Tevatron SM and BSM Higgs Searches

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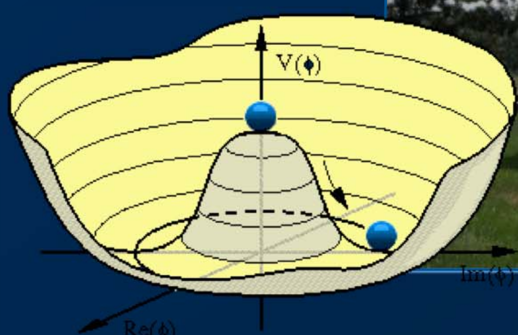
For the CDF and DØ Collaborations

43rd Fermilab Users' Meeting

June 2, 2010

Outline

- Overview
- Standard Model Higgs at the Tevatron
- Beyond the Standard Model (BSM) Higgs at the Tevatron
- Tevatron Projections
- Conclusions



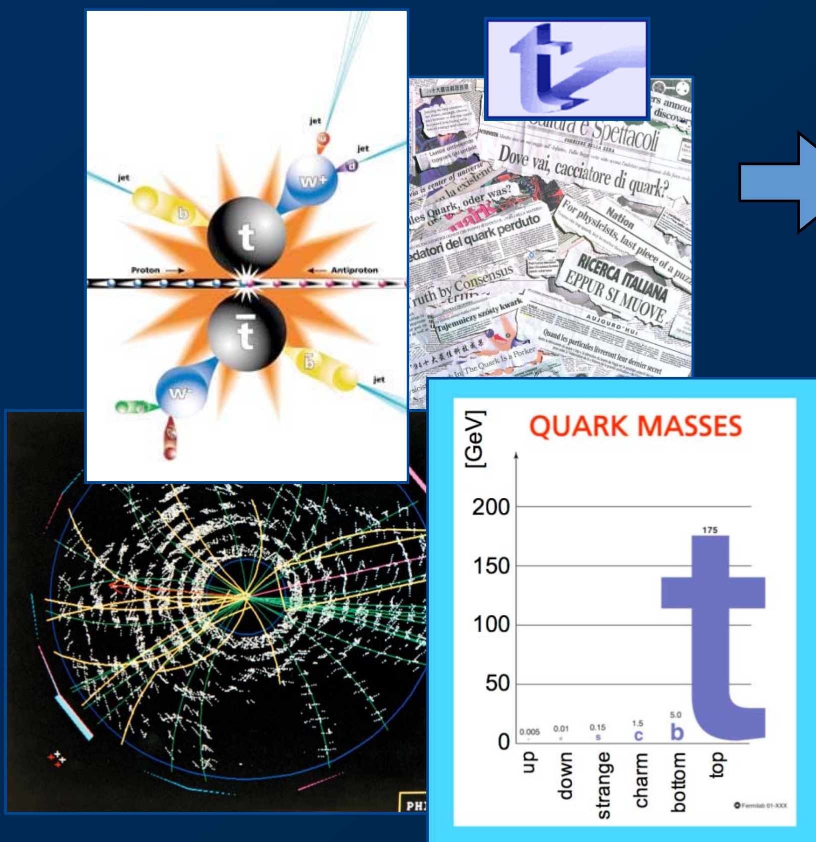
Broken Symmetry

The Fermilab Tevatron

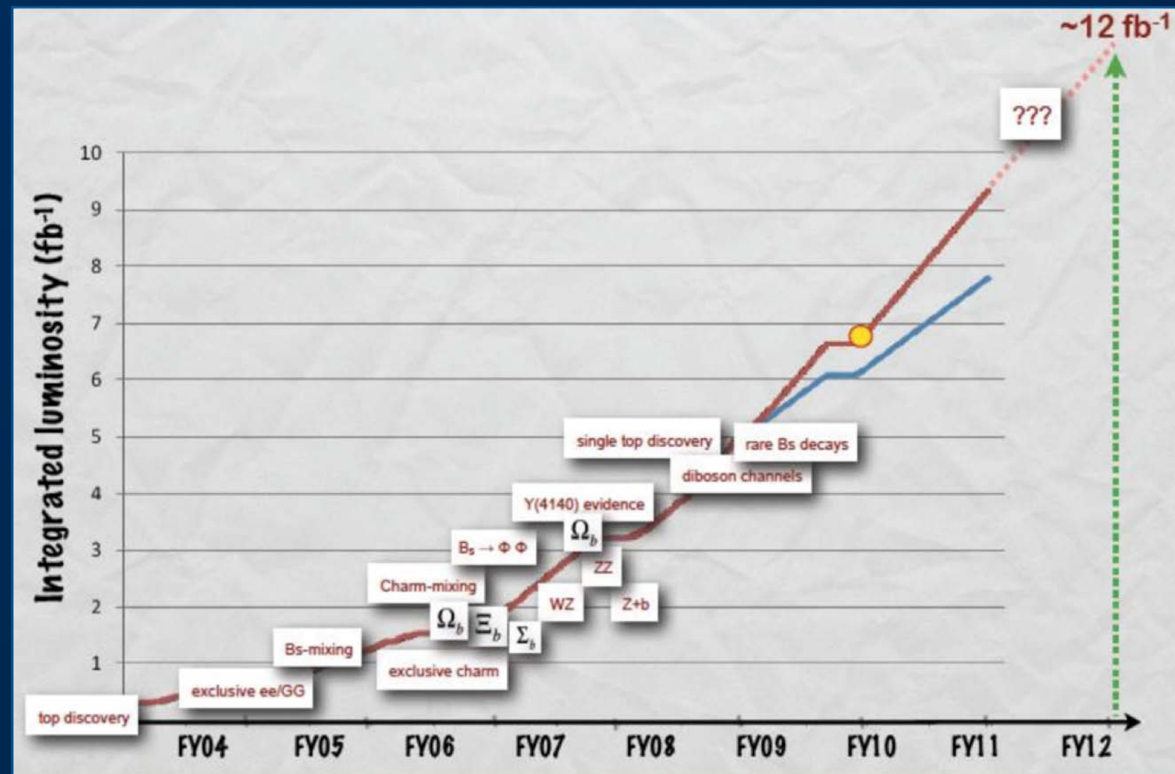
The Fermilab Tevatron is ...

... a Discovery Machine !

Top Quark Discovery (1995)



New Physics discoveries continue to appear!



Today, the collider experiments have collected 125 times more data than we used to discover the top quark.

Recently, the Tevatron has been running beautifully, setting many new luminosity records.

Collider Physics at the Tevatron

The Tevatron Research Program

Precision Measurements &
New Discoveries

- Mixing, CKM Constraints and CP Violation
- Heavy Flavor Spectroscopy
- New Heavy Baryon States
- Tests of Quantum Chromodynamics
- Precise measurement of Top Quark and W Boson masses
- Top Quark Properties
- Diboson production and SM gauge couplings
- New Exclusive/Diffractive Processes

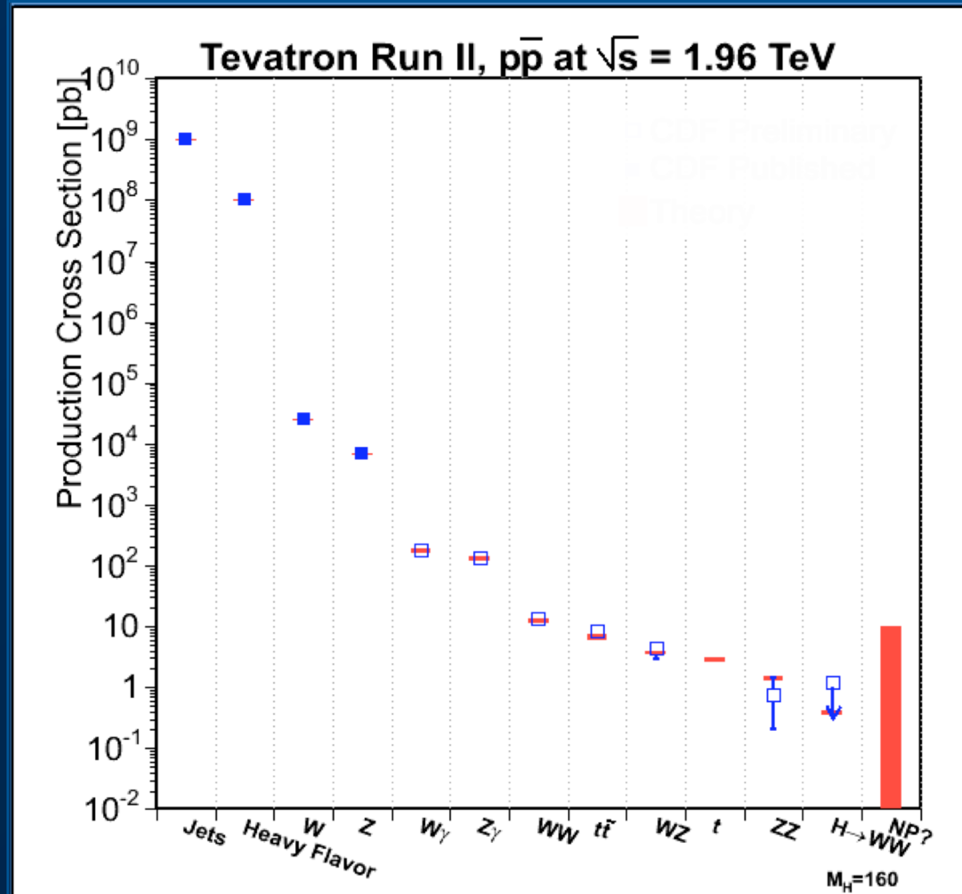
⋮

We're still probing the **Terascale** as the integrated luminosity of our data increases

CDF & DØ are running at ~90% efficiency

Are we on the verge of another discovery?

Harder to Produce

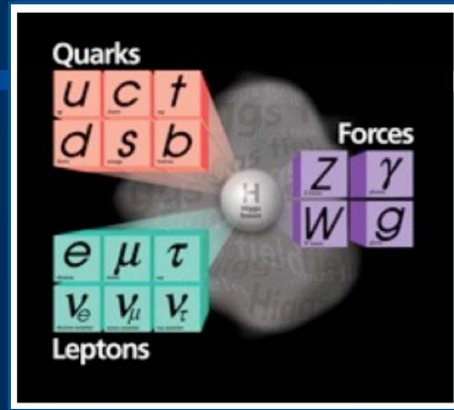


Harder to Observe

The Standard Model Higgs Boson is within reach!

The Higgs Boson

Fermilab

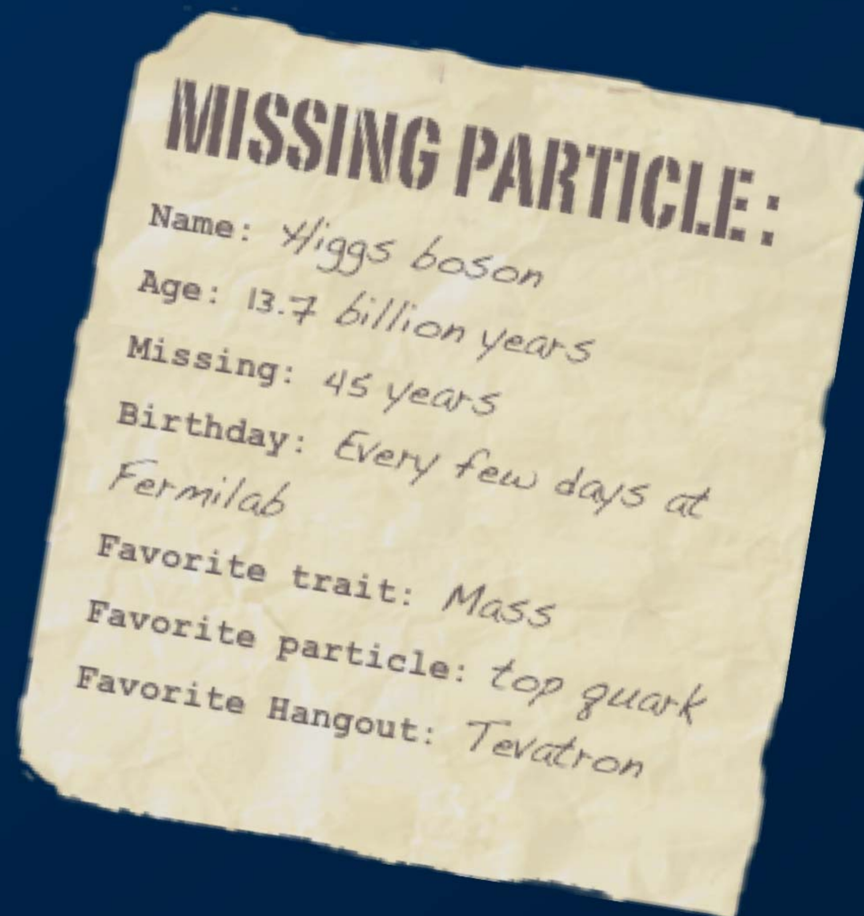


The Standard Model ...

- Describes the fundamental constituents of matter and the interactions between them
- Says nothing about the masses of particles!

The Higgs Mechanism predicts the existence of a single, scalar Higgs Boson...

...that has not yet been observed in nature



Through the "Higgs Mechanism" ...

- Spontaneous Symmetry Breaking is explained
- The W and Z bosons acquire large masses, yet the photon remains massless
- The masses of quarks and leptons are also generated

The Higgs Boson

Fermilab

Discovering the Higgs Boson would be an extraordinary achievement!

... but even more broadly, humankind is eagerly waiting with intense interest!

It would bring closure to the work of six prominent physicists of the 1960's...

"...being able to claim the '**discovery**' of the **Higgs** will be a feather in the cap of the successful laboratory."

"...it will almost certainly bring a prize for the experimentalists who confirm it."

"...it will almost certainly have implications on the modern world as large as the discovery of the electron..."

The 2010 J. J. Sakurai Prize for Theoretical Particle Physics

Kibble Guralnik Hagen Englert Brout

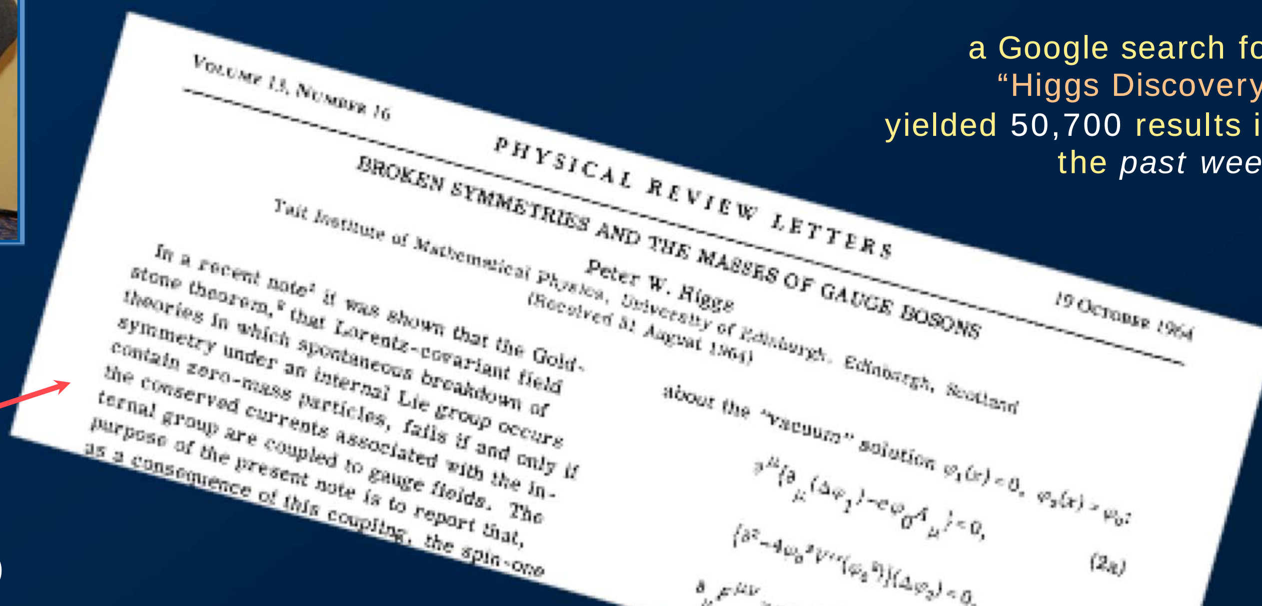
(Where is the elusive Higgs?)

a Google search for "Higgs Discovery" yielded 50,700 results in the *past week*

Englert & Brout, PRL 13, 321-323 (1964)

Higgs, PRL 13, 508-509 (1964)

Guralnik, Hagen & Kibble, PRL 13, 585-587 (1964)



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs

Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland

(Received 31 August 1964)

In a recent note[1] it was shown that the Goldstone theorem,[2] that Lorentz-covariant field theories in which spontaneous breakdown of symmetry under an internal Lie group occurs contain zero-mass particles, fails if and only if the conserved currents associated with the internal group are coupled to gauge fields. The purpose of the present note is to report that, as a consequence of this coupling, the spin-one

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

The Higgs Boson

The Higgs Mechanism generates the masses of particles...

...yet, ironically, it reveals no hint of what the Higgs boson mass is.

If the Higgs boson exists, its mass must be determined experimentally.

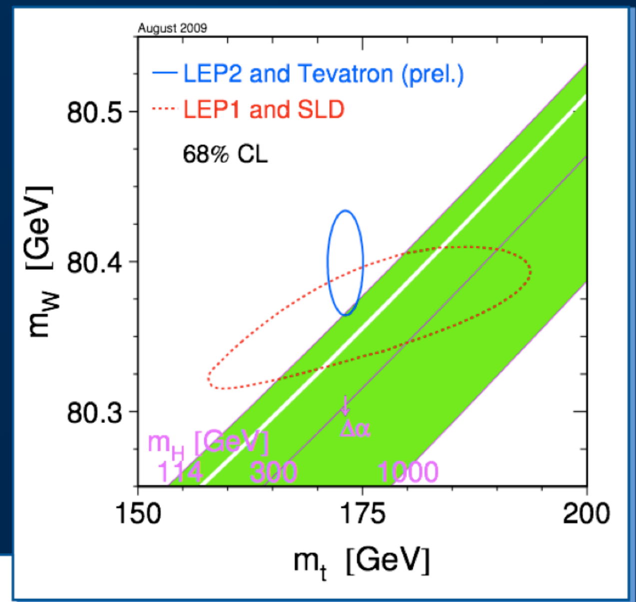
Here's what we've learned so far:

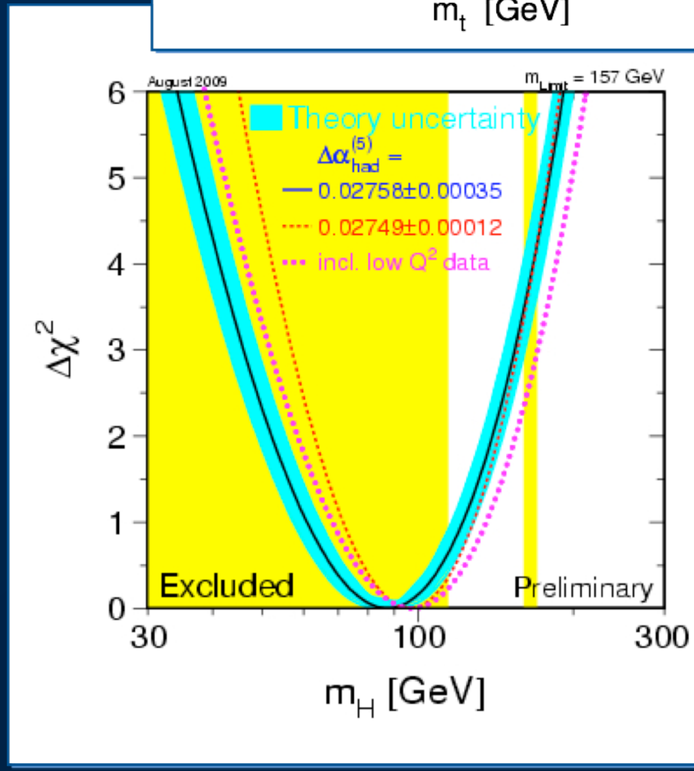
- Based on a direct search at LEP II:

$$m_H > 114 \text{ GeV}/c^2 \text{ @ } 95\% \text{ CL}$$

- According to precision electroweak measurements (involving the top quark mass, W boson mass, etc):

$$m_H < 186 \text{ GeV}/c^2 \text{ @ } 95\% \text{ CL}$$





Probing the range

$$100 < m_H < 200 \text{ GeV}/c^2$$

is crucial!

This is exactly the range where the Tevatron is sensitive

Standard Model Higgs Production

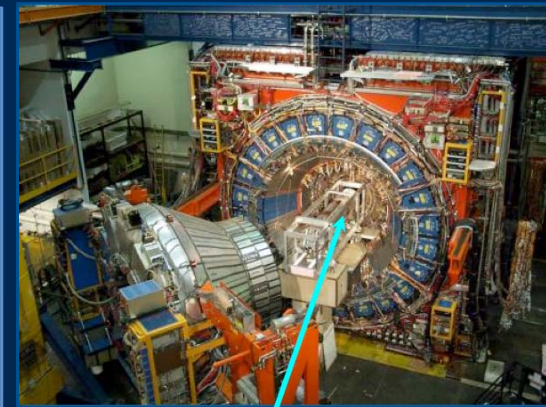
If the Higgs boson exists according to the Standard Model ...

we definitely know where to look for it!

The problem is it's produced only rarely: in one out of every 10^{12} collisions.

about 2 Higgs bosons produced each week

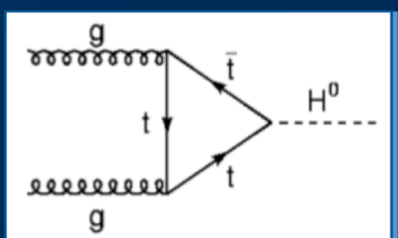
in here



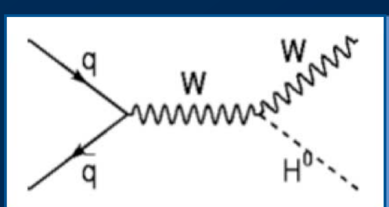
and in here

How is the Higgs produced?

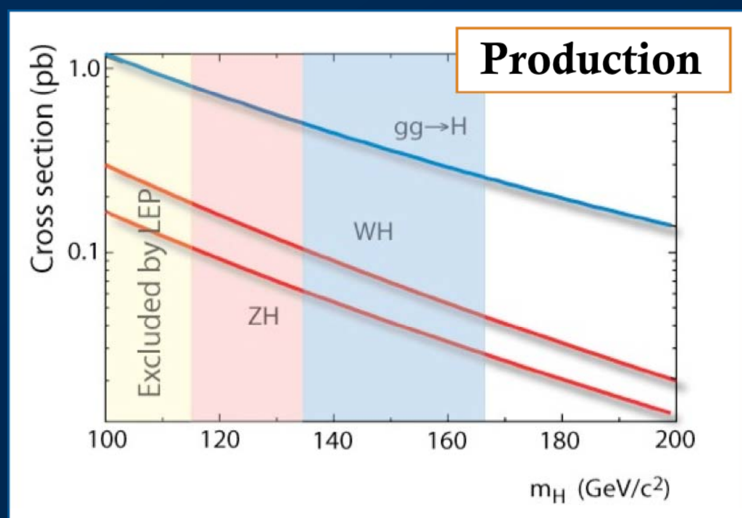
- Direct production ($gg \rightarrow H$)



- Associated production (WH, ZH)

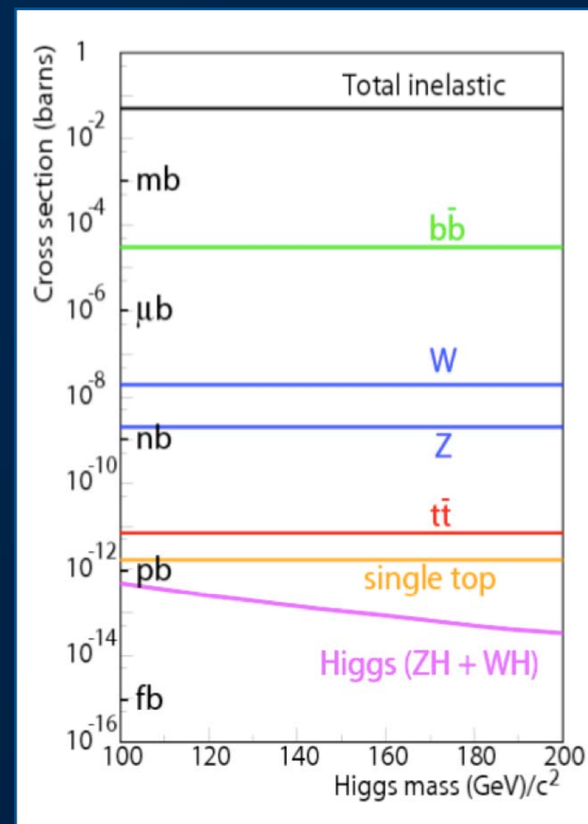


*also Vector Boson Fusion



The cross section for WH is about 35x less than the cross section for $t\bar{t}$ in Run 1!

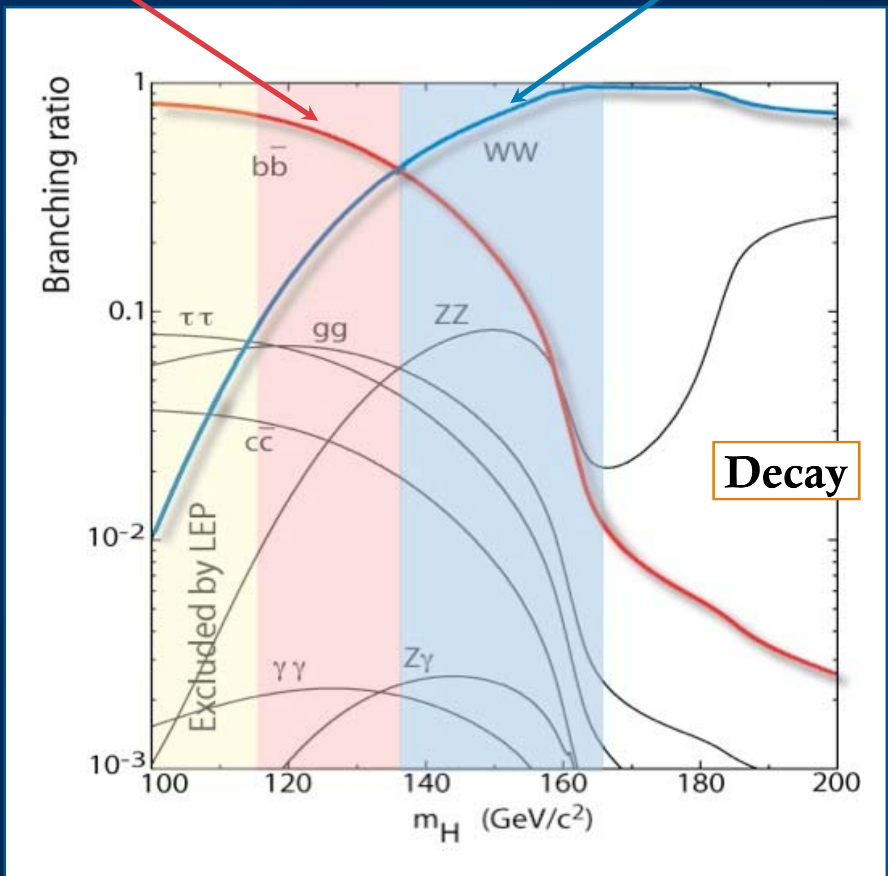
(We have our work cut out for us.)



Standard Model Higgs Decay

Since the exact mass of the Higgs boson is unknown, we seek the Higgs through various search channels in order to maximize the chance of finding it.

Some channels are sensitive to a Higgs boson at low mass. Others are sensitive at high mass.



High Mass Higgs ($m_H > 135$ GeV/c^2)

- The main decay mode is $H \to W^+W^-$
- A very promising channel. We've already excluded SM Higgs masses around 160 GeV/c^2

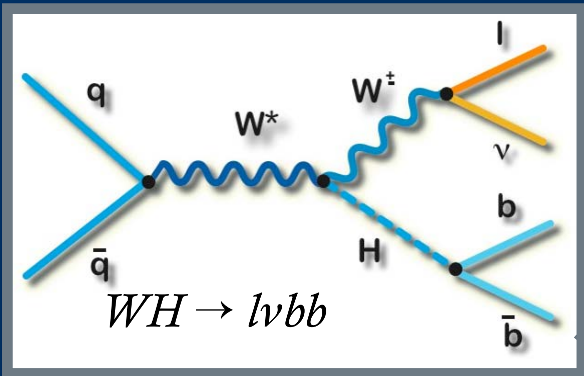
Low Mass Higgs ($m_H < 135$ GeV/c^2)

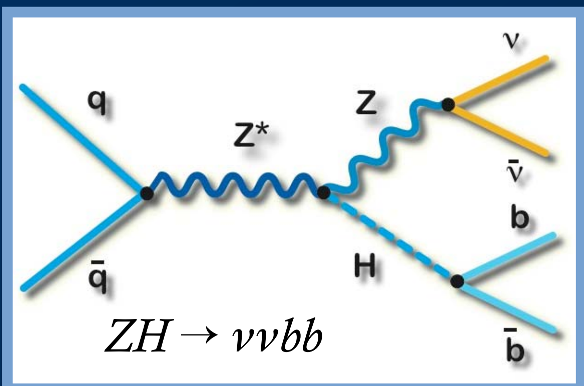
- The main decay mode is $H \to bb$
- However, $gg \to H \to bb$ is overwhelmed by multijet background events
- Rely on associated production (WH/ZH).
- We use the decays of W and Z bosons to leptons as a tag for trigger and analysis

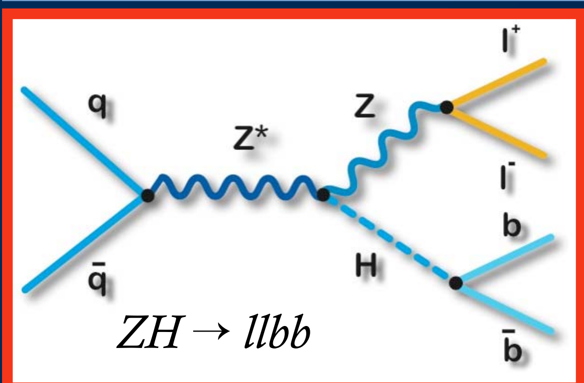
Higgs Search Channels at the Tevatron

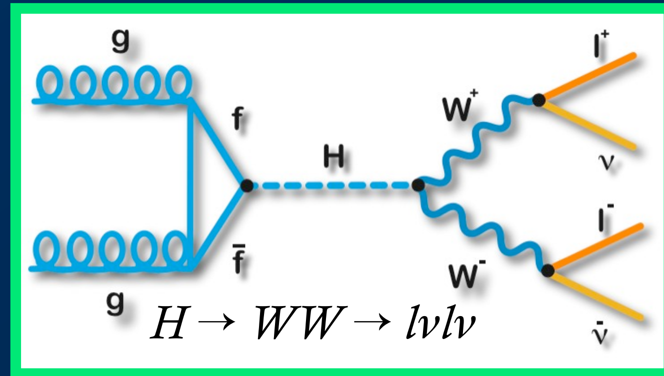
Fermilab

low mass



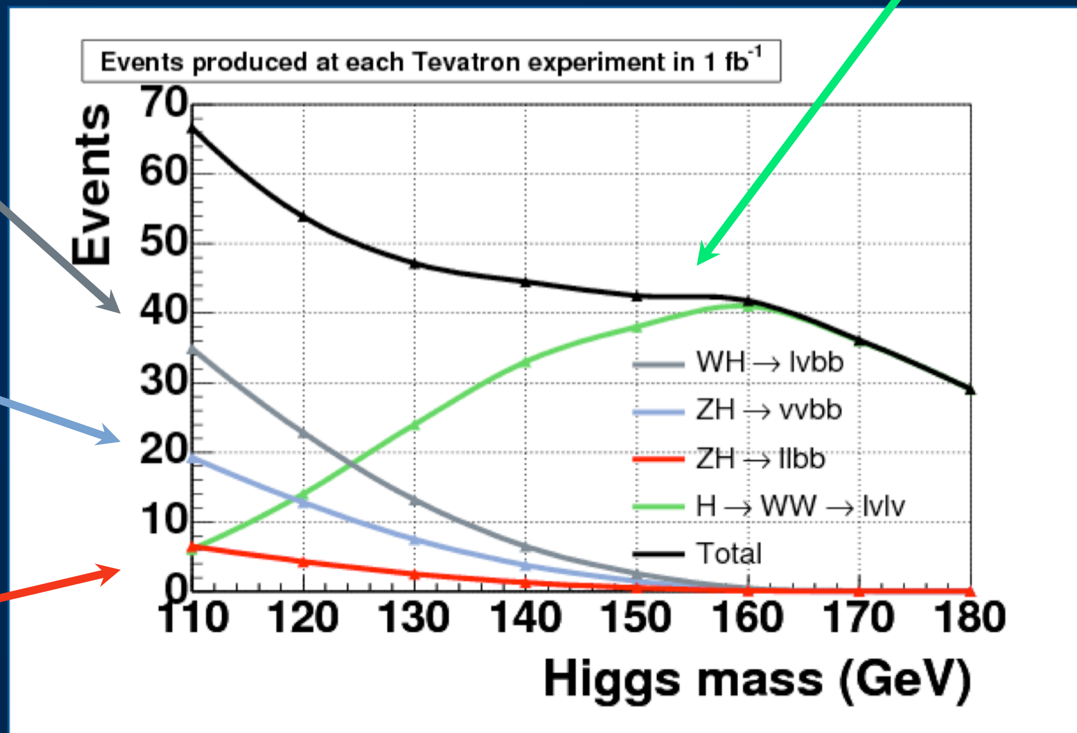






high mass

(also beneficial at low mass)



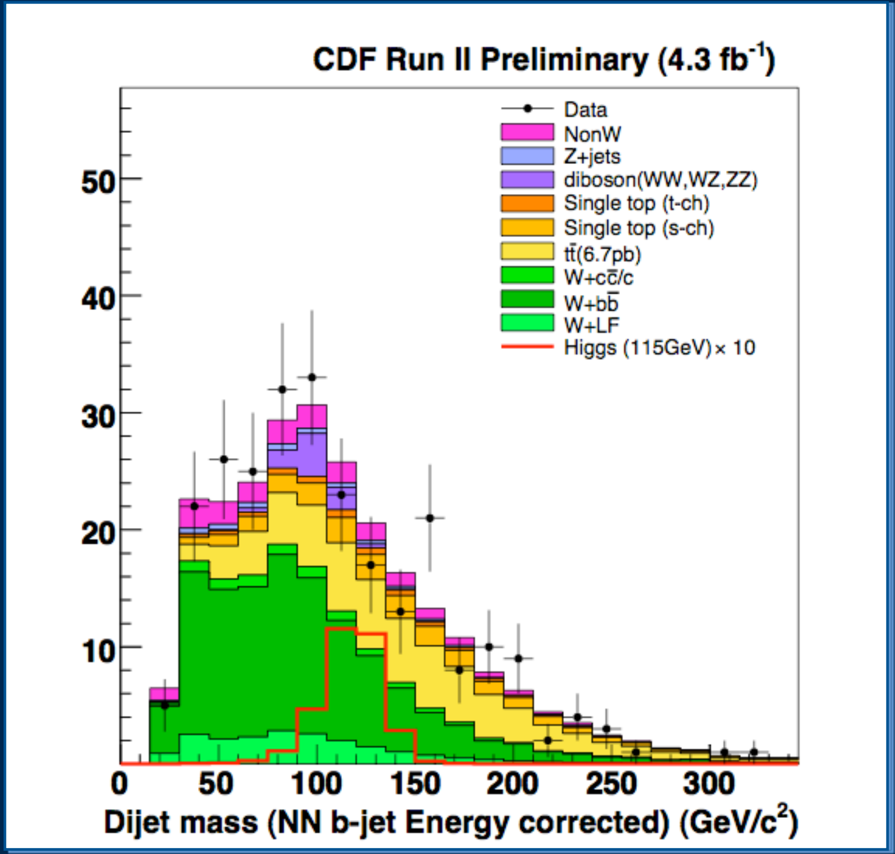
x 2 experiments

These are the major search channels, but the Tevatron has a comprehensive search program exploiting many other production and decay channels to maximize search sensitivity

Higgs Search Strategy

In the search for the top quark in the early 90's, physicists at DØ and CDF employed novel analysis strategies to discover it with the smallest possible amount of data.

We're doing it again.
But it takes time, patience, and hard work.



Improving the dijet mass resolution

We use a three-fold strategy:

I. Maximize Signal Acceptance

- Increase the number of real Higgs events in our sample of data.

II. Reduce Background

- Decrease the number of events that resemble Higgs, but aren't really Higgs

III. Employ Multivariate Techniques

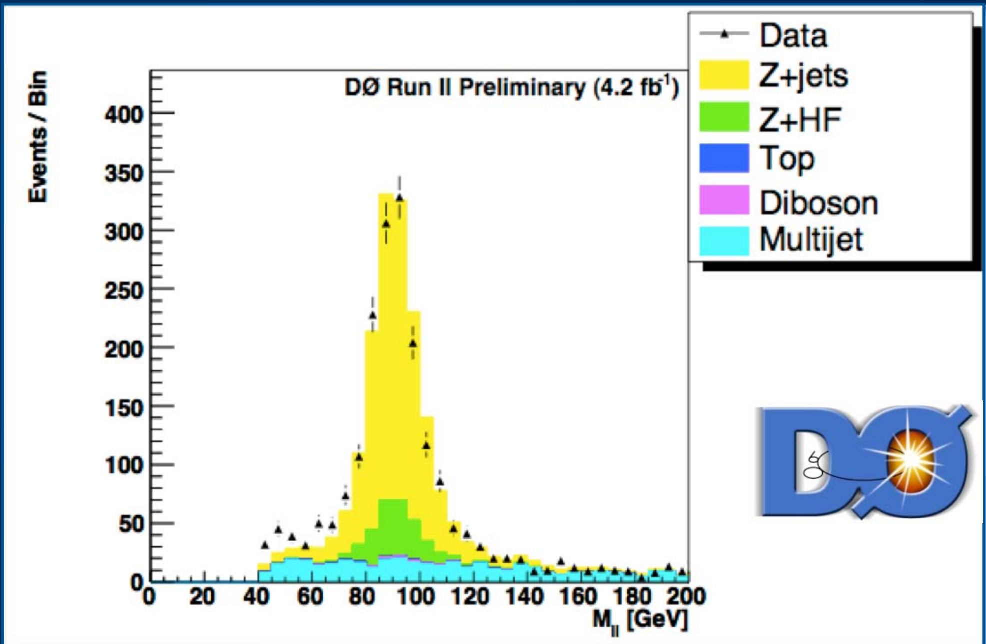
- Connect different quantities in the data in clever ways to make the Higgs stand out more

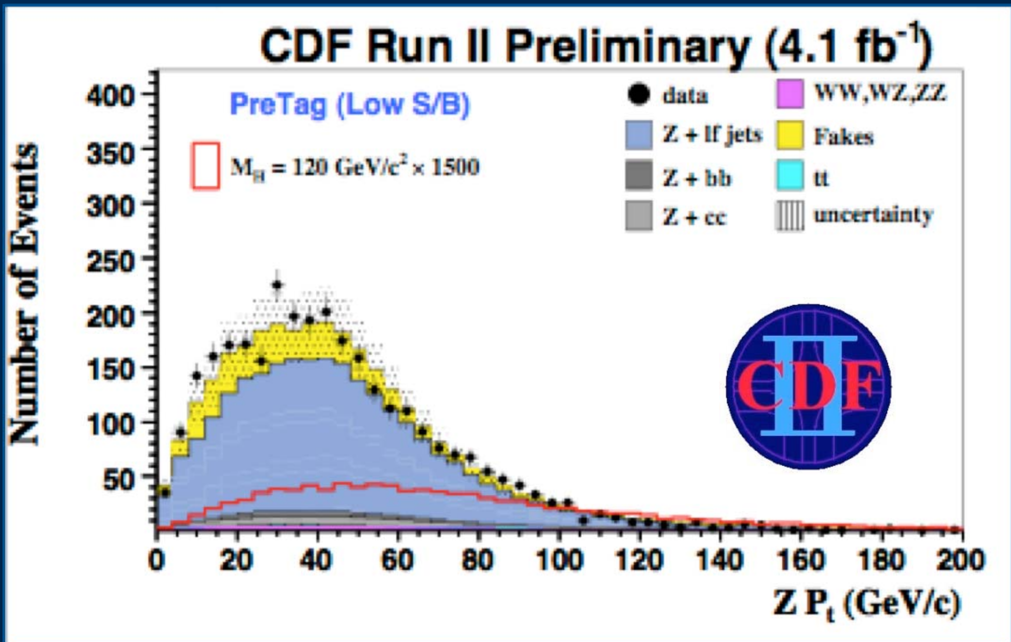
Higgs Search Strategy

I. Maximize Signal Acceptance

- Example: $ZH \rightarrow llbb$ channel
  - Small expected signal – so acceptance is key!
  - Reconstruction of Z and H resonances control background rates, allowing for loose selection requirements
  - Additional signal from expanded lepton identification

~15% signal gain



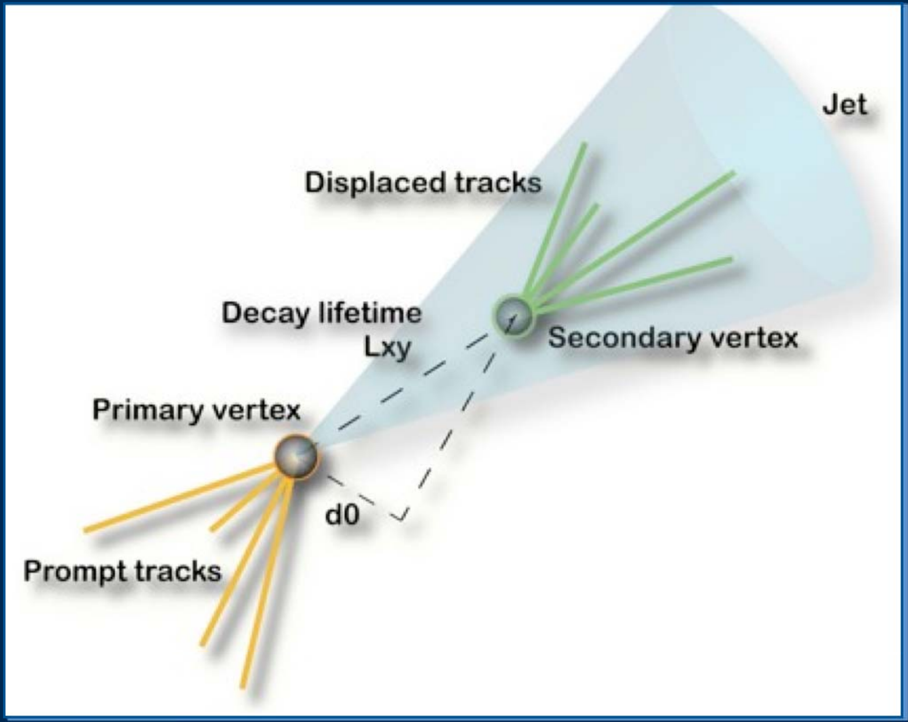


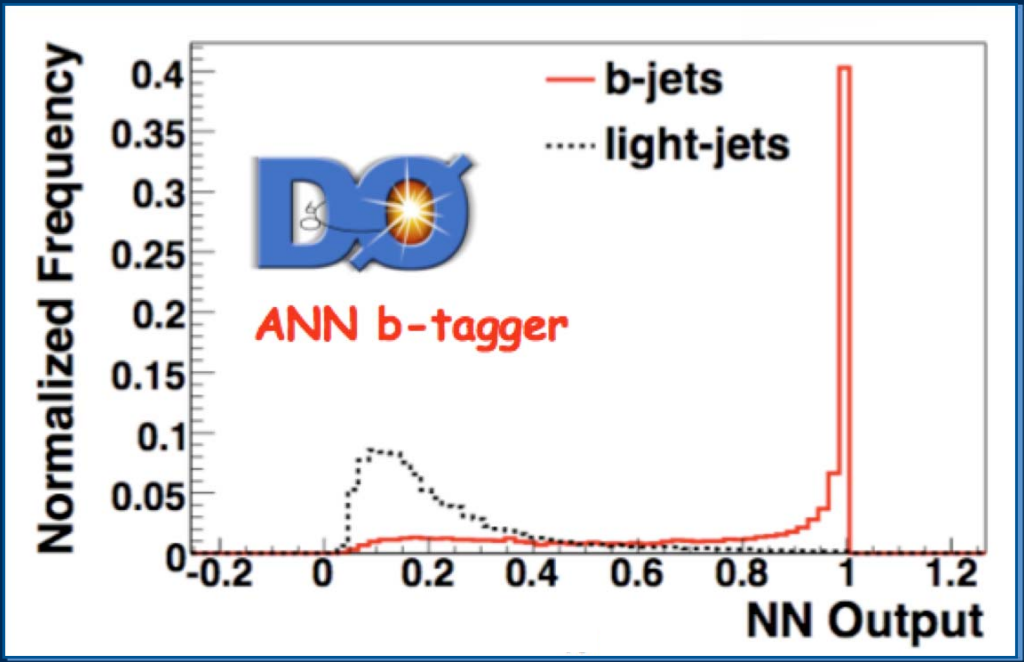
- reconstruct Z candidates from a muon and an isolated track
- reconstruct Z candidates from two forward calorimeter clusters

Higgs Search Strategy

II. Reduce Background

- Identifying *b*-jets (*b*-tagging)
  - Distinguish *b*-jets from charm and light flavor jets
  - Exploits long lifetime of *b*
  - Various algorithms available at CDF & DØ
  - Tag 50–60% of *b*-jets with only ~1% light-flavor tag rate





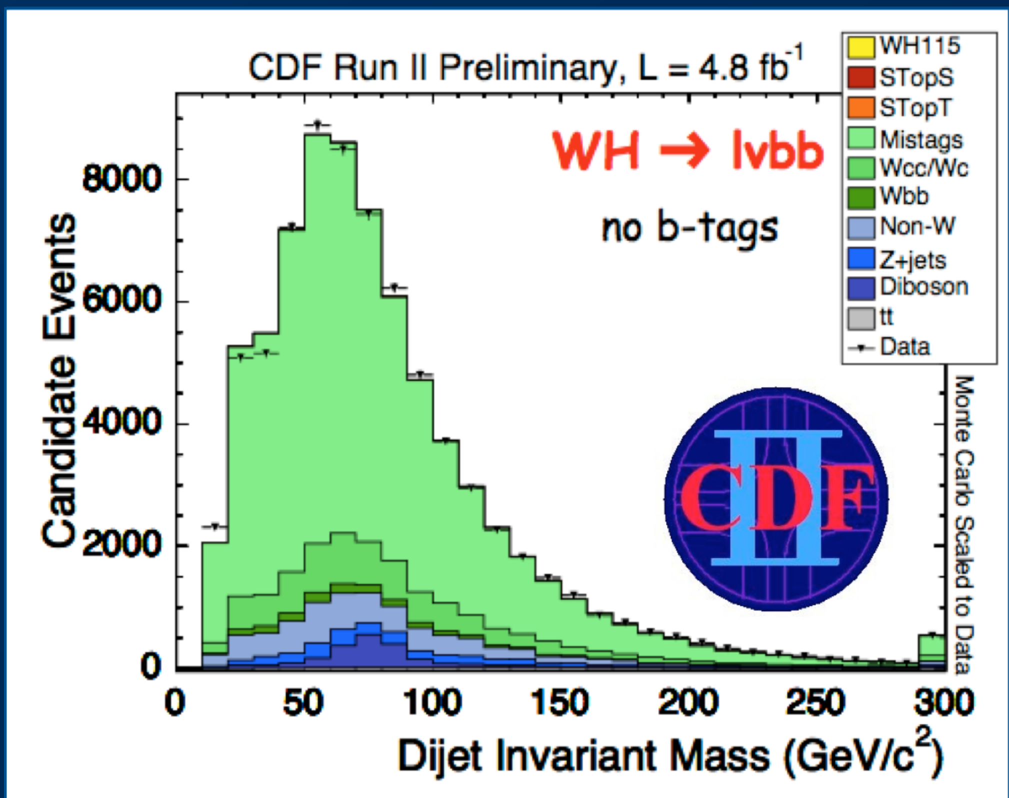
Higgs Search Strategy

II. Reduce Background *(continued)*

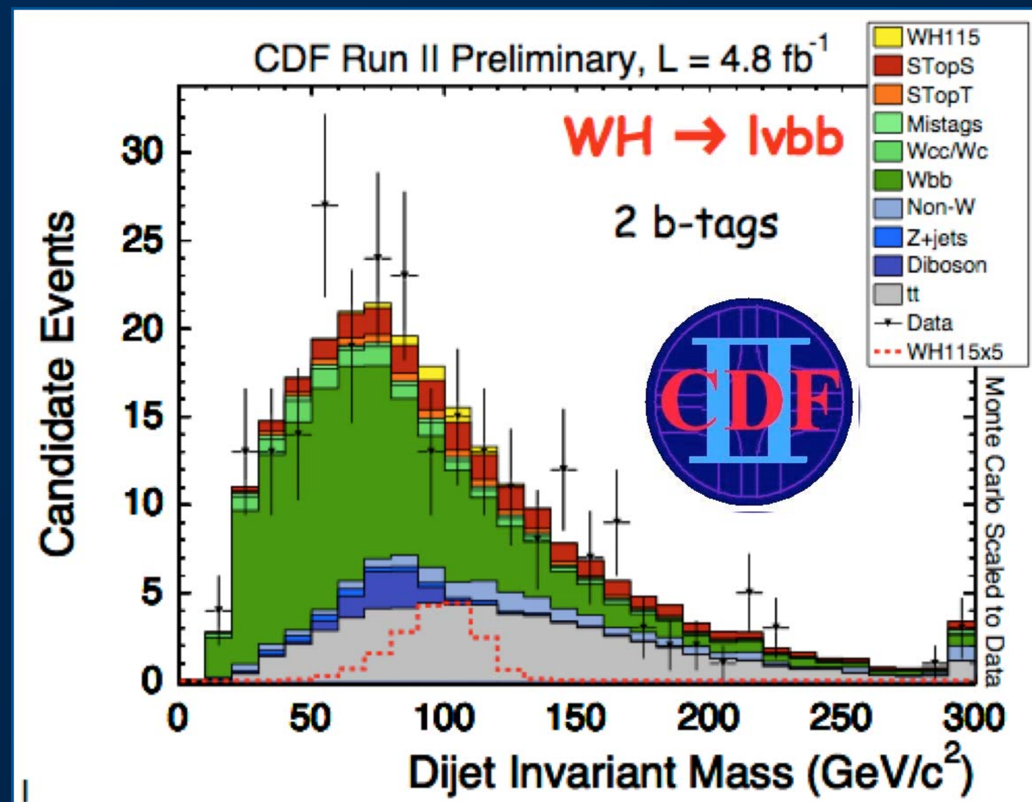
Identifying *b*-jets (*b*-tagging)

- Example: $WH \rightarrow l\nu bb$ channel
  - Tagging both jets dramatically reduces background (W + light flavor jets)

without *b*-tagging



with *b*-tagging

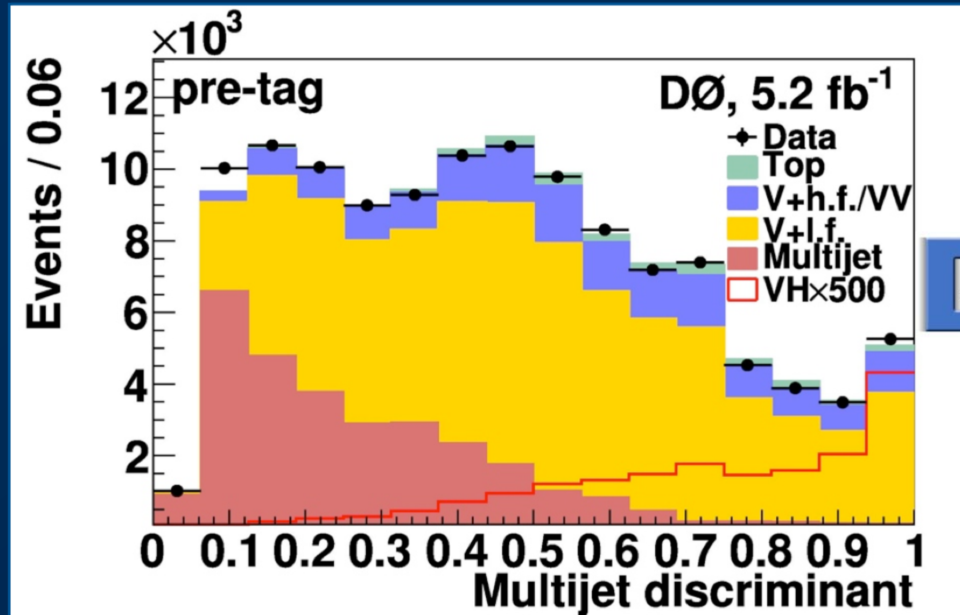


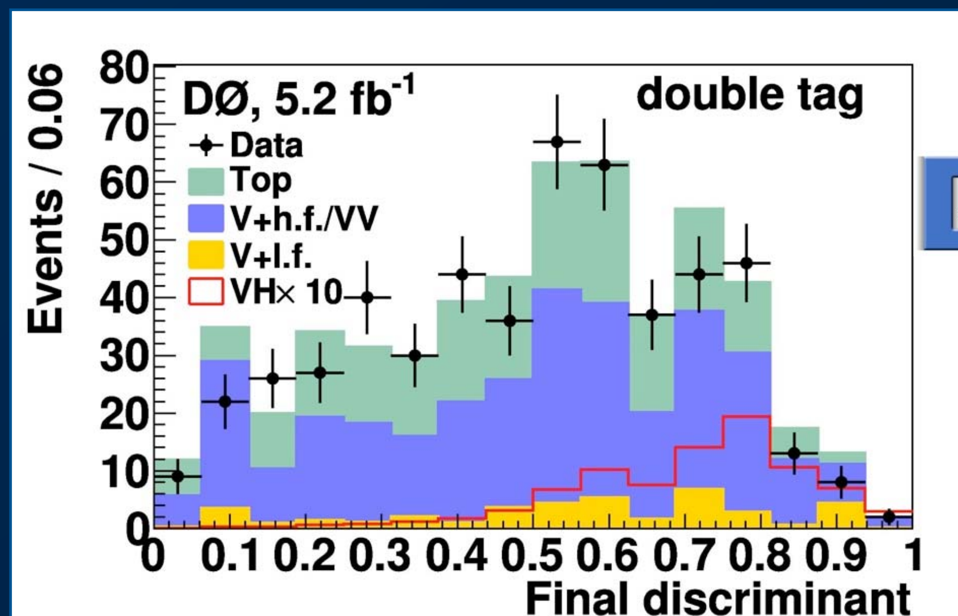
Higgs Search Strategy

III. Employ Multivariate Techniques

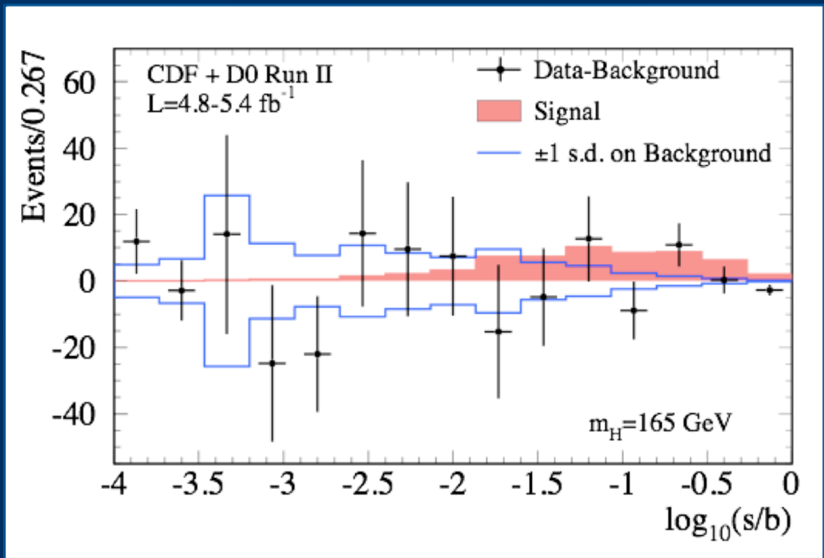
- Common Multivariate Discriminants:
  - Artificial Neural Network (NN)
  - Boosted Decision Trees (BDT)
  - Matrix Element Probabilities (ME)
- Multivariate techniques combine many variables
- Example: $WH \to l\nu bb$ and $ZH \to \nu\nu bb$
  - Multijet backgrounds are large
  - BDT's separate WH/ZH (VH) from multijet background
  - Second set of multivariate discriminants employed for signal vs. non-multijet background

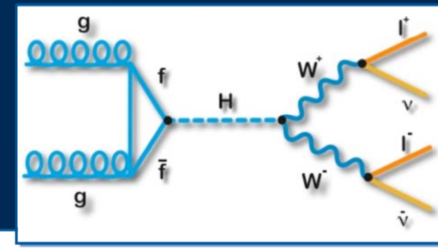
Multivariate techniques proven to work in recent diboson (WW/WZ) & single top observation!

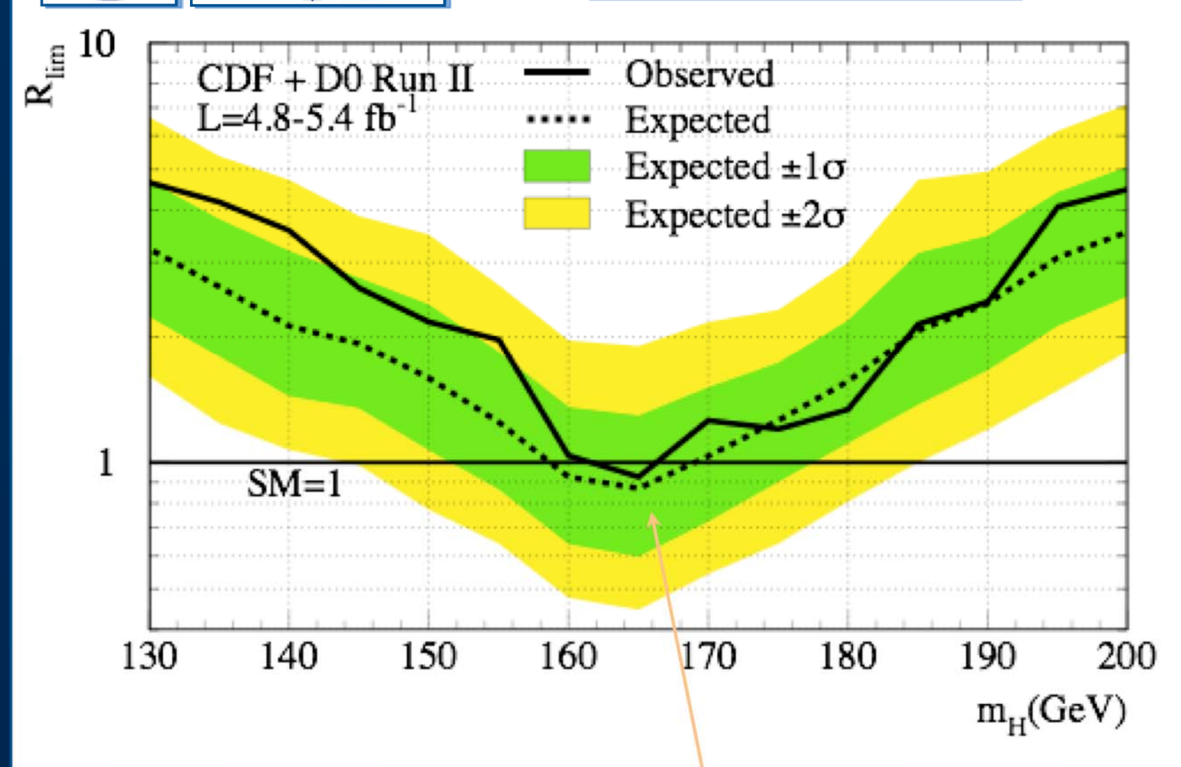




Combination of $H \to W^{+}W^{-}$ Searches







January 2010

Although no single experiment can currently exclude the Higgs,

CDF + DØ Combined

The Standard Model Higgs is excluded in the range

162–166 GeV/c^2 @ 95% CL

(expected exclusion range 159–169 GeV/c^2)

At $m_H = 165$ GeV/c^2:

Expected / σ_{SM} = 0.87

Observed / σ_{SM} = 0.93

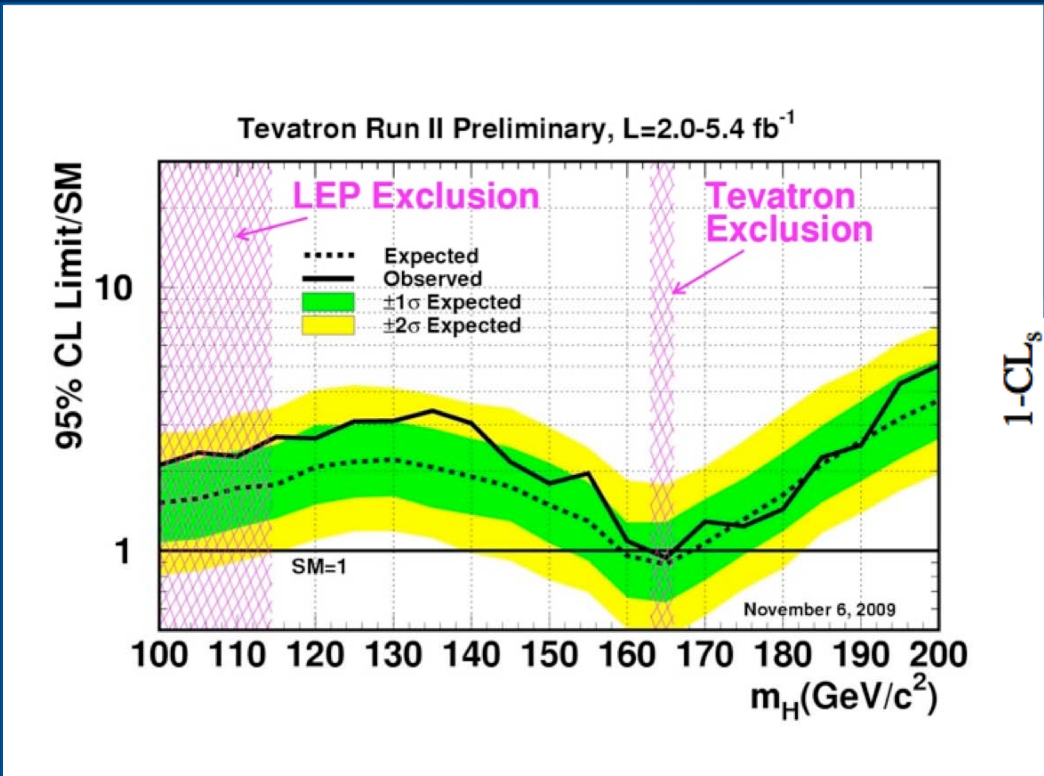
(using Bayesian Technique)

First Combination Publication! PRL 104, 061802 (2010)

~5 fb^{-1} of data, fast turnaround for PRL

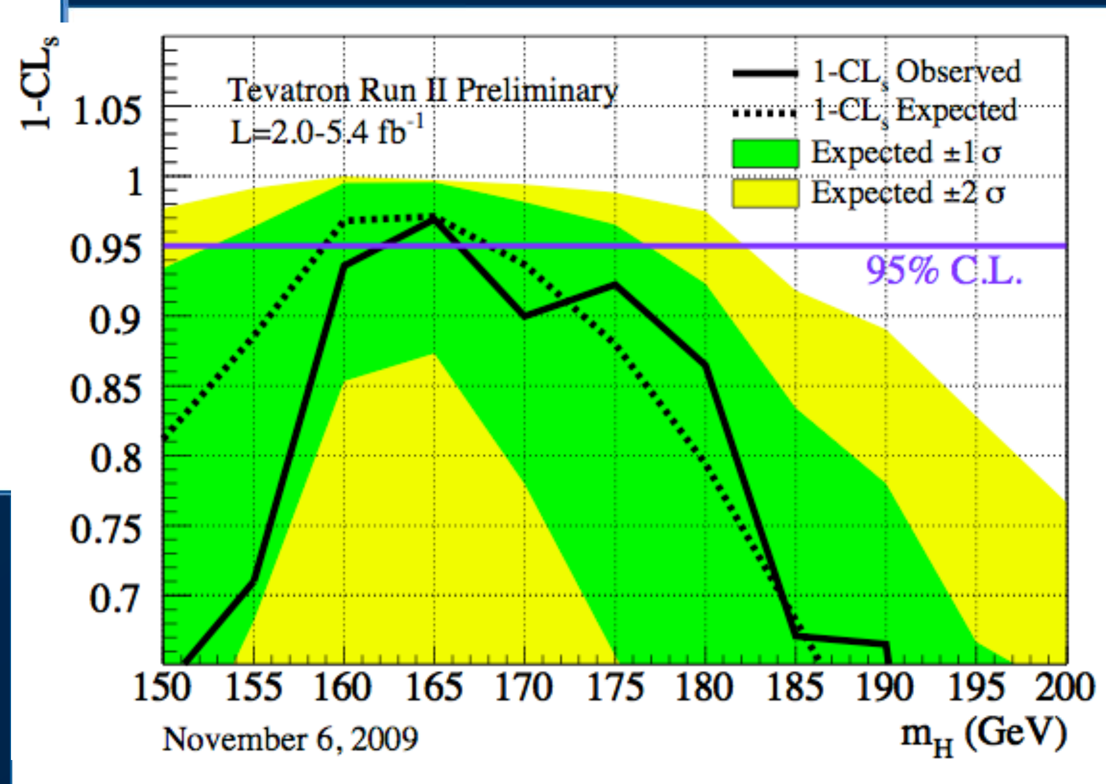
Standard Model Higgs Combination

Latest Tevatron Higgs Combination!



Fall 2009

Low mass and high mass channels combined.



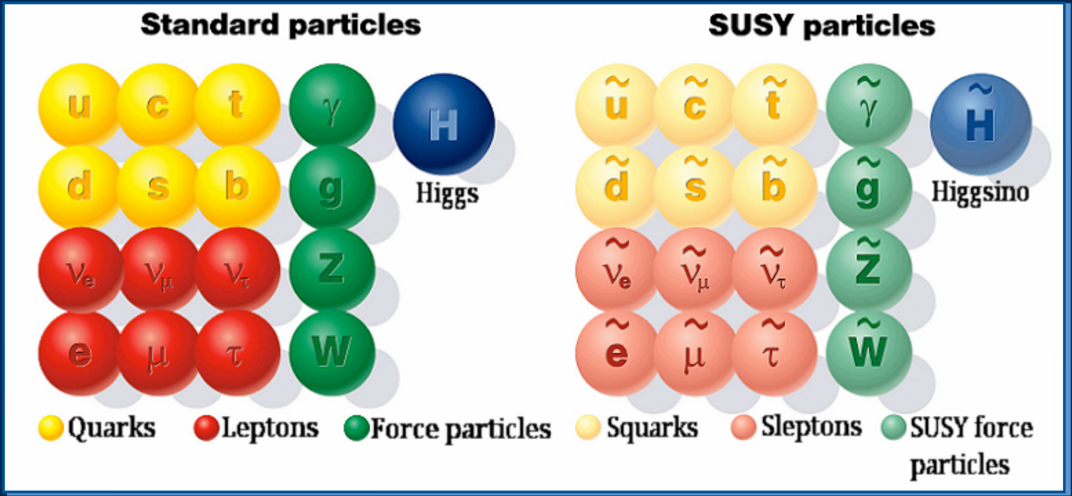
A new Tevatron combination for Summer 2010 (~6 fb^{-1}) is underway...

BSM Higgs – A Brief Primer

Fermilab

What if nature doesn't follow the SM Higgs mechanism?

- Reality could be a refinement of the SM or a more exotic theory like Supersymmetry (SUSY)



Need a minimum of 5 Higgs bosons:

3 neutral: $h \quad H \quad A$

2 charged: $H^+ \quad H^-$

- In the Minimal SUSY Model (MSSM):
  - Need at least two parameters:

    $m_A \qquad \tan(\beta)$

  - Coupling of neutral Higgs bosons to b quarks is enhanced by $\tan(\beta)$, and production is enhanced by $\tan^2(\beta)$

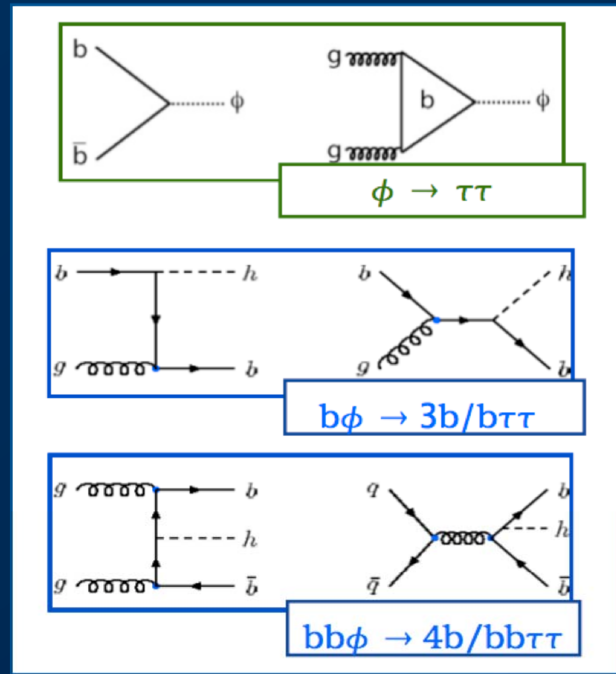
- In Two-Higgs Doublet Model extensions to the SM:
  - Scalar field mixing angle α can lead to different couplings to fermions for h and H:

    $\sin(\alpha)$ for H and $\cos(\alpha)$ for h

  - Limit of $\alpha \to \pi/2$ yields a Higgs that couples only to bosons: a Fermiophobic Higgs!

MSSM Higgs Searches

- Neutral MSSM Higgs decays
  - $bb \sim 90\%$ (large background)
  - $\tau\tau \sim 10\%$ (more distinct signature)
- 3 channels best suited to benefit from enhanced *b*-quark coupling
  - $\phi \to \tau\tau$
  - $b\phi \to b\,b\,b$ $\quad(\phi = h,\ H,\ or\ A)$
  - $b\phi \to \tau\tau\, b$
- Good *b*-jet and τ identification are essential!

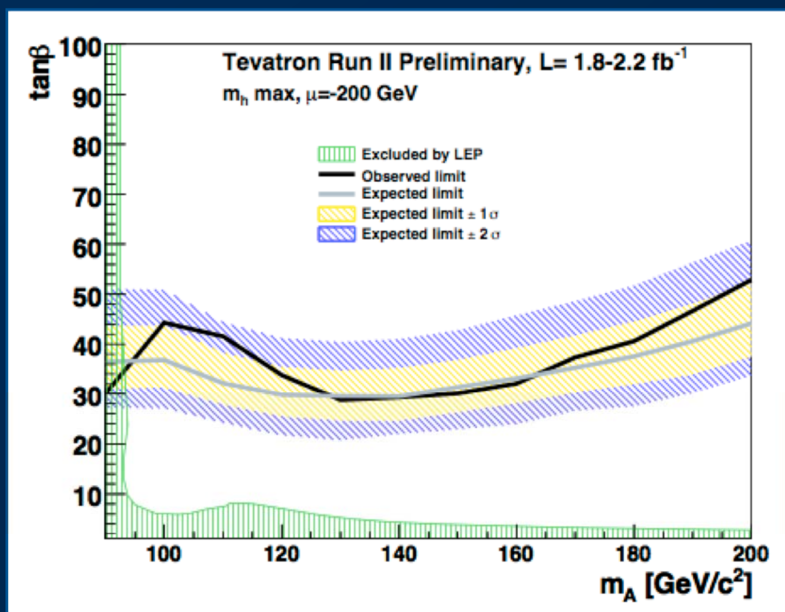


Similar overall sensitivities

Analyses don't attempt to identify individual Higgs bosons, but look for an overall excess instead.

Tevatron combination of $\tau^+\tau^-$ results

March 2010



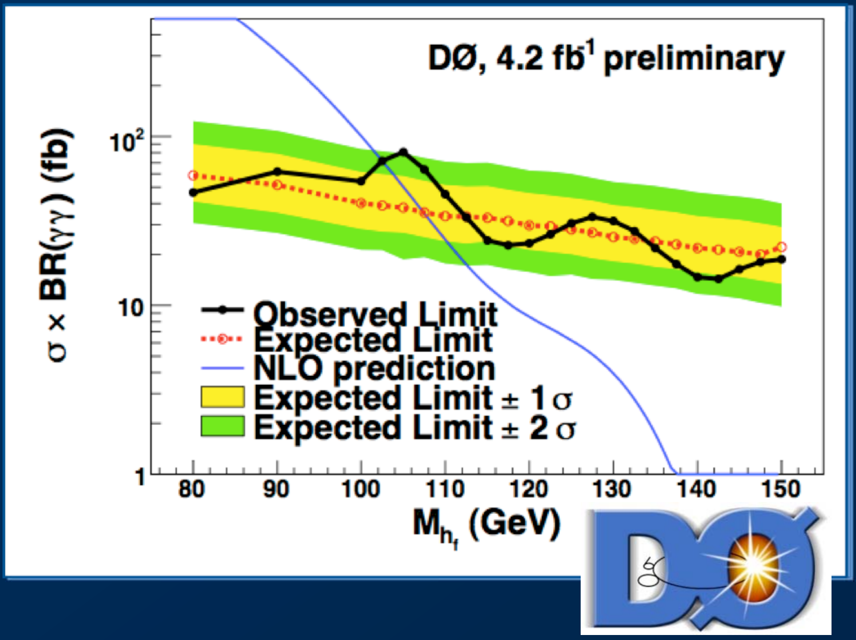
- Probing down toward $\tan(\beta) \sim 30$, a region of interest
- Still have much more data to add!
- And ... This result is from only one of the three channels — we have three with nearly equal sensitivities

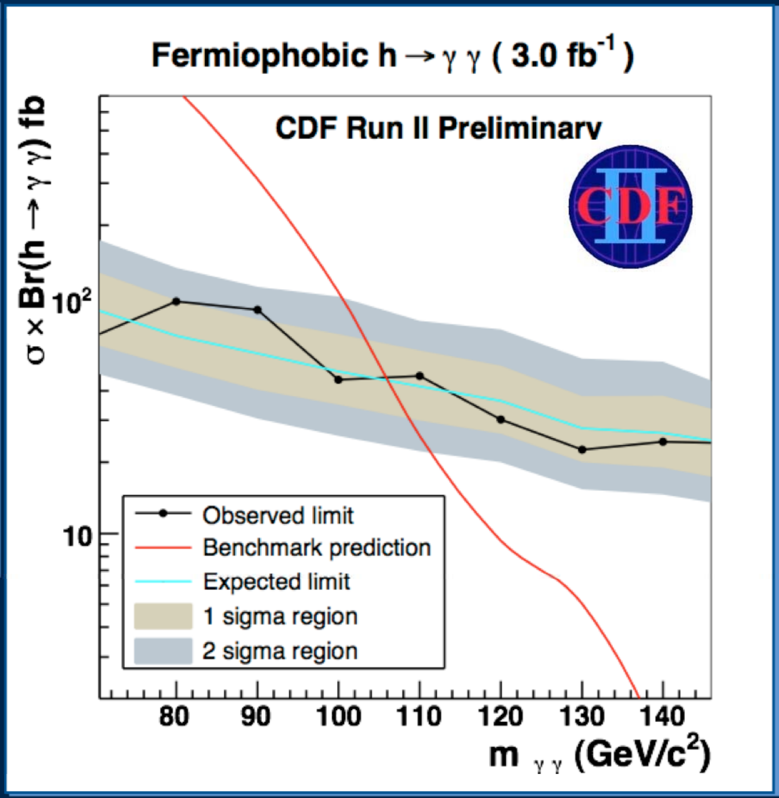
Fermiophobic Higgs

- In the Fermiophobic Higgs scenario,

  $gg \to H \to \gamma\gamma$ could be greatly enhanced, since $H \to bb$ is not allowed!
- Therefore, we select events with two photons and search for a $\gamma\gamma$ mass peak
  - 3% mass resolution
- Backgrounds
  - Direct production
  - γ + jets/dijets
  - Drell-Yan

No excess observed in data, so we set limits





- Limits from each experiment, with only 3–4 fb^{-1}, are about as sensitive as the LEP combination
- Probing much higher mass range

Many other analyses: nMSSM, Charged Higgs, ...

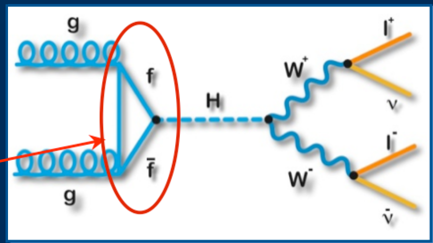
Constraints on 4th-Generation Fermion Models

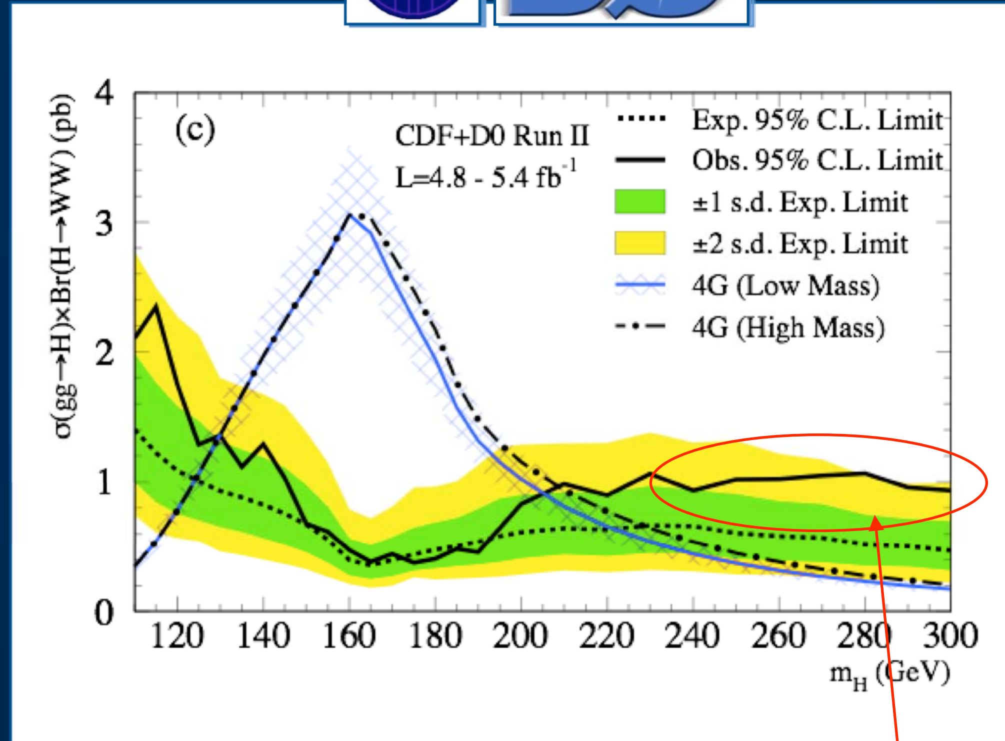
Fermilab

New! Combined CDF + DØ result
May 2010

This search focuses only on the $gg \rightarrow H$ production mode, since this is the only one that is enhanced by a 4th generation of fermions

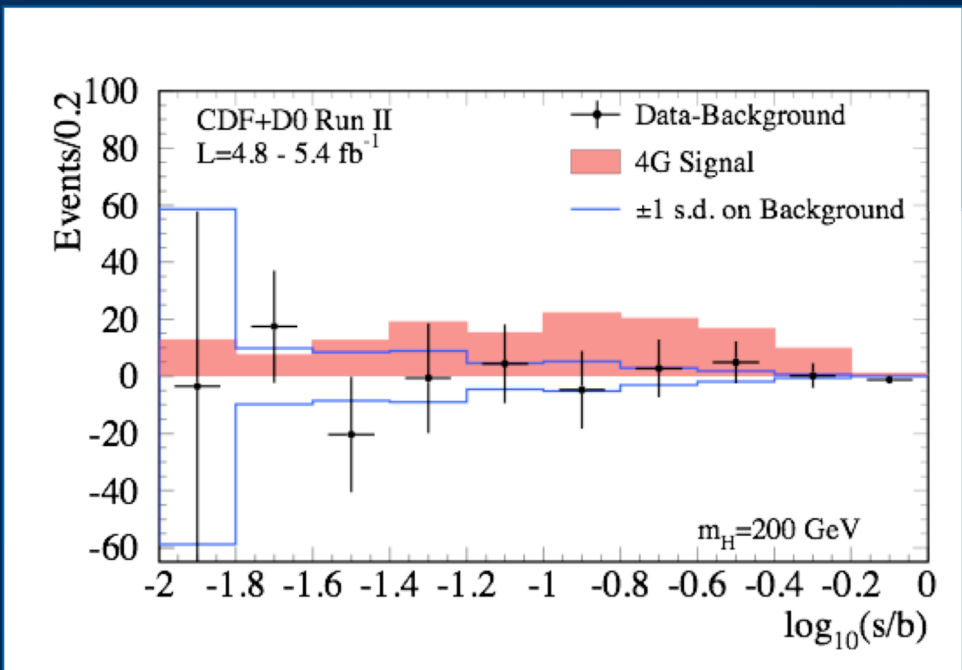
massive 4th generation fermion here





May 2010

Natural mass region for heavy Higgs



Assuming a heavy sequential 4th generation of fermions:

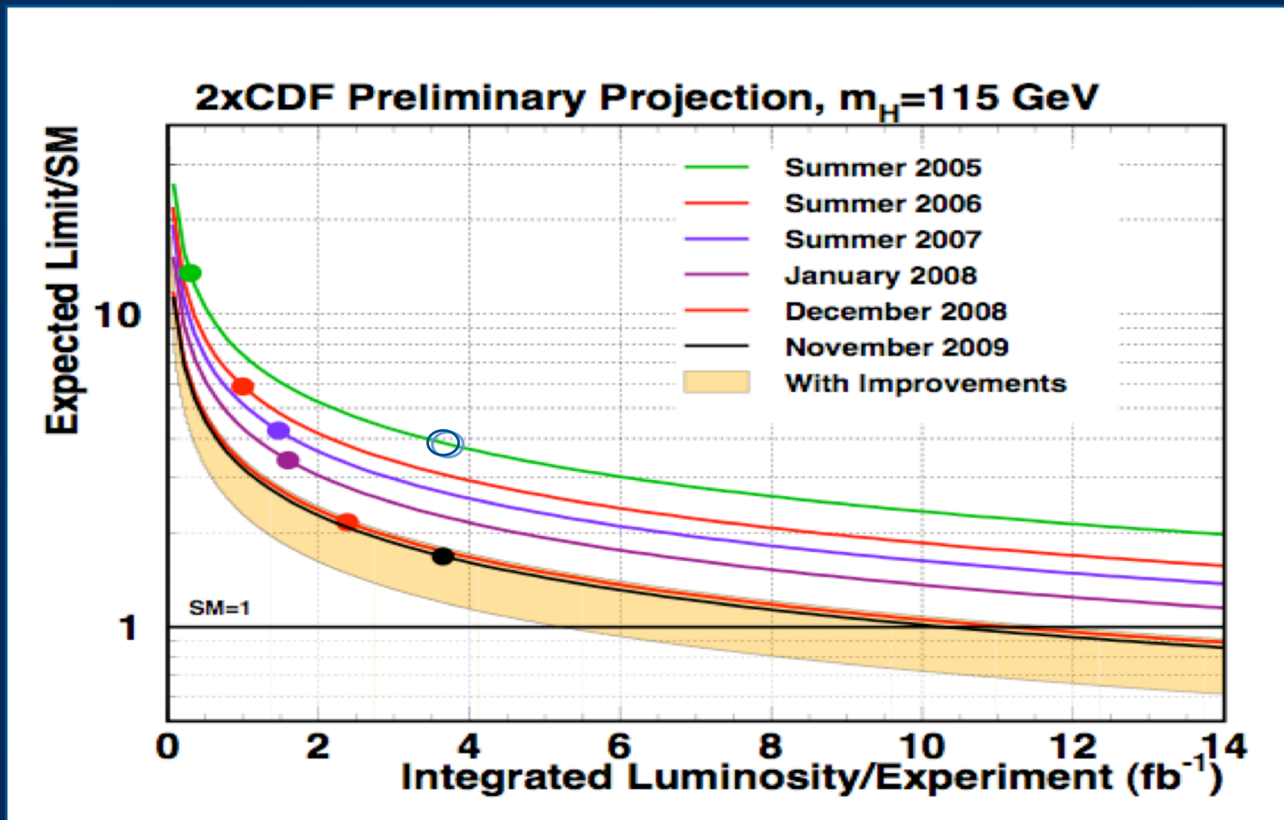
we exclude a SM-like Higgs boson with a mass between 131 and 204 GeV/c^2 (95% CL)

arXiv:1005.3216 [hep-ex]

Tevatron Projections

Tevatron Projections

- Delivered luminosity now ~8.5 fb^{-1} (per experiment)
- Tevatron will deliver 10–12 fb^{-1} per experiment by end of 2011

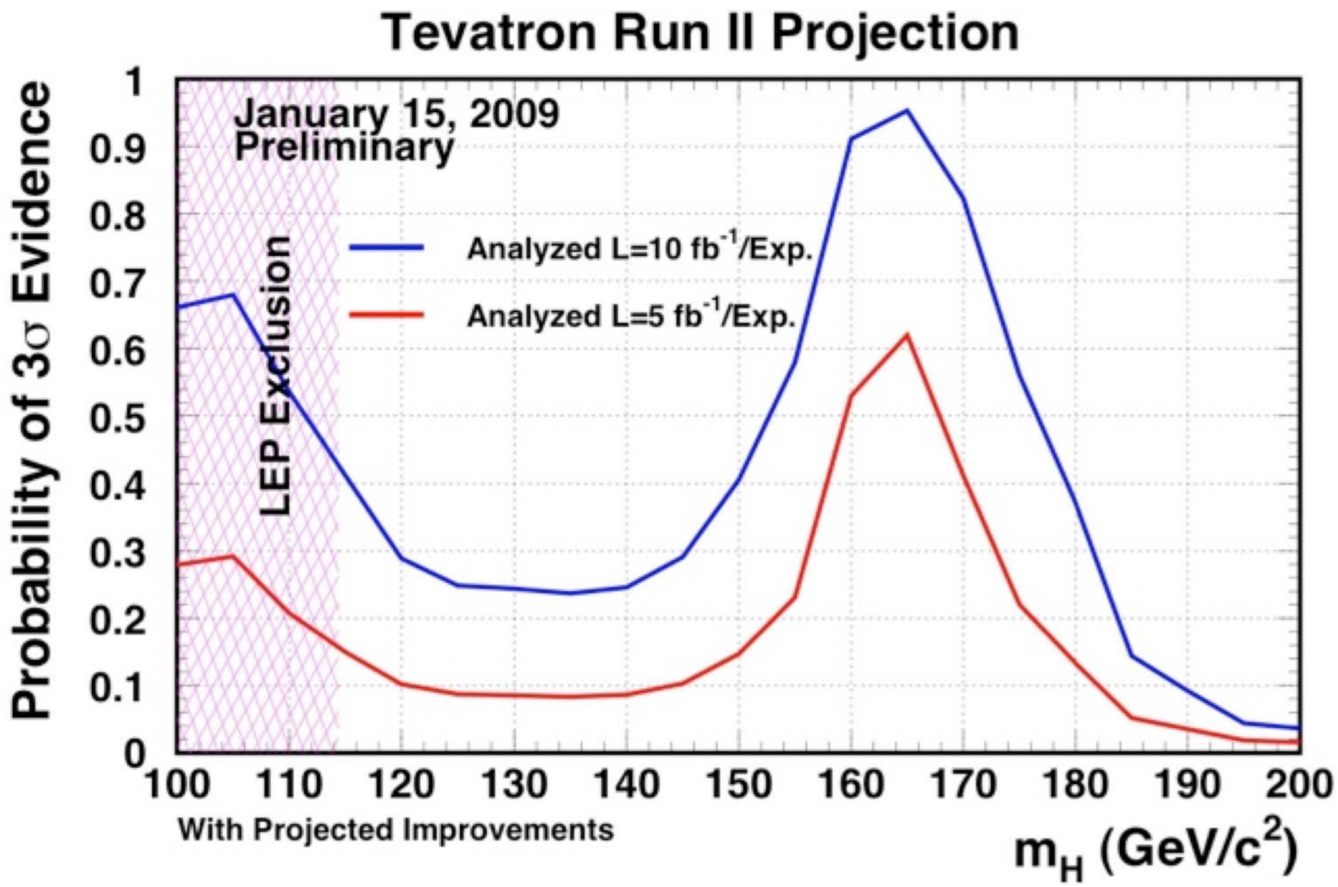


CDF and DØ have already made *substantial* improvements, and we know how to make many more!

- expanded e/μ selection
- final states with τ's
- better b-tagging
- improved jet energy resolution
- migration of improvements across channels

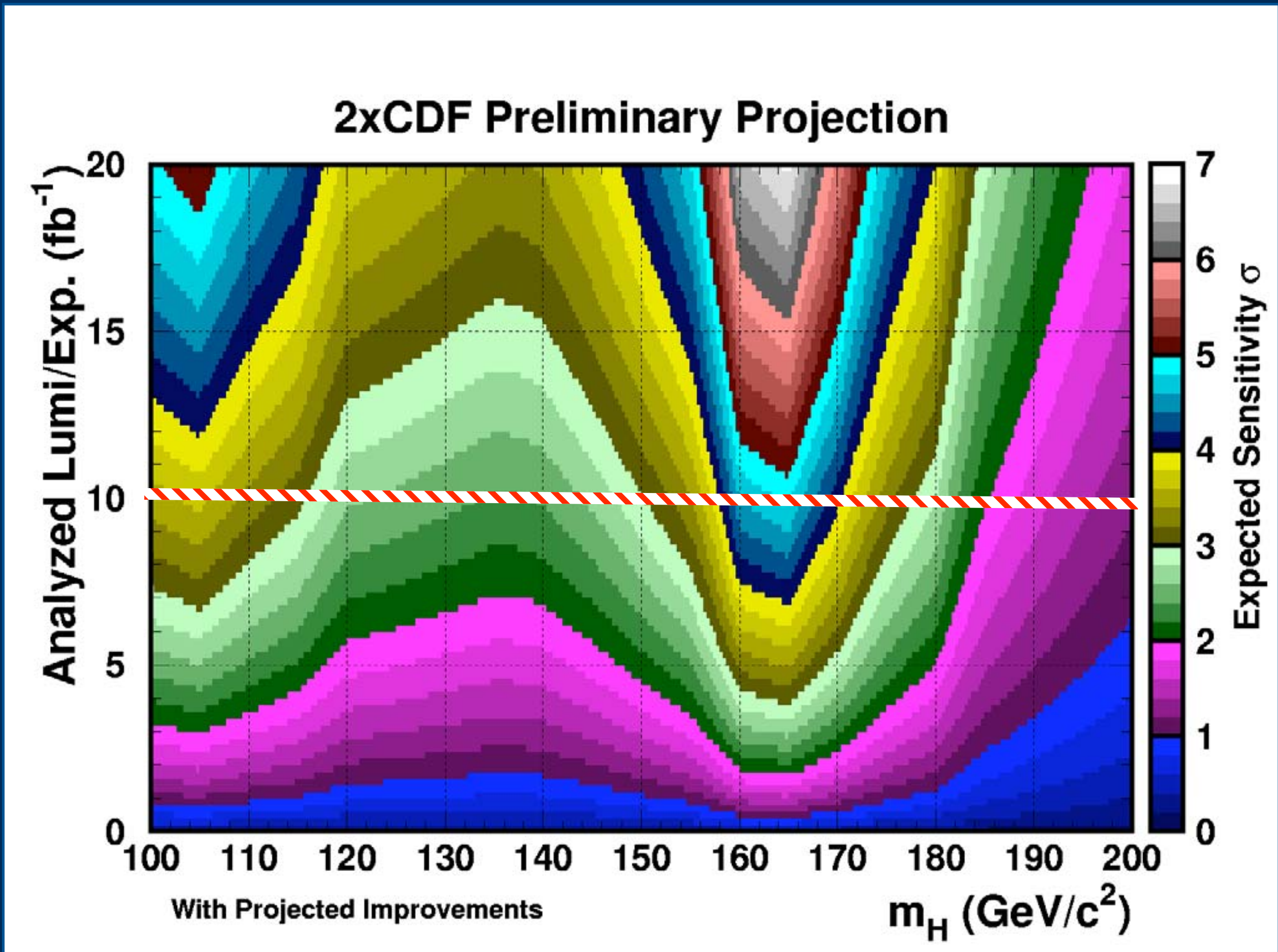
Tevatron Projections

- Sensitivity to SM Higgs with 10 fb^{-1} per experiment



Tevatron Projections

- How sensitive are we to the Standard Model Higgs?



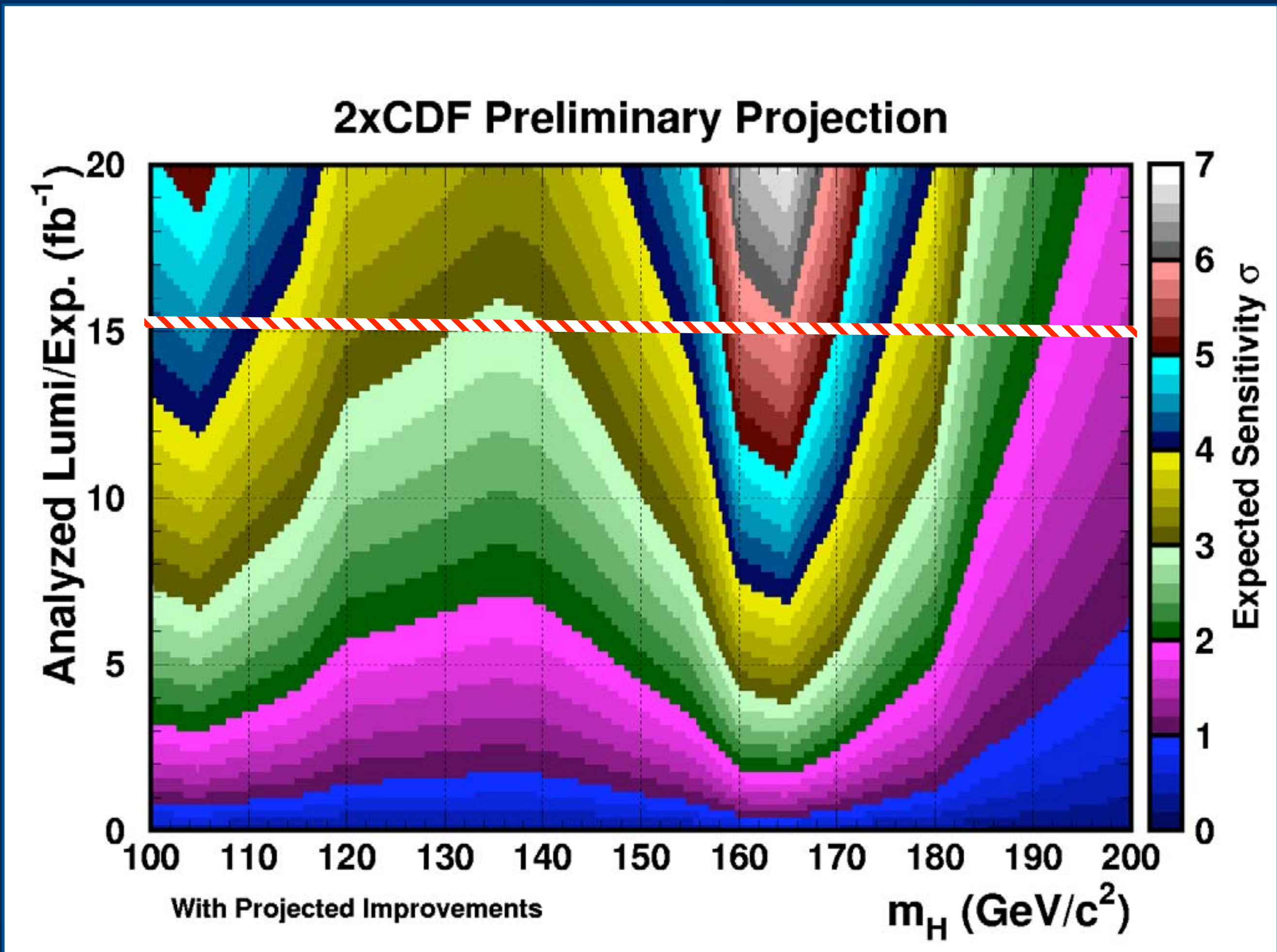
With ~10 fb^{-1}, and projected improvements, we can already exclude the Higgs at the 2σ level from 100 GeV/c^2 to well above 180 GeV/c^2

...nearly the full mass range!

This is Huge!

Tevatron Projections

- How sensitive are we to the Standard Model Higgs?



With ~15 fb^{-1}, and projected improvements, we could observe the Higgs at the 3σ level over a very broad mass range.

Terrific motivation to collect data beyond 2011.

Can make very broad exclusions of SM (and even BSM) Higgs!

Conclusions

- The Tevatron is a Discovery Machine.
  - Beginning with the top quark, increases in luminosity have led to discovery after discovery.
  - The machine continues to achieve new record luminosities!

- CDF and DØ are working hard to discover the Higgs.
  - New, clever analysis techniques
  - Broad, "no channel too small" strategy

Evidence for the Higgs is within reach at the Tevatron!

- We know exactly "where" to look
- We know exactly how to analyze the data
- CDF and DØ have a proven track record

With 10 fb^{-1} of data, we can exclude the SM Higgs boson at the 2σ level over most of the mass range

... and make significant statements about BSM Higgs...

...and the possibilities with even more data are extremely exciting !!

Acknowledgments

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  - Taka Yasuda

Mary Anne Kluth   The Search for the Higgs Boson
(Watercolor and acrylic on paper)

... and everyone working on Higgs Physics at the Tevatron!

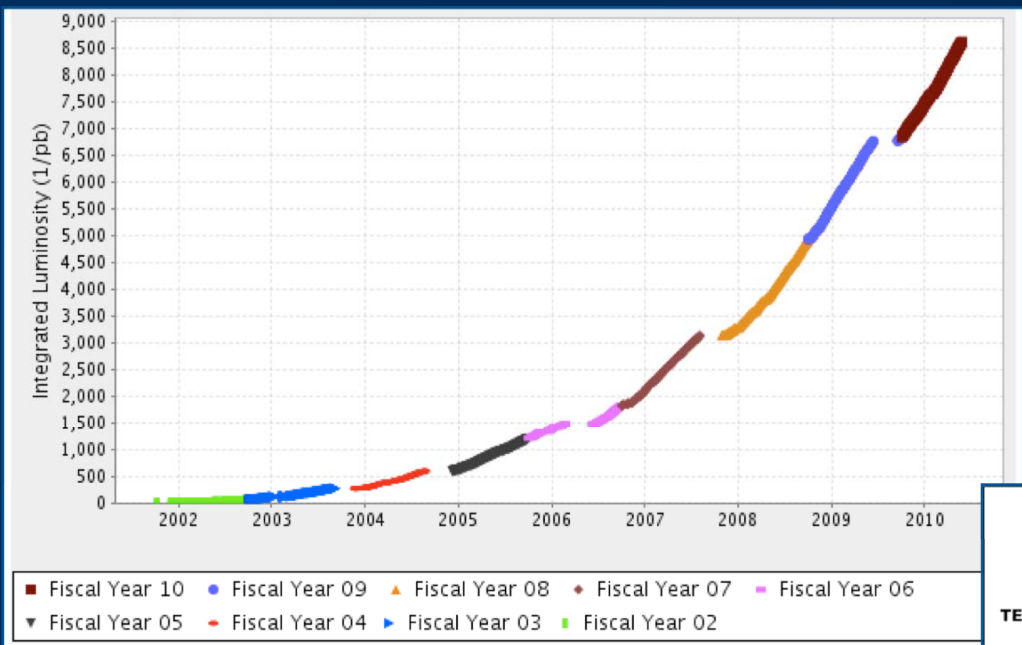
Please visit the Users' Meeting Poster Session to see the details of many fine analyses!

Backup Slides

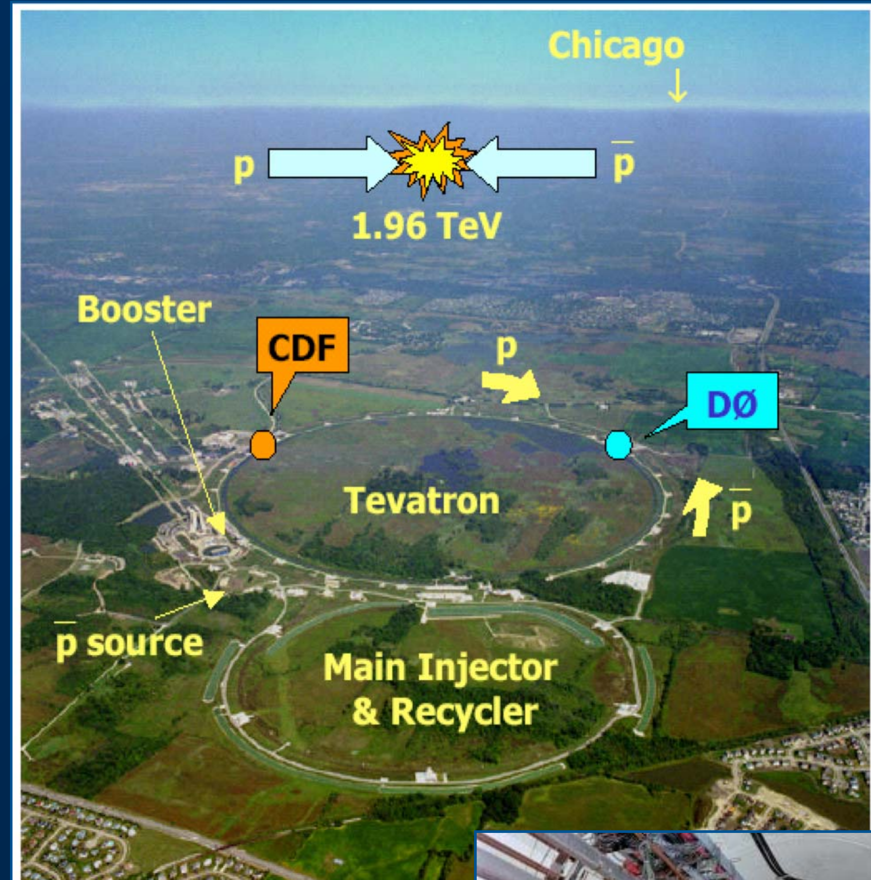
The Fermilab Tevatron

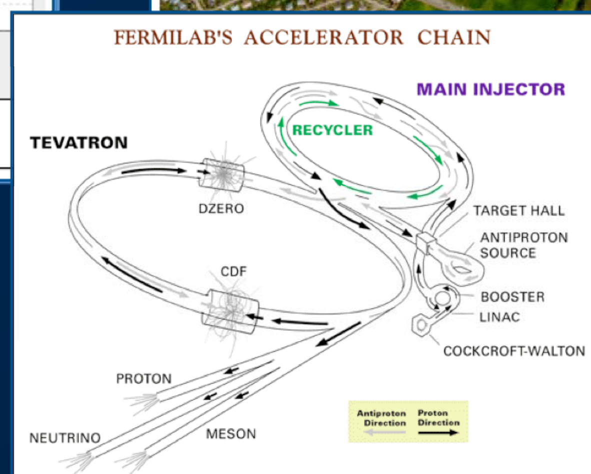
Fermilab

- Proton-antiproton collisions at 1.96 TeV
- Run 2 started in March 2001
- Delivered luminosity now ~8.5 fb^{-1} (per experiment)
- Projection ~10–12 fb^{-1} by end of 2011



The Tevatron has been running beautifully, setting many recent new records

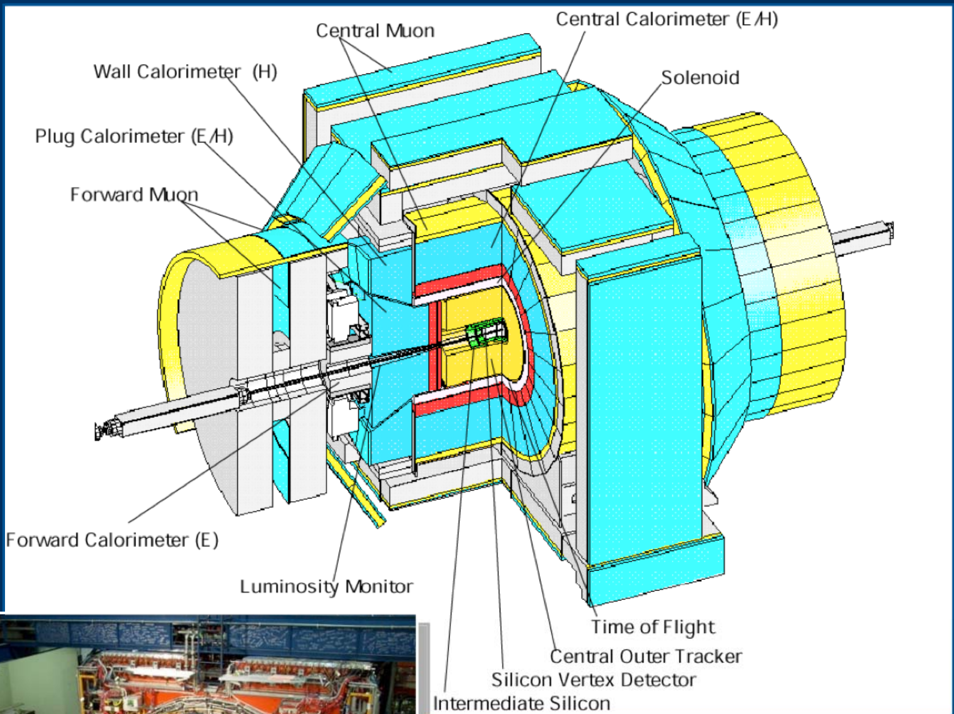


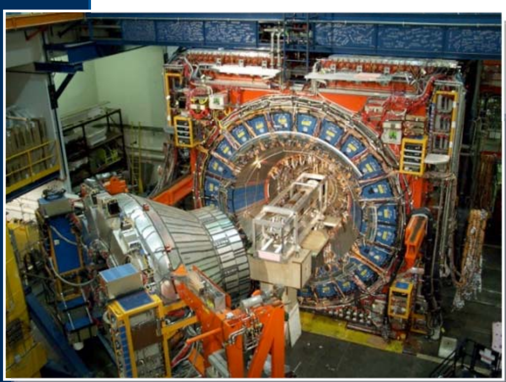


The CDF and DØ Experiments

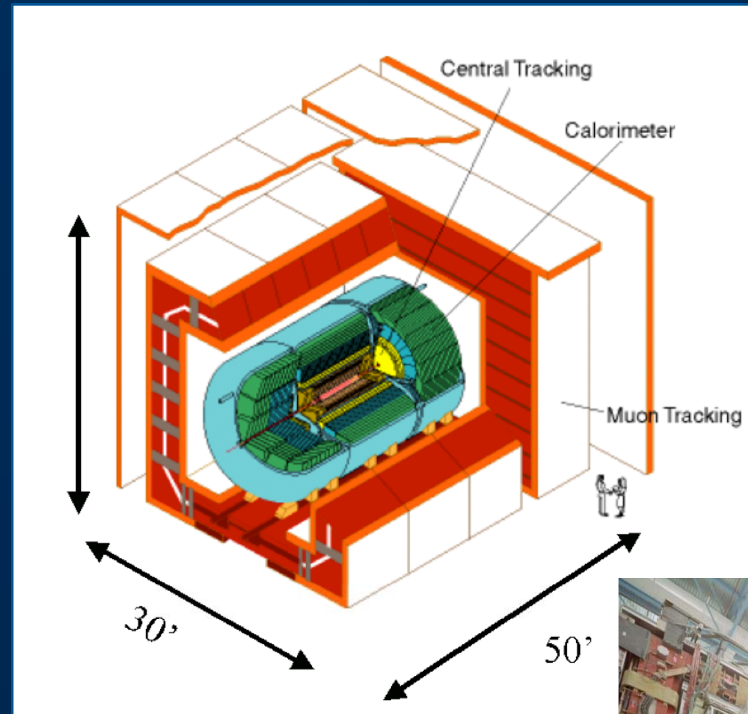
Fermilab

The CDF Experiment





The DØ Experiment



Two Multi-Purpose Detectors:

- e, μ, and τ identification
- jet and missing energy measurement
- heavy-flavor tagging through displaced vertices and soft leptons

The data-taking efficiency for both experiments is ~90%