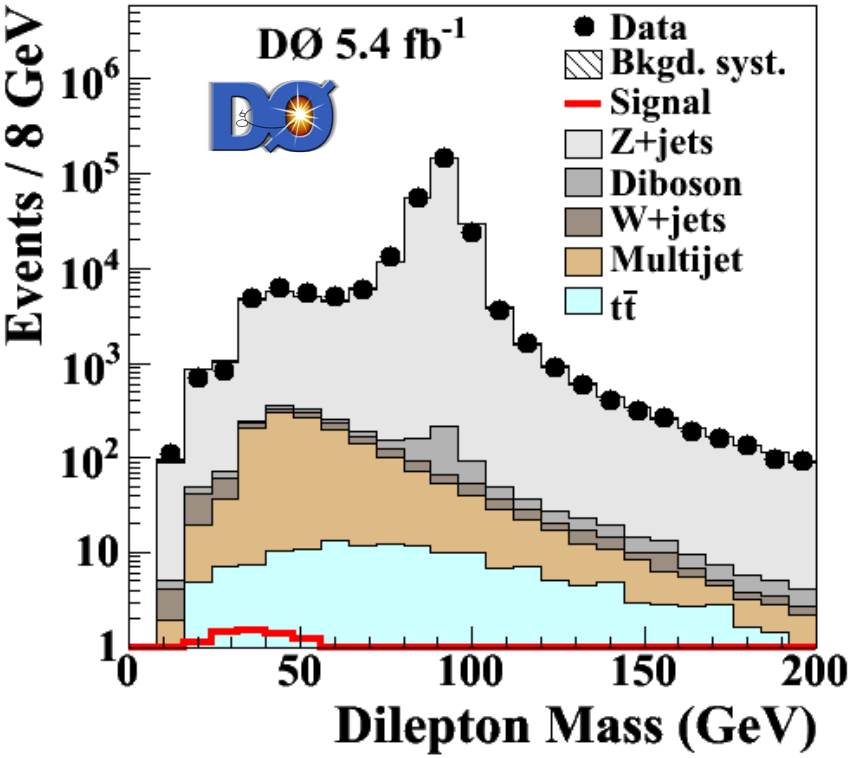
H→WW Search Region

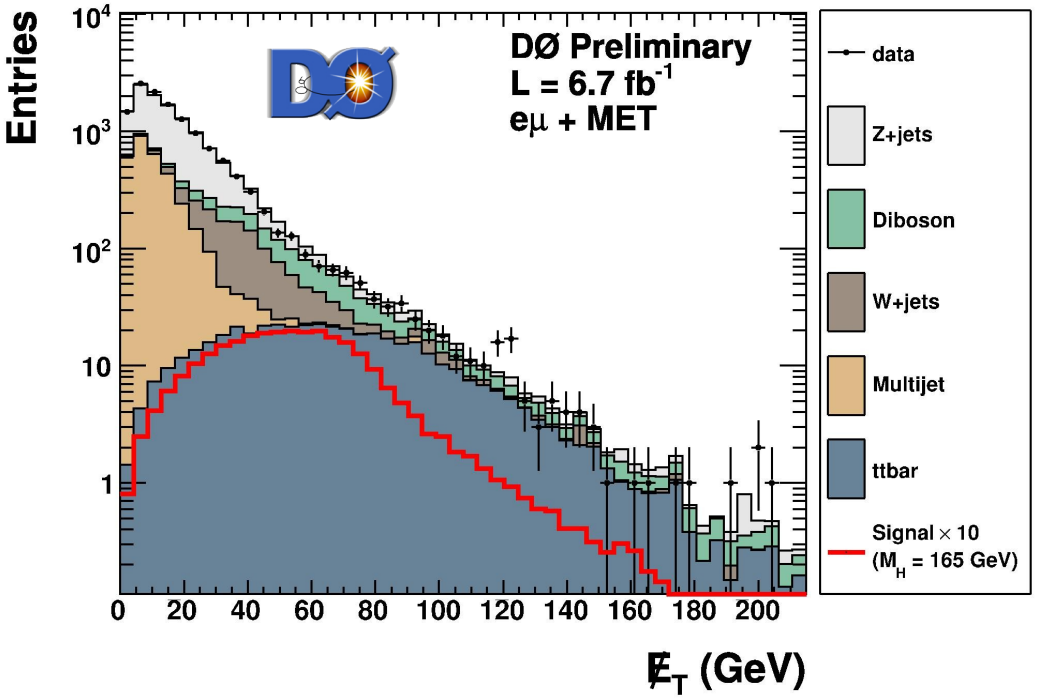
High Mass Basics

The traditional workhorse of the high mass Higgs search has been the dilepton+MET final state

- Clean signature helps reduce major backgrounds



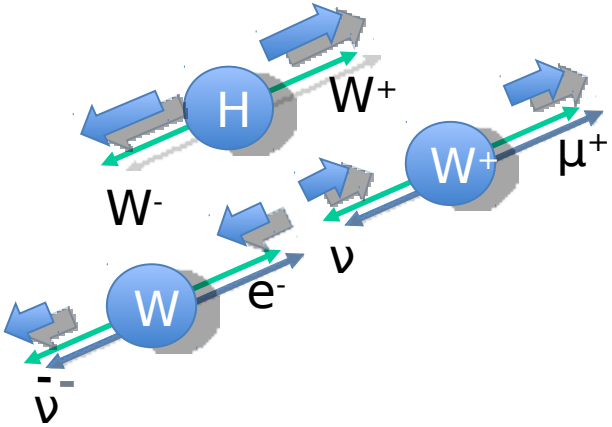


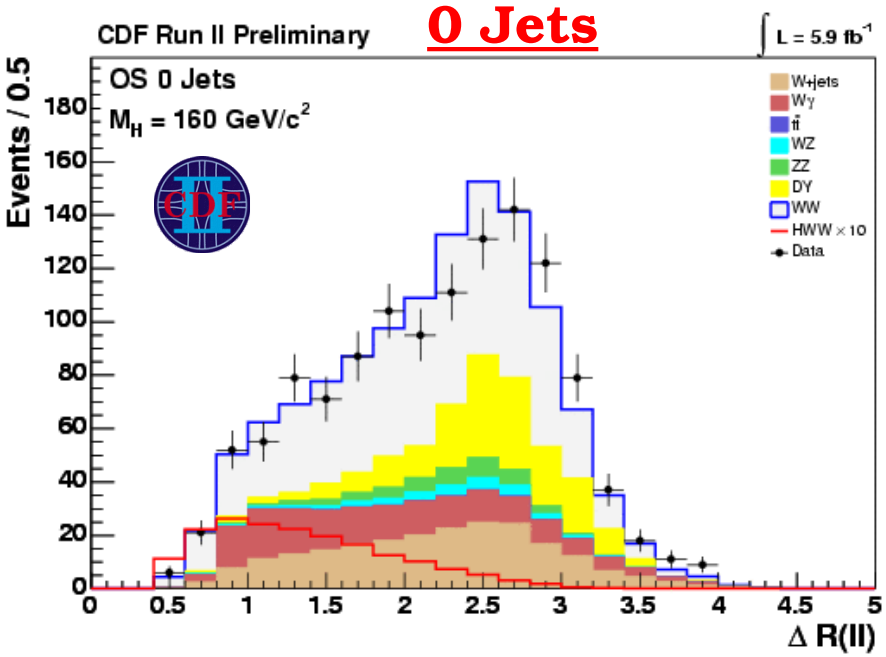


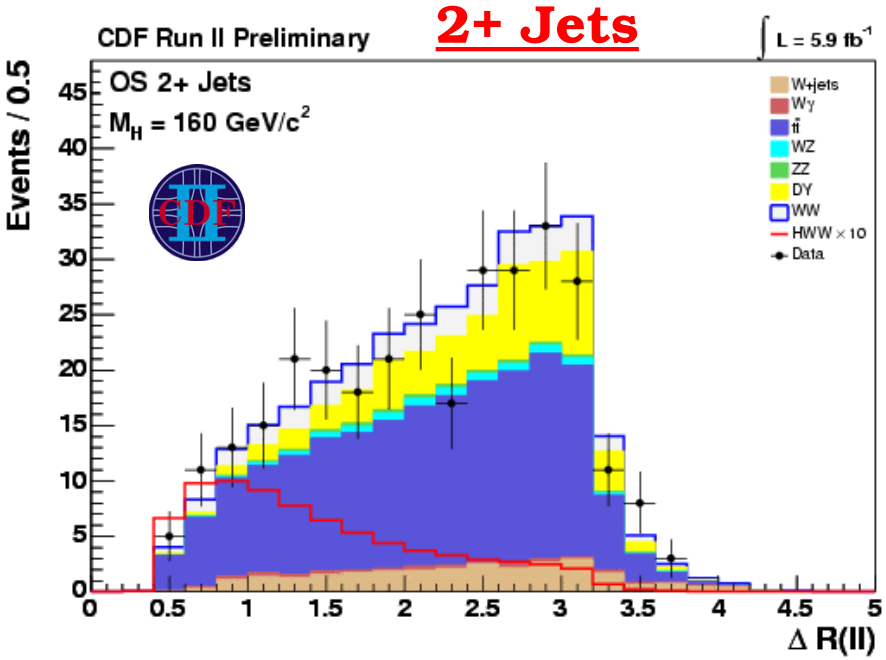
High Mass Basics

The traditional workhorse of the high mass Higgs search has been the dilepton+MET final state

- Clean signature helps reduce major backgrounds
- Spin conservation helps to separate H→WW from SM WW production.
- Analyzing exclusive jet final states helps to isolate different background classes.



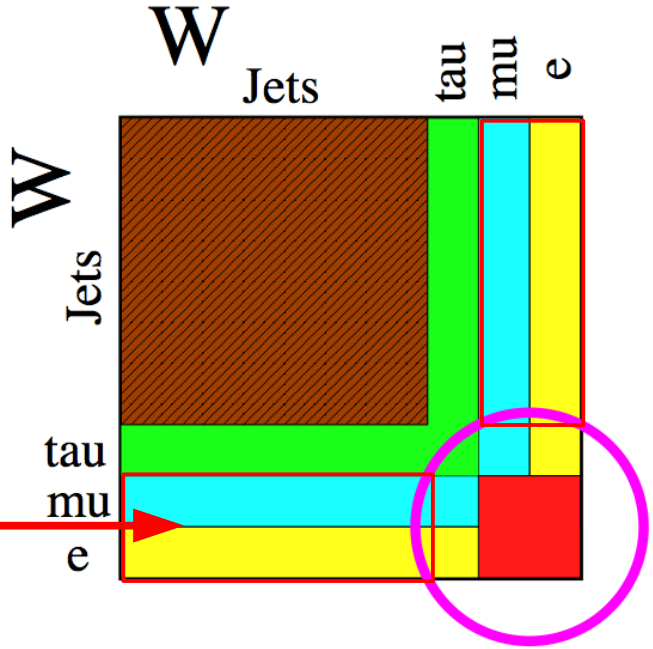




Digging Deeper

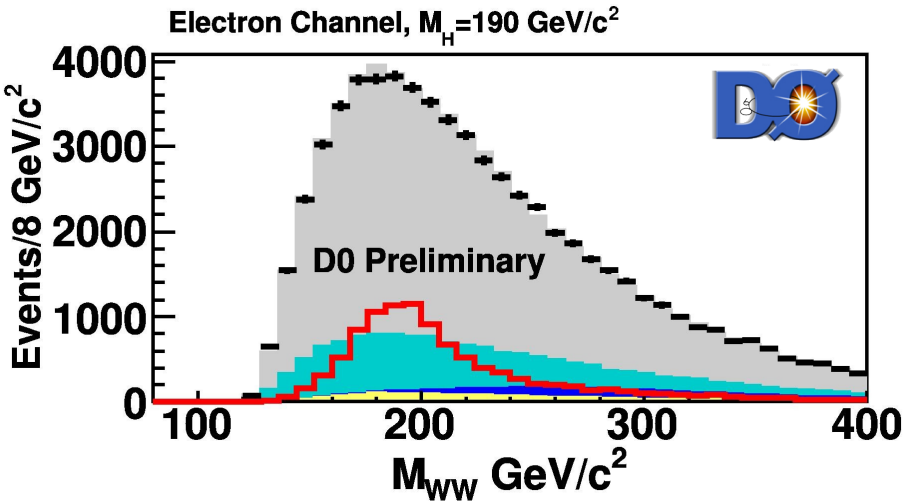
A strong push to **"Leave No Higgs Behind"** has led to several promising new channels.

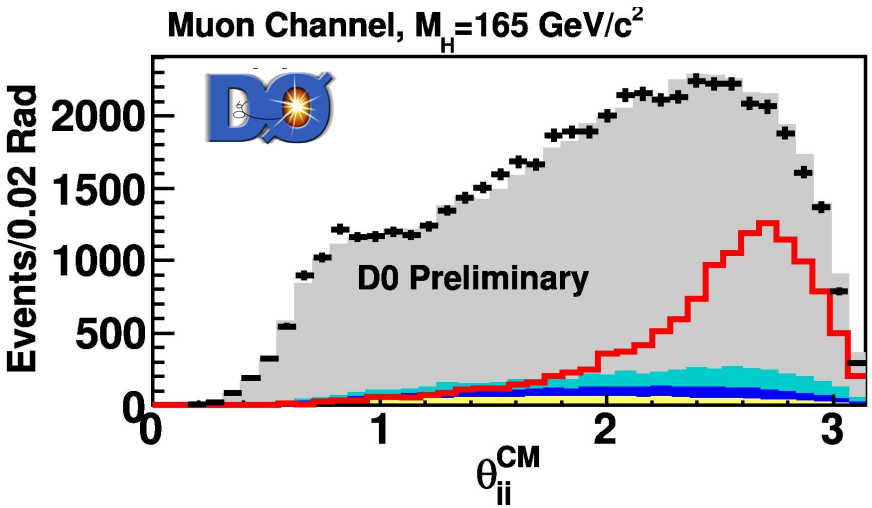
H→WW→lνjj decays



Tapping into a large "lost" well of events!

Traditional H→WW→lνlν search

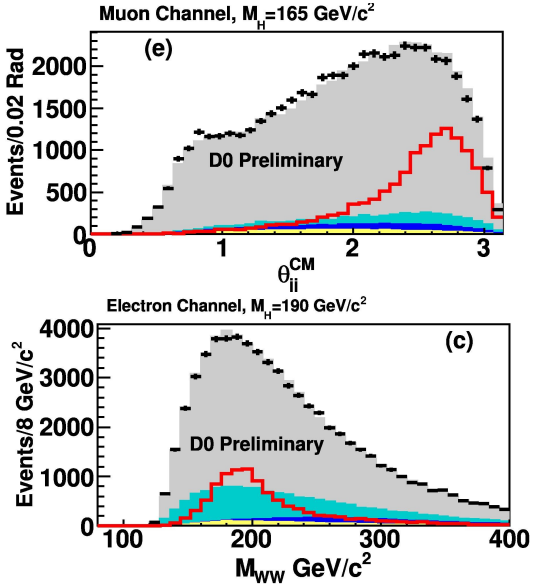




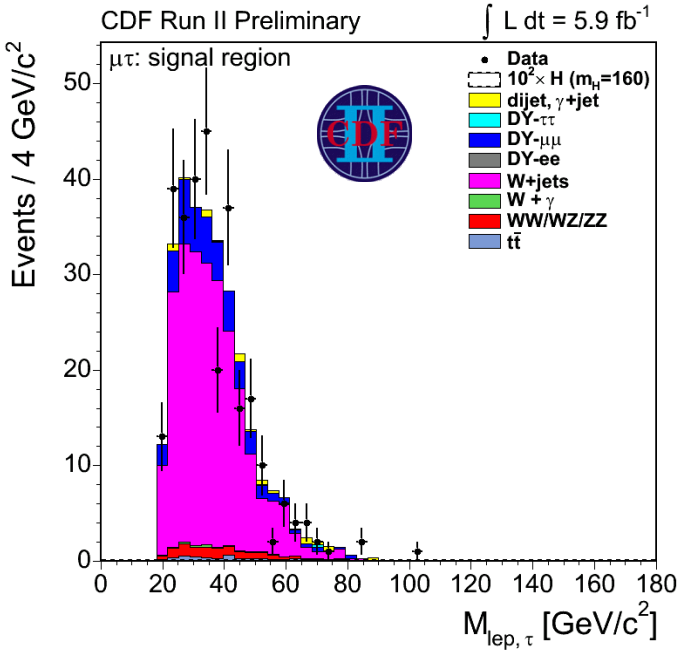
Digging Deeper

A strong push to **"Leave No Higgs Behind"** has led to several promising new channels.

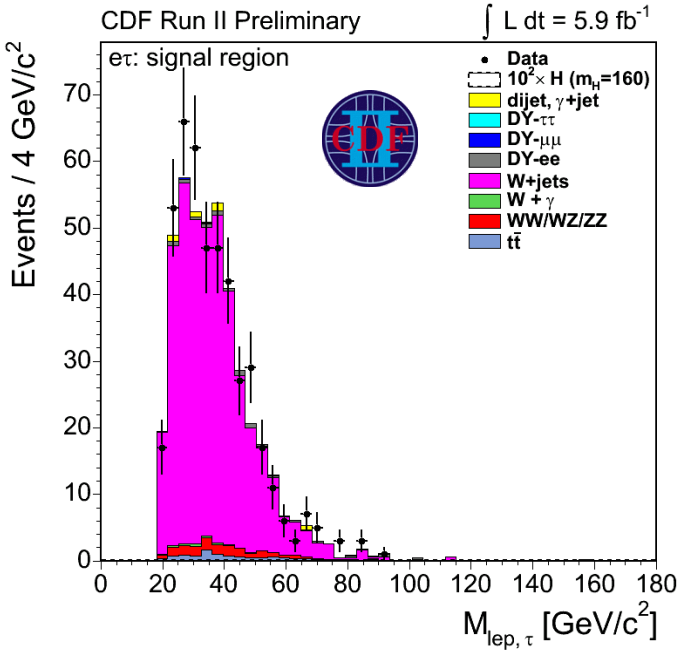
- $H \rightarrow WW \rightarrow l\nu jj$ decays
- $H \rightarrow WW \rightarrow e/\mu\nu + \tau_{had}\nu$ + MET decays



$\mu + \tau_{had}$ + MET



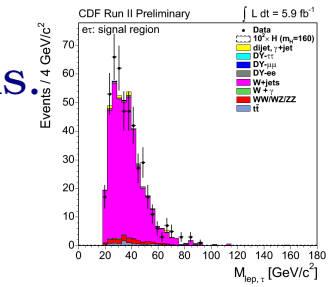
$e + \tau_{had}$ + MET

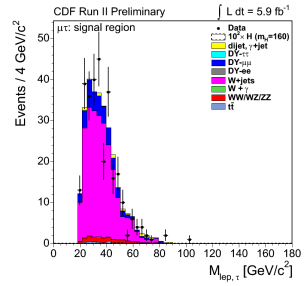


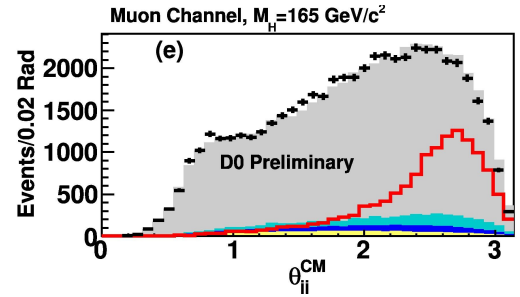
Digging Deeper

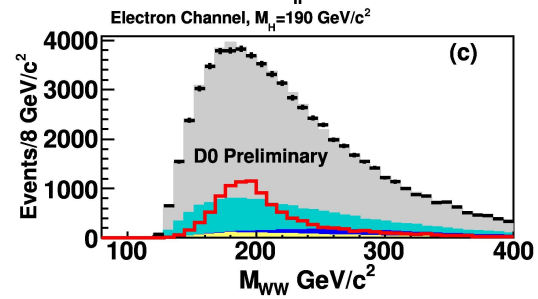
A strong push to **"Leave No Higgs Behind"** has led to several promising new channels.

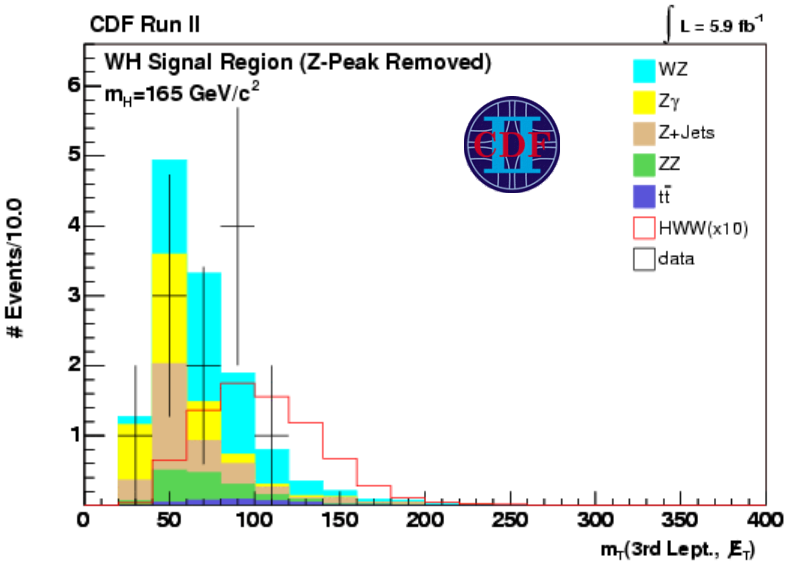
- H→WW→lνjj decays
- H→WW→e/μν + $\tau_{had}\nu$ + MET decays
- VH→VVV→same-sign di-lepton & tri-lepton decays

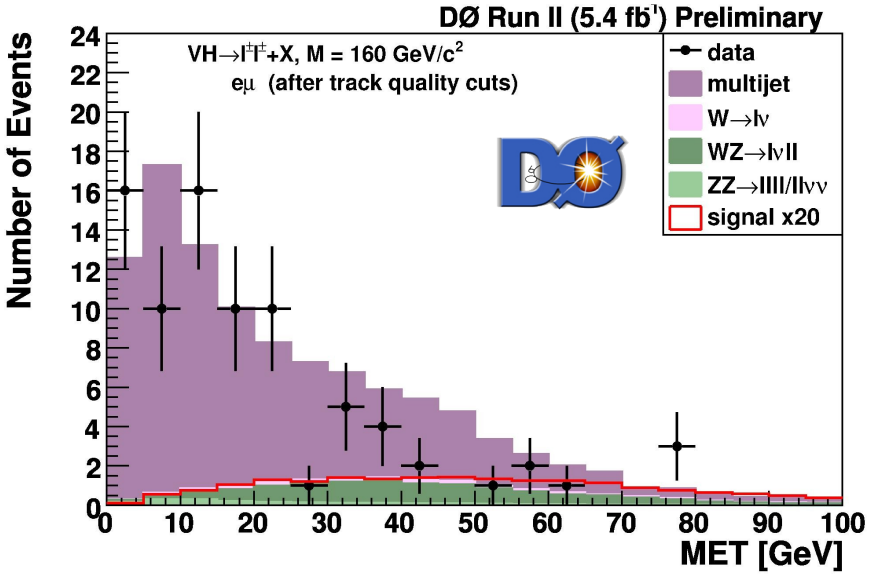








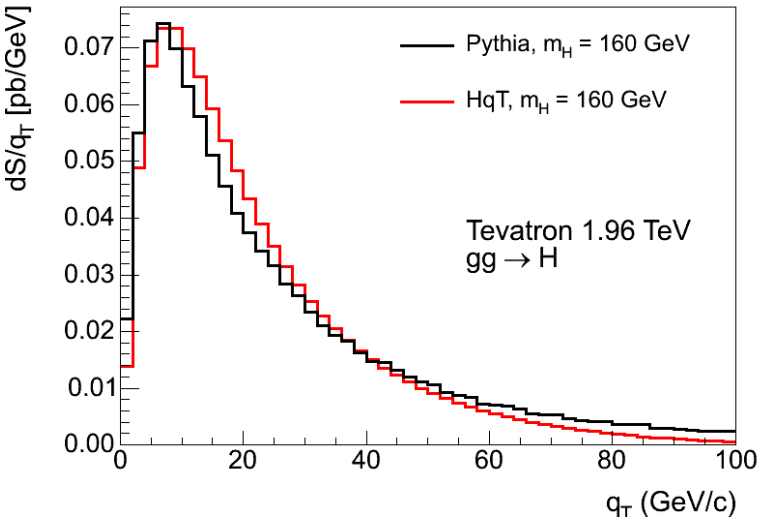


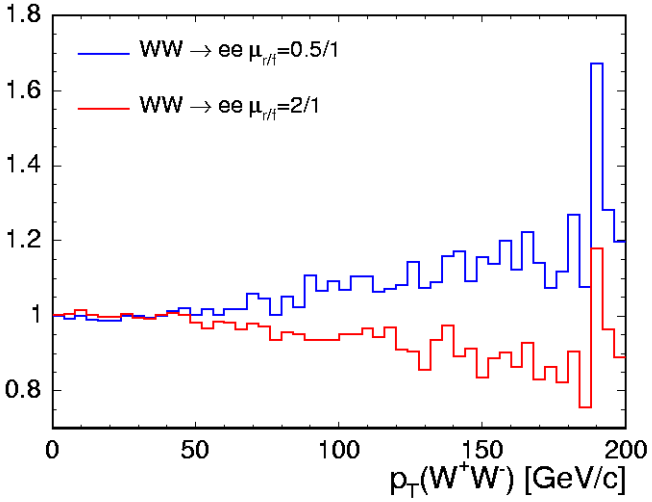


Theory & Uncertainties

Tevatron progress has brought much interest from the theory community

- State of the art gg→H cross section calculations appear frequently (currently NNLL+NNLO)
- de Florian & Grazzini (Phys.Lett.B674:291-294, 2009)
  - Soft-gluon resummation treatment
  - MSTW2008 PDFs
- Anastasiou, Boughezal, Petriello (JHEP:0904:003, 2009)
  - Proper treatment of b-quarks at NLO
  - Inclusion of two-loop EW effects



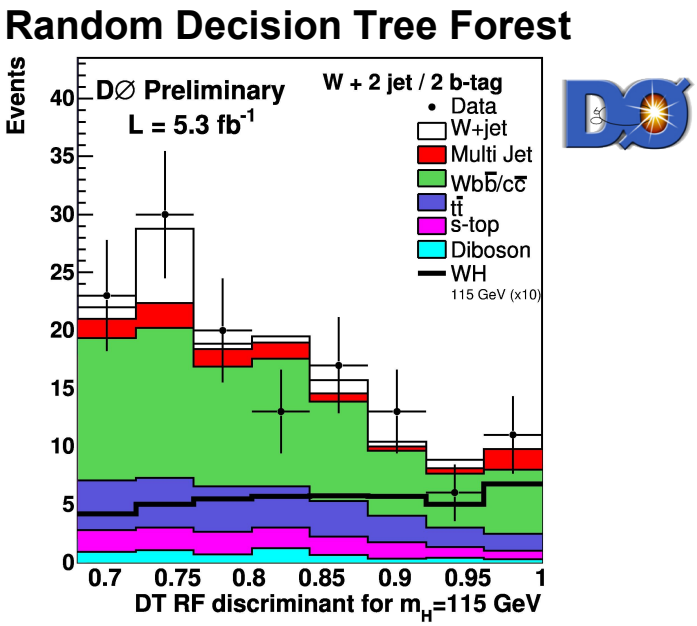


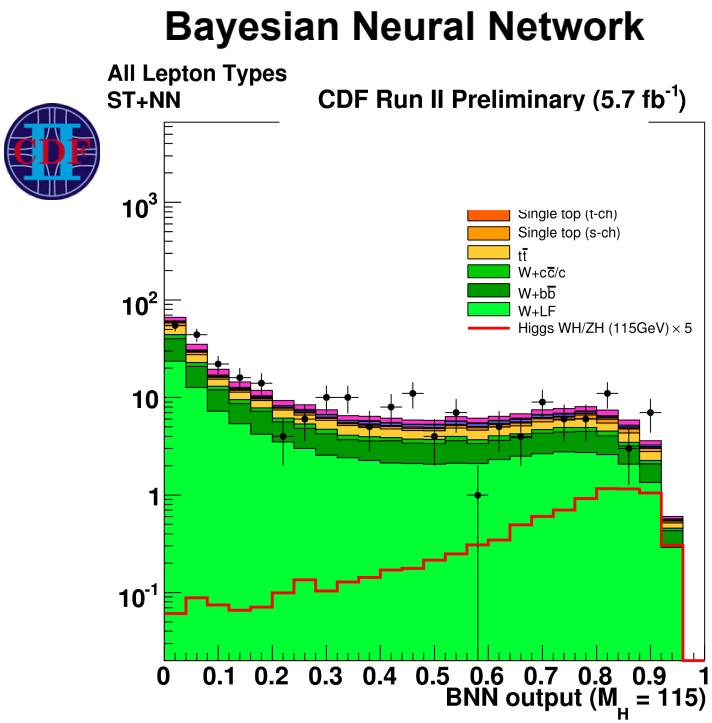
More information of our choices and comparisons with alternative approaches:

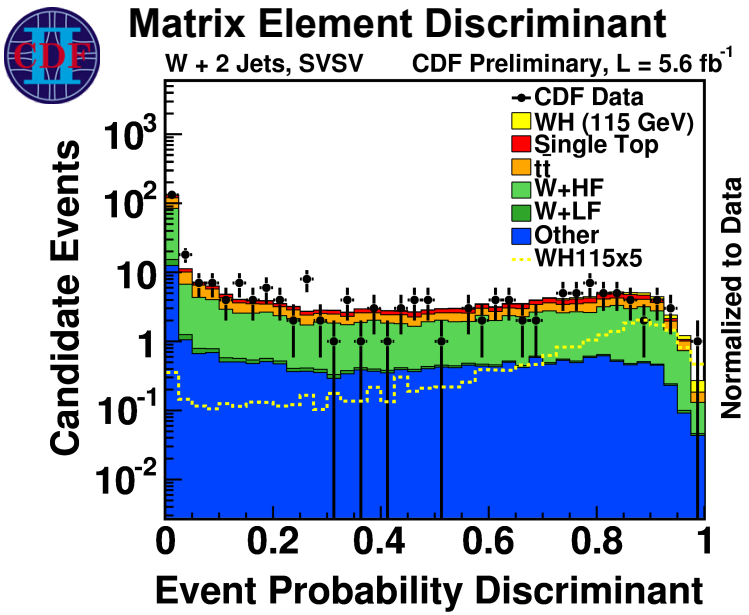
http://tevnphwg.fnal.gov/results/SMHPubWinter2010/gghtheoryreplies_may2010.html

Extracting a Signal

- Signal extraction has come to rely heavily upon Multivariate Analysis (MVA)
  - Boosted decision trees, Neural Networks, Matrix Element Discriminants
  - Native S/B ratios too small on their own (~1/1000)
- Techniques not always clear to non-experts, leading to a "black box" perception
  - **Validation steps taken in many areas**



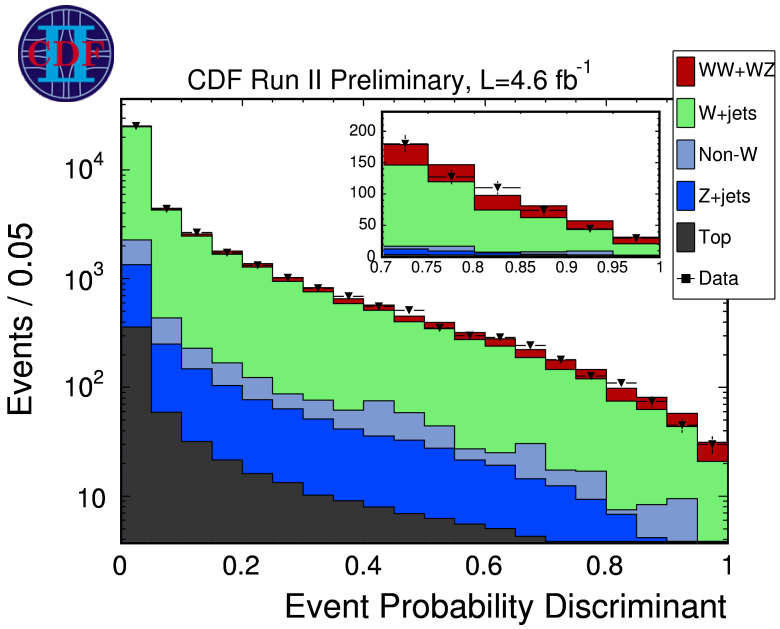


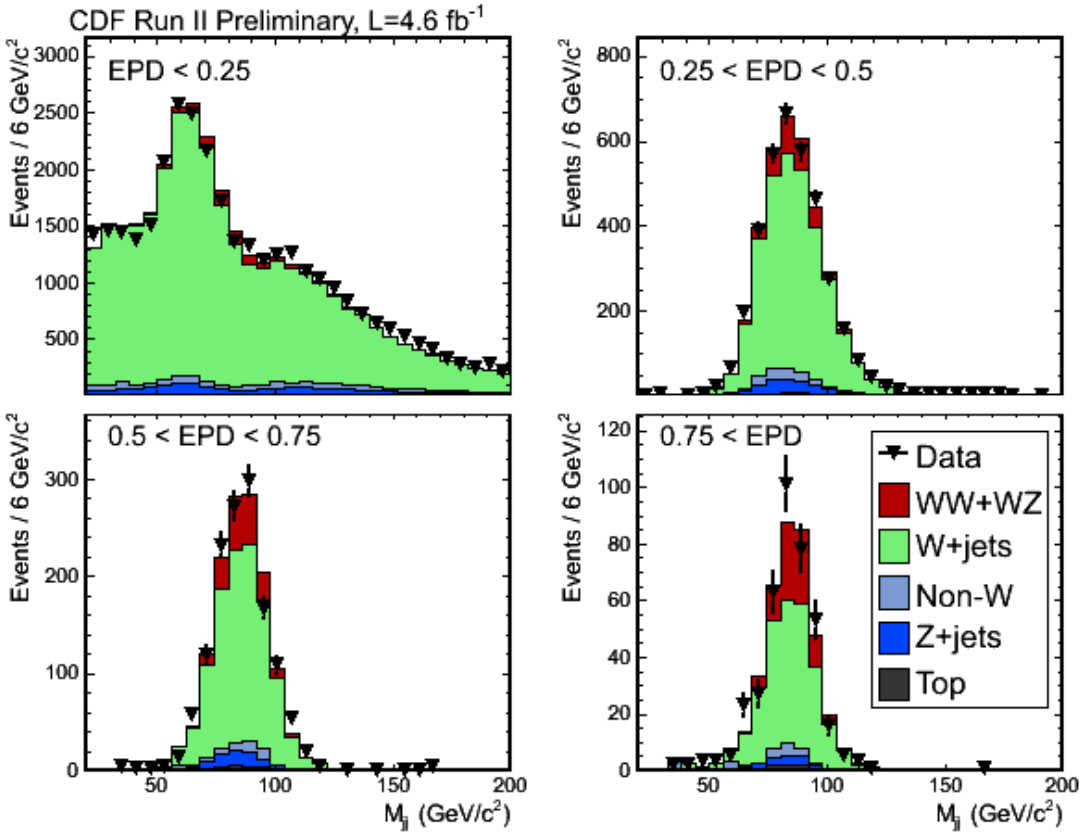


MVA Validation Steps

Both CDF and DØ have studied SM diboson production to test MVA validity

- Analyses measure production of **WW+WZ→lvjj**
- Analog of **WH→lvbb** search using a calibration signal
- Utilize nearly identical search strategies: capitalize on **W→jj resonant mass**





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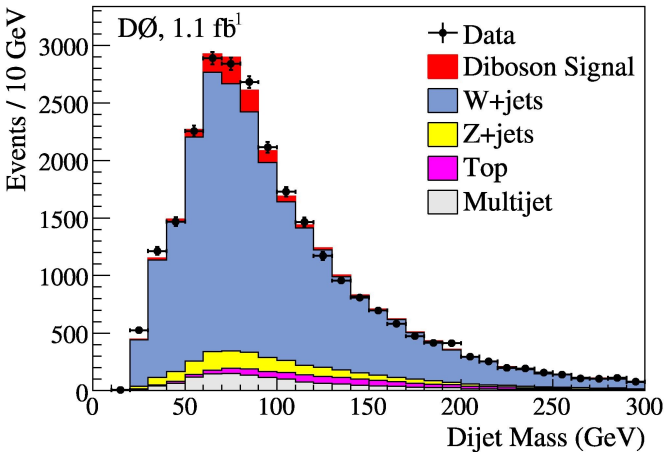
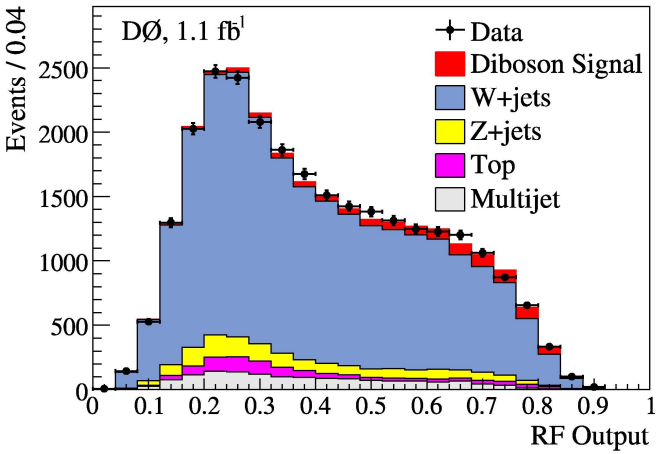
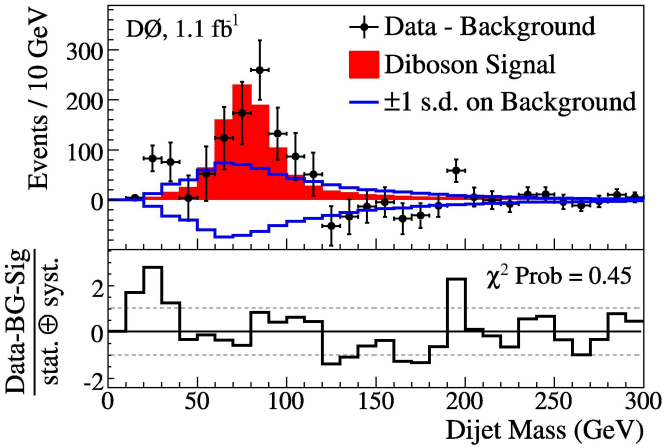
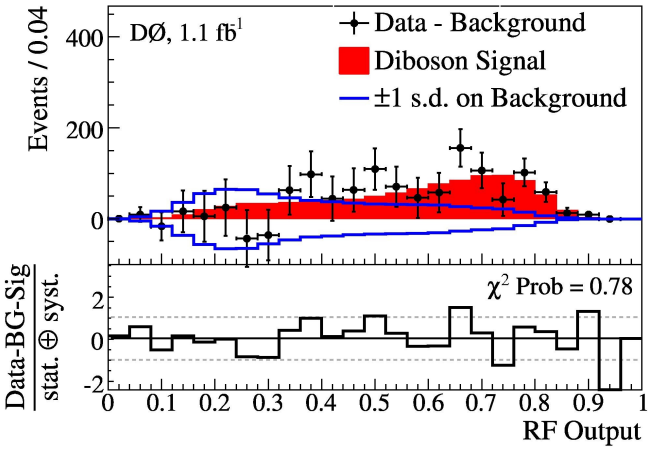
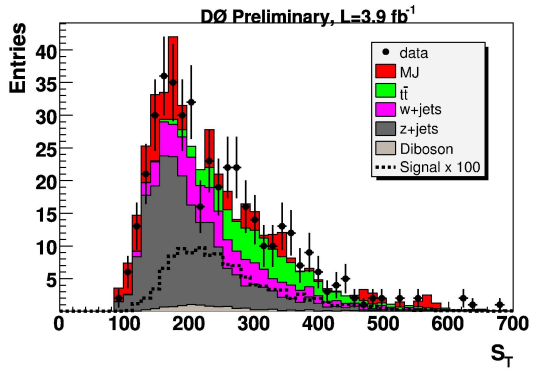


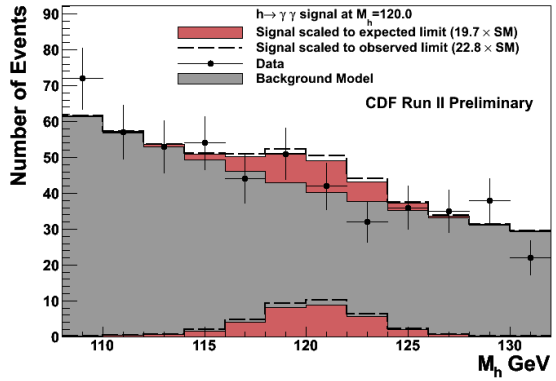


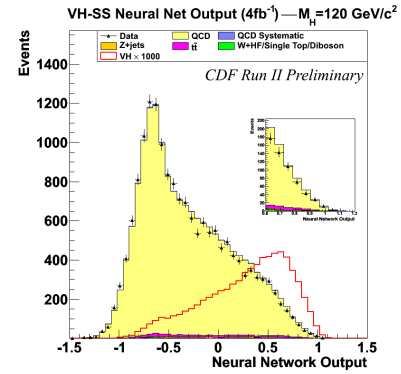


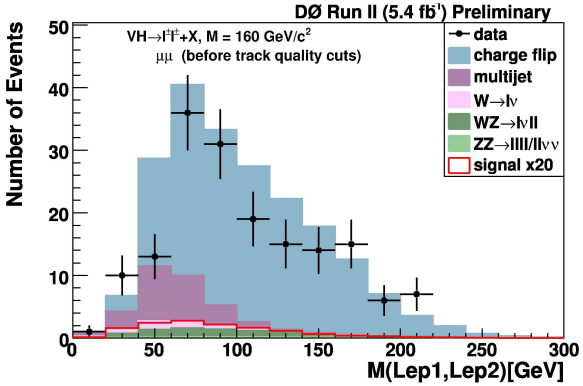


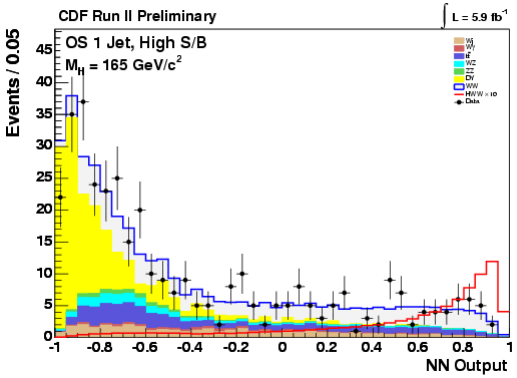
Many More Channels to Cover!

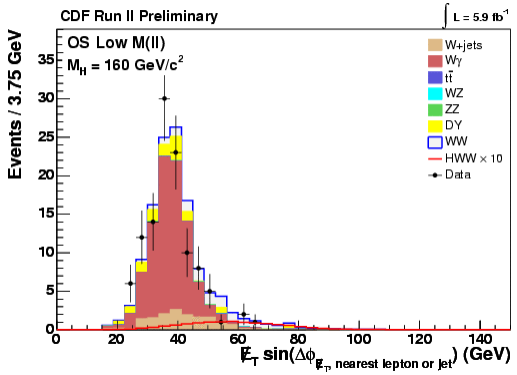


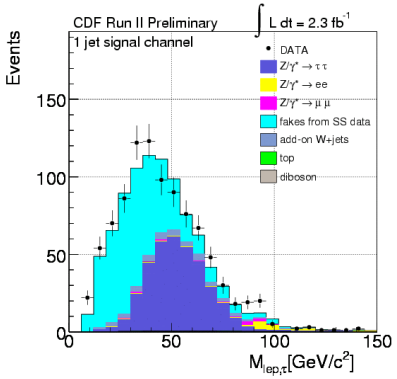


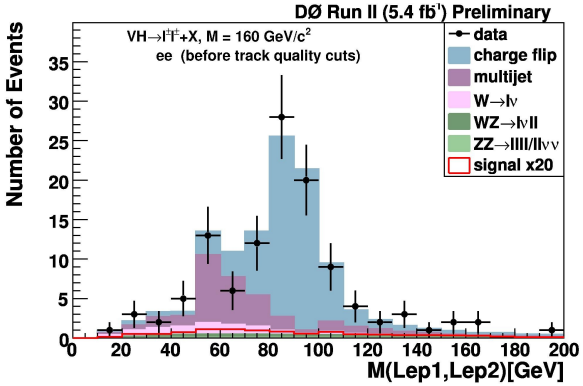


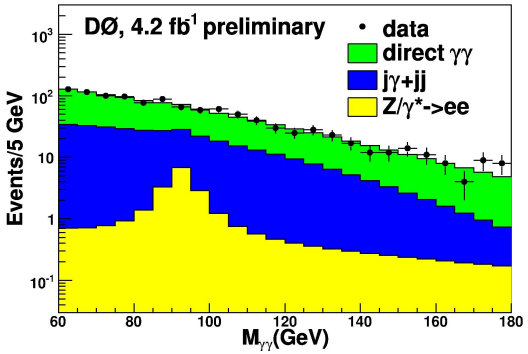












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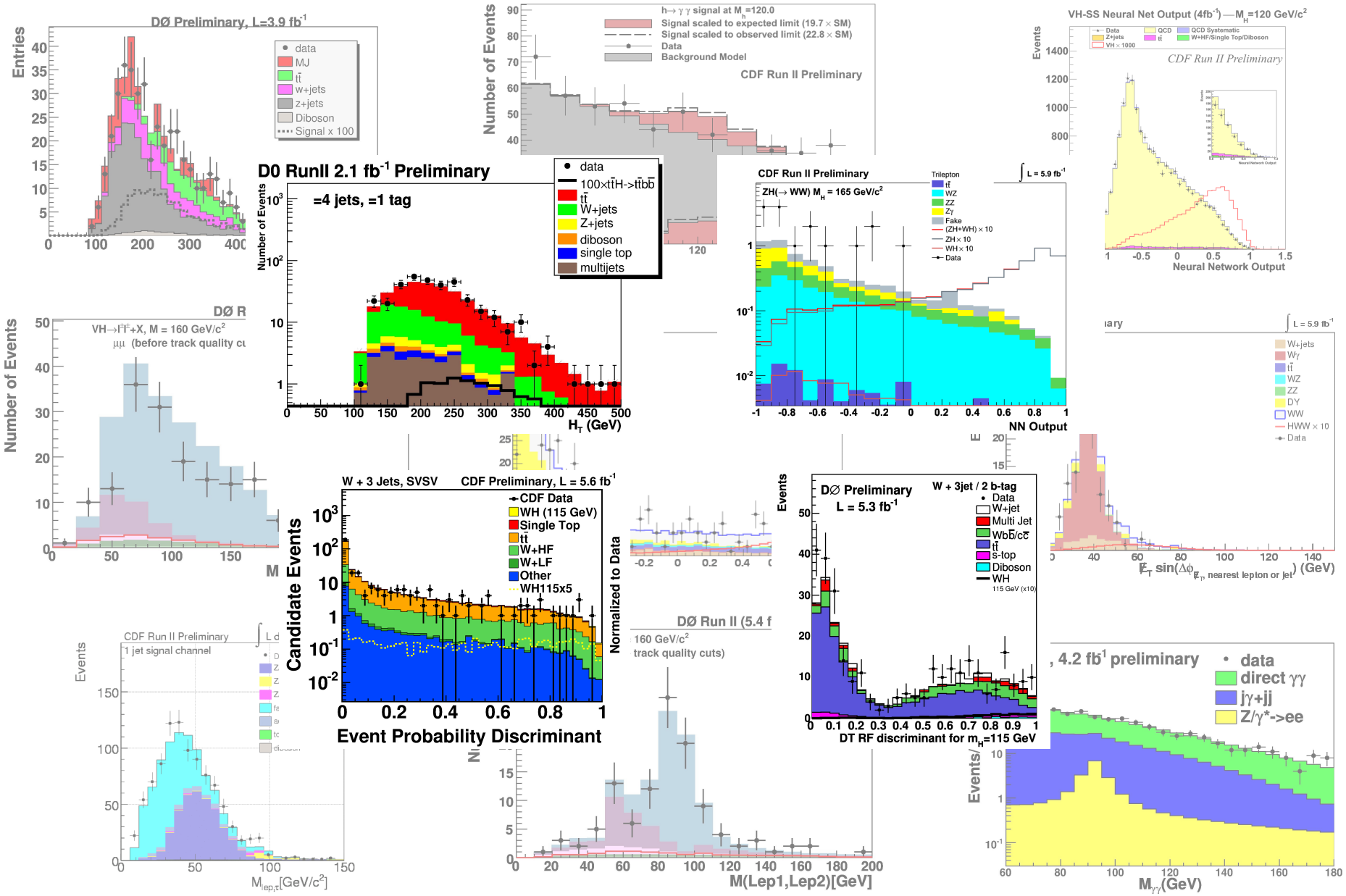
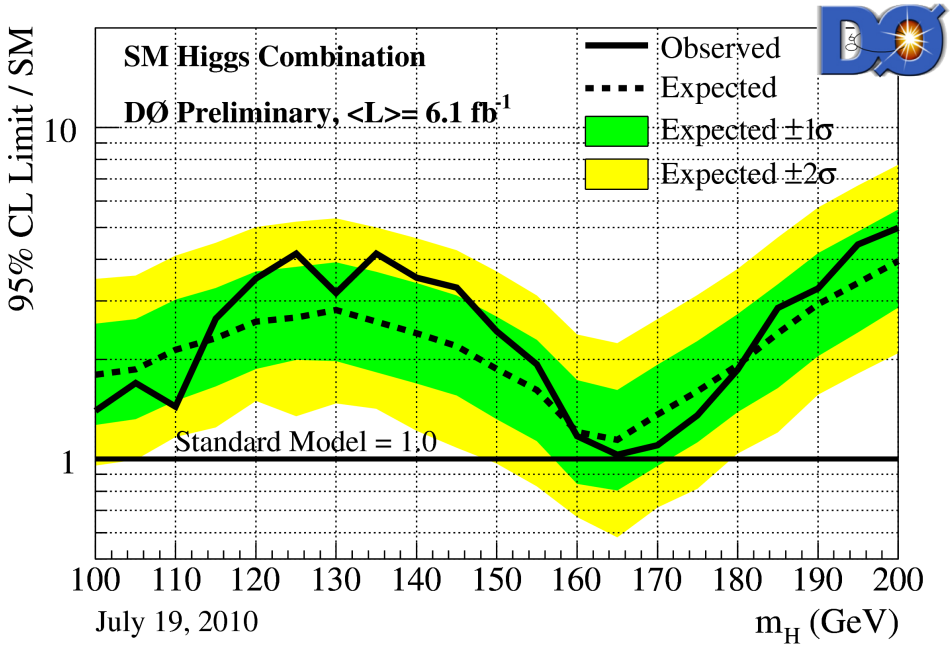
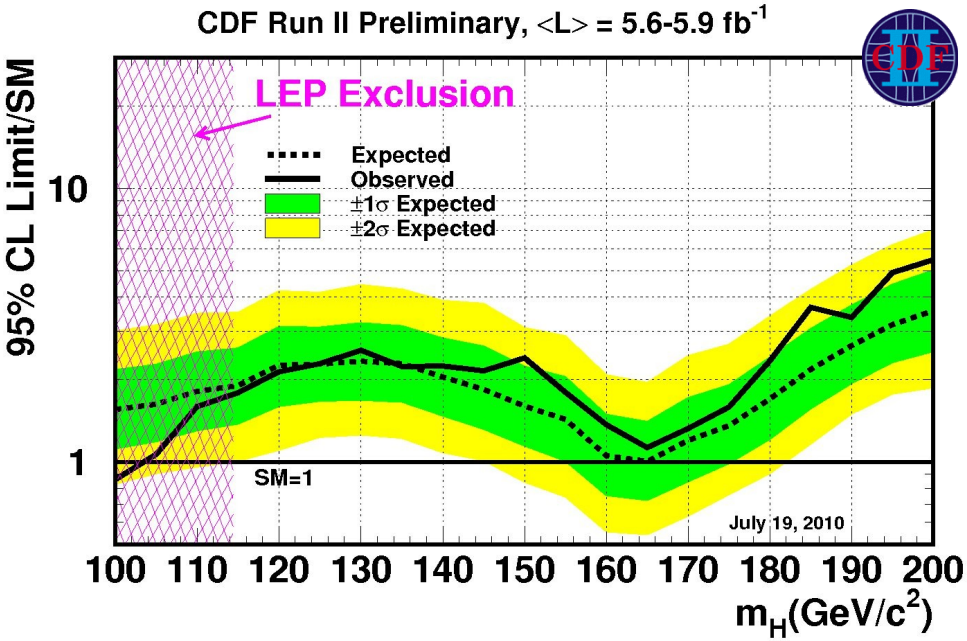


On to the search results!

Limits on Higgs Production





Combined results for 20 Higgs search channels for CDF + DØ (10 each!)

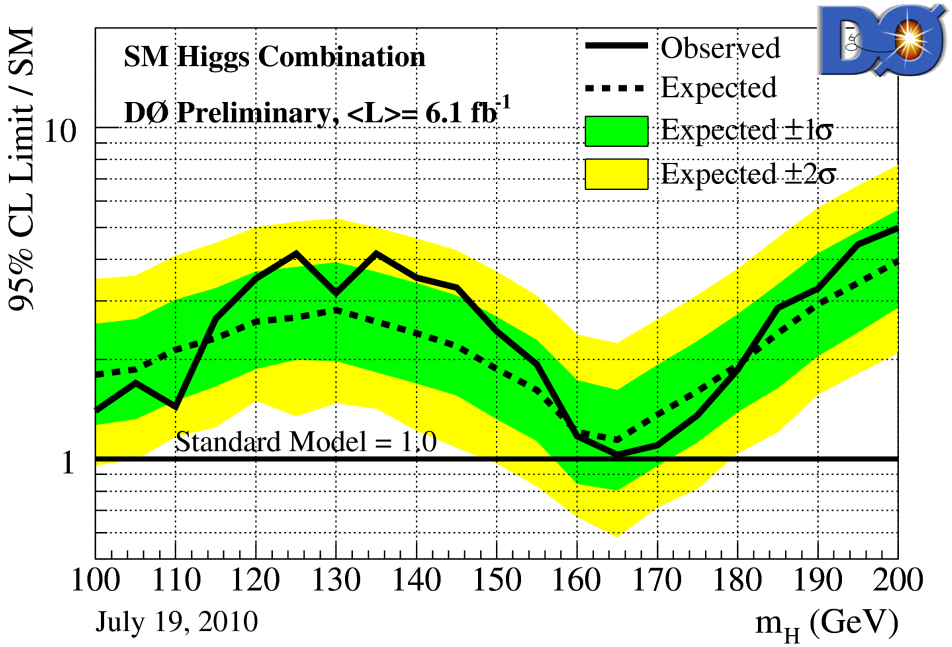
We combine many Higgs production mechanisms:

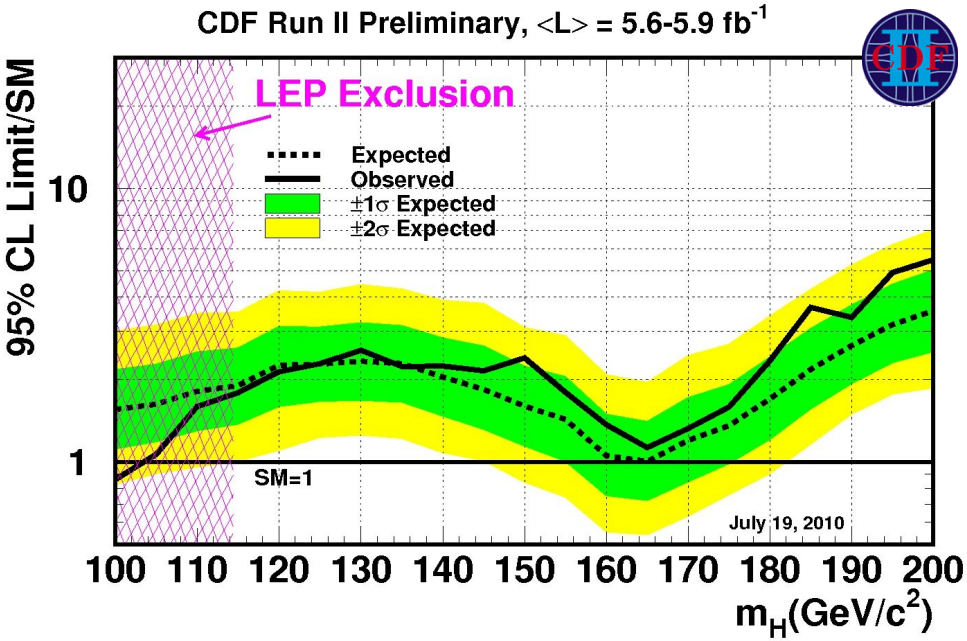
Results are reported as multiples of the SM prediction

M_H=115 GeV: DØ 2.7 (2.3) observed (expected)

M_H=115 GeV: CDF 1.8 (1.9) observed (expected)

Limits on Higgs Production





Combined results for 20 Higgs search channels for CDF + DØ (10 each!)

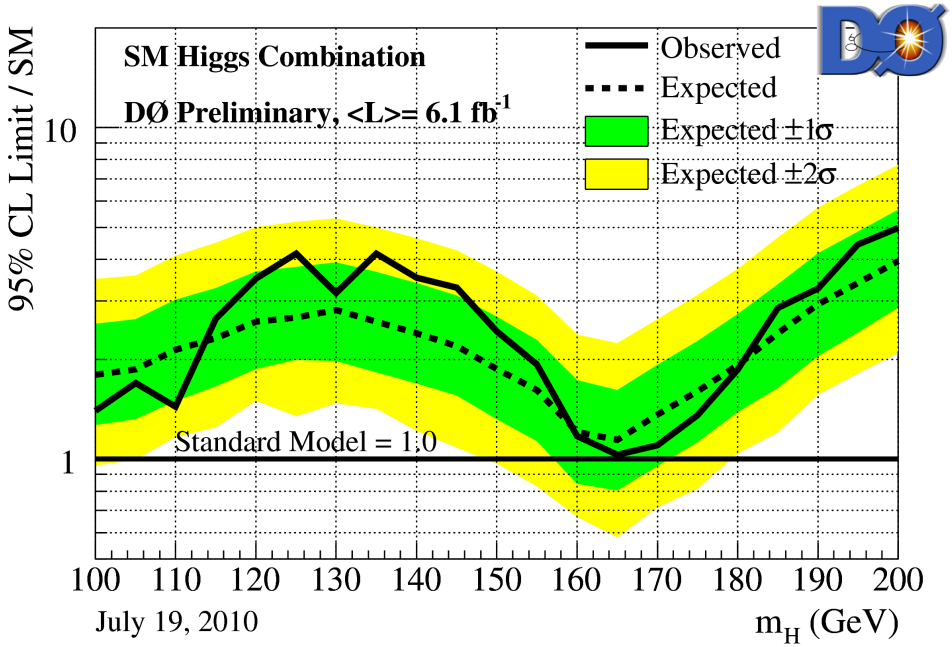
We combine many Higgs production mechanisms:

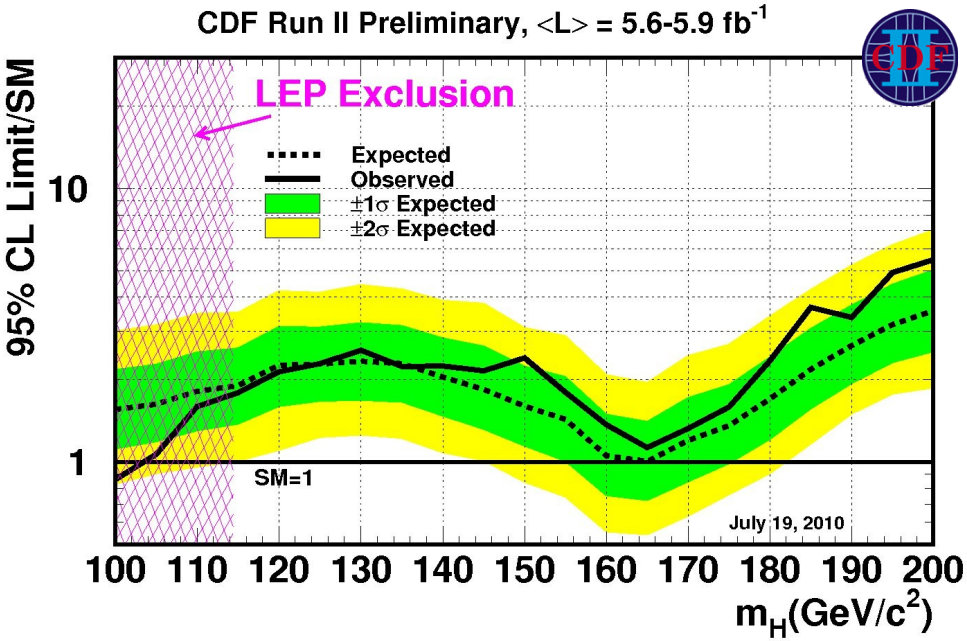
Results are reported as multiples of the SM prediction

M_H=165 GeV: DØ 1.0 (1.1) observed (expected)

M_H=165 GeV: CDF 1.1 (1.0) observed (expected)

Limits on Higgs Production





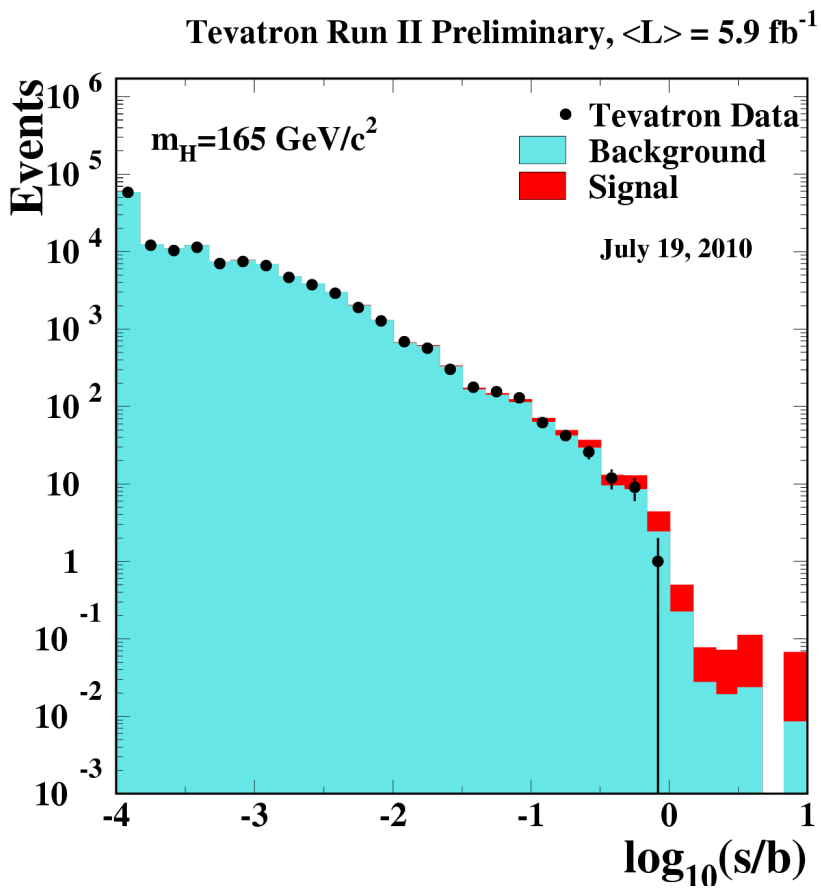
Major milestones achieved!

1) CDF expected limit reaches exclusion level
2) DØ observed limit reaches exclusion level

M_H=165 GeV: DØ 1.0 (1.1) observed (expected)

M_H=165 GeV: CDF 1.1 (1.0) observed (expected)

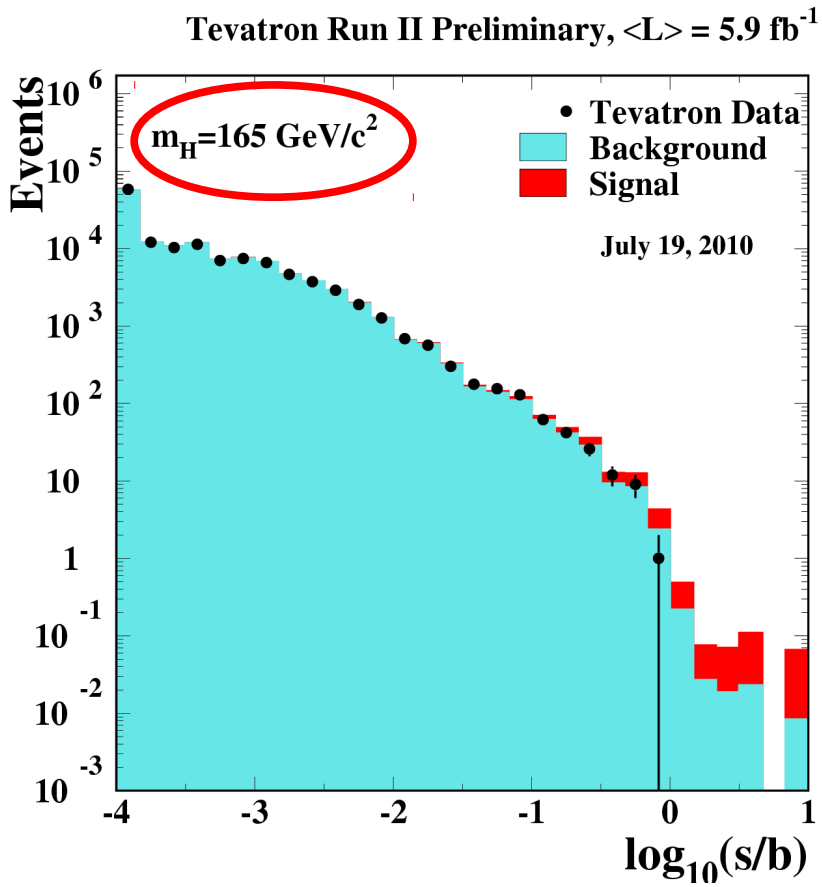
Putting It All Together

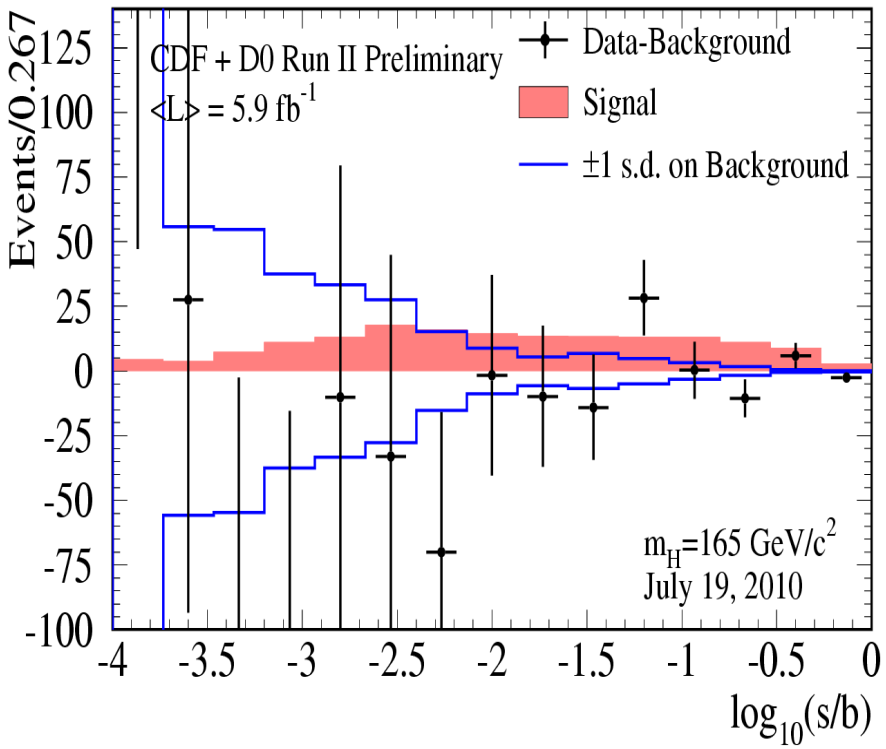


A simple way to visualize the sum of input channels is to simply reorder **ALL** of the input histogram bins on one plot

This figure shows all bins for **M_H=165 GeV** reordered based on the signal to background ratio in each bin.

Putting It All Together





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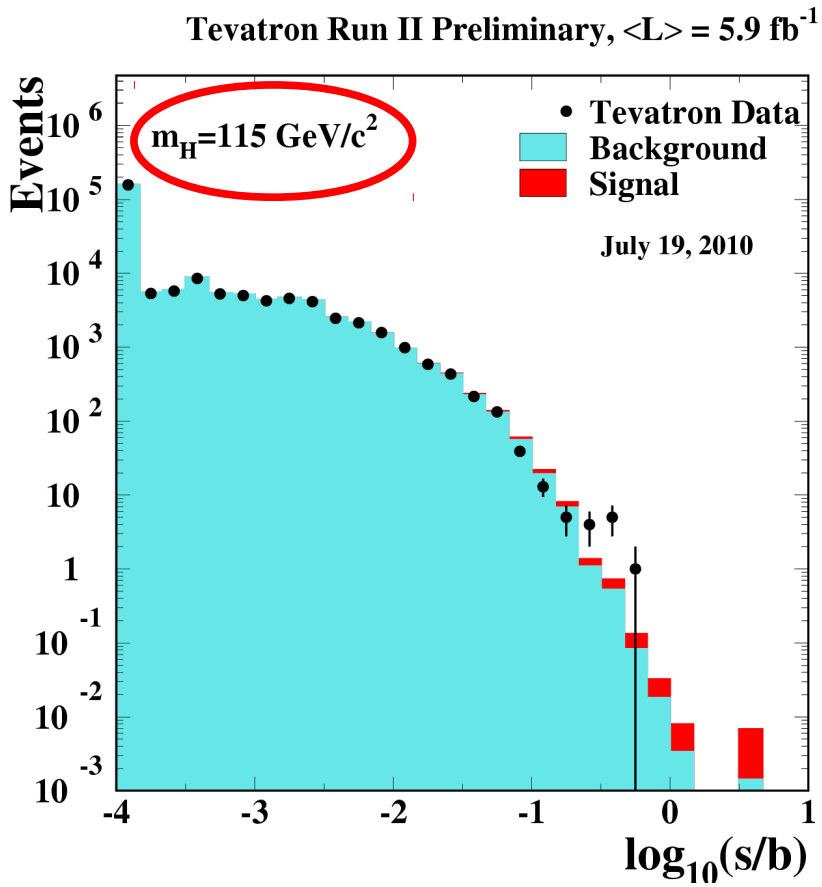
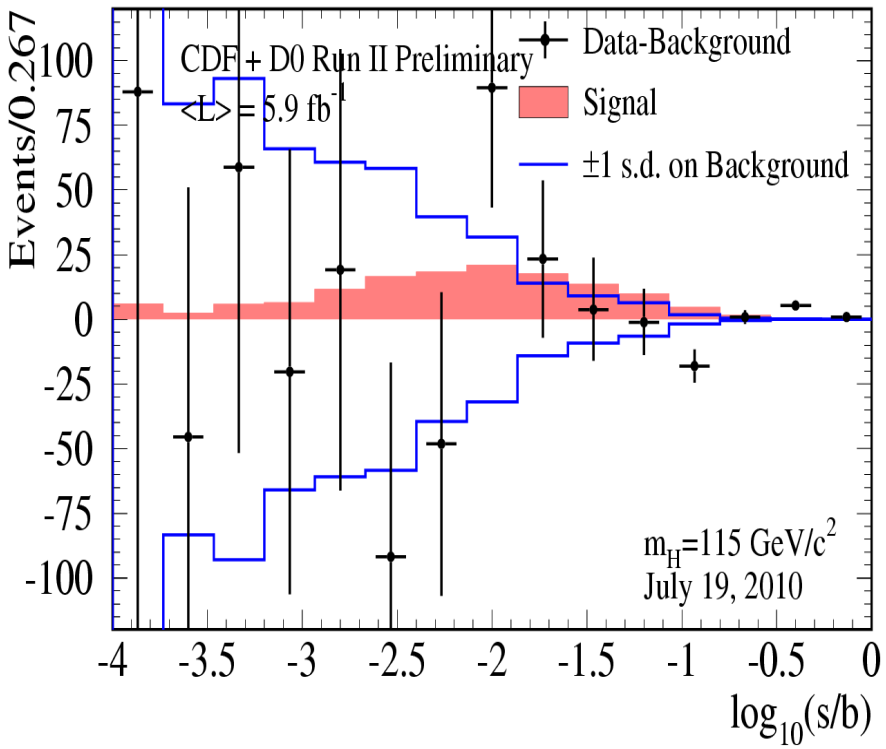
Putting It All Together





A simple way to visualize the sum of input channels is to simply reorder **ALL** of the input histogram bins on one plot

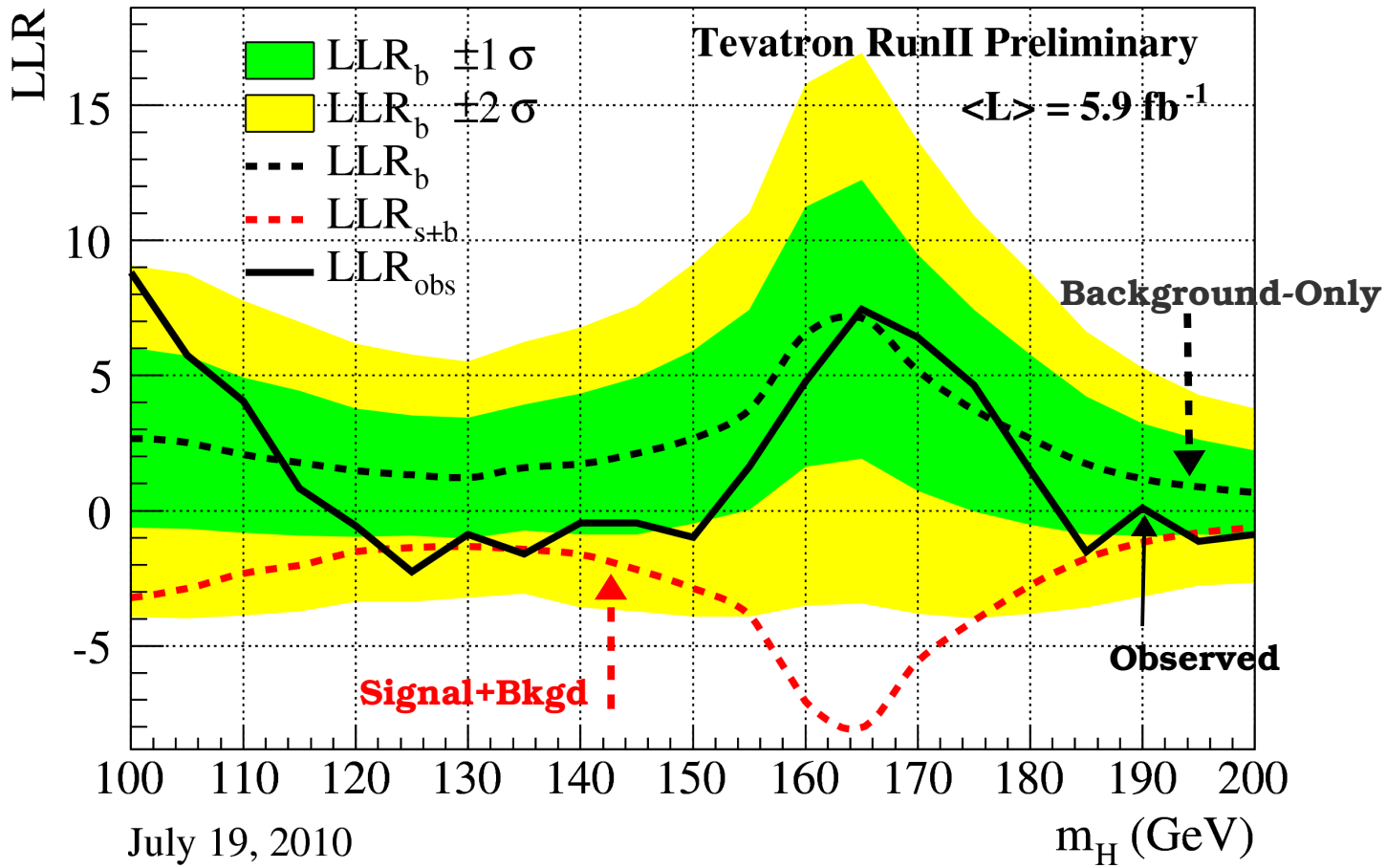
This figure shows all bins for **M_H=115 GeV** reordered based on the signal to background ratio in each bin.

Limits on Higgs Production

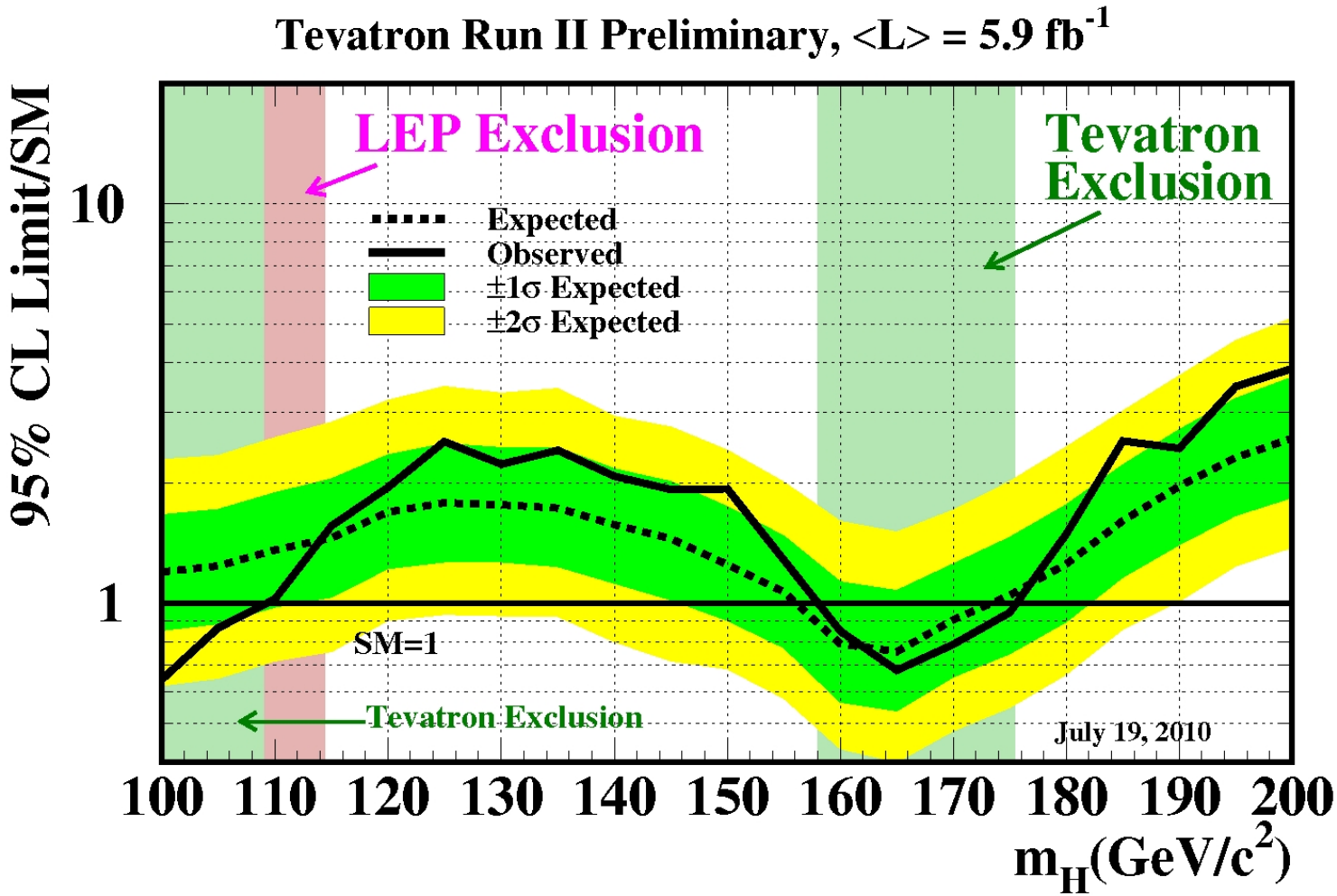
Another way to test significance: The Log-Likelihood Ratio

Basic test statistic of the Frequentist statistical method used here.

Arise from the ratio of Poisson likelihoods for Background-Only and S+B hypotheses.



Limits on Higgs Production

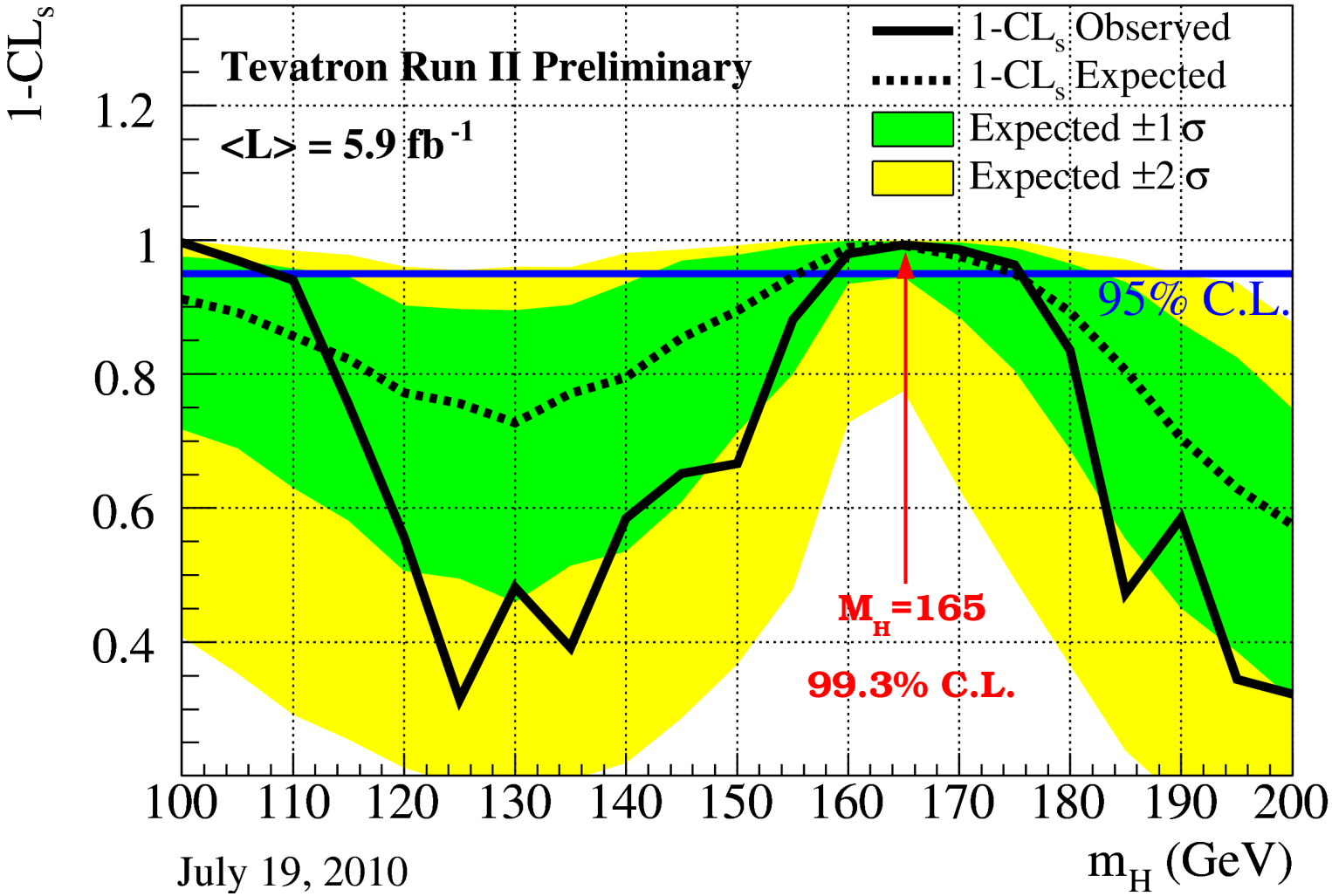


Combined 95% CL exclusion values from the Bayesian calculation

High mass exclusion grows to $158 \leq M_H \leq 175$ GeV (**M_H=165: 0.68 × SM**)

Sensitivity to low mass Higgs growing rapidly (**M_H=115: 1.56 × SM**)

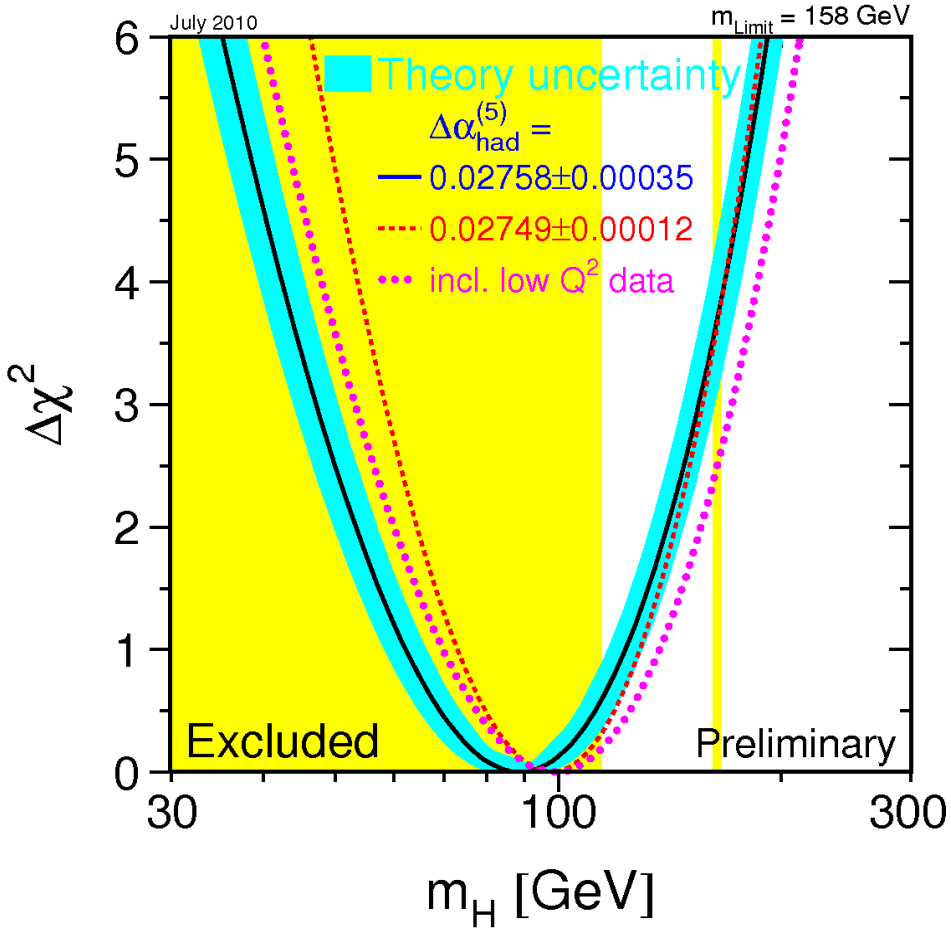
Limits on Higgs Production

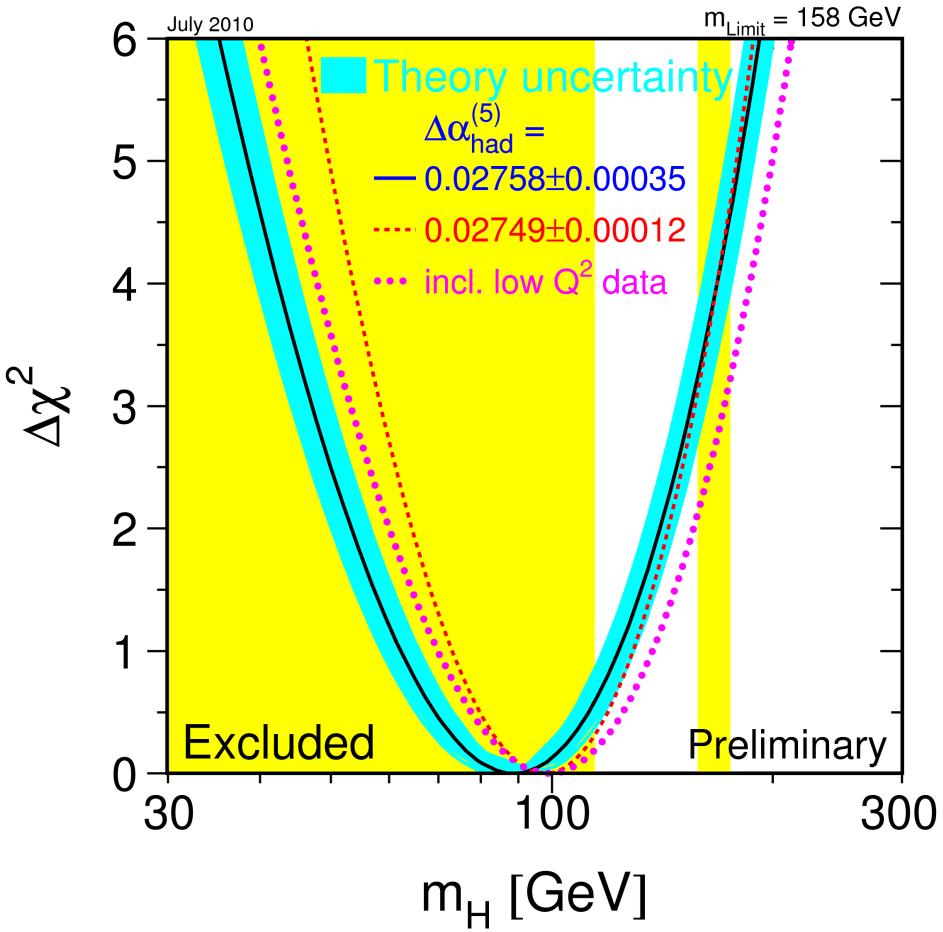


Exclusion probability shows the Tevatron has >80% CL exclusion ability over most of the mass range probed.

Impact to the Global Fit

At first glance, the impact to the EW global fit may not seem significant.



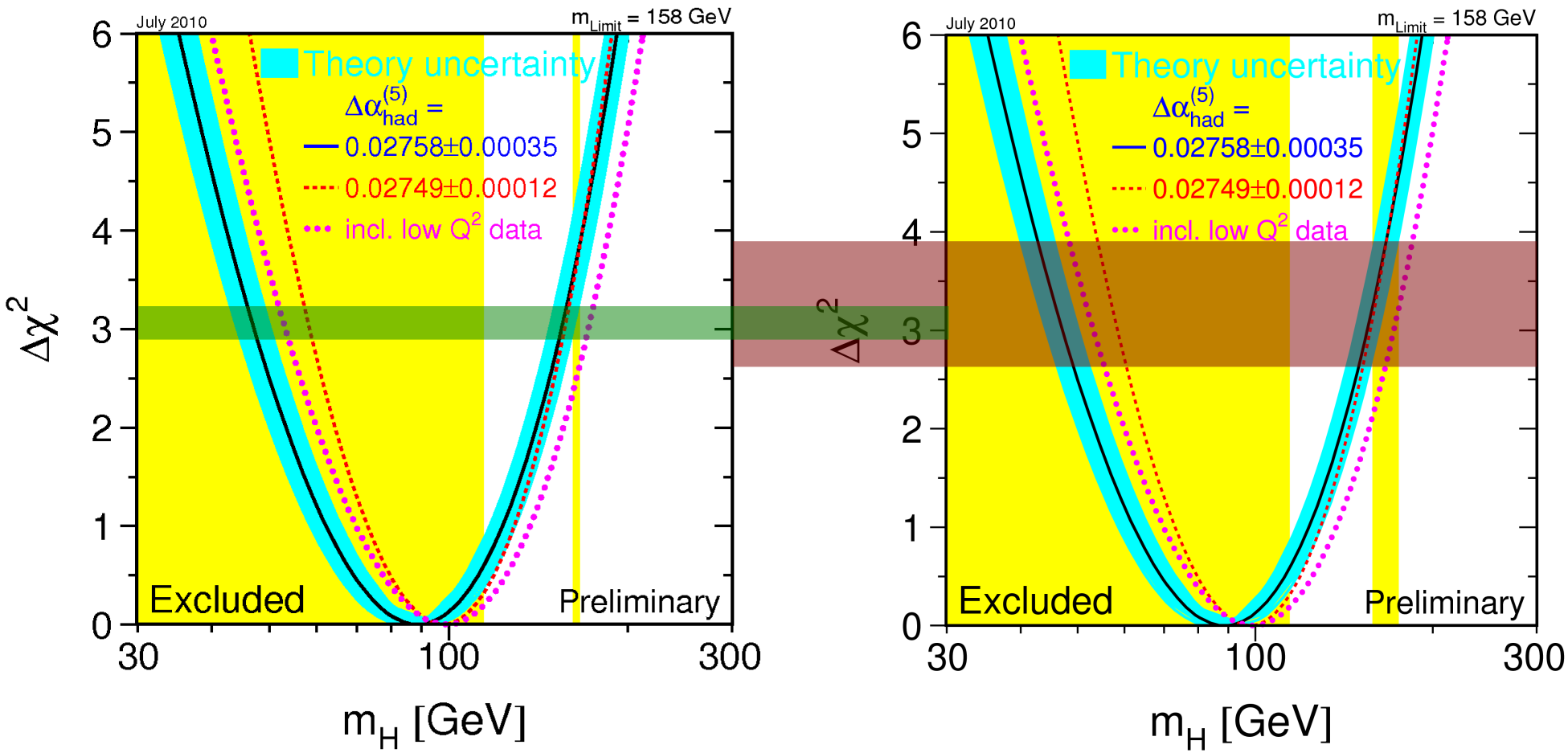


Impact to the Global Fit

At first glance, the impact to the EW global fit may not seem significant.

However, the $\Delta\chi^2$ separating low and high mass regions has more than **tripled**!

The fit is pointing even more to low M_H, where the Tevatron search is strong.



Impact to the Global Fit

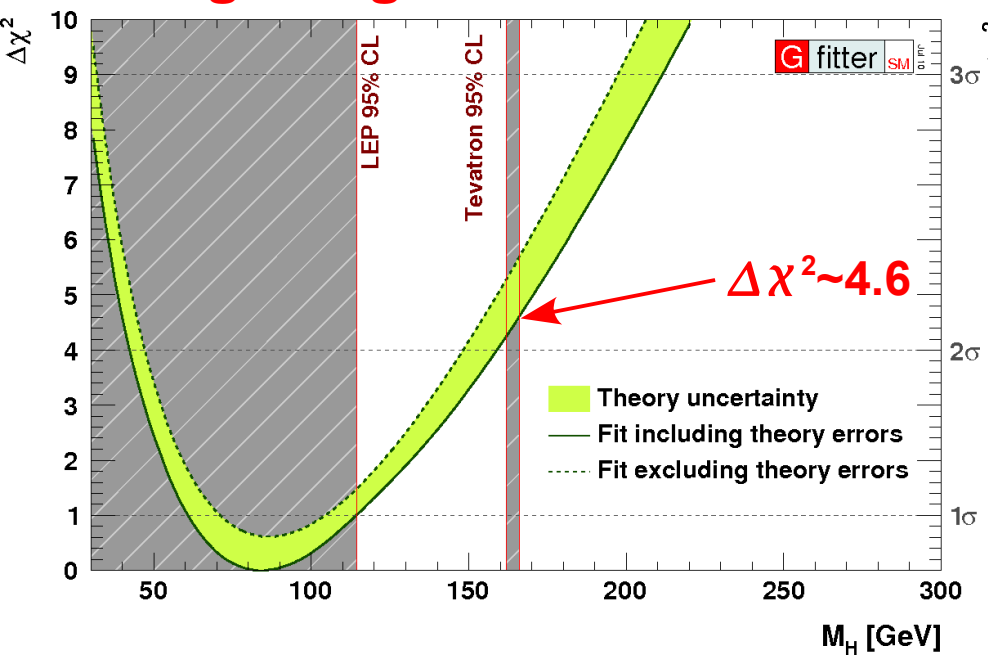
The Tevatron direct search information can be combined with the global fits.

At low M_H, Tevatron results now drive the most favored values.

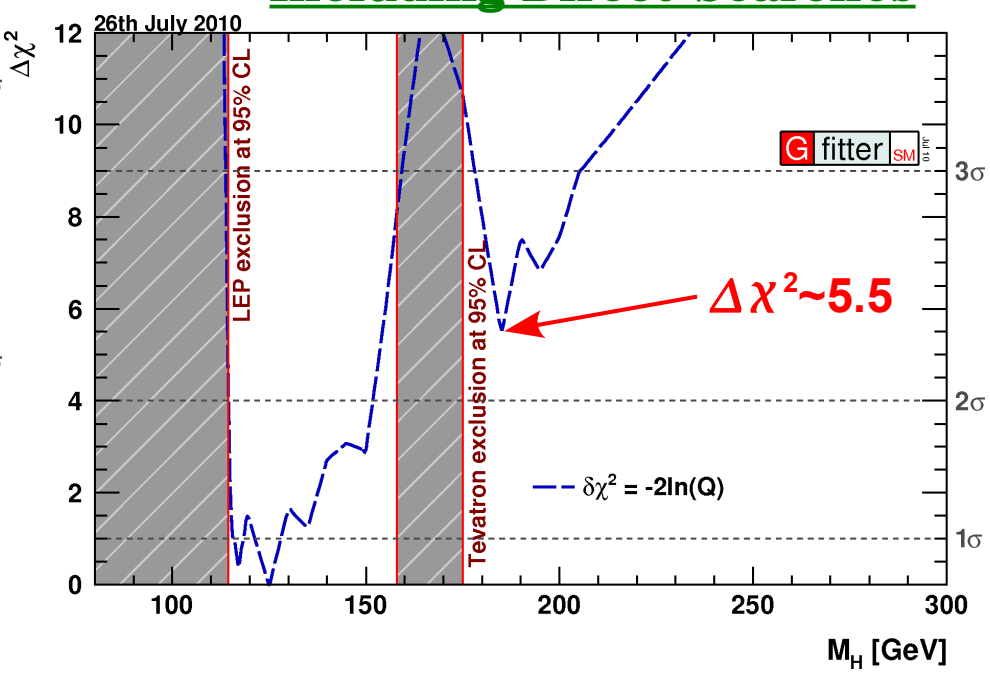
The allowed regions are getting very tight: *hiding places are disappearing quickly!*

Can compare with and without LEPII & Tevatron direct searches (today's result!)

Ignoring Direct Searches



Including Direct Searches



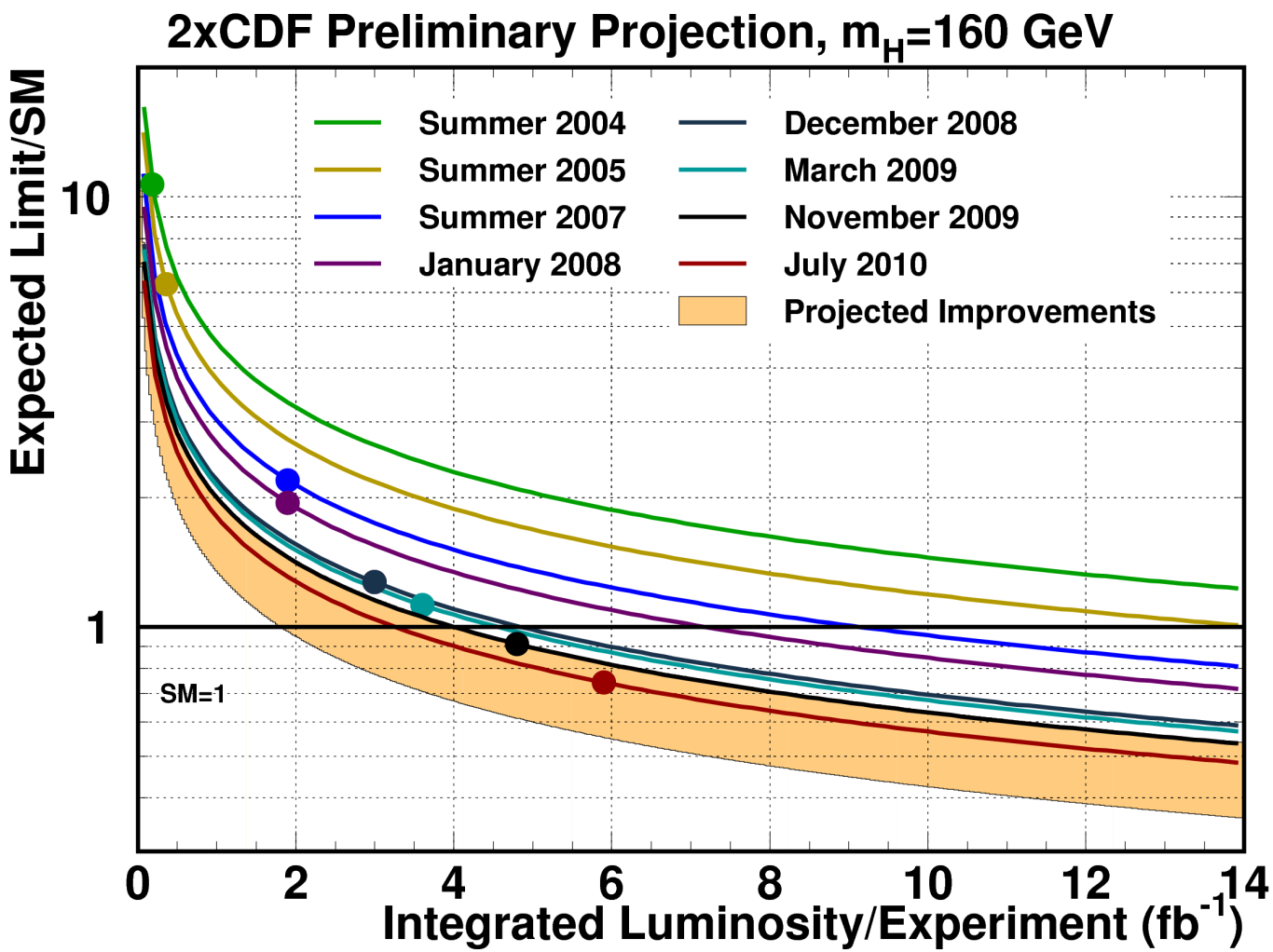
The Tevatron's Road to the Higgs

FNAL W&C
July 26th 2010

The Tevatron's Road to the Higgs

FNAL W&C
July 26th 2010

Higgs Sensitivity Projections

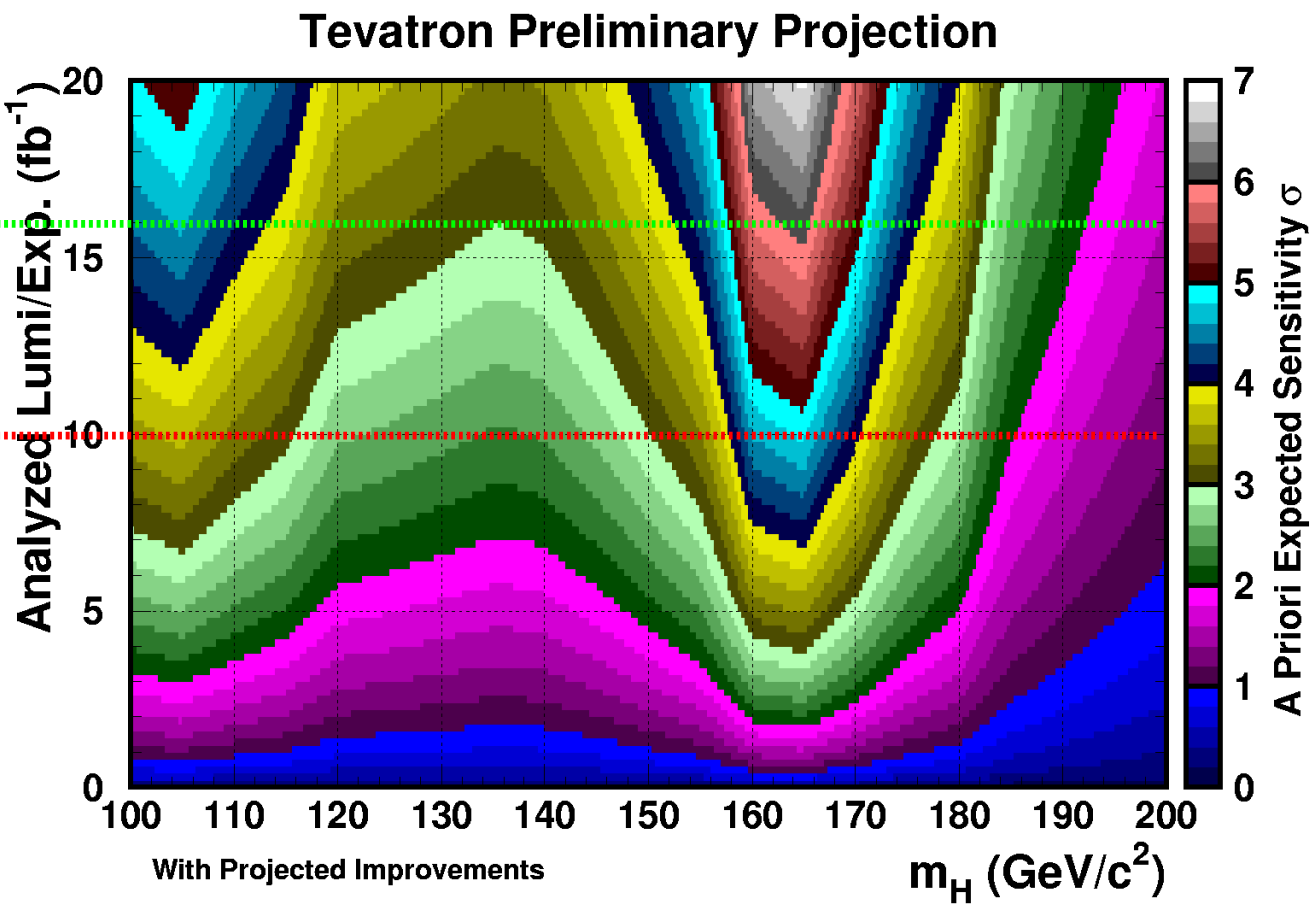


Higgs Sensitivity Projections

16 fb^{-1}:
3σ expected from 100-180 GeV

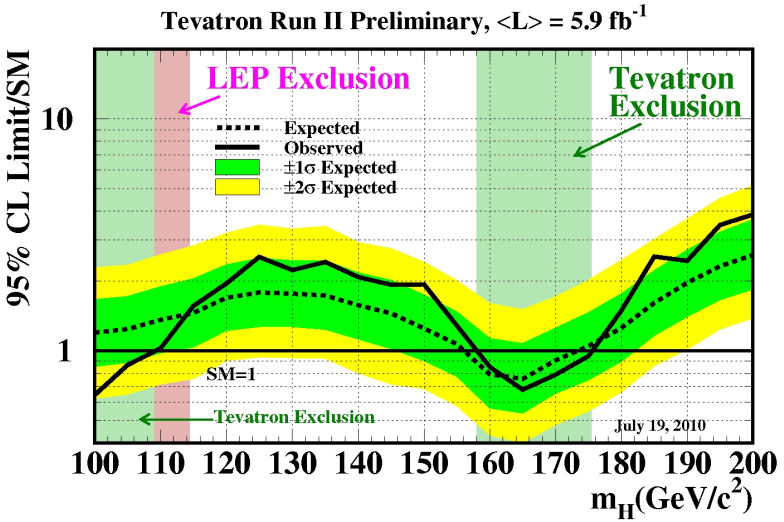
~4σ at 115 GeV

2011 Data:
>2.4σ expected over entire mass range



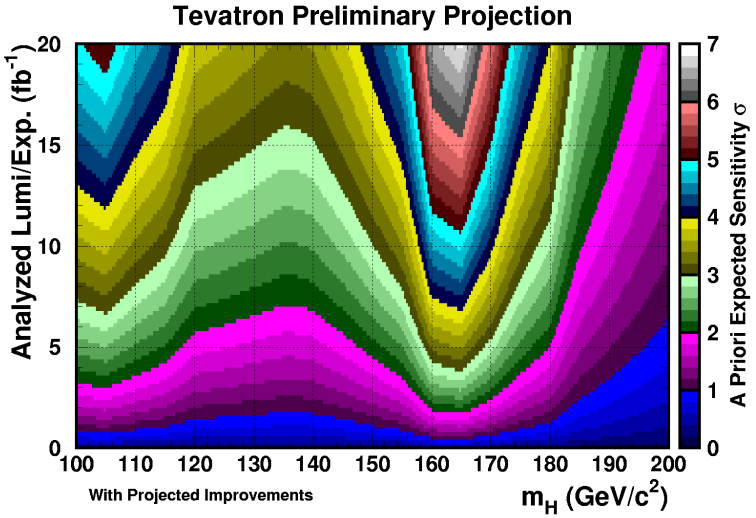
Conclusions

- We are working hard to find a Higgs boson
  - Dedicated efforts at CDF & DØ are boosted by excellent Tevatron performance
  - Low mass Higgs searches are mature and beginning to explore broad improvements to analysis technique
  - Expected limits are **below a factor of 1.8** of the SM prediction up to M_H=190 GeV



- Our exclusion region is growing!
  - We exclude **$158 \leq M_H \leq 175$ GeV**
  - CDF & DØ have each hit exclusion milestones
  - Low mass search getting very interesting

Expect constant improvement for all mass ranges as our search matures



Reliable Higgs Web Resources

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

CDF HIGGS PAGE

Welcome Results Plain English Published Graphics Links Milestones

MISSING PARTICLE:

Name: Higgs boson
Age: 13.7 billion years
Missing: 45 years
Birthday: Every few days at Fermilab
Favorite trait: Mass
Favorite particle: top quark
Favorite Hangout: Tevatron

CDF physicists make progress in search for Higgs

WELCOME

CDF (the Collider Detector at Fermilab) is a multi-purpose experiment, which does an in depth study of the forces,

http://www-d0.fnal.gov/Run2Physics/higgs/

Welcome to D0 Higgs

Fermilab | Preprints

Main Page | Public Results | D0 internal Higgs page

Higgs Physics Group at DØ

Conveners: Wade Fisher, Aurelio Juste and Krisztian Peters

Quest for the Higgs

ge symmetries. In the Standard Model, Higgs is the last piece the weak force and the electromagnetic force is achieved by flavor, thereby giving it a large "effective" mass and reducing ce "weak". This effective mass depends on the coupling n accommodate the masses of fundamental particles, which metry of the Standard Model (SM).

There is abundant evidence that the Higgs particle in the Standard Model is light. Consistency of the standard model places some loose bounds on the range of the Higgs mass possible from theory. Direct searches from LEP 2 experiments places the lower limit on the Higgs mass at M_H>114 GeV. Indirect evidence from fits to the electroweak observables points to the preferred mass of the Higgs at 87+36-27 GeV at 68% C.L. However, the sensitivity isn't great and the 95% C.L. upper limit is 160 GeV (without LEP 2 direct search limit), or 190 GeV (including this limit). Plot to the left shows the expected reach of the Tevatron.

2010
2009
2007

Fermi National Accelerator Laboratory

Tevatron New Phenomena & Higgs Working Group

Current Representatives:

CDF: Doug Benjamin, Matt Herndon, Eric James, Tom Junk, Nils Krumnack, Weiming Yao

DØ: Gavin Davies (Higgs), Jonathan Hays (Higgs), Todd Adams (New Physics), Patrice Verdier (New Physics)

DØ *Ex Officio:* Wade Fisher (Higgs), Aurelio Juste (Higgs), Krisztian Peters (Higgs), Gustaaf Brooijmans (New Physics), Arnaud Duperrin (New Physics)

Theory: Stephen Mrenna

Send Mail to the TEVNPHWG mailing list

This working group combines CDF and DØ results on searches for New Phenomena and Higgs bosons on behalf of the collaborations.

New 4th Generation Higgs Search Results

May 2010 Combined CDF and DØ upper limits on $gg \to H \to W^+W^-$ and Constraints on Fourth-Generation Fermion Models, with L=4.8 fb^{-1} (CDF) and 5.4 fb^{-1} (DØ). Submitted to *Phys. Rev. D Rapid Communications*. Assuming a heavy sequential fourth generation of fermions, 95% C.L. exclusion for a Higgs boson with mass m_H between 131 and 204 GeV/c^2.

New MSSM Higgs Search Results

March 2010 Combined CDF and DØ upper limits on neutral MSSM Higgs boson production in the $h/A/H \to \tau\tau$ decay mode with L=1.8fb^{-1} (CDF) and 2.2 fb^{-1} (DØ). Preliminary results.

New SM Higgs Search Results

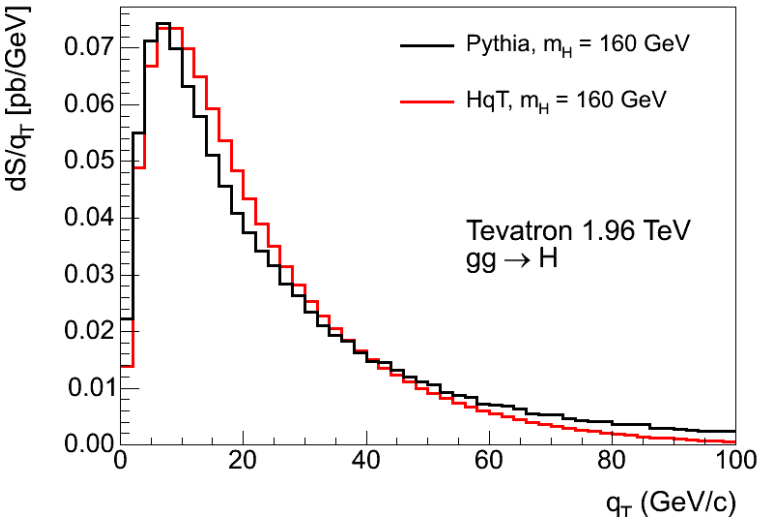
http://tevnphwg.fnal.gov/

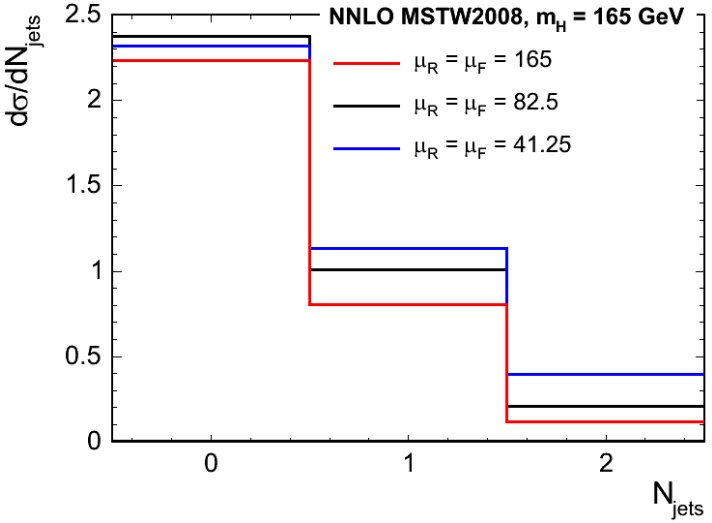
Extra Slides

Theory & Uncertainties

Tevatron progress has brought much interest from the theory community

- State of the art gg→H cross section calculations appear frequently (currently NNLL+NNLO)
- de Florian & Grazzini (Phys.Lett.B674:291-294, 2009)
  - Soft-gluon resummation treatment
  - MSTW2008 PDFs
- Anastasiou, Boughezal, Petriello (JHEP:0904:003, 2009)
  - Proper treatment of b-quarks at NLO
  - Inclusion of two-loop EW effects





More information of our choices and comparisons with alternative approaches:

http://tevnphwg.fnal.gov/results/SMHPubWinter2010/gghtheoryreplies_may2010.html

Issues with gg→H

1. Use NNLO cross-section instead of NNLO + NNLL we currently use
    1. We disagree as our parton shower model of gg→H uses PYTHIA which contains a "resummation" based on multiple gluon emission, and we reweight to NNLO+NNLL Higgs P_T

2. A wider variation of scales should be used for cross-section uncertainty & cross-section uncertainty should be larger due to differences at higher orders
    1. Several studies in the community point to $M_H/2$ being the appropriate scale
    2. Research has been done to show that the NNLO+NNLL expansion and higher order expansion terms are converging and do not require such a large uncertainty

3. Need to include α_s uncertainties into PDF uncertainties
    1. As of ICHEP July 2010 combination, we include this

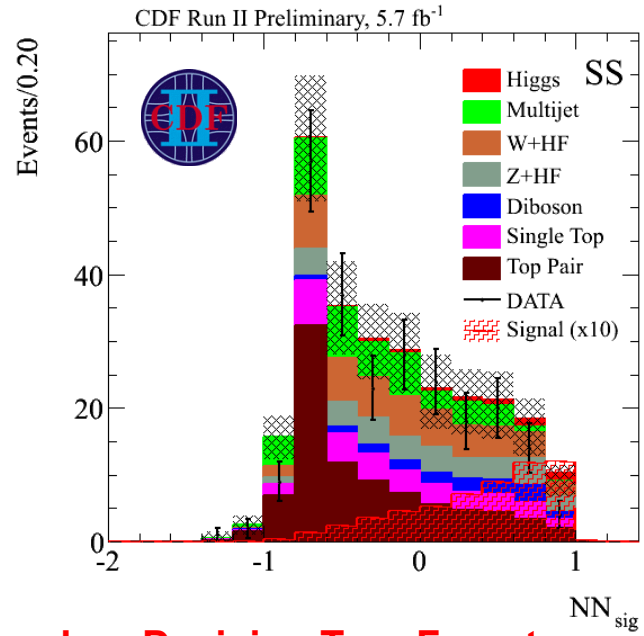
4. Reconsider how to combine uncertainties from PDF and α_s
    1. We consider them uncorrelated because PDFs are determined largely experimentally, and scale is a choice in perturbative expansion
    2. We tested the recommended reconsideration to our procedure, and found negligible dependence of PDF on scale choice

Multivariate Analysis

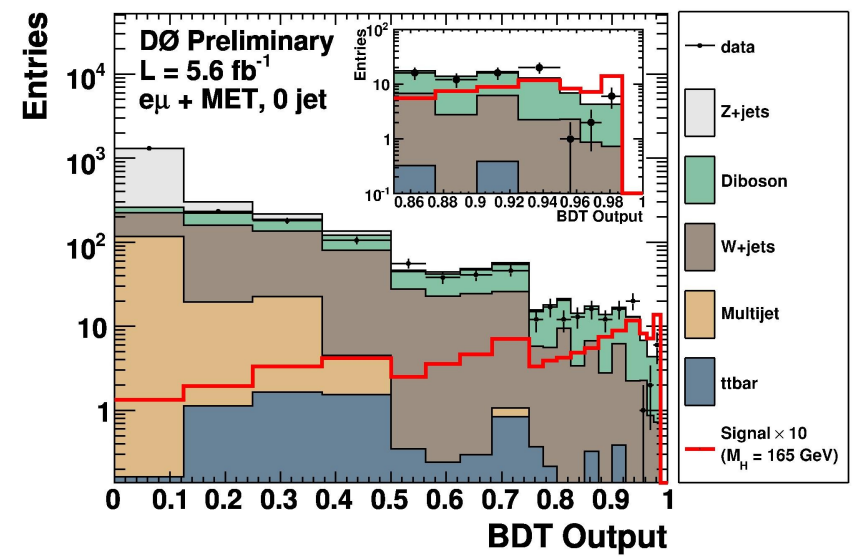
We utilize a range of different techniques

- Some techniques are less sensitive to modeling of correlations
- Some techniques are less sensitive to degrading effects of systematic uncertainties
- Different tools are appropriate for different jobs, and each is scrutinized in fine detail

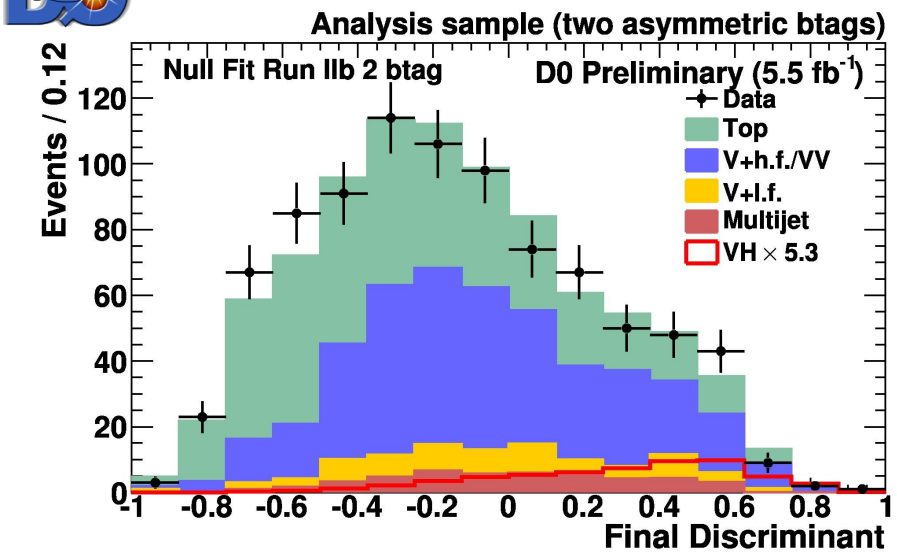
Neural Network



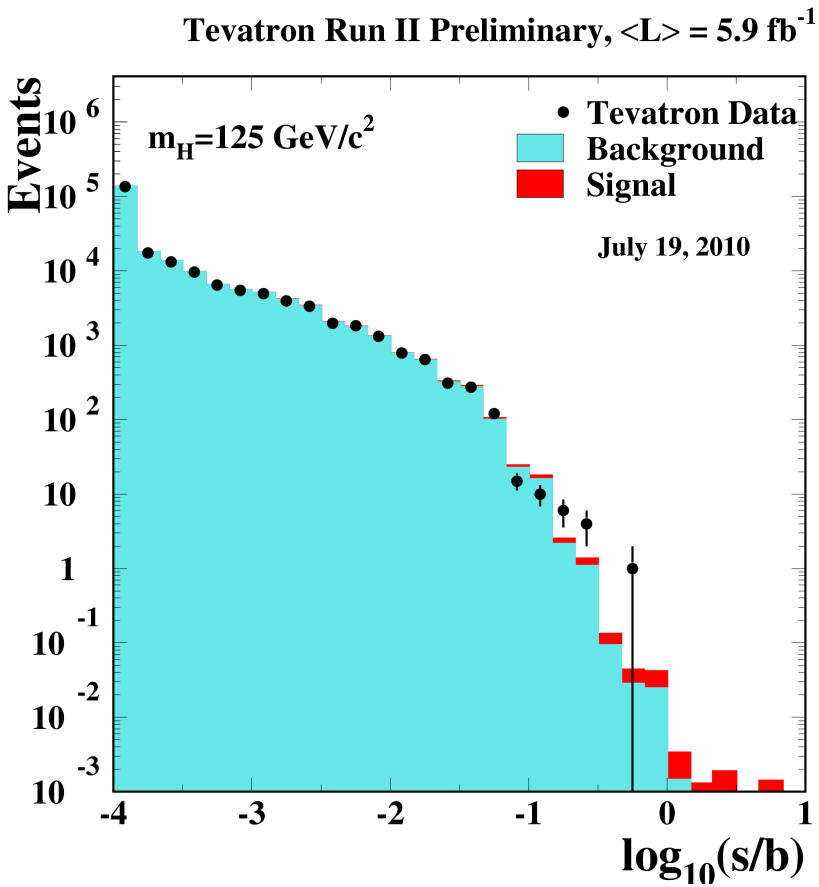
Boosted Decision Tree

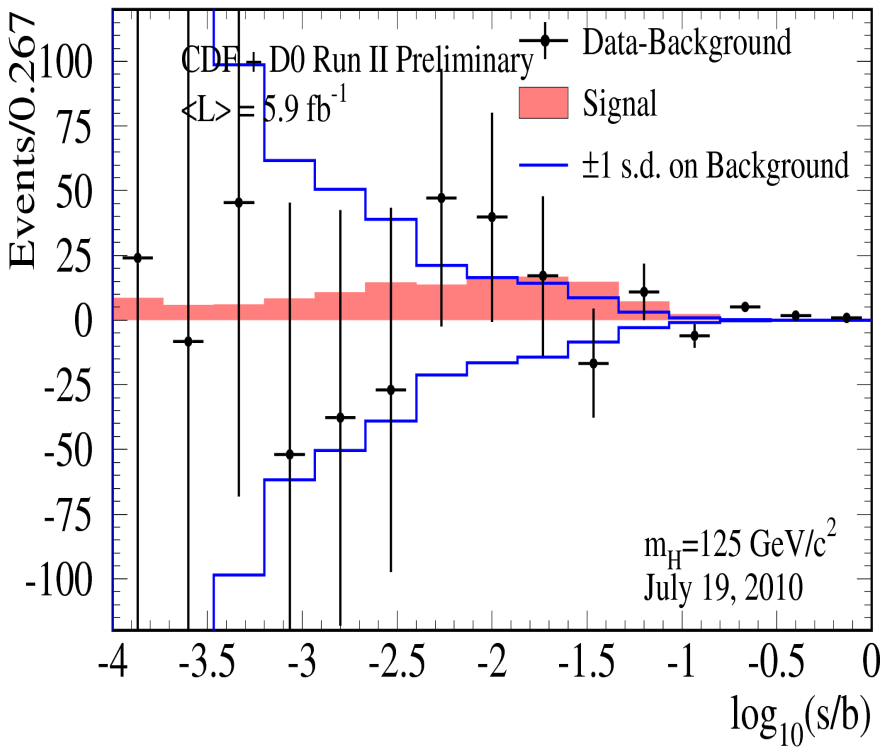


Random Decision Tree Forest



Putting It Together: M_H=125 GeV





A simple way to visualize the sum of input channels is to simply reorder **ALL** of the input histogram bins on one plot

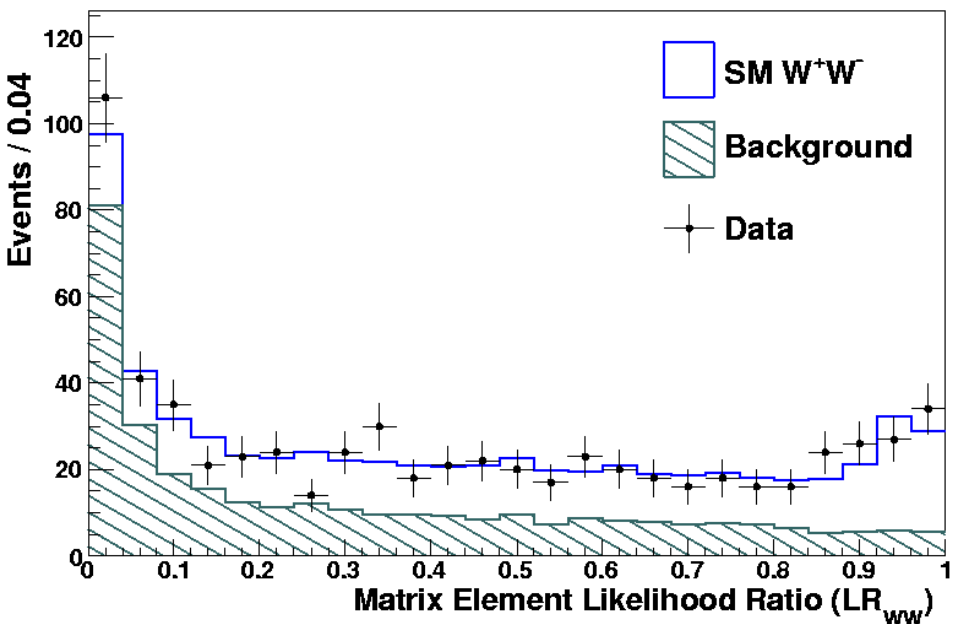
This figure shows all bins for **M_H=125 GeV** reordered based on the signal to background ratio in each bin.

MVA Validation

The diboson card can be played at high mass, too!

- Test in CDF WW+0jet final state
- Matrix Element discriminant used to measure WW xsec
- Matrix Element discriminant input to Neural Network for Higgs search

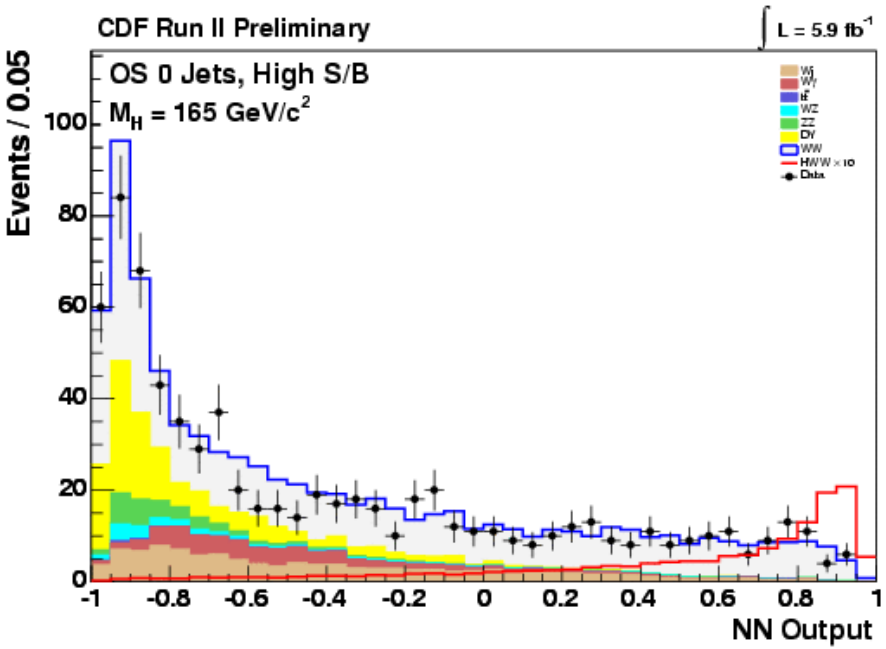
SM WW Measurement



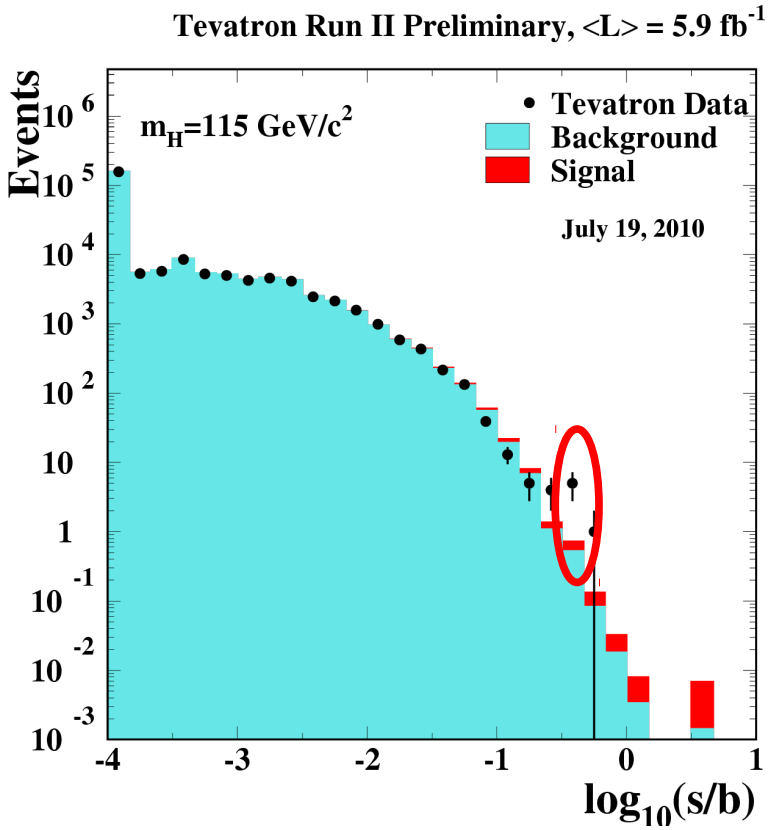
$\sigma(p\bar{p} \to WW) = 12.1 \pm 0.9\ (\text{stat.})^{+1.6}_{-1.4}\ (\text{syst.})$ [pb]

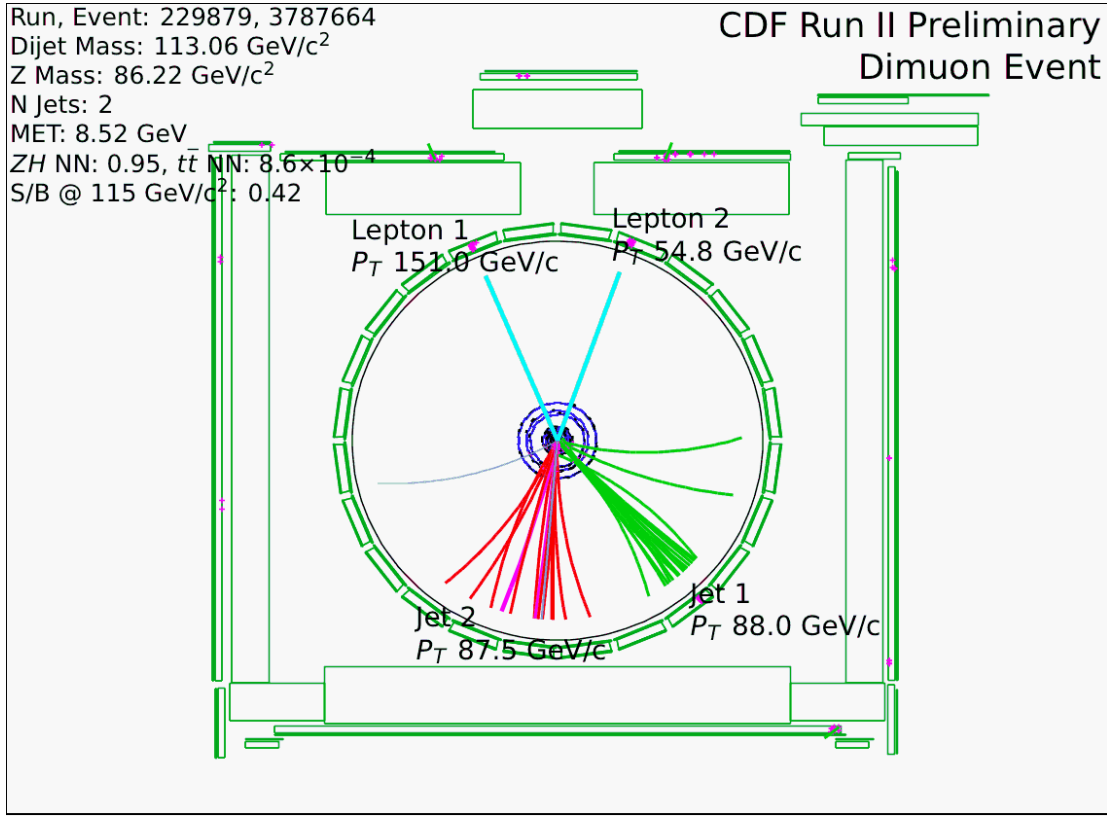
Syst. **includes** 5.9% luminosity uncertainty

gg→H→WW Search



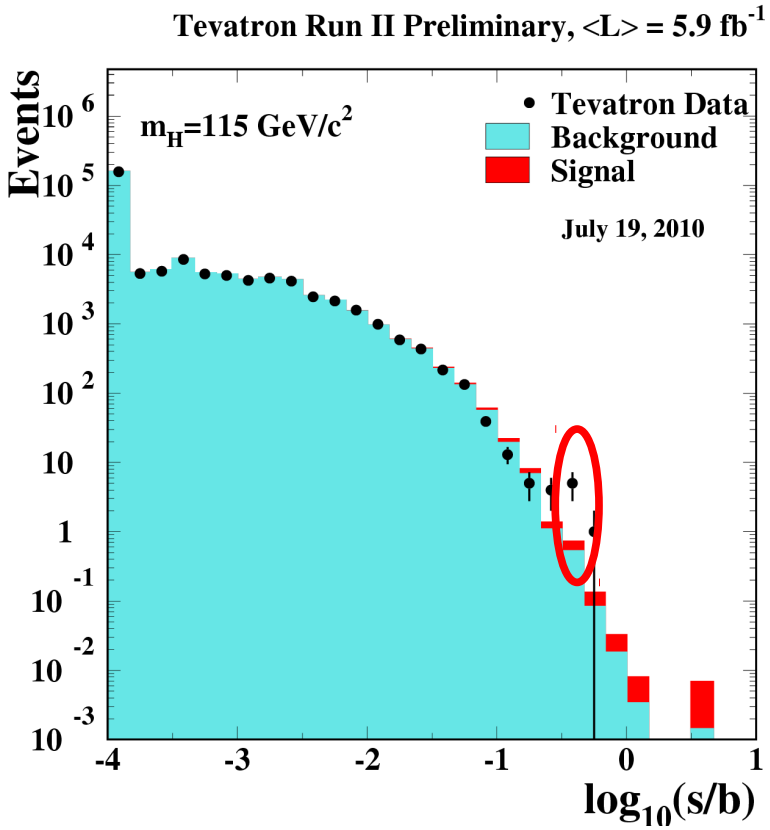
Candidate Event: M_H=115 GeV

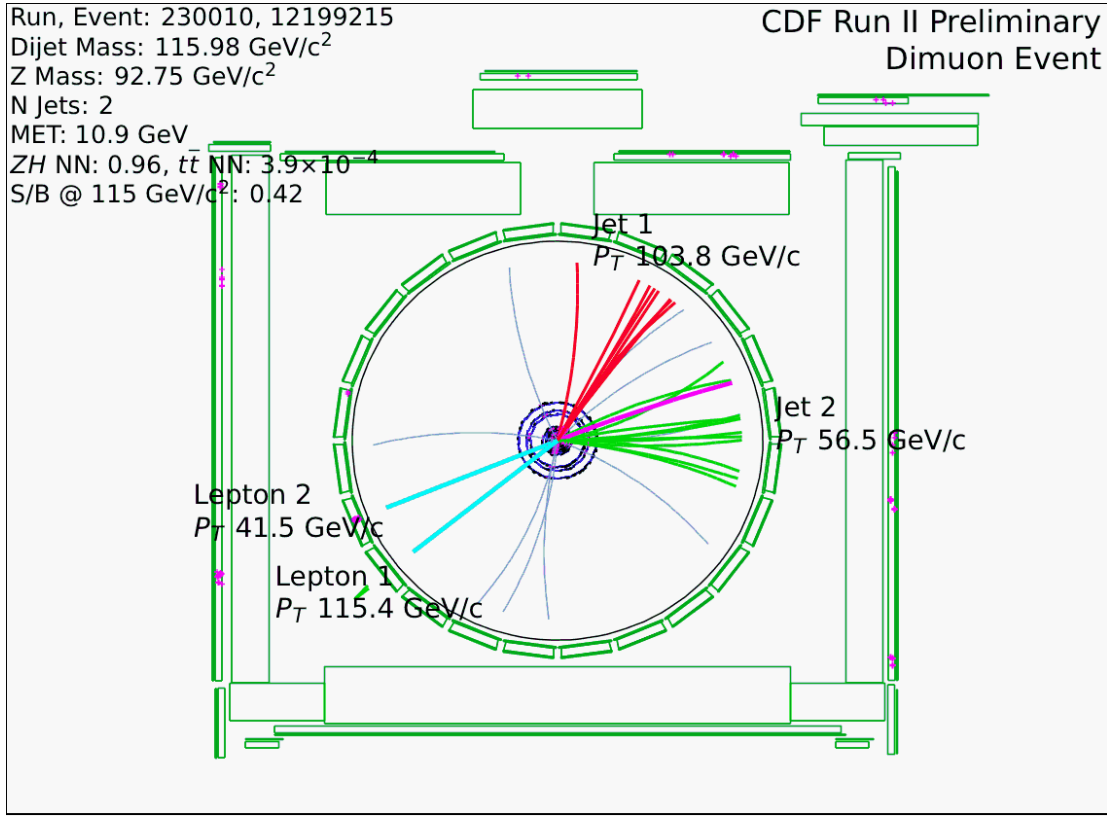




Data: 5 events
Expectation: 0.8 events
S/B: ~1/2

Candidate Event: M_H=115 GeV





Data: 5 events
Expectation: 0.8 events
S/B: ~1/2