

Discovery of Single Top Quark Production

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Thank you!

- **SFU High Energy Physics Group**

Dugan, Yann, Zhiyi, Mike, Marco, Jen, Doug, Erf, Bernd, Rod, Jyothsna, Teresa, Michele, Michel, Noel, Rogayeh, Sara ...

- **DØ Single Top Group**

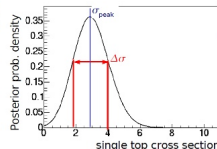
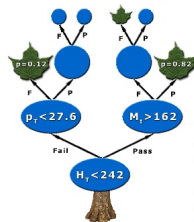
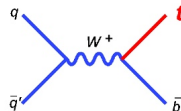
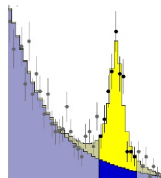
Reinhard, Ann, Aran, Cecilia, Jorge, Monica, Andres, Gustavo, Liang ...

- **The committee**

Dugan, Mike, Reda

Outline

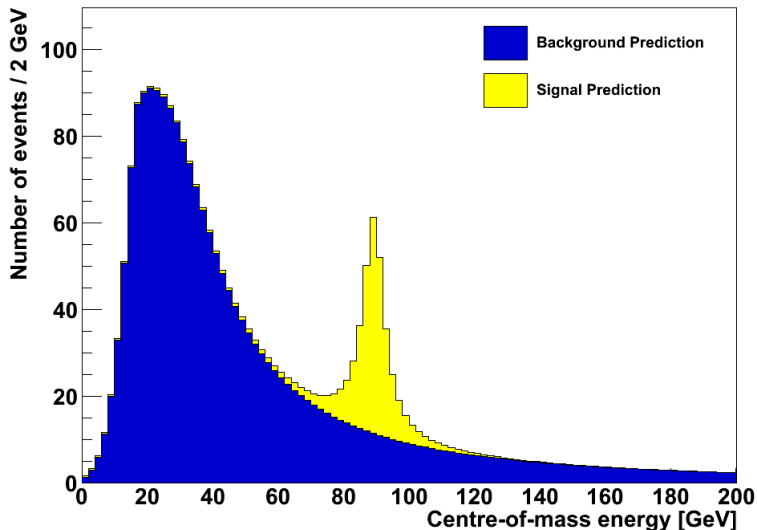
- 1 What is a **“discovery”**?
- 2 What is **single top** quark production?
- 3 Experimental setup and data collection
- 4 Event selection, signal and background modeling
- 5 **Boosted decision trees** and the measurements
- 6 Summary



1. WHAT IS A “DISCOVERY”?

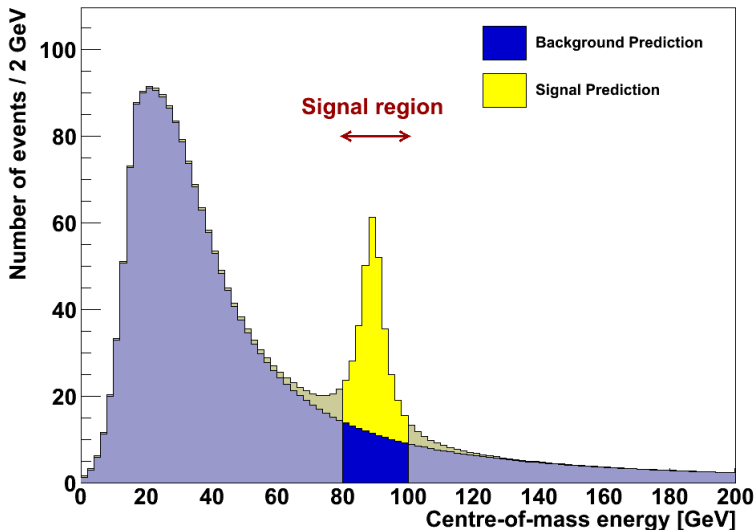


What is a discovery?



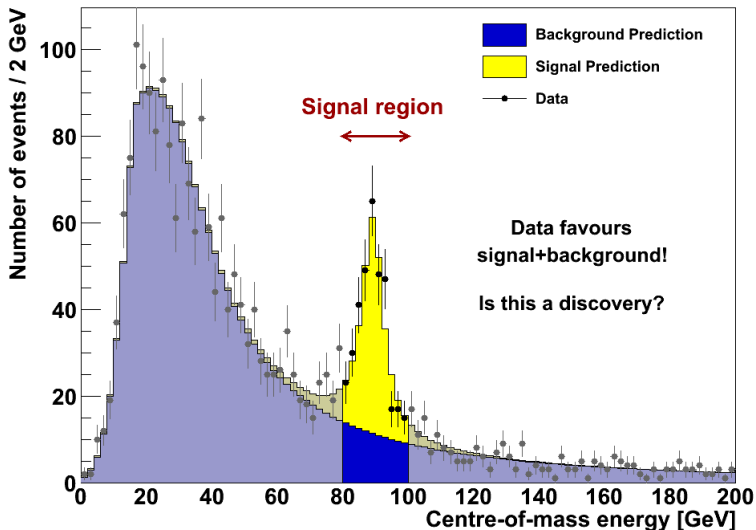
Distribution of background from known sources and a potential signal source.

What is a discovery?



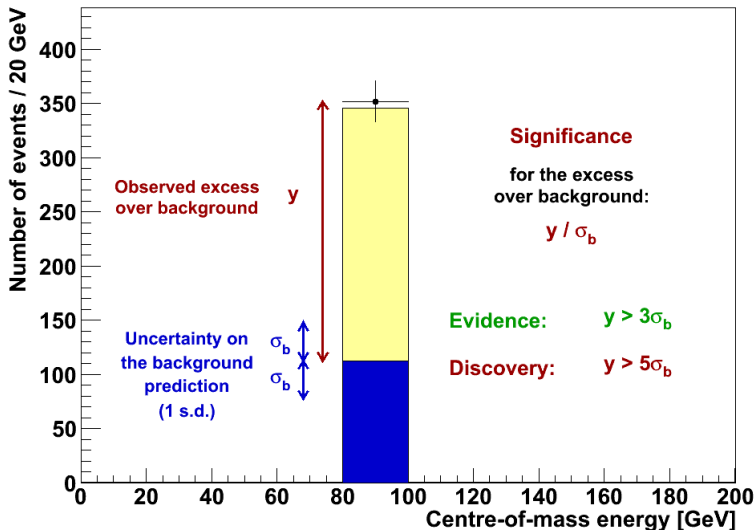
Signal model predicts an excess between 80 and 90 GeV

What is a discovery?



Signal model predicts an excess between 80 and 90 GeV

What is a discovery?



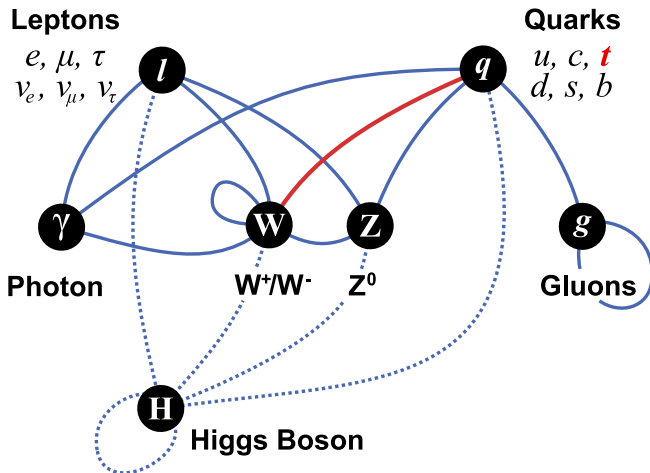
Probability for 3σ upward fluctuation: **0.135%**, 5σ : **0.000029%**

2. WHAT IS SINGLE TOP QUARK PRODUCTION?

The standard model

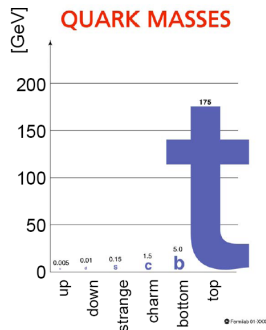
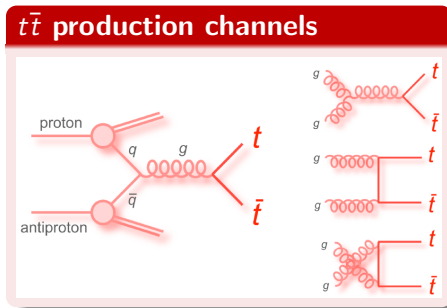
Describes 3 of the 4 fundamental interactions:

The *electromagnetic*, *weak* & *strong* interactions, but not gravity.



The top quark – strong production

- Discovered 1995 produced in **pairs** ($t\bar{t}$) via the **strong interaction** by the DØ and the CDF collaborations at Fermilab

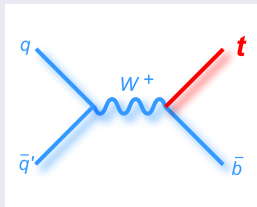


- By far the **heaviest fundamental particle** we know of
- Only quark that **decays before it hadronizes**: $t \rightarrow Wb$
- Couples strongly to the **Higgs** – might provide clues of the **origin of mass**

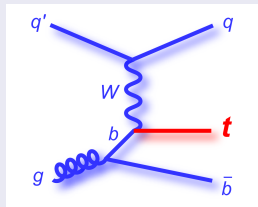
Electroweak **single top quark** production

Electroweak single top production:

s-channel (tb)



t-channel (tqb)



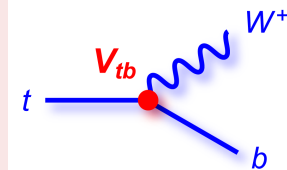
Standard model cross sections at the Tevatron:
 $\sigma_s = 1.12 \text{ pb}$, $\sigma_t = 2.34 \text{ pb}$, $\sigma_{s+t} = 3.46 \text{ pb}$ [†]

Motivation

- Measurement of top properties, e.g., **polarization**
- **Probe new physics**: 4th quark generation?
 $tb: W', H^\pm?$ $tqb: \text{FCNC?}$
- Background for $WH \rightarrow Wb\bar{b}$, **similar analysis**

Motivation: Wtb coupling

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & \mathbf{V_{tb}} \end{pmatrix}$$



- Direct $|V_{tb}|$ measurement
- Test CKM unitarity
- Anomalous Wtb couplings

[†] (N)NLO Cross section for $m_t = 170 \text{ GeV}$
 N. Kidonakis, Phys. Rev. D 74, 114012 (2006)

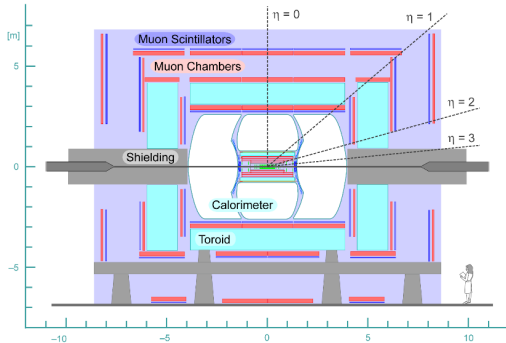
3. EXPERIMENTAL SETUP AND DATA COLLECTION



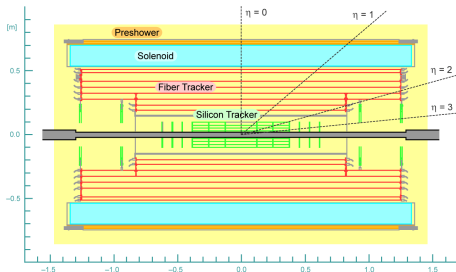
The **Tevatron**: $p\bar{p}$ collider, circumference 6.7 km

- Protons and antiprotons accelerated to 99.99995% of the speed of light
- Collided at centre-of-mass energy 1.96 TeV

The DØ detector



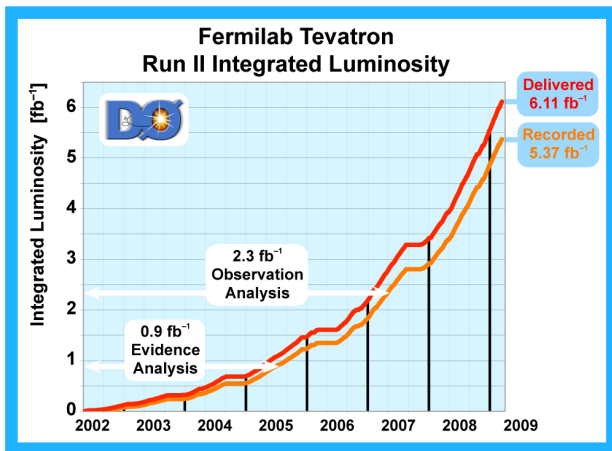
- Silicon and fiber tracker
- 2T Superconducting Solenoid
- Ur-LAr Calorimeter
- Muon system



Dataset

The data was recorded Aug 2002–Aug 2007 (weeks 65–330 in the plot)

Total integrated luminosity $\mathcal{L} = 2.3 \text{ fb}^{-1}$

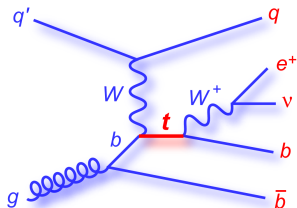


$2.3 \text{ fb}^{-1} \times 3.46 \text{ pb} \approx 7800 \text{ single top quark events}$ expected in dataset
(before any selection)

4. EVENT SELECTION AND BACKGROUND MODELING

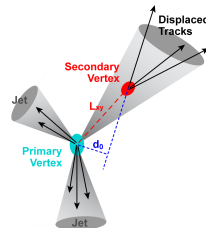
Event selection

Event signature:



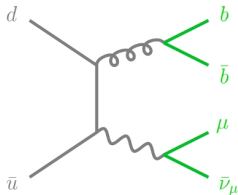
Event selection criteria

- High p_T isolated e or μ
- $\cancel{E}_T$ from neutrino
- 2-4 jets
- At least 1 b -tagged jet

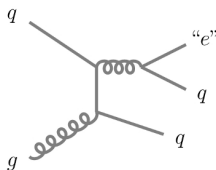


Major background processes:

W+jets



Multijet (QCD)



Multijet reduction

Removal of events with

- $\cancel{E}_T$ and lepton aligned or anti-aligned
- low scalar p_T sum of all reconstructed objects

Signal and background modeling

Single top signal, MC

- COMPHEP-SINGLETOP generator

W+jets, MC

- Largest background
- Shapes from ALPGEN (MLM-matched)
- Normalization and heavy flavour fraction from data

$t\bar{t}$, MC

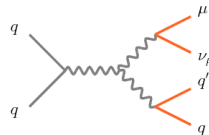
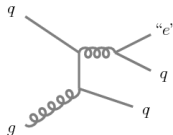
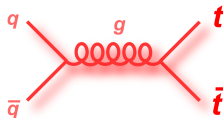
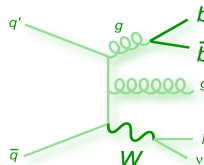
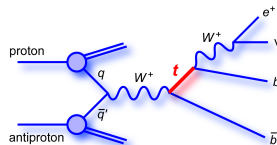
- ALPGEN (MLM-matched)
- Normalized to $\sigma_{NNLO} = 7.91$ pb

Multijet events, from data

- misidentified lepton

Z+jets and diboson

- ALPGEN and PYTHIA



Data-background comparison

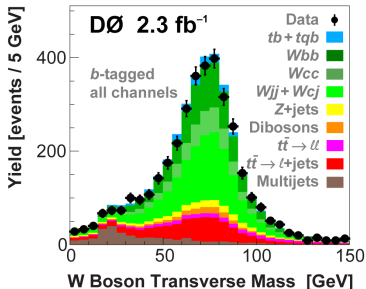
Event Yields in 2.3 fb⁻¹ of DØ Data

e,μ, 2,3,4-jets, 1,2-tags combined

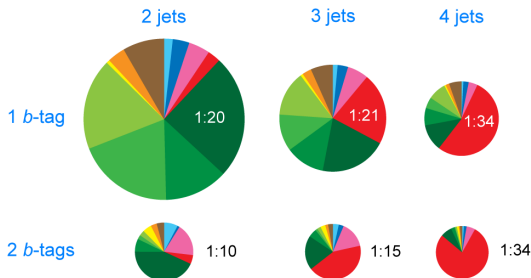
<i>tb + tqb</i>	223 ± 30
<i>W</i> +jets	2,647 ± 241
<i>Z</i> +jets, dibosons	340 ± 61
<i>t</i> $\bar{t}$ pairs	1,142 ± 168
Multijets	300 ± 52
Total prediction	4,652 ± 352
Data	4,519

Huge background!

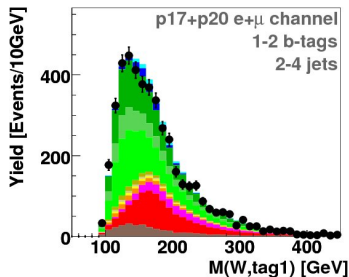
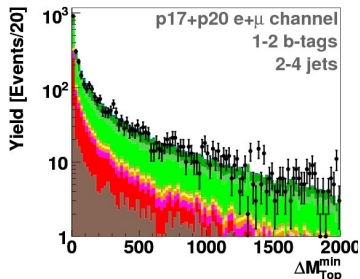
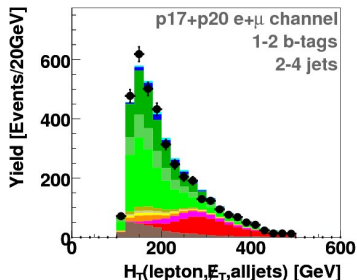
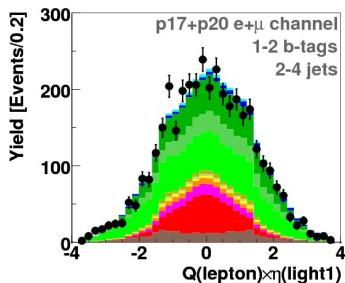
- $S : B \approx 1 : 20$
- Signal acceptance 2–3% (7800 → 220)
- Counting experiment not possible!
- Sophisticated multivariate methods needed



DØ Single Top 2.3 fb⁻¹ Signals and Backgrounds



Data-background agreement

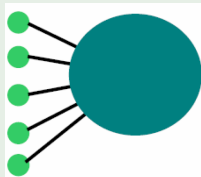


Good data-background agreement, but no clear signal excess...

5. BOOSTED DECISION TREES AND THE MEASUREMENTS

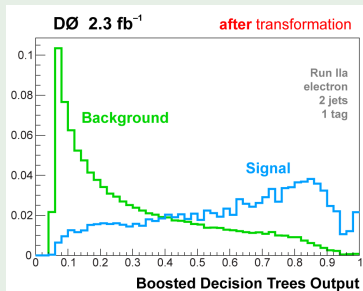
Final analysis steps

1. Boosted Decision Trees

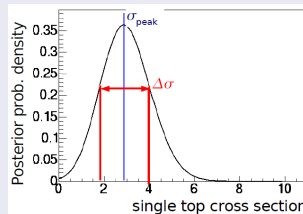


- **Combine** many (64) variables into one powerful discriminant
- **Optimize** different (ℓ , N_{tag} , N_{jet}) sub samples individually

Result:

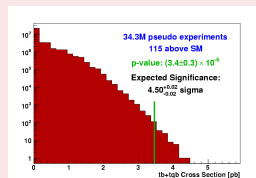


2. Measure Cross Section



Bayesian calculation using data and predicted **discriminant distributions** → **posterior**

3. Derive Significance



Significance derived from large ensemble of pseudo-experiments

Boosted decision trees

A decision tree (DT) **classifies** events depending on event specific **variables** $\vec{x}$ (features)

DT Analysis procedure: Split signal and background model in **3 parts** and

1. Grow the trees

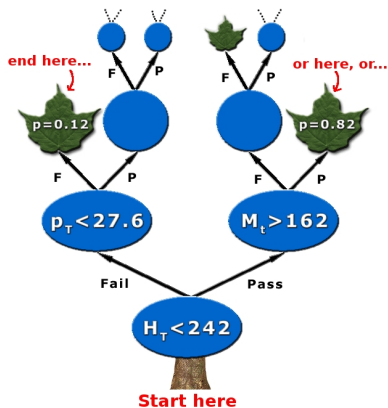
- Use **known** signal and background events
- Start at root node, then recursively:
 - find **best split** (minimal **gini**), apply it
 - create two new daughter nodes
- Define node as **leaf** when few events
- Each leaf is assigned a **purity**

2. Find optimal DT parameters

- Evaluate DTs created with different parameters

3. Final result

- Optimized DTs applied to “un-touched” 3rd → measurements conducted



Purity of left leaf = 0.12 → **background**

Purity of right leaf = 0.82 → **signal**

Boosted decision trees

A decision tree (DT) **classifies** events depending on event specific **variables** $\vec{x}$ (features)

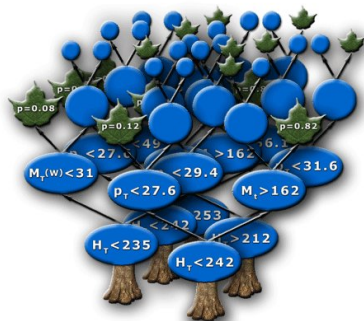
DT Analysis procedure: Split signal and background model in **3 parts** and

Boosting

- Boost mis-classified events (assign higher weight), and grow a new tree
- Repeat many times $\rightarrow$ many trees
- Average the tree outputs

$$D(\vec{x}) = \frac{1}{\sum_{n=0}^{N_{\text{trees}}} \alpha_n} \sum_{n=0}^{N_{\text{trees}}} \alpha_n D_n(\vec{x})$$

- **Improves performance!**
- Takes a few hours to create a forest of 50 boosted trees
- At the end of the day: 24 optimized forest, each with 50 boosted decision trees

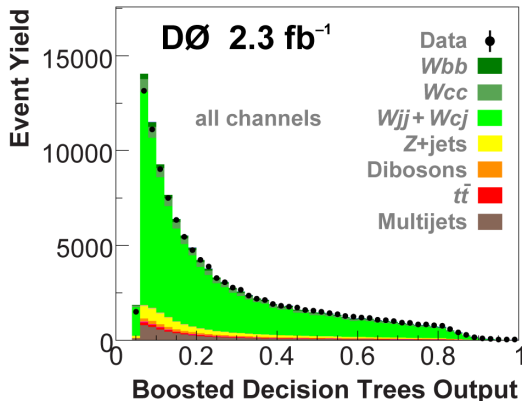


Cross-checks of the final trees

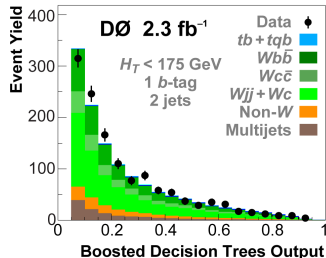
The final decision trees applied to background enriched control samples

Good agreement between the background model and data

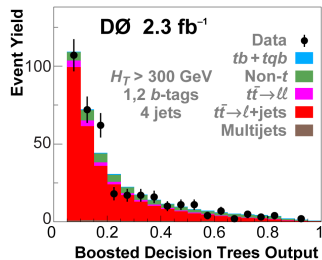
Pretagged Cross-Check Sample



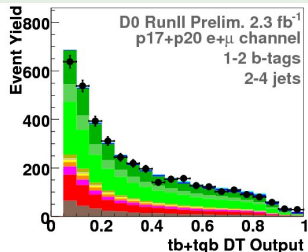
W+Jets Cross-Check Sample



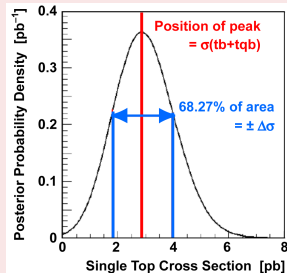
$t\bar{t}$ -Pairs Cross-Check Sample



Measuring a cross section



Decision Tree Output



Bayesian posterior

- Bayesian posterior probability density:
$$p(\sigma|\mathbf{D}) = \frac{1}{N} \iint L(\mathbf{D}|\sigma, \mathbf{a}, \mathbf{b}) \pi(\mathbf{a}, \mathbf{b}) \pi(\sigma) d\mathbf{a} d\mathbf{b}$$
- Shape and normalization systematics treated as nuisance parameters
- Correlations between uncertainties properly accounted for

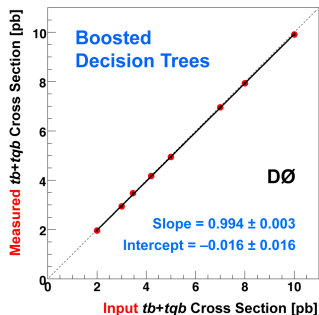
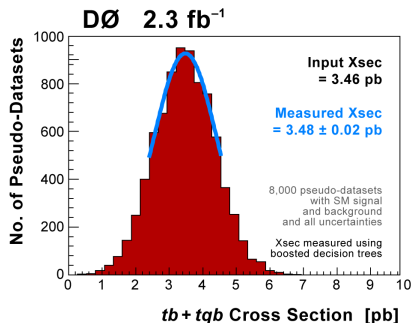
Main systematics

- *b*-tagging efficiency
- Jet energy scale
- *W*+jets heavy flavour correction
- Integrated luminosity
- Jet resolution

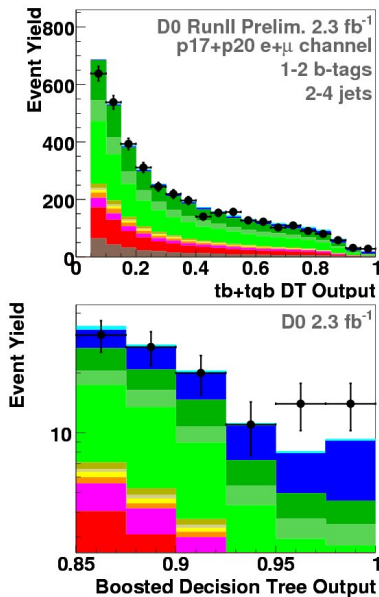
Ensemble testing

Tested machinery with many sets of **pseudo-data**

- Subset of our total pool of background events
- Individual statistical and systematical fluctuations
- **Wonderful tool** – like running $\sqrt{s}$ millions of times!
- Generated several ensembles with different single top content



Boosted decision tree results



← Good agreement!

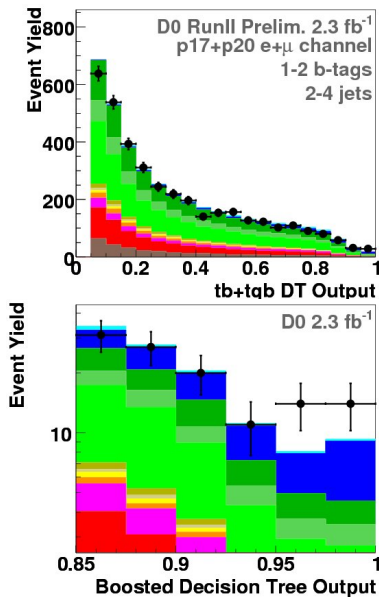
Key for Plots

- Data
- Signal: $t\bar{b}$
- Signal: $tq\bar{b}$
- $Wb\bar{b}$ +jets
- $Wc\bar{c}$ +jets
- W +light jets
- $Zb\bar{b}$ +jets
- $Zc\bar{c}$ +jets
- Z +light jets
- $WW+WZ+ZZ$
- $t\bar{t} \rightarrow l\bar{l}$
- $t\bar{t} \rightarrow l+jets$
- Multijets

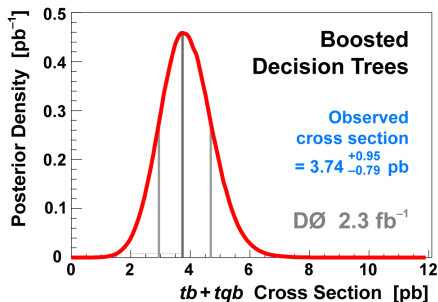
Signal region ($O_{DT} > 0.85$) shows

← excess over background!

Boosted decision tree results

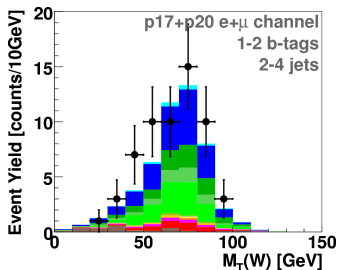
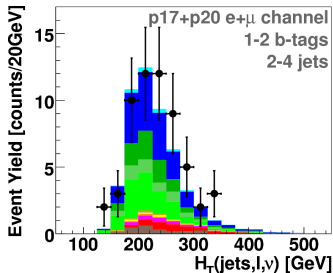
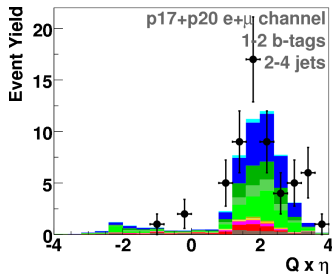
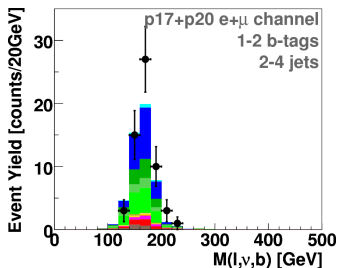


Measured cross section:



Result: $\sigma_{\text{single top}} = 3.74^{+1.0}_{-0.8}$ pb

Signal event characteristics



All events have $O_{\text{BDT}} > 0.9$

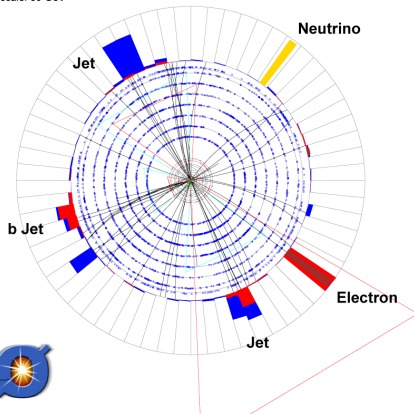
Single top quark candidates

DØ Experiment Event Display

Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis

Run 229388 Evt 13339887 Wed Jan 3 21:05:14 2007

ET scale: 39 GeV



Properties of this event:

$$Q \times \eta = 2.386$$

$$M_{\text{top}} = 162.3 \text{ GeV}$$

$$H_T(\ell, \cancel{E}_T, \text{all jets}) = 258.3 \text{ GeV}$$

The BDTs say:

$$O_{BDT} = \mathbf{0.991}$$

Signal Probability: **53.6%**

Signal significance

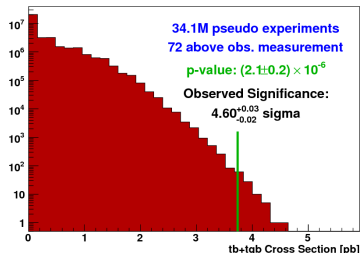
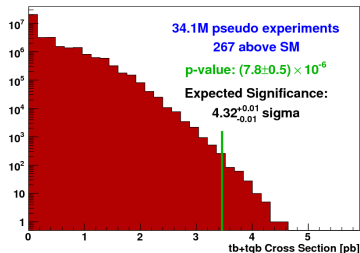
The **significance** for the excess over background determined from an ensemble containing 34 million pseudo-datasets **without single top** content

- **Expected significance:**
fraction of pseudo-datasets with measured cross section $> \sigma_{SM}$

- **Observed significance:**
fraction of pseudo-datasets with measured cross section above the measurement in data

Results

Expected significance	4.3σ	(0.00078%)
Observed significance	4.6σ	(0.00021%)



Combined significance

Two other multivariate analyses were performed using the same dataset:

Bayesian Neural Networks (BNN)

- Weighted average of several hundred NNs
- 18-25 input variables

The Matrix Element Method (ME)

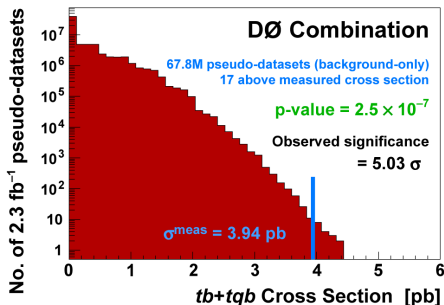
- Use parton level matrix elements
- given all reconstructed four-momenta:
compute prob. for signal and bkg hypotheses

Analyses not fully correlated →

the **BDT**, **BNN** and **ME** discriminant outputs
combined using a second **BNN**

Results:

DØ 2.3 fb ⁻¹ Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	3.74 ^{+0.95} _{-0.79} pb	4.3 σ	4.6 σ
Bayesian Neural Networks	4.70 ^{+1.18} _{-0.93} pb	4.1 σ	5.2 σ
Matrix Elements	4.30 ^{+0.99} _{-1.20} pb	4.1 σ	4.9 σ
Combination	3.94 ± 0.88 pb	4.5 σ	5.0 σ



Observed significance: **5.03σ** → **Discovery!**

Direct measurement of $|V_{tb}|$

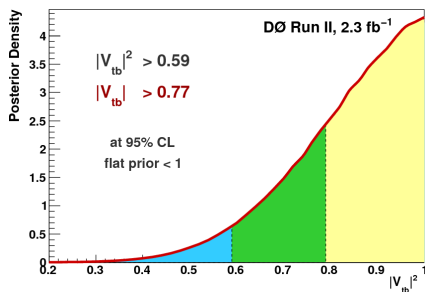
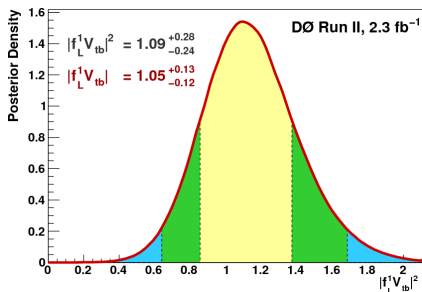
- In SM, single top cross section proportional to $|V_{tb}|^2$
- Can introduce left-handed Wtb coupling f_L^1 ($= 1$ in SM)
- Possible to measure $|f_L^1 V_{tb}|^2$ from BDT output
- Measurement assumptions:
 - $|V_{td}|^2 + |V_{ts}|^2 \ll |V_{tb}|^2$
(in agreement with measurements)
 - Standard model like Wtb interaction

Additional Systematic Uncertainties for the $|V_{tb}|$ Measurement

DØ 2.3 fb⁻¹

For the $tb+qb$ theory cross section

Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%



No assumption about number of quark families or CKM unitarity

Summary

This thesis presents the **first observation** of single top quark production

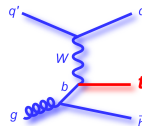
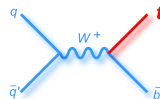
- **Boosted decision trees** used to isolate the single top signal from background processes
- The single top cross section is measured to:
$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.74^{+0.95}_{-0.74} \text{ pb}$$
- Combining the decision trees with two other multivariate techniques yields a **significance** for the observed excess over predicted background of **5.03σ**
- The **CKM matrix element** $|V_{tb}|$ is measured to

$$|V_{tb}f_1^L| = 1.05^{+0.13}_{-0.12},$$

where f_1^L is a generic left-handed Wtb coupling.

Constraining the measurement to the standard model region gives the 95% confidence bound:

$$0.77 < |V_{tb}| \leq 1$$

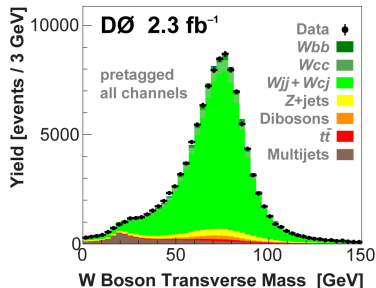
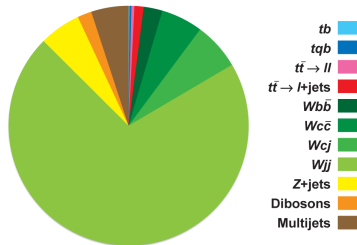


BACKUP SLIDES

Predicted yields before b tagging

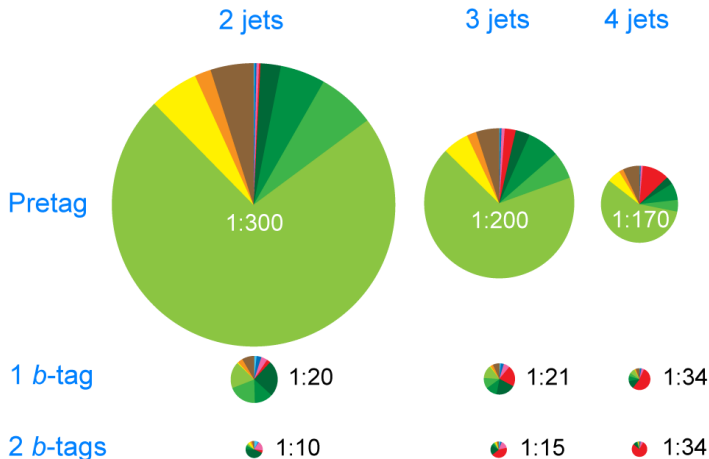
Event Yields in 2.3 fb^{-1} of DØ Data	
e, μ , 2,3,4-jets, pretag	
$tb + tqb$	444
W +jets	98,444
Z +jets, dibosons	8,631
$t\bar{t}$ pairs	1,895
Multijets	5,798
Total background	114,777
Data	114,777

DØ Single Top 2.3 fb^{-1} Signals and Backgrounds
(All channels combined, before b -tagging)



Predicted yields before b tagging

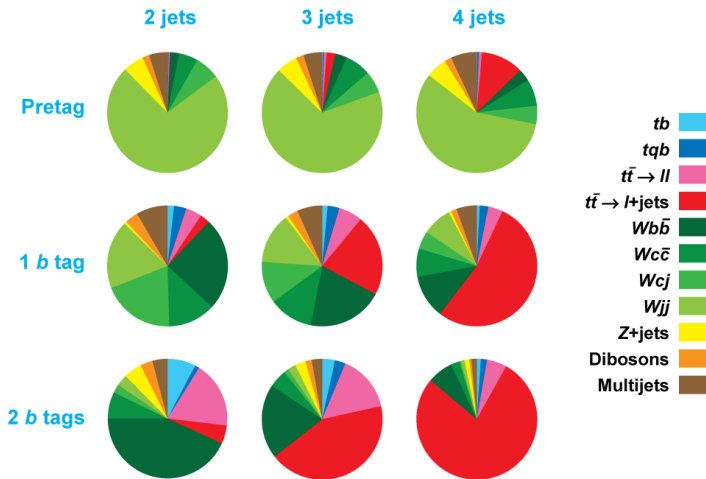
DØ Single Top 2.3 fb^{-1} Signals and Backgrounds



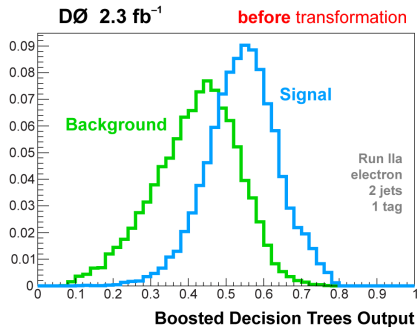
Predicted yields

Event Yields in 2.3 fb⁻¹ of DØ Data			
Electron + muon, 1 tag + 2 tags combined			
Source	2 jets	3 jets	4 jets
s-channel tb	62 ± 9	24 ± 4	7 ± 2
t-channel tqb	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \rightarrow \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \rightarrow \ell + \text{jets}$	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	$2,615 \pm 192$	$1,294 \pm 107$	742 ± 80
Data	2,579	1,216	724

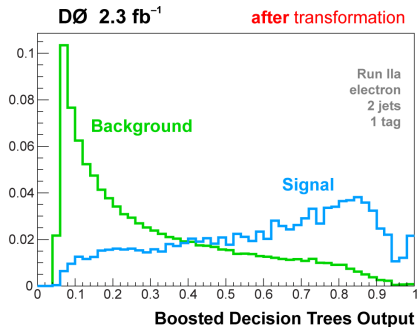
DØ Single Top 2.3 fb⁻¹ Signals and Backgrounds



Binning transformation

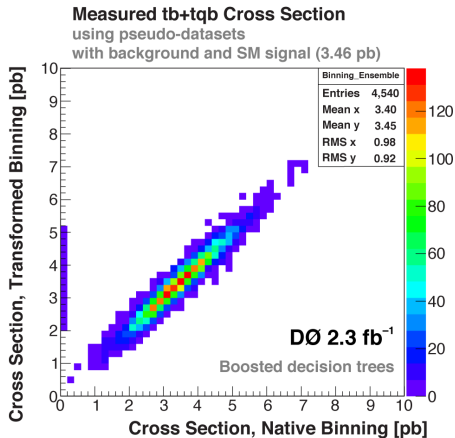
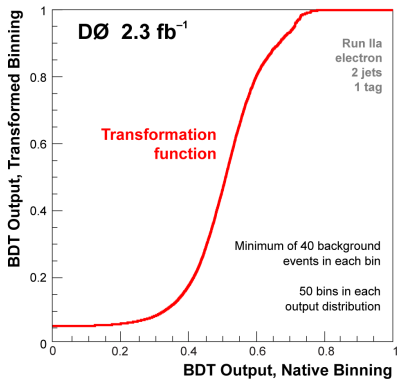


Before



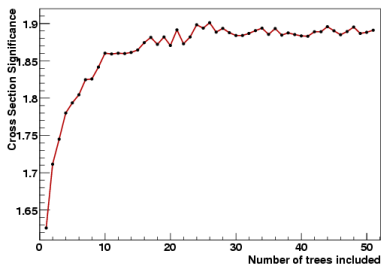
After

Binning transformation

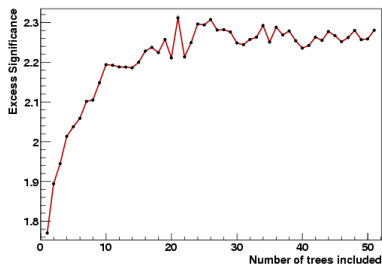


Evaluating the performance

Cross Section Significance vs number of trees included

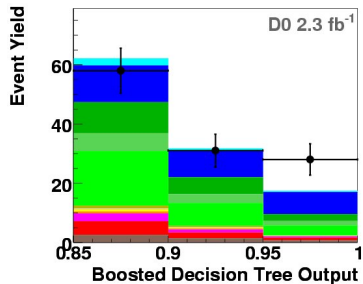
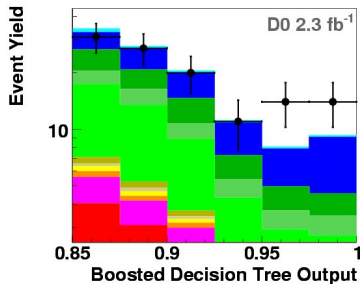
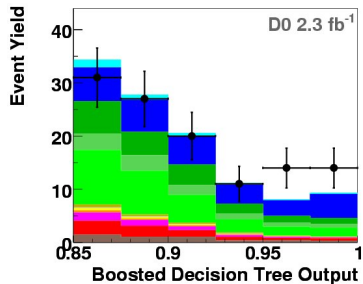
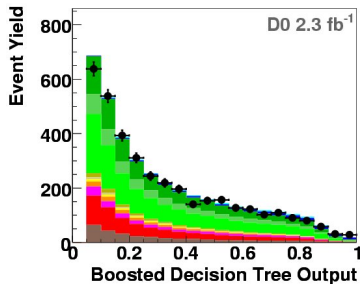


Excess Significance vs number of trees included

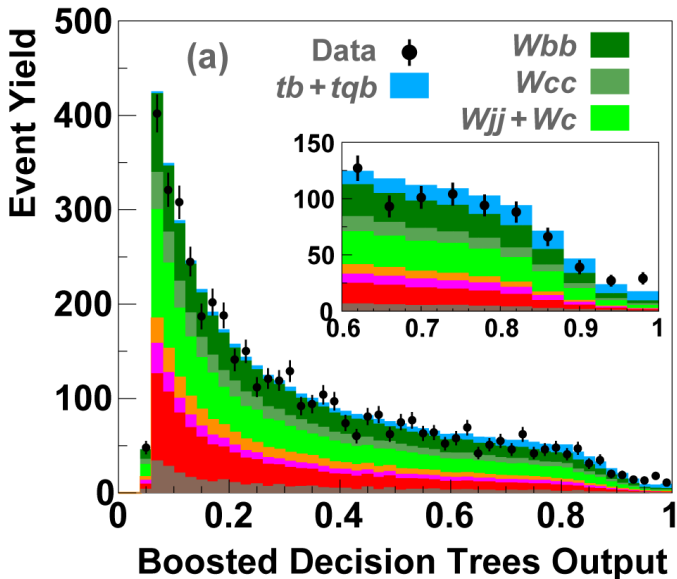


Performance increase as more boosted trees are added

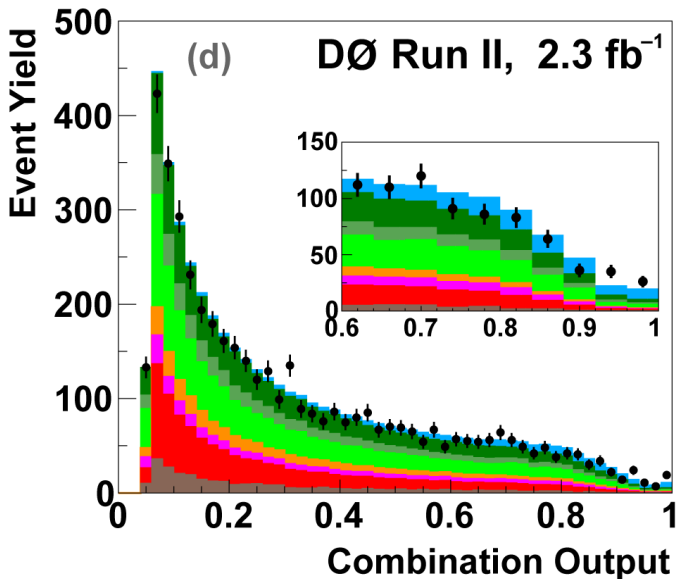
Boosted decision tree discriminant – zoom



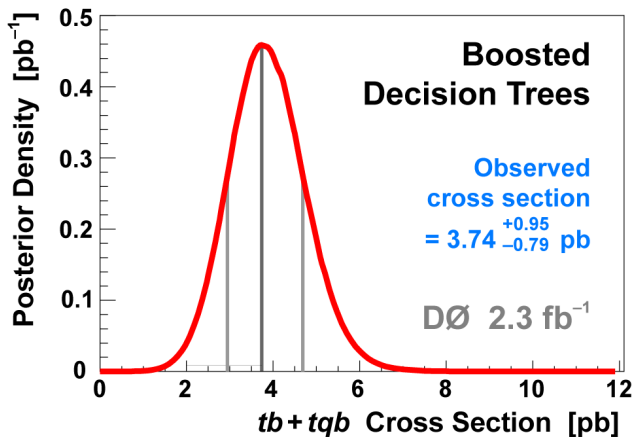
Boosted decision tree discriminant



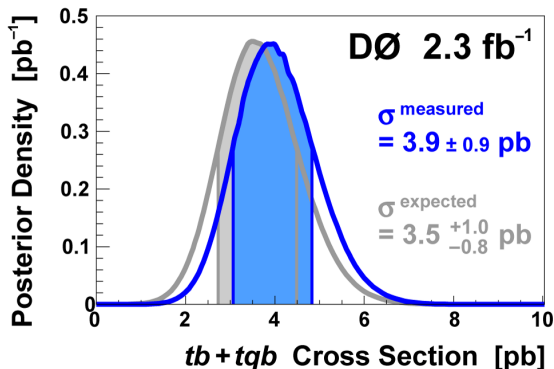
Combination discriminant



Cross section measurement



Combined cross section measurement

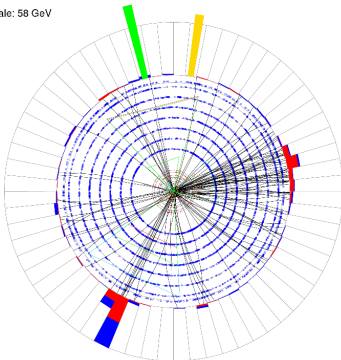


Bayesian posterior density

Event displays

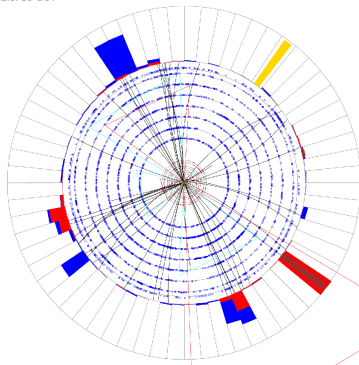
Run 231567 Evt 11944716 Sat Mar 24 05:43:39 2007

ET scale: 58 GeV



Run 229388 Evt 13339887 Wed Jan 3 21:05:14 2007

ET scale: 39 GeV



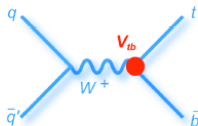
Direct measurement of $|V_{tb}|$

General form of Wtb vertex:

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

Assume

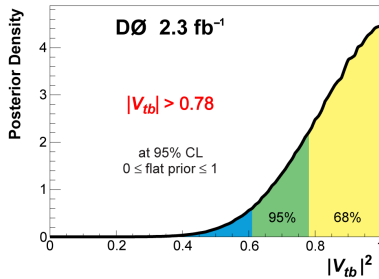
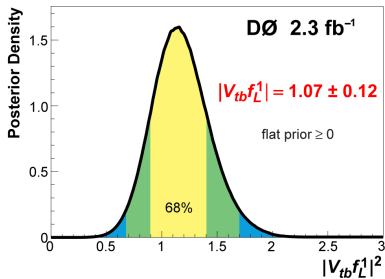
- SM top quark decay : $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$
- Pure V-A : $f_1^R = 0$
- CP conservation : $f_2^L = f_2^R = 0$
- No need to assume only three quark families or CKM matrix unitarity (unlike for previous measurements using $t\bar{t}$ decays)
- Measure the strength of the V-A coupling, $|V_{tb} f_1^L|$, which can be > 1



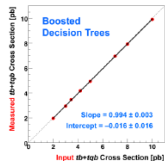
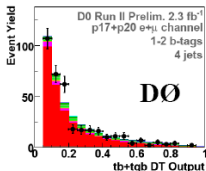
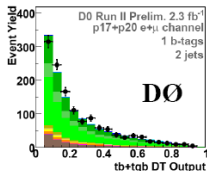
Additional theoretical uncertainties

	tb	tqb
Top mass	13 %	8.5 %
Scale	5.4 %	4.0 %
PDF	4.3 %	10 %
α_s	1.4 %	0.01 %

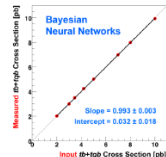
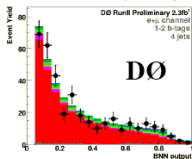
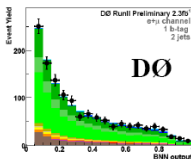
Combined $|V_{tb}|$ measurement



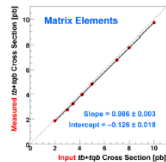
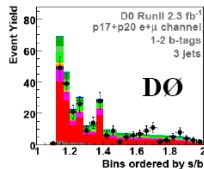
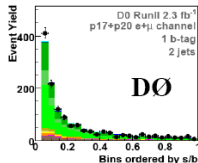
Cross-checks and linearity tests



BDT



BNN



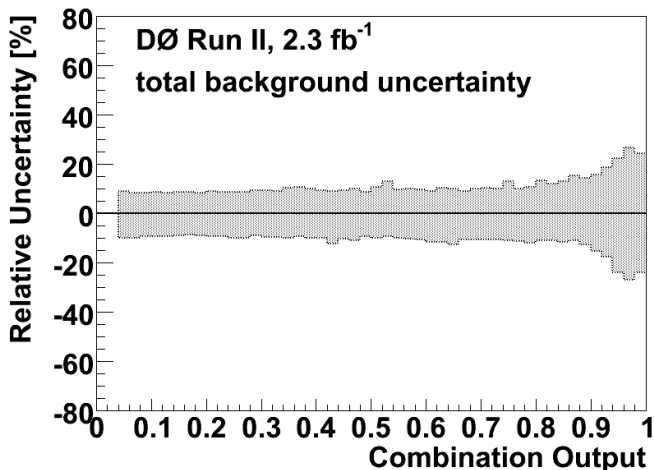
ME

Systematics uncertainties

Systematic Uncertainties Ranked from Largest to Smallest Effect on Single Top Cross Section DØ 2.3 fb⁻¹	
Larger terms	
<i>b</i> -ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
W+jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
<i>b</i> -jet fragmentation	2.0%
<i>t</i> $\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
<i>Wbb/Wcc</i> correction ratio	5%
Primary vertex selection	1.4%

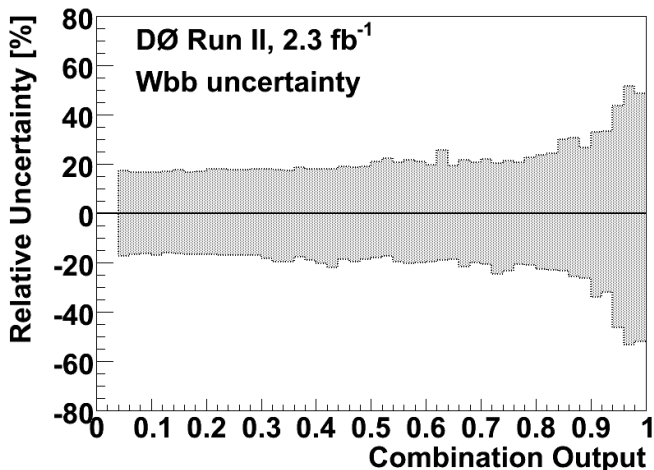
Systematic Uncertainties Ranked from Largest to Smallest Effect on Single Top Cross Section DØ 2.3 fb⁻¹	
Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%
W+jets and multijets normalization to data	(1.8–3.9)% (<i>W</i> +jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen <i>W</i> +jets shape corrections	shape only
Trigger	5%

DØ Systematics uncertainties – all backgrounds



Returned by Bayesian binned likelihood fit to data – all systematics and their correlations taken into account and constraints from the data

DØ Systematics uncertainties – $Wb\bar{b}$



Returned by Bayesian binned likelihood fit to data – all systematics and their correlations taken into account and constraints from the data

Measuring a cross section

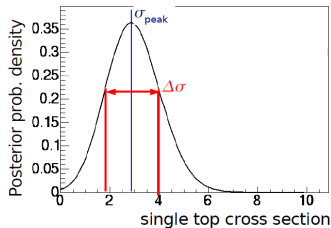
Probability to observe data distribution D , expecting y :

$$y = \alpha l \sigma + \sum_{s=1}^N b_s \equiv a \sigma + \sum_{s=1}^N b_s$$

$$P(D|y) \equiv P(D|\sigma, a, b) = \prod_{i=1}^{nbins} P(D_i|y_i)$$

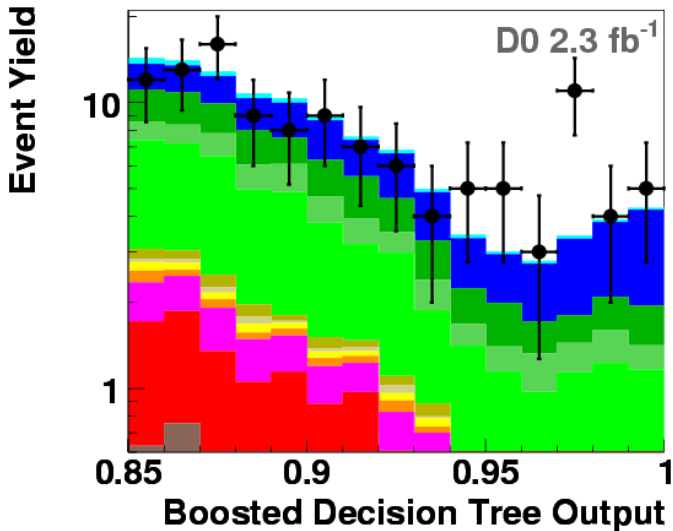
The cross section is obtained

$$Post(\sigma|D) \equiv P(\sigma|D) \propto \int_a \int_b P(D|\sigma, a, b) Prior(\sigma) Prior(a, b)$$



- Bayesian posterior probability density
- Shape and normalization systematics treated as nuisance parameters
- Correlations between uncertainties properly accounted for
- Flat prior in signal cross section

DT discriminant zoom



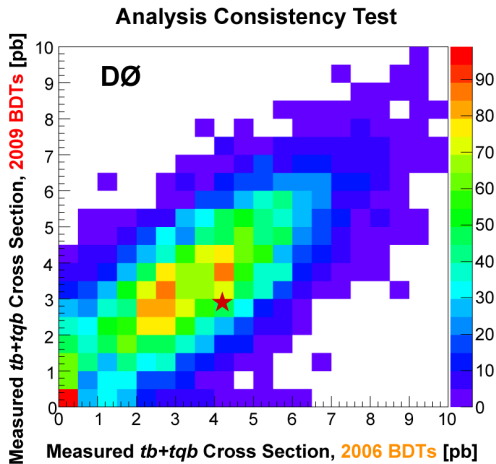
Measurements in different channels

Measured $tb+tbq$ Cross Section [pb] $D\bar{O}$ 2.3 fb ⁻¹ Analysis					
Method	All Channels	Electron Only	Muon Only	Run IIa Only	Run IIb Only
BDT	3.74 +0.95 -0.79	4.4 +1.5 -1.2	3.3 +1.2 -1.0	2.5 +1.3 -1.2	4.9 +1.4 -1.2
BNN	4.70 +1.18 -0.93	5.3 +1.5 -1.4	4.0 +1.3 -1.2	3.4 +1.4 -1.3	5.7 +1.5 -1.3
ME	4.30 +0.98 -1.20	3.2 +1.9 -1.6	3.9 +1.2 -1.2	2.6 +1.3 -1.2	5.4 +1.7 -1.4
Combination	3.94 +0.88 -0.88	4.5 +1.3 -1.2	3.5 +1.1 -1.0	2.6 +1.2 -1.1	5.0 +1.2 -1.2

Previous (2006) results

Single Top Cross Section	Signal Significance		CKM Matrix Element V_{tb}
	Expected	Observed	
December 2006 DØ (0.9 fb⁻¹)			PRL 98, 181802 (2007)
4.7 ± 1.3 pb	2.3σ	3.6σ	$ V_{tb}f_1^L = 1.31^{+0.25}_{-0.21}$ $ V_{tb} > 0.68$ at 95% CL
September 2008 CDF (2.2 fb⁻¹)			PRL 101, 252001 (2008)
2.2 ± 0.7 pb	4.9σ	3.7σ	$ V_{tb}f_1^L = 0.88^{+0.13}_{-0.12}$ $ V_{tb} > 0.66$ at 95% CL

Comparison with previous (2006) results



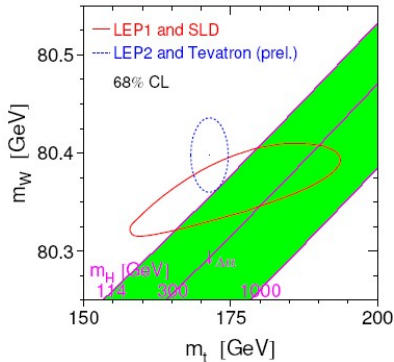
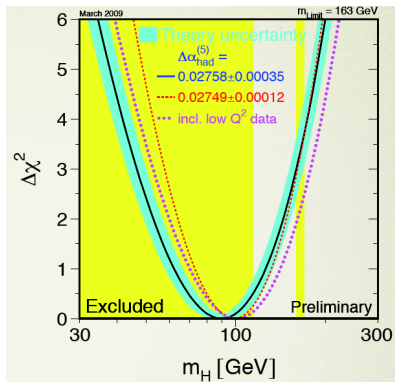
Measured single top cross sections using the 2009 and the 2006 decision trees on 5,000 pseudo-datasets generated from the 2009 Run IIa e+jets samples.

The red star shows the measurements in real data: 4.2 pb from the 2006 analysis and 2.9 pb from the 2009 analysis. This 1.3 pb shift is not uncommon, as seen from the width of the distribution from the pseudo-datasets.

Result comparison between DØ and CDF

Single Top Cross Section	Signal Significance		CKM Matrix Element V_{tb}
	Expected	Observed	
March 2009 DØ (2.3 fb⁻¹) arXiv:0903.0850 ($m_{\text{top}} = 170$ GeV)			
3.94 ± 0.88 pb	4.5σ	5.0σ	$ V_{tb} f_1^L = 1.07 \pm 0.12$ $ V_{tb} > 0.78$ at 95% CL
March 2009 CDF (3.2 fb⁻¹) arXiv:0903.0885 ($m_{\text{top}} = 175$ GeV)			
$2.3^{+0.6}_{-0.5}$ pb	$>5.9 \sigma$	5.0σ	$ V_{tb} f_1^L = 0.91 \pm 0.13$ $ V_{tb} > 0.71$ at 95% CL

The Higgs Boson



Heavy Flavour Fraction

For any of the six b -tagging operating points:

$$S_{\text{HF}} = \frac{(N'_{\text{data}} - N'_{\text{bkg}}) \times N''_{W+\text{jets}} - (N''_{\text{data}} - N''_{\text{bkg}}) \times N'_{W+\text{jets}}}{(N'_{\text{data}} - N'_{\text{bkg}}) \times N''_{W+\text{HF}} - (N''_{\text{data}} - N''_{\text{bkg}}) \times N'_{W+\text{HF}}}$$

' and ' non/single/double tagged data (orthogonal samples)

N_{data} number of observed events in data

N_{bkg} non- W +jets backgrounds ($t\bar{t}$, multijets, $Z + \text{jets}$, dibosons) from simulations (MC)

N_{bkg} non- W +jets backgrounds ($t\bar{t}$, multijets, $Z + \text{jets}$, dibosons) from simulations (MC)

$N_{W+\text{jets}}$ number of predicted events in the simulated W +jets samples

$N_{W+\text{HF}}$ number of predicted events in the simulated W +HF samples