Observation of Single Top Quarks at DØ

Dugan O'Neil

Simon Fraser University and CEA Saclay

LAPP
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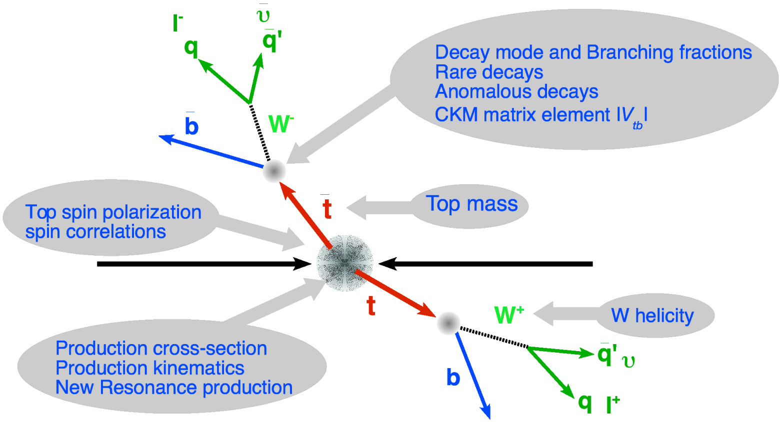
Outline

- Introduction/Motivation
- Single Top at the Tevatron
- From Evidence to Observation
- Background model, Event selection, etc.
- Cross Section Measurement
- Isolating the t-Channel
- Measuring $|V_{tb}|$
- Combination with CDF
- Summary

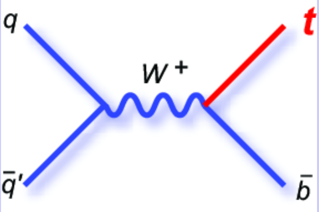
Top Quark Physics

Top quark discovered in pairs (strong interaction) in 1995.



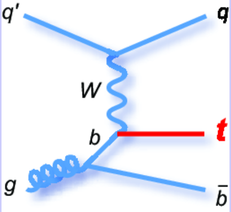
Single top quark production @ 1.96TeV

s-channel (tb)



- $\sigma_{NLO} = 1.12 \pm 0.04$ pb(*)

t-channel (tqb)



- $\sigma_{NLO} = 2.34 \pm 0.12$ pb (*)

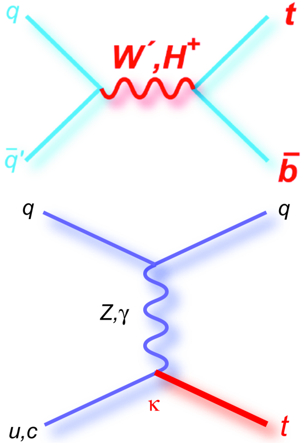
(*) N. Kidonakis, Phys. Rev. D 74, 114012 (2006), M_t=170GeV

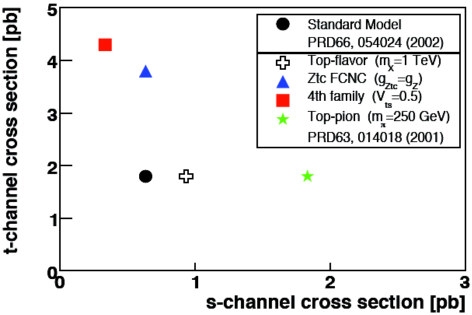
Motivation - Measure the Cross Section

A cross section allows direct measurement of $|\mathrm{V_{tb}}|$ for the first time (more later).

Motivation - Measure the Cross Section

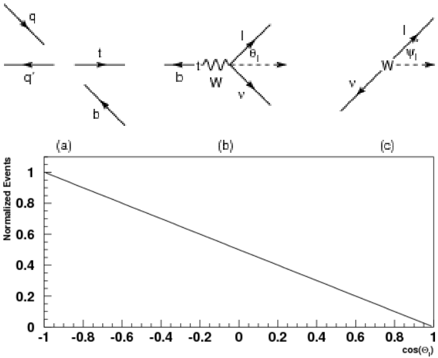
A cross section allows direct measurement of $|V_{tb}|$ for the first time (more later). The s-channel and t-channel cross sections are sensitive to different new physics



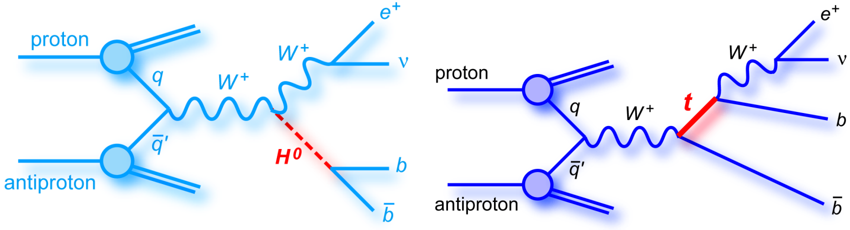


Motivation - Top Quark Spin

- Top decays before it can hadronize (no top jets)
- V-A nature of weak interaction should mean 100% polarized top quarks.
- First chance to measure the polarization of a bare quark!



Motivation - Looks Like Higgs

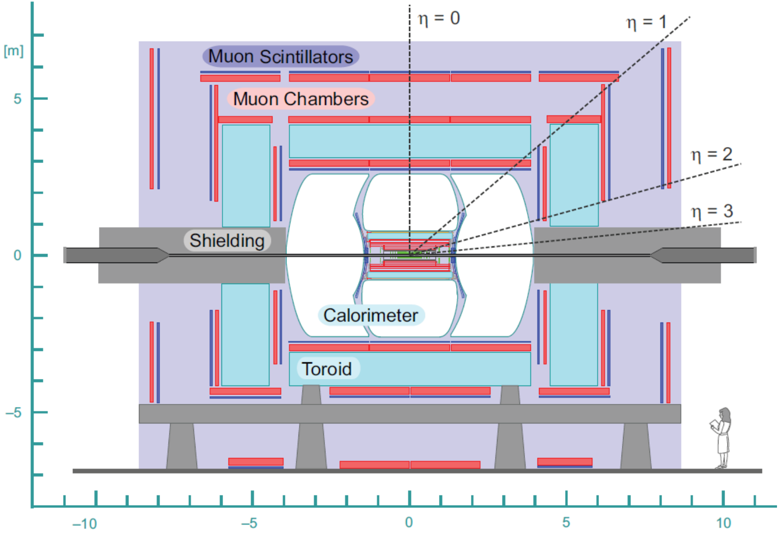


- This looks a lot like single top!
- One of the most promising Tevatron channels for Higgs discovery is like single top with 1/10 the cross section.
- Approach to measure Higgs is tested on single top. It is also an important background.
- As soon as we discover it, somebody tries to get rid of it....

The Fermilab Tevatron

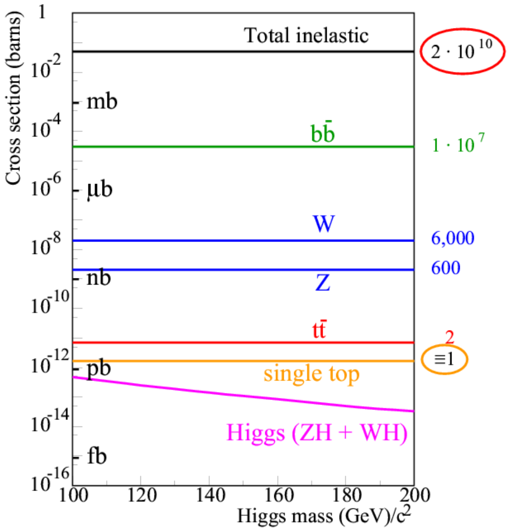
- Run II began in March 2001
- Proton-antiproton collisions at 1.96TeV
- Luminosity up to $3.5 \times 10^{32} cm^{-2} s^{-1}$
- Int. Luminosity (recorded) >6.1 fb^{-1}

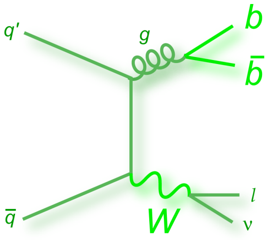
The DØ Cartoon



The Collaboration

Finding Single Top is a Challenge!





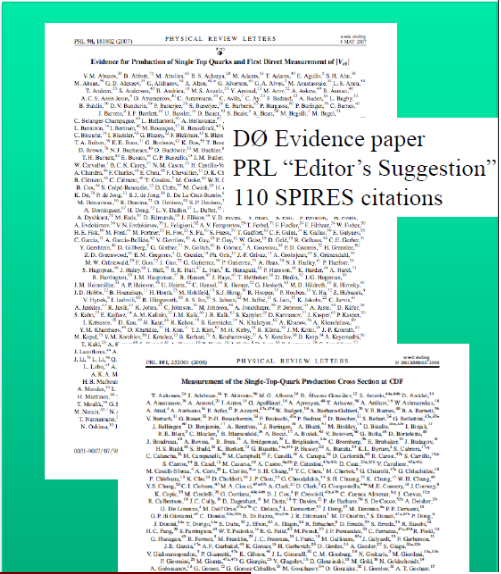
Search History (Wine+Cheese - Gerber)

DØ

- Search: PRD 63, 031101 **(2000)**
- Search: PLB 517, 282 **(2001)**
- Search: PLB 622, 265 **(2005)**
- W': PLB 641, 423 **(2006)**
- Search: PRD 75, 092007 **(2007)**
- **Evidence**: PRL 98, 181802 **(2007)**
- FCNC: PRL 99, 191802 **(2007)**
- W': PRL 100, 211802 **(2007)**
- Evidence: PRD 78, 012005 **(2008)**
- Wtb: PRL 101, 221801 **(2008)**
- Wtb: PRL 102, 092002 **(2009)**
- H$^+$: (PRL) arXiv:0807.0859
- **Observation**: **(PRL) arXiv:0903.0850**

CDF

- Search: PRD 65, 091102 **(2002)**
- W' PRL 90, 081802 **(2003)**
- Search: PRD 69, 052003 **(2004)**
- Search: PRD 71, 012005 **(2005)**
- **Evidence:** PRL 101, 252001 **(2008)**
- FCNC: (PRL) arXiv:0812.3400
- W': (PRL) arXiv:0902.3276
- **Observation**: **(PRL) arXiv:0903.0885**


PRL 98, 181802 (2007) PHYSICAL REVIEW LETTERS

Evidence for Production of Single Top Quarks and First Direct Measurement of $|V_{tb}|$

PRL 101, 252001 (2008) PHYSICAL REVIEW LETTERS

Measurement of the Single-Top-Quark Production Cross Section at CDF

DØ Evidence paper

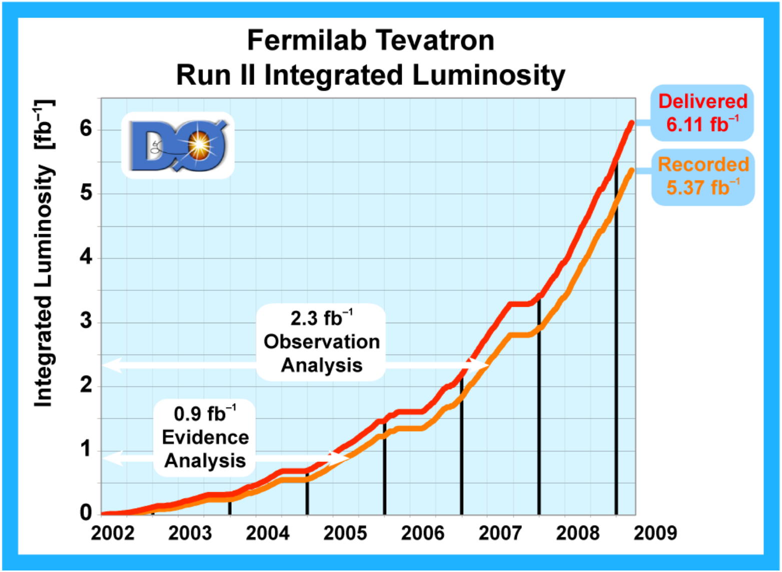
PRL "Editor's Suggestion"

110 SPIRES citations

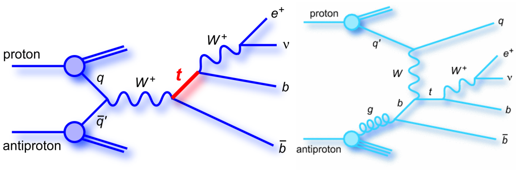
General Analysis Strategy (2006 or 2009)

- Design triggers and loose pre-selections maximizing signal acceptance.
- Build background model from MC and data sources.
- Normalize background model to data.
- Check data/background model agreement in many variables.
- b-tag.
- Check data/background model agreement in many variables.
- Apply MV discriminants.
- Check discriminants in data control samples.
- Use ensembles of pseudo-data to test for method bias.
- Cross sections measured using binned likelihood calculation for signal+background to data.

Improvements Since 2006



Event Selection Improvements



Signature

- isolated lepton
- $\not{E}_T$
- 2-4 jets
- at least 1 b-jet

- Logical OR of many triggers (was l+jets)
- Leading jet acceptance extended to $|\eta| < 3.4$ (was 2.5)
- Non-leading jet P_T cut lowered to 15GeV (was 20)
- Muon P_T cut 15GeV (was 18GeV)
- Loosened b-tag cut for 2-tag case
- New H_T,$\not{E}_T$cuts

The Background Model

- Signal modeled using SINGLETOP+PYTHIA. Based on COMPHEP, reproduces NLO distributions.
- W+jets, Z+jets and ttbar from ALPGEN+PYTHIA:
  - MLM parton-jet matching to avoid double-counting final states.
  - $\eta(jets), \Delta\phi(jet1, jet2), \Delta\eta(jet1, jet2)$ corrected in W+jets samples to match data.
- QCD multijets taken from data - misidentified leptons.
- Dibosons modeled using PYTHIA.
- Normalization of W+jets and multijets performed by iterative fits to data in three sensitive variables before tagging

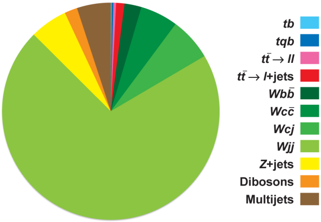
$$N^{data}_{pretag} - N^{MC}_{bkgd} = S_{W+jets} N^{MC}_{W+jets} + S_{multijet} N^{data}_{multijet}$$

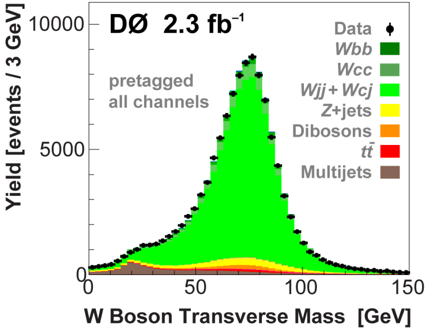
Event Selection - Agreement Before Tagging

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)

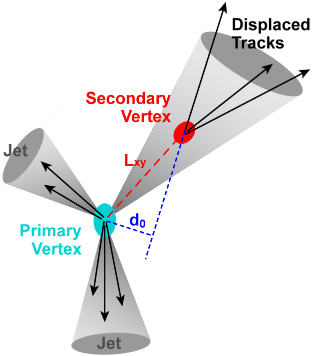




S:B = 1:259

B Tagging

- Separate b-jets from light-quark and gluon jets to reject most W+jets background.
- Two operating points
  - TIGHT ($\epsilon_b = 40\%, \epsilon_c = 9\%, \epsilon_l = 0.4\%$)
  - LOOSE ($\epsilon_b = 50\%, \epsilon_c = 14\%, \epsilon_l = 1.5\%$)



- DØ uses a NN with 7 input variables based on secondary vertex and impact parameter.
- Define exclusive samples: 1T, 0 L and 2L

Event Selection - Agreement After Tagging

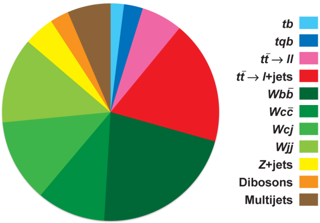
Event Yields in 2.3 fb^{-1} of DØ Data

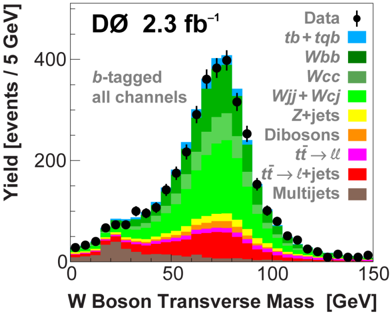
e,μ, 2,3,4-jets, 1,2-tags combined

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

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

(All channels combined, after *b*-tagging)





Systematic Uncertainties

Systematic Uncertainties

Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

Larger terms	
b-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)%
b-jet fragmentation	2.0%
$t\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
Wbb/*Wcc* 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)% (*W*+jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen *W*+jets shape corrections	shape only
Trigger	5%

Multivariate Analysis Techniques

Selection cuts are not sufficient to "see" single top. We perform three independent analyses using multivariate techniques:

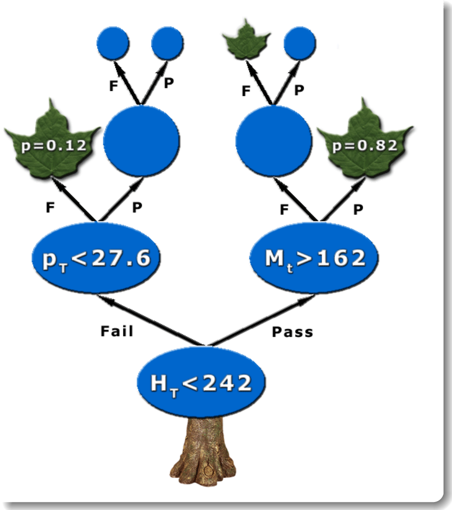
1. Boosted Decision Trees (BDTs)
2. Matrix Elements Method (ME)
3. Bayesian Neural Networks (BNN)

and then combine their outputs in a super-BNN at the end.

Decision Trees

Train

- Start with all events (first node)
- For each variable, find the splitting value with best separation between children (best cut).
- select best variable and cut and produce Failed and Passed branches
- Repeat recursively on each node
- Stop when improvement stops or when too few events left. Terminal node = leaf.



Splitting a node

Impurity $i(t)$

- maximum for equal mix of signal and background
- symmetric in p_{signal} and $p_{background}$
- minimal for signal only or background only
- strictly concave $\Rightarrow$ reward purer nodes

- Decrease of impurity for split s of node t into children t_L and t_R : $\Delta i(s,t) = i(t) - p_L \cdot i(t_L) - p_R \cdot i(t_R)$
- Aim: find split s^* such that:

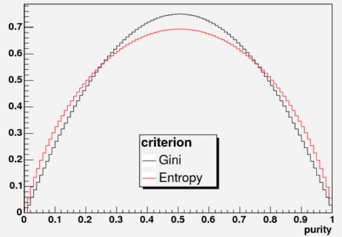
$$\Delta i(s^*,t) = \max_{s \in \{\text{splits}\}} \Delta i(s,t)$$

- Maximizing $\Delta i(s,t) \equiv$ minimizing overall tree impurity

Examples

$$Gini = 1 - \sum_{i=s,b} p_i^2 = \frac{2sb}{(s+b)^2}$$

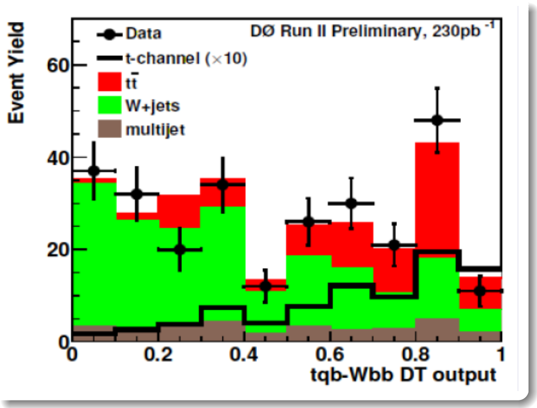
$$entropy = -\sum_{i=s,b} p_i \log p_i$$



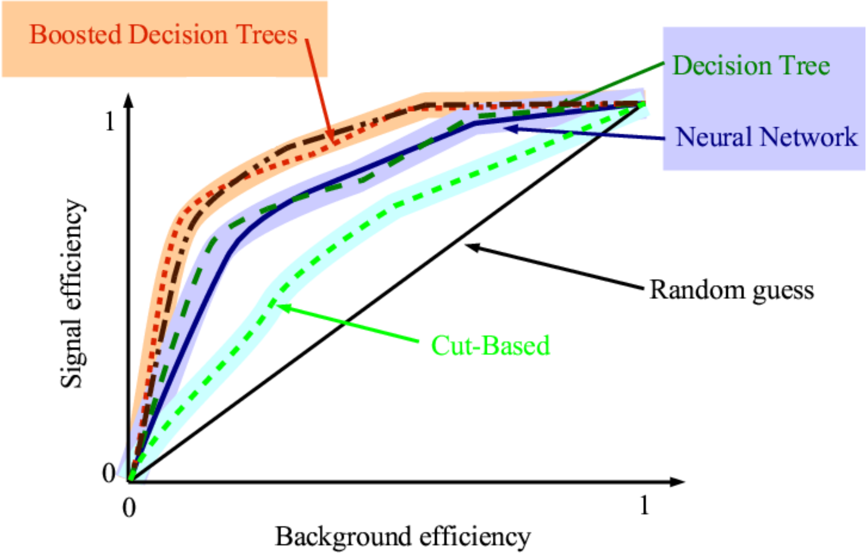
Decision Trees

Measure and Apply

- Take trained tree and run on independent simulated sample, determine purities.
- Apply to Data
- Should see enhanced separation (signal right, background left)
- Could cut on output and measure, or use whole distribution to measure.



Decision Trees - Boosting



Decision Trees - Boosting

Boosting

- Recent technique to improve performance of a weak classifier
- Recently used on DTs by GLAST and MiniBooNE
- Basic principal on DT:
  - train a tree T_k
  - $T_{k+1} = \text{modify}(T_k)$

AdaBoost algorithm

- Adaptive boosting
- Check which events are misclassified by T_k
- Derive tree weight α_k
- Increase weight of misclassified events
- Train again to build T_{k+1}
- Boosted result of event i: $T(i) = \sum_{n=1}^{N_{\text{tree}}} \alpha_k T_k(i)$

- Averaging dilutes piecewise nature of DT
- Usually improves performance

Ref: Freund and Schapire, "Experiments with a new boosting algorithm", in *Machine Learning: Proceedings of the Thirteenth International Conference*, pp 148-156 (1996)

Decision Trees - Application to this Analysis

DT Choices

- 1/3 of MC for training
- Adaboost $\beta = 0.2$
- Boosting cycles $= 50$
- Signal leaf if purity > 0.5
- Minimum leaf size $= 100$ events
- Same total weight to signal and background to start
- Goodness of split - Gini factor

Analysis Strategy

- Train 24 separate trees: (Run IIa,Run IIb) x (e,μ) x (2,3,4 jets) x (1,2 tags)
- For each signal train against the sum of backgrounds

Decision Trees - Powerful Variables

Best Variables to Separate Single Top from W+Jets

DØ 2.3 fb^{-1} Analysis

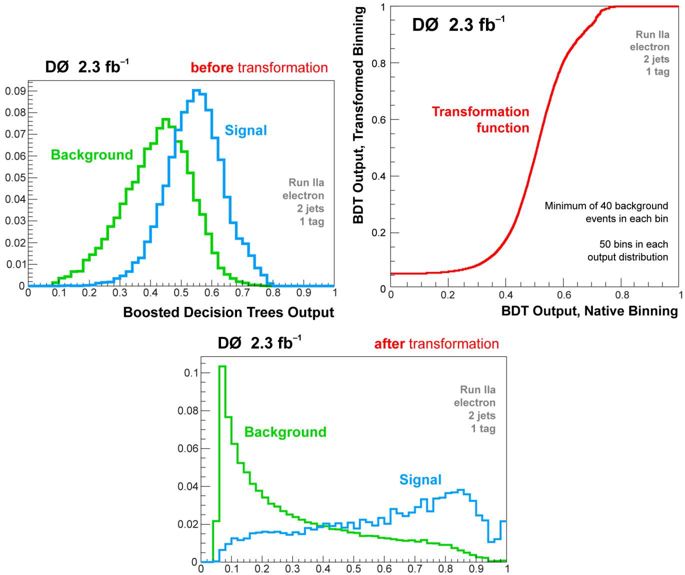
Object kinematics	$\not\!\!E_T$
	p_T(jet2)
	p_T^{rel}(jet1,tag-μ)
	E(light1)
Event kinematics	M(jet1,jet2)
	M_T(W)
	H_T(lepton,$\not\!\!E_T$,jet1,jet2)
	H_T(jet1,jet2)
	H_T(lepton,$\not\!\!E_T$)
Jet reconstruction	Width_ϕ(jet2)
	Width_η(jet2)
Top quark reconstruction	$M_{top}(W,\text{tag1})$
	ΔM_{top}^{min}
	$M_{top}(W,\text{tag1,S2})$
Angular correlations	$\cos(\text{light1,lepton})_{\text{btaggedtop}}$
	$\Delta\phi$(lepton,$\not\!\!E_T$)
	Q(lepton) x η(light1)

Best Variables to Separate Single Top from Top Pairs

DØ 2.3 fb^{-1} Analysis

Object kinematics	pT(notbest2)
	pT(jet4)
	pT(light2)
Event kinematics	M(alljets–tag1)
	Centrality(alljets)
	M(alljets–best1)
	H_T(alljets–tag1)
	H_T(lepton,$\not\!\!E_T$,alljets)
	M(alljets)
Jet reconstruction	Width_η(jet4)
	Width_ϕ(jet4)
	Width_ϕ(jet2)
Angular correlations	$\cos(\text{lepton}_{\text{btaggedtop}}, \text{btaggedtop}_{\text{CMframe}})$
	Q(lepton) x η(light1)
	ΔR(jet1,jet2)

Decision Trees - Output Transformation



Matrix Element Technique

A matrix elements analysis takes a very different approach:

- Use the 4-vectors of all reconstructed leptons and jets
- Use matrix elements of main signal and background diagrams to compute an event probability density for signal and background hypotheses.
- Goal: calculate a discriminant:

$$D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{Signal}(\vec{x})}{P_{Signal}(\vec{x}) + P_{Background}(\vec{x})}$$

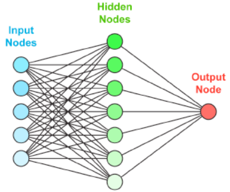
- Define P_{Signal} as properly normalized differential cross section

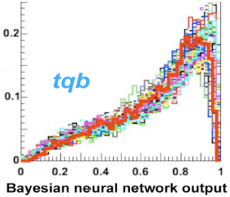
$$P_{Signal}(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}) \quad \sigma_S = \int d\sigma_S(\vec{x})$$

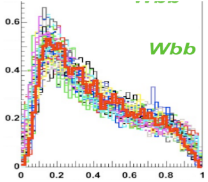
- Shared technology with mass measurement in $t\bar{t}$(eg. transfer functions)

Bayesian Neural Network

- Neural networks are non-linear functions defined by weights at the nodes.
- Instead of choosing one set of weights, a BNN find posterior probability density over all possible weights.
- Averaging over many networks weighted by the probability of each network given the training data. Less prone to overtraining
- For this analysis use highest-ranked 18-28 variables in each channel.

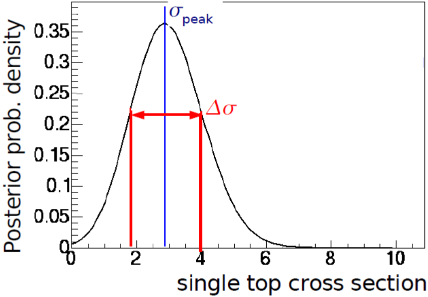






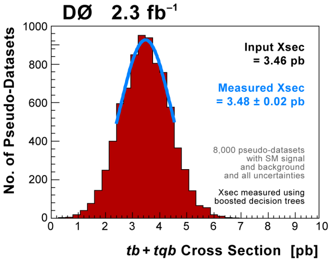
Measuring the Cross Section

- Cross sections are measured by building a Bayesian posterior probability density.
- Shape and normalization systematics treated as nuisance parameters
- Correlations between uncertainties properly accounted for
- Flat prior in signal cross section
- The cross section is given by the peak of the posterior, the width containing 68% is the uncertainty.

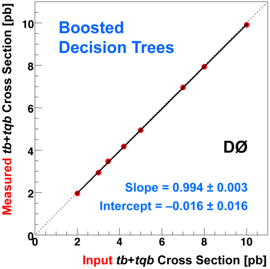


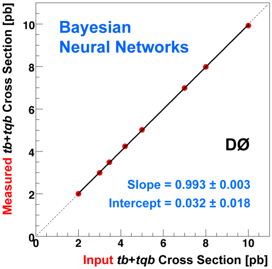
Ensemble Testing

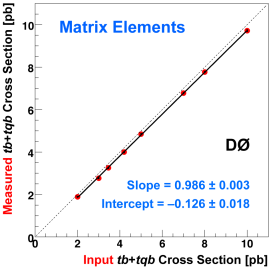
- To verify that all of this machinery is working properly we test with many sets of **pseudo-data**.
- Wonderful tool to test analysis methods! Run DØ experiment 1000s of times!
- Generated ensembles include:
  1. 0-signal ensemble ($s + t\ \sigma = 0pb$)
  2. SM ensemble ($s + t\ \sigma = 3.46pb$)
  3. Several other test values
- Each analysis tests linearity of "response" to single top.



Ensemble Results







Significance/Sensitivity Determination

We use our 0-signal ensemble to determine a significance for each measurement.

Expected p-value

The fraction of 0-signal pseudo-datasets in which we measure at least 3.46pb.

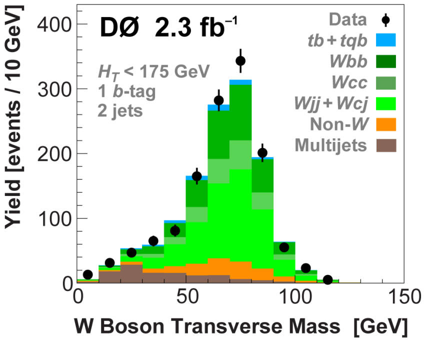
Observed p-value

The fraction of 0-signal pseudo-datasets in which we measure at least the measured cross section.

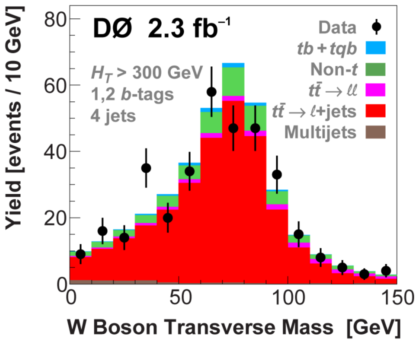
Data Cross-check samples

We define a W-enriched data sample and a ttbar-enriched sample (almost no signal) in which to test the agreement.

W+Jets Cross-Check Sample

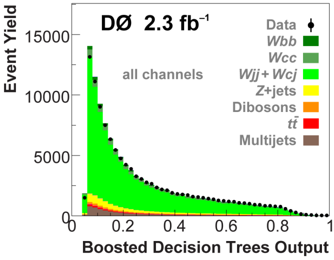


$t\bar{t}$-Pairs Cross-Check Sample

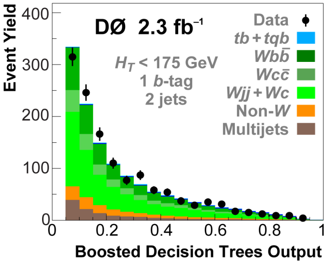


Data Cross-check samples

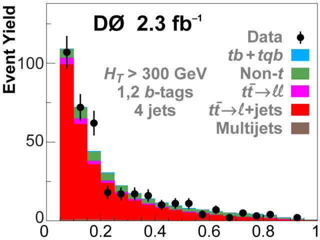
Pretagged Cross-Check Sample



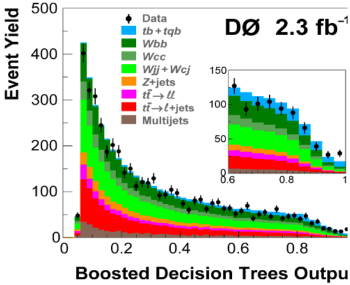
***W*+Jets Cross-Check Sample**

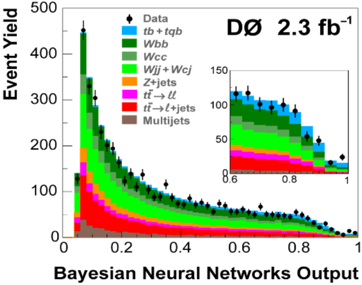


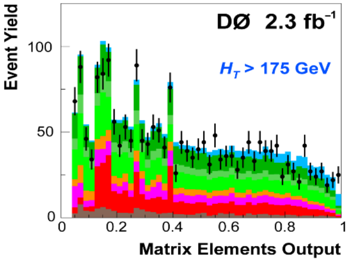
$t\bar{t}$-Pairs Cross-Check Sample

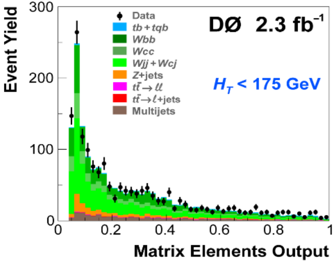


Individual MV Outputs



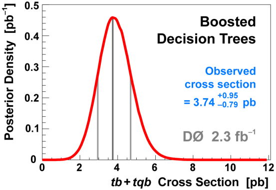


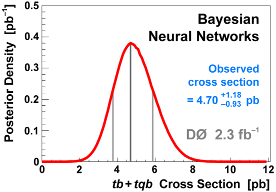


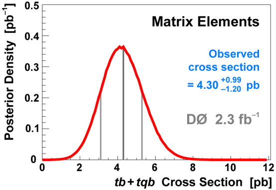


Individual Results

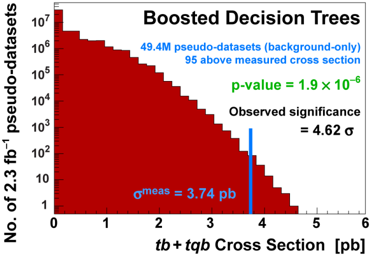
DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	$3.74^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70^{+1.18}_{-0.93}$ pb	4.1 σ	5.4 σ
Matrix Elements	$4.30^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ

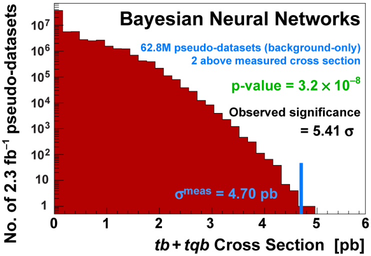


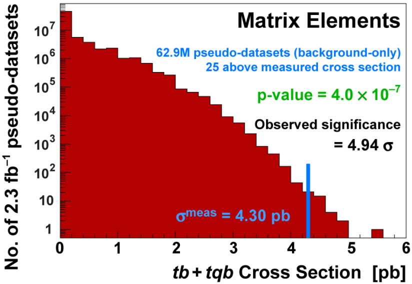




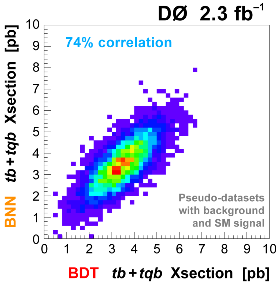
Individual Significances

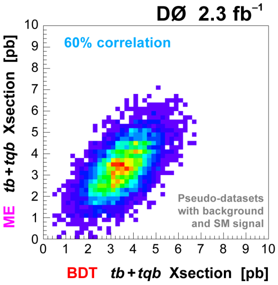


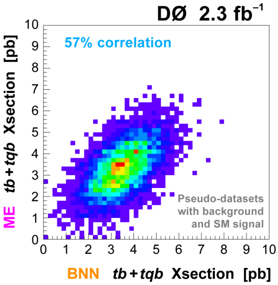




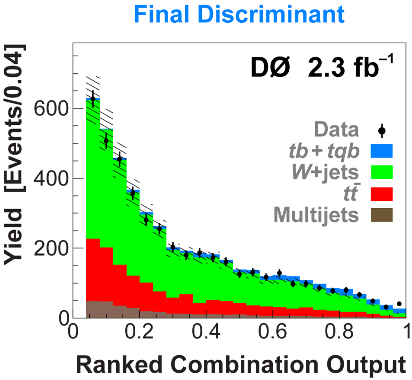
Combination of DØ Results

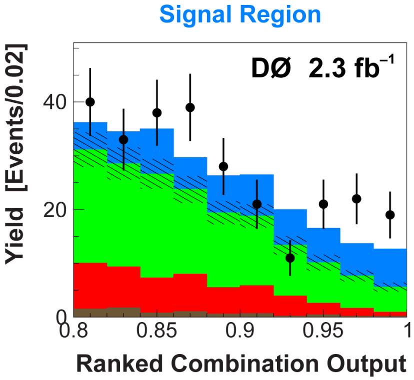




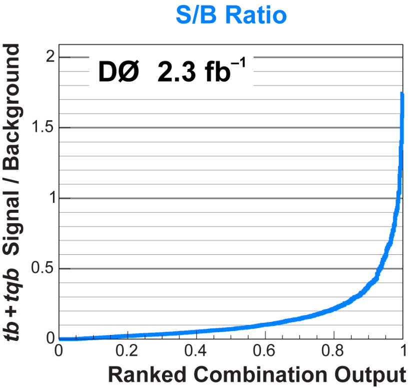


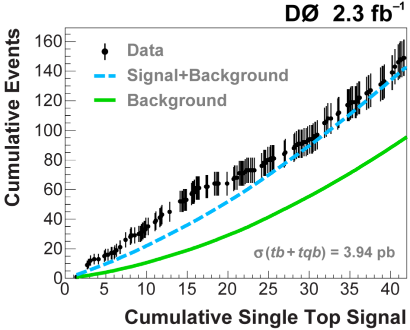
Combination of DØ Results



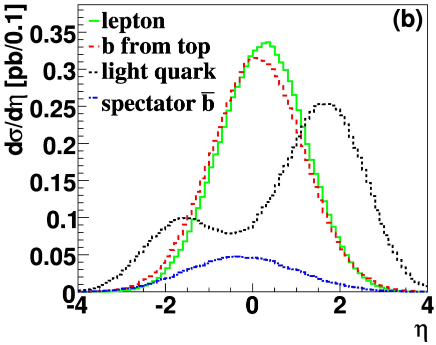


Combination of DØ Results



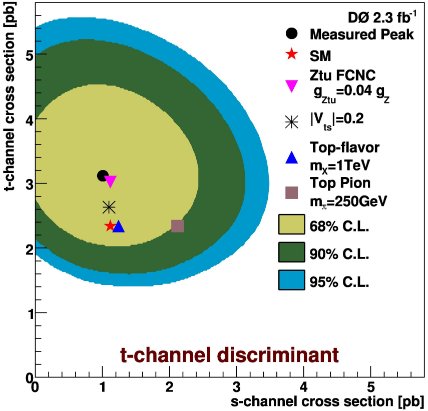


t-channel Alone



- It is interesting to attempt to separate the t-channel from the s-channel to search for new physics.
- The eta distribution of the light quark jet (left) is one distinguishing feature between s- and t-channel.
- DØ has taken the observation analysis and retrained the discriminants to separate the two sources.

t-channel Alone

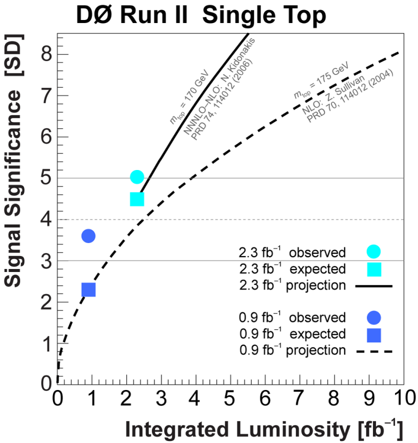


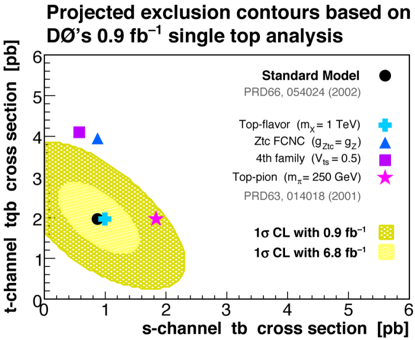
- Do a 2D measurement, no restriction on relative s and t channel cross sections.
- Integrate along s-channel axis to get t-channel measurement and vice versa:

$$\sigma_t = 3.14^{+0.94}_{-0.80} pb$$
$$\sigma_s = 1.05 \pm 0.81 pb$$

- Consistent with SM, 4.8σ excess on t-channel alone.

DØ Future Projections





CKM Matrix Element $\mathrm{V_{tb}}$

Direct access to V_{tb}

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

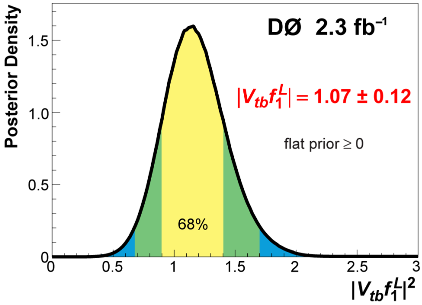
- Weak interaction eigenstates are not mass eigenstates
- In SM: top must decay to a W and d, s or b quark
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 = 1$
  - constraints on V_{td} and V_{ts}: $V_{tb} > 0.998$
- New physics that couples to the top quark:
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 < 1$
  - no constraint on V_{tb}

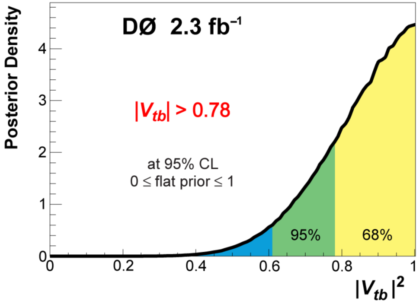
Measuring $|V_{tb}|$

- Given that we now have a measurement of the single top cross section, we can make the first direct meassurement of $|V_{tb}|$.
- Use the same infrastructure as cross section measurement but make a posterior in $|V_{tb}|^2$.
- Caveat: assume SM top quark decays.
- Additional theoretical errors are needed (see hep-ph/0408049)

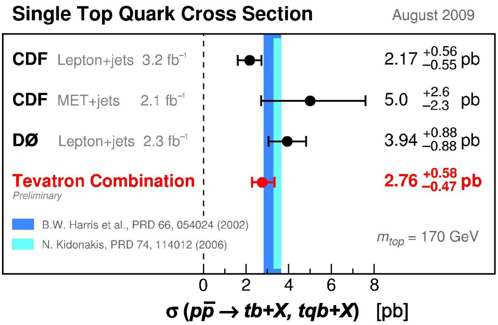
Additional Systematic Uncertainties for the $|V_{tb}|$ Measurement DØ 2.3 fb^{-1}	
For the *tb+tqb* theory cross section	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%

Measuring or Limiting $|V_{tb}|^2$



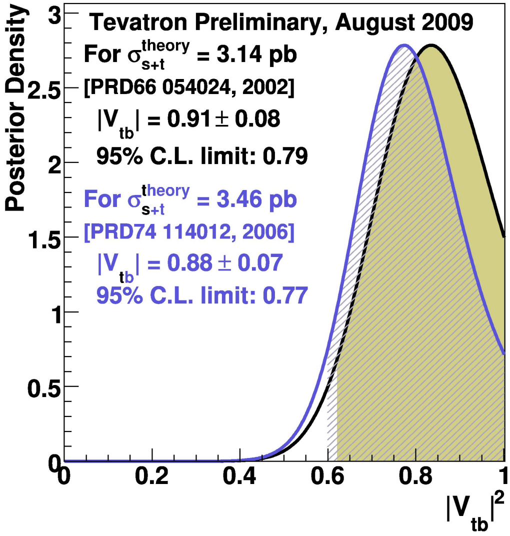


Combining with CDF - Cross Section



- Same Bayesian method used to combine experiments as was used to combine channels within an experiment.
- Common systematics are assume 100% correlated, the rest are assumed uncorrelated.
- Cross section uncertainty improves from 22% to 19%. Two experiments are compatible at the 1.6 sigma level.

Combining with CDF - $|V_{tb}|$



Summary

Observation of Single Top Quark Production!!

- Single top has finally been observed at the 5 sigma level by both Dzero and CDF.

Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
DØ (2.3 fb^{-1})	**March 2009**	PRL **103**, 092001 (2009)	(m_{top} = 170 GeV)
3.94 ± 0.88 pb	4.5 σ	5.0 σ	$\lvert V_{tb} f_1^L \rvert = 1.07 \pm 0.12$ $\lvert V_{tb} \rvert > 0.78$ at 95% CL
CDF (3.2, 2.1 fb^{-1})	**March 2009**	PRL **103**, 092002 (2009)	(m_{top} = 175 GeV)
$2.3\ ^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ	$\lvert V_{tb} f_1^L \rvert = 0.91 \pm 0.13$ $\lvert V_{tb} \rvert > 0.71$ at 95% CL
DØ & CDF combined	**August 2009**	FERMILAB-TM-2440-E	(m_{top} = 170 GeV)
$2.76\ ^{+0.58}_{-0.47}$ pb			$\lvert V_{tb} f_1^L \rvert = 0.88 \pm 0.07$ $\lvert V_{tb} \rvert > 0.77$ at 95% CL

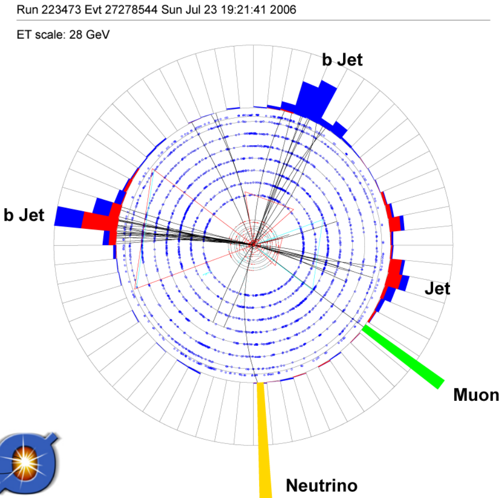
BACKUP SLIDES

BACKUP SLIDES

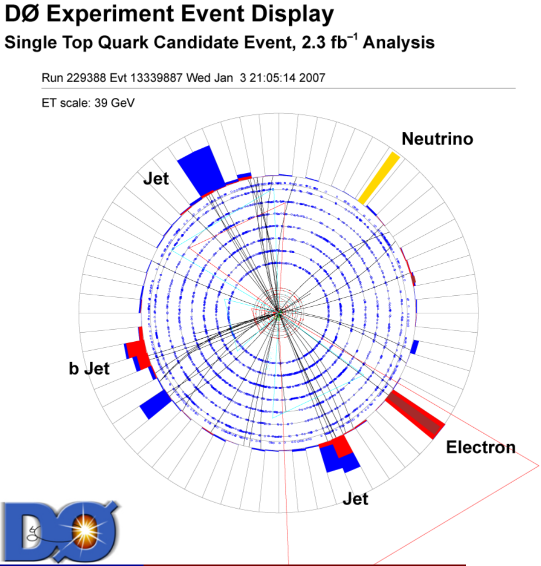
Event Displays I

DØ Experiment Event Display

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



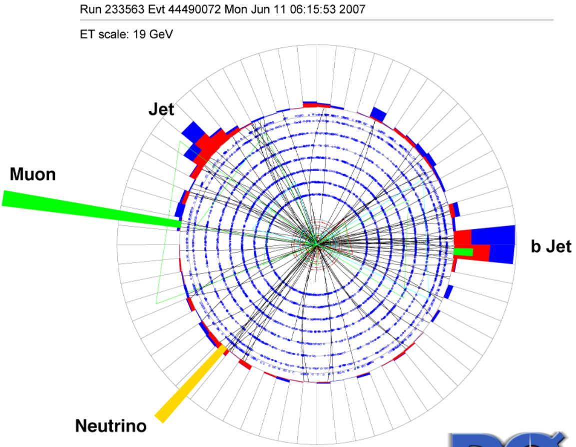
Event Displays II



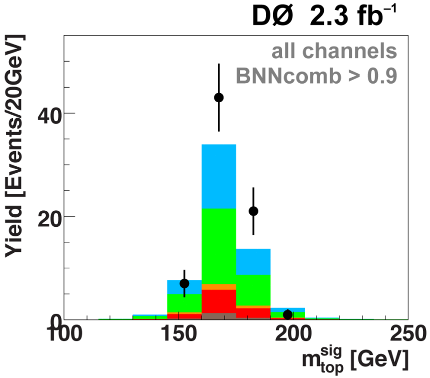
Event Displays III

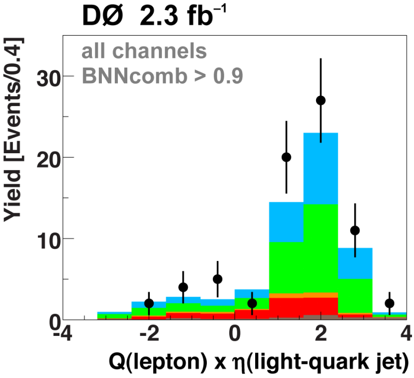
DØ Experiment Event Display

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



Kinematics in the Signal Region





Yields in More Detail

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
$t\bar{t} \to \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \to \ell$+jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

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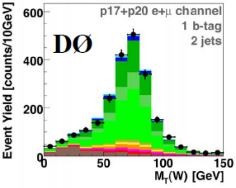
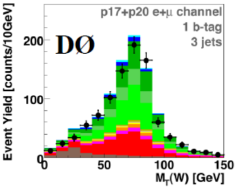
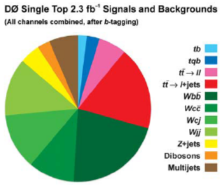
W+jets HF Scaling Factor

- W + heavy flavor normalized to theory (MCFM-NLO)
  - 1.47 (Wbb,Wcc), 1.38 (Wcj)
- Additional empirical correction
  - derived from two-jet data and simulation: includes zero-tag events
  - 0.95 ± 0.13 (Wbb, Wcc)
- Uncertainties considered
  - Data statistics ± 9%
  - ± 40% single top cross section → ± 7% in SF
  - ± 10% on the Wcj theory SF → ± 8% in SF
  - Additional ± 10% Wbb/Wcc → ± 5% in SF

S:B = 1:21 in 1Tag
S:B = 1:15 in 2Tag







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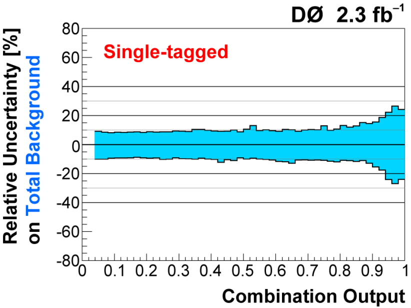
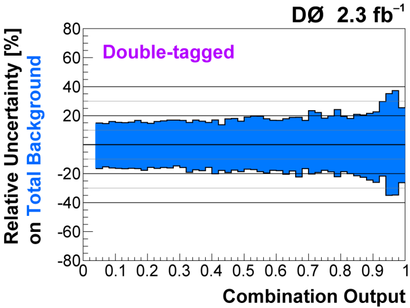
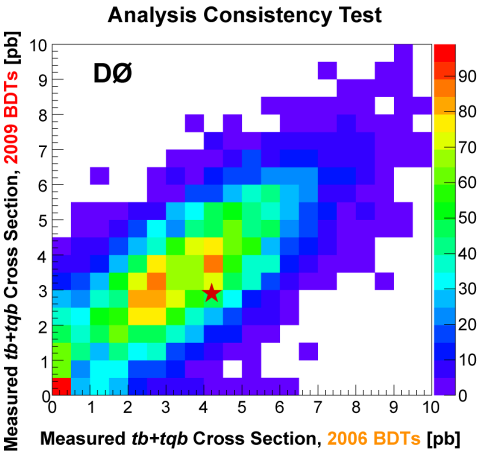
Systematic Uncertainties





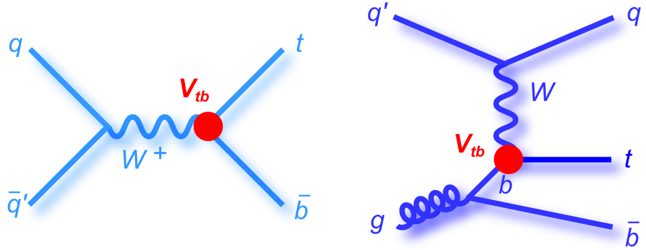
Evidence Cross-Check



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.

More on $\mathrm{V_{tb}}$



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

CDF+DØ Combination Uncertainties

Systematic Uncertainty	CDF		D0		Correlated between the two experiments
	Rate	Shape	Rate	Shape	
Luminosity from detector	4.5%		4.6%		
Luminosity from cross section	4.0%		4.0%		•
Signal modeling	2.2–19.5%	•	3.5–13.6%		•
Background from MC	12.1–12.4%	•	15.1 %		•
Background from data	17–40%	•	13.7–54%	•	
Detector modeling	0–9%	•	7.1 %		
b-tagging	0–29%	•	2–30%	•	
dJES	0-16%	•	0.1–13.1%	•	