SM Higgs Boson Searches at the Tevatron

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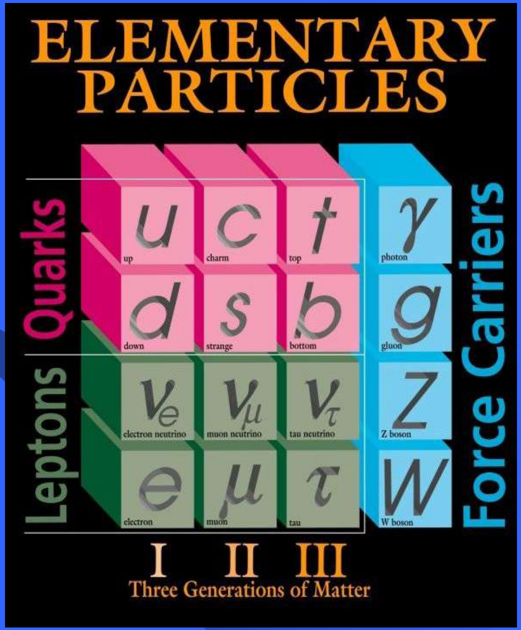
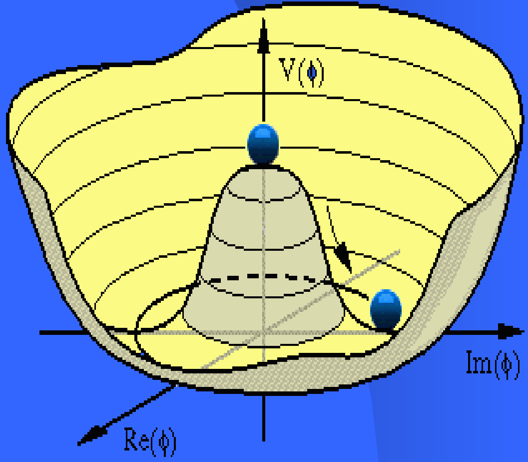
OutLine

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

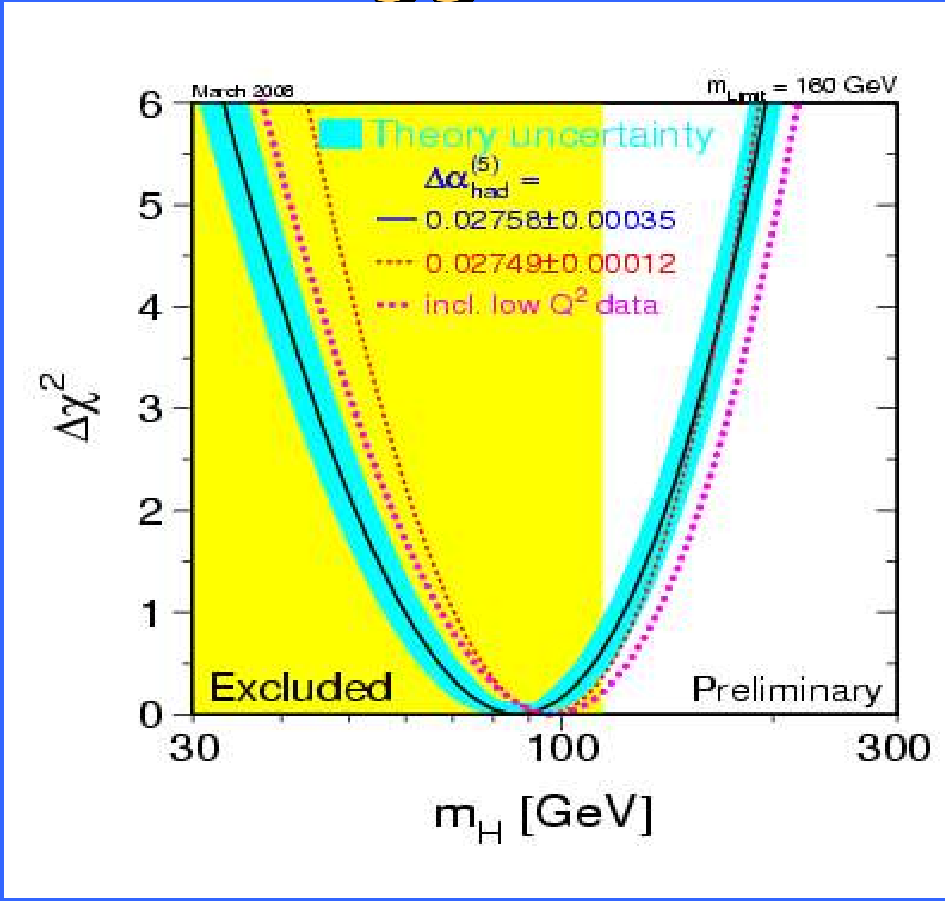
Introduction

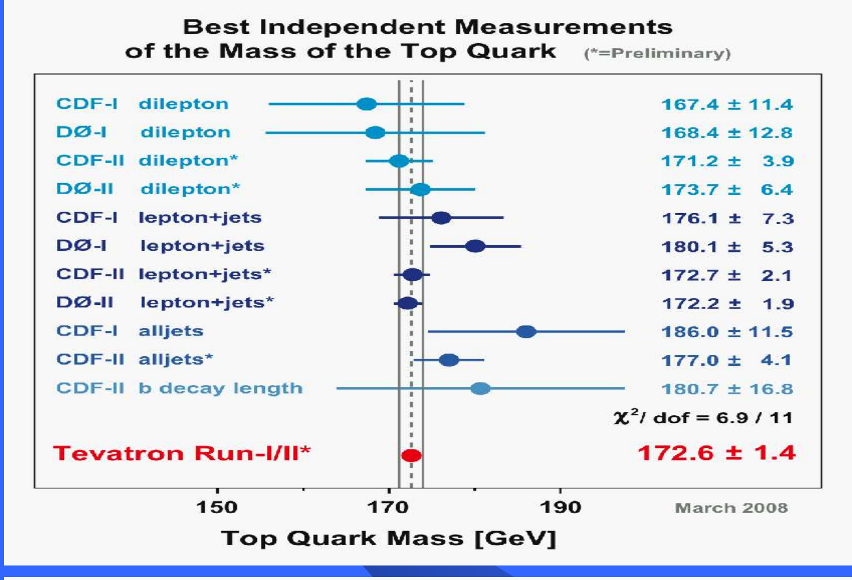
- The Standard Model describes nature well in terms of fundamental particles, but provides no explanation about the origin of mass.
- The Higgs mechanism:
  - provides a clue for EWSB
  - predicts the existence of Higgs boson, that has yet observed experimentally.
- LHC has the best shot for Higgs discovery, 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…

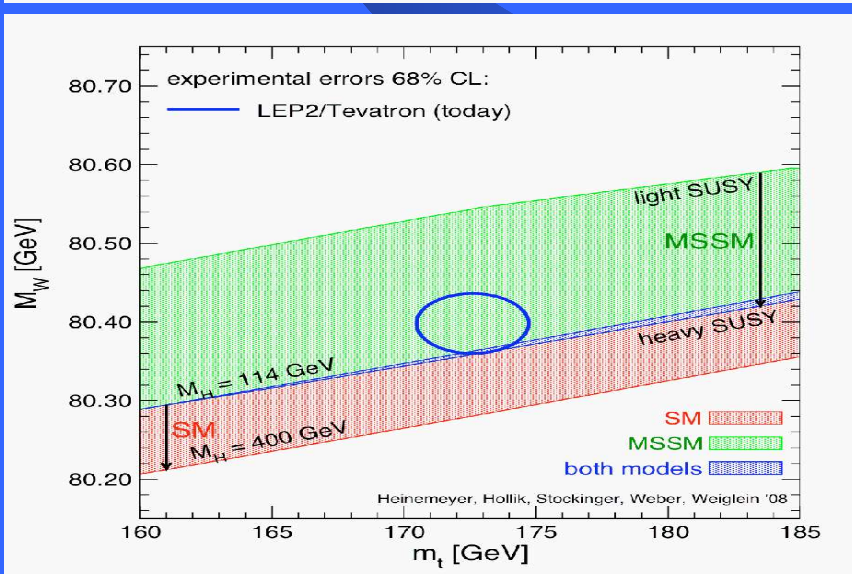




What we know about the Higgs Boson







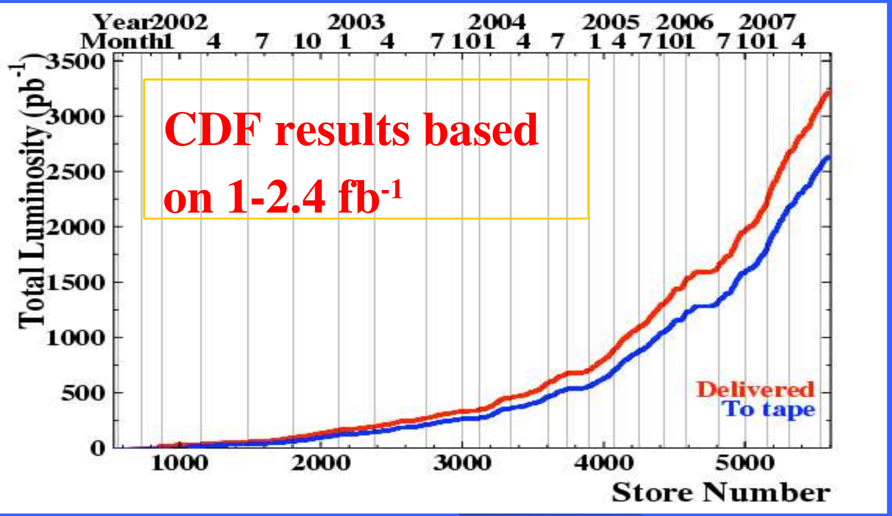
- Direct Searches at LEP: exclude M_H<114.4 GeV at 95% C.L.
- Global fit give best fit of M_H= 87^{+36}_{-27} or <160 GeV at 95% C.L.
- The low-mass Higgs hard to reach with early LHC data.

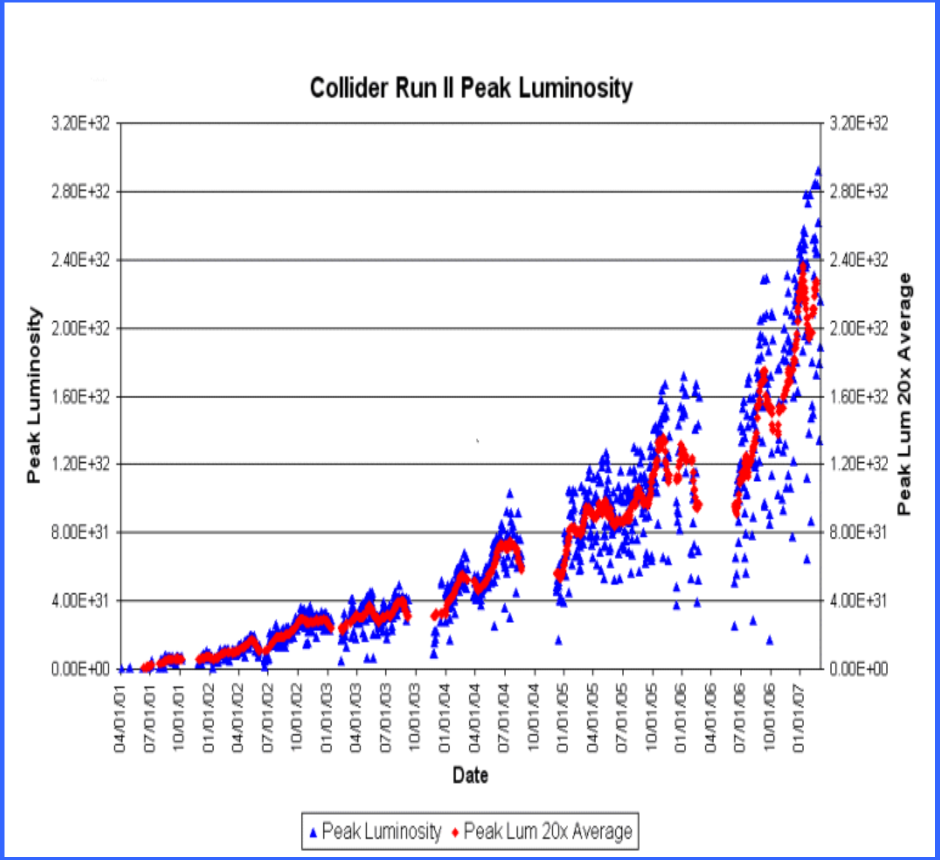
Tevatron Status

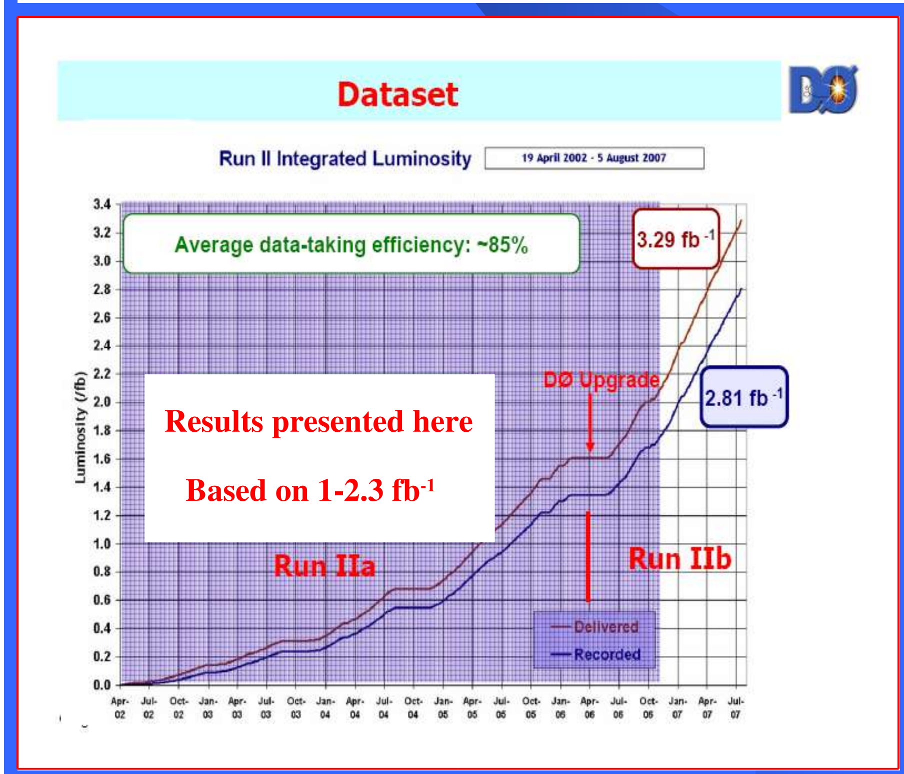
Tevatron are doing great !

Record luminosity: 3.15*x10*^{32}

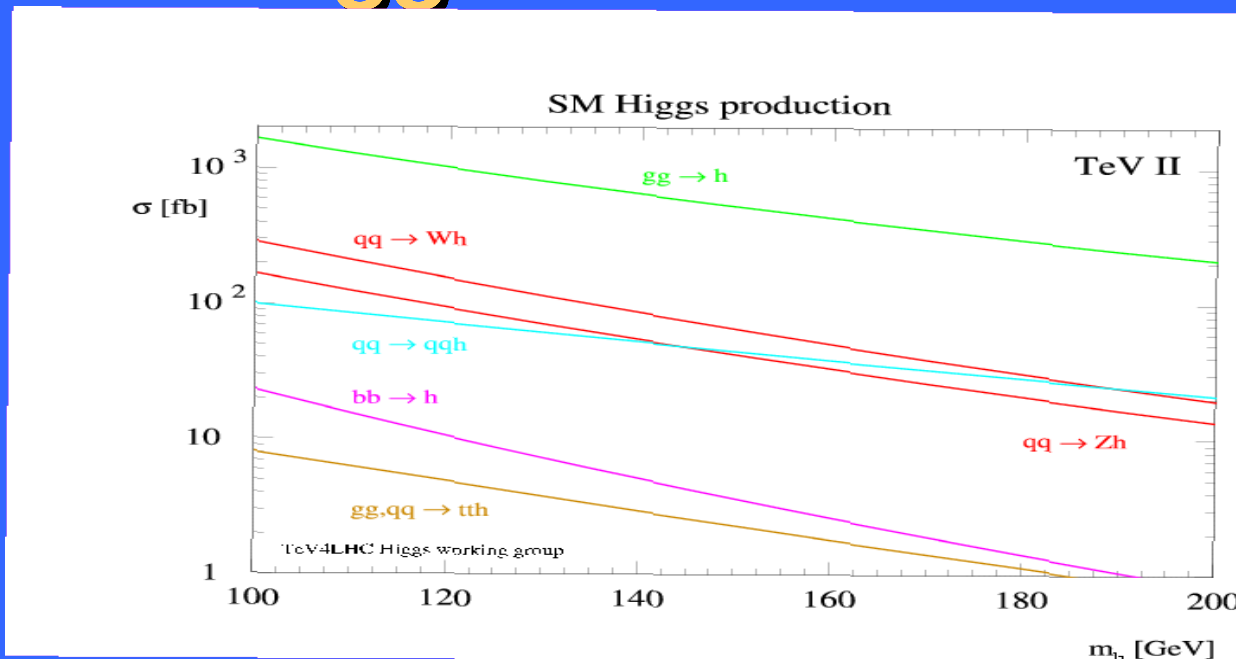
Delivered >4 fb^{-1} and will double the dataset if running through 2010

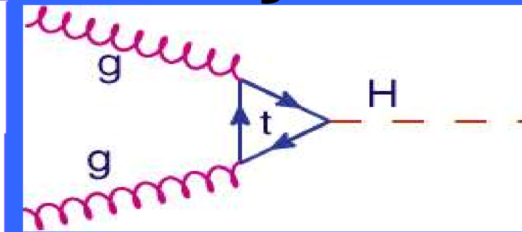


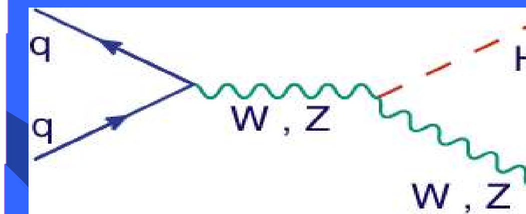


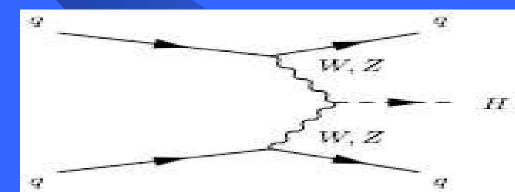


SM Higgs Production and Decays

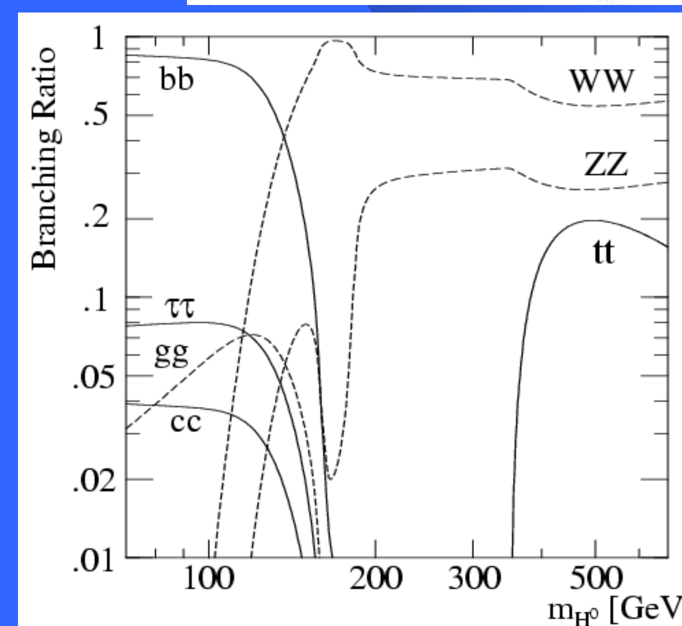




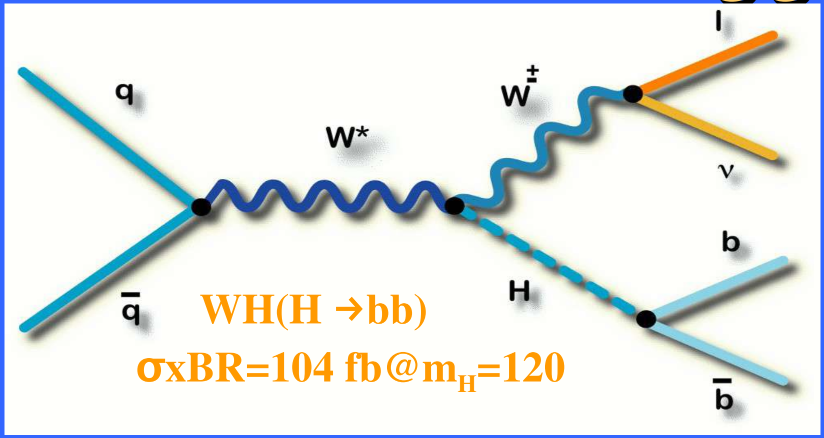


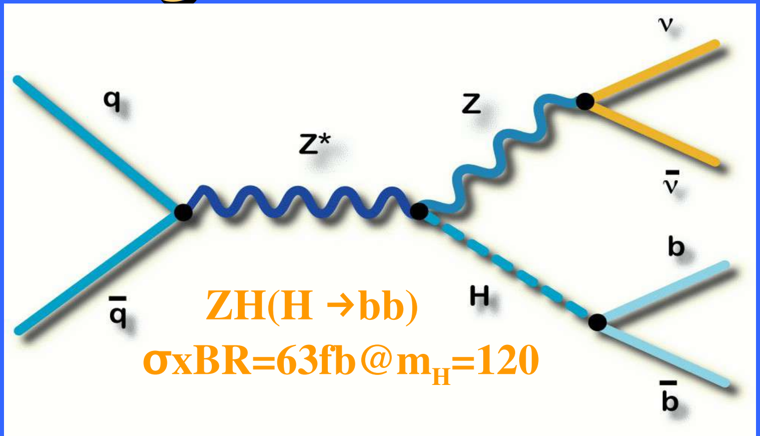


- M_H<135 GeV: H→bb
  - WH→lvbb; ZH→vvbb, llbb most accessible (easy to trigger)
  - Excellent b-tag and dijet mass
- M_H>135 GeV: H→WW*
  - Exploit large σ (gg→H)
  - H→WW→lvlv:clean final states

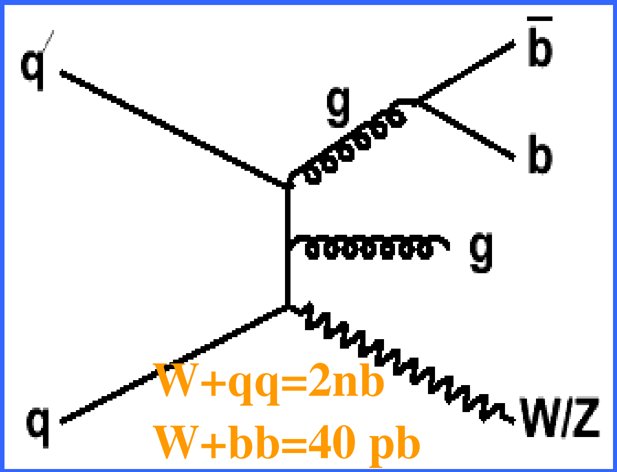


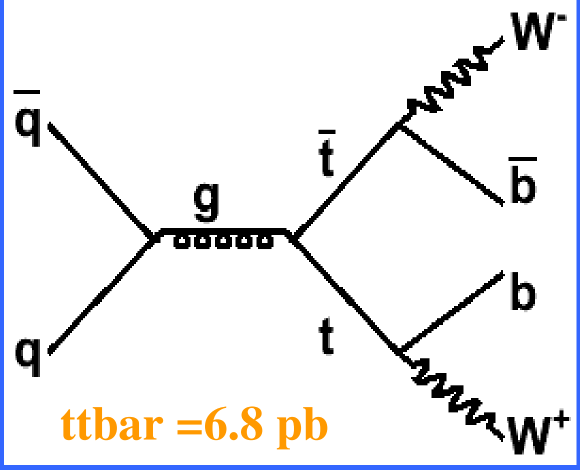
Low Mass Higgs Signatures

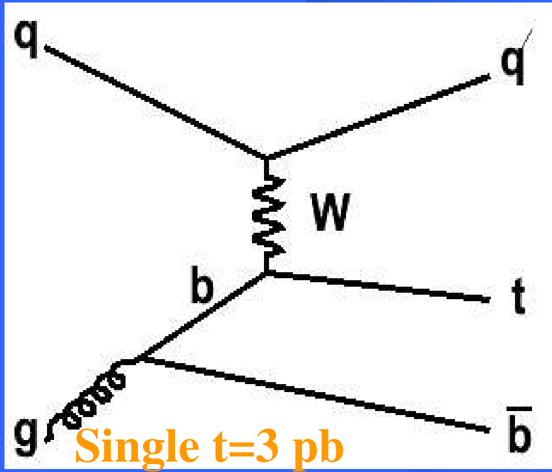




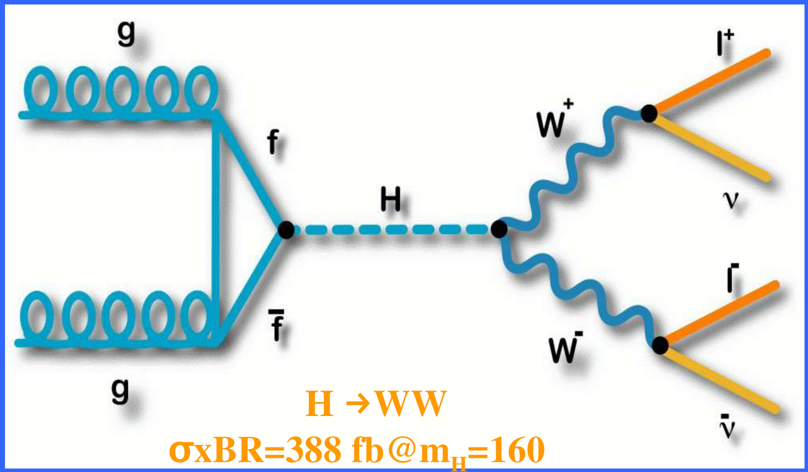
- WH→lν bb: 1 Lepton(Isotrk)+Met+2b
- ZH→llbb: 2 Leptons +2b
- WH→(l)νbb, ZH→ννbb: Met +2b
- VH→jjbb: 4jets
- (V)H →ττ+2jets: $\tau_{lep}\tau_{had}$+2jets
- H→γγ: di-photon
- Major Backgrounds: Wbb, ttbar, single-top, QCD…

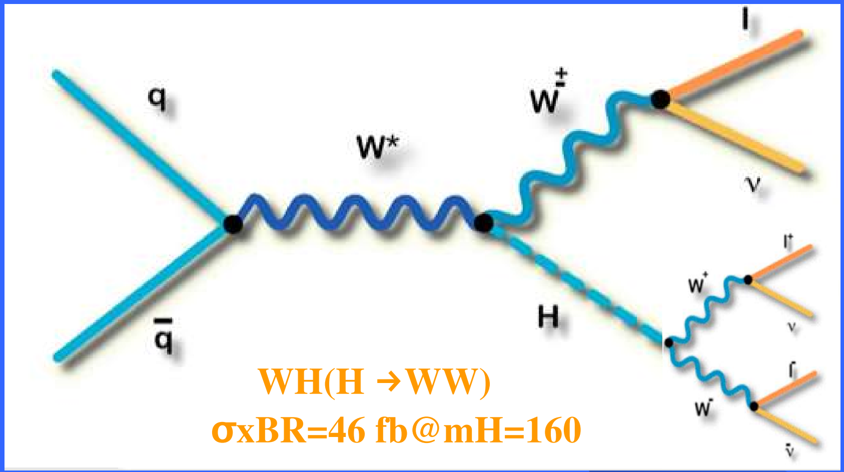




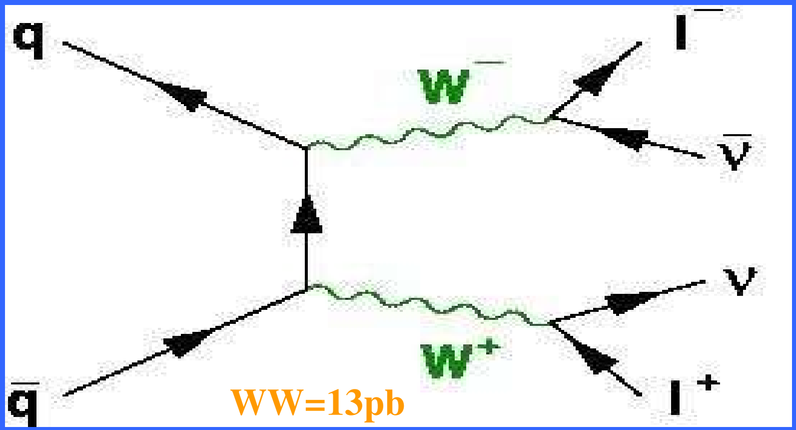


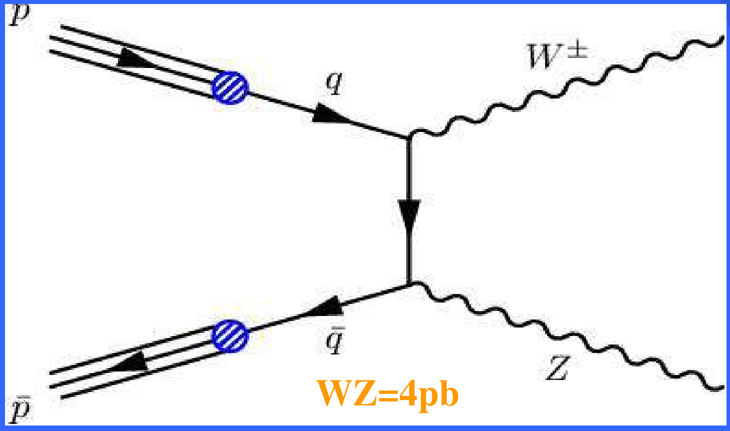
High Mass Higgs Signatures





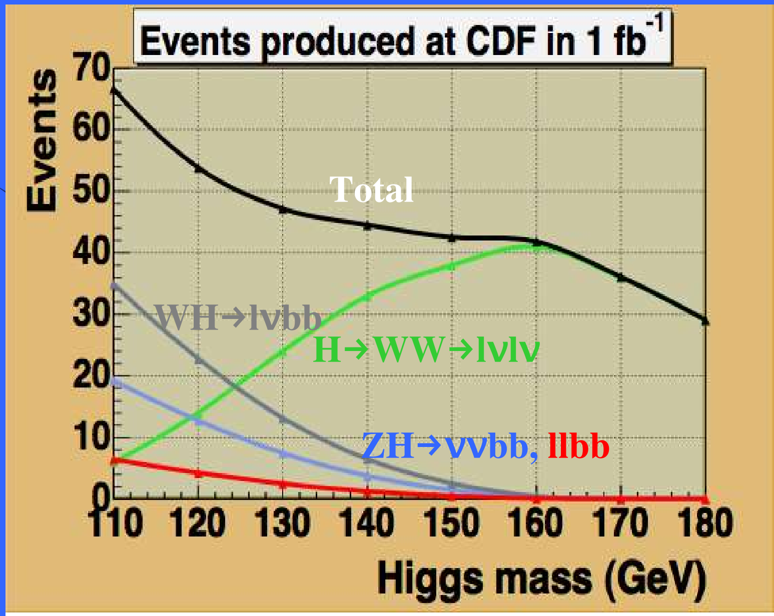
- H→WW*→llvv: 2 opp-sign Leptons + Met
- WH →WWW*->$l^{\pm}l^{\pm}$vvX: 2 same-sign Leptons + Met
- Major Backgrounds: WW, WZ, ZZ, top, QCD…



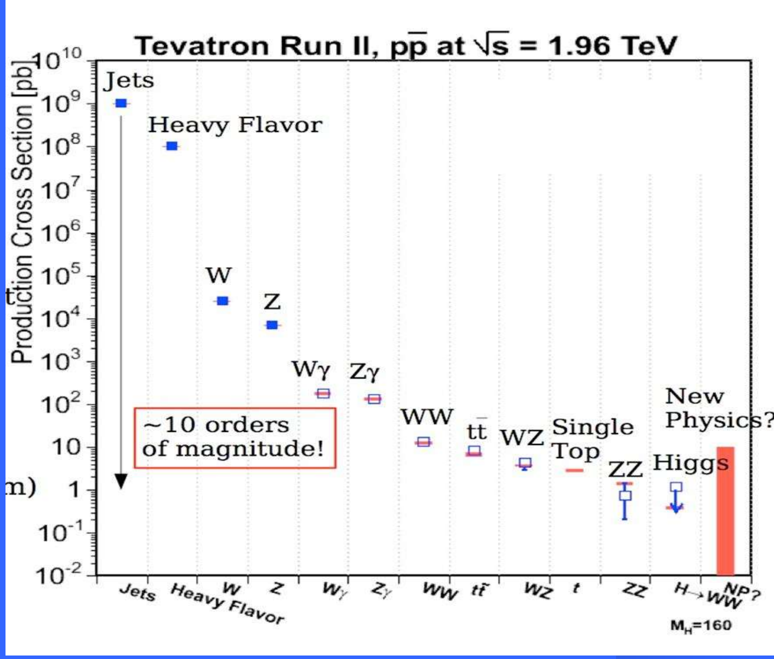


The Search Strategies…

- SM Higgs production rate is very small at the Tevatron.
- There are huge backgrounds with many orders of magnitude higher.



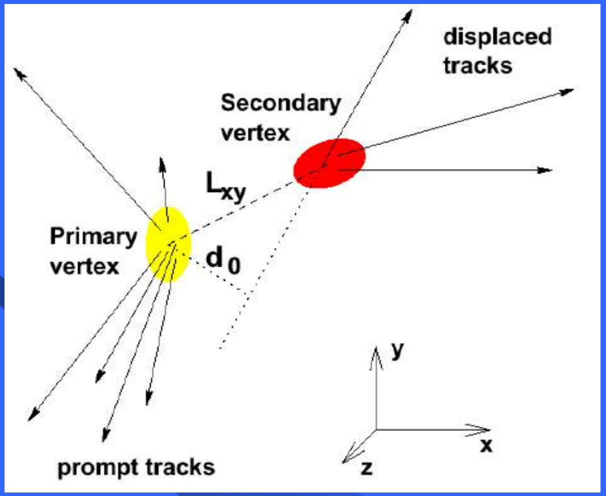
- Strategies: to achieve >10^{10} signal to background rejection
  - Focus on final states with leptons
  - Selecting events with large met
  - Require btagging and good M_{bb}
  - Using more advanced techniques

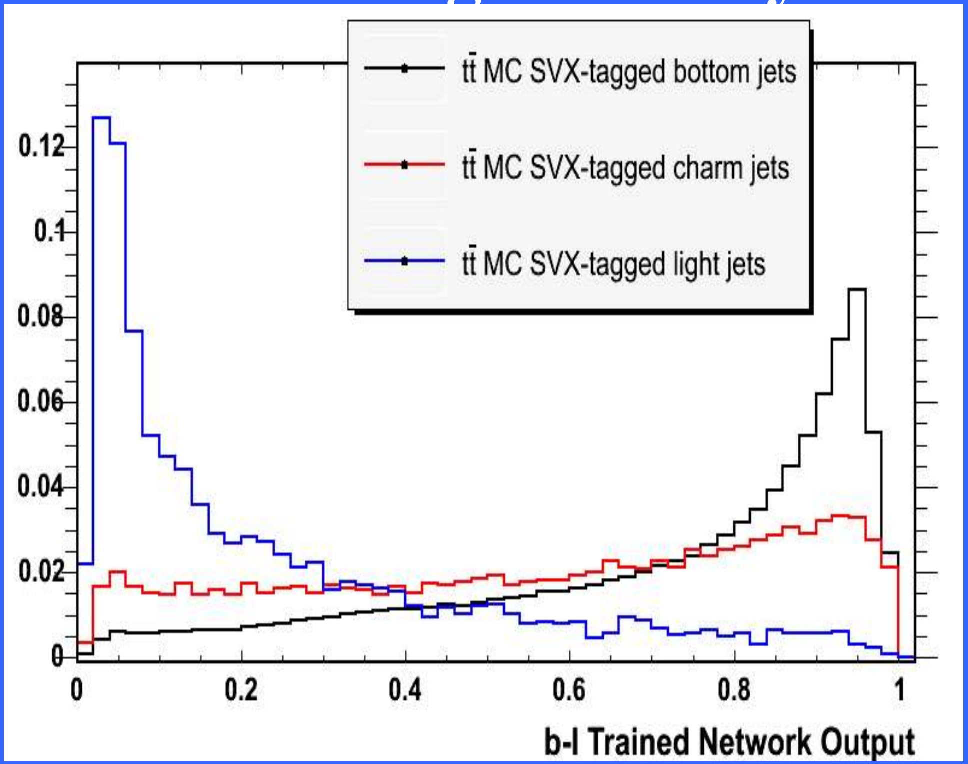


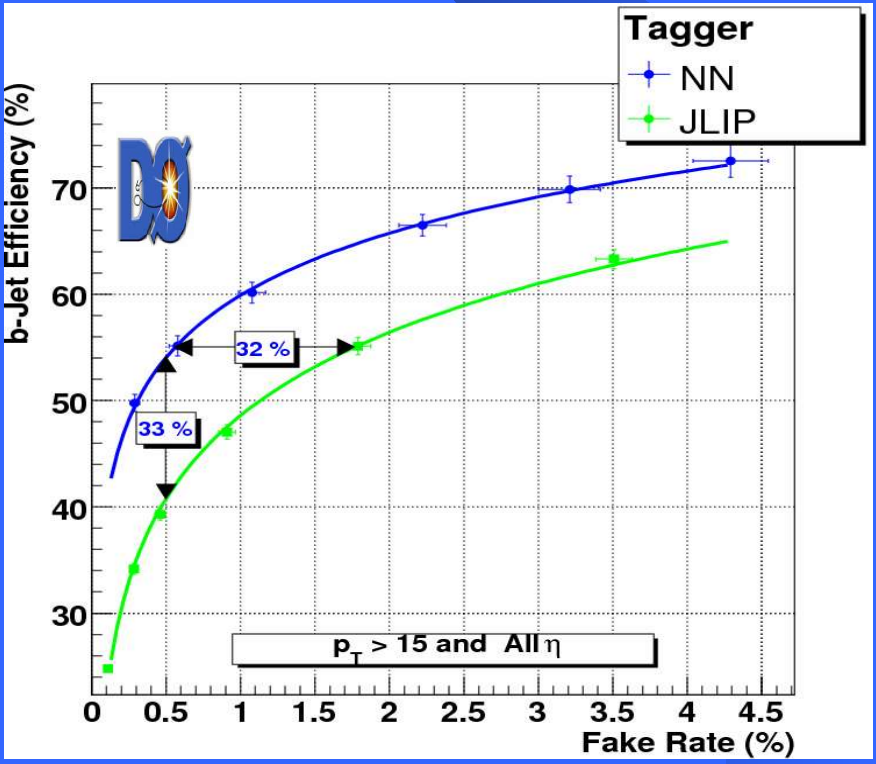
- Discovery Higgs at Tevatron is extremely challenge that requires the best of all these and lots of data.

B-jet Identificaton (B-tagging)

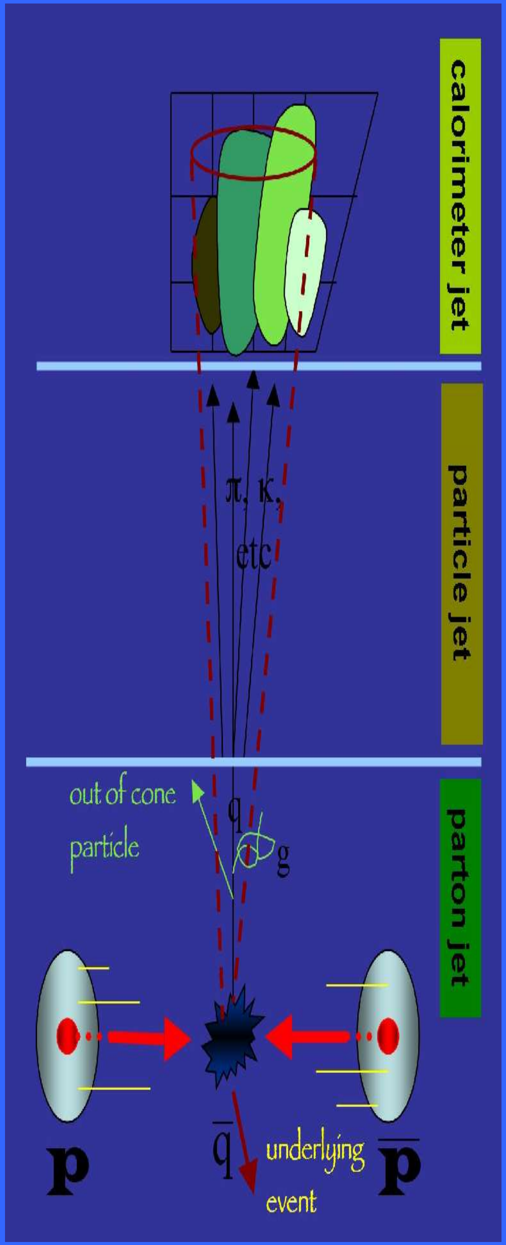
- **B-hadron are long-lived – search for displaced tracks/vertex inside the jet**
- **Combining existing taggers with neural network: to purify mistags or increase btag efficiency**





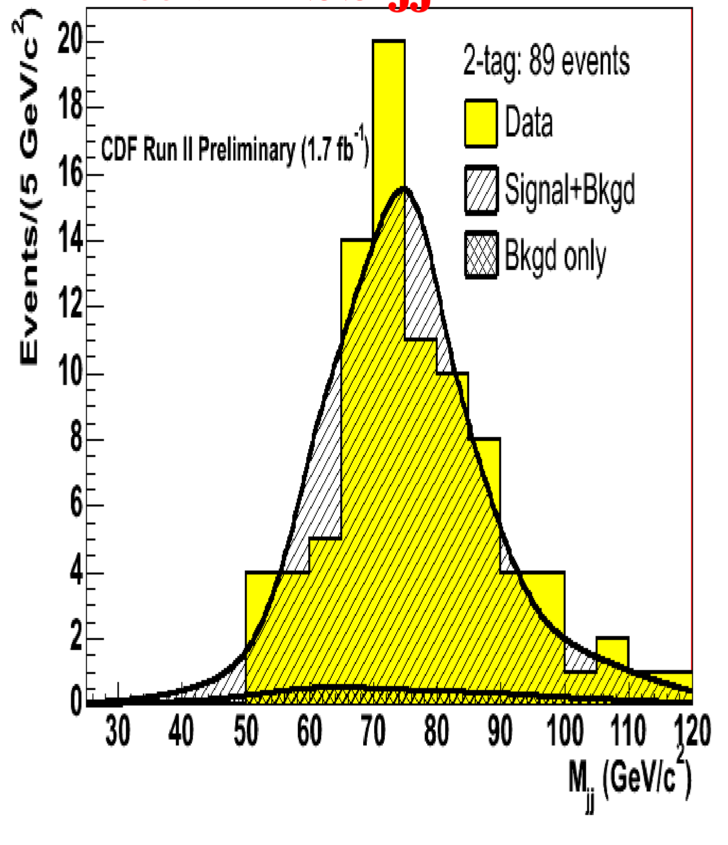


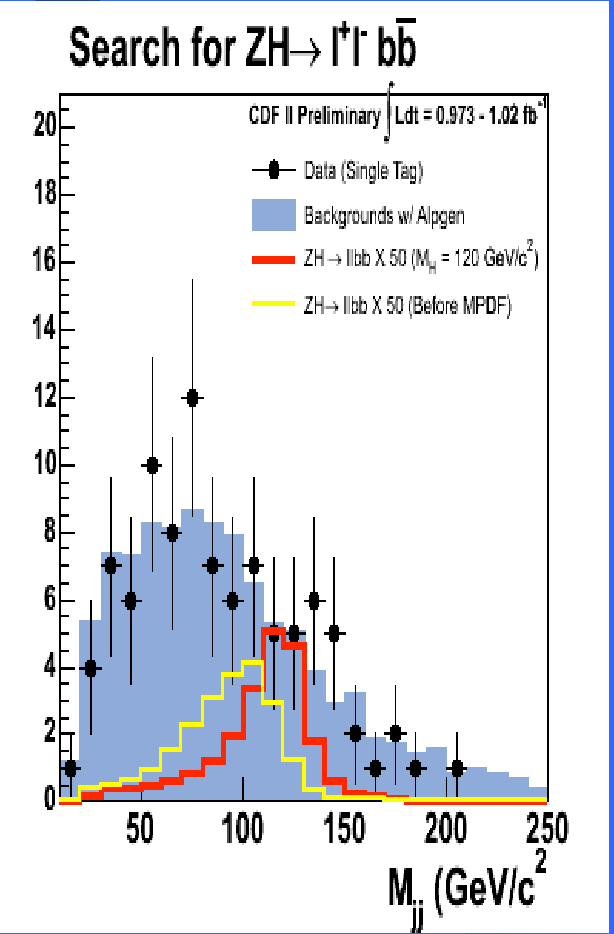
Jet Energy Resolution (Di-jet Mass)



- 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…

tt->lν bb jj





Advanced Multivariate Techniques

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

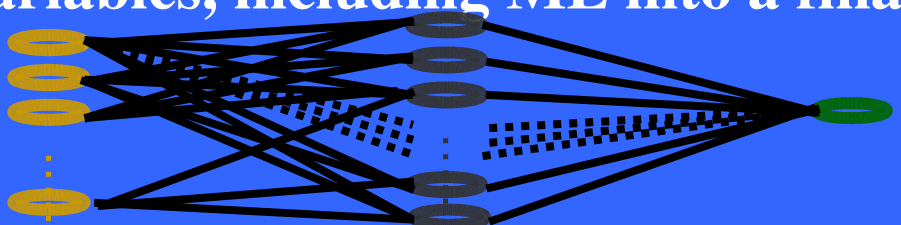
- **<u>LO Matrix Elements (ME):</u> are used to calculate event probabilities and calculate likelihood ratio:**

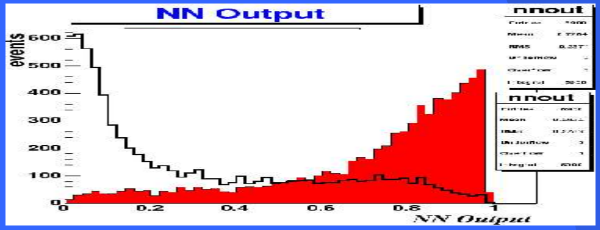
$$P_m(x_{obs}) = \frac{1}{<\sigma_m>} \int \frac{d\sigma_m^{th}(y)}{dy} \epsilon(y) G(x_{obs}, y) dy$$

ME efficiency resolution

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

- **<u>Neural network (NN):</u> combine various kinematic variables, including ME into a final discriminant variable.**

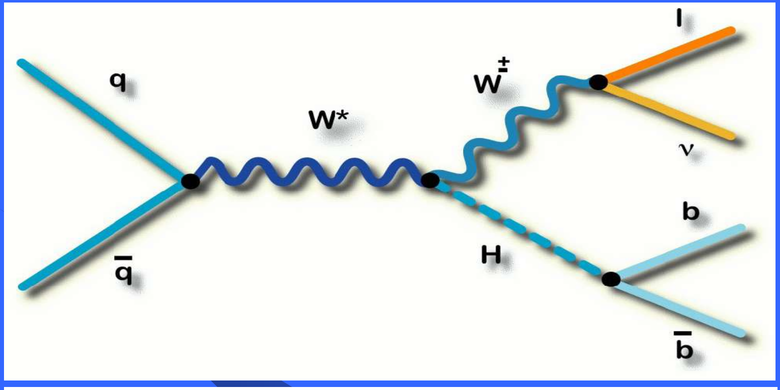


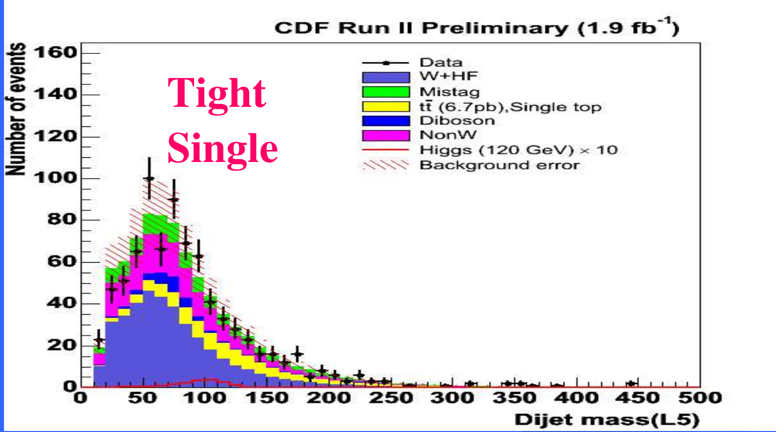


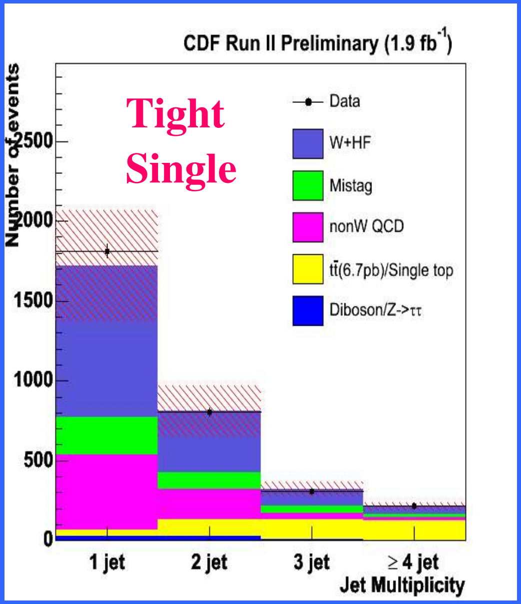
- **<u>Boosted Decision Tree(BDT):</u> an alternative to NN**
- **On-going intense optimization efforts in terms of trigger, lepton selections, btagging, and dijet mass resolution.**

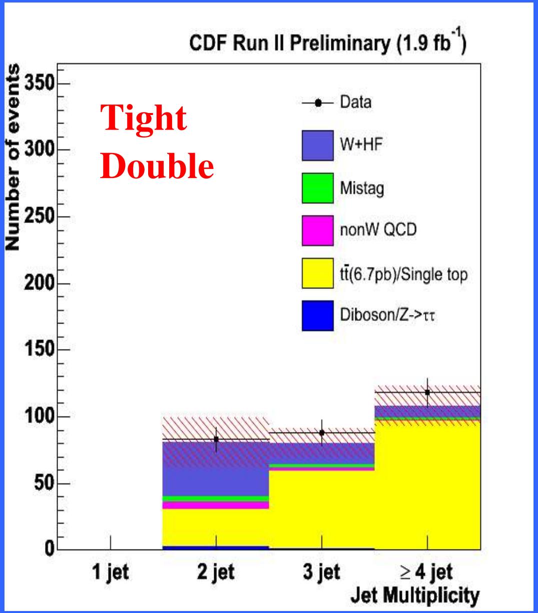
Search for WH→lνbb

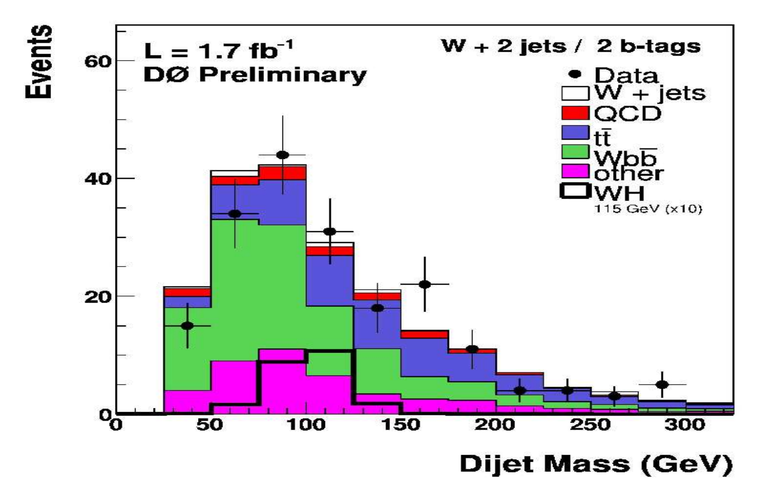
- Selecting W+2jets:
  - 1 Isolated high Pt lepton (>20 GeV)
  - Large missing Et >20 GeV
  - 2 jets with Et>20 GeV and |eta|<2
- Btagging: 2b(tight+loose) + 1b(tight)
- W+bb: dominant and irreducible
- Data consistent with SM backgrounds
- Discriminant: dijet mass + kinematics





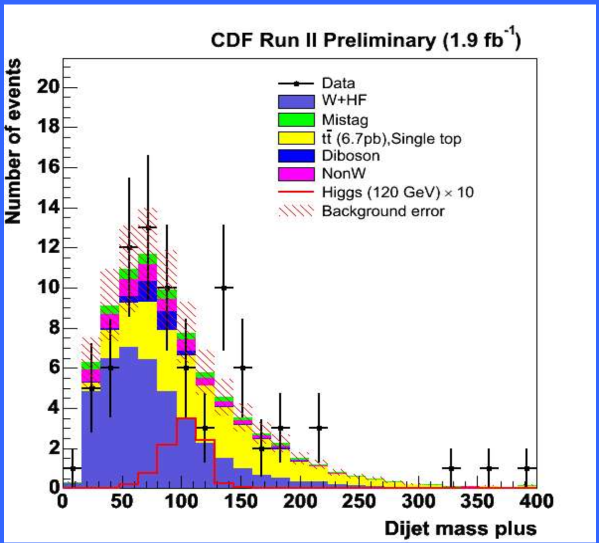


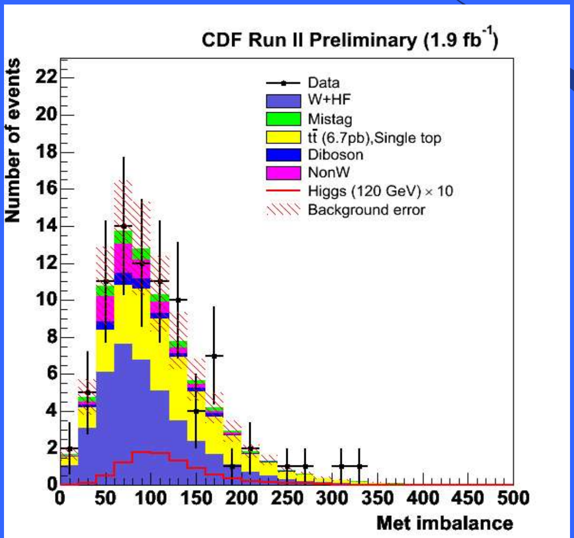


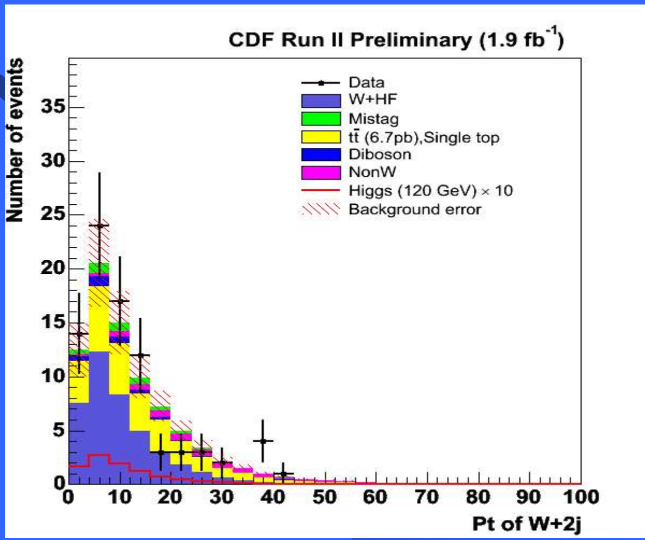


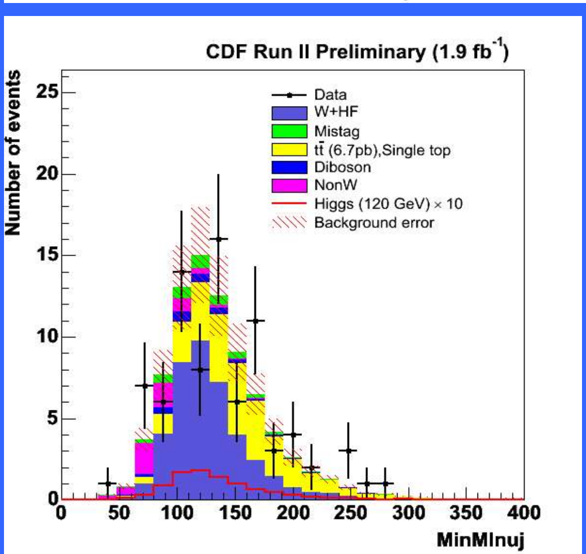
Discriminating Signal from Background

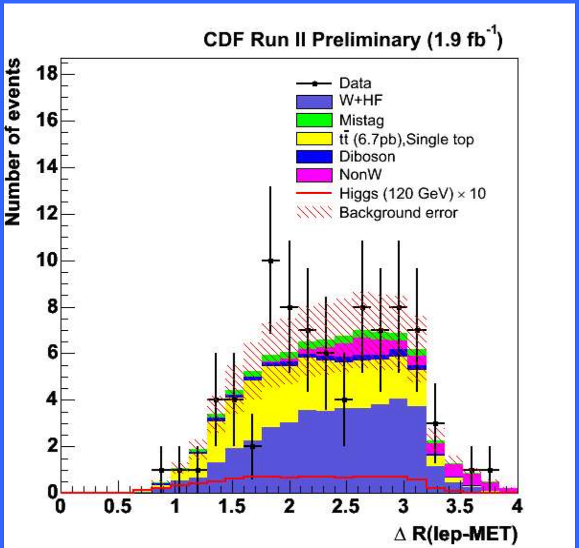
- ➢Validation data with Monte Carlo background modeling
- ➢Combine 6 variables with ANN to optimize sensitivity

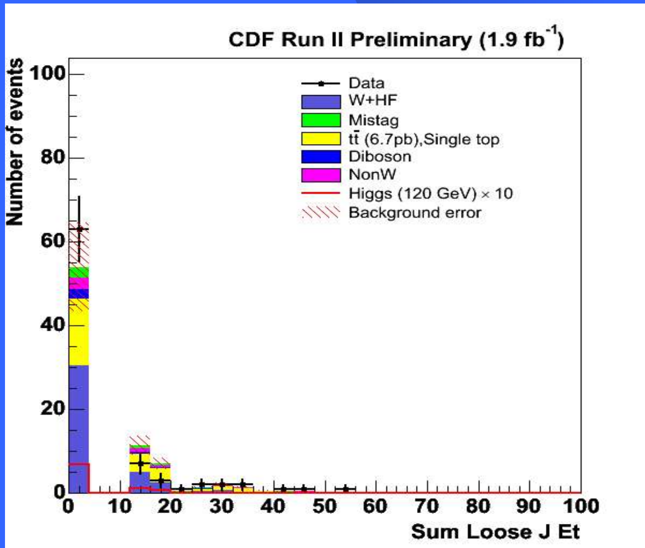




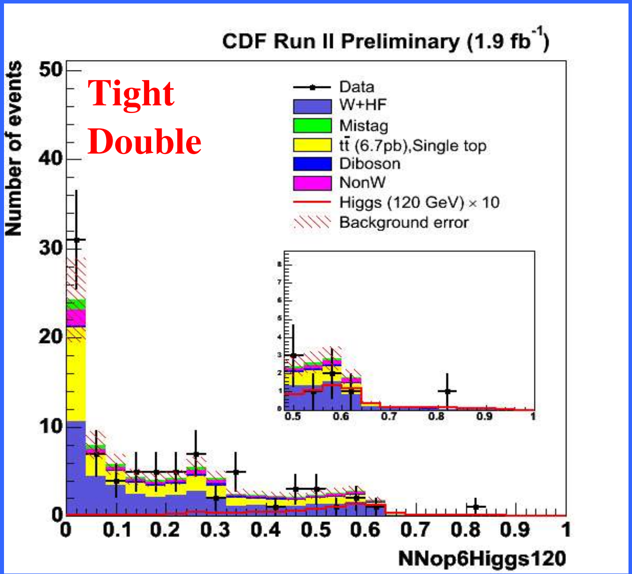


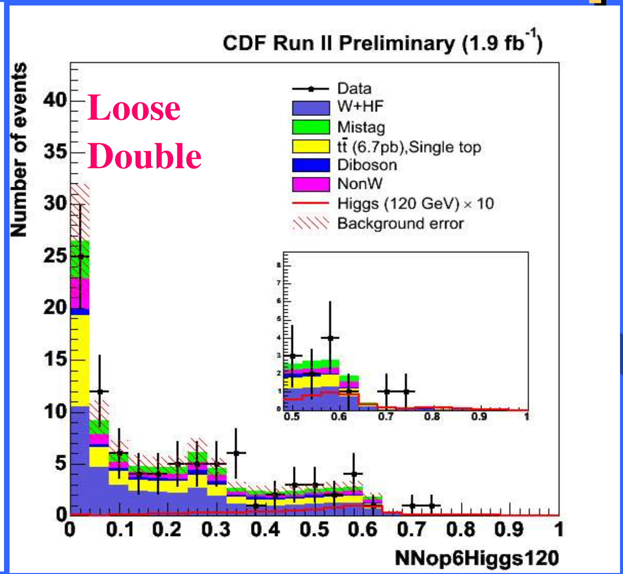


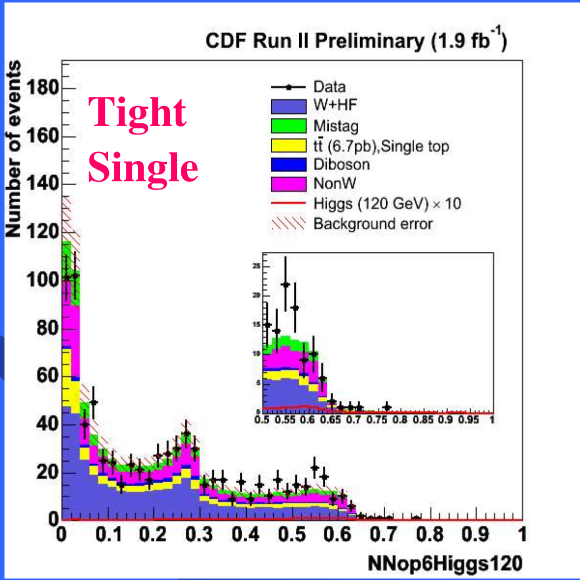


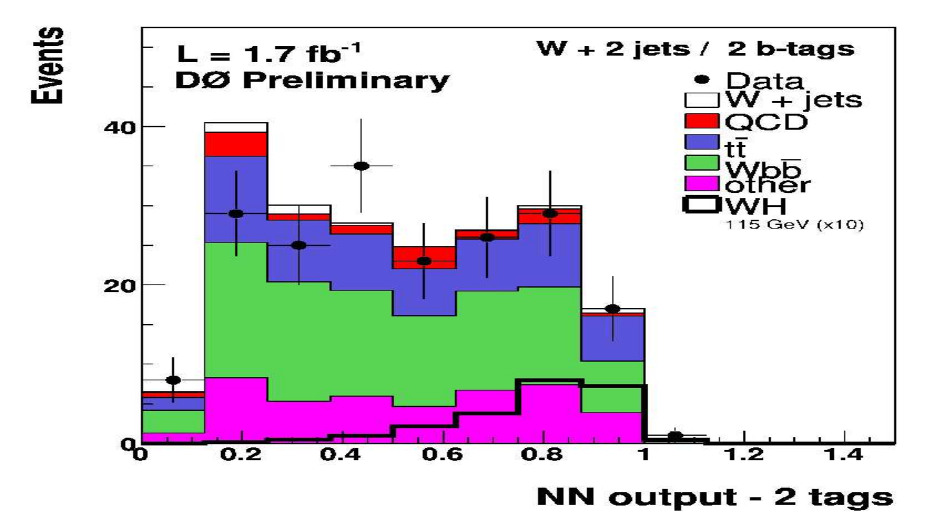


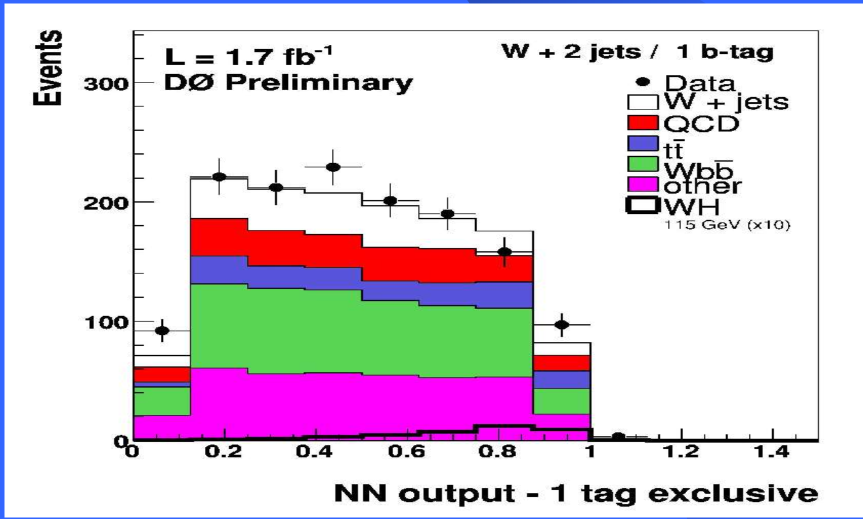
Neural Network Output









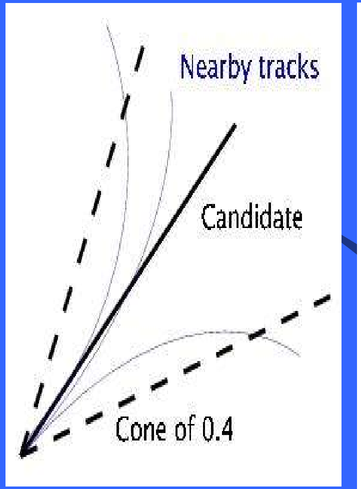


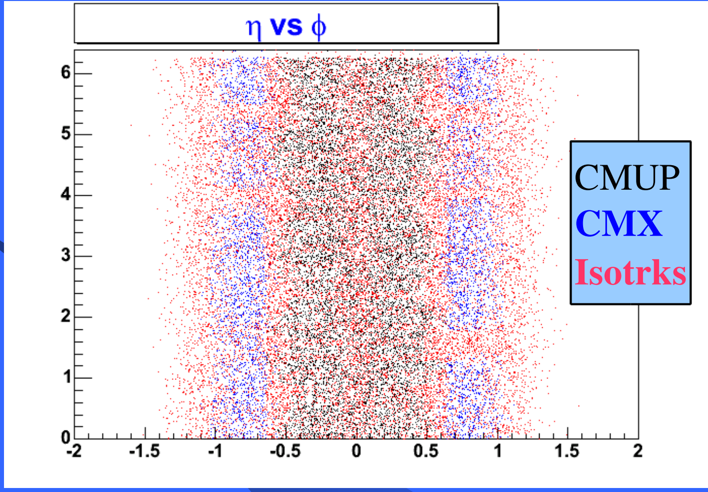
- Improves sensitivity by 10% over dijet mass alone
- Analysis refinement and optimization still ongoing

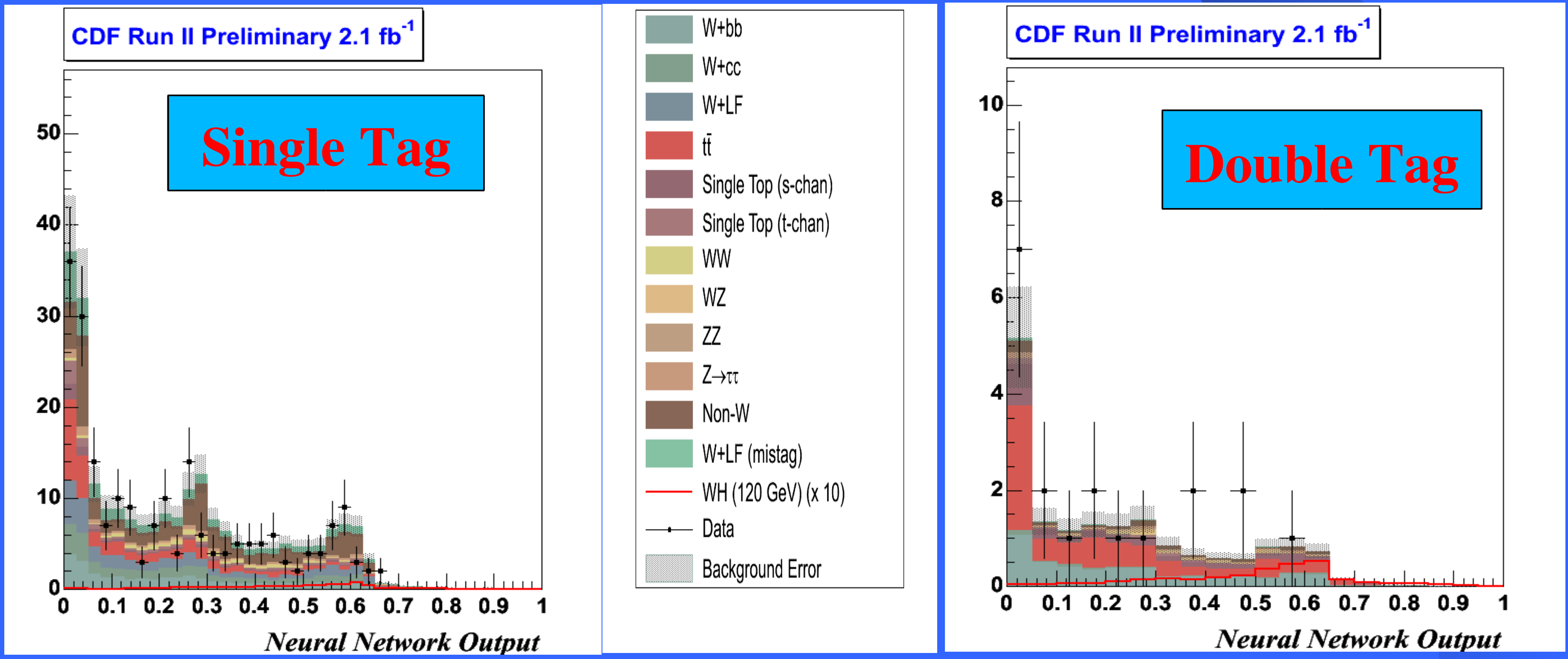
Extended Lepton Coverage with Isolated Track(CDF)

New

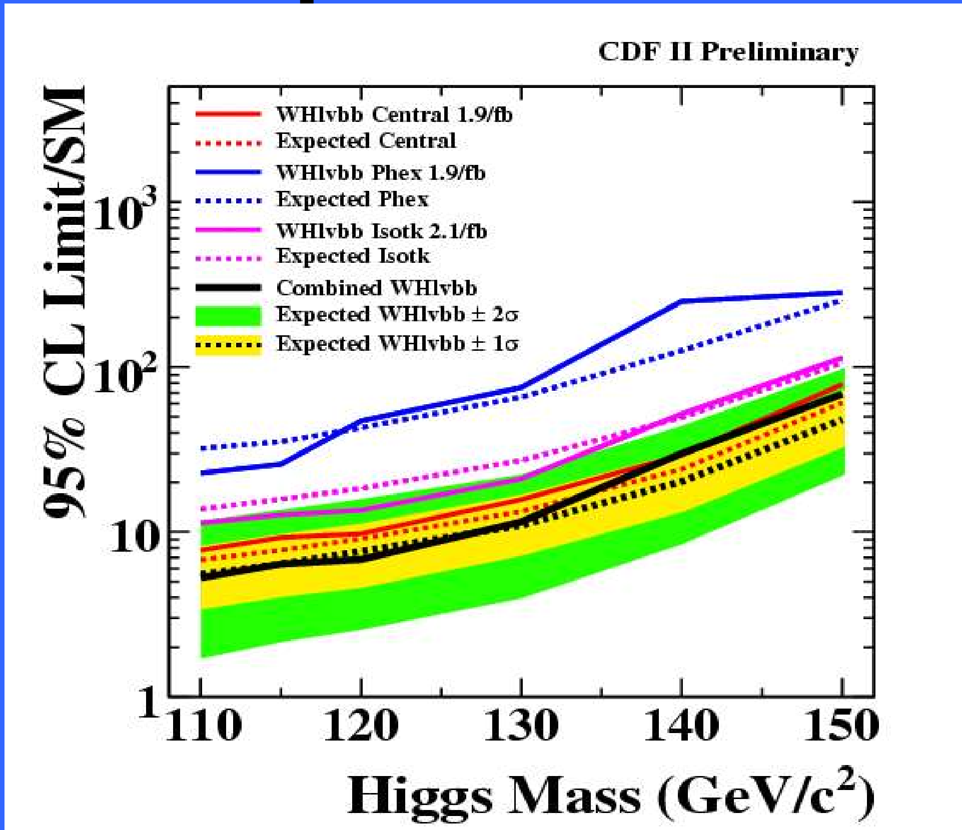
- Identify high-Pt, isolated track lepton not fiducial to μ chamber
- Require $\Sigma Pt/Pt_{cand}<0.1$
- New trigger: Met+2jets(>40)
- 25% increase in WH→lνbb acceptance with similar purity

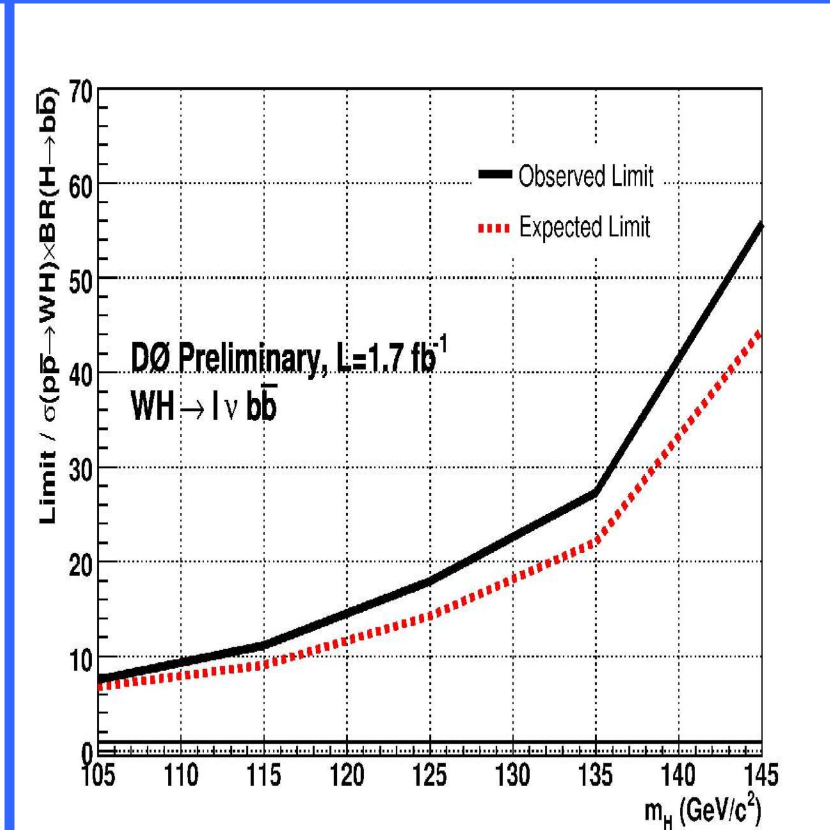






Expected and Observed Limits

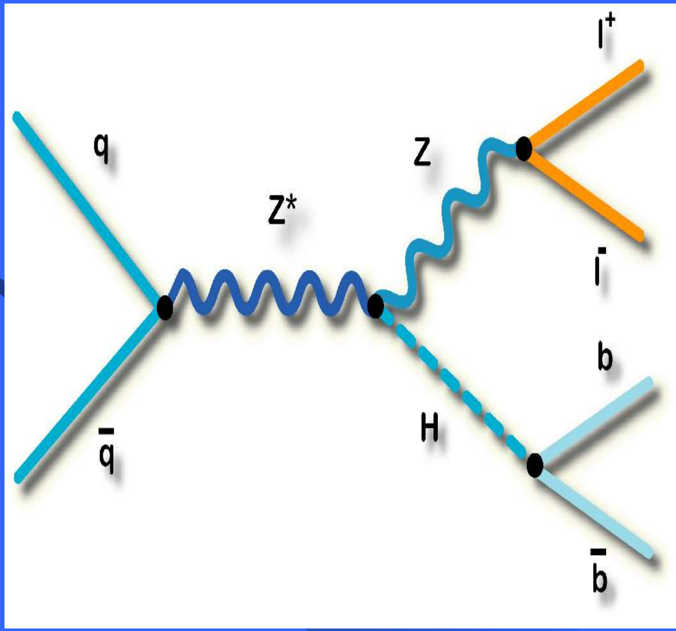




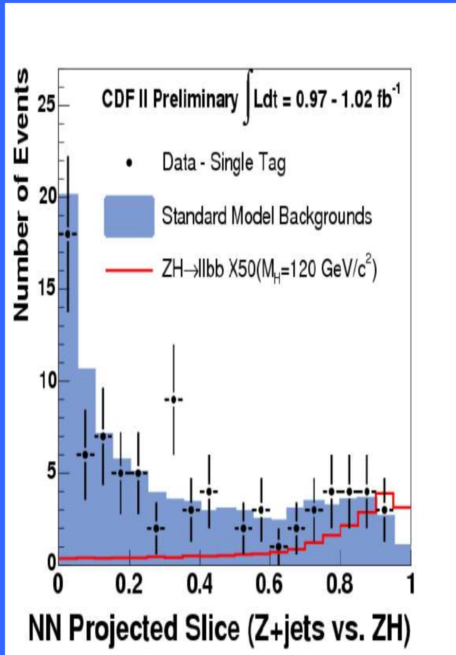
- CDF observed/expected limit: 6.4/6.4 x SM at mH=115 GeV
- D0 observed/expected limit: 11/9 x SM at mH=115 GeV.
- CDF sensitivity improved by 80% over sqrt(L) since summer 06
- Future improvements: improving btagging, dijet mass resolution and combination with ME analysis …

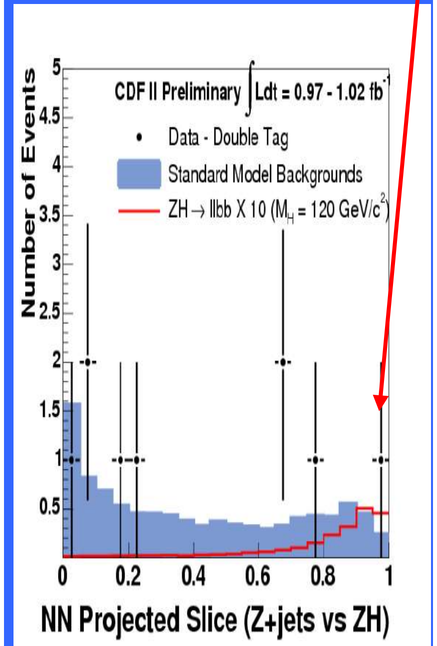
Search for ZH→llbb

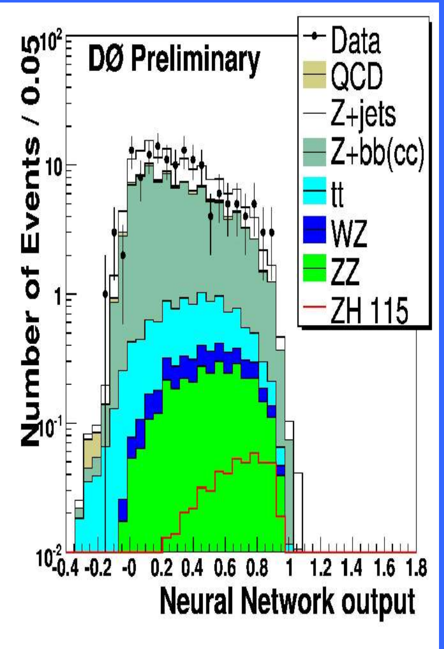
- Low event rate but clean signature
- Select two high Pt leptons from Z
- Split off 1 or 2 b-tags
- Improve dijet mass using measured missing Et.
- NN trained to separate ZH from top and Z+jets backgrounds.

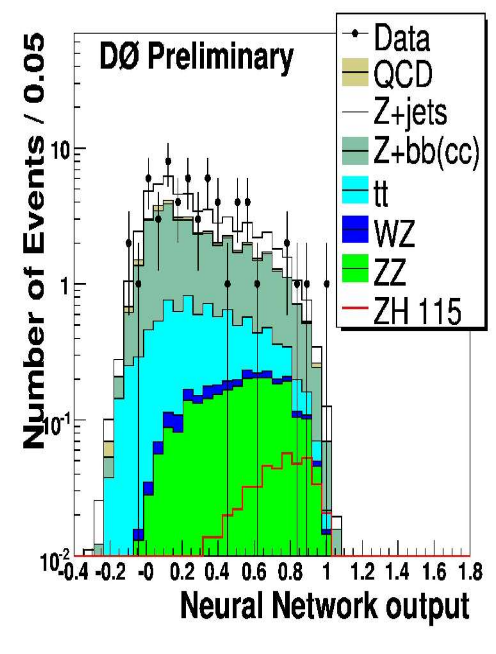


Higgs-like event



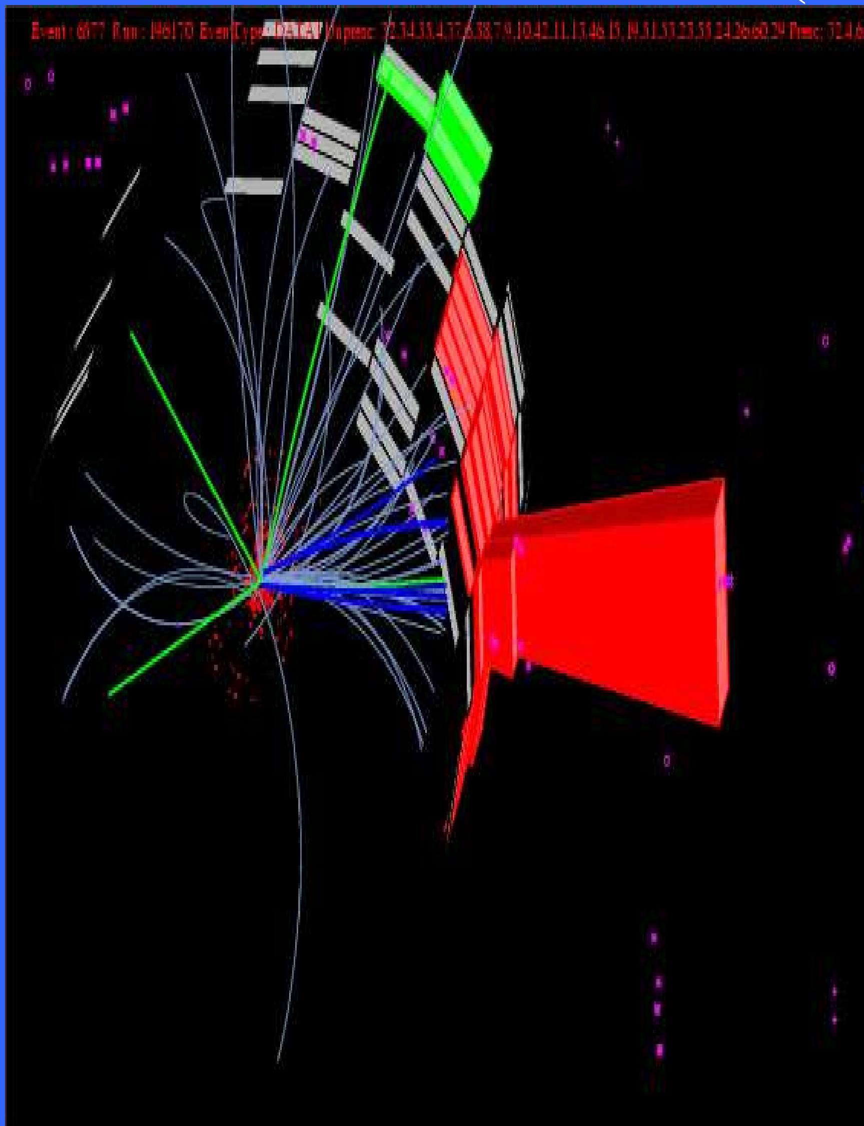


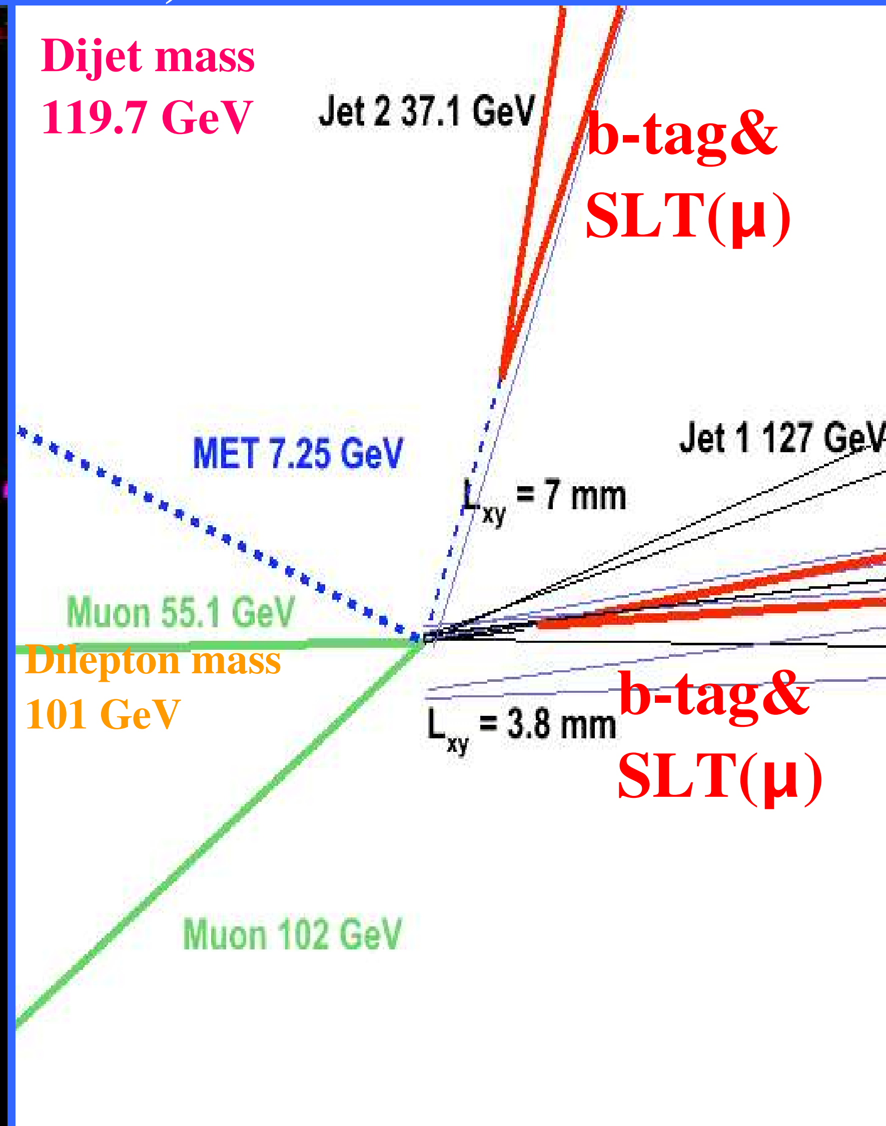




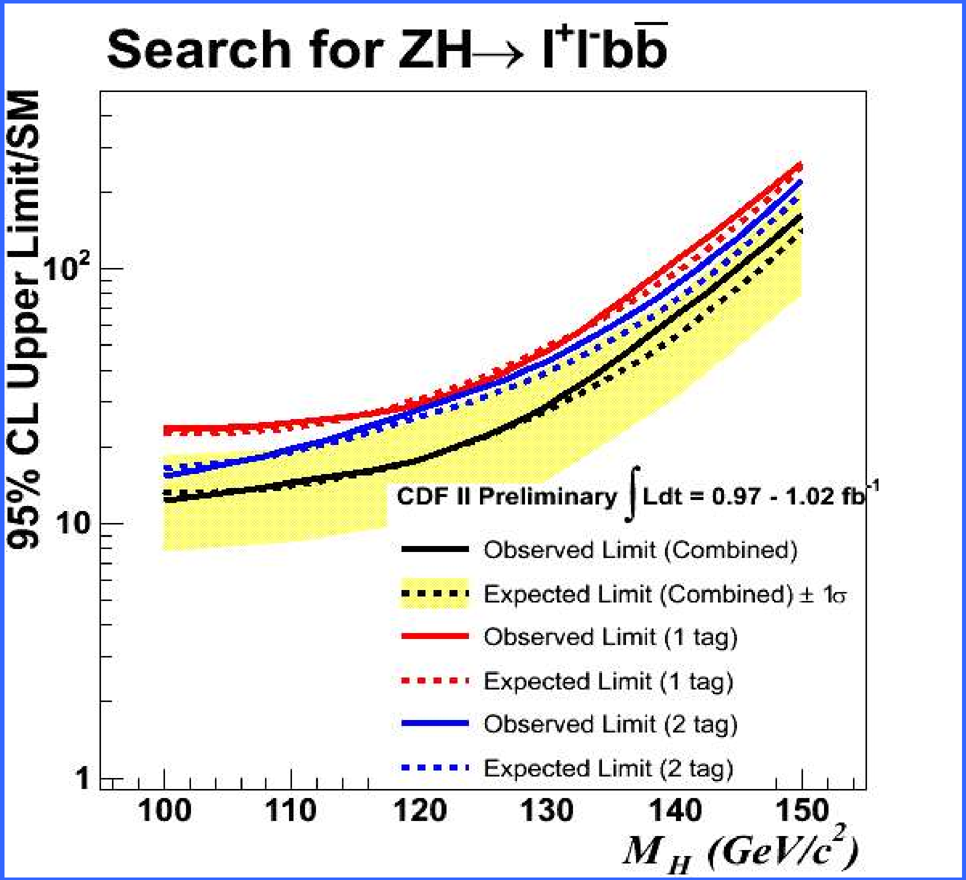
Most Higgs-Like Candidate

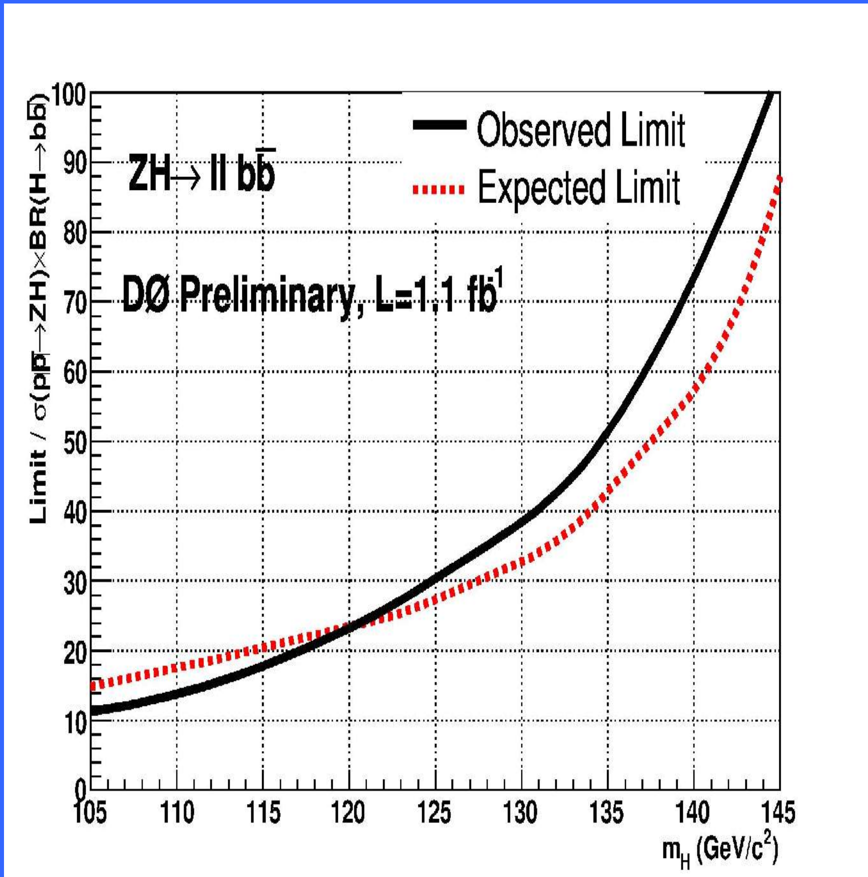
CDF run 196170 event 6577 (S:B=1:4)





Search for ZH→llbb

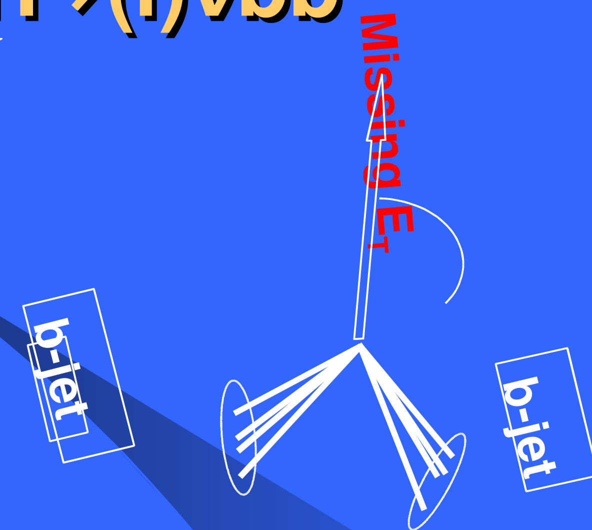


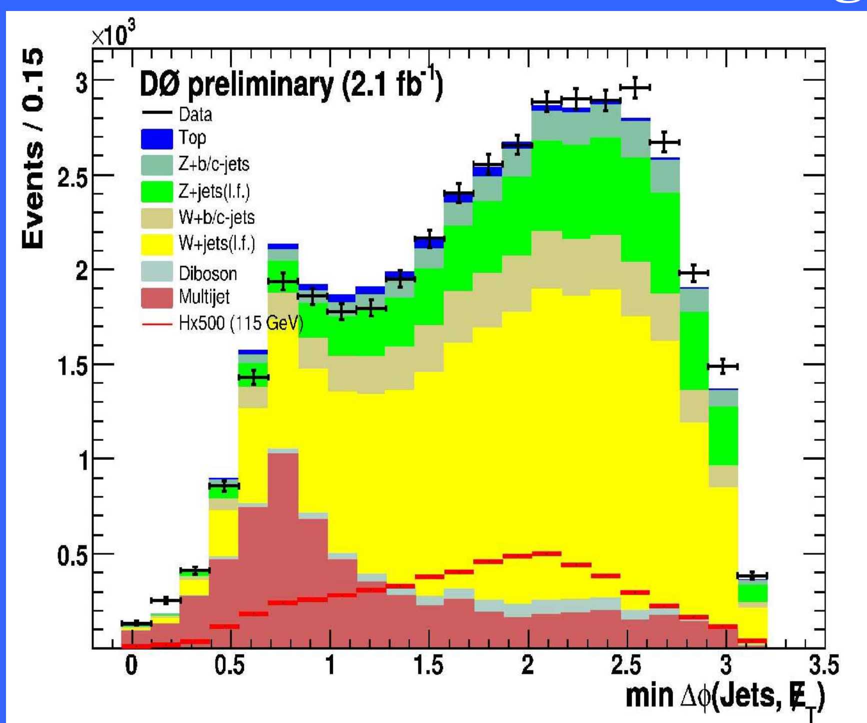


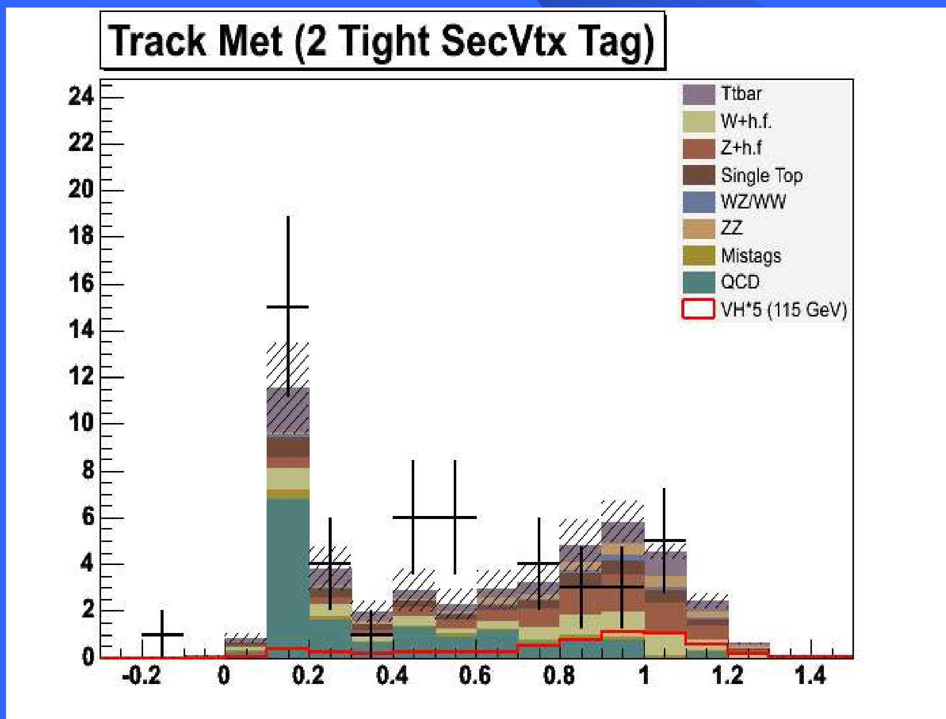
- CDF observed/expected limit is 16/16 x SM @ m_H =115 GeV
- D0 observed/expected limit is 18/20 x SM @ mH =115 GeV
- Future Improvements: update with more data, improving Z selection with loose lepton, optimizing b-tagging, and more …

Search for ZH→ννbb, WH→(ł)νbb

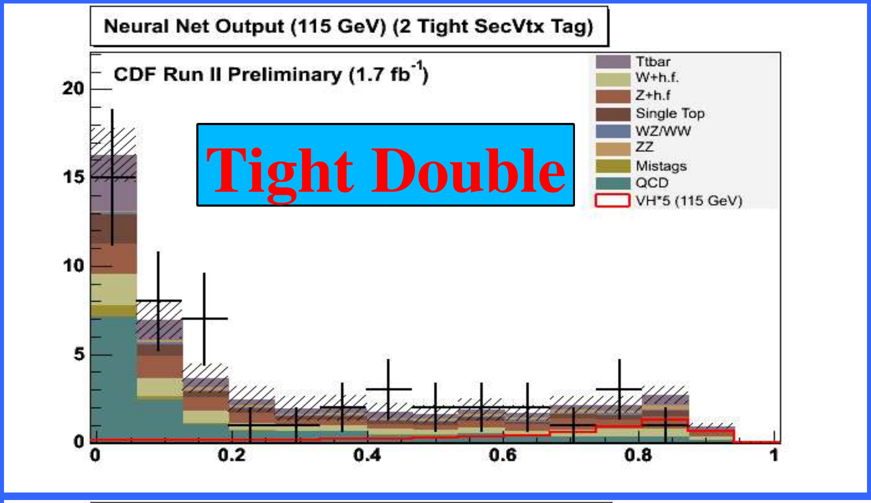
- Large xsec*Br, but large QCD, difficulty
- Rely on large Met>50 GeV +2jet
- Requiring double btag (tight and loose)
- Rejection of instrumental backgrounds:
  - dφ(Et1, MET)
  - Track Met: NN with charged tracks

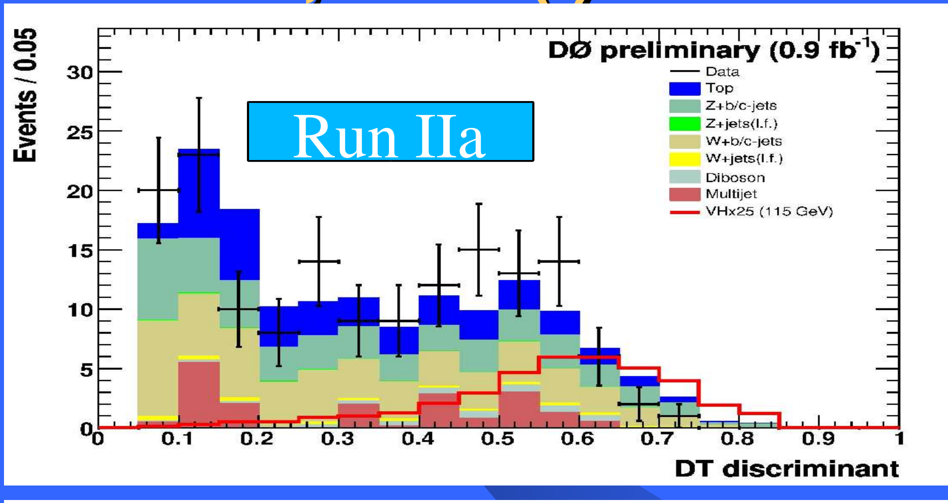


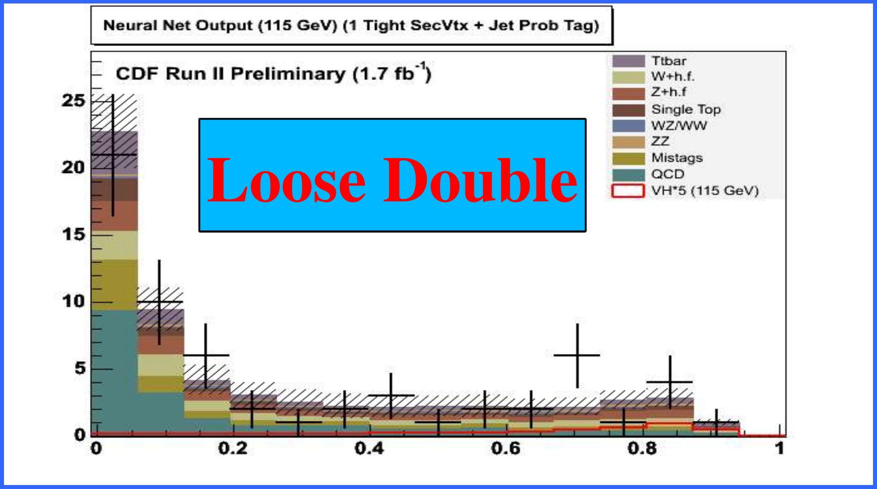


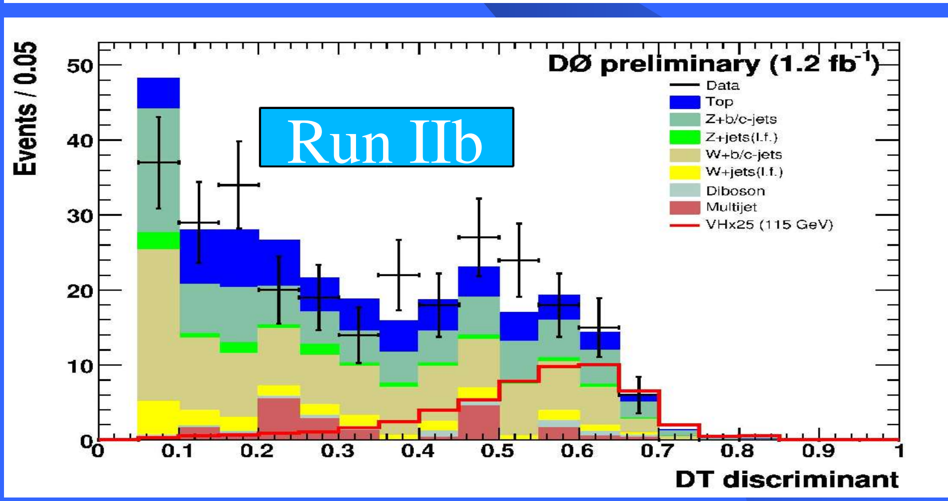


Final Discriminant for ZH→ννbb, WH→(ł)νbb



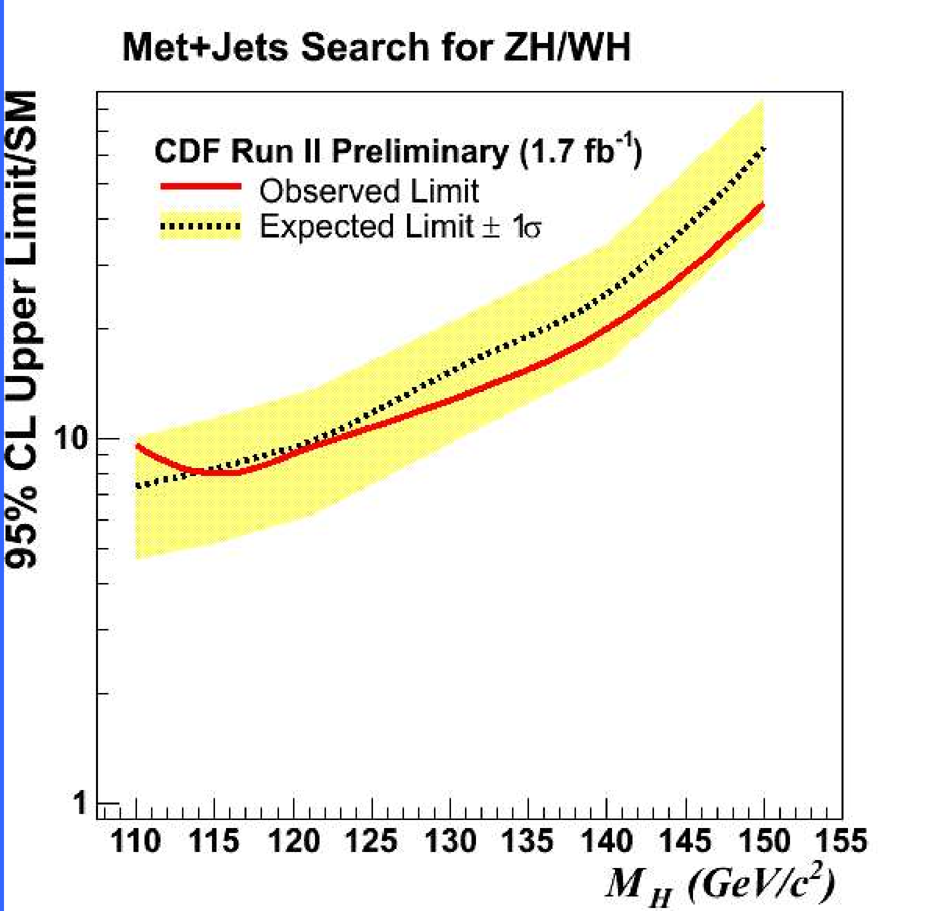


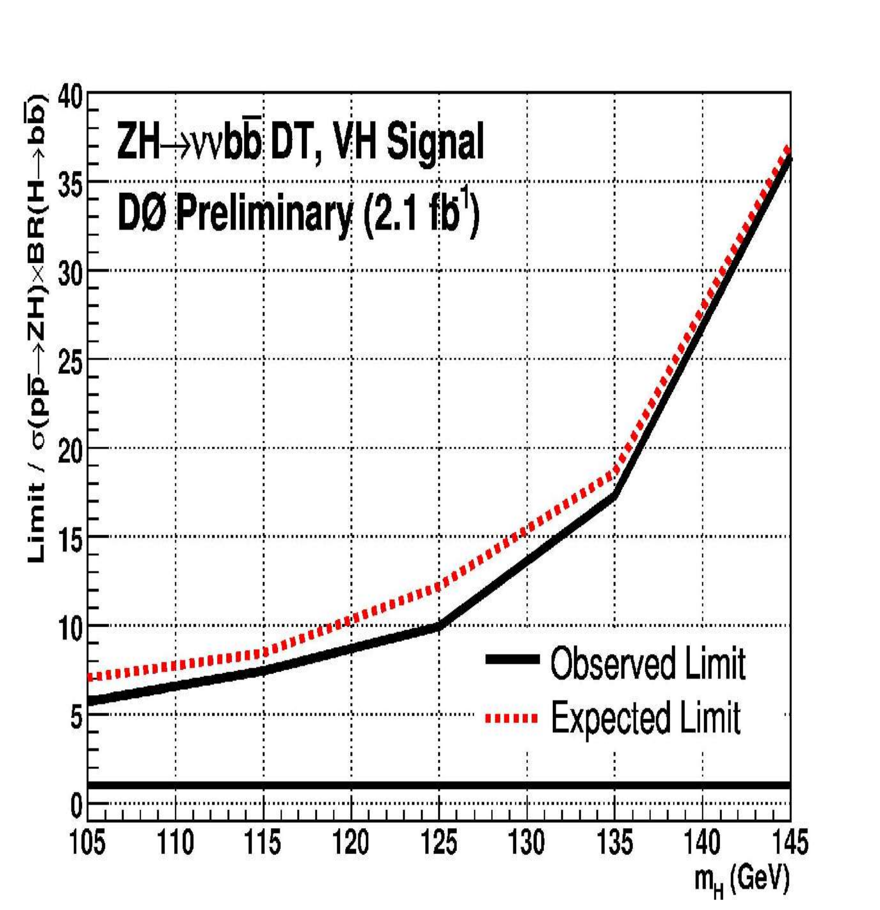




- Combining Mjj, track met, and other kinematics into final NN (CDF) or Boosted Decision Tree (D0)

Search for ZH→ννbb and WH→(ł)νbb

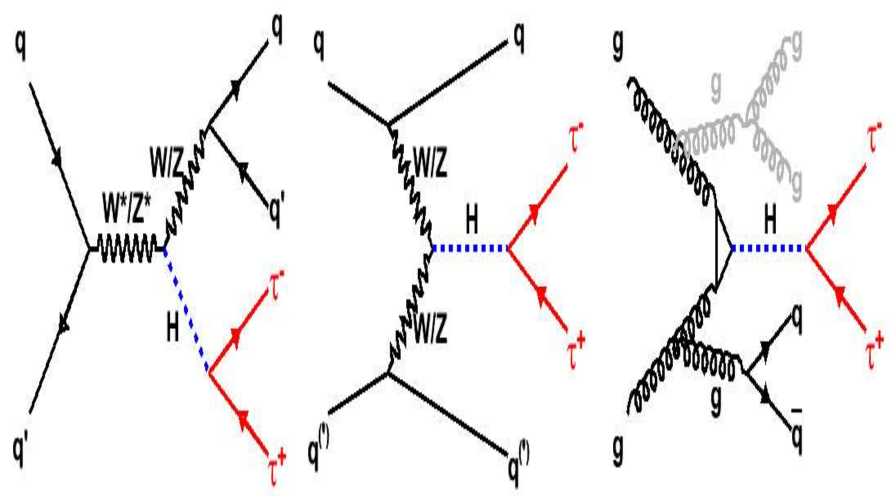


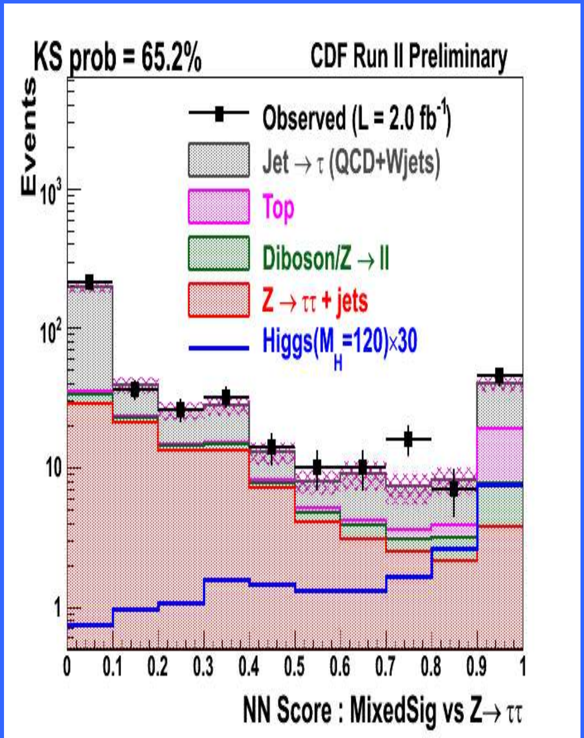


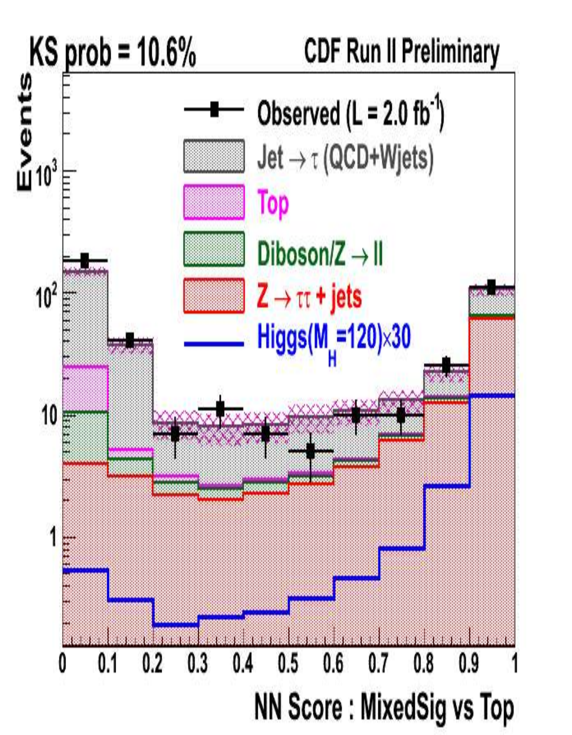
- CDF observed/expected limit is 8/8.3 x SM @ m_H =115 GeV
- D0 observed/expected limit is 7.5/8.4 x SM @ mH =115 GeV
- Future improvements: using single tag and improving the trigger

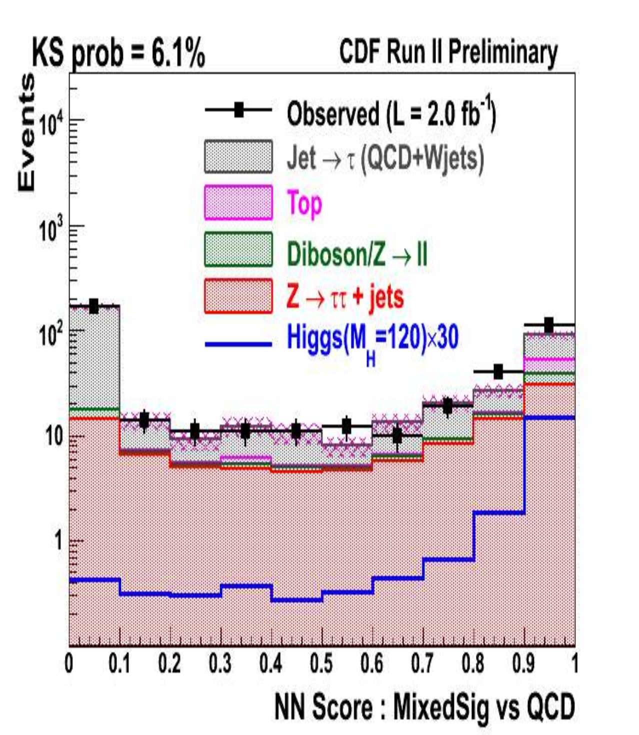
Search for (V)H→ττ +2jets

- New decay, but small Br~8%.
- H→ τ_{lep}(Pt>10) + τ_{had}(Pt>15)
- Opposite sign, not Z , +≥2 jets
- Train 3 NN(H vs DY, H vs top, H vs QCD) with m(ττ), m(lτν), other kin. variables and take the minimum score.

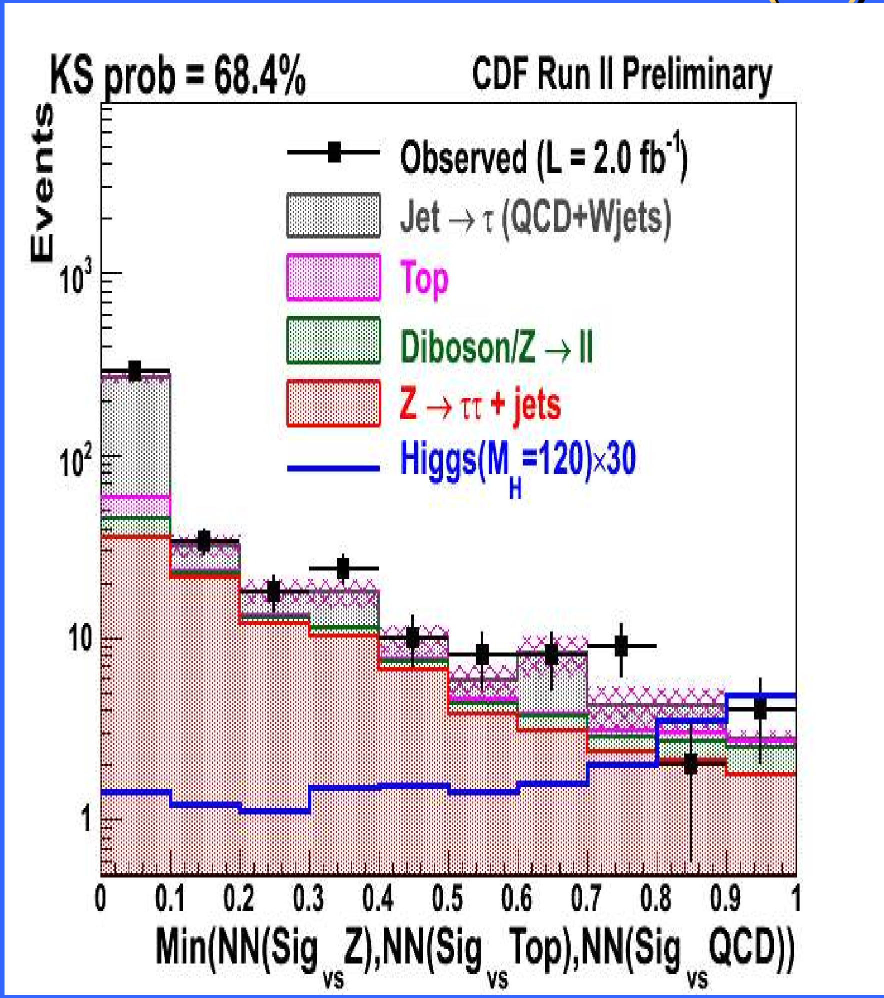


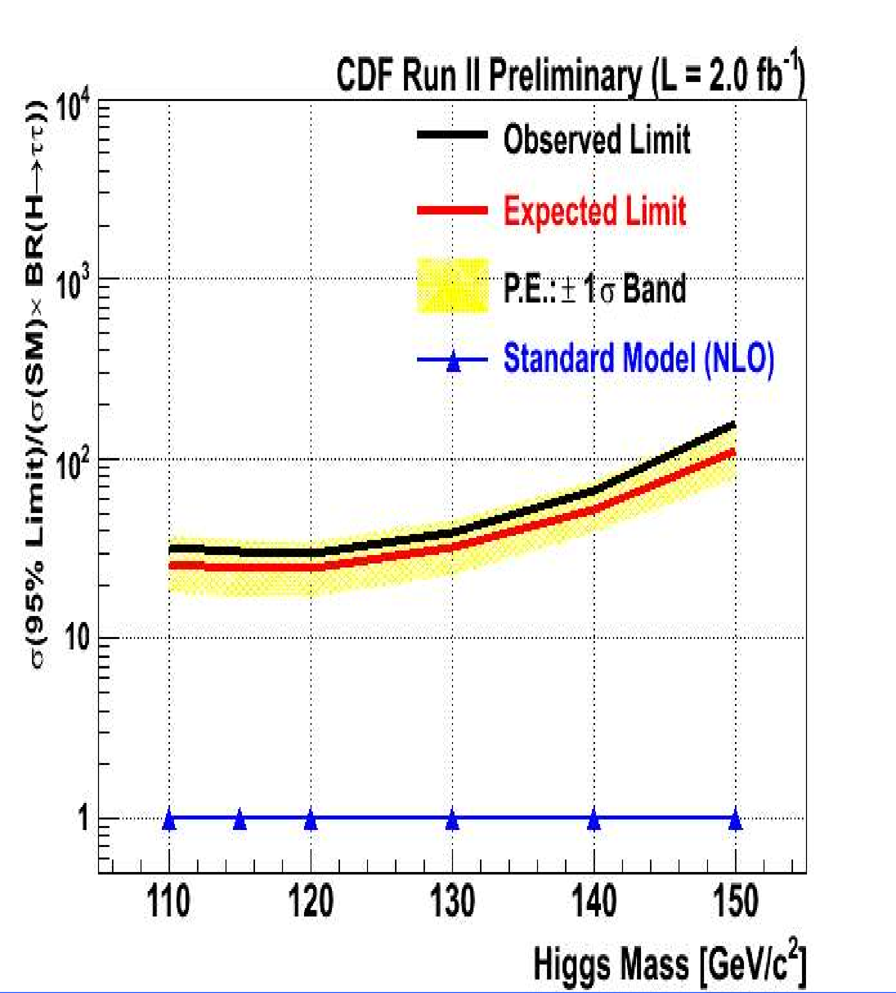






Search for (V)H→ττ +2jets



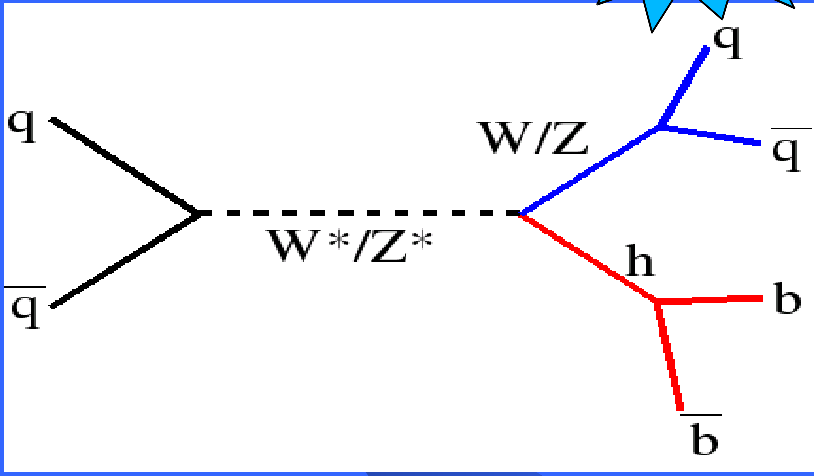


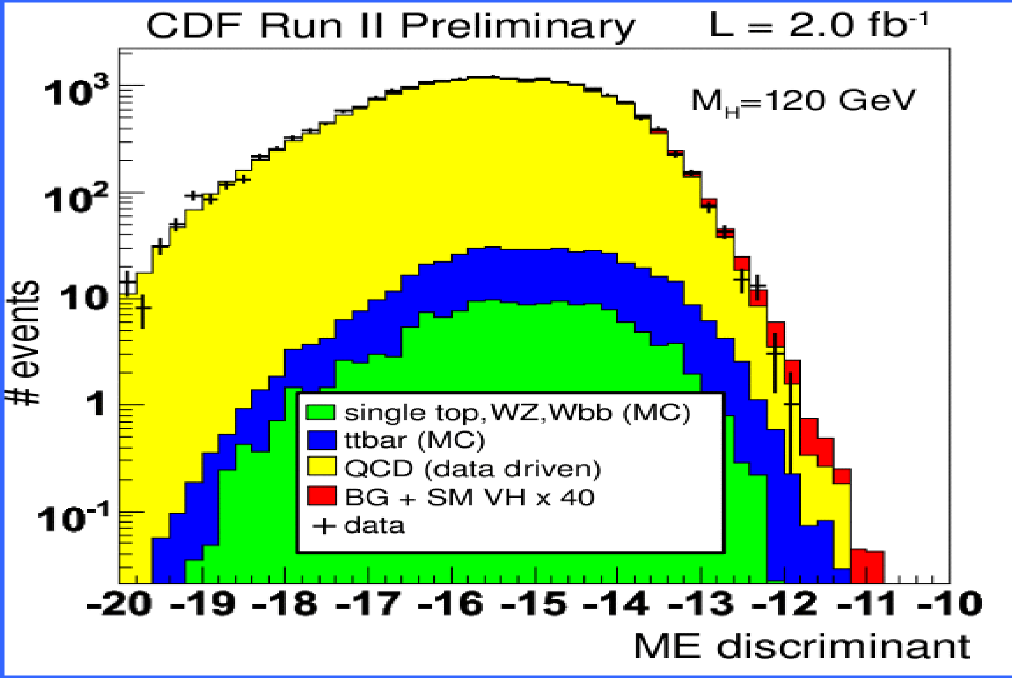
- CDF first time set H→ττ limits: 30.5/24.8 @ mH=115 GeV
- Future improvements: better trigger and optimized analysis

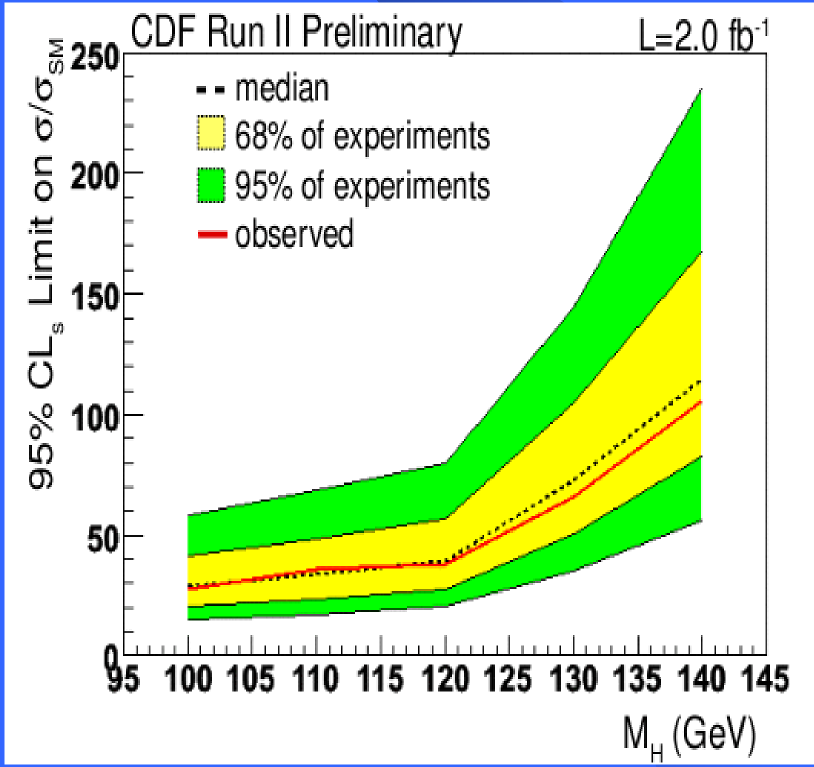
Search for VH→jjbb with ME

New

- Associated production with hadronically decaying W or Z
  - 4jets, 2 of wich are tagged
  - Large branching fraction, but huge QCD backgrounds =>S/B=5.3/21,000
  - Discriminating S from B with ME



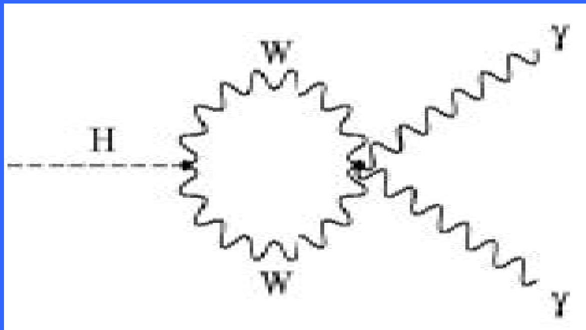


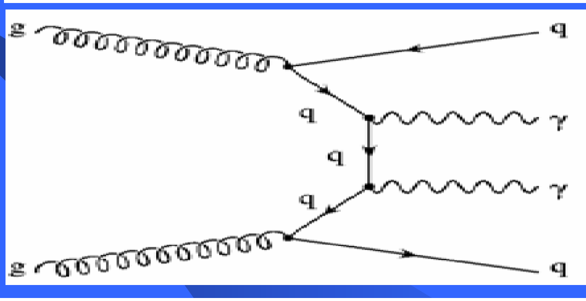


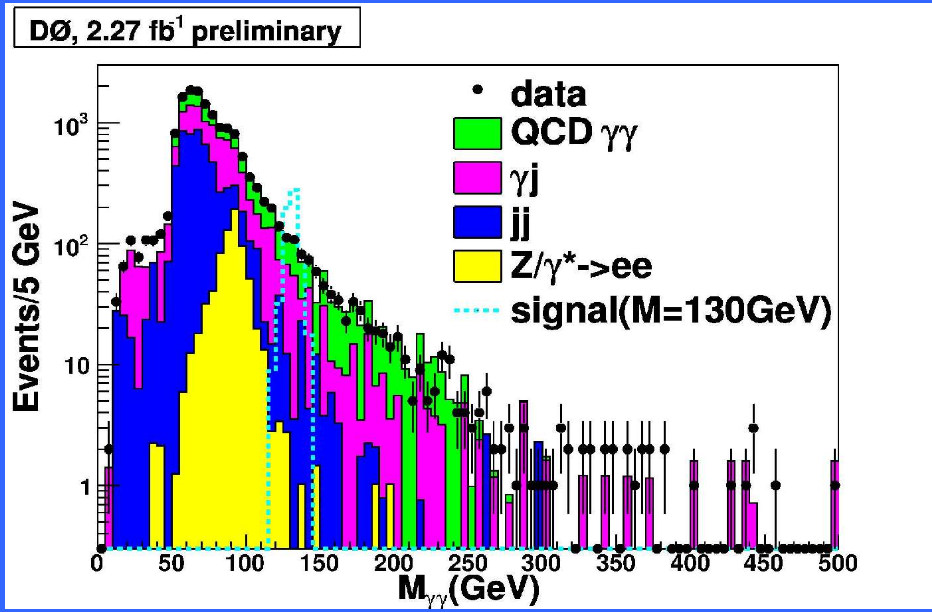
- CDF set limit: ~40 x SM @ M_H =120 GeV

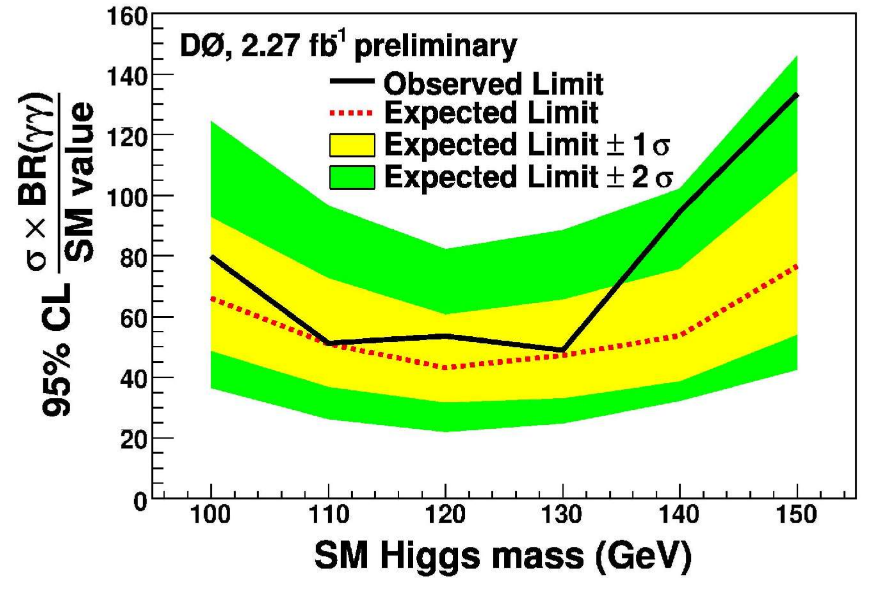
Search for H→γγ

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





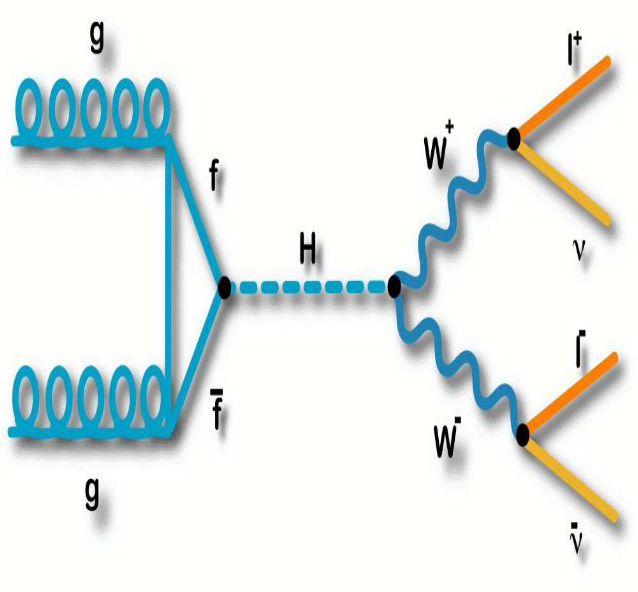


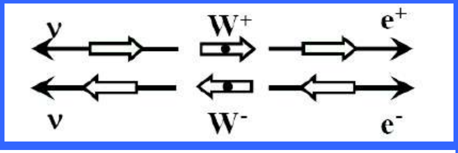


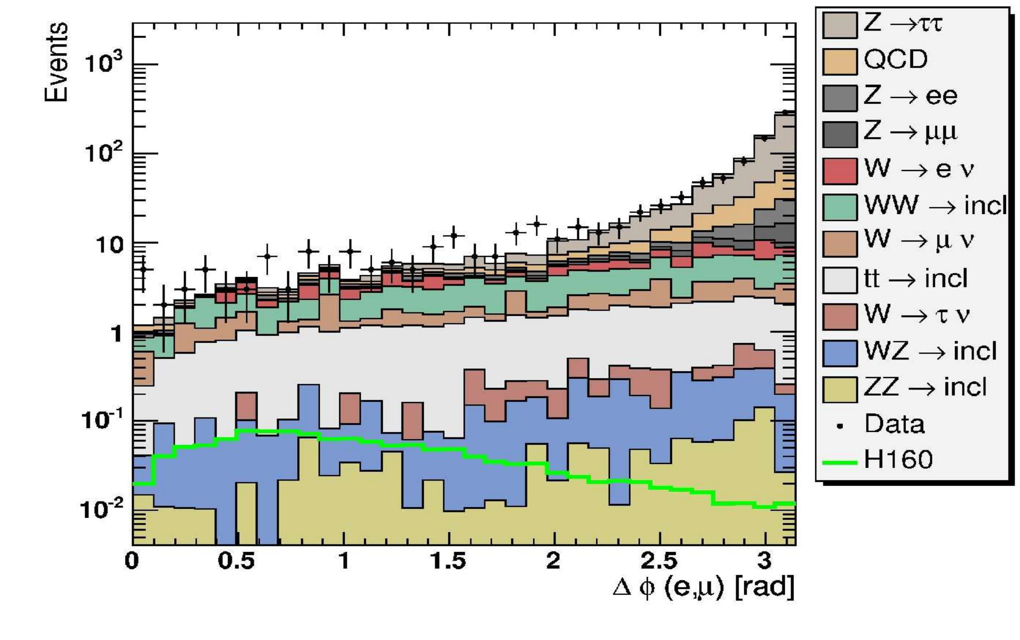
- D0 set limits: 56(Obs)/46(exp) @m_H=120 GeV

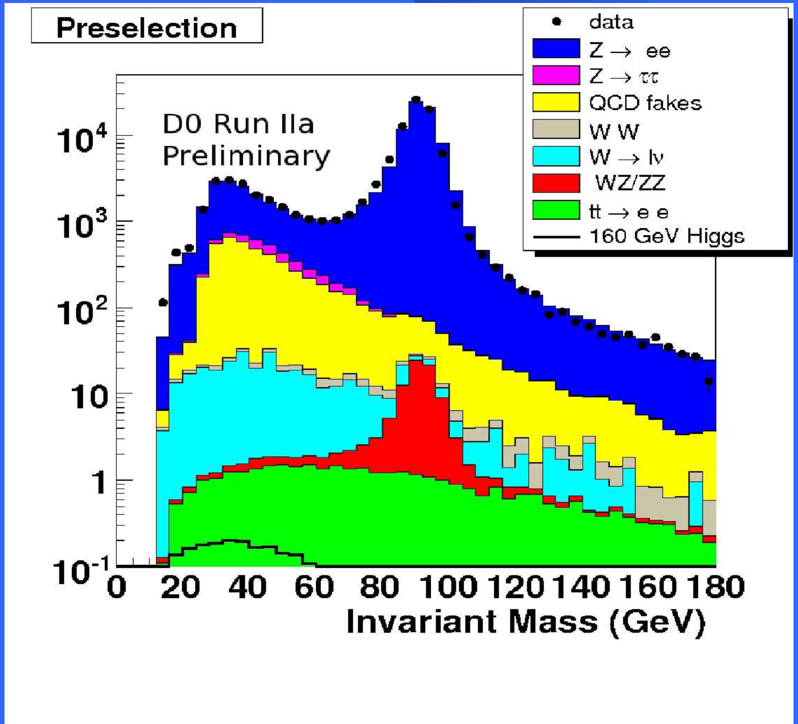
Search for H→WW*→lνlν

- Three main channels (ee, μμ, eμ)
- Two opp-sign high Pt leptons
- Large Met and njets<2
- Dominant Backgrounds: WW*
- Higgs mass can't be reconstructed, but the angular correlation provides handle to reduce WW*.

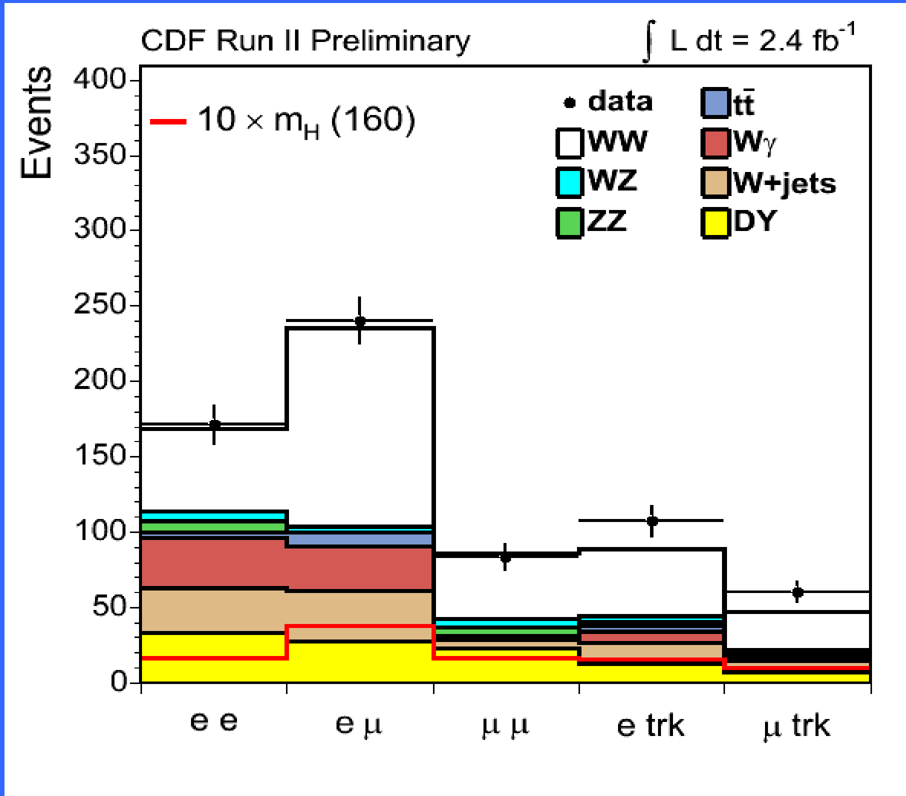








Increase Acceptance with Loose Leptons



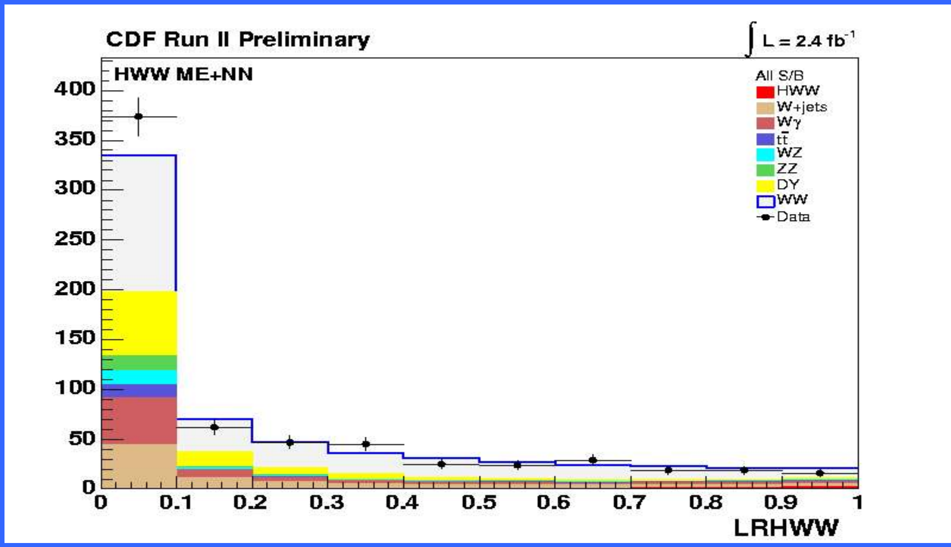
CDF Run II Preliminary		$\int \mathcal{L} = 2.4\,\mathrm{fb}^{-1}$	
$M_H = 160$ GeV/c^2			
$H \to WW$	9.5	±	1.1
WW	300.3	±	38.1
WZ	20.5	±	3.1
ZZ	18.2	±	2.7
$t\bar{t}$	20.8	±	3.8
DY	104.0	±	23.0
$W\gamma$	72.4	±	18.7
$W+$jets	89.2	±	22.8
Total BG	**626**	±	**54**
Data		**661**	

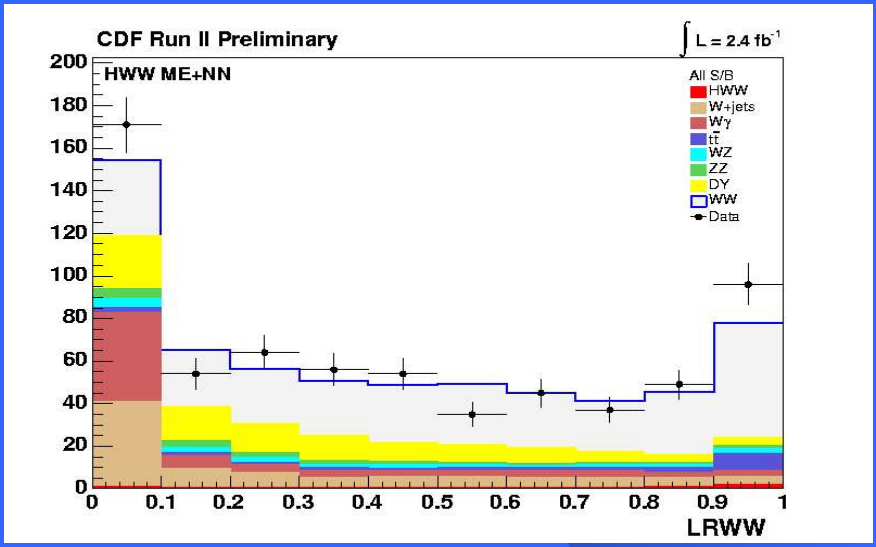
HWW ME+NN

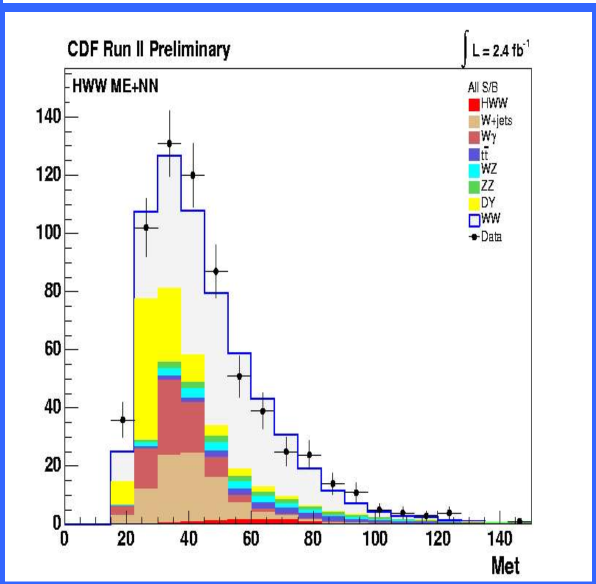
- Data in five classes are well described by SM expectations
- The expected signal events is 9.5 for Higgs mass 160 GeV/c2
- The events are further divided into high, low S/B based on lepton types.

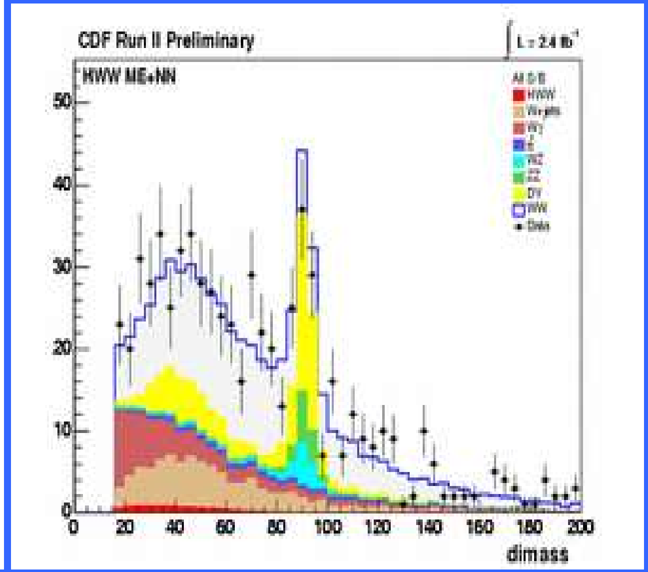
Separating Higgs from Backgrounds

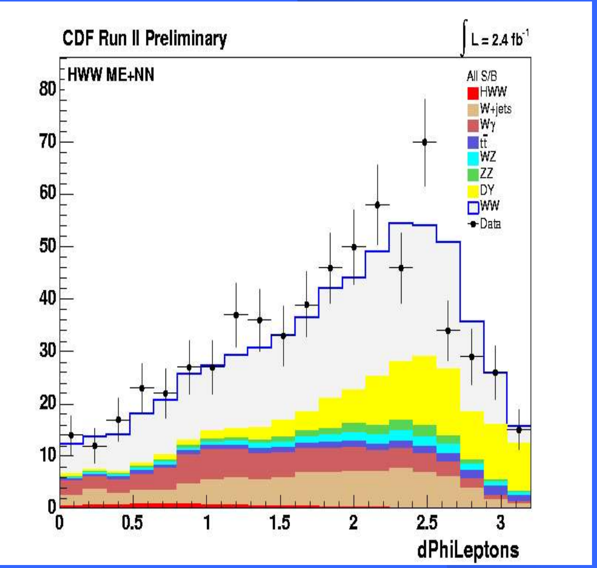
- ➢Validation data with Monte Carlo background Modeling
- ➢NN Discriminant: Combine LO ME and kinematic distributions.





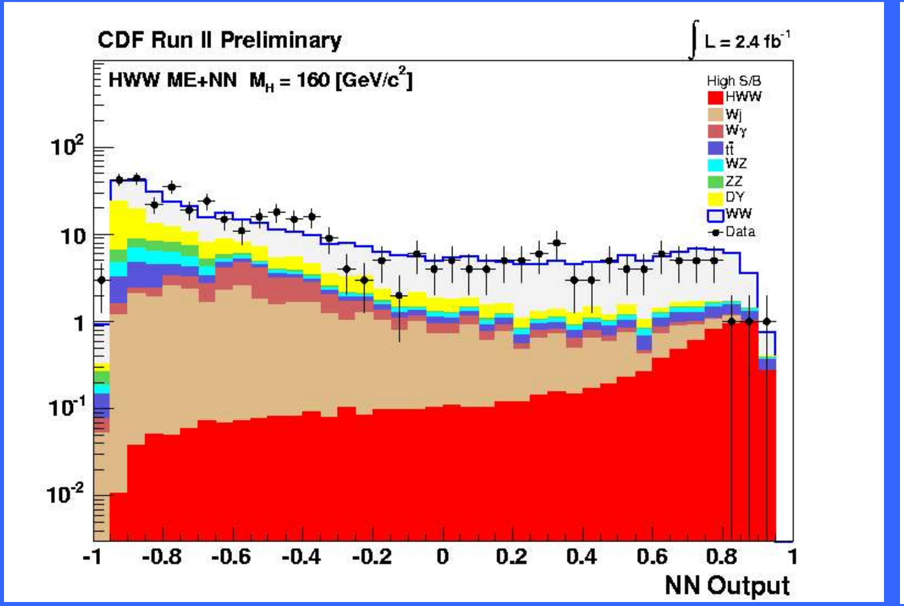


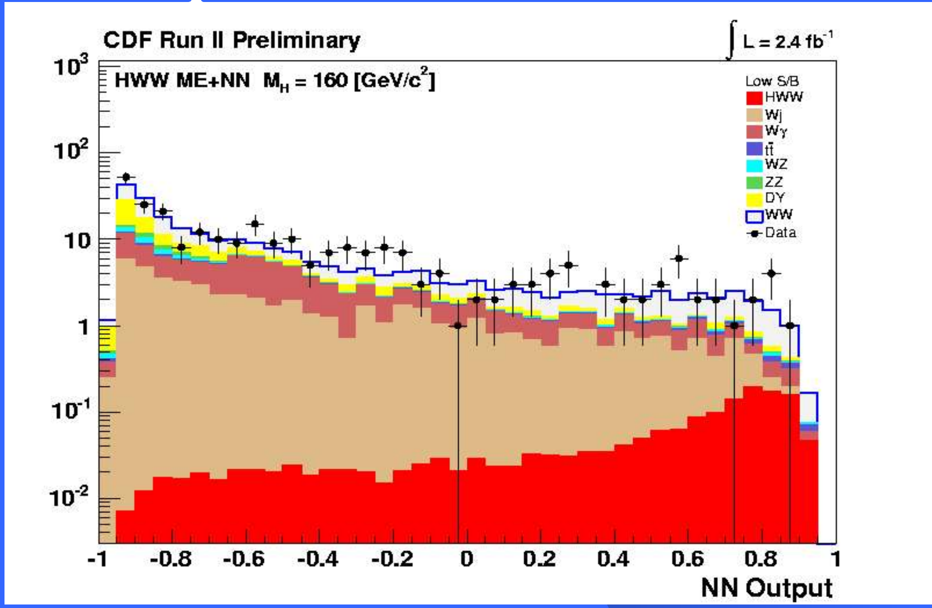


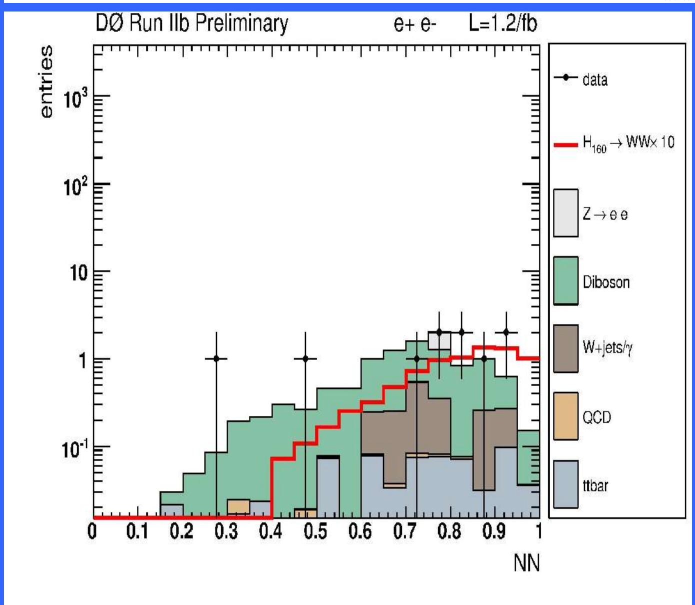


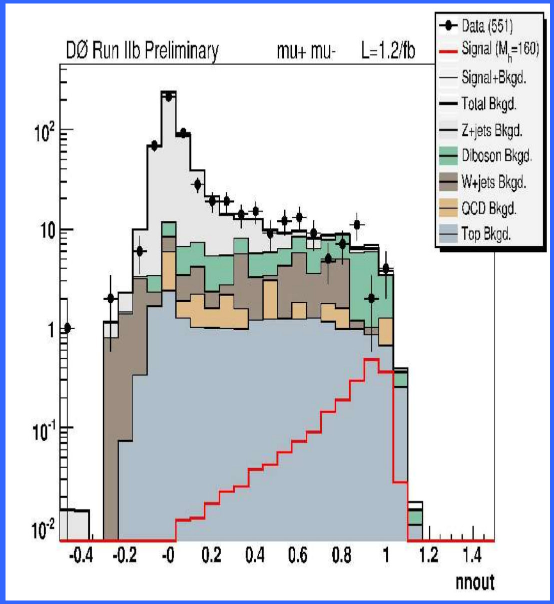
Higgs Discriminant

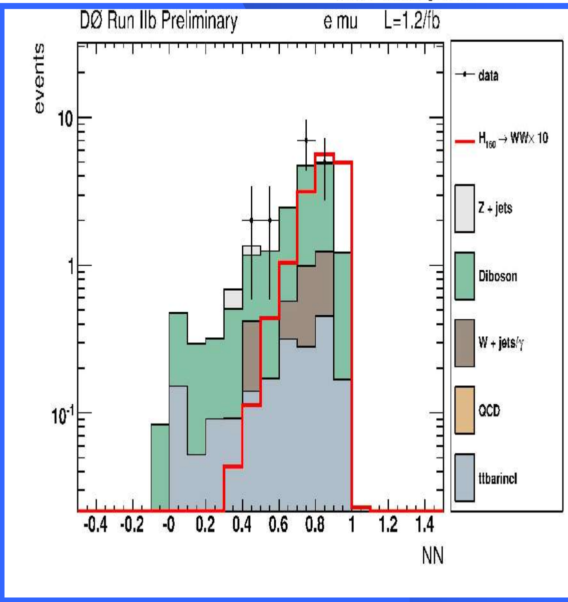
- Final discriminant based on NN output



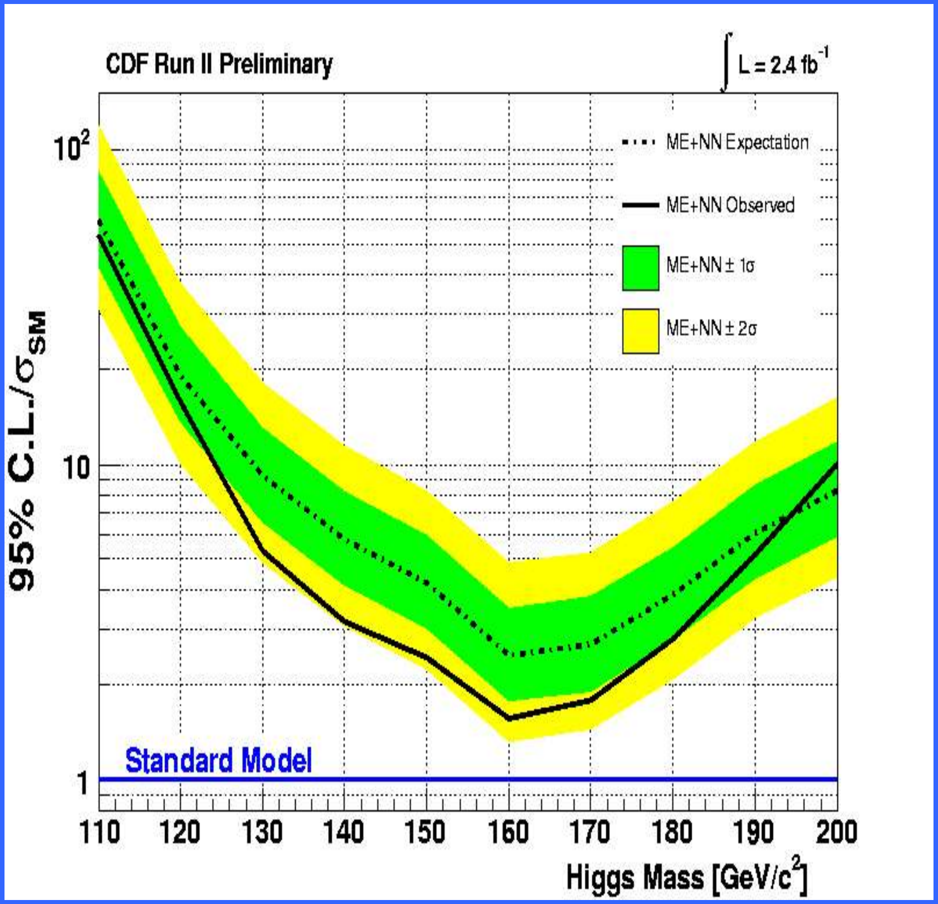


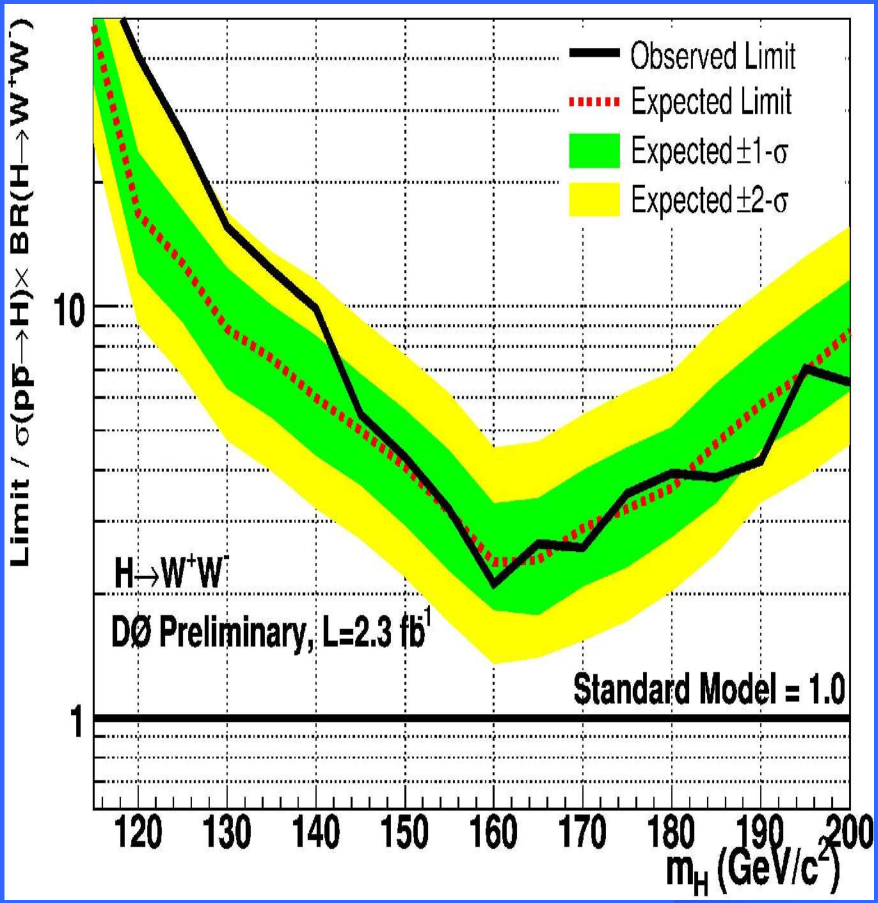






H→WW*→llνν Limits

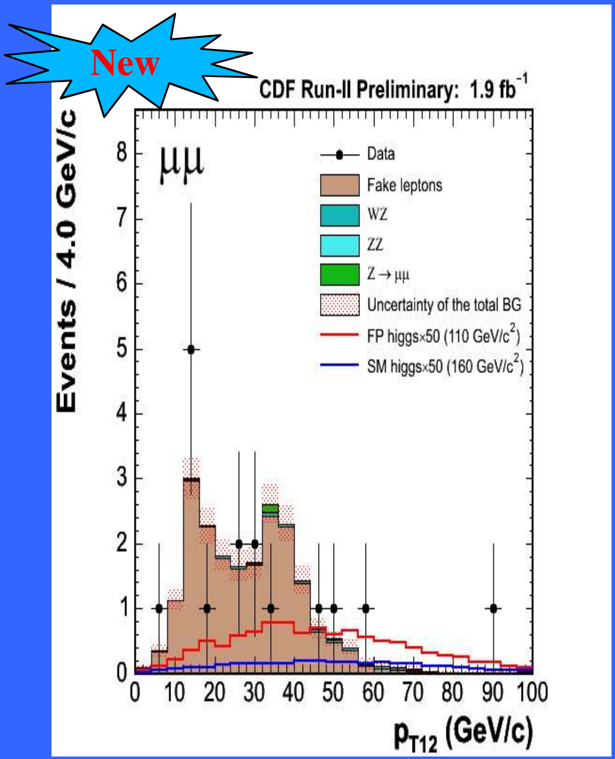


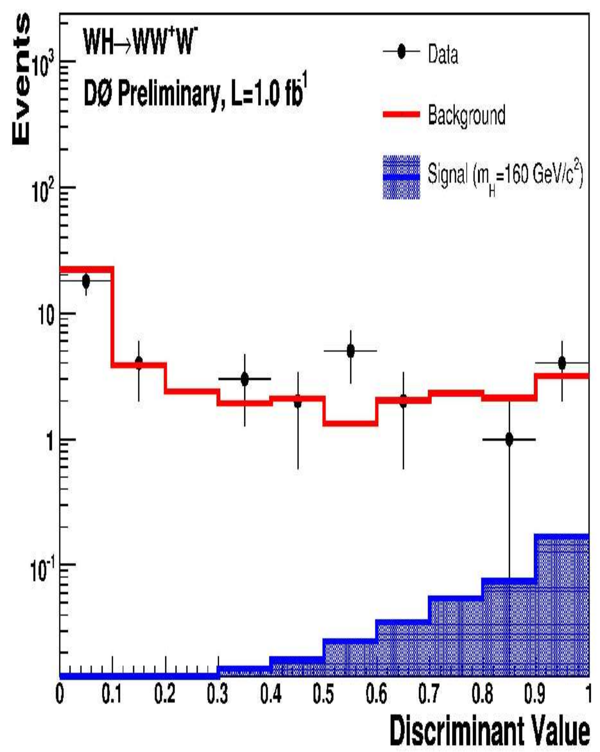


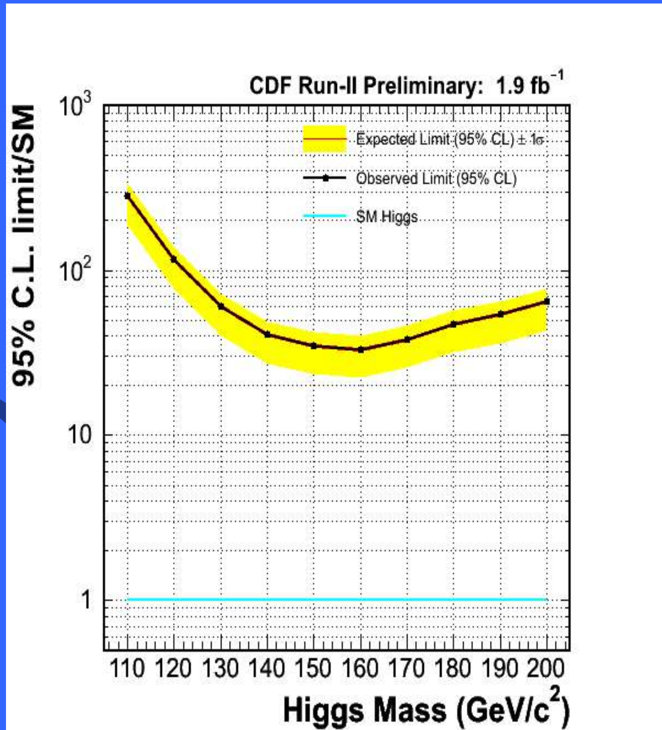
- CDF obs/exp limit is 1.6/2.4 x SM @ mH =160 GeV
- D0 obs/exp limit is 2.1/2.4 x SM @ mH =160 GeV
- Future improvements: Optimizing lepton selections, including contributions from VH, BVF, and H+2jets

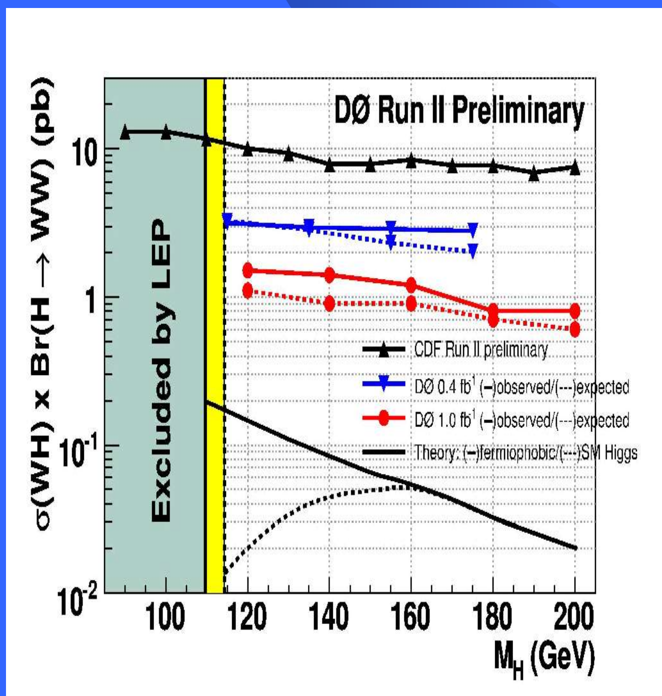
WH→WWW*→$l^{\pm}l^{\pm}\nu\nu$+X

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







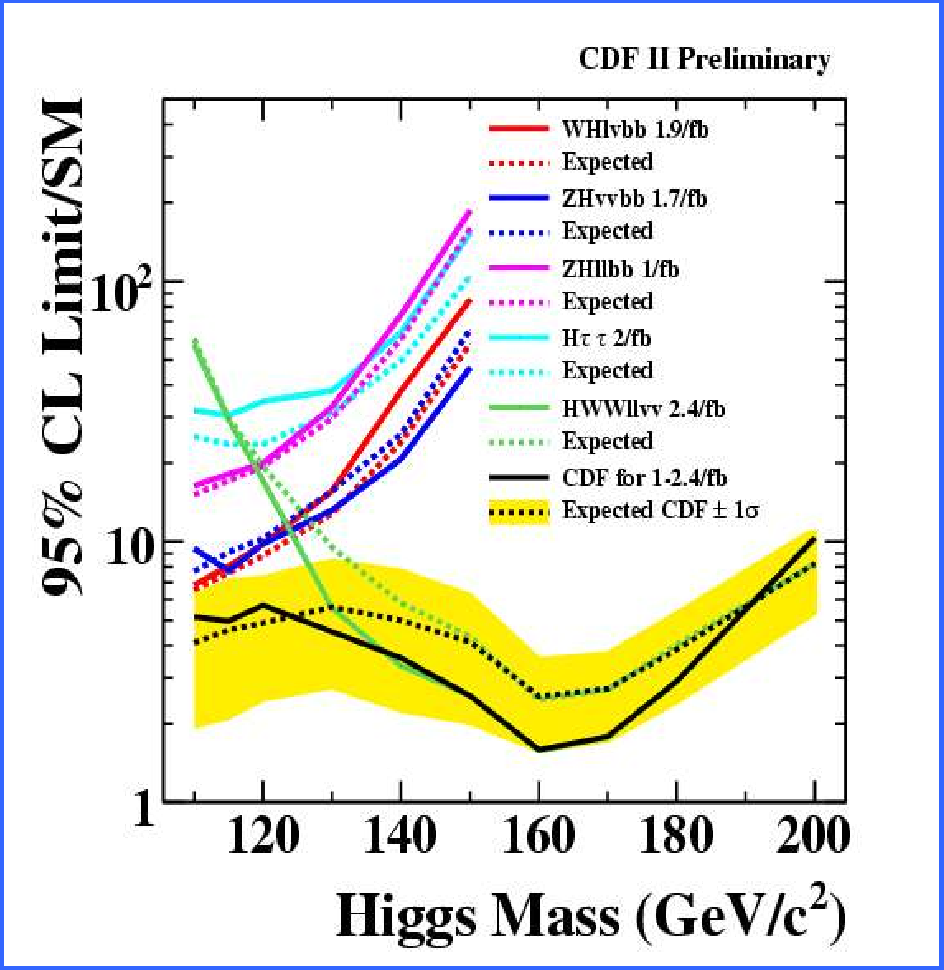


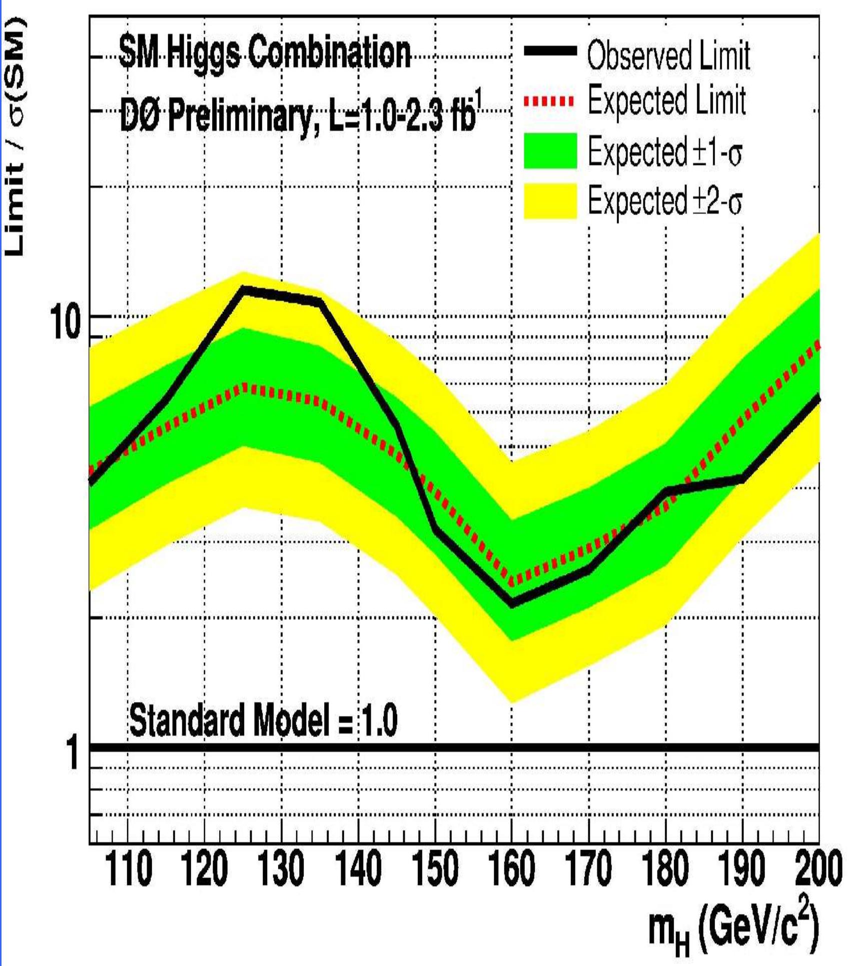
- ➢CDF obs/exp limit: 33/33 @mh=160
- ➢D0 obs/exp limits: 26.5/20 @mh=160

Combination Procedure

- Normalized to SM rate, we can combine σ×Br/SM statistically to improve the final result.
- Use Bayesian and Frequentist approaches:
  - Bayesian: $\mathcal{L}(R,\vec{s},\vec{b}|\vec{n},\vec{\theta}) = \prod_{i=1}^{N_C}\prod_{j=1}^{Nbins} \mu_{ij}^{n_{ij}} e^{-\mu_{ij}}/n_{ij}! \times \prod_{k=1}^{n} e^{-\theta_k^2/2}$
  - Frequentist (CLs): $LLR_n = 2\sum_{i=1}^{N}(s_i - n_i Log(1+\frac{s_i}{b_i}))$
  - 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

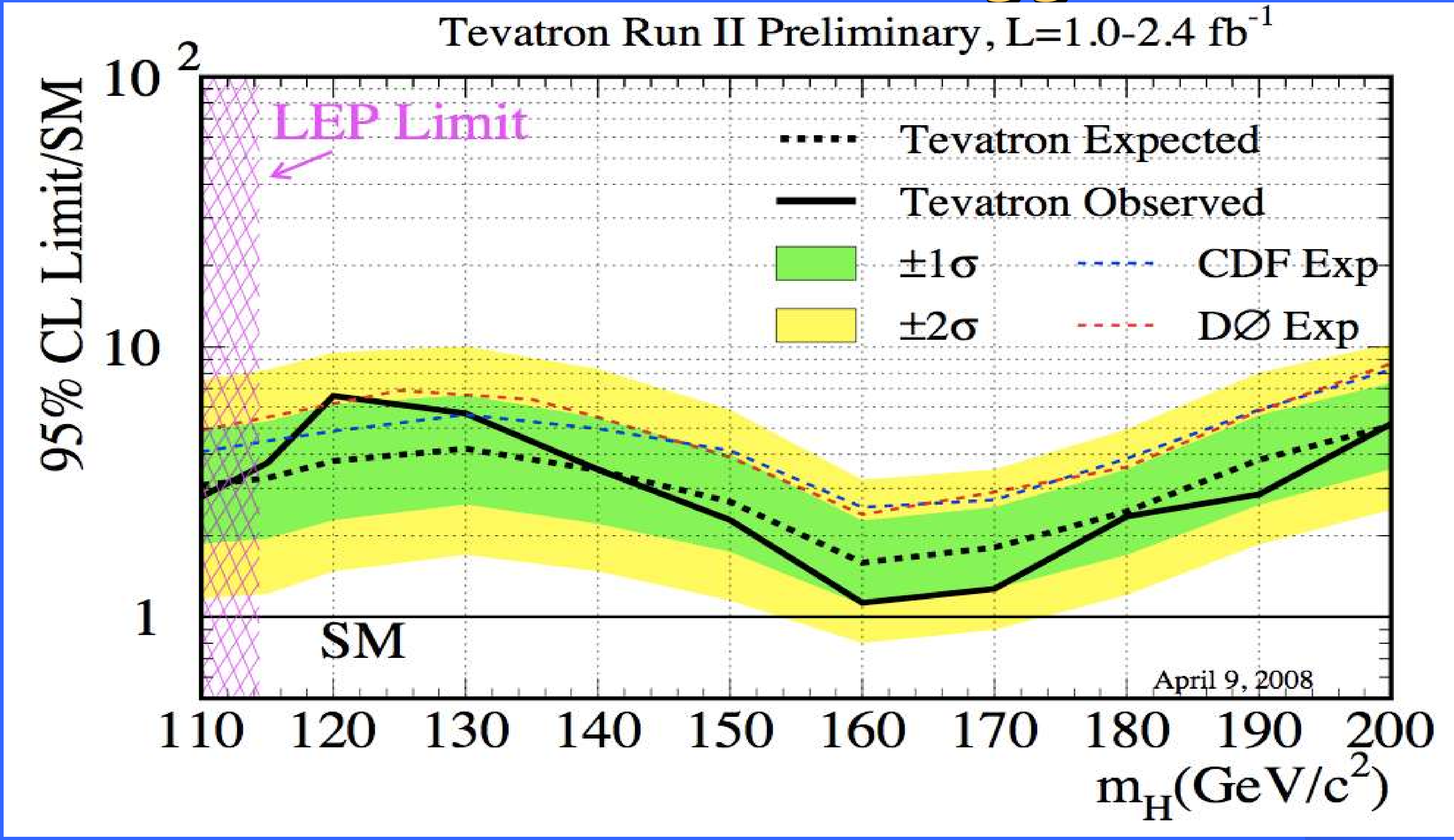
CDF and D0 Combined Limit





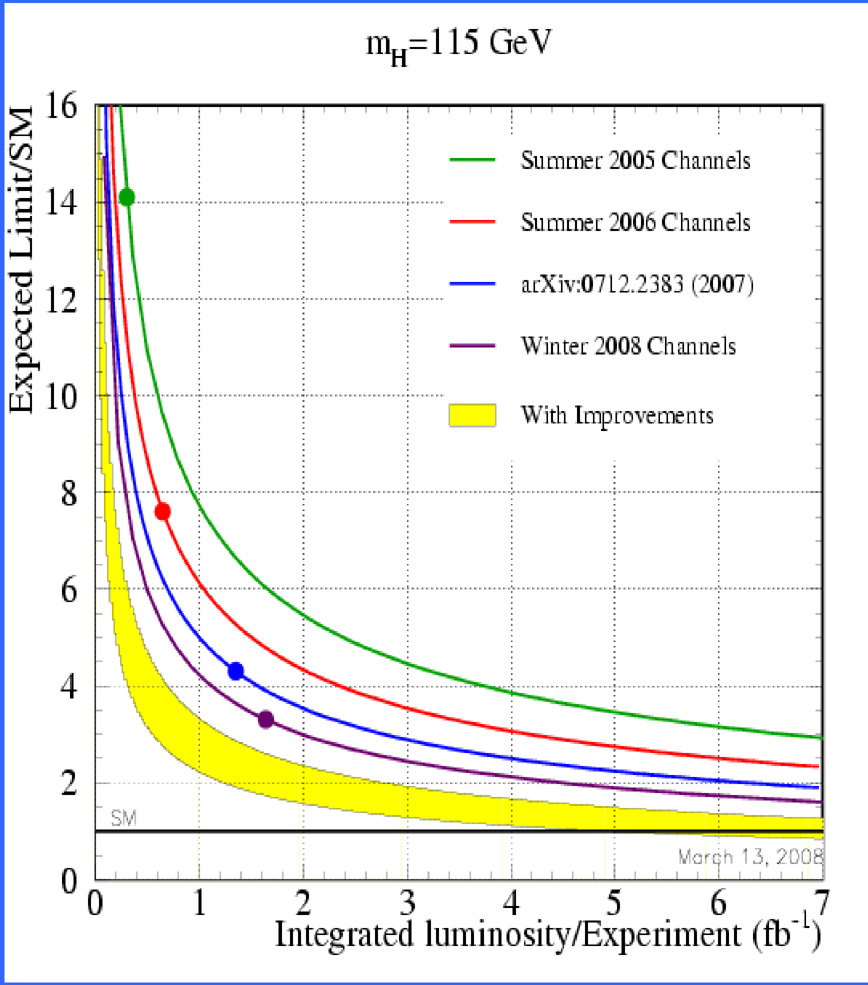
- Both Collaborations give comparable Observed(Expected) limits:
  - CDF: 5.0(4.5) & 1.6(2.6) for mh=115 & 160 GeV
  - D0: 6.4(5.5) & 2.2(2.4) for mh=115 & 160 GeV

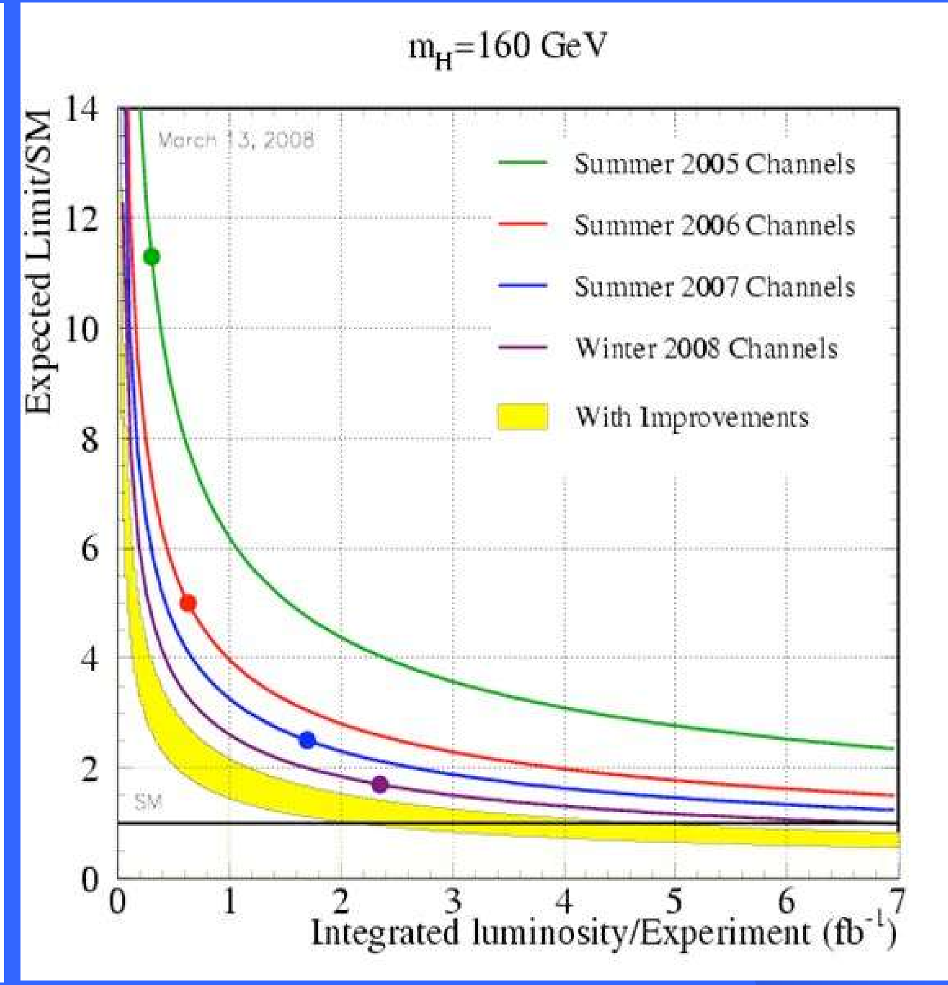
Tevatron Combined SM Higgs Limits



- Tevatron Obs(Exp) Limits: 3.7(3.3) & 1.1(1.6) for mh=115&160 GeV
- Hep-ex/arXiv:0804.3423V1

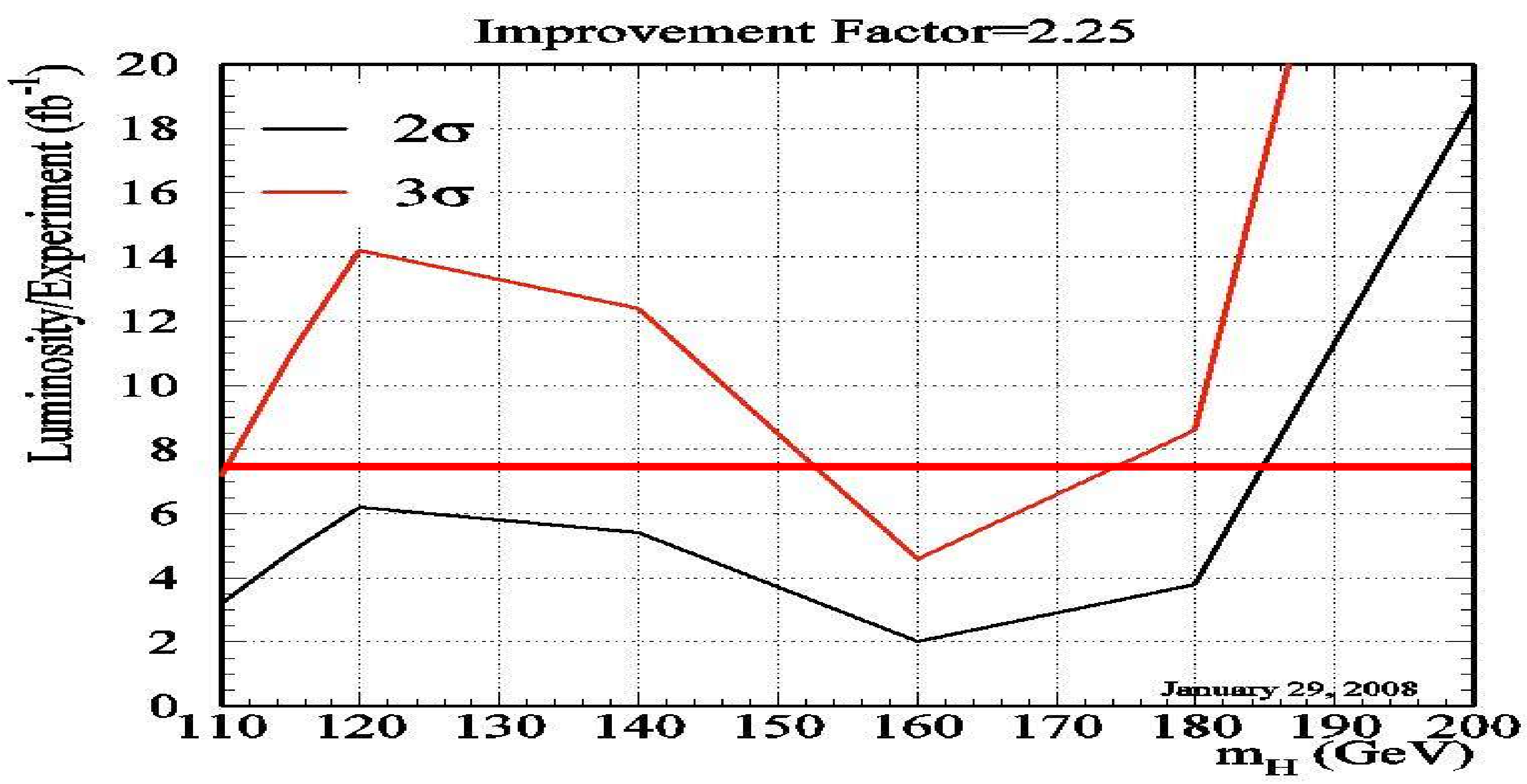
Tevatron Sensitivities





- 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 mH<185 @ 95% C.L.
  - or find 3-σ evidence Higgs near mH=160 GeV.

Conclusions

- We are closing in sensitivity towards less than 3.3(1.6) times SM Higgs @ mh=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 3 σ 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	$WH \to e\nu b\bar{b}$ DT(ST)	$WH \to \mu\nu b\bar{b}$ DT(ST)	$WH \to WW^+W^-$	$H \to W^+W^-$
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	$ZH \to \nu\bar{\nu}b\bar{b}$	$ZH \to e^+e^-b\bar{b}$ DT(ST)	$ZH \to \mu^+\mu^-b\bar{b}$ DT(ST)	$H \to \gamma\gamma$
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