

Higgs Physics from the Experimental Viewpoint

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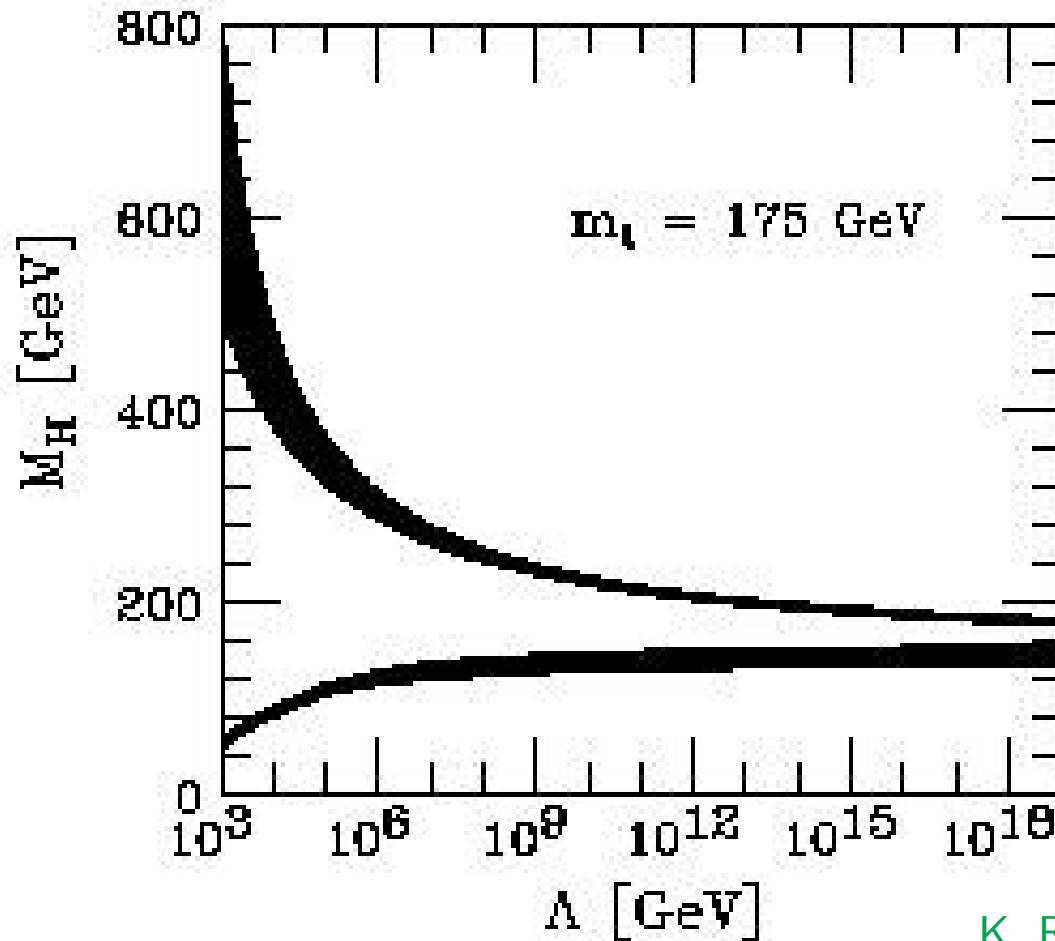
- Introduction
- Current Experimental Limits
- Higgs Sensitivity at the Tevatron
- Recent Higgs Results at the Tevatron
- Future Prospects at LHC and beyond
- Conclusions



Introduction

- Standard Model is an effective theory of particle physics at the electroweak scale.
- Precision tests of electroweak theory show no signs of deviation, with extraordinary accuracy.
- SM predicts the existence of Higgs boson and requires “new physics” to stabilize the Higgs mass (**the hierarchy problem**).
- Possible source of new physics
 - SUSY and its variants
 - Extra dimensions
 - Little Higgs ($m_h \approx m_t$, t' and other Higgs at TeV scale)
 - ...
- Need experimental evidences to point the way

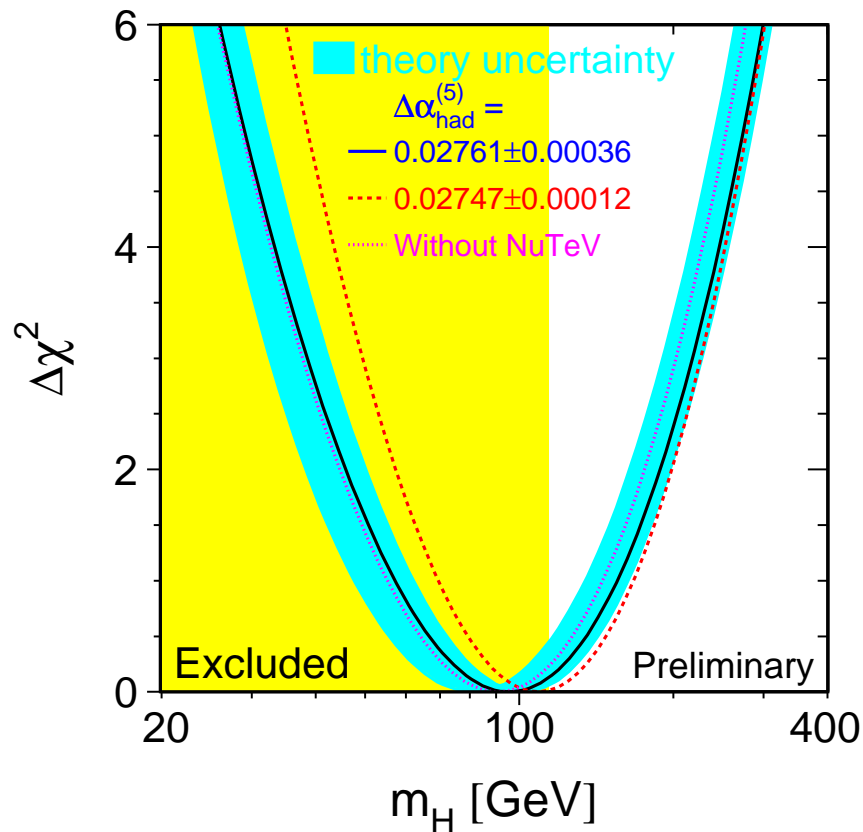
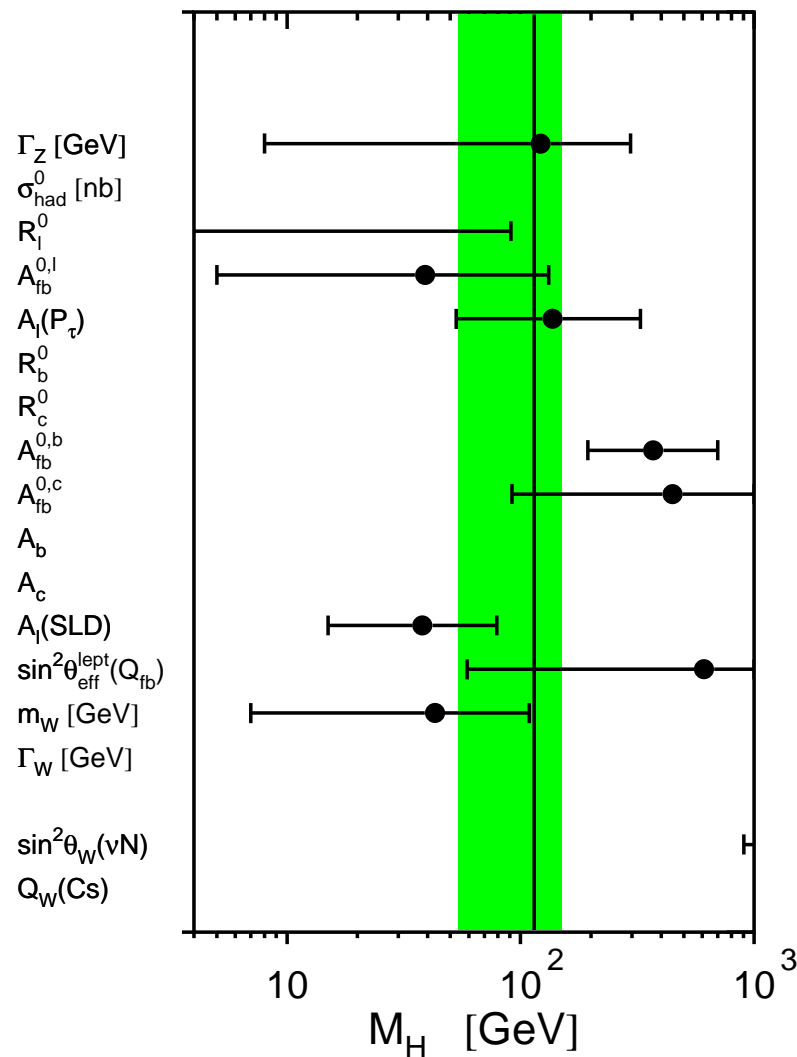
Theoretical Bounds



K. Riesselmann hep-ph/9711456

- Theoretical Higgs Mass Bounds imposed by the structure of gauge coupling ($\lambda = M_h^2/(2v^2)$)
- Triviality: Finite coupling gives an upper bound.
- Vacuum Stability: Requirements of Spontaneous Symmetry Breaking requires a lower bound.

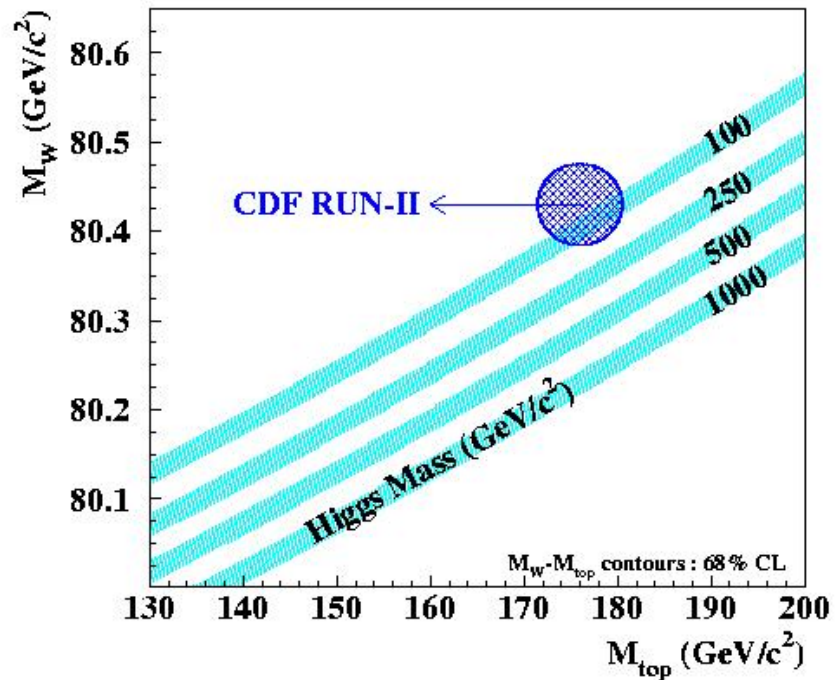
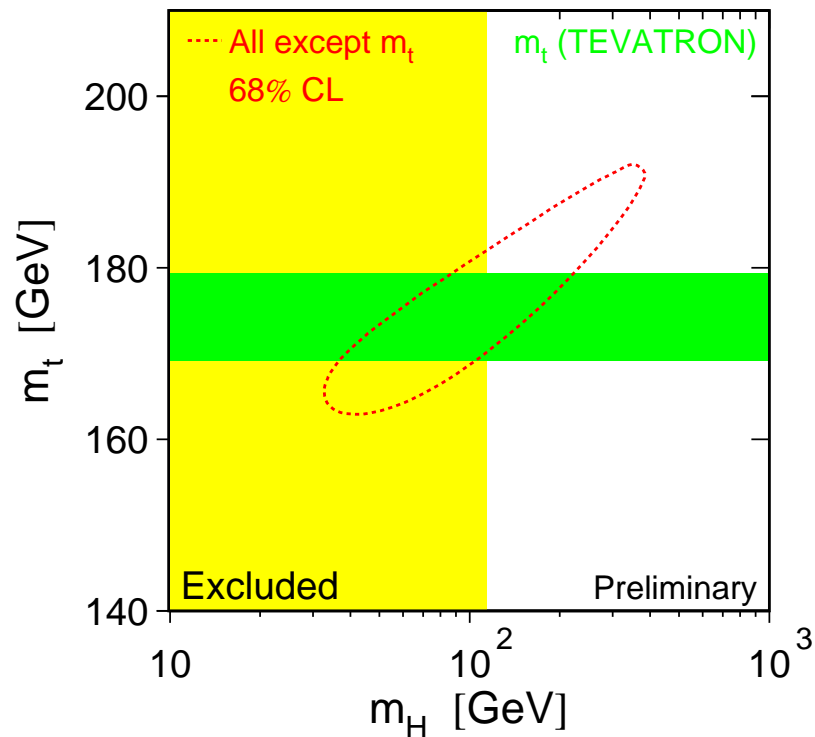
Precision measurements predict light m_h



- $m_h = 96_{-38}^{+60} \text{ GeV}$

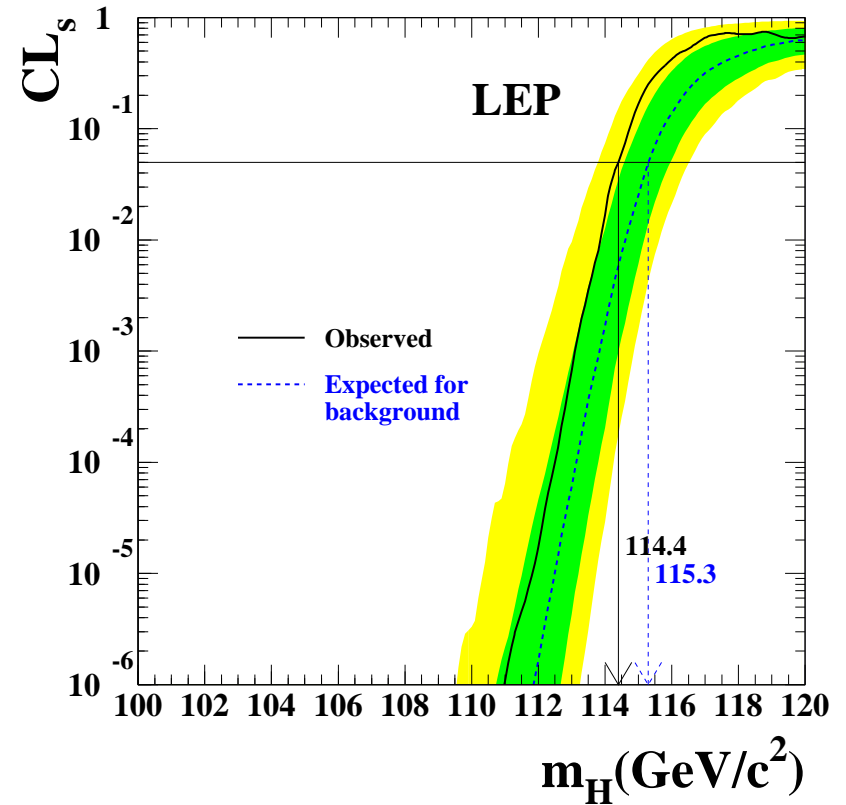
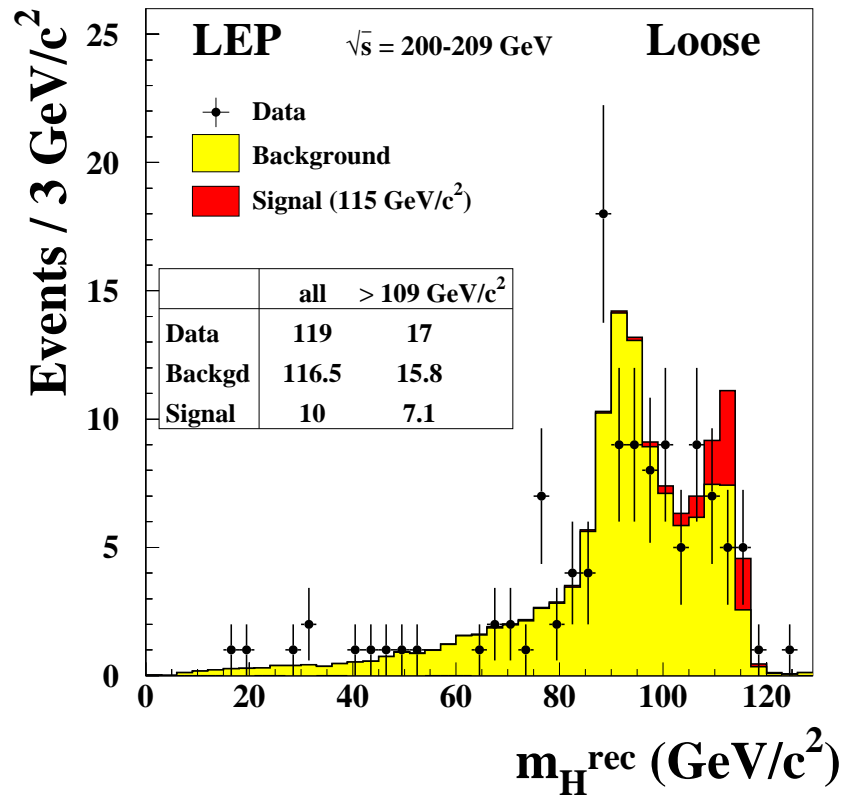
- $m_h \leq 219 \text{ GeV at 95\% C.L.}$

Measurement of Top Mass Crucial...



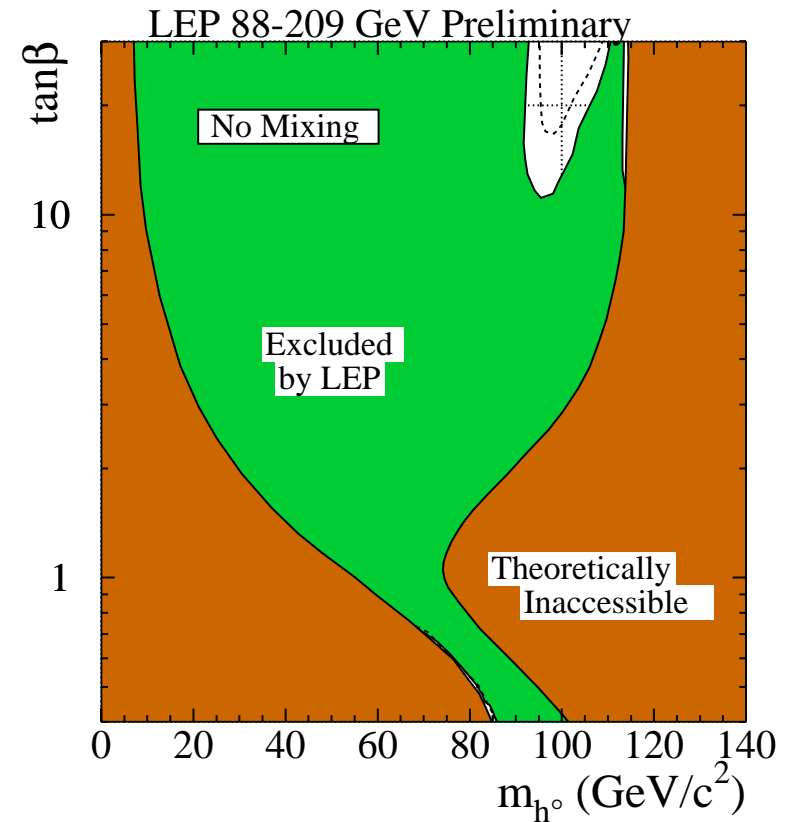
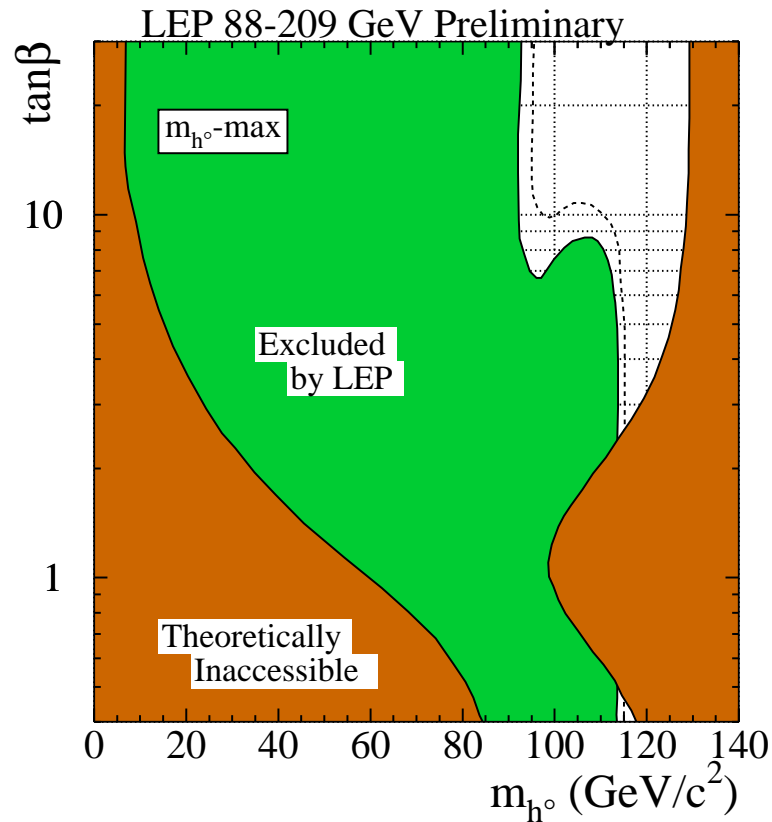
- EWK fits predicted correct M_{top} in the past
- With 2 fb^{-1} , CDF/D0 will measure $\delta M_{top} = 3 \text{ GeV}$ and $\delta M_W = 25 \text{ MeV}$.
- Increasing M_{top} by 5 GeV increases M_h limit by 35 GeV.

SM Higgs Search at LEP II



- Signal: $e^+e^- \rightarrow Zh, h \rightarrow b\bar{b}$
- Main Backgrounds: $e^+e^- \rightarrow ZZ$
- LEP excludes $m_h \leq 114.4\text{ GeV}$ at 95% C.L.

MSSM Higgs Search at LEP II

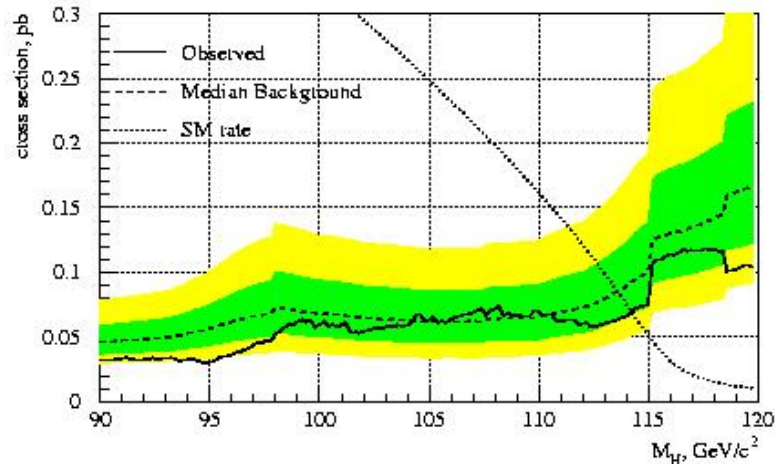


- No evidence yet
- LEP excludes MSSM $m_h < 91.0$ GeV at 95% C.L.

Other Higgs Searches at LEP II

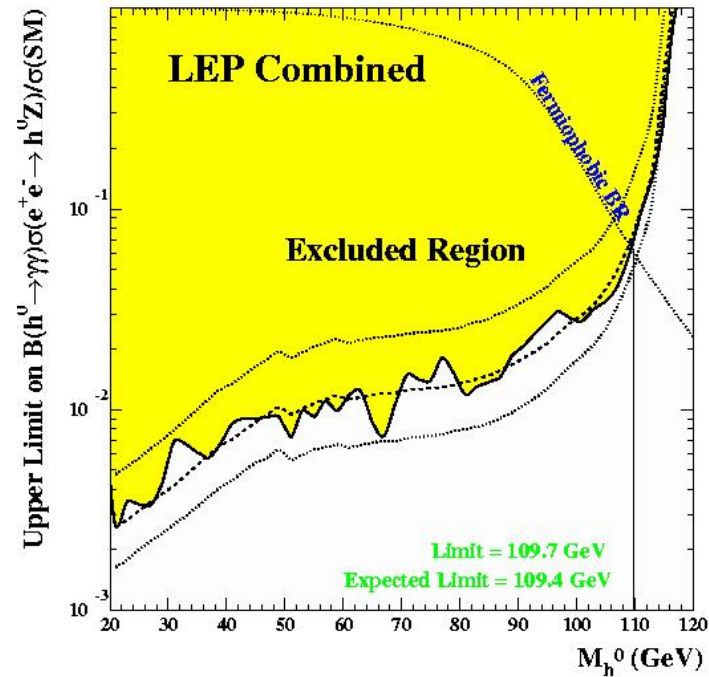
Invisible Higgs Search

- $h \rightarrow \chi^0 \chi^0$ can dominate for some MSSM
- no significant excess of events observed
- set $m_h > 114.4$ at 95% CL for $B(h \rightarrow \chi^0 \chi^0) = 100\%$



Fermiophobic Higgs Search

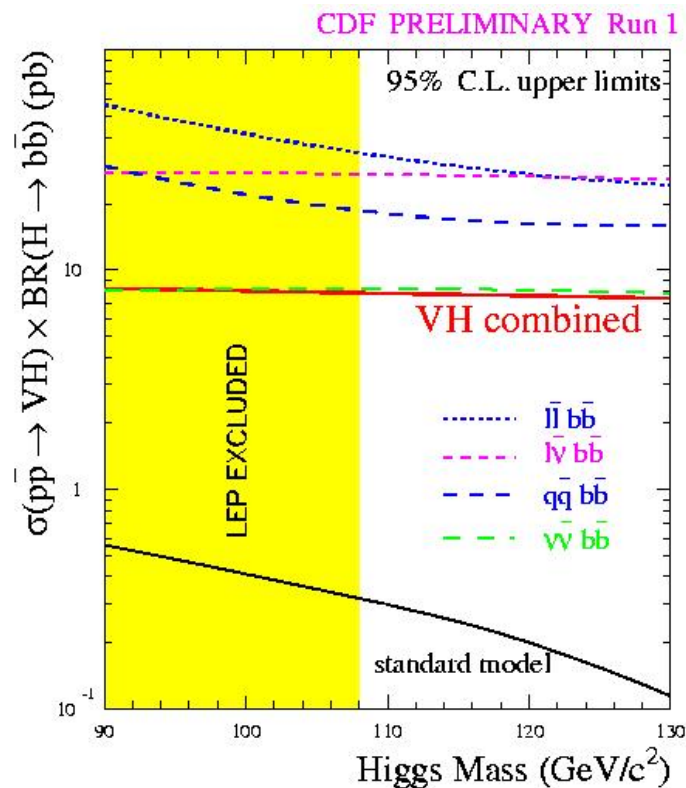
- $h \rightarrow \gamma\gamma$ can dominate in some 2 Higgs doublet models
- no significant excess of events observed
- set $m_h > 108.2$ GeV at 95% C.L.



Higgs Search at Tevatron (Run1)

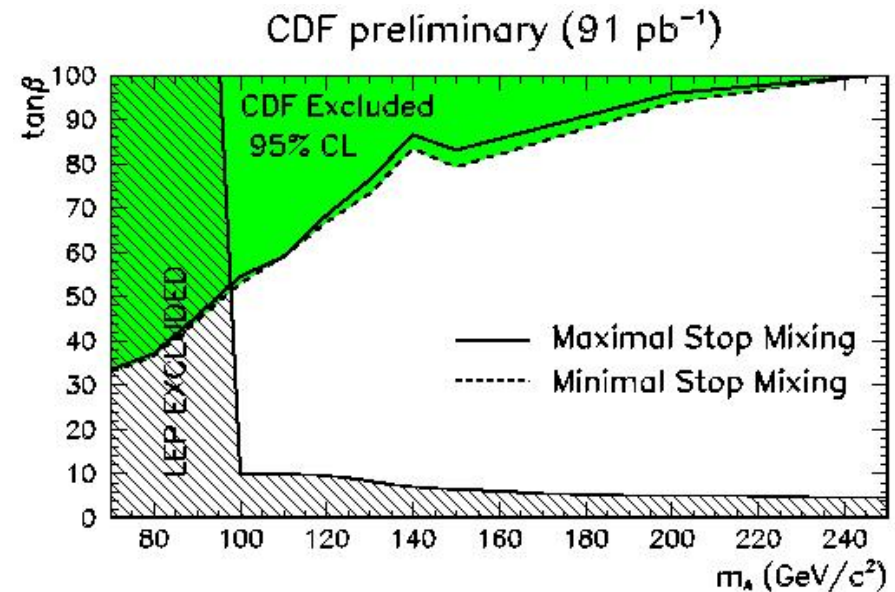
SM Higgs Search

- $Wh \rightarrow (l\nu, q\bar{q}')b\bar{b}$
- $Zh \rightarrow (l^+l^-, \nu\bar{\nu})b\bar{b}$
- set $\sigma_{Vh} \cdot B < 8$ pb at 95% CL



MSSM Higgs Search

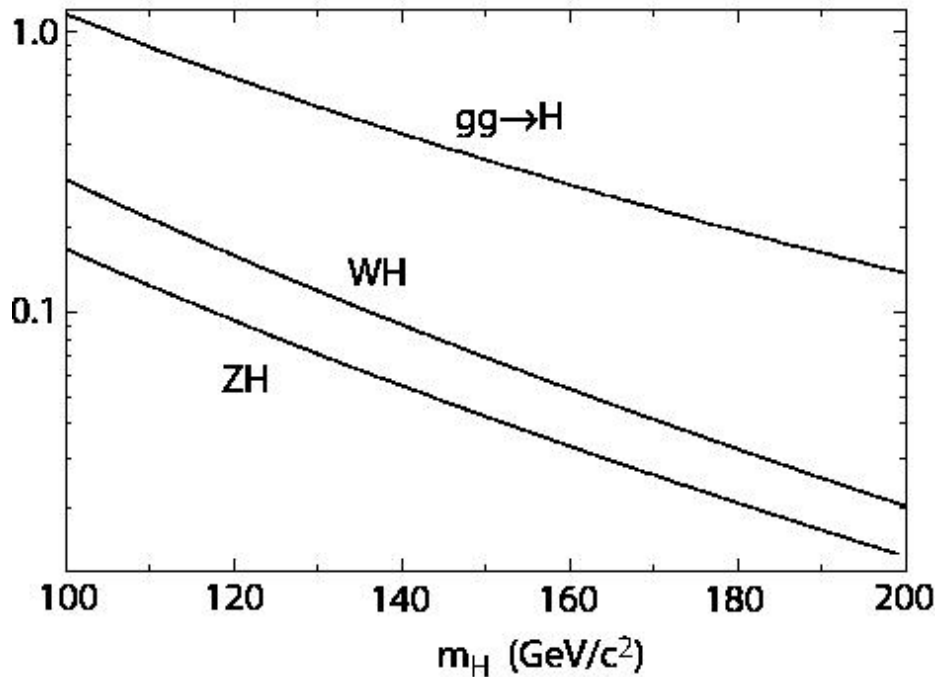
- Due to enhancement of $b\bar{b}h/H/A \rightarrow b\bar{b}b\bar{b}$ xsec at large $\tan\beta$
- Selecting 3 b-jets from multi-jet sample
- set $\tan\beta > 50$ at 95% CL for $m_A = 100$ GeV



No real sensitivity yet ...

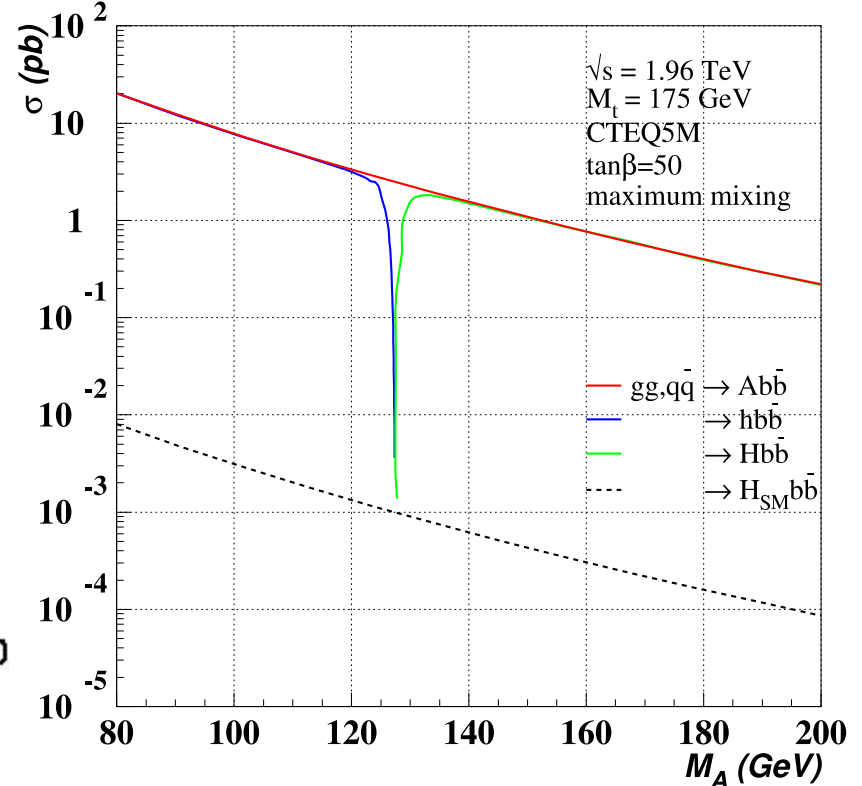
Higgs Production at Tevatron

SM Higgs



- $gg \rightarrow h$ dominates, but very difficult to see for $m_h < 130$ GeV
- Wh, Zh are most accessible, easy to trigger

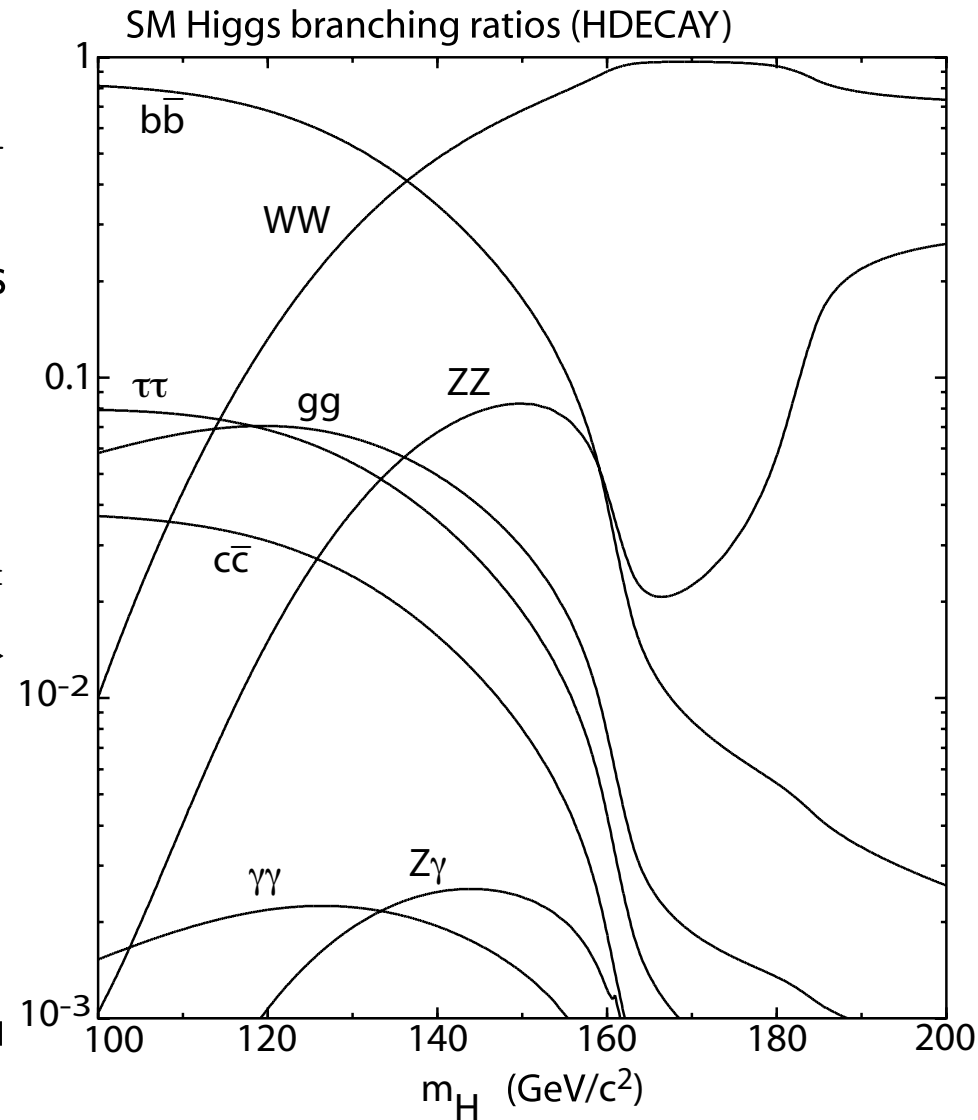
MSSM Higgs



- $b\bar{b}A/b\bar{b}h/b\bar{b}H$ enhanced at large $\tan\beta$
- Need much less luminosity for discovery compared to SM Higgs !

Higgs Decay and Search Strategies

- $m_h < 130$ GeV: $h \rightarrow b\bar{b}$
 - $Wh/Zh \rightarrow l\nu b\bar{b}, \nu\bar{\nu} b\bar{b}, l^+l^- b\bar{b}$
 - SM backgrounds: $W/Zbb/cc, t\bar{t} + tb + tbq$ and WZ
 - Excellent btag and dijet mass resolution
- $m_h > 130$ GeV: $h \rightarrow WW^*$
 - Identify clean final states: $l^\pm l^\mp, l^\pm l^\pm$
 - Exploit the spin correction of $h \rightarrow WW^*$
 - SM background: WW, WZ and $t\bar{t}$
- A : $A \rightarrow b\bar{b}, \tau\bar{\tau}$
 - Exploit the multi-jet and ditau triggers
 - Excellent btag and τ ID



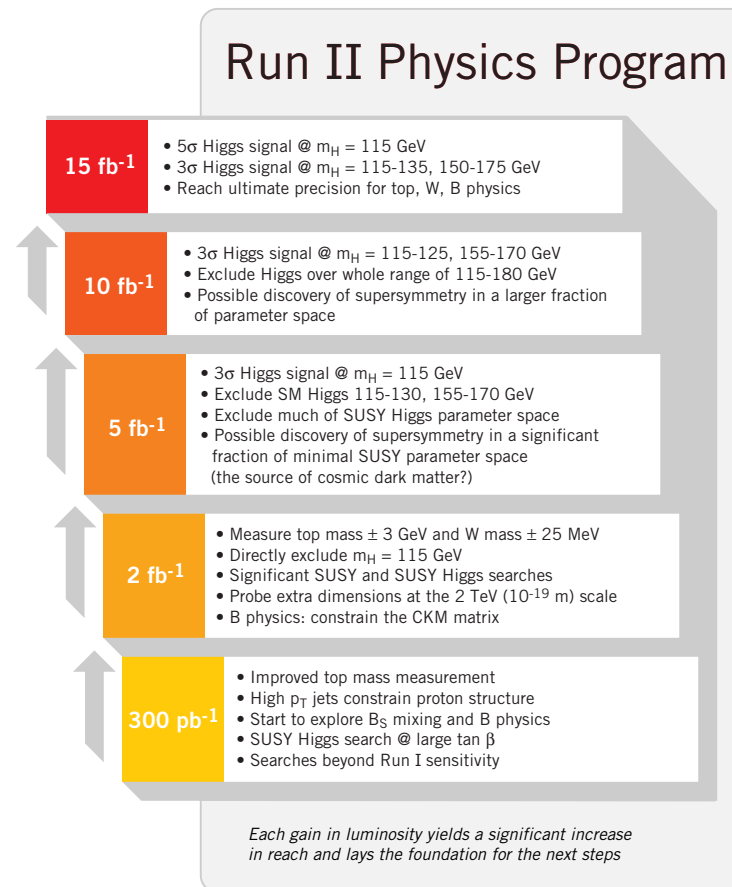
A Brief History of Tevatron Higgs Sensitivity Studies

- 1994: Stange, Marciano and Willenbrock made initial studies “ Higgs bosons at the Fermilab Tevatron “ PR D49 1354 (1994)
- 1995: Report of the TeV 2000 Study Group
- 1996: Snowmass 1996 studies
- 1998: SUSY-Higgs Workshop (SHW)
- 2003: CDF-D0 Higgs Sensitivity Studies (HSS)
- Despite some optimistic assumptions in the old studies, the conclusions are more or less consistent with recent studies.
- There is no single, golden discovery channel:
combining all channels, and both experiments, is crucial!

Tevatron Higgs Sensitivity Studies (2003)

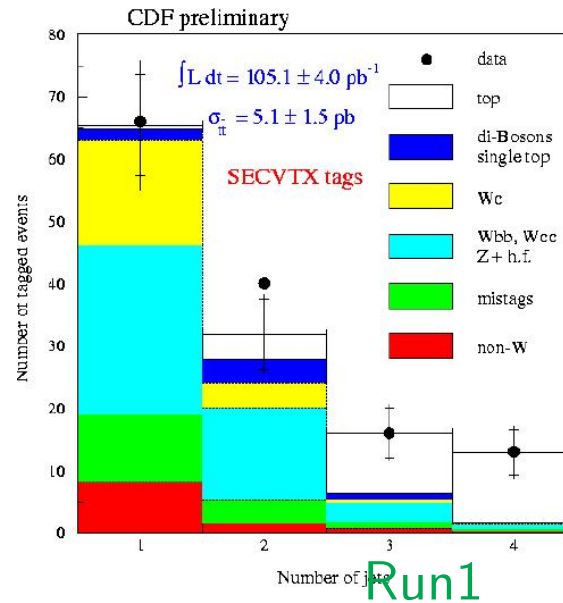
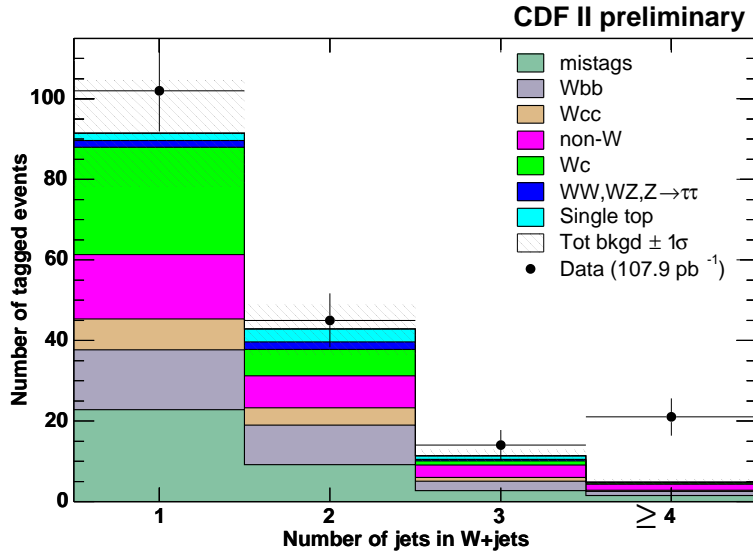
- CDF/D0 were asked by DOE office of science about 1 year ago to provide a new estimate for the Higgs sensitivity during Run II based on our current understanding of detectors and offline analysis.
- Timescale was about 6 months – very short
- Strategies
 - Focus on the low mass Higgs ($115 < m_h < 140$ GeV)
 - Form a CDF/D0 working group and divided the work
CDF: $WH \rightarrow l\nu b\bar{b}$; D0: $ZH \rightarrow \nu\bar{\nu} b\bar{b}$
 - Based on the Run 2A detector performance and Extrapolate to our abilities in 4-5 years using simulation.
 - Focus on the improvement of detectors and analysis techniques.
- Details can be found at FERMILAB-PUB-03/320-E

Run II is not just for Higgs...



- Tevatron is still HEP energy frontier before LHC era.
- There is an extremely rich physics program - every time we double the integrated luminosity we open a new window (to, SUSY, large extra dimension, ...)

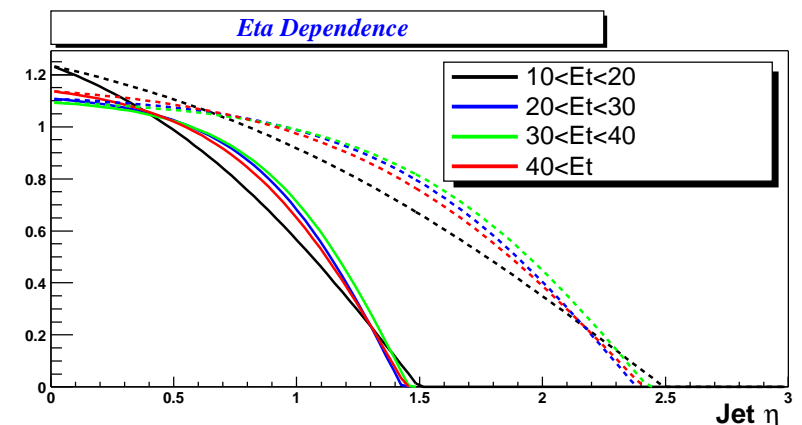
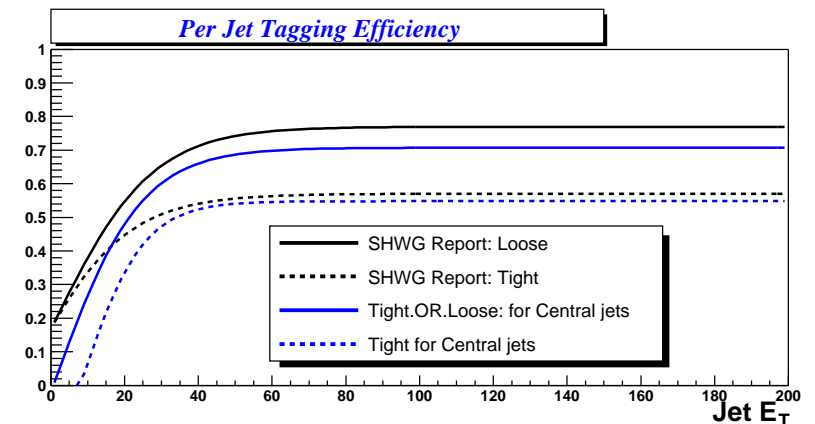
Top studies set the stage...



- Selecting one high P_t isolated lepton ($P_t > 20$ GeV)
- Missing $E_T > 20$ GeV and at least one b-tag in $W + \geq 3$ jets
- Find 35 tagged events and expect 15.1 ± 2 background events
- $\sigma_{t\bar{t}} = 4.5 \pm 1.4(stat) \pm 0.8(syst)pb$
- $\sigma_{t\bar{t}}(NLO) = 6.7^{+0.71}_{-0.88}pb$ (Mangano et al hep-ph/0303085)

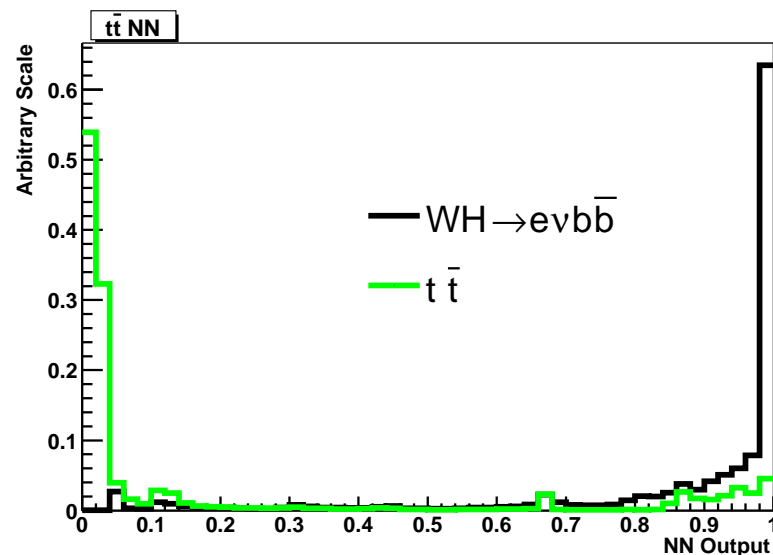
Event Selection and B-tagging

- Events selection and B-tagging are based on current top quark analysis
- B-tagging developed over the past decade of data analysis
- Improvements including:
 - Expand acceptance for Lepton ID to new portions of the detector
 - Expand b-tagging for jets in the forward region $1 < |\eta| < 2$
 - Increase acceptance by including the isolated track from $W \rightarrow \tau \nu$
- We are in the process of reevaluate the btag performance using Run II detector since the Run2b Silicon project was canceled.



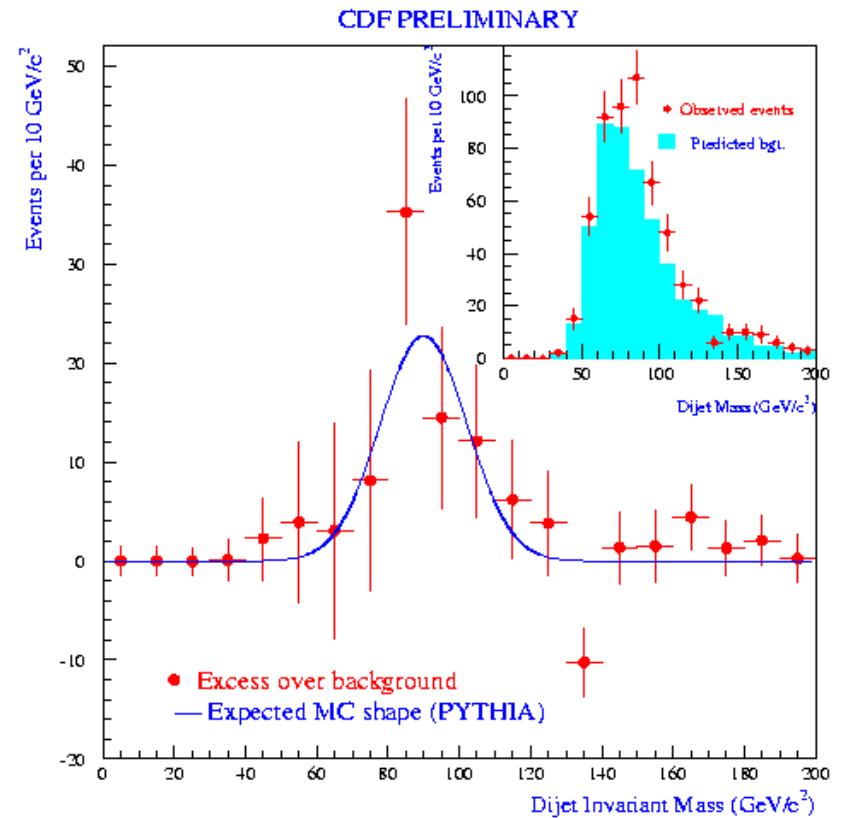
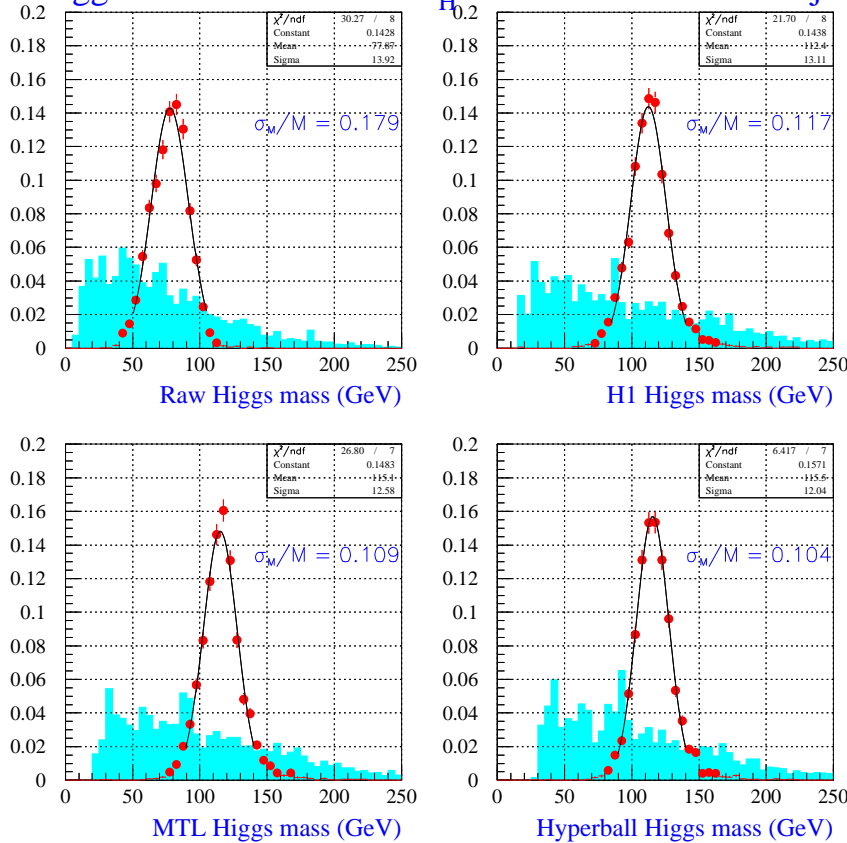
Advanced Event Selections (Neural Network)

- To discriminate against the large contribution of $t\bar{t}$ and $Wb\bar{b}$ with a similar topology to the Higgs signal, a NN was trained to eliminate these events.
 - H_T
 - Aplanarity
 - The net pt imbalance of $\nu + l + b\bar{b}$
 - The first four modified Fox-Wolfram moments
- Requiring NN output > 0.9 improves the sensitivity (S/\sqrt{B}) by 30%.



Dijet Mass Resolution

Higgs mass corrections - $M_H=115$ GeV - two central jets



- Assuming 10% dijet mass resolution
- Achievable 10% resolution using additional tracking and other information in the event.
- Need $Z \rightarrow b\bar{b}$ for calibration, which requires 400 pb^{-1} data

Evaluating Sensitivity

- Evaluate sensitivity by running “pseudo-experiments”
- Includes: expected signal and background rates for two experiments
- Allow the statistical fluctuation
- For each pseudo-experiment
 - Construct and fit dijet mass
 - Ask what statistical statement each can make
- The systematic uncertainties are under study.

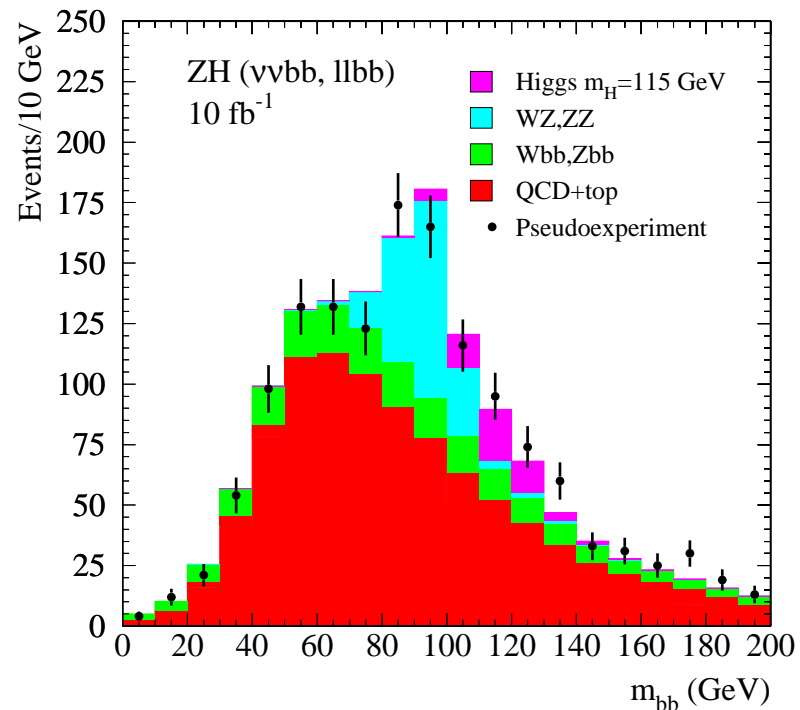
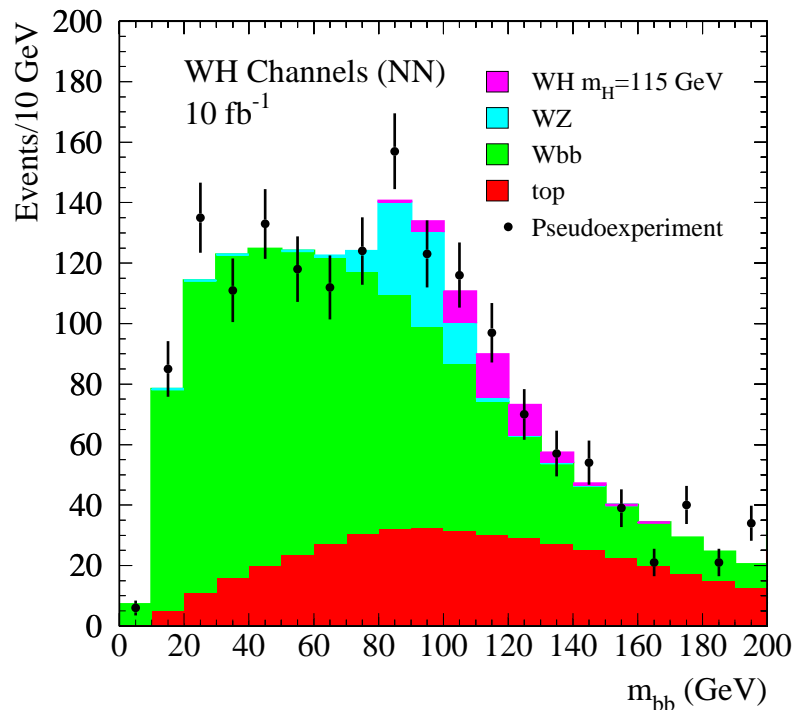
Signal and Backgrounds

- Signal and Background per fb at mass window of 115 GeV
- HSC and SHW differences are understood due to the improvement of detectors and analysis techniques
- Will be very challenging

	$WH \rightarrow l\nu bb$		$ZH \rightarrow \nu\nu bb$	
	HSC	SHW	HSC	SHW
Signal	2.4	4.6	3.8	5.5
$t\bar{t}$	3.9	7.8	2.2	3.0
tqb/tb	2.9	5.3	1.2	5.0
Wbb/Zbb	9.1	7.7	3.3	13.8
WZ/ZZ	0.9	1.4	2.7	3.3
QCD	-	-	19.6	25.1
Total(B)	16.8	22	19.6	50
S/\sqrt{B}	0.58	0.98	0.86	0.78

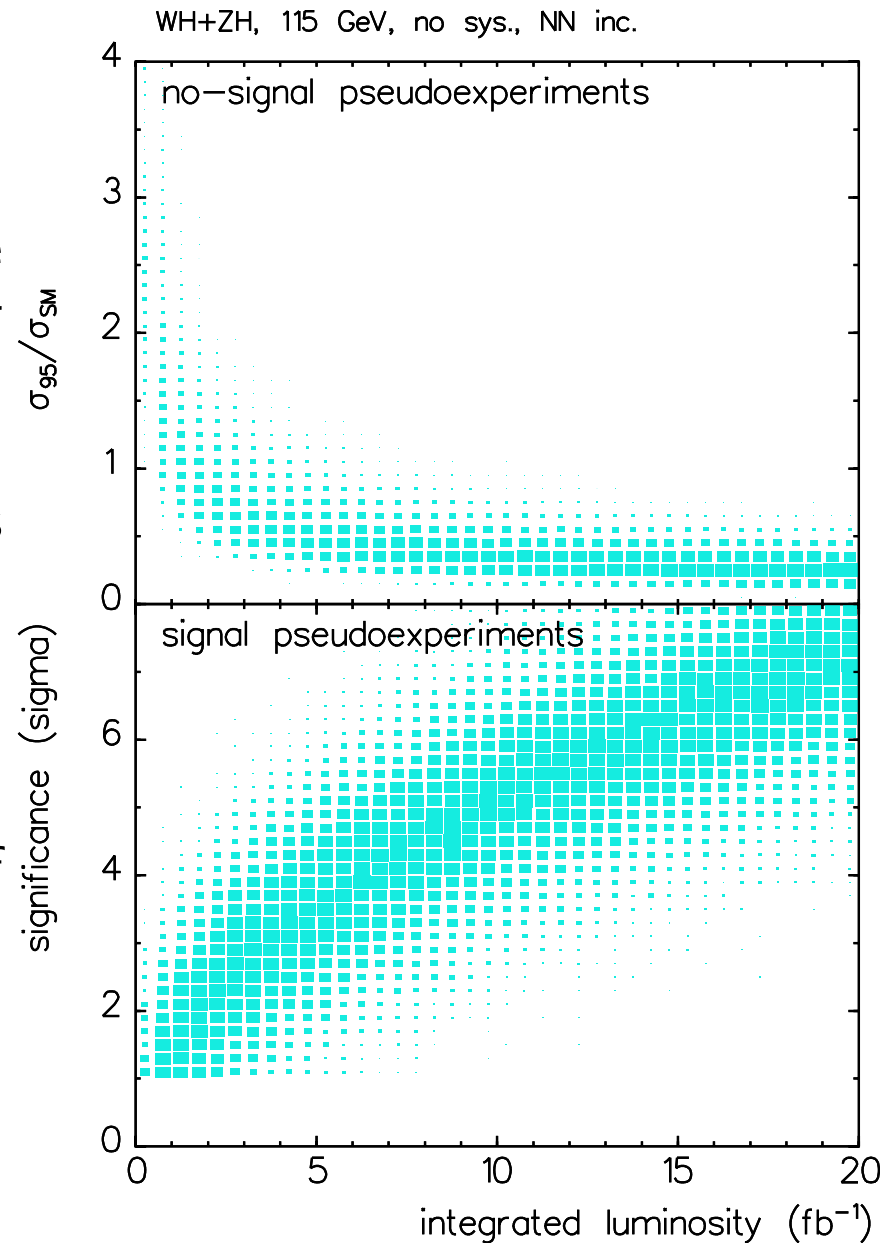
A Pseudo Experiment with Signal (115) and backgrounds

- Fit the dijet mass with signal and background
- Control the systematic errors on the background shapes are crucial



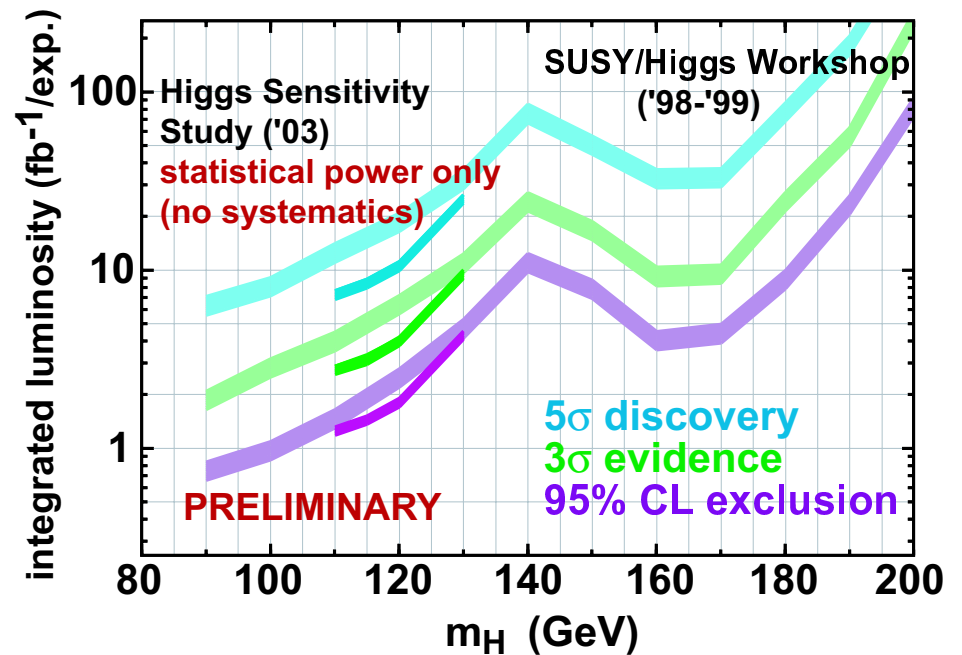
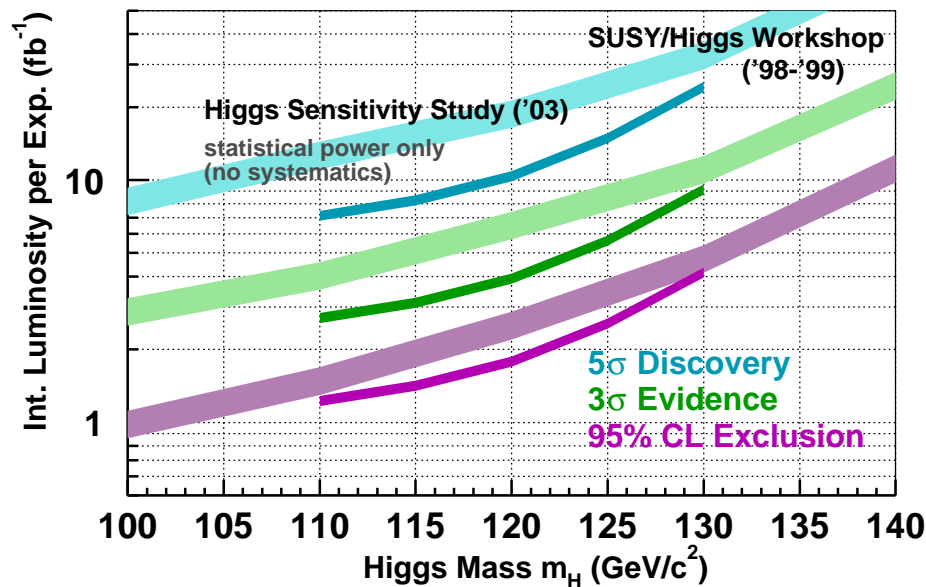
Combined Pseudo-Experiments

- the 95% CL limit and significance vs the int. luminosity per experiment
- Broad range of statistical outcomes
- With 5 fb^{-1} , most likely at 3.5 sigma
- We will quote the median value of int. luminosity needed for the limit, 3 sigma and 5 sigma discovery.



Higgs Sensitivity CDF + D0

- Uses the 50% of Pseudo experiment threshold
- No systematic included
- Consistent with SHW conclusion, the improvement due mainly to sophisticated analysis techniques.



Background Systematics

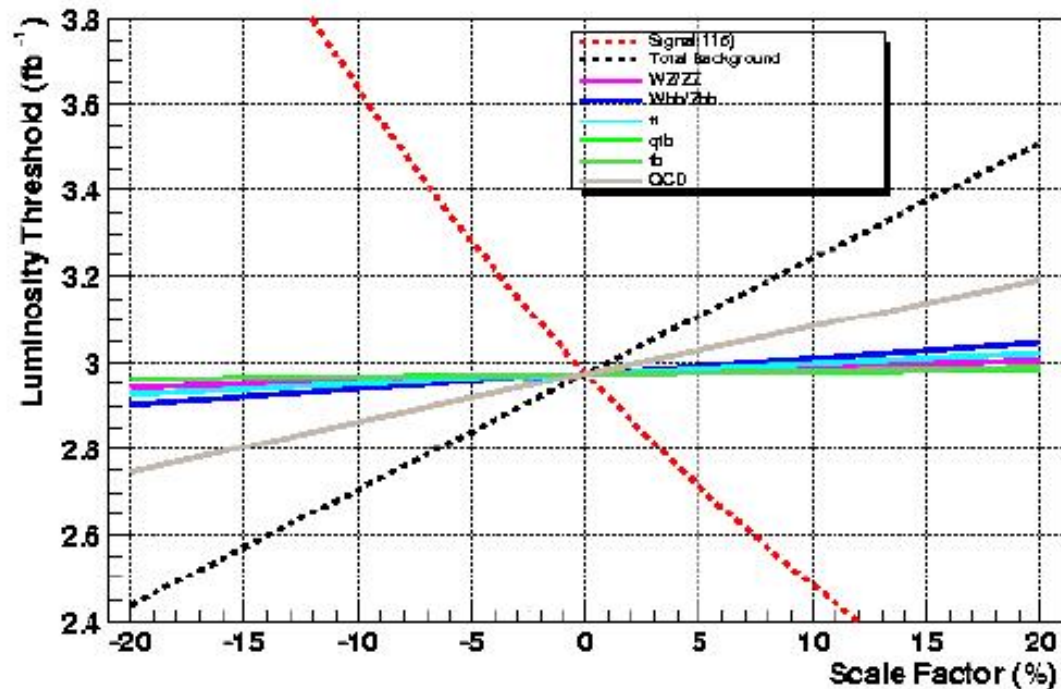
- $t\bar{t}$
 - The top xsec will be measured from data
 - Residual contributions in 2jet bin, can be modeled well using simulation and fully reconstructed $t\bar{t}$ ($\approx 300/fb$) by removing some jets to mimic 2jet bin.
- single top
 - Should be observed by then
 - Similar signature $W^* \rightarrow tb \rightarrow wbb$
 - Monte Carlo indicates the shape similar to $t\bar{t}$, but have to rely on the data as well.
- WZ, ZZ
 - Excellent calibration for low mass Higgs($m_h = m_Z$)
 - Purely leptonic decays should provide a normalization
 - Dijet mass shape constrained from inclusive $Z \rightarrow b\bar{b}$ data

$W/Zb\bar{b}, c\bar{c}$ Background

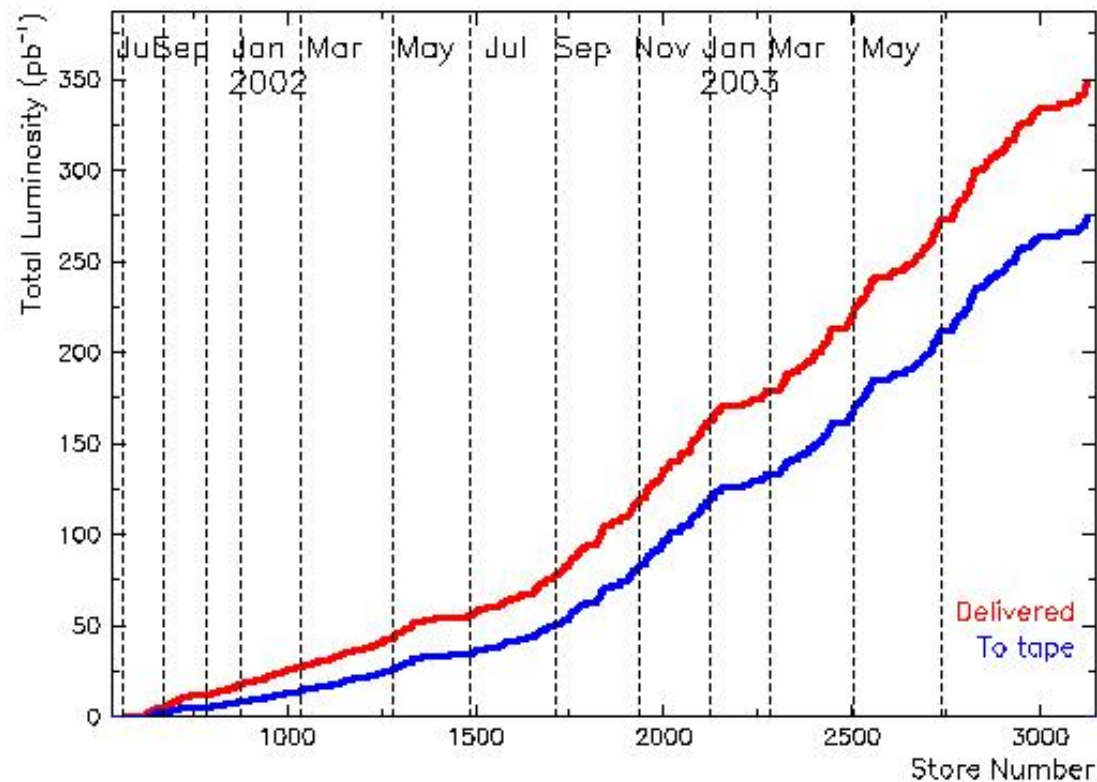
- Method II: $n_{wbb} = F_{wbb} \cdot n_{wjet}^{obs}$
- Run1 F_{wbb}
 - VECBOS: $g \rightarrow b\bar{b}$ large emission(2b)
 - Herwig: $g \rightarrow b\bar{b}$ merged b's (1b)
 - A scale factor of MC/Data derived from inclusive jet (Herwig)
- Run2 F_{wbb} in progress
 - Advanced ME+PS tools: ALPGEN, Madgraph, GRAPPA...
 - MLM-Matching/CKKM recipe for double counting
 - Preliminary ALPGEN results consistent with run1, but limited by the large uncertainties due to Q^2 and matching procedures.
 - One of useful test is to measure the HF in inclusive jets using same procedure and hopefully we can reduce some of uncertainties in short term.
- In next couple years, we should be able to measure the $W/Zb\bar{b}, c\bar{c}$ backgrounds precisely using combination of data and MC tools available by then.

A Final Remark

- Control the normalization and shape systematic on each background crucial.
- Need to fully exploit the potential of Run II and work with MC community to insure that physics are well described.
- The understanding of the Higgs sensitivity will improve over time as top discovery during Run I - the final sensitivity was much better than expected.



Run2 Performance

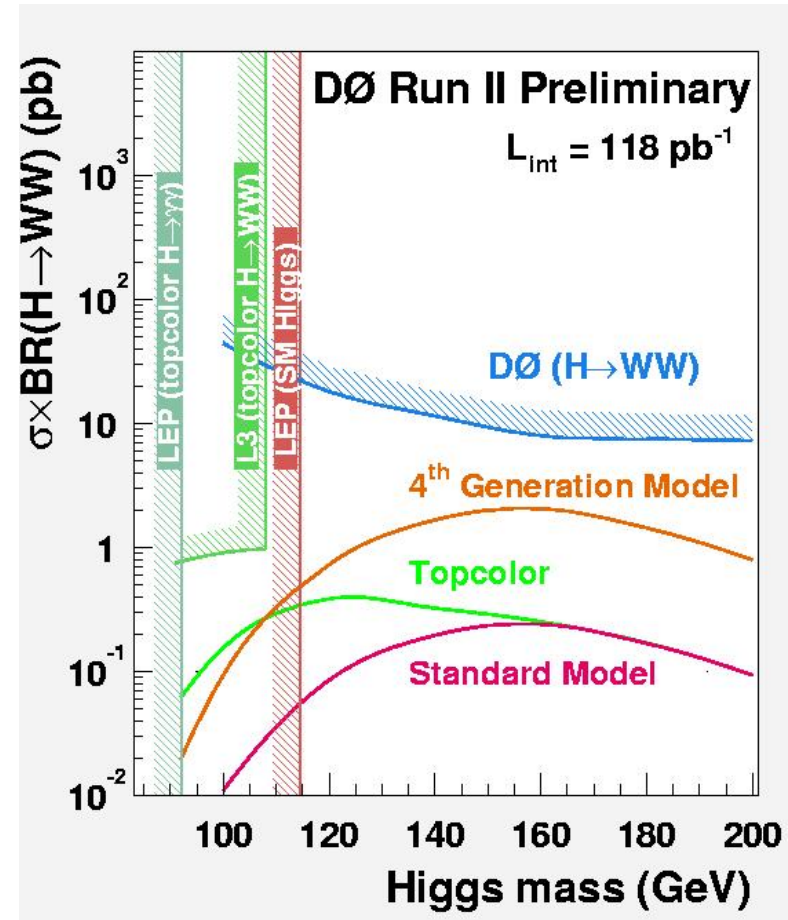
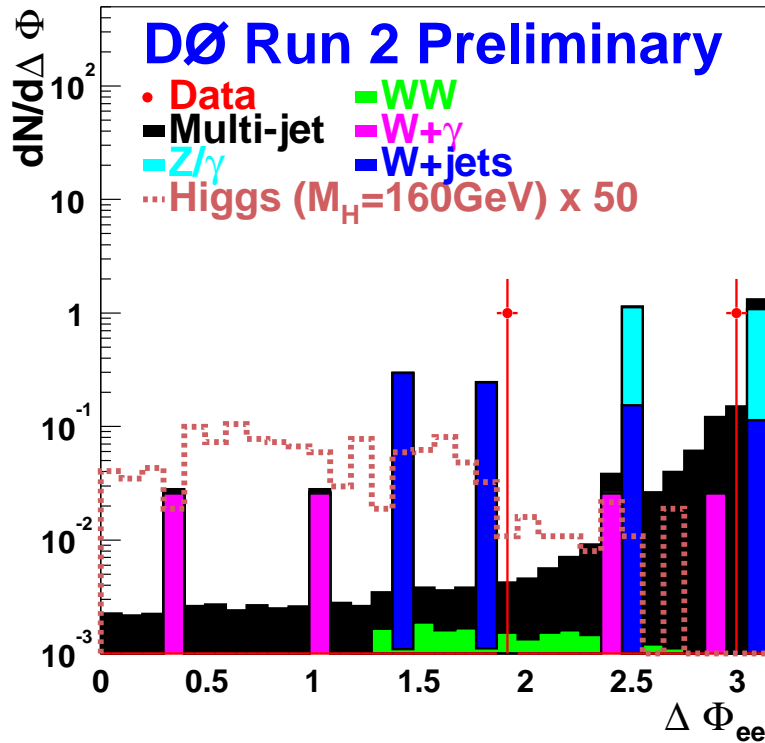


- CDF/D0 are doing well.
- Have doubled run1 statistic on tape ($\approx 200pb^{-1}$)
- Anticipate achieving int. luminosity $1 fb^{-1}$ in 2005
- Total expected int luminosity $4.4-8.6 fb^{-1}$ in 2009

Recent Run2 Results

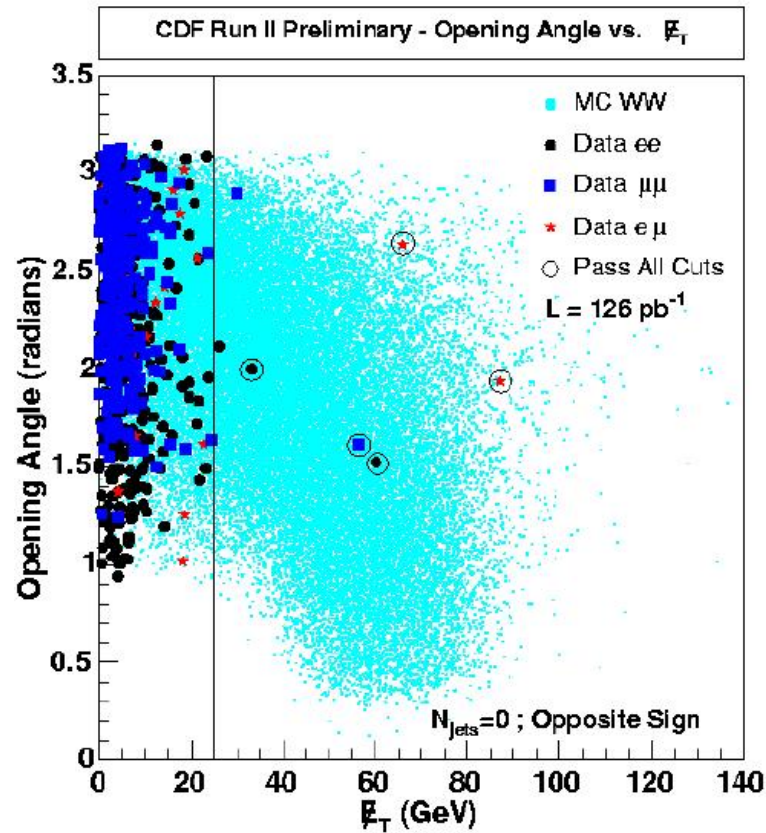
- Re-established the top signal in lepton + jets and dileptons
- Higgs searches still at the engineering stage, more interesting results will merge soon.
- SM searches – challenging
 - $h \rightarrow WW^*$, similar to the dilepton
 - $Wh \rightarrow l\nu b\bar{b}$, similar to the lepton+jets
 - $Zh \rightarrow \nu\bar{\nu} b\bar{b}$, similar to the met+jets
- MSSM searches – best bet !
 - $A/H/h \rightarrow b\bar{b}, \tau\bar{\tau}$ in multi-jets
 - $t\bar{H}^+b$, Disappearance of $t \rightarrow W^+b$

Search for $h \rightarrow W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ (D0)



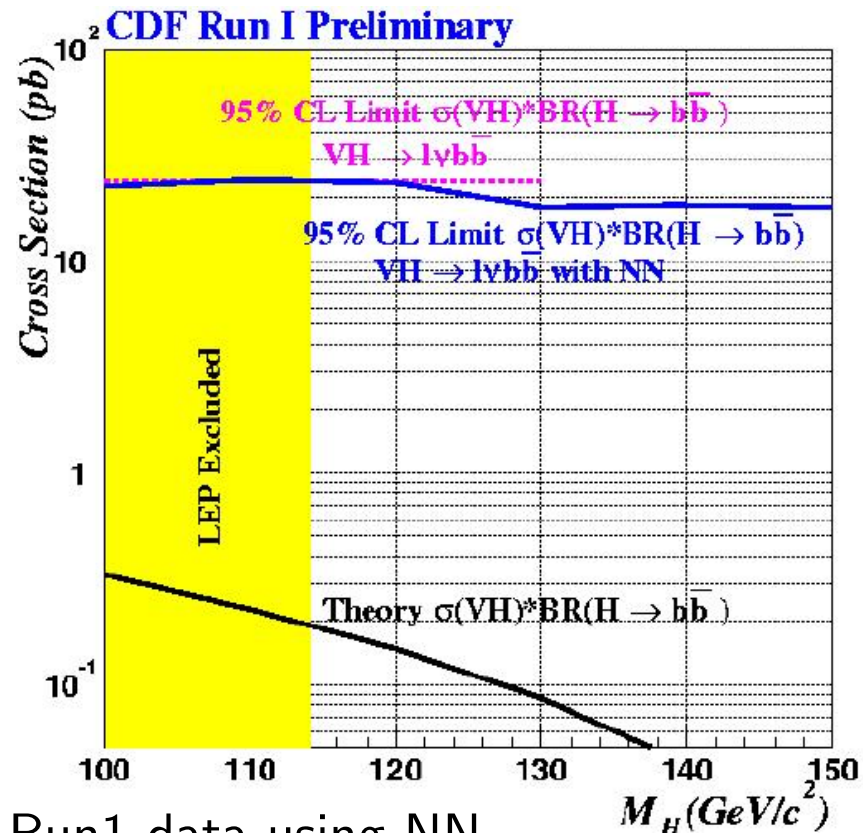
- Two high pt isolated lepton (e or μ) + large met
- Major background: W^+W^- production
- Exploit spin correlations of $H \rightarrow W^+W^-$
- Set a limit $\sigma \times Br < 8 \text{ pb}$

Diboson: $W^+W^- \rightarrow l^+l^-\nu\bar{\nu}$ (CDF)



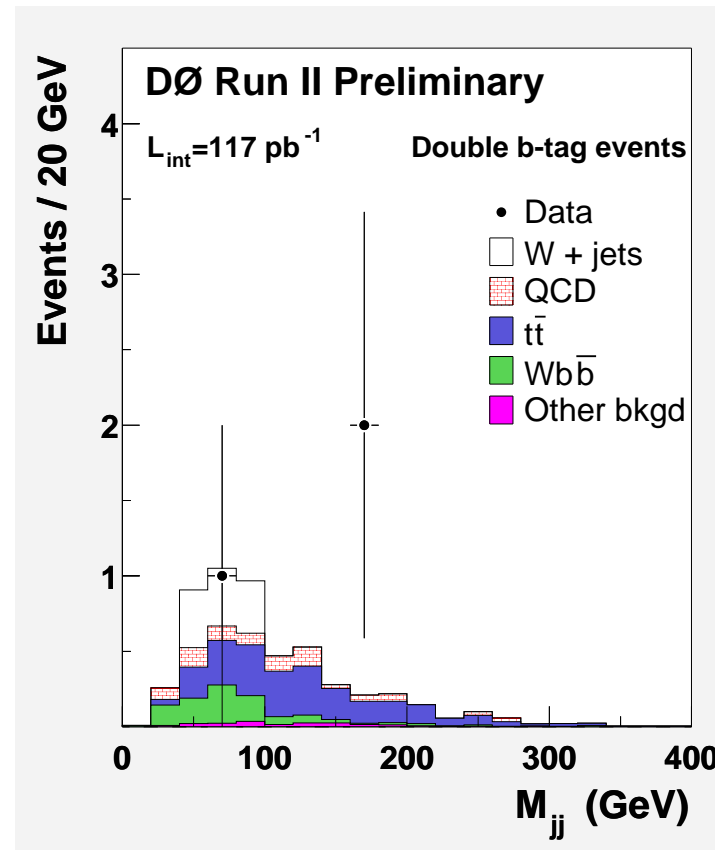
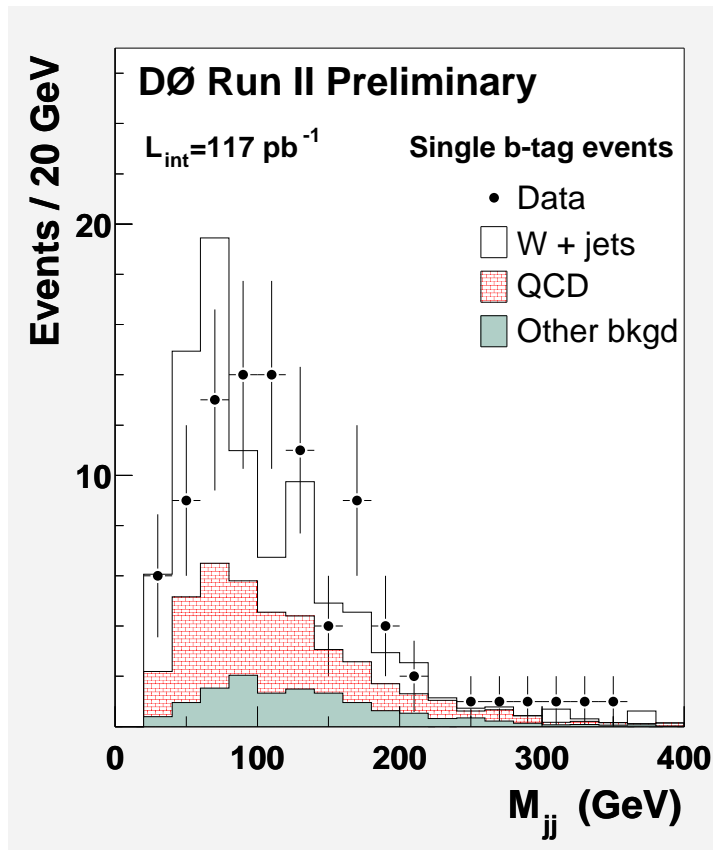
- CDF find 5 candidates and expected 2.34 ± 0.38 bkg with 126 pb^{-1}
- $\sigma_{W^+W^-} = 5.1_{-3.6}^{+5.4}(\text{stat}) \pm 1.3(\text{syst}) \text{ pb}$
- $\sigma(NLO) = 13.25 \pm 0.25 \text{ pb}$ (Campbell et al hep-ph/9905386)

Search for $Wh \rightarrow l\nu b\bar{b}$ (CDF)



- CDF reanalysis the Run1 data using NN
- Start with loose selection of $W2jet + btag$
- A NN was trained to eliminate $t\bar{t}$ and $Wb\bar{b}$ events
- Improve the Higgs sensitivity by 1.6 over the cut-based analysis

Search for $Wh \rightarrow l\nu b\bar{b}$ (D0)



- Select events with a high pt lepton and two b-tagged jets
- Observe 3 events with expected 5.5 ± 1.6
- set a limit of $\sigma_{wbb} < 33.4 \text{ pb}$ at 95% CL.

Search for $Zh \rightarrow (\nu\bar{\nu}, l^+l^-)b\bar{b}$ (CDF)

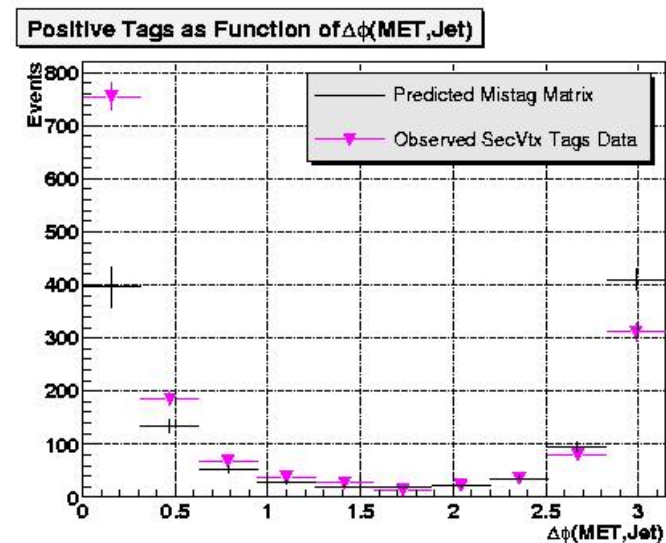
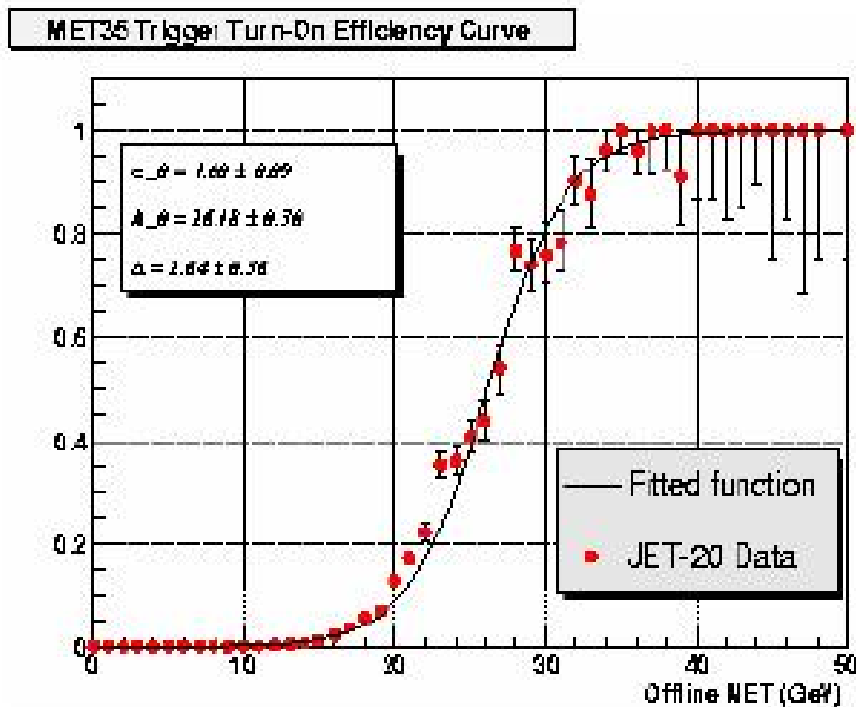
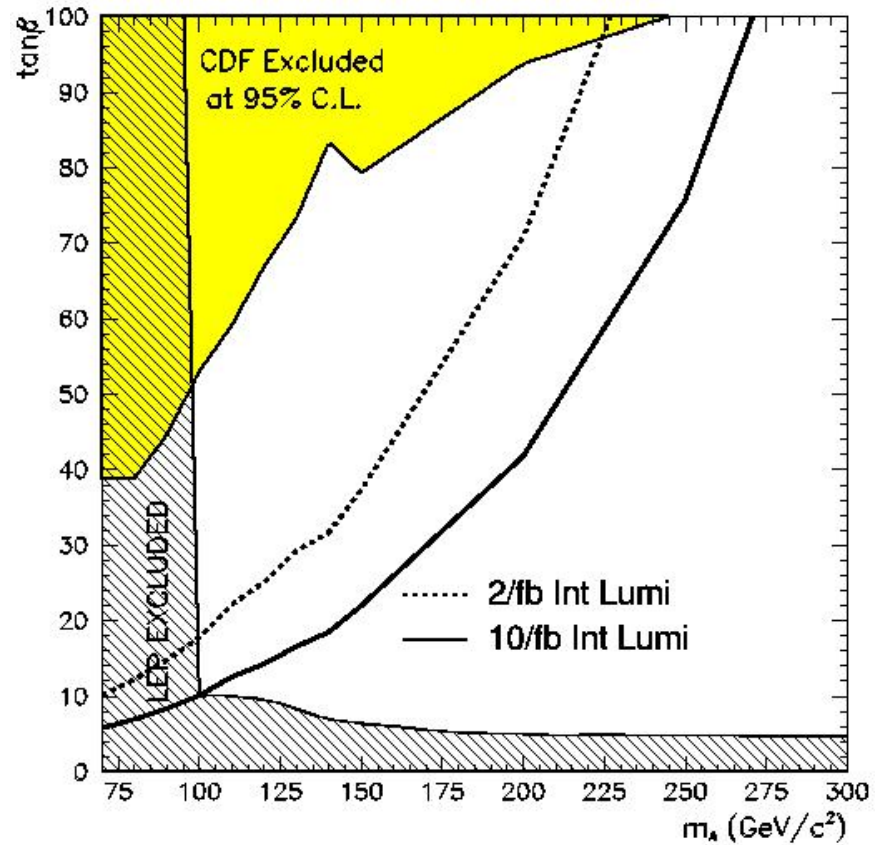
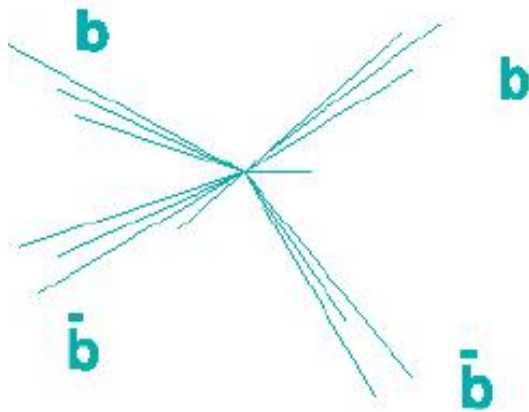


Figure 10: Comparison of the $\Delta\phi(E_T, \text{tagged jet})$ distribution for data and computed with the SecVtx Tagging Matrix rate prediction.

- Select events with large missing E_T and two b-tagged jets
- large dijet backgrounds, but less top contributions
- key is to understand the dijet background
- Most sensitivity channel.

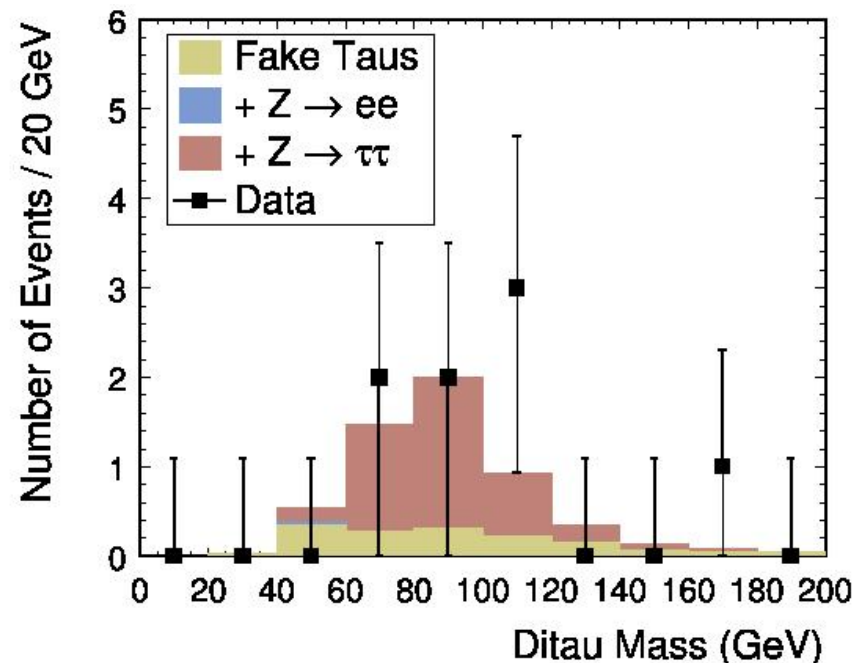
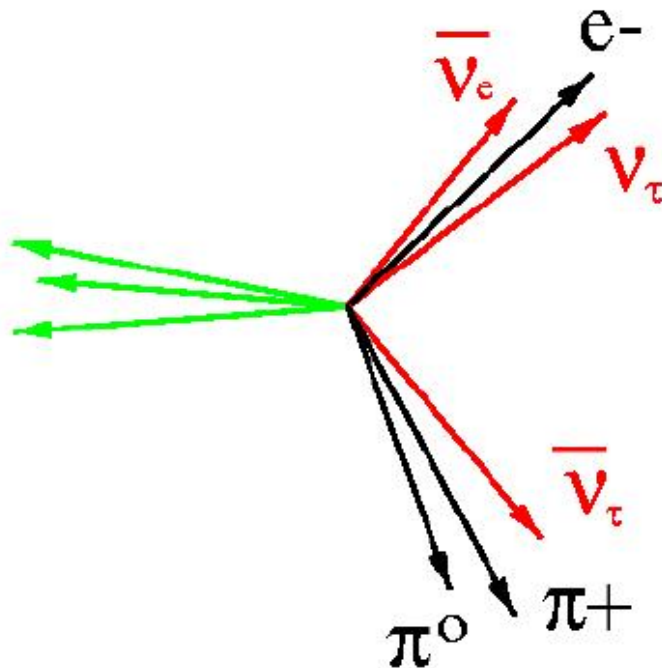
Search for MSSM Higgs: $Ab\bar{b} \rightarrow b\bar{b}b\bar{b}$



- $b\bar{b}(h/H/A)$ enhanced at large $\tan\beta$
- Selecting 4 jets with 3 b-tags

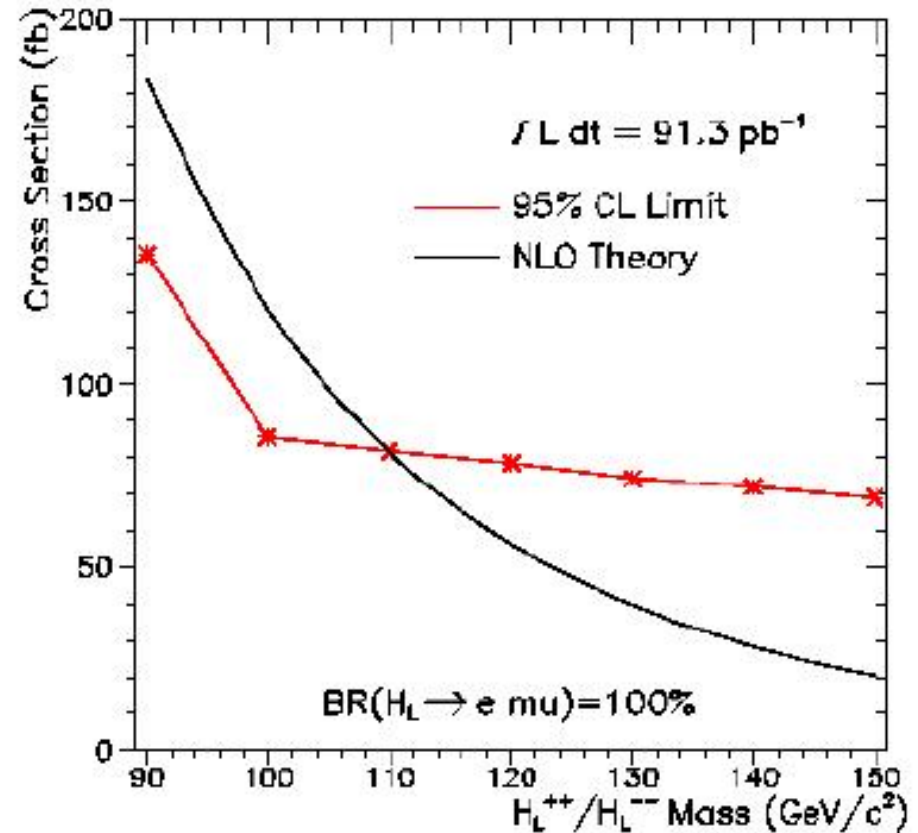
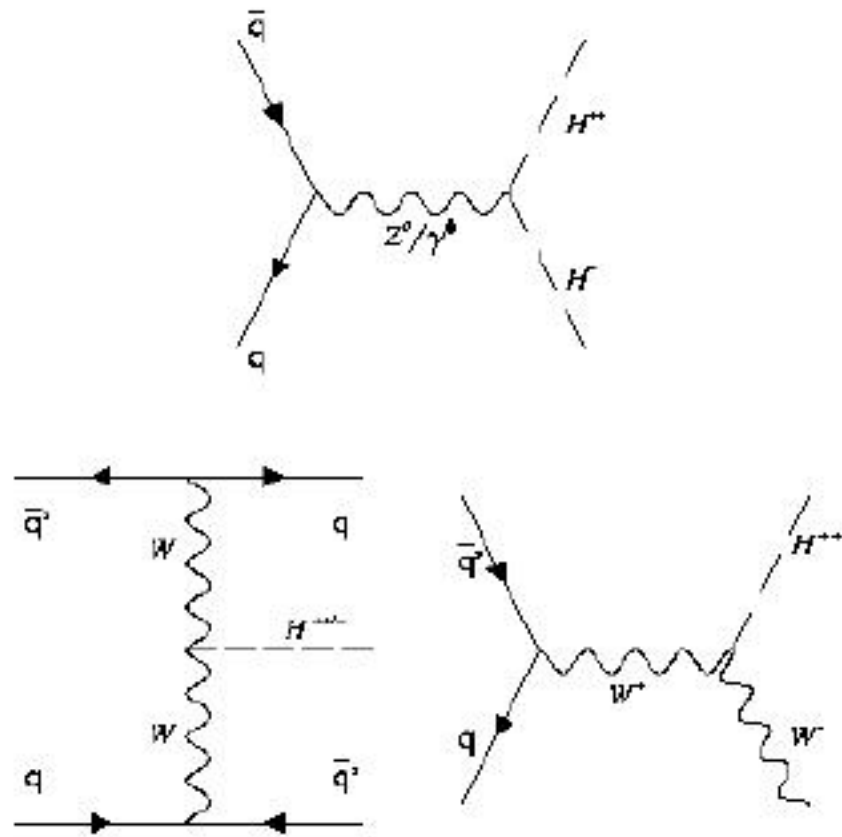
- Game is to trigger on ≥ 3 jets with SVT
- Potential from $gb \rightarrow b(h/H/A) \rightarrow 3b$

Search for MSSM Higgs: $h/A/H \rightarrow \tau^+\tau^-$ (CDF)



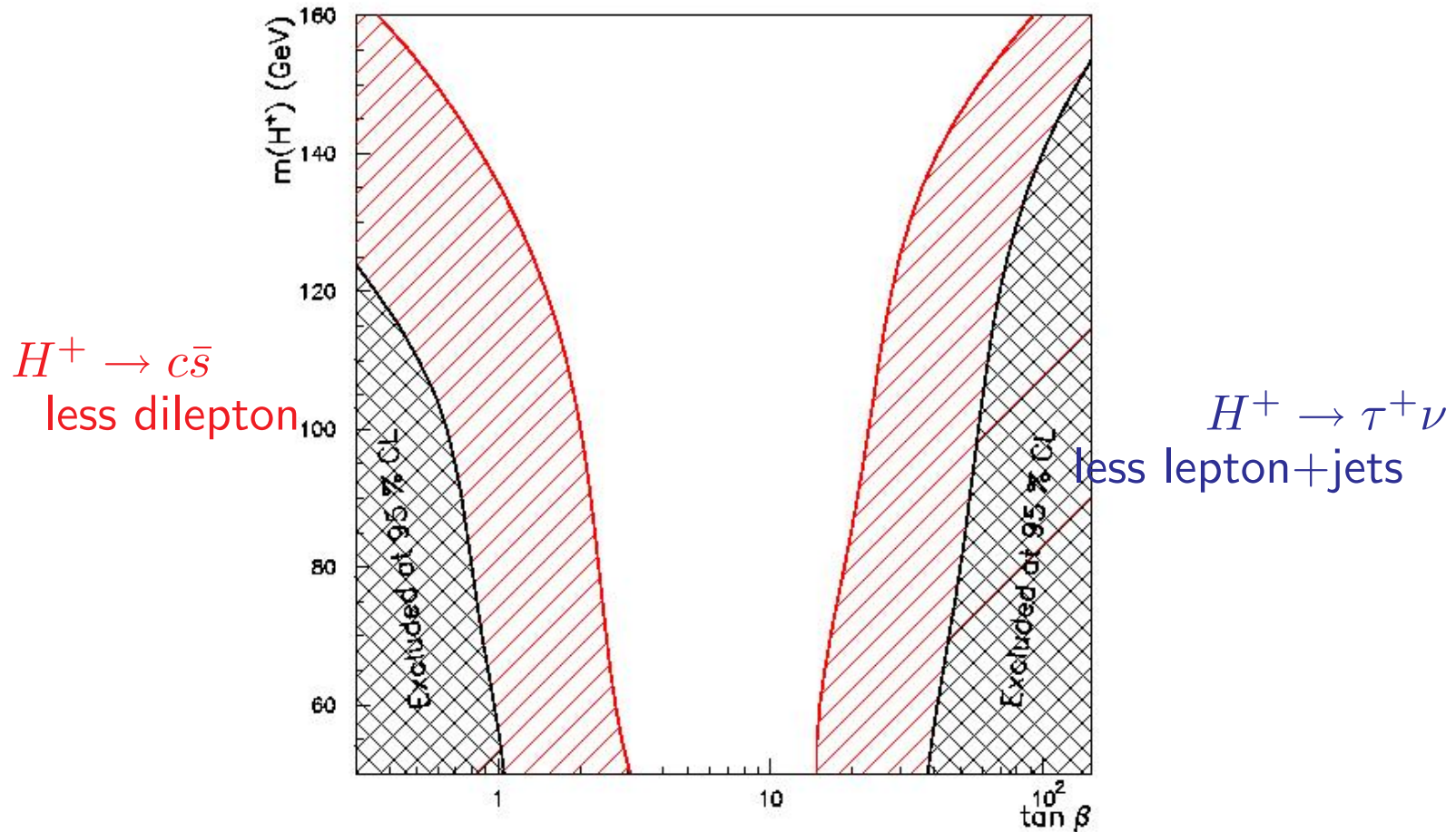
- Take the advantage of enhanced xsec at large $\tan\beta$
- Selecting ditau in Run1 inclusive electron sample: one leptonic, one hadronic
- Reconstructed ditau mass through \cancel{E}_T and τ jets by assuming the neutrinos along the τ direction.
- $Z \rightarrow \tau^+\tau^-$ signal is evident
- Excellent Run2 tau triggers and will have results soon !

Search for Doubly-Charged Higgs Bosons (H^{++}/H^{--})



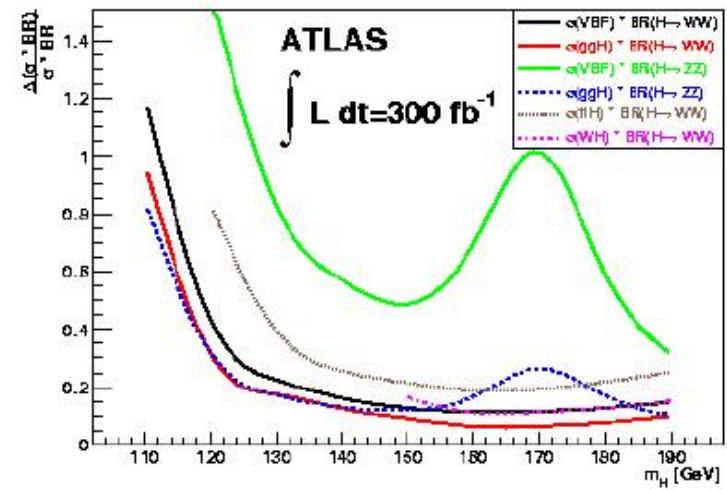
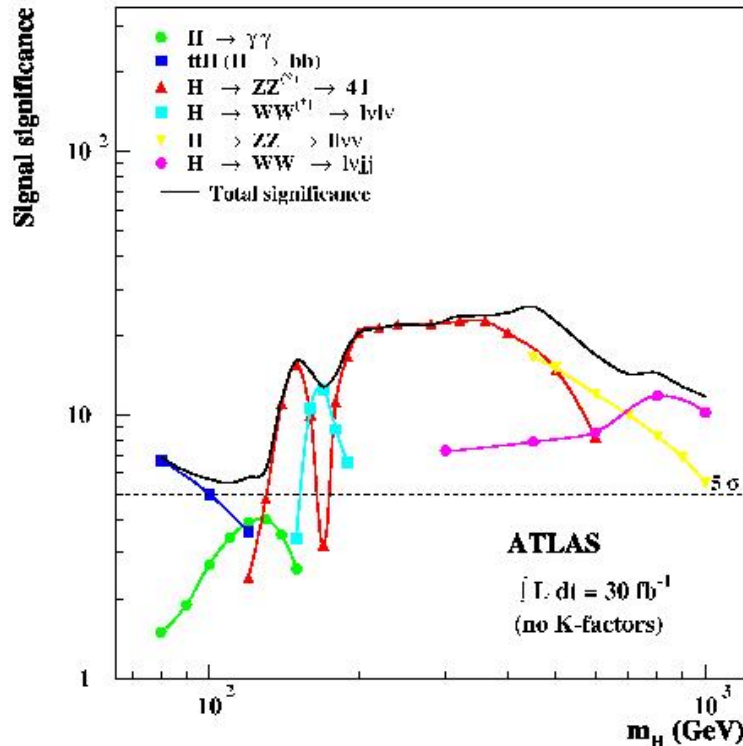
- LR symmetric & Triplet Models
- Decay into like-sign di-leptons
- set $M_{H^{++}} > 110 \text{ GeV}/c^2$ at 90 % CL in both $e^+ \mu^+$ and $\mu^+ \mu^+$

Charged Higgs Search at the Tevatron



- Disappearance search for $t \rightarrow H^+b$ by taking the advantage of large $t\bar{t}$ xsec.
- Compare top pair yield in lepton +jets and dilepton to SM predictions, can rule out or discover competing decay mode of $t \rightarrow H^+b$.

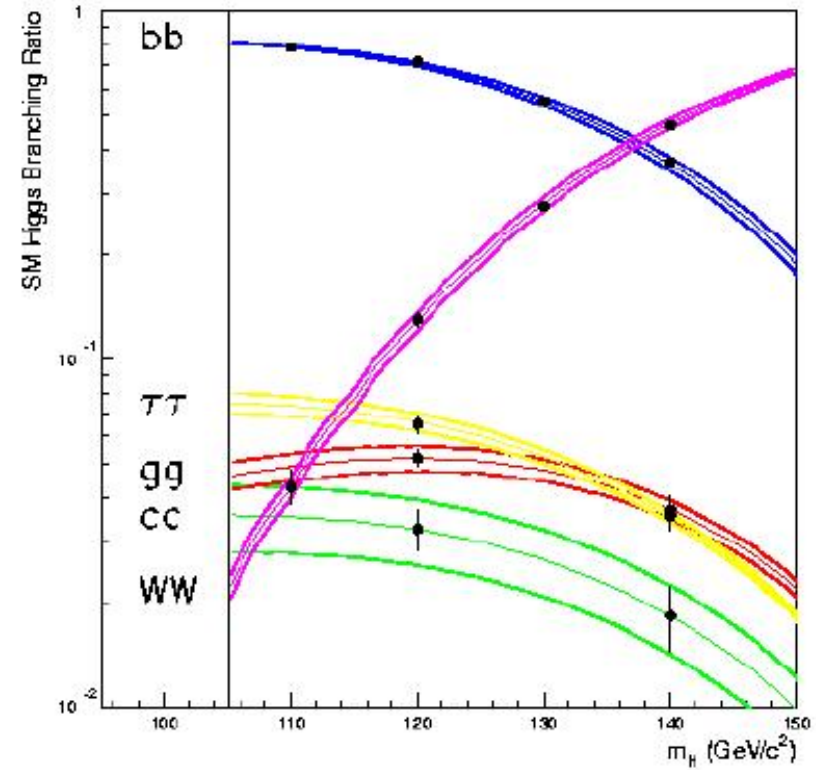
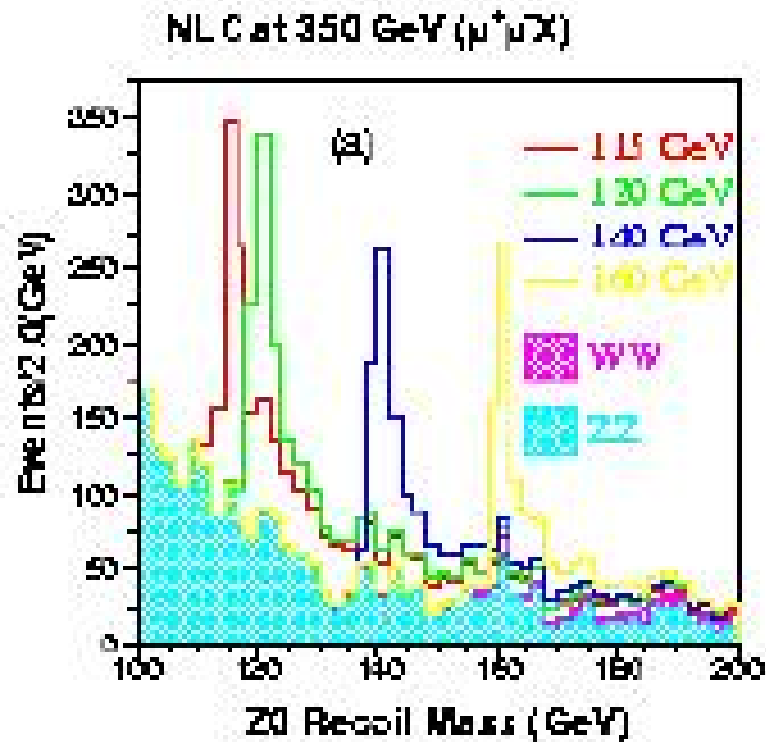
Higgs Physics at LHC



- pp interactions at $\sqrt{s} = 14$ TeV
- Design to discover Higgs boson up to $m_h < 1$ TeV
- Physics starts > 2007

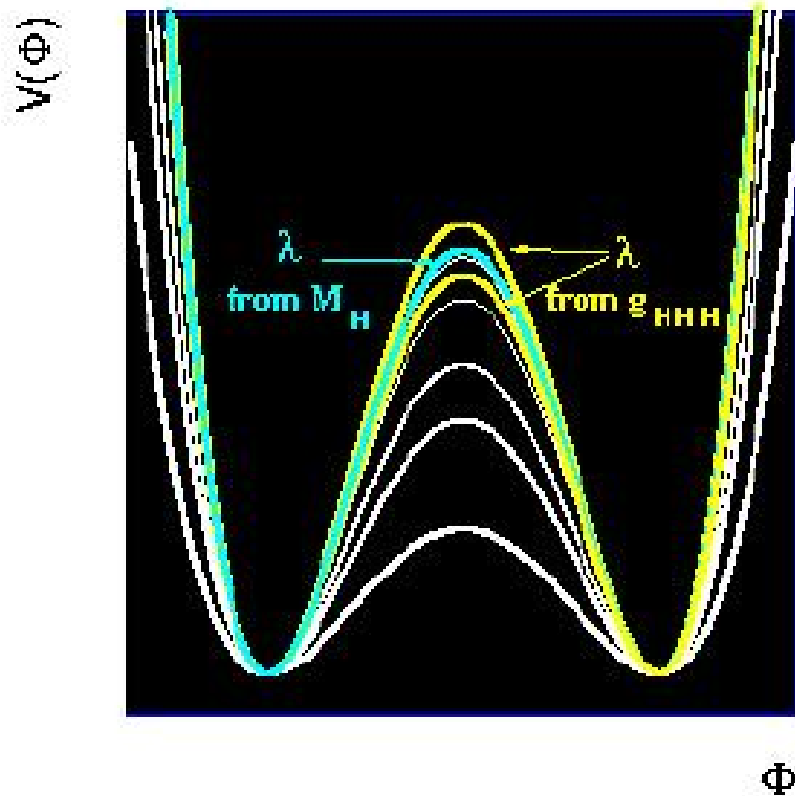
- Once the Higgs found, ratio of coupling will be measured at LHC with some precision.
- Super LHC will improve these couplings by factor 2
- More precise measurements needed for differential models.

Higgs Physics at LC



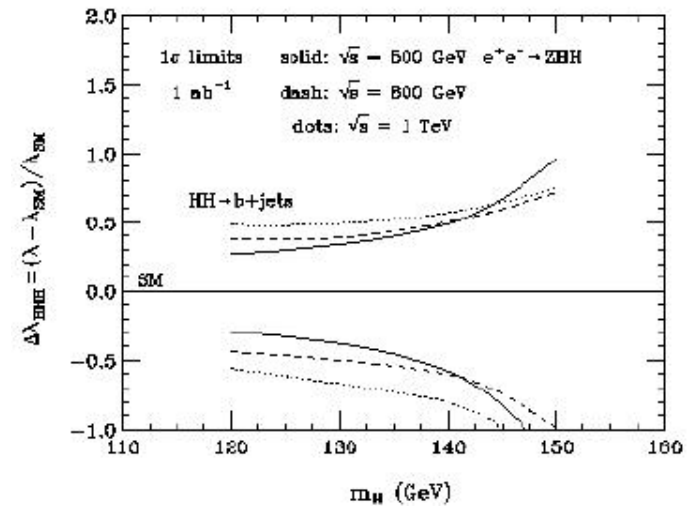
- LC produces Higgs from $e^+e^- \rightarrow Zh, h\nu\bar{\nu}$
- The initial state has a fixed cm energy and well-defined quantum state
- The recoil from Z gives unbiased Higgs decays and one can measure the Higgs decay precisely.
- The LC will establish the Higgs quantum states, measure the $t\bar{t}H$ coupling, and Higgs potential.
- **It's likely that LHC will discover the Higgs and LC tells us what it really is**

The Higgs Potential

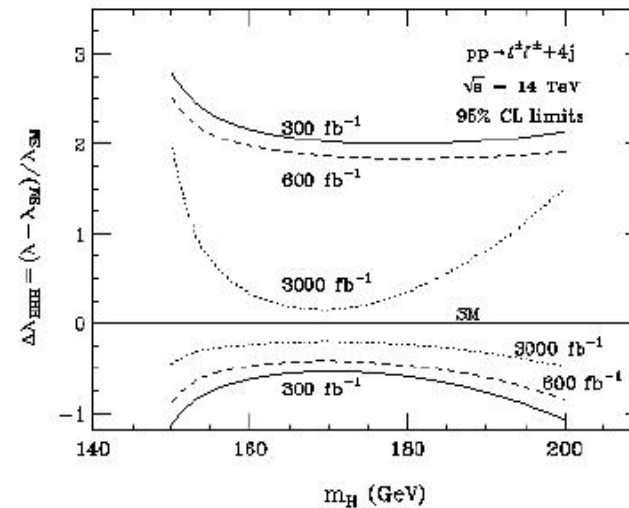


- $V(\phi) = \frac{M_h^2}{2}\phi^2 + \lambda_{hhh}v\phi^3 + \frac{\lambda_{hhhh}}{4}\phi^4$
- $\lambda_{hhh} = \lambda_{hhhh} = \frac{M_h^2}{2}v^2$
- LC sensitive to low m_h and LHC sensitive to $m_h > 150$ GeV

- $e^+e^- \rightarrow Zh\bar{h} \rightarrow Zbb\bar{b}\bar{b}$



- $pp \rightarrow hh \rightarrow W^+W^-W^+W^- \rightarrow l^\pm l^\pm X$



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Conclusions

- The Higgs boson remains elusive, but the discovery may be just on the corner.
- The Tevatron is still at the world's frontier energy until the LHC era. The higgs sensitivity will improve over time as we get more data, better understand our detector, use smarter analysis techniques, and develop new ideas, but challenging...
- The LHC is very likely to find some Higgs bosons, but may not find all of them or may not be able to tell what it really is.
- LC is the ideal tool for making detailed studies of Higgs bosons and exploring the properties.
- In a decade from now, we will learn lot more about EWSB...