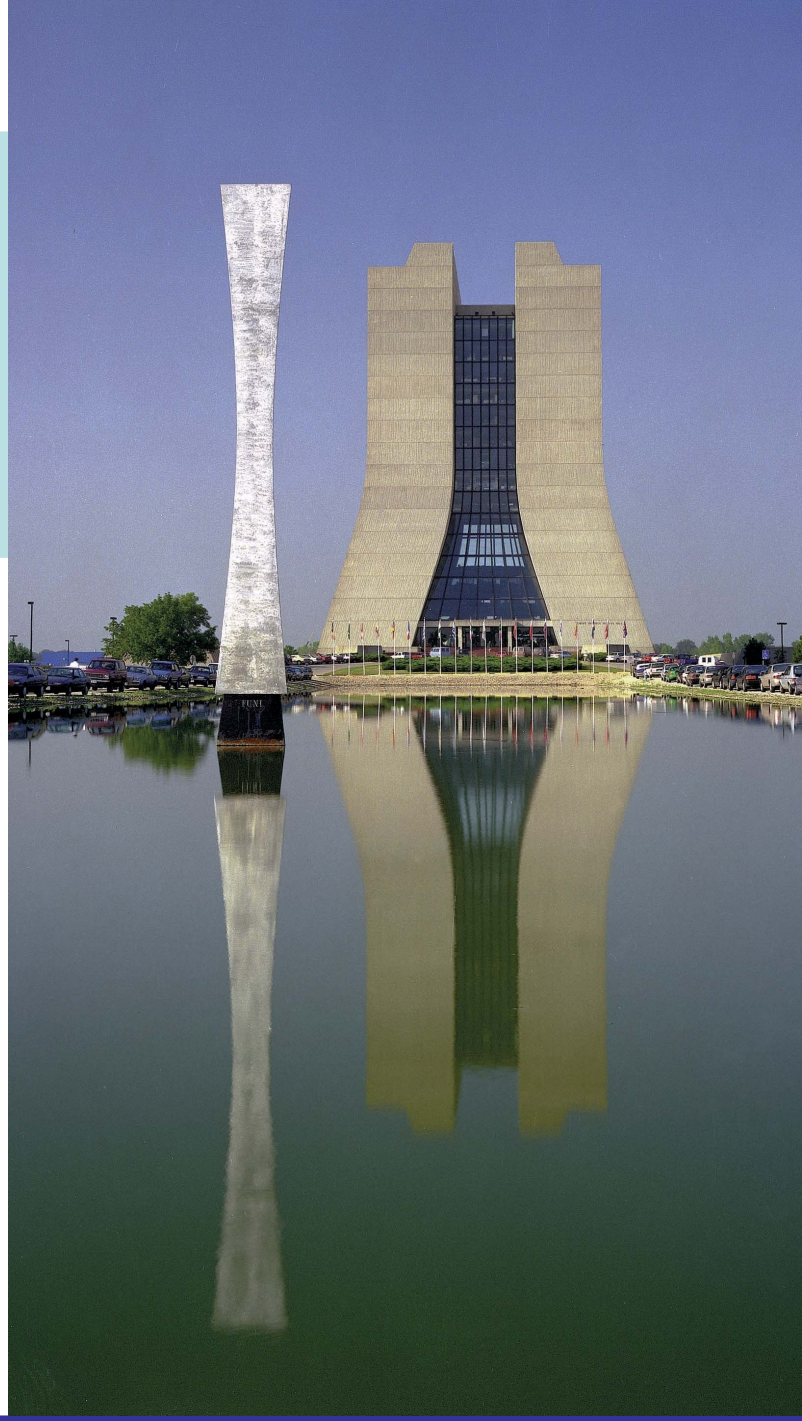
The Tevatron's Search for Higgs Bosons

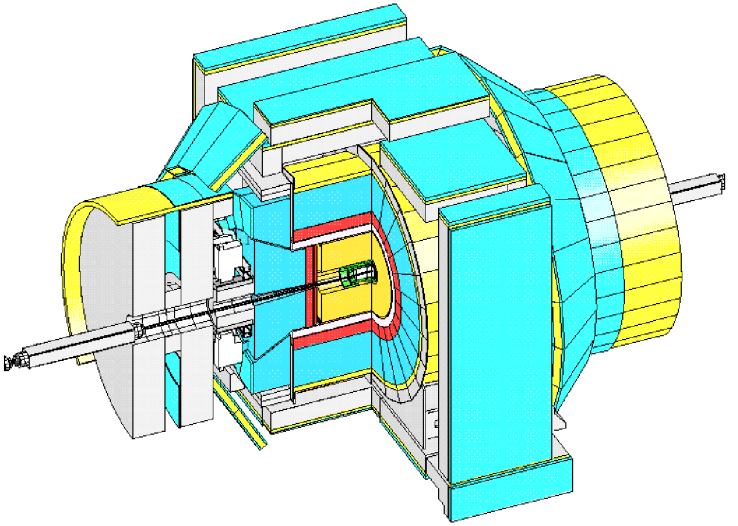
Wade Fisher, Fermilab

On behalf of the CDF & DØ Collaborations



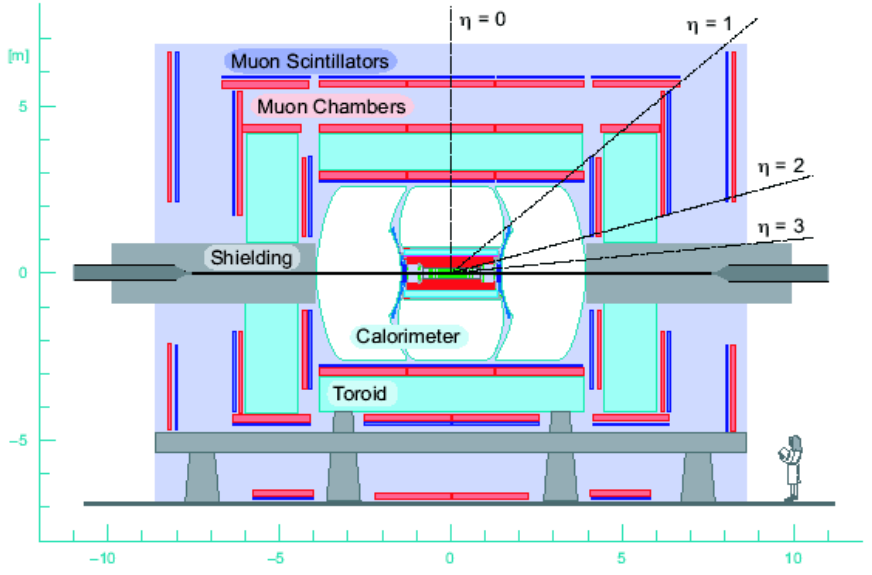
Outline

- Standard Model Higgs Boson Searches
  - Theory and existing evidence
  - Production, decay & search strategies
  - SM Higgs combined limits and prospects



- Beyond the Standard Model Higgs Searches
  - Fermiophobic Higgs
  - SUSY Higgs (MSSM)

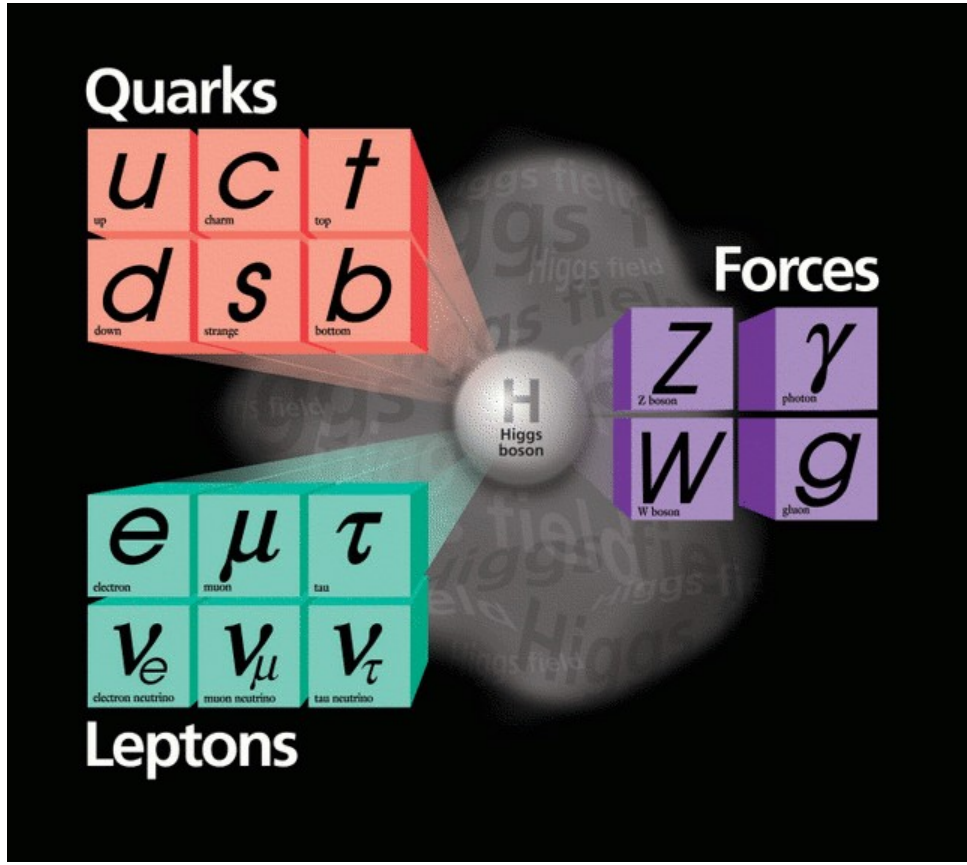
- Conclusions & Outlook



The Case for the Higgs

The Standard Model of particle physics

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



The mass of the Higgs boson is not predicted

- If it exists, the mass must be determined experimentally

Experimental Constraints

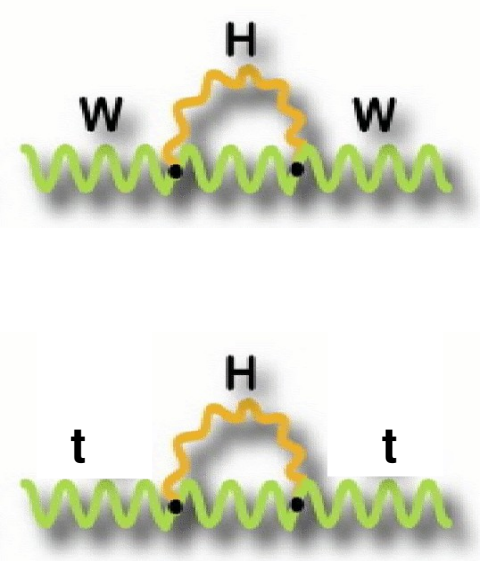
- The interactions between SM particles and the Higgs give indirect evidence

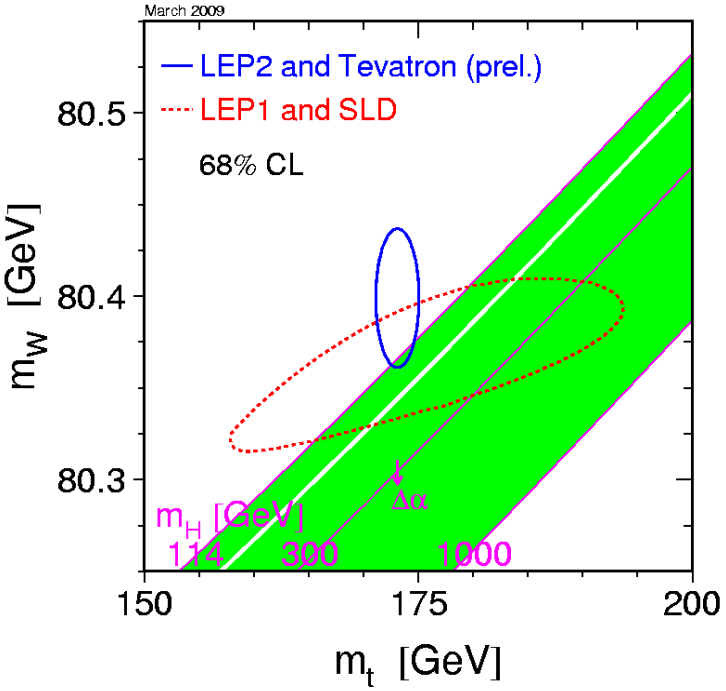
  Direct search at LEPII resulted in lower mass bound: $M_H > 114.4$ GeV

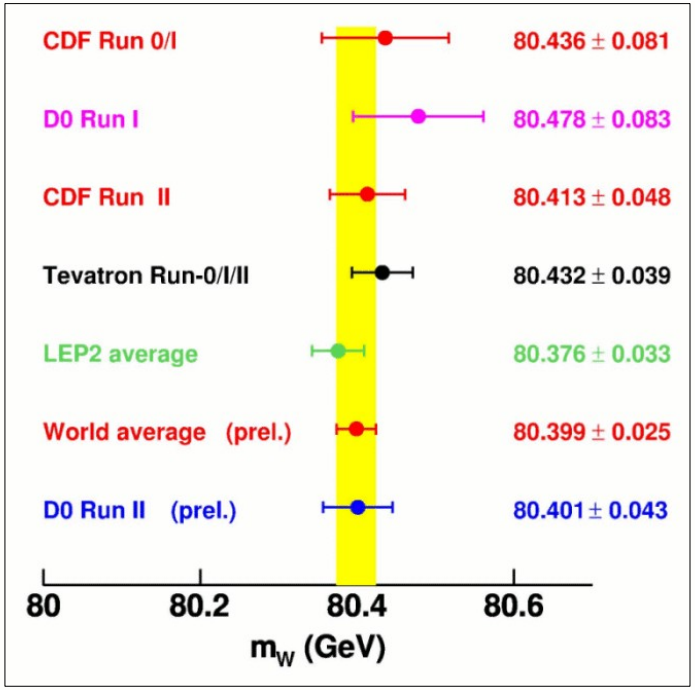
  Refinements of top-quark and W-boson masses can indicate Higgs mass

  M_{top} CDF+DZero: 173.1 ± 0.6 *(stat)* ± 1.1 *(syst)* GeV

  M_W: Tevatron measurements on track to dominate world average







Indirect Experimental Evidence

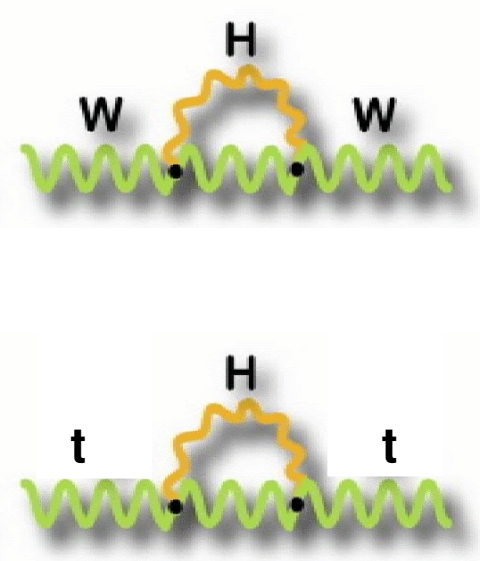
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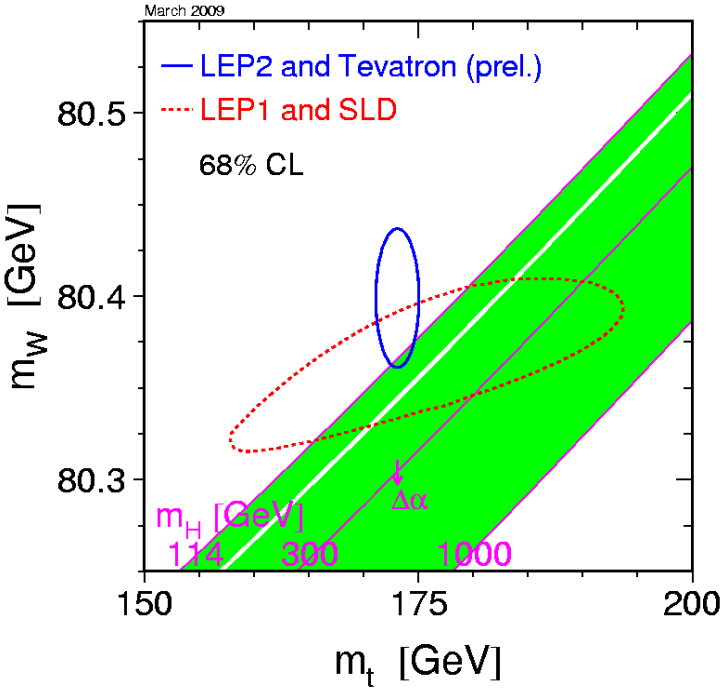
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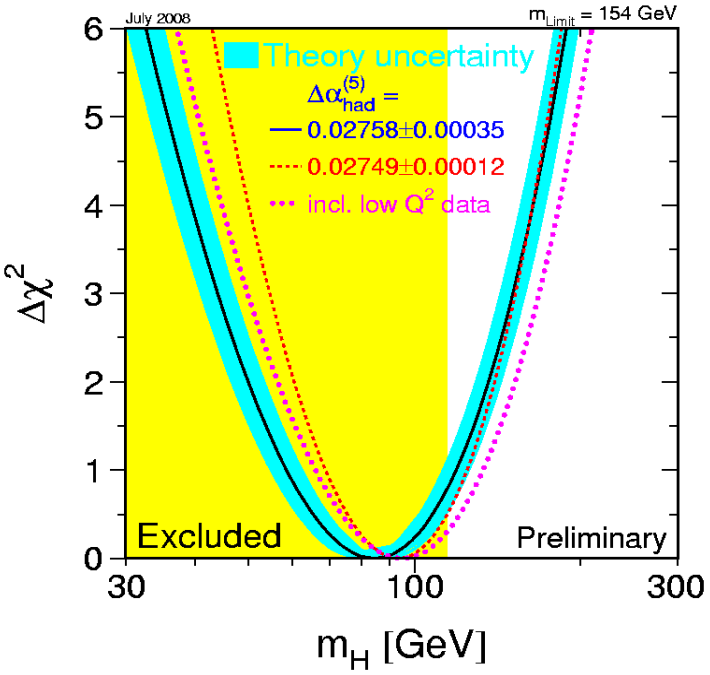
  Refinements of top-quark and W-boson masses can indicate Higgs mass

  A fit of precision electroweak data yields: $M_H < 185$ GeV at 95% CL

  ($M_H < 154$ GeV not including the LEP II limit)







Indirect Experimental Evidence

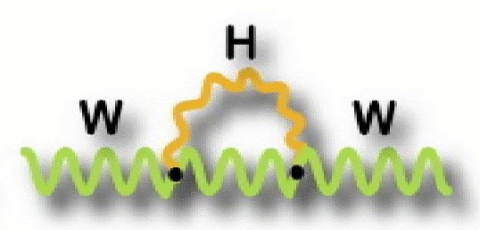
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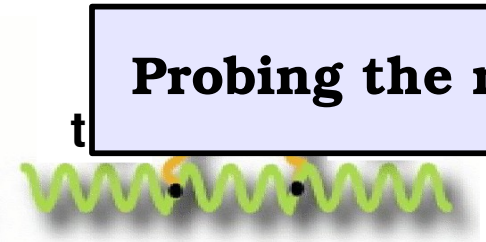
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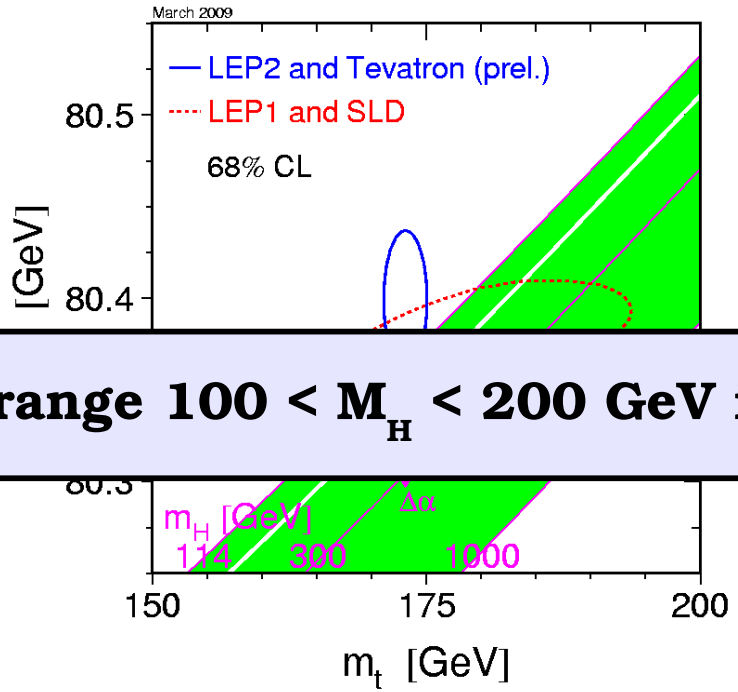
  Refinements of top-quark and W-boson masses can indicate Higgs mass

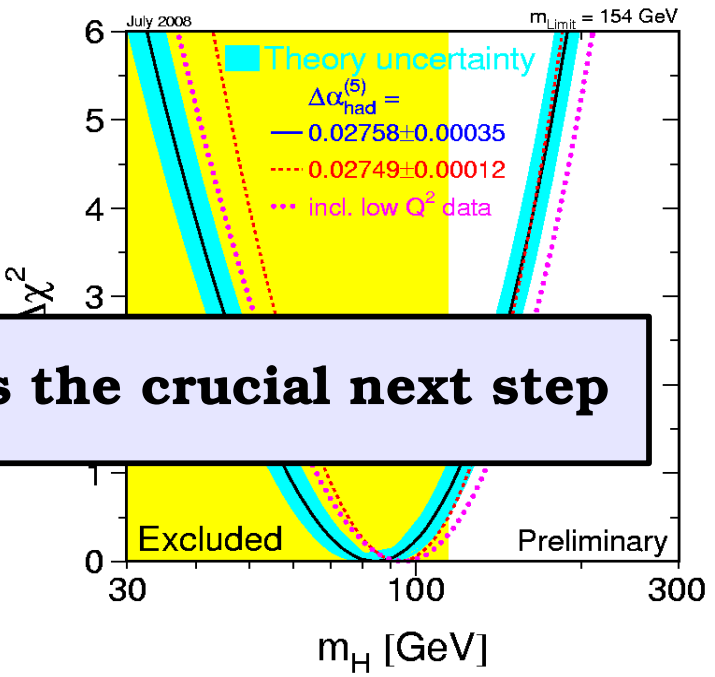
  A fit of precision electroweak data yields: M_H < 163 GeV at 95% CL

  (M_H < 191 GeV including LEP II limit)









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

The Continued Higgs Search

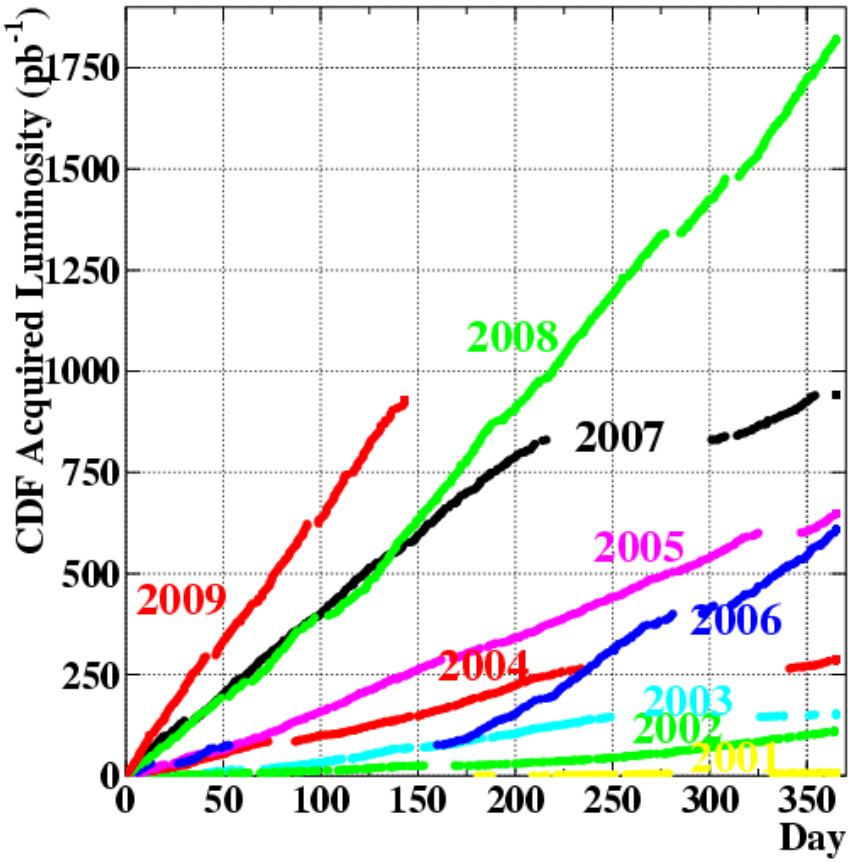
- Generations of physicists are eagerly awaiting the next chapter

  The Tevatron is most sensitive to the Higgs in the range $100 < M_H < 200$ GeV

  Dedicated lab-wide efforts are making this goal a reality!



Steadily Improving Accelerator & Detector Performances



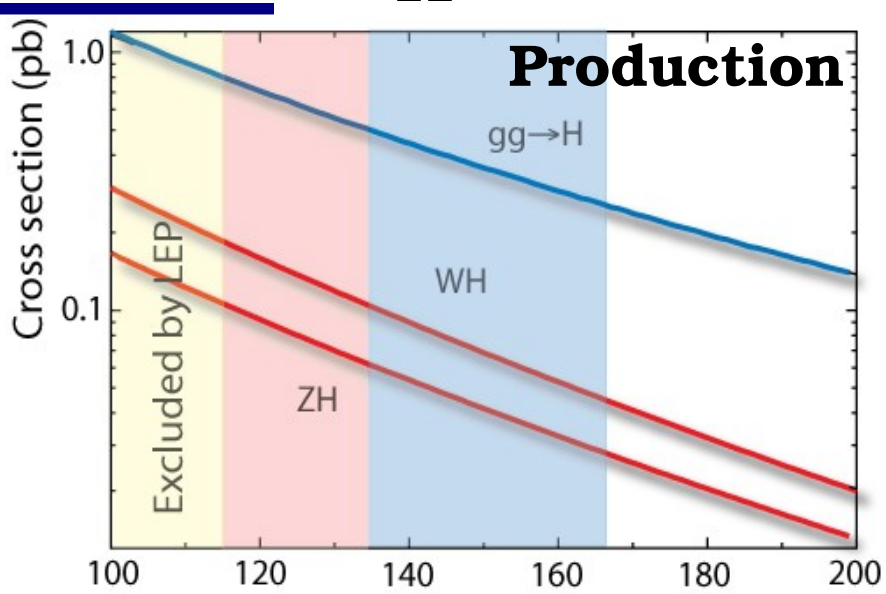
SM Higgs at the Tevatron

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 tag for trigger and analysis

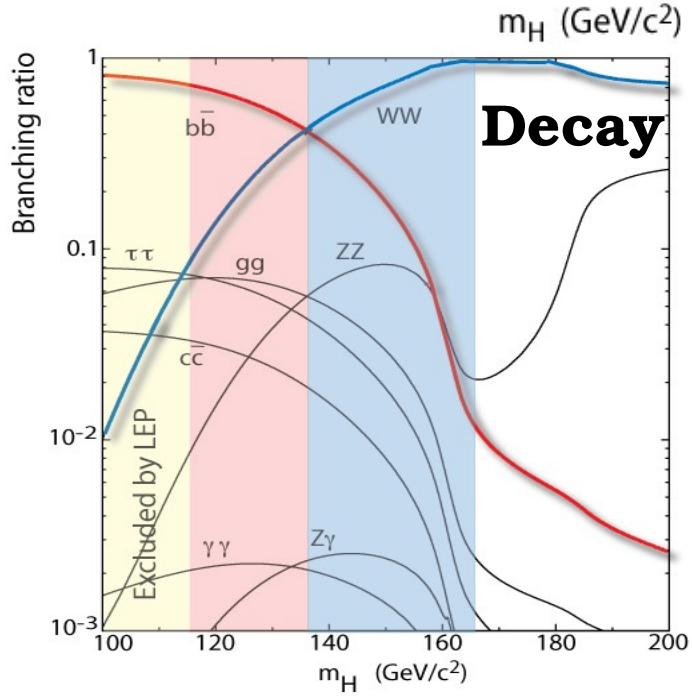


A low-mass Higgs (M_H<135 GeV) prefers to decay to bottom-quark pairs

Need efficient identification of bottom quarks to reduce backgrounds

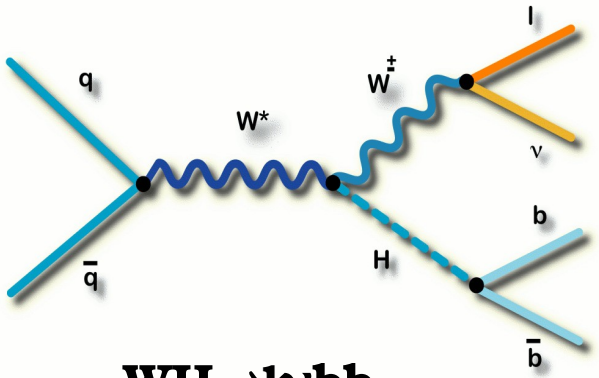
At high mass (M_H>135 GeV), search for $H \to WW^*$

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

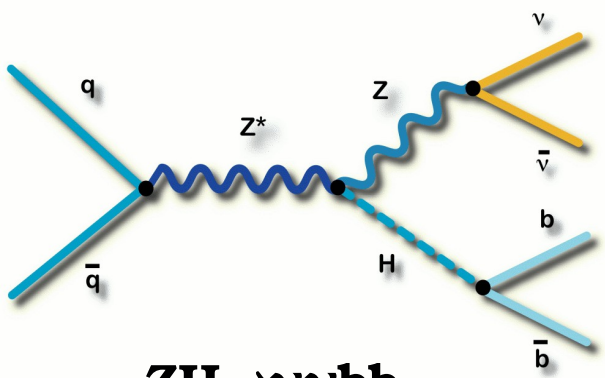


Higgs Search Channels

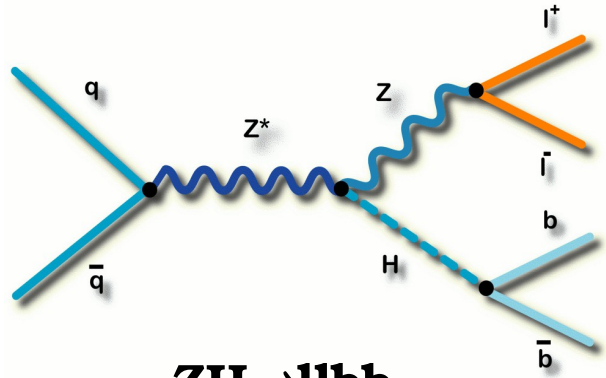
Associated Production: Low mass only, 3 final states



WH→lνbb



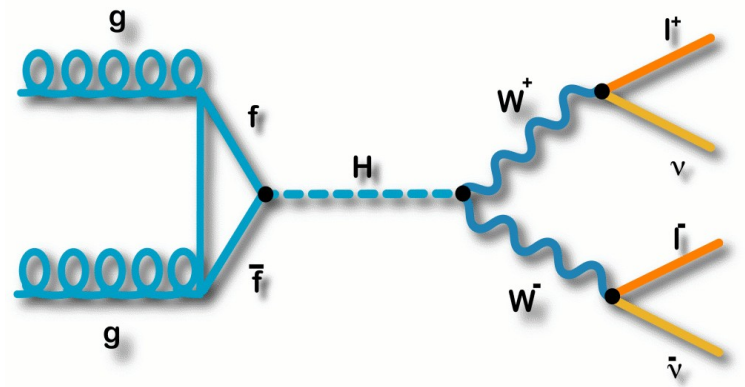
ZH→ννbb



ZH→llbb

Gluon Fusion Production:

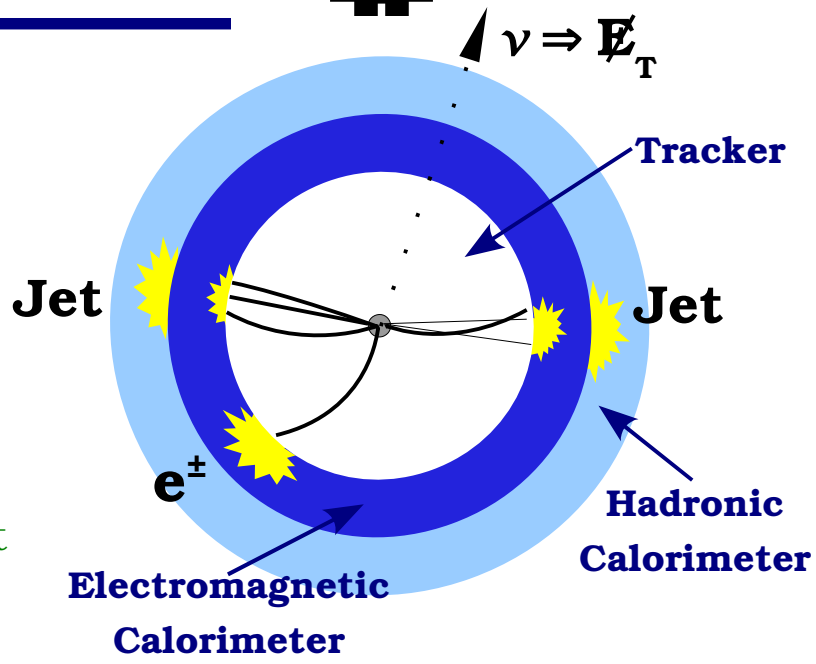
Maximum sensitivity at high mass, also useful at low mass

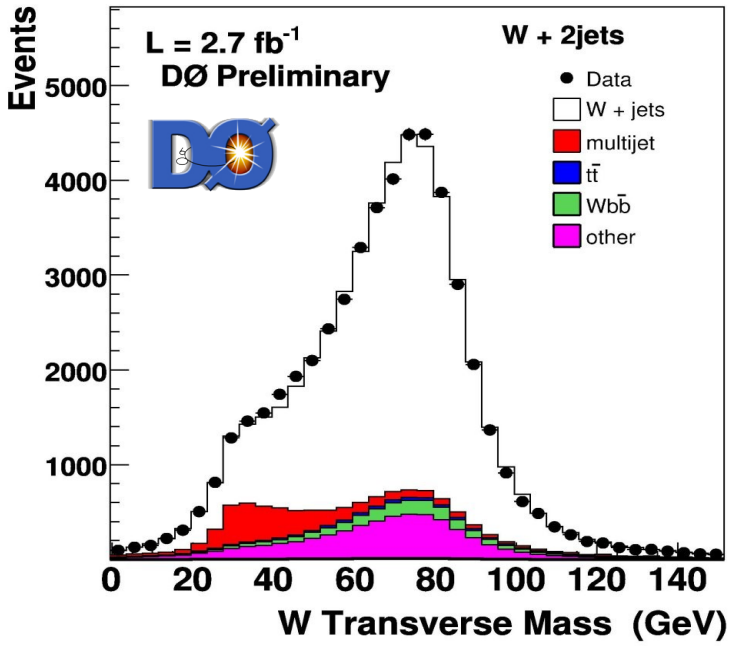


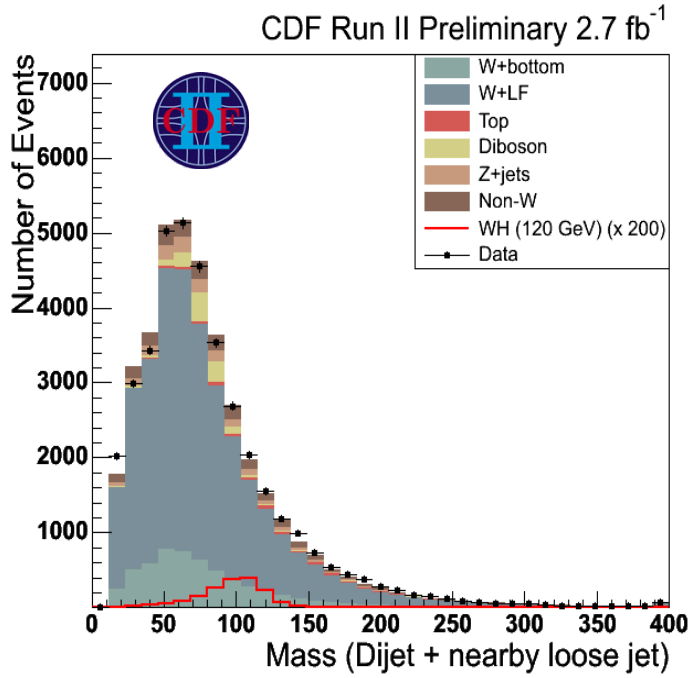
These are the major search channels, but the Tevatron has a comprehensive search program exploiting many other production and decay modes in an effort to maximize search sensitivity.

$WH \rightarrow l\nu bb$

- Identify events consistent with W decays
  - Trigger on **electrons** or **muons**
  - Select significant missing transverse energy (MET) as a signature for neutrinos
- Select events with 2 or 3 jets
  - Eventually require b-tagging, but much effort goes into understanding W+jets modeling at pre-tag levels







ZH → llbb

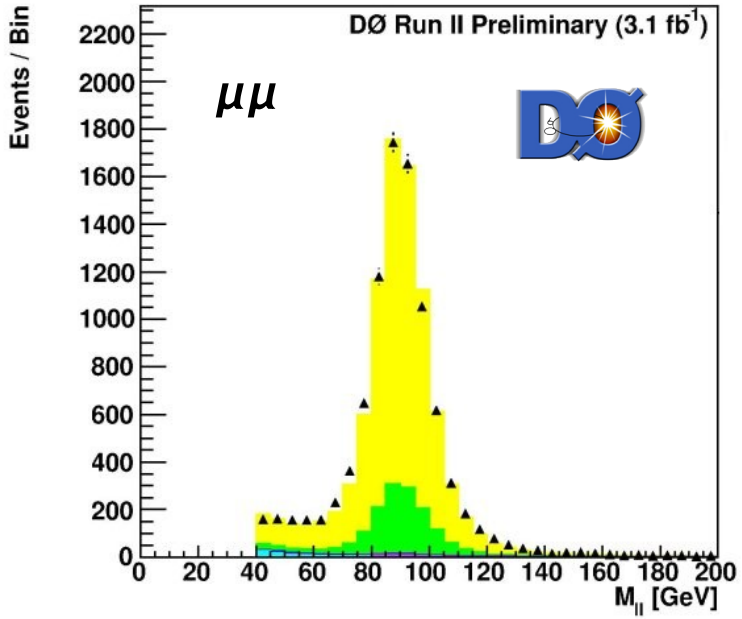
- Di-lepton Z boson decays make this channel:

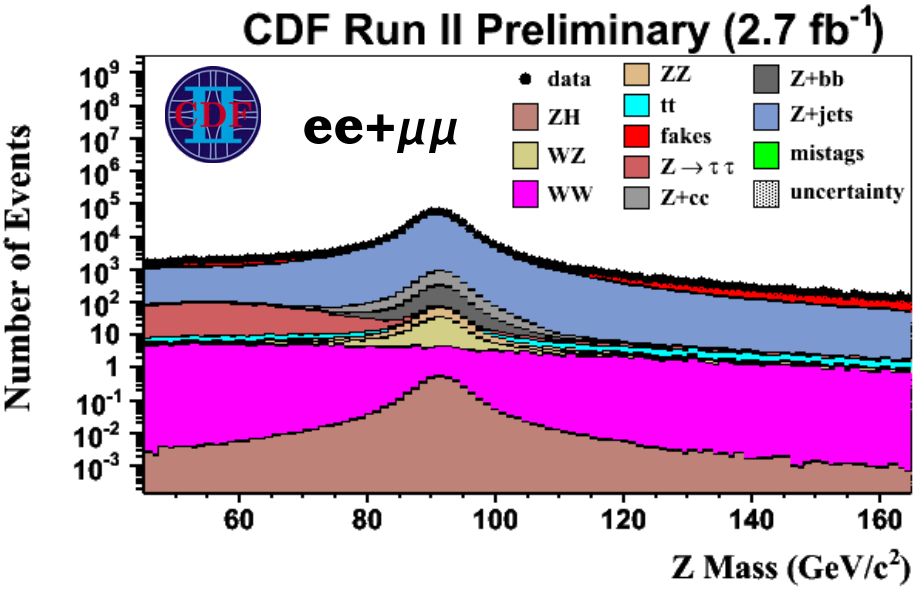
  Easier: More efficient trigger, smaller multijet background, reconstructed Z mass provides reliable handle on event.

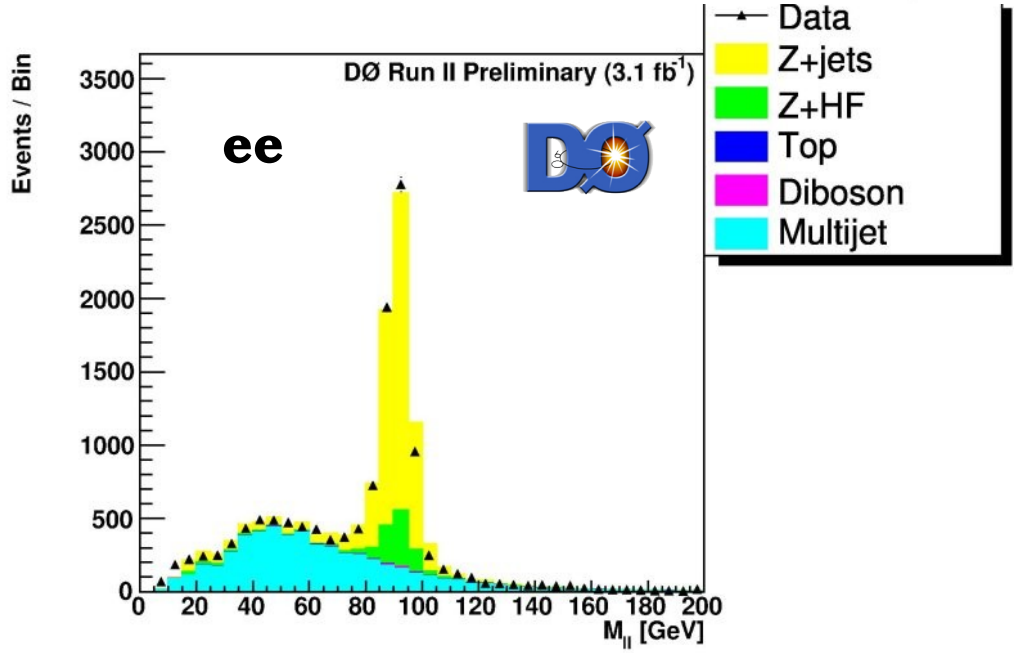
  Harder: Very small signal rate, more sensitive to lepton ID efficiency loss.

- Select two leptons & at least two jets

  Require little or no MET

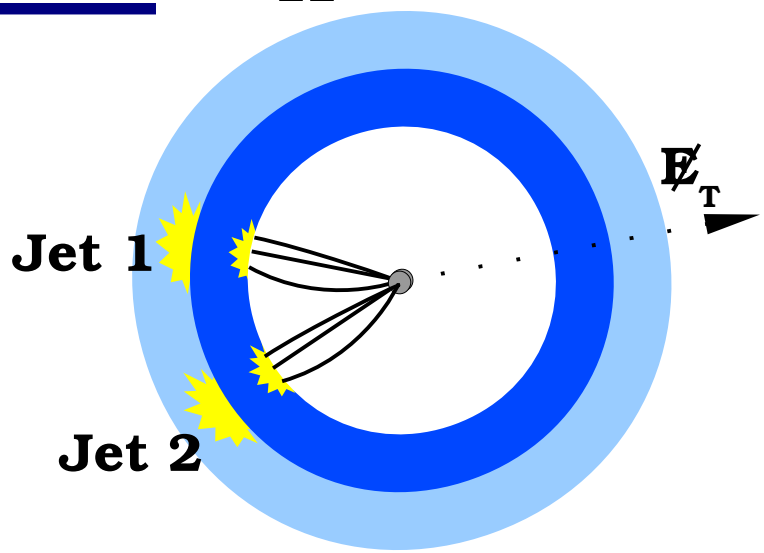




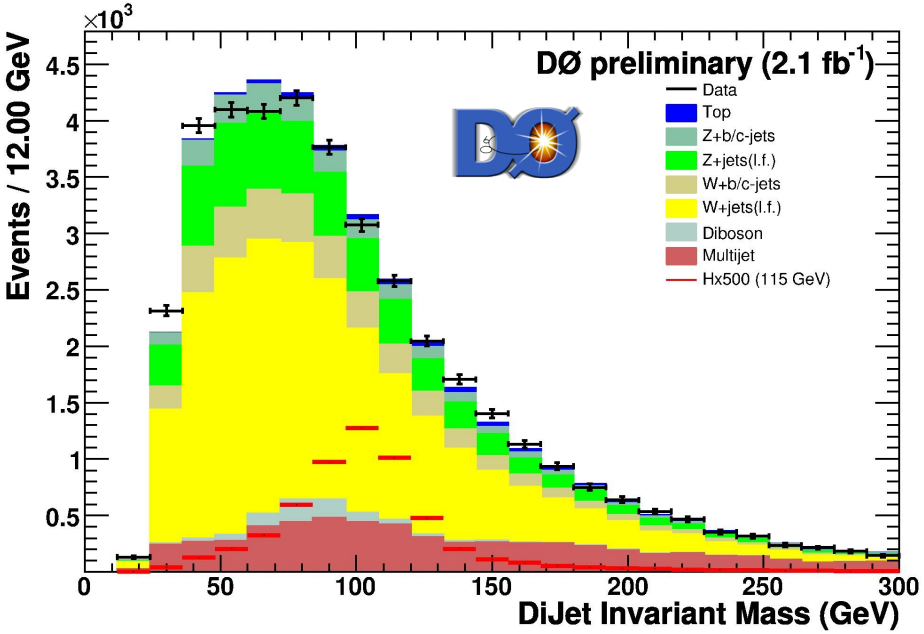


$ZH \rightarrow \nu\nu bb$

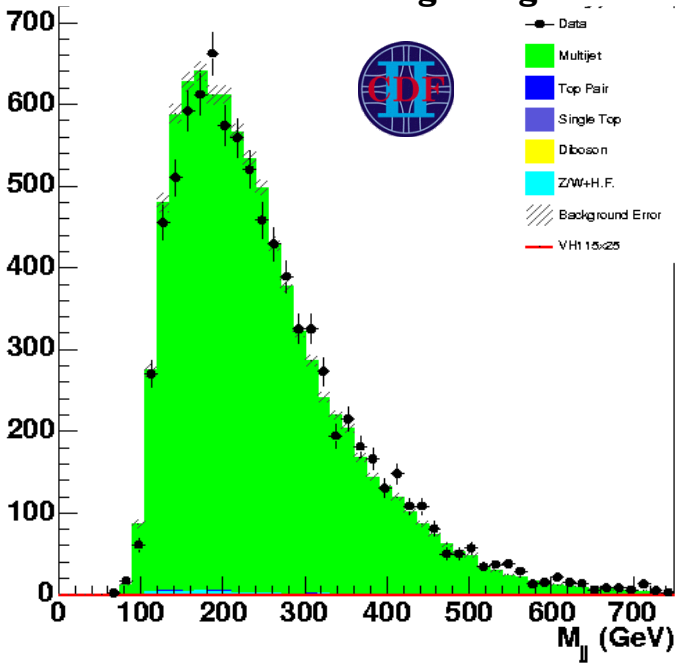
- For $ZH \rightarrow \nu\nu bb$ the search is more difficult: no charged leptons!
  - Rely on large MET (neutrinos!)
  - Backgrounds:
  - "Physics": Z+jets, W+jets, top-pair, ZZ, WZ
  - "Instrumental": Multijets with mis-measured jets



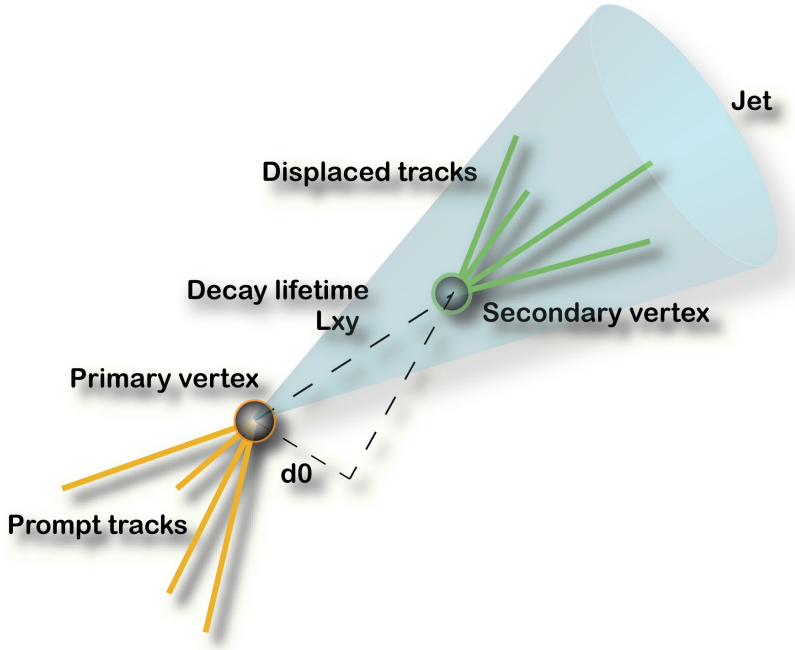
Trigger on large MET + 2 jets, veto on leptons, remove events with back-to-back jets.



Multijet Control Sample
Exclusive Single-Tag



b-Tagging



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

Typical tag efficiency:

50-70% real b-quarks

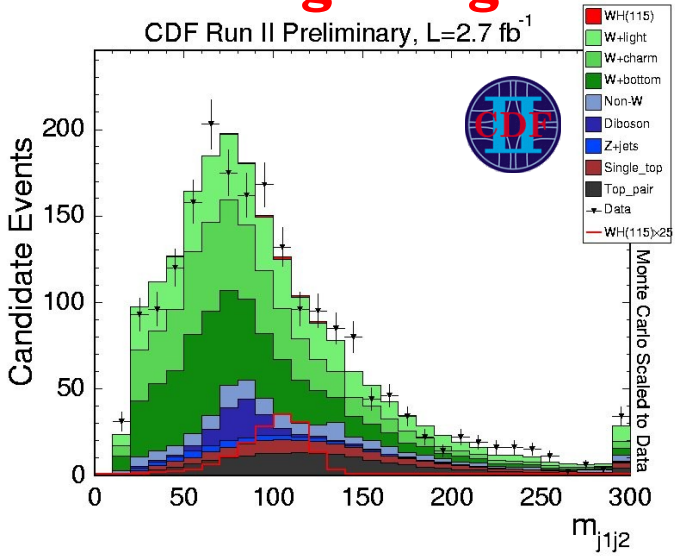
0.5-5% light quarks

Categorize events based on number and quality of b-tagged jets. Select orthogonal samples of:

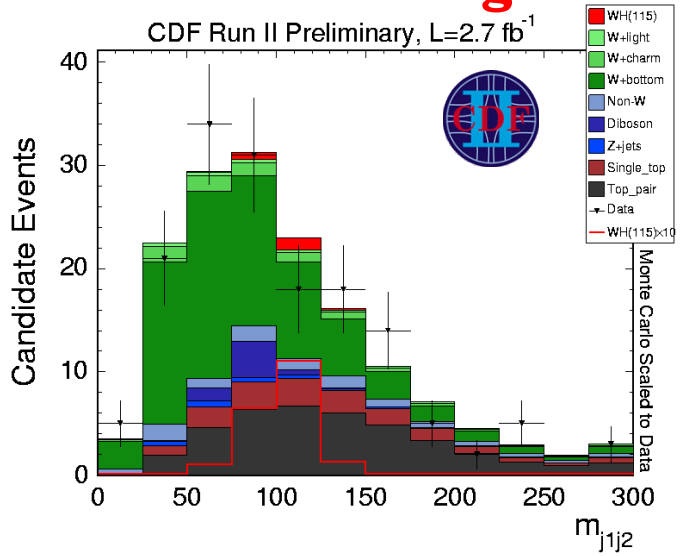
Two b-tagged jets

Exactly one b-tagged jet

Single Tag



Double Tag



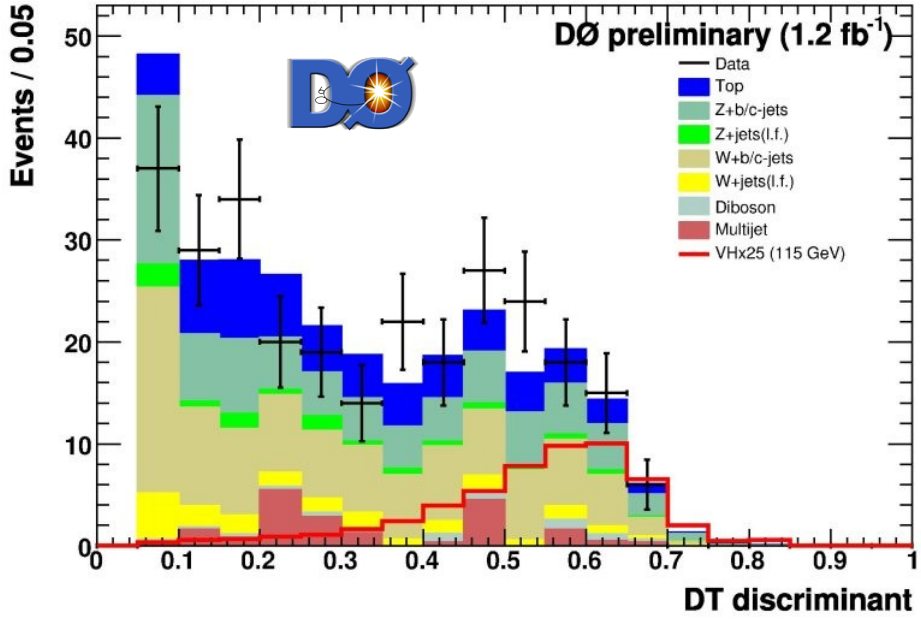
Multivariate Analysis

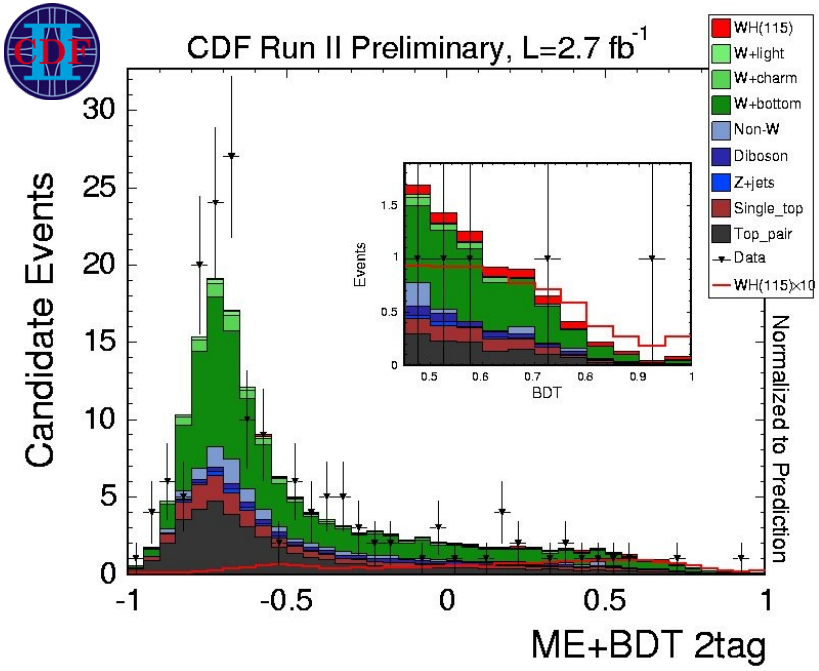
Multivariate techniques are used to improve signal to background ratios

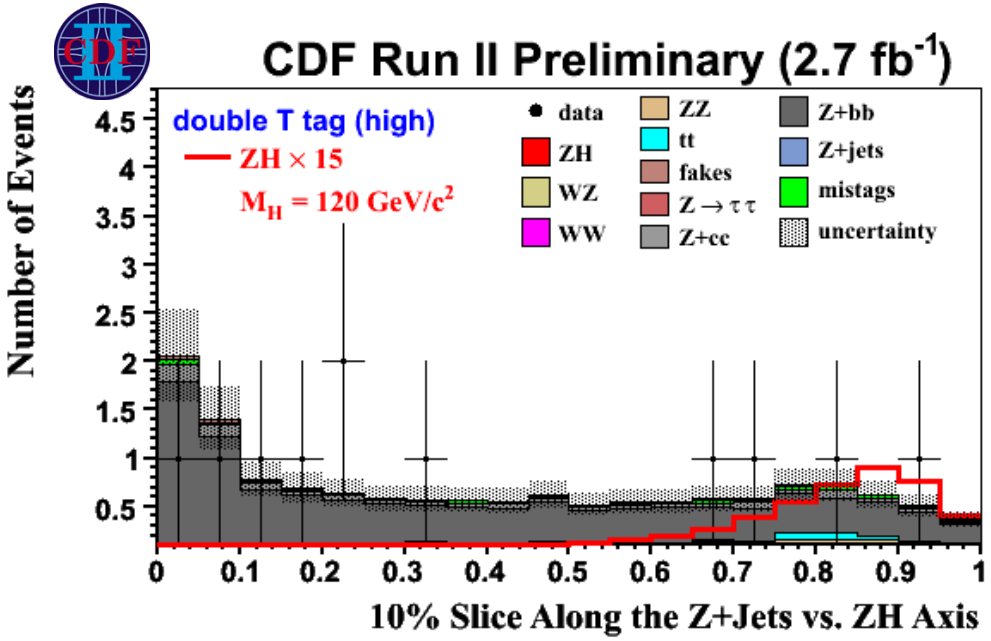
- Boosted decision trees
- Neural Networks
- Matrix Element Discriminants

Typically achieve S/B of ~1/10-1/50

S/B ~1/100 for dijet mass alone

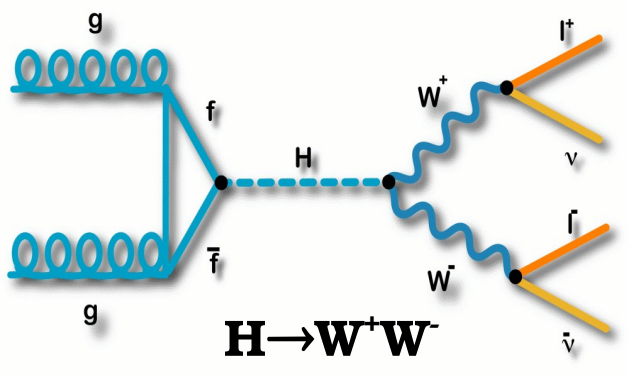


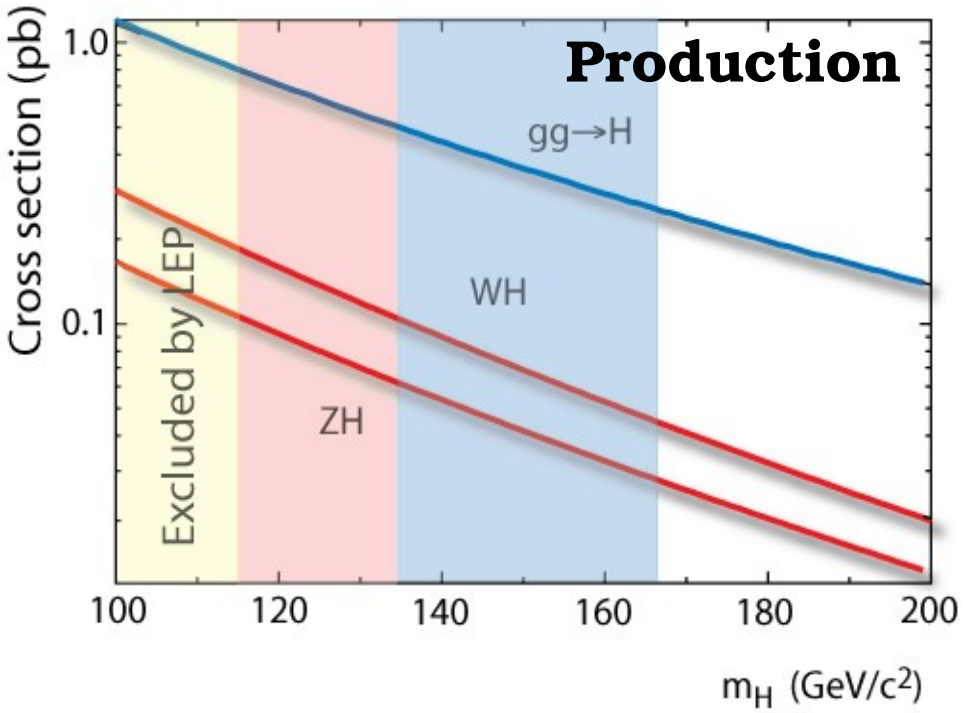


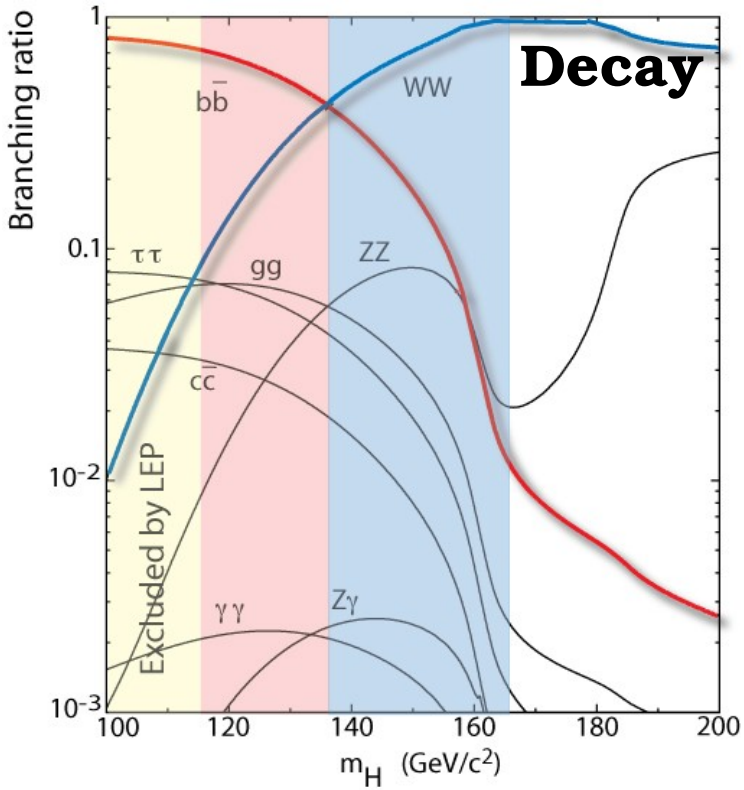


Searching for $H \rightarrow W^+W^-$

- For M_H>135 GeV, Higgs decays to W boson pairs is the dominant decay mode
  - Gluon fusion is the dominant production mechanism
  - Also can include "cross efficiency" from associated production

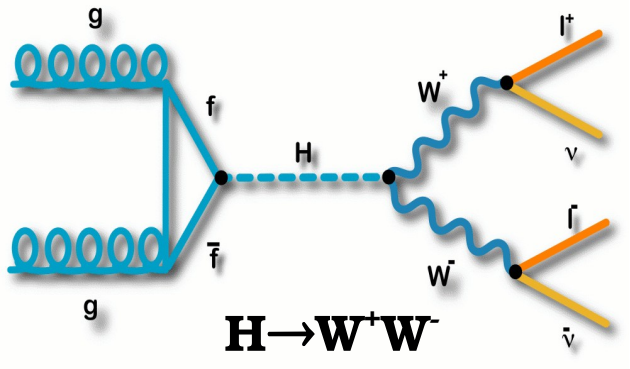




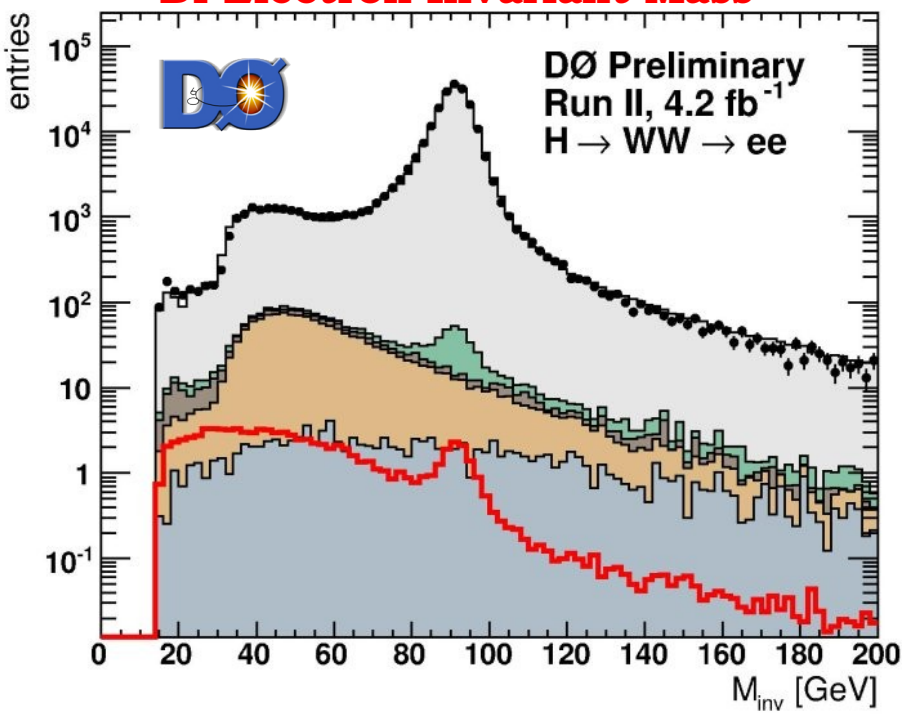


Searching for $H \rightarrow W^+W^-$

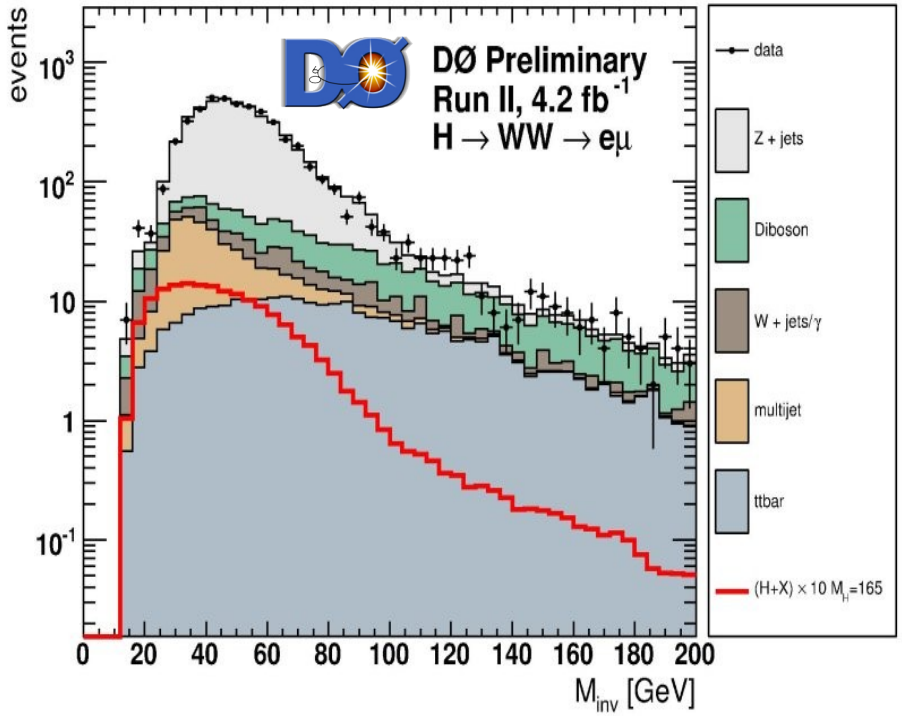
- Select only leptonic W-boson decays to reduce the very large multijet backgrounds
  - Use Z mass for normalization, veto region near peak
  - Include all Higgs production/decay processes: W/Z+H, vector boson fusion, etc.



Di-Electron Invariant Mass



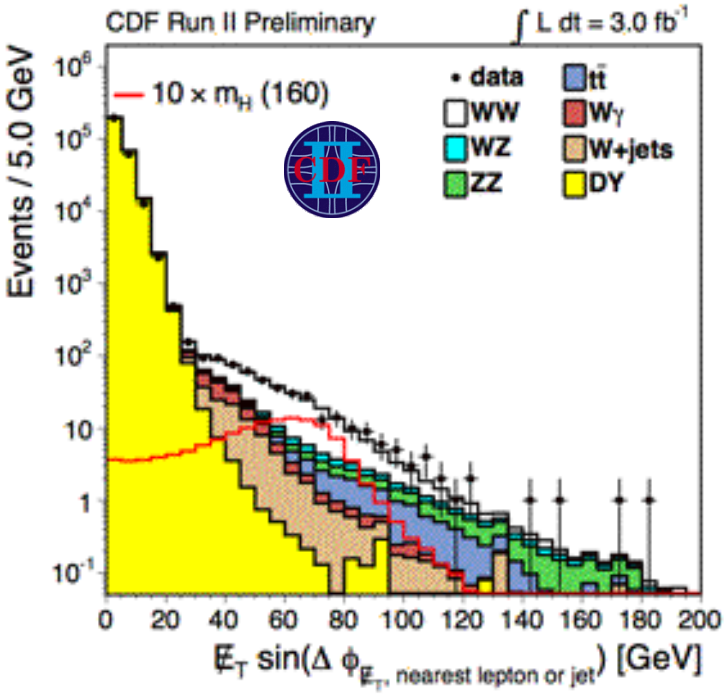
Electron + Muon Invariant Mass



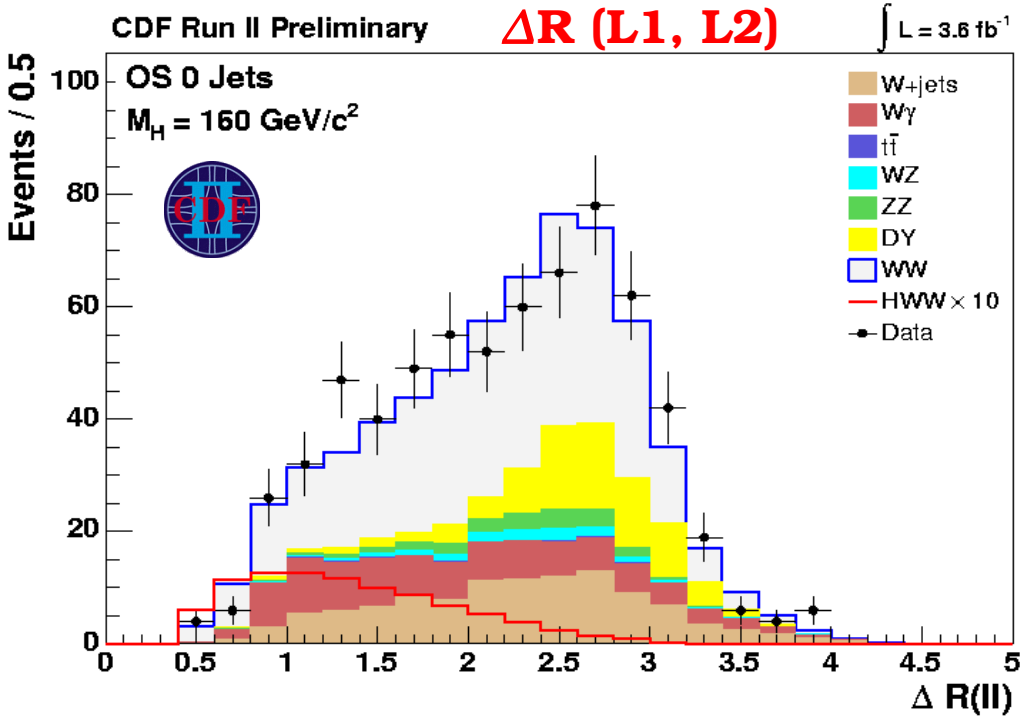
Searching for $H \rightarrow W^+W^-$

- Require large missing transverse energy signature from neutrinos
  - Preselection removes W/Z+jets, but SM W^+W^- production remains
  - Two-neutrinos ⇒ *cannot directly reconstruct the Higgs boson mass*
- Scalar Higgs (spin-0) provides discrimination due to spin correlation
  - Leptons prefer to be collinear

Missing Transverse Energy Significance



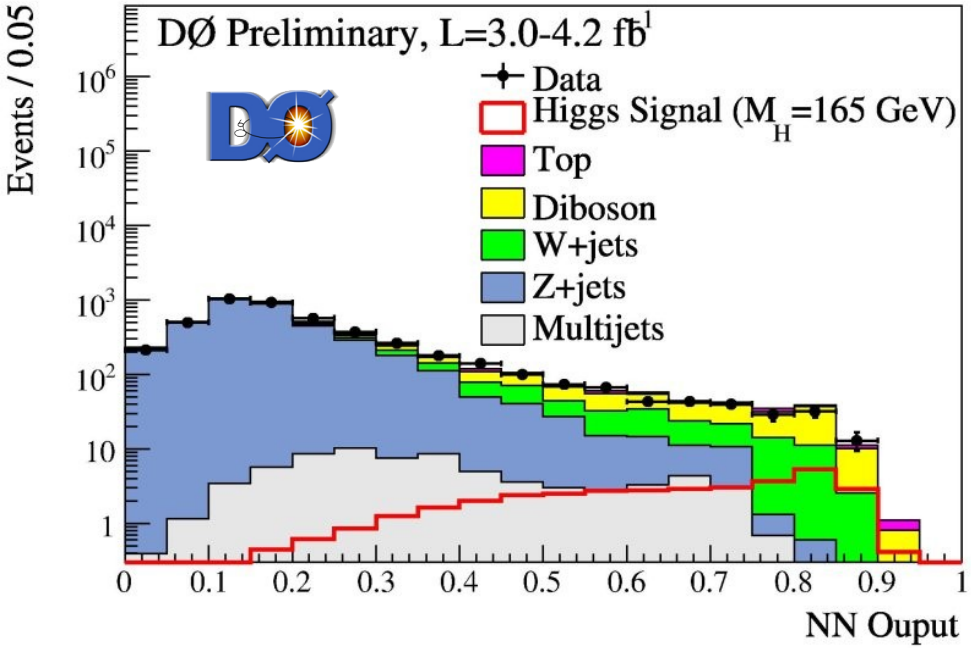
ΔR (L1, L2)

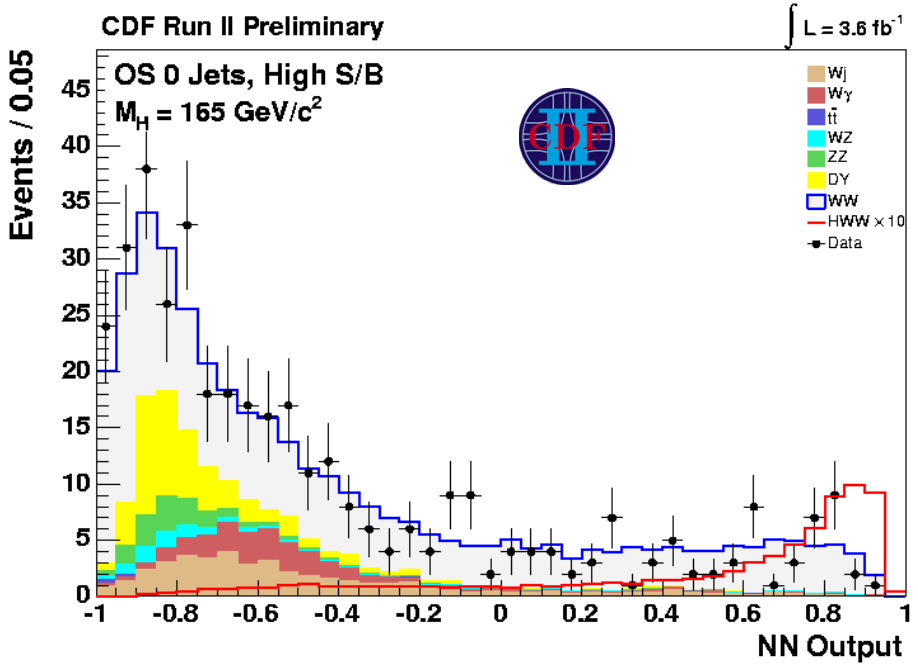


Searching for $H \rightarrow W^+W^-$

- Neural Networks are used to enhance the $H \rightarrow W^+W^-$ search

  Input variables derived from: p_T of leptons, MET, $\Delta\phi(l,l)$, $\Delta\phi(\text{MET},l)$, $M^{inv}(l,l)$





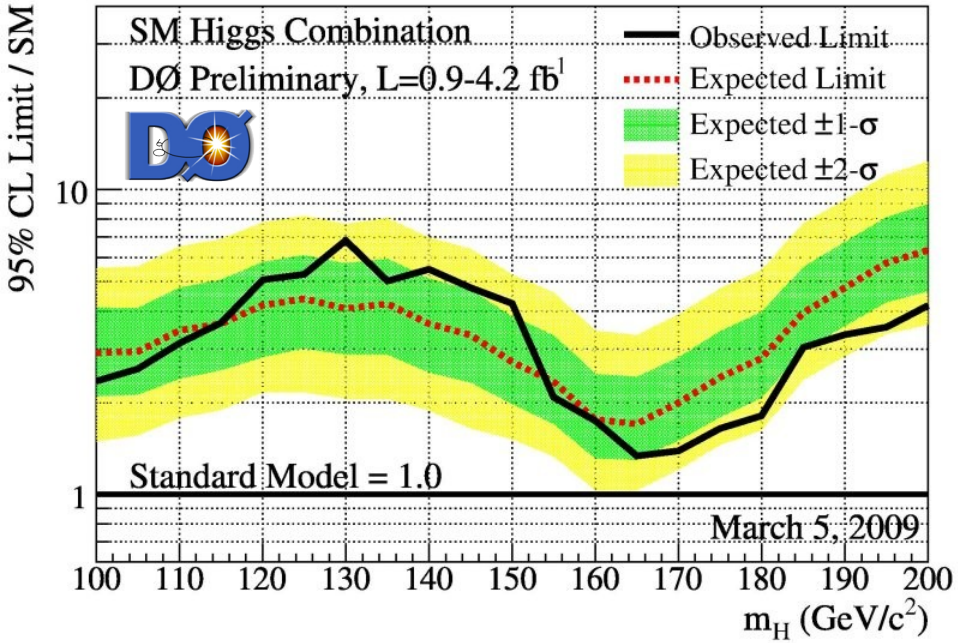
- Can also optimize this signature into final states of # of jets

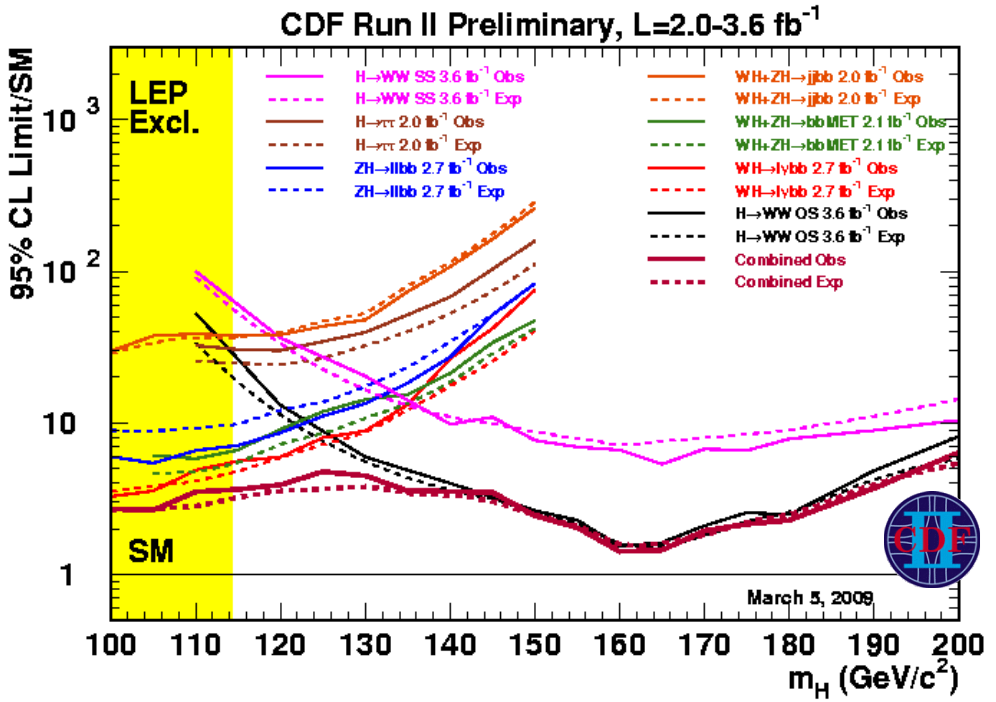
  0 jets: almost exclusively $gg \rightarrow H \rightarrow W^+W^-$ signal

  1 & 2 jets: ~equal contributions of W/Z+H, vector boson fusion and $gg \rightarrow H \rightarrow W^+W^-$ signals

Limits on Higgs Production

Results presented at Moriond 2009





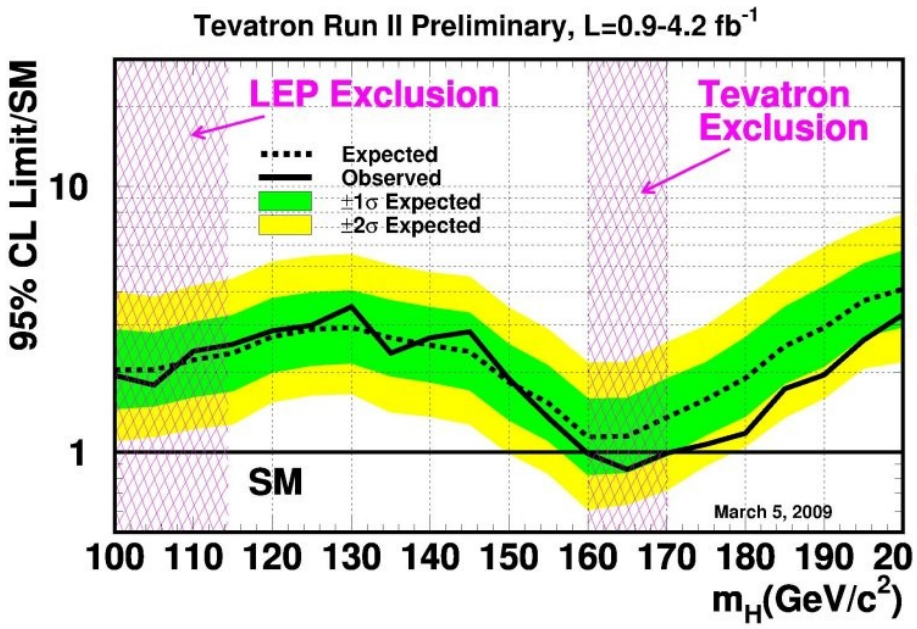
Combined results for all Higgs search channels for each experiment

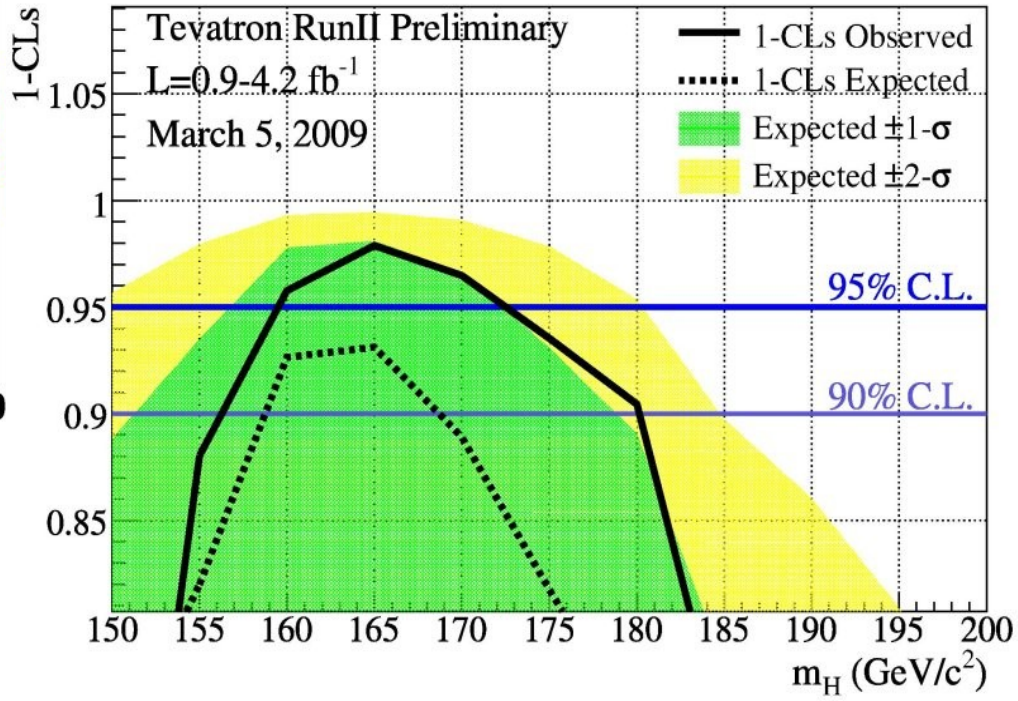
Both experiments find limits within **~2.0×SM at M_H = 165 GeV.**

M_H=115 GeV: CDF / DZero 3.6/3.7 (3.2/3.6) observed (expected)

M_H=165 GeV: CDF / DZero 1.5/1.3 (1.6/1.7) observed (expected)

Limits on Higgs Production





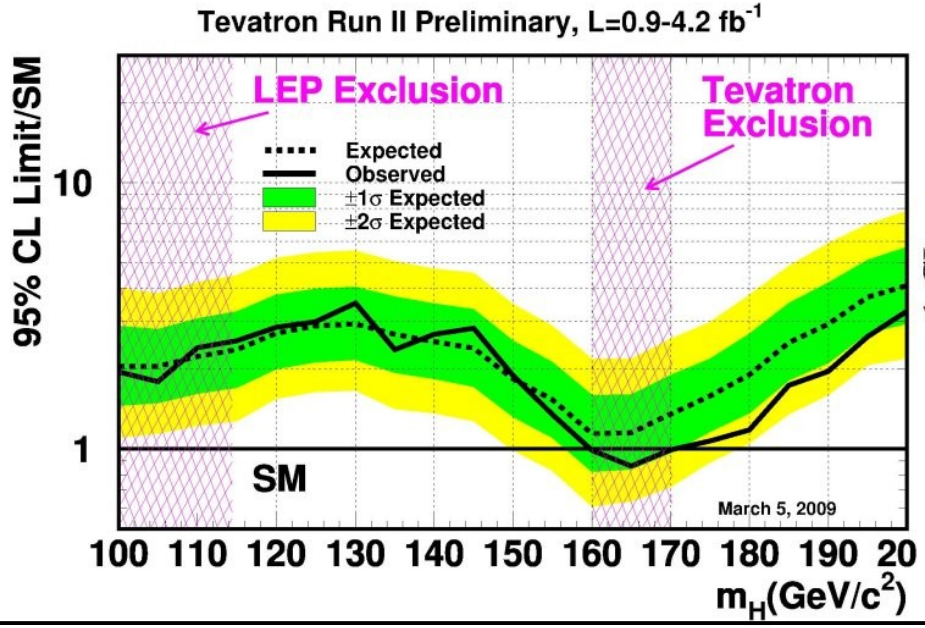
Combined CDF+DZero results in 0.9-4.2 fb^{-1}

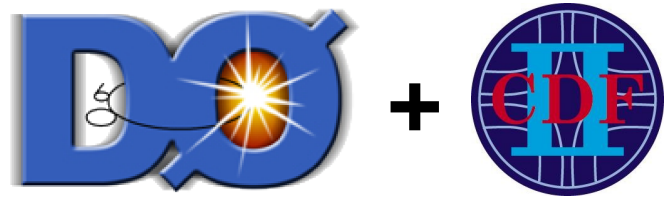
Higgs boson with mass 160 < M_H < 170 GeV excluded at 95% CL

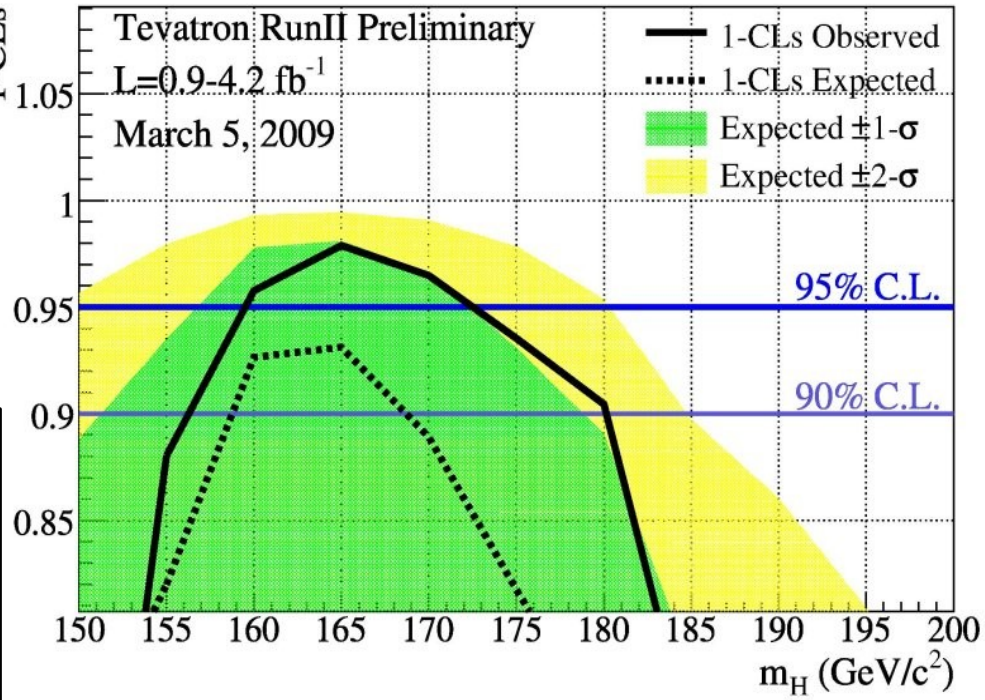
M_H=115 GeV: 2.5 (2.4) observed (expected)

M_H=165 GeV: 0.86 (1.1) observed (expected)

Limits on Higgs Production







Sensitivity-weighted lumi analyzed:

M_H = 115 GeV: 2.6 fb^{-1}

M_H = 165 GeV: 3.8 fb^{-1}

Combined CDF+DZero results in 0.9-4.2 fb^{-1}

Higgs bosons with mass 160 < M_H < 170 GeV excluded at 95% CL

M_H=115 GeV: 2.5 (2.4) observed (expected)

M_H=165 GeV: 0.86 (1.1) observed (expected)

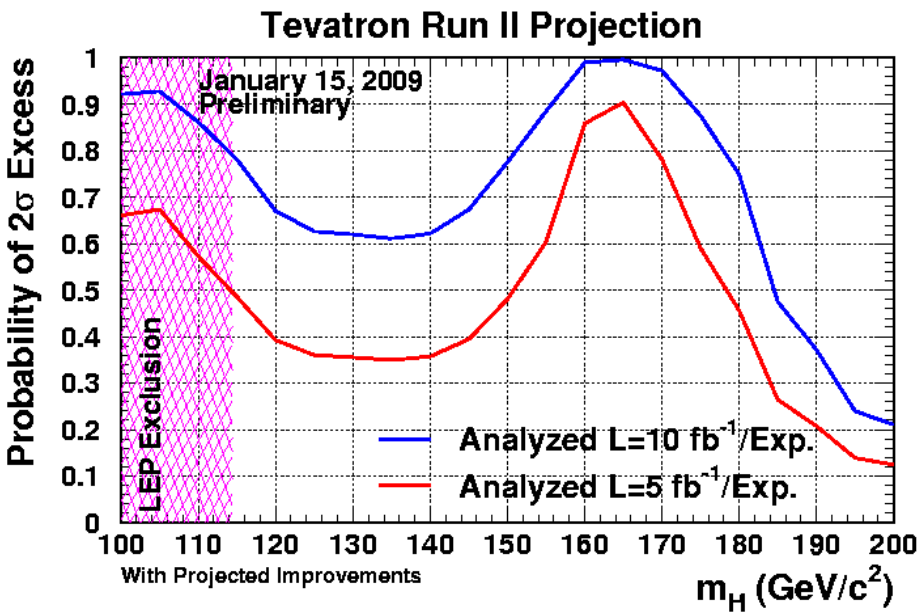
Higgs Sensitivity Projections

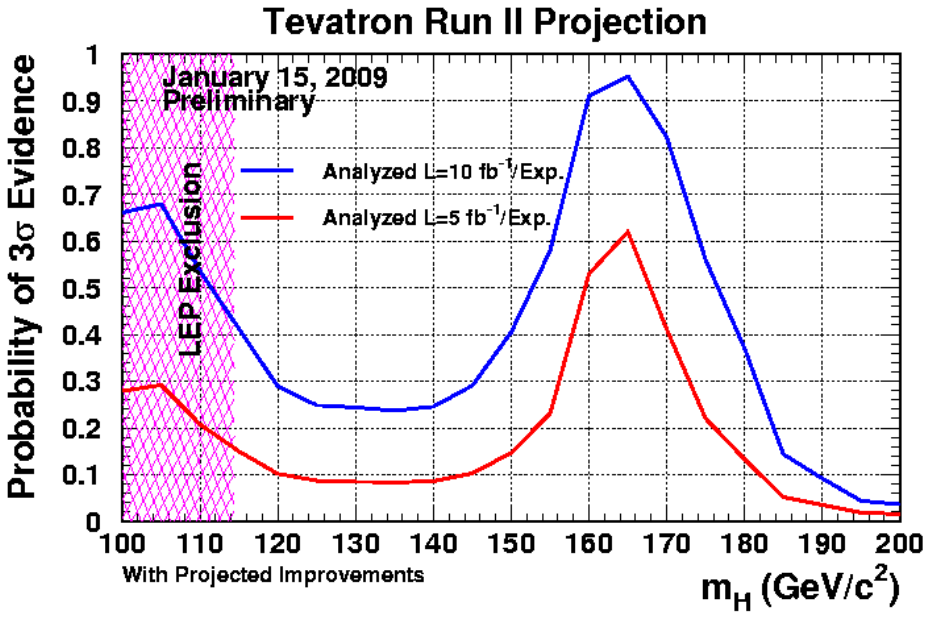
Can project sensitivity as a function of analyzed luminosity

- ~5.5 fb^{-1} analyzed in 2009
- ~10 fb^{-1} analyzed in 2011

Benchmark scenario:

- Assumes analysis design will remain similar to today's designs
- Assumes we achieve potential for known sources of improvement
- We expect to improve a broad range of analysis aspects including: dijet mass resolution, detector acceptance, add missing channels





Beyond the Standard Model

The nominal SM Higgs mechanism may not be the truth

Reality could be ***a refinement of SM*** or more exotic theory, such as ***Super-Symmetry***

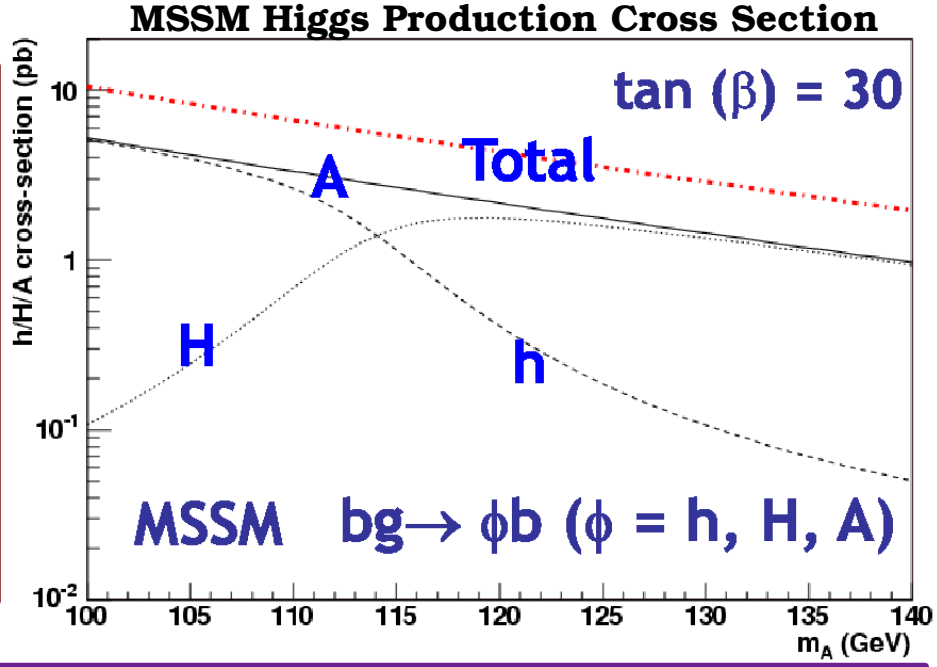
Two Higgs doublet models: Total of 8 degrees of freedom results in 5 Higgs bosons:

3 Neutral: h, H, A **2 Charged: $H^{\pm}$**

In the Minimal SUSY Model (MSSM):

Need at least 2 parameters to calculate all Higgs masses and couplings at tree level: **M_A** and **tan(β)** (ratio of vacuum expect'n values for the two Higgs doublets)

Coupling of neutral Higgs bosons to bottom quarks is **enhanced by tan(β)**, production **enhanced by $\tan^2(\beta)$**



In 2HDM extensions to the SM:

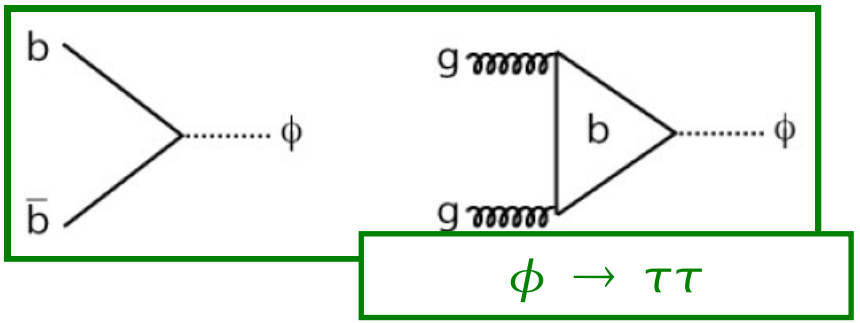
Scalar field mixing angle ***α*** can lead to different couplings to fermions for h and H

sin(α) for H and cos(α) for h

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

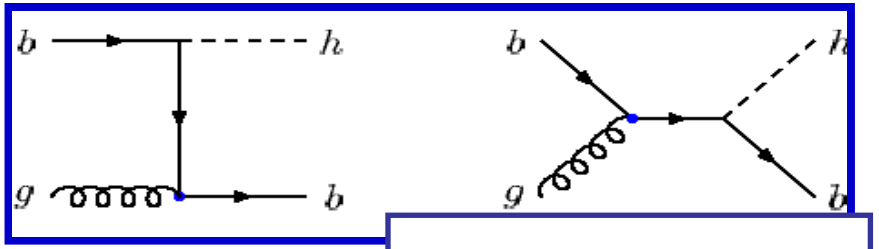
MSSM Higgs Searches

- Neutral MSSM Higgs decays
  - bb ~ 90%
    - Large background
  - $\tau\tau$ ~ 10%
    - More distinct signature

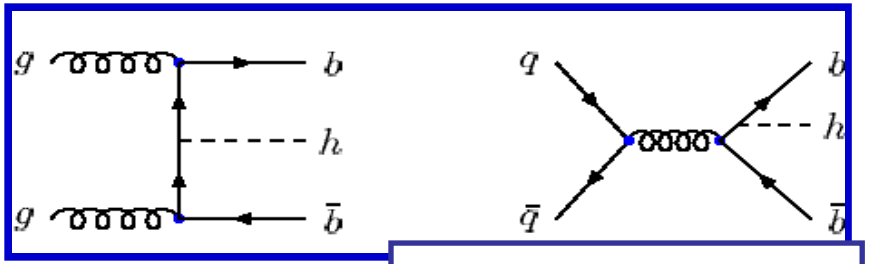


$\phi \rightarrow \tau\tau$

- 3 channels best suited to benefit from enhanced b-quark coupling
  - $\phi \rightarrow \tau\tau$
  - $b\phi \rightarrow bbb$
  - $b\phi \rightarrow \tau\tau b$



$b\phi \rightarrow 3b/b\tau\tau$



$bb\phi \rightarrow 4b/bb\tau\tau$

- Good b-jet and τ identification are essential

Similar overall sensitivities

$\phi \rightarrow \tau\tau$ / $b\phi \rightarrow b\tau\tau$

✗Signal definition:

$\phi \rightarrow \tau\tau$: Isolated e or μ separated from opposite-signed hadronic τ (τ^{had})

$b\phi \rightarrow b\tau\tau$: Isolated μ +τ^{had} and b jet

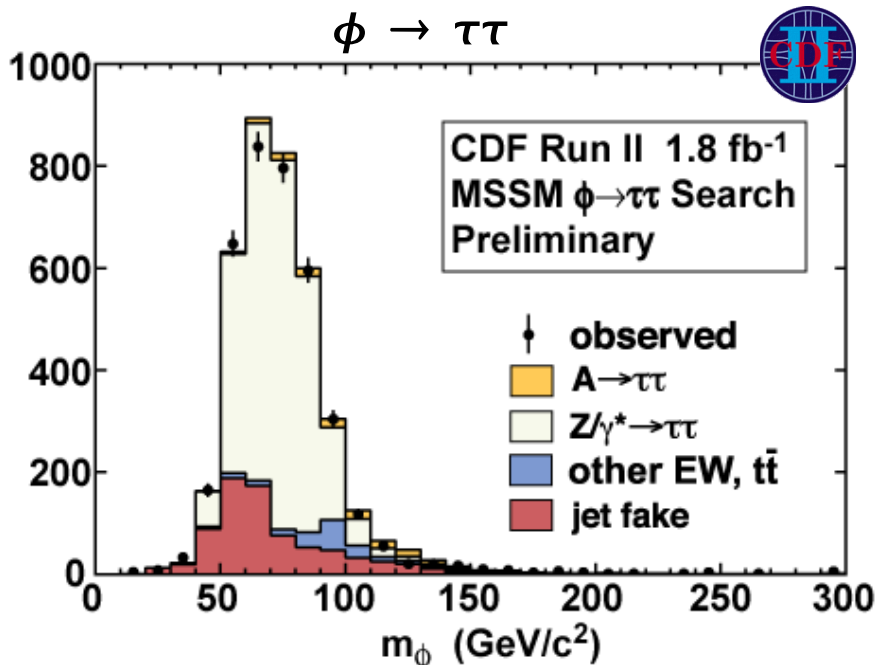
✗ Main backgrounds:

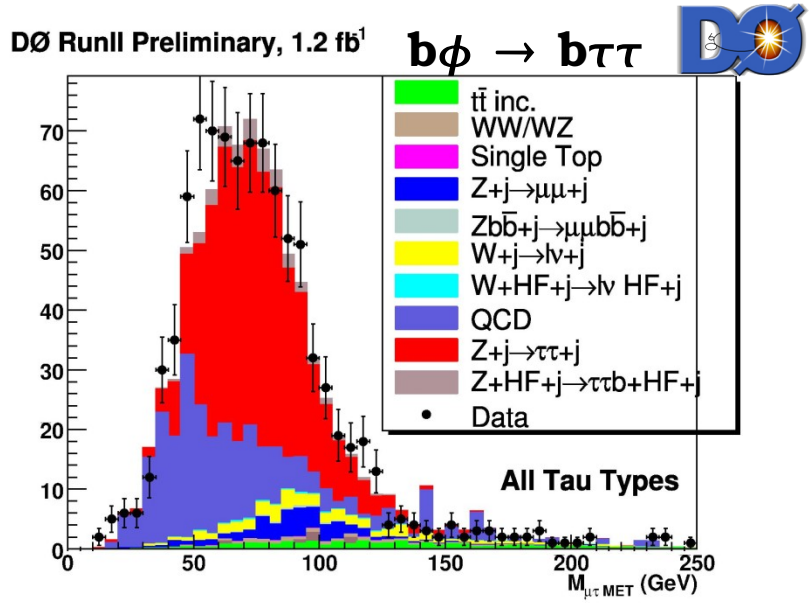
$Z\rightarrow\tau\tau$ (*irreducible*), multi-jet, W+jets, $Z\rightarrow\mu\mu$/ee

✗ Z resonance provides built-in calibration

$Z\rightarrow\tau\tau$ peak helps control normalization and tau energy scale

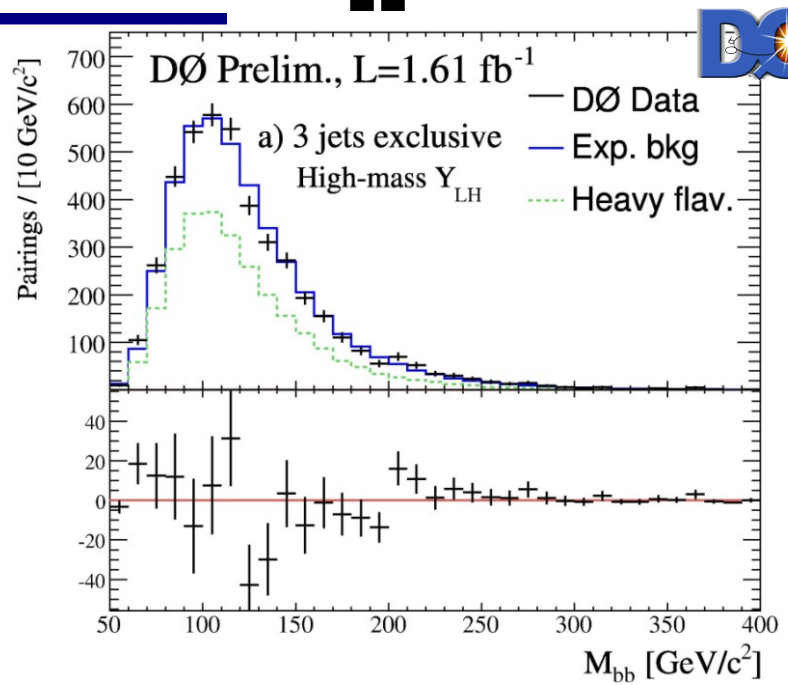
Top quark backgrounds become important for $b\phi \rightarrow b\tau\tau$

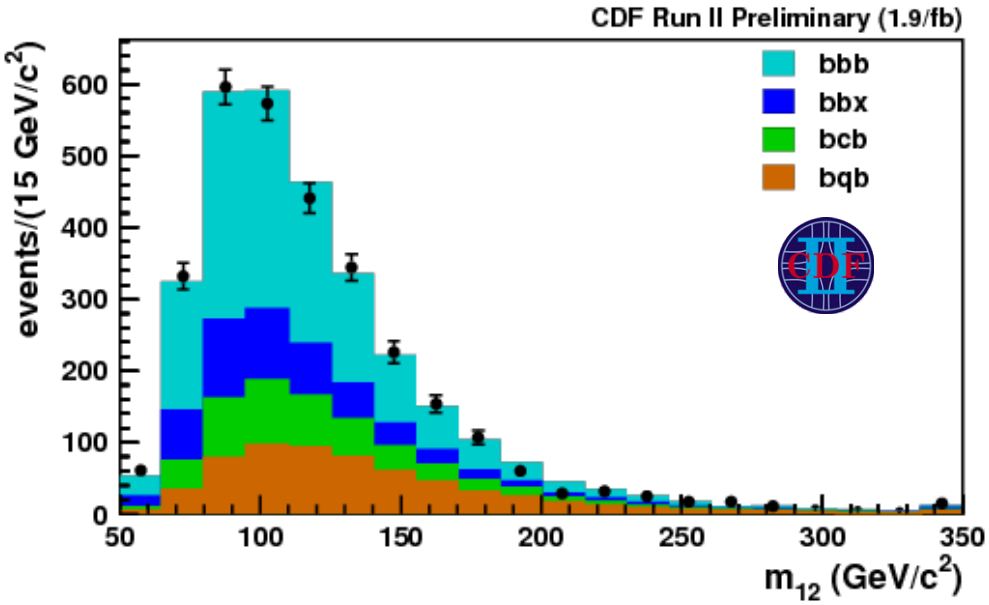




b[b]ϕ → b[b] + bb

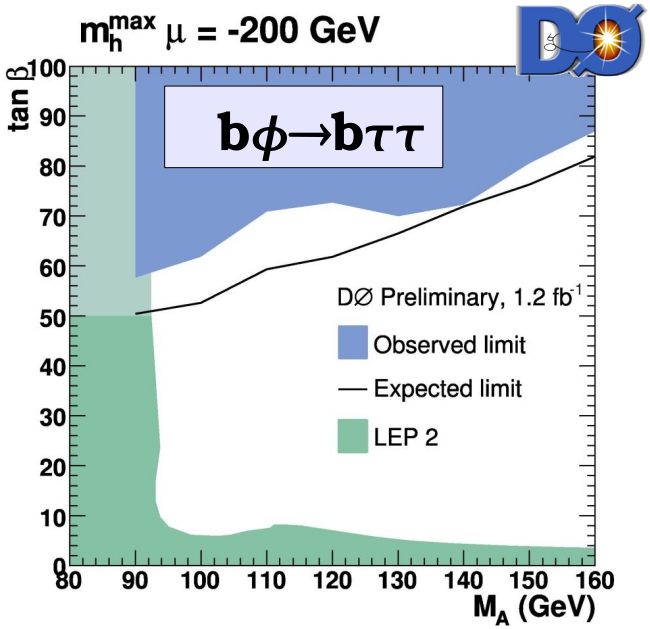
- Signal
  - At least 3 b-tagged jets
  - Look for a peak in the dijet mass spectrum
- Backgrounds
  - Heavy flavor multijet production
  - Predicted from data/MC
- DØ: Summer 2008
  - Train kinematic likelihood
  - Separate 3, 4 and 5-jet channels
  - Keep multiple jet pairings
  - Cut on likelihood
  - Use dijet invariant mass to set limits
- CDF: Winter 2008
  - Use dijet invariant mass to set limits

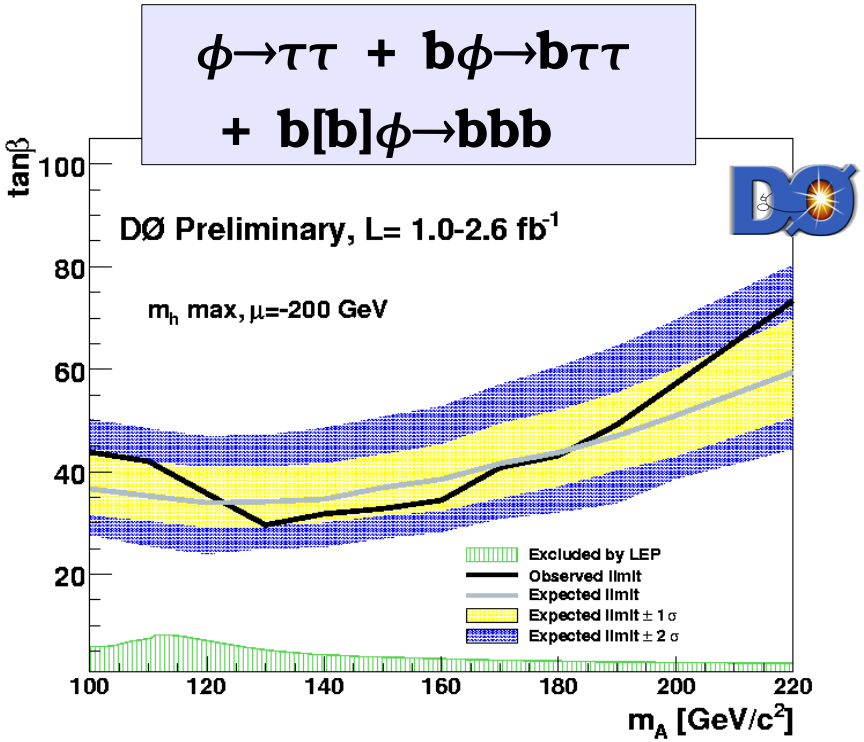


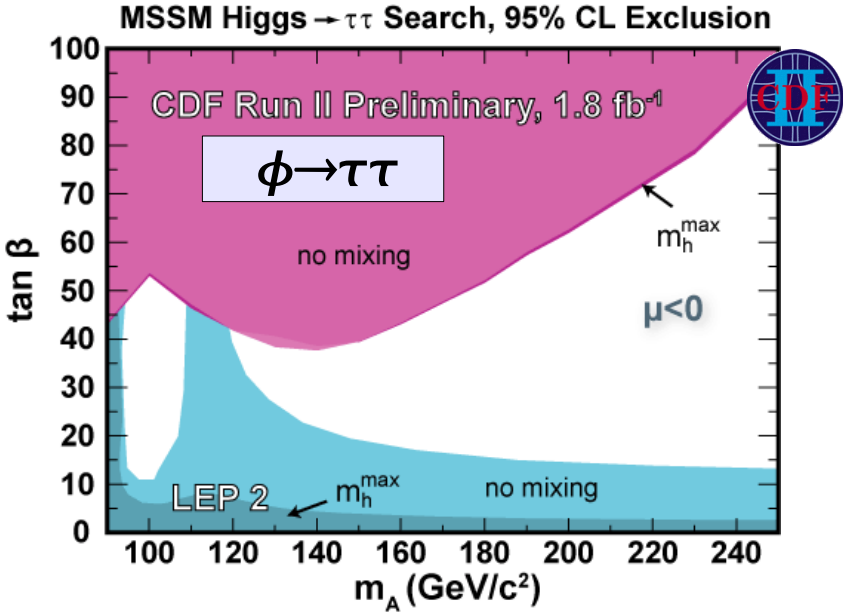


Limits on MSSM Higgs

- Limits on MSSM set in M_A vs tan(β) plane
- Two common benchmarks
  - Max-mixing - Higgs mass close to max possible for each tanβ
  - No-mixing – ~zero mixing in stop sector → small mass for h
- **Reaching interesting point of tan(β) ~ M_{top}/M_b ~ 35 with a fraction of the final dataset**







Fermiophobic Higgs

- For this scenario, $H\to\gamma\gamma$ can be greatly enhanced. Thus, search for $\gamma\gamma$ mass peak
  - ~3% mass resolution
- Backgrounds
  - Direct production, γ+jets/dijets, Drell-Yan
- Selection: 2 photons
  - DØ: Central, pT($\gamma\gamma$) > 35 GeV
  - CDF: Central\Endcap, pT($\gamma\gamma$) > 75 GeV
  - Adding one EC electron ~doubles acceptance
- No excess observed in data, set limits on:

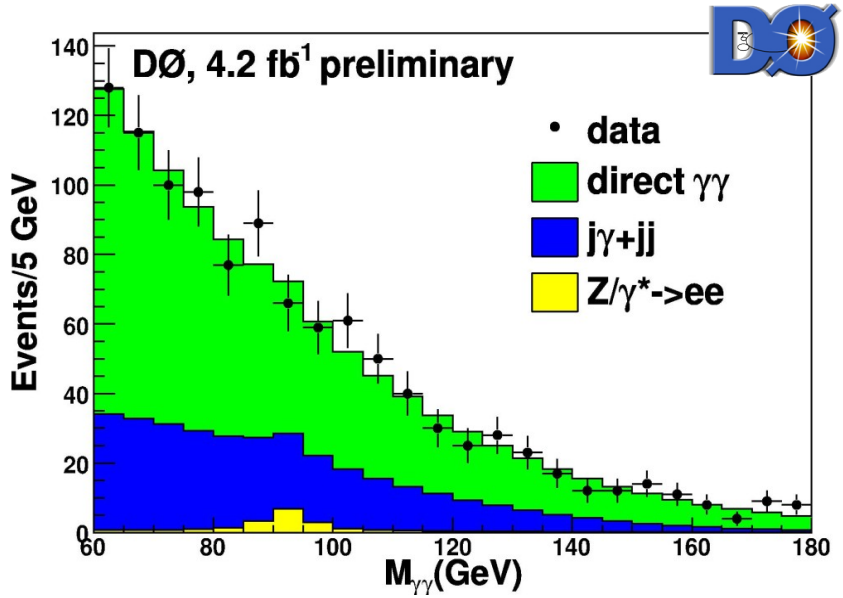
Sigma×BR vs M_H

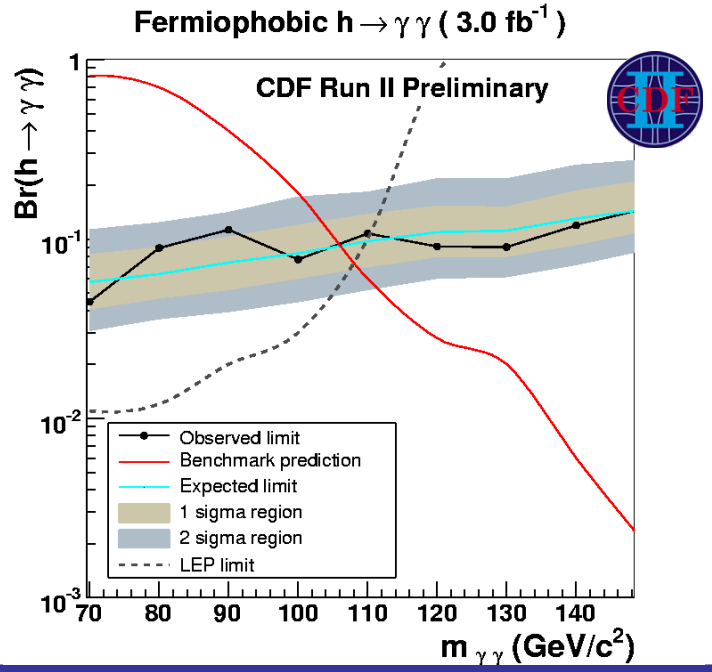
CDF: M_H>106 (106) GeV **obs (exp)**

DØ: M_H>102.5 (107.5) GeV

BR(H→$\gamma\gamma$) vs M_H

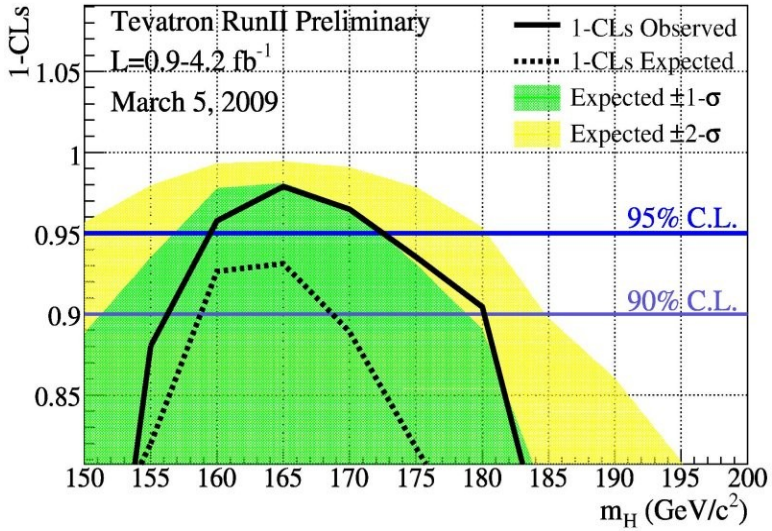
TeV expts access regions unavailable at LEP



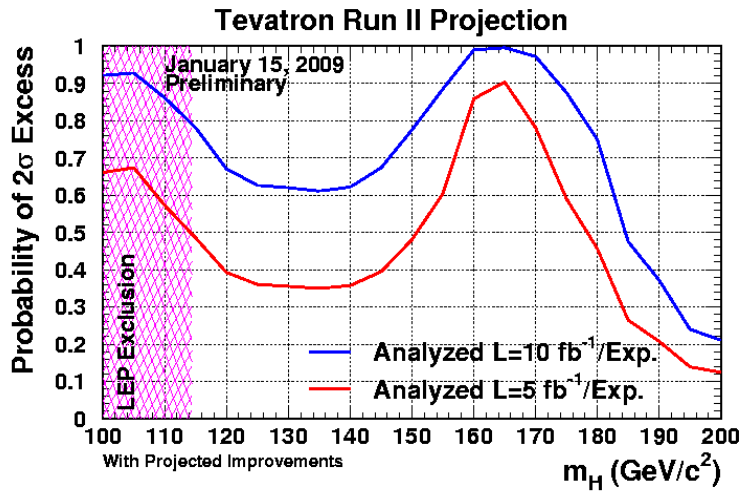


Conclusions

- We are working hard to find a Higgs boson
  - Dedicated efforts at CDF & DØ are boosted by excellent Tevatron performance
  - We **exclude a Higgs mass** of $160 < M_H < 170$ GeV
  - Progress in MSSM searches is reaching region interesting for theory



- It's an exciting time to be a Higgs hunter!
  - SM: We expect **>3.3x** more lumi to analyze for M_H<140 GeV (**>2.2x** for higher masses)
  - BSM: We are now driving world's best limits in MSSM & Fermiophobic Higgs



Expect constant improvement in all areas

as our data samples grow