Searches for Diboson production in final states with heavy flavor jets at CDF

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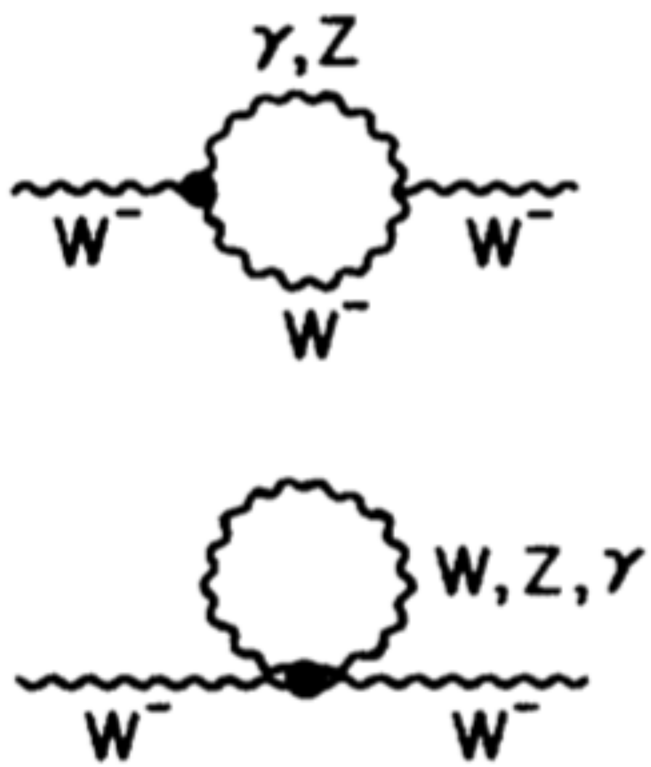
Outline

- Motivations
- Experimental Environment
- Milestones on diboson searches at CDF
- b-tagging
- Diboson searches as:
  - ✳ benchmarks for Higgs analyses
  - ✳ validation of the SM

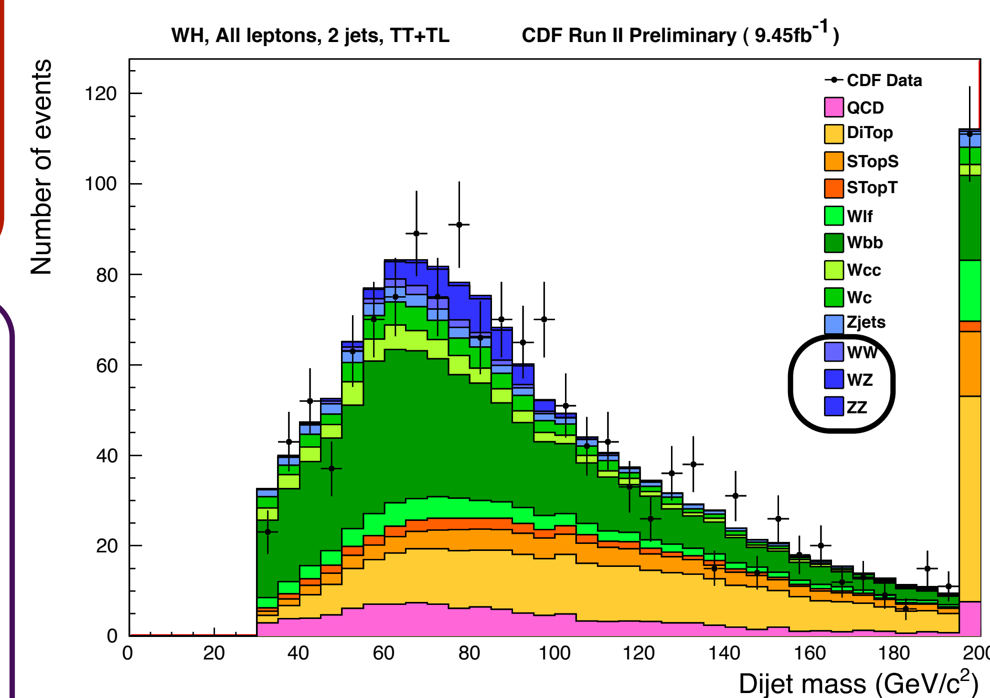
Motivation

- Important test of the EWK sector of the SM
  - ➡ deviations from the SM would hint to:
    - anomalous gauge couplings
    - new physics

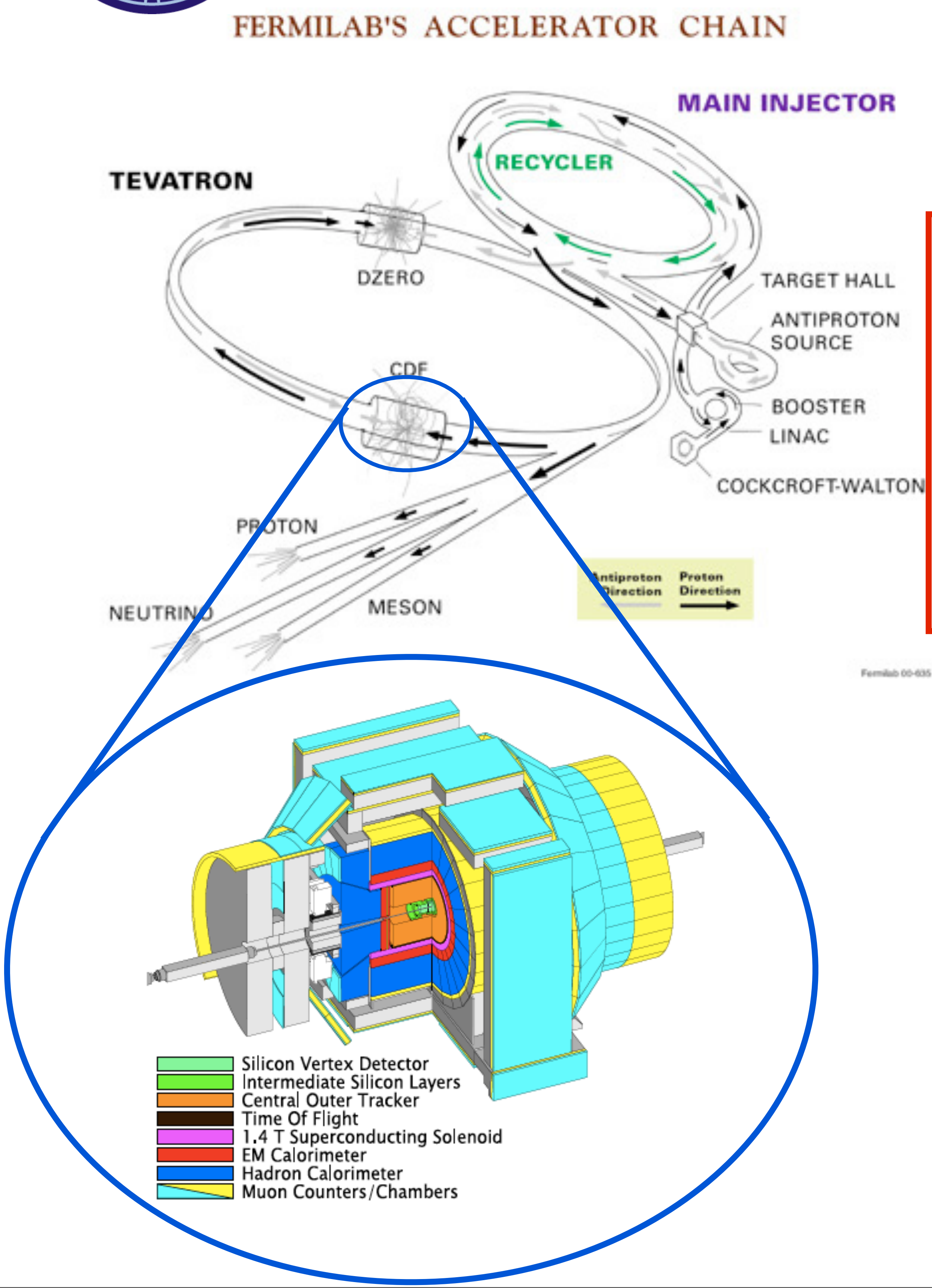


- Important background to Top, Higgs, SUSY searches

- "Known" territory to test analysis techniques used for the CDF (low mass) Higgs analyses



Experimental Environment



Tevatron

- proton-antiproton collisions at $\sqrt{s} = 1.96\ TeV$
- delivered ~12/fb
  - ~10/fb for analyzers

CDF

- Accurate tracking system with silicon
- Projective-towers calorimeters to measure e,γ, jet energy
- Muon detection system

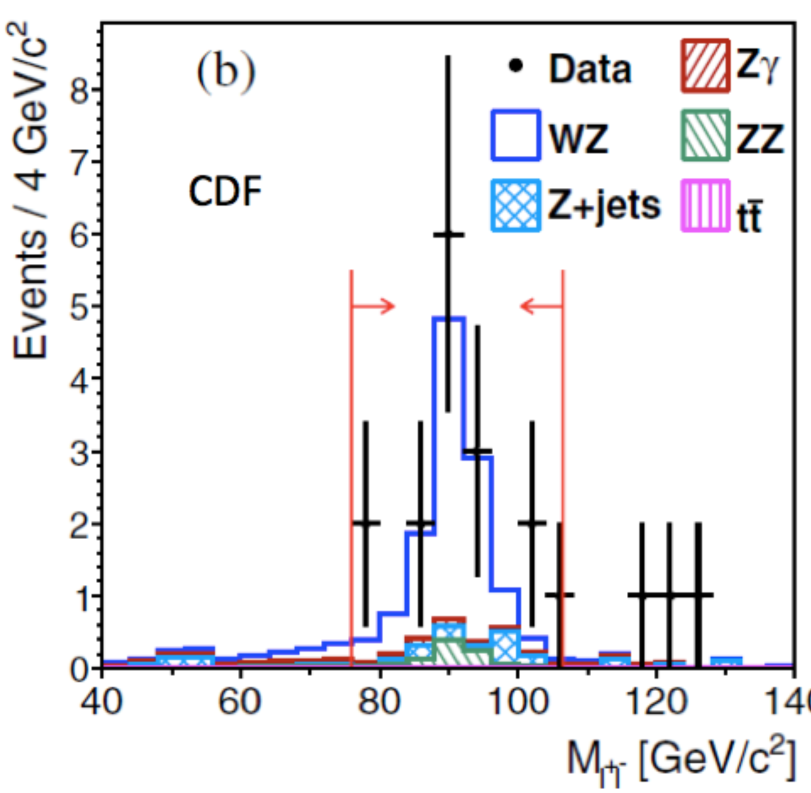
Diboson at CDF: history

- Observation in fully leptonic states
  - $WZ \to l\nu ll,\ ZZ \to llll,\ WW \to l\nu l\nu$

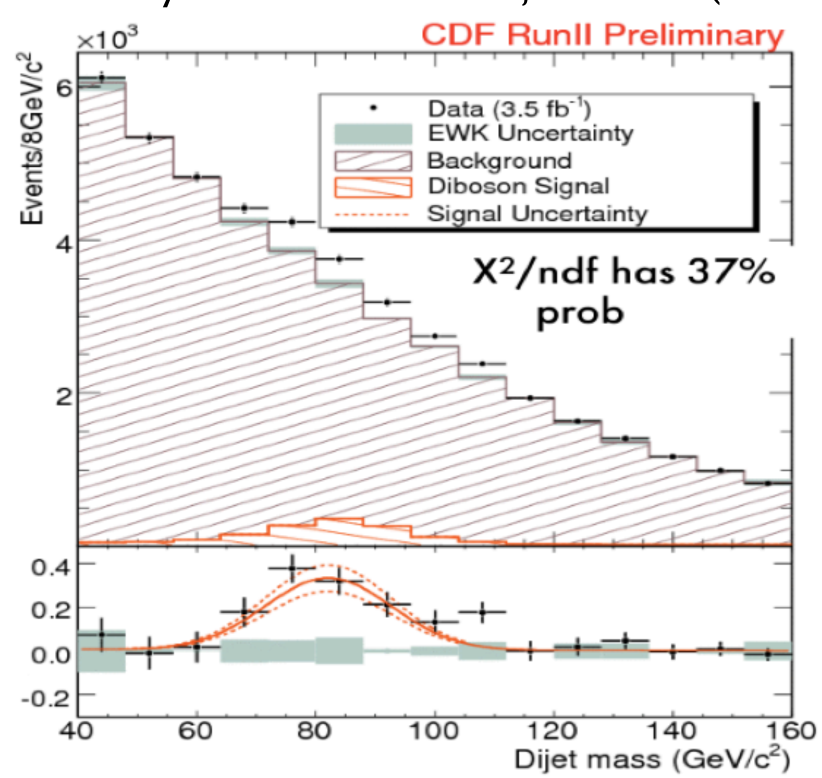
- Observation in semileptonic states
  - MET+jets, lepton+MET+jets

WZ

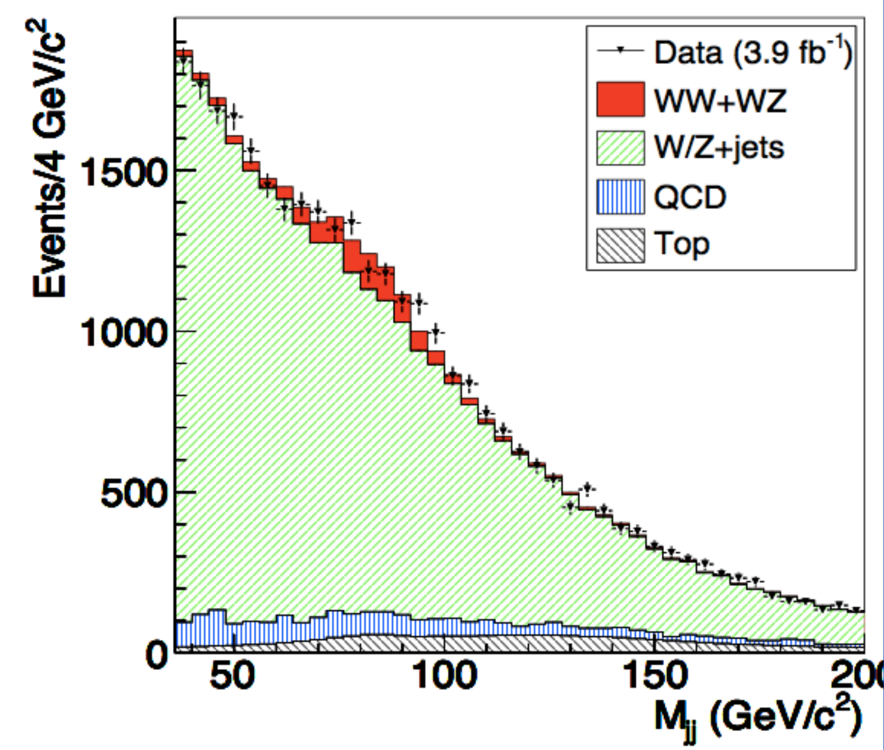
Phys. Rev. Lett. **98**, 161801 (2007)



Phys. Rev. Lett. **103**,091803 (2009)

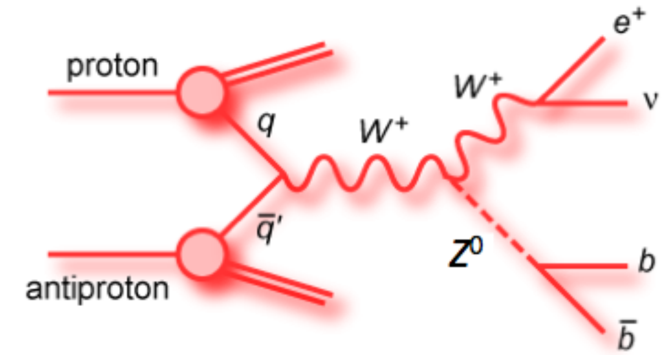


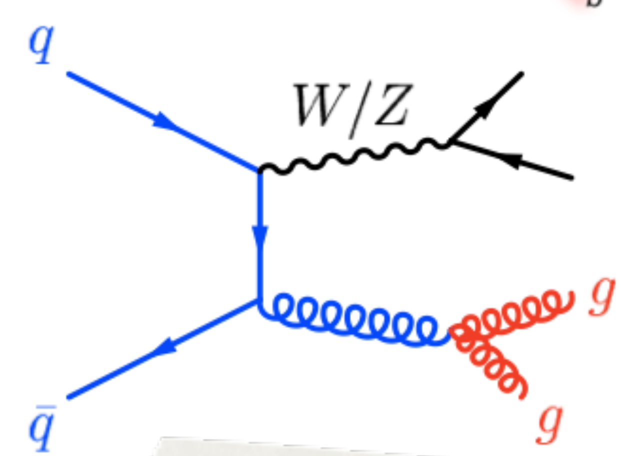
Phys. Rev. Lett. **104**, 101801 (2010)



cannot separate WW and WZ due to dijet mass resolution

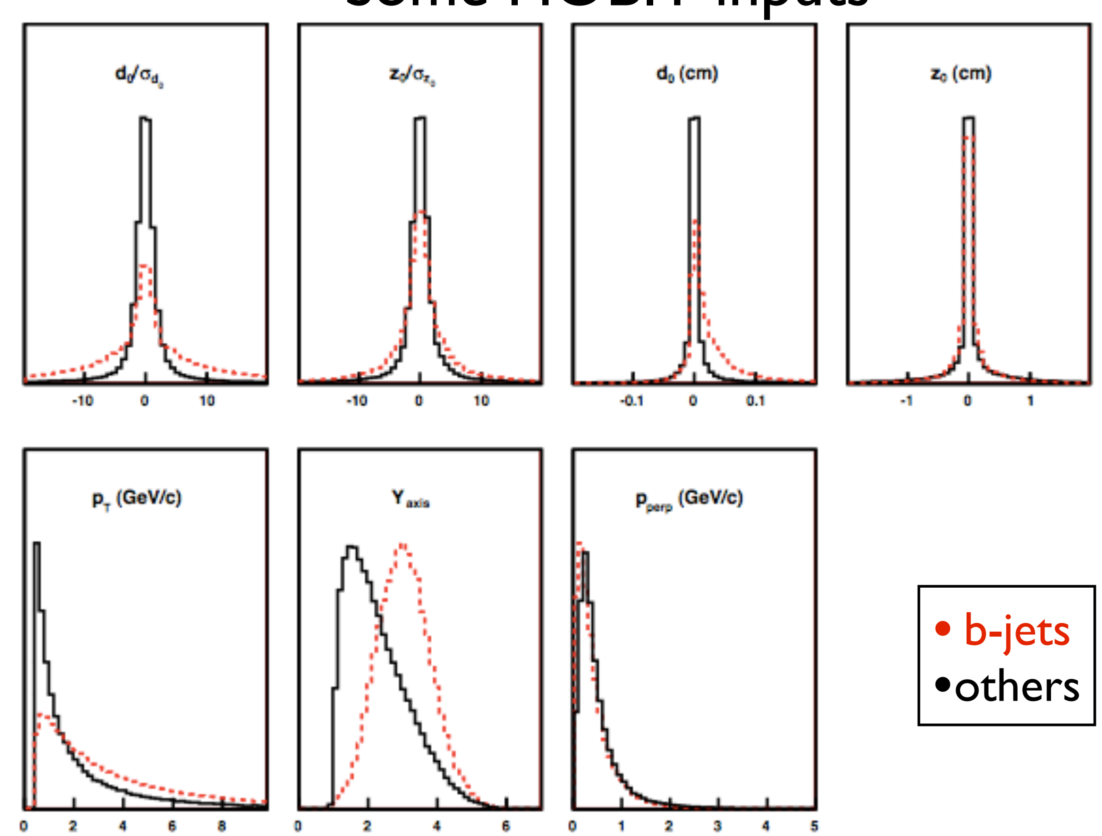
b-tagging





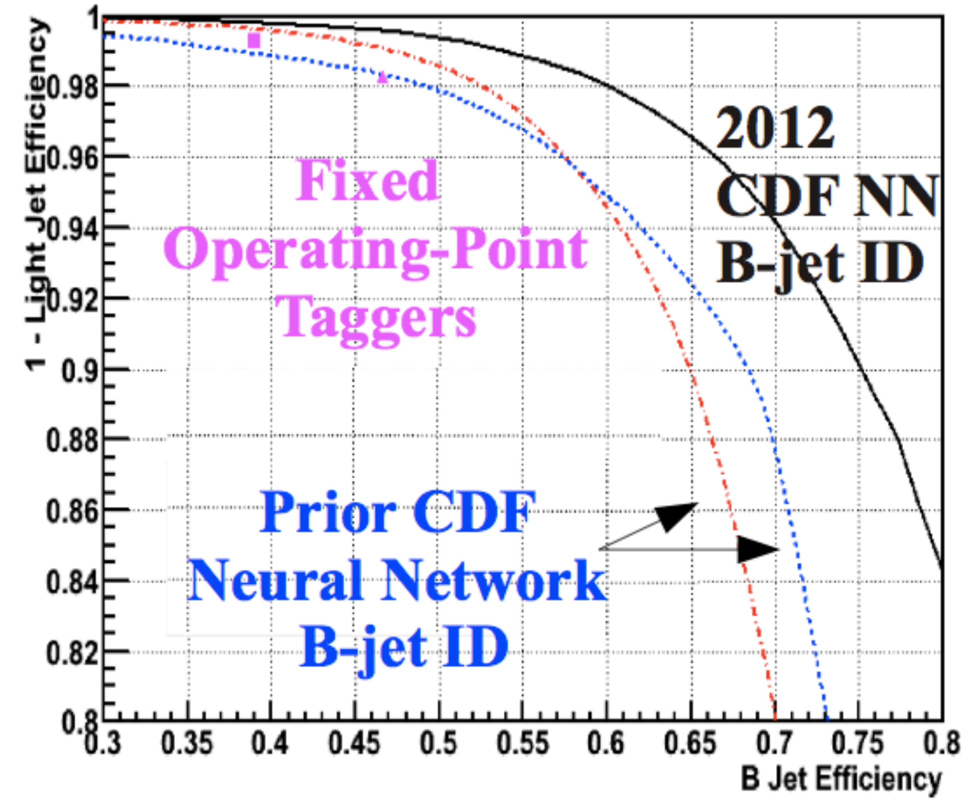
- Goal: separate jets containing B hadrons from other jets
  - key to separate WZ/ZZ from WW
- Solution: brand new multivariate tagger (HOBIT)
  - continuous output
    - operation points can be optimized upon search sensitivity
  - trained on Higgs and W+jets MC
  - built upon the strength of previous CDF taggers
    - using the most powerful inputs

Some HOBIT inputs

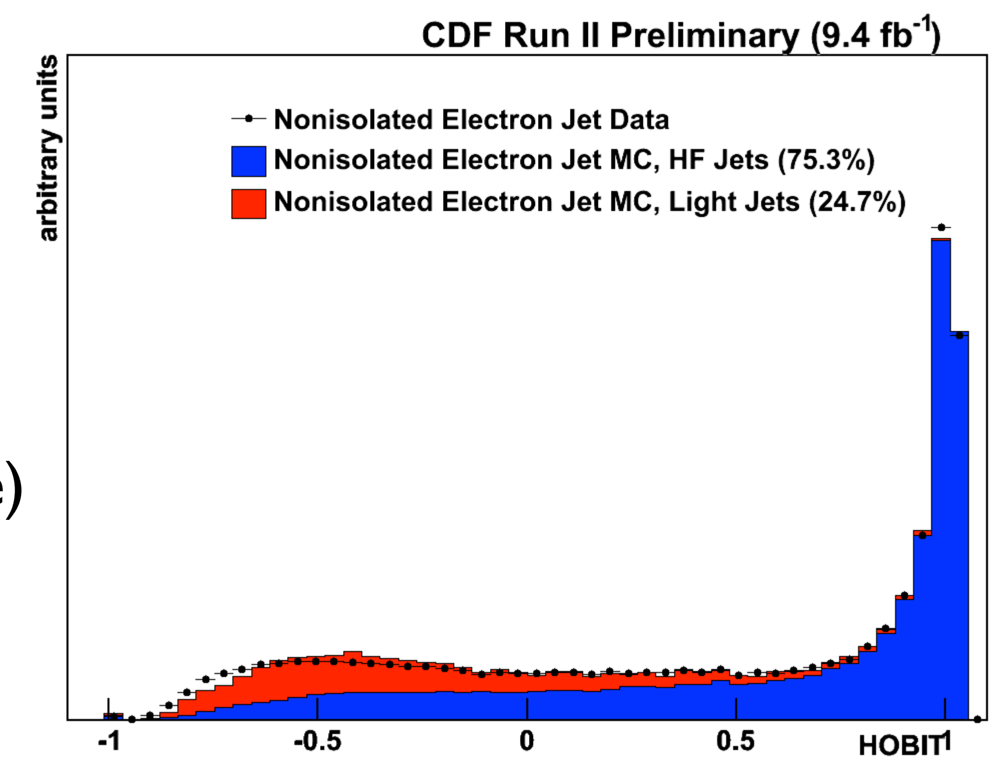


b-tagging

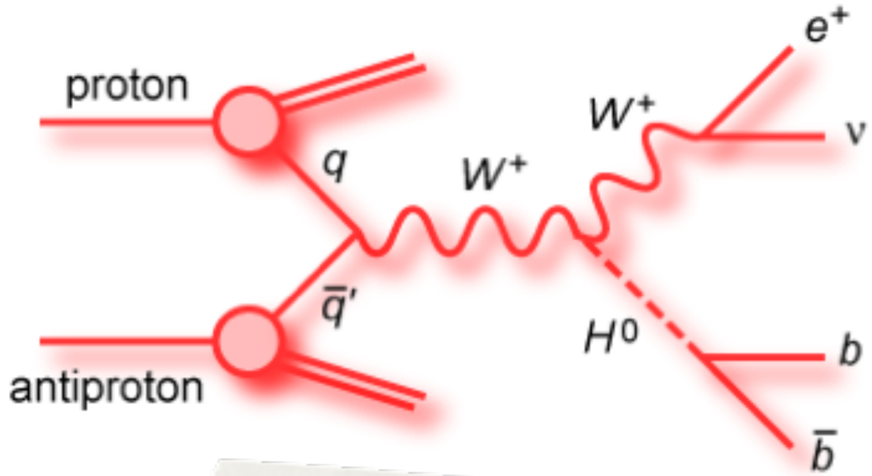
- Higher perfomances than previous CDF b-taggers
  - For identical u,d,s,g-jet accept rate (mistag rate), b-jet efficiency:
    - Tight: 38.6% → 53.6% (mistag rate: 1.4%)
    - Loose: 47.1 → 59.3% (mistag rate: 2.8%)



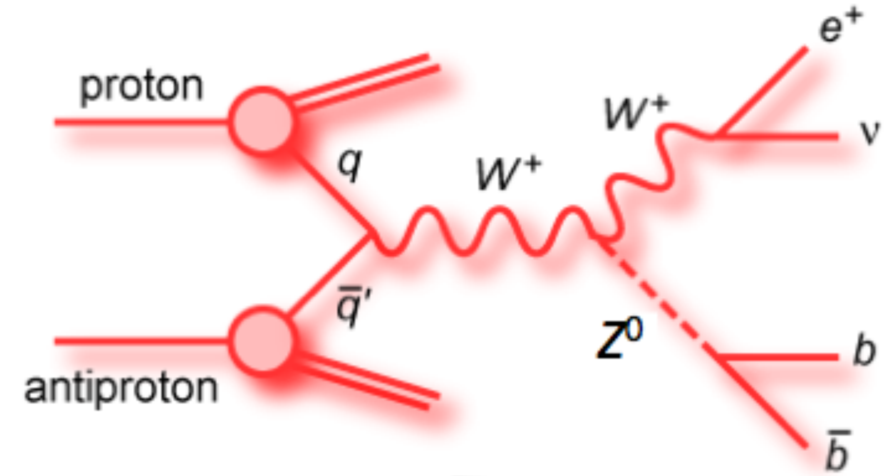
- Calibrated on two orthogonal samples
  - Results combined to improve the precision
  - Corrections for:
    - b-jet efficiency: 0.95 +/- 0.04 (tight), 0.96 +/- 0.04 (loose)
    - mistag-rate: 1.52 +/- 0.23 (tight), 1.48 +/- 0.17 (loose)



Diboson with heavy flavor jets as Higgs benchmark



Higgs (MH = 115 GeV)



Diboson

Process	σxBR (fb)
$WH->l\nu bb$	27
$ZH->llbb$	5
$ZH->\nu\nu bb$	15
Total	46

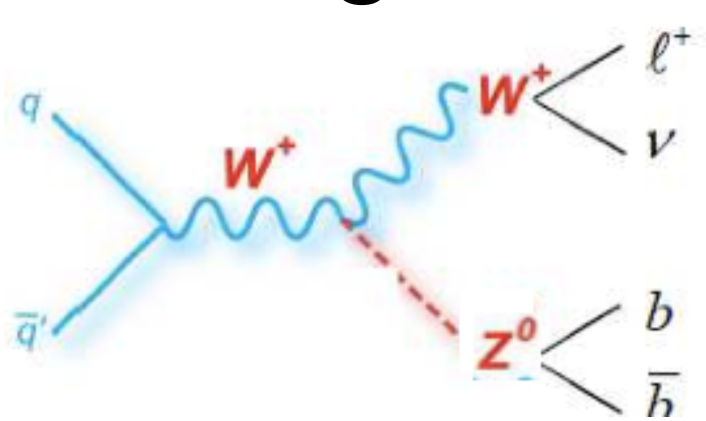
l=e,μ

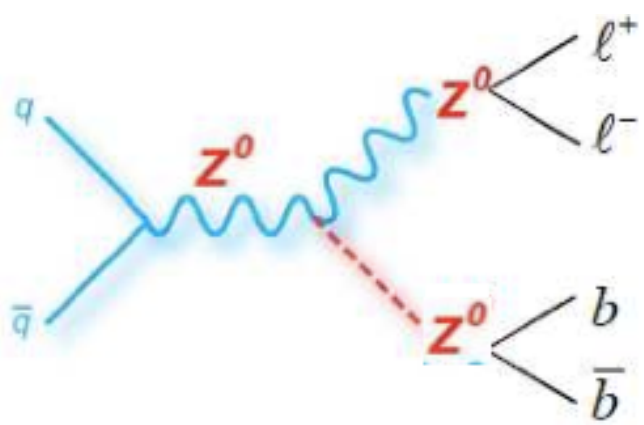
Process	σxBR (fb)
$WZ->l\nu bb$	105
$ZZ->llbb$	24
$ZZ->\nu\nu bb$	73
Total	202

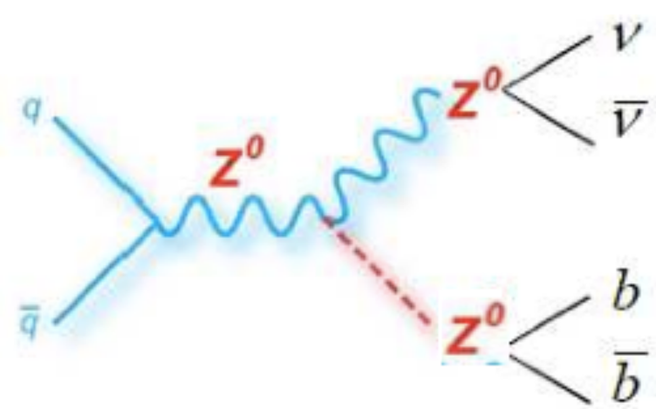
- Diboson searches share the same final states as low mass Higgs analyses
- 4-5 times larger cross-sections

Diboson with heavy flavor jets

- Replicate low-mass Higgs analyses
  - ★ 3 main final states:
    - 2,3 jets (>=1 b-tagged jet) and
      - 2 identified leptons (**“llbb”**)or
      - 1 identified lepton and large MET (**“lνbb”**) or
      - large MET (**“ννbb”**)
- Re-train multivariate discriminants to extract VZ=WZ+ZZ signal
- Some signal contribution from $W \to cs,\ Z \to cc$

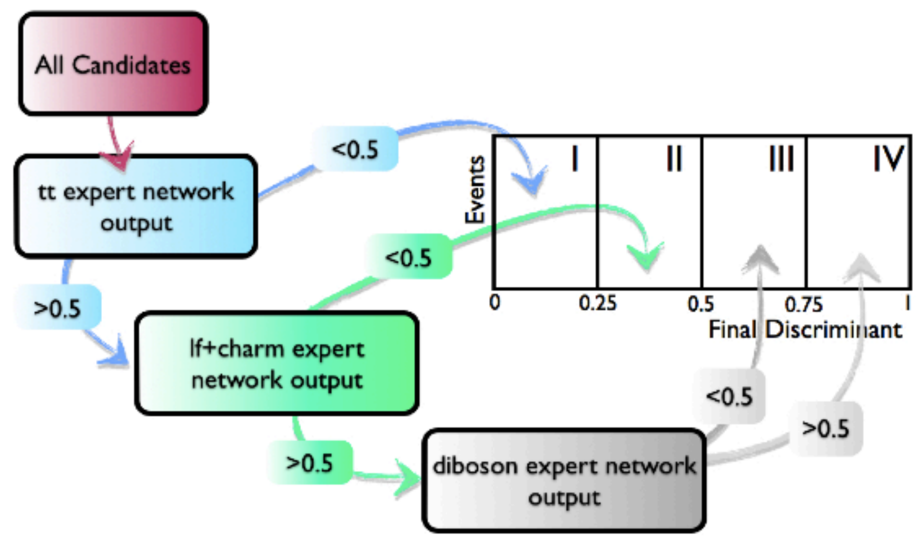


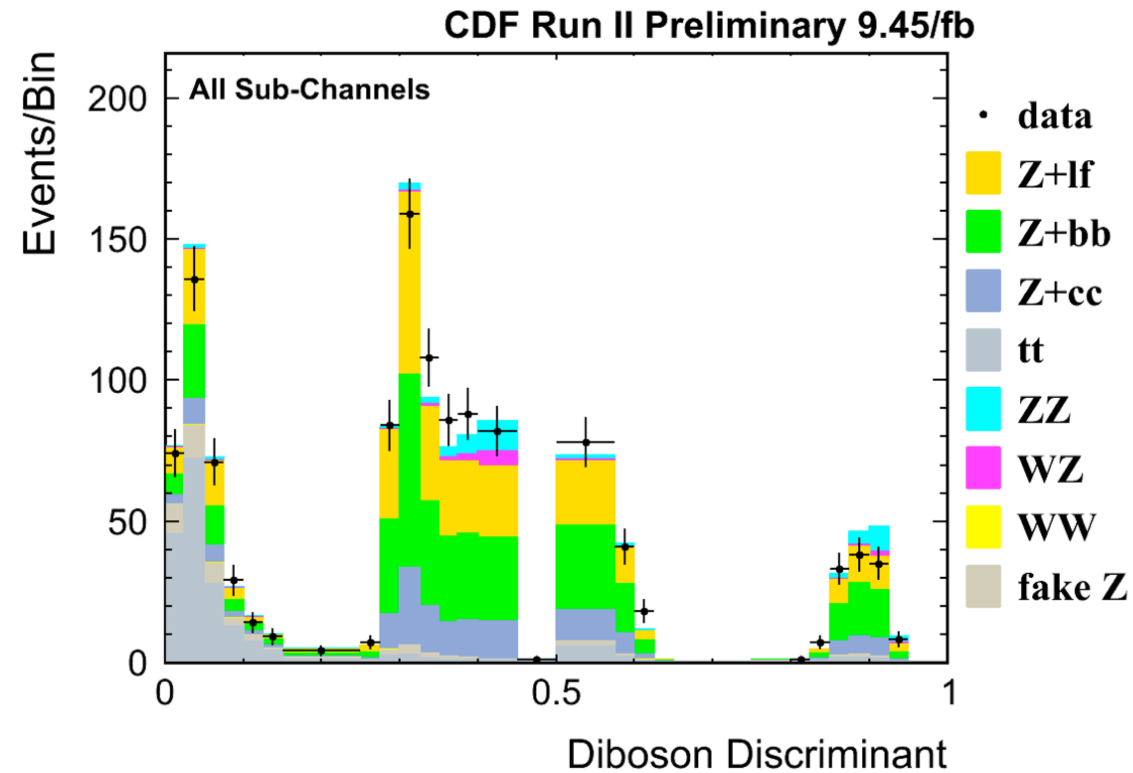




llbb

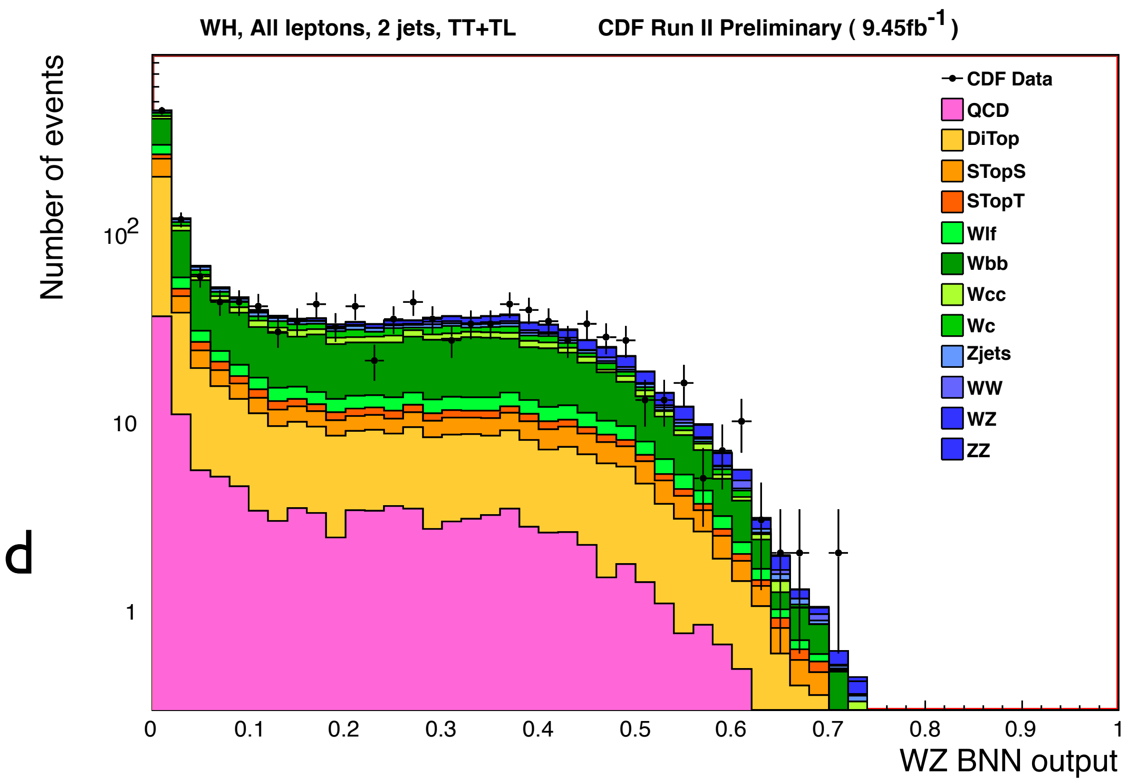
- Cleaner sample, lowest signal rate
- Selection:
  - ➡ 2 High P_T electrons/muons
    - $75 < M_{ll}/GeV < 105$
  - ➡ 2,3 large E_T jets
    - >= 1 b-tagged jet
- Analysis strategy:
  - ➡ 16 orthogonal channels examined simultaneously
    - channels divided upon lepton flavor, number of jets, heavy flavor content
  - ➡ multivariate discriminant for extracting the signal
    - full reconstruction of the final state
    - improved sensitivity compared to using dijet invariant mass

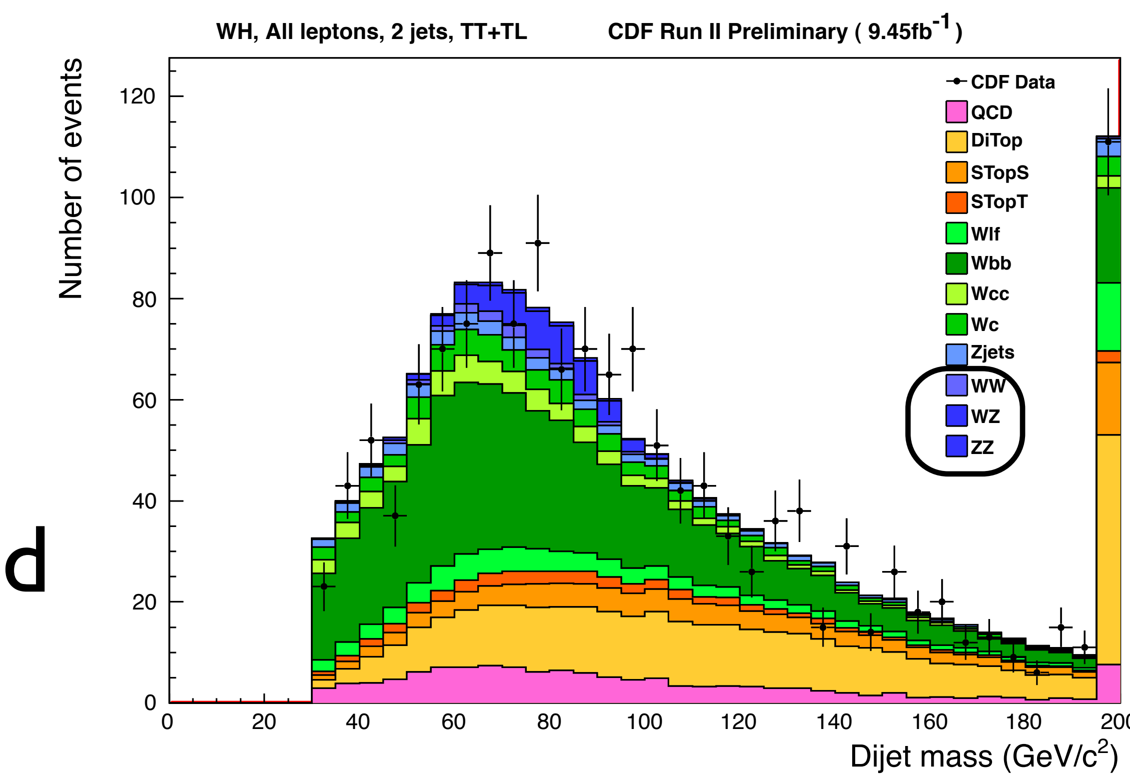




lvbb

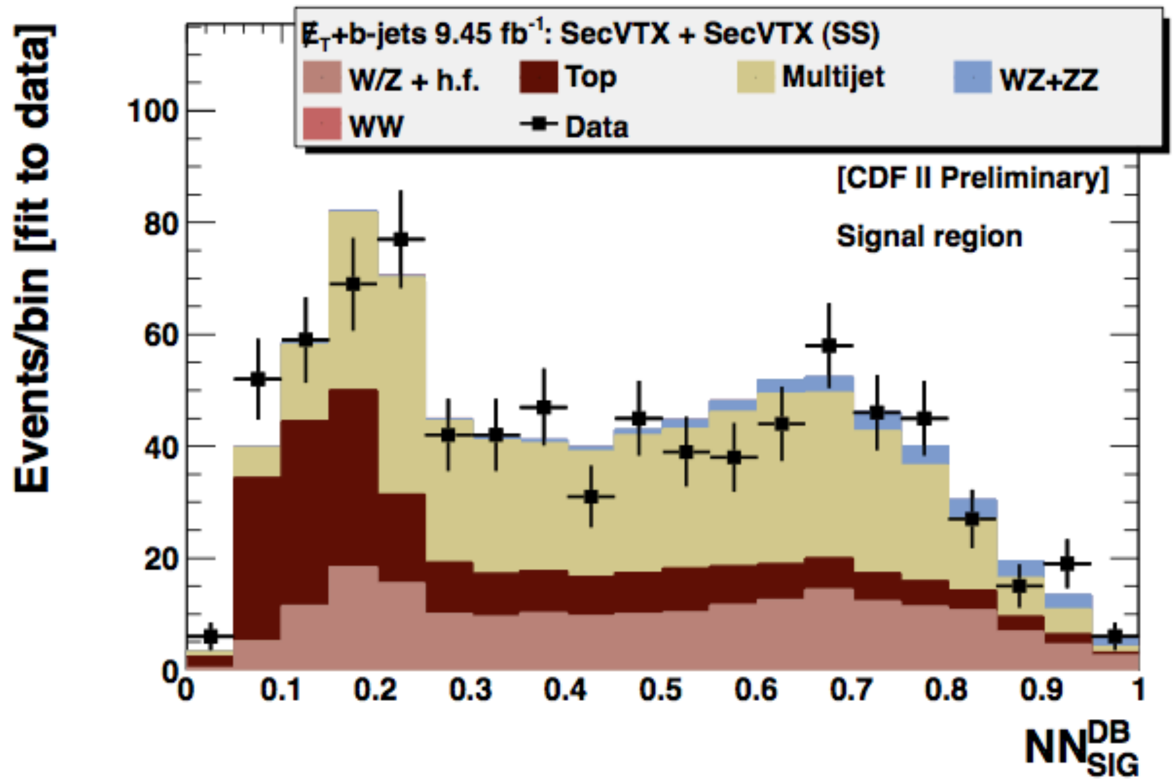
- Highest signal yield
- Selection:
  - =1 High P_T electron/muon
    - ✓ extended lepton acceptance due to a more inclusive triggers
  - large MET
  - 2,3 large E_T jets
  - multivariate techniques to reject multi-jet background
- Analysis strategy:
  - 7 orthogonal channels depending on the flavor content, number of jets
    - sensitivity improved thanks to HOBIT
  - Bayesian neural network to discriminate signal from background
    - different optimization in 2 and 3 jets channels





ννbb

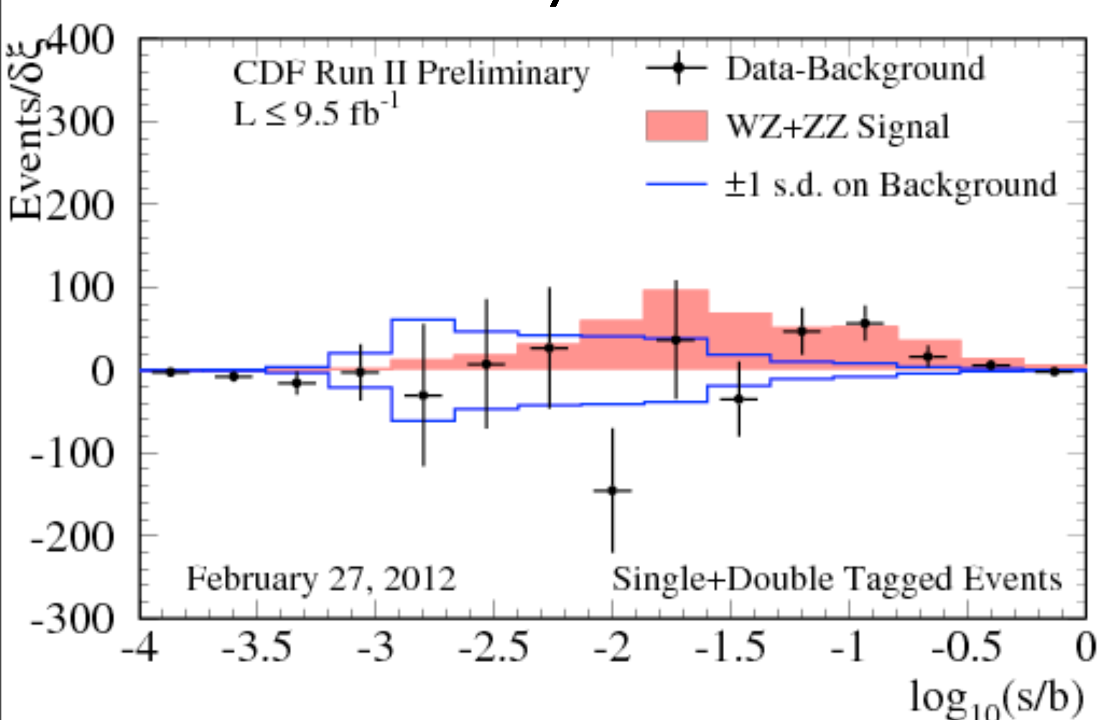
- Selection:
  - ➡ lepton veto
  - ➡ large MET
  - ➡ 2,3 large E_T jets
  - ➡ NN-based discriminant to reject the large instrumental background
  - ➡ NN to parameterize trigger efficiency curve
    - allows for more relaxed kinematic cuts

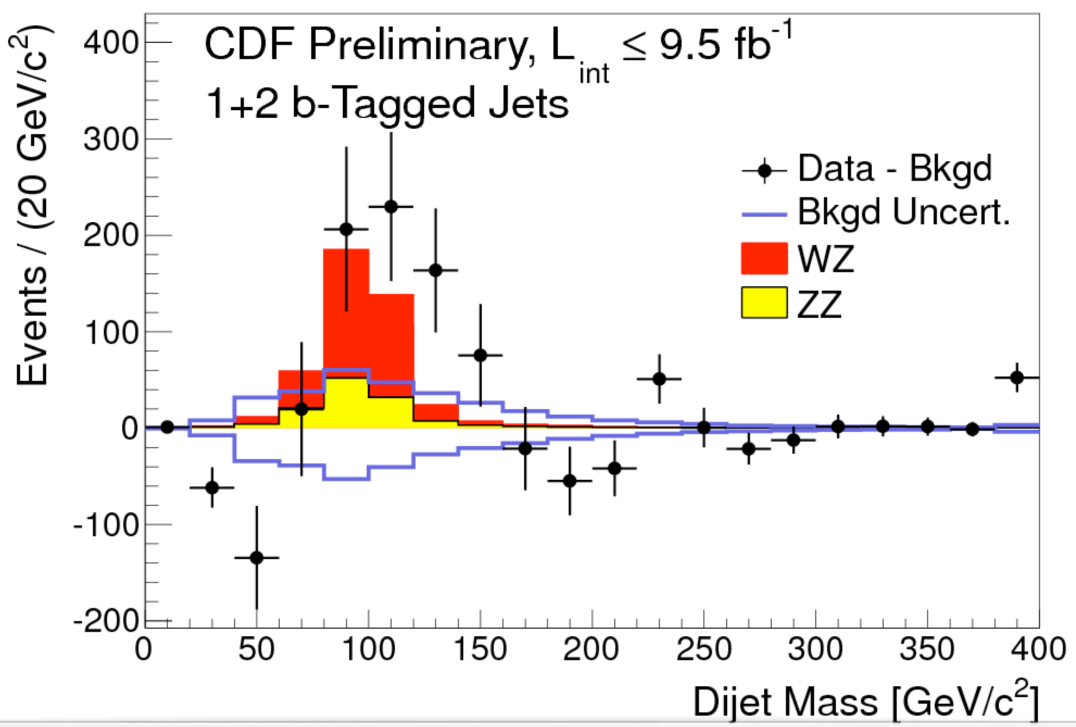


- Analysis strategy:
  - ➡ 3 orthogonal channels depending on the flavor content
    - still using "pre-HOBIT" CDF taggers
  - ➡ Final neural network to discriminate signal from background
    - trained separately in 2 and 3 jet sample

CDF combination

- Simultaneous fit on the discriminant distributions of all (26) sub-channels
- Systematic uncertainties either fully correlated or uncorrelated
  - b-tagging efficiency, jet energy scale correlated
  - multi-jet rate uncorrelated
  - uncertainties on background rates do not contribute much
    - heavily constrained across different channels



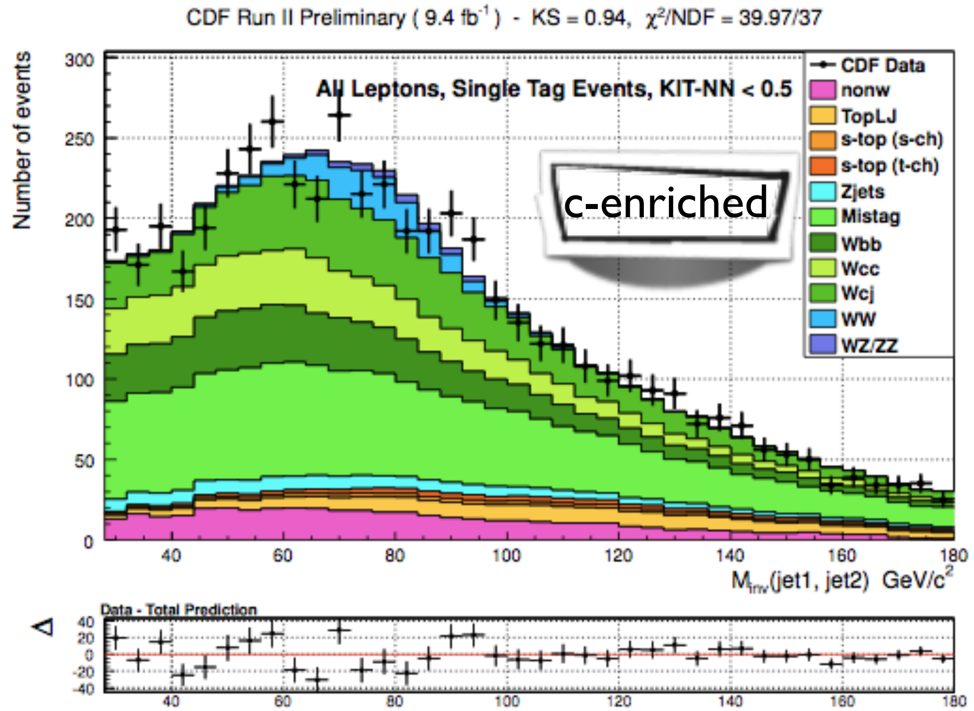


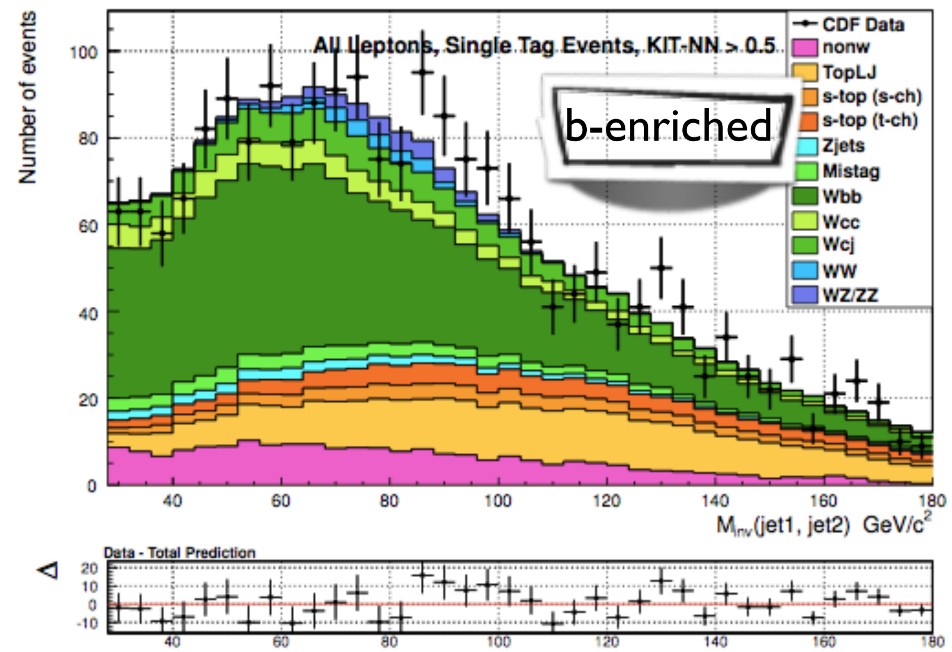
$$\sigma(VZ) = 4.08^{+1.38}_{-1.26}\ pb$$

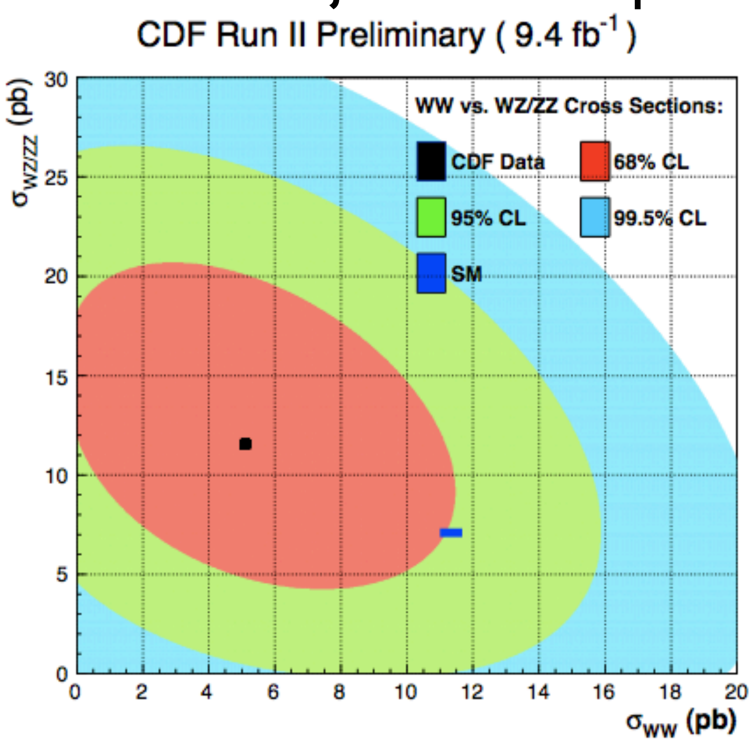
- Significance ~ 3.2 σ
- Result compatible with SM
  - $\sigma^{SM}(VZ)$ = 4.42 pb

Diboson with heavy flavor jets as test of the SM

- Optimized analysis to isolate WZ/ZZ from WW
- Uses the same tools and signature of lνbb analysis
  - ➡ multivariate techniques to reject multi-jet background
  - ➡ at least 1 b-tagged jet
- 2-D fit to extract σ(WZ/ZZ), σ(WW)
  1. dijet invariant mass
  2. NN-based jet flavor separator







$$\sigma(WW) = 5.10^{+3.97}_{-3.63}\ pb \qquad (\sigma^{SM} = 11.34\ pb)$$

$$\sigma(WZ+ZZ) = 7.25^{+3.67}_{-3.40}\ pb\ (\sigma^{SM} = 4.42\ pb)$$

Consistent with SM

Summary

✓ CDF is sensitive to diboson in final states with heavy-flavor jets

- paving the way for (low mass) Higgs analyses
- but also as a sanity check of the SM / search for new physics

✓ $\sigma(VZ) = 4.08^{+1.38}_{-1.26}\ pb$

- compatible with SM expectations

✓ 3.2 σ evidence for WZ+ZZ

- assuming SM σ(WZ)/σ(ZZ)

More details at http://www-cdf.fnal.gov/physics/new/hdg/Results.html

- backup

llbb: NN for jet corrections

Inputs to the NN jet-energy correction algorithm
lead jet E_T
lead jet η
$\Delta\phi(\vec{\not{E}}_T,$ lead jet)
Z projection onto the lead jet
$\vec{\not{E}}_T$ projection onto the lead jet
second jet E_T
second jet η
$\Delta\phi(\vec{\not{E}}_T,$ second jet)
Z projection onto the second jet
$\vec{\not{E}}_T$ projection onto the second jet
$\not{E}_T$
$\Delta\phi$(lead jet, second jet)
number of jets

TABLE I: Inputs to the jet-energy correction neural network.

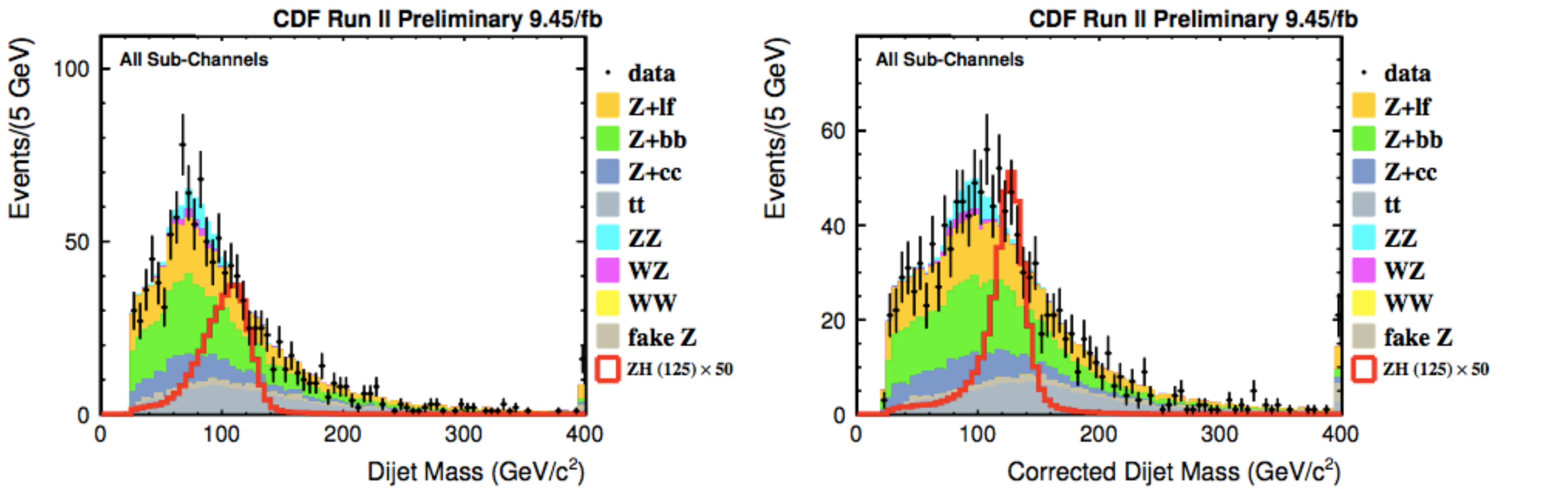
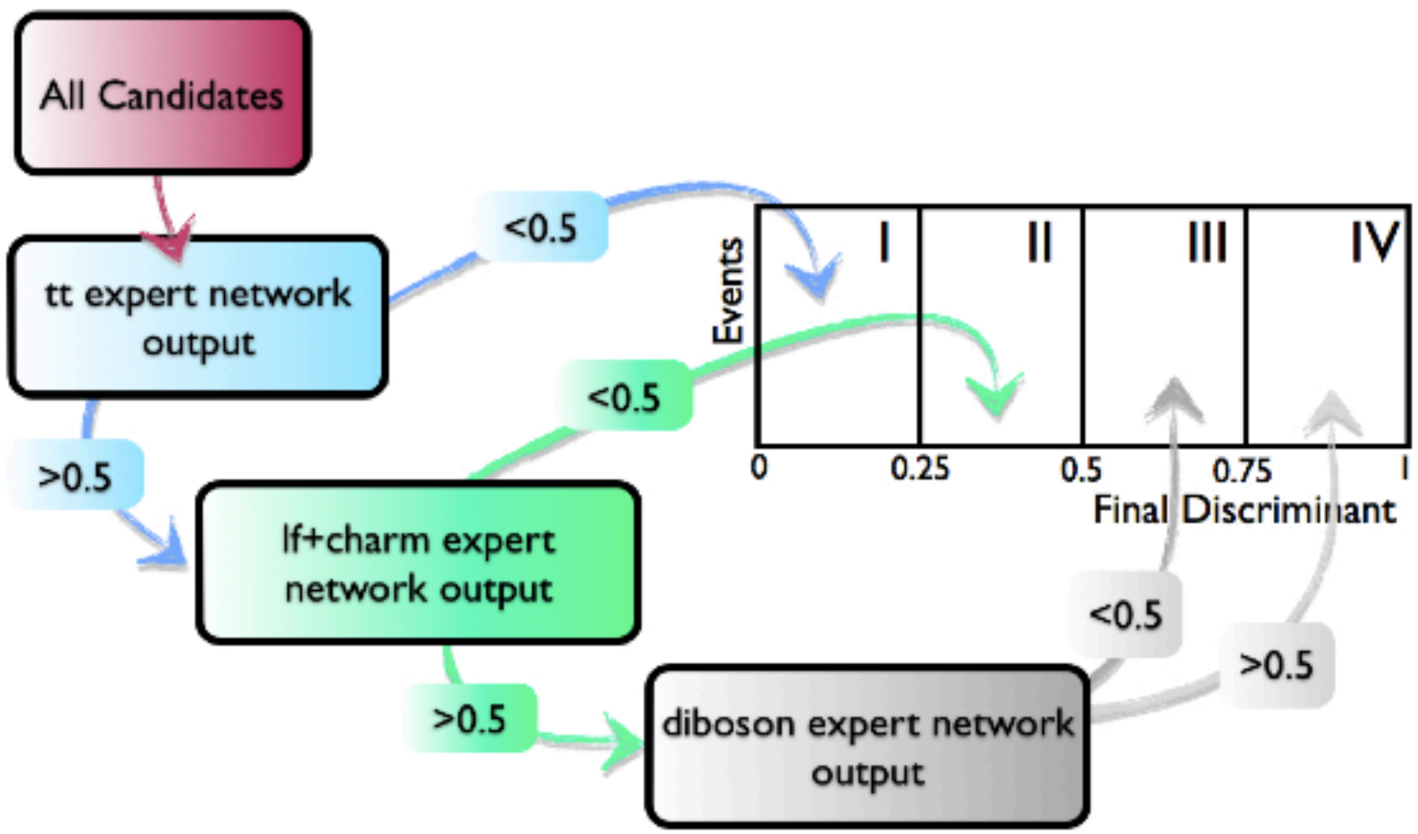


FIG. 1: The dijet invariant mass distribution for all b-tagged candidates before (left) and after (right) NN correction. The bin at 400 GeV/c^2 contains the histogram overflow.

llbb: Final discriminant

Inputs to the expert neural networks		
$t\bar{t}$ Expert	$Z + l.f./Z + c\bar{c}$ Expert	WZ/ZZ Expert
$\not{E}_T$	NN Corrected M_{jj}	NN Corrected M_{jj}
$\vec{\not{E}}_T$ projection onto the all jets	2nd jet E_T	2nd jet E_T
E_T of Z+all jets	H_T [23]	$\cos(\theta^*)$ [24]
$\vec{\not{E}}_T$ projection onto the lead jet	$\Delta R(Z,$ jet 1)	$\Delta R(Z,$ jet 1)
E_T of Z+H candidates	combined mass of Z and all jets	$\Delta R(Z, H)$
$\vec{\not{E}}_T$ projection onto the 2nd jet	combined mass of Z and H candidates	H_T
$\Delta R(Z,$ all jets) [22]	ΔR(lepton 1, lepton 2)	Z projection onto all jets
NN Corrected M_{jj}	Z projection onto all jets	ΔR(lepton 1, lepton 2)
	Z p_T	Z p_T
	$\vec{\not{E}}_T$ projection onto all jets	
	jet 1 E_T	

TABLE II: Inputs to the expert neural networks, listed in descending order of importance.



llbb: modeling of the final discriminant - pretag

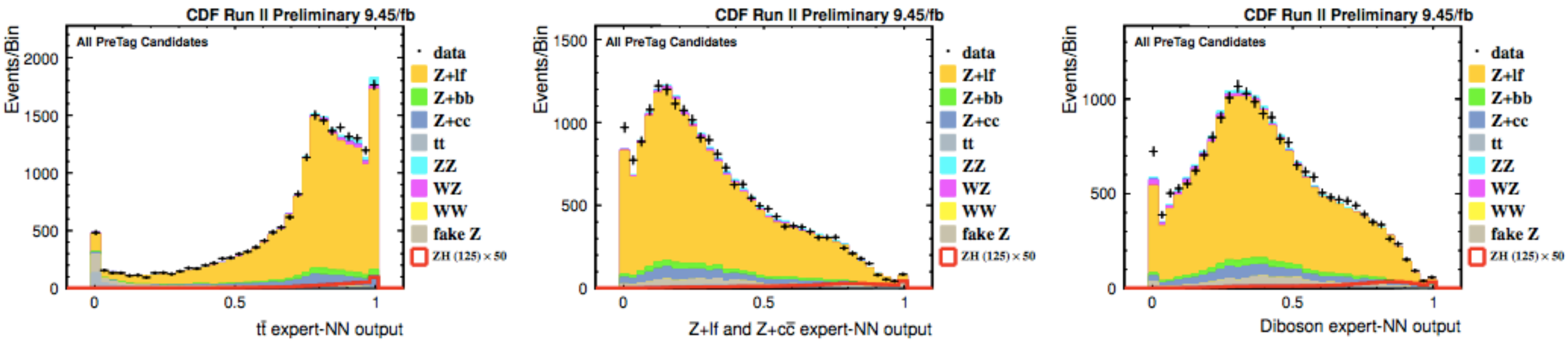


FIG. 3: Output of the expert discriminants in the PreTag (defined in text) sample. The bin at zero (one) contains the histogram underflow (overflow).

llbb: event yields

Process	Two Jets TT	Two Jets TL	Two Jets Tx	Two Jets LL	Three Jets TT	Three Jets TL	Three Jets Tx	Three Jets LL
$t\bar{t}$	20.1 ± 2.8	21.5 ± 2.8	36.1 ± 4.7	6.1 ± 0.8	7.5 ± 1.2	9.3 ± 1.4	13.5 ± 1.9	2.9 ± 0.5
Diboson	4.7 ± 0.6	6.5 ± 0.9	19.6 ± 1.8	3.9 ± 0.4	0.7 ± 0.1	1.3 ± 0.2	3.0 ± 0.4	1.0 ± 0.1
$Z + b\bar{b}$	19.1 ± 8.0	26.8 ± 11.3	81.5 ± 34.2	10.2 ± 4.4	4.5 ± 2.0	6.5 ± 2.9	14.1 ± 6.2	2.5 ± 1.1
$Z + c\bar{c}$	1.5 ± 0.6	6.9 ± 2.9	39.0 ± 16.8	7.3 ± 3.1	0.5 ± 0.2	1.7 ± 0.8	7.4 ± 3.3	2.4 ± 1.1
$Z + l.f.$	0.7 ± 0.3	8.3 ± 2.0	124.9 ± 27.5	27.5 ± 6.6	0.3 ± 0.1	2.8 ± 0.8	20.3 ± 5.5	8.1 ± 2.3
mis-ID Z	0.1 ± 0.0	5.1 ± 2.6	7.7 ± 3.9	1.1 ± 0.6	0.0 ± 0.0	2.1 ± 1.0	5.2 ± 2.6	3.0 ± 1.5
Total Bkg.	46.2 ± 8.6	75.2 ± 12.4	309.2 ± 47.4	56.1 ± 8.6	13.6 ± 2.3	23.6 ± 3.5	63.5 ± 9.5	19.9 ± 3.2
ZH(120) GeV/c^2	1.1 ± 0.1	1.1 ± 0.1	1.6 ± 0.2	0.3 ± 0.03	0.2 ± 0.04	0.2 ± 0.04	0.3 ± 0.1	0.1 ± 0.01
Data	45	83	352	66	16	23	59	23

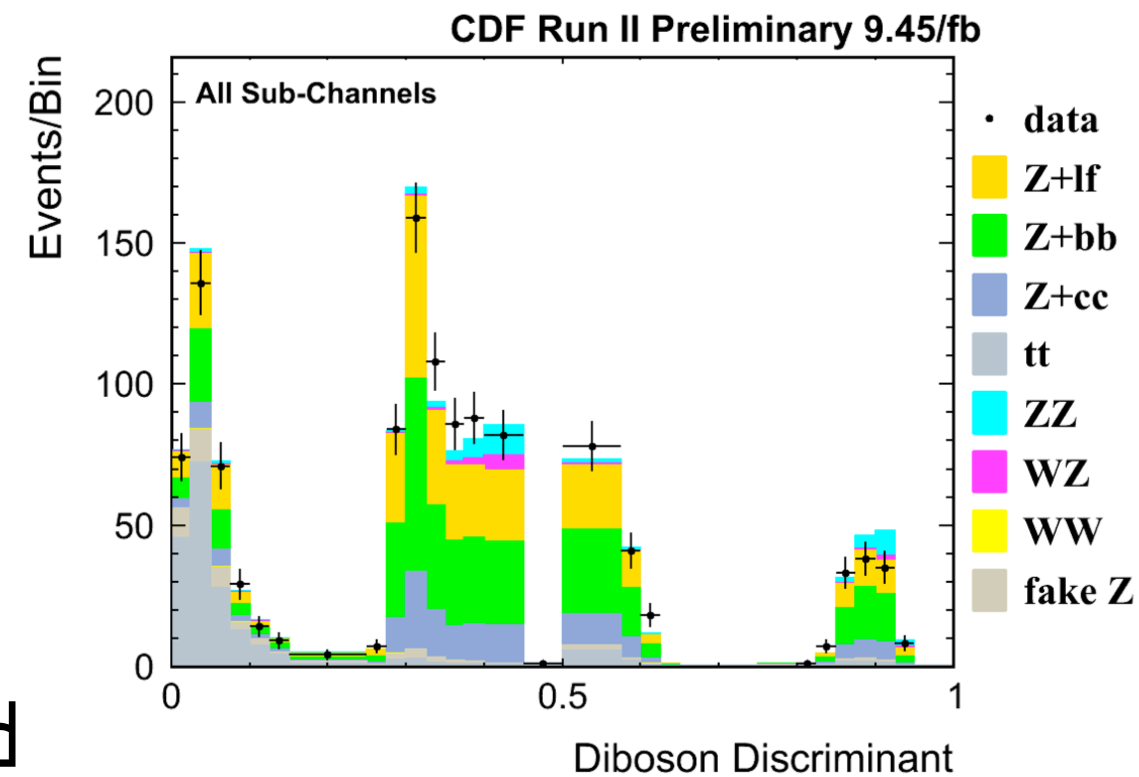
TABLE IV: Comparison of the expected mean event totals for background and ZH signal with the observed number of data events for the $ZH \to e^+e^- + b\bar{b}$ channels. The totals are for full event selection, and uncertainties are systematic.

Process	Two Jets TT	Two Jets TL	Two Jets Tx	Two Jets LL	Three Jets TT	Three Jets TL	Three Jets Tx	Three Jets LL
$t\bar{t}$	20.8 ± 3.1	22.1 ± 3.1	30.4 ± 3.9	5.7 ± 0.8	6.4 ± 1.2	7.4 ± 1.2	10.4 ± 1.5	2.4 ± 0.4
Diboson	3.8 ± 0.6	5.1 ± 0.7	15.1 ± 1.5	3.0 ± 0.4	0.6 ± 0.1	0.9 ± 0.2	2.3 ± 0.3	0.8 ± 0.1
$Z + b\bar{b}$	15.0 ± 6.3	21.0 ± 8.8	64.4 ± 27.0	7.7 ± 3.2	3.5 ± 1.5	5.2 ± 2.4	11.3 ± 5.0	2.3 ± 1.1
$Z + c\bar{c}$	1.0 ± 0.4	4.6 ± 2.0	30.0 ± 12.6	6.3 ± 2.6	0.4 ± 0.2	1.5 ± 0.7	5.8 ± 2.5	1.9 ± 0.8
$Z + l.f.$	0.6 ± 0.3	6.2 ± 1.5	91.7 ± 20.2	19.4 ± 4.5	0.3 ± 0.1	2.2 ± 0.6	15.3 ± 4.0	6.3 ± 1.7
mis-ID Z	1.0 ± 0.1	0.0 ± 0.0	10.0 ± 0.5	1.0 ± 0.1	1.0 ± 0.1	8.0 ± 0.4	8.0 ± 0.4	5.0 ± 0.3
Total Bkg.	42.3 ± 7.1	58.9 ± 9.7	241.5 ± 36.3	43.0 ± 6.2	12.2 ± 1.9	25.2 ± 2.8	53.0 ± 7.0	18.8 ± 2.2
ZH(120) GeV/c^2	0.9 ± 0.1	0.9 ± 0.1	1.4 ± 0.1	0.3 ± 0.03	0.2 ± 0.03	0.2 ± 0.04	0.2 ± 0.05	0.1 ± 0.01
Data	41	69	273	51	15	24	46	25

TABLE V: Comparison of the expected mean event totals for background and ZH signal with the observed number of data events for the $ZH \to \mu^+\mu^- + b\bar{b}$ channels. The totals are for full event selection, and uncertainties are systematic.

llbb

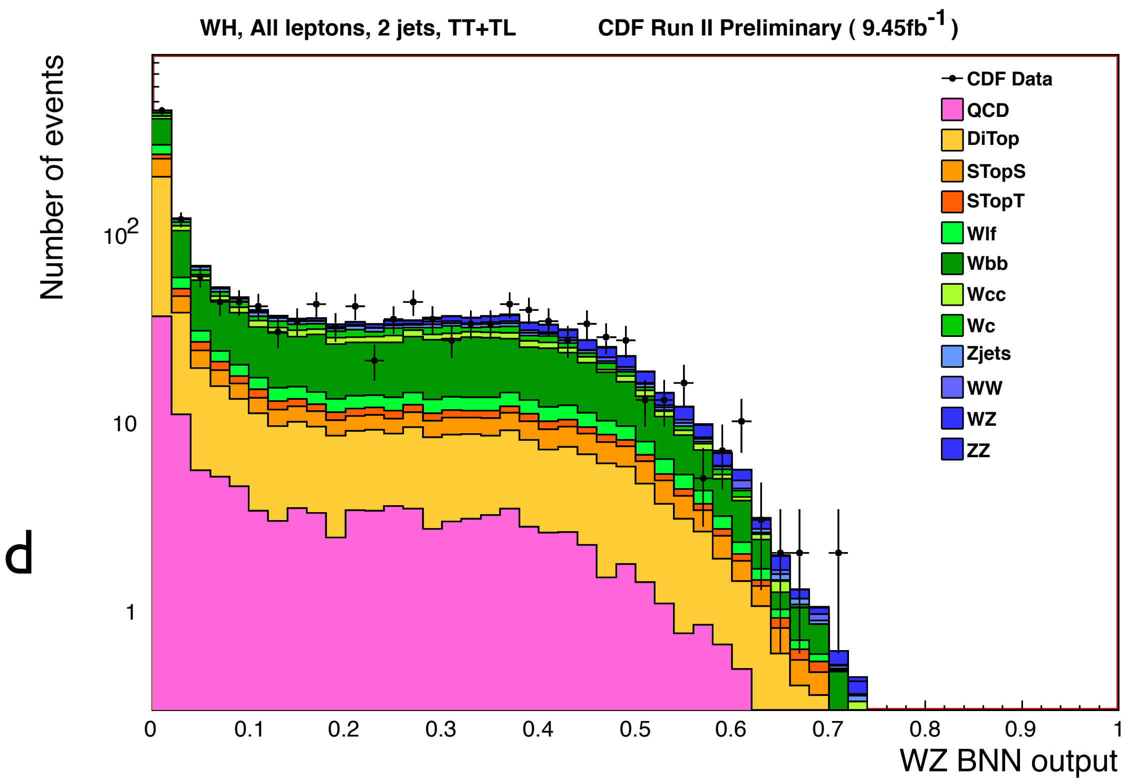
- Cleaner sample, lowest signal rate
- Selection:
  - ➡ 2 High PT electrons/muons
    - $75 < M_{ll}/GeV < 105$
  - ➡ 2,3 large ET jets
    - >= 1 b-tagged jet
- Analysis strategy:
  - ➡ 16 orthogonal channels examined simultaneously
    - channels divided upon lepton flavor, number of jets, heavy flavor content
  - ➡ multivariate discriminant for extracting the signal
    - full reconstruction of the final state
    - improved sensitivity wrt using dijet invariant mass



$$\sigma(VZ) = 0.79^{+1.68}_{-0.70}\ pb$$

lvbb

- Highest signal yield
- Selection:
  - ➡ =1 High PT electron/muon
    - ✓ extended lepton acceptance due to a more inclusive triggers
  - ➡ large MET
  - ➡ 2,3 large ET jets
  - ➡ multivariate techniques to reject multi-jet background



- Analysis strategy:
  - ➡ 7 orthogonal channels depending on the flavor content, number of jets
    - sensitivity improved thanks to HOBIT
  - ➡ Bayesian neural network to discriminate signal from background
    - different optimization in 2 and 3 jets channels

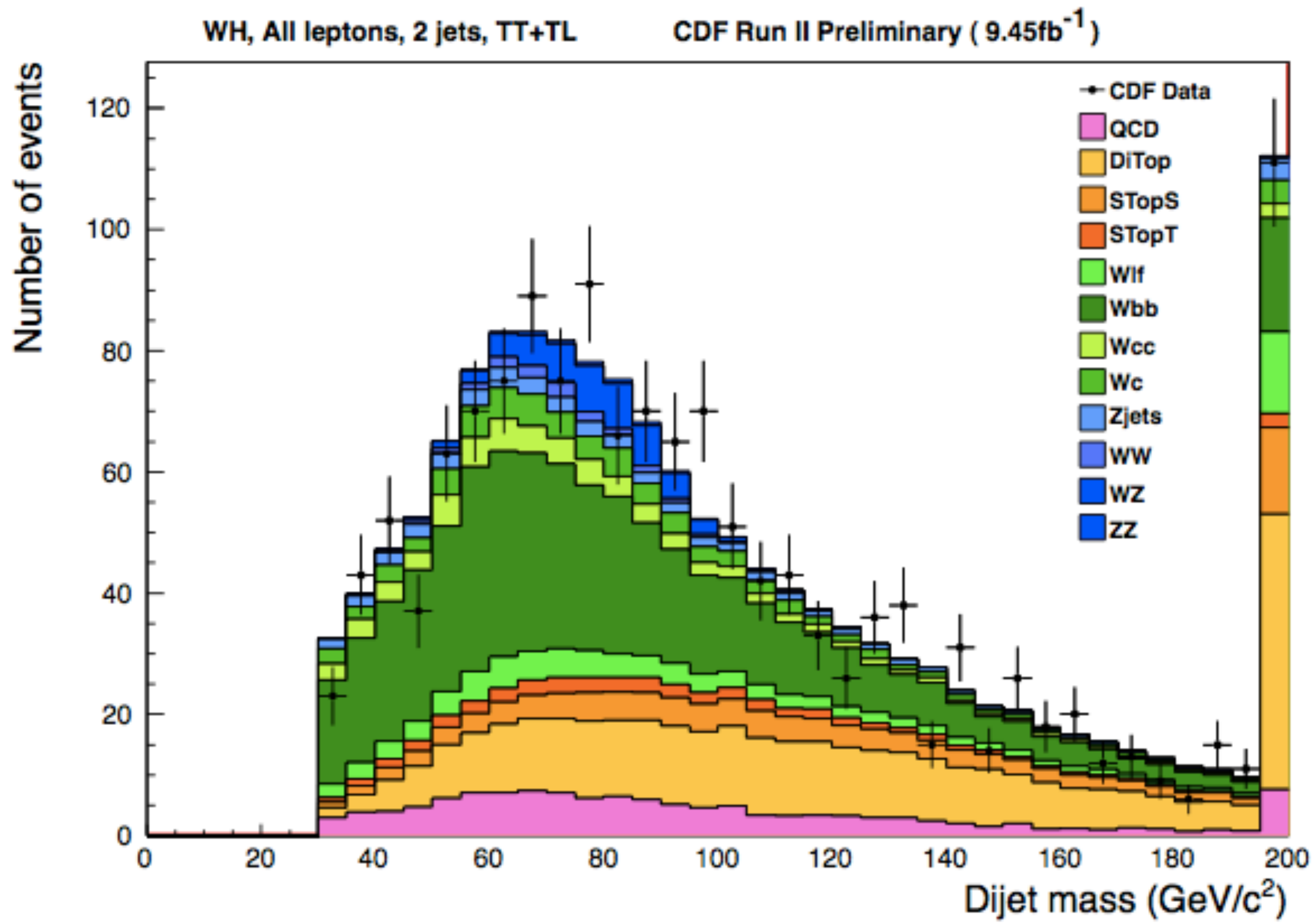
$$\sigma(VZ) = 7.78^{+2.47}_{-2.25}\ pb$$

lνbb: even yield

Number of Jets	2 jets					3 jets	
Tagging categories	TT	TL	T	LL	L	TT	TL
DiTop	177.49±22.17	211.19±19.8	544.5±52.06	63.04±6.93	327.74±33.71	495.7±61.59	581.77±54.47
STopS	59.1±7.06	66.39±5.85	118.38±10.68	19.35±2.19	69.4±7.13	19.34±2.33	22.66±2.01
STopT	17.4±2.48	32.45±3.98	228.45±25.63	12.21±1.32	134.83±15.56	22.13±3.03	29.87±3.32
WW	1.9±0.48	15.54±3.13	217.47±27.09	29.26±4.5	719.24±70.55	1.8±0.35	8.04±1.43
WZ	21.86±2.63	25.97±2.28	63.3±6.23	11.8±1	115.13±10.59	4.19±0.51	6±0.57
ZZ	2.6±0.3	2.73±0.24	7.87±0.77	1.08±0.09	11.98±1.08	0.96±0.11	1.22±0.11
Zjets	11.94±1.29	23.24±2.47	184.32±19.71	30.93±3.46	815.82±85.61	7.03±0.75	15.4±1.62
Wbb	284.99±116.78	382.43±155.86	1372.45±559.67	129.59±52.89	948.67±387.04	107.98±45.01	162.42±67.48
Wcc	22.54±9.39	141.43±58.32	1379.5±564.72	196.66±80.63	3332.54±1360.1	12.59±5.31	71.59±30.04
Wlf	5.17±1.54	73.93±16.53	1179.09±191.85	293.49±47.08	9732.87±1094.5	3.21±1.1	41.46±10.51
QCD	12.35±7.94	101.82±41.71	680.92±272.42	125.62±50.72	2031.95±812.95	5.79±5.17	68.53±28.41
Bkg	617.34±172.05	1077.12±309.74	5976.25±1730.5	913.03±250.76	18240.17±3877.7	680.72±125.24	1008.96±200.09
Obs	556	907	5737	865	18606	643	850
WH115	9.57±0.98	9.98±0.62	16.29±1.04	2.7±0.27	9.07±0.75	2.2±0.22	2.41±0.14

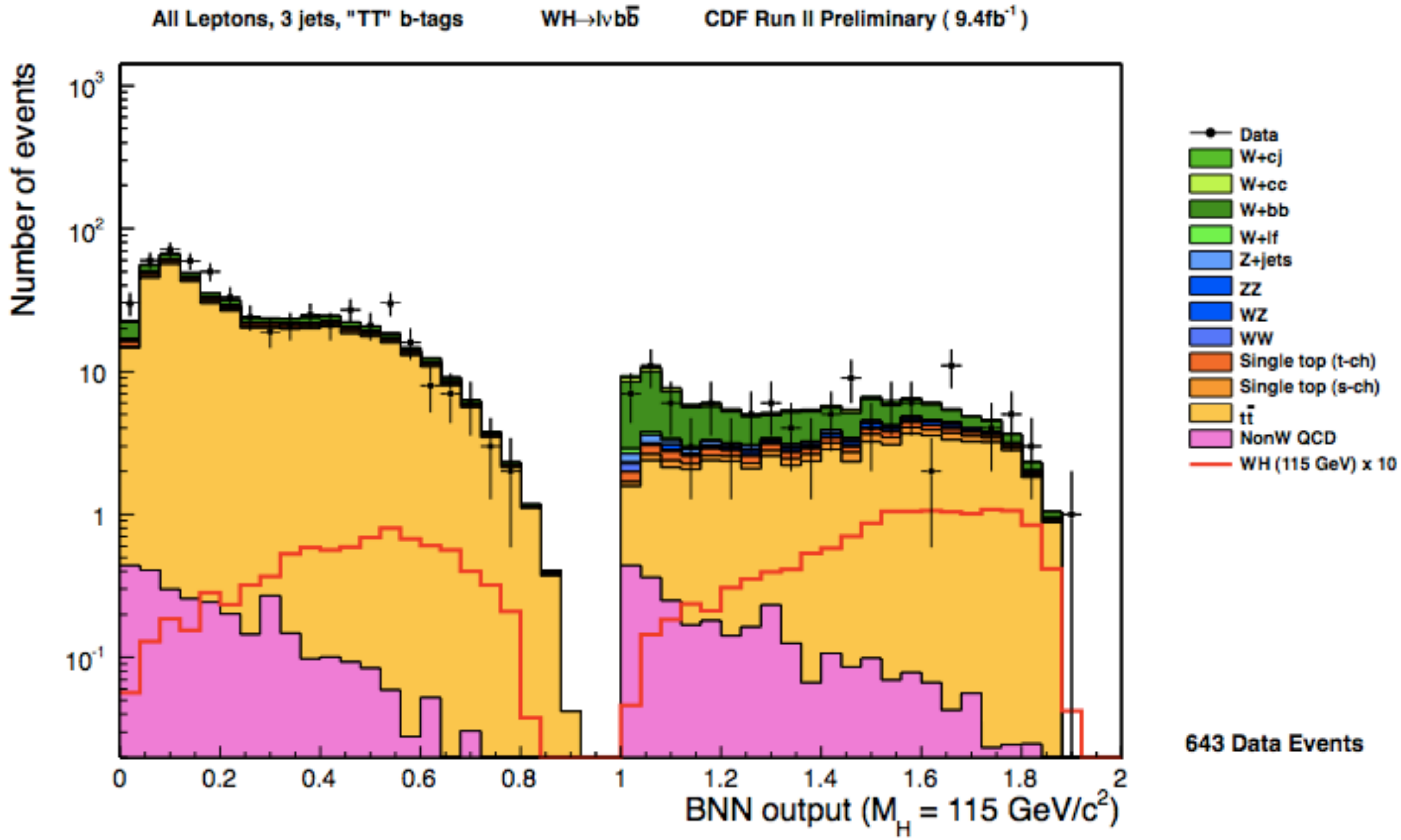
TABLE I: Background summary, signal expectation and data yield for the events with two jets in all *b*-tagging categories for central leptons.

lvbb: Mj1j2



WH, All leptons, 2 jets, TT+TL
CDF Run II Preliminary (9.45fb^{-1})
CDF Data
QCD
DiTop
STopS
STopT
Wlf
Wbb
Wcc
Wc
Zjets
WW
WZ
ZZ
Number of events
Dijet mass (GeV/c^2)

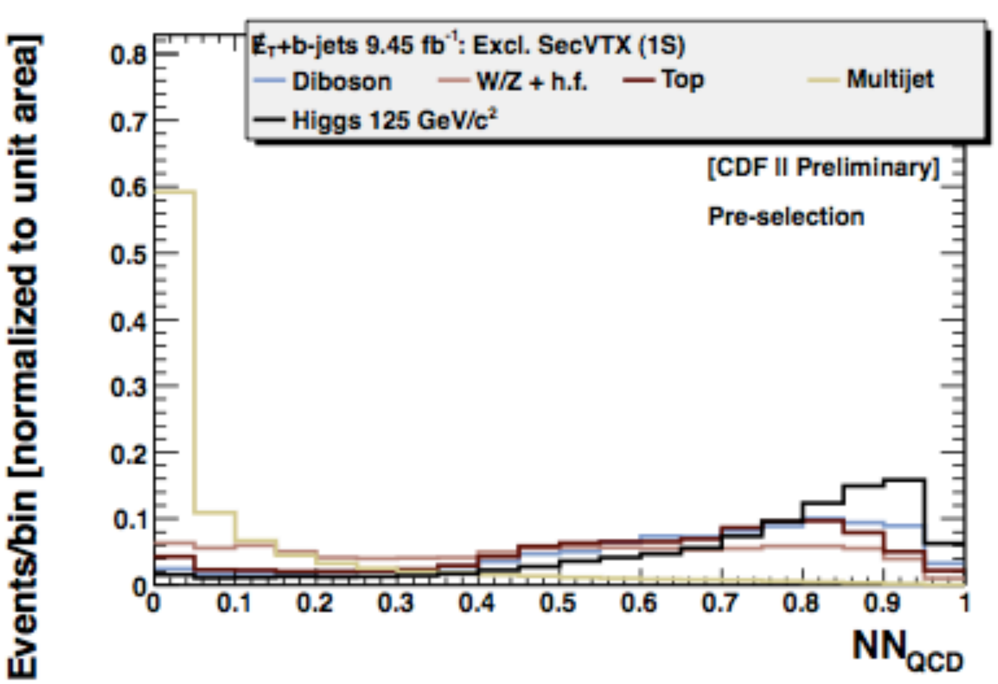
lνbb: BNN 3 jets



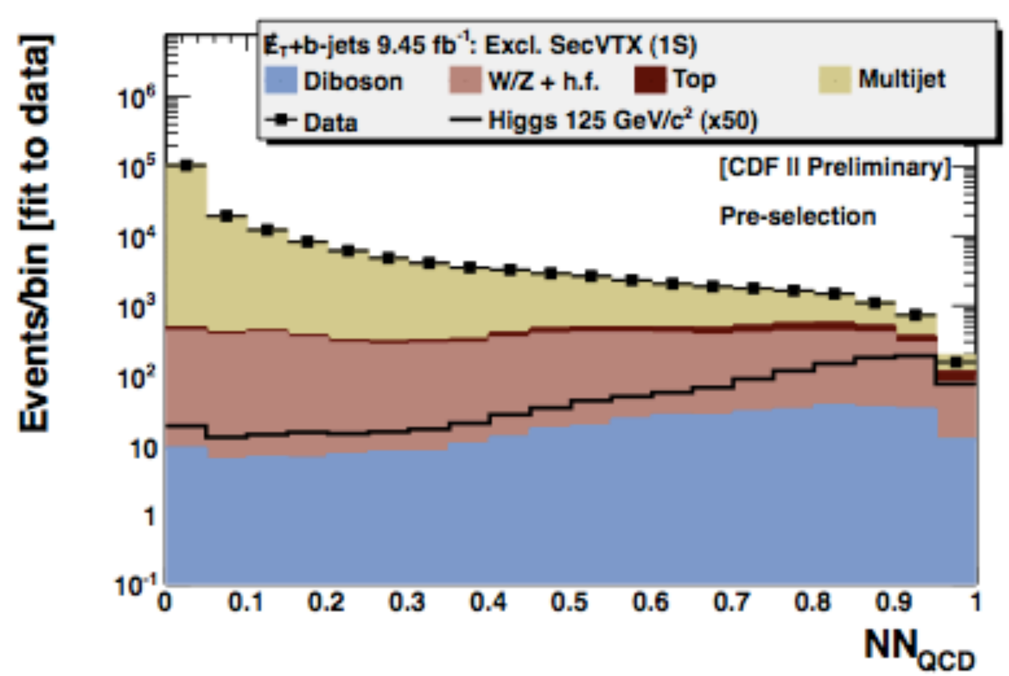
ννbb

Variable
Magnitude of $\vec{\not\!E}_T$
Magnitude of $\vec{\not\!p}_T$
$\not\!E_T/\sqrt{\sum E_T}$
$\not\!E_T/H_T$
$\not\!H_T$ / $\not\!E_T$
$M(\vec{\not\!E}_T, \vec{j}_1, \vec{j}_2)$
$\Delta\varphi$ between $\vec{\not\!E}_T$ and $\vec{\not\!p}_T$
Maximum of $\Delta\varphi$ between any two jets
Maximum of ΔR between any two jets
Minimum of $\Delta\varphi$ between the $\vec{\not\!E}_T$ and $\vec{j}_i$
Minimum of $\Delta\varphi$ between the $\vec{\not\!p}_T$ and $\vec{j}_i$
$\Delta\varphi(\vec{j}_1, \vec{j}_2)$ in the 2-jet rest frame
Sphericity
Centrality

TABLE III: Input variables to the neural network devised to suppress the QCD background, and the background coming from production of light flavor jets.



(a) Exclusive SecVtx



(b) Exclusive SecVtx

νvbb: inputs NN to correct jet ET

Variable	Description
Raw E_T	Uncorrected transverse jet energy
L5 m_T	Transverse jet mass corrected to hadronic level
H1 E_T	H1-corrected transverse jet energy
π^0 Energy	CES detector energies of π^0 candidates within jet cone
EM Fraction	Fraction of jet energy collected in EM calorimeter
Jet η	Jet pseudorapidity
Maximum Track p_T	Maximum transverse momentum of track within jet cone
Sum Track p_T	Linear sum of transverse momenta of tracks within jet cone

TABLE II: Description of the NN_{JER} input variables.

ννbb: inputs final discriminant

Variable
Invariant mass of the two leading jets in the event (M_{jj})
Invariant mass of $\vec{\not{E}_T}$, $\vec{j_1}$ and $\vec{j_2}$
Difference between the scalar sum of transverse energy of the jets (H_T) and $\not{E}_T$
Difference between the vector sum of transverse energy of the jets ($\not{H}_T$) and $\not{E}_T$
The output of the TrackMET neural network
Maximum of the difference in the $\eta - \phi$ space between the directions of two jets, taking two jets at the time
The output of NN_{QCD}

TABLE VII: Input variables to the final discriminant neural network.

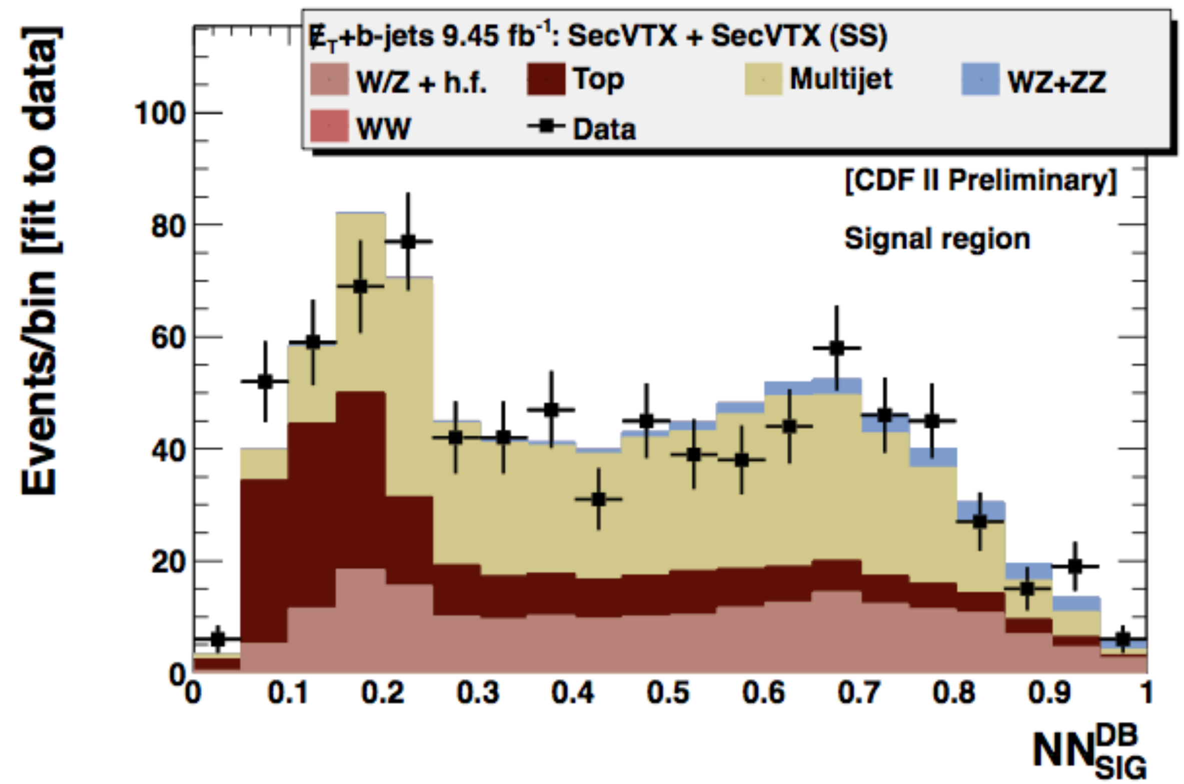
ννbb: event yields

$\not{E}_T$+b-jets 9.45 fb^{-1} [CDF II Preliminary]

	1S			SS			SJ		
WW	158.8	±	17.2	0.8	±	0.1	2.5	±	0.3
WZ/ZZ	133.9	±	14.3	31.3	±	3.9	27.6	±	3.2
Single Top	273.6	±	35.2	48.3	±	7	41	±	5.6
Top Pair	741.5	±	93.1	147.2	±	21.1	133.3	±	18
$Z + h.f.$	812.2	±	146.2	73.6	±	14.2	72.4	±	13.5
$W + h.f.$	2868.1	±	528.8	123.5	±	23.9	154.4	±	29.3
QCD Multijet	10824.6	±	177.3	376.9	±	11.9	923.1	±	19.2
EWK Mistags	2287.8	±	283	16.5	±	5.4	38.4	±	20.3
Total	18100.6	±	1295.1	818	±	87.5	1392.7	±	109.5
Data	18165			807			1310		

vvbb

- **Selection:**
  - ➡ lepton veto
  - ➡ large MET
  - ➡ 2,3 large ET jets
  - ➡ NN-based discriminat to reject the large instrumental background
  - ➡ NN to paramaterize trigger efficiency curve
    - allows for more relaxed kinematic cuts

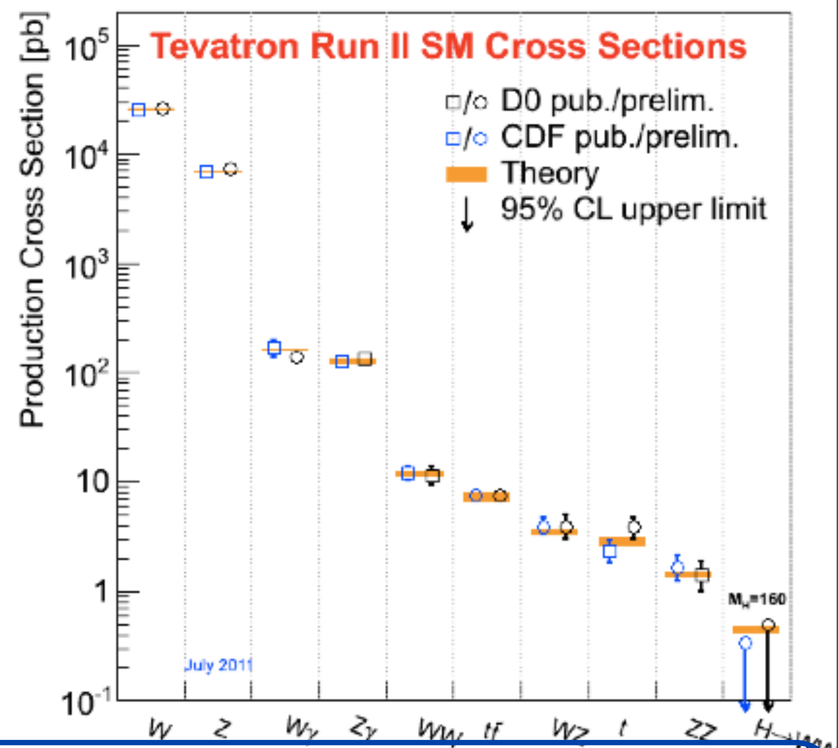


- **Analysis strategy:**
  - ➡ 3 orthogonal channels depending on the flavor content
    - still using "pre-HOBIT" CDF taggers
  - ➡ Final neural network to discriminate signal from background
    - trained separately in 2 and 3 jet sample

$$\sigma(VZ) = 3.09^{+2.21}_{-1.77}\ pb$$

Diboson at CDF: history

- Observation in fully leptonic states
  - $WZ \to l\nu ll,\ ZZ \to llll,\ WW \to l\nu l\nu$
- Observation in semileptonic states
  - MET+jets, lepton+MET+jets



WZ

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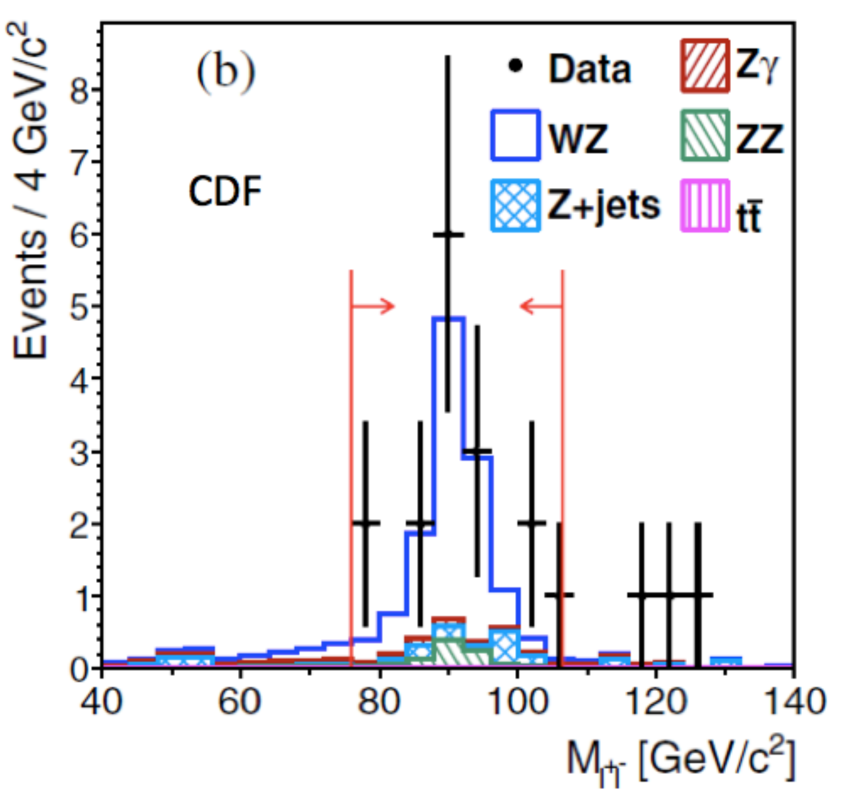
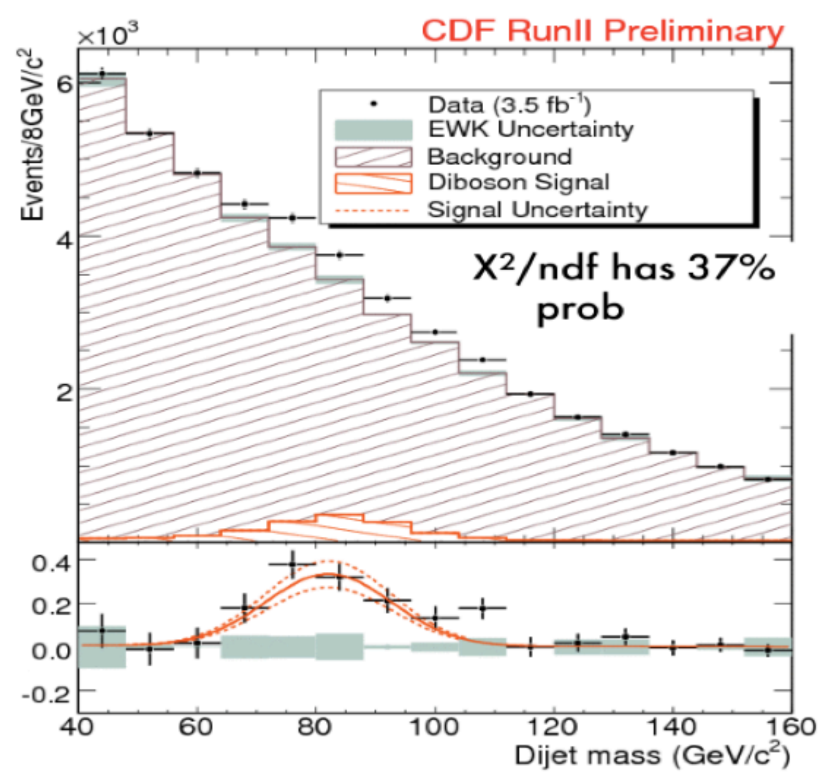
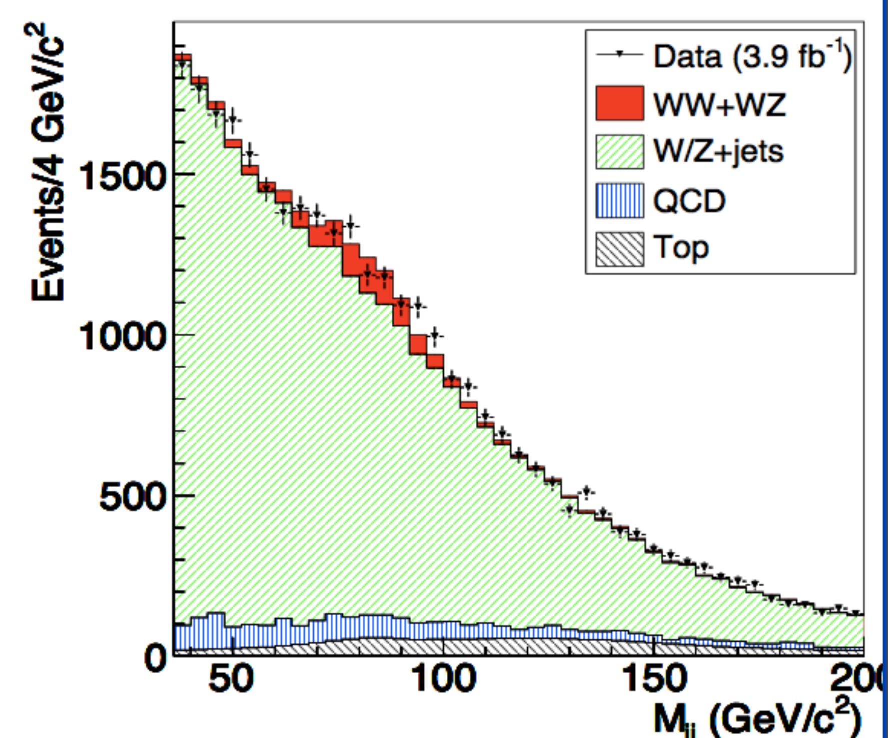


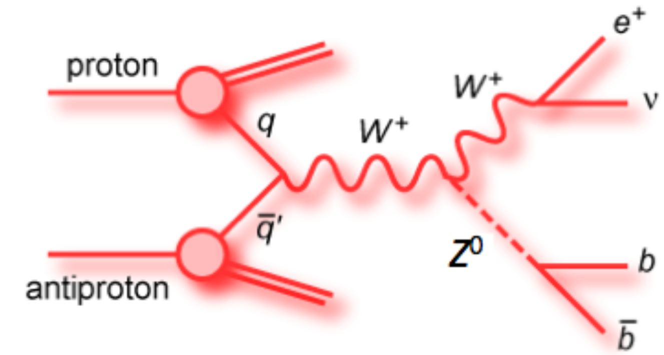


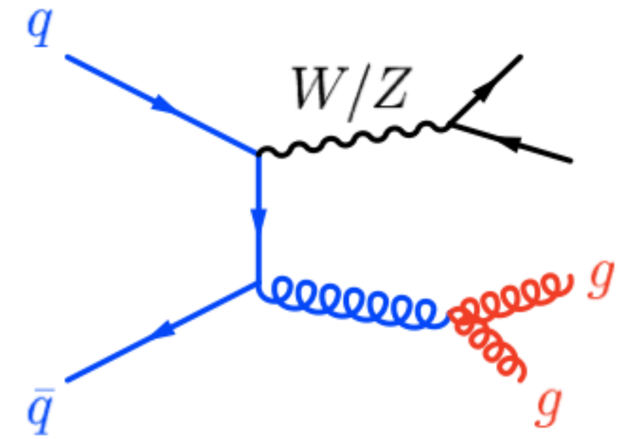


cannot separate WW and WZ due to dijet mass resolution

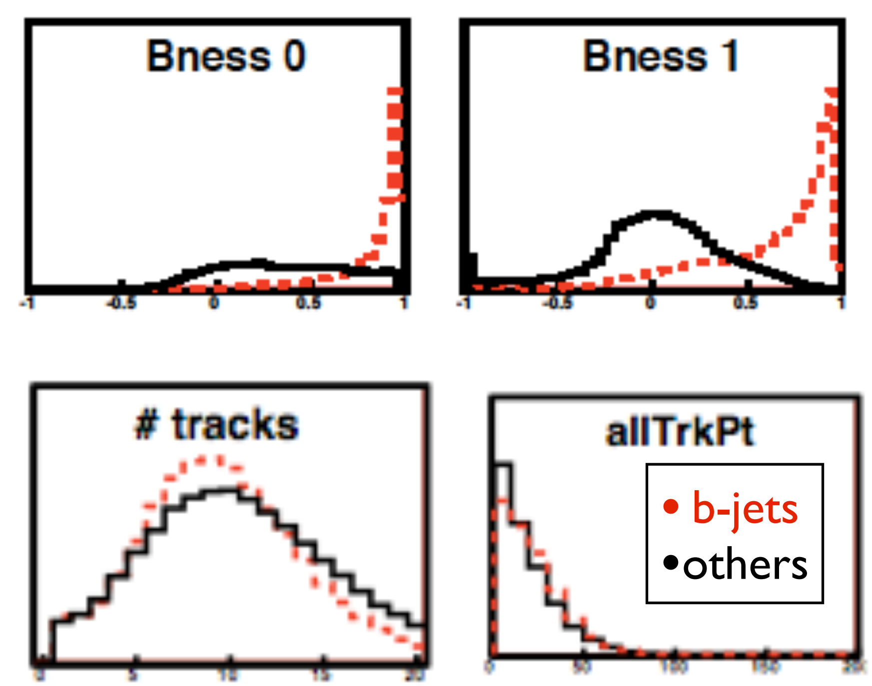
b-tagging

- Goal: separate jets containing B hadrons from other jets
  - key to separate WZ/ZZ from WW
- Solution: brand new multivariate tagger (HOBIT)
  - continuous output
    - operation points can be optimized upon search sensitivity
  - trained on Higgs and W+jets MC
  - built upon the strength of previous CDF taggers
    - using the most powerful inputs

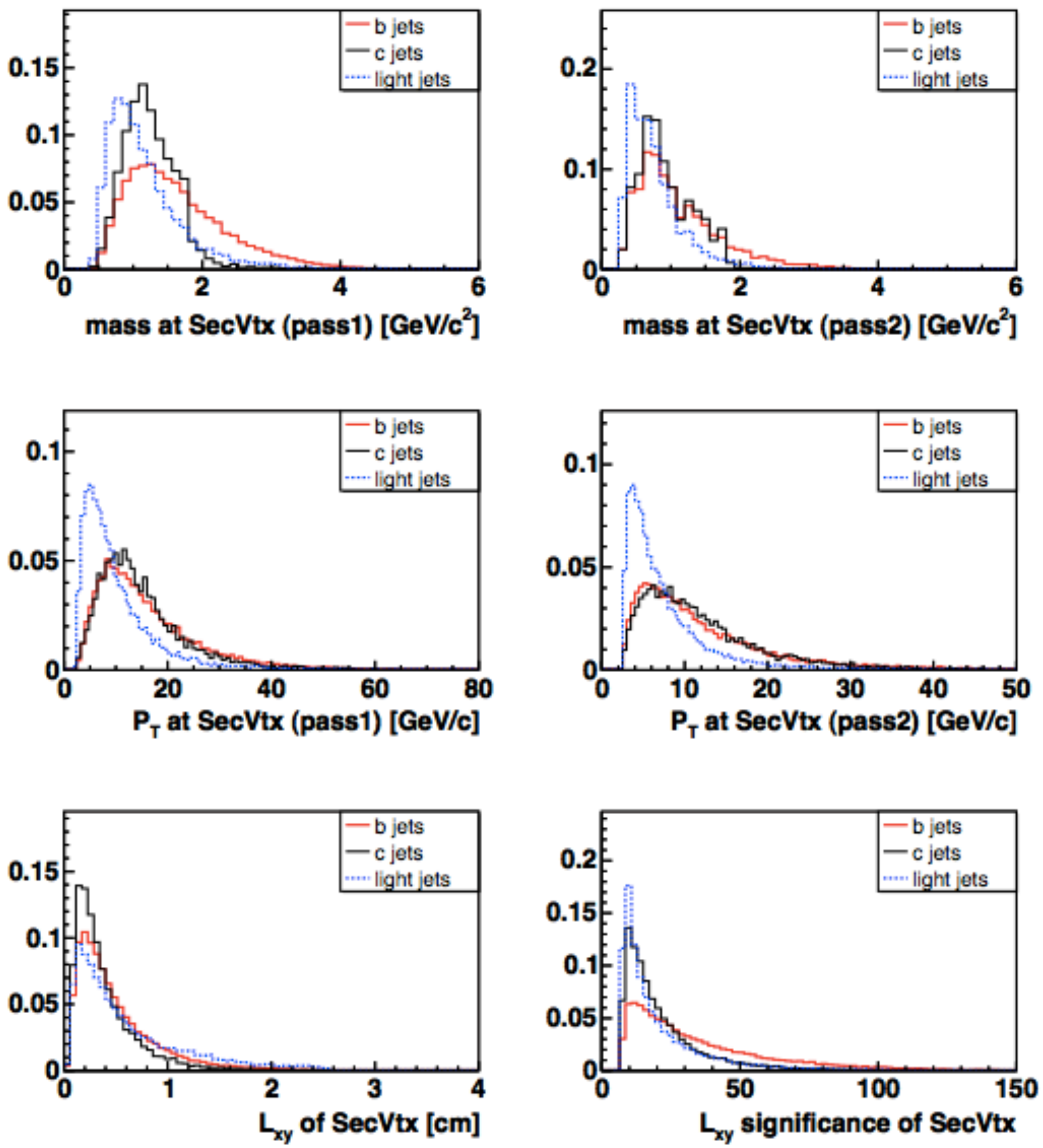




Some HOBIT inputs



KIT input variables



KIT input variables