Cross Section Measurements of Top Quark Production at CDF

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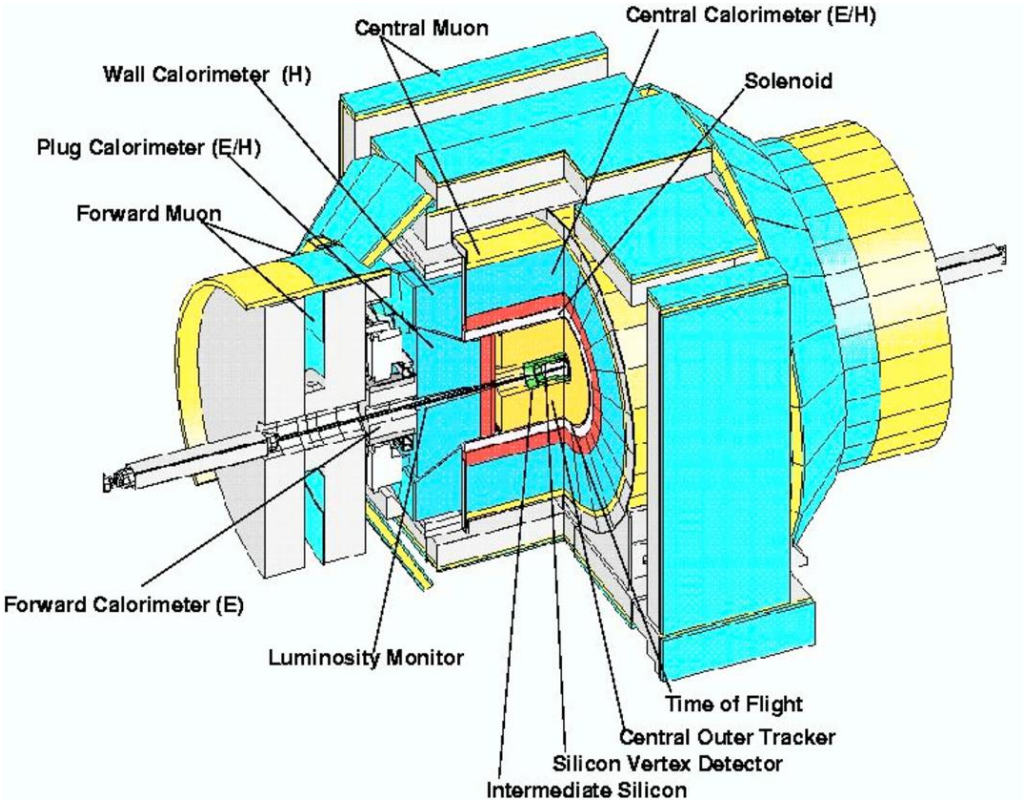
on behalf of
CDF Collaboration

CDF detector

- p-pbar collisions at Tevatron
  - sqrt(s) = 1.96 TeV
- Run II (2002-2011)
  - Recorded luminosity 10 fb^{-1}
- Multipurpose detector
  - Almost cylindrical symmetry
  - Highly performing tracking system
  - L1 and L2 track triggers

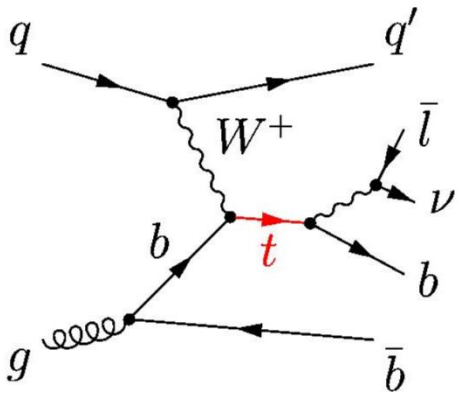


Single Top: Theoretical Interest

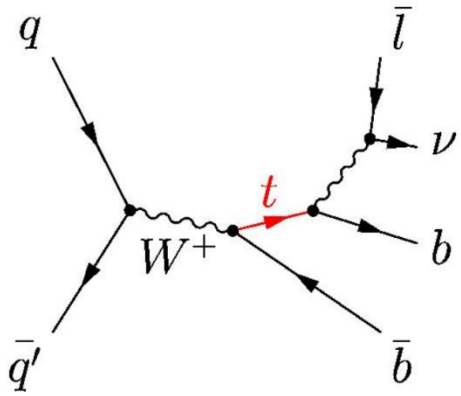
Conf.Note 10878

- Single top quark is produced via electroweak interaction
  - Its production rate is proportional to $|V_{tb}|^2$
  - Direct measurement of CKM matrix element $|V_{tb}|$
- s plus t channel observation obtained with 3.2 fb^{-1}
  - $2.3^{+0.6}_{-0.5}$ (stat+sys) pb Phys.Rev.D82:112005,2010

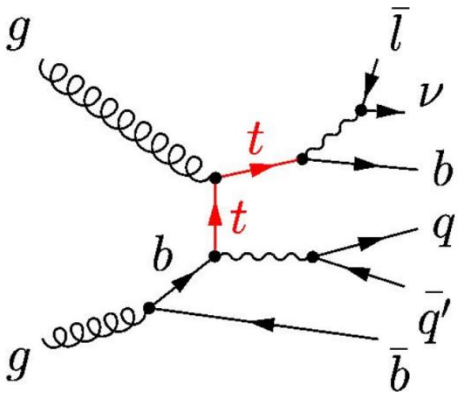
- **s-channel evidence**



t-channel
$\sigma = 2.10 \pm 0.19$ pb



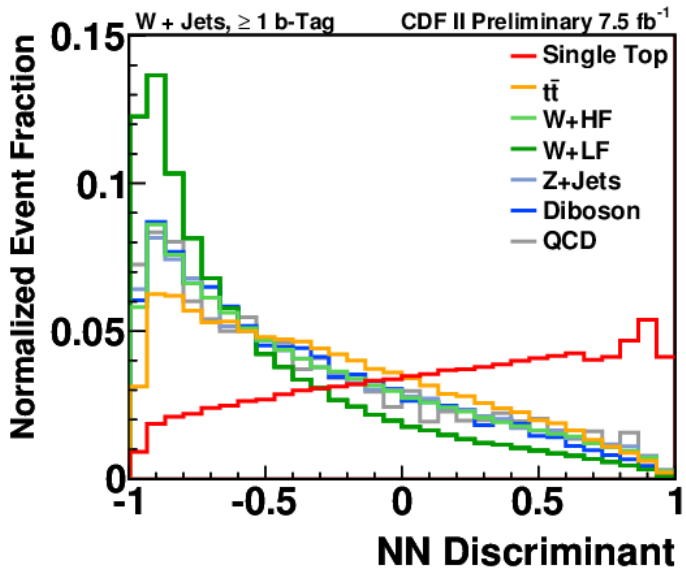
s-channel
$\sigma = 1.05 \pm 0.07$ pb

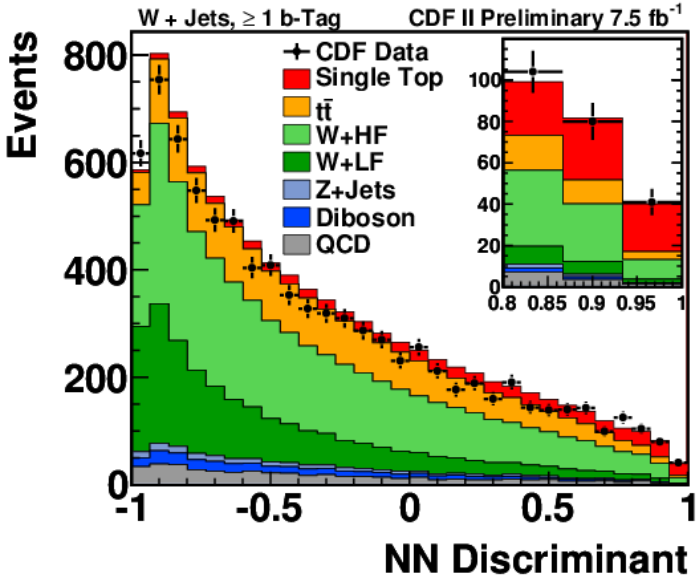


Wt associated production
$\sigma = 0.22 \pm 0.08$ pb

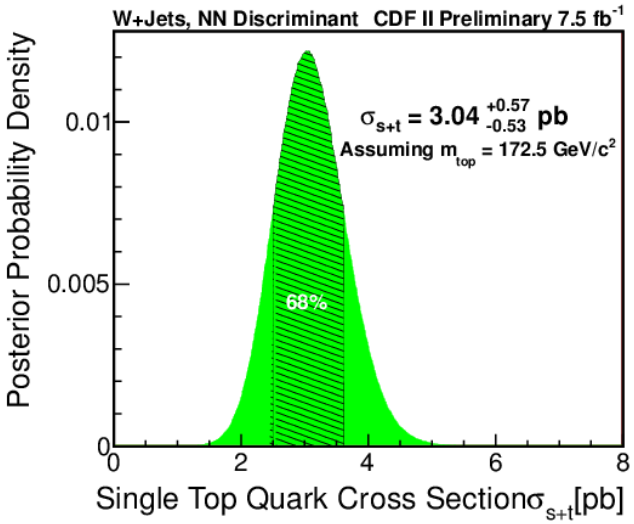
NN Multivariate Selection

- NLO simulated events for better signal description
- Overwhelming background from W plus jets
  - Artificial neural network
  - NeuroBayes ®package
- Improvements:
- Introduction of more input variables
- 4 event categories
  - 2 jets, 1 and 2 b-tag
  - 3 jets, 1 and 2 b-tag
- 2 trigger samples
  - Lepton triggers
  - ME_T plus jets triggers





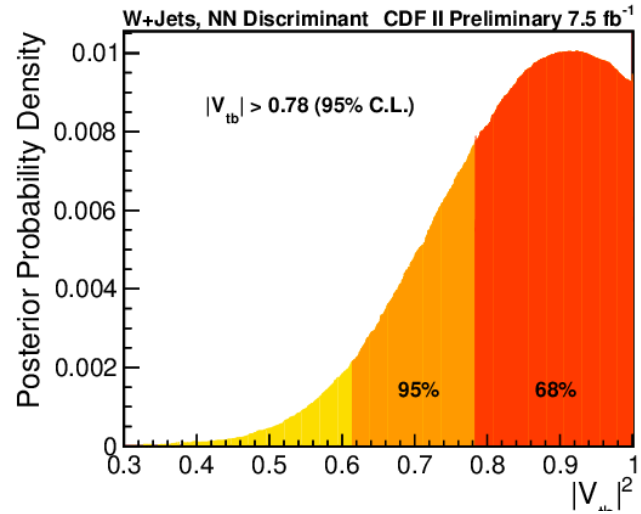
Single Top Cross Section and $|V_{tb}|$



$\sigma_{st} = 3.04\ ^{+0.57}_{-0.53}$ pb

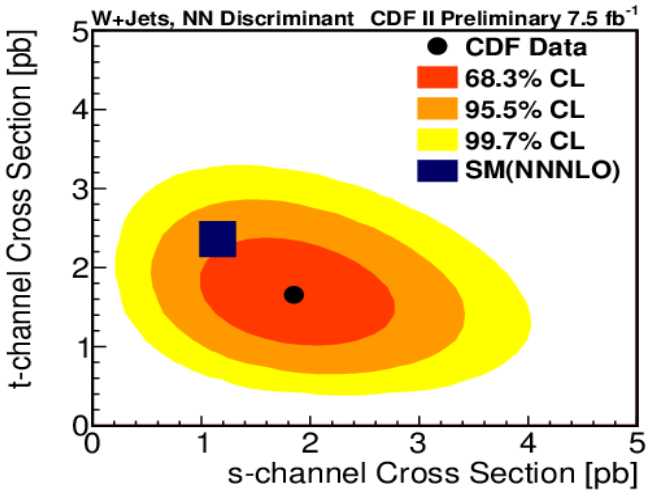
$\sigma_{st}^{SM} = 3.37 \pm 0.34$ pb

N. Kidonakis
arXiv:0909.0037



$$|V_{tb}|^2_{\text{measured}} = \sigma_{s+t}^{\text{measured}} |V_{tb}|^2_{\text{SM}} / \sigma_{s+t}^{\text{SM}}$$

V_{tb}= 0.96 ± 0.09 (stat.+syst.) ± 0.05 (theory)
V_{tb} > 0.78 at 95% C.L.



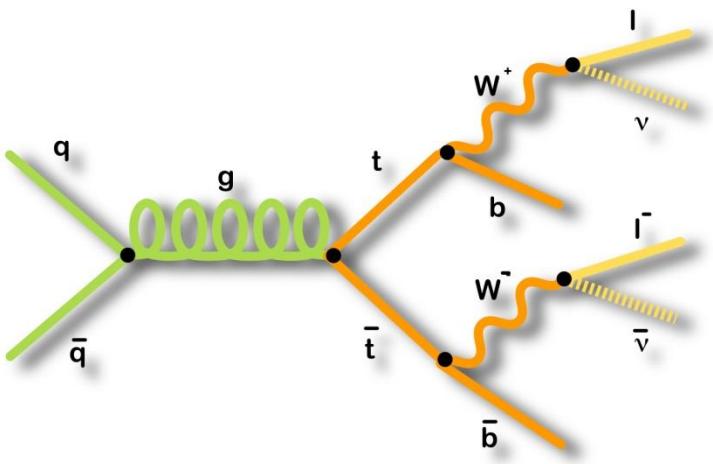
- 2-dimentional fit
  - Wt-channel with t-channel combined
  - s-channel
- Result:
  - $\sigma_s = 1.81\ ^{+0.63}_{-0.58}$ pb
  - $\sigma_t = 3.04\ ^{+0.47}_{-0.42}$ pb

Top Pair Decay in Dilepton Channels

Conf.Note 10878

- Motivation
  - QCD calculation of top pair production cross section
  - Connection top pair A_{fb} study
    - Signal selection
    - Understanding of background composition

- Signature
  - Exactly 2 leptons: electron or muon
  - ME_T
  - Two jets

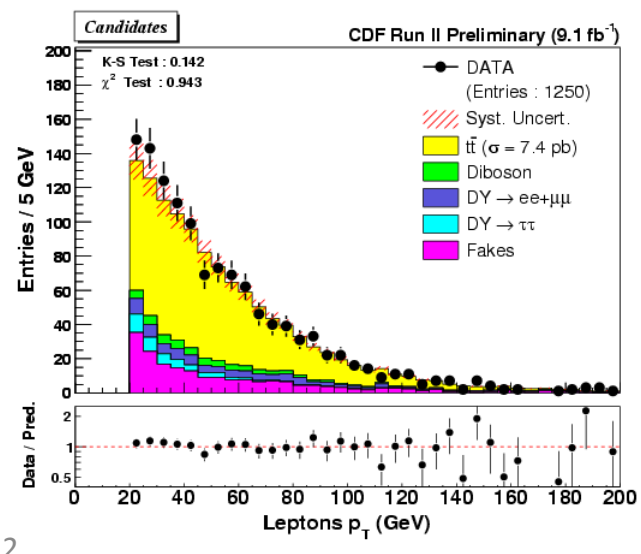


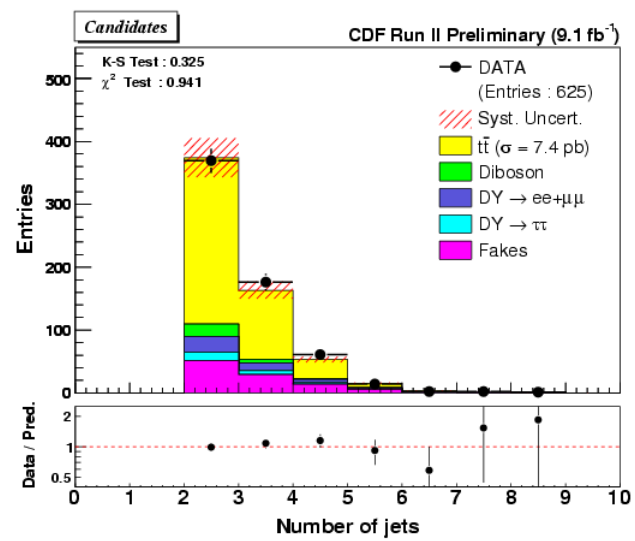
- Physics Background
  - Diboson
  - Z+jets
- Background with Fakes
  - Jet misidentified as electrons or muons

Pre-tag Selection

CDF II preliminary (9.1 fb^{-1})

$t\bar{t}$ Signal Events per Dilepton Flavor Category before b-tagging				
Source	ee	$\mu\mu$	eμ	$\ell\ell$
WW	5.03±1.04	3.90±0.81	9.23±1.86	18.16±3.61
WZ	2.62±0.45	1.56±0.27	1.52±0.27	5.70±0.96
ZZ	1.71±0.26	1.30±0.20	0.68±0.11	3.69±0.54
Wγ	0.73±0.77	0.00±0.00	0.00±0.00	0.73±0.77
DY$\rightarrow \tau\tau$	5.30±1.04	5.31±1.02	11.58±2.12	22.19±3.96
DY$\rightarrow ee + \mu\mu$	22.27±4.14	17.11±2.95	5.54±1.52	44.92±5.98
Fakes	12.57±3.90	23.27±7.26	67.04±20.46	102.87±28.38
Total background	50.21±6.89	52.45±8.36	95.60±21.24	198.26±31.44
$t\bar{t}$ ($\sigma = 7.4$ pb)	97.61±4.73	92.97±4.49	221.97±10.62	412.55±19.65
Total SM expectation	147.82±10.97	145.42±12.53	317.56±31.67	610.81±50.76
Observed	147	165	313	625

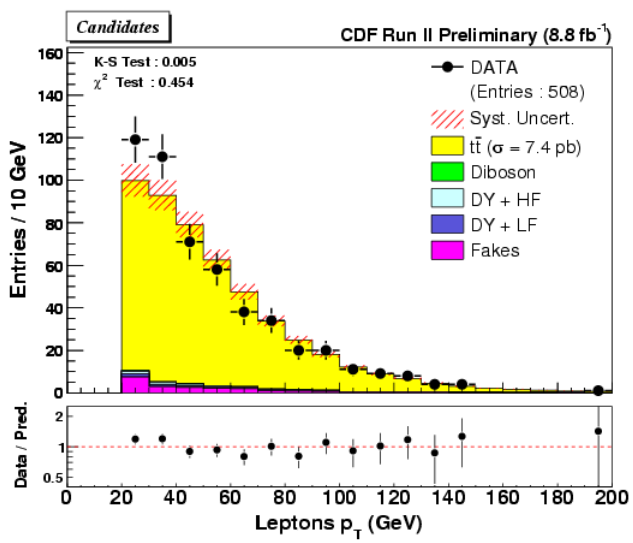


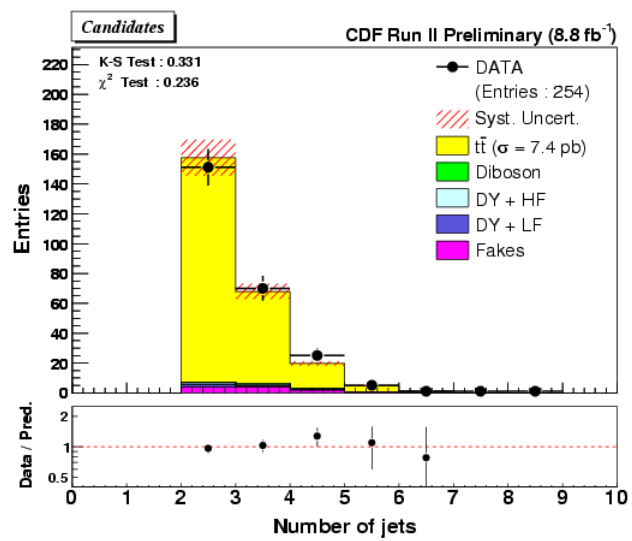


b-tag Selection

CDF II preliminary (8.8 fb^{-1})

$t\bar{t}$ Signal Events with the tight SecVtx b-tag				
Source	ee	$\mu\mu$	eμ	$\ell\ell$
WW	0.13±0.06	0.14±0.05	0.33±0.10	0.60±0.16
WZ	0.04±0.02	0.05±0.02	0.05±0.02	0.13±0.03
ZZ	0.14±0.03	0.12±0.03	0.03±0.01	0.29±0.06
DY+LF	1.07±0.12	1.17±0.15	0.56±0.06	2.80±0.31
DY+HF	0.99±0.17	1.34±0.22	0.50±0.10	2.83±0.45
Fakes	1.88±0.69	2.16±0.85	6.72±2.16	10.76±3.06
Total background	4.24±0.76	4.99±0.94	8.19±2.18	17.41±3.20
$t\bar{t}$ (σ = 7.4 pb)	55.64±3.90	52.02±3.64	126.23±8.76	233.88±16.17
Total SM expectation	59.88±4.55	57.01±4.42	134.41±10.80	251.29±19.21
Observed	53	71	130	254





Cross section Measurement

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bkg}}{\sum_i \mathcal{A}_i x \mathcal{L}_i}$$

A_i Acceptance of dilepton categories
L_i Luminosity of the dilepton categories

- Pretag: 625 events selected

$\boldsymbol{\sigma_{pretag} = 7.66 \pm 0.46_{stat} \pm 0.66_{syst} \pm 0.47_{lumi}}$ **pb**

- One secondary vertex requirement: 254 events selected

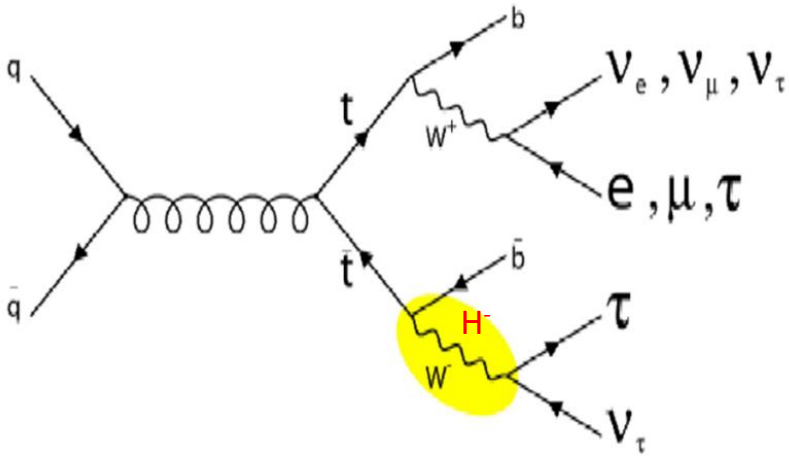
$\boldsymbol{\sigma_{btag} = 7.47 \pm 0.50_{stat} \pm 0.53_{syst} \pm 0.46_{lumi}}$ **pb**

Previous result: $\boldsymbol{\sigma_{pretag} = 7.40 \pm 0.58_{stat} \pm 0.63_{syst} \pm 0.45_{lumi}}$ **pb**

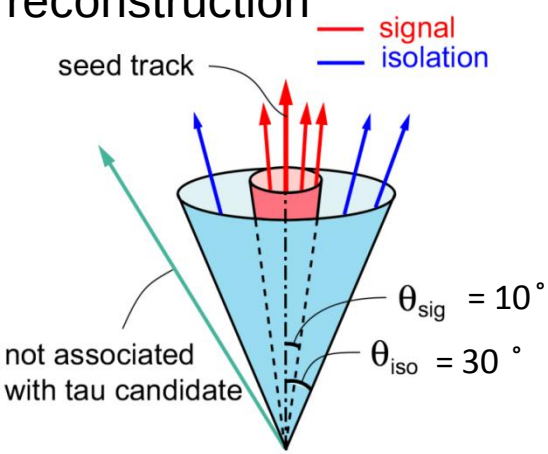
Conf. Note 10163 $\boldsymbol{\sigma_{btag} = 7.25 \pm 0.66_{stat} \pm 0.47_{syst} \pm 0.44_{lumi}}$ **pb**

Top pair in dilepton decay mode with Tau

- Signal processes
  - $\tau_{had} + \tau_{lep}$
  - τ_{had} + "prompt" electron or muon
- Interest
  - Test for lepton universality
  - Probe for alternative Higgs mechanism phenomenology
    - $t \rightarrow b+H^{\pm}$
    - Enhance of the decay channel
- Measurements
  - Cross section
  - Branching ratio of $t \rightarrow \tau\nu b$
- Signature
  - Electron or muon
  - Narrow jet tagged as tau
  - ME_T
  - Two jets
- Most complete study of top pair into ditau decay mode

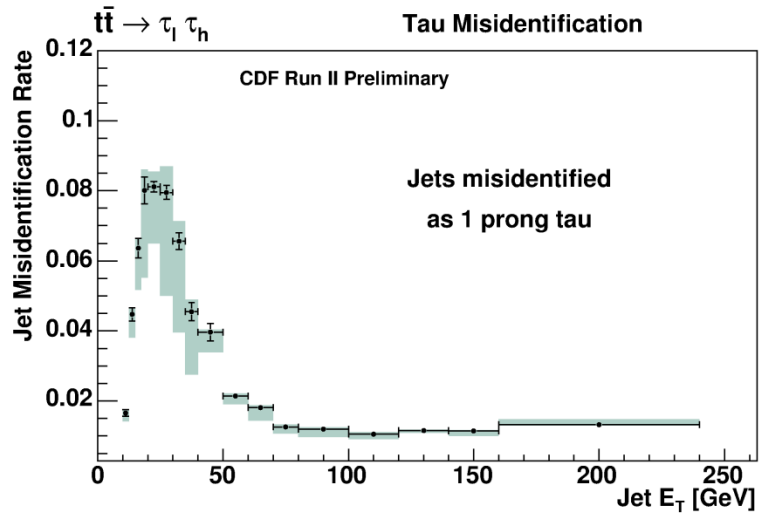


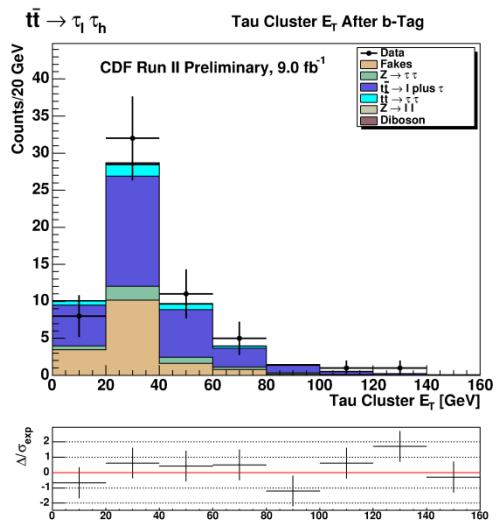
Tau reconstruction

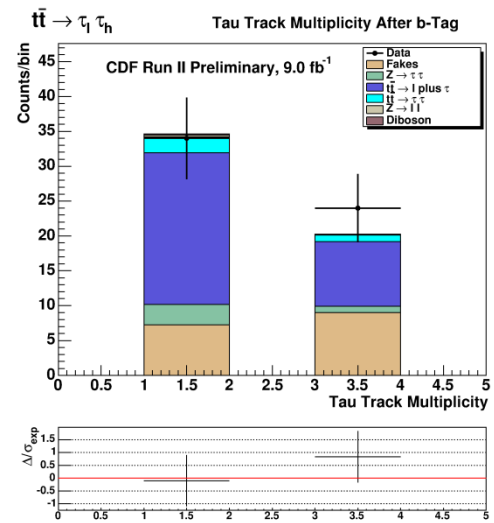


Samples and Background

- Low P_T trigger samples
  - Lepton E_T > 8 GeV
  - Isolated track P_T > 5 GeV/c
- Background with jets misidentified as tau
- Events with fakes from data
  - Jet misidentification rate
  - Inclusive single lepton sample
- Physics Background
  - Z+jets
  - Diboson

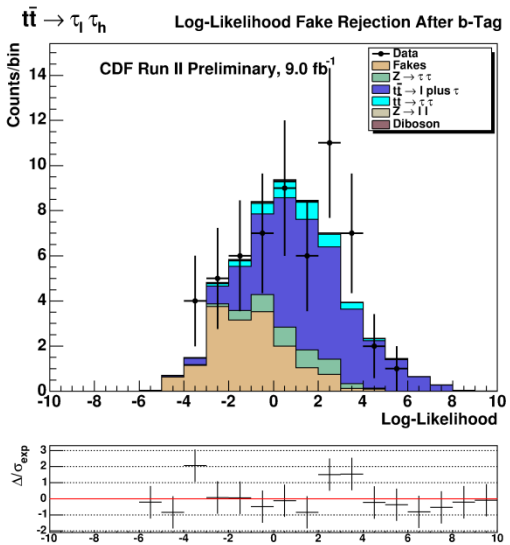






Log-Likelihood Discrimination of Fakes

- Background from events with fakes
  - Top pair in single lepton mode
- Log-Likelihood Ratio discrimination
  - Signal sample: top into lepton plus tau as
  - Background sample: top pair in single lepton as
- Variables
  - Tau E/P
  - Tau Isolation
  - Third jet E_T
  - ME_T
  - M_T^W
- Log-Likelihood > 0



Selection Result, Cross Section and Branching Ratio of top into tau, neutrino, b

$t\bar{t} \to \tau_\ell \tau_h + X$		Events of Final Selection	
Process	**Muon Sample**	**Electron Sample**	**Total**
Fakes	$1.80 \pm 0.31^{+0.13}_{-0.31}$	$2.20 \pm 0.64^{+0.18}_{-0.48}$	$4.01 \pm 0.71^{+0.31}_{-0.80}$
$Z/\gamma^* \to \tau\tau$	$1.12 \pm 0.07 \pm 0.25$	$1.41 \pm 0.08 \pm 0.29$	$2.53 \pm 0.11 \pm 0.53$
$Z/\gamma^* \to \ell\ell$	$0.10 \pm 0.03 \pm 0.03$	$0.03 \pm 0.01 \pm 0.01$	$0.13 \pm 0.03 \pm 0.04$
Diboson	$0.09 \pm 0.02 \pm 0.03$	$0.09 \pm 0.02 \pm 0.03$	$0.17 \pm 0.03 \pm 0.05$
$t\bar{t} \to \tau\ell + X$	$10.56 \pm 0.08 \pm 1.34$	$13.73 \pm 0.10 \pm 1.75$	$24.29 \pm 0.13 \pm 3.09$
$t\bar{t} \to \tau\tau + X$	$1.07 \pm 0.03 \pm 0.14$	$1.37 \pm 0.03 \pm 0.18$	$2.44 \pm 0.04 \pm 0.32$
Total Expected	$14.7 \pm 0.3^{+1.6}_{-1.7}$	$18.8 \pm 0.6^{+2.1}_{-2.1}$	$33.6 \pm 0.7^{+3.7}_{-3.8}$
Observed	12	24	36

CDF Run II Preliminary, 9.0 fb^{-1}

$$\sigma_{t\bar{t}} = \frac{N_{sel} - \sum N^i_{bg}}{\sum_{CMX,\ CMUP,\ CEM} [(BR_{\ell\tau}\epsilon_{\ell\tau} + BR_{\tau\tau}\epsilon_{\tau\tau}) \int \mathcal{L}_i dt]}$$

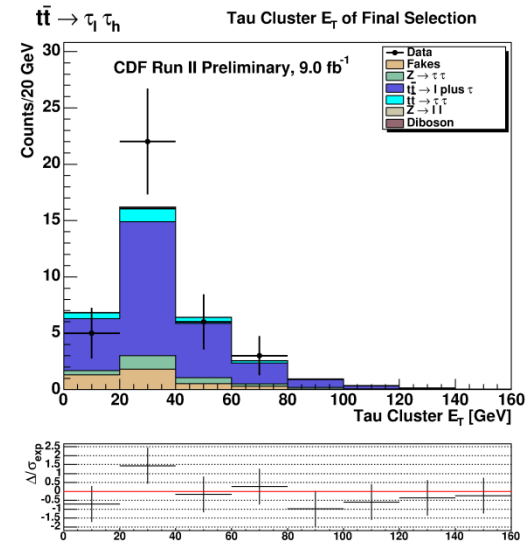
$$BR_{\ell\tau} = 2 \cdot BR(t \to \ell\nu b) \cdot BR(t \to \tau\nu b) \cdot BR(\tau \to \text{jet } \nu)$$

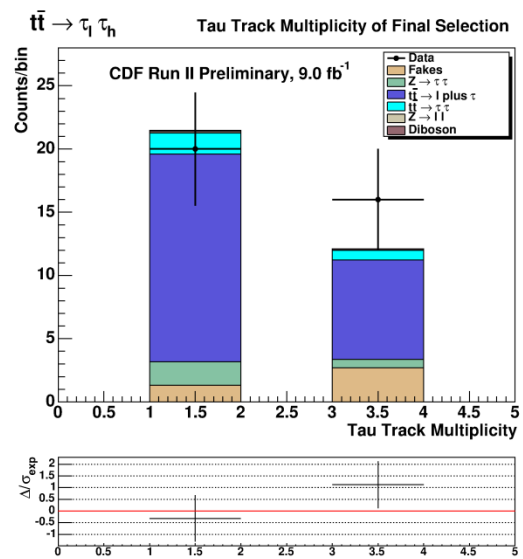
$$BR_{\tau\tau} = 2 \cdot BR(t \to \tau\nu b)^2 \cdot BR(\tau \to \ell\nu\nu) \cdot BR(\tau \to \text{jet } \nu)$$

$$\sigma_{t\bar{t}} = 8.2 \pm 2.3(stat.)^{+1.2}_{-1.1}(syst.) \pm 0.5(lum.) \text{ pb}$$

$$BR(t \to \tau\nu b) = \frac{1}{2BR(W \to \ell\nu)} \frac{N_{sel} - \sum_i N^i_{bg}}{\sigma_{t\bar{t}} \sum_{CMX,\ CMUP,\ CEM} \epsilon_{\ell\tau} \int \mathcal{L}_i dt}$$

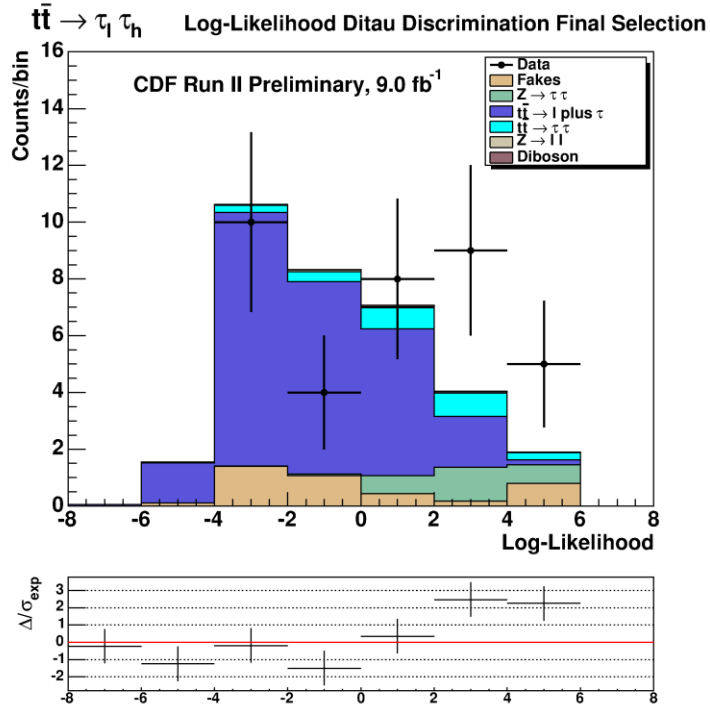
$$BR(t \to \tau\nu b) = 0.120 \pm 0.030(stat.)^{+0.022}_{-0.019}(syst.) \pm 0.007(lum.)$$





Ditau Event Discrimination

- Log-Likelihood ratio discriminant for ditau separation
  - Signal: top pair into ditau decay mode
  - Background: top pair into lepton plus tau mode
- Variables
  - $M_T(lep, ME_T)$
  - $|\Delta\phi(lep, MET)|$
  - Pt_{lep}



- Fit on the Log-Likelihood distribution
  - BR ($t \rightarrow \tau\nu b$)

$$BR(t \rightarrow \tau\nu b) = 0.098 \pm 0.022(stat.) \pm 0.014(syst.)$$

$$BR(t \rightarrow \tau\nu b) < 0.159 \text{ at } 95\% \text{ C.L.}$$

Summary

- Single top cross section measurement

$\sigma_{st} = 3.04^{+0.57}_{-0.53}$ pb $\sigma_s = 1.81^{+0.63}_{-0.58}$ pb $\sigma_t = 1.49^{+0.47}_{-0.42}$ pb.

$|V_{tb}|$ measurement

$|V_{tb}| = 0.96 \pm 0.09(\text{stat} + \text{sys}) \pm 0.05(\text{theory})$ $|V_{tb}| > 0.78$ @ 95% CL

- Top pair cross section in dileptonic modes

Electron and muon pre-tag $\sigma_{t\bar{t}} = 7.66 \pm 0.46_{\text{stat}} \pm 0.66_{\text{syst}} \pm 0.47_{\text{lumi}}$ pb

Electron and muon 1 b-tag $\sigma_{t\bar{t}} = 7.47 \pm 0.50_{\text{stat}} \pm 0.53_{\text{syst}} \pm 0.46_{\text{lumi}}$ pb

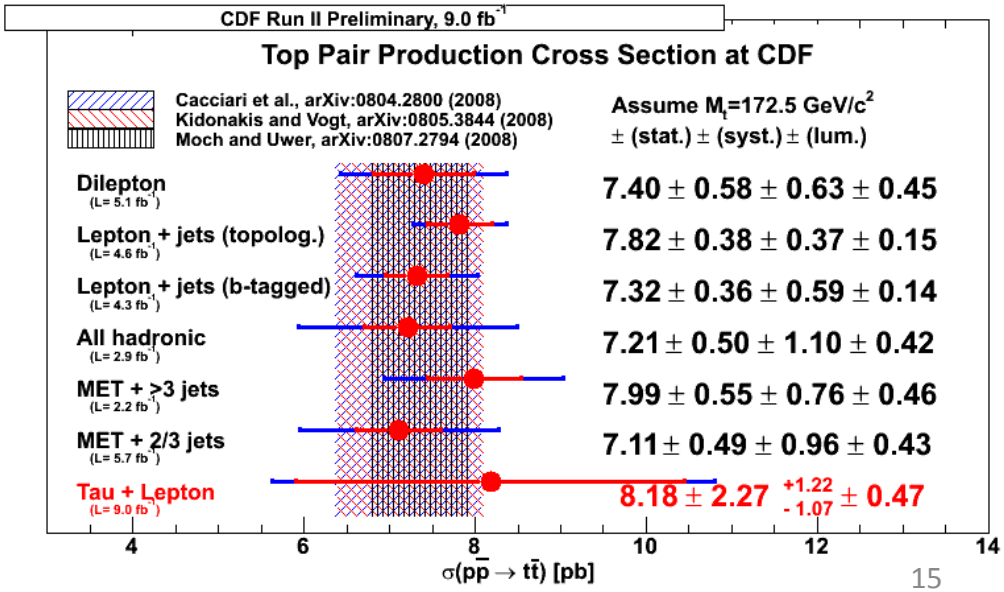
Electron plus tau final state:

$\sigma_{t\bar{t}} = 8.2 \pm 2.3(stat.)^{+1.2}_{-1.1}(syst.) \pm 0.5(lum.)$ pb.

Ditau component

$BR(t \to \tau\nu b) = 0.098 \pm 0.022(stat.) \pm 0.014(syst.)$

$BR(t \to \tau\nu b) < 0.159$ at 95% C.L.



Back Up

Single Top: Selection Requirements

- Exactly 1 lepton $E_T > 20$ GeV
- $ME_T > 25$ GeV
- Exactly 2 or 3 Jets, $E_T > 20$ GeV
- 1 b-tagged jet
- QCD Veto
  - $M_T^W > 20$ GeV (> 10 GeV for central muons)
  - Correlation ME_T^{sig} and ME_T with $|\Delta\phi(\text{jet}, ME_T)|$

EW Processes	Theoretical Cross Section (pb)
$t\bar{t}$	7.3 ± 0.6
Single Top (s-ch)	1.0 ± 0.1
Single Top (t-ch)	2.1 ± 0.2
Single Top (Wt-ch)	0.2 ± 0.1
WW	11.3 ± 0.7
WZ	3.2 ± 0.2
ZZ	1.2 ± 0.1
Z+Jets	787 ± 85

Processes	W + 2 jets, 1 tag	W + 3 jets, 1 tag	W + 2 jets, 2 tag	W + 3 jets, 2 tag
$t\bar{t}$	474 ± 49	1067 ± 109	98 ± 14	284 ± 42
WW	148 ± 21	48 ± 7	1.1 ± 0.3	1.2 ± 0.3
WZ	53 ± 6	14 ± 2	8.8 ± 1.3	2.4 ± 0.4
ZZ	1.7 ± 0.2	0.7 ± 0.1	0.3 ± 0.0	0.1 ± 0.0
Z+Jets	118 ± 15	46 ± 6	4.8 ± 0.7	2.7 ± 0.4
Wbb	1452 ± 437	434 ± 131	183 ± 56	65 ± 20
Wcc	766 ± 233	254 ± 77	10 ± 3	7 ± 2
Wcj	583 ± 177	128 ± 39	7.8 ± 2.4	3.5 ± 1.1
W+Mistags	1459 ± 148	433 ± 47	7.4 ± 1.5	5.4 ± 1.1
Non-W	316 ± 126	141 ± 57	6.8 ± 3.5	3.4 ± 3.2
t-channel	193 ± 25	84 ± 11	6 ± 1	15 ± 2.4
s-channel	128 ± 11	43 ± 4	32 ± 4	12 ± 1.6
Wt-channel	16 ± 4	26 ± 7	0.7 ± 0.2	2.3 ± 0.6
Total Prediction	5707 ± 877	2719 ± 293	367 ± 66	403 ± 53
Observed	5533	2432	335	355

Single Top: NN Input Variables

- Most Sensitive variables
  - Reconstructed top mass
  - Flavor separator
  - Dijet invariant mass
  - (lepton Q) x (jet h)

	2-jet		3-jet	
variable	1-tag	2-tag	1-tag	2-tag
$M_{\ell\nu b}$	✓	✓	✓	
$M_{\ell\nu bb}$		✓		✓
$M_{\mathrm{t}}^{\ell\nu b}$	✓	✓	✓	✓
M_{jj}	✓	✓	✓	✓
M_{t}^{w}	✓	✓		
$E_{\mathrm{t}}^{b_{\mathrm{top}}}$		✓	✓	
$E_{\mathrm{t}}^{b_{\mathrm{other}}}$				✓
$\sum e_{\mathrm{t}}^{jj}$			✓	✓
$E_{\mathrm{t}}^{\mathrm{light}}$	✓			✓
p_{t}^{ℓ}	✓			
$p_{\mathrm{t}}^{\ell\nu jj}$			✓	✓
H_{t}	✓		✓	
$\not{E}_T$		✓		
$\not{E}_{T\,\mathrm{sig}}$			✓	
$\cos\theta_{\ell j}$	✓		✓	✓
$\cos\theta_{\ell w}^{w}$	✓			
$\cos\theta_{\ell w}^{t}$	✓			
$\cos\theta_{jj}^{t}$		✓		✓
$Q \times \eta$	✓		✓	✓
η_{ℓ}		✓		
η_{w}	✓	✓		
$\sum \eta_{j}$	✓		✓	
$\Delta\eta_{jj}$			✓	✓
$\Delta\eta_{t,\mathrm{light}}$			✓	
$\sqrt{\hat{s}}$				✓
Centrality				✓
Jet flavor separator	✓	✓	✓	

Single Top: Systematics

- Rate and Shape Systematics

Source of Uncertainty	Rate	Shape	Processes affected
Jet energy scale	0–8%	X	all
Initial and final state radiation	0–6%	X	single top, $t\bar{t}$
Parton distribution functions	0–1%	X	single top, $t\bar{t}$
Acceptance and efficiency scale	1–7%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Luminosity	6%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Jet flavor separator		X	all
Mistag model		X	W+light
Non-W model		X	Non-W
Factorization and renormalizatio		X	$Wb\bar{b}$
Jet η and ΔR distribution		X	W+light
Non-W normalization	40%		Non-W
$Wb\bar{b}$ and $Wc\bar{c}$ norm	30%		$Wb\bar{b}$, $Wc\bar{c}$
Wc normalization	30%		Wc
Mistag normalization	10–20%		W+light
$t\bar{t}$ normalization	8%		$t\bar{t}$
Monte Carlo generator	3–7%		single top, $t\bar{t}$
Single top normalization	7%		single top
Top mass	2-12%	X	single top, $t\bar{t}$

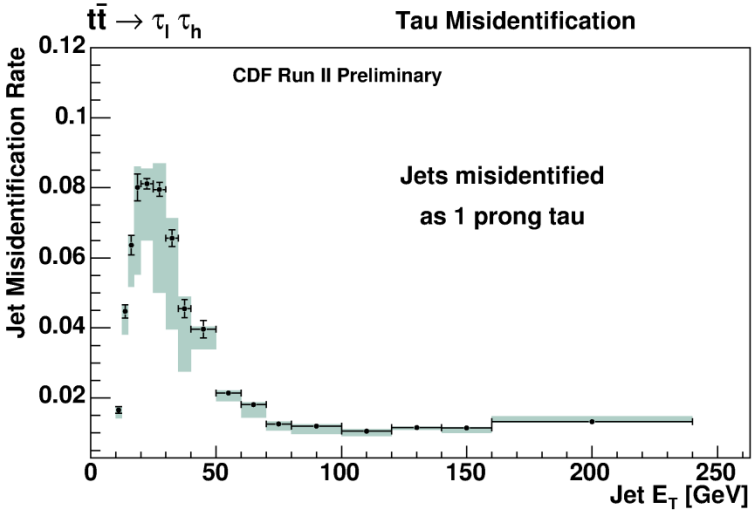
$*$ X indicates the sources of uncertainty from shape variation
$*$ Sources listed below double line are used only in $|V_{tb}|$ measurement

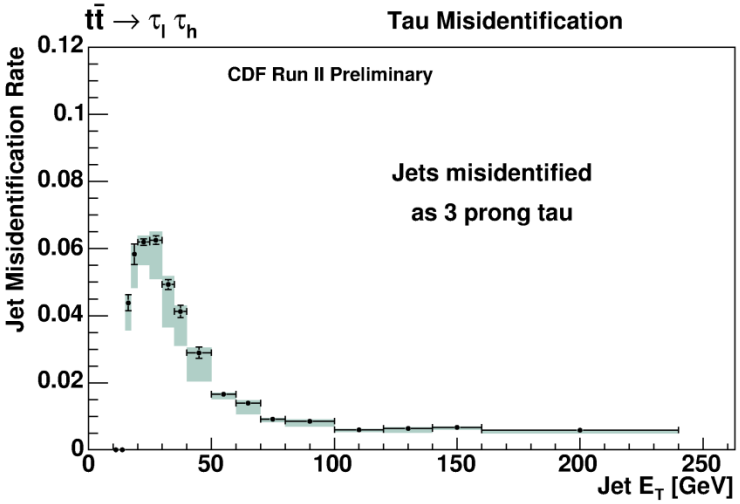
Top Pair into Dilepton Mode: Selection

- Selection
  - 2 leptons requirement: electron or muon
    $P_T > 20$ GeV/c
    Opposite sign
  - At least 2 jets
    $E_T > 15$ GeV, $|\eta| < 2.5$
  - $ME_T > 25$ GeV
    (> 50 GeV if $|\Delta\phi(\text{lep,MEt})| < 20^\circ$)
  - $M_{ll} > 5$ GeV
  - Summed transverse energy $H_T > 200$ GeV

Top Pair into Dilepton Mode with Tau: Samples and Background

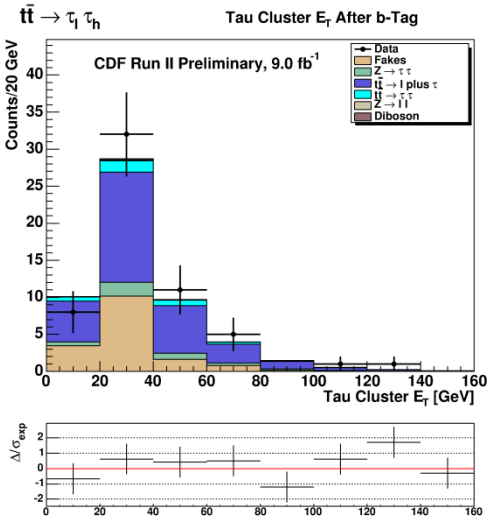
- Low P_T trigger samples
  - Lepton E_T > 8 GeV
  - Isolated track P_T > 5 GeV/c
- Physics Background
  - Drell-Yan process
  - Diboson: WZ, ZZ, WW
- Background with misidentified objects
  - Jet misidentification in tau
- Events with fakes from data
  - Evaluate jet misidentification rate
  - Inclusive single lepton sample

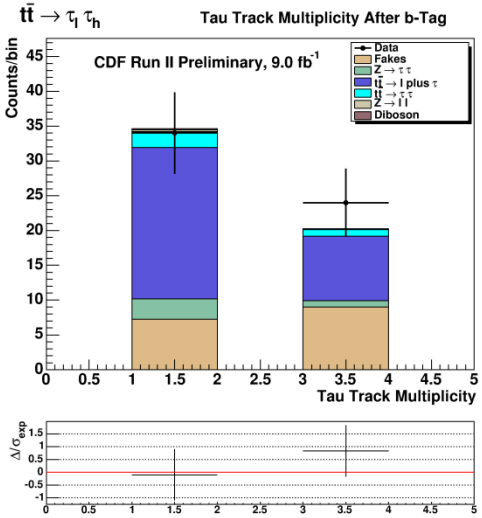




Top Pair into Dilepton Mode with Tau: Kinematic Selection

- Exactly 1 lepton and 1 tau
  - Opposite charge
- Z → ll removal
- At least 2 jets
  - Leading Jet E_T > 20 GeV
  - Second Jet E_T > 15 GeV
  - $|\eta| < 2$
- ME_T > 10 GeV
- **Ht ≡ Et_τ + MEt + ΣEt_{jet}> 150 GeV** (> 155 GeV for 3 prong taus)
- At least 1 b-tag jet





Log-Likelihood Discrimination of Fakes

- Rate systematics
  - Theoretical
  - MC generator
  - Jet and tau energy correction
  - b-tag
  - Fake rate

$t\bar{t} \to \tau_\ell \tau_h + X$	Uncertainties of Final Selection					
Process	$Z/\gamma^* \to \tau\tau$	$Z/\gamma^* \to \ell\ell$	**Diboson**	$t\bar{t} \to \tau\ell + X$	$t\bar{t} \to \tau\tau + X$	**fakes**
Trigger	±3%	±3%	±3%	±3%	±3%	±3%
Cross Section	±15%	±15%	±6%	–	–	–
PDF	–	–	–	±0.5%	±0.5%	–
Showering	–	–	–	±3%	±3%	–
Color Recon.	–	–	–	±4%	±4%	–
ISR/FSR	–	–	–	±9%	±9%	–
Pile Up	–	–	–	±2.5%	±3%	–
JEC	±9%	±20%	±20%	±2%	±3%	–
τ E_T scale	±4%	±20%	±20%	±0.5%	±1.5%	–
τ ID scale	±3%	–	±3%	±3%	±3%	–
SECVTX Tag	±5%	±5%	±5%	±5%	±5%	–
SECVTX Mistag	±20%	±20%	±20%	–	–	–
Fake Rate	–	–	–	–	–	$^{+7\%}_{-20\%}$

CDF Run II Preliminary, 9.0 fb^{-1}