
# Searches for the Higgs Boson at the Tevatron

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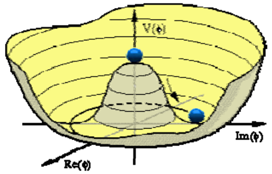
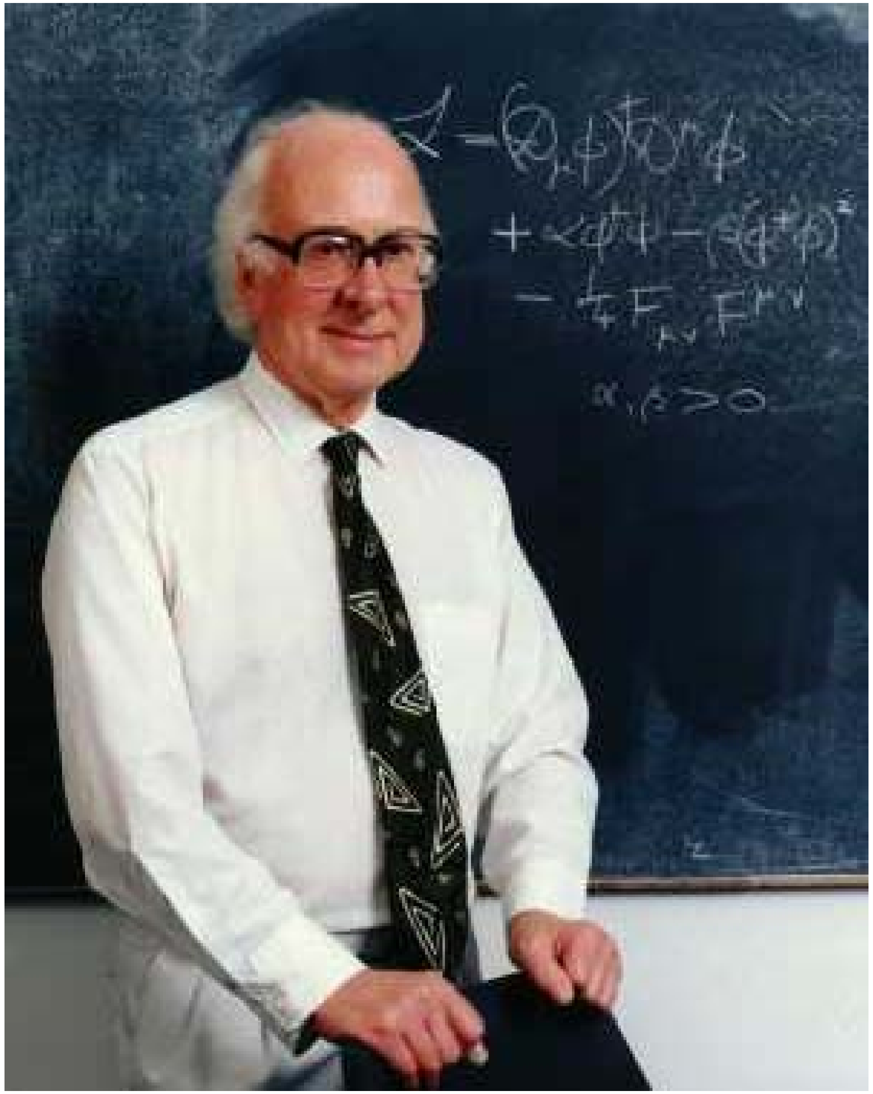
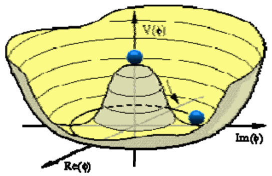
US CMS JTERM III Meeting



# Searches for the Higgs Boson

- Introduction
- Tools of the Trade
- BSM Higgs Searches
- SM Higgs Searches
- Combination of SM Higgs Results
- Conclusions





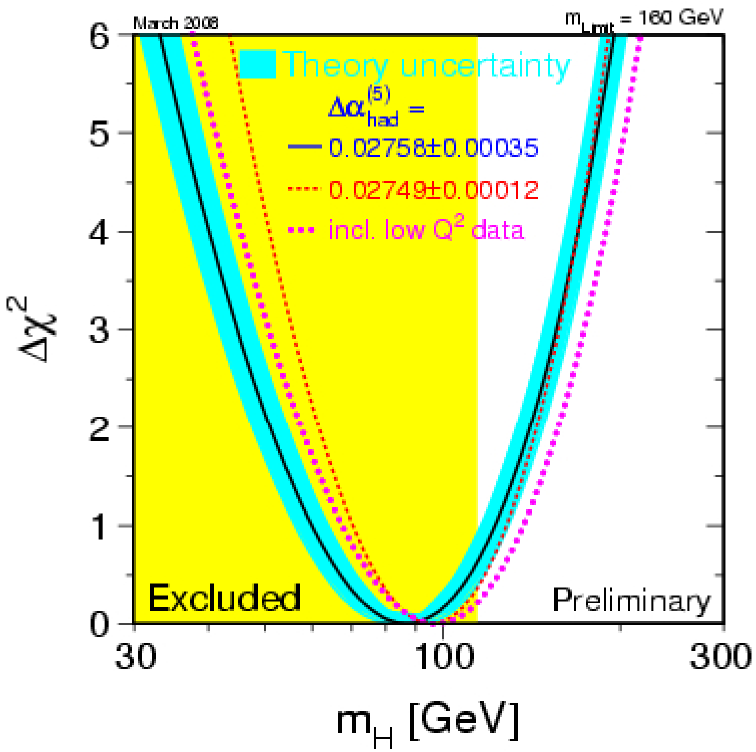

# Electroweak Symmetry Breaking

- An experimentalists conception
- Consider the Electromagnetic and the Weak Forces
- Coupling at low energy: EM: $\sim\alpha$, Weak: $\sim\alpha/(M_{W,Z})^2$
  - Fundamental difference in the coupling strengths at low energy, but apparently governed by the same dimensionless constant
  - Difference due to the massive nature of the W and Z bosons
- SM postulates a mechanism of electroweak symmetry breaking via the Higgs mechanism
  - Results in massive vector bosons and mass terms for the fermions
  - Directly testable by searching for the Higgs boson

A primary goal of the Tevatron and LHC

# Electroweak Constraints

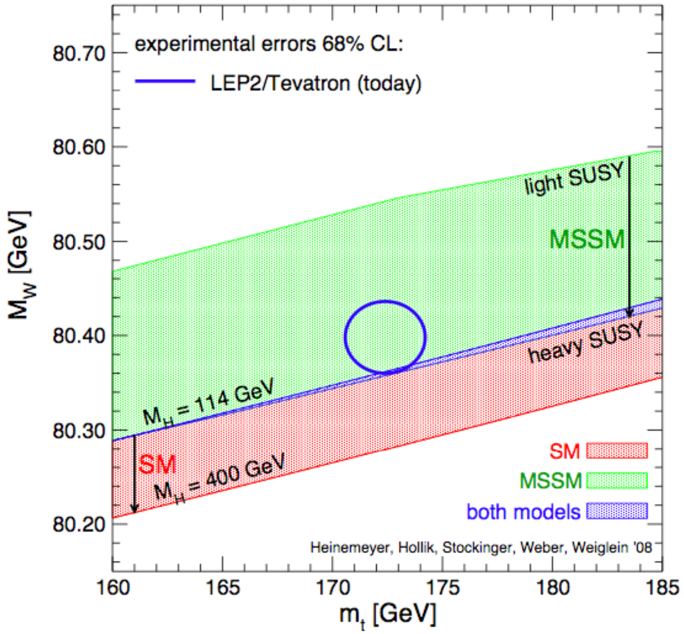
- Higgs couples strongly to massive particles
  - Introduces corrections to W and top masses - sensitivity to Higgs mass




SM LEP Direct search: $m_H > 114$GeV

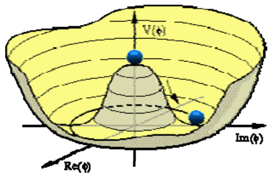
SM indirect constraint: $m_H < 154$GeV

@ 95% CL



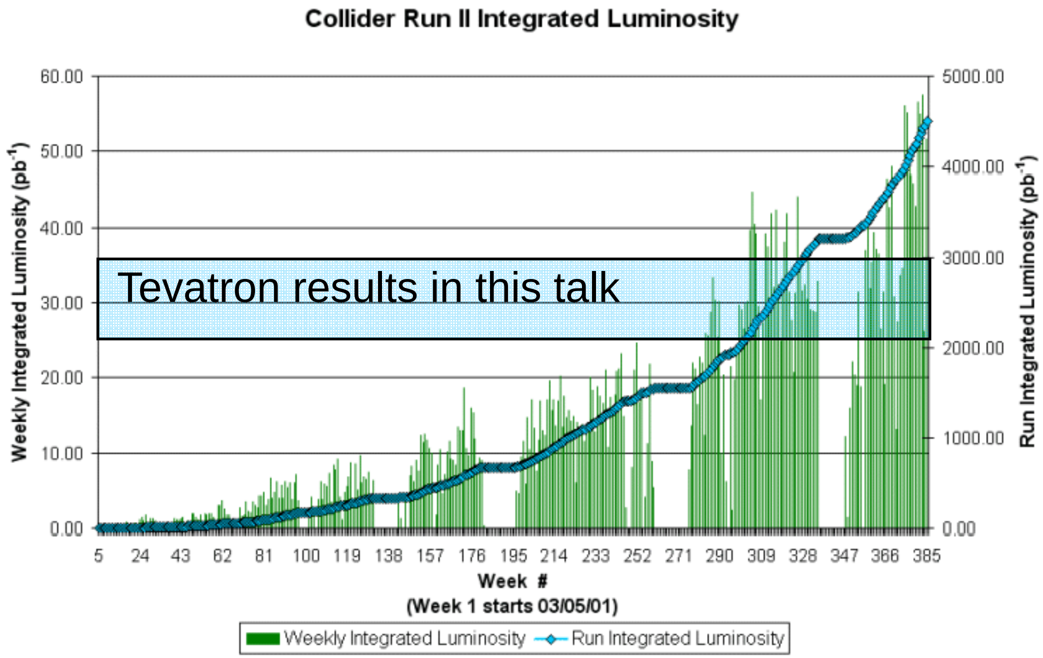

SM: We know where to look

SUSY Higgs looks interesting




# Colliders and Experiments

- Tevatron: 2TeV $p\bar{p}$ collider with two general purpose detectors: CDF, DØ
  - Excellent lepton Id
  - Good to excellent calorimeters for jet and MET reconstruction
  - Excellent silicon detectors for b jet identification
  - Higgs analysis uses full capabilities of the detectors

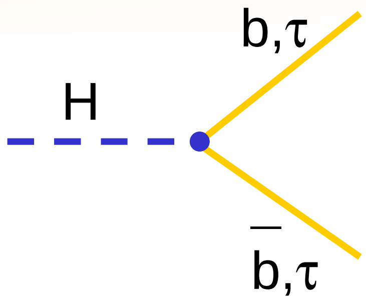



Given a SM Higgs

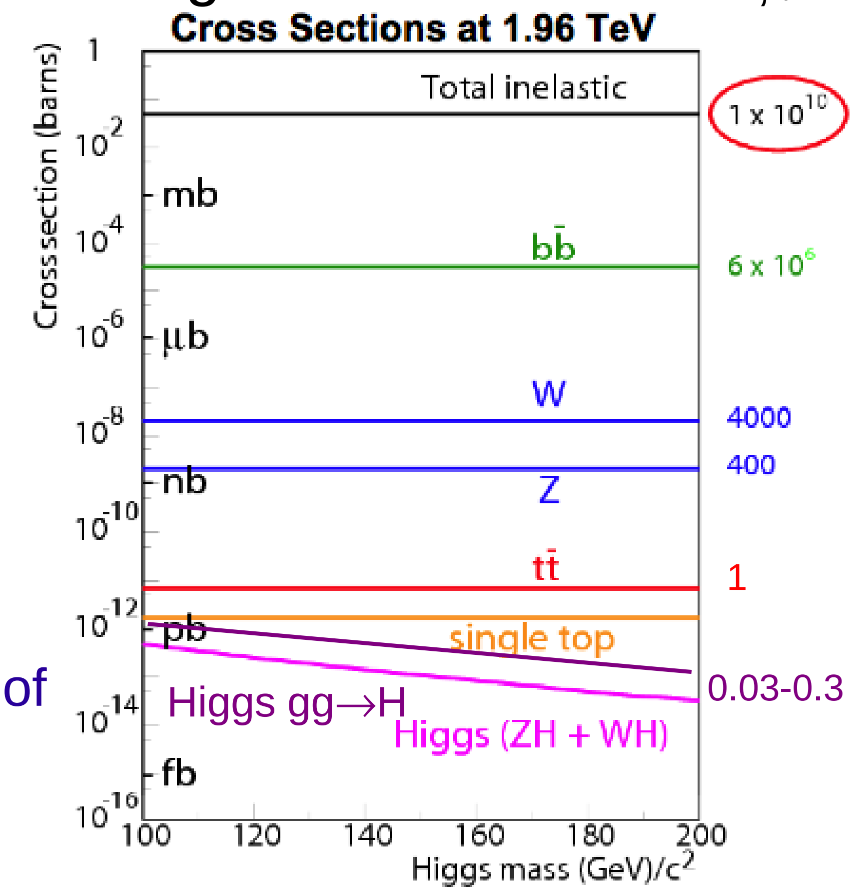
Tevatron: Higgs mass exclusions and perhaps evidence

LHC: Observation over full mass range. Study Higgs properties

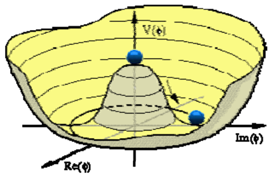
# Tools: Triggers and Leptons




- Higgs decays to heavy particles
- Extract handful of Higgs events from a background 11 orders of magnitudes larger
- Primary triggers: High $p_T$ e and μ
  - Jet+MET triggers: modes with no charged leptons, supplement lepton triggers for gaps in coverage
  - Dedicated τ triggers: track+MET+Cal Energy
- Lepton Id
  - Optimize lepton Id on large samples of W, Z bosons

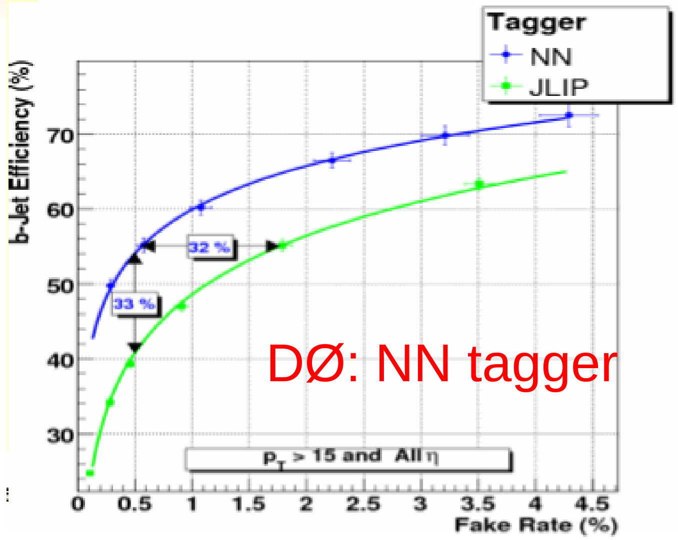


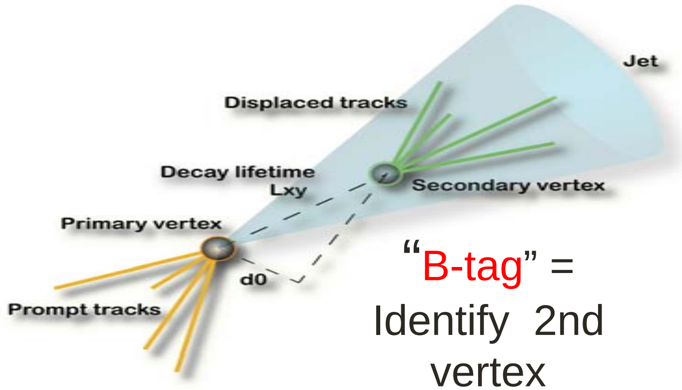

Maximizing Higgs acceptance



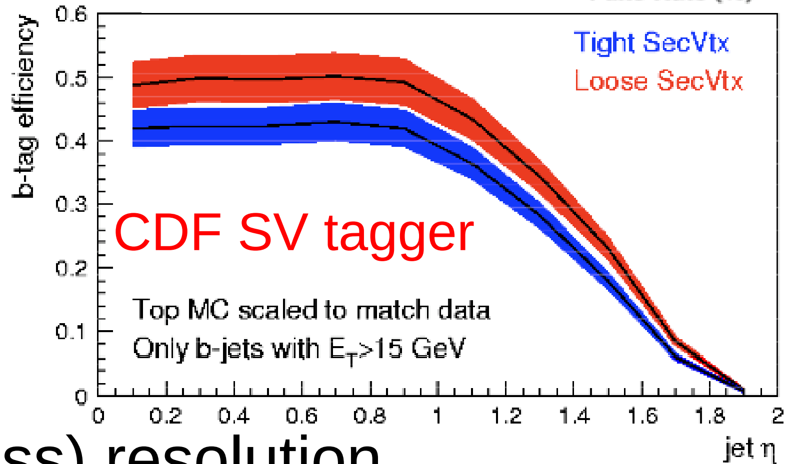
# Tools: b quark jets

- b jet tagging
  - CDF: Secondary Vertex tagger, jet probability tagger, and NN flavor separators
  - DØ: NN tagger with multiple operating points
  - 40-70% Efficient with 0.3-5% mistag rate

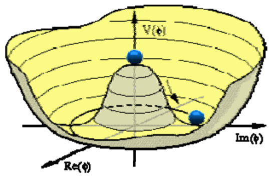



"B-tag" = Identify 2nd vertex

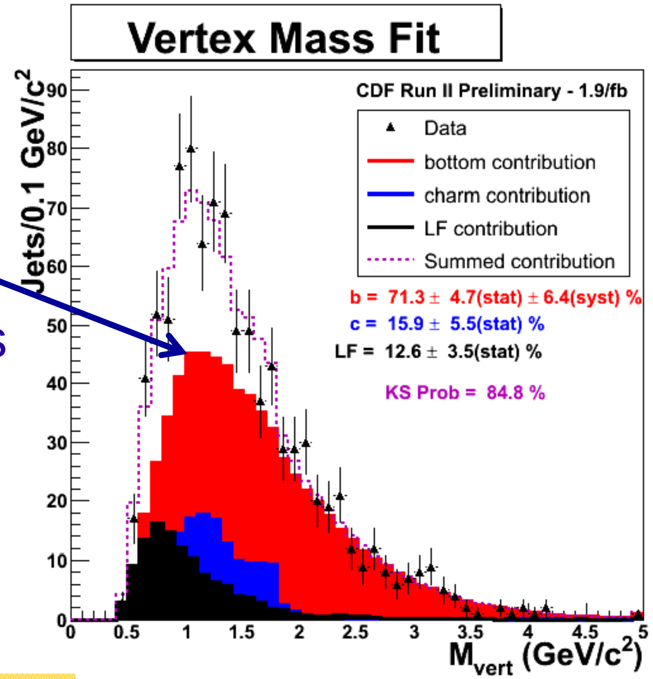



- Improvements in jet energy(dijet mass) resolution
  - Jet energy measurement combining calorimeter and tracking information
  - NN based jet energy corrections, constrained kinematic fits

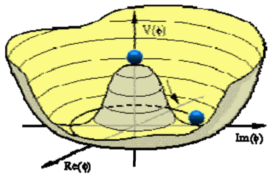


# Tools: Backgrounds

- SM processes create a variety backgrounds to Higgs detection
- Discovery analyses: WW, WZ, ZZ, single top, and even top pairs
- Total and differential cross section measurements
  - QCD dijets, W+c, W+b, Z+b
- Critical to Higgs
  - Some backgrounds cannot be predicted using MC. QCD with fake lepton signatures
  - Constrain background predictions
  - Testing ground for tools and techniques
  - Control regions

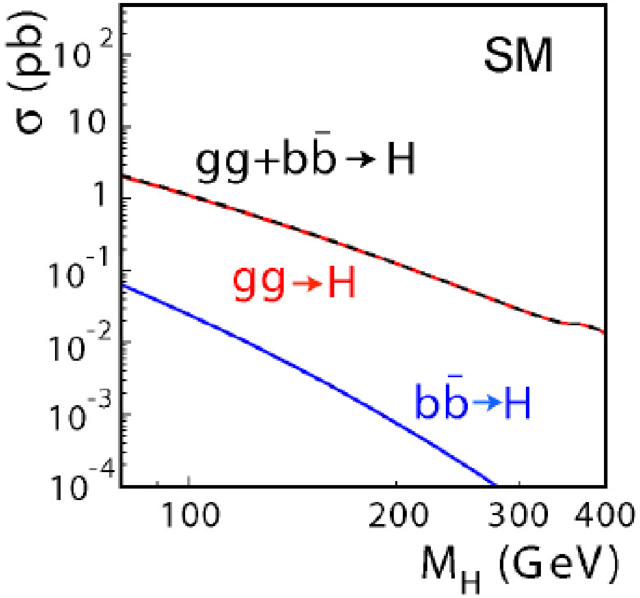


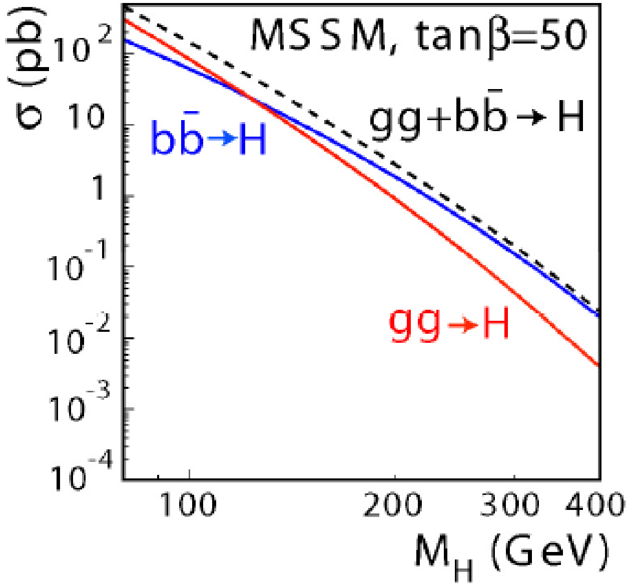

Higgs search built on a foundation of the entire collider physics program

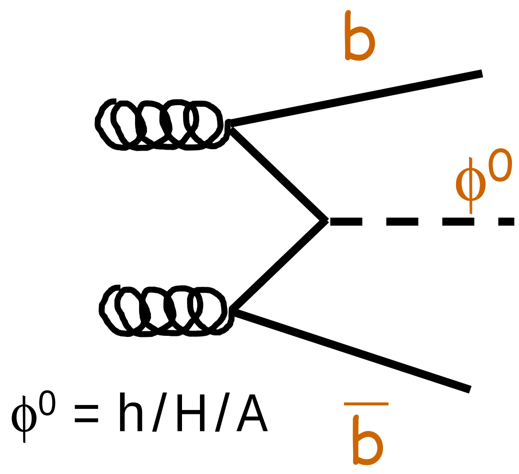


# BSM Higgs

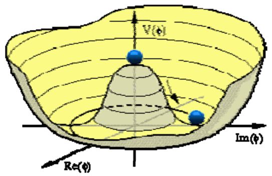
- Many Beyond the Standard Model Higgs Possibilities
  - SUSY Higgs: tanβ enhanced couplings to b quarks and tau leptons
  - h, H, A, $H^+$, $H^-$ or alternative models with doubly charged Higgs
  - Fermiophobic Higgs with enhanced couplings to W bosons or photons



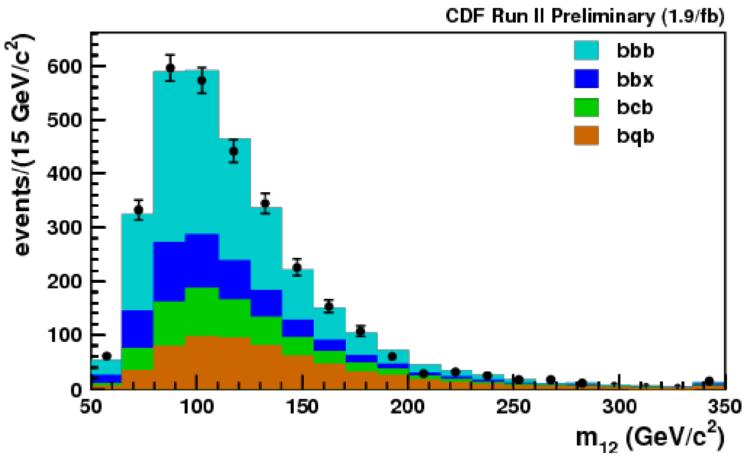



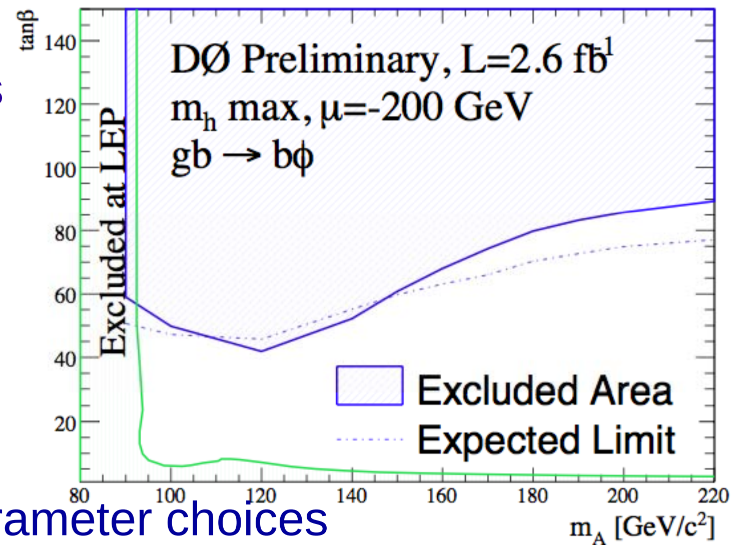

Observable at Tevatron or LHC



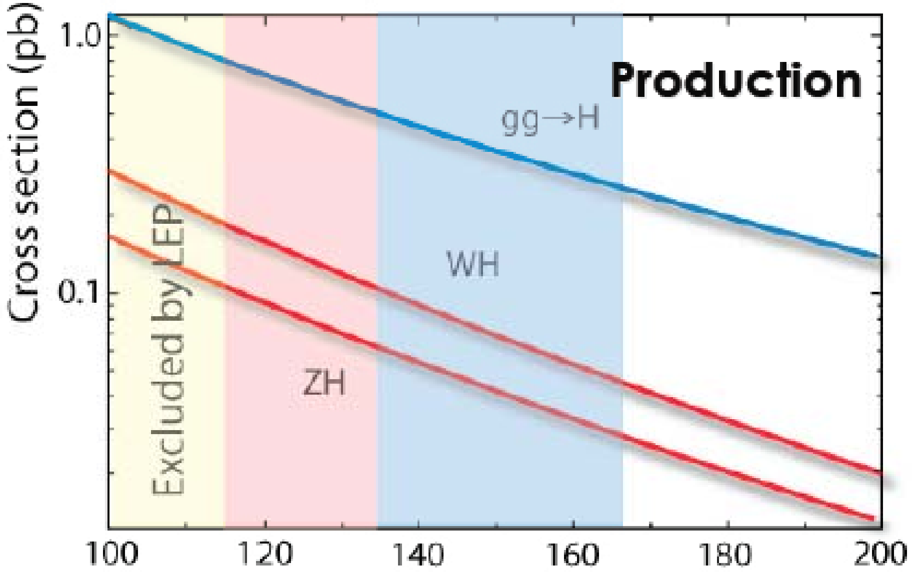
# BSM Higgs: $\phi \to bb$

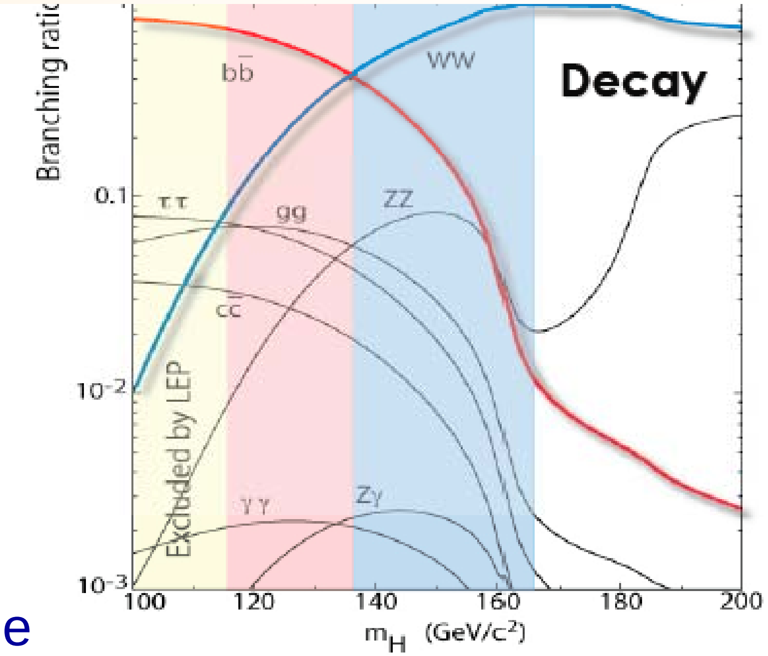
- CDF and DØ 3b channel: $b\phi \to bbb$.
  - Di-b-jet background too large in $\phi \to bb$ channel
  - Search for peak in di-b-jet mass distribution of leading jets
- Key issue: understanding the quark content of the 3 jets
  - CDF: Secondary vertex tagger and vertex mass
  - D0: NN tagger using multiple operating points
  - Simulation/data driven studies of background
- No Evidence for Higgs:
  - Limits $\tan\beta$ vs $m_A$
  - 3b search very sensitive with certain SUSY parameter choices
  - $\phi \to \tau\tau$ and $b\phi \to b\tau\tau$ of similar sensitivity.
  - Six SUSY Higgs searches with sensitivity to $\tan\beta$: 40-50, combination interesting



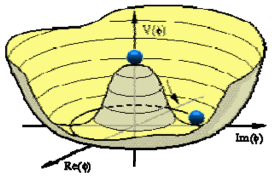



# SM Higgs Production and Decay

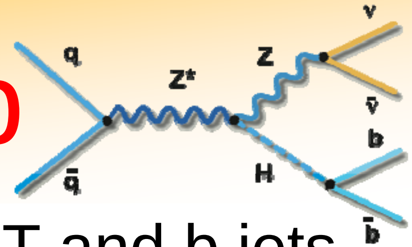


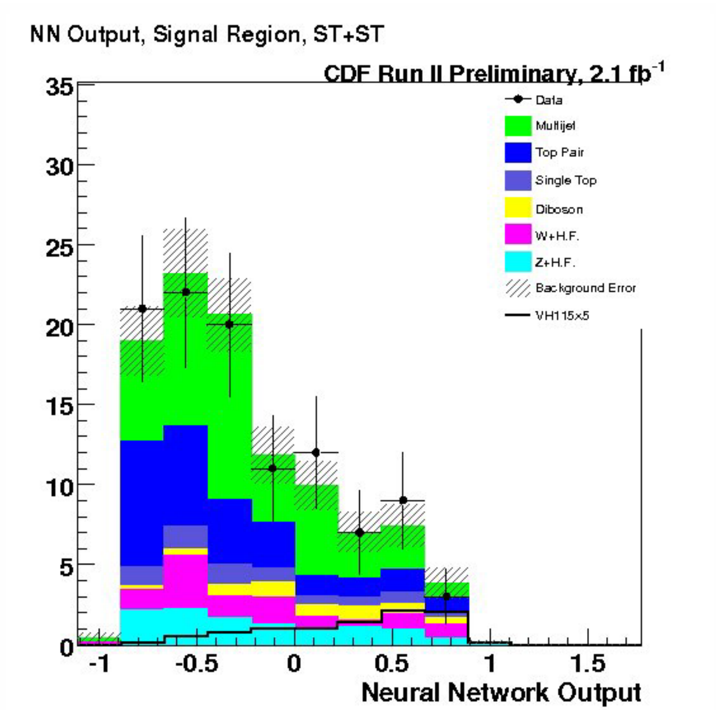

- High mass: H→WW→lνlν decay available
  - Take advantage of large gg→H production cross section, ZZ in progress
- Low Mass: H→bb, QCD bb background overwhelming
  - Use associated production with W or Z for background discrimination
  - WH→lνbb, ZH→ννbb (MET+bb), ZH→llbb
  - Also: VBF Production, VH→qqbb, H→ττ(with 2jets), H→γγ, WH->WWW, ttH



# SM Higgs: VH→METbb




- ZH→ννbb, WH→lνbb(l not detected) - signature: MET and b jets
  - Primary Bkg: QCD b jets and mistagged light quark jets with false MET
  - Key issue: Building a model of the QCD background
    - Shape from 0 and 1 b tagged data samples with tag and mistag rates applied
  - Innovations:




CDF/DØ : Use of track missing $p_T$ to define control regions and suppress backgrounds

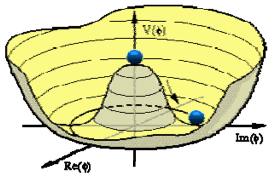
CDF: Uses of H1 Jet Algorithm combining tracking and calorimeter information

3 jet events including W→τμ acceptance

DØ also performs a dedicated W→τμ

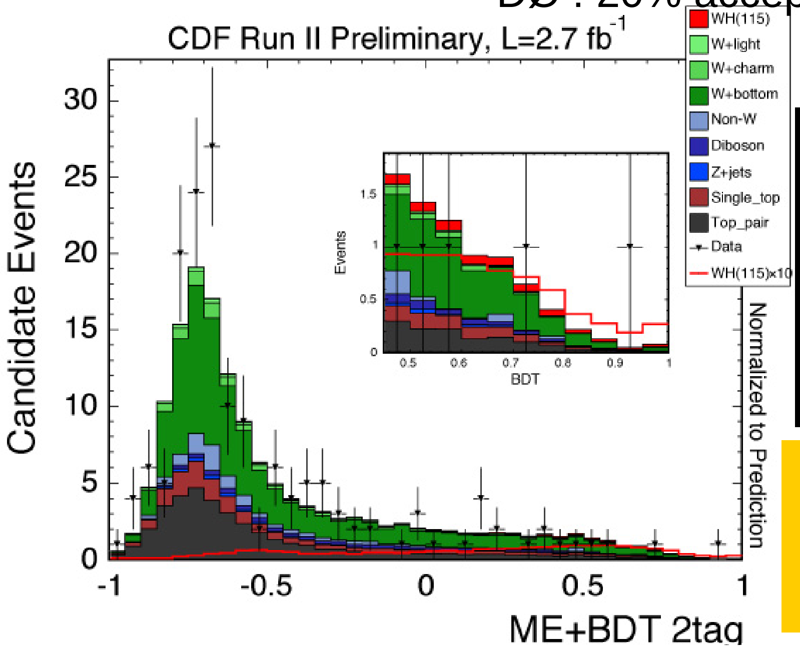
Results at mH = 115GeV: 95%CL Limits/SM

| Analysis | Lum ($fb^{-1}$) | Higgs Events | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF NN, new | 2.1 | 7.6 | 5.5 | 6.6 |
| DØ BDT | 2.1 | 3.7 | 8.4 | 7.5 |



# SM Higgs: WH→lνbb


- WH→lνbb - signature: high pT lepton, MET and b jets
  - Backgrounds: W+bb, W+qq(mistagged), single top, Non W(QCD)
  - Single top: yesterday's discovery is today's background
  - Key issue: estimating W+bb background
    - Shape from MC with normalization from data control regions
  - Innovations: CDF: 20% acceptance from isolated tracks, ME with NN jet corrections
    DØ : 20% acceptance from forward leptons, use 3 jet events



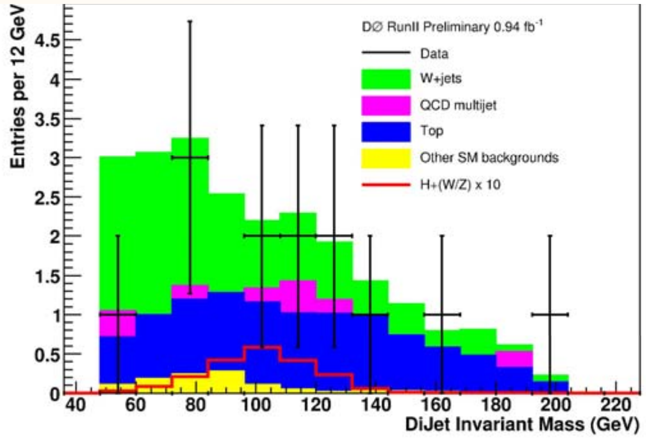

Results at mH = 115GeV: 95%CL Limits/SM

| Analysis | Lum (fb$^{-1}$) | Higgs Events | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF NN+ME+BDT new | 2.7 | 8.4 | 4.8 | 5.8 |
| DØ NN | 1.7 | 7.5 | 8.5 | 9.3 |

**Worlds most sensitive low mass Higgs search - Still a long way to go!**

# Low Mass Higgs Searches

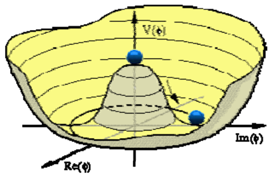
- We gain our full sensitivity by searching for the Higgs in every viable production and decay mode



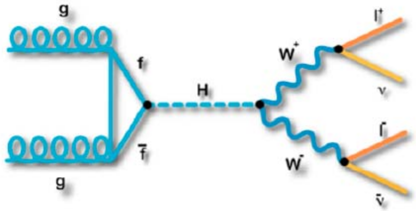

| Analysis | Lum ($fb^{-1}$) | Higgs Events | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF NN: ZH→llbb, new | 2.7 | 2.2 | 9.9 | 7.1 |
| DØ NN,BDT | 2.3 | 2.0 | 12.3 | 11.0 |
| CDF NN: VH→METbb, new | 2.1 | 7.6 | 5.5 | 6.6 |
| DØ BDT | 2.1 | 3.7 | 8.4 | 7.5 |
| CDFComb: WH→lνbb, new | 2.7 | 8.4 | 4.8 | 5.8 |
| DØ NN | 1.7 | 7.5 | 8.5 | 9.3 |

| Analysis: Limits | Exp. Limit | obs. Limit |
|---|---|---|
| CDF WH→WWW | 20 | 25 |
| DØ WH→WWW | 20 | 26 |
| DØ H→γγ | 23 | 31 |
| CDF H→ττ | 25 | 31 |
| CDF VH→qqbb | 37 | 37 |
| DØ WH→τνbb | 42 | 35 |
| DØ ttH | 45 | 64 |

- With all analysis combined we have a sensitivity of <2.5xSM at low mass.
- A new round of analysis, 2x data and 1.5x improvements will bring us to SM sensitivity.

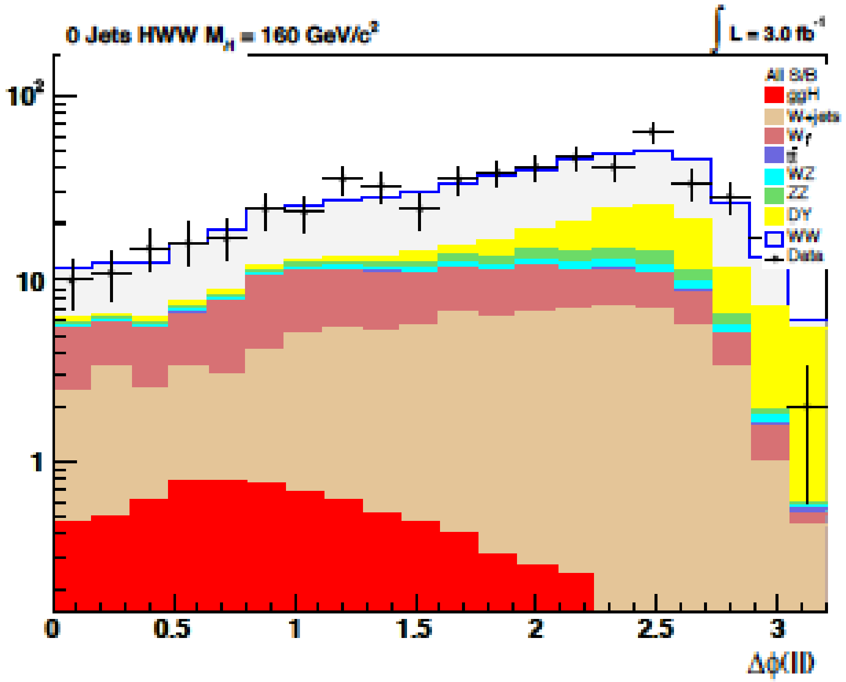


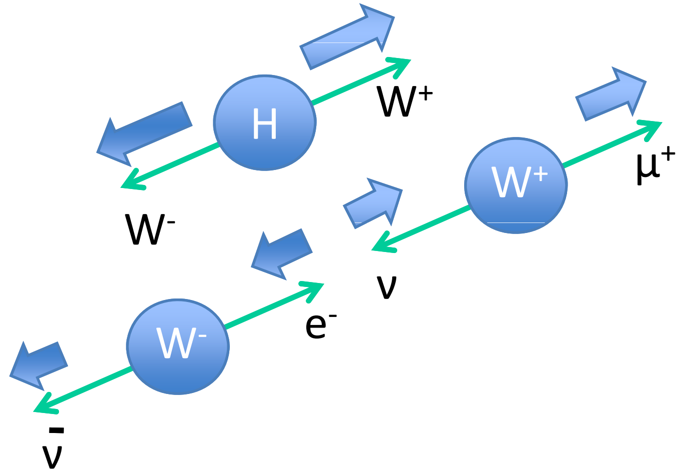
# SM Higgs: H→WW



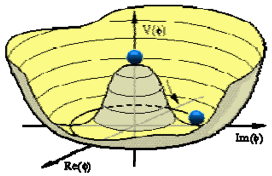
- H→WW→lνlν - signature: Two high $p_T$ leptons and MET
  - Primary backgrounds: WW and top in di-lepton decay channel
  - Key issue: Maximizing lepton acceptance
  - Innovations: CDF/DØ : Inclusion of acceptance from VH(CDF) and VBF

    CDF : Combination of ME and NN approaches, DØ Re-optimized NN



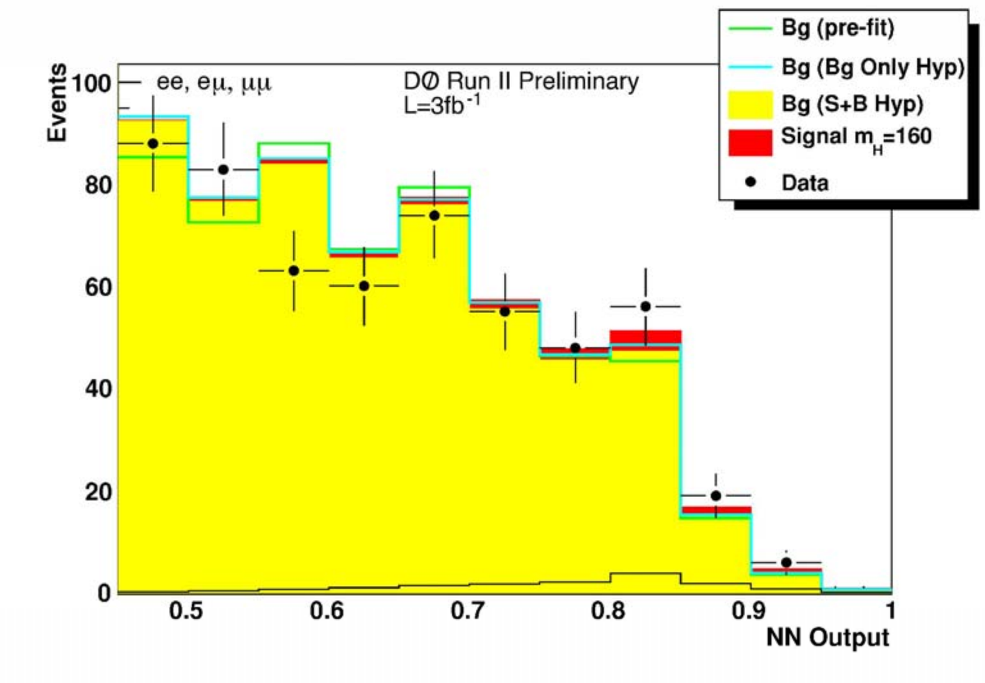



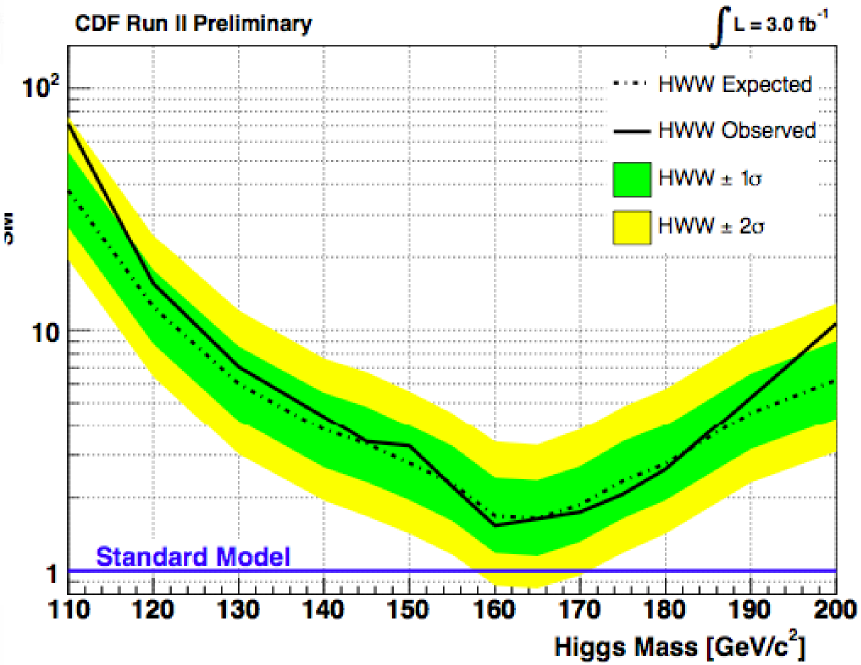

Spin correlation: Charged leptons go in the same direction



# SM Higgs: H→WW

- Most sensitive Higgs search channel at the Tevatron

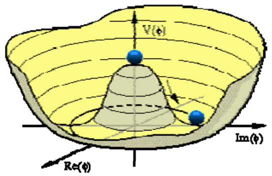



Results at mH = 165GeV : 95%CL Limits/SM

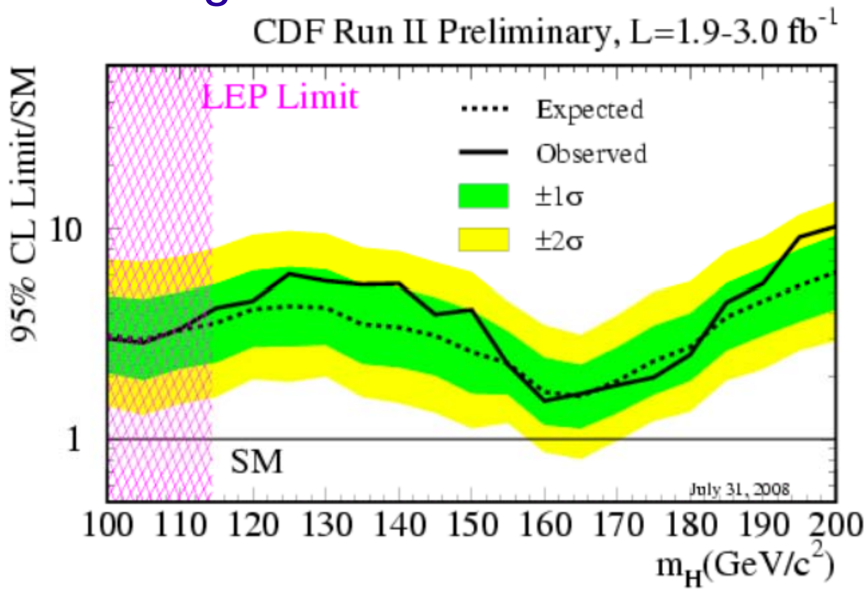
Both experiments Approaching SM sensitivity!

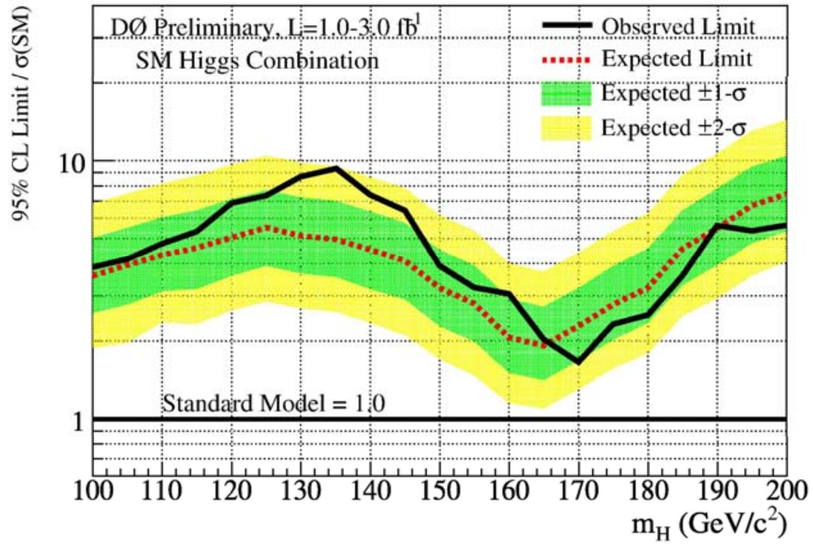
| Analysis | Lum ($fb^{-1}$) | Higgs Events | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF ME+NN | 3.0 | 17.2 | 1.6 | 1.6 |
| DØ NN | 3.0 | 15.6 | 1.9 | 2.0 |




# SM Higgs Combined Limits

- Limits calculation and combination
  - Using Bayesian and CLs methodologies.
  - Incorporate systematic uncertainties using pseudo-experiments (shape and rate included) (correlations taken into account between experiments)
  - Backgrounds can be constrained in the fit

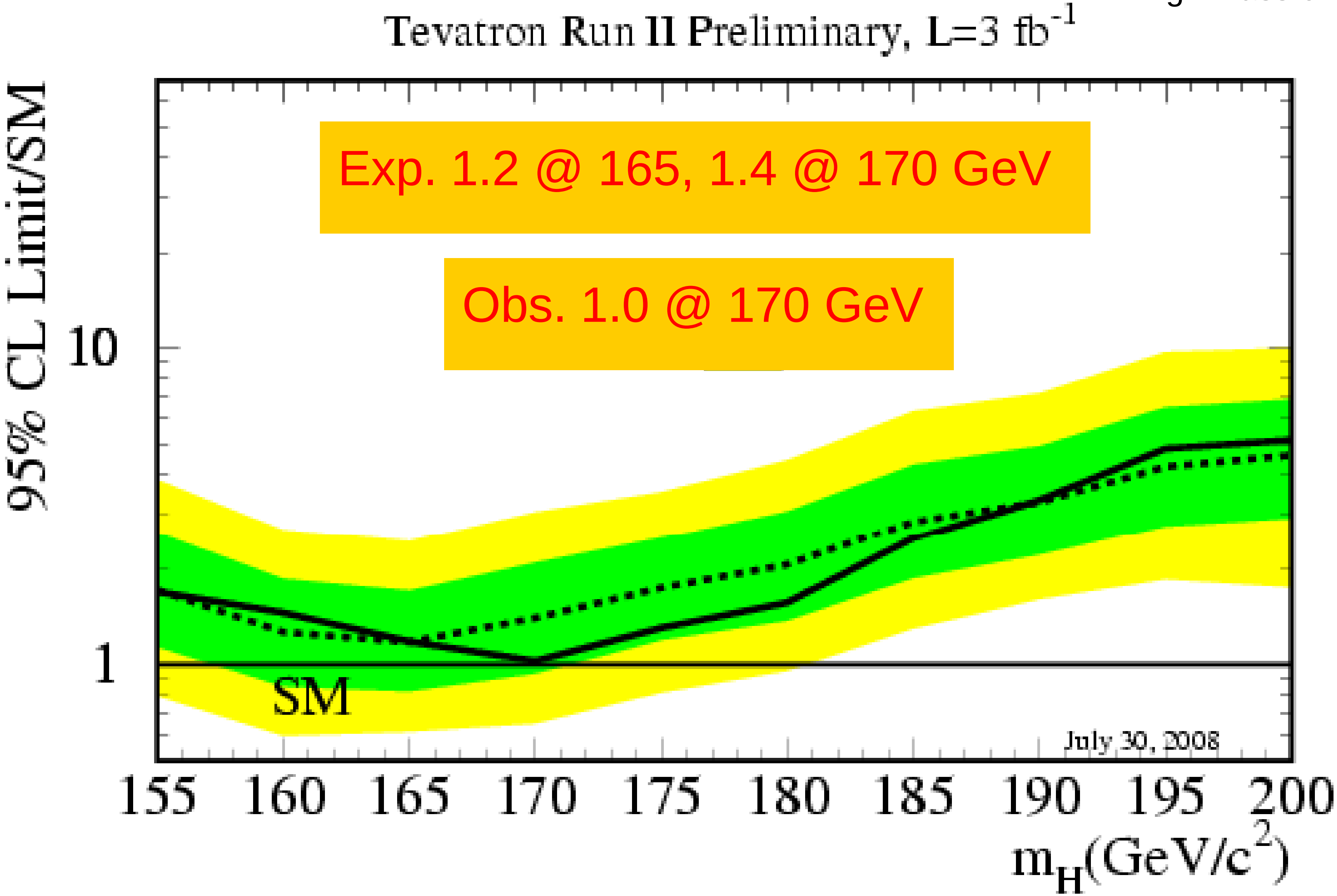



- Low mass combination difficult due to ~75 channels
  - Expected sensitivity of CDF/DØ combined: <2.5xSM @ 115GeV

# SM Higgs Combination

High mass only

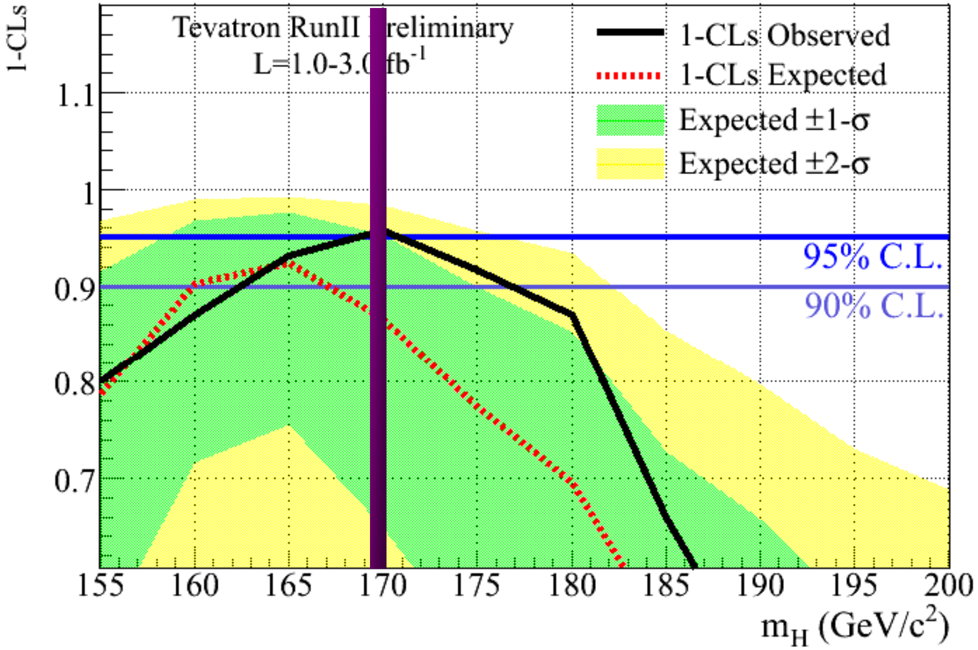



Exp. 1.2 @ 165, 1.4 @ 170 GeV

Obs. 1.0 @ 170 GeV

# SM Higgs Combination

- Result verified using two independent methods(Bayesian/CLs)

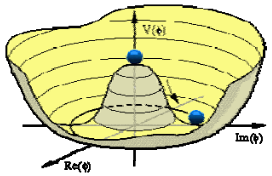



95%CL Limits/SM

| M Higgs(GeV) | 160 | 165 | **170** | 175 |
|---|---|---|---|---|
| Method 1: Exp | 1.3 | 1.2 | 1.4 | 1.7 |
| Method 1: Obs | 1.4 | 1.2 | **1.0** | 1.3 |
| Method 2: Exp | 1.2 | 1.1 | 1.3 | 1.7 |
| Method 2: Obs | 1.3 | 1.1 | **0.95** | 1.2 |

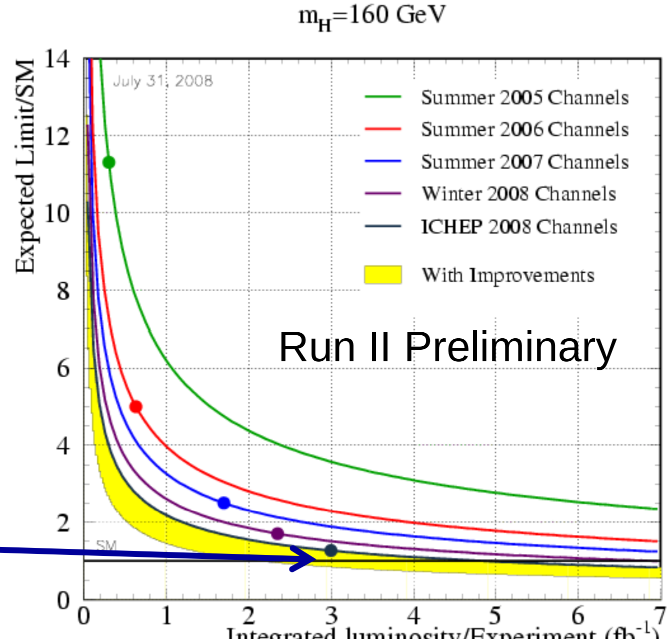
SM Higgs Excluded: $m_H$ = 170 GeV

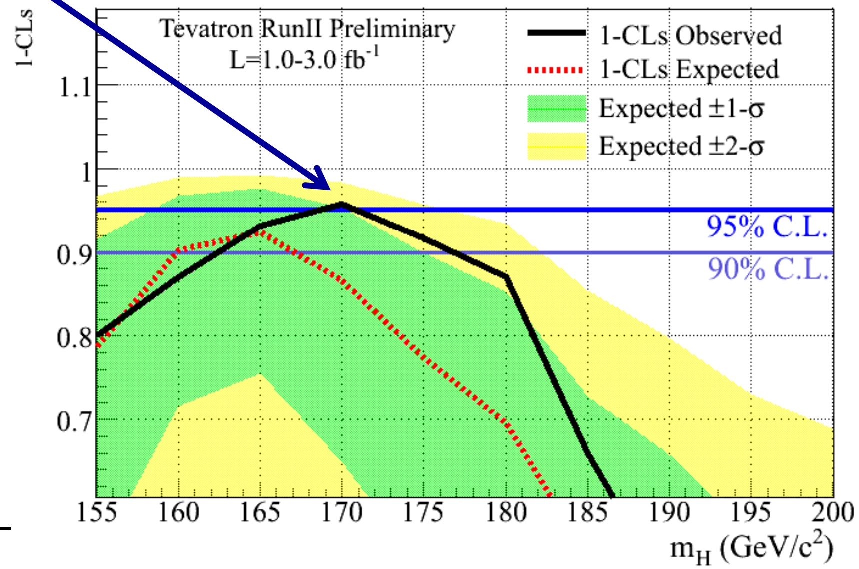
- We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV



# Projections

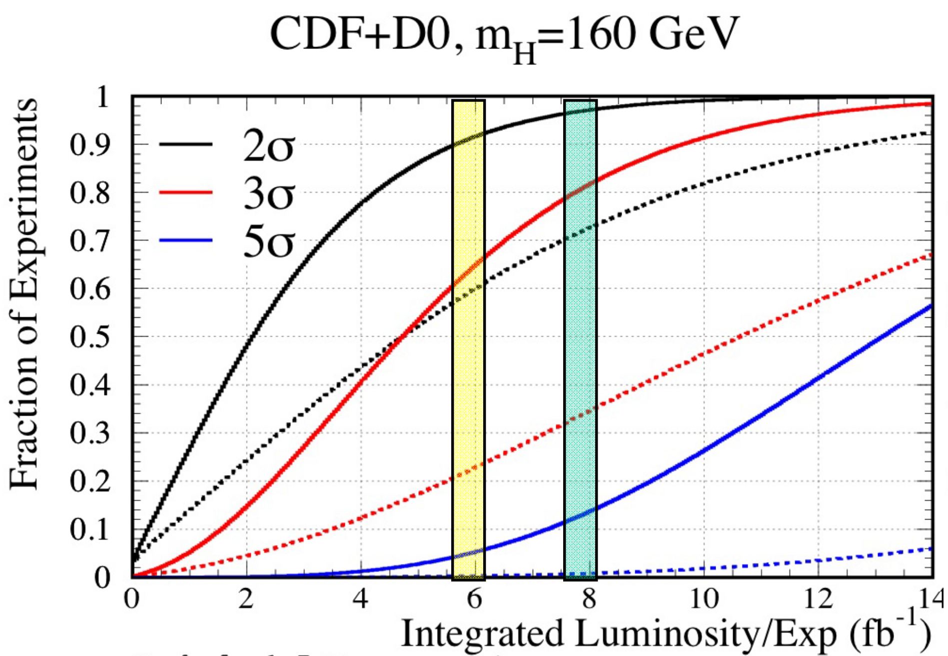
- Goals for increased sensitivity achieved
  - Goals set after 2007 Lepton Photon conference
  - First stage target was sensitivity for possible exclusion at high mass
    A a similar magnitude improvement factor target was set at low mass
  - Second stage goals in progress
  - Expect large exclusion, or evidence, with full Tevatron dataset and further improvements.

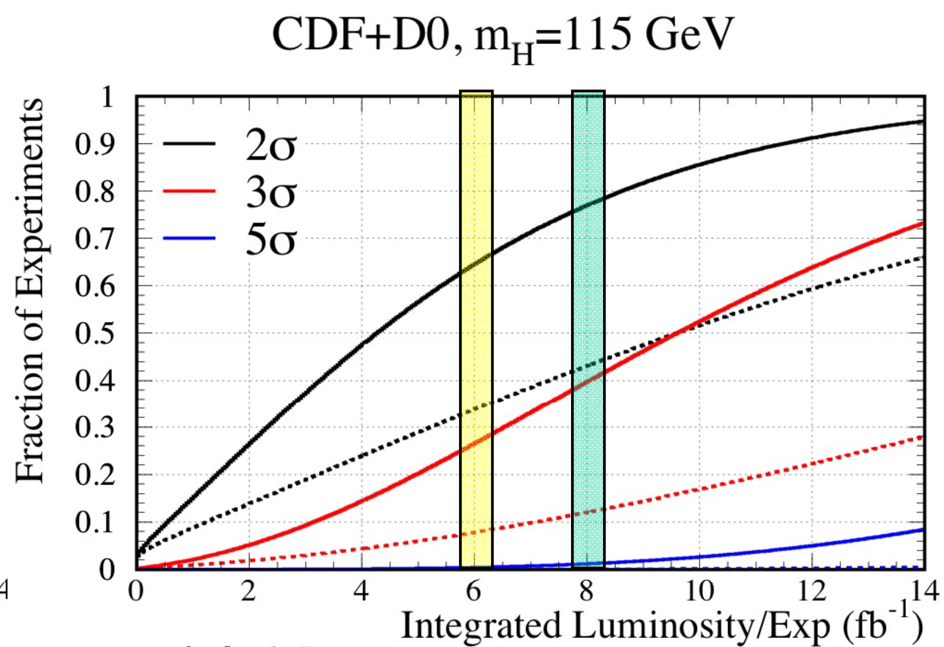


# Discovery

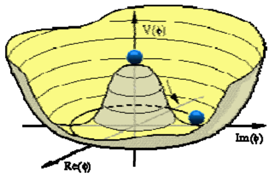
- Discovery projections: chance of 3σ or 5σ discovery
  - Two factors of 1.5 improvements examined relative to summer Lepton Photon 2007 analyses.
  - First 1.5 factor achieved for summer ICHEP 2008 analysis
  - Resulted in exclusion at $m_H$ = 170 GeV.




Dashed: 1.5*Improvement
Solid: 2.25*Improvement

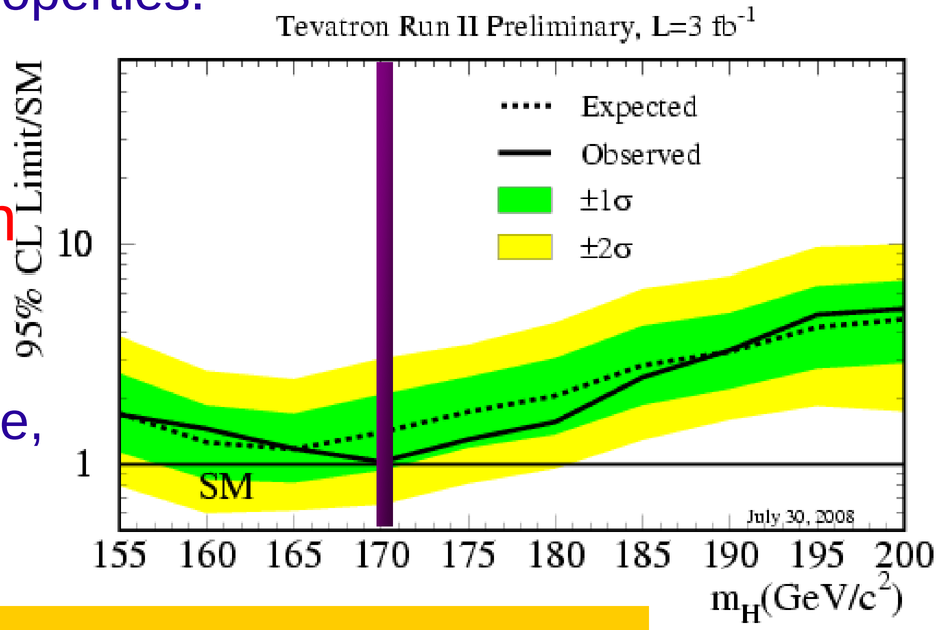
Dashed: 1.5*Improvement
Solid: 2.25*Improvement



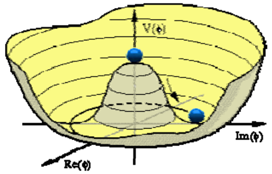

# Conclusions

- The Higgs boson search is in its most exciting era ever
  - The Tevatron experiments have achieved sensitivity to the SM Higgs boson production cross section
  - With the advent of the LHC we will have the potential to observe the SM Higgs boson and study it's properties.

- We exclude at 95% C.L. the production of a SM Higgs boson of 170 GeV
  - Expect large exclusion, or evidence, with full Tevatron data set and improvements



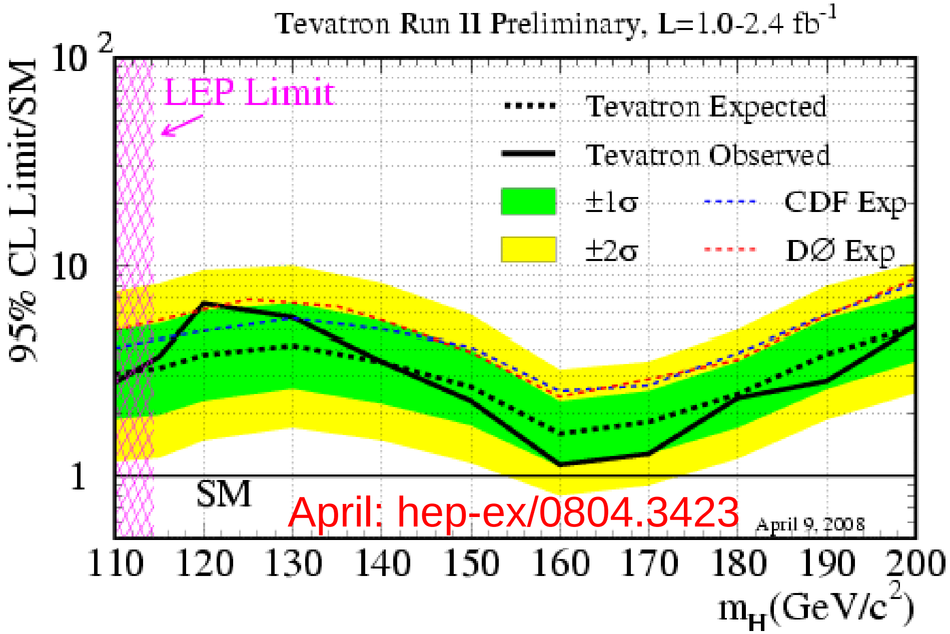

SM Higgs Excluded: $m_H$ = 170 GeV




# Backup

# SM Higgs Combined Limits

- Limits calculating and combination
  - Using Bayesian and CLs methodologies.
  - Incorporate systematic uncertainties using pseudo-experiments (shape and rate included) (correlations taken into account between experiments)
  - Backgrounds can be constrained in the fit
- Winter conferences combination



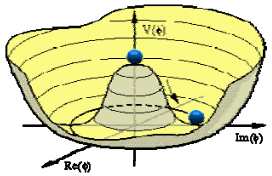
# H→WW Some Details

- Used NNLL cross section: S. Catani, D. de Florian, M. Grazzini, and P. Nason, JHEP 07, 028 (2003), hep-ph/0306211 with CTEQ5L
  - Include VH and VBF Higgs production
  - Include two loop EW diagrams: U. Aglietta, B. Bonciani, G. Degrassi, and A. Vivini (2006), hep-ph/0610033.
  - Kinematics HNNL0 S. Catani and M. Grazzini, Phys. Rev. Lett. 98, 222002 (2007), hep-ph/0703012. JHEP 0802, 043 (2008), hep-ph/0801.3232 .
- Work in progress to update to state of the art predictions
  - Latest gluon PDF, full treatment of EW contribution, better treatment of quark masses C Anastasiou, R Boughezal, F Petriello, hep-ph/0811.3458
- Example systematic table
  - Rates and shapes considered
  - Shape: Scale variations, ISR, gluon pdf, Pythia vs. NNL0 kinematics, jet energy scale: for signal and backgrounds. Included in limit setting if significant.

CDF: $H \to WW \to \ell^{\pm}\ell'^{\mp} + 0$ Jets Analysis

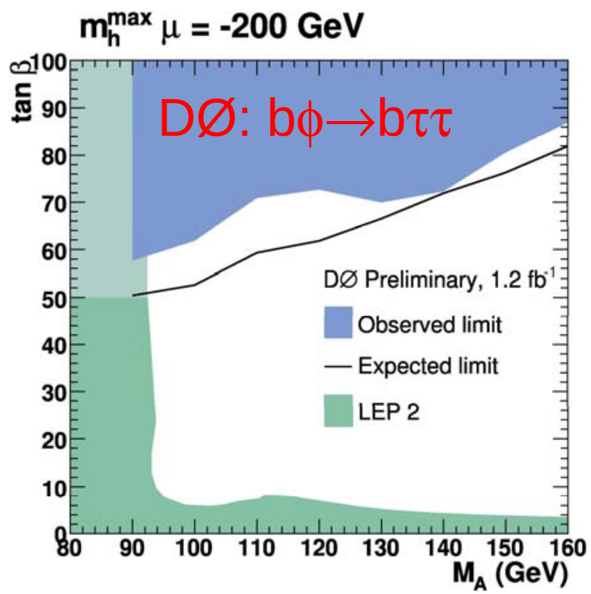
| Uncertainty Source | $WW$ | $WZ$ | $ZZ$ | $t\bar{t}$ | DY | $W\gamma$ | $W$+jet | $gg \to H$ | $WH$ | $ZH$ | VBF |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cross Section** | | | | | | | | | | | |
| Scale | | | | | | | | 10.9% | | | |
| PDF Model | | | | | | | | 5.1% | | | |
| Total | *10.0%* | *10.0%* | *10.0%* | 15.0% | 5.0% | 10.0% | | 12.0% | | | |
| **Acceptance** | | | | | | | | | | | |
| Scale (leptons) | | | | | | | | 2.5% | | | |
| Scale (jets) | | | | | | | | 4.6% | | | |
| PDF Model (leptons) | 1.9% | 2.7% | 2.7% | 2.1% | 4.1% | 2.2% | | 1.5% | | | |
| PDF Model (jets) | | | | | | | | 0.9% | | | |
| Higher-order Diagrams | **5.5%** | **10.0%** | **10.0%** | 10.0% | **5.0%** | **10.0%** | | | | | |
| Missing Et Modeling | 1.0% | 1.0% | 1.0% | 1.0% | 20.0% | 1.0% | | 1.0% | | | |
| Conversion Modeling | | | | | | 20.0% | | | | | |
| Jet Fake Rates | | | | | | | | | | | |
| (Low S/B) | | | | | | | 21.5% | | | | |
| (High S/B) | | | | | | | 27.7% | | | | |
| MC Run Dependence | 3.9% | | | 4.5% | | 4.5% | | 3.7% | | | |
| Lepton ID Efficiencies | 2.0% | 1.7% | 2.0% | 2.0% | 1.9% | 1.4% | | 1.9% | | | |
| Trigger Efficiencies | 2.1% | 2.1% | 2.1% | 2.0% | 3.4% | 7.0% | | 3.3% | | | |
| **Luminosity** | 5.9% | 5.9% | 5.9% | 5.9% | 5.9% | 5.9% | | 5.9% | | | |

Treatment developed jointly by CDF and DØ

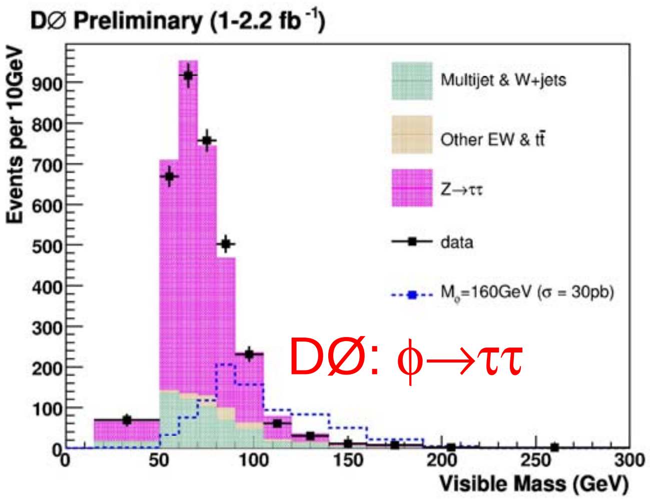


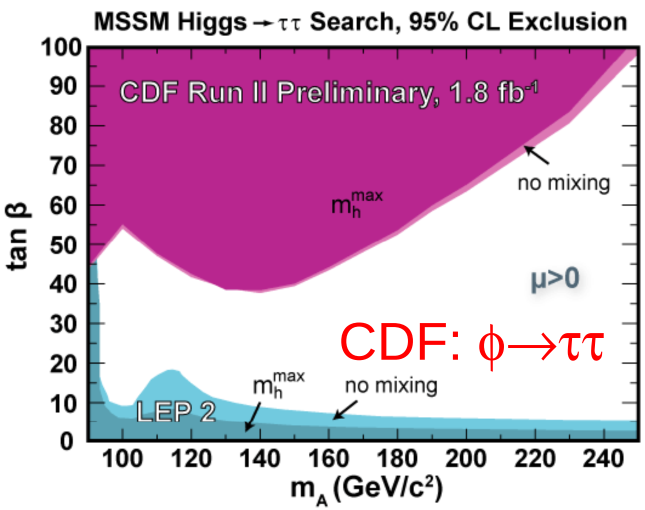

# BSM Higgs: $\phi\rightarrow\tau\tau$

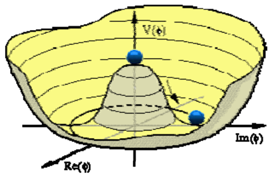
- CDF and DØ $\phi\rightarrow\tau\tau$ channel
  - $\tau\tau$ pure enough for direct production search
  - DØ adds associated production search: $b\phi\rightarrow b\tau\tau$
- Key issue: understanding $\tau$ Id efficiency
  - Large calibration samples: W for Id optimization and Z for confirmation of Id efficiency




- No Evidence for SUSY Higgs
  - Limits: tanβ vs $m_A$
  - $\phi\rightarrow\tau\tau$ generally sensitive at high tanβ

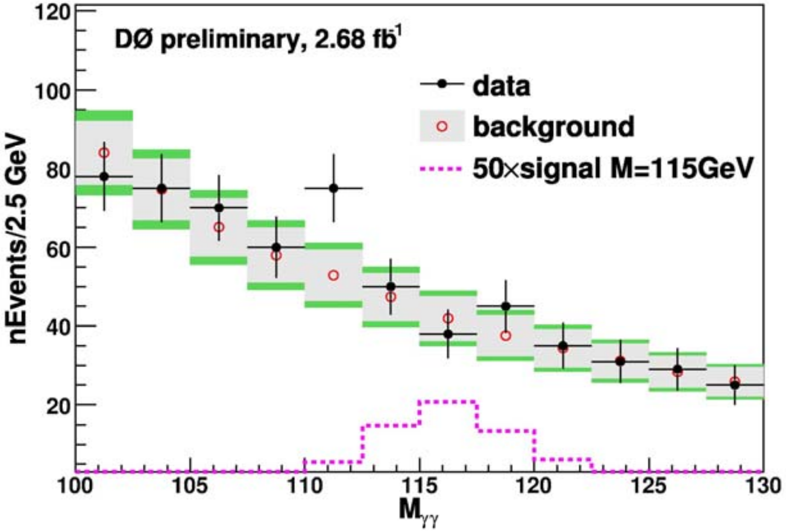


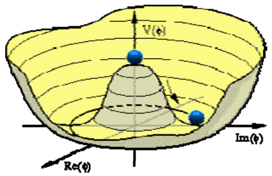



# BSM/SM Higgs Searches

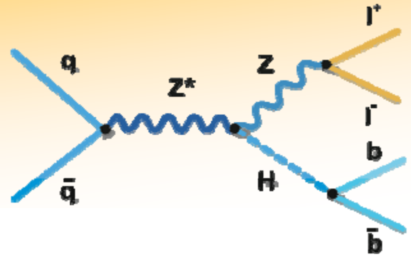
- H→γγ
  - At lower mass large BR(H→γγ) ~10% for Fermiophobic Higgs
  - SM search also sensitive at low mass
  - Key issue: understanding QCD background: uses excellent calorimeter
  - CDF - has not yet calculated SM limits
- WH→WWW
  - Strong sensitivity as both a SM and a fermiophobic Higgs search
  - Same sign dilepton signature
  - SM Search sensitive at high and medium mass




| Analysis: Limits at 160 and 115GeV | Exp. Limit | obs. Limit |
|---|---|---|
| DØ H→γγ | 23 | 31 |
| CDF WH→WWW new | 20 | 25 |
| DØ WH→WWW | 20 | 26 |




# SM Higgs: ZH→llbb

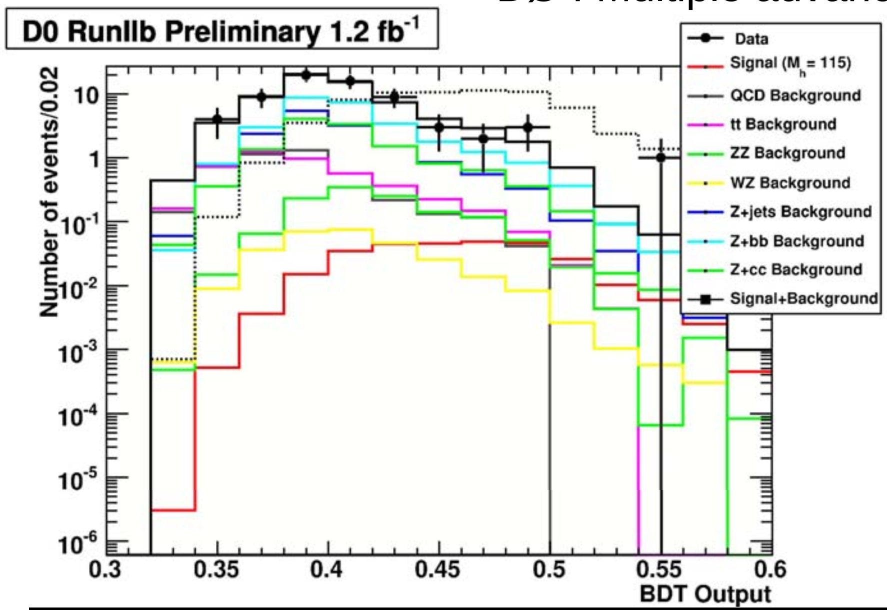



- ZH→llbb - signature: two leptons and b jets
  - Primary background: Z + b jets
  - Key issue: Maximize lepton acceptance and b tagging efficiency
  - Innovations: CDF/DØ: Extensive use of loose b tagging

    CDF: Use of isolated tracks and calorimeter only electrons,

    MET used to correct jet energies, ME analysis

    DØ : Multiple advanced discriminates, NN and BDT

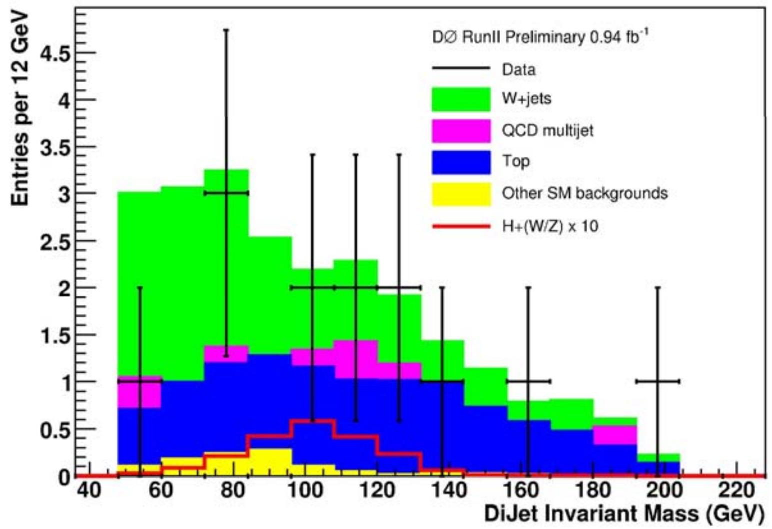



Results at mH = 115GeV: 95%CL Limits/SM

| Analysis | Lum ($fb^{-1}$) | Higgs Events | Exp. Limit | Obs. Limit |
|---|---|---|---|---|
| CDF NN new | 2.7 | 2.2 | 9.9 | 7.1 |
| CDF ME(120) | 2.0 | 1.4 | 15.2 | 11.8 |
| DØ NN,BDT | 2.3 | 2.0 | 12.3 | 11.0 |

# Other SM Higgs Searches

- CDF and DØ are performing searches in every viable mode
  - CDF: VH→qqbb: 4 Jet mode.
  - CDF: H→ττ with 2jets
    - Simultaneous search for Higgs in VH, VBF and gg→H production modes
    - Interesting benchmark for LHC
  - DØ: WH→τνbb
    - Dedicated search with hadronic τ decays
  - DØ: ttH
    - Leverages strong coupling to top




| Analysis: Limits at 160 and 115GeV | Exp. Limit | obs. Limit |
|---|---|---|
| CDF VH→qqbb | 37 | 37 |
| CDF H→ττ | 25 | 31 |
| DØ WH→τνbb | 42 | 35 |
| DØ ttH | 45 | 64 |