IOP Half day meeting on Vector Boson Fusion: VBF Higgs Analysis at the Tevatron

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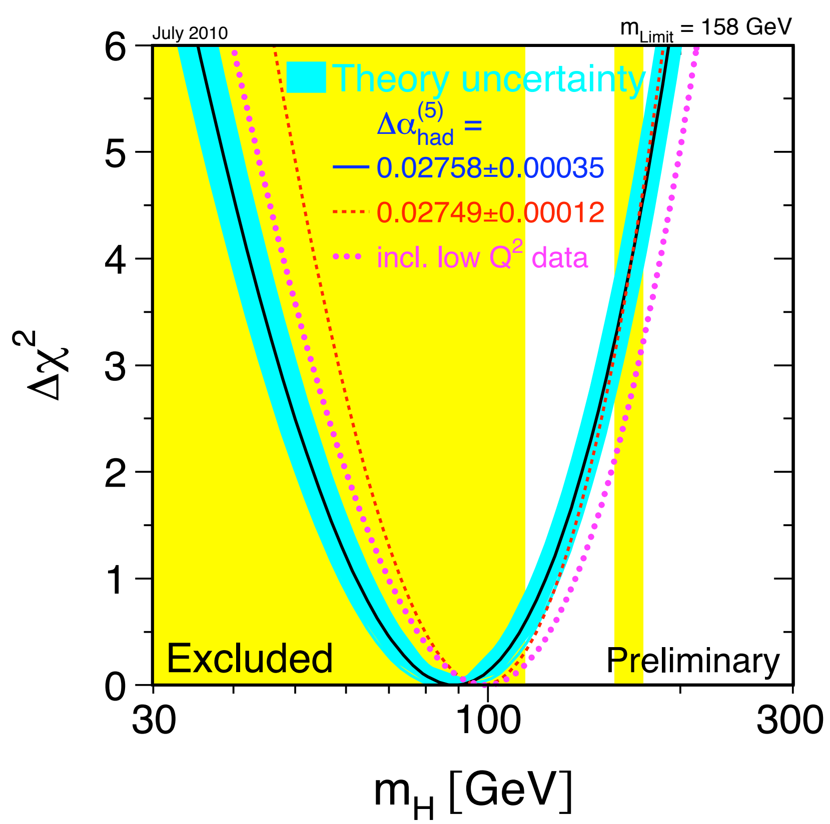
on behalf of the CDF & D0 collaboration

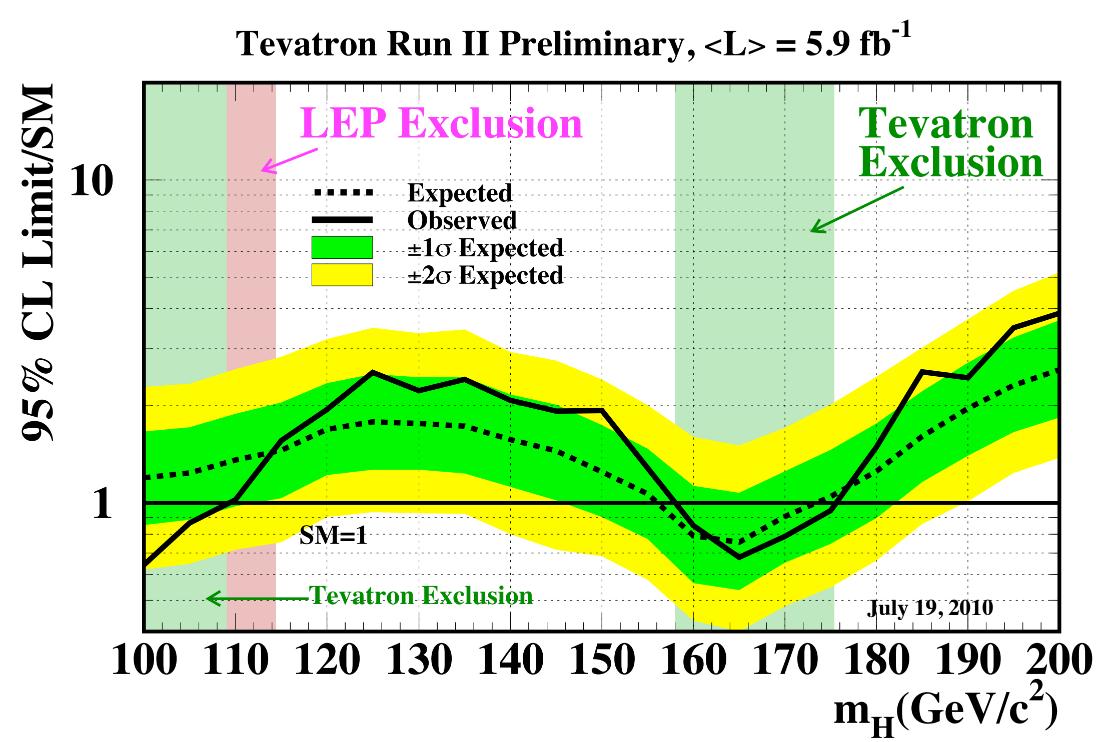
The Higgs Boson

- The Higgs field is responsible for Electroweak symmetry breaking
  - Allows particles to acquire mass
  - It predicts a new scalar particle: The Higgs Boson
- Higgs Boson: Only undiscovered particle of the Standard Model
- *If Standard Model is true*, the data suggests a low mass Higgs (M_H < 157 GeV/c^2)

Global Fit to Precision Electroweak data



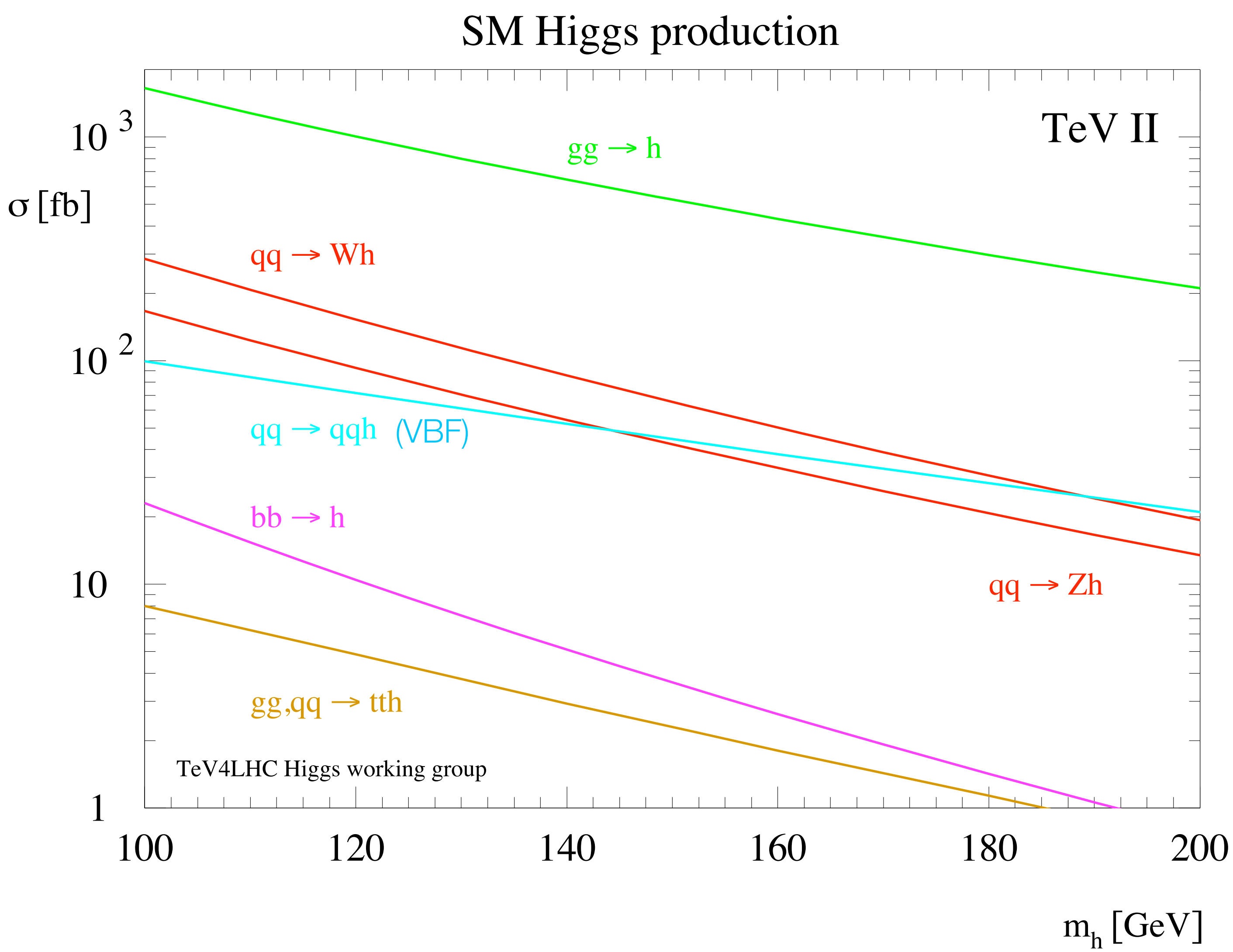
Exclusions from direct searches

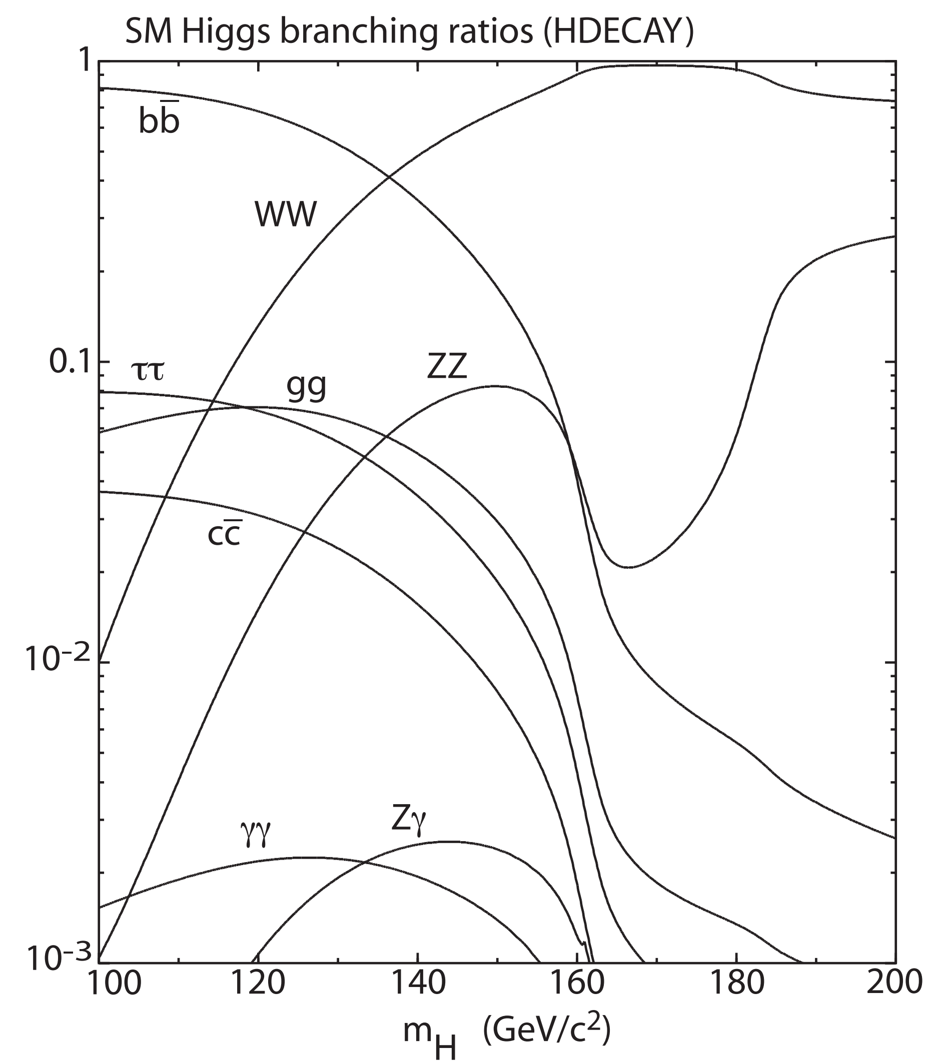


Global fits : M_H < 157 GeV/c^2 (LEPEWWG)

M_H > 114 GeV/c^2 (LEP)
M_H <158 or M_H > 175 GeV/c^2 (Tevatron)

Higgs production & decay at the Tevatron

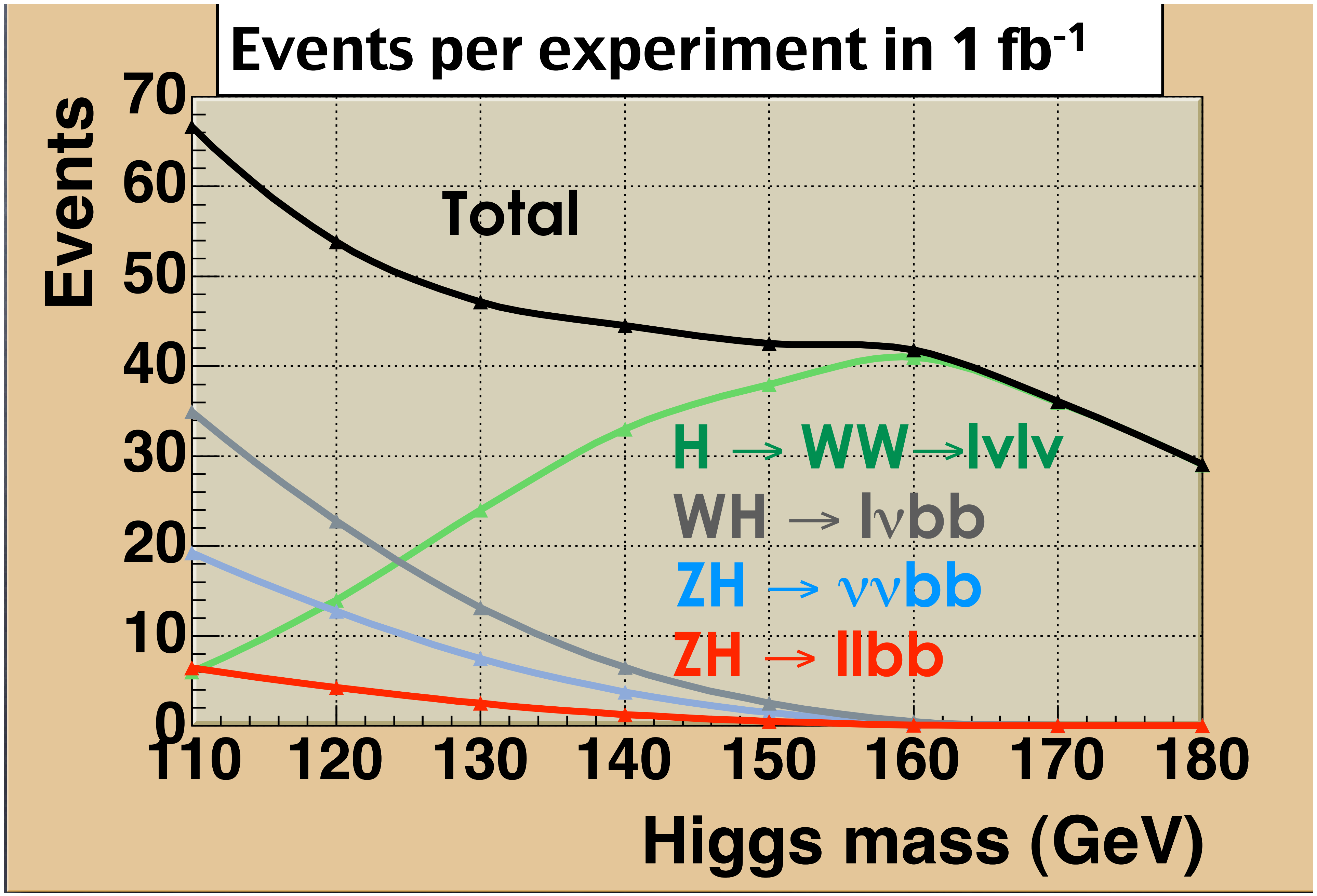




- At the Tevatron, gluon fusion is largest production mode, followed by WH,ZH and VBF

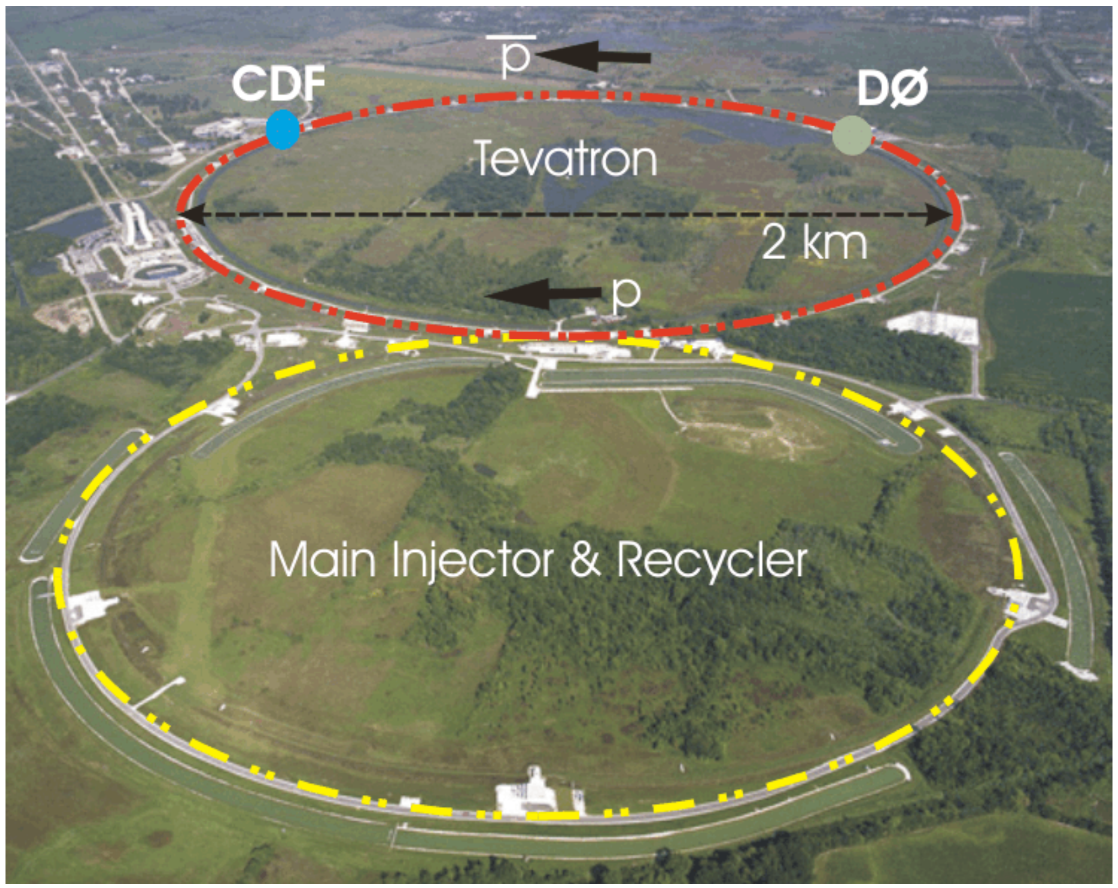
- Higgs decays to bb for low mass Higgs (M_H<135 GeV/c^2)
- Higgs decays to WW for high mass Higgs (M_H>135 GeV/c^2)

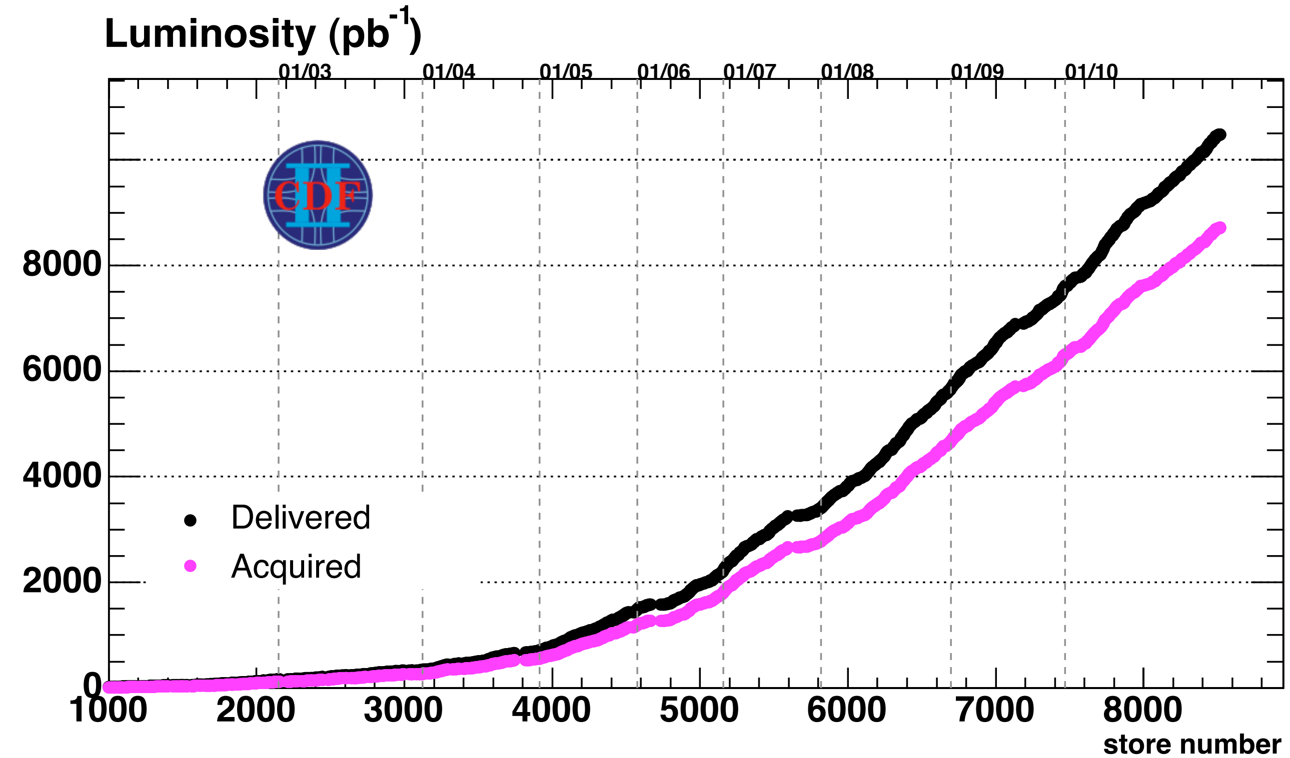
Higgs production & decay at the Tevatron

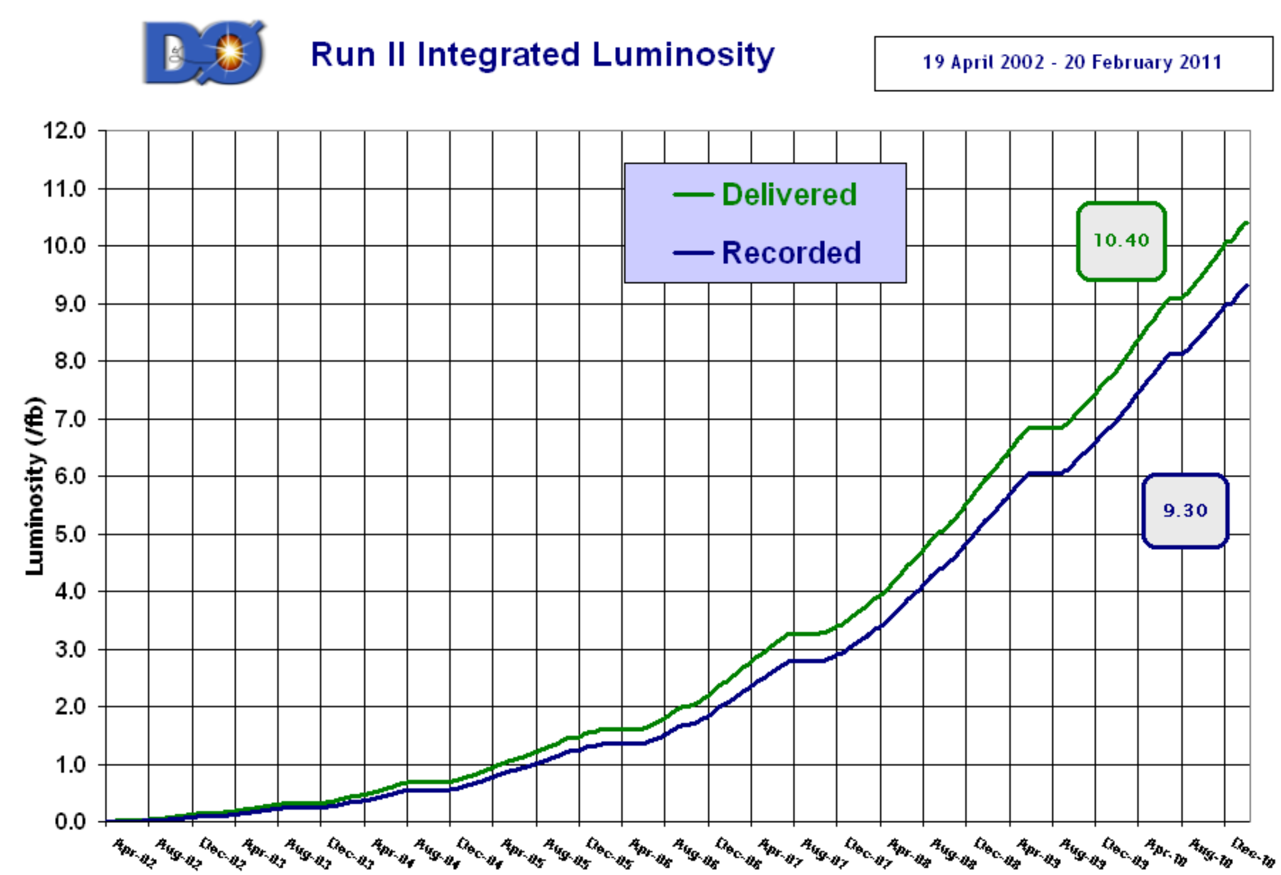


- Number of events for flagship analyses.
- NB: Does not include detector efficiencies !

Tevatron

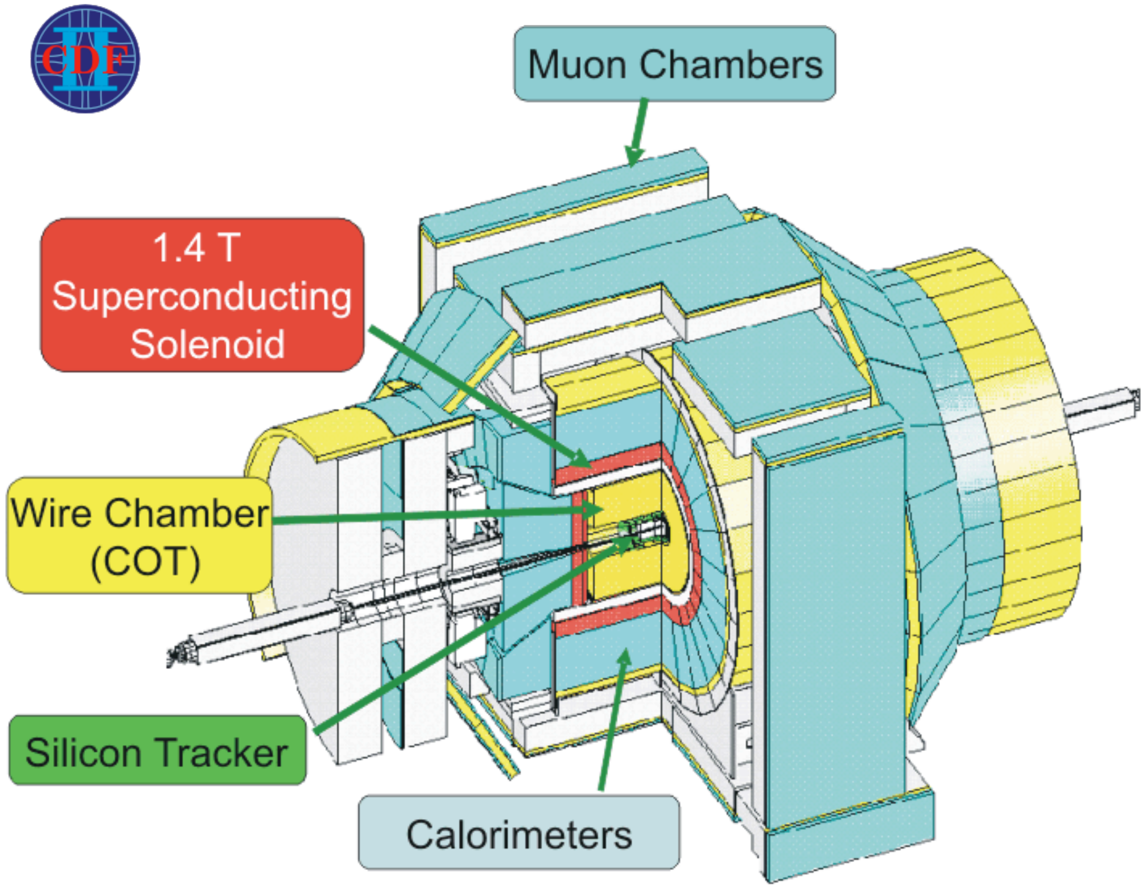


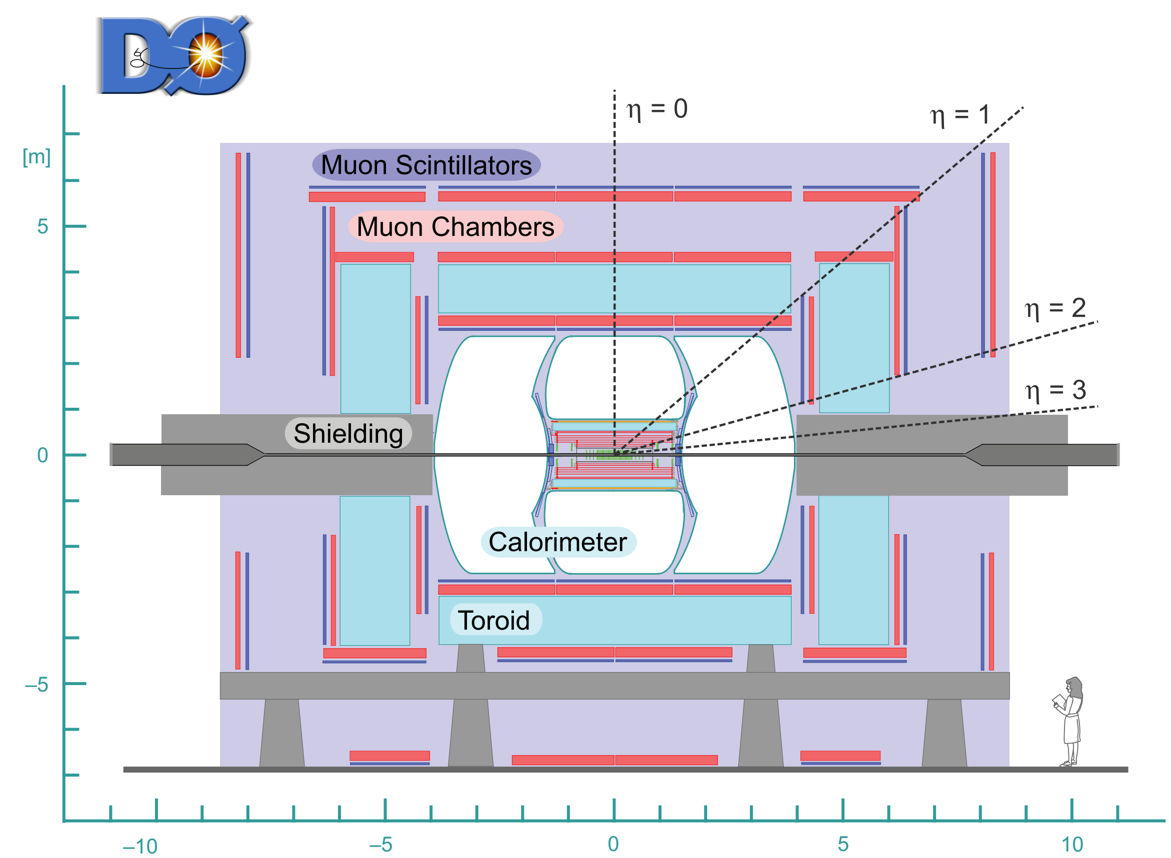




- Proton-Antiproton collider
- $\sqrt{s}$ = 1.96 TeV
- Peak instantaneous luminosity $\approx 300\times10^{30}$ cm^{-2} s^{-1}
- Average 50-60 pb^{-1}/week recorded
- ~9 fb^{-1}/experiment on tape. Expect final dataset ~10 fb^{-1}/experiment

CDF and D0

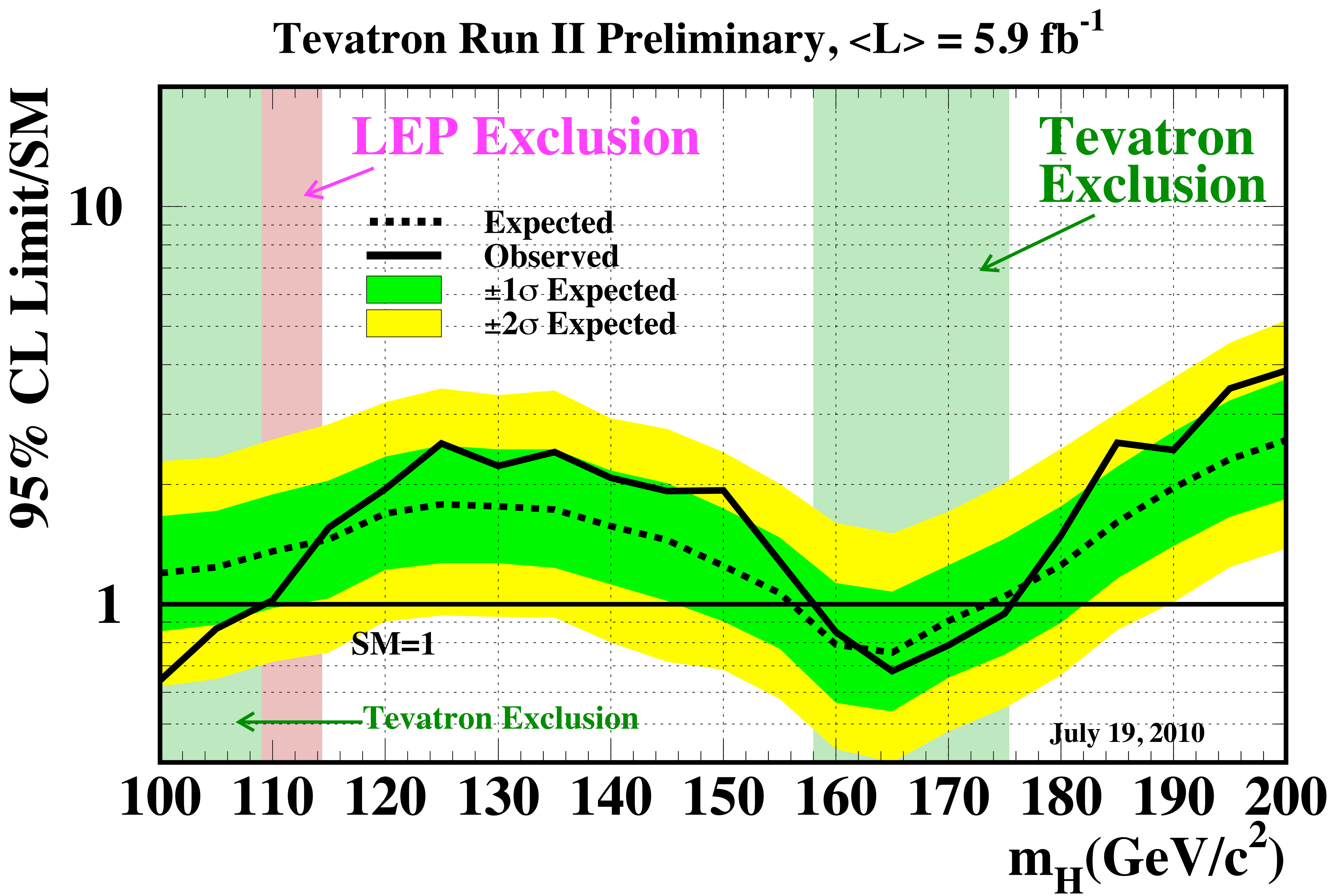




- Tracker: Silicon + Wire Chamber
- Lead/Steel+scintillator calorimeter
- Outer Muon chambers
- 1.4 Tesla Magnetic field

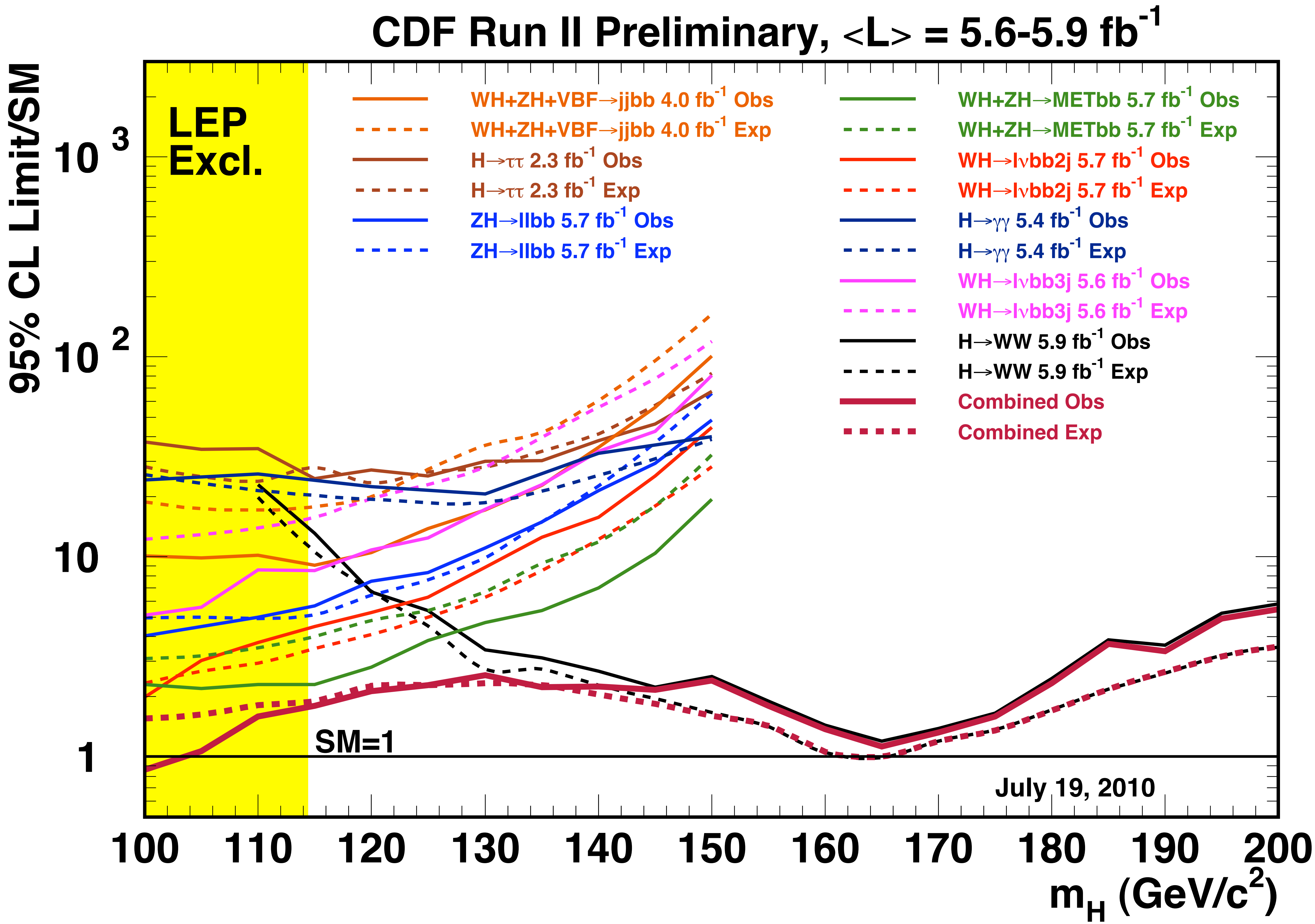
- Tracker: Silicon + Fibre tracker
- Uranium/Steel + Liquid-Argon calorimeter
- Outer Muon chambers
- 1.8 Tesla Magnetic Field

Combined Tevatron Higgs Limit

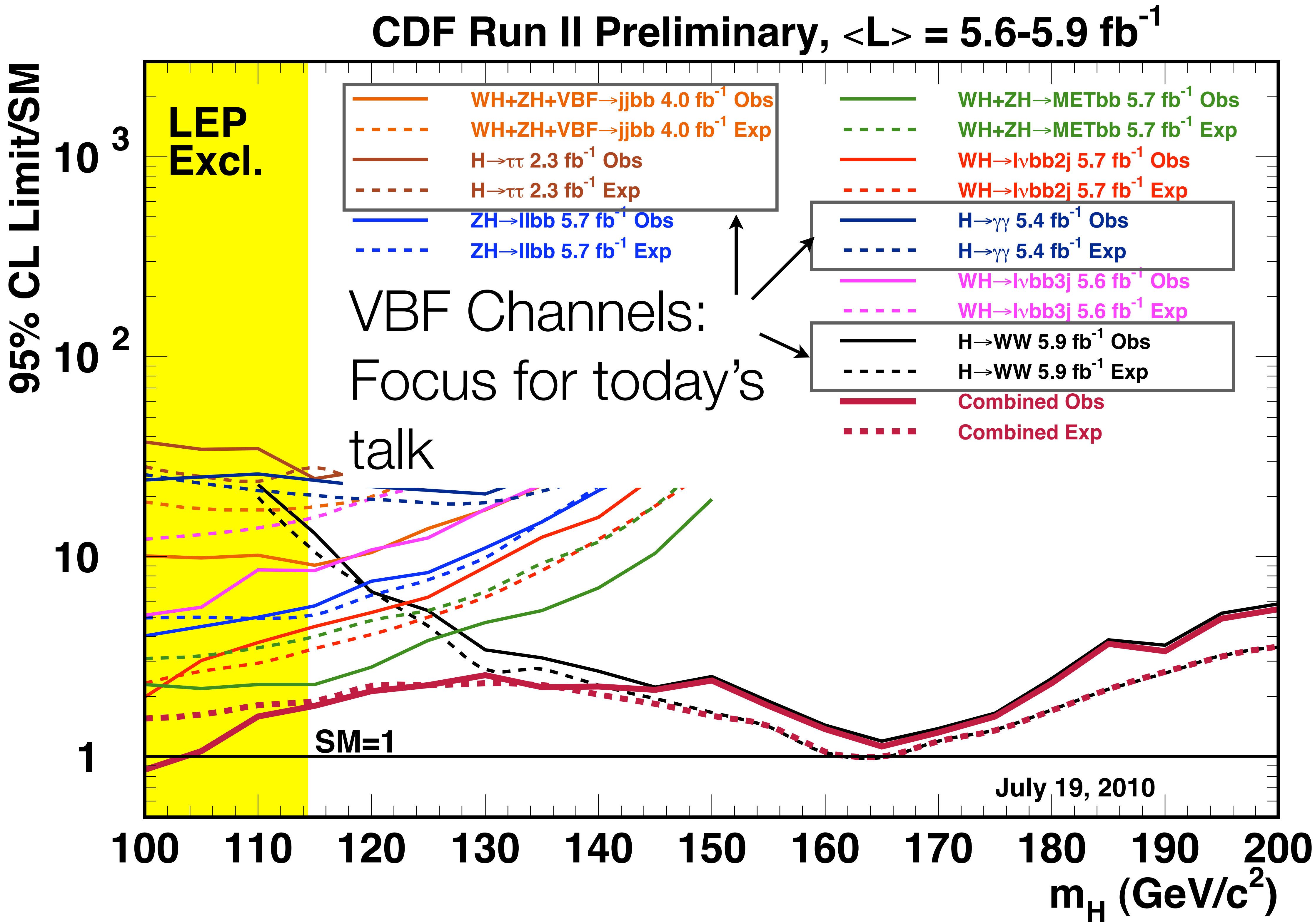


- This result is the combination of many different analyses

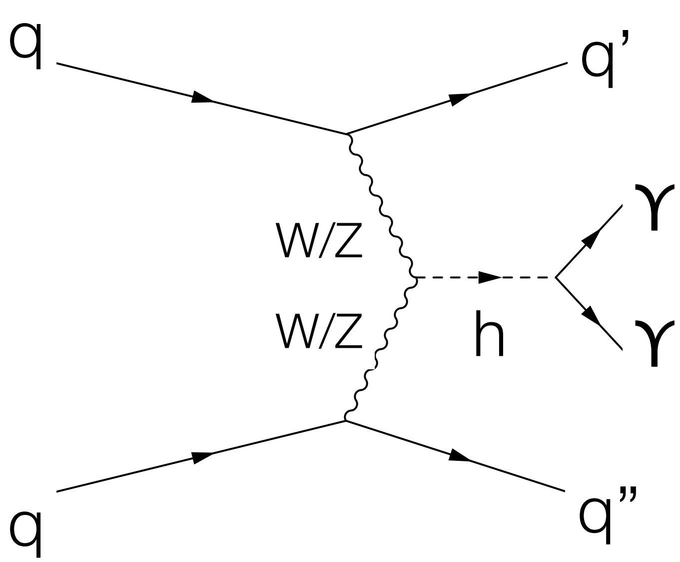
Limits for individual channels (CDF)



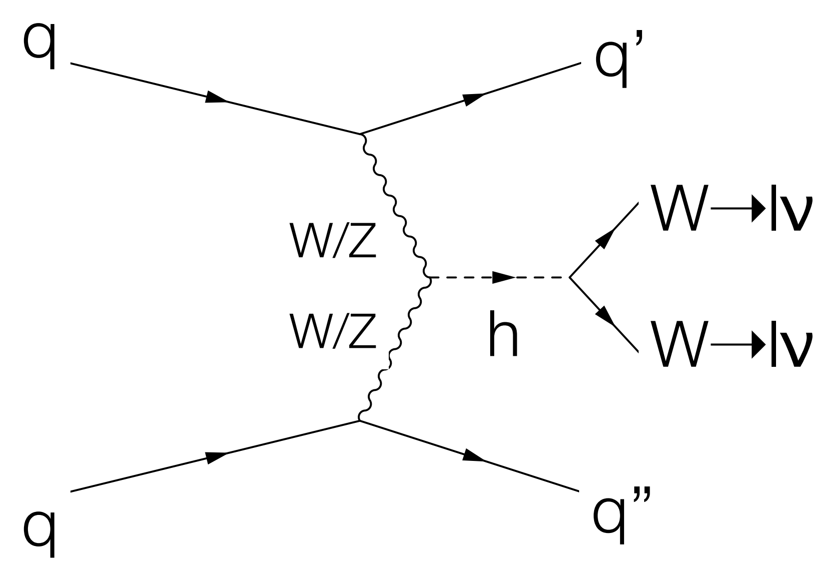
Limits for individual channels (CDF)



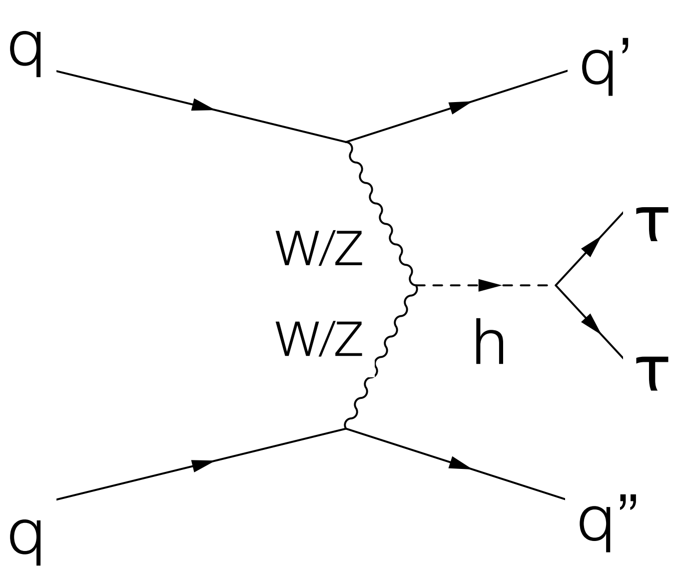
Tevatron VBF channels



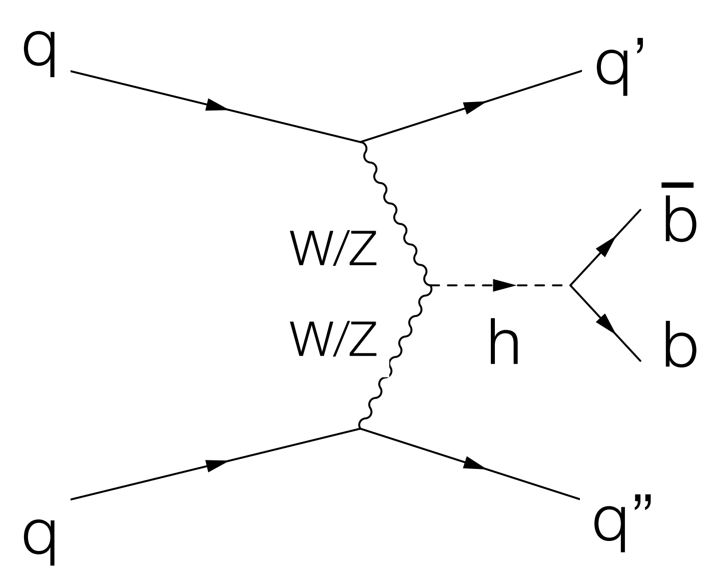
2 Photons



2 opposite sign leptons + ≥1 jet



2 Taus + ≥1 jet



2 b-tagged jets + 2 untagged jets

- Each analysis channel tends to be split by final state (eg: n-leptons, jets, MET, etc) rather than production process
- For many of the analysis, the limits are not quoted for specific production processes

VBF: H → ϒϒ [CDF 5.4 fb^{-1} / D0 4.2 fb^{-1}]

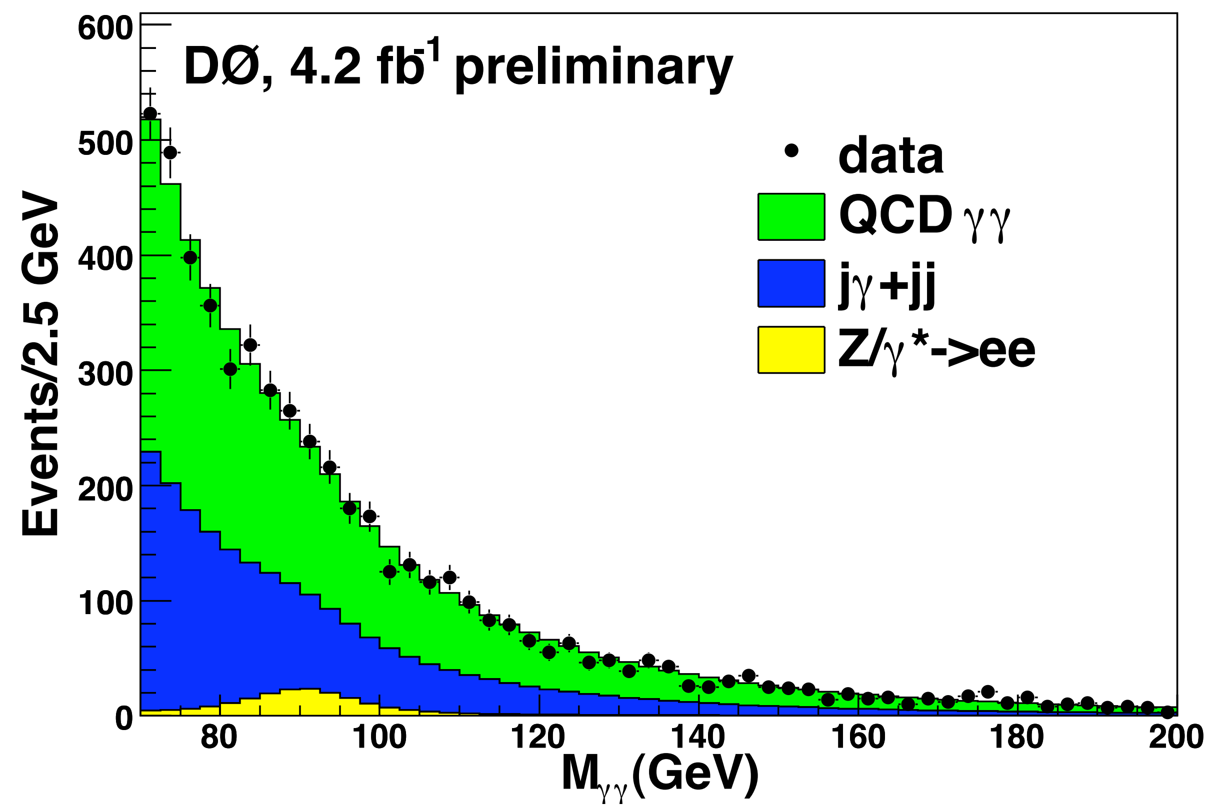
- Event Signature: 2 photons
    - CDF: 2 central photons
    - D0: 2 photons
        - Uses NN to distinguish real photons from jets faking photons:
          rejects ~50% jet-fakes with almost no loss of real photons
- Search is also sensitive to gluon-gluon fusion and VH

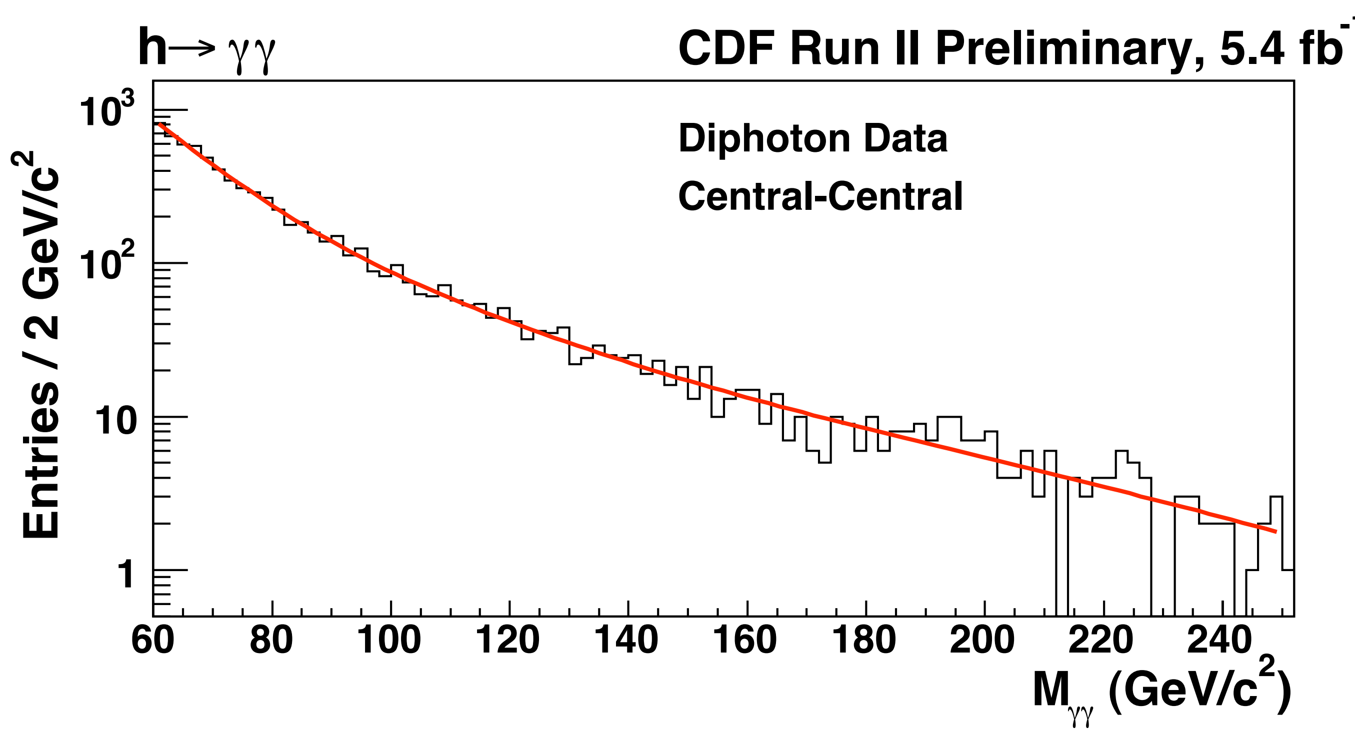
Acceptance (%)			
M_h (GeV/c^2)	g fusion	$h + W/Z$	VBF
100	11.5	12.2	13.0
105	11.7	12.2	13.3
110	11.8	12.6	13.4
115	12.1	12.7	13.6
120	12.3	12.8	13.6
125	12.5	13.0	13.8
130	12.7	13.2	14.0
135	12.9	13.3	14.1
140	13.1	13.6	14.3
145	13.4	13.7	14.4
150	13.5	13.9	14.7

Acceptance for CDF diphoton analysis

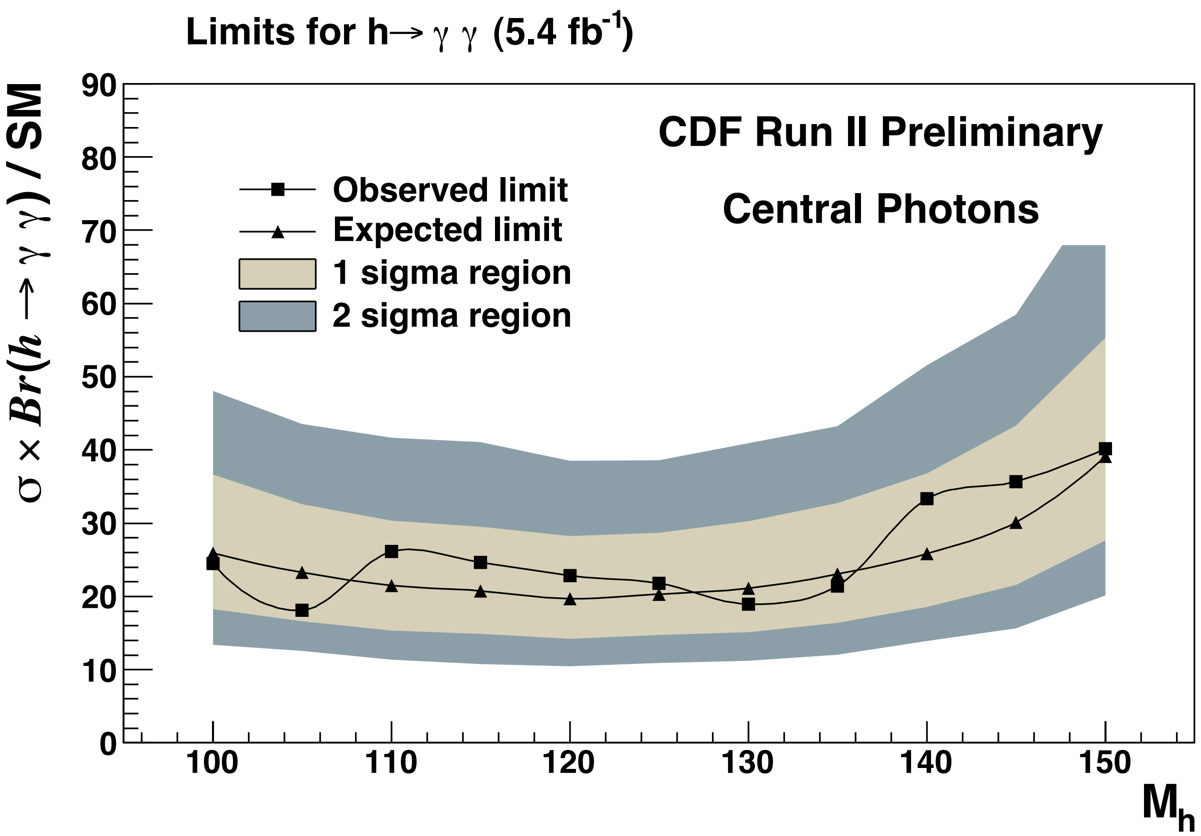
VBF: $H \rightarrow \Upsilon\Upsilon$ [CDF 5.4 fb^{-1} / D0 4.2 fb^{-1}]

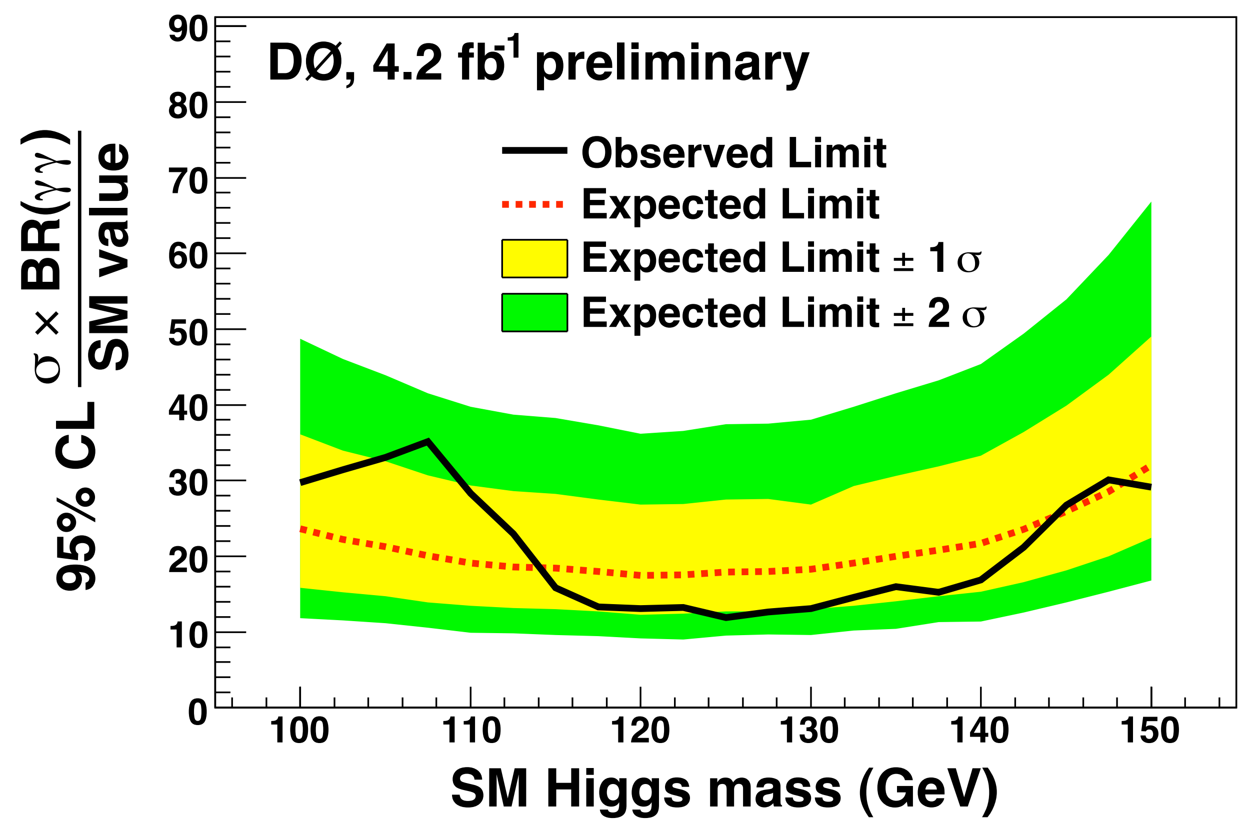
- Backgrounds: Drell-Yan(DY), ϒ+jet, jet+jet, direct QCD photon production
    - D0: modelled using MC and data-driven methods
    - CDF: simple fit to $M_{\gamma\gamma}$ spectrum





VBF: H → ϒ ϒ [CDF 5.4 fb^{-1} / D0 4.2 fb^{-1}]





- CDF: 19.7(Obs)/22.8(Exp) x σ_{SM} for M_H=120 GeV/c^2
- D0: 13.1(Obs)/17.5(Exp) x σ_{SM} for M_H=120 GeV/c^2

CDF VBF: H → ττ [2.3 fb^{-1}]

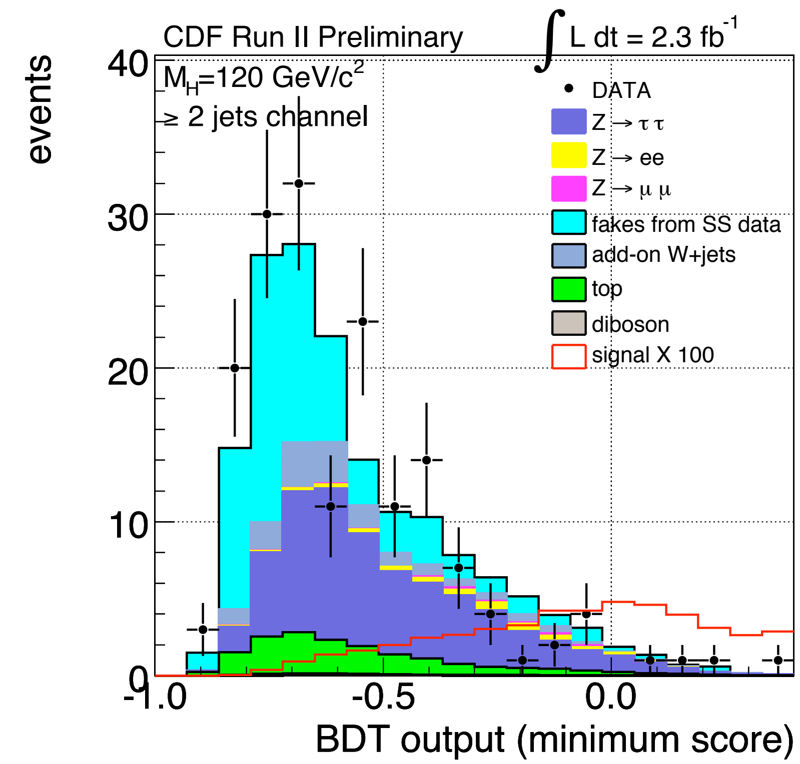
- 2.3 fb^{-1} analysed
- Search for 2 Taus + ⩾1 jet
  - 1 hadronic Tau (Pt>15GeV) + 1 leptonic Tau (Pt>10GeV)
  - jet-Et>20GeV & jet-|η|<2.5
- The additional jet adds sensitivity to VBF
- BDT used to identify Taus: 15% ID gain w.r.t standard CDF cuts for same fake rate
- Signal is divided by number of jets: 1-jet & ⩾2-jets
- Search is also sensitive to gluon-gluon fusion & VH

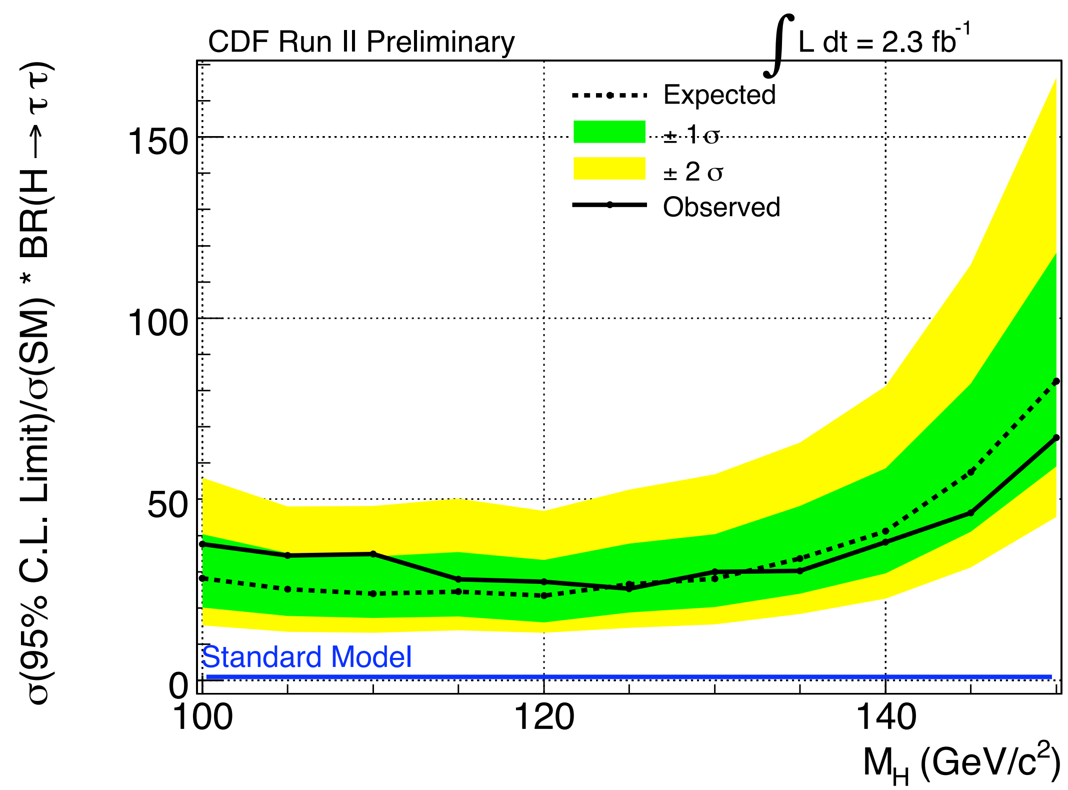
CDF Run II Preliminary			$\int L = 2.3\ fb^{-1}$
1 jet signal channel $M_H = 120$ GeV/c^2			
$Z/\gamma^* \to \tau\tau$	357.9	±	33.1
$Z/\gamma^* \to ee/\mu\mu$	26.4	±	2.0
WW/WZ/ZZ	3.9	±	0.4
$t\bar{t}$	4.6	±	0.6
fakes from SS data	483.0	±	48.3
add-on W+jets	45.8	±	8.2
Total Background	921.7	±	48.9
Data		965	
ggH	0.535	±	0.154
WH	0.091	±	0.010
ZH	0.050	±	0.005
VBF	0.070	±	0.009
Total Signal	0.746	±	0.163

CDF Run II Preliminary			$\int L = 2.3\ fb^{-1}$
≥ 2 jets signal channel $M_H = 120$ GeV/c^2			
$Z/\gamma^* \to \tau\tau$	59.3	±	8.8
$Z/\gamma^* \to ee/\mu\mu$	4.8	±	0.7
WW/WZ/ZZ	0.9	±	0.1
$t\bar{t}$	16.3	±	1.9
fakes from SS data	64	±	6.4
add-on W+jets	14.1	±	4.2
Total Background	159.4	±	11.6
Data		166	
ggH	0.129	±	0.092
WH	0.150	±	0.014
ZH	0.099	±	0.009
VBF	0.099	±	0.013
Total Signal	0.477	±	0.121

CDF VBF: $H \rightarrow \tau\tau$ [2.3 fb^{-1}]

- Background:
  - MC: $Z/\Upsilon^* \rightarrow ee/\mu\mu/\tau\tau$, $t\bar{t}$, diboson
  - Data-driven: Υ+jet, QCD multijet, W+jets [validated in 0-jet control regions]
- BDT trained to separate signal from background.
  - Separate BDT for each background.
- Limit: 23.4(Exp)/27.2(Obs) x σ_{SM} for M_H=120 GeV/c^2





D0 VBF: H → ττ [4.9 fb^{-1}]

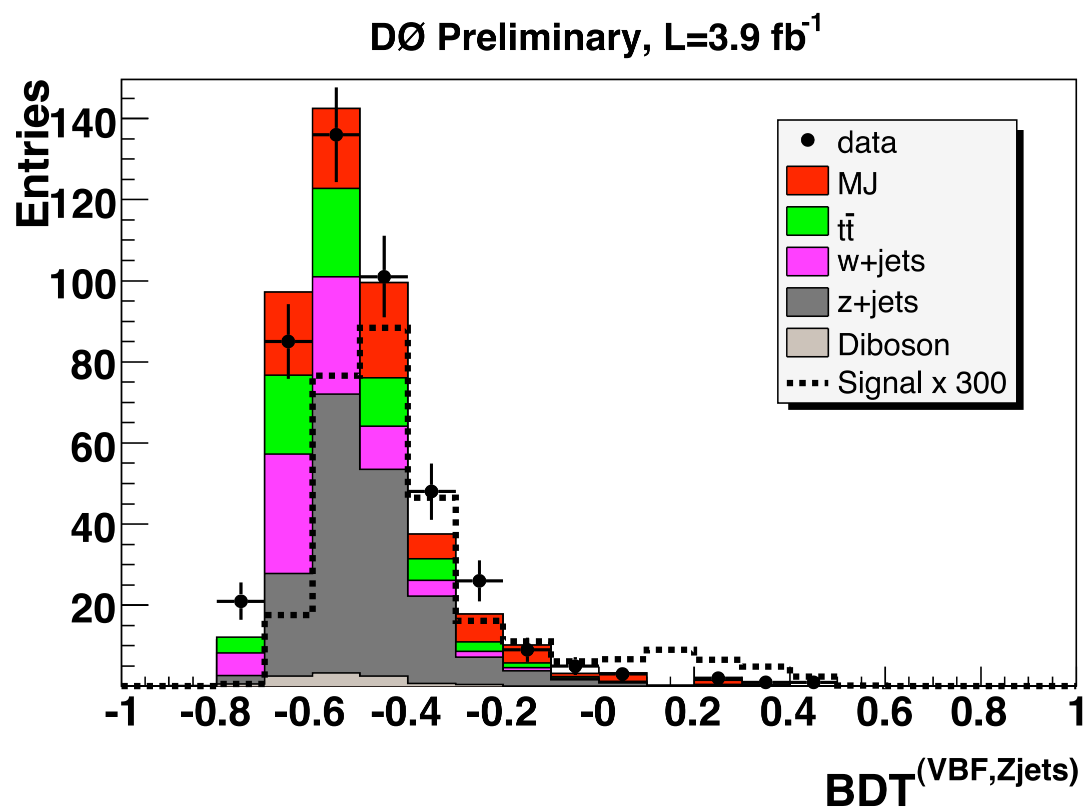
- Search for ττqq final state
  - 1 leptonic Tau, 1 hadronic Tau & 2-jets
  - NN used to ID hadronic Taus
- Sensitive to
  - ZH → ττ+bb
  - HZ → ττ+qq
  - HW → ττ+qq
  - gluon-gluon fusion & VBF

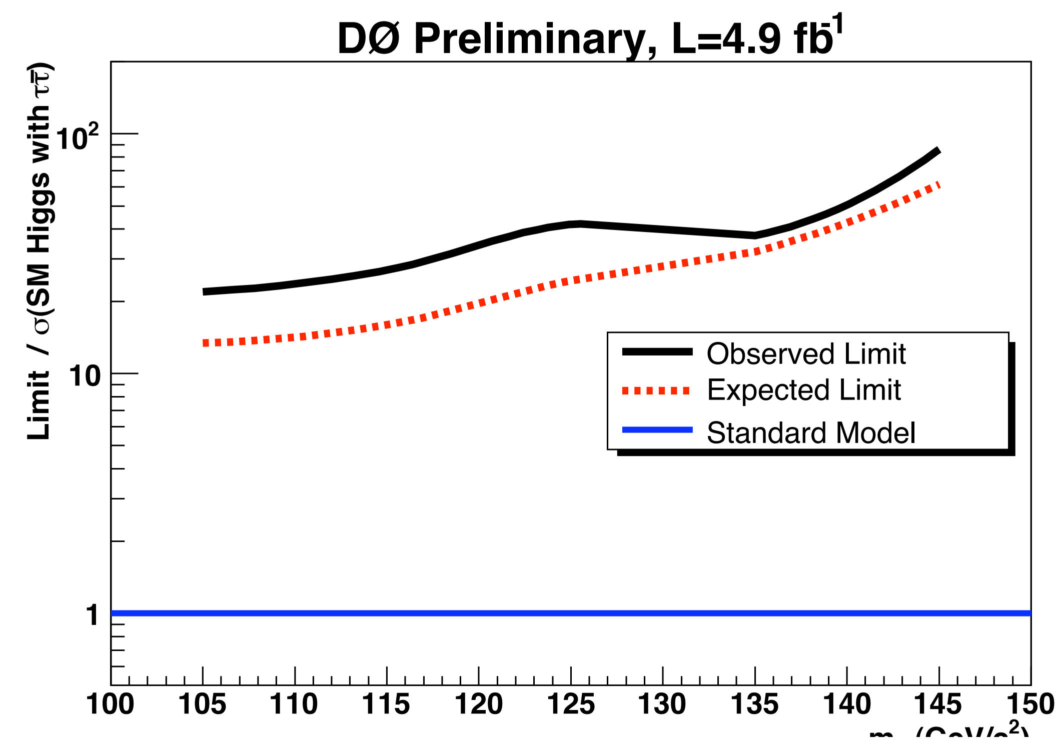
- Backgrounds:
  - MC: $t\bar{t}$, W/Z+jets, diboson,
  - Data-driven: QCD multijet
- 3.9 fb^{-1} analysed
  - 4.9 fb^{-1} when combined with Run IIa (1 fb^{-1})

D0 VBF: H → ττ [4.9 fb^{-1}]

- BDT used to separate signal from background
  - BDT trained for each signal process
  - Separate BDTs combined to calculate limit
- Limit: 24.4(Exp)/41.9(Obs) x σ_{SM} for M_H=125 GeV/c^2

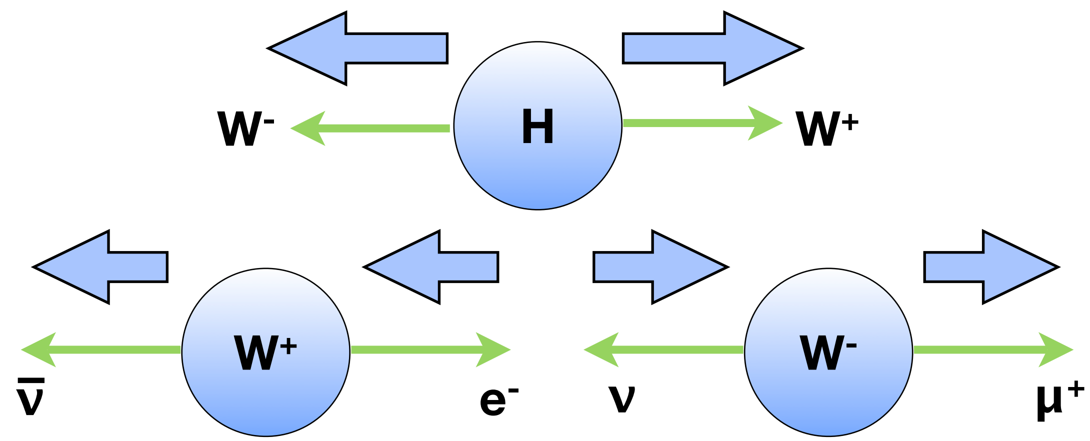
  (when Run IIa (1.0 fb^{-1}) and Run IIa (3.9f b^{-1}) are combined)





VBF: H → WW [CDF 6 fb^{-1} / D0 6.7 fb^{-1}]

- Search for 2 leptons + $\not{E}_T$
  - Exploits spin correlation
- Most sensitive analysis
- gluon-gluon fusion dominates but VBF does contribute
- Many sub-channels: same-sign leptons, opposite-sign leptons, 0,1,+2 jets, etc
- Focus on Opposite-sign leptons + N jets (OS+NJet) as it is sensitive to VBF

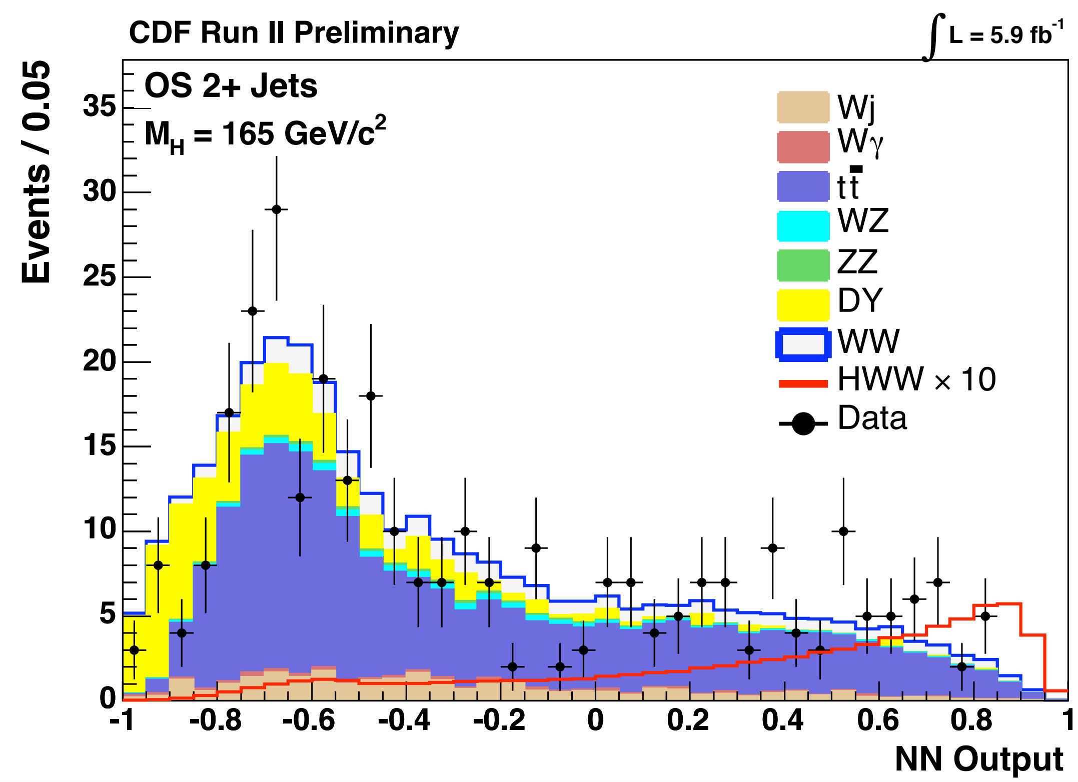


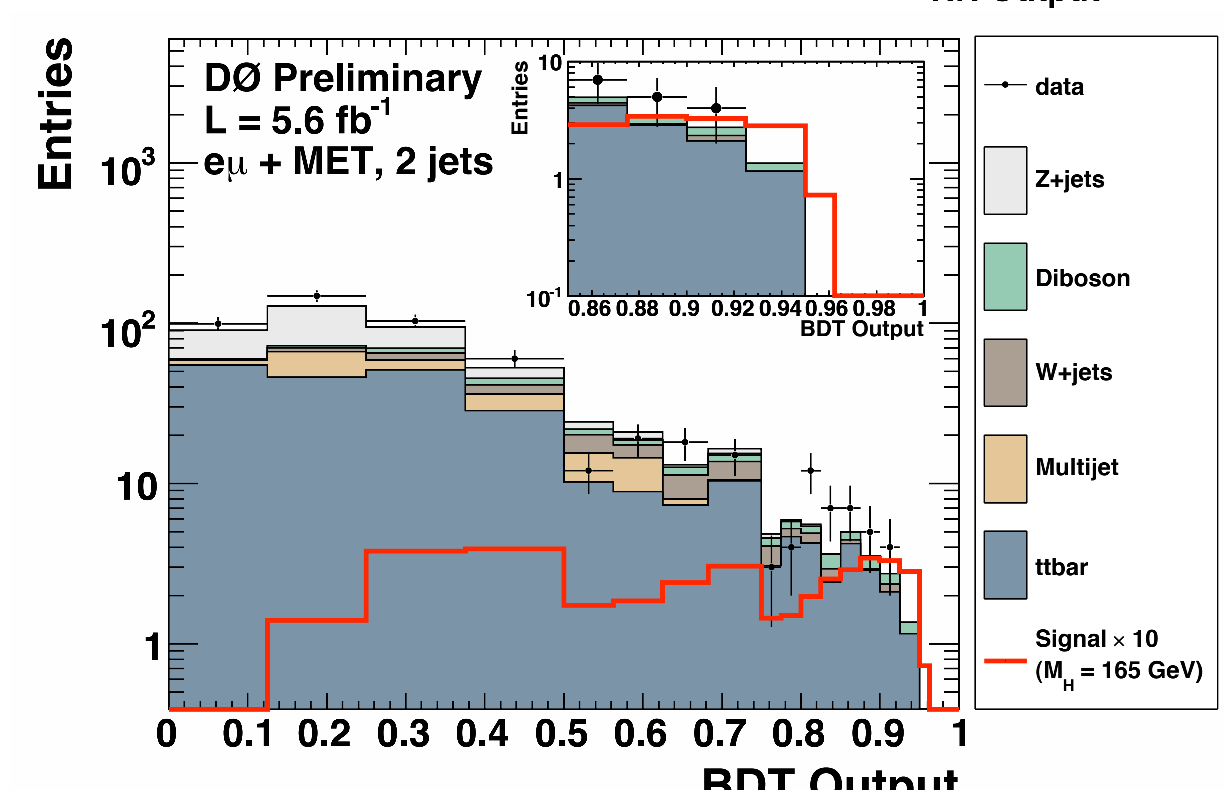
CDF Run II Preliminary $\int \mathcal{L} = 5.9\ \text{fb}^{-1}$			
$M_H = 165\ \text{GeV}/c^2$			
$t\bar{t}$	169	±	24
DY	80	±	31
WW	33.6	±	6.1
WZ	6.8	±	1.3
ZZ	3.10	±	0.57
W+jets	26.7	±	7.5
$W\gamma$	4.4	±	1.2
Total Background	324	±	50
$gg \to H$	2.6	±	1.8
WH	2.50	±	0.35
ZH	1.28	±	0.17
VBF	1.37	±	0.23
Total Signal	7.8	±	2.0
Data		307	

AllSB-2JOS

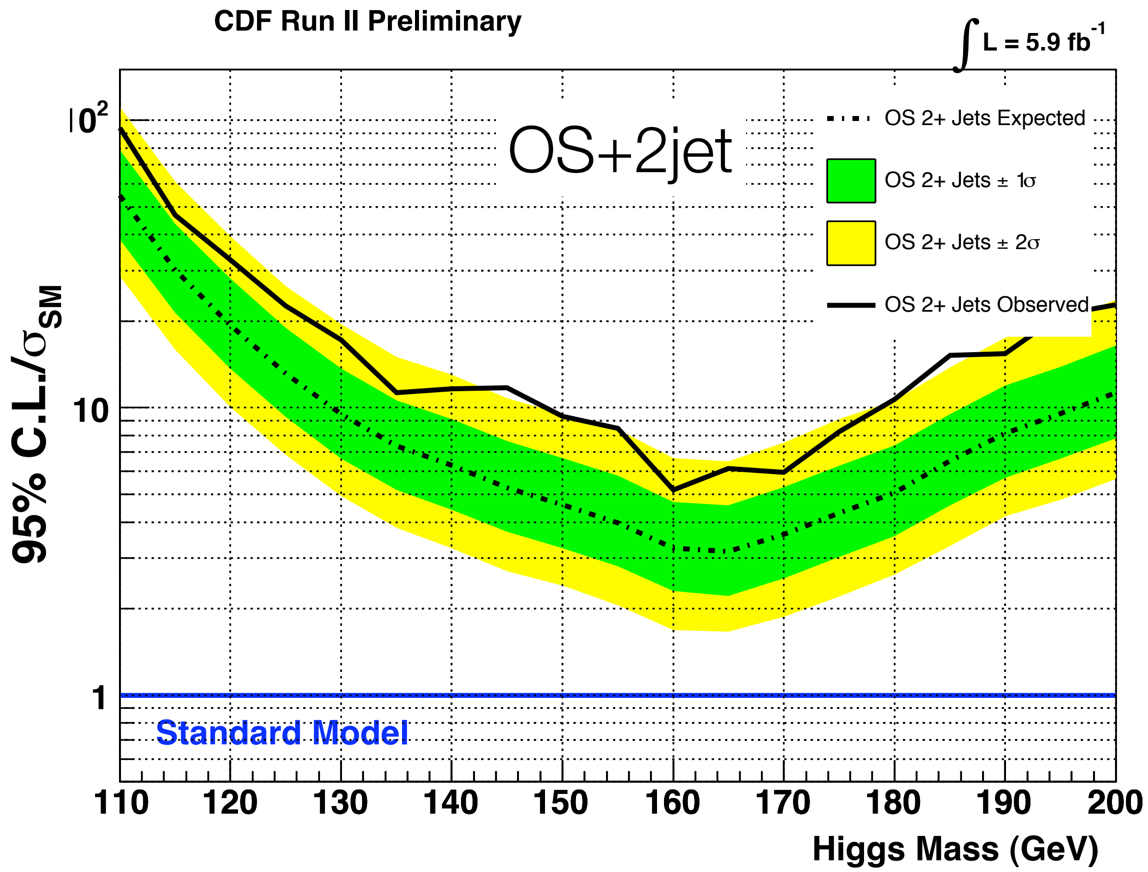
VBF: H → WW [CDF 6 fb^{-1} / D0 6.7 fb^{-1}]

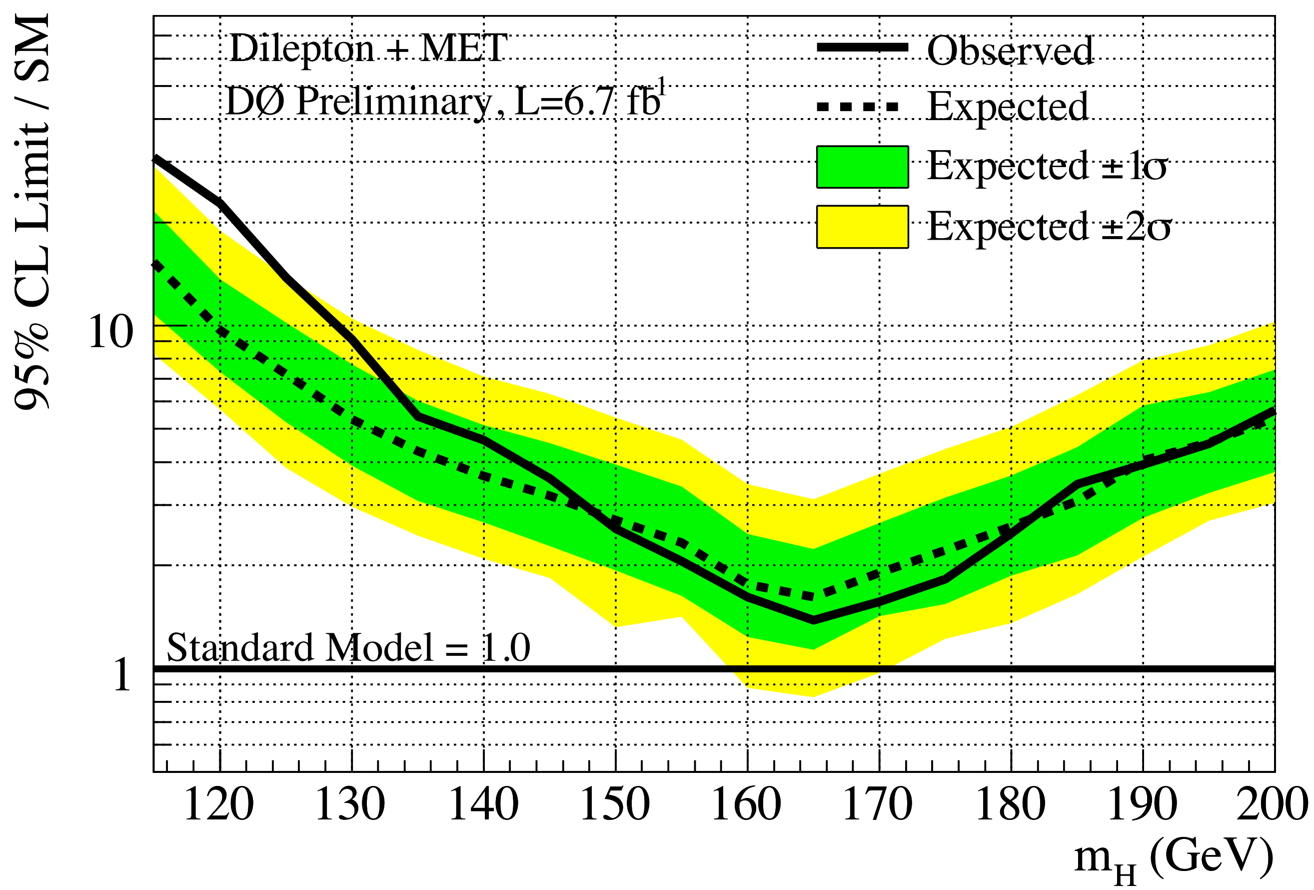
- Backgrounds: Drell-Yan, diboson, W+jets, WΥ, ZΥ, $t\bar{t}$
- Multivariate analysis techniques used to separate signal from background
    - CDF: NN
    - D0: Random Forrest Decision Tree





VBF: H → WW [CDF 6 fb^{-1} / D0 6.7 fb^{-1}]

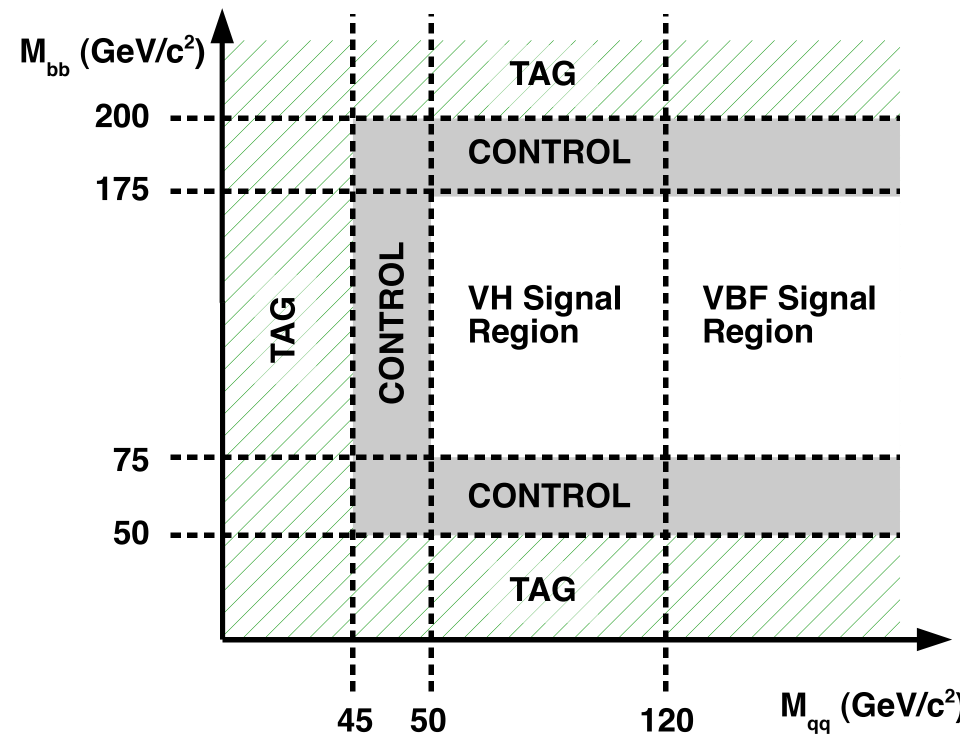




- CDF 0S+2-jet limit: 3.16(Exp)/ 6.14(Obs) x σ_{SM} for M_H=165 GeV/c^2
- CDF Full Combination: 1.00(Exp)/ 1.08(Obs) x σ_{SM} for M_H=165 GeV/c^2
- D0 Dilepton+MET: 1.62(Exp)/ 1.39(Obs) x σ_{SM} for M_H=165 GeV/c^2

CDF VBF: H → $b\bar{b}$ [4 fb^{-1}]

- Search for events with 2 b-jets and 2 non b-jets (q-jets)
- Largest signal yield for low mass Higgs
- Dominated by large QCD multijet background
- Event Selection
  - 4 or 5 jets [jet-Et>15GeV & jet-|η|<2.4]
  - Exactly 2 b-tagged jets
  - VH & VBF signal regions: Defined by M_{bb}-M_{qq} plane

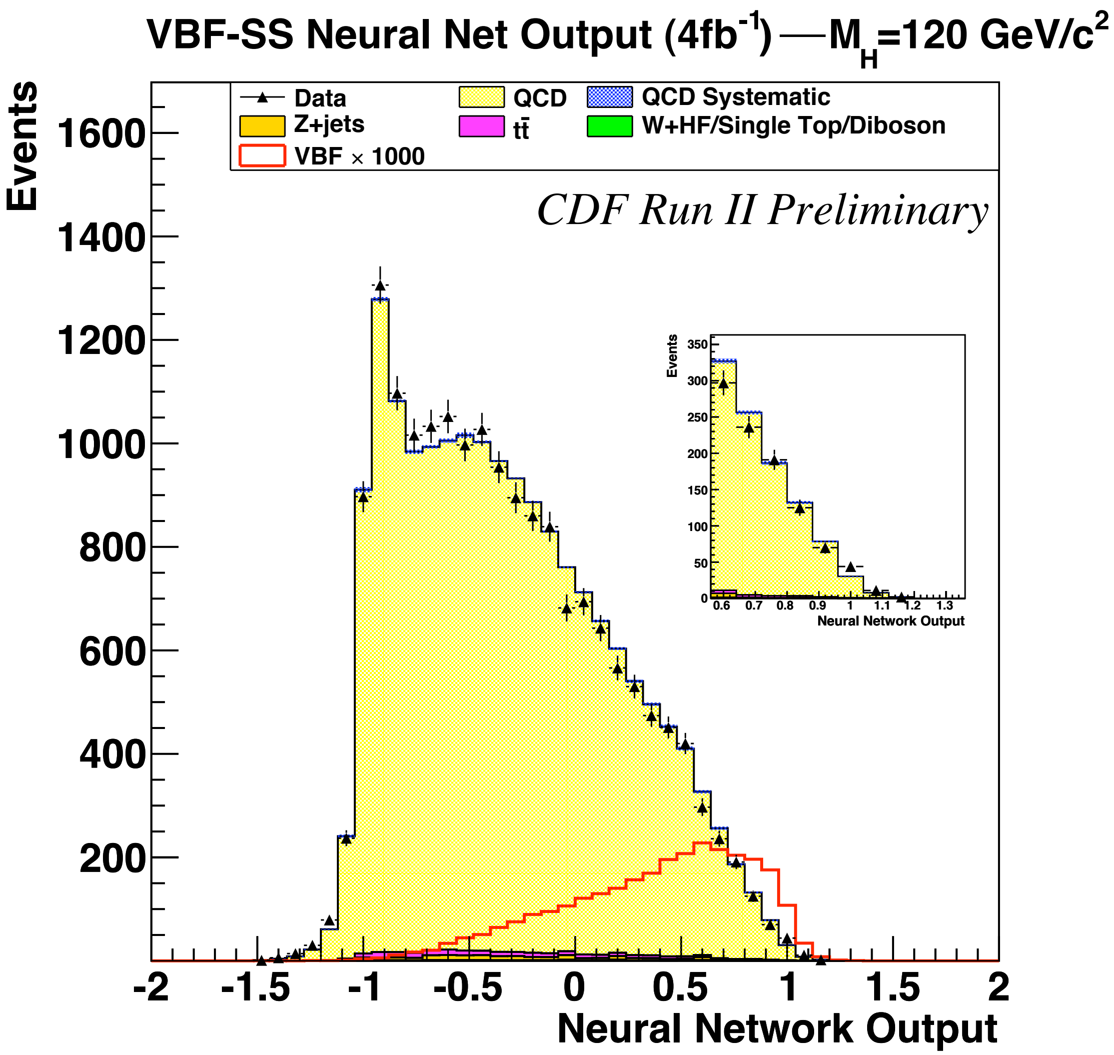


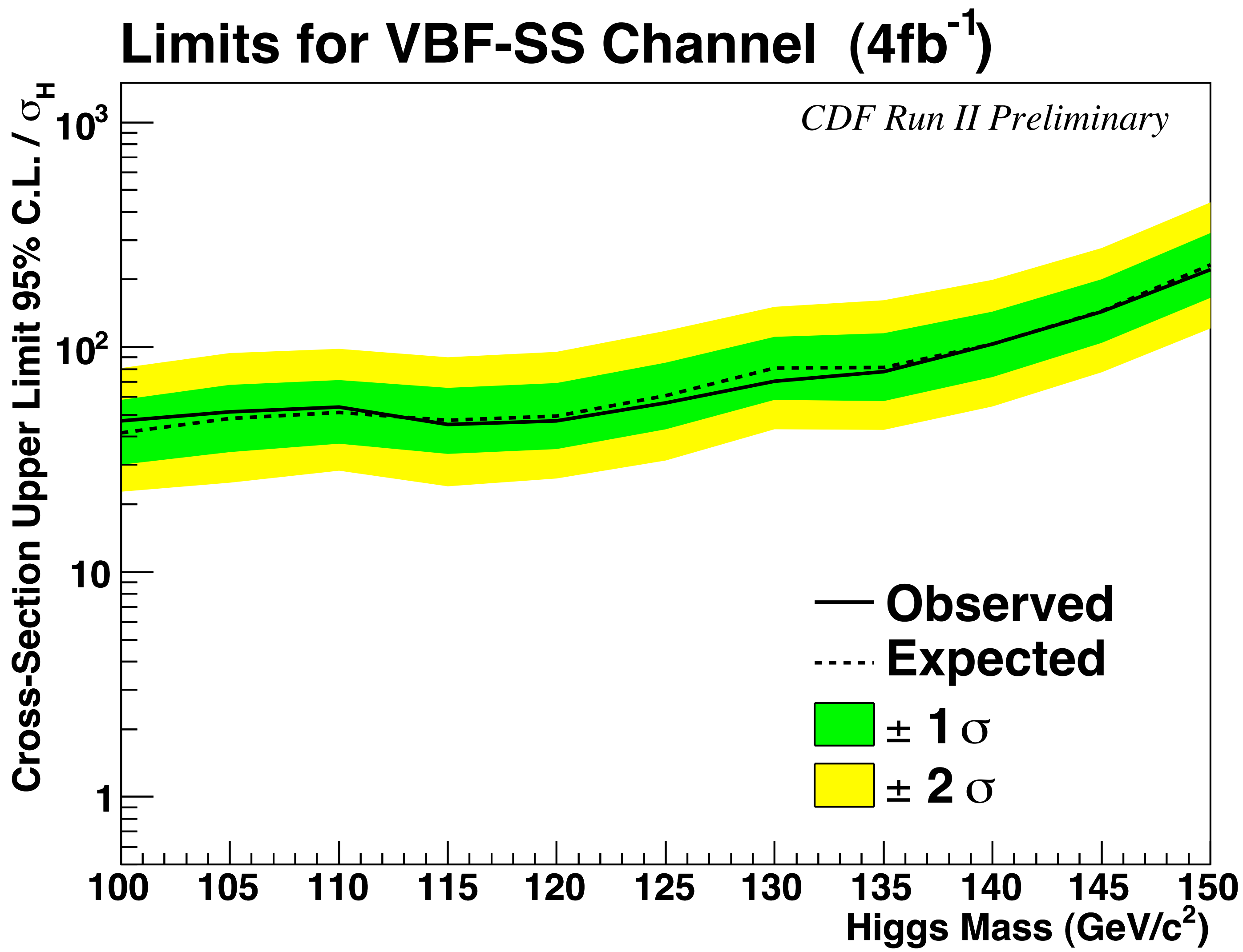
Higgs mass	VH	VBF
100	14.0	3.5
110	12.8	4.9
120	10.7	4.4
130	7.6	3.4
140	4.4	2.2
150	1.9	1.1

Number of events after passing trigger, event selection and has two b-tagged jets

CDF VBF: $H \rightarrow b\bar{b}$ [4 fb^{-1}]

- NN used to separate signal from background
  - Training variables: Mbb, Mqq, q-jet widths
- Best Limit for VBF: 49.4(Exp)/ 47.0(Obs) x σ_{SM} for M_H=120 GeV/c^2





Conclusion

- At the Tevatron, VBF is a secondary production channel after associated Higgs production (low mass Higgs) and gluon-gluon fusion (high mass Higgs)
  - But VBF makes a valuable contribution
  - Every channel counts: Leave no channel behind !
- Work on updating & improving analysis still continues in earnest
- Most analyses are getting updated for 2011 Winter conferences
  - Expect Tevatron Higgs results to continue to summer 2012
  - ….Tevatron may still surprise you !

References

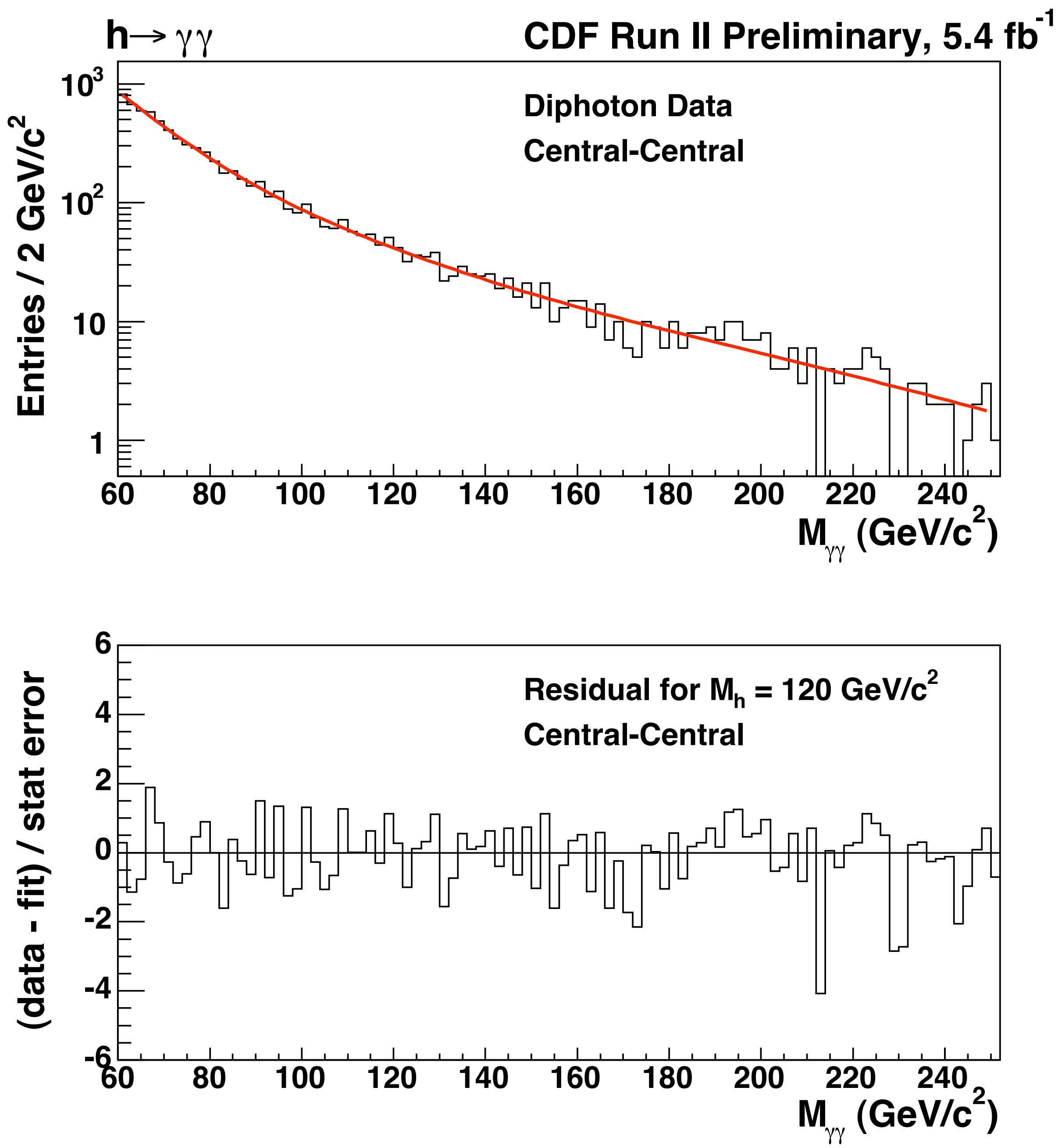
- CDF Public Higgs Result: http://www-cdf.fnal.gov/physics/new/hdg/Results.html
- D0 Public Higgs Result: http://www-d0.fnal.gov/Run2Physics/WWW/results/higgs.htm
- Tevatron Higgs Combination: http://tevnphwg.fnal.gov/results/SM_Higgs_Summer_10/
- H → ϒ ϒ
    - CDF: http://www-cdf.fnal.gov/physics/new/hdg//Results_files/results/hgamgam_jul10/
    - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H66/

References

- H → ττ
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg//Results_files/results/smtautau_jul10/home.html
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H79/
- H → WW
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg//Results_files/results/hwwmenn_100618/
  - D0: http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H94/
- H → bb
  - CDF: http://www-cdf.fnal.gov/physics/new/hdg//Results_files/results/vhqqbb_oct09/AllHadronicHiggsSearch/Analysis.html

Backup

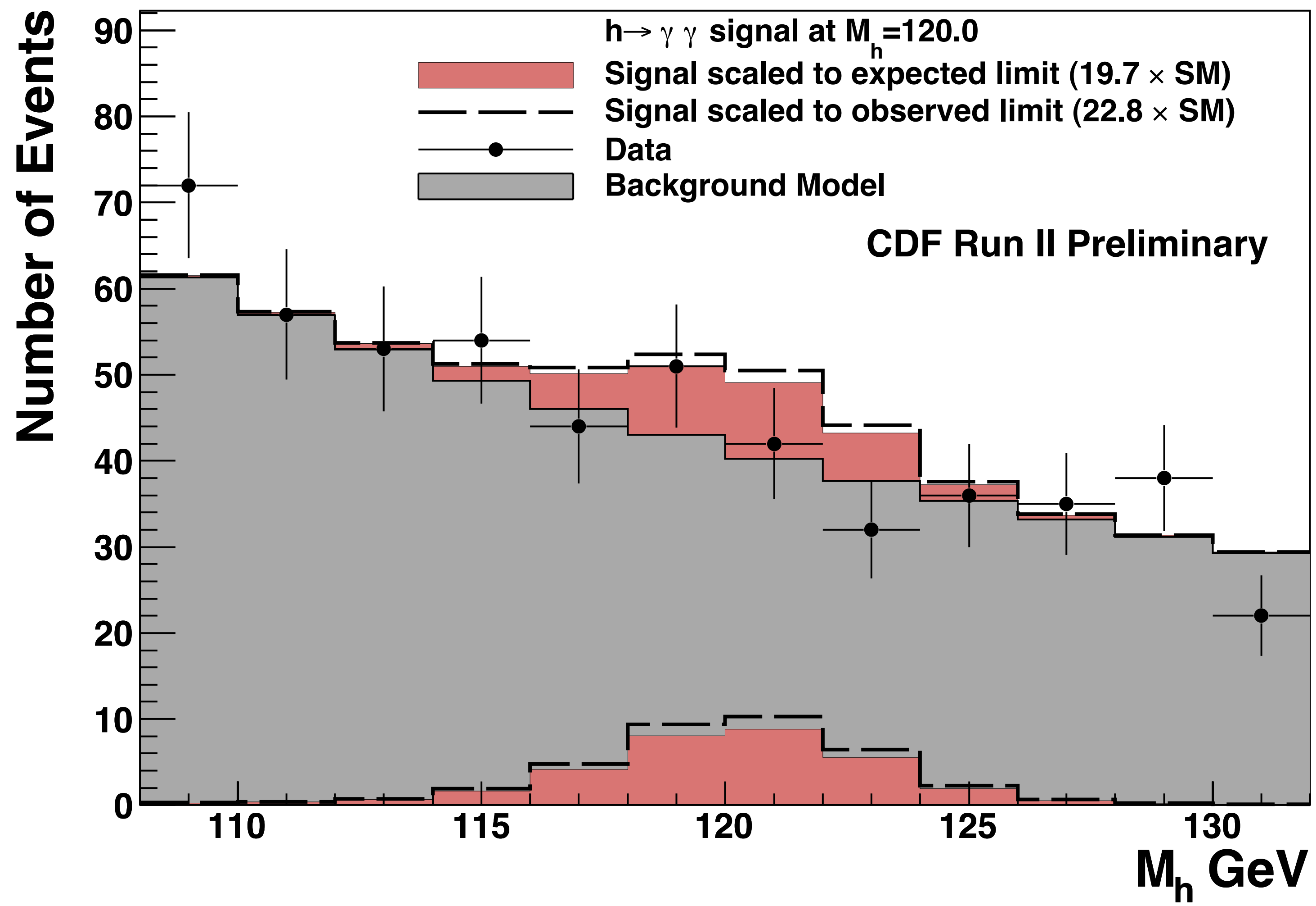
CDF: H → ϒ ϒ



- Residuals from fit show no significant bumps or structure.

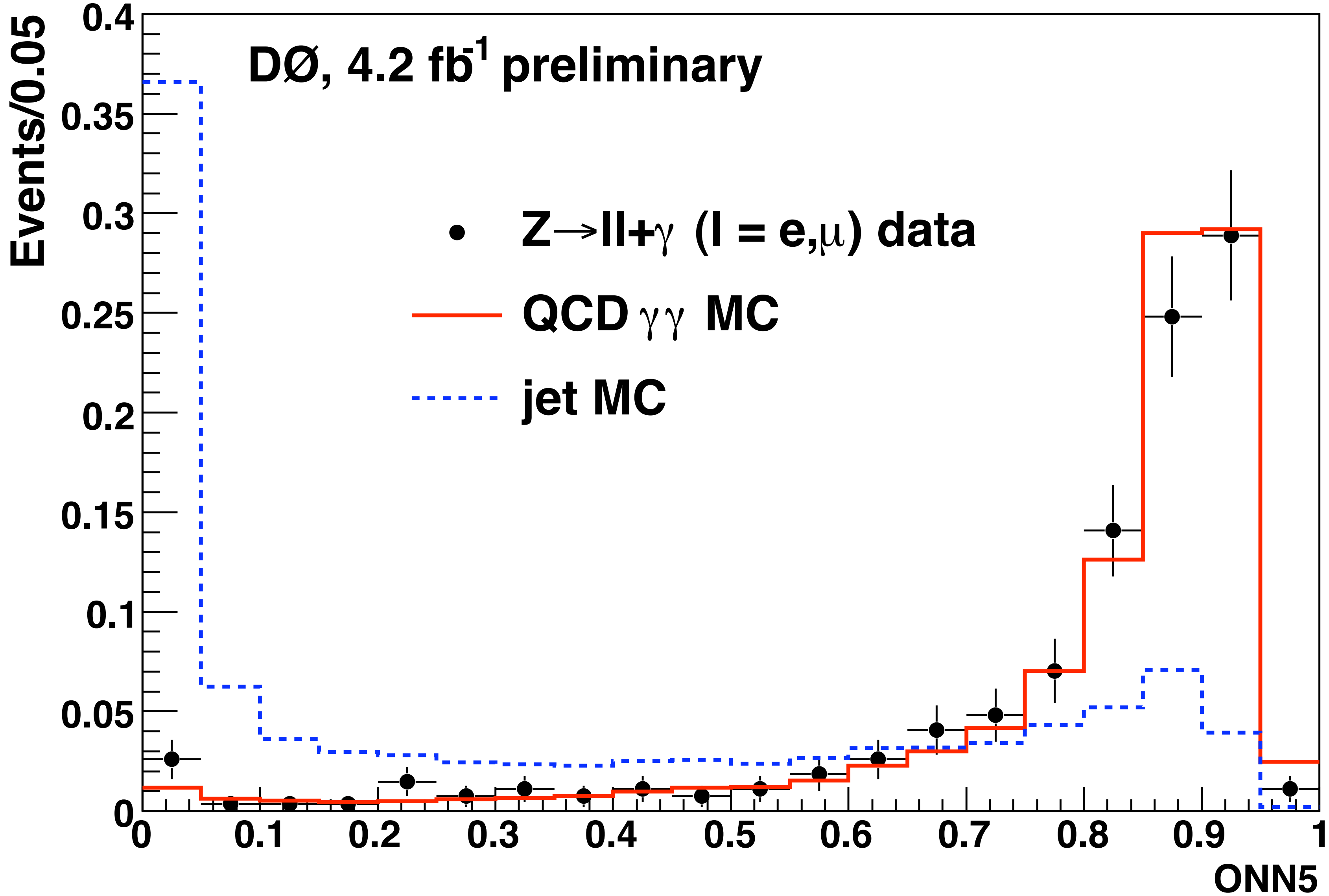
CDF: H → γ γ

- Stacked signal & background
- Expected & observed signal are shown



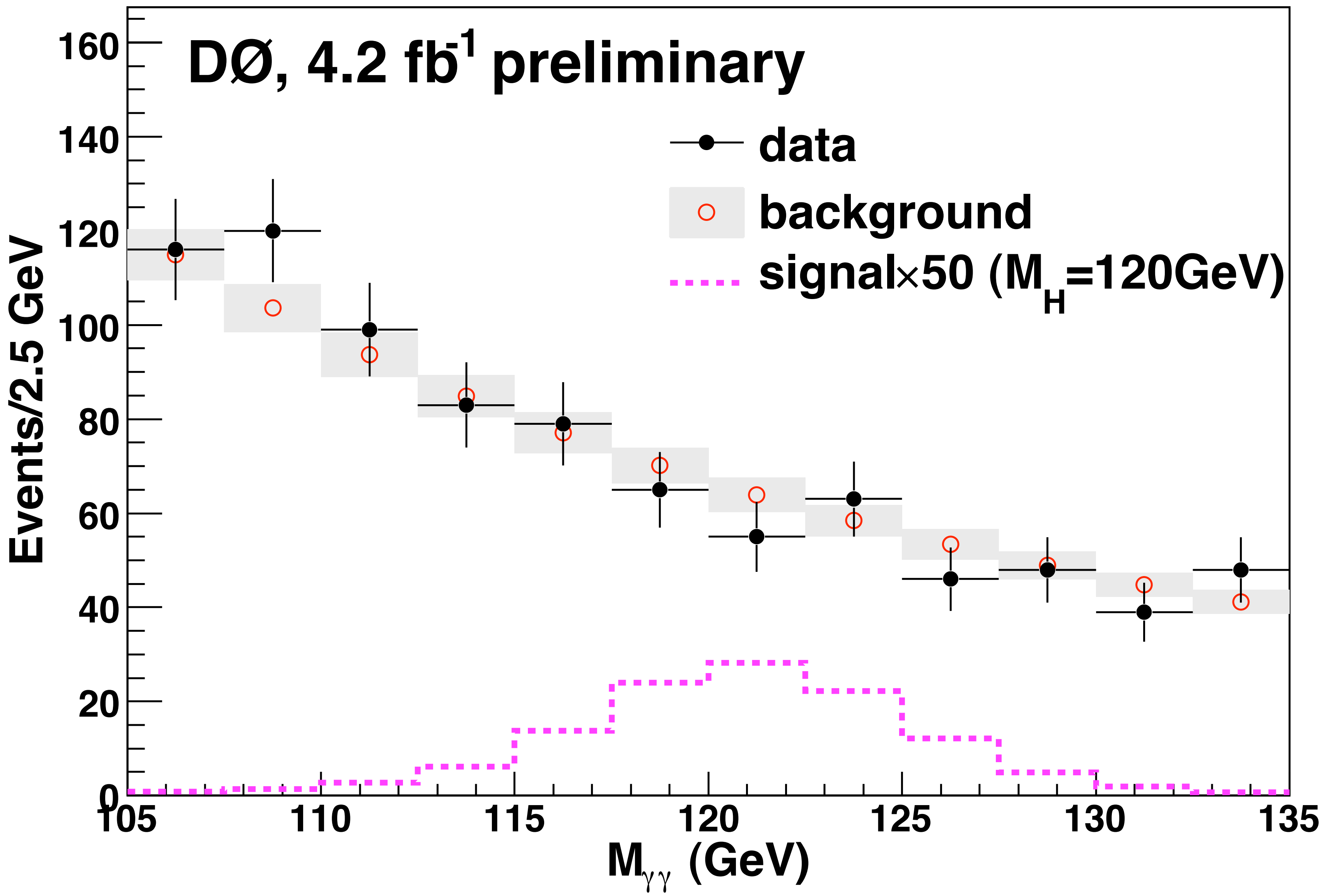
D0: H → Υ Υ

- Performance of D0's NN jet-fake photon rejecter
- Cut on ONN5>0.1 to select photons
    - Rejects ~50% fake photons



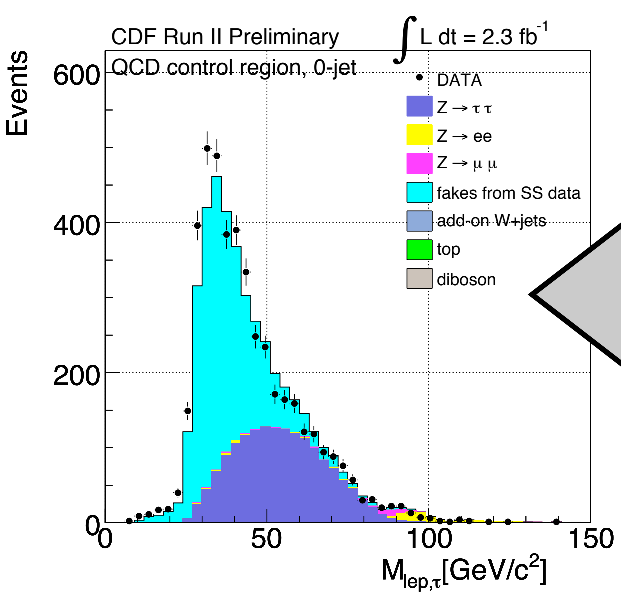
D0: H → ϒ ϒ

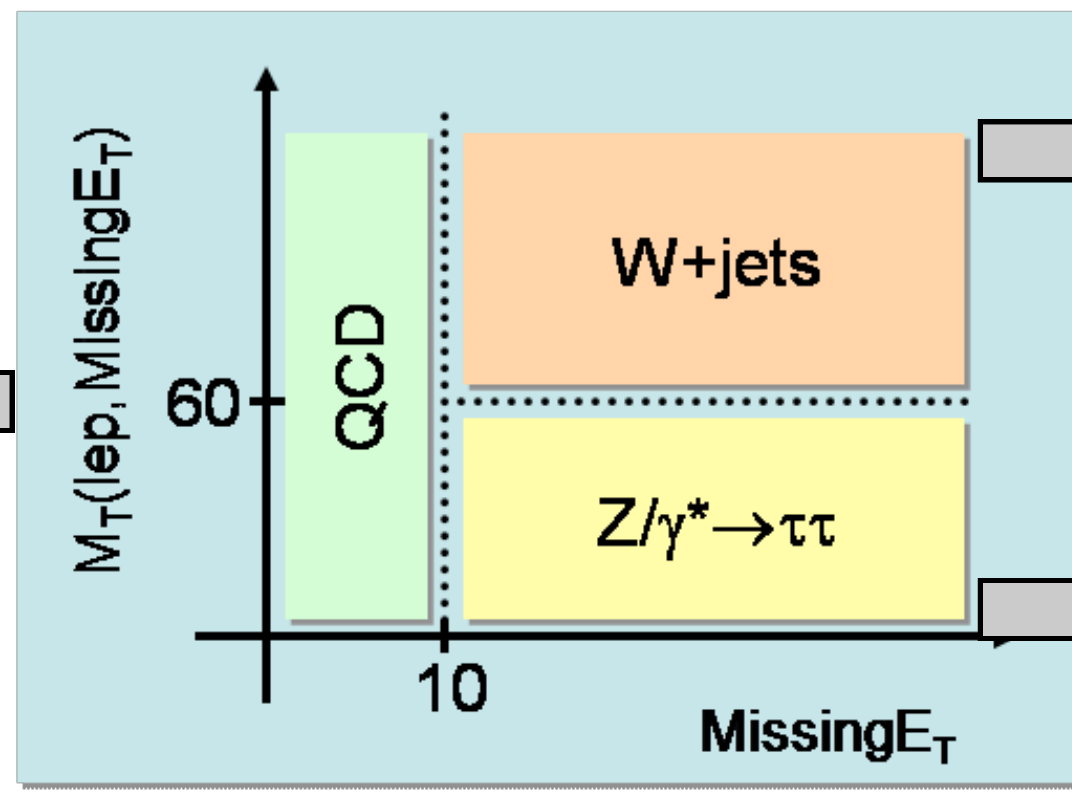
- Final fit of data & background with signal scaled by x50

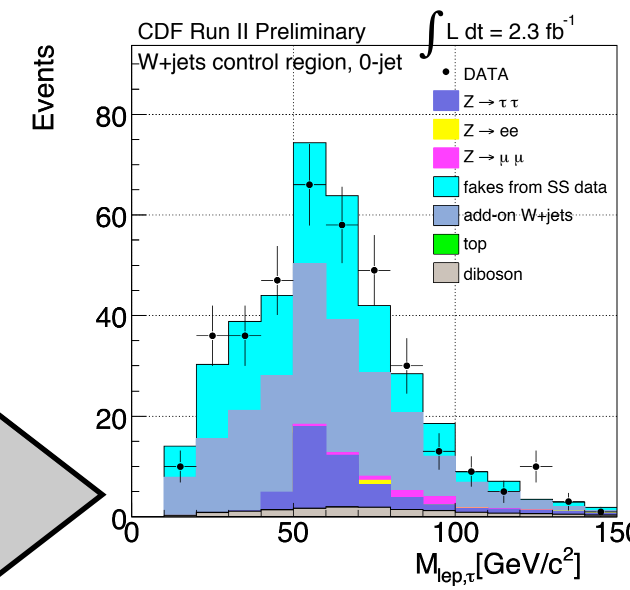


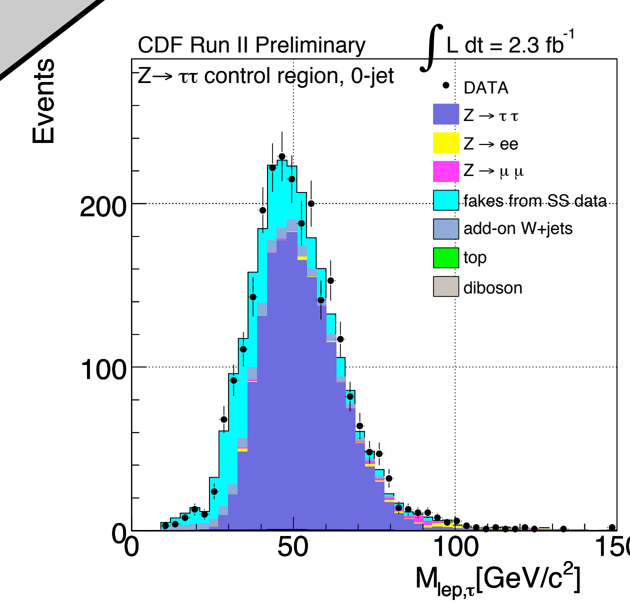
CDF VBF: H → ττ

- Background models validated in 0-jets in 3 control regions: QCD, $Z/\Upsilon^* \rightarrow \tau\tau$, W+Jets

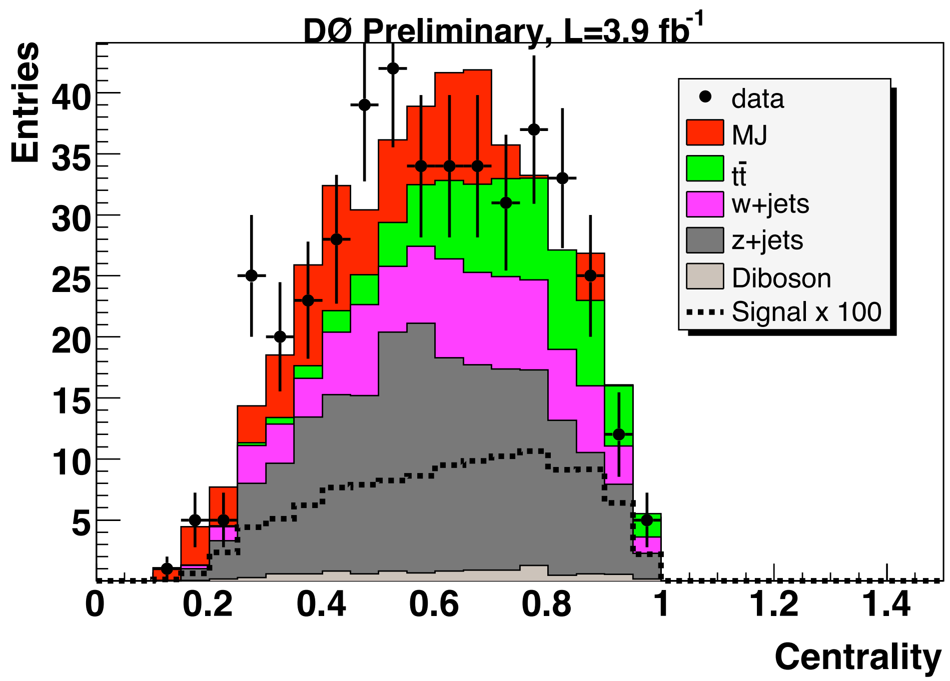


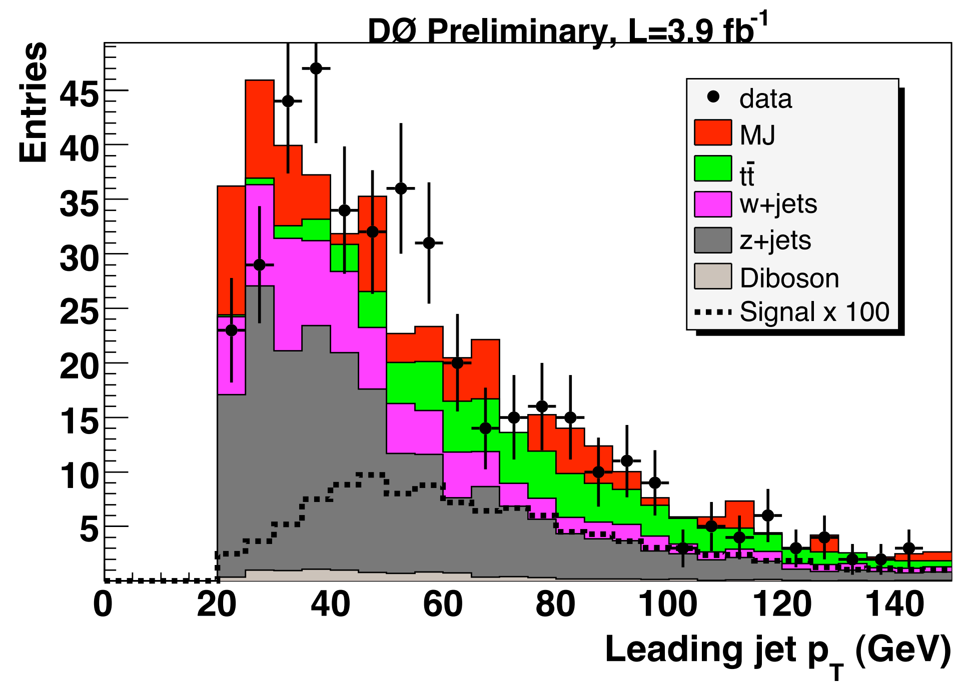


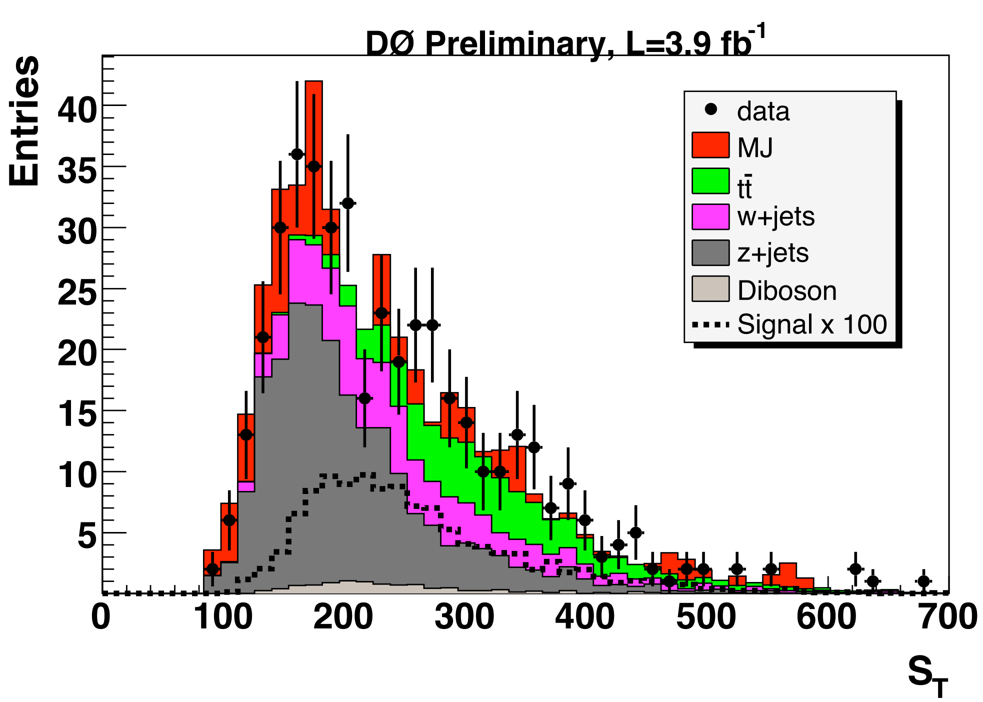




D0 VBF: H → ττ

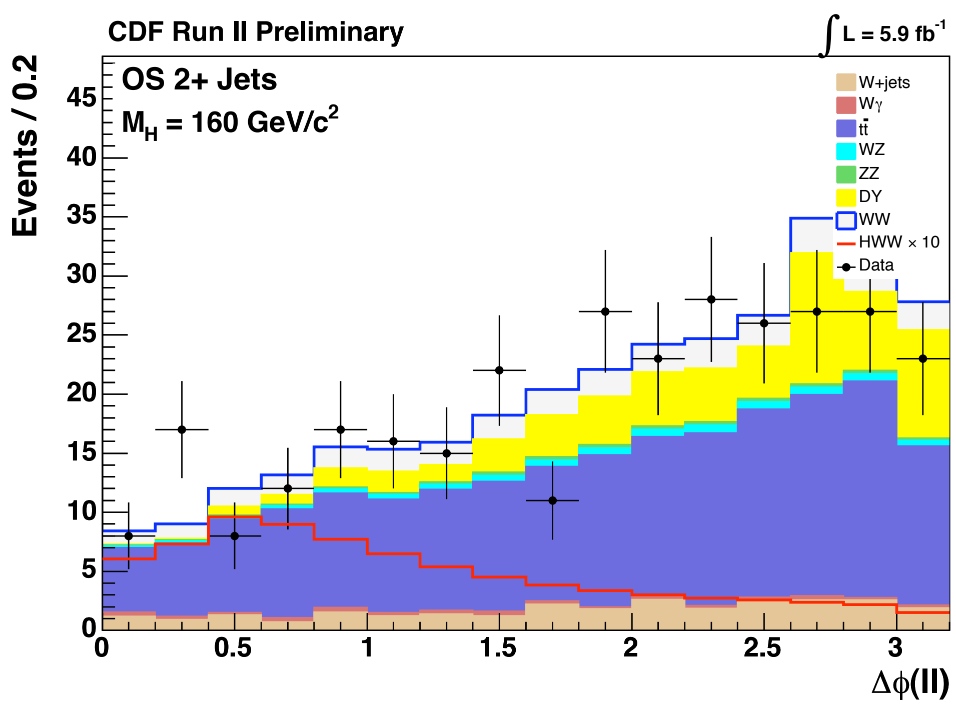


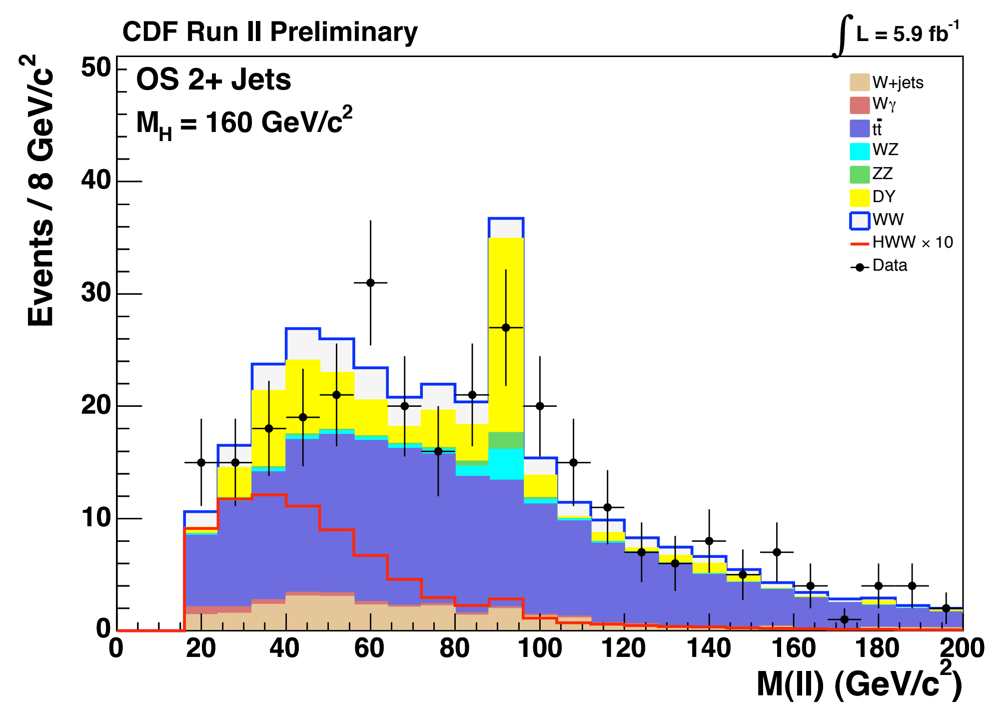


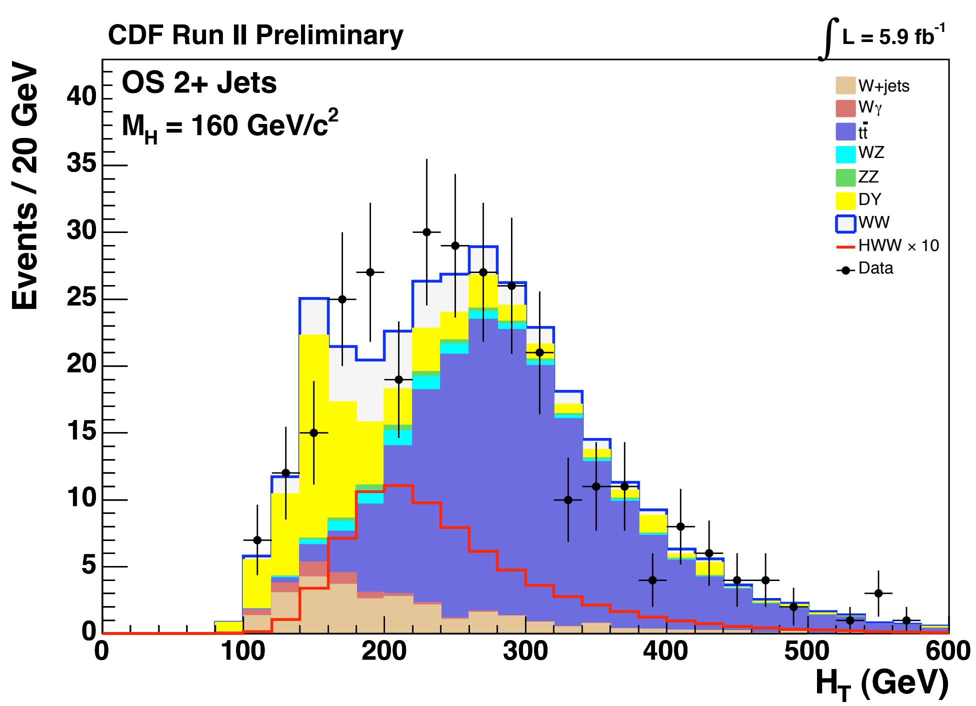


- Distribution of data, background & signal for key kinematic variables

CDF : H → WW

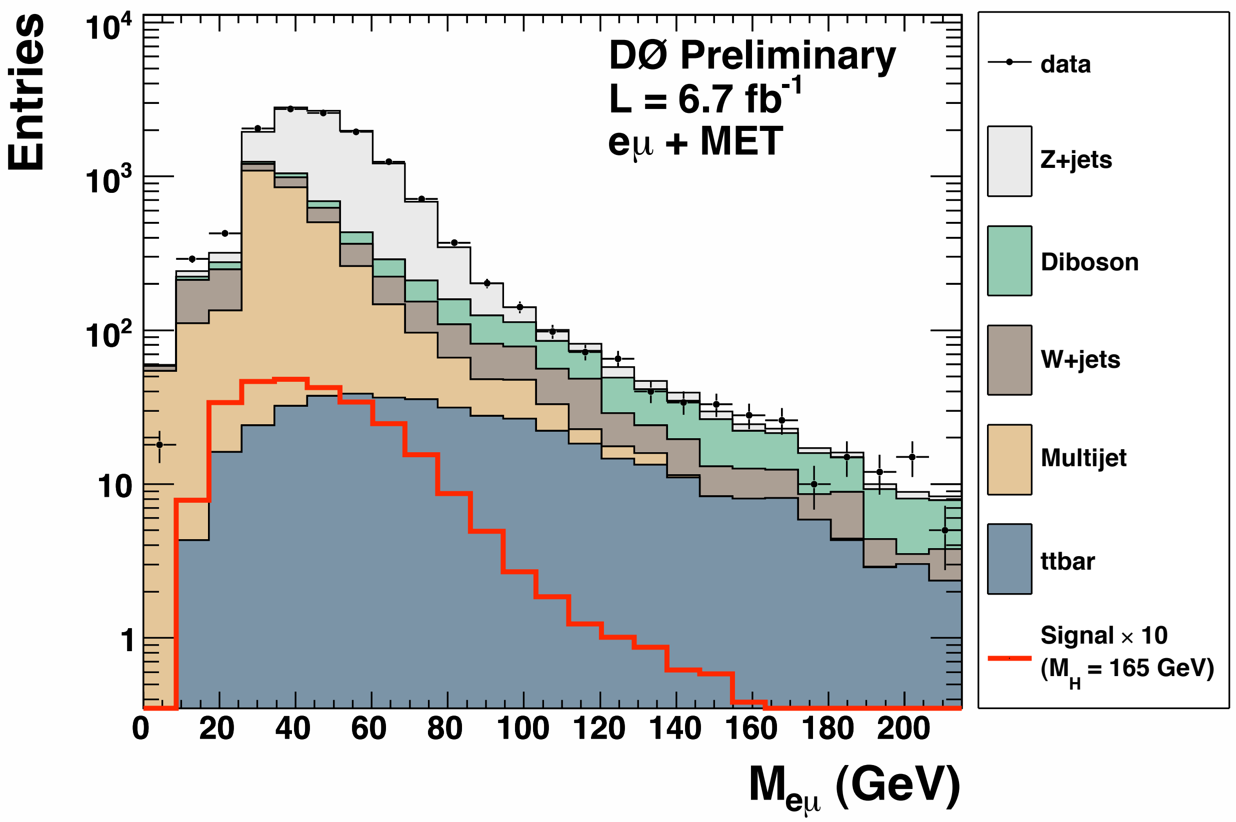


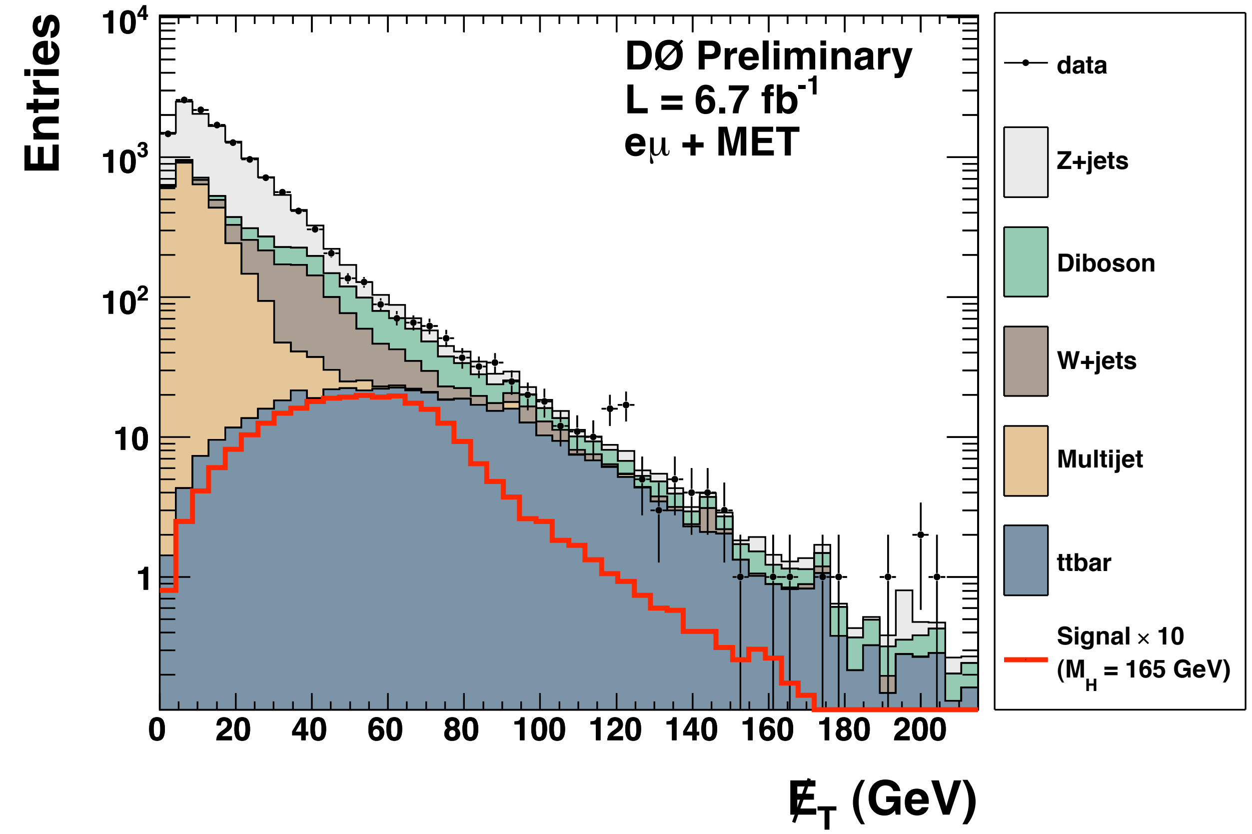




- Distributions of some of the NN input variables for OS+2Jet

D0 : H → WW





- Distributions of some BDT inputs

D0 : H → WW

TABLE III: List of leading correlated systematic uncertainties in % change of the total event yield, averaged over backgrounds and signals. All uncertainties within a group are considered 100% correlated across channels. The correlated systematic uncertainty on the background cross section (σ) and shape-dependent background modeling are subdivided according to the different background processes in each analysis. Uncertainties listed as shape only (s.o.) do not affect the total event yield but do affect the shape of the final variable.

Source	$H \to W^+W^- \to \ell\nu\ell\nu$
Luminosity	6.1
Jet Energy Scale	4.0
Jet ID	1.0
Electron ID/Trigger	3-6
Muon ID/Trigger	4.0
Background cross section	6-10
Signal cross section	6-80
Multijet	2.0
Shape-Dependent Bkgd Modeling	2.0

Table of systematic errors

- Take from the D0's combined Higgs limit note

http://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/HIGGS/H96/H96.pdf

CDF : H → WW

Systematic Errors

Uncertainty Source	WW	WZ	ZZ	$t\bar{t}$	DY	$W\gamma$	W+jet	$gg \to H$	WH	ZH	VBF
Cross Section											
Scale								67.5%			
PDF Model								29.7%			
Total	*6.0%*	*6.0%*	*6.0%*	10.0%					**5.0%**	**5.0%**	10.0%
Acceptance											
Scale (leptons)								3.1%			
Scale (jets)	*-8.2%*							-6.8%			
PDF Model (leptons)								*4.8%*			
PDF Model (jets)	*4.2%*							-12.3%			
Higher-order Diagrams		*10.0%*	*10.0%*	10.0%		10.0%			**10.0%**	**10.0%**	**10.0%**
$\not\!\!E_T$ Modeling					25.5%						
Conversion Modeling						10.0%					
Jet Fake Rates							28.0%				
Jet Energy Scale	*-14.8%*	*-12.9%*	*-12.1%*	*-1.7%*	*-29.2%*	*-22.0%*		*-17.0%*	*-4.0%*	*-2.3%*	*-4.0%*
b-tag Veto				3.8%							
Lepton ID Efficiencies	*3.0%*	*3.0%*	*3.0%*	*3.0%*	*3.0%*			*3.0%*	*3.0%*	*3.0%*	*3.0%*
Trigger Efficiencies	*2.0%*	*2.0%*	*2.0%*	*2.0%*	*2.0%*			*2.0%*	*2.0%*	*2.0%*	*2.0%*
Luminosity	*5.9%*	*5.9%*	*5.9%*	*5.9%*	*5.9%*			*5.9%*	*5.9%*	*5.9%*	*5.9%*

CDF All Hadronic Higgs: Total number of events

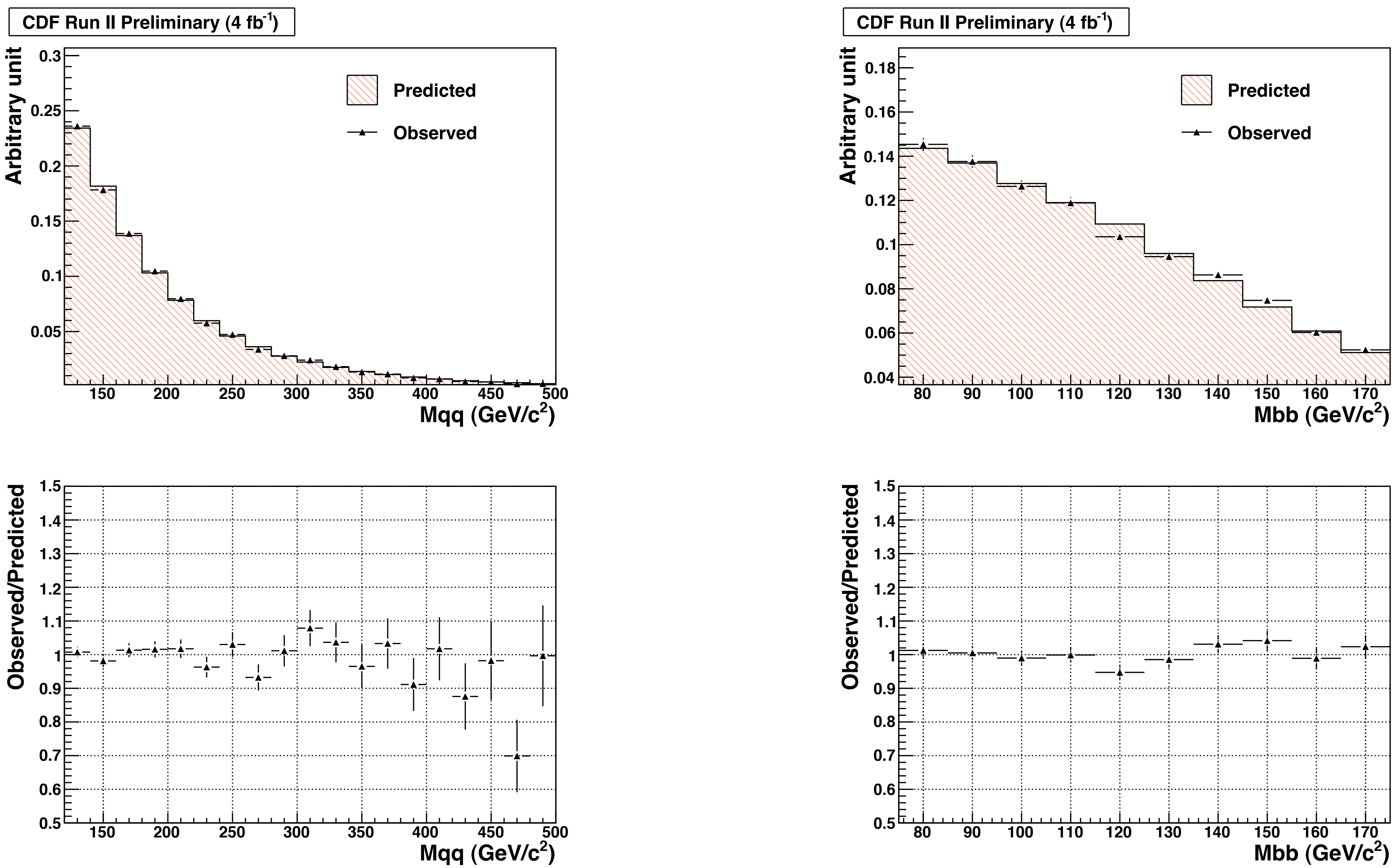
CDF Run II Preliminary (4 fb^{-1})
Expected number of background events which pass the trigger, event selection and have two b-tags (SecVtx-SecVtx [SS] or SecVtx-SetProbJ [SJ]).

Signal regions	VH (WH+ZH)		VBF	
Backgrounds	SS	SJ	SS	SJ
$t\bar{t}$	281.7	115.3	177.3	75.7
single-top	44.1	17.7	17.2	10.0
$W + bb/cc$	27.9	12.0	4.8	3.3
$Z(bb, cc)$+jets	127.5	55.4	135.0	62.9
Diboson	11.4	8.5	5.3	3.8
Data	16857	9341	17776	9518

CDF Run II Preliminary (4 fb^{-1})
Expected number of signal events which pass the trigger, event selection, have two b-tags (SecVtx-SecVtx [SS] or SecVtx-SetProbJ [SJ]).

Signal regions	WH		ZH		VBF	
Higgs Mass (GeV/c^2)	SS	SJ	SS	SJ	SS	SJ
100	5.9	2.2	4.4	1.5	3.4	1.2
105	5.7	2.2	4.1	1.5	3.5	1.3
110	5.4	2.0	4.0	1.4	3.6	1.3
115	5.1	1.9	3.7	1.3	3.4	1.3
120	4.5	1.7	3.3	1.2	3.2	1.2
125	3.9	1.5	2.8	1.0	2.9	1.1
130	3.3	1.2	2.3	0.8	2.5	0.9
135	2.5	1.0	1.8	0.6	2.1	0.7
140	1.9	0.7	1.3	0.5	1.6	0.6
145	1.3	0.5	0.9	0.3	1.2	0.4
150	0.8	0.3	0.6	0.2	0.8	0.3

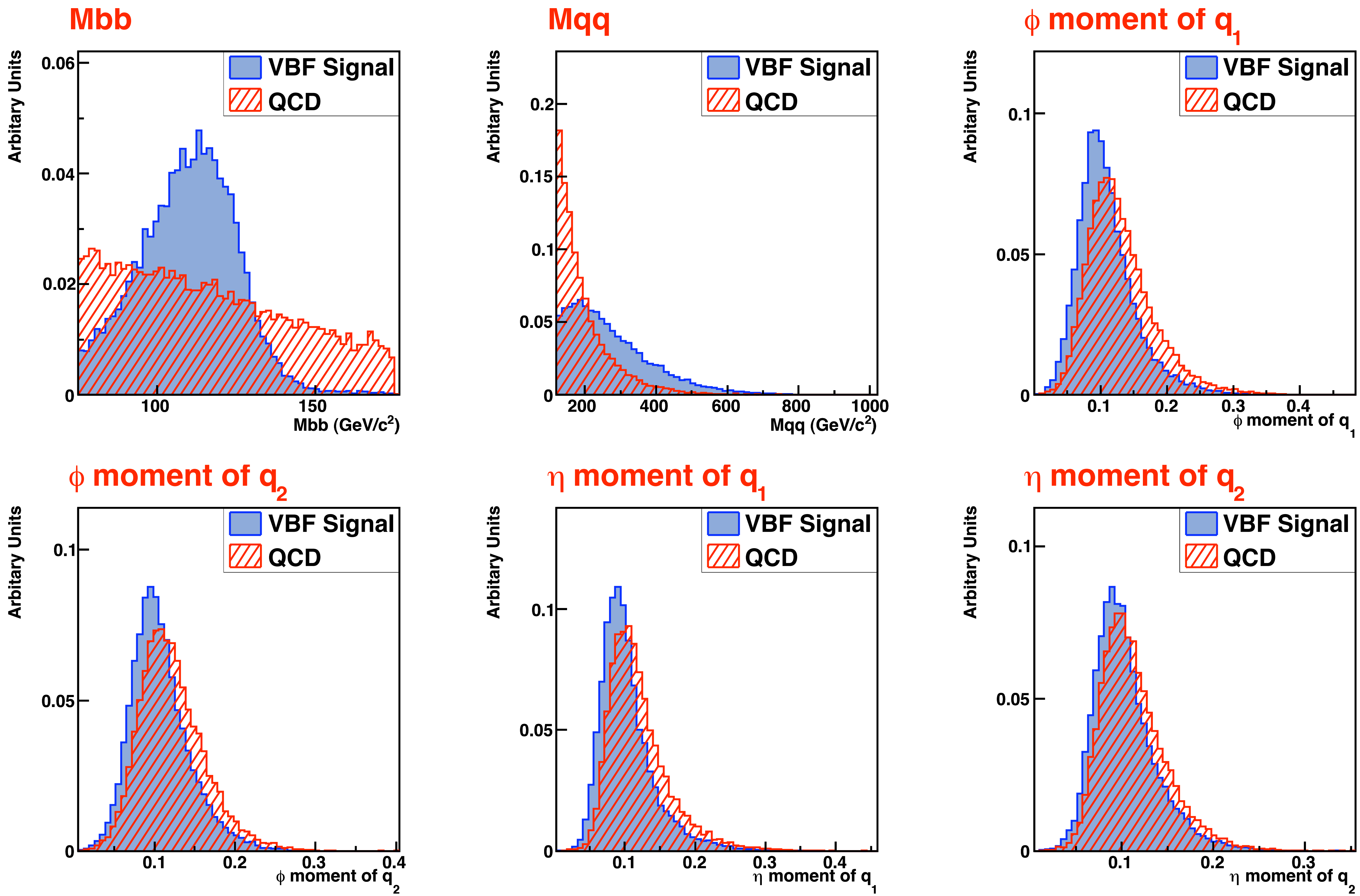
CDF: H → bb   [$4fb^{-1}$]



- Data-driven QCD prediction
- M_{bb} & M_{qq} validation

VBF (M_H=120 GeV/c^2) Signal Vs Background
(shape comparison)

CDF Run II Preliminary



Neural Net : VBF Training Variables

6 training variables for VBF channel :

- M_{bb} & M_{qq}
- Jet Shapes

Systematics

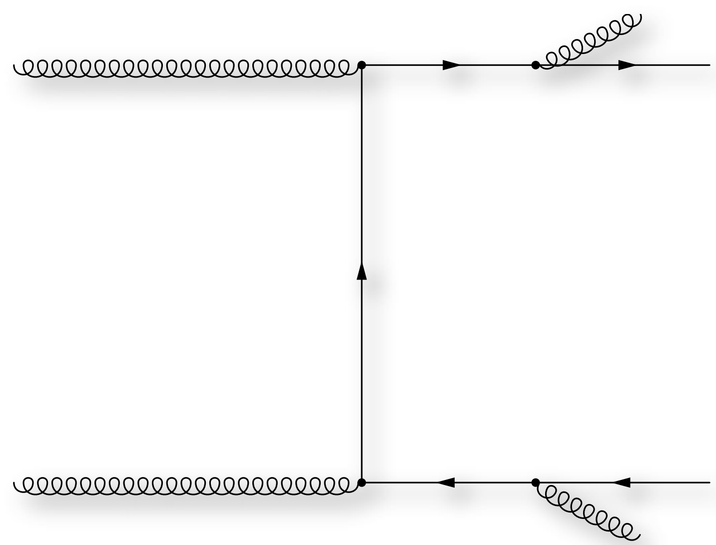
- Two types of systematic errors are evaluated
  - Rate (normalisation)
  - Shape
- QCD shape errors are the dominant systematic

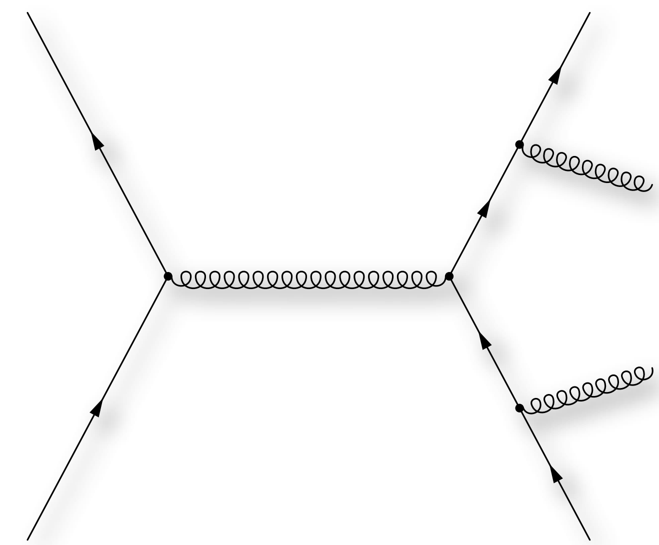
Summary of all systematic errors

Jet Energy Correction	±7% Rate Shape
PDF	± 2% Rate
SecVtx+SecVtx	7.6% Rate
SecVtx+JetProb	9.7% Rate
Luminosity	6% Rate
ISR/FSR	± 2% for VH Rate ± 3% for VBF Rate Shape for VH & VBF
Jet shape	Shape
Trigger	± 4% Rate
QCD Interpolation	Shape
QCD m_{qq} Tuning	Shape
QCD Jet Moment Tuning	Shape
$t\bar{t}$ & single-top cross-section	± 10% Rate
Diboson (WW/WZ/ZZ) cross-section	± 6% Rate
W+Jets & Z+Jets cross-section	± 50% Rate

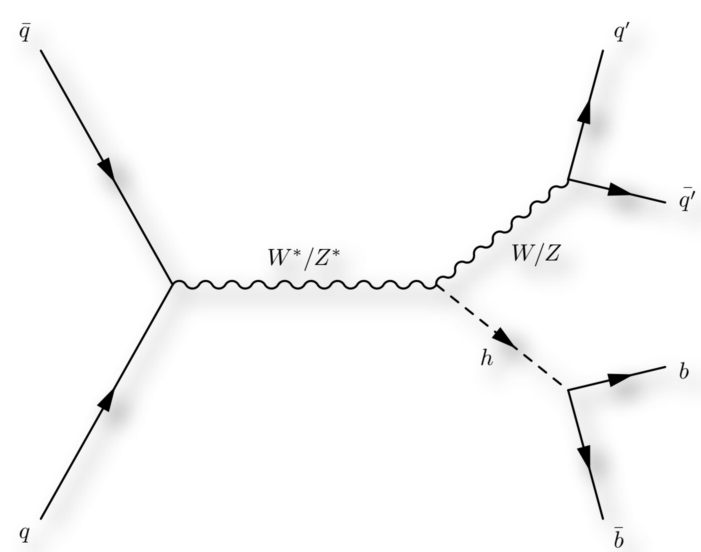
Jet Shapes - Introduction

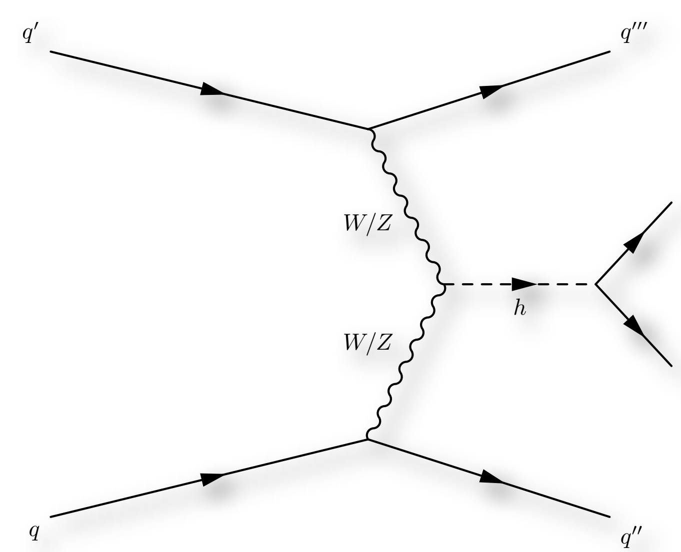
- 4-Jet QCD events are a mixture of quark & gluon jets





- Higgs signal are just quark jets





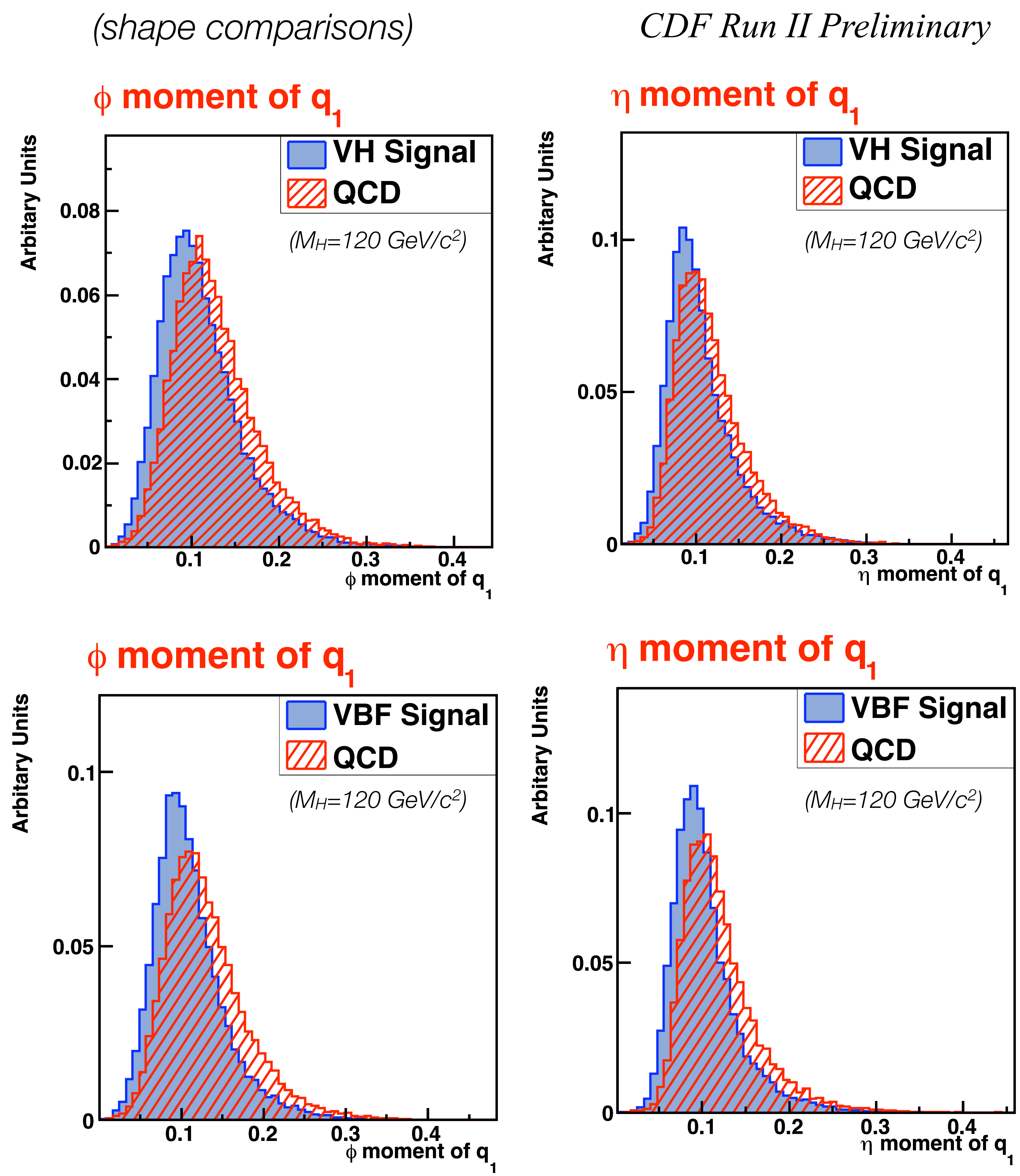
- Gluon jets are broader than quark jets. This can be used to suppress some of the QCD background.

Jet-Shapes

- Use jet-width to separate gluon & quark jets
- Dependencies upon jet-E_T, jet-η and number of reconstructed vertices are removed.

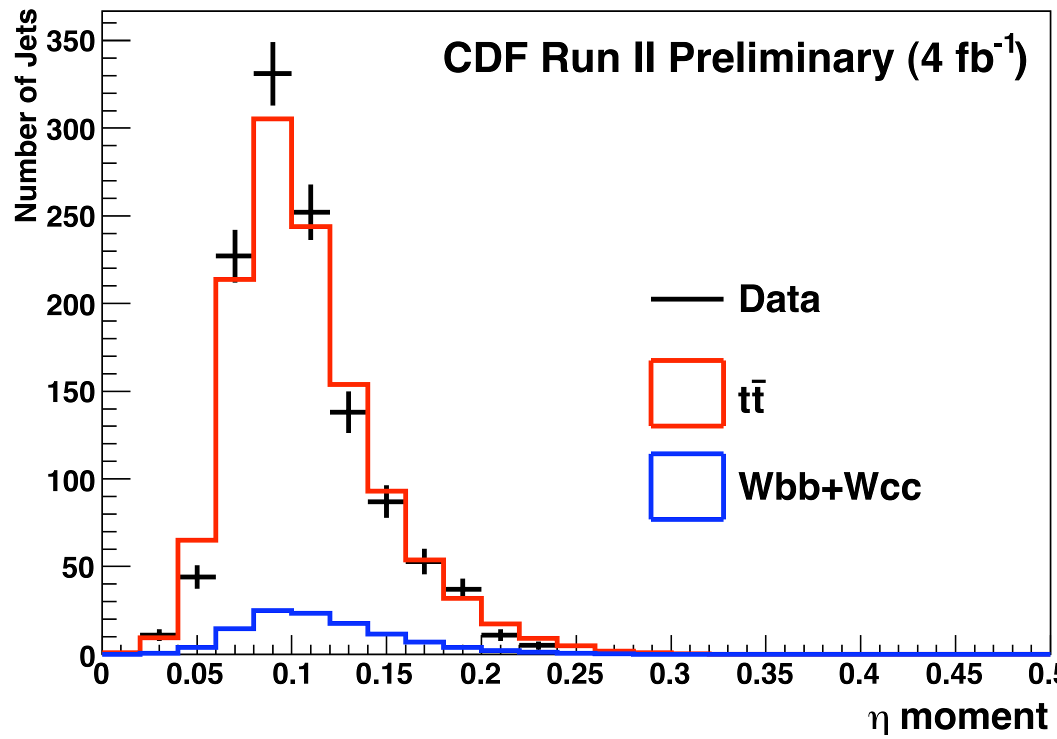
$$\langle\phi\rangle = \sqrt{\sum_{\text{towers}} \left[\frac{E_t^{\text{tower}}}{E_t^{\text{jet}}} \left(\Delta\phi(\phi_{\text{tower}}, \phi_{\text{jet}})\right)^2 \right]}$$

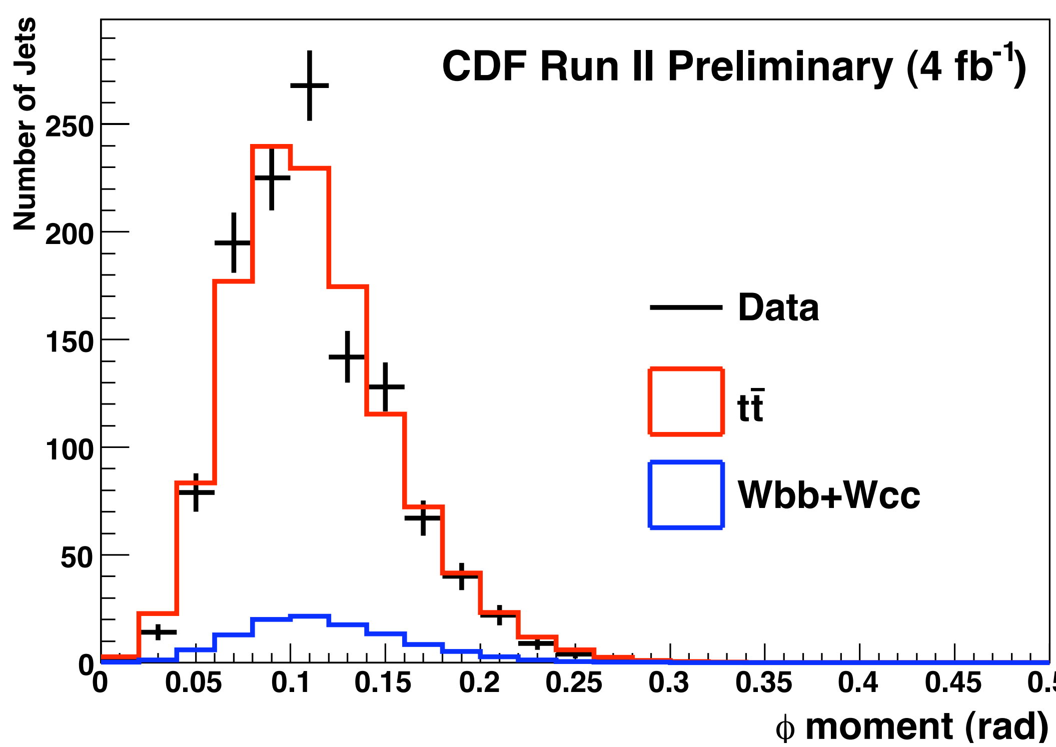
$$\langle\eta\rangle = \sqrt{\sum_{\text{towers}} \left[\frac{E_t^{\text{tower}}}{E_t^{\text{jet}}} \left(\Delta\eta(\eta_{\text{tower}}, \eta_{\text{jet}})\right)^2 \right]}$$



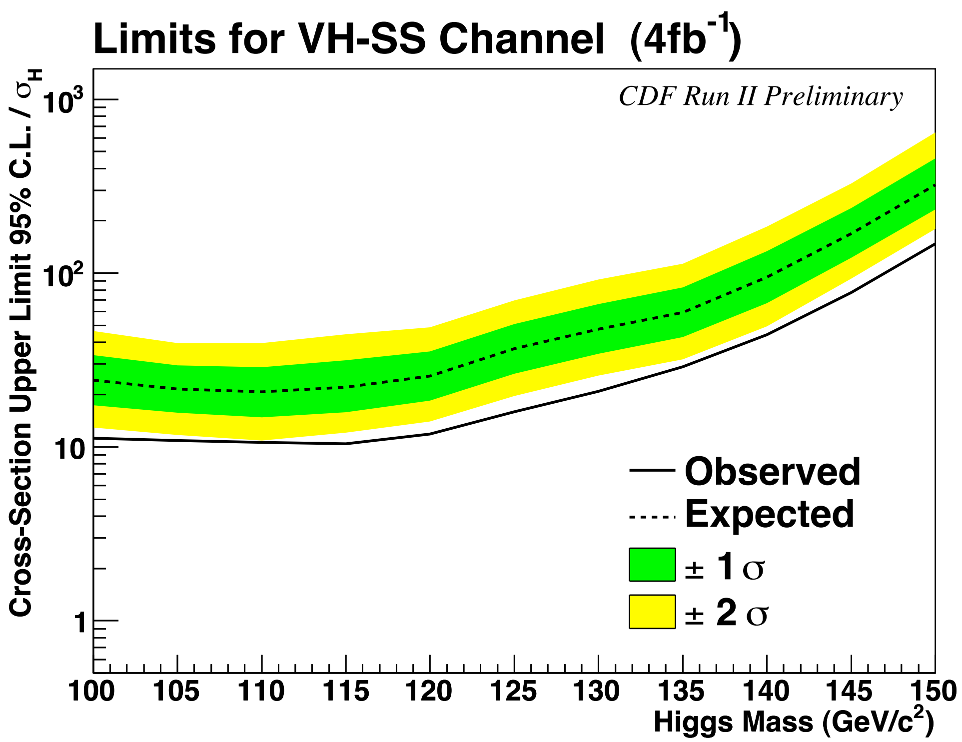
Jet Shapes : MC Simulation-Data Validation

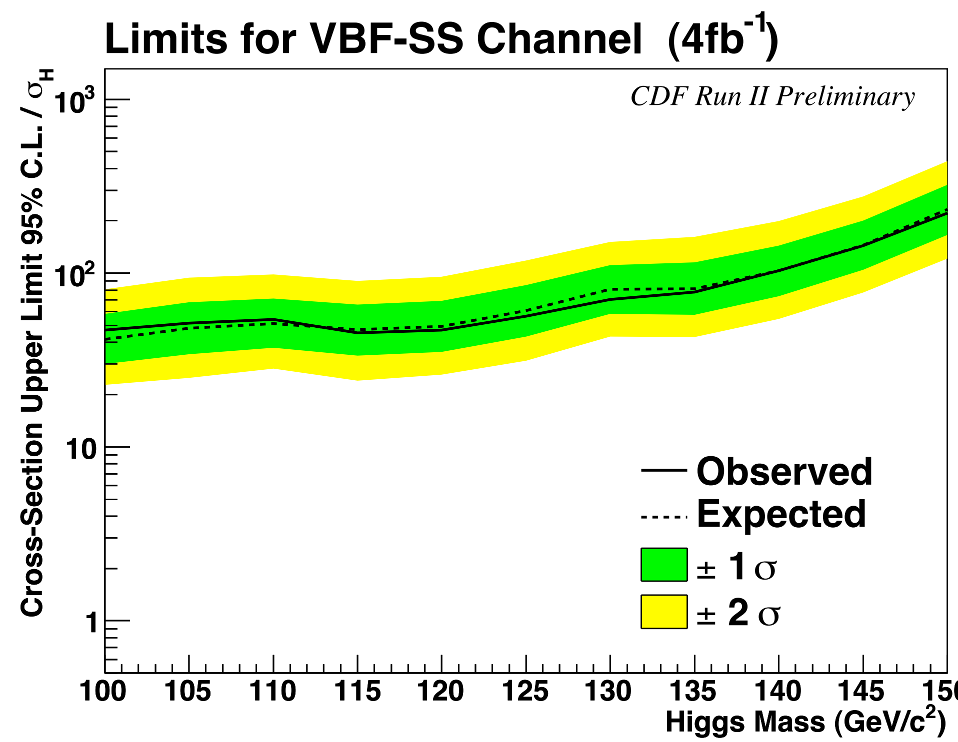
- Use events from tt→bbWW→bblνjj
    - Selected tt data events are:
      ~86% tt
      ~14% Wbb+Wcc+others
    - Non b-jets are quark jets from W decay
- After performing corrections to the MC, the two agree well

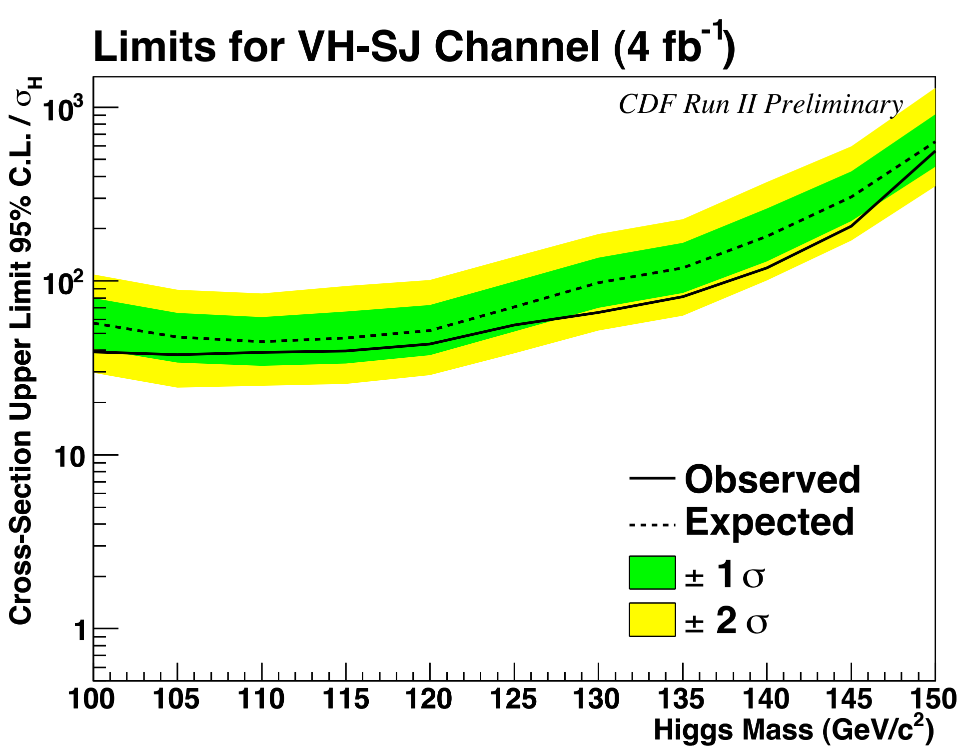


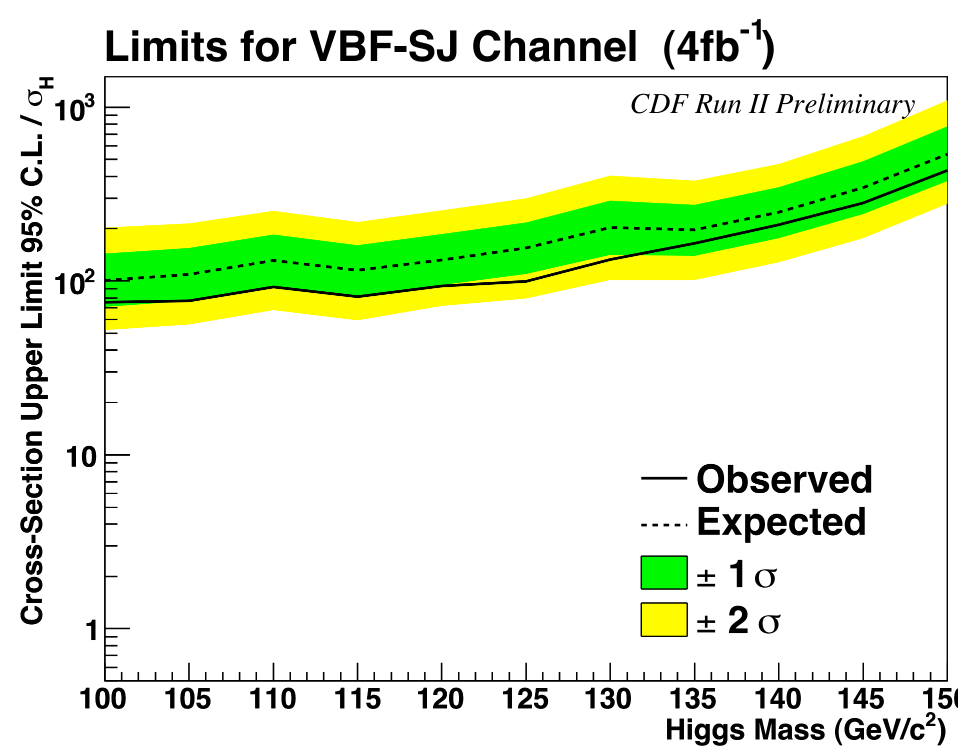


CDF All Hadronic Higgs: Limits for each analysis channel









CDF All Hadronic Higgs: Combined Limit