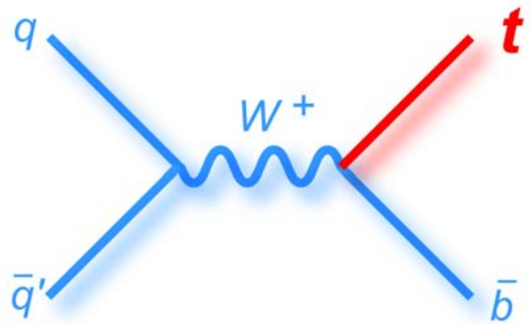
Evidence for Single Top Quark Production at DØ

Outline

- Single Top - Introduction and Motivation
- Event Signatures and selection
- Signal and Background Modeling
- Search Strategy
- Decision Tree Analysis
- Results with 1 fb^{-1} Data

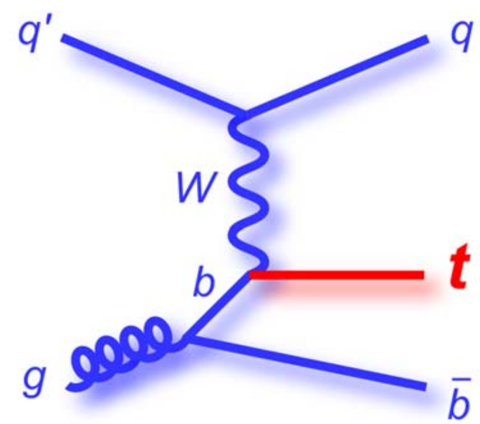
Single Top Overview

NLO cross sections at mt = 175 GeV,
Phys. Rev. D **70** 114012 (2004)



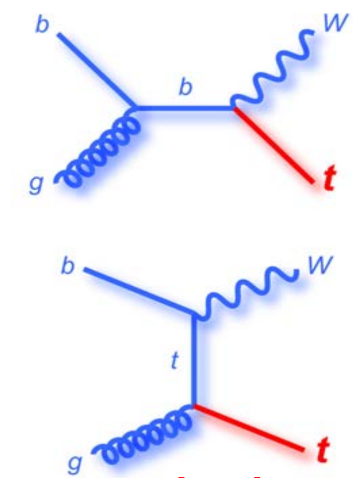
s-channel: "*tb*"

σ_{NLO} = 0.88 ± 0.11 pb



t-channel: "*tqb*"

σ_{NLO} = 1.98 ± 0.25 pb



"*tW* production"

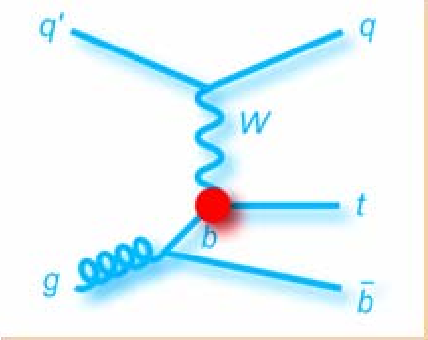
σ_{NLO} = 0.21 pb

(Too small to see at the Tevatron)

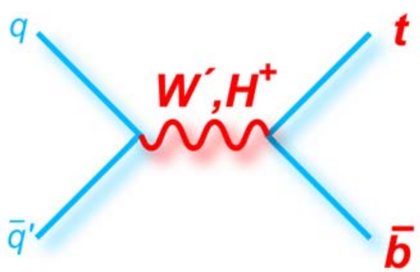
Experimental results (95% C.L.)

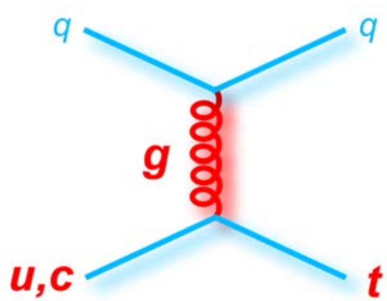
- DØ *tb* < 5.0 pb (370 pb^{-1})
- CDF *tb* < 3.2 pb (700 pb^{-1})
- DØ *tqb* < 4.4 pb (370 pb^{-1})
- CDF *tqb* < 3.1 pb (700 pb^{-1})
- CDF *tb+tqb* < 2.7 pb Likelihoods (960 pb^{-1})
  tb+tqb < 2.6 pb Neural networks
  tb+tqb = $2.7^{+1.5}_{-1.3}$ pb Matrix elements (significance of 2.3 σ)

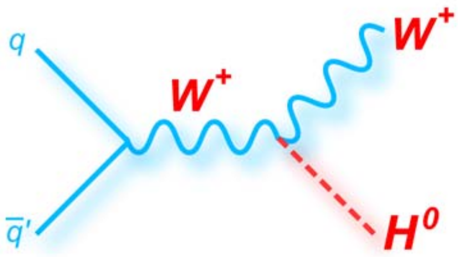
Why Look for Single Top?



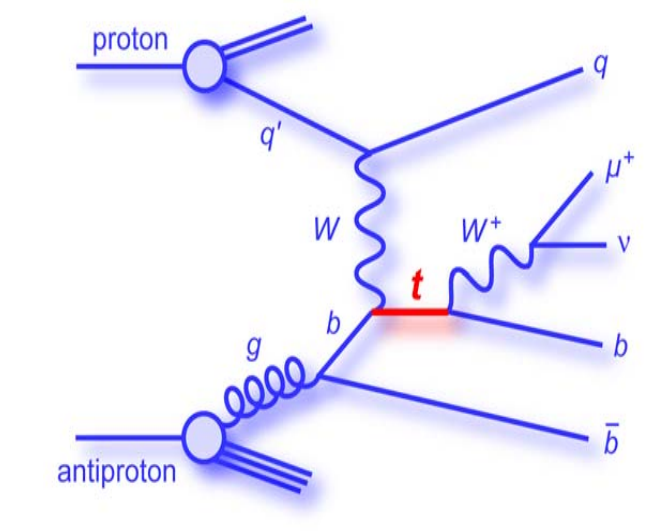
- Prediction of SM not observed so far
- Study *Wtb* coupling in top production
  - Measure $|V_{tb}|$ directly
  - Test unitarity of CKM matrix
  - Anomalous *Wtb* couplings
- Cross sections sensitive to new physics
  - s-channel: resonances (heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.)
  - t-channel: flavor-changing neutral currents ($t - Z / \gamma / g - c / u$ couplings)
  - Fourth generation of quarks
- Similar search for *WH* associated Higgs production
  - Backgrounds the same – must be able to model them successfully
  - Test of techniques to extract a small signal from a large background



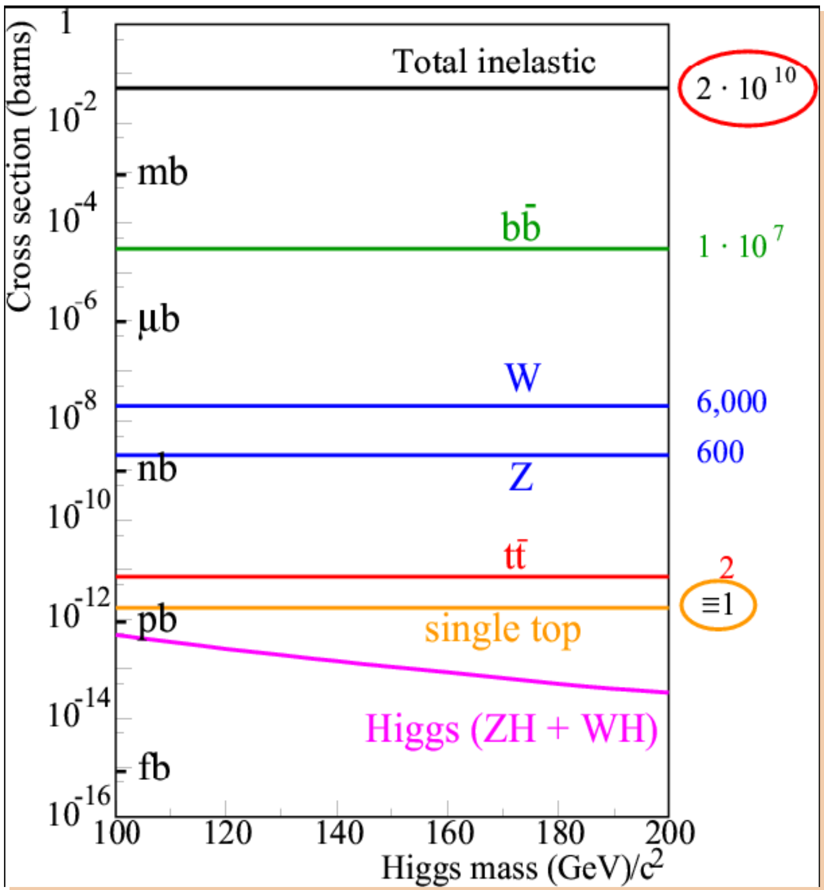




Event Signatures and Selection



$t\bar{t}$, W+jets, and multijets are the main processes that can mimic signal signatures

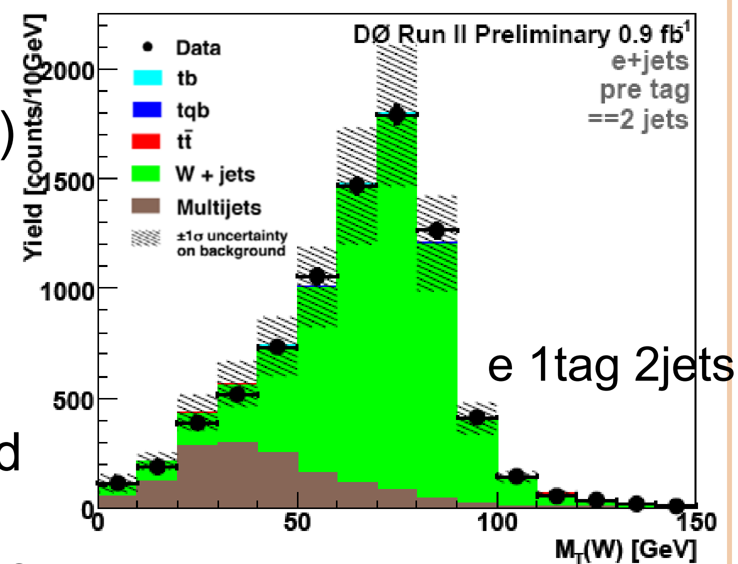


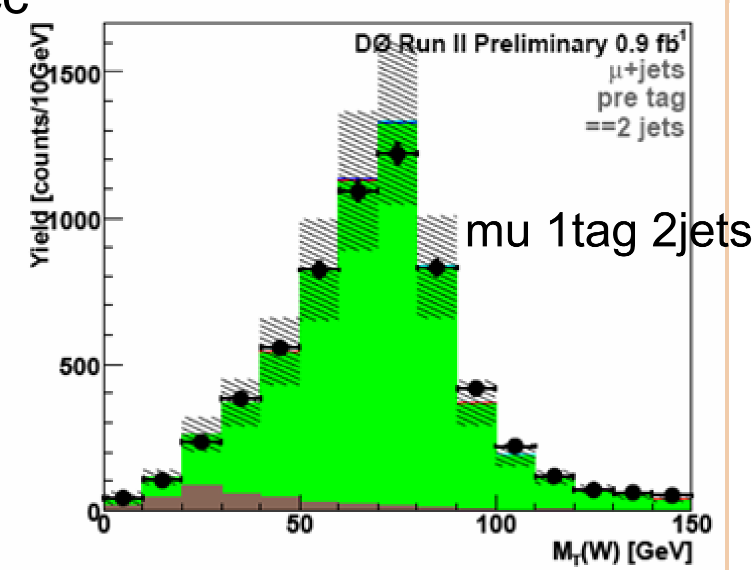
- One isolated electron or muon
  - Electron $p_T > 15$ GeV, $|\eta| < 1.1$
  - Muon $p_T > 18$ GeV, $|\eta| < 2.0$
- Missing transverse energy > 15 GeV
- One b-tagged jet and at least one more jet
  - 2–4 jets with $p_T > 15$ GeV, $|\eta| < 3.4$
  - Leading jet $p_T > 25$ GeV, $|\eta| < 2.5$
  - Second leading jet $p_T > 20$ GeV

Signal and Background Modeling

- Single top signal:
  - -Modeled with CompHEP (effective NLO)
  - -Pythia for hadronization
- *W+jets* background:
  - -Event kinematics modeled using ALPGEN
  - -Normalized to data before b tagging and after subtracting other backgrounds
  - -Additional scale factor for Wbb and Wcc
- $t\bar{t}$ pair backgrounds:
  - -Modeled using ALPGEN
  - -PYTHIA for parton hadronization
  - -Normalized to NNLO cross section
- Multijet background

  Modeled using data with a non-isolated lepton and jets





Event Yields After *b*-Tagging

Before b-tagging

- Signal acceptances: *tb* = 5.1%, *tqb* = 4.5%
- S:B ratio for *tb*+*tqb* = 1:180
- To improve S:B select only events with *b*-jets in them

Source	Event Yields in 0.9 fb^{-1} Data — Electron+muon, 1tag+2tags combined: 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \to ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \to l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

After b-tagging

- Signal acceptances: *tb* = (3.2 ± 0.4)%, *tqb* = (2.1 ± 0.3)%
- Signal:background ratios for *tb*+*tqb* are 1:10 to 1:50

Source of Uncertainty	Size
Top pairs normalization	18%
W+jets & multijets normalization	18–28%
Integrated luminosity	6%
Trigger modeling	3–6%
Lepton ID corrections	2–7%
Jet modeling	2–7%
Other small components	Few %
Jet energy scale	1–20%
Tag rate functions	2–16%

- Single top signal is smaller than total background uncertainty

Counting events is not a sensitive enough method –

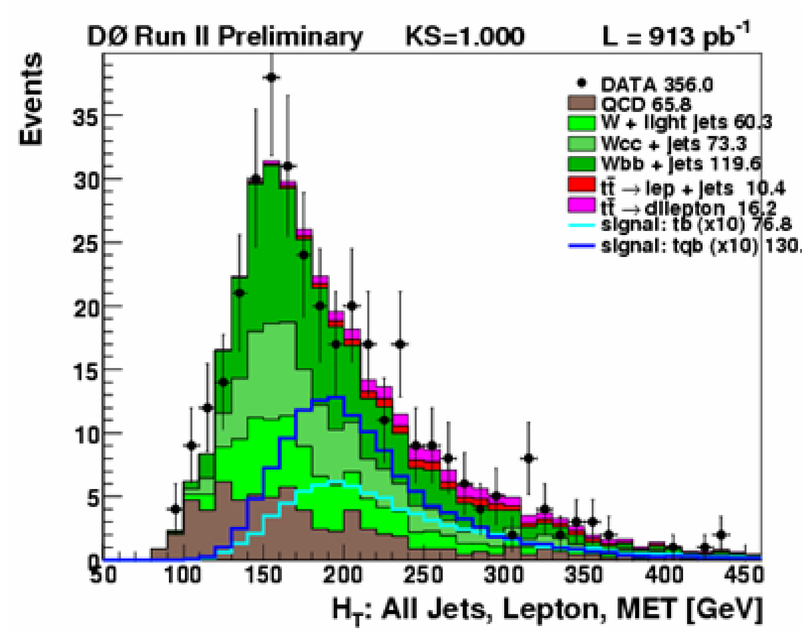
Multivariate discriminant to separate signal from background

Search Strategy

- Maximize the signal acceptance
- Separate signal from background using multivariate techniques
  - 12 independent sets of data for final analysis
  - ~50 variables in every channel
  - Calculate discriminants that separate signal from background
    - Boosted decision trees
    - Matrix elements
    - Bayesian neural networks
- control samples
- Use ensembles of pseudo-data to test validity of methods

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

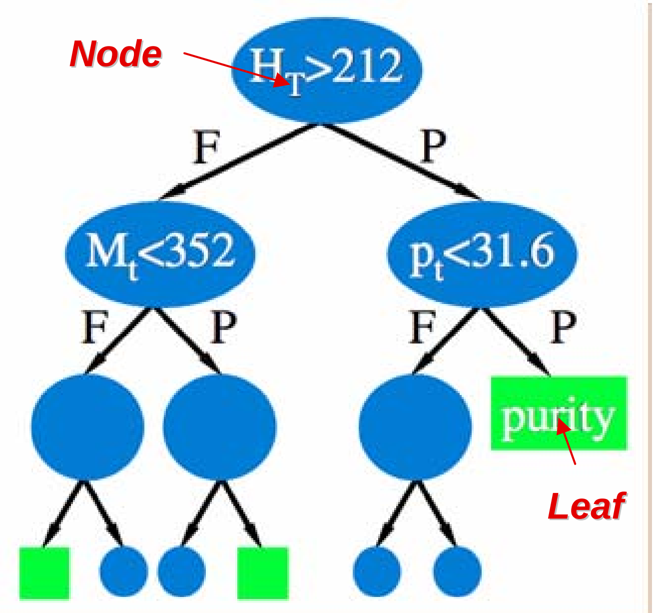


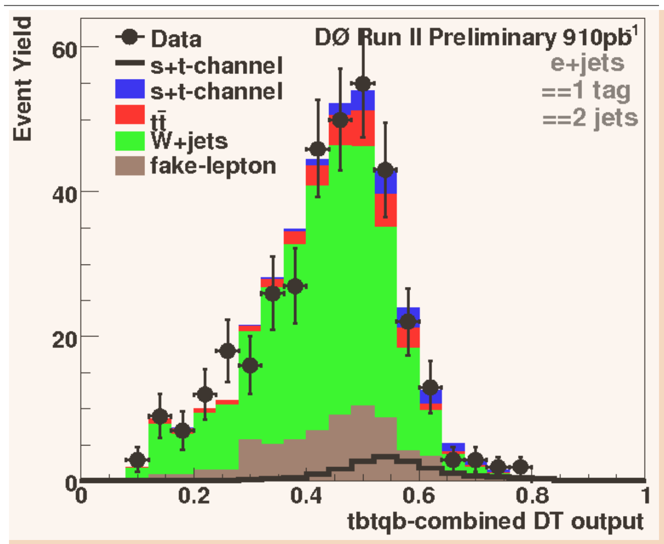
Boosted Decision Trees

- Machine-learning technique, widely used in social sciences, some use in HEP
  - Start at first "node": For each variable, find splitting value (cut) with best separation between two children nodes (mostly signal in one, mostly background in the other)
  - Select variable and splitting value with best separation to produce two "branches". Repeat recursively on each node
  - Stop when improvement stops or when too few events are left
  - Decision tree output for each event = leaf purity closer to 1(0) for signal (background)

$$Purity = \frac{N_{Signal}}{N_{Signal} + N_{Background}}$$

- Improve performance of DT by using boosting, which averages over many trees





Decision Tree Analysis

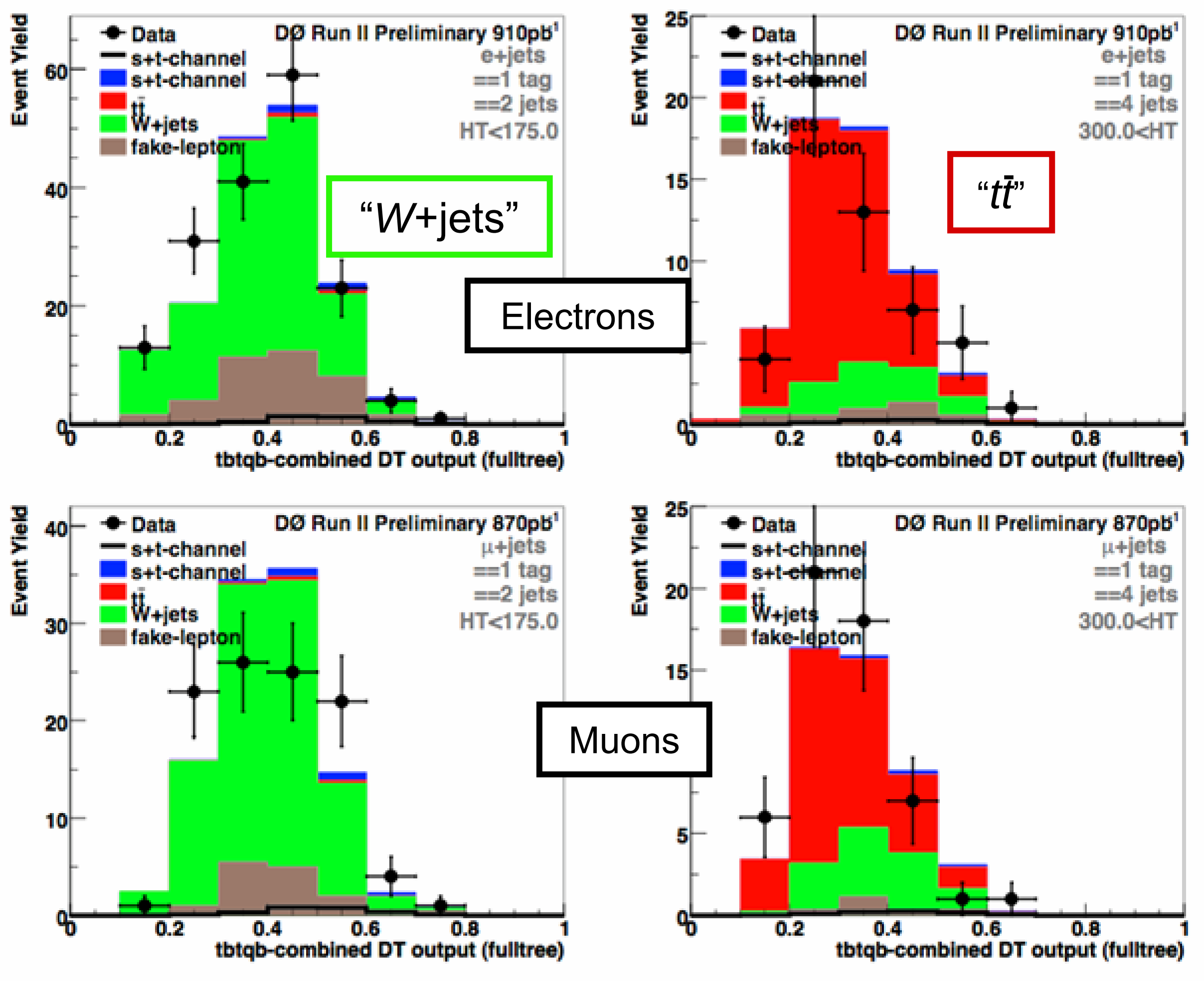
- Trained 12 sets of trees: (*tb*+*tqb*) x (*e*,μ) x (2,3,4 jets) x (1,2 *b*-tags)
- Search for *tb*+*tqb* has best sensitivity to see a signal
- 49 input variables - Same list of variables used for all analysis channels

Cross Checks

- Select two background-dominated samples:

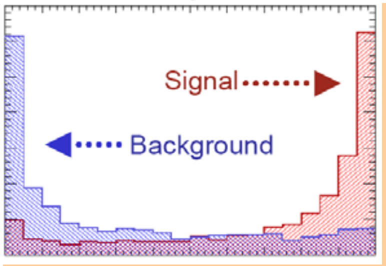
"*W*+jets": = 2 jets, 1 tag, HT(lepton,MET,alljets)<175GeV

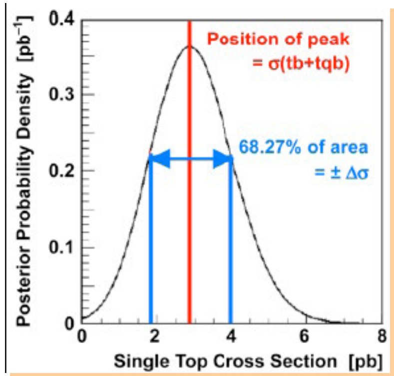
"$t\bar{t}$": = 4 jets, =1 tag HT(lepton,MET,alljets)>300GeV



Statistical Analysis

- Cross Section Measurement
  - Binned likelihood from discriminant distribution
  - Compute posterior probability density of tb+tqb using Bayes' theorem:
    - Flat positive-defined prior for the cross section
    - Systematic uncertainties are treated as Gaussian nuisance parameters
  - 12 distributions (e, mu, 1tag, 2tag, 2,3,4 jets) with 100 bins each go into this calculation



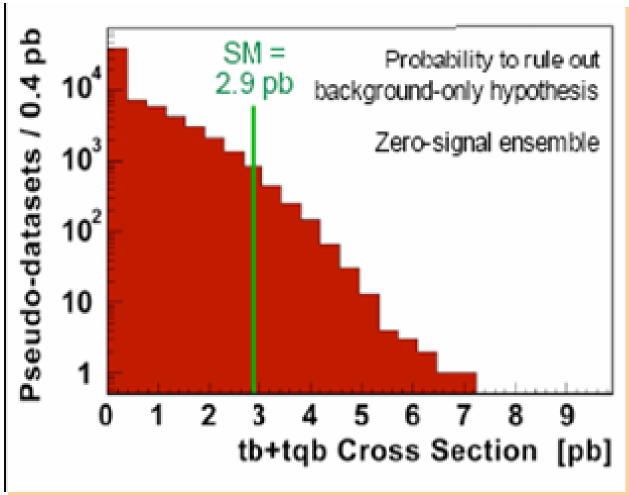


- Significance

"excess in data over background"

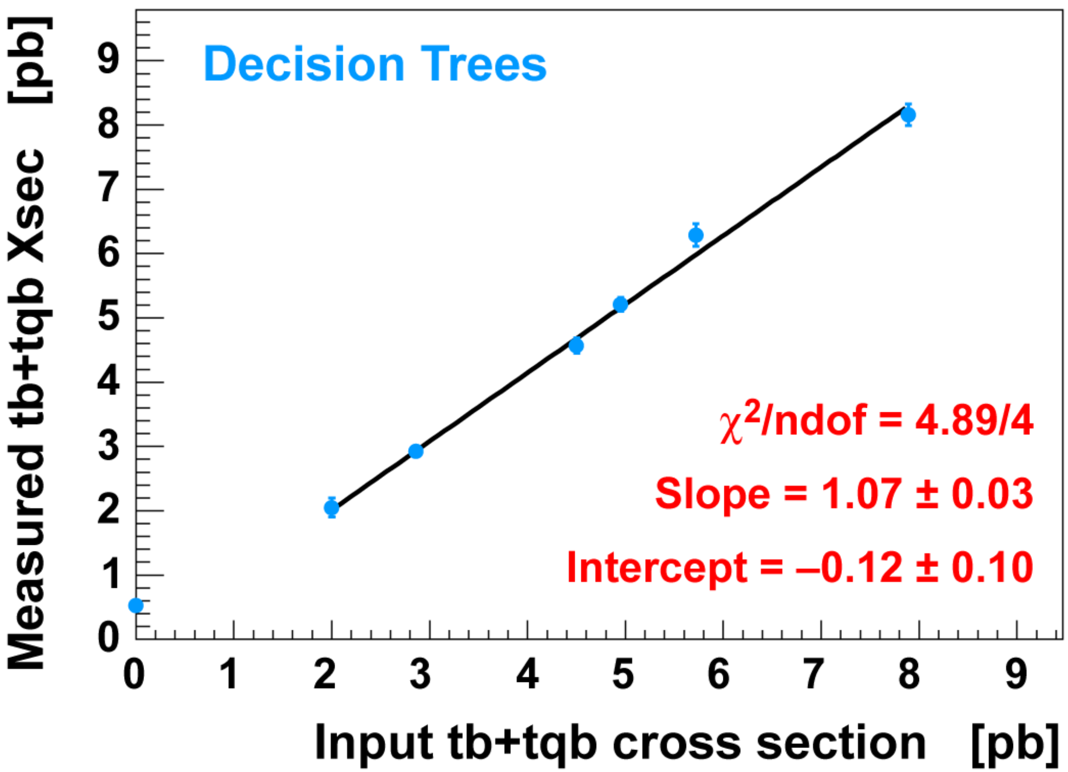
P-value: assuming a null hypothesis,
what the probability to get a count equal to or greater than the count observed

We use "background only" ensembles to calculate p-value

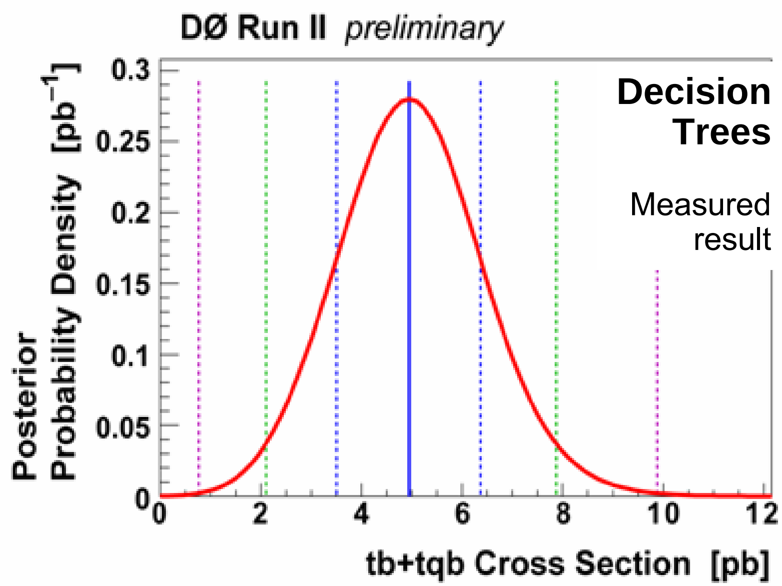


Decision Tree Verification

- Use many ensembles with different input signal cross sections but assuming a SM cross section ration of σs/σt = 0.44
- Measure signal cross section using decision tree outputs
- Compare measured cross sections to input ones



Decision Tree Results



Expected:

$\sigma(tb+tqb)$ = $2.7^{+1.6}_{-1.4}$ pb

p-value = 1.9 %

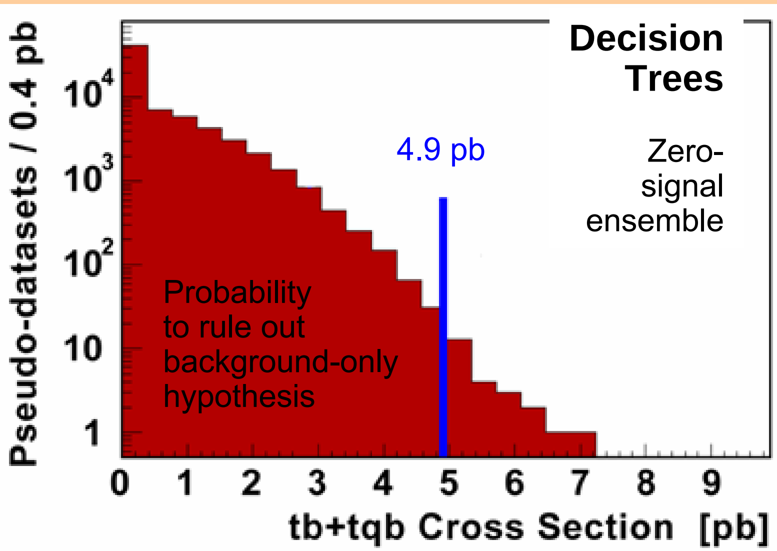
Significance = 2.1 σ

Measured:

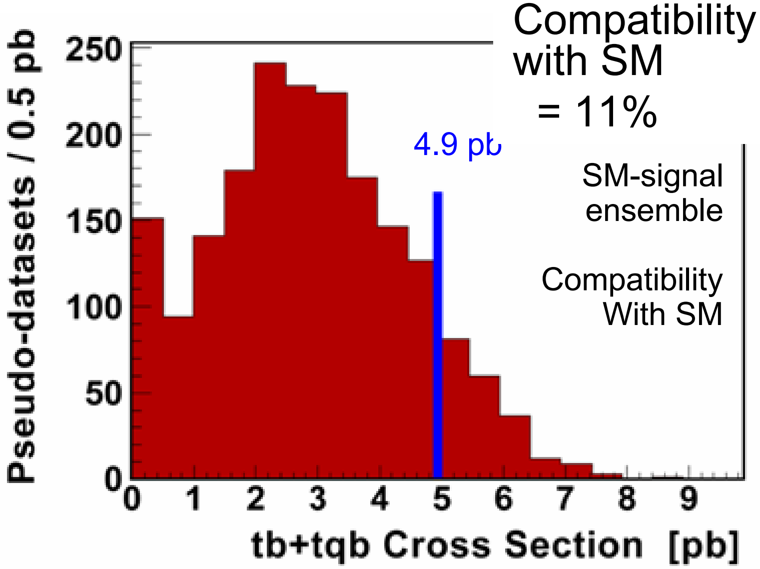
$\sigma(tb+tqb)$ = 4.9 ± 1.4 pb

p-value = 0.035 %

significance = 3.4 σ



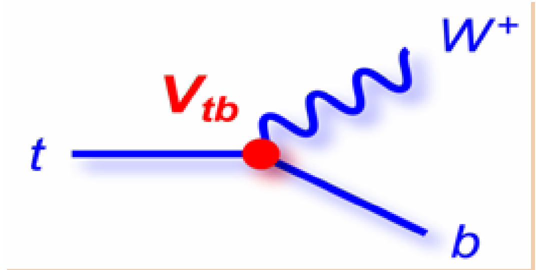
Compatibility with SM = 11%



Measuring |*Vtb*|

Most general *tbW* vertex:

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu \left[f_2^L P_L + f_2^R P_R \right] \right\}$$



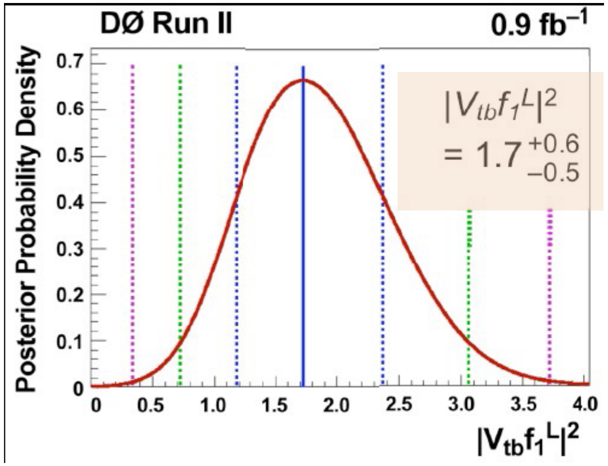
Within the SM:

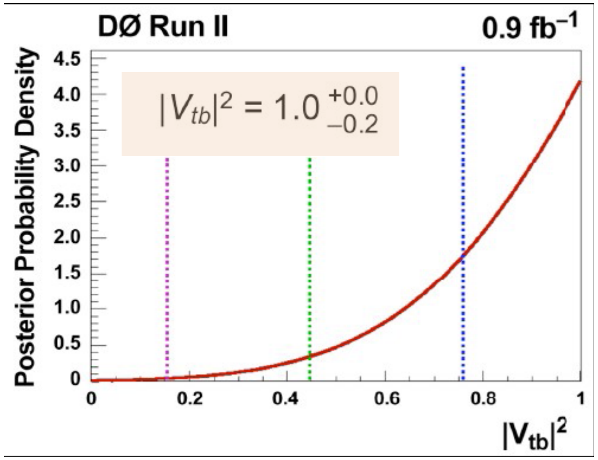
- 3-generation and unitary CKM matrix
- CP conserving pure V–A interaction:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Measure V_{tb} assuming:

- No constraint on number of generation and unitarity of CKM matrix
- CP conserving pure V-A interaction, but not necessarily of SM strength





Strength of $V-A$:

$$|V_{tb} f_1^L| = 1.3 \pm 0.2$$

assuming $f_1^L = 1$:

$$0.68 \le |V_{tb}| \le 1 \ @ \ 95\% \ CL$$

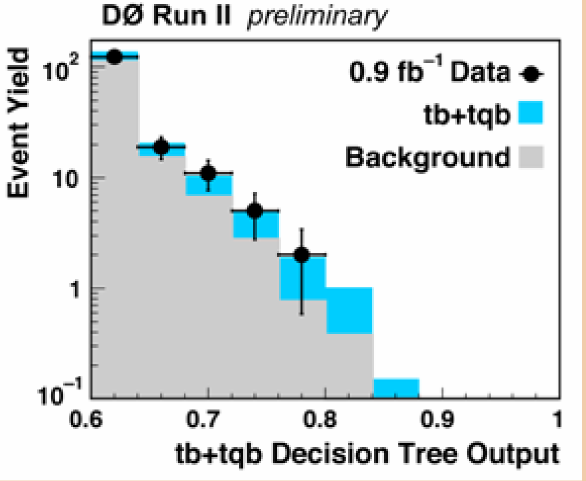
Summary:

First Evidence for Single Top Production

We calculate a cross section for single top production

$$\sigma\left(p\bar{p} \to tb + tqb + X\right) = 4.9^{+1.4}_{-1.4}\ \text{pb}$$

3.4 σ significance



First direct measurement of |*Vtb*|

$0.68 < |V_{tb}| \leq 1$ at 95% C.L.

Outlook:

- We have already collected more than twice the data used for this analysis
Hopefully, evidence will turn into observation soon!

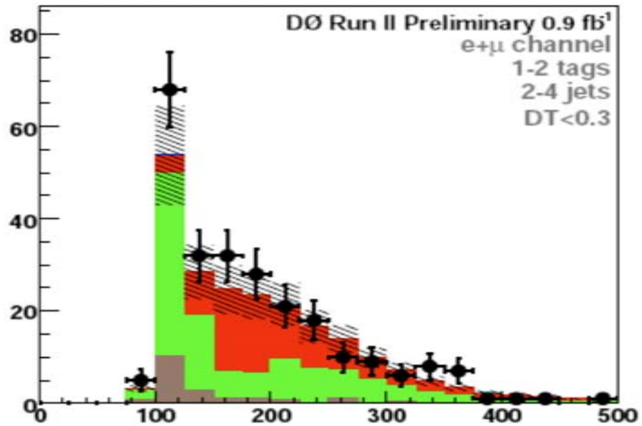
- With Tevatron breaking its own Luminosity records every week, and with all the experience gained in search for single top, we are already closing in on many things, including Higgs – so,

stay tuned for more exciting news from the Tevatron!!!

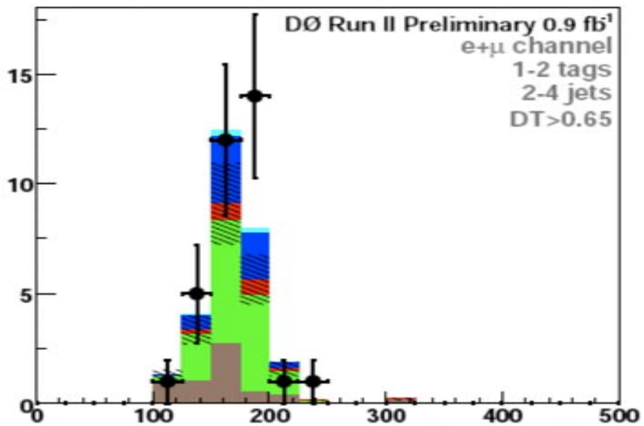
DT Event Characteristics

DT Discriminant < 0.3

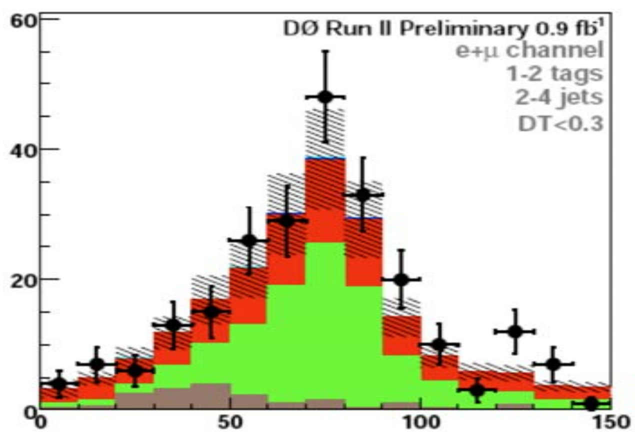
DT Discriminant > 0.65



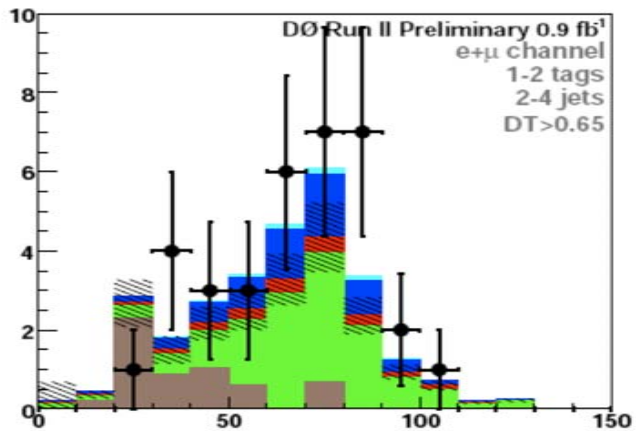
Mass (lepton,$\not{E}_T$,btagged-jet) [GeV]



Mass (lepton,$\not{E}_T$,btagged-jet) [GeV]



W Transverse Mass [GeV]



W Transverse Mass [GeV]