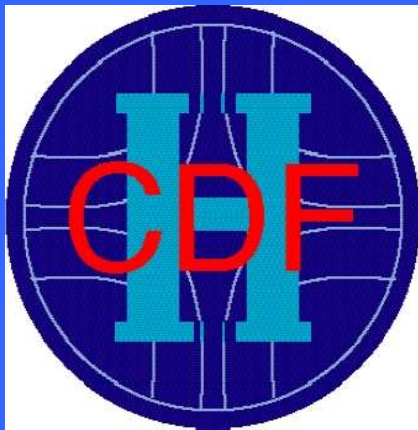


SM Higgs Boson Searches at the Tevatron

Wei-Ming Yao (LBNL)

HEP Seminar@University of Oregon, May 12 2008

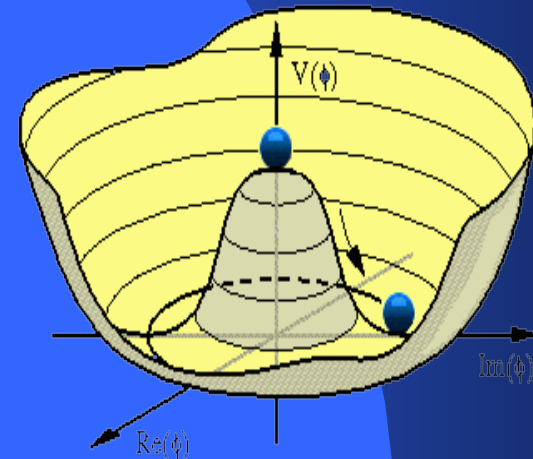
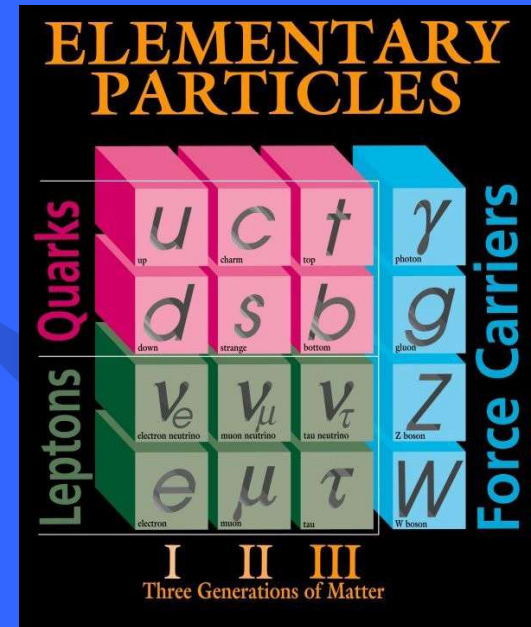


OutLine

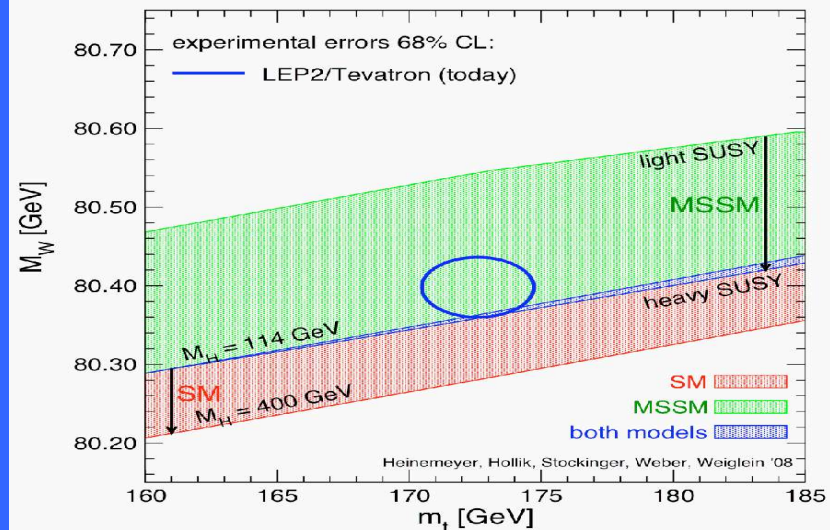
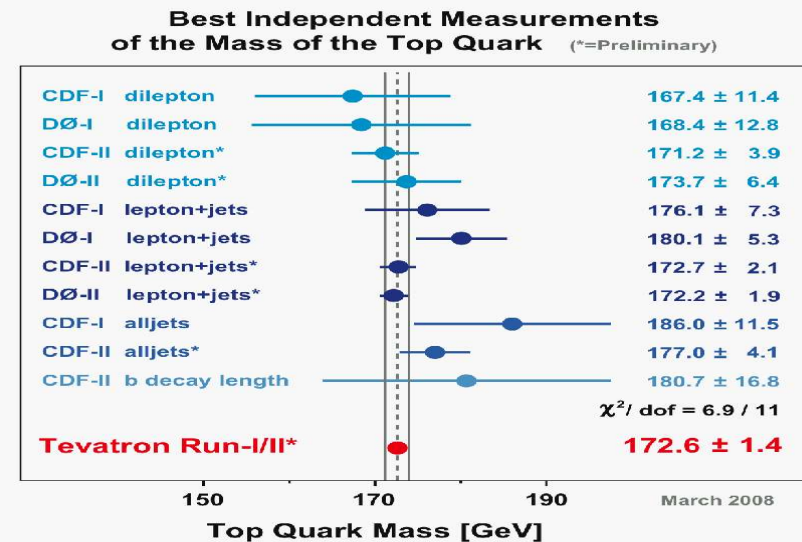
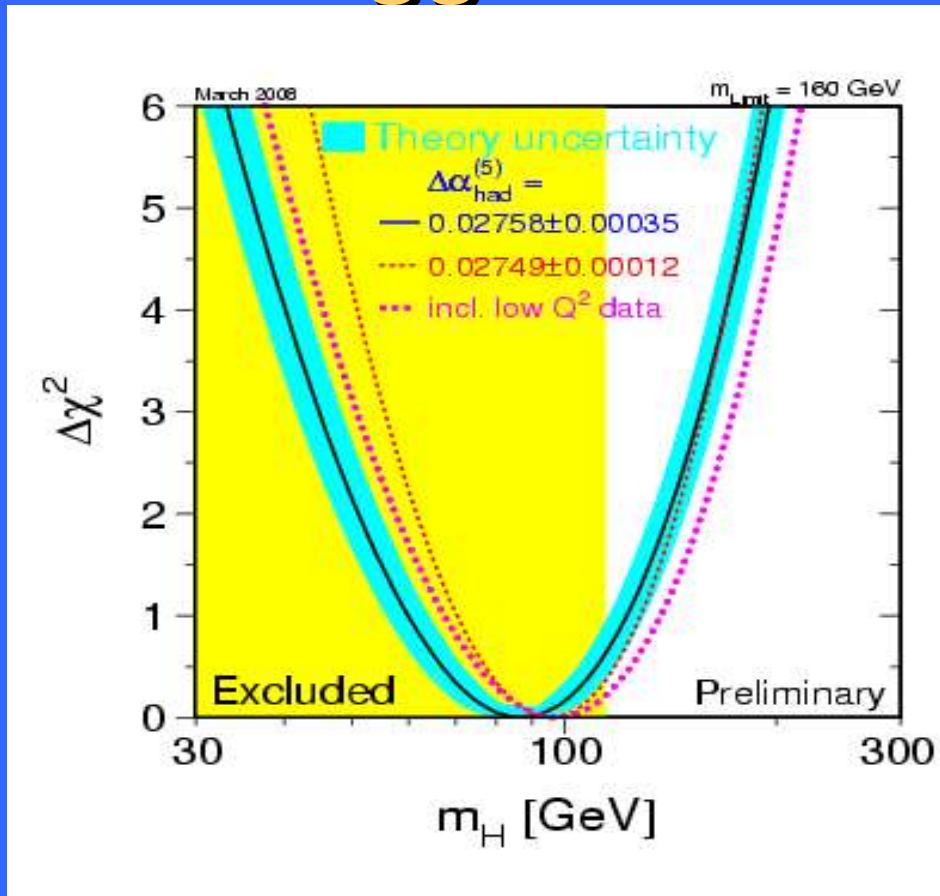
- Introduction
- SM Higgs Search Strategies and Challenges
- CDF and D0 Results with up to 2.4fb^{-1}
- Tevatron Combination
- Future Prospects
- Conclusion

Introduction

- The Standard Model describes nature well in terms of fundamental particles, but provides no explanation about the origin of mass.
- The Higgs mechanism:
 - provides a clue for EWSB
 - predicts the existence of Higgs boson, that has yet observed experimentally.
- LHC has the best shot for Higgs discovery, but Tevatron has lots of data and would be the hunting ground until 2010.
- If Higgs does exist that requires some new physics beyond SM to stabilize its mass, such as SUSY, EDM...

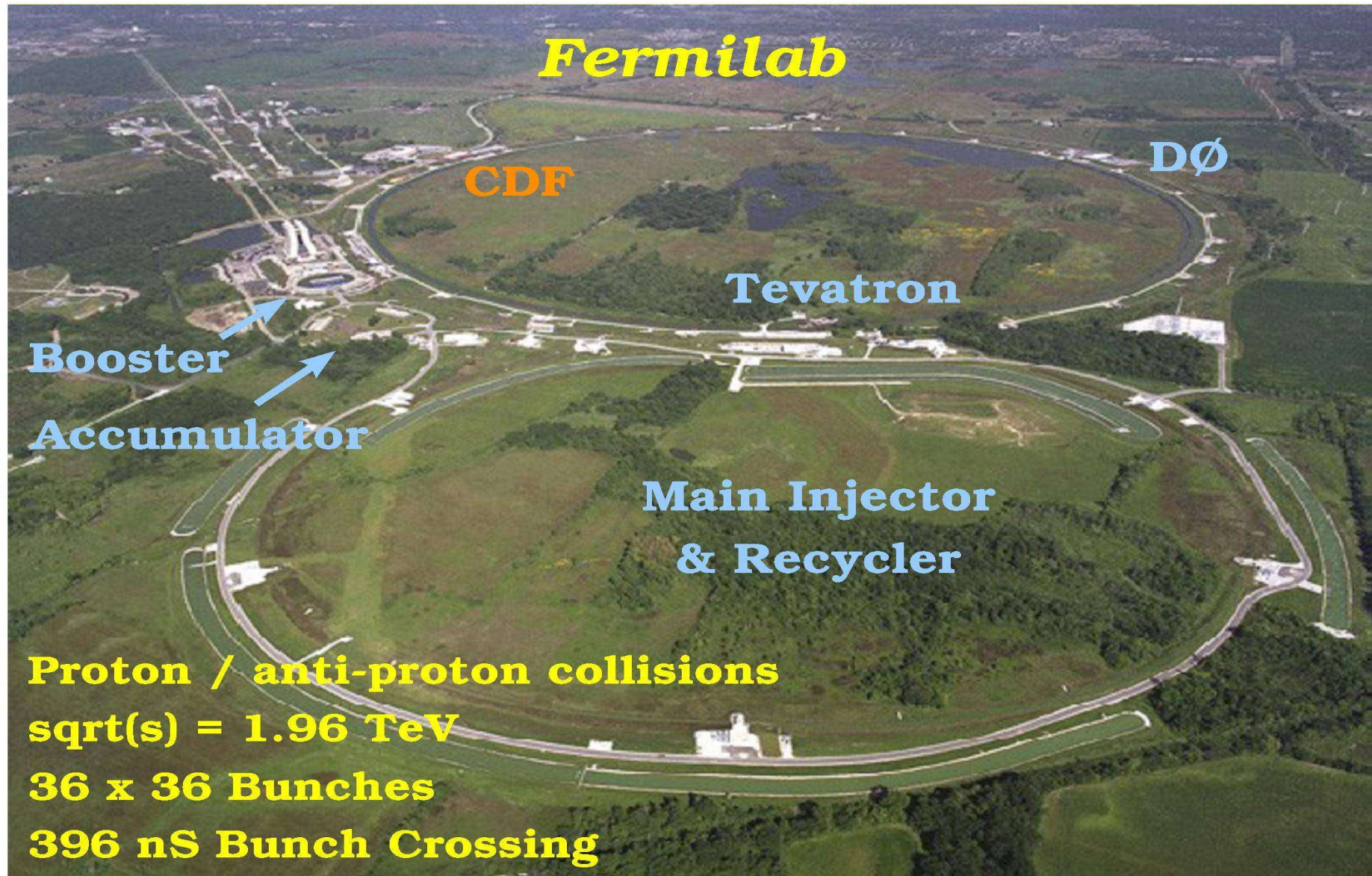


What we know about the Higgs Boson



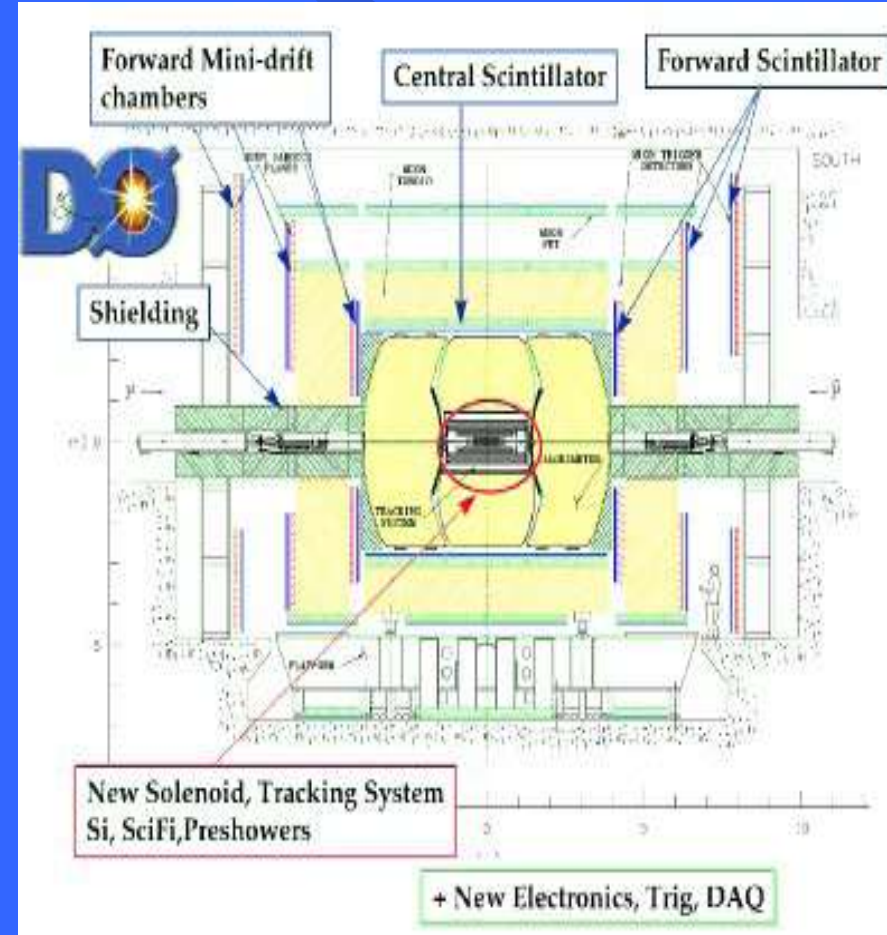
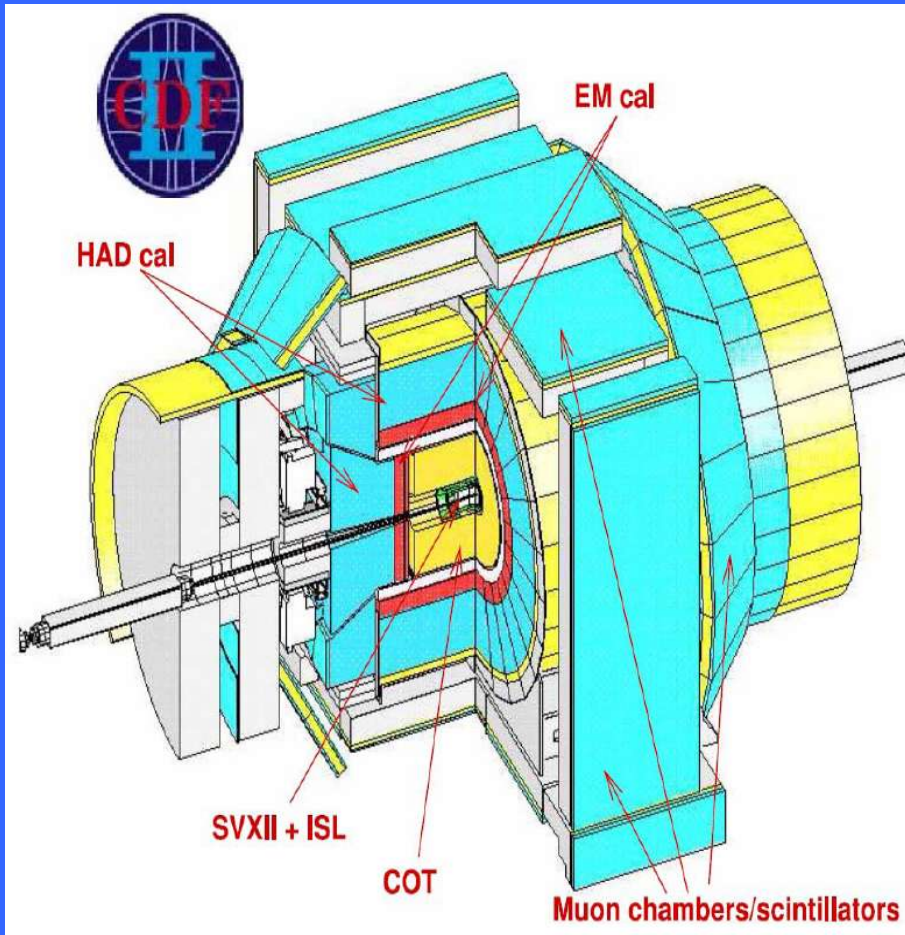
- Direct Searches at LEP: exclude $M_H < 114.4 \text{ GeV}$ at 95% C.L.
- Global fit give best fit of $M_H = 87^{+36}_{-27}$ or $< 160 \text{ GeV}$ at 95% C.L.
- The low-mass Higgs hard to reach with early LHC data.

The Tevatron Complex

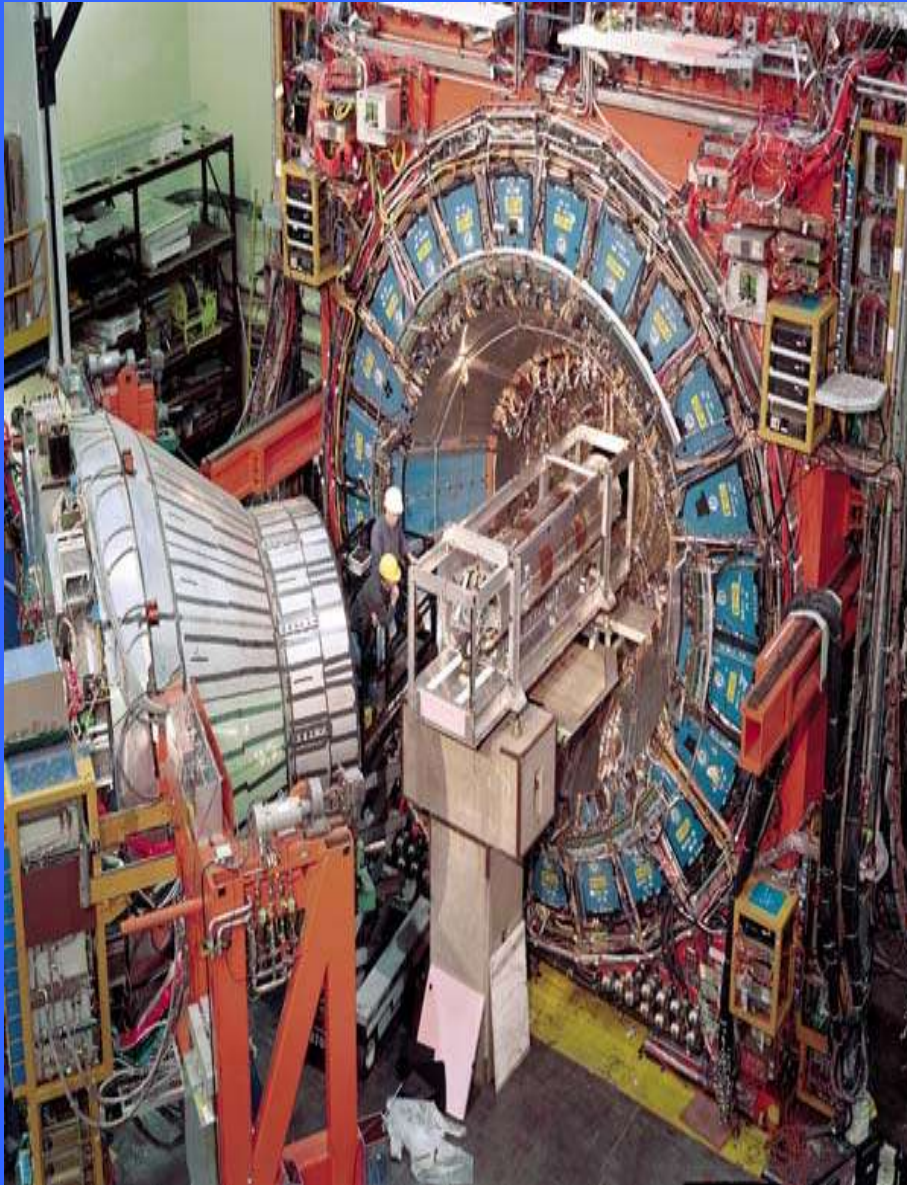


The CDF and D0 Detectors

- Both detectors are upgraded in Run II
- New silicon, central tracking, upgraded μ chamber
- New electronics, Triggers, DAQ upgrades



The CDF and D0 Detectors

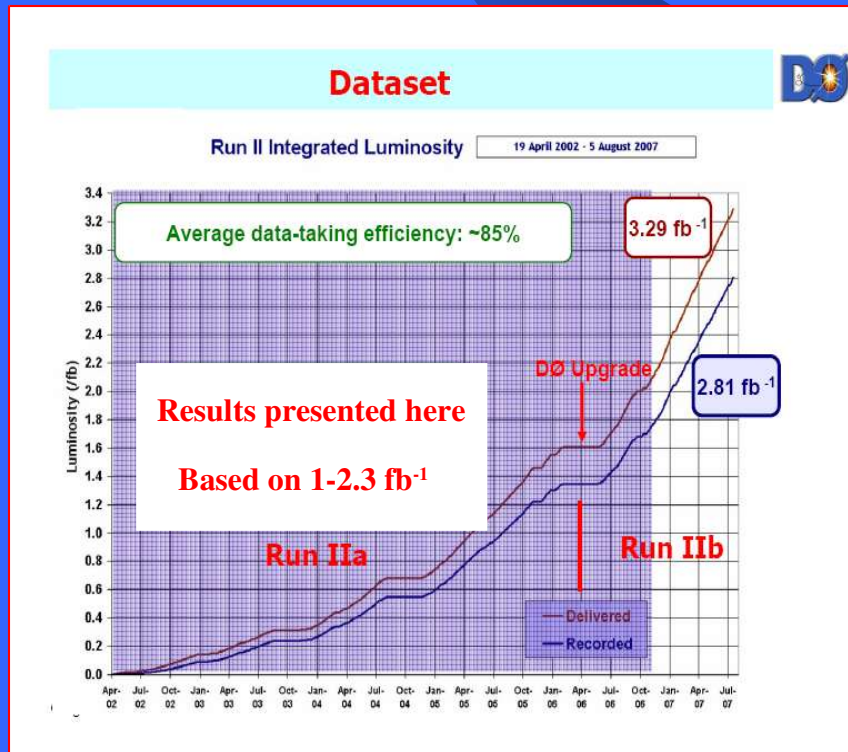
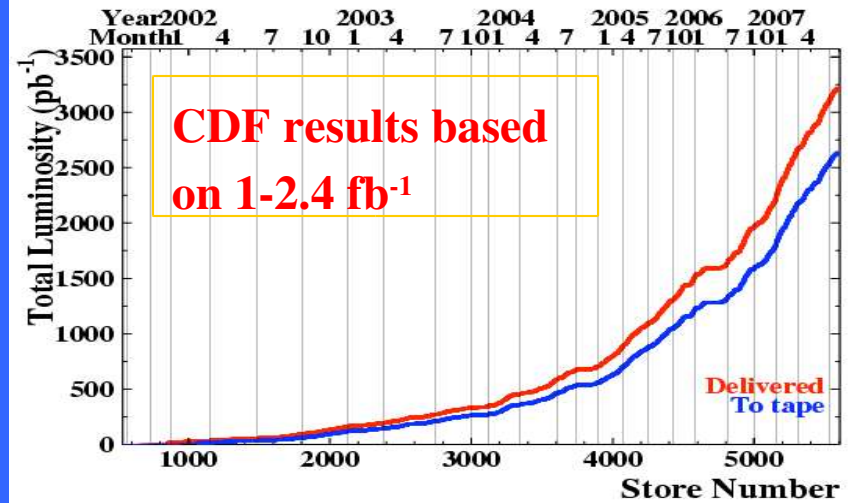
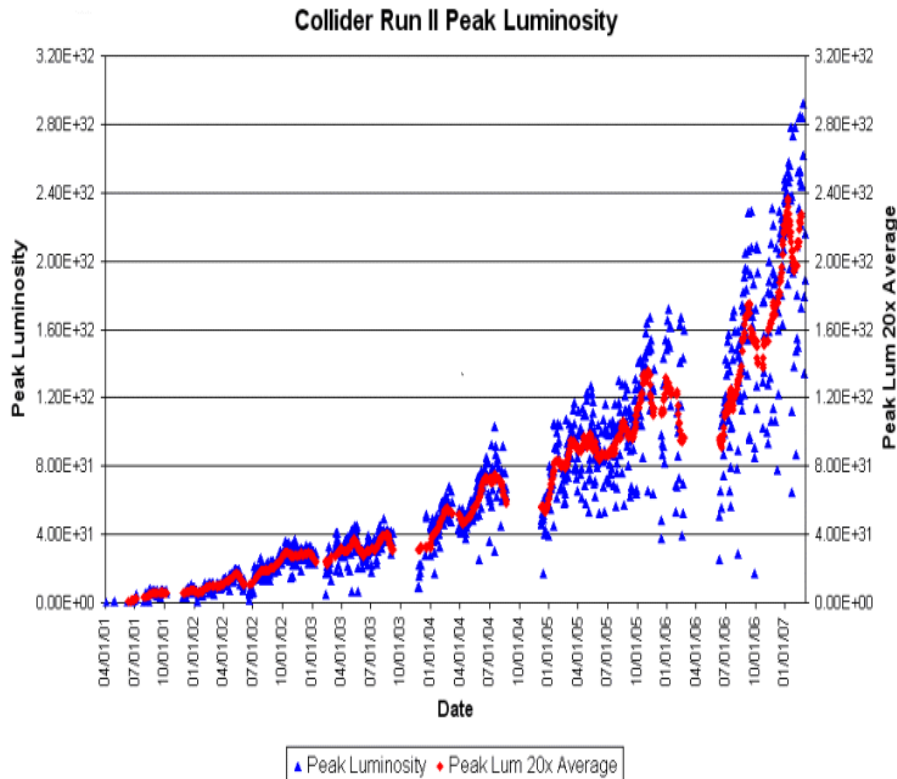


Tevatron Status

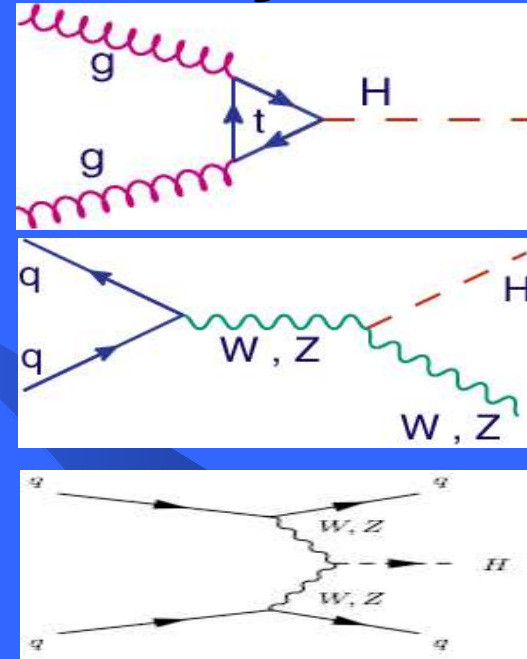
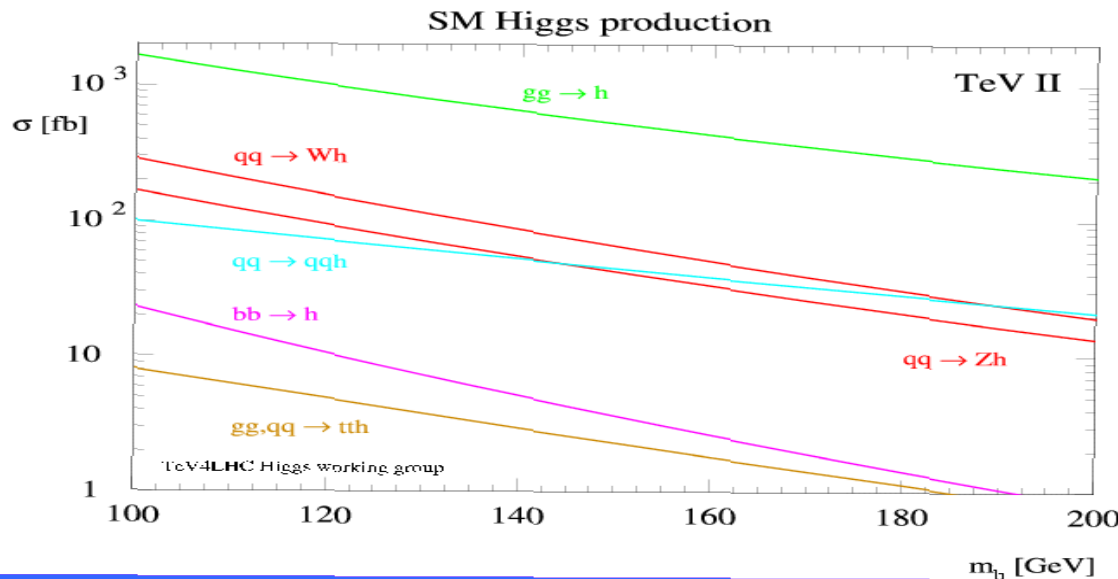
Tevatron are doing great !

Record luminosity: 3.15×10^{32}

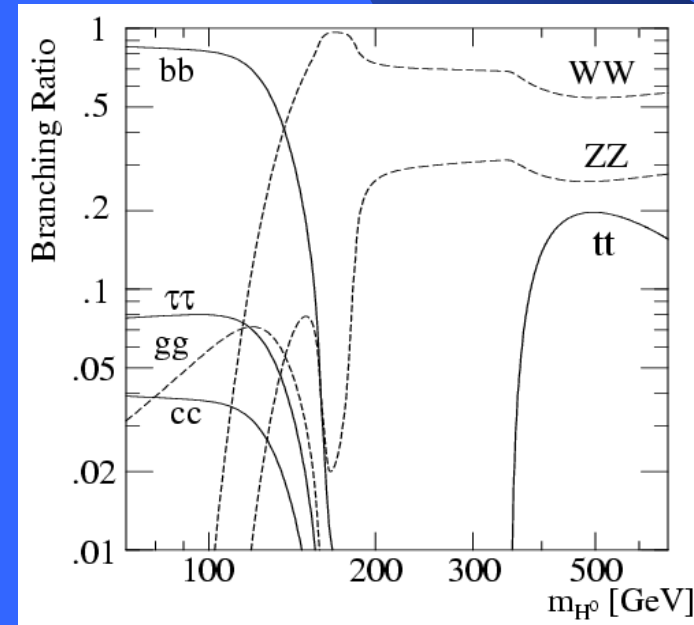
Delivered $>4 \text{ fb}^{-1}$ and will double the dataset if running through 2010



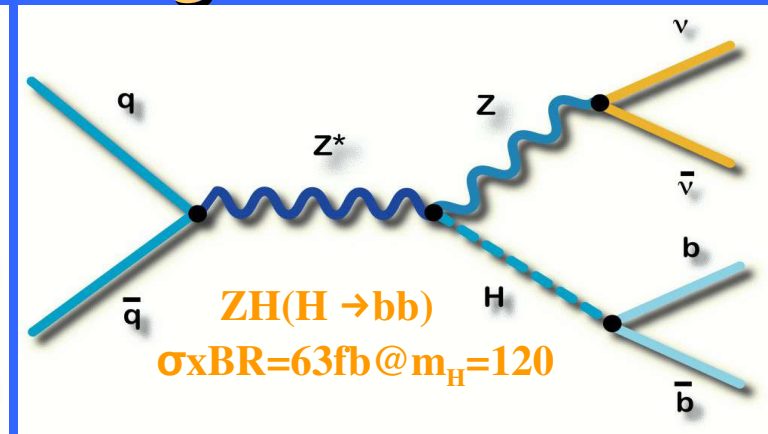
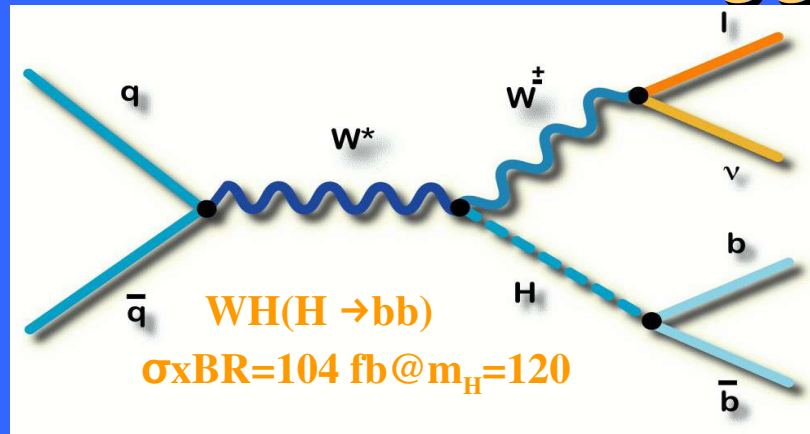
SM Higgs Production and Decays



- $M_H < 135$ GeV: $H \rightarrow bb$
 - $WH \rightarrow l\nu bb$; $ZH \rightarrow \nu\nu bb$, $llbb$ most accessible (easy to trigger)
 - Excellent b-tag and dijet mass
- $M_H > 135$ GeV: $H \rightarrow WW^*$
 - Exploit large σ ($gg \rightarrow H$)
 - $H \rightarrow WW \rightarrow l\nu l\nu$: clean final states



Low Mass Higgs Signatures



➤ **WH $\rightarrow l\nu$ bb: 1 Lepton(Isotr)+Met+2b**

➤ **ZH $\rightarrow ll$ bb: 2 Leptons +2b**

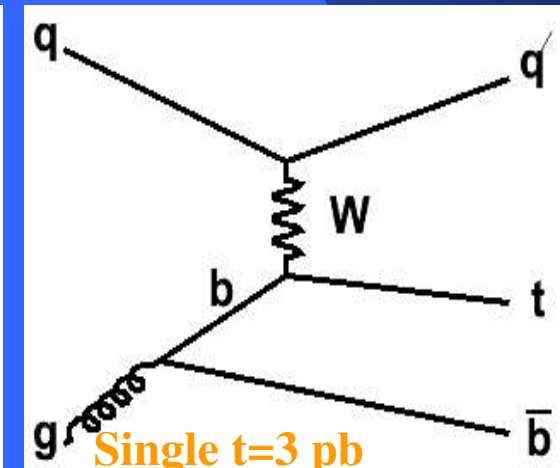
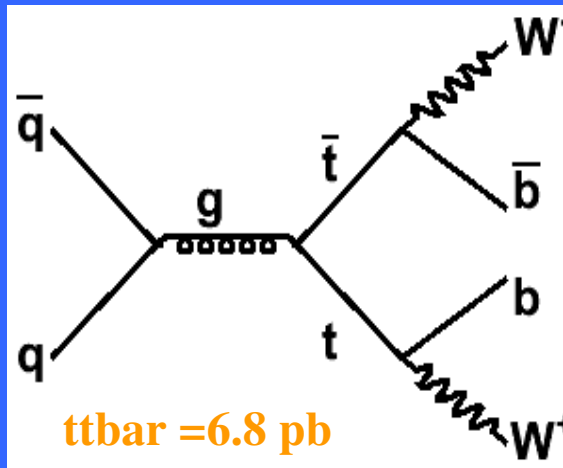
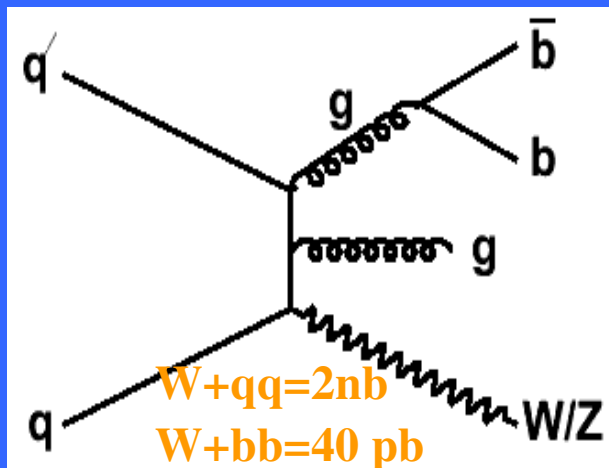
➤ **WH $\rightarrow (l)\nu$ bb, ZH $\rightarrow \nu\nu$ bb: Met +2b**

➤ **Major Backgrounds: Wbb, ttbar, single-top, QCD...**

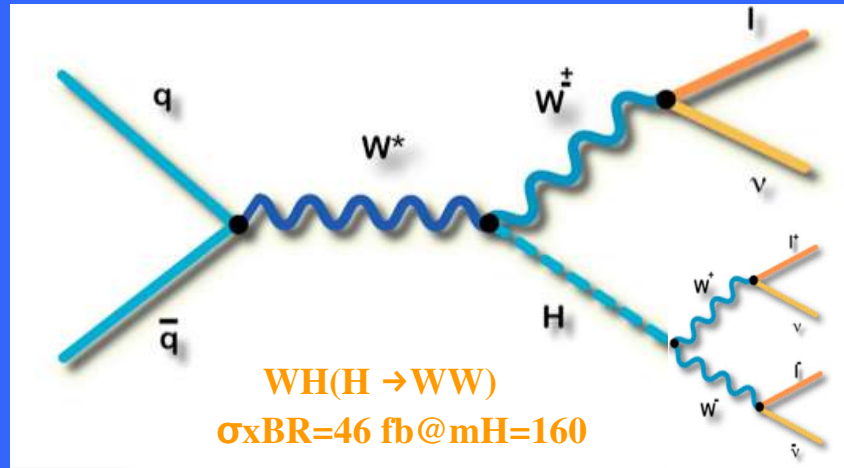
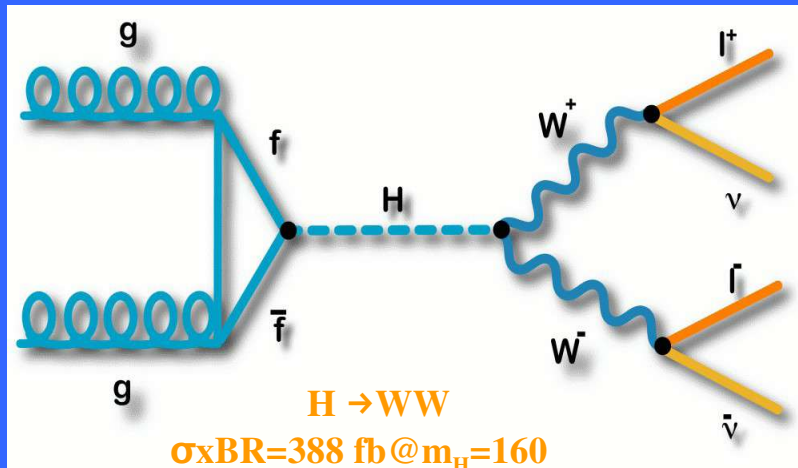
➤ **(V)H $\rightarrow \tau\tau$ +2jets: $\tau_{lep}\tau_{had}$ +2jets**

➤ **VH $\rightarrow jj$ bb: 4jets**

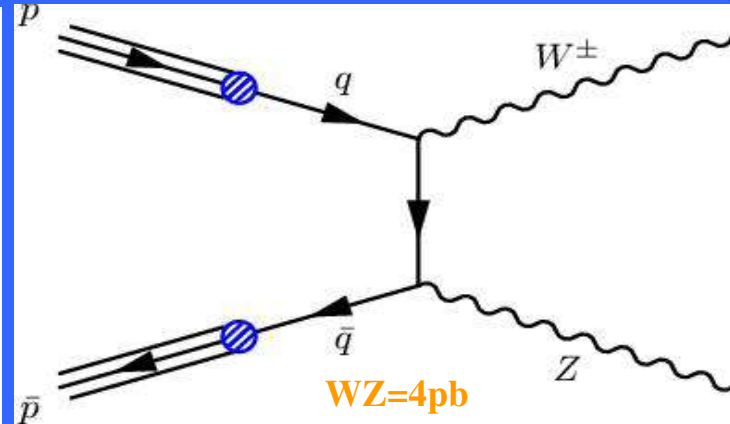
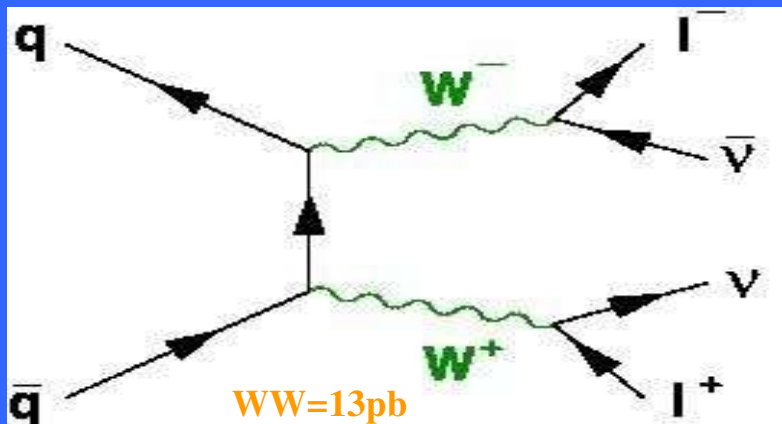
➤ **H $\rightarrow \gamma\gamma$: di-photon**



High Mass Higgs Signatures

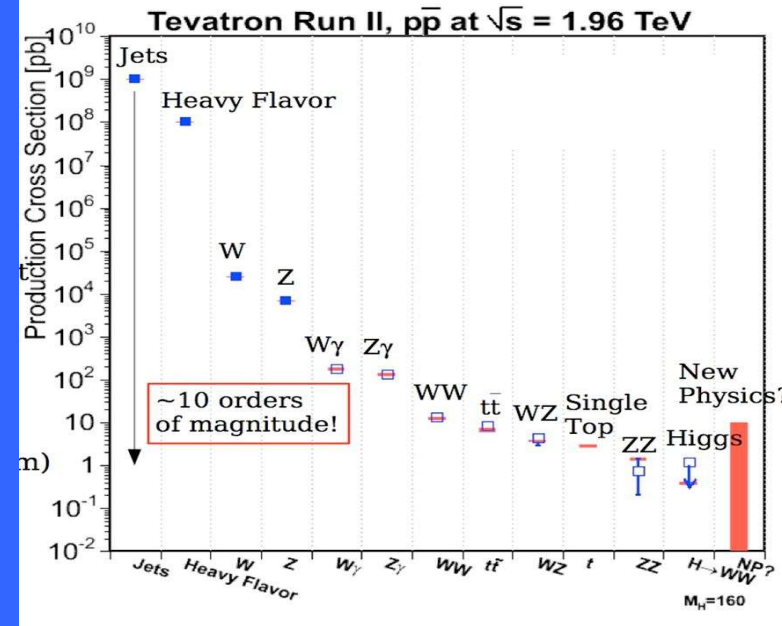
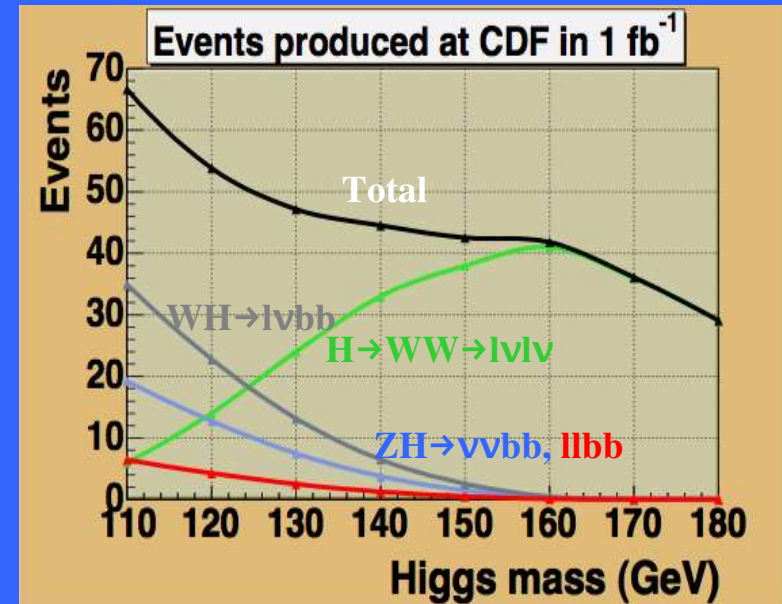


- $H \rightarrow WW^* \rightarrow ll\nu\nu$: 2 opp-sign Leptons + Met
- $WH \rightarrow WW^* \rightarrow l^\pm l^\pm \nu\nu X$: 2 same-sign Leptons + Met
- Major Backgrounds: WW , WZ , ZZ , top, QCD...



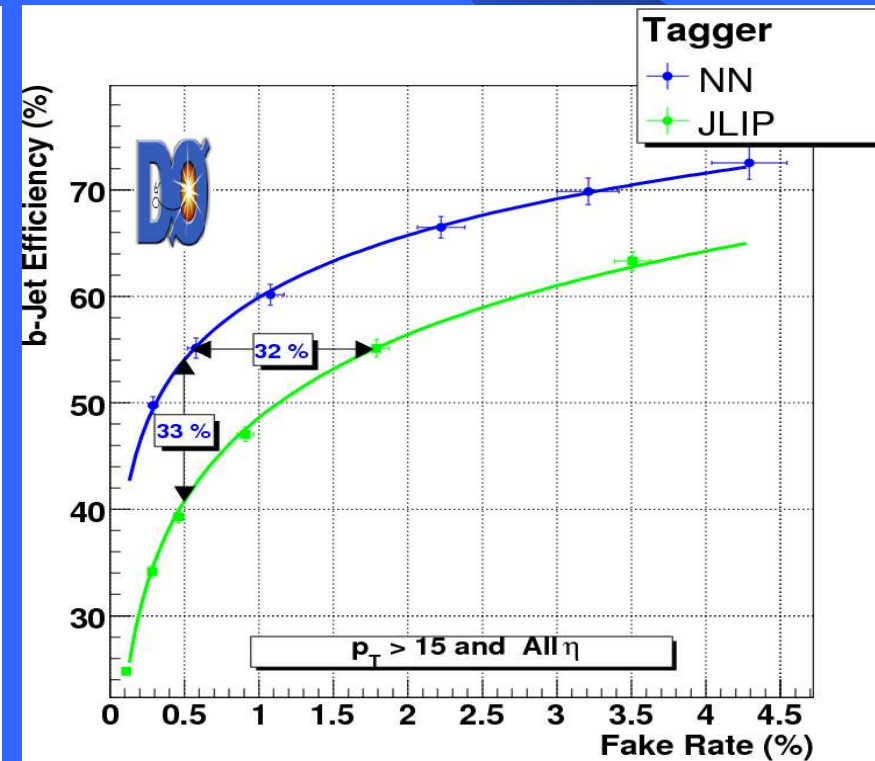
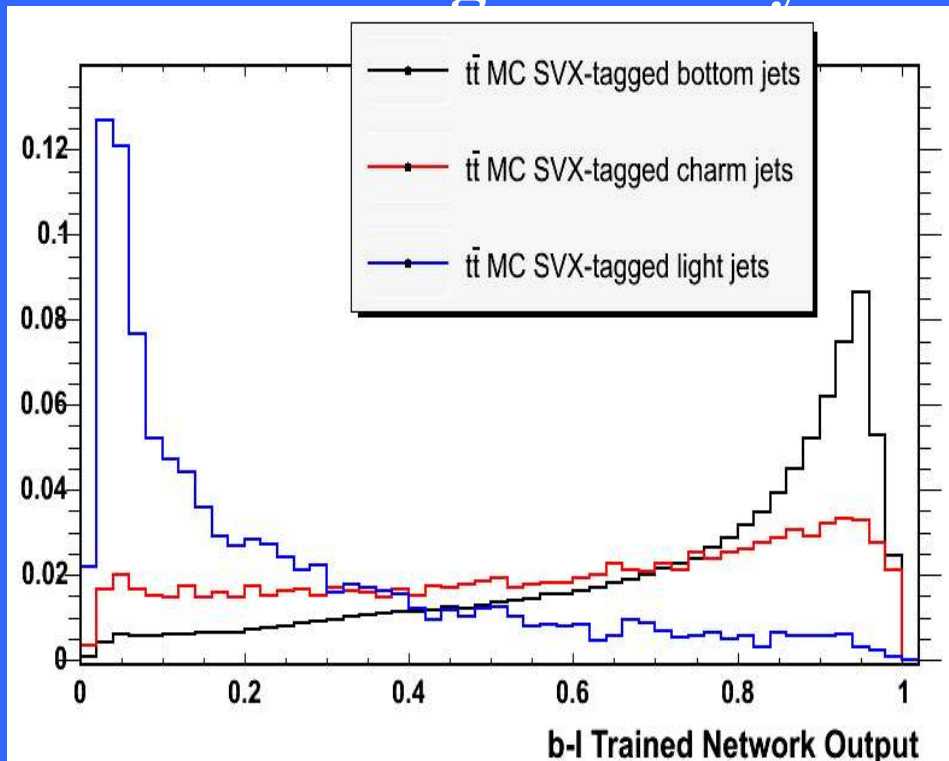
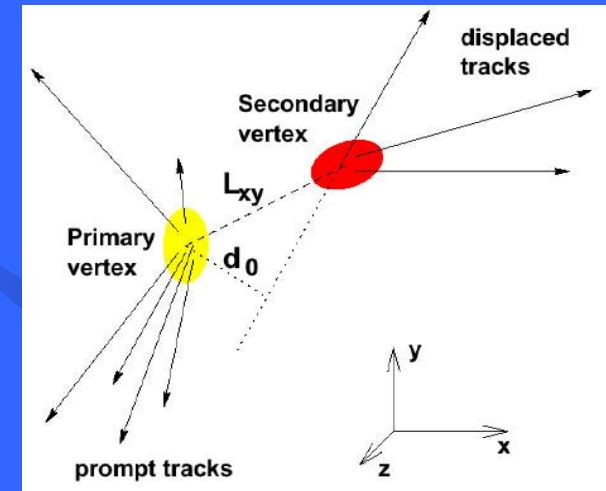
The Search Strategies...

- SM Higgs production rate is very small at the Tevatron.
- There are huge backgrounds with many orders of magnitude higher.
- Strategies: **to achieve $>10^{10}$ signal to background rejection**
 - Focus on final states with leptons
 - Selecting events with large met
 - Require btagging and good M_{bb}
 - Using more advanced techniques
- Discovery Higgs at Tevatron is extremely challenge that requires the best of all these and lots of data.



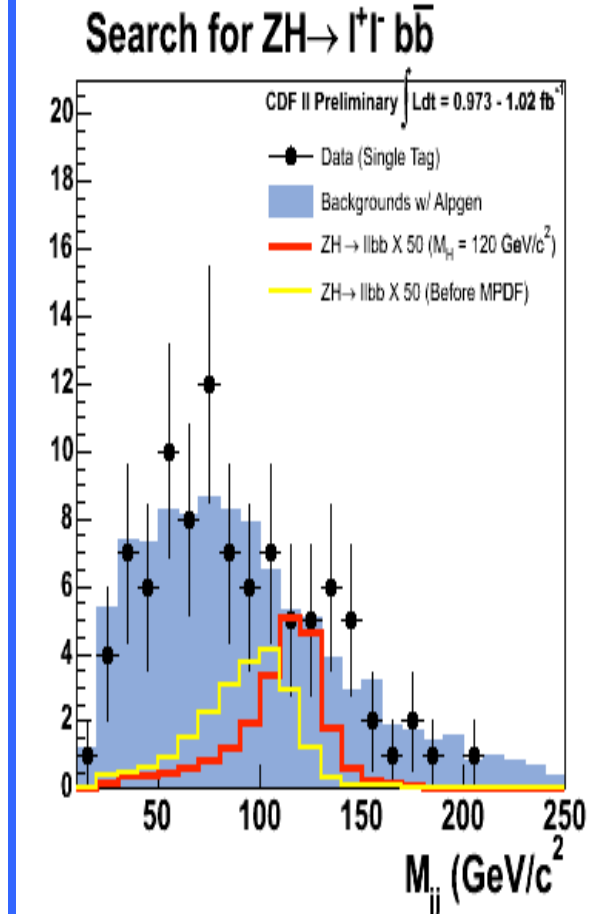
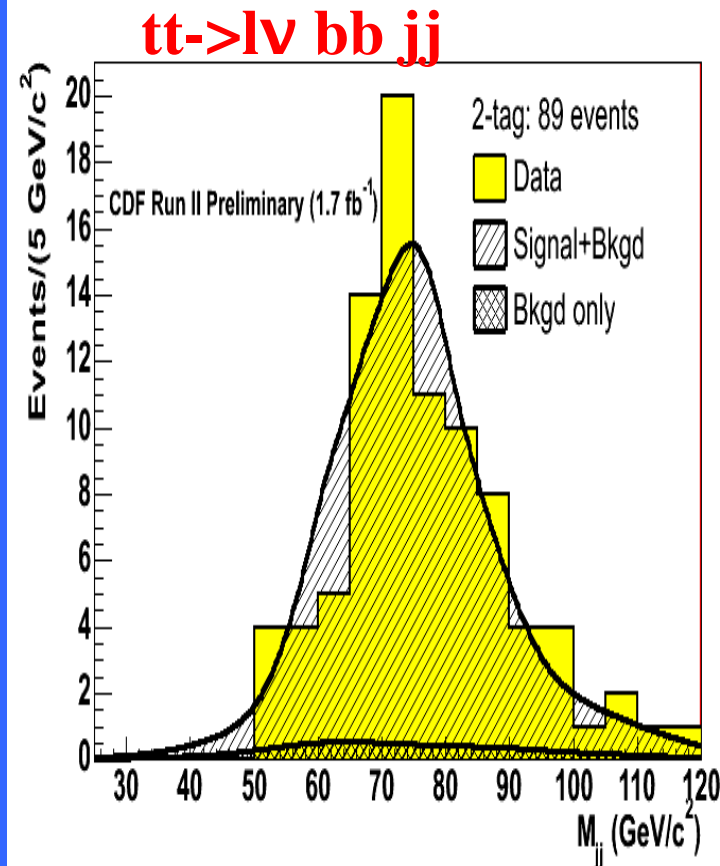
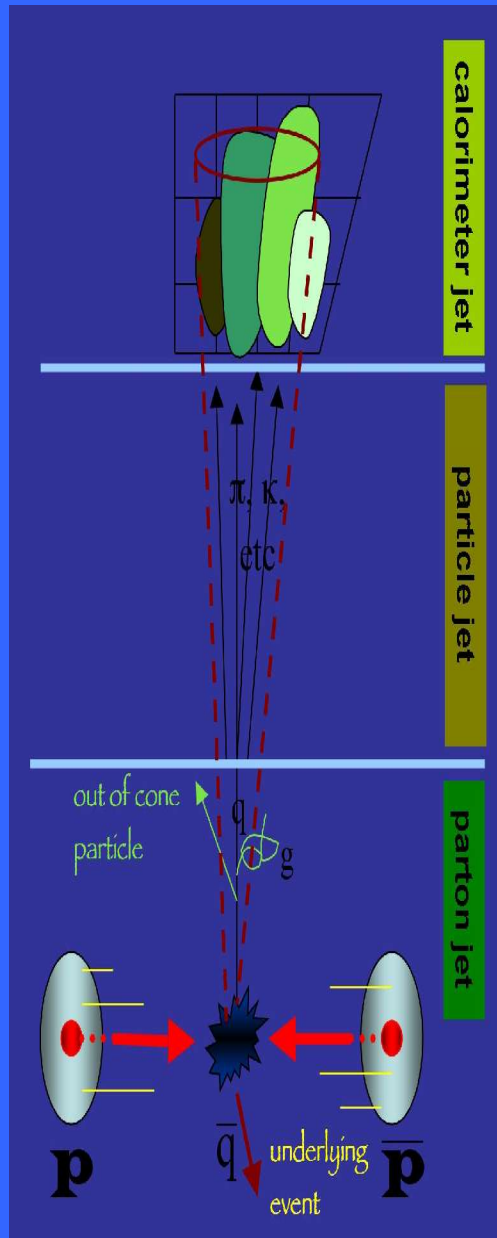
B-jet Identification (B-tagging)

- B-hadron are long-lived – search for displaced tracks/vertex inside the jet
- Combining existing taggers with neural network: to purify mistags or increase btag efficiency



Jet Energy Resolution (Di-jet Mass)

- Jet Et depends on the cal. response to hadrons: energy scale, non-linearity, out-cone, underlying activities.
- Particle flow, b-jet specific correction, and more advanced techniques would help...



Advanced Multivariate Techniques

➤ In order to suppress large background, we use various advanced multivariate techniques

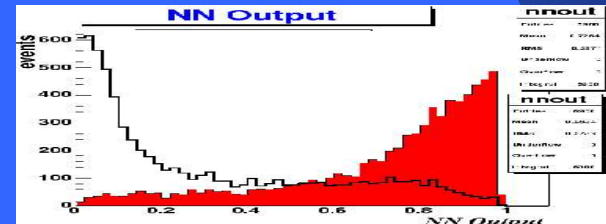
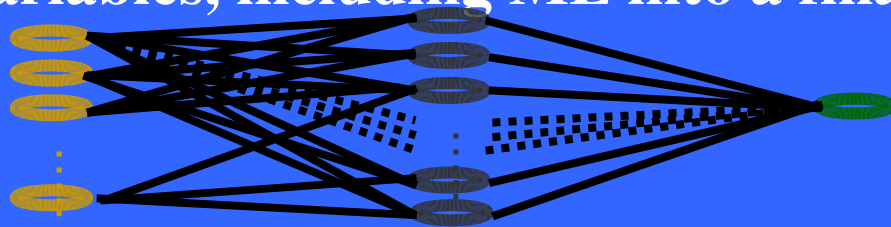
➤ LO Matrix Elements (ME): are used to calculate event probabilities and calculate likelihood ratio:

$$P_m(x_{obs}) = \frac{1}{\langle \sigma_m \rangle} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

ME efficiency resolution

$$LR(x_{obs}) \equiv \frac{P_H(x_{obs})}{P_H(x_{obs}) + \sum_i k_i P_i(x_{obs})}$$

➤ Neural network (NN): combine various kinematic variables, including ME into a final discriminant variable.

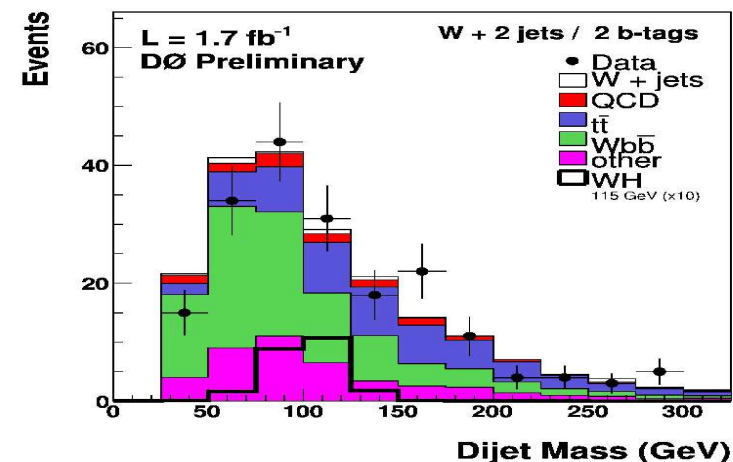
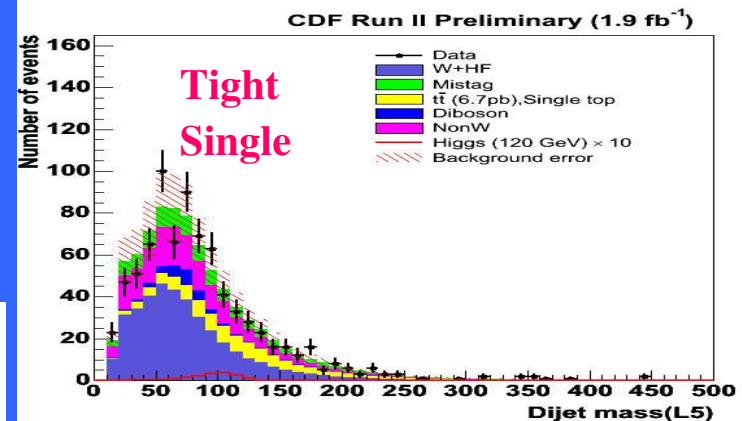
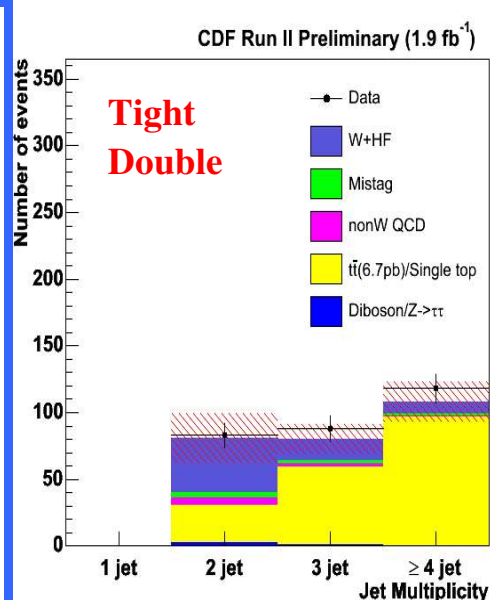
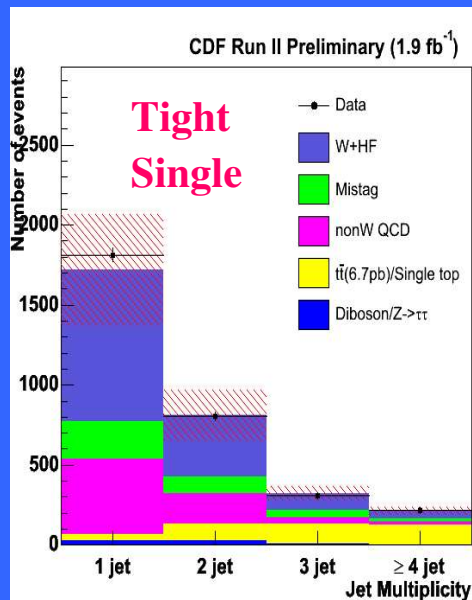
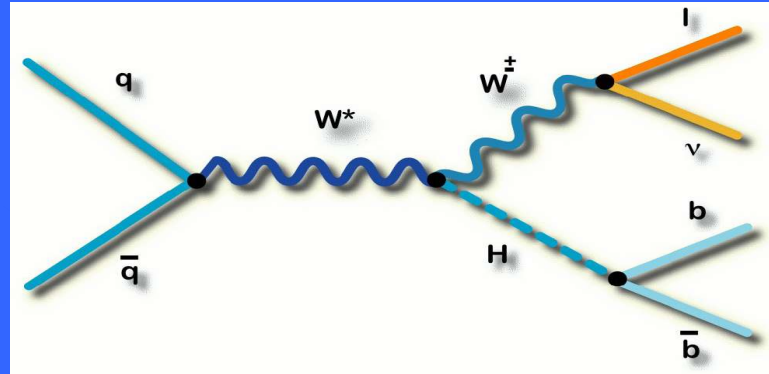


➤ Boosted Decision Tree(BDT): an alternative to NN

➤ On-going intense optimization efforts in terms of trigger, lepton selections, btagging, and dijet mass resolution.

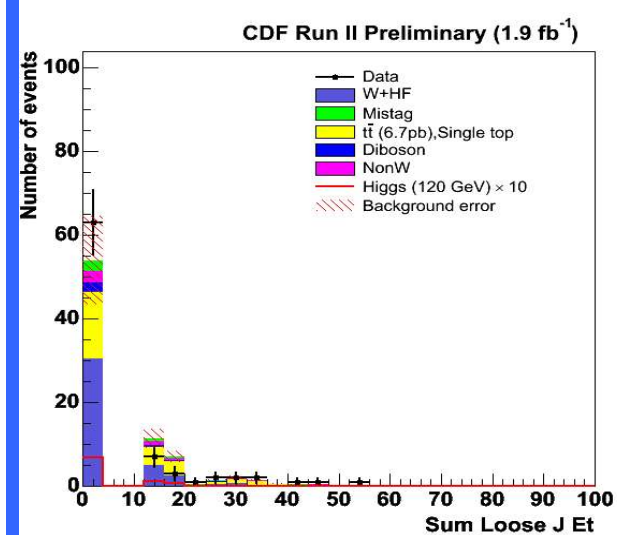
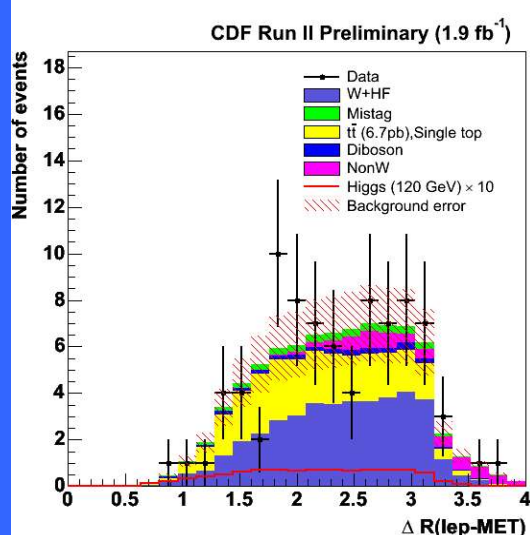
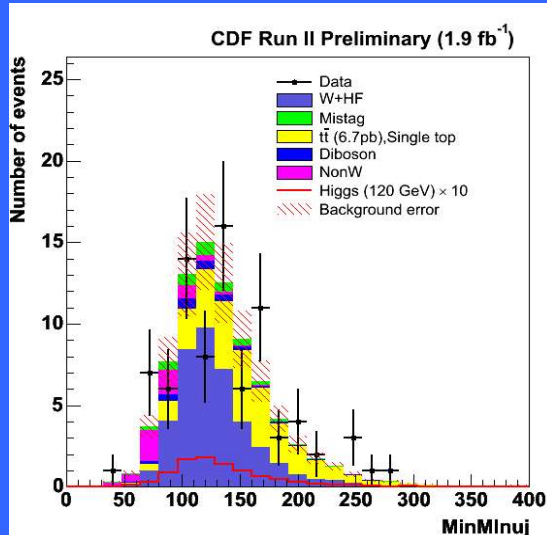
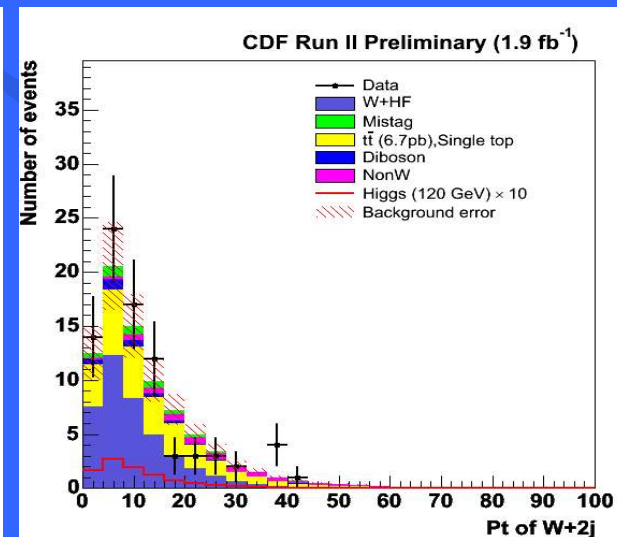
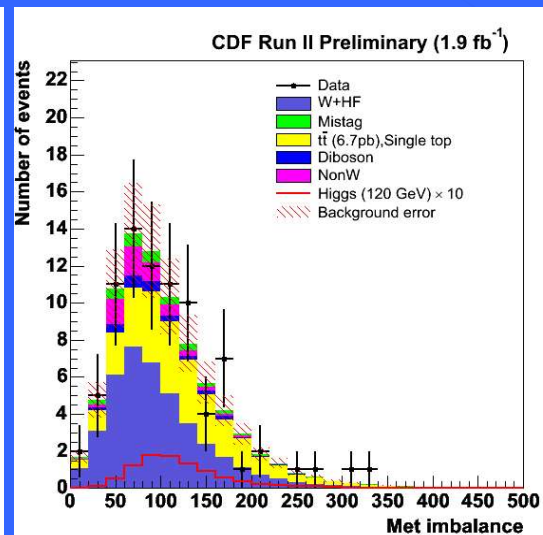
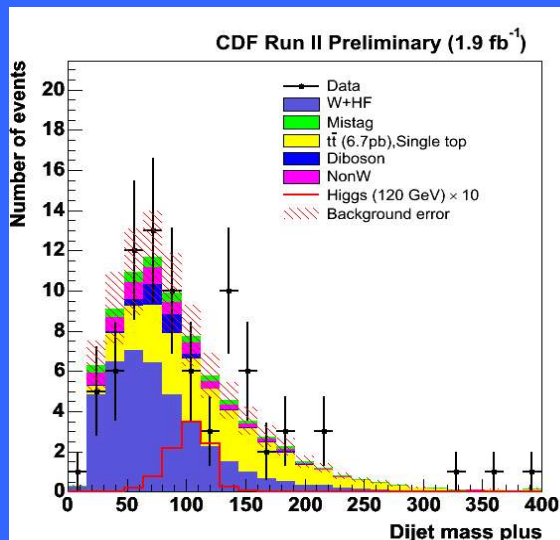
Search for $WH \rightarrow l\nu b\bar{b}$

- Selecting W+2jets:
 - 1 Isolated high Pt lepton (>20 GeV)
 - Large missing $E_t > 20$ GeV
 - 2 jets with $E_t > 20$ GeV and $|\eta| < 2$
- Btagging: 2b(tight+loose) + 1b(tight)
- W+bb: dominant and irreducible
- Data consistent with SM backgrounds
- Discriminant: dijet mass + kinematics

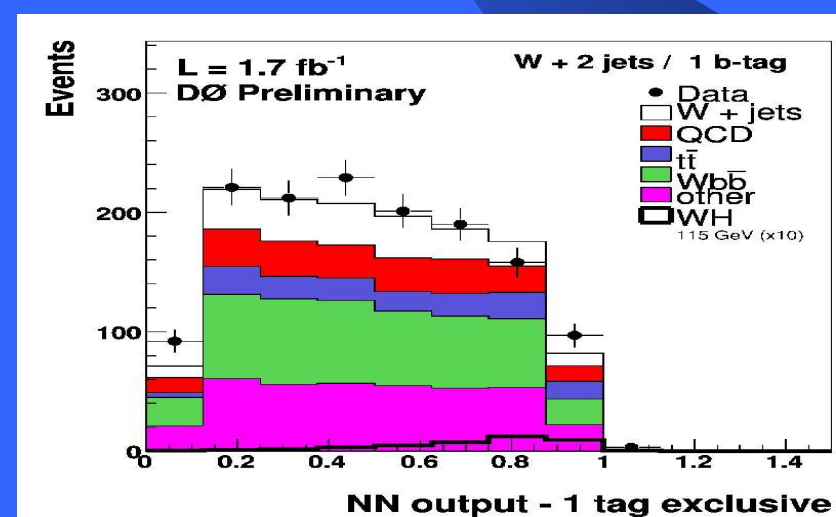
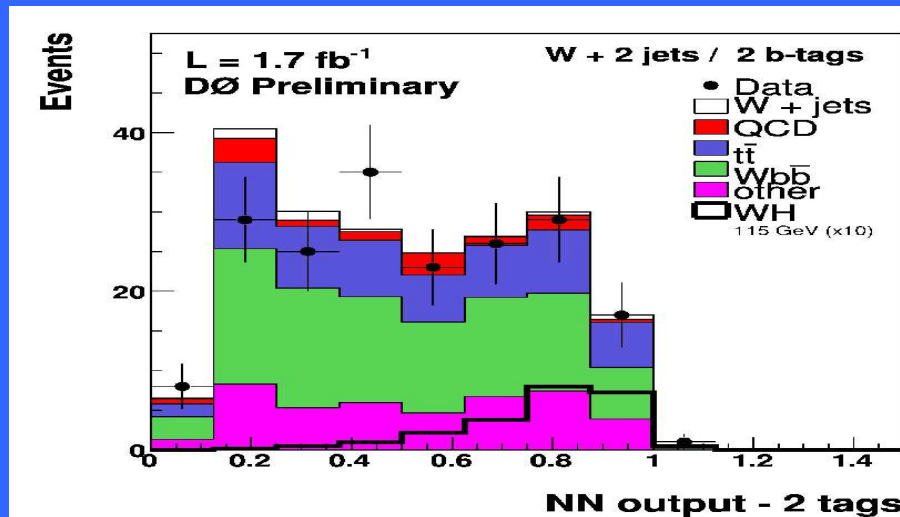
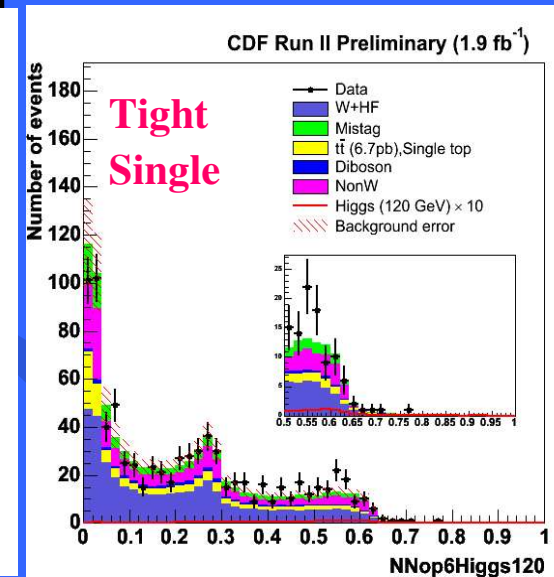
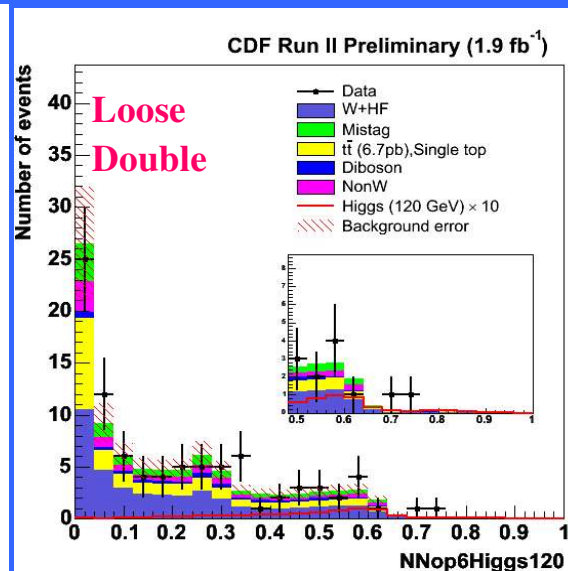
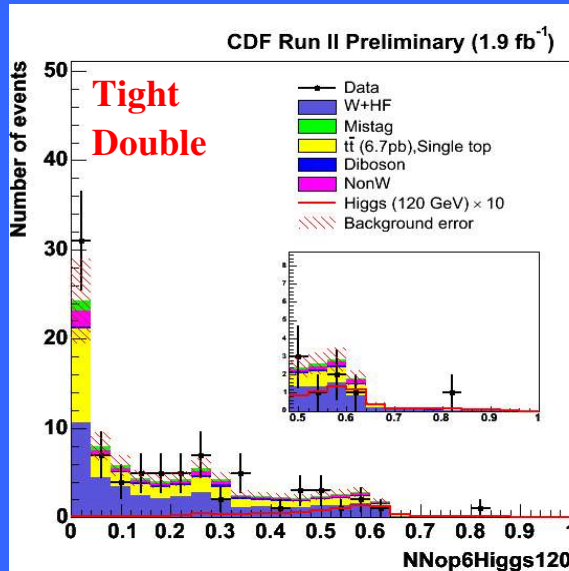


Discriminating Signal from Background

- Validation data with Monte Carlo background modeling
- Combine 6 variables with ANN to optimize sensitivity



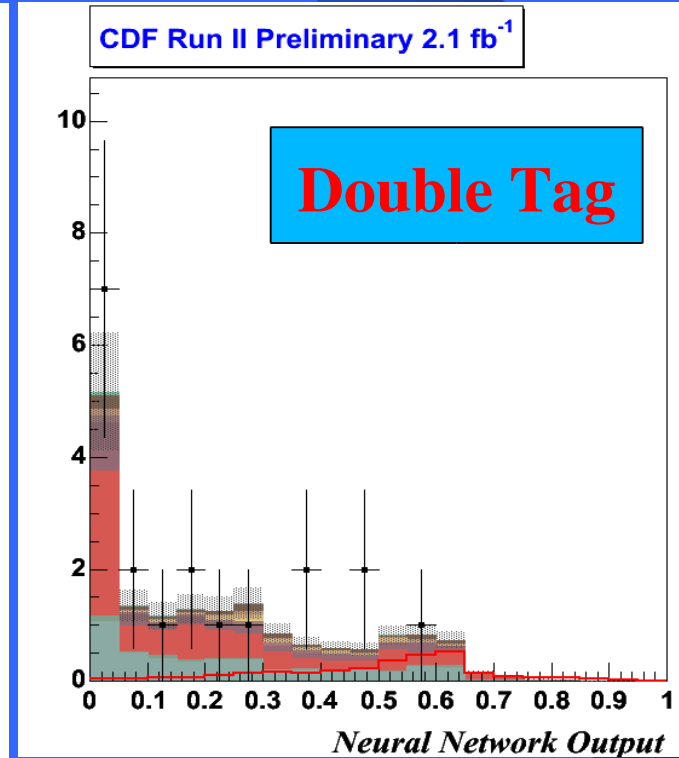
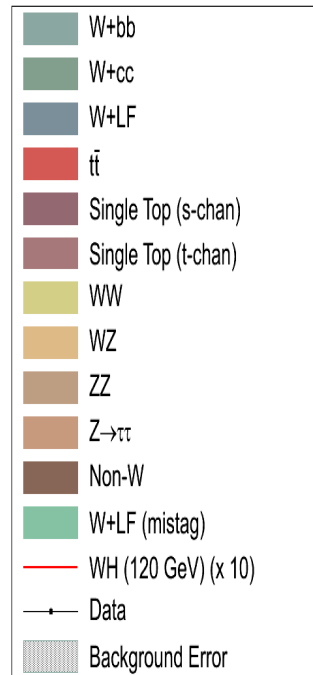
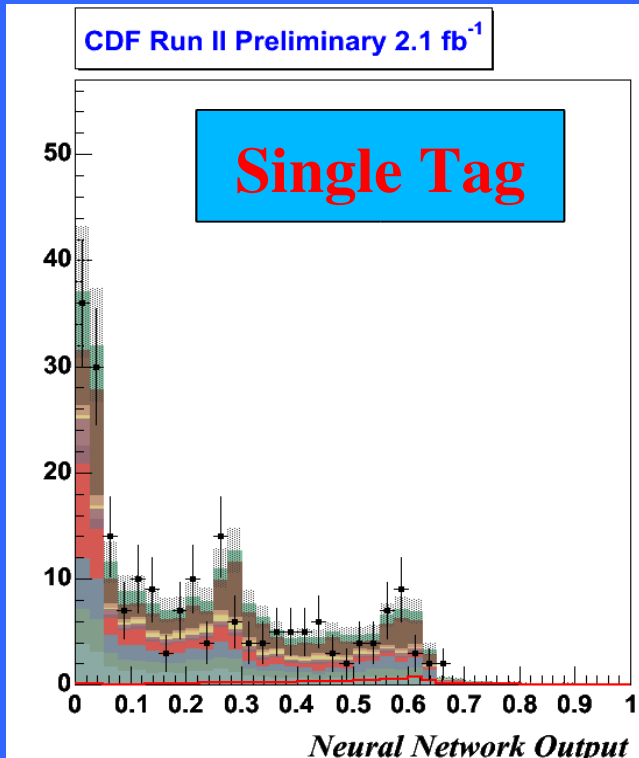
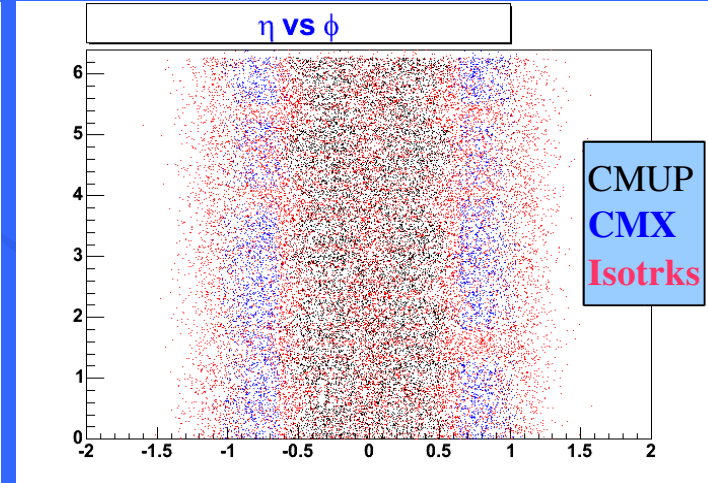
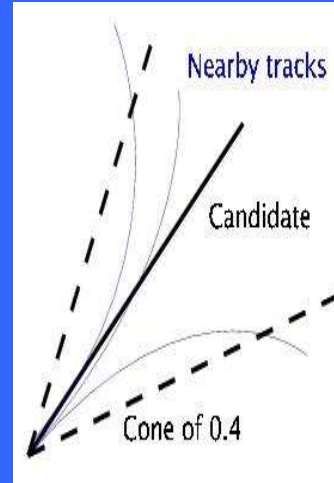
Neural Network Output



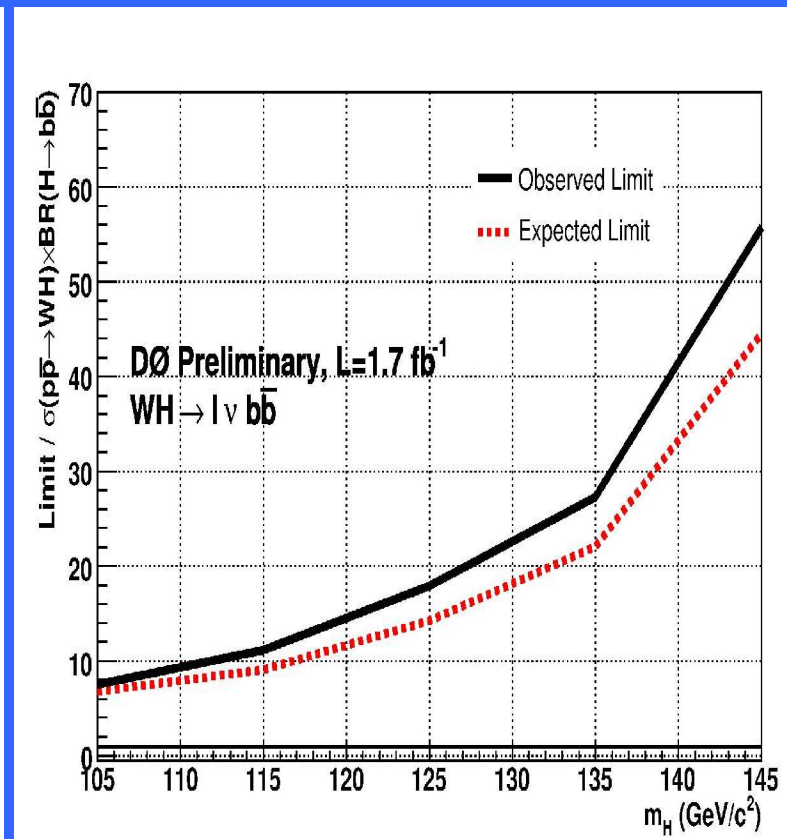
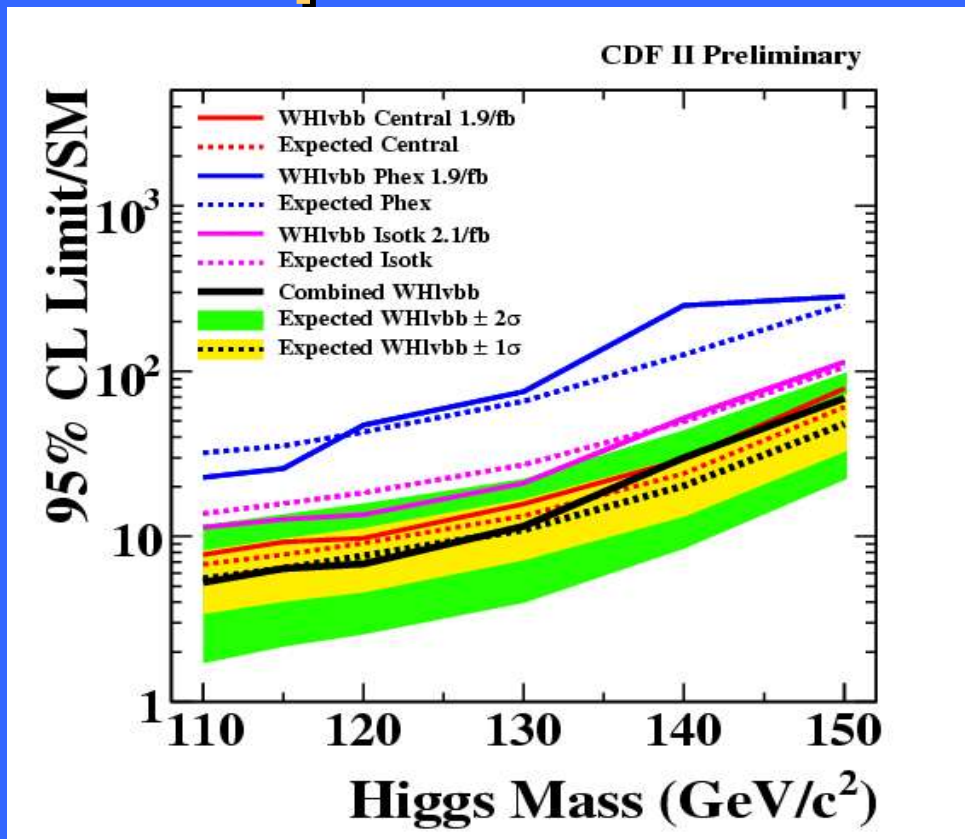
- Improves sensitivity by 10% over dijet mass alone
- Analysis refinement and optimization still ongoing

Extended Lepton Coverage with Isolated Track(CDF) New

- Identify high-Pt, isolated track lepton not fiducial to μ chamber
- Require $\Sigma Pt/Pt_{\text{cand}} < 0.1$
- New trigger: Met+2jets(>40)
- 25% increase in $WH \rightarrow lvbb$ acceptance with similar purity



Expected and Observed Limits

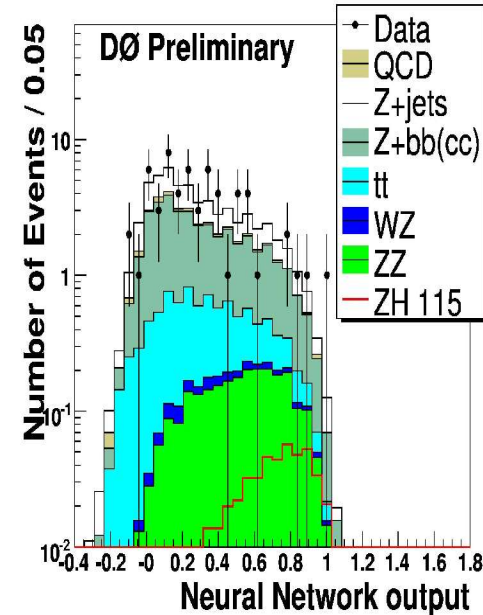
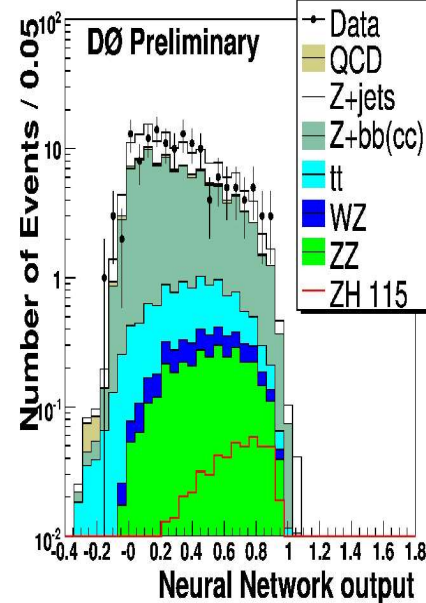
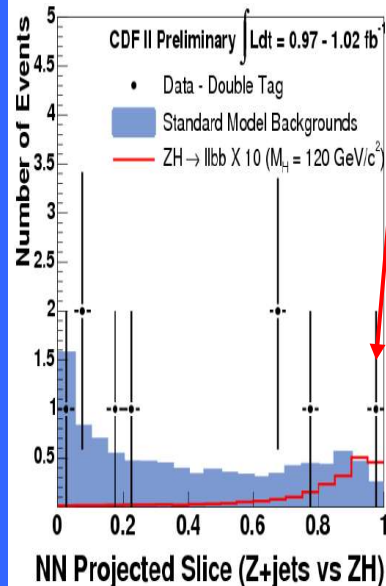
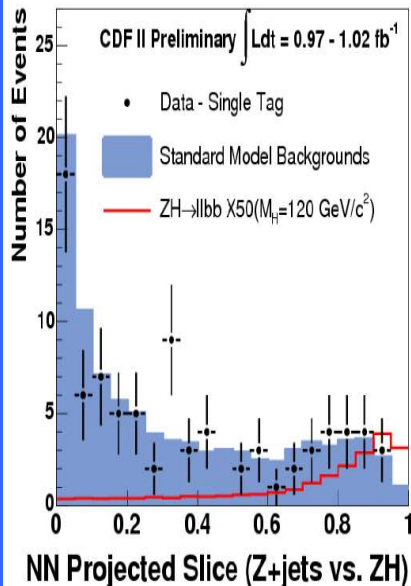
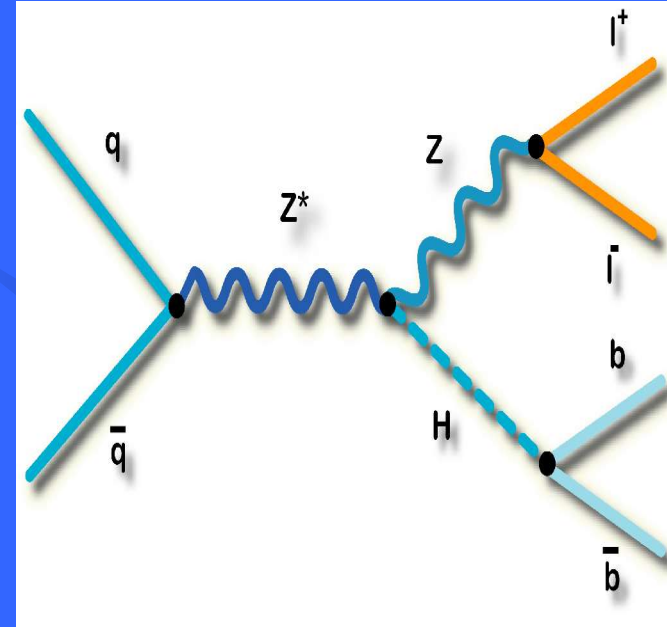


- CDF observed/expected limit: 6.4/6.4 x SM at $m_H=115 \text{ GeV}$
- D0 observed/expected limit: 11/9 x SM at $m_H=115 \text{ GeV}$.
- CDF sensitivity improved by 80% over $\sqrt{L}$ since summer 06
- Future improvements: improving btagging, dijet mass resolution and combination with ME analysis ...

Search for $ZH \rightarrow l\bar{l}b\bar{b}$

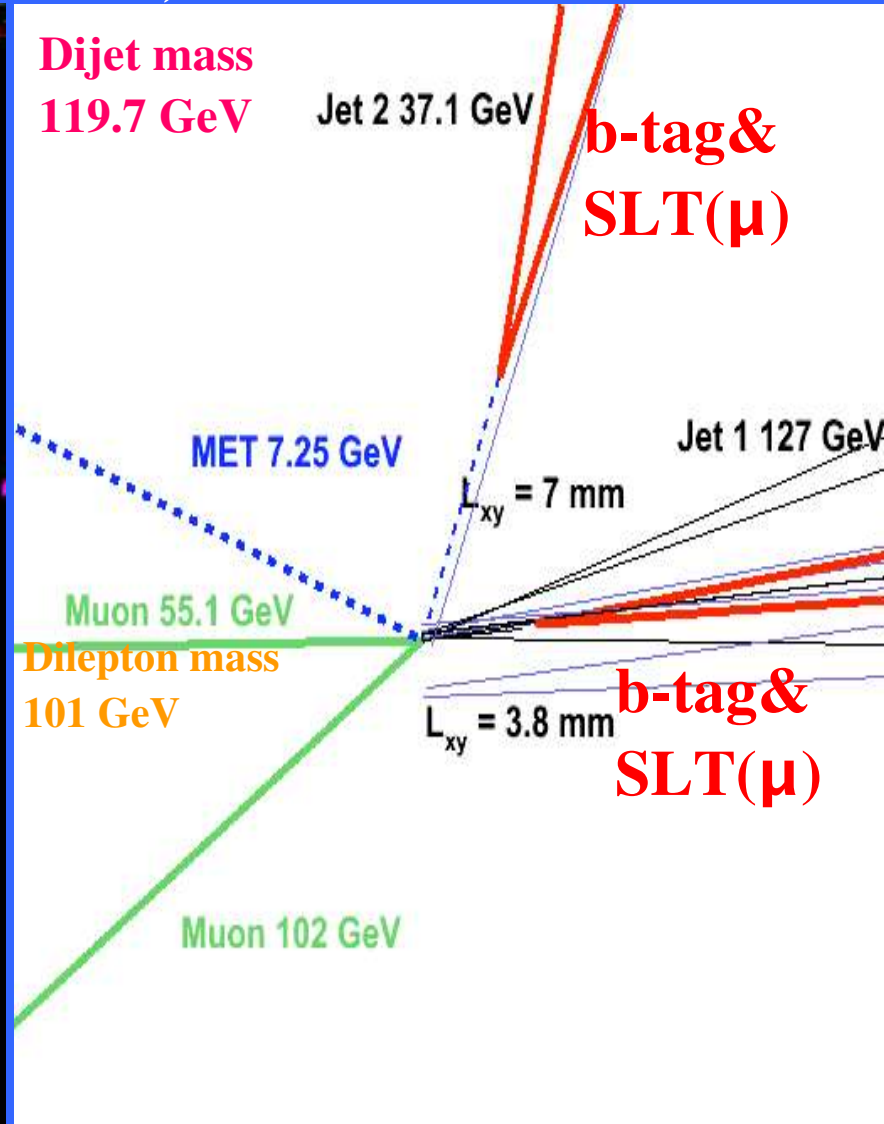
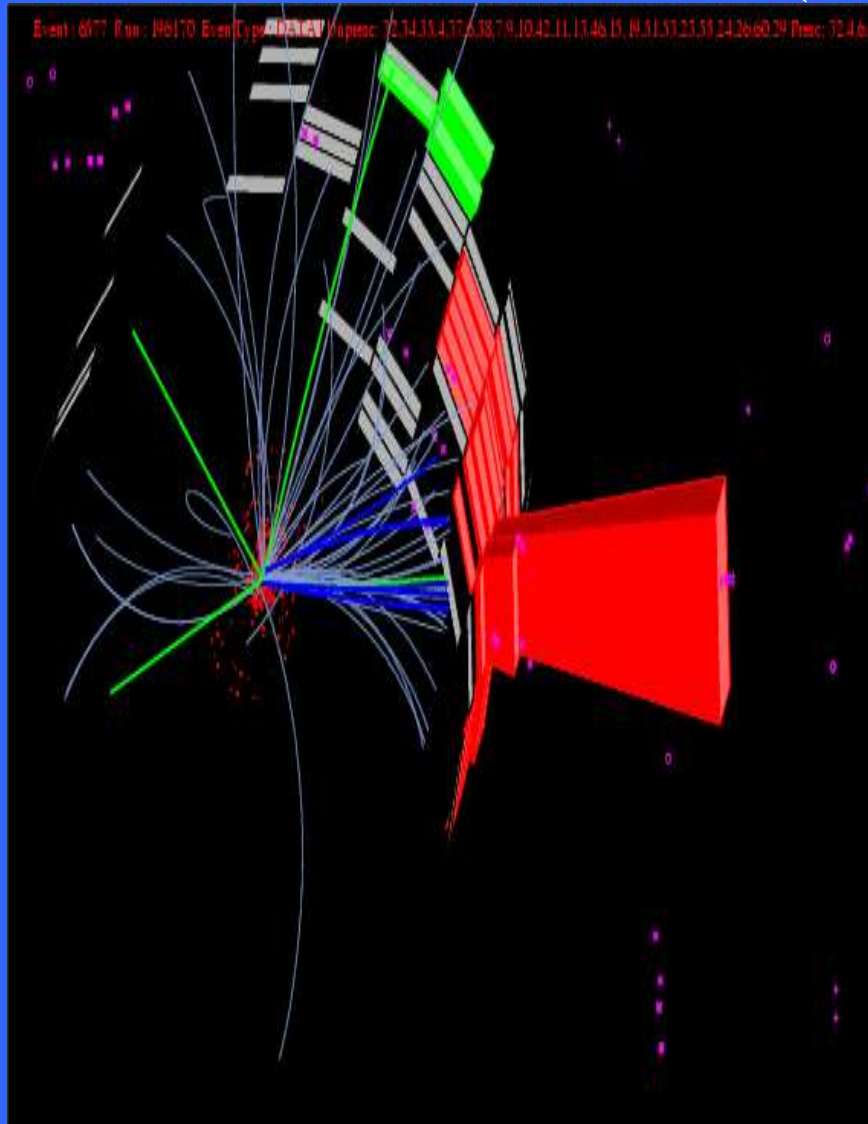
- Low event rate but clean signature
- Select two high Pt leptons from Z
- Split off 1 or 2 b-tags
- Improve dijet mass using measured missing Et.
- NN trained to separate ZH from top and Z+jets backgrounds.

Higgs-like event

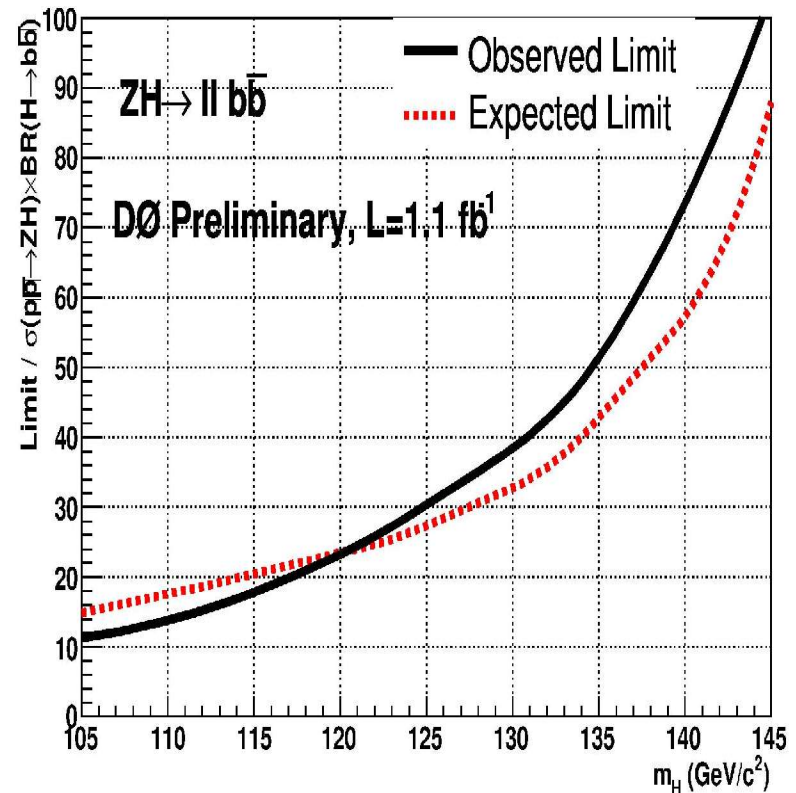
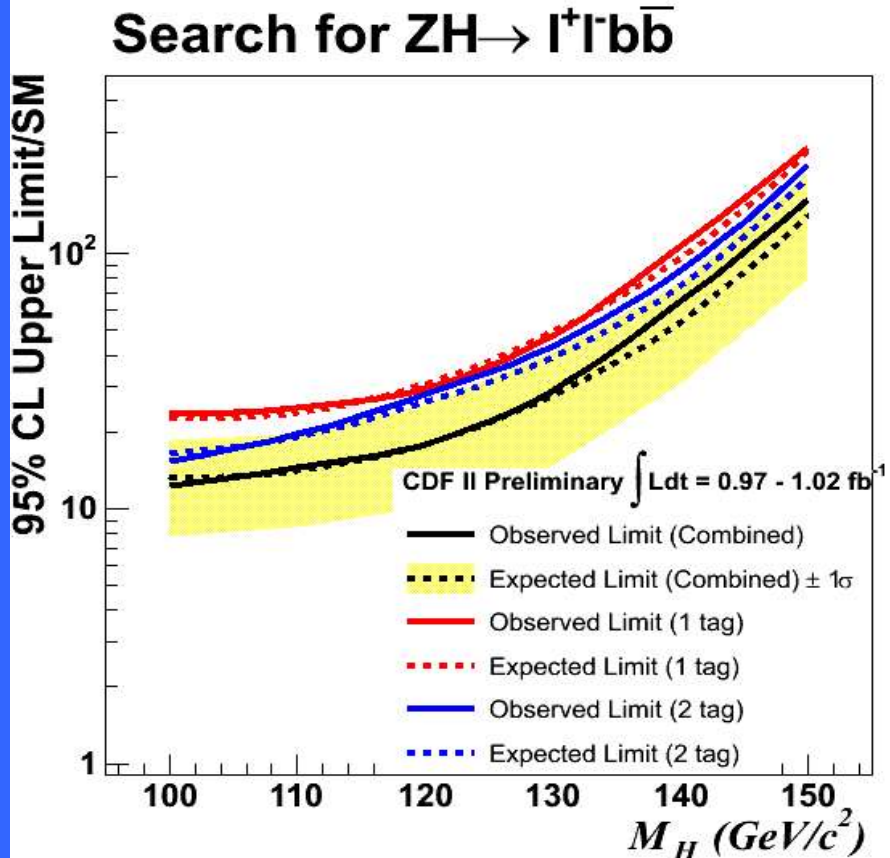


Most Higgs-Like Candidate

CDF run 196170 event 6577 (S:B=1:4)



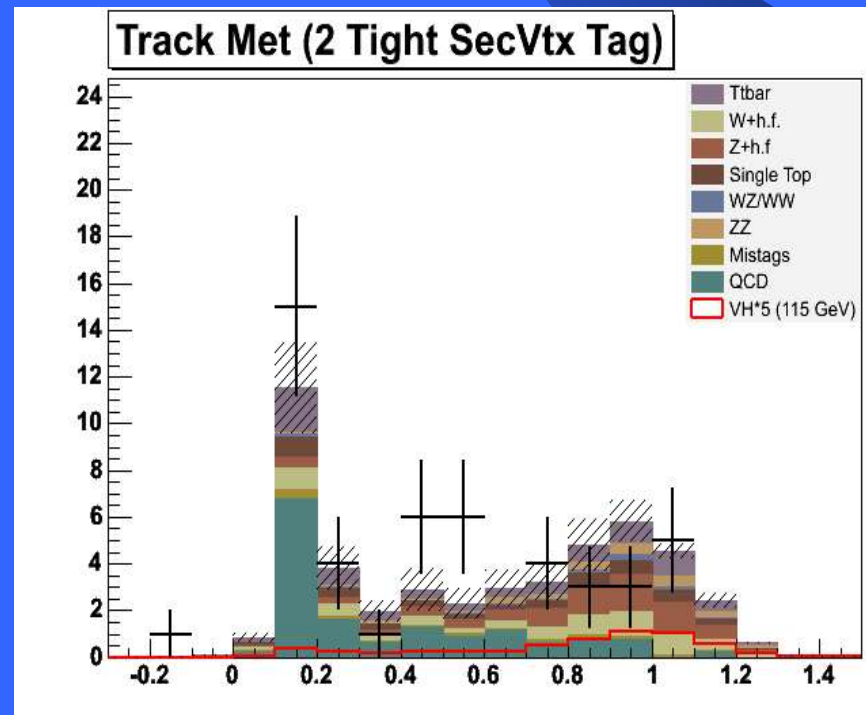
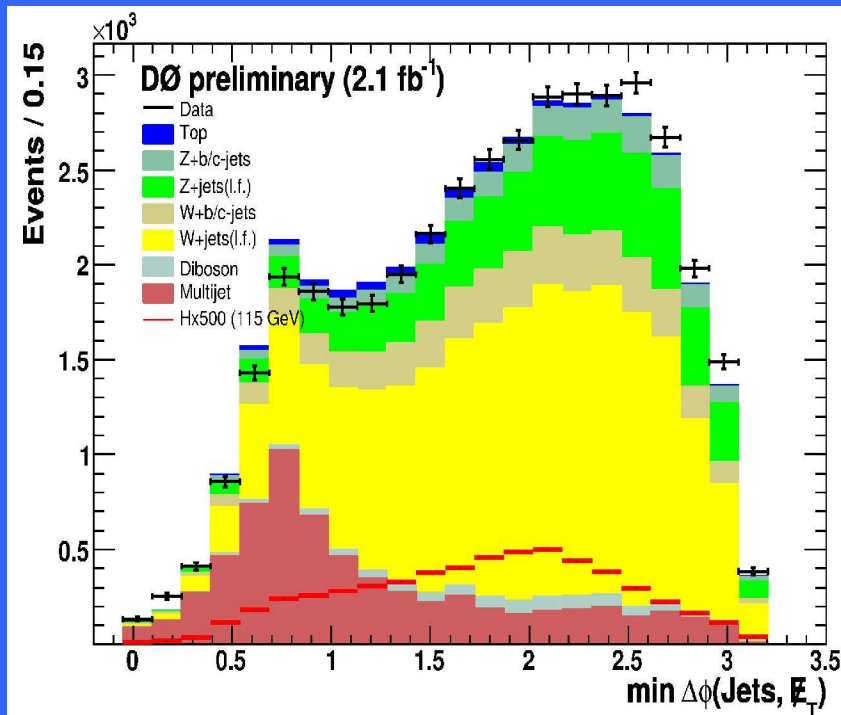
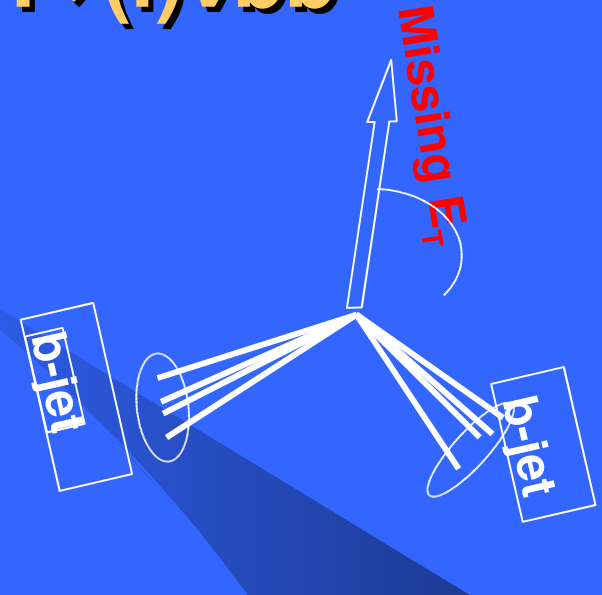
Search for $ZH \rightarrow l l b \bar{b}$



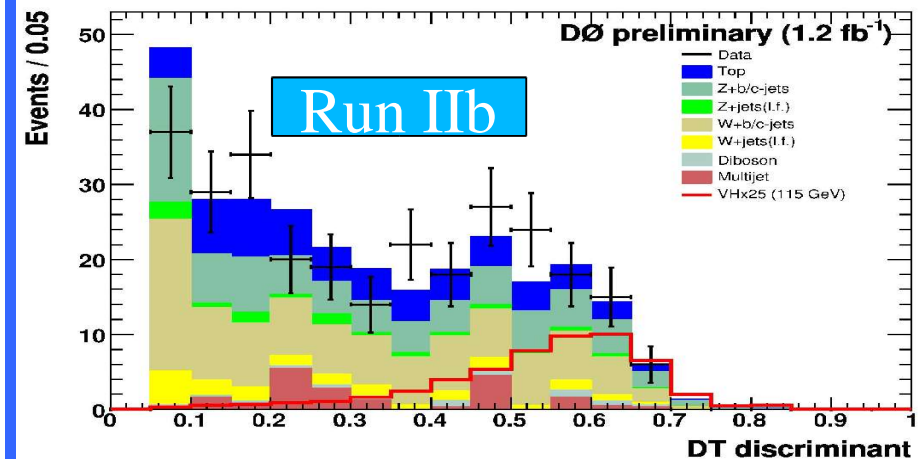
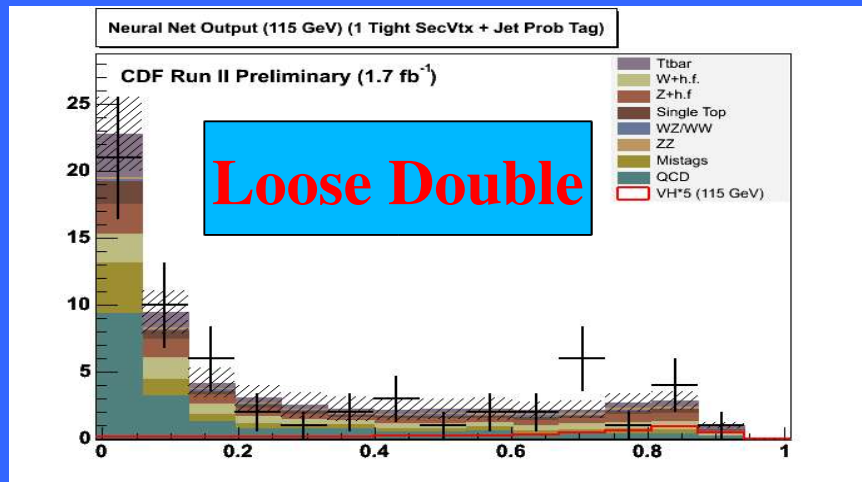
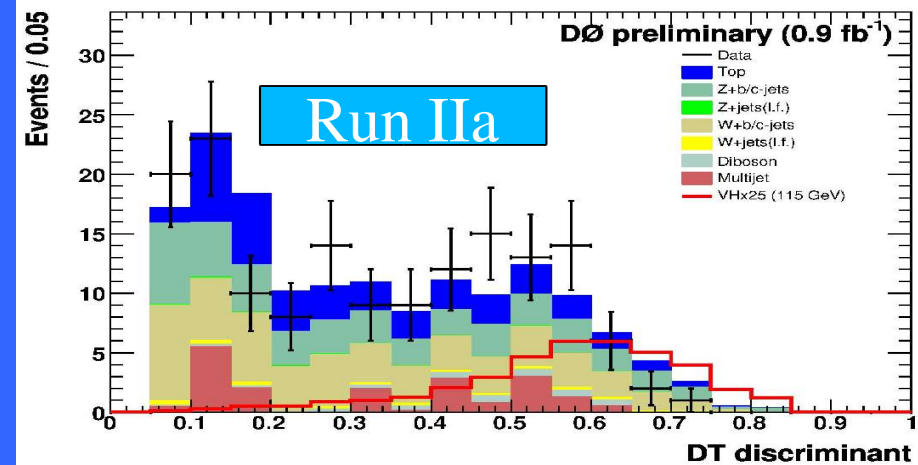
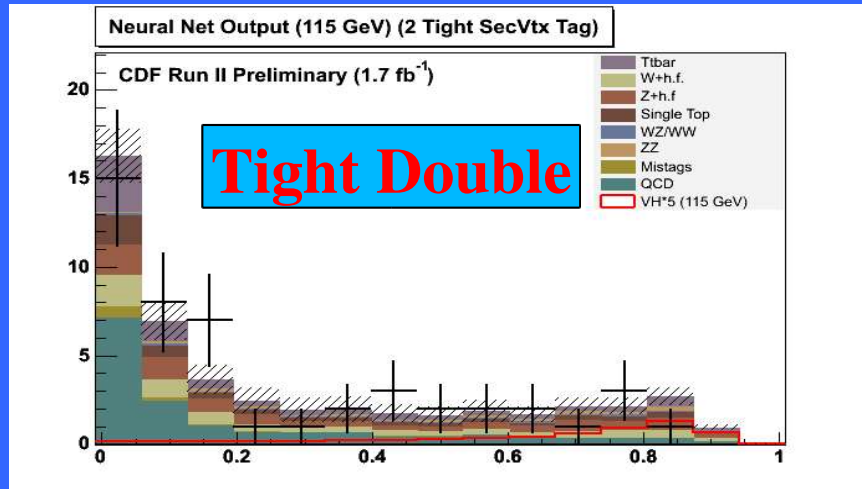
- CDF observed/expected limit is 16/16 x SM @ $m_H = 115 \text{ GeV}$
- D0 observed/expected limit is 18/20 x SM @ $m_H = 115 \text{ GeV}$
- Future Improvements: update with more data, improving Z selection with loose lepton, optimizing b-tagging, and more ...

Search for $ZH \rightarrow \nu\nu b\bar{b}$, $WH \rightarrow (l)\nu b\bar{b}$

- Large $\sigma \cdot \text{Br}$, but large QCD, difficulty
- Rely on large $\text{Met} > 50 \text{ GeV} + 2\text{jet}$
- Requiring double btag (tight and loose)
- Rejection of instrumental backgrounds:
 - $d\phi(\text{Et1}, \text{MET})$
 - Track Met: NN with charged tracks

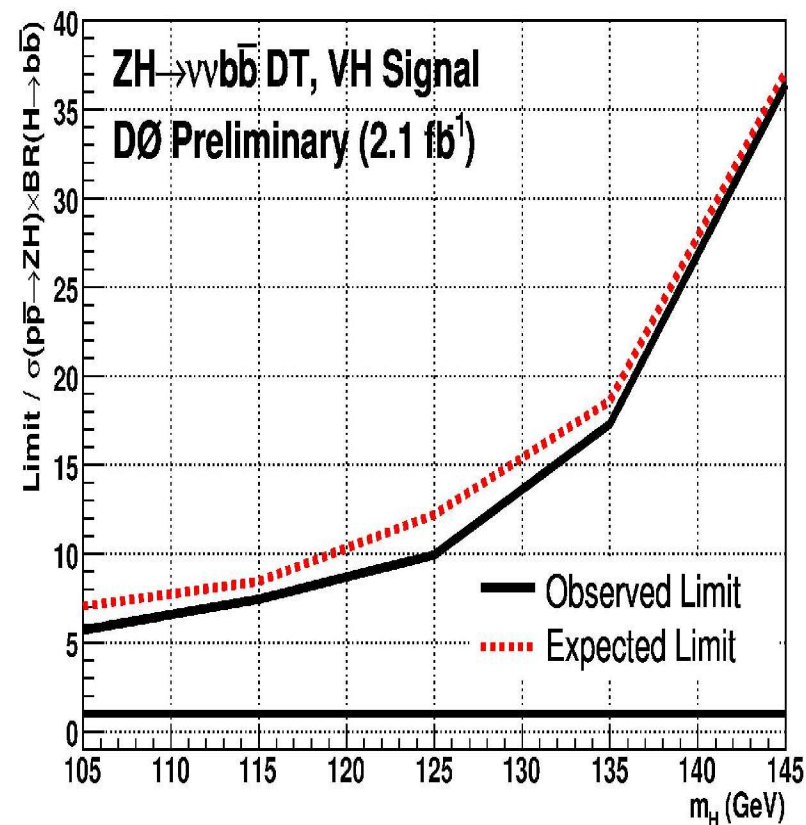
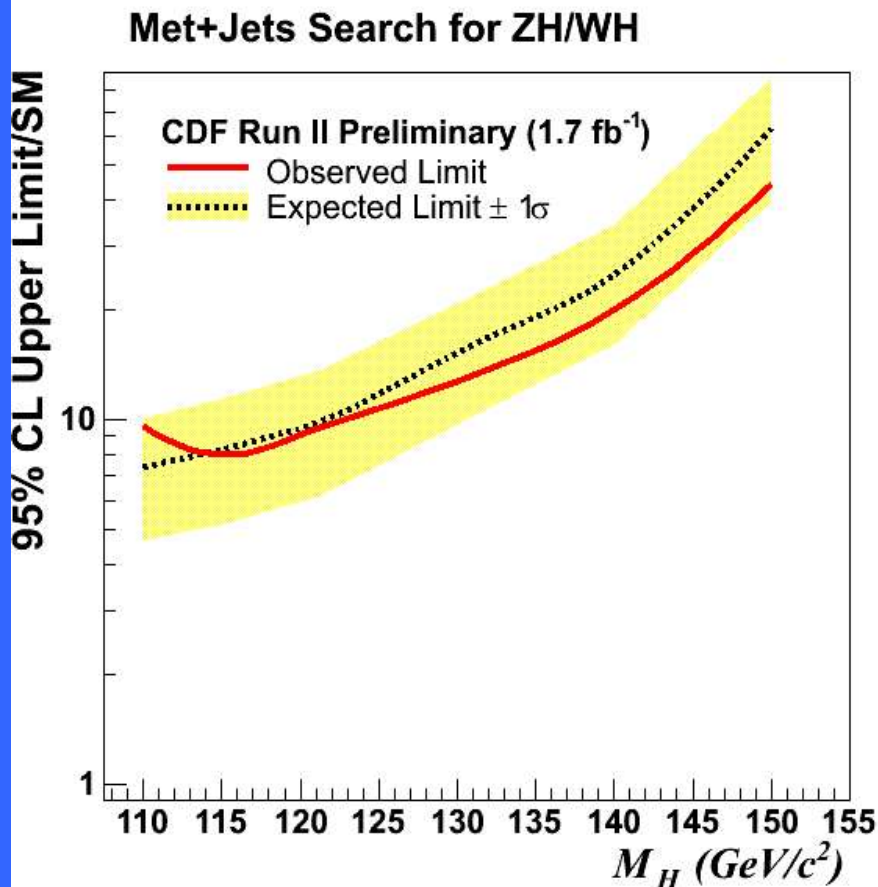


Final Discriminant for $ZH \rightarrow \nu\nu b\bar{b}$, $WH \rightarrow (l)\nu b\bar{b}$



□ Combining M_{jj} , track met, and other kinematics into final NN (CDF) or Boosted Decision Tree (DØ)

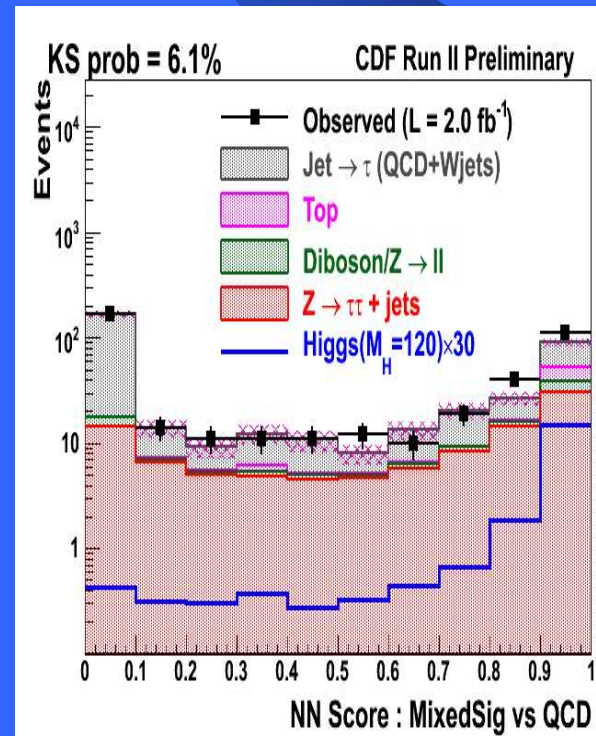
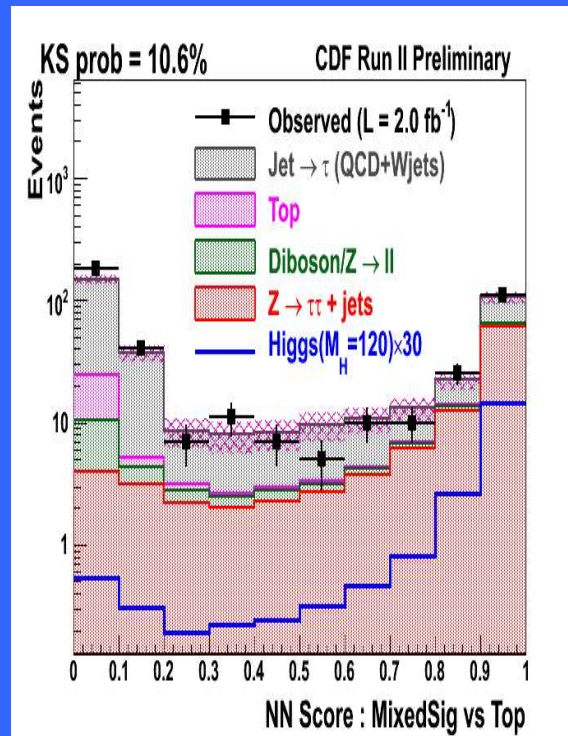
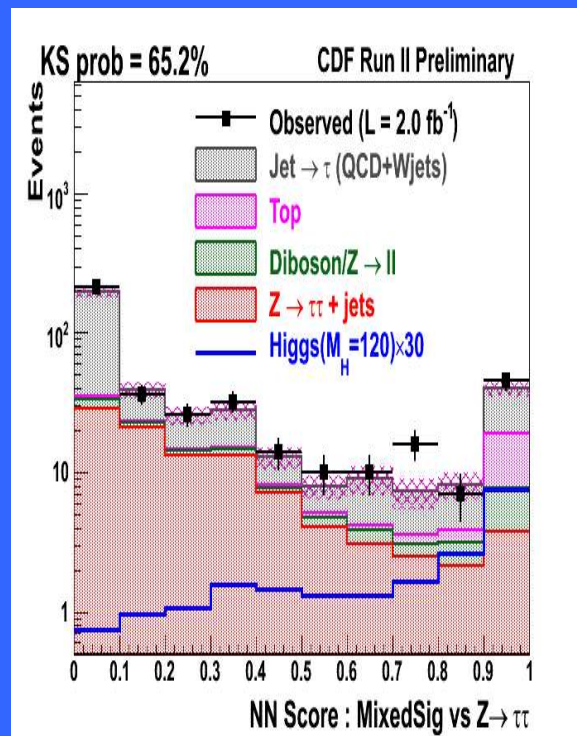
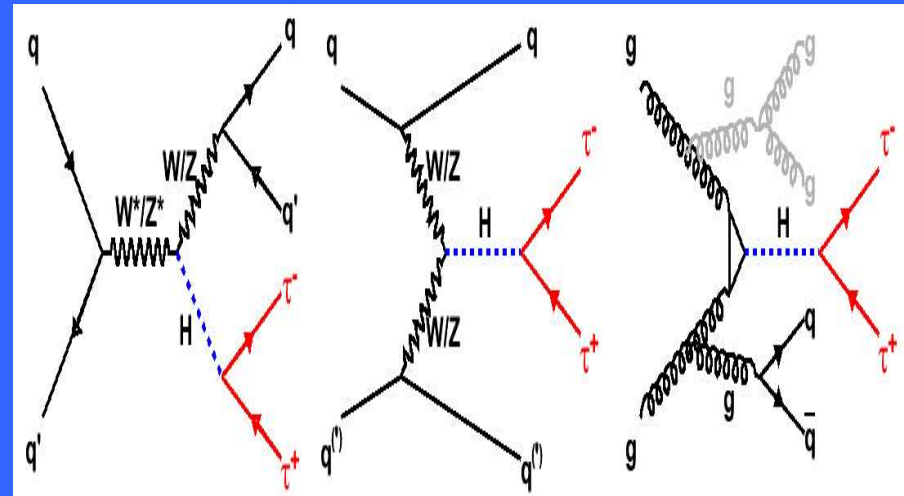
Search for $ZH \rightarrow \nu\nu b\bar{b}$ and $WH \rightarrow (t)\nu b\bar{b}$



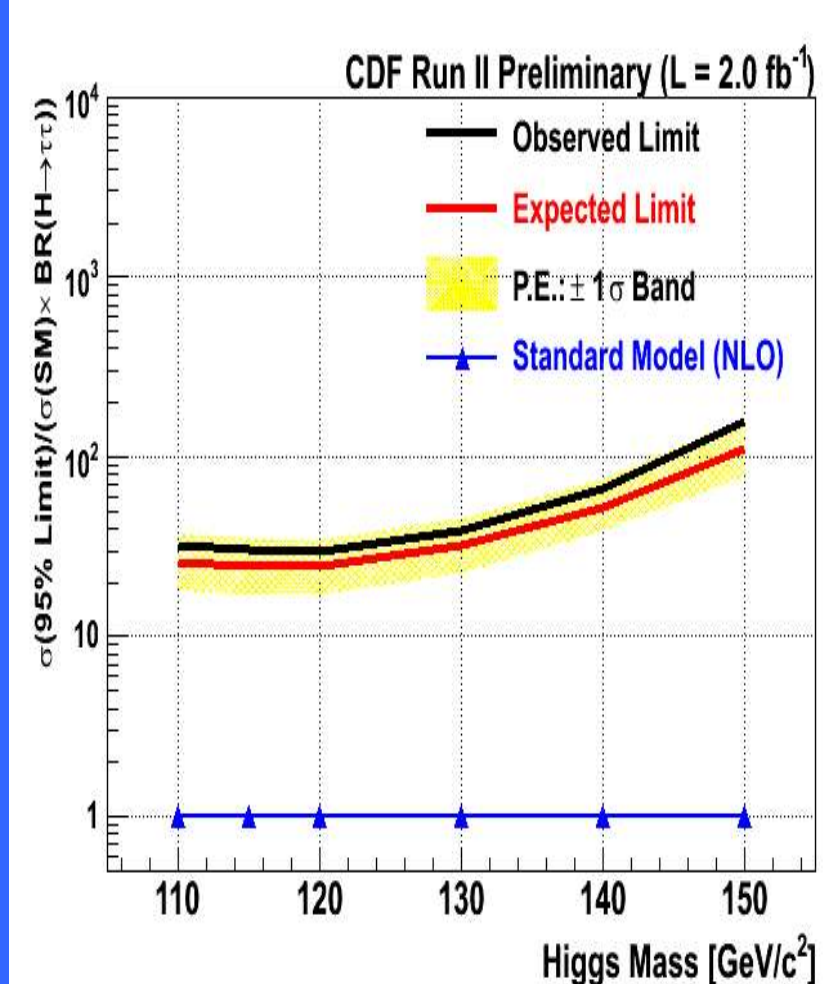
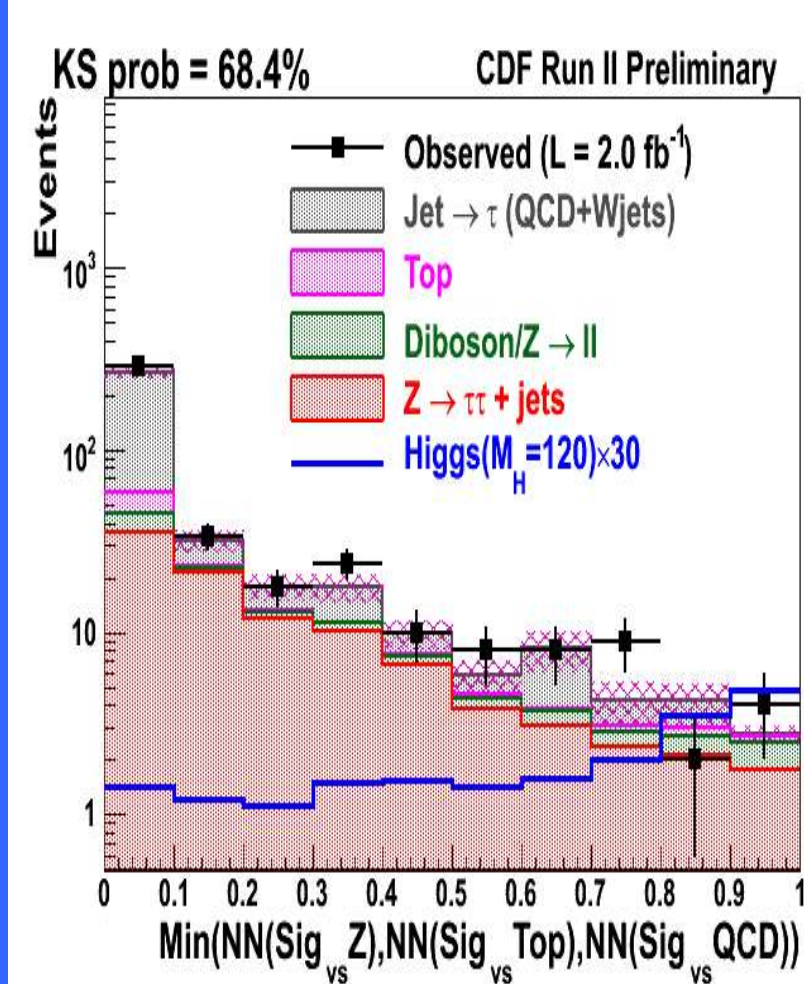
- CDF observed/expected limit is 8/8.3 x SM @ $m_H = 115 \text{ GeV}$
- DØ observed/expected limit is 7.5/8.4 x SM @ $m_H = 115 \text{ GeV}$
- Future improvements: using single tag and improving the trigger

Search for $(V)H \rightarrow \tau\tau + 2\text{jets}$

- New decay, but small $\text{Br} \sim 8\%$.
- $H \rightarrow \tau_{\text{lep}}(\text{Pt} > 10) + \tau_{\text{had}}(\text{Pt} > 15)$
- Opposite sign, not Z, $+ \geq 2$ jets
- Train 3 NN(H vs DY, H vs top, H vs QCD) with $m(\tau\tau)$, $m(l\nu)$, other kin. variables and take the minimum score.



Search for $(V)H \rightarrow \tau\tau + 2\text{jets}$



- CDF first time set $H \rightarrow \tau\tau$ limits: 30.5/24.8 @ $m_H = 115 \text{ GeV}$
- Future improvements: better trigger and optimized analysis

Search for $VH \rightarrow jjbb$ with ME

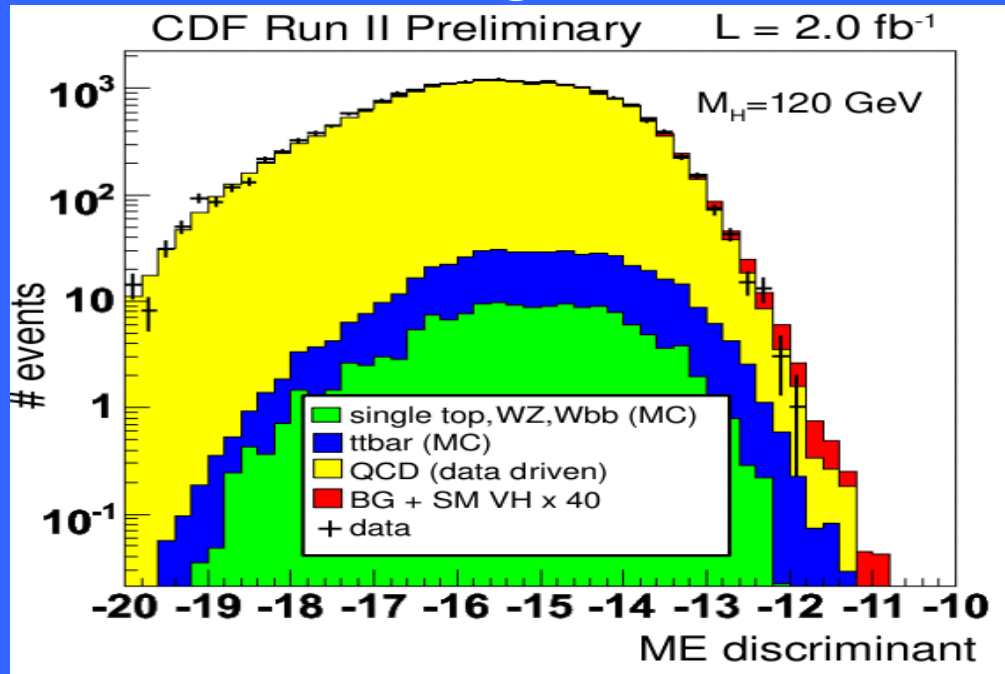
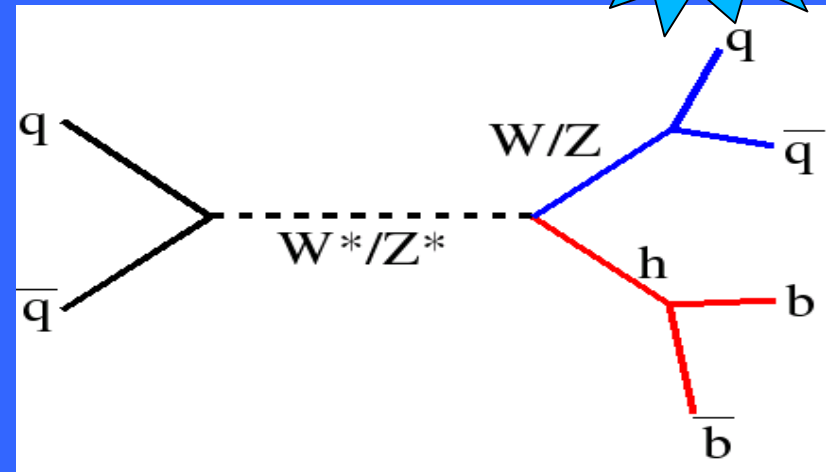
New

➤ Associated production with hadronically decaying W or Z

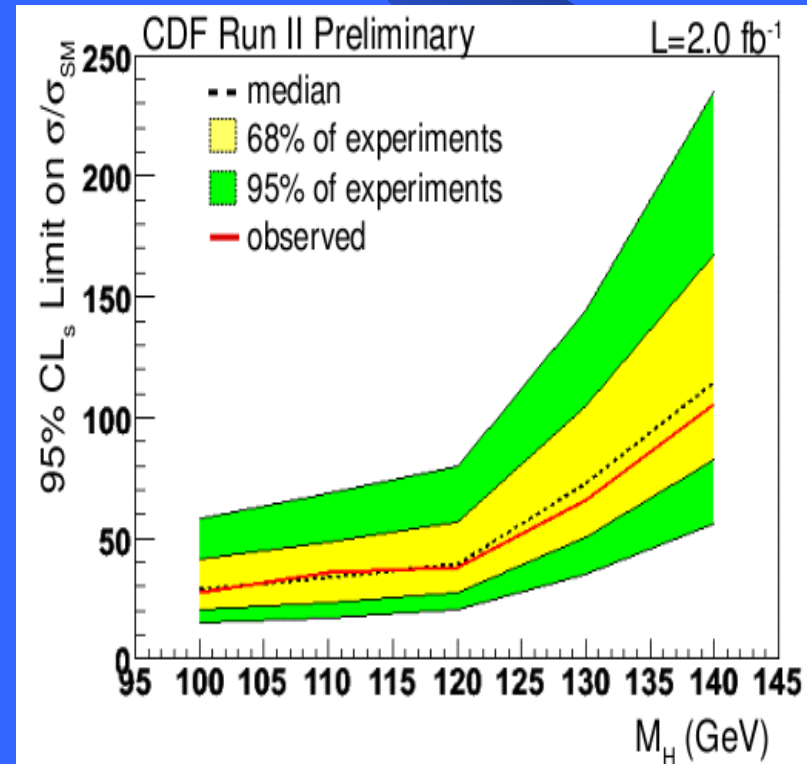
➤ 4jets, 2 of which are tagged

➤ Large branching fraction, but huge QCD backgrounds $\Rightarrow S/B=5.3/21,000$

➤ Discriminating S from B with ME

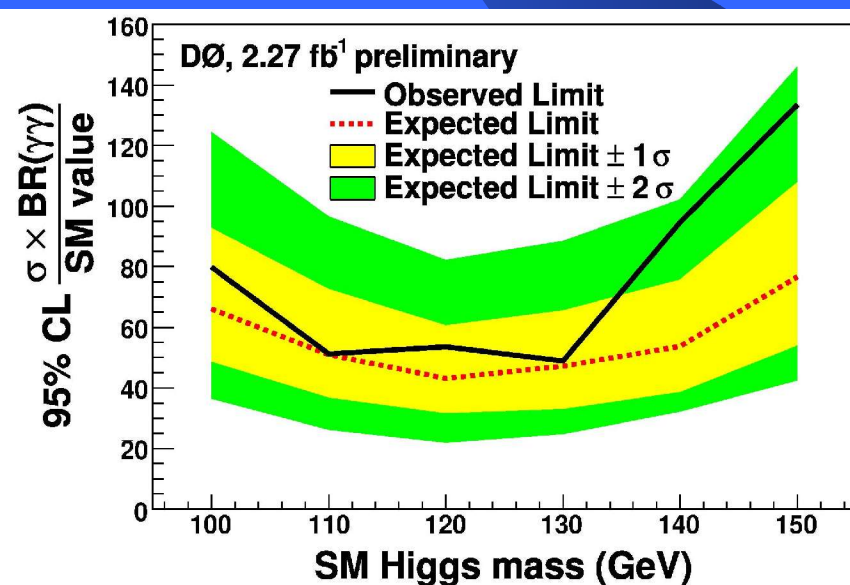
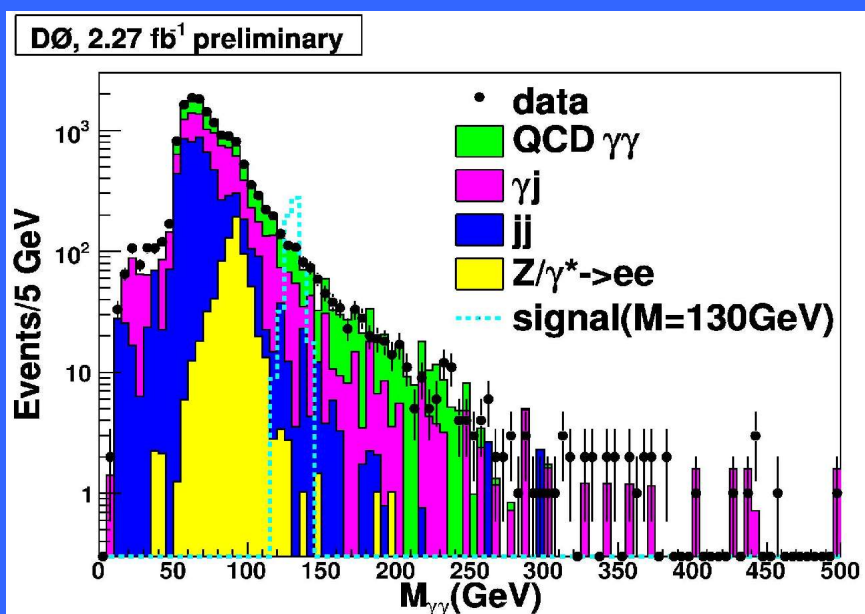
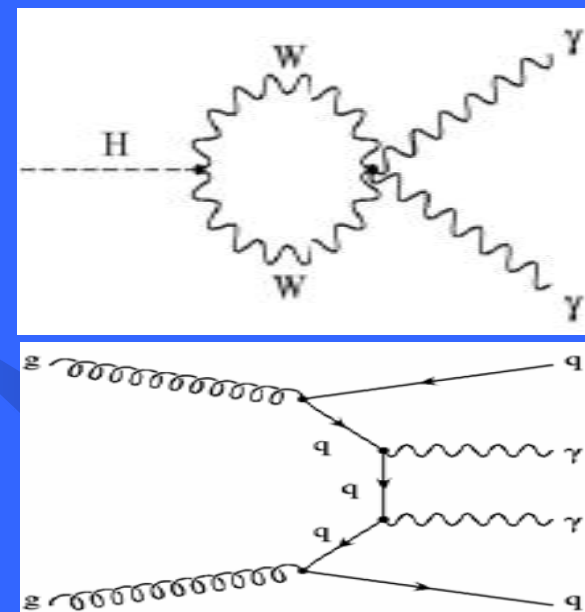


➤ CDF set limit: $\sim 40 \times \text{SM}$ @ $M_H = 120 \text{ GeV}$



Search for $H \rightarrow \gamma\gamma$

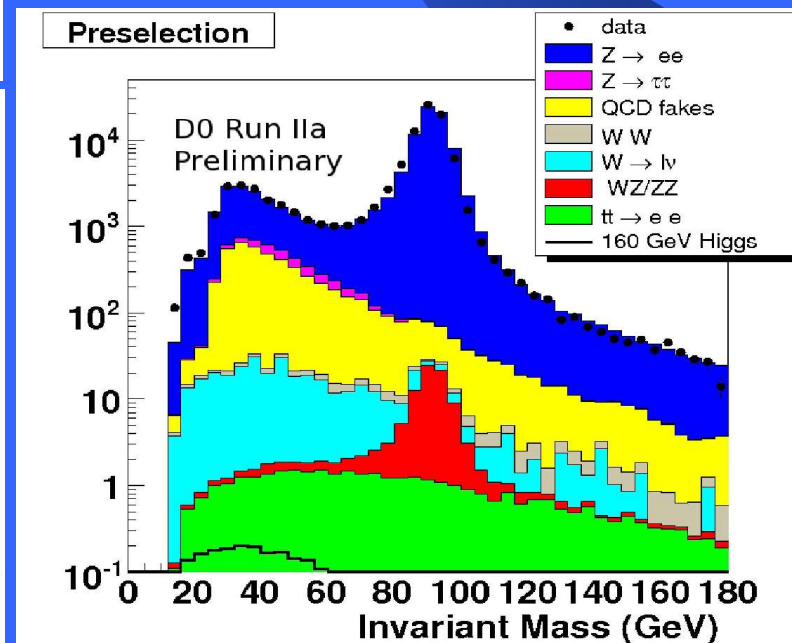
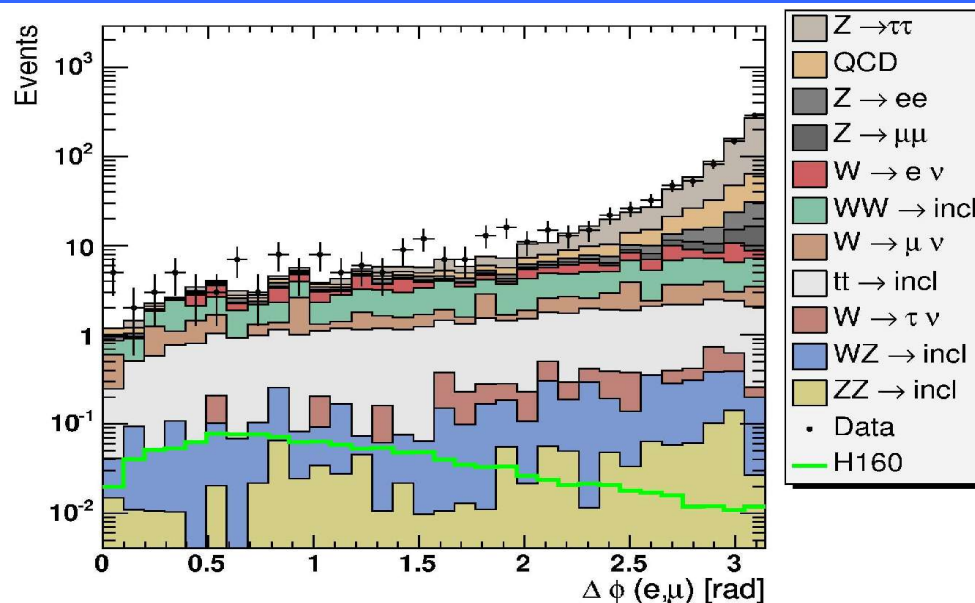
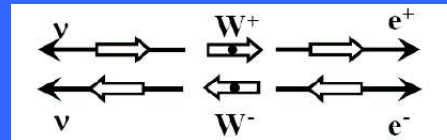
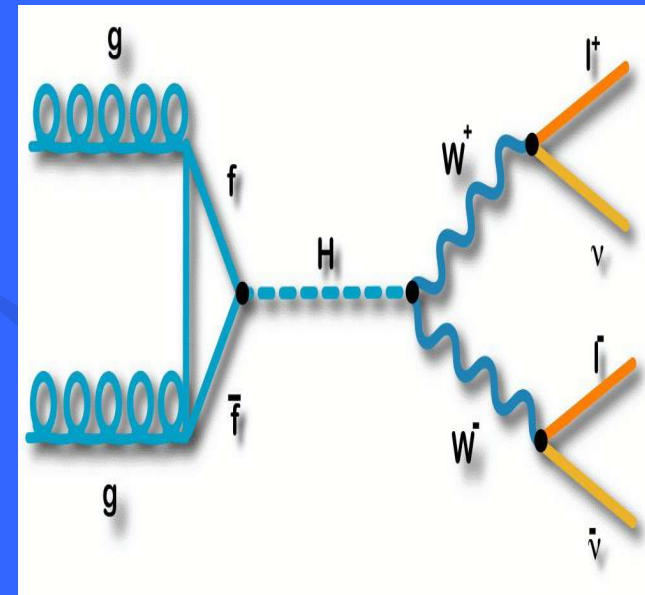
- LHC's gold channel: low mass Higgs
- Neural net to identify photon
- Selecting 2 isolated γ with $E_t > 25$ GeV
- Look for a peak in $M_{\gamma\gamma}$ mass spectrum
- Main Backgrounds: $\gamma+\gamma$, DY , γ +jet, dijet



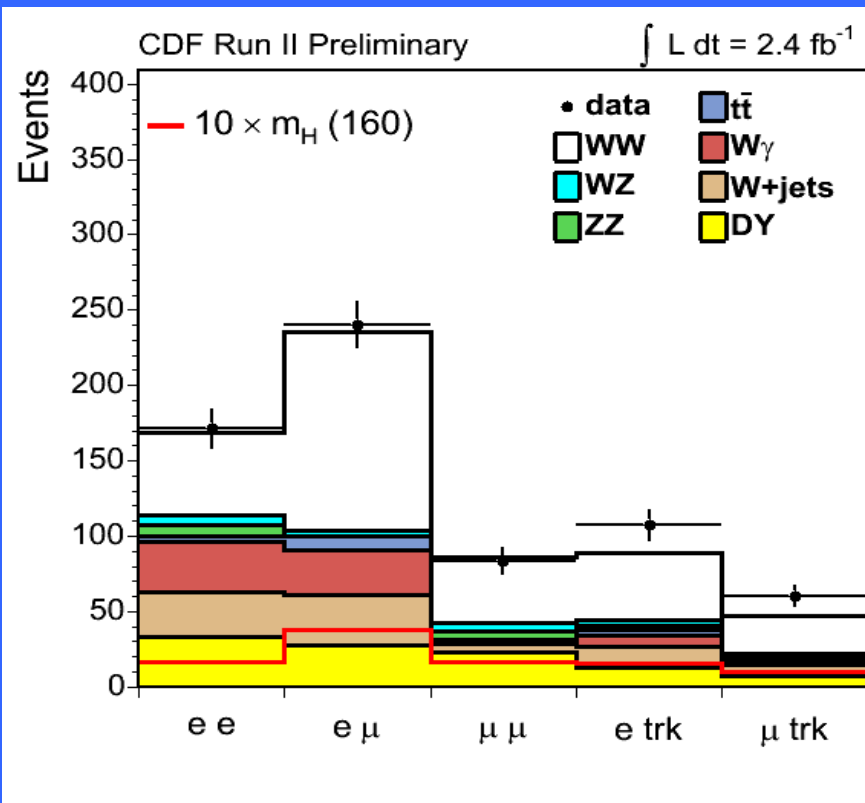
- DØ set limits: 56(Obs)/46(exp) @ $m_H=120$ GeV

Search for $H \rightarrow WW^* \rightarrow \ell\nu\ell\nu$

- Three main channels ($ee, \mu\mu, e\mu$)
- Two opp-sign high Pt leptons
- Large Met and $n_{\text{jets}} < 2$
- Dominant Backgrounds: WW^*
- Higgs mass can't be reconstructed, but the angular correlation provides handle to reduce WW^* .



Increase Acceptance with Loose Leptons



CDF Run II Preliminary $\int \mathcal{L} = 2.4 \text{ fb}^{-1}$

$M_H = 160 \text{ GeV}/c^2$

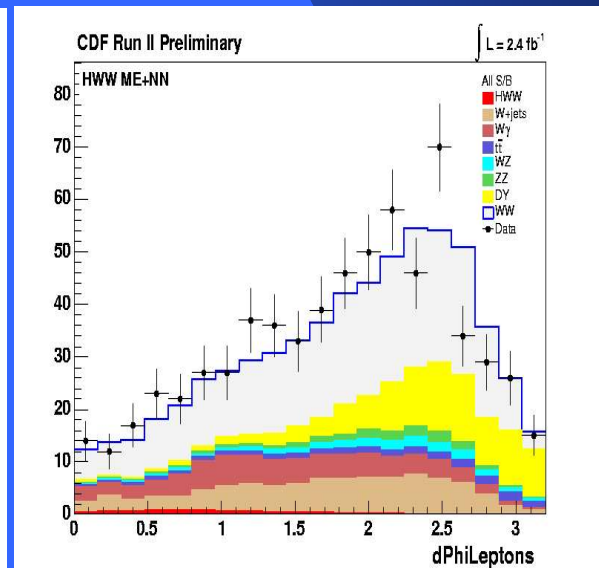
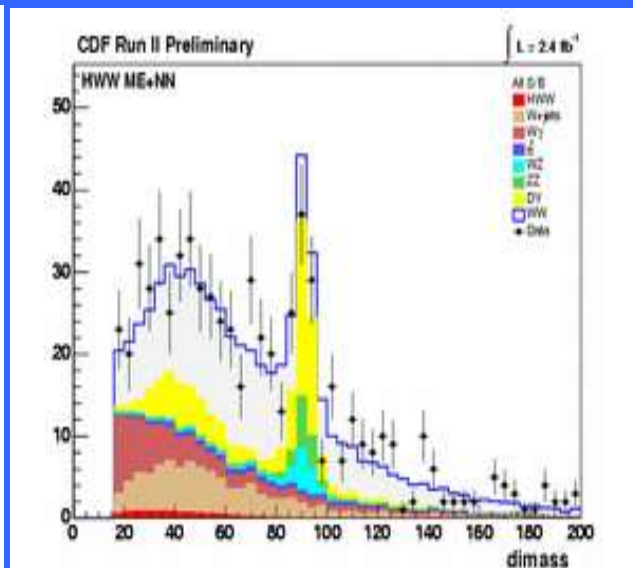
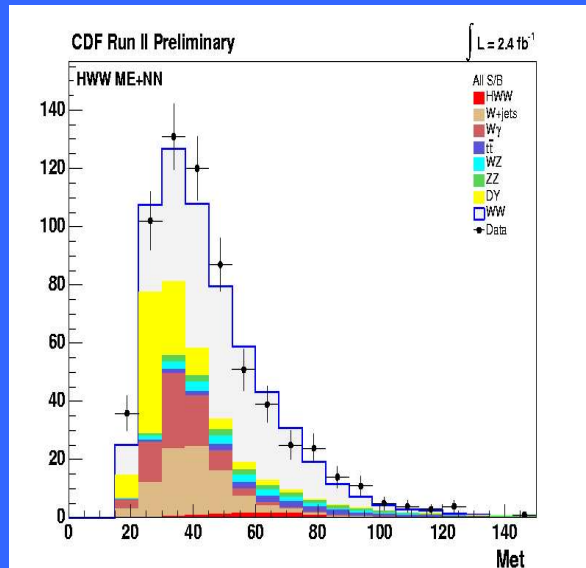
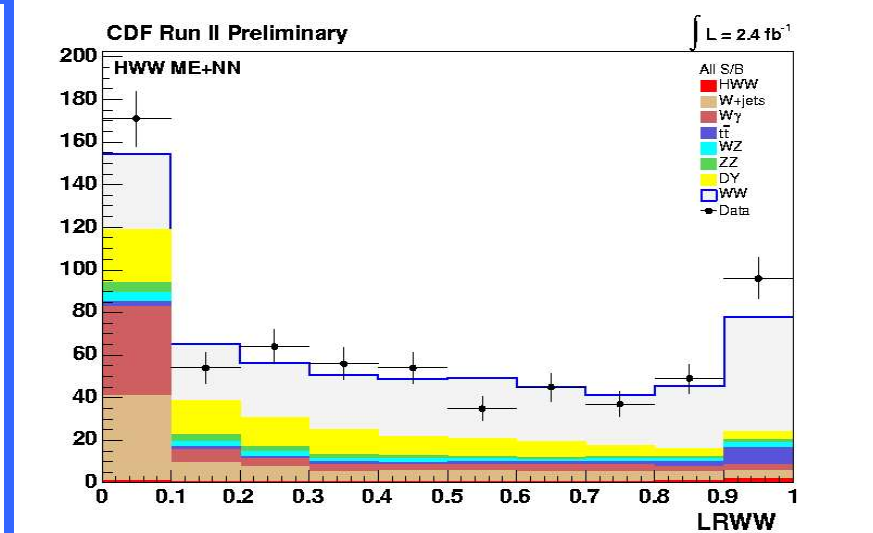
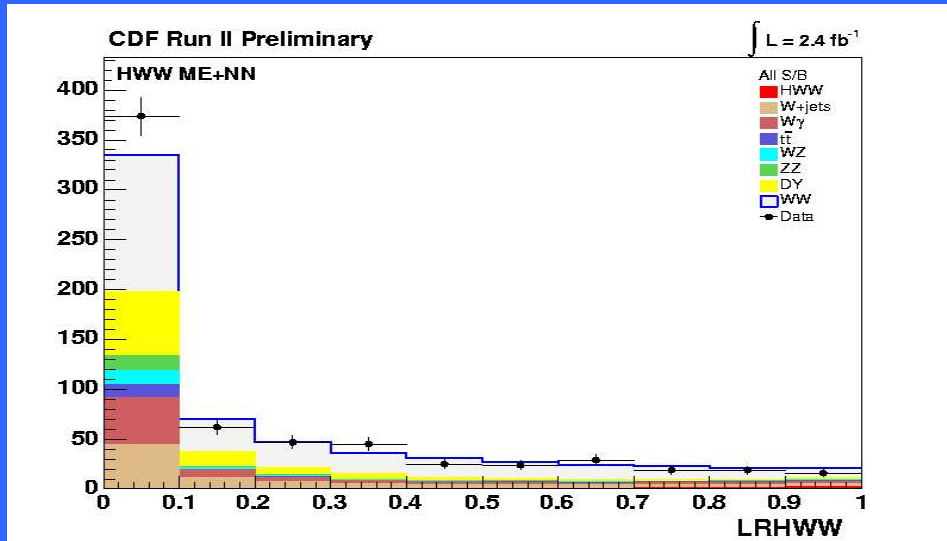
$H \rightarrow WW$	9.5	$\pm$	1.1
WW	300.3	$\pm$	38.1
WZ	20.5	$\pm$	3.1
ZZ	18.2	$\pm$	2.7
$t\bar{t}$	20.8	$\pm$	3.8
DY	104.0	$\pm$	23.0
$W\gamma$	72.4	$\pm$	18.7
$W + \text{jets}$	89.2	$\pm$	22.8
Total BG	626	$\pm$	54
Data	661		

HWW ME+NN

- Data in five classes are well described by SM expectations
- The expected signal events is 9.5 for Higgs mass 160 GeV/c^2
- The events are further divided into high, low S/B based on lepton types.

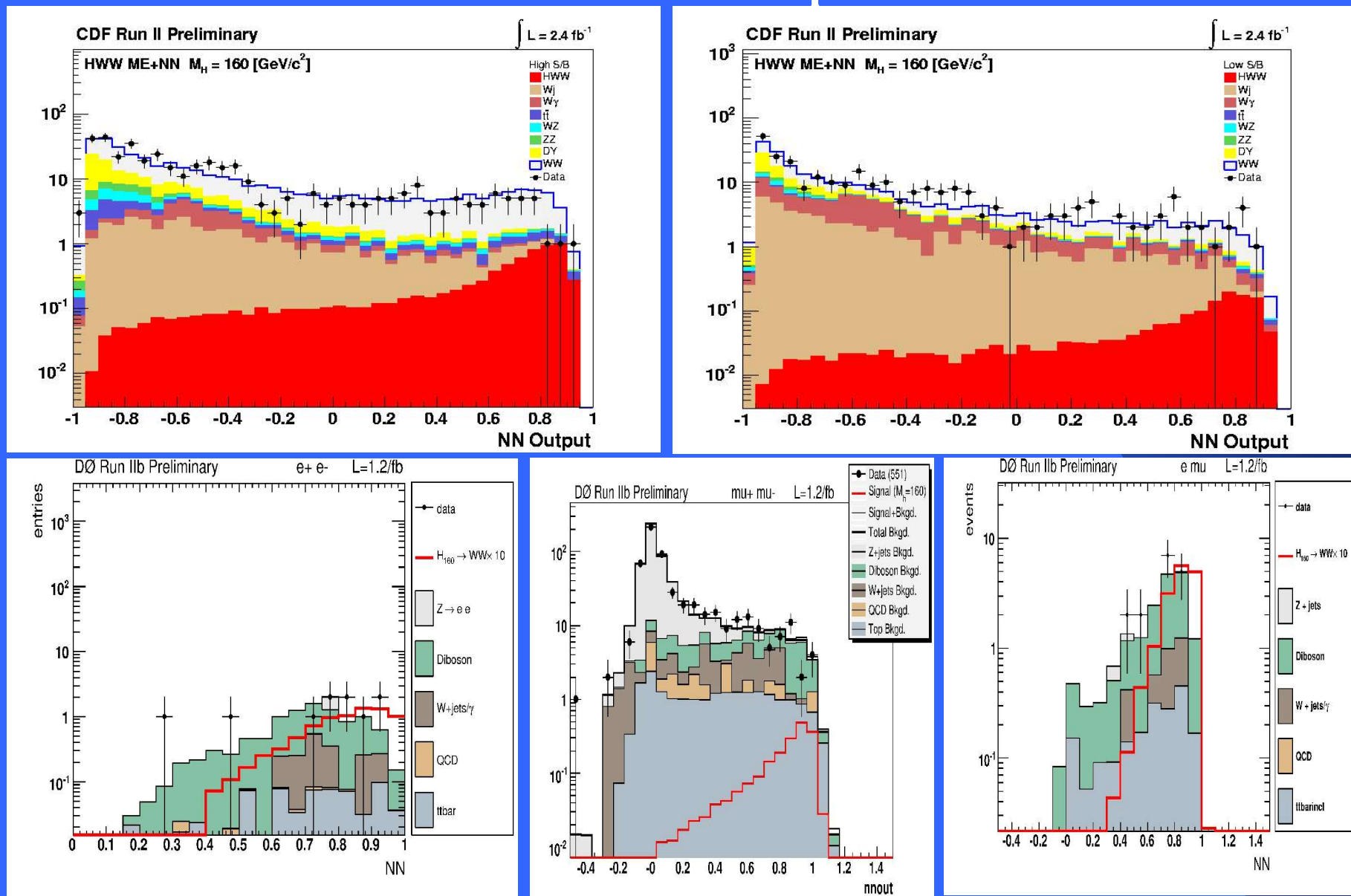
Separating Higgs from Backgrounds

- Validation data with Monte Carlo background Modeling
- NN Discriminant: Combine LO ME and kinematic distributions.

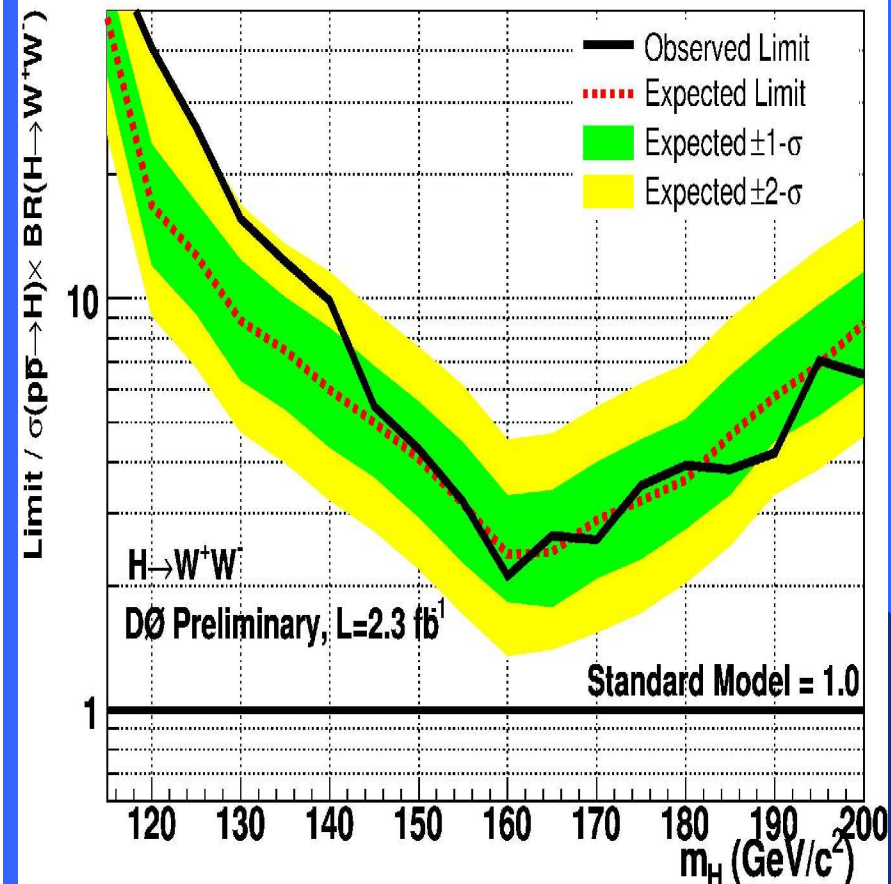
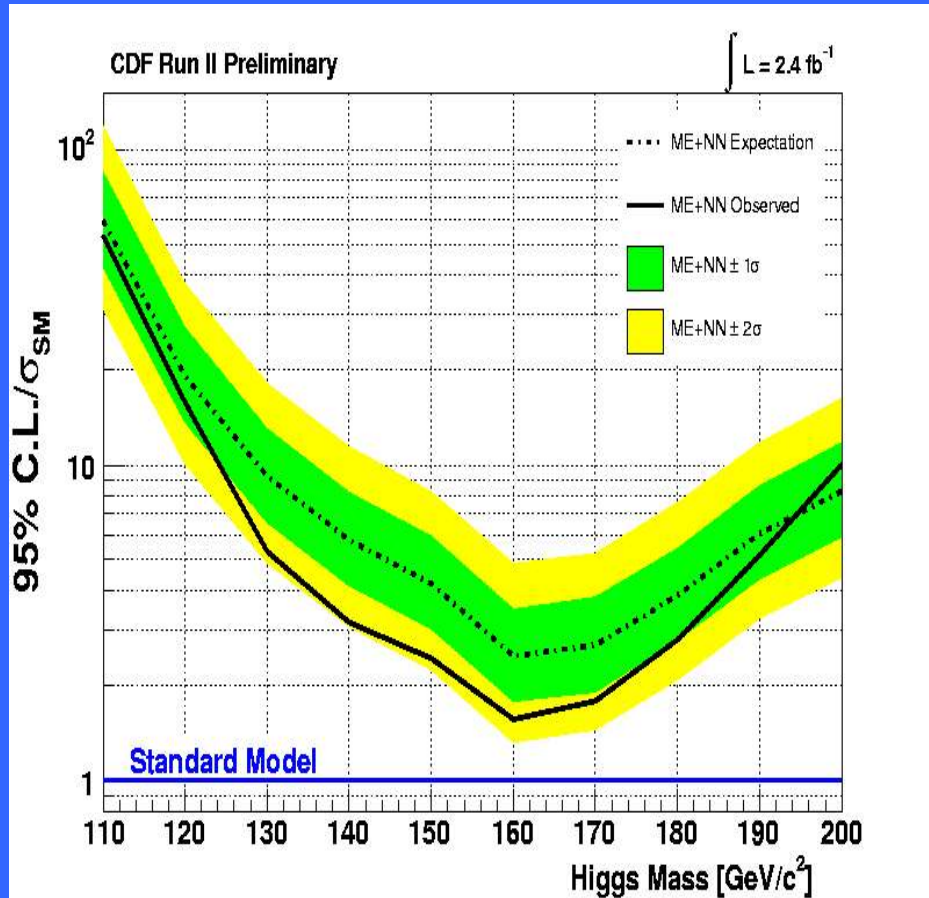


Higgs Discriminant

➤ Final discriminant based on NN output



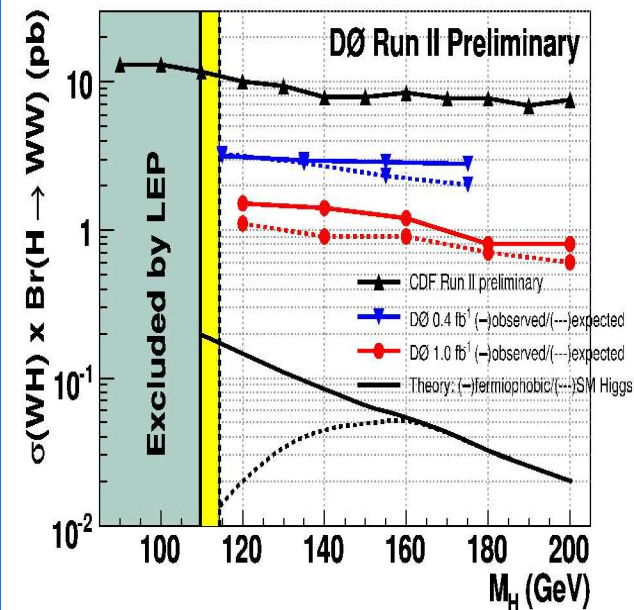
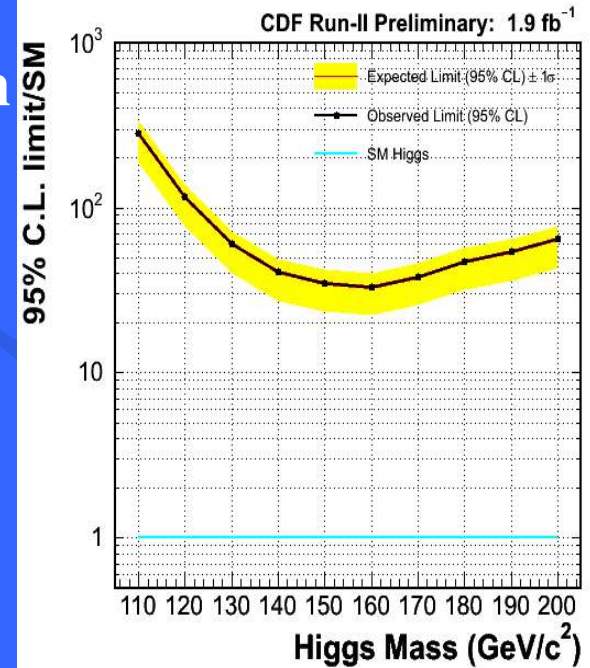
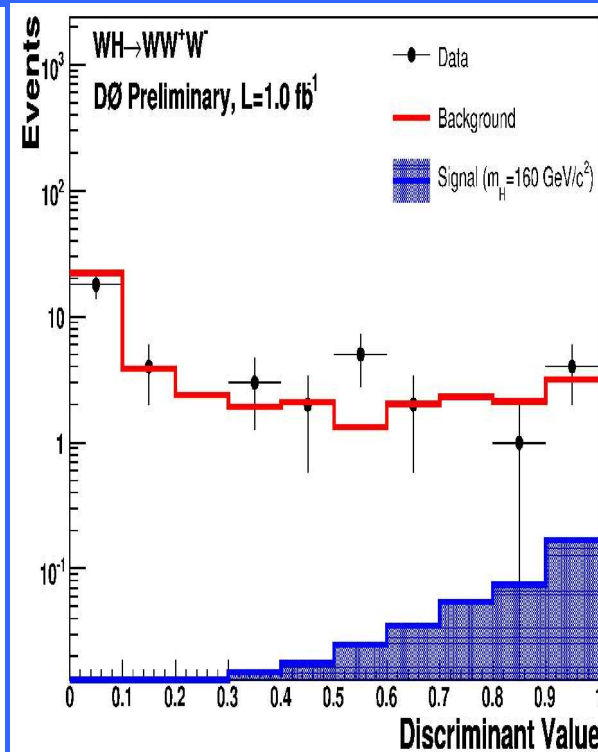
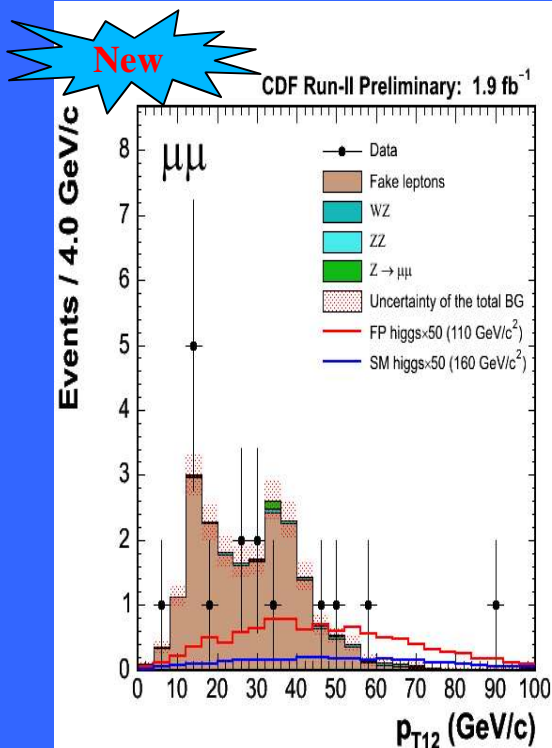
$H \rightarrow WW^* \rightarrow ll\nu\nu$ Limits



- CDF obs/exp limit is 1.6/2.4 x SM @ $m_H = 160 \text{ GeV}$
- DØ obs/exp limit is 2.1/2.4 x SM @ $m_H = 160 \text{ GeV}$
- Future improvements: Optimizing lepton selections, including contributions from VH, BVF, and H+2jets

$$WH \rightarrow WWW^* \rightarrow l^\pm l^\pm \nu \nu + X$$

- Helps to cover intermediate mass region
- Selection: two same charged lepton
- Main backgrounds: WZ and fakes



- CDF obs/exp limit: 33/33 @ $m_H=160$
- DØ obs/exp limits: 26.5/20 @ $m_H=160$

Combination Procedure

- Normalized to SM rate, we can combine $\sigma \times \text{Br}/\text{SM}$ statistically to improve the final result.

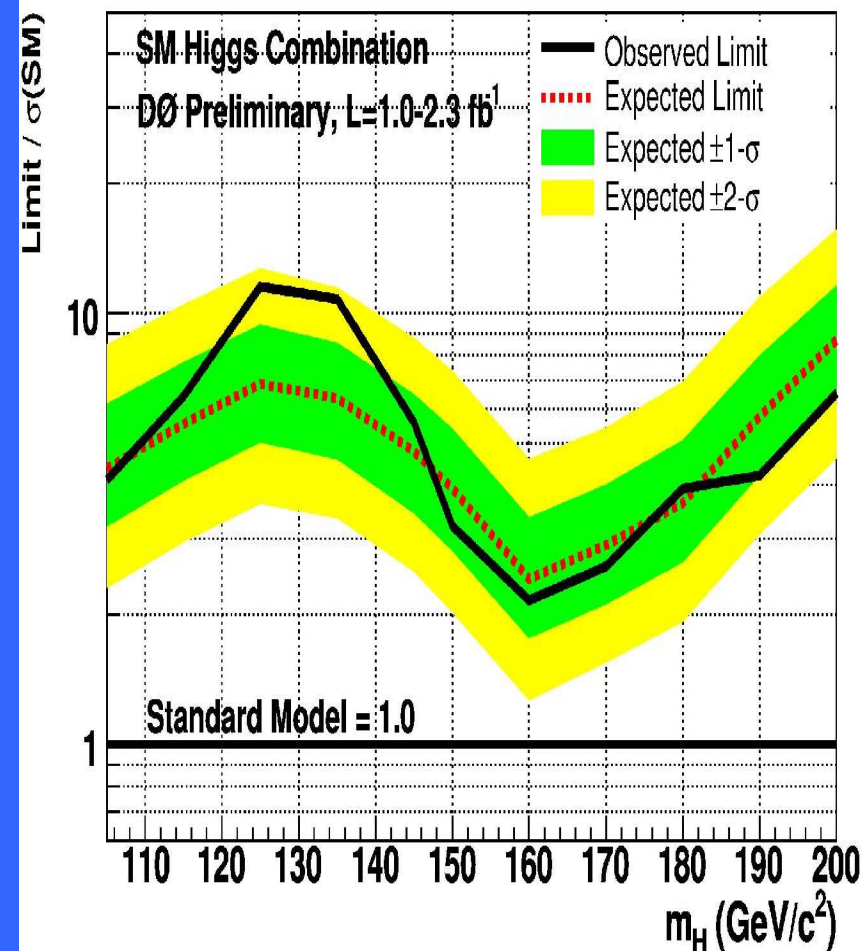
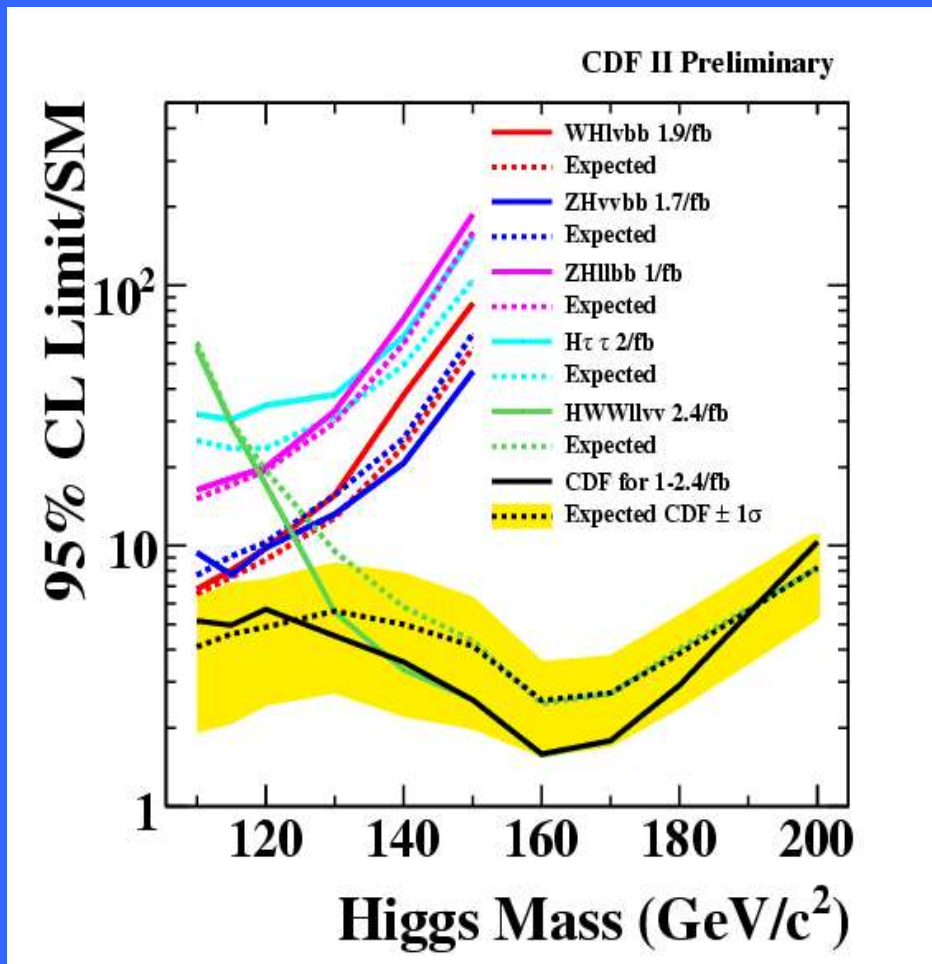
- Use Bayesian and Frequentist approaches:

➤ Bayesian:
$$\mathcal{L}(R, \vec{s}, \vec{b} | \vec{n}, \vec{\theta}) = \prod_{i=1}^{N_C} \prod_{j=1}^{N_{bins}} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}} / n_{ij}! \times \prod_{k=1}^n e^{-\theta_k^2/2}$$

➤ Frequentist (CLs):
$$LLR_n = 2 \sum_{i=1}^N \left(s_i - n_i \text{Log} \left(1 + \frac{s_i}{b_i} \right) \right)$$

- All systematics treated as nuisance parameters with truncated Gaussian constrain
- If the excess is significant after combination, do more checks to make sure not statistic fluctuation.
- If no excess, set 95% CL upper limit vs m_H

CDF and D0 Combined Limit

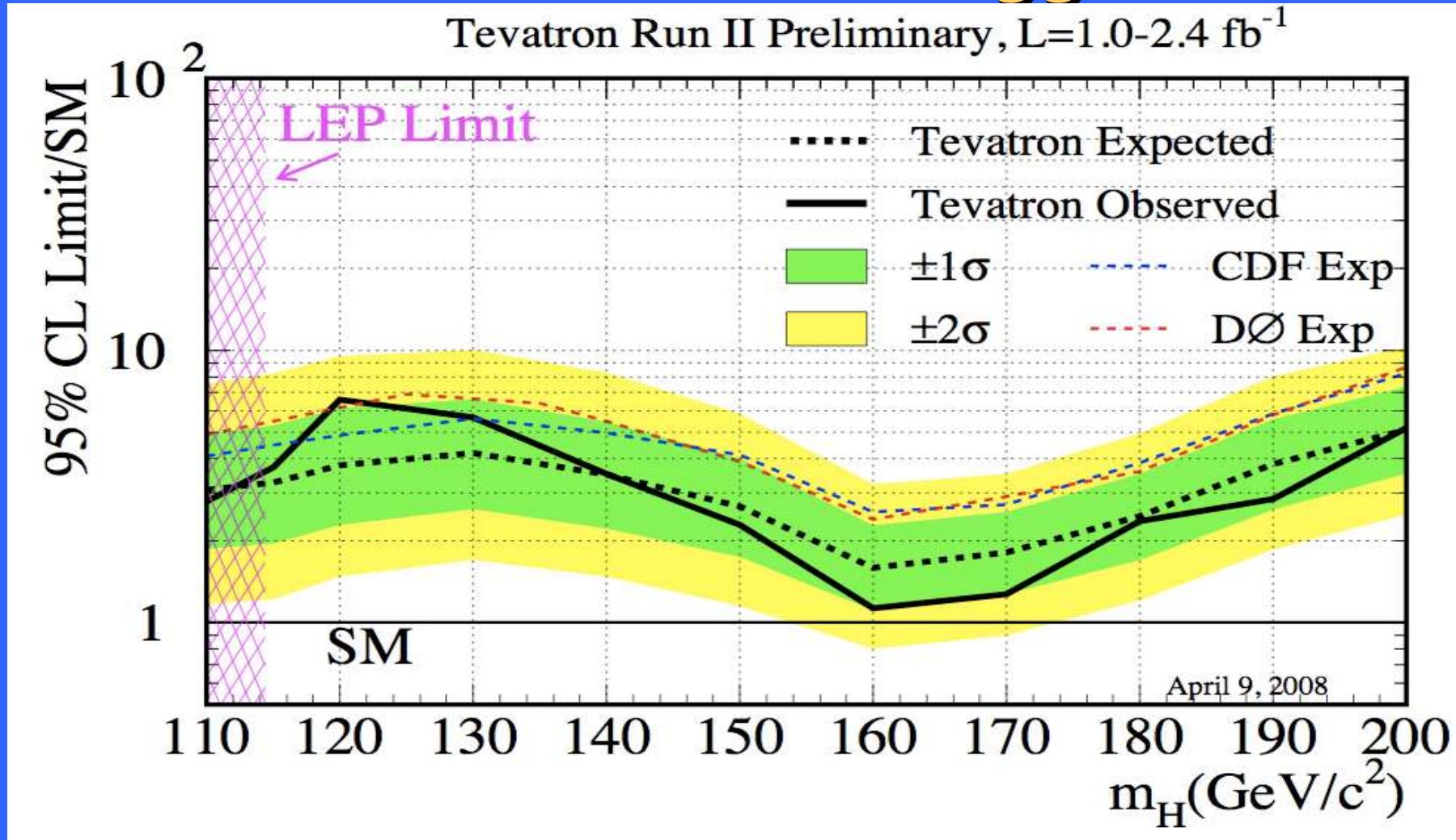


➤ Both Collaborations give comparable Observed(Expected) limits:

➤ CDF: 5.0(4.5) & 1.6(2.6) for $m_H=115$ & 160 GeV

➤ D0: 6.4(5.5) & 2.2(2.4) for $m_H=115$ & 160 GeV

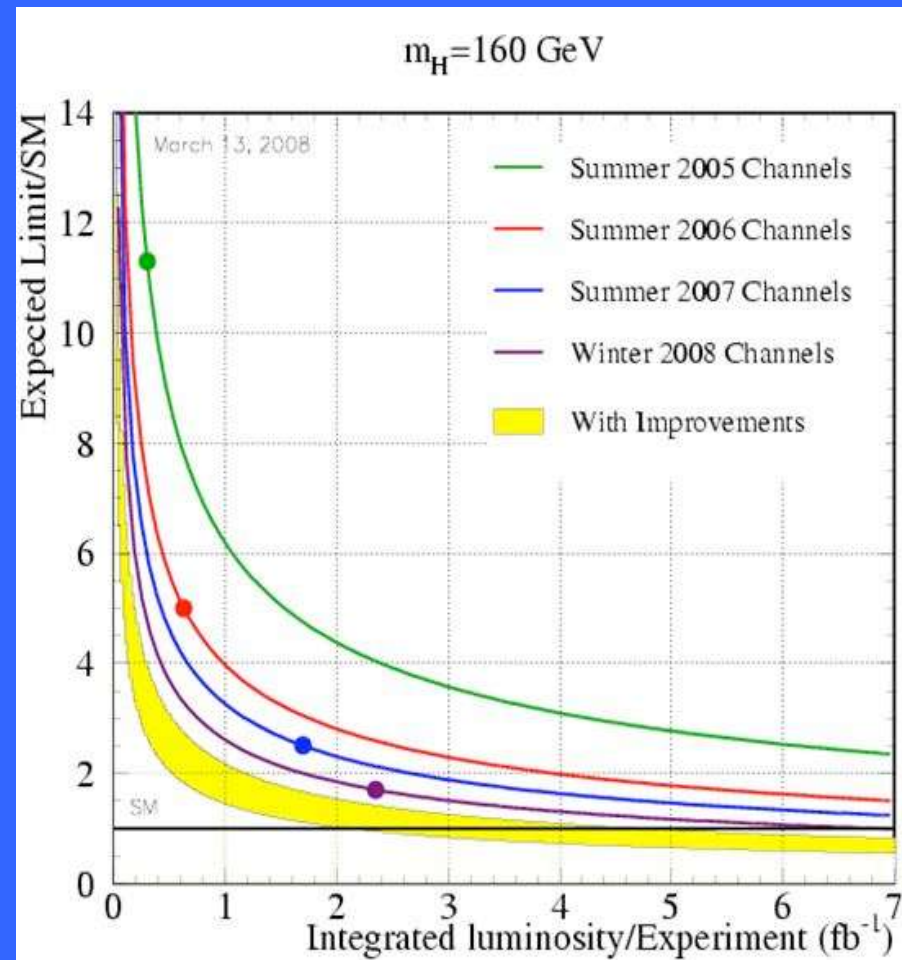
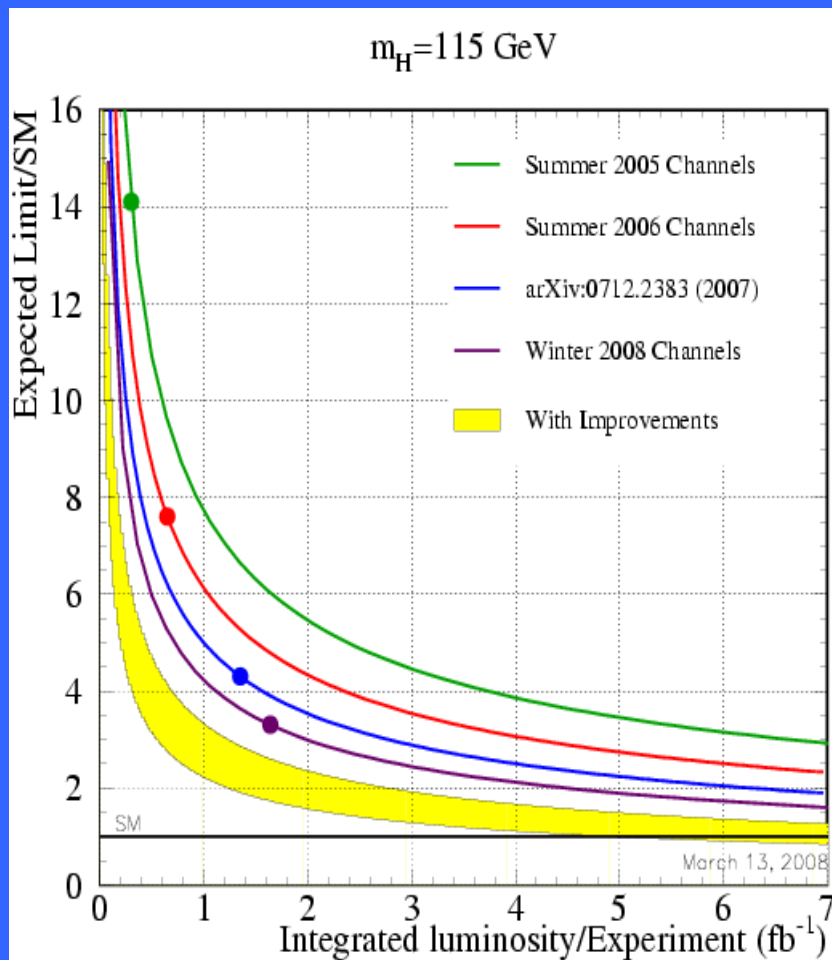
Tevatron Combined SM Higgs Limits



➤ Tevatron Obs(Exp) Limits: 3.7(3.3) & 1.1(1.6) for $m_H=115$ & 160 GeV

➤ Hep-ex/arXiv:0804.3423V1

Tevatron Sensitivities



- The Higgs sensitivity improves better than $1/\sqrt{L}$ over time
 - with more data, new ideas
 - more advanced analysis techniques.

Future Prospects



- With 8 fb^{-1} data, Tevatron would
 - either exclude Higgs $m_H < 185$ @ 95% C.L.
 - or find 3- σ evidence Higgs near $m_H = 160$ GeV.

Conclusions

- We are closing in sensitivity towards less than 3.3(1.6) times SM Higgs @ $m_h=115$ (160) GeV
- There is no magic bullet, 10% effects matter most and no stone is left unturned.
- CDF have improved the sensitivity by 80% over the gaining of luminosity since summer 06 and expect the trend will continue in next two years.
- A factor of 2 improvement over the current analysis by 2010 will put the Tevatron within a reach of 3σ evidence for Higgs mass near 160 GeV
- This is very exciting time for Higgs search at Tevatron



BACKUP

CDF Systematic Uncertainties

Channels	$l\nu b\bar{b}$			$\nu\bar{\nu} b\bar{b}$		$l^+l^- b\bar{b}$		W^+W^-		$\tau^+\tau^-$
	STST	STJP	STNN	STST	STJP	ST	DT	HS/B	LS/B	
Acceptance										
Lumi (%)	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0
btag (%)	8.4	8.9	5.0	8.6	9.2	5.3	16	0.0	0.0	0.
Lepton (%)	2.0	2.0	2.0	2.0	2.0	1.	1.	1.5	1.5	5.0
JES (%)	3.0	3.0	3.0	S	S	3.0	3.0	0.0	0.0	5.0
MC (%)	5.6	4.9	5.0	4.0	4.0	3.0	3.0	2.2	2.2	4.0
Trigger (%)	0.0	0.0	0.	S	S	0.0	0.0	0.0	0.0	0.0
Backgrounds										
Mistag (%)	9	8	9	20	29	13	24	0.0	0.0	-6.7
QCD (%)	18	18	18	-50	-50	-50	-50	-29	-23	-15
V+HF (%)	45	45	42	40	40	40+S	40+S	0	0	-20
Top (%)	15	15	15	16	18	20	20	15	15	13
Diboson (%)	10	10	10	20	20	20	20	10	10	10

- The WW systematics are divided into various sources (met, conversion, NNLO, xsec, PDF, lepton ID, and triggers) which are treated corrected with other channels.
- The positive value means correlated, the negative value means uncorrelated, but corrected in the same dataset.
- Shape systematic uncertainties (S) included

D0 Systematic Uncertainties

Source	$WH \rightarrow e\nu b\bar{b}$ DT(ST)	$WH \rightarrow \mu\nu b\bar{b}$ DT(ST)	$WH \rightarrow WW^+W^-$	$H \rightarrow W^+W^-$
Luminosity (%)	6.1	6.1	-	-
Normalization (%)	-	-	6.1	4-6
Jet Energy Scale (%)	3.0	3.0	0	3.0
Jet ID (%)	3.0	3.0	-	-
Electron ID/Trigger (%)	6.0	-	11	3-10
Muon ID/Trigger (%)	-	11.0	11	7.7-10
b-Jet Tagging (%)	9.2(4.6)	9.2(4.6)	-	-
Background σ (%)	6-20	6-20	6-18	6-18
Signal σ (%)	0	0	0	10.0
QCD multijets (%)	14	14	30-50	15-40

Source	$ZH \rightarrow \nu\bar{\nu} b\bar{b}$	$ZH \rightarrow e^+e^- b\bar{b}$ DT(ST)	$ZH \rightarrow \mu^+\mu^- b\bar{b}$ DT(ST)	$H \rightarrow \gamma\gamma$
Luminosity (%)	6.1	6.1	-	6.1
Normalization (%)	-	-	6.1	-
Jet Energy Scale (%)	3.0	2.0	2.0	-
Jet ID (%)	2.0	5.0	5.0	-
Jet Triggers (%)	5.5	-	-	-
Electron ID/Trigger (%)	0	4.0	-	12-17
Muon ID/Trigger (%)	0	-	4.0	-
b-Jet Tagging (%)	6.0	7.5(3.0)	7.5(3.0)	-
Background σ (%)	6-16	10-30	10-30	5-26
Heavy-Flavor Scale (%)	50	-	-	-
QCD multijets (%)	-	41-50	50	20