Search for the Standard Model Higgs Boson Produced in Association with Top Quarks at the Tevatron

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On Behalf of the CDF and DØ Collaborations

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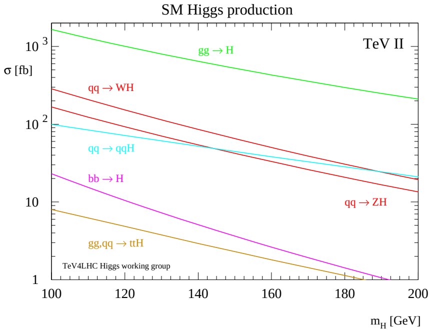
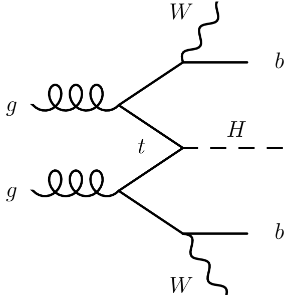
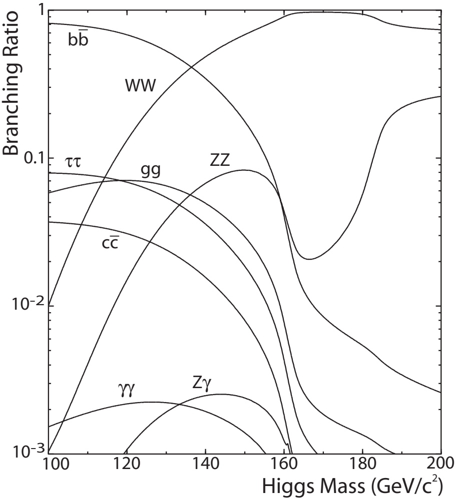
WANTED

FOR SYMMETRY BREAKING

- In the Standard Model, $t\bar{t}H$ cross section is small compared to $gg \to H$, VBF, and VH
- Top quarks are quite distinctive, giving good background discrimination
- If a new particle is discovered, measuring its coupling to top is important in establishing whether or not it is a Standard Model Higgs
- Beyond the Standard Model, many models enhance the $t\bar{t}H$ cross section





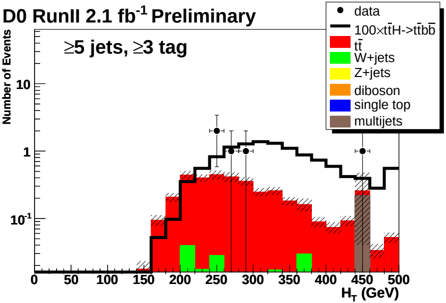


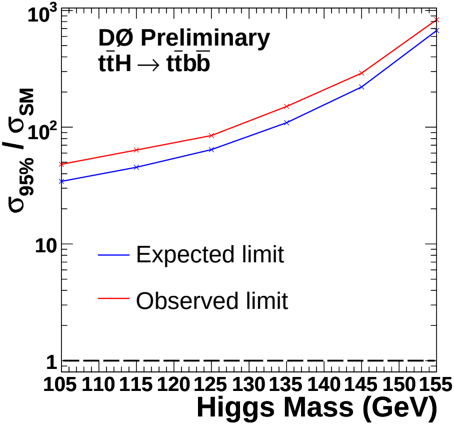
- Tops both decay to Wb, so channels determined by W decays:

$\ell +$ jets	One W decays to e or μ
$\not{E}_T +$ jets	One W decays to τ or to e/μ but lepton is missed
All jets	Both Ws decay hadronically

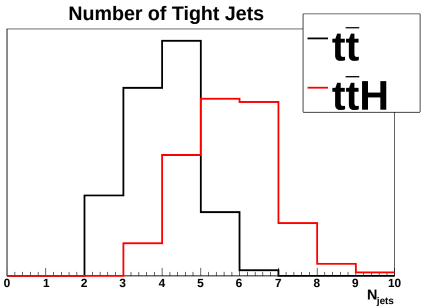
- Although b tagging is employed, we include non-$b\bar{b}$ Higgs decays.
- Additional acceptance from $H \to WW$ and other decays improves sensitivity, especially at higher masses.

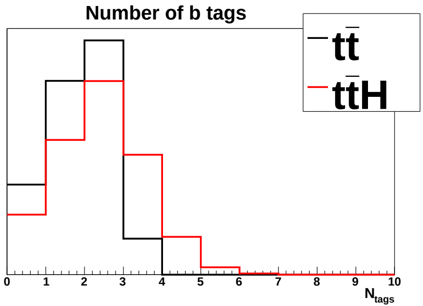
- Before summer 2011, best $t\bar{t}H$ search result was from DØ in 2009.
- Using $2.1\,\text{fb}^{-1}$, a 95 % C.L. upper limit of ~ 45 was set on $\sigma \times \mathcal{BR}/\text{SM}$ at $m_H = 120\,\text{GeV}/c^2$.
- This summer, CDF produced new $t\bar{t}H$ searches in multiple channels.
- I will concentrate on these new results in this talk.



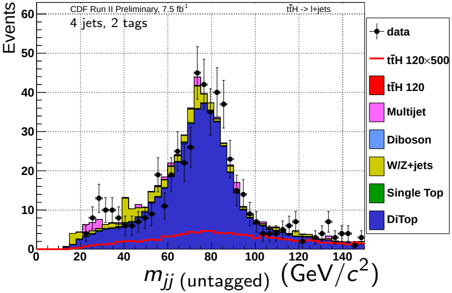


- Top decay final state $\ell\nu bbqq$
- Higgs decay final state bb, $WW/ZZ \to qqqq$, $\tau\tau$, etc.
- Select sample of events with
  - Well-reconstructed e or μ, with $p_T > 20\,\text{GeV}\,c^{-1}$
  - $\not{E}_T > 20\,\text{GeV}$
  - ≥ 4 jets:
    - $E_T > 20\,\text{GeV}$
    - $|\eta| < 2.0$
  - ≥ 2 b tags
- Further divide this into 4 regions with different S/B:
  - exactly 4 jets vs. ≥ 5 jets
  - exactly 2 b tags vs. ≥ 3 b tags

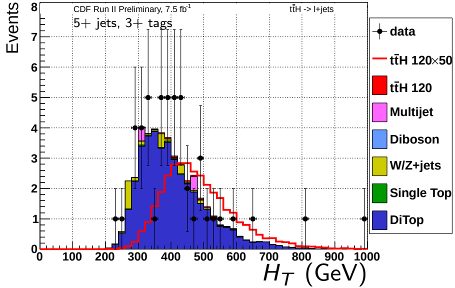


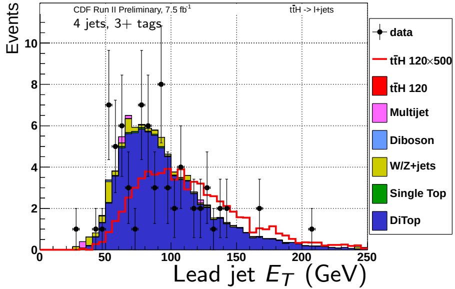


- Signal modeled using Monte Carlo, with assumed Higgs masses 100 – 170 GeV/c^2.
- Most background modeled using Monte Carlo, with $m_{\mathrm{top}} = 172.5\,\mathrm{GeV}/c^2$.
- Multijet production modeled using data driven technique.
- Tagging algorithms applied to MC jets that are matched to generator level b or c.
- Other MC jets tagged using measured light jet tag rate from data.



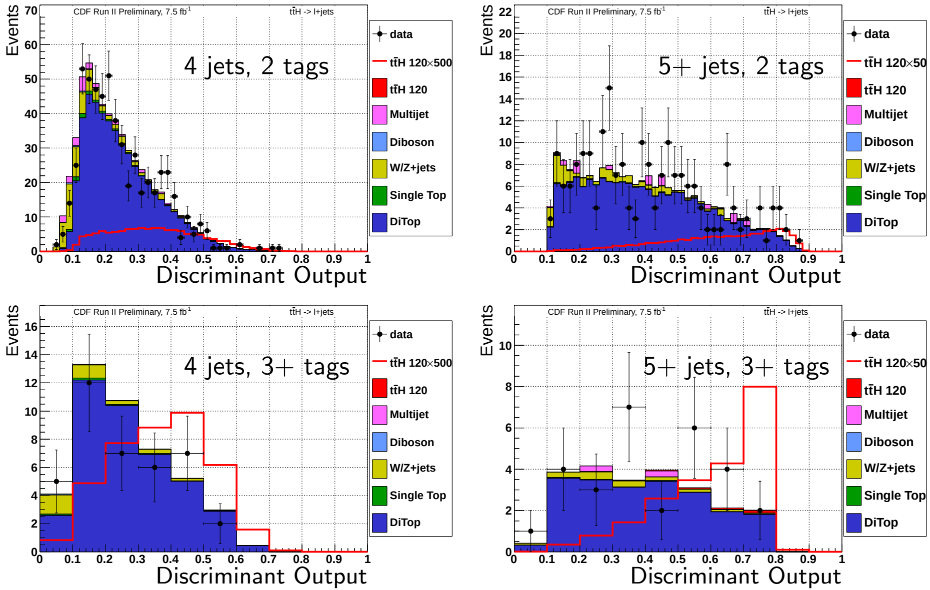
Process	≥ 4 jets, ≥ 2 b tags
$t\bar{t}$	781.42 ± 44.01
W/Z+jets	70.36 ± 11.22
Multijet	25.54 ± 13.08
Single Top	12.28 ± 0.50
Diboson	3.56 ± 0.29
Total Background	893.16 ± 47.27
$t\bar{t}H$	1.83 ± 0.05
Observed	892



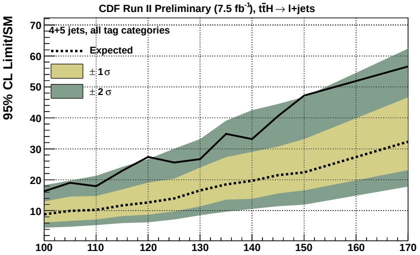


- For each Higgs mass point, train a Bayesian neural network ensemble to discriminate $t\bar{t}H$ from $t\bar{t}$
- 24 input variables, including
  - Dijet mass of leading untagged jets
  - H_T, lead jet E_T, $\not{E}_T$
  - Minimum ΔR between b jets
  - etc.

Outputs $m_H = 115\,\mathrm{GeV}/c^2$



- Since no significant excess observed, set upper bounds on cross section × branching ratio at 95 % confidence level using a standard Bayesian calculation
- Sources of systematic uncertainty:
  - *b* tag efficiency
  - Cross sections
  - Jet energy scale
  - Luminosity measurement
  - Intial- and final-state radiation
  - Mistag rate



m_H	Obs	-2σ	-1σ	Exp	$+1\sigma$	$+2\sigma$
100	**16.3**	4.5	6.2	**8.9**	13.0	18.3
105	**19.0**	4.8	6.7	**10.0**	14.5	19.7
110	**18.0**	5.4	7.2	**10.3**	14.8	21.3
115	**22.9**	6.0	8.3	**11.7**	16.9	24.1
120	**27.4**	6.3	8.7	**12.7**	19.1	26.7
125	**25.6**	7.2	9.7	**14.0**	20.4	30.1
130	**26.6**	8.5	11.4	**16.6**	24.0	33.1
135	**34.9**	9.7	13.6	**18.5**	27.3	39.1
140	**33.1**	10.6	13.9	**19.7**	29.0	42.5
145	**40.6**	11.5	15.6	**21.5**	30.7	44.5
150	**47.2**	11.9	16.6	**22.4**	33.2	46.7
170	**56.6**	17.8	23.1	**32.3**	46.6	62.4

CDF Run II Preliminary, $7.5\,\mathrm{fb}^{-1}$, $t\bar{t}H \to \ell + \mathrm{jets}$

- Base selection is shared between $\not\!\!E_T +$ jets and all jets channels:
  - high-p_T e/μ veto
  - ≥ 4 jets:
    - $E_T > 15$ GeV
    - $|\eta| < 2.0$
  - leading jet $E_T > 50$ GeV
  - second jet $E_T > 40$ GeV
  - $H_T > 300$ GeV
- $\not\!\!E_T +$ jets channel additional cuts:
  - $\not\!\!E_T/\sqrt{\sum E_T} \geq 2\,\text{GeV}^{1/2}$
  - $5 \leq N_{\text{jets}} \leq 8$
  - $\text{NN}_{\text{QCD}} > 0.8$
- All jets channel additional cuts:
  - $\not\!\!E_T/\sqrt{\sum E_T} < 2\,\text{GeV}^{1/2}$
  - $7 \leq N_{\text{jets}} \leq 10$
  - $\text{NN}_{\text{QCD1}} > 0.9$, $\text{NN}_{\text{QCD2}} > 0.7$

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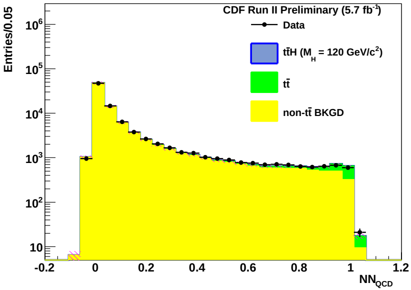
MET+Jets before correction (≥ 1tag)



NN_{QCD} trained to discriminate $t\bar{t}H$ from multijet production

- Base selection is shared between $\not\!\!E_T +$ jets and all jets channels:
  - high-p_T e/μ veto
  - ≥ 4 jets:
    - $E_T > 15$ GeV
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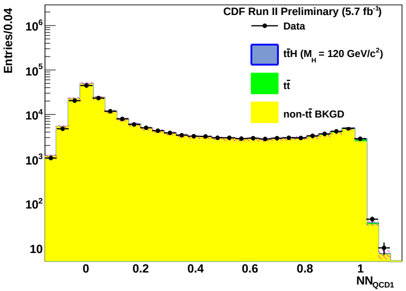
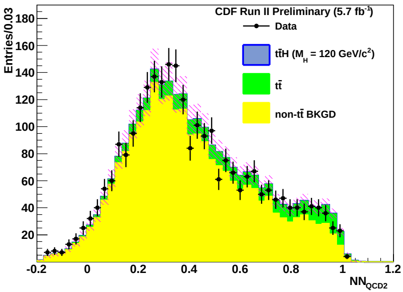
All jets before correction (≥ 1tag)



All jets pre-signal region (2-tag)

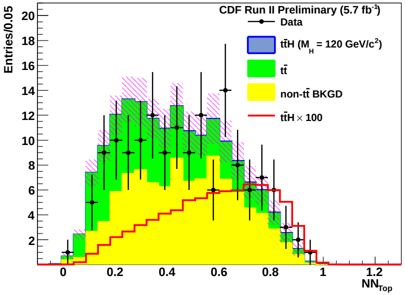


CDF II Preliminary 5.7 fb^{-1}

	2-tag ($\not\!\!E_T$ +jets)	3-tag ($\not\!\!E_T$ +jets)	2-tag (all jets)	3-tag (all jets)
Signal	1.0 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	0.8 ± 0.1
$t\bar{t}$	316.1 ± 43.3	66.6 ± 9.8	120.7 ± 16.5	43.1 ± 6.4
non-$t\bar{t}$	488.9 ± 41.4	98.5 ± 12.6	328.9 ± 35.3	82.7 ± 11.8
Total Expected	806.0 ± 59.8	165.9 ± 16.0	450.3 ± 38.9	126.6 ± 13.4
Observed	756	151	424	133

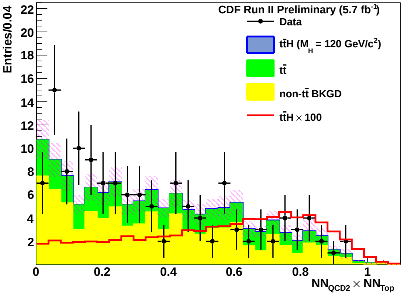
Train another neural network to discriminate $t\bar{t}$ from $t\bar{t}H$ (NN_{Top})

MET+Jets signal region (3-tag)



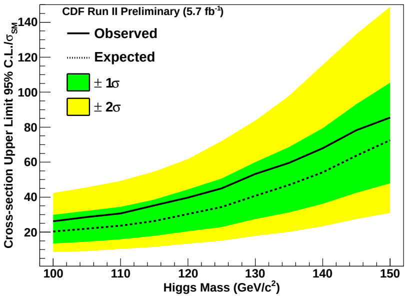
Final discriminant is $NN_{Top} \times NN_{QCD}$ ($NN_{Top} \times NN_{QCD2}$ for all jets)

All jets signal region (3-tag)

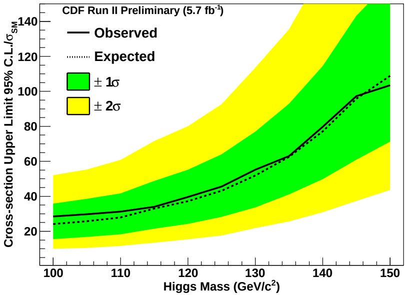


- Again, no significant excess is observed, so set 95 % C.L. upper bounds on production rate.
- Systematic uncertainties from:
    - Cross sections
    - luminosity
    - trigger modeling
    - *b* tag scale factor
    - jet energy scale
    - initial-/final-state radiation
    - PDFs
    - non-$t\bar{t}$ background model
    - *b*-tag categorization

Limits for tt̄H in MET+Jets channel



Limits for tt̄H in All Jets channel



- Again, no significant excess is observed, so set 95 % C.L. upper bounds on production rate.
- Systematic uncertainties from:
  - Cross sections
  - luminosity
  - trigger modeling
  - b tag scale factor
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  - initial-/final-state radiation
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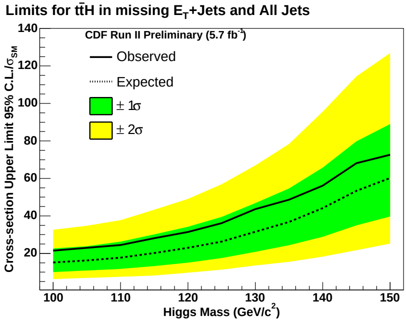
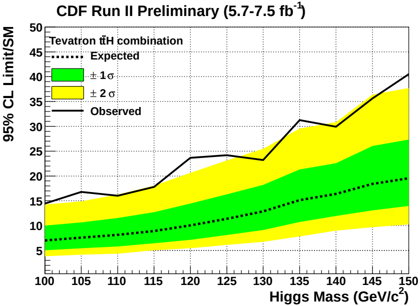


CDF II Preliminary 5.7 fb^{-1}

M_H (GeV/c^2)	Expected Limits -2σ	-1σ	**Median**	1σ	2σ	Observed Limits
100	6.3	10.0	**15.2**	22.6	32.6	**21.5**
105	6.9	10.8	**16.3**	23.8	34.8	**23.0**
110	7.6	11.7	**17.8**	26.3	37.7	**24.5**
115	8.2	13.2	**20.2**	30.1	43.3	**28.1**
120	9.7	15.1	**22.9**	34.2	49.1	**31.4**
125	11.3	17.5	**26.2**	39.5	56.9	**36.2**
130	13.5	20.8	**31.5**	46.8	66.9	**43.6**
135	15.4	24.3	**36.8**	54.6	78.4	**48.6**
140	18.3	28.9	**44.2**	65.8	95.6	**56.2**
145	21.7	35.0	**53.4**	79.8	114.5	**68.1**
150	25.2	39.7	**60.3**	89.9	126.9	**72.6**

- We also produce 95 % C.L. upper limits on $t\bar{t}H$ production in combined ℓ + jets, $\not{E}_T$ + jets, and all jets channels.
- This combination makes $t\bar{t}H$ the fourth most sensitive low-mass channel at CDF, behind $WH \rightarrow \ell\nu b\bar{b}$, $VH \rightarrow \not{E}_T b\bar{b}$, and $ZH \rightarrow \ell\ell b\bar{b}$.



m_H	Obs	-2σ	-1σ	Exp	$+1\sigma$	$+2\sigma$
100	**14.4**	3.8	5.0	**7.0**	10.0	14.2
105	**16.8**	4.1	5.5	**7.6**	10.7	14.9
110	**16.0**	4.4	5.8	**8.1**	11.6	16.3
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150	**40.5**	10.2	14.0	**19.5**	27.3	37.7

CDF Run II Preliminary, 5.7–7.5 fb^{-1}, $t\bar{t}H$ combination

- We have searched for $t\bar{t}H$ at CDF in three channels: $\ell +$ jets, $\not{E}_T +$ jets, and all jets.
- We set 95 % C.L. upper limits on the $\sigma(t\bar{t}H) \times \mathcal{BR}/\mathrm{SM}$ using the combination of all three channels.
- At $m_H = 120\,\mathrm{GeV}/c^2$, we obtain:
  - Expected limit: 10.4,
  - Observed limit: 22.2.
- These results were included for the first time in the Tevatron Higgs search combination presented at EPS 2011.
- $t\bar{t}H$ is a very sensitive Higgs search channel with potential for observation of BSM physics.
- Observation of $t\bar{t}H$ will be important post discovery at the LHC to verify that the Higgs is the Higgs.

- $t\bar{t}$ and $t\bar{t}H$ modeled using same Monte Carlo as $\ell +$ jets
- Non-$t\bar{t}$ background (mainly multijet) model is data driven
- Need to model multijet rate and shape in 2 and ≥ 3 b tags regions ($b$ness tagger)
- Select 3 (4) jet events in $\not{E}_T +$ jets (all jets) channel
- This sample is uncontaminated by $t\bar{t}$ and $t\bar{t}H$
- Find per-jet b-tag rate, parameterized in three variables
    - jet E_T, N_{tracks} in jet cone
    - $\not{E}_T +$ jets: $\not{E}_T \cos\Delta\phi(\not{E}_T, \text{jet})$
    - all jets: N_{vertices}
- b-tag rate applied to pre-tag data in signal region
- $t\bar{t}$ contribution is iteratively removed from multijet model
- Reweight in N_{jets} using control region $0.05 < \text{NN}_{\text{QCD}} < 0.4$
- Correct for tag rate correlations due to pair production

MET+Jets background region (1-tag)