

# Observation of Single Top Quarks at DØ

Dugan O'Neil

Simon Fraser University and CEA Saclay

LAPP

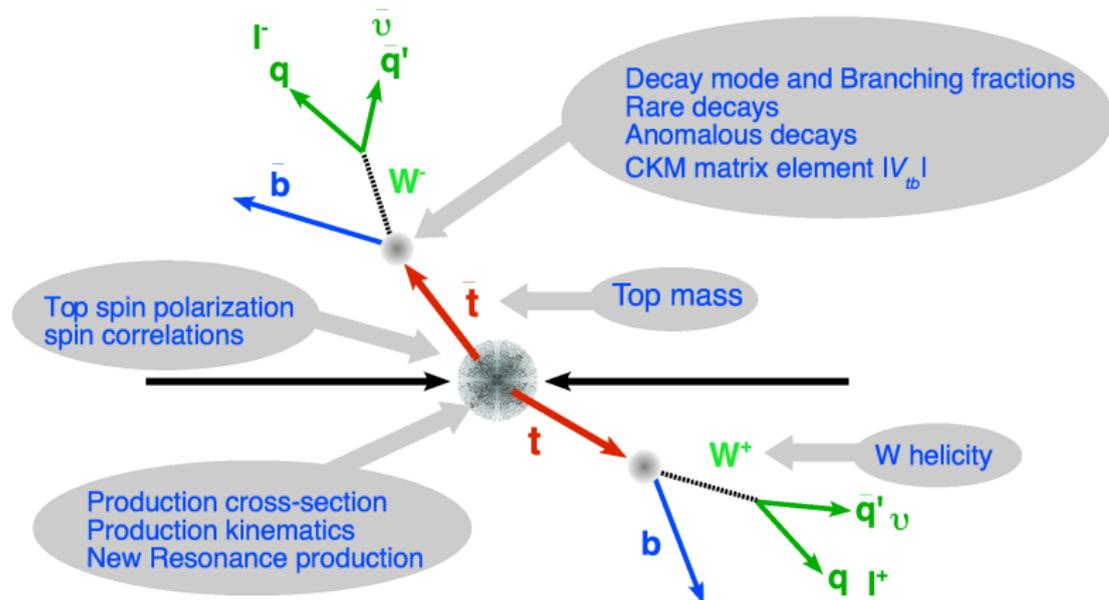
September 25, 2009



- 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

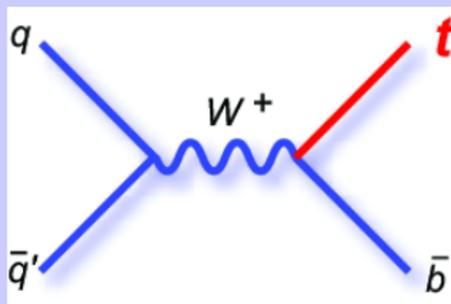
# Top Quark Physics

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



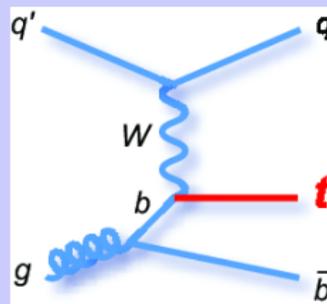
## Single top quark production @ 1.96TeV

## s-channel (tb)



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

## t-channel (tqb)



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

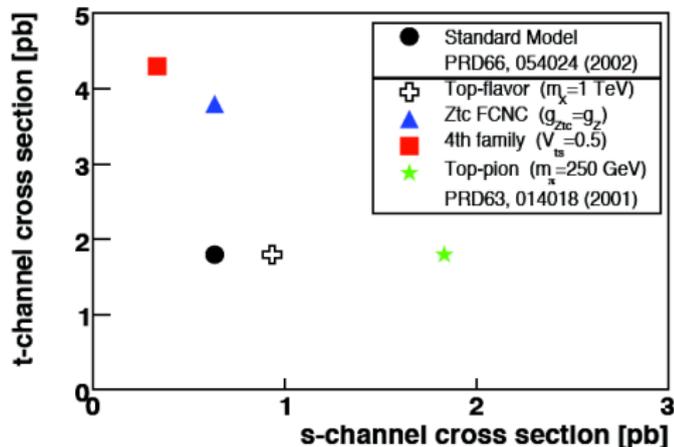
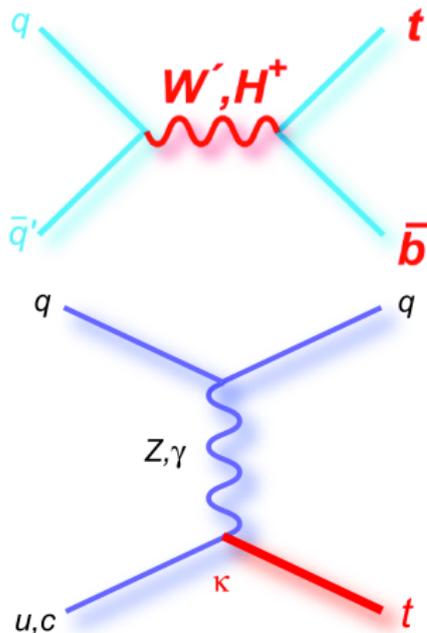
(\*) N. Kidonakis, Phys. Rev. D 74, 114012 (2006),  $M_t=170\text{GeV}$

# Motivation - Measure the Cross Section

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

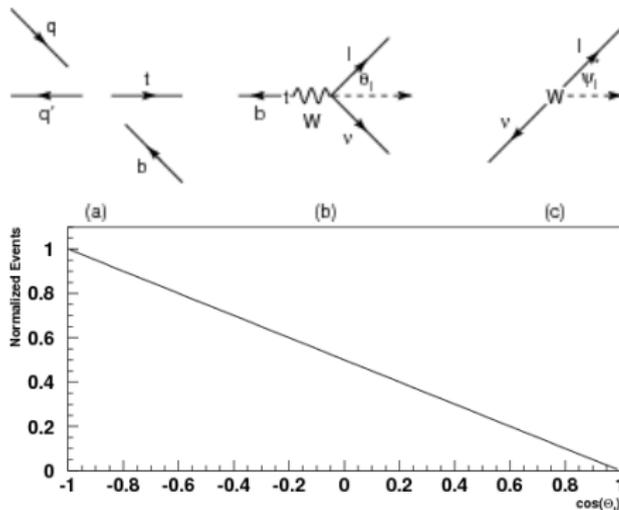
# Motivation - Measure the Cross Section

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

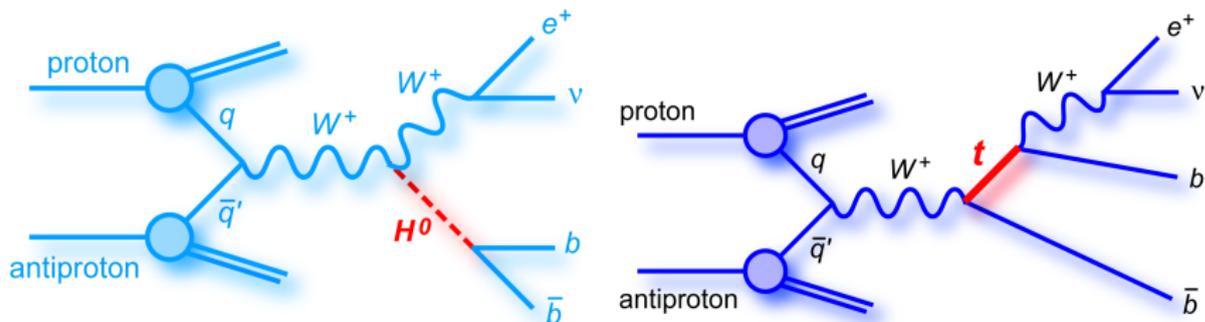


# Motivation - Top Quark Spin

- 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



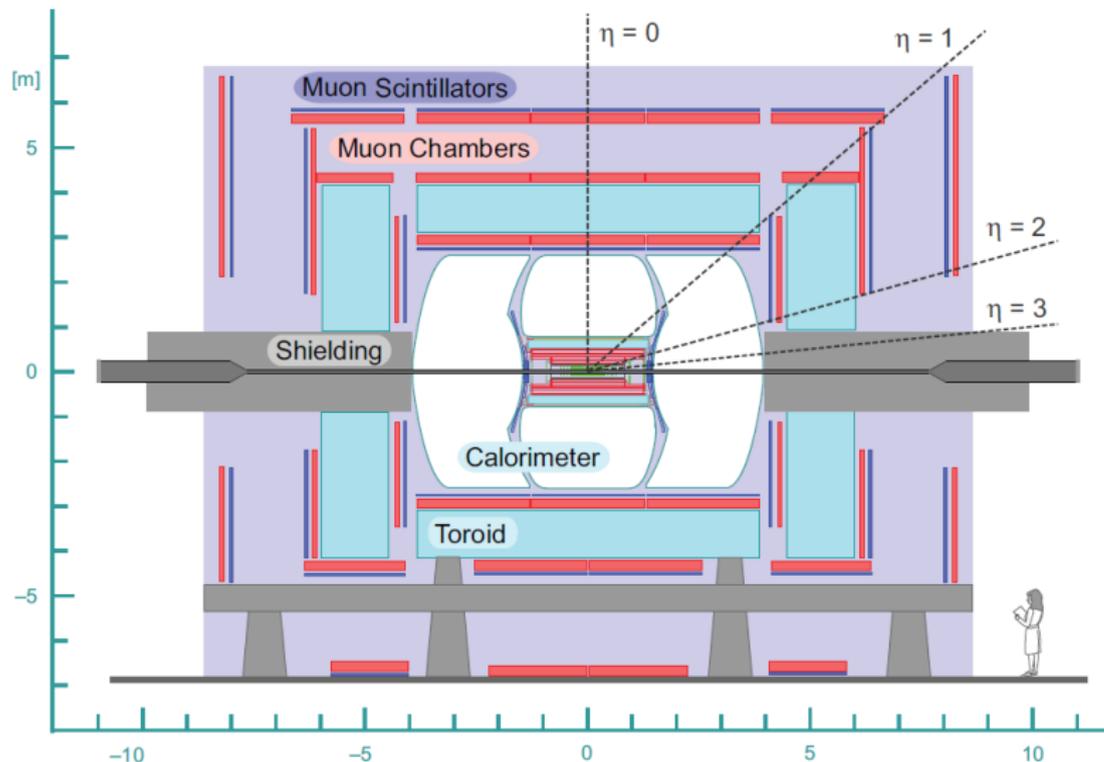
- This looks a lot like single top!
- One of the most promising Tevatron channels for Higgs discovery is like single top with 1/10 the cross section.
- Approach to measure Higgs is tested on single top. It is also an important background.
- As soon as we discover it, somebody tries to get rid of it....

# The Fermilab Tevatron



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

# The DØ Cartoon



# The Collaboration



AZ U. of Arizona  
 CA U. of California, Berkeley  
 U. of California, Riverside  
 Lawrence Berkeley Nat. Lab.

FL Florida State U.  
 IL Fermilab  
 U. of Illinois, Chicago  
 Northern Illinois U.  
 Northwestern U.

IN Indiana U.  
 U. of Notre Dame  
 Purdue U. Calumet

IA Iowa State U.  
 KS U. of Kansas  
 Kansas State U.

LA Louisiana Tech U.  
 MD U. of Maryland  
 MA Boston U.

Northeastern U.  
 MI U. of Michigan  
 Michigan State U.

MS U. of Mississippi  
 NE U. of Nebraska  
 NJ Princeton U.

NY Brookhaven Nat. Lab.  
 Columbia U.  
 SUNY, Buffalo  
 SUNY, Stony Brook

U. of Rochester  
 OK Langston U.  
 U. of Oklahoma  
 Oklahoma State U.

RI Brown U.  
 TX Southern Methodist U.  
 U. of Texas at Arlington  
 Rice U.

VA U. of Virginia  
 WA U. of Washington

Ann Henson, UC Riverside



U. de Buenos Aires



LAFEX, CBPF, Rio de Janeiro  
 State U. do Rio de Janeiro  
 U. Federal do ABC, São Paulo  
 State U. Paulista, São Paulo



U. of Alberta  
 McGill U.  
 Simon Fraser U.  
 York U.



U. of Science and Technology  
 of China, Hefei



U. de los Andes, Bogotá



Charles U., Prague  
 Czech Tech. U., Prague  
 Academy of Sciences, Prague



U. San Francisco de Quito



LPC, Clermont-Ferrand  
 ISN, IN2P3, Grenoble  
 CPPM, IN2P3, Marseille  
 LAL, IN2P3, Orsay  
 LPNHE, IN2P3, Paris  
 DAPNIA/SP, CEA, Saclay  
 IRaS, Strasbourg  
 IPN, IN2P3, Villeurbanne



RWTH Aachen  
 Bonn U.  
 Freiburg U.  
 Göttingen U.  
 Mainz U.  
 LMU München  
 Wuppertal U.

## The DØ Collaboration



Panjab U. Chandigarh  
 Delhi U., Delhi  
 Tata Institute, Mumbai



University College, Dublin



KDL, Korea U., Seoul  
 SungKyunKwan U., Suwan



CINVESTAV, Mexico City



FOM-NIKHEF, Amsterdam  
 U. of Amsterdam / NIKHEF  
 U. of Nijmegen / NIKHEF



JINR, Dubna  
 ITEP, Moscow  
 Moscow State U.  
 IHEP, Protvino  
 PNPI, St. Petersburg

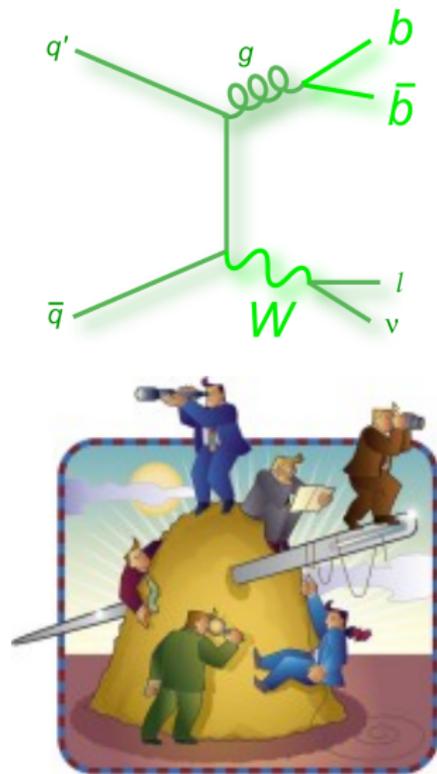
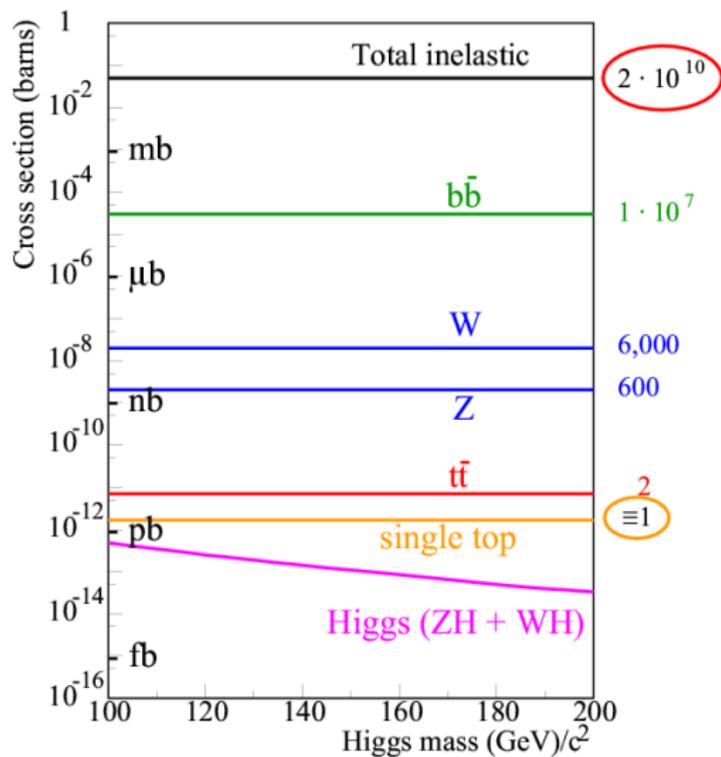


Stockholm U.  
 Uppsala U.



Lancaster U.  
 Imperial College, London  
 U. of Manchester

# 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<sup>+</sup>: PLB 641, 423 (2006)
- Search: PRD 75, 092007 (2007)
- Evidence: PRL 98, 181802 (2007)
- FCNC: PRL 99, 191802 (2007)
- W<sup>+</sup>: PRL 100, 211802 (2007)
- Evidence: PRD 78, 012005 (2008)
- Wtb: PRL 101, 221801 (2008)
- Wtb: PRL 102, 092002 (2009)
- H<sup>+</sup>: (PRL) arXiv:0807.0859
- Observation: (PRL) arXiv:0903.0850

## CDF

- Search: PRD 65, 091102 (2002)
- W<sup>+</sup>: 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<sup>+</sup>: (PRL) arXiv:0902.3276
- Observation: (PRL) arXiv:0903.0885

PRL 98, 181802 (2007) PHYSICAL REVIEW LETTERS

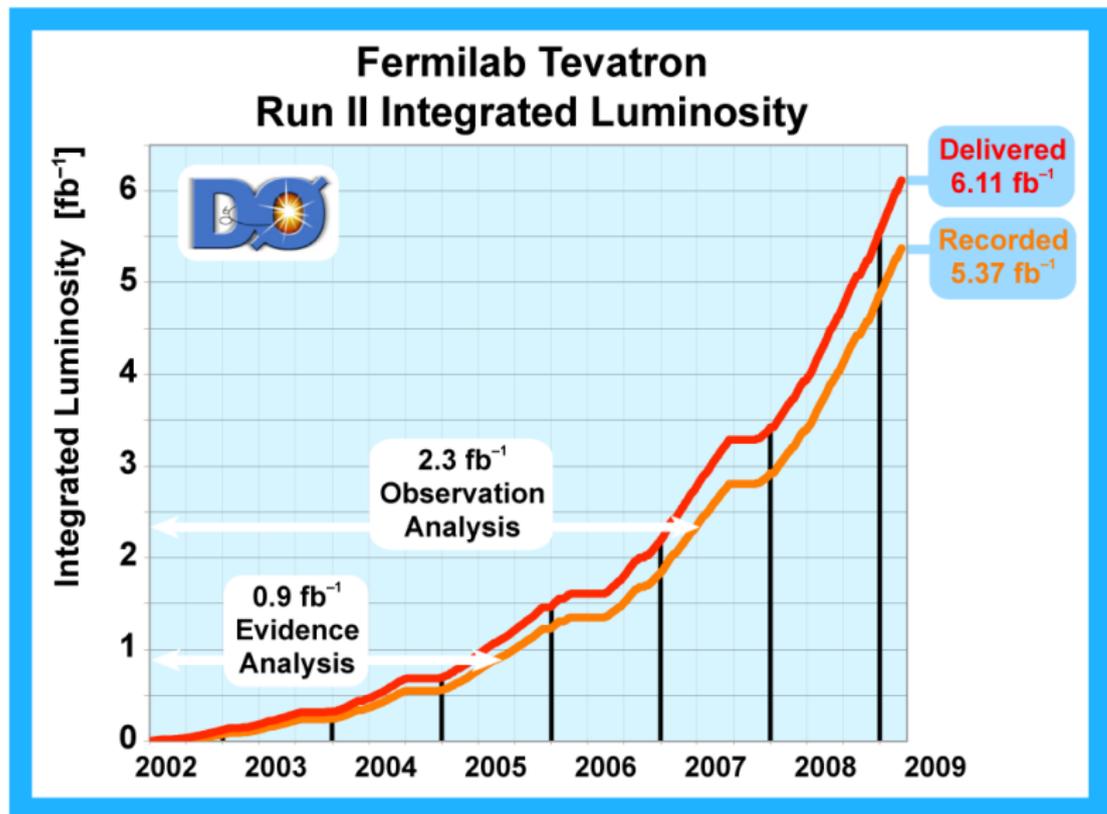
Evidence for Production of Single Top Quarks and First Direct Measurement of  $|V_{cb}|$ 

V.M. Abazov,<sup>20</sup> B. Abler,<sup>21</sup> M. Abolins,<sup>22</sup> B.S. Acharya,<sup>23</sup> M. Adams,<sup>24</sup> T. Adams,<sup>25</sup> G. Aguilo,<sup>26</sup> S.H. Ahn,<sup>27</sup> M. Akhmetov,<sup>28</sup> G.D. Alexeev,<sup>29</sup> G. Altheimer,<sup>30</sup> Z. Altarelli,<sup>31</sup> A. Amorim,<sup>32</sup> S. Amoroso,<sup>33</sup> W. Andersson,<sup>34</sup> S. Andersson,<sup>35</sup> T. Andersson,<sup>36</sup> S. Androsov,<sup>37</sup> M. Andreola,<sup>38</sup> V. Andreev,<sup>39</sup> M. Aoki,<sup>40</sup> A. Arafat,<sup>41</sup> B. Aures,<sup>42</sup> A.C.E. Aspin,<sup>43</sup> D. Atarotescu,<sup>44</sup> C. Atteneo,<sup>45</sup> C. Avila,<sup>46</sup> C. Ay,<sup>47</sup> P. Baidin,<sup>48</sup> A. Baheti,<sup>49</sup> J. Baker,<sup>50</sup> B. Baker,<sup>51</sup> D. Baker,<sup>52</sup> S.V. Barakat,<sup>53</sup> P. Baranov,<sup>54</sup> P. Baratta,<sup>55</sup> E. Barbagli,<sup>56</sup> P. Barile,<sup>57</sup> C. Barlow,<sup>58</sup> J. Barrow,<sup>59</sup> J.F. Barstow,<sup>60</sup> U. Becker,<sup>61</sup> D. Becker,<sup>62</sup> S. Becher,<sup>63</sup> A. Bean,<sup>64</sup> M. Begalli,<sup>65</sup> M. Begel,<sup>66</sup> C. Bejarano-Champagnon,<sup>67</sup> L. Bellarosa,<sup>68</sup> A. Bellini,<sup>69</sup> L. Bellizzi,<sup>70</sup> J. Bellizzi,<sup>71</sup> M. Bellizzi,<sup>72</sup> H. Benz,<sup>73</sup> T.A. Beroz,<sup>74</sup> R.E. Berry,<sup>75</sup> D. Bhattarai,<sup>76</sup> H. Bhatti,<sup>77</sup> D. Bhowmik,<sup>78</sup> N.J. Bhattacharya,<sup>79</sup> D. Blackburn,<sup>80</sup> M. Bhatker,<sup>81</sup> T.H. Bhattacharya,<sup>82</sup> E. Bhatti,<sup>83</sup> C.P. Bhowmik,<sup>84</sup> J.M. Bixler,<sup>85</sup> W. Blandin,<sup>86</sup> R.C. Blum,<sup>87</sup> N.M. Brack,<sup>88</sup> M. Brackley,<sup>89</sup> A. Chandra,<sup>90</sup> J. Charin,<sup>91</sup> R. Chen,<sup>92</sup> J. Chen,<sup>93</sup> D.K. Chharia,<sup>94</sup> B. Chiarin,<sup>95</sup> C. Chiu,<sup>96</sup> M. Cifarelli,<sup>97</sup> W. R.F. Cline,<sup>98</sup> S. Cifuni,<sup>99</sup> R. Cozzani,<sup>100</sup> M. Czakaj,<sup>101</sup> H. K. Do,<sup>102</sup> P. Datta,<sup>103</sup> S.J. de Jong,<sup>104</sup> E. De La Cruz-Brazda,<sup>105</sup> M. Demaree,<sup>106</sup> S. Dierken,<sup>107</sup> D. Diakonov,<sup>108</sup> S.P. Dierker,<sup>109</sup> A. Dominguez,<sup>110</sup> H. Dong,<sup>111</sup> V. Duhan,<sup>112</sup> L. Duhan,<sup>113</sup> A. Dvorkin,<sup>114</sup> M. Eide,<sup>115</sup> D. Edla,<sup>116</sup> V.D. Ermiyev,<sup>117</sup> S. Ermiyev,<sup>118</sup> S. Ermiyev,<sup>119</sup> S. Ermiyev,<sup>120</sup> S. Ermiyev,<sup>121</sup> S. Ermiyev,<sup>122</sup> S. Ermiyev,<sup>123</sup> S. Ermiyev,<sup>124</sup> S. Ermiyev,<sup>125</sup> S. Ermiyev,<sup>126</sup> S. Ermiyev,<sup>127</sup> S. Ermiyev,<sup>128</sup> S. Ermiyev,<sup>129</sup> S. Ermiyev,<sup>130</sup> S. Ermiyev,<sup>131</sup> S. Ermiyev,<sup>132</sup> S. Ermiyev,<sup>133</sup> S. Ermiyev,<sup>134</sup> S. Ermiyev,<sup>135</sup> S. Ermiyev,<sup>136</sup> S. 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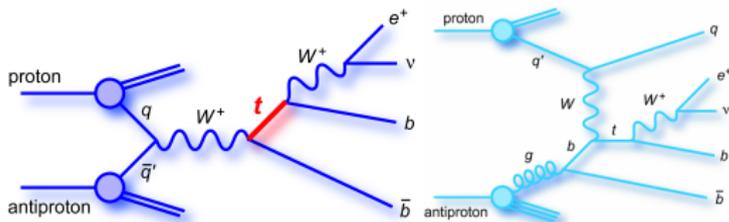
# General Analysis Strategy (2006 or 2009)

- 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
- $\cancel{E}_T$
- 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  $H_T, \cancel{E}_T$  cuts

# The Background Model

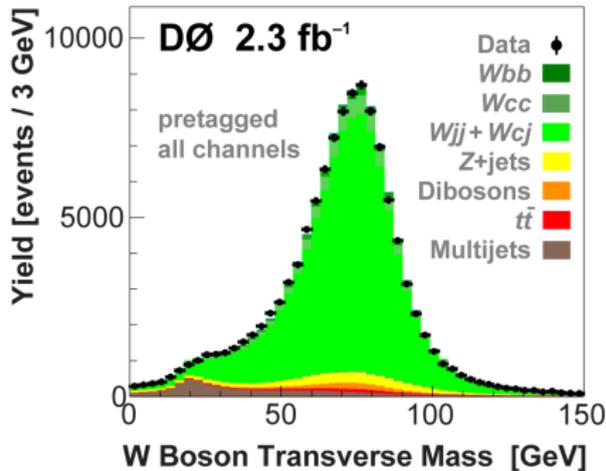
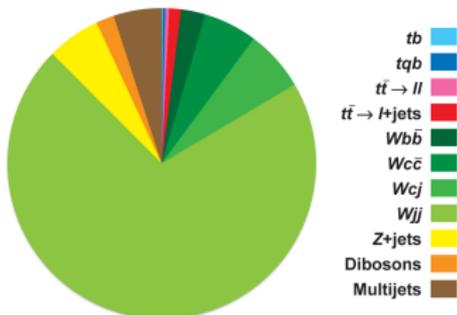
- Signal modeled using SINGLETOP+PYTHIA. Based on COMPHEP, reproduces NLO distributions.
- W+jets, Z+jets and ttbar from ALPGEN+PYTHIA:
  - MLM parton-jet matching to avoid double-counting final states.
  - $\eta(jets)$ ,  $\Delta\phi(jet1, jet2)$ ,  $\Delta\eta(jet1, jet2)$  corrected in W+jets samples 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

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

# Event Selection - Agreement Before Tagging

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

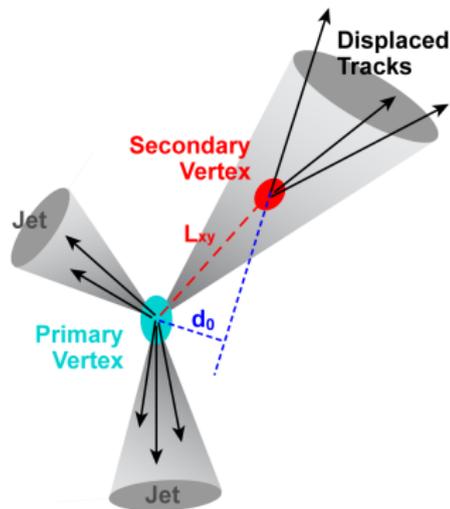
DØ Single Top 2.3 fb<sup>-1</sup> Signals and Backgrounds  
(All channels combined, before *b*-tagging)



$$S:B = 1:259$$

## 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  
( $\epsilon_b = 50\%, \epsilon_c = 14\%, \epsilon_l = 1.5\%$ )

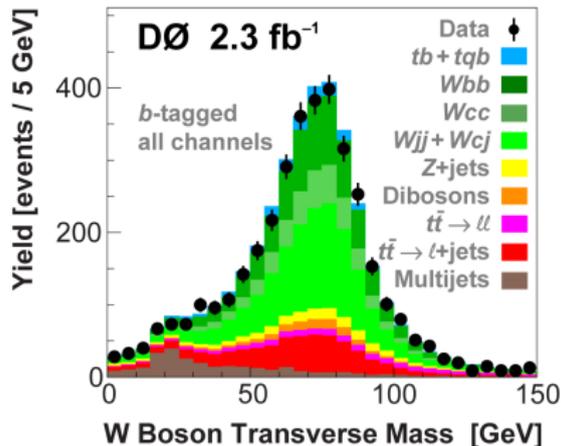
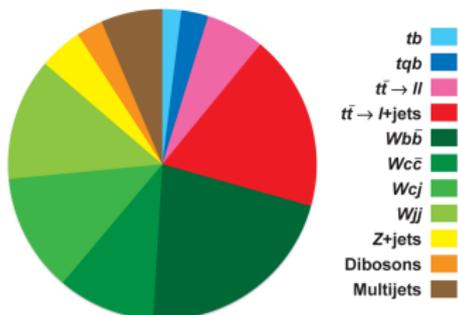


- $D\Phi$  uses a NN with 7 input variables based on secondary vertex and impact parameter.
- Define exclusive samples: 1T, 0 L and 2L

# Event Selection - Agreement After Tagging

Event Yields in $2.3 \text{ fb}^{-1}$ of $D\bar{O}$ Data	
$e, \mu, 2,3,4\text{-jets}, 1,2\text{-tags}$ combined	
$tb + tqb$	$223 \pm 30$
$W+\text{jets}$	$2,647 \pm 241$
$Z+\text{jets}, \text{dibosons}$	$340 \pm 61$
$t\bar{t}$ pairs	$1,142 \pm 168$
Multijets	$300 \pm 52$
<b>Total prediction</b>	<b><math>4,652 \pm 352</math></b>
<b>Data</b>	<b>4,519</b>

$D\bar{O}$  Single Top  $2.3 \text{ fb}^{-1}$  Signals and Backgrounds  
(All channels combined, after  $b$ -tagging)



# Systematic Uncertainties

## Systematic Uncertainties

Ranked from Largest to Smallest Effect  
on Single Top Cross Section

$D\bar{D}$  2.3 fb<sup>-1</sup>

### 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)
<i>W</i> +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</i> / <i>Wcc</i> correction ratio	5%
Primary vertex selection	1.4%

## Systematic Uncertainties

Ranked from Largest to Smallest Effect  
on Single Top Cross Section

$D\bar{D}$  2.3 fb<sup>-1</sup>

### Smaller terms

Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
<i>Z</i> +jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
<i>Z</i> +jets theory cross sections	5.8%
<i>W</i> +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%

# Multivariate Analysis Techniques

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

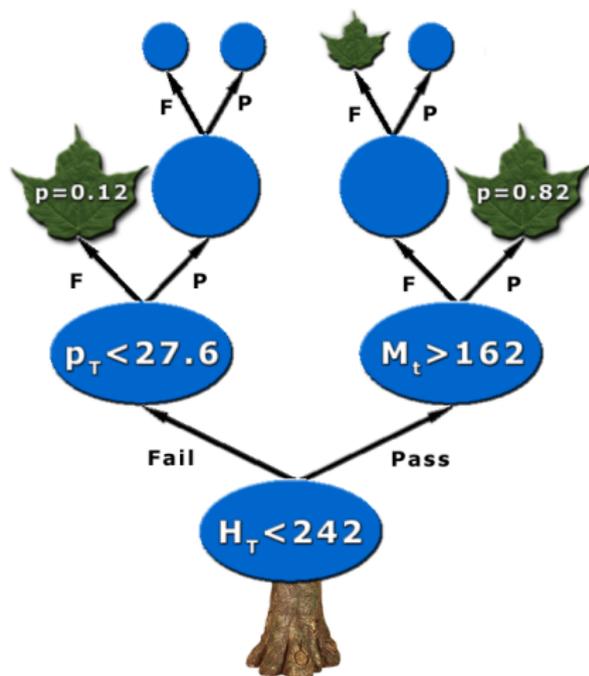
- 1 Boosted Decision Trees (BDTs)
- 2 Matrix Elements Method (ME)
- 3 Bayesian Neural Networks (BNN)

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 **F**ailed and **P**assed 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  $p_{\text{signal}}$  and  $p_{\text{background}}$
- 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:

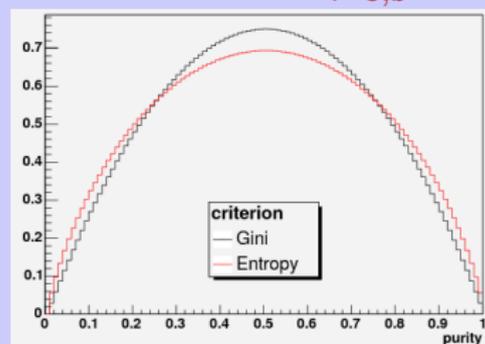
$$\Delta i(s^*, t) = \max_{s \in \{\text{splits}\}} \Delta i(s, t)$$

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

## Examples

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

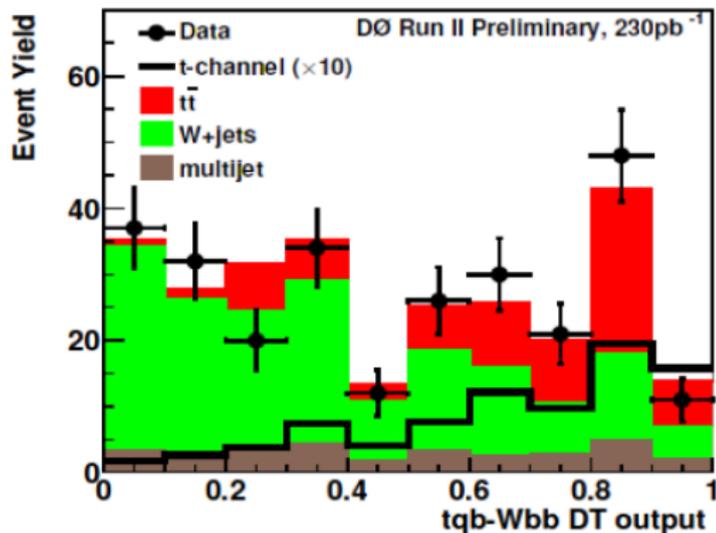
$$\text{entropy} = - \sum_{i=s,b} p_i \log p_i$$



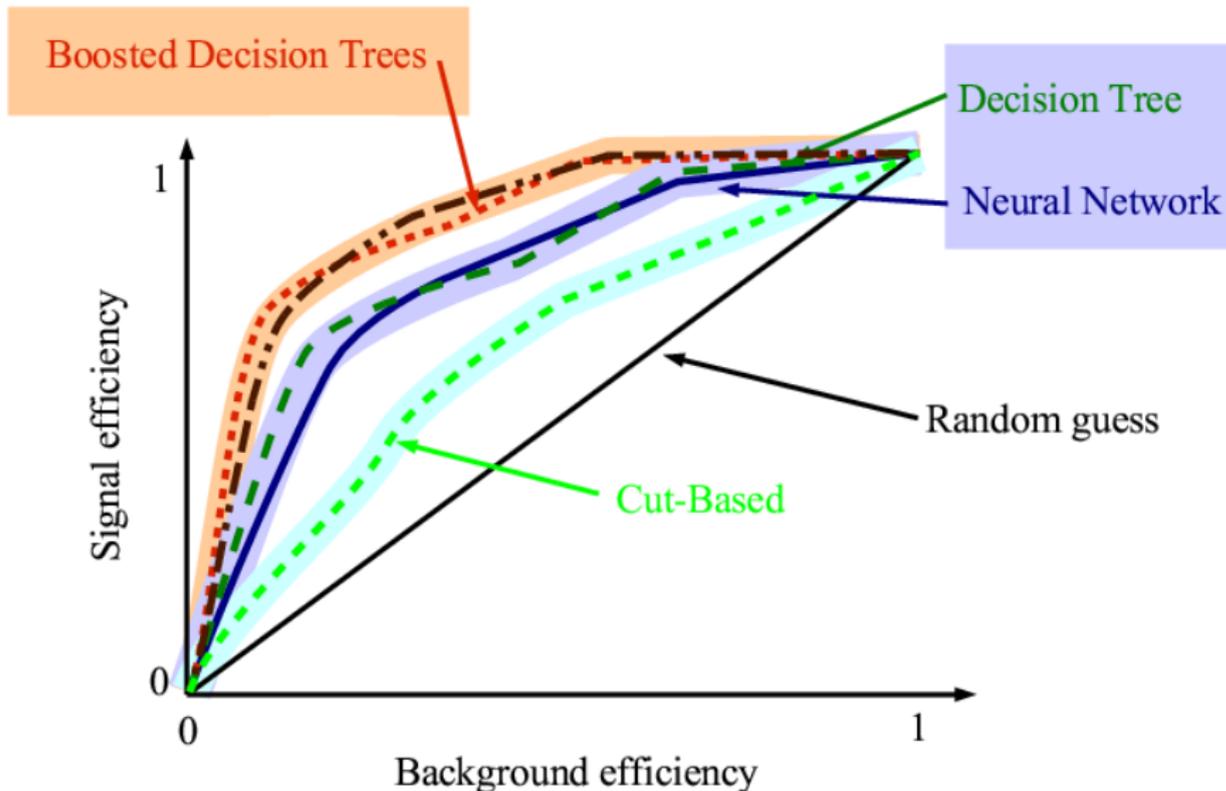
# Decision Trees

## 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  $\alpha_k$
- 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)  $\times$  ( $e, \mu$ )  $\times$  (2,3,4 jets)  $\times$  (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<sup>-1</sup> Analysis

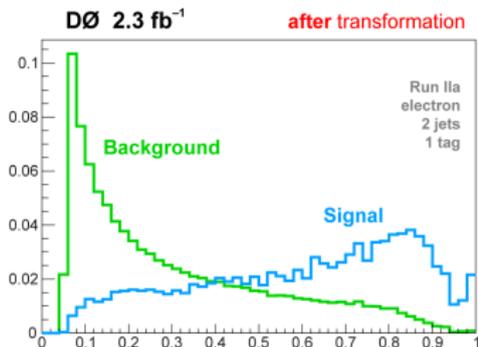
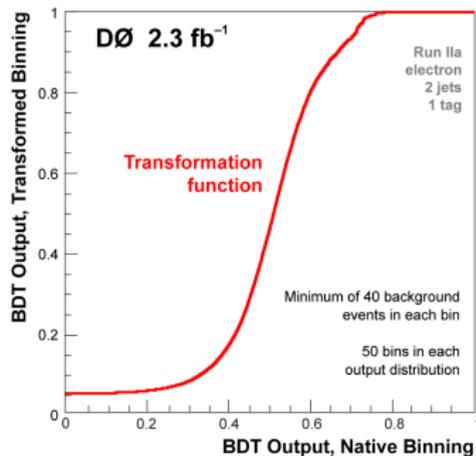
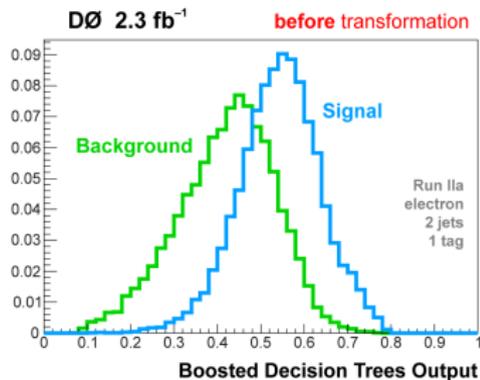
Object kinematics	$\cancel{E}_T$
	$p_T(\text{jet}2)$
	$p_T^{\text{rel}}(\text{jet}1, \text{tag}-\mu)$
	$E(\text{light}1)$
Event kinematics	$M(\text{jet}1, \text{jet}2)$
	$M_T(W)$
	$H_T(\text{lepton}, \cancel{E}_T, \text{jet}1, \text{jet}2)$
	$H_T(\text{jet}1, \text{jet}2)$
	$H_T(\text{lepton}, \cancel{E}_T)$
Jet reconstruction	$\text{Width}_\phi(\text{jet}2)$
	$\text{Width}_\eta(\text{jet}2)$
Top quark reconstruction	$M_{\text{top}}(W, \text{tag}1)$
	$\Delta M_{\text{top}}^{\text{min}}$
	$M_{\text{top}}(W, \text{tag}1, S2)$
Angular correlations	$\cos(\text{light}1, \text{lepton})_{\text{btaggedtop}}$
	$\Delta\phi(\text{lepton}, \cancel{E}_T)$
	$Q(\text{lepton}) \times \eta(\text{light}1)$

## Best Variables to Separate Single Top from Top Pairs

DØ 2.3 fb<sup>-1</sup> Analysis

Object kinematics	$p_T(\text{notbest}2)$
	$p_T(\text{jet}4)$
	$p_T(\text{light}2)$
Event kinematics	$M(\text{alljets}-\text{tag}1)$
	$\text{Centrality}(\text{alljets})$
	$M(\text{alljets}-\text{best}1)$
	$H_T(\text{alljets}-\text{tag}1)$
	$H_T(\text{lepton}, \cancel{E}_T, \text{alljets})$
	$M(\text{alljets})$
Jet reconstruction	$\text{Width}_\eta(\text{jet}4)$
	$\text{Width}_\phi(\text{jet}4)$
	$\text{Width}_\phi(\text{jet}2)$
Angular correlations	$\cos(\text{lepton}_{\text{btaggedtop}}, \text{btaggedtop}_{\text{CMframe}})$
	$Q(\text{lepton}) \times \eta(\text{light}1)$
	$\Delta R(\text{jet}1, \text{jet}2)$

# 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:

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

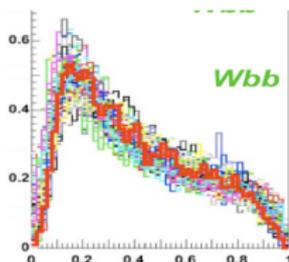
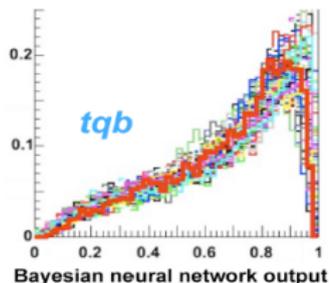
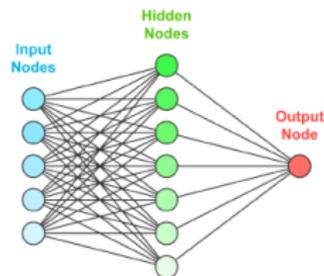
- Define  $P_{Signal}$  as properly normalized differential cross section

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

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

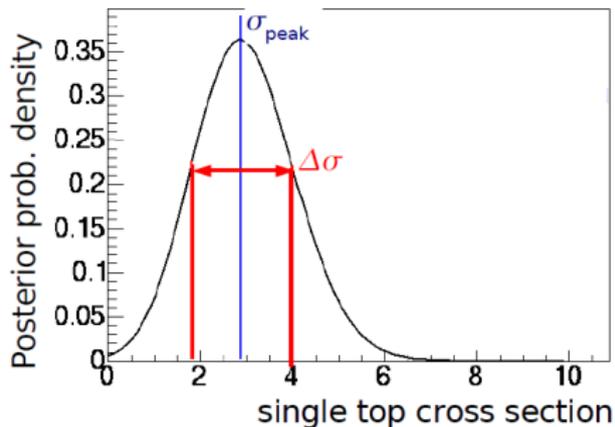
# Bayesian Neural Network

- 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.



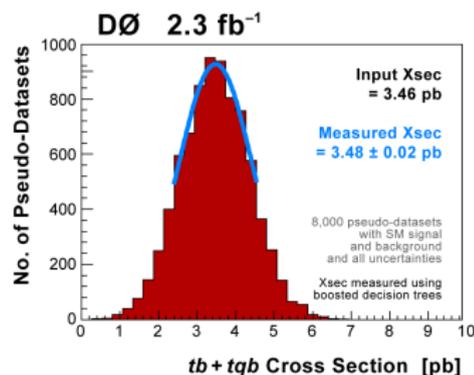
# Measuring the Cross Section

- 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.

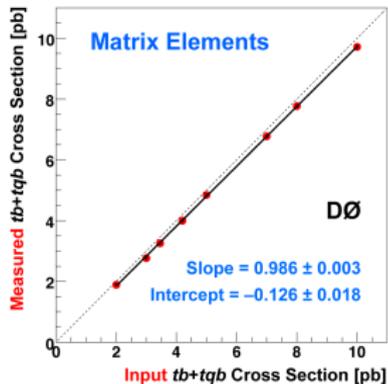
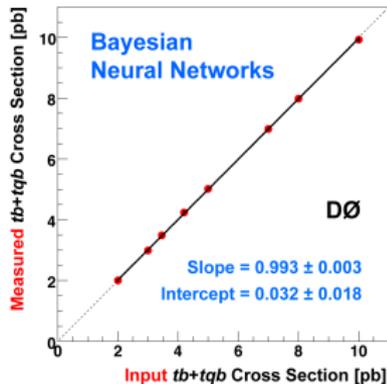
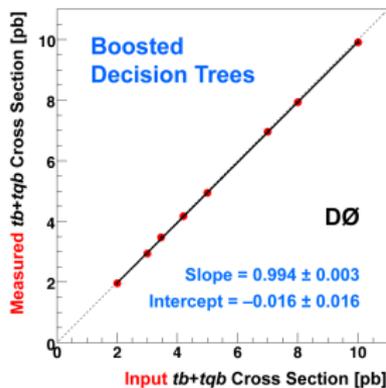


# Ensemble Testing

- 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:
  - 0-signal ensemble ( $s + t \sigma = 0 pb$ )
  - SM ensemble ( $s + t \sigma = 3.46 pb$ )
  - 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.

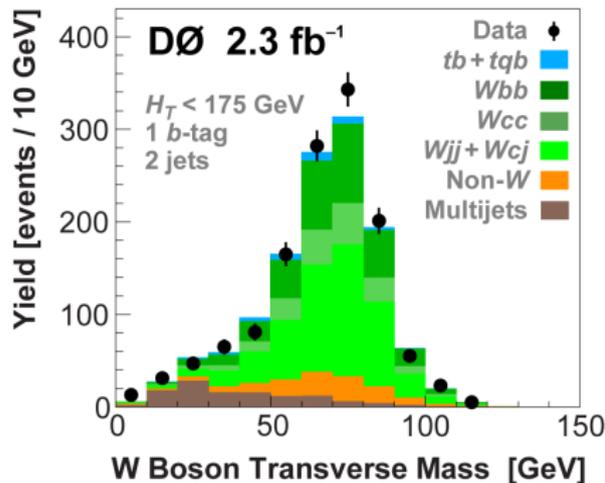
## Observed $p$ -value

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

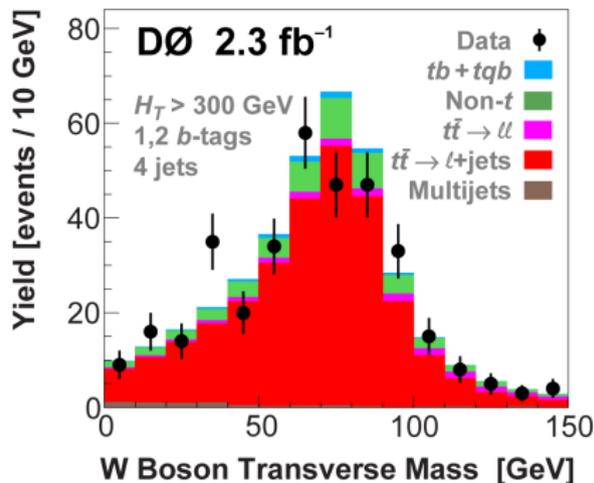
# Data Cross-check samples

We define a W-enriched data sample and a  $t\bar{t}$ -enriched sample (almost no signal) in which to test the agreement.

### W+Jets Cross-Check Sample

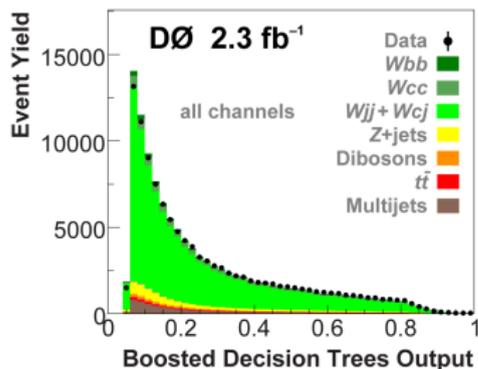


### $t\bar{t}$ -Pairs Cross-Check Sample

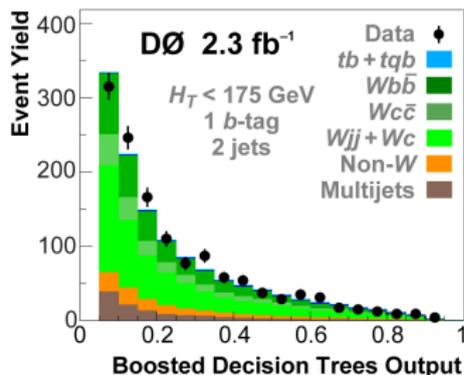
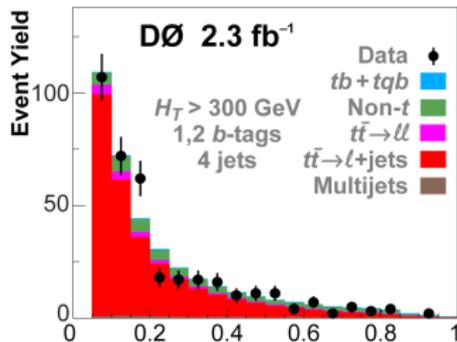


## Data Cross-check samples

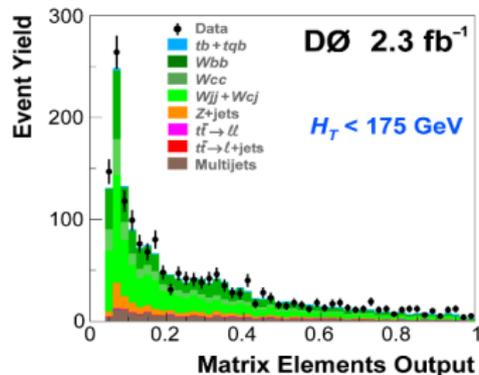
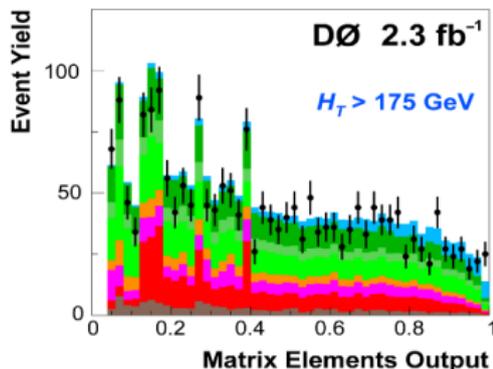
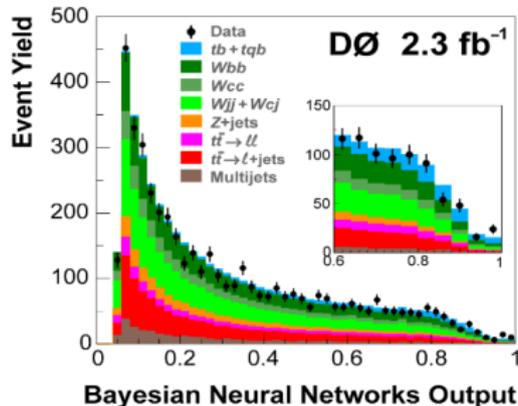
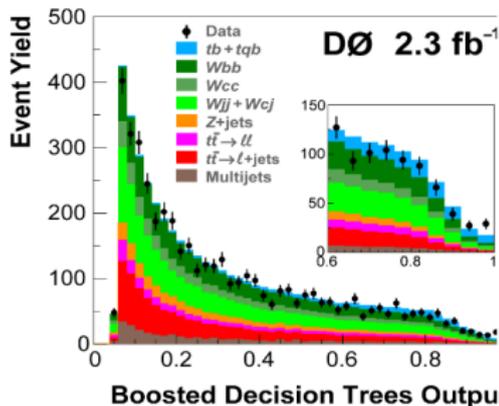
Pretagged Cross-Check Sample



W+Jets Cross-Check Sample

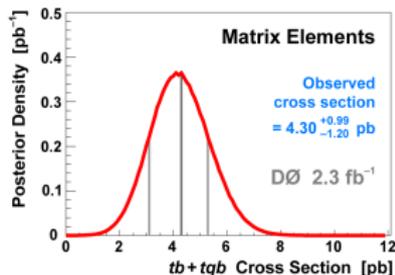
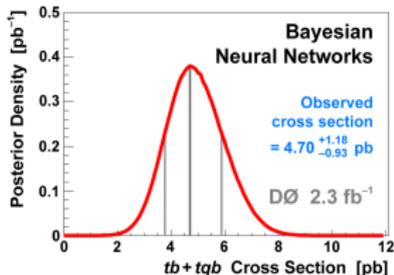
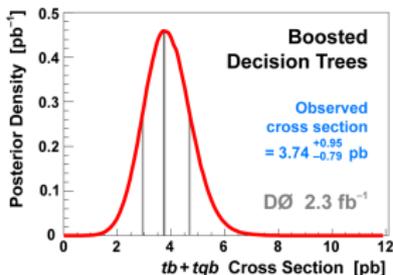
t $\bar{t}$ -Pairs Cross-Check Sample

# Individual MV Outputs

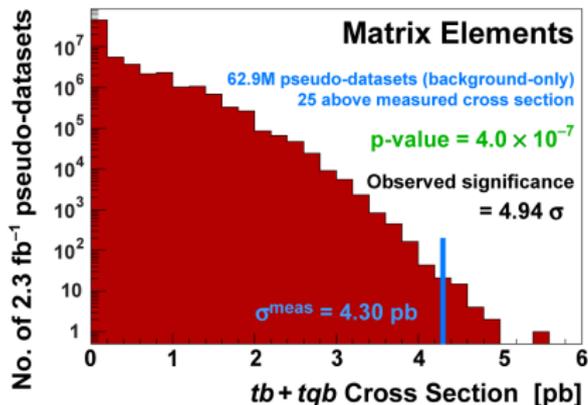
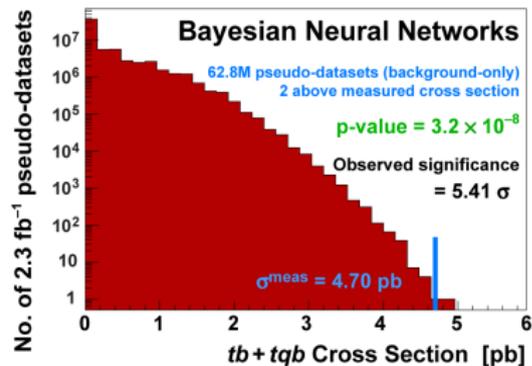
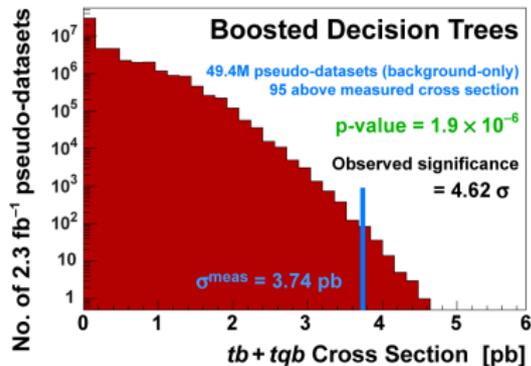


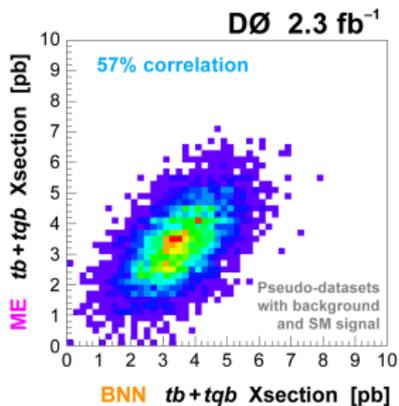
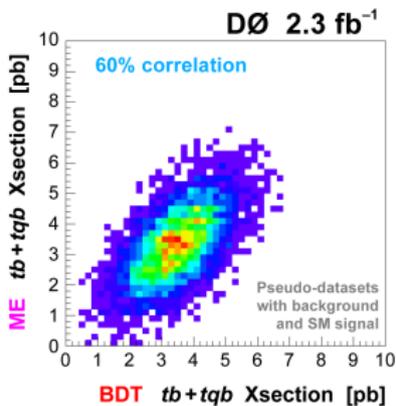
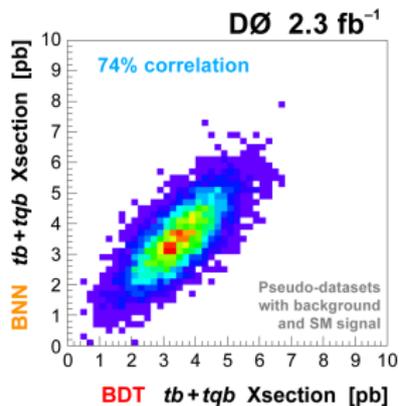
## Individual Results

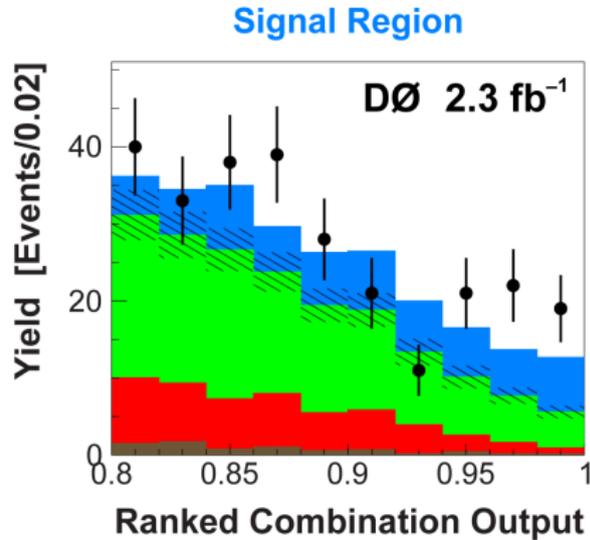
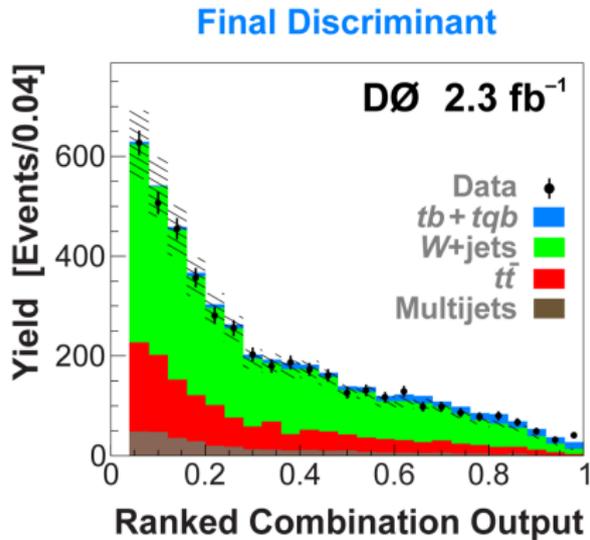
<b>DØ 2.3 fb<sup>-1</sup> Single Top Results</b>			
Analysis Method	<b>Single Top Cross Section</b>	Significance	
		Expected	Measured
Boosted Decision Trees	<b>3.74<sup>+0.95</sup><sub>-0.79</sub> pb</b>	4.3 $\sigma$	4.6 $\sigma$
Bayesian Neural Networks	<b>4.70<sup>+1.18</sup><sub>-0.93</sub> pb</b>	4.1 $\sigma$	5.4 $\sigma$
Matrix Elements	<b>4.30<sup>+0.99</sup><sub>-1.20</sub> pb</b>	4.1 $\sigma$	4.9 $\sigma$

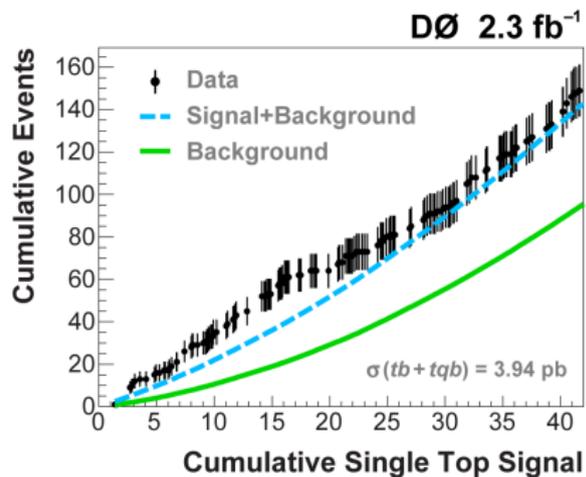
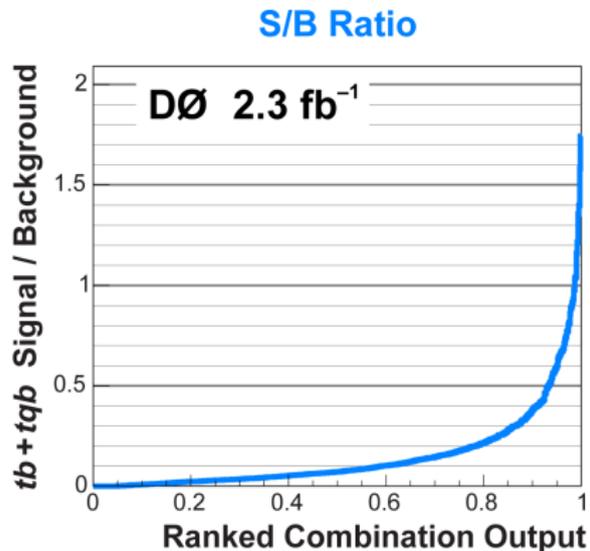


# Individual Significances

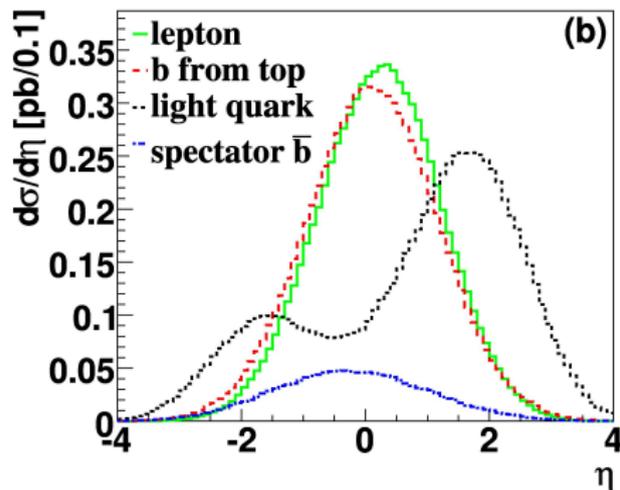


Combination of  $D\emptyset$  Results

Combination of  $D\emptyset$  Results

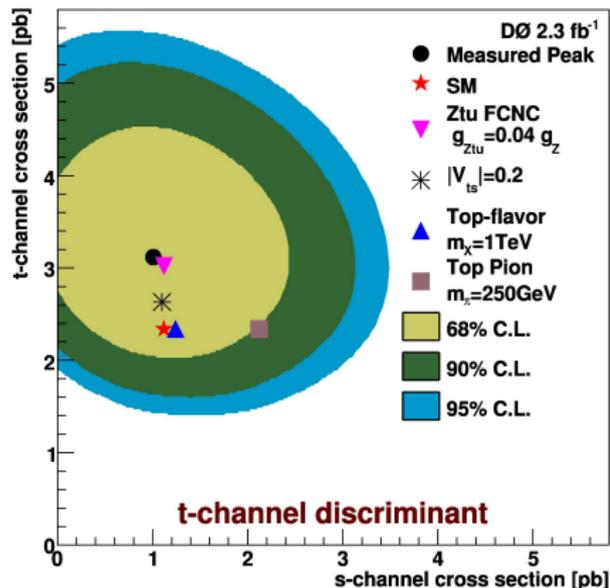
Combination of  $D\bar{O}$  Results

## 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.
- $D\emptyset$  has taken the observation analysis and retrained the discriminants to separate the two sources.

## t-channel Alone



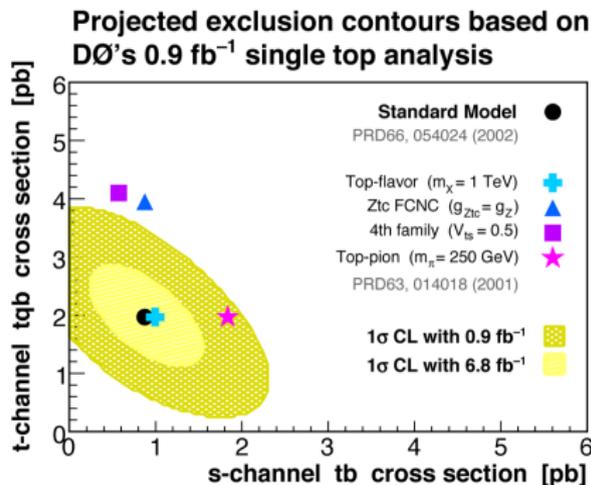
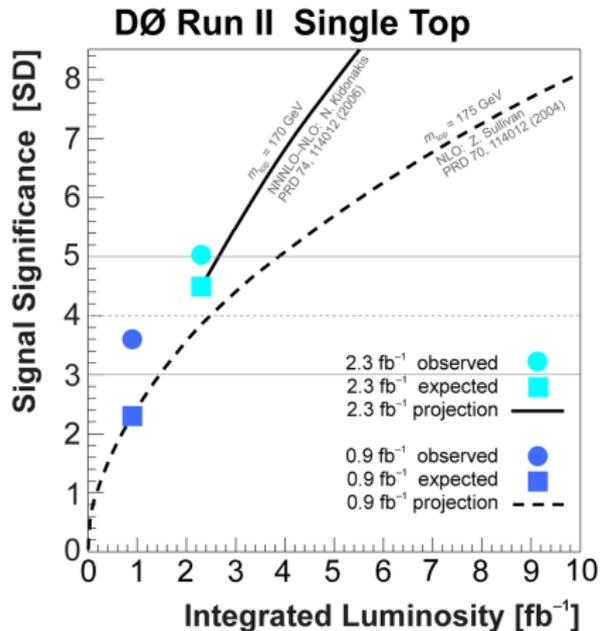
- Do a 2D measurement, no restriction on relative s and t channel cross sections.
- Integrate along s-channel axis to get t-channel measurement and vice versa:

$$\sigma_t = 3.14_{-0.80}^{+0.94} pb$$

$$\sigma_s = 1.05 \pm 0.81 pb$$

- Consistent with SM,  $4.8\sigma$  excess on t-channel alone.

# DØ Future Projections



# CKM Matrix Element $V_{tb}$

Direct access to  $V_{tb}$

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

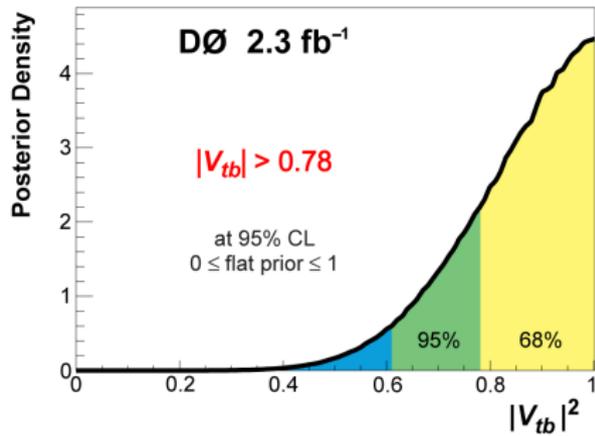
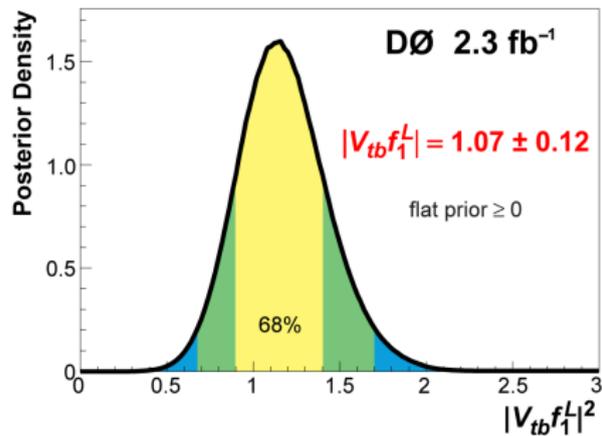
- Weak interaction eigenstates are not mass eigenstates
- In SM: top must decay to a  $W$  and  $d$ ,  $s$  or  $b$  quark
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 = 1$
  - constraints on  $V_{td}$  and  $V_{ts}$ :  $V_{tb} > 0.998$
- New physics that couples to the top quark:
  - $V_{td}^2 + V_{ts}^2 + V_{tb}^2 < 1$
  - 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 measurement 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)

<b>Additional Systematic Uncertainties for the <math> V_{tb} </math> Measurement</b>	
<b>DØ 2.3 fb<sup>-1</sup></b>	
<b>For the <math>tb+tbq</math> theory cross section</b>	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling $\alpha_s$	0.5%

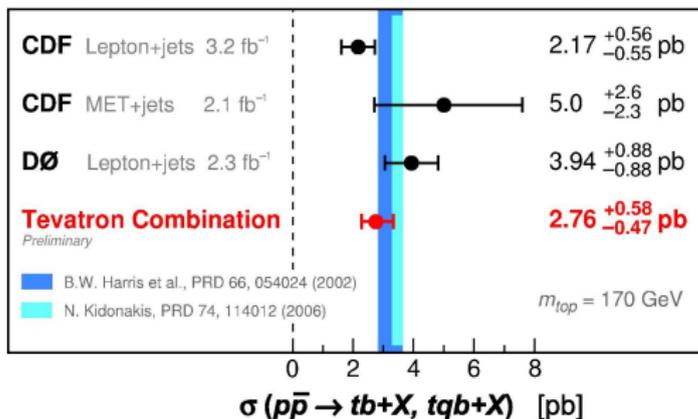
# Measuring or Limiting $|V_{tb}|^2$



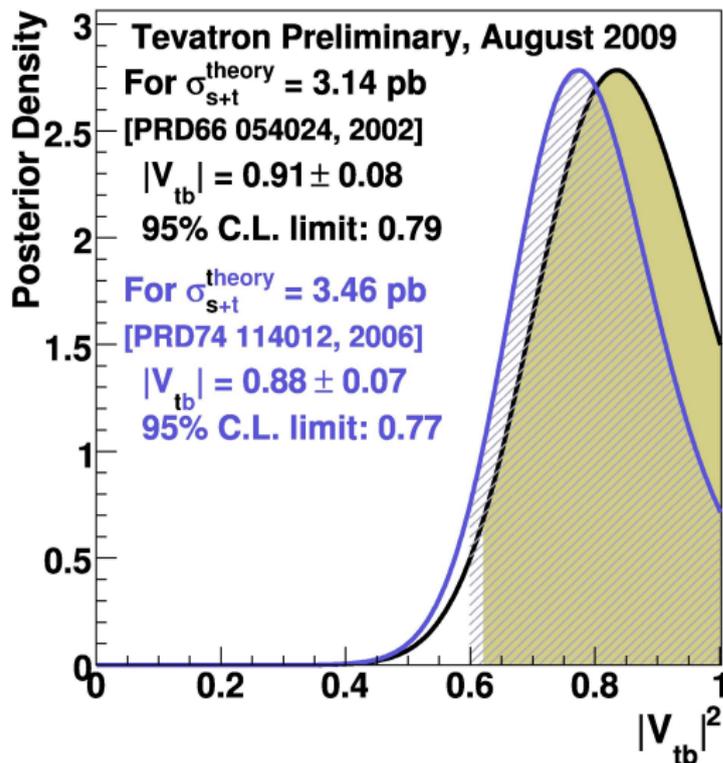
# Combining with CDF - Cross Section

## Single Top Quark Cross Section

August 2009



- Same Bayesian method used to combine experiments as was used to combine channels within an experiment.
- Common systematics are assumed 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		CKM Matrix Element $V_{tb}$
	Expected	Observed	
<b>DØ (2.3 fb<sup>-1</sup>) March 2009</b> PRL 103, 092001 (2009) ( $m_{top} = 170$ GeV)			
$3.94 \pm 0.88$ pb	$4.5 \sigma$	$5.0 \sigma$	$ V_{tb}f_1^L  = 1.07 \pm 0.12$ $ V_{tb}  > 0.78$ at 95% CL
<b>CDF (3.2, 2.1 fb<sup>-1</sup>) March 2009</b> PRL 103, 092002 (2009) ( $m_{top} = 175$ GeV)			
$2.3^{+0.6}_{-0.5}$ pb	$>5.9 \sigma$	$5.0 \sigma$	$ V_{tb}f_1^L  = 0.91 \pm 0.13$ $ V_{tb}  > 0.71$ at 95% CL
<b>DØ &amp; CDF combined August 2009</b> FERMILAB-TM-2440-E ( $m_{top} = 170$ GeV)			
$2.76^{+0.58}_{-0.47}$ pb			$ V_{tb}f_1^L  = 0.88 \pm 0.07$ $ V_{tb}  > 0.77$ at 95% CL

# BACKUP SLIDES

BACKUP SLIDES

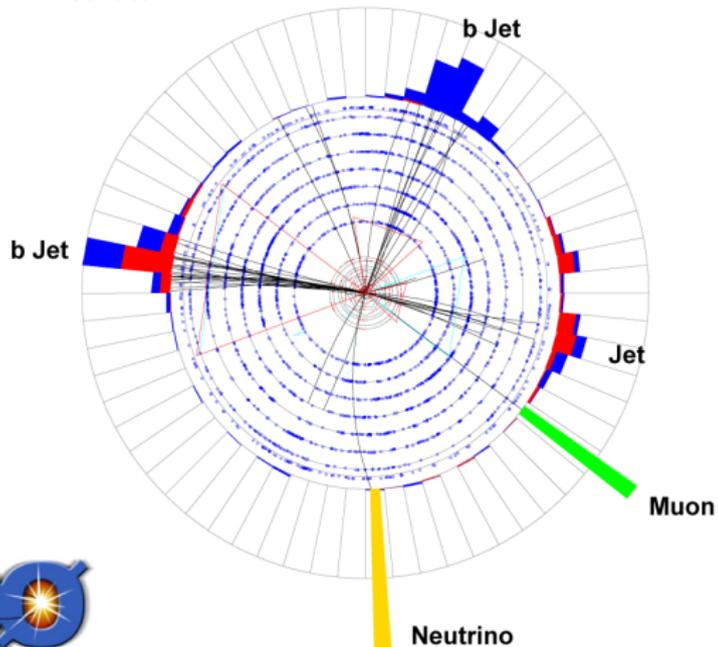
# Event Displays I

## DØ Experiment Event Display

### Single Top Quark Candidate Event, $2.3 \text{ fb}^{-1}$ Analysis

Run 223473 Evt 27278544 Sun Jul 23 19:21:41 2006

ET scale: 28 GeV

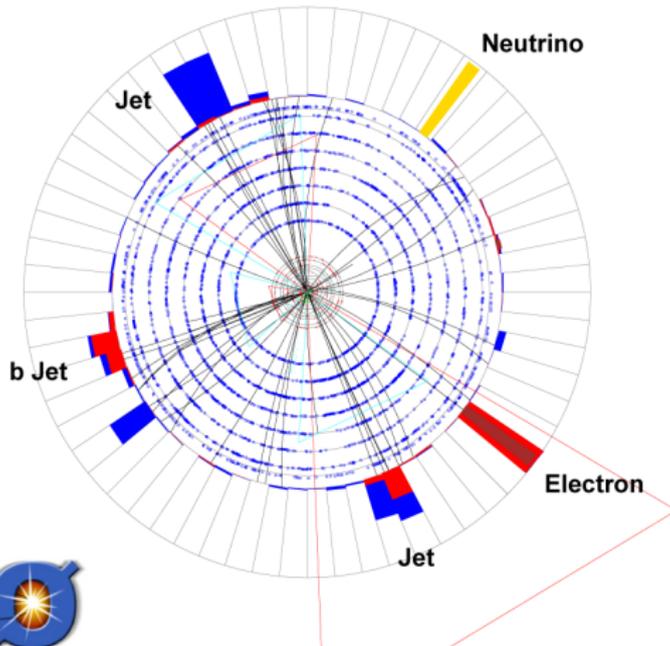


# Event Displays II

## DØ Experiment Event Display Single Top Quark Candidate Event, 2.3 fb<sup>-1</sup> Analysis

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

ET scale: 39 GeV

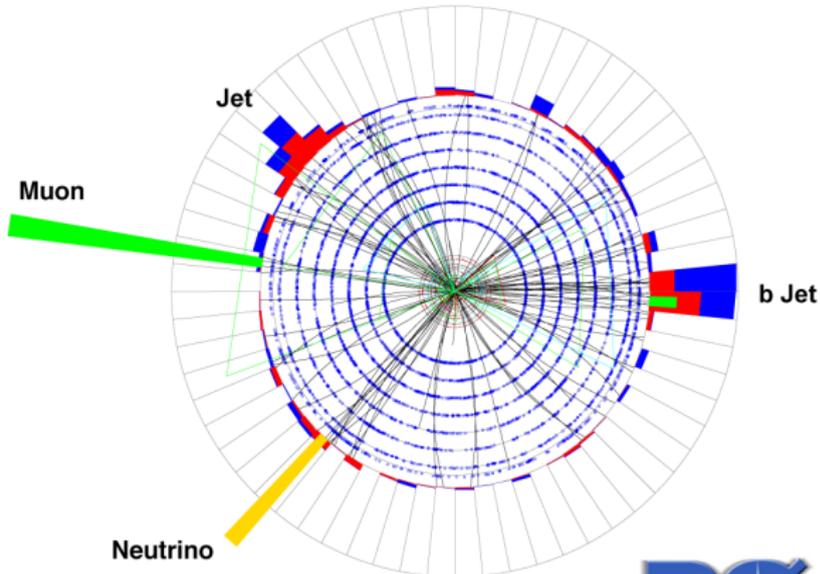


# Event Displays III

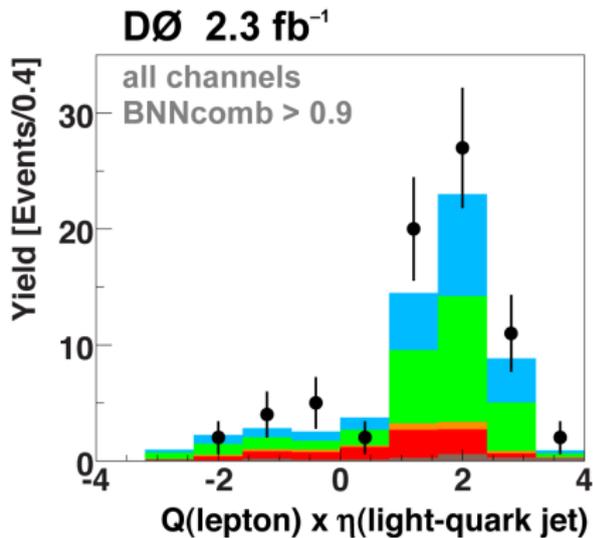
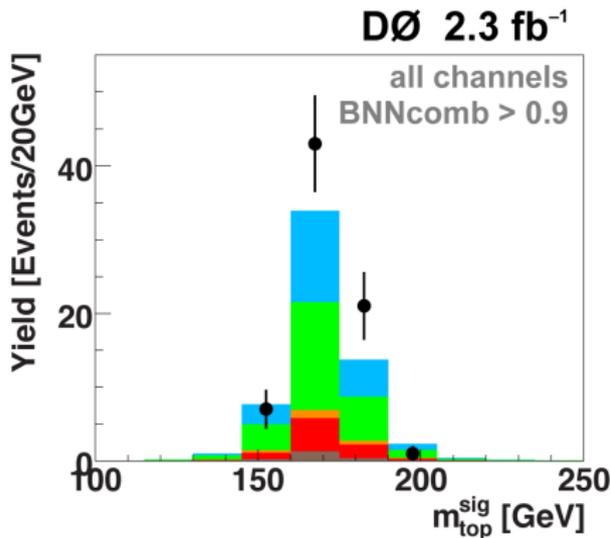
## DØ Experiment Event Display Single Top Quark Candidate Event, $2.3 \text{ fb}^{-1}$ Analysis

Run 233563 Evt 44490072 Mon Jun 11 06:15:53 2007

ET scale: 19 GeV



# Kinematics in the Signal Region



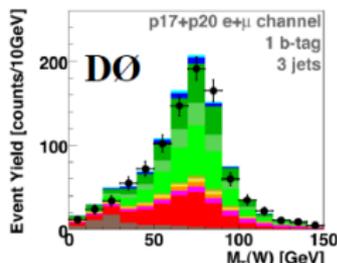
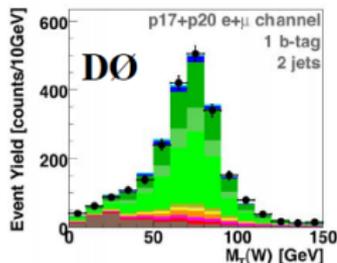
# Yields in More Detail

Event Yields in 2.3 fb <sup>-1</sup> 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
$t\bar{t} \rightarrow \ell+jets$	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
<b>Total prediction</b>	2,615 ± 192	1,294 ± 107	742 ± 80
<b>Data</b>	2,579	1,216	724

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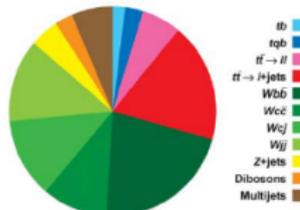
# W+jets HF Scaling Factor

- 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
  - $0.95 \pm 0.13$  (Wbb, Wcc)
- Uncertainties considered
  - Data statistics  $\pm 9\%$
  - $\pm 40\%$  single top cross section  $\rightarrow \pm 7\%$  in SF
  - $\pm 10\%$  on the Wcj theory SF  $\rightarrow \pm 8\%$  in SF
  - Additional  $\pm 10\%$  Wbb/Wcc  $\rightarrow \pm 5\%$  in SF



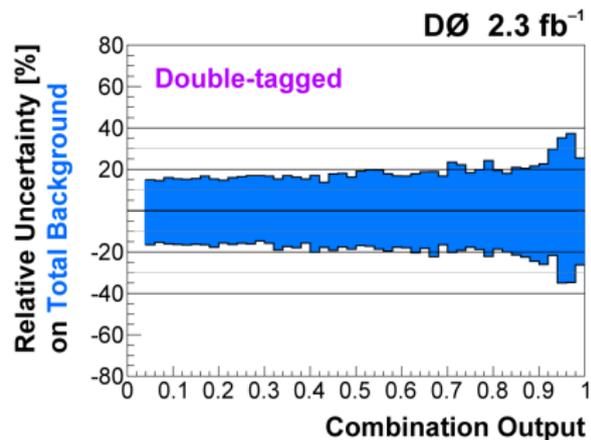
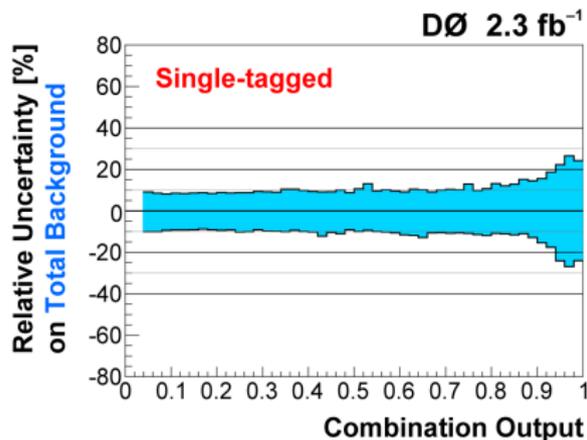
S:B = 1:21 in 1Tag  
S:B = 1:15 in 2Tag

D0 Single Top 2.3 fb<sup>-1</sup> Signals and Backgrounds  
(All channels combined, after b-tagging)

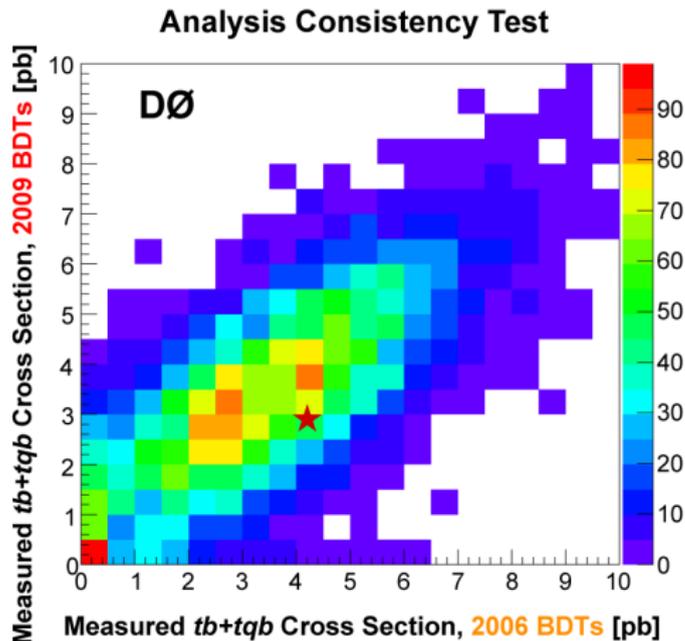


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# Systematic Uncertainties

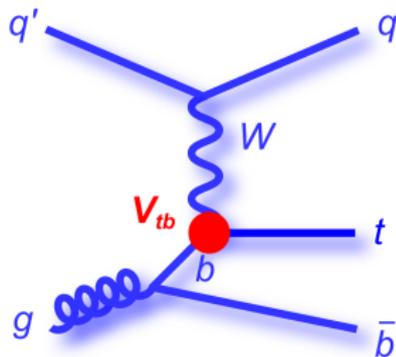
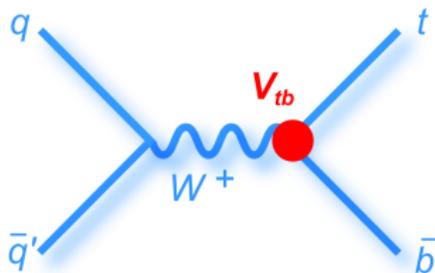


# Evidence Cross-Check



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  $V_{tb}$ 

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

# 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%	•	