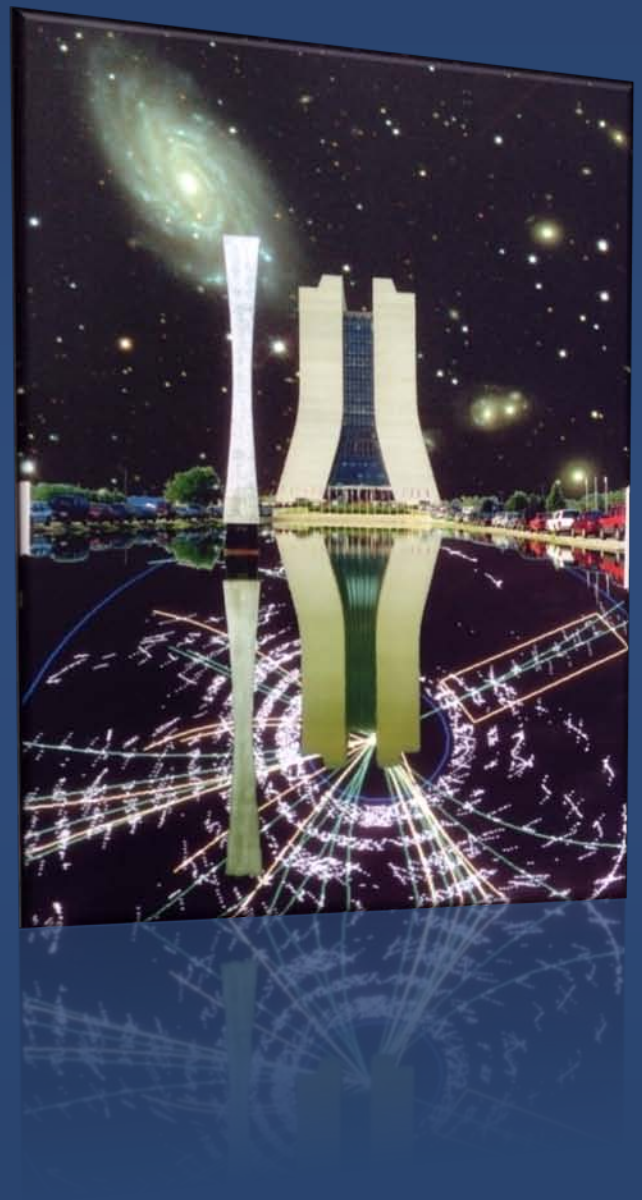


Discovery of Single Top Quark Production at the Tevatron

Shabnam Jabeen

Boston University

Outline

Introduction

Understanding the data
- Event Selection
- Background Modeling

Multivariate Analysis Techniques
- Boosted Decision Trees
- Bayesian Neural Networks
- Matrix Elements Method

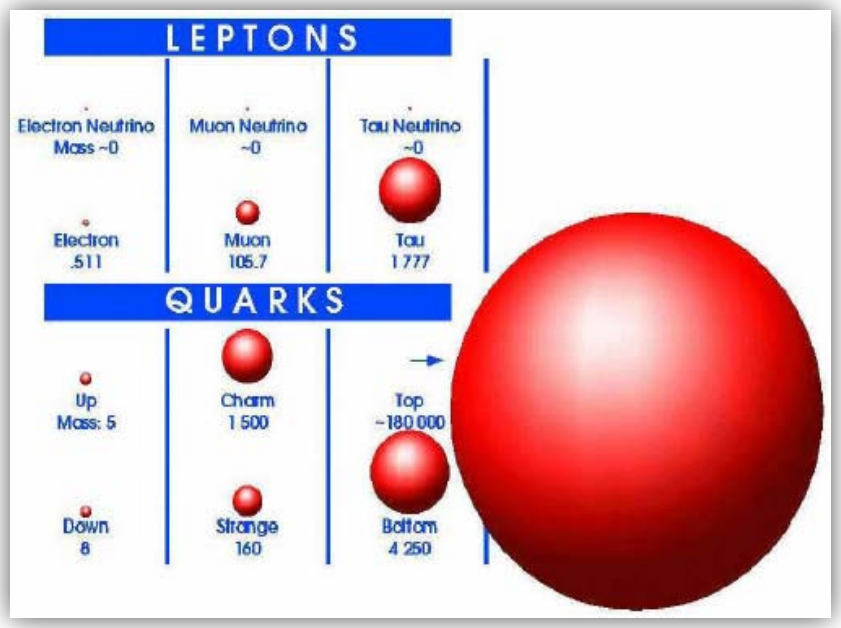
Cross Sections and Significance

Direct Measurement of $|V_{tb}|$

Why Look at the Top Quark

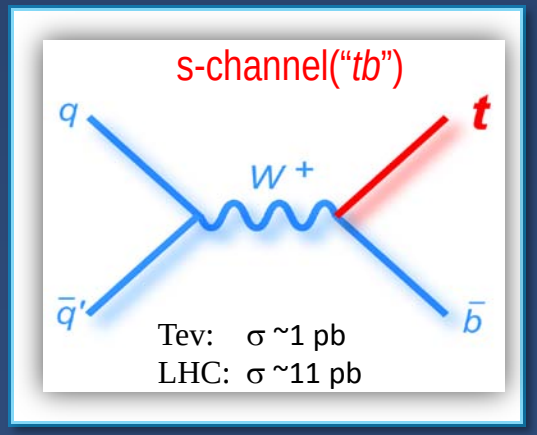
- Was discovered at Fermilab in1995
- The heaviest known fundamental particle
  - m_t = 172.4 1.4 GeV (~1% precision)
    Close to a gold atom
- τ = 5 10^{-25} s <<Λ_{QCD}^{-1}
  Decays before hadronization
- Mass close to scale of electroweak symmetry breaking
  - Only quark for which coupling to Higgs is significant
  - May shed light on EWSB mechanism
- Top quark plays special role in many of the new physics models

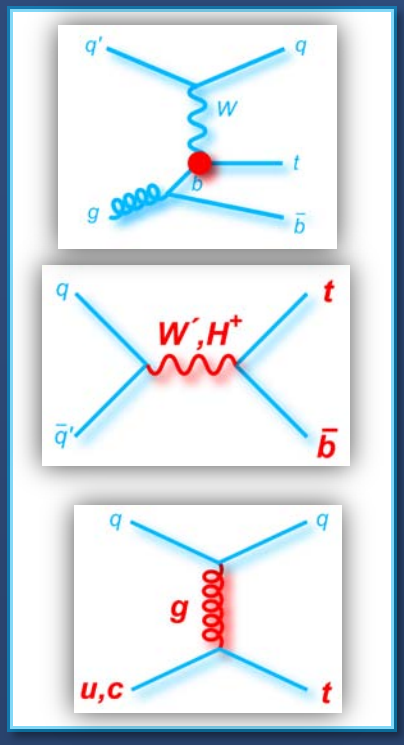
Discovered at Fermilab in1995



Why Being Single is Good?

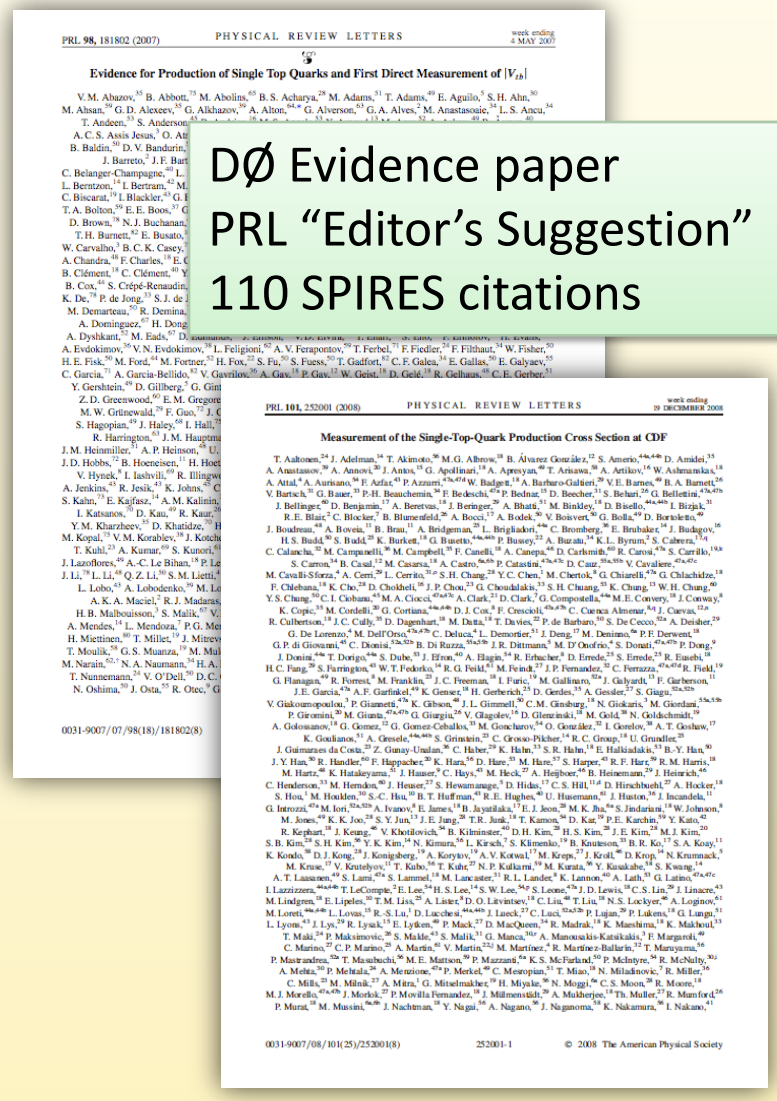
- Study *Wtb* coupling in top production
  - Measure $|V_{tb}|$ directly: $\sigma \propto |V_{tb}|^2$
- Cross sections sensitive to new physics
  - s-channel: resonances (heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.),
  - t-channel: flavor-changing neutral currents ($t - Z/\gamma/g - c/u$ couplings), Fourth generation of quarks
- Top properties
  - Polarized top quarks – spin correlations measurable in decay products, Measure top quark partial decay width and lifetime, CP violation (same rate for top and antitop?)
- Similar search for *WH* associated Higgs production





Culmination of a Long History

- **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**



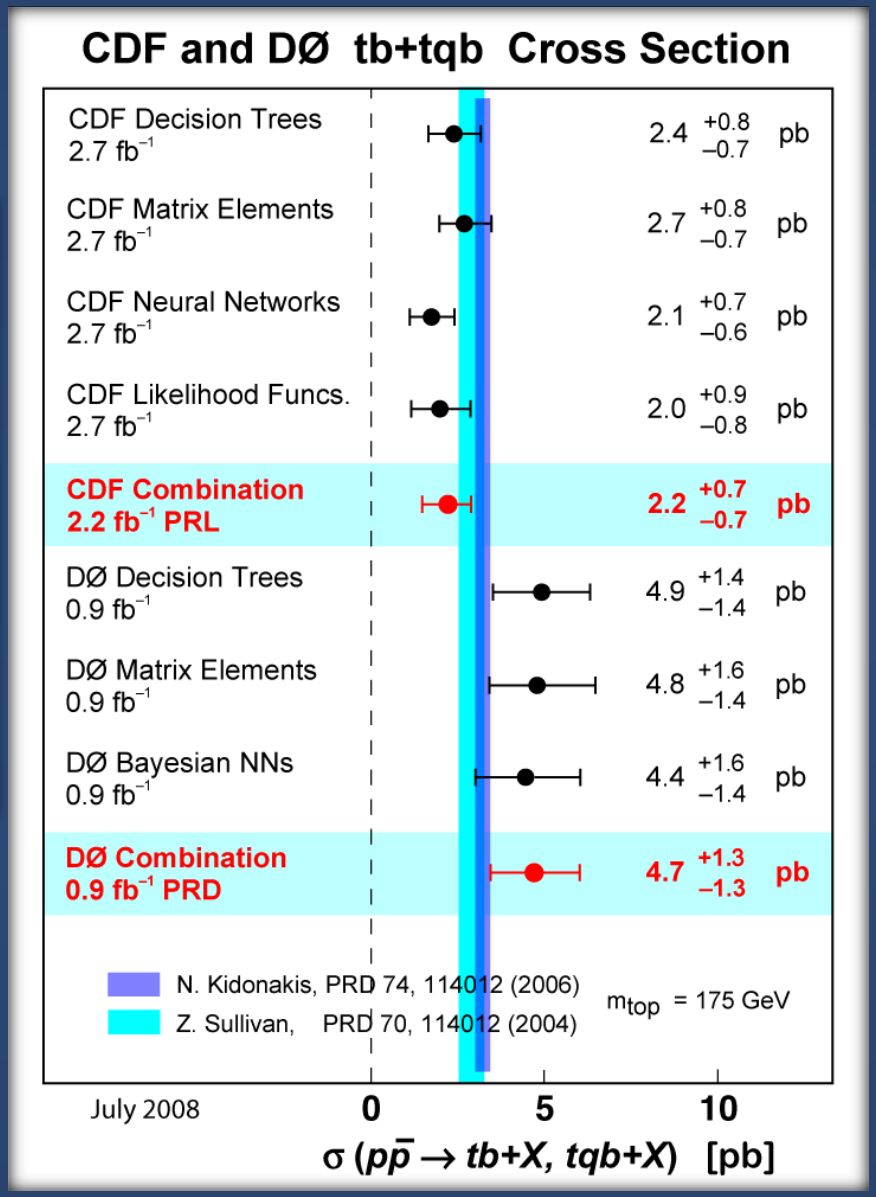
DØ Evidence paper
PRL "Editor's Suggestion"
110 SPIRES citations

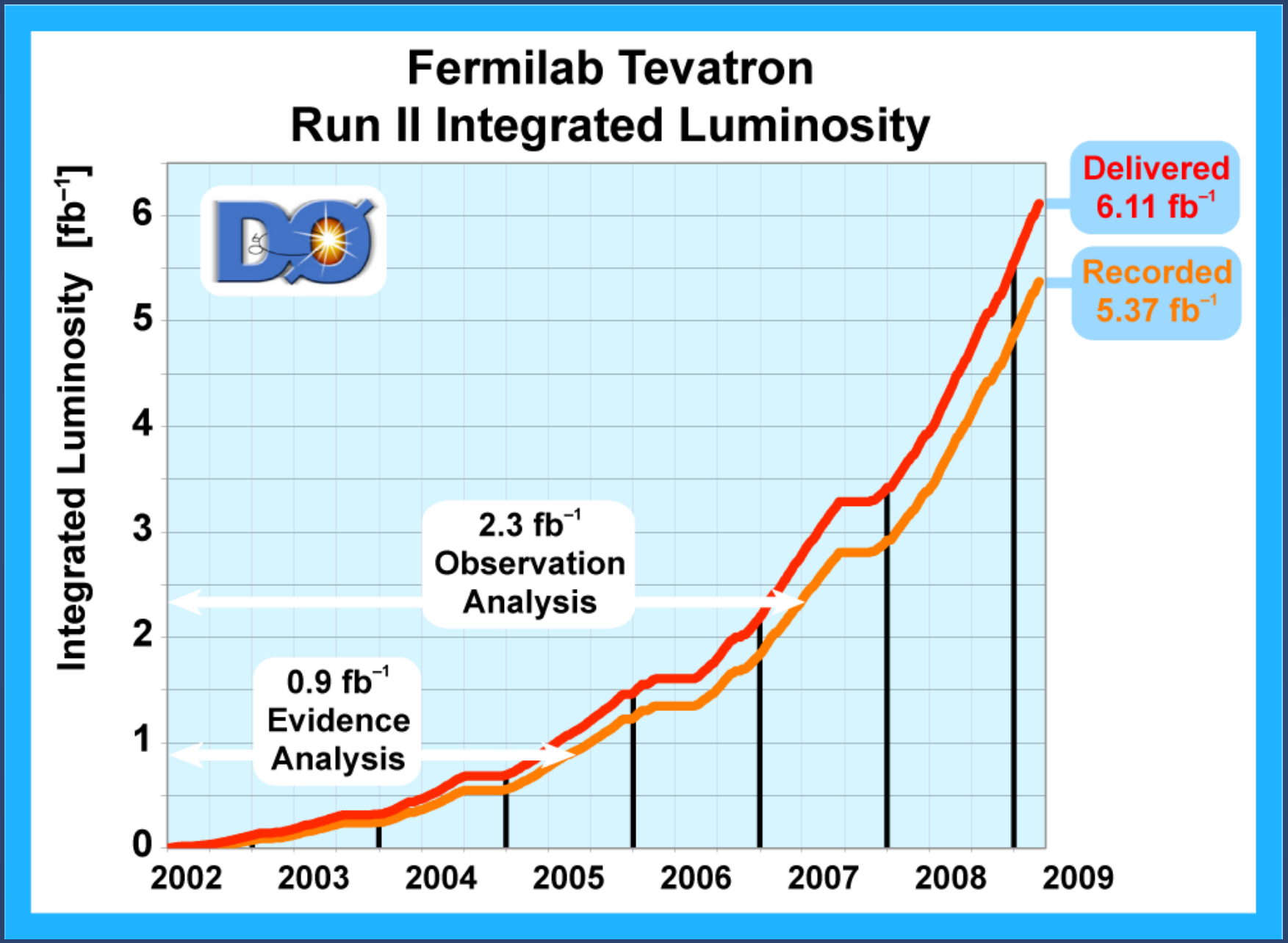
Evidence for Single Top Production

Status as of March 3, 2009

Signal Significance		Cross Section
Expected	Observed	Measured
DØ (0.9 fb^{-1}) PRL 98, 181802 (2007)		
2.3σ	3.6σ	4.7±1.3 pb
$\|V_{tb}\|$ = 1.31 + 0.25 - 0.21		
CDF (2.2 fb^{-1}) PRL 101, 252001 (2008)		
4.9σ	3.7σ	2.2 ± 0.7 pb
$\|V_{tb}\|$ = 0.88 ± 0.12± 0.07		

Observed significance is a measure of how likely it is to measure the cross section in the absence of signal

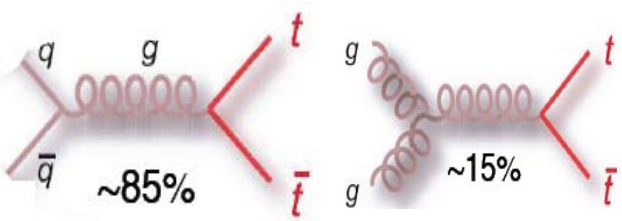



Fermilab Tevatron
Run II Integrated Luminosity
Integrated Luminosity [fb⁻¹]
0
1
2
3
4
5
6
2002
2003
2004
2005
2006
2007
2008
2009
Delivered
6.11 fb⁻¹
Recorded
5.37 fb⁻¹
2.3 fb⁻¹
Observation
Analysis
0.9 fb⁻¹
Evidence
Analysis

Production

Top quark pair production

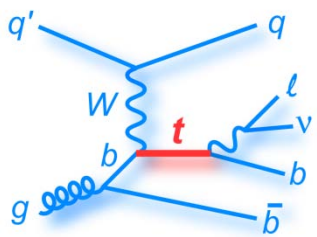
σ_{tt} ~7 pb



Single Top quark production

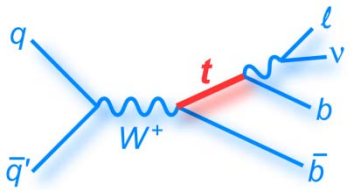
***t*-channel**

σ ~2 pb



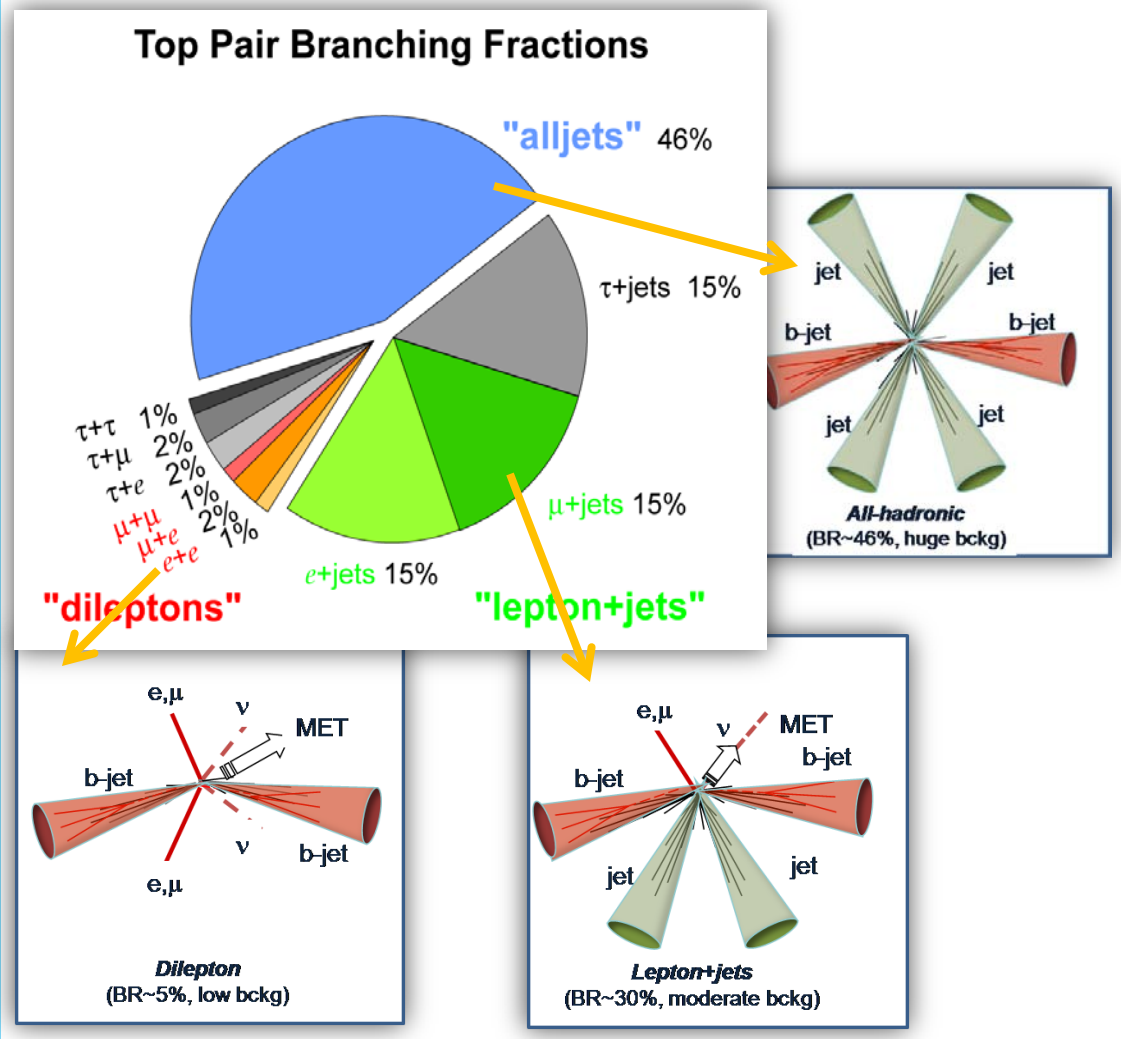
***s*-channel**

σ ~1 pb

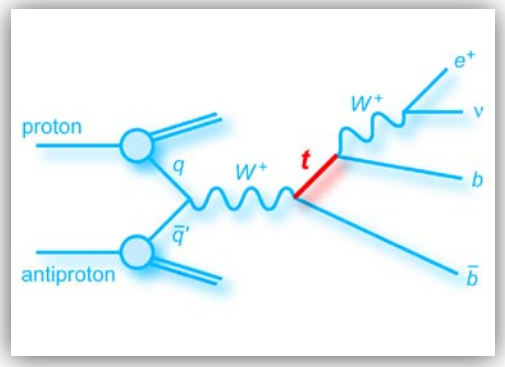


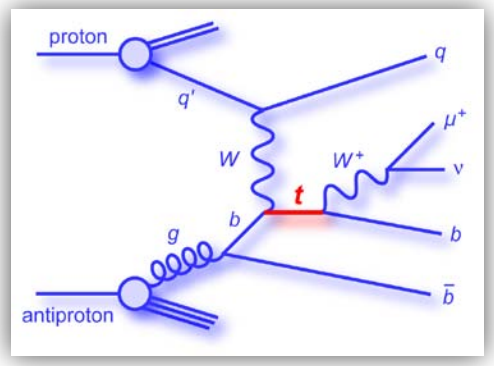
Decay

Within Standard Model t→Wb ~ 100%



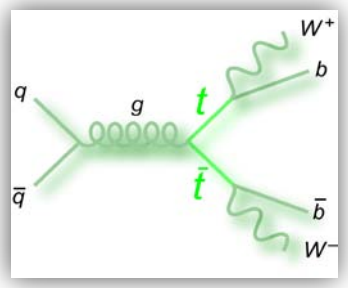
Event Signatures and Event Selection

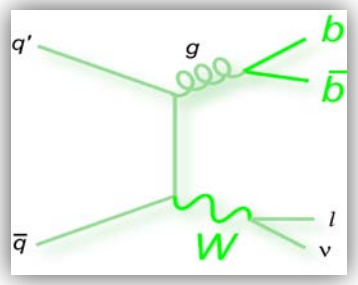


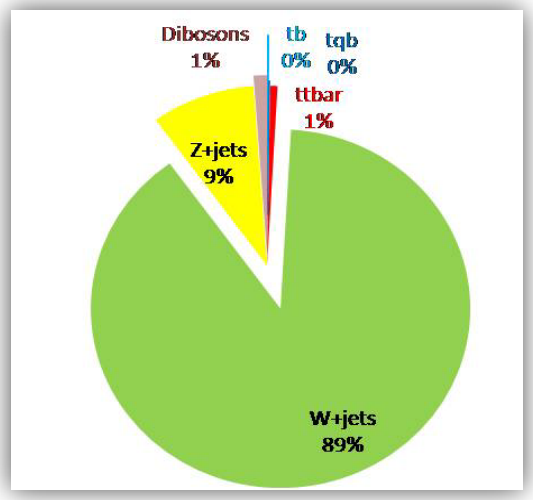


e :	$p_T > 15\,GeV, \lvert\eta\rvert < 1.1$
μ :	$p_T > 18\,GeV, \lvert\eta\rvert < 2.0$
Missinng E_T	$15 < MET < 200\,GeV$
Jets	$2-4,\ p_T > 15\,GeV, \lvert\eta\rvert < 3.0$
	$p_{T,1} > 25\,GeV, \lvert\eta\rvert < 2.5$
	$p_{T,2} > 20\,GeV$
B − jet	1 or 2

Backgrounds







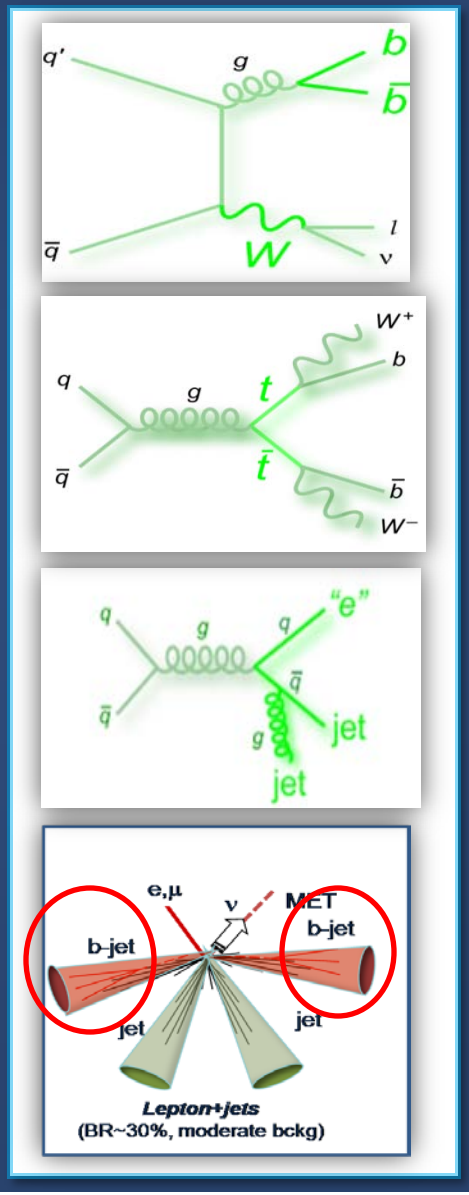
- Top pairs W+jets, and Multijets are the main processes that can mimic these signatures
- Single top signal is negligible compared to these backgrounds

Background Modeling

- Single top signal

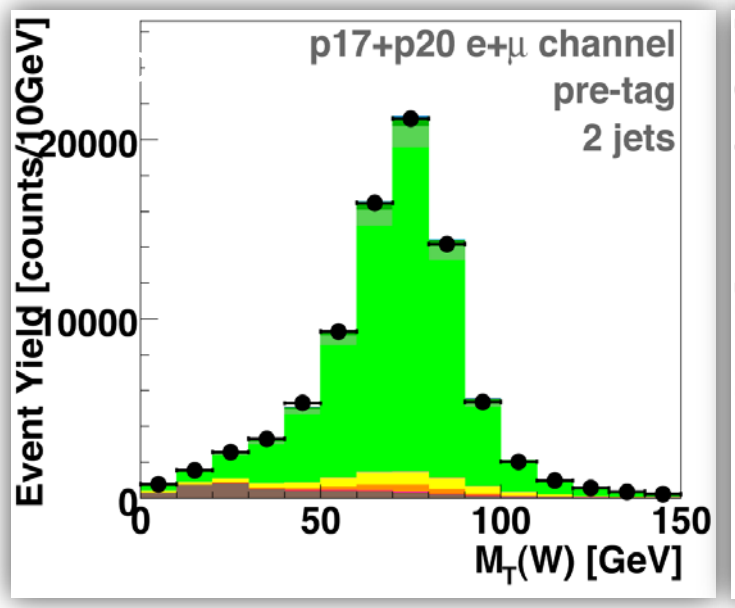
Modeled using SINGLETOP based on COMPHEP

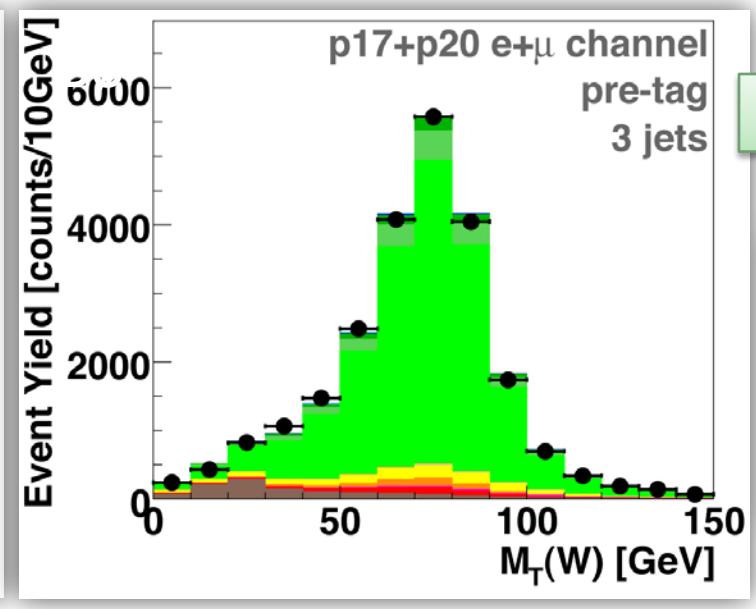
- W+jets background
  - Event kinematics and flavor composition modeled using Alpgen generator and PYTHIA for parton hadronization
  - η(jets), $\Delta\phi$(jet1,jet2), $\Delta\eta$(jet1,jet2) corrected to match data
  - Normalized to data before b tagging and after subtracting other backgrounds
- Multijet background
  - Modeled using data with a non-isolated lepton and jets
  - Kept small (~5%) with topological selection cut
- Top pair backgrounds modeled using ALPGEN +PYTHIA
- Z+jets modeled using ALPGEN + PYTHIA
  - Z+ heavy flavor corrected to theory, with 20% uncertainty
- Dibosons modeled using PYTHIA



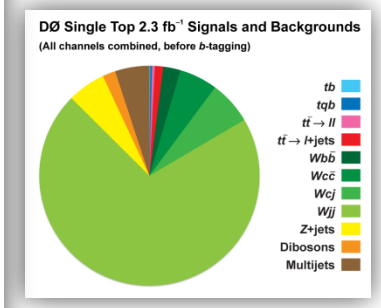
Background Normalization

- W+jets and multijet normalized using iterative template fits to data BEFORE TAGGING on three sensitive variables: $p_T(\ell)$, $\not{E}_T$, $M_T(W)$



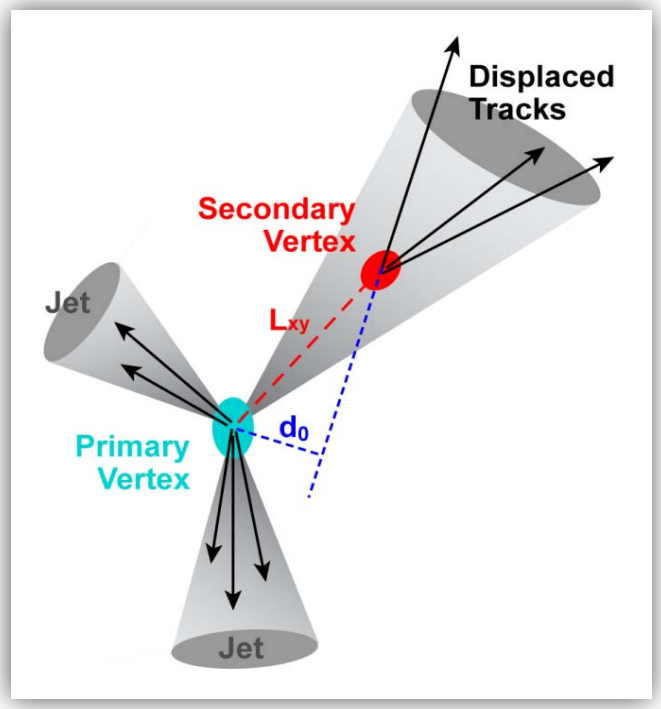


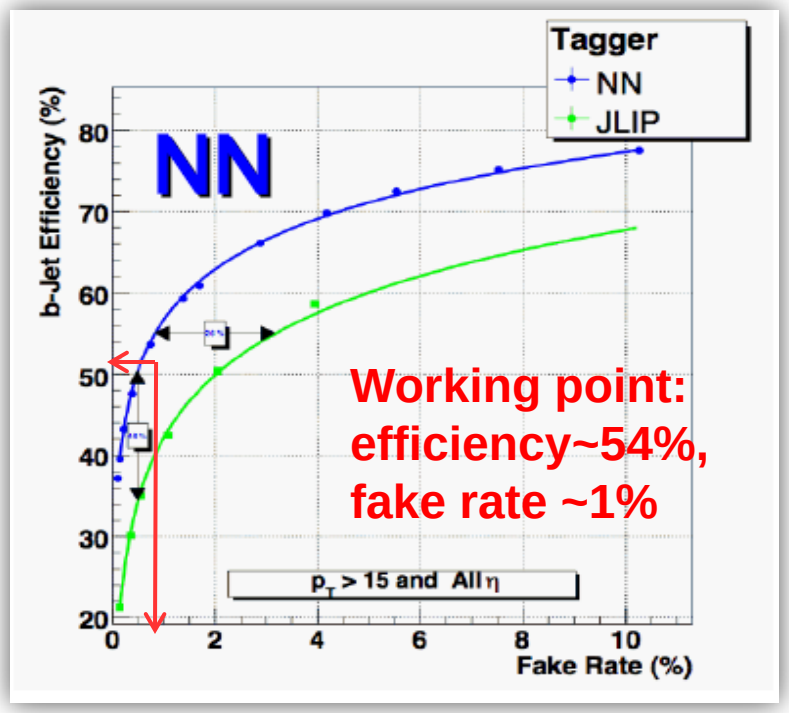
S:B = 1:259



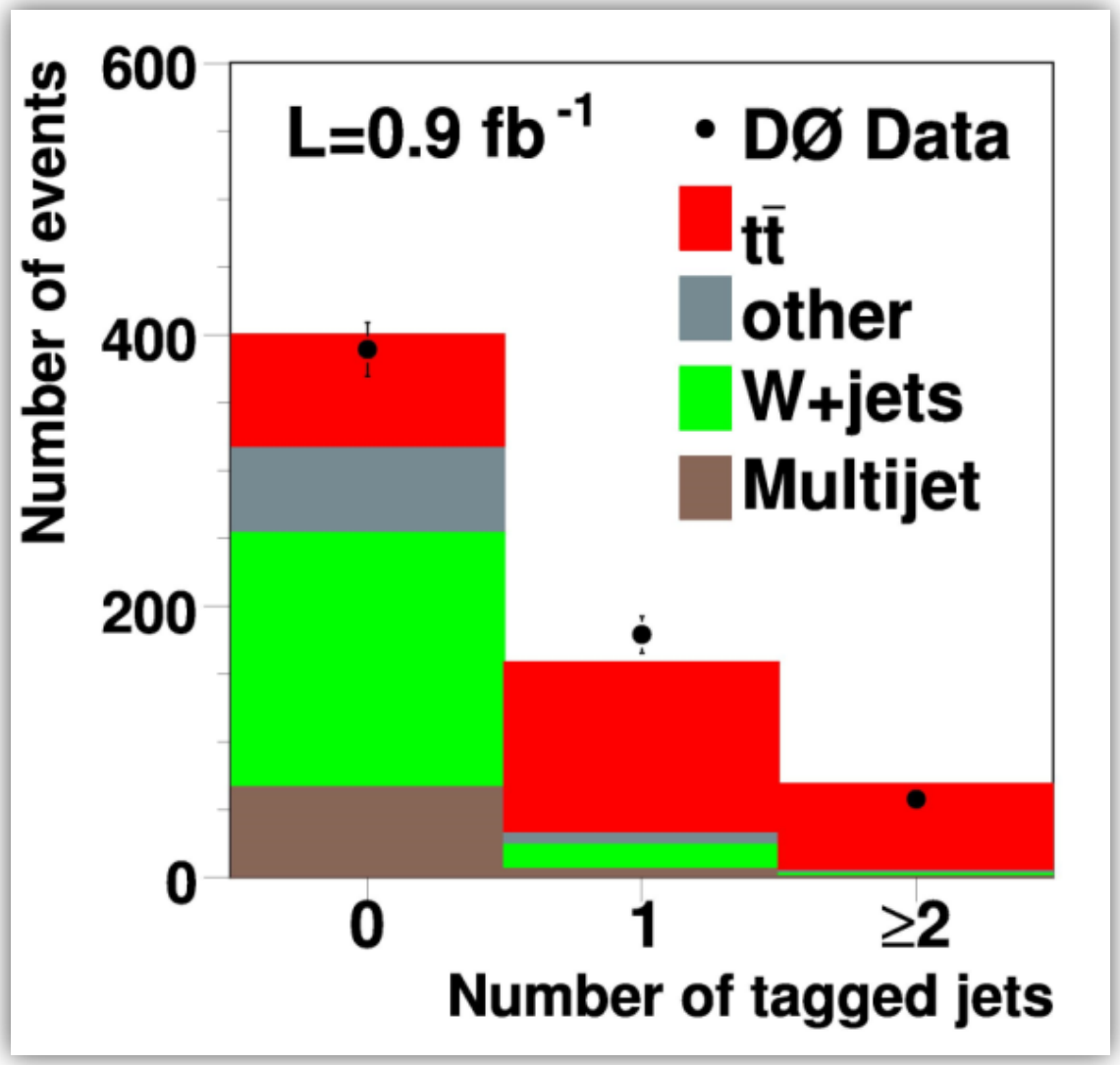
B-jet Identification (aka b-tagging)

- Separate *b*-jets from light-quark and gluon jets to reject most W+jets background
- DØ uses a neural network algorithm with seven input variables based on impact parameter and reconstructed vertex





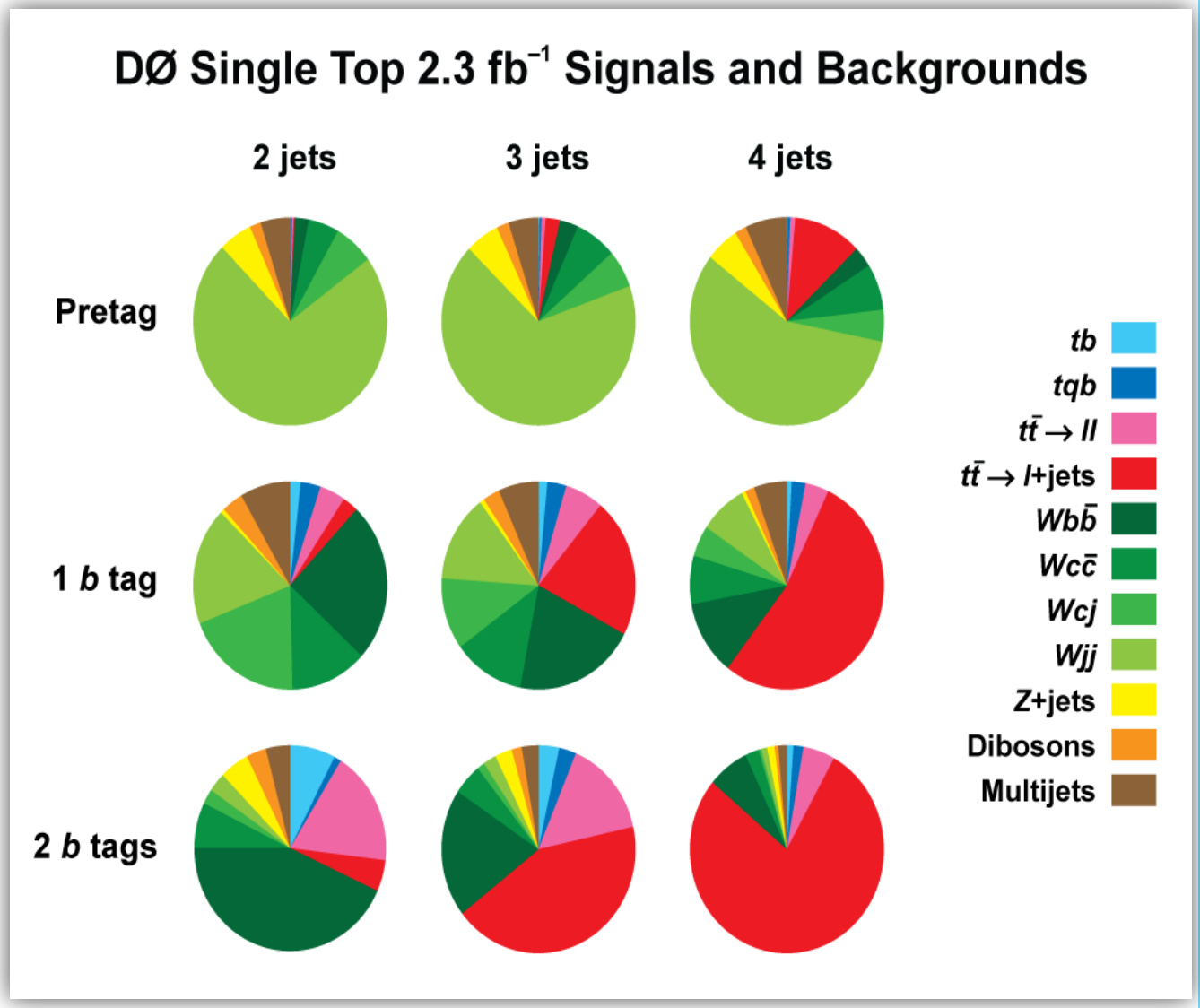
B-jet Identification (aka b-tagging)



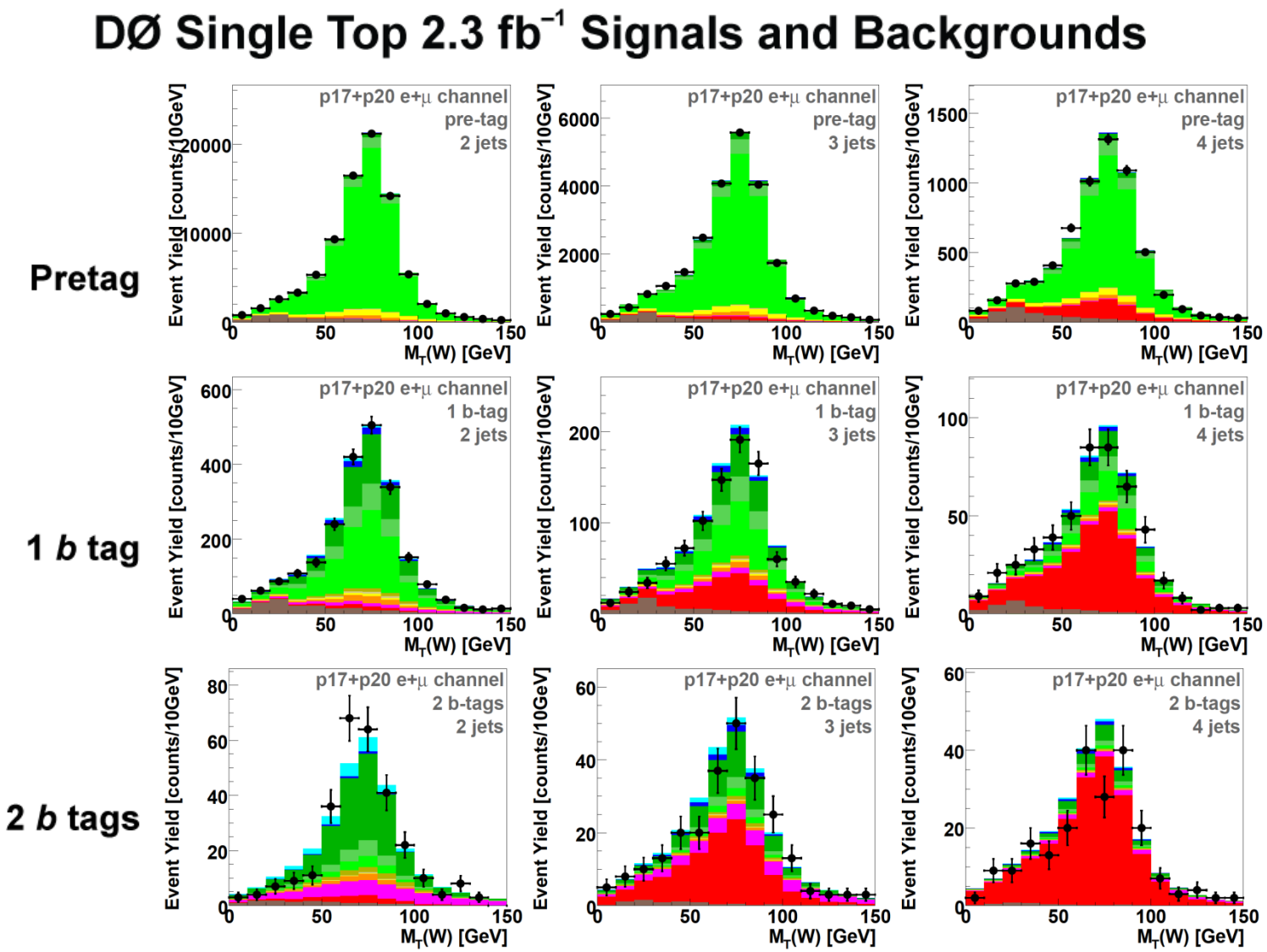
Before and After .....

~100,000 Evts

~5000 Evts



Before and After .....

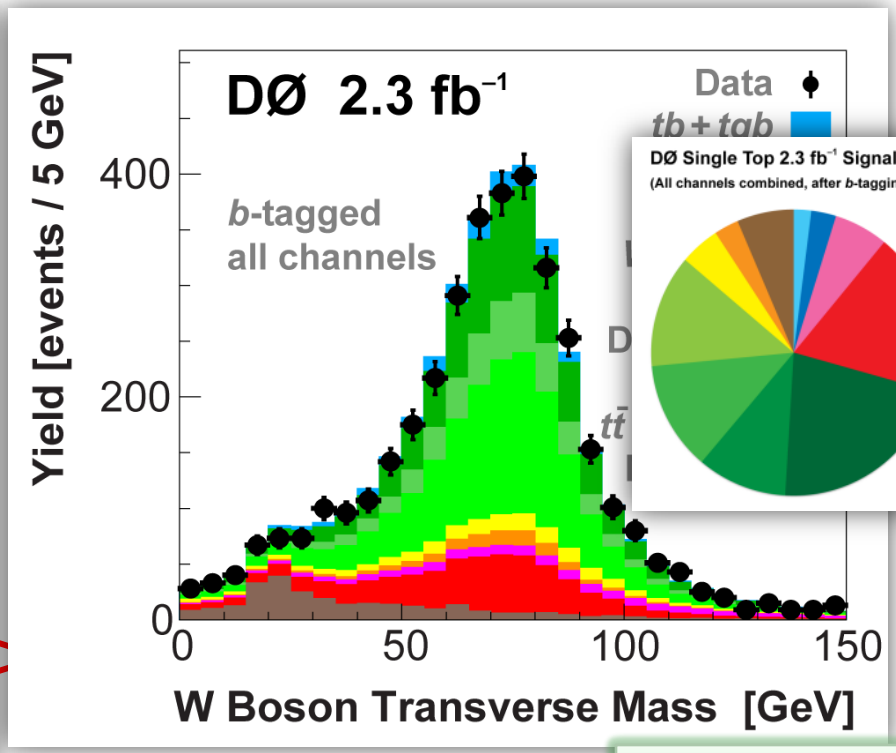


Event Yields After B-Tagging

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
$t\bar{t} \rightarrow \ell$+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

Event Yields After B-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



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

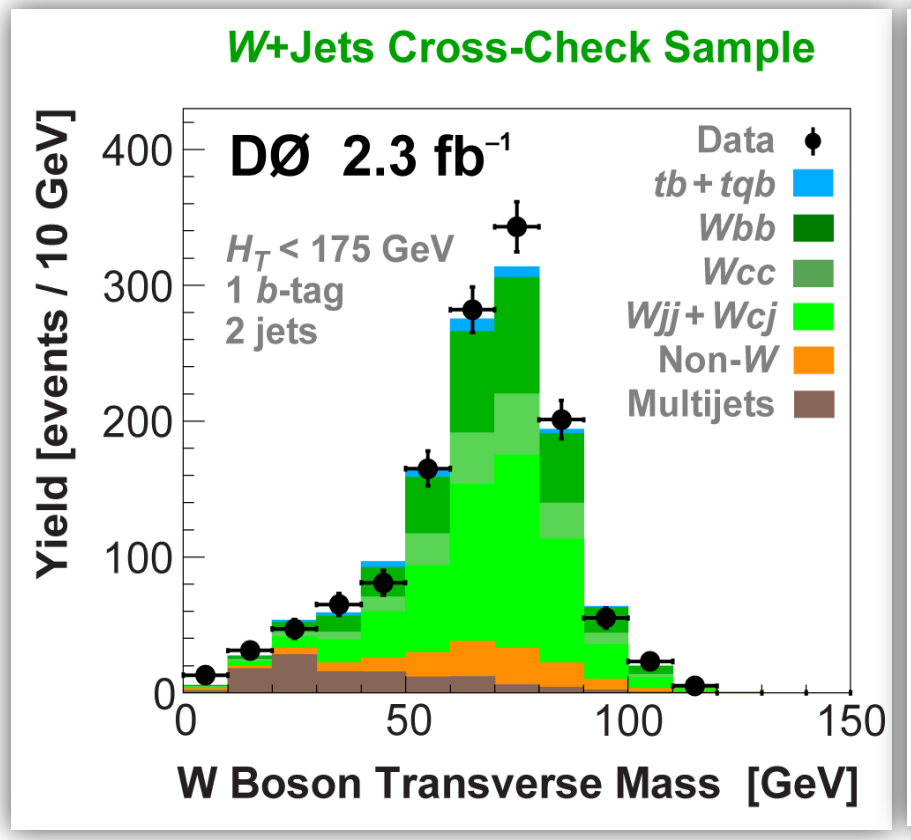
- Single top signal is smaller than total background uncertainty
- Counting events is not a sensitive enough method

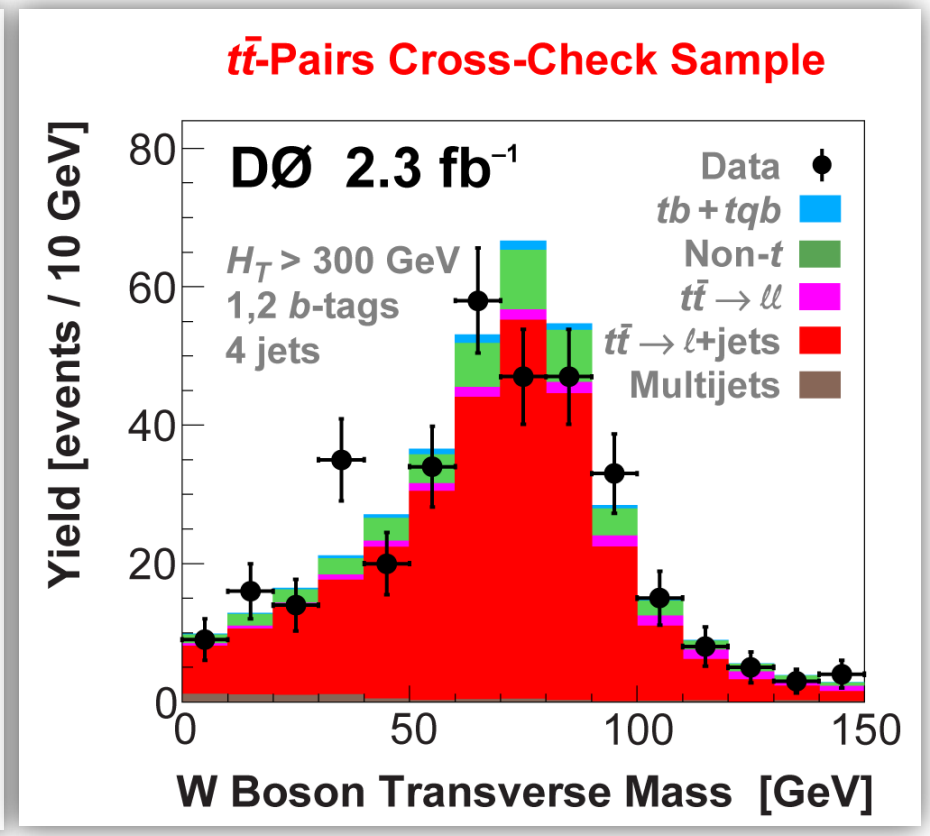
Cross Check Samples

Validate a background model in side-band regions

a) An enriched W+jets background

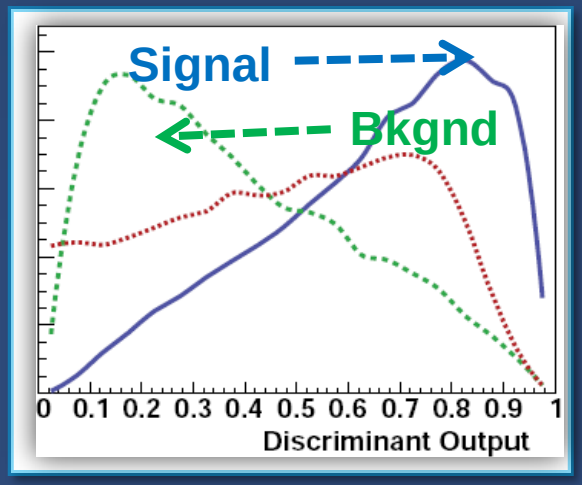
b) An enriched top pair background





Search Strategy

- **Maximize the signal acceptance**
  - Particle ID definitions set as loose as possible
  - Transverse momentum thresholds set low, pseudo-rapidities wide
  - As many decay channels used as possible
  - All channels analyzed separately since S:B and background compositions differ
- **Use multivariate techniques**
- **Three techniques used for this analysis**
  - Boosted Decision Trees
  - Matrix Elements
  - Bayesian Neural Networks
- Check discriminant Performance using data control samples
- **Use ensembles of pseudo-data to test validity of methods**
- **Cross sections measured using binned likelihood calculation of signal + background to data**

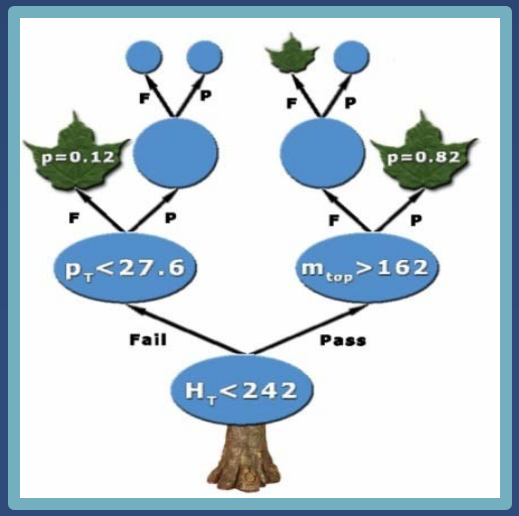


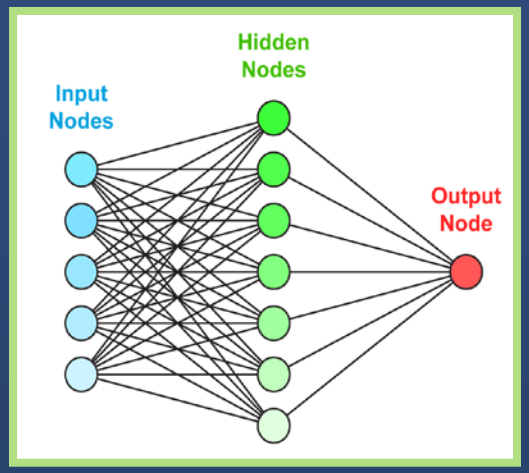
Multivariate Analyses: BDT & BNN

Use common Object and Event Kinematics, Angular Correlations, Jet Reconstruction and Top Quark Reconstruction variables

Boosted Decision Trees (BDT)

- Recover events that fail criteria in cut-based analysis
- Boosting averages the results over many trees, improving the performance
- Uses highest ranked common 64 variables





Bayesian Neural Network (BNN)

- NN train on signal and background, producing one output discriminant
- Bayesian NN average over many networks, improving the performance
- Uses highest ranked 18-28 variables in each channel

Matrix Element (ME)

- Method pioneered by DØ for the top quark mass measurement in Run I
- Use the 4-vectors of all reconstructed leptons and jets
- Use Feynman diagrams to compute an event probability density for signal and background hypotheses

differential cross section (LO matrix element)

parton distribution functions

transfer function: mapping from parton-level variables (y) to reconstruction-level variables (x)

$$P_i(\vec{x}) = \frac{1}{\sigma}\int \ldots \int \sum_{comb} d^n\sigma_i(\vec{y})\, dq_1 dq_2\, f(q_1)\, f(q_2)\, W(\vec{x}\,|\,\vec{y})$$

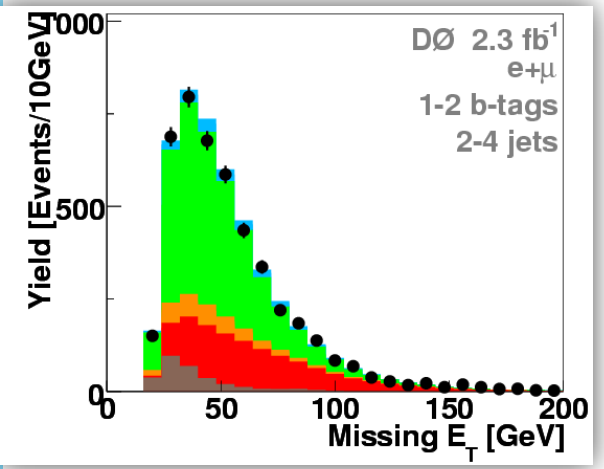
Calculate a discriminant using above probability:

$$D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bckg}(\vec{x})}; \qquad S = tb \text{ or } tqb$$

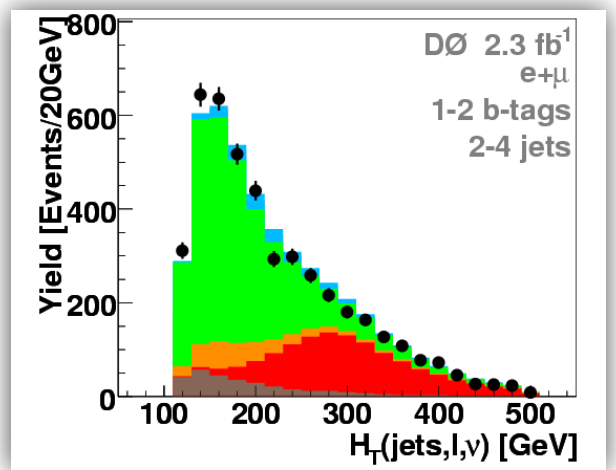
- Uses events with 2 and 3 jets only
- Split the sample in high and low H_T

Discriminating Variables–BDT/BNN

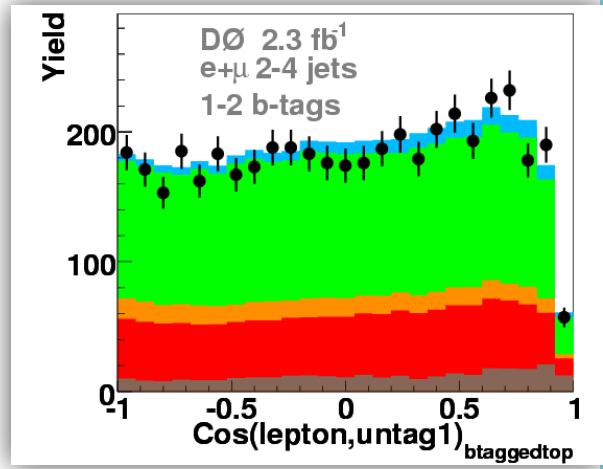
OBJECT KINEMATICS



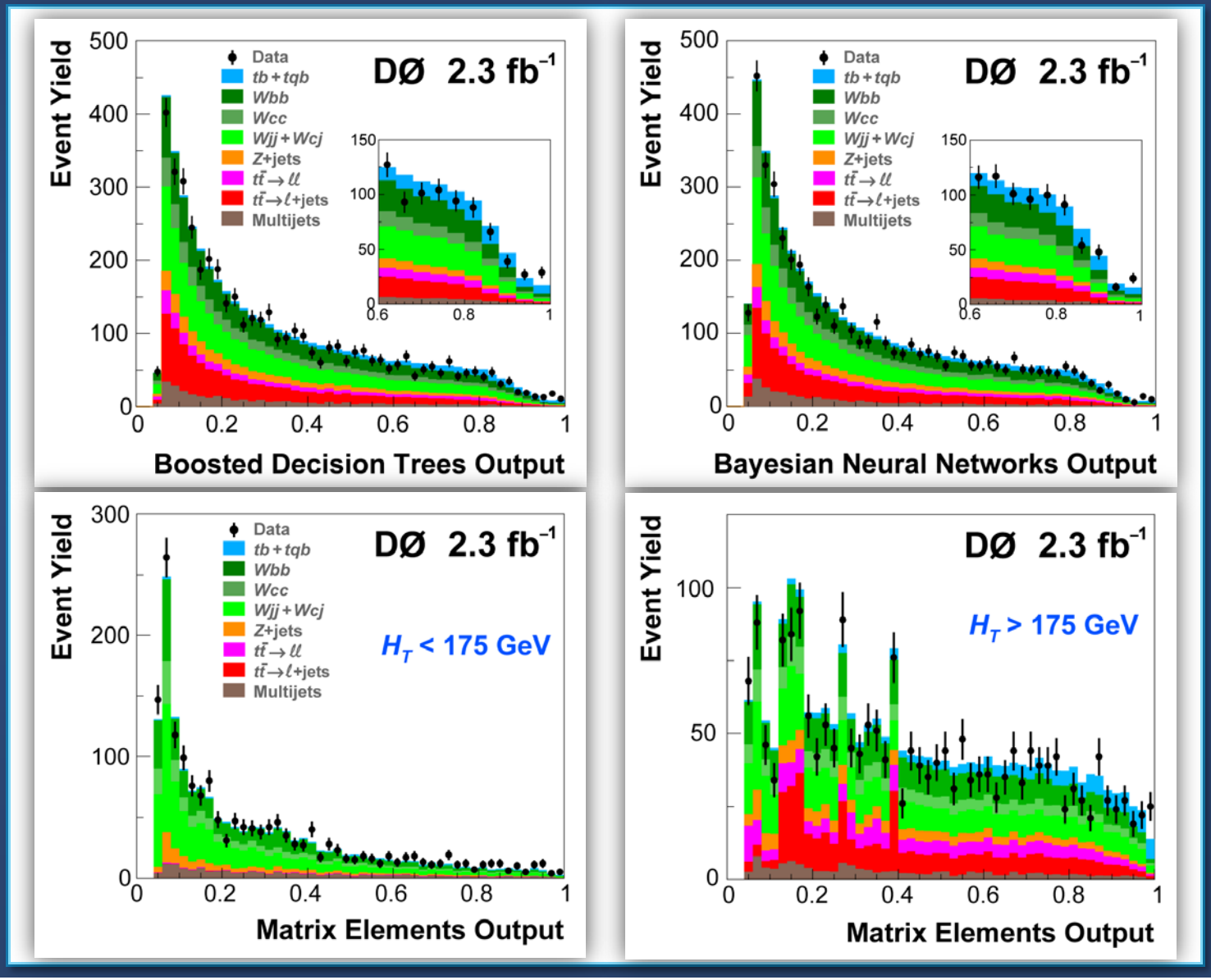
EVENT KINEMATICS



ANGULAR CORRELATIONS



Multivariate Discriminant Output



Systematic Uncertainties

Systematic Uncertainties	
Components for normalization	
Integrated luminosity	6.1%
tt cross section	12.7%
Z+jets and dibosons cross section	5.8%
Branching fractions	1.5%
Parton distribution functions (signal only)	3.0%
Triggers	5.0%
Instantaneous luminosity reweighting	1.0%
Primary vertex selection	1.4%
Lepton identification	2.5%
Jet fragmentation	(0.7–4.0)%
Initial-state and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
Jet reconstruction and identification	1.0%
Jet energy resolution	4.0%
W+jets and *Z*+jets heavy flavor correction	13.7%
Multijets normalization to data	(30–54)%
Monte Carlo and multijets statistics	(0.5–16)%

Components for normalization and shape	
Jet energy scale for signal	(1.1–13.1)%
Jet energy scale for total background	(0.1–2.1)%
b tagging for single-tagged	(2.1–7.0)%
b tagging for double-tagged	(9.0–11.4)%
Component for shape only	
ALPGEN reweighting	–

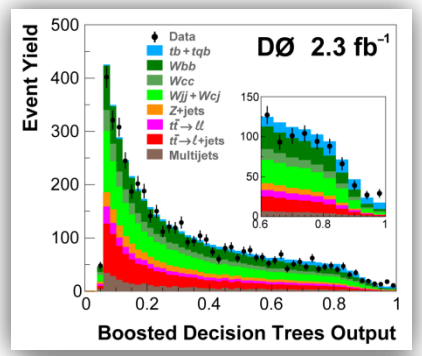
Components that most affect the cross section measurement are shown in yellow

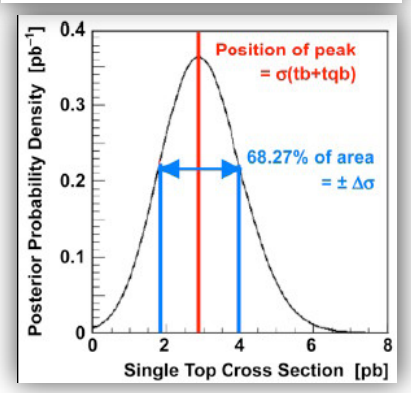
Other important contributions are shown in *pink*

Statistical Analysis

Cross Section Measurement

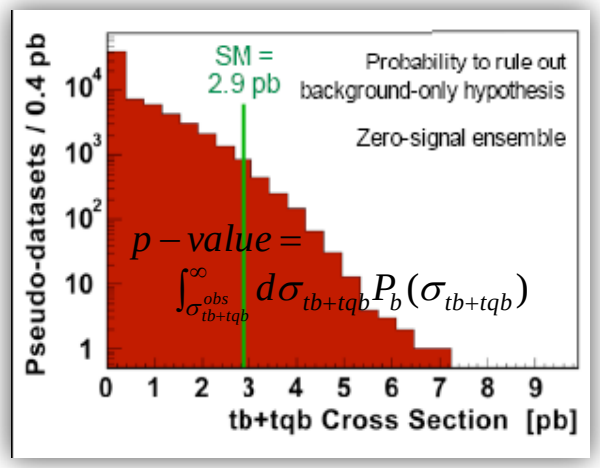
- Calculate cross sections using binned likelihood fits of (floating) signal + (fixed) background to data
- Compute posterior probability density of tb+tqb using Bayes' theorem:
  - Flat positive-defined prior for the cross section
  - Systematic uncertainties are treated as Gaussian nuisance parameters



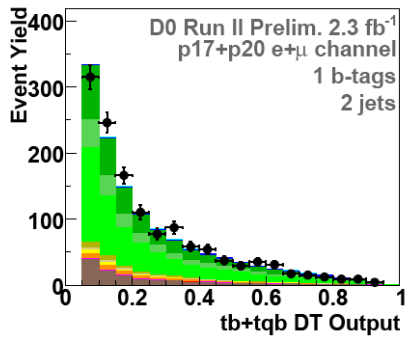


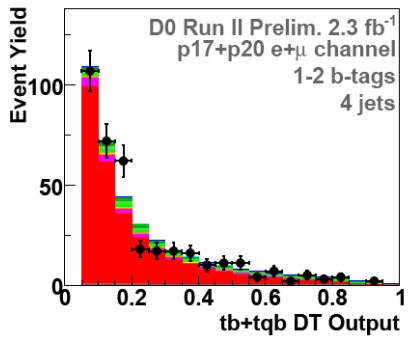
Significance

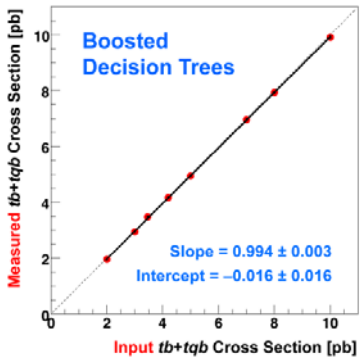
- Use the ensemble of zero-signal pseudo-datasets to find what fraction give a cross section at least as large as the measured value: the "measured p-value"
- Convert p-value to "measured significance



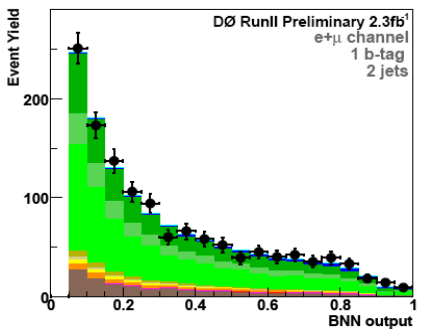
Cross Check Samples and Linearity

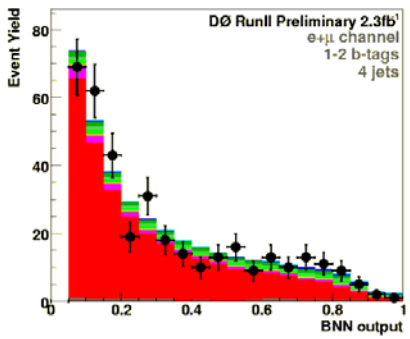


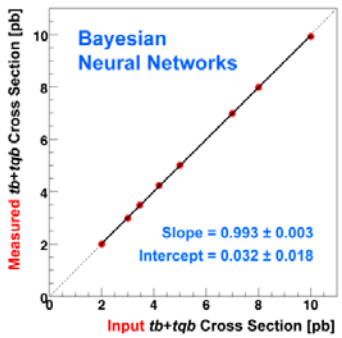




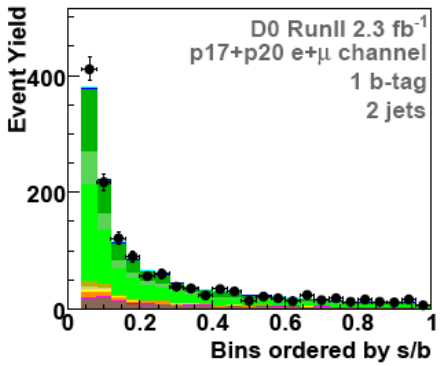
BDT

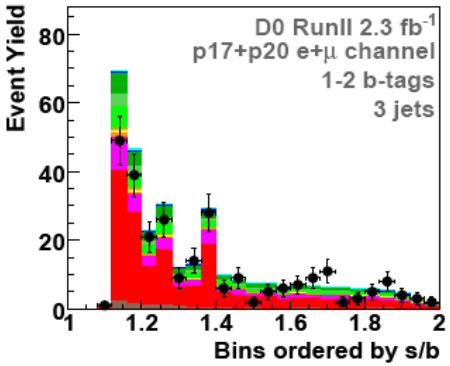


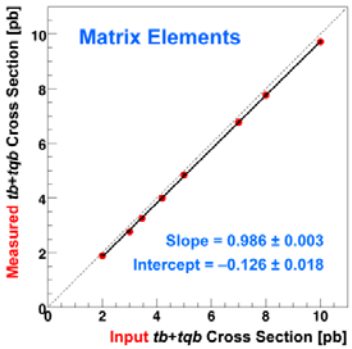




BNN



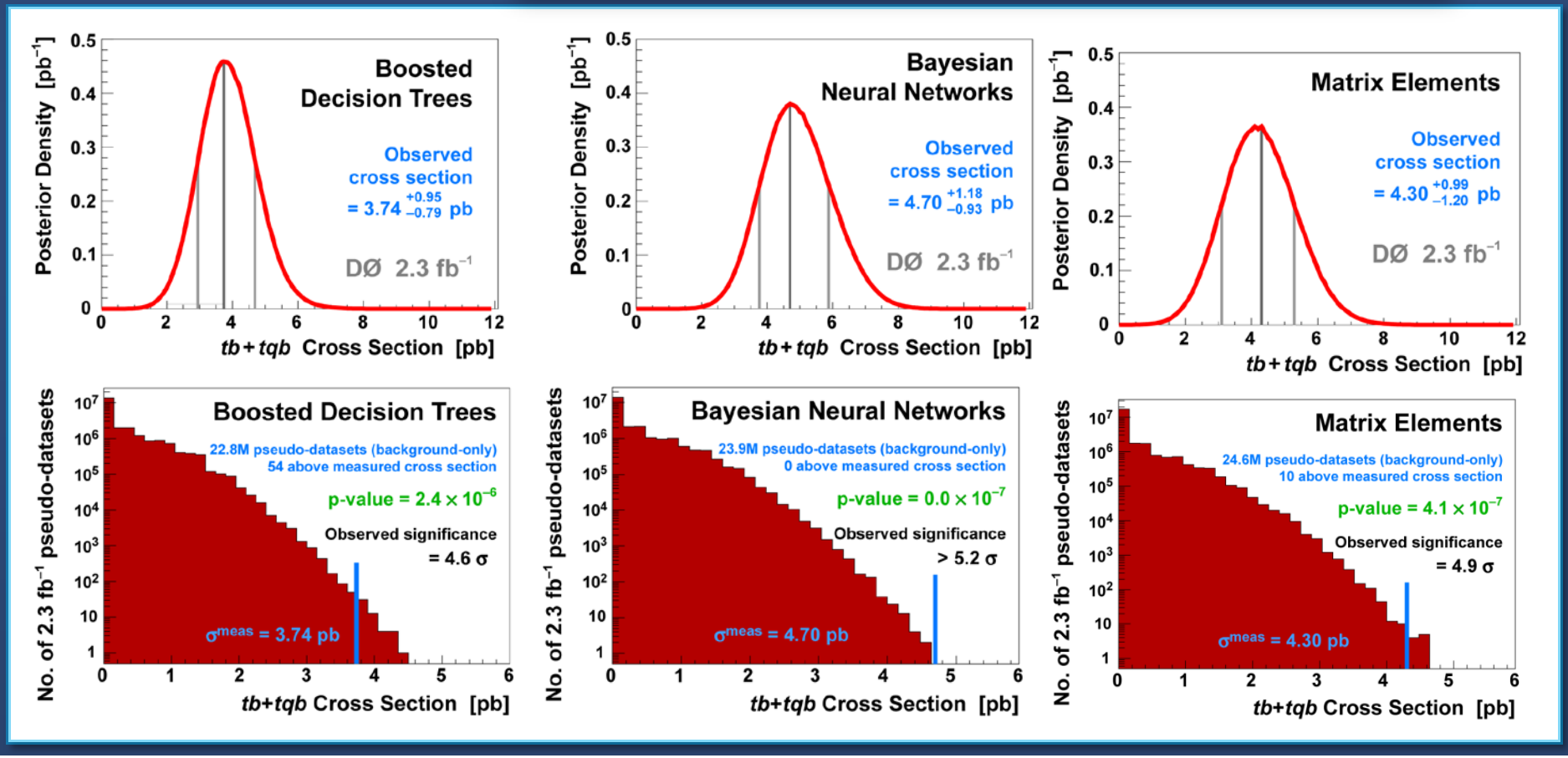




ME

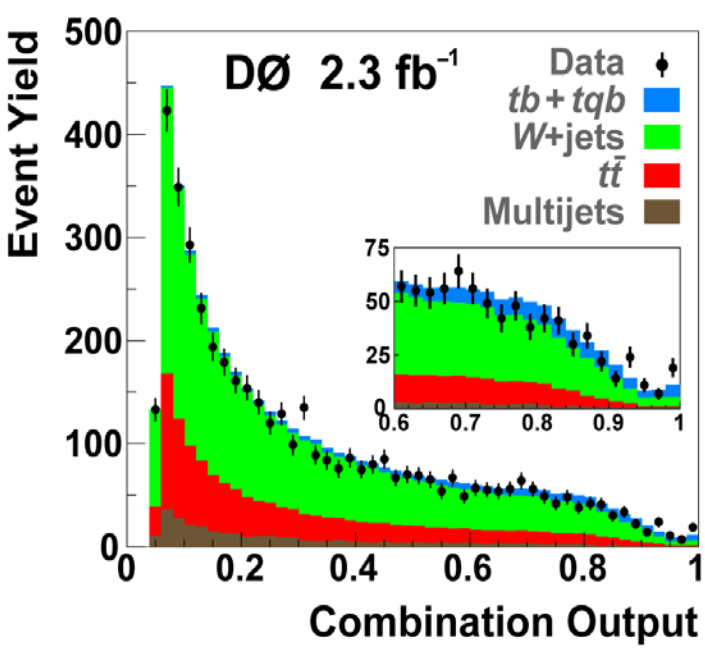
Results

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

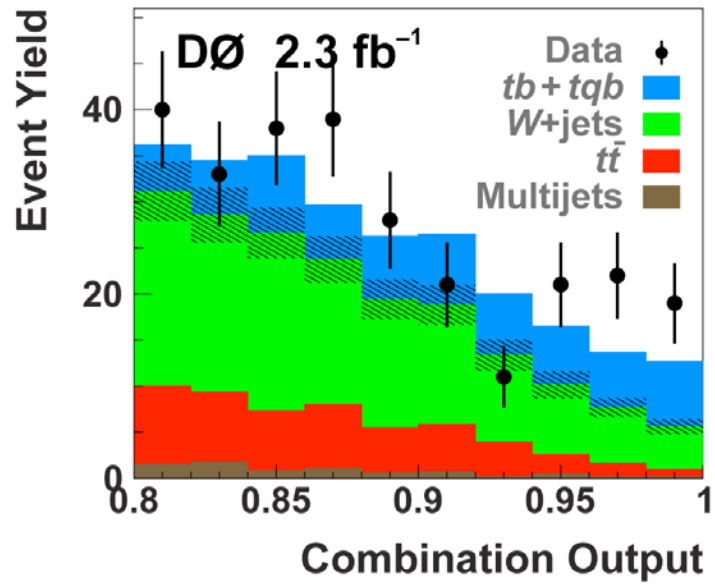


Combination of Results

- All MVA analyses use the same data, but they are not 100% correlated
- We use a BNN to combine the three methods. The BNN takes as input variables the output discriminants of the individual methods
- Expected sensitivity for the BNN Combination:**4.5σ**

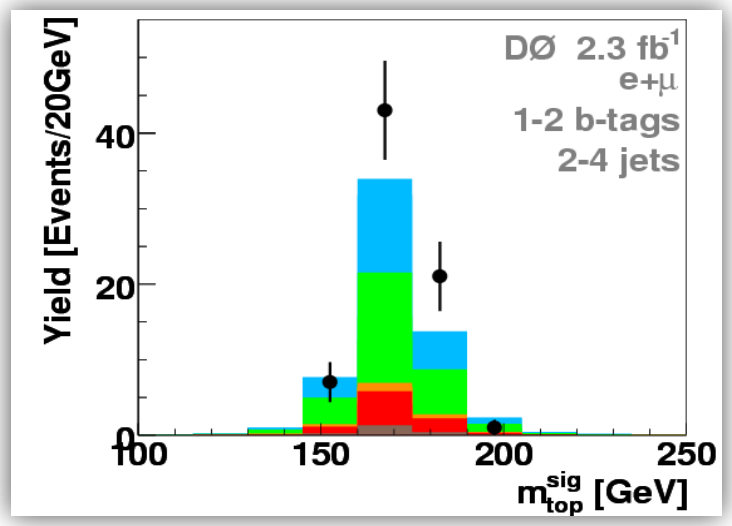


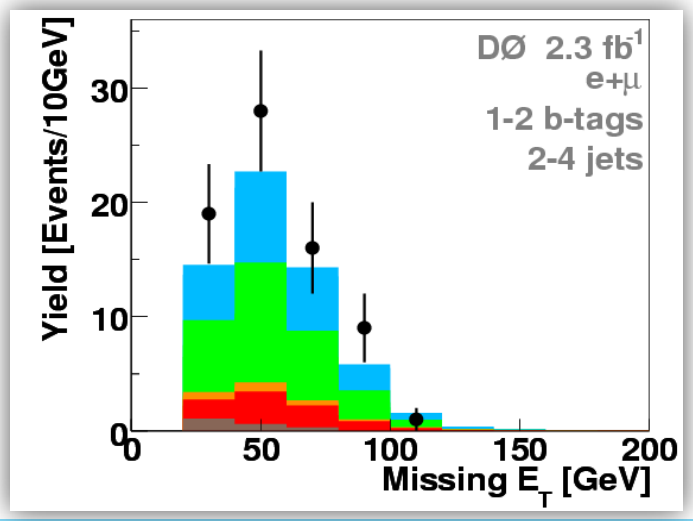
Re-binned in order of S:B

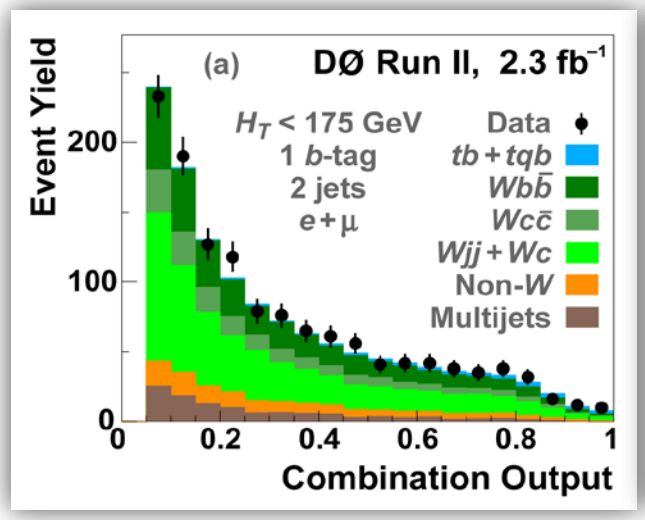


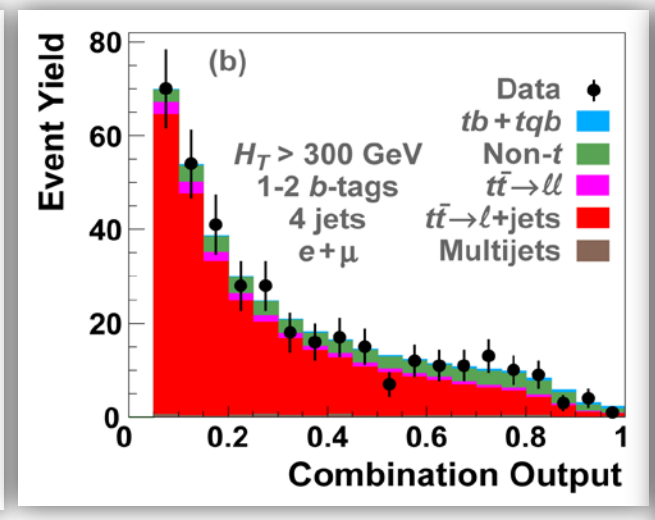
Combination of Results

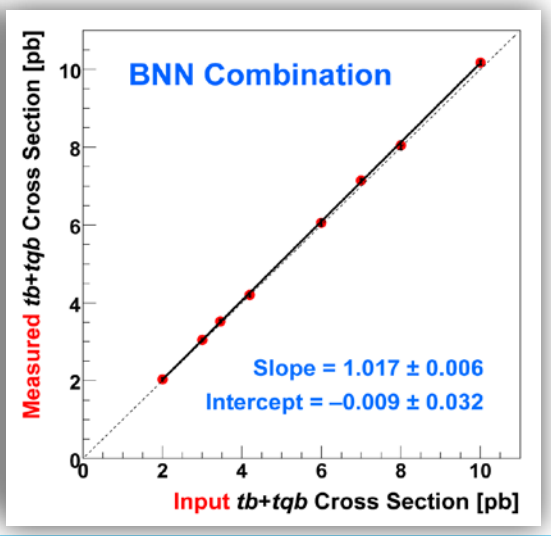
Distributions for BNN Comb > 0.9



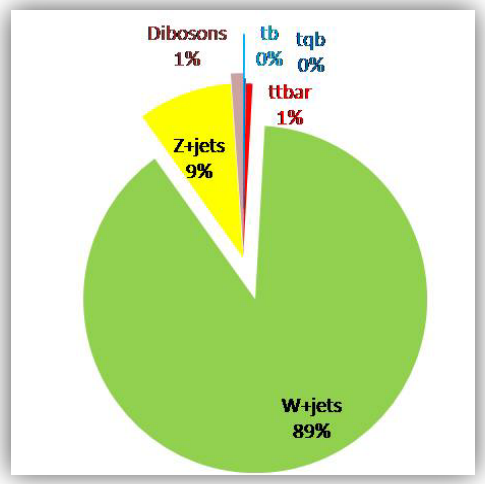


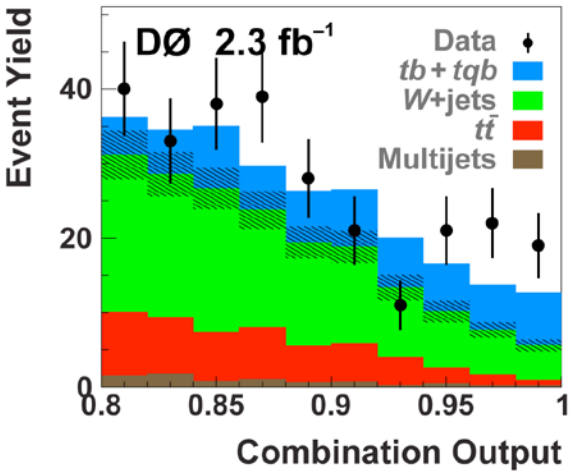






Combined Results





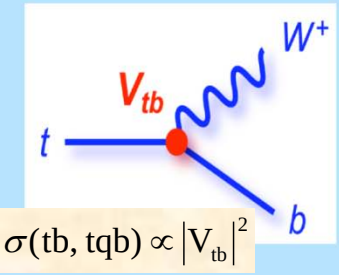
$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

Measured Significance = **5.03σ**

Discovery of single top production!!

CKM Matrix Element Vtb

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



$\sigma(\mathrm{tb}, \mathrm{tqb}) \propto |V_{tb}|^2$

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

DØ 2.3 fb^{-1}

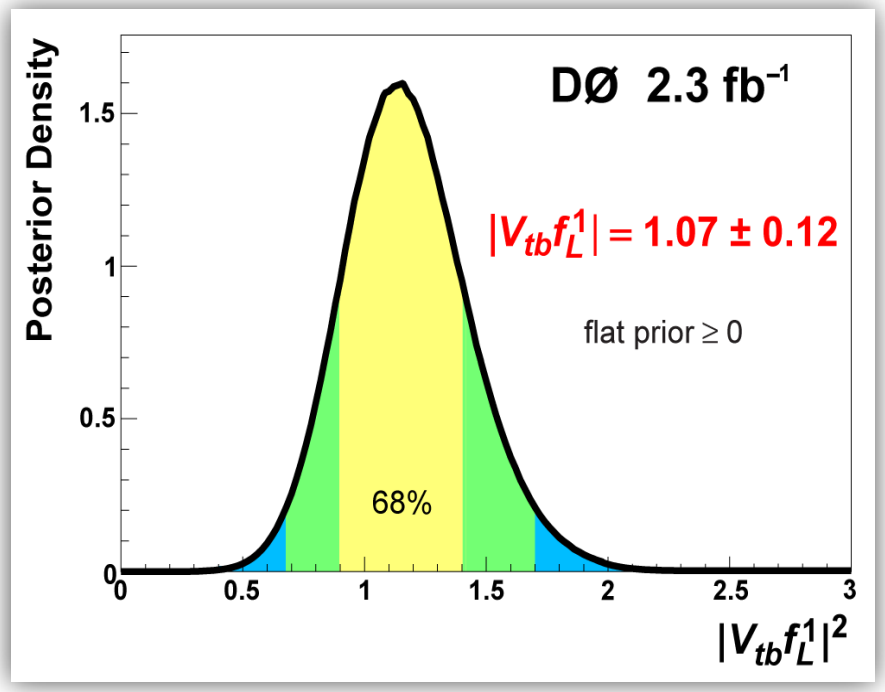
For the *tb+tqb* theory cross section	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%

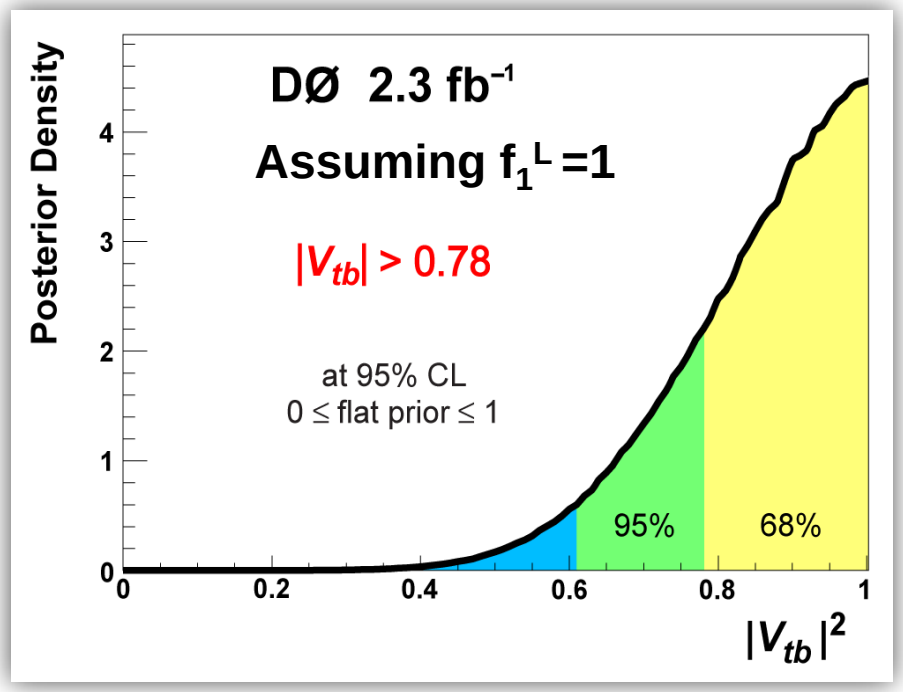
- General form of the Wtb vertex

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

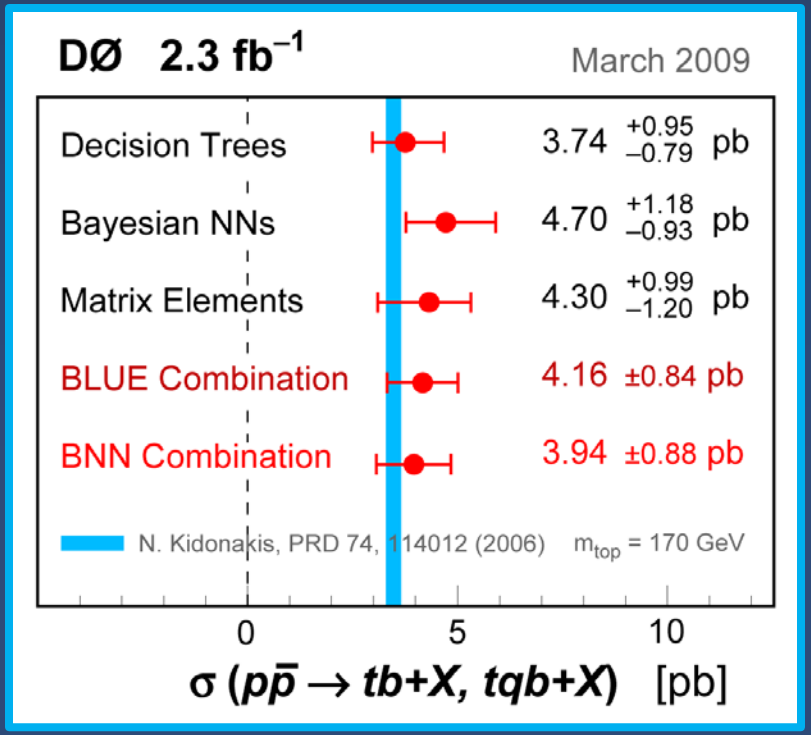
- Measurement assumes SM production mechanisms
- Pure V–A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)
- f_1^L: strength of the left-handed Wtb coupling, is allowed to be anomalous
- $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ (supported by CDF & DØ “ratio” measurements)
- Does not assume 3 generations or unitarity of the CKM matrix

Measurement of $|V_{tb}|$



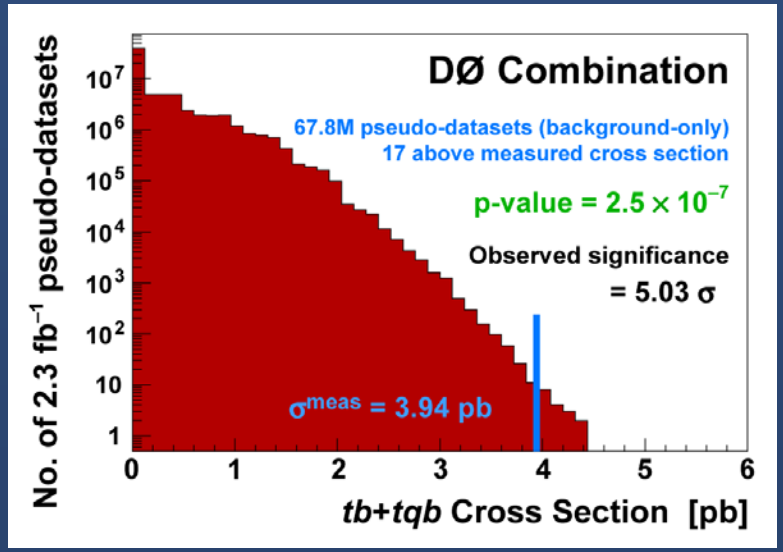


Cross Section Summary



MVA	ExpectedSignif.	Observed Signif.
BDT	4.3σ	4.6 σ
BNN	4.1σ	5.2 σ
ME	4.1σ	4.9 σ
BNNComb	4.5σ	5.0 σ

Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
March 2009	**DØ (2.3 fb^{-1})**	arXiv:0903.0850 (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
March 2009	**CDF (3.2 fb^{-1})**	arXiv:0903.0885 (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



Conclusions

- Both DØ and CDF collaborations at Tevatron have observes single top quark production in Run II data (I have presented only DØ analysis)

$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

Measured Significance 5.03σ

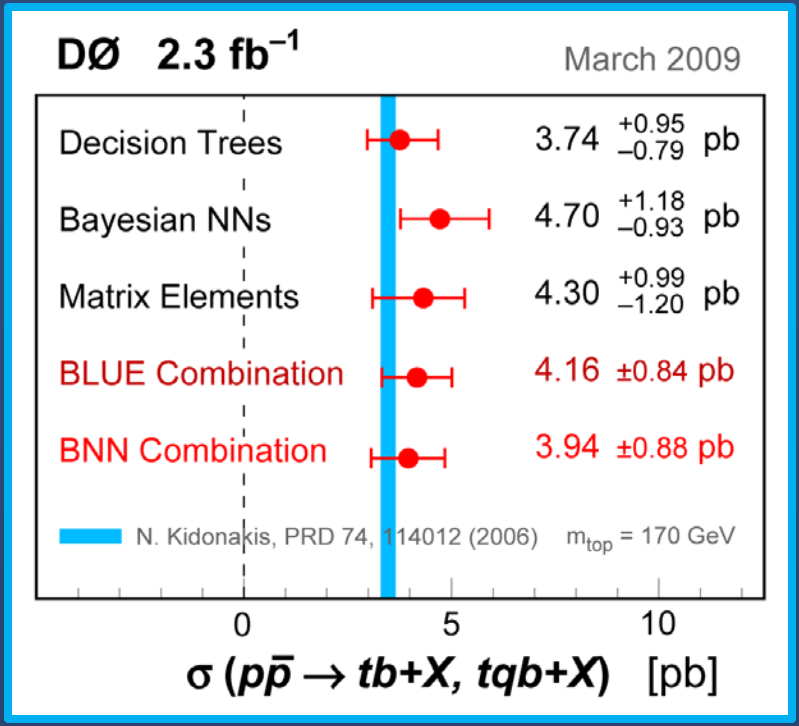
- Direct measurement of $|V_{tb}|$

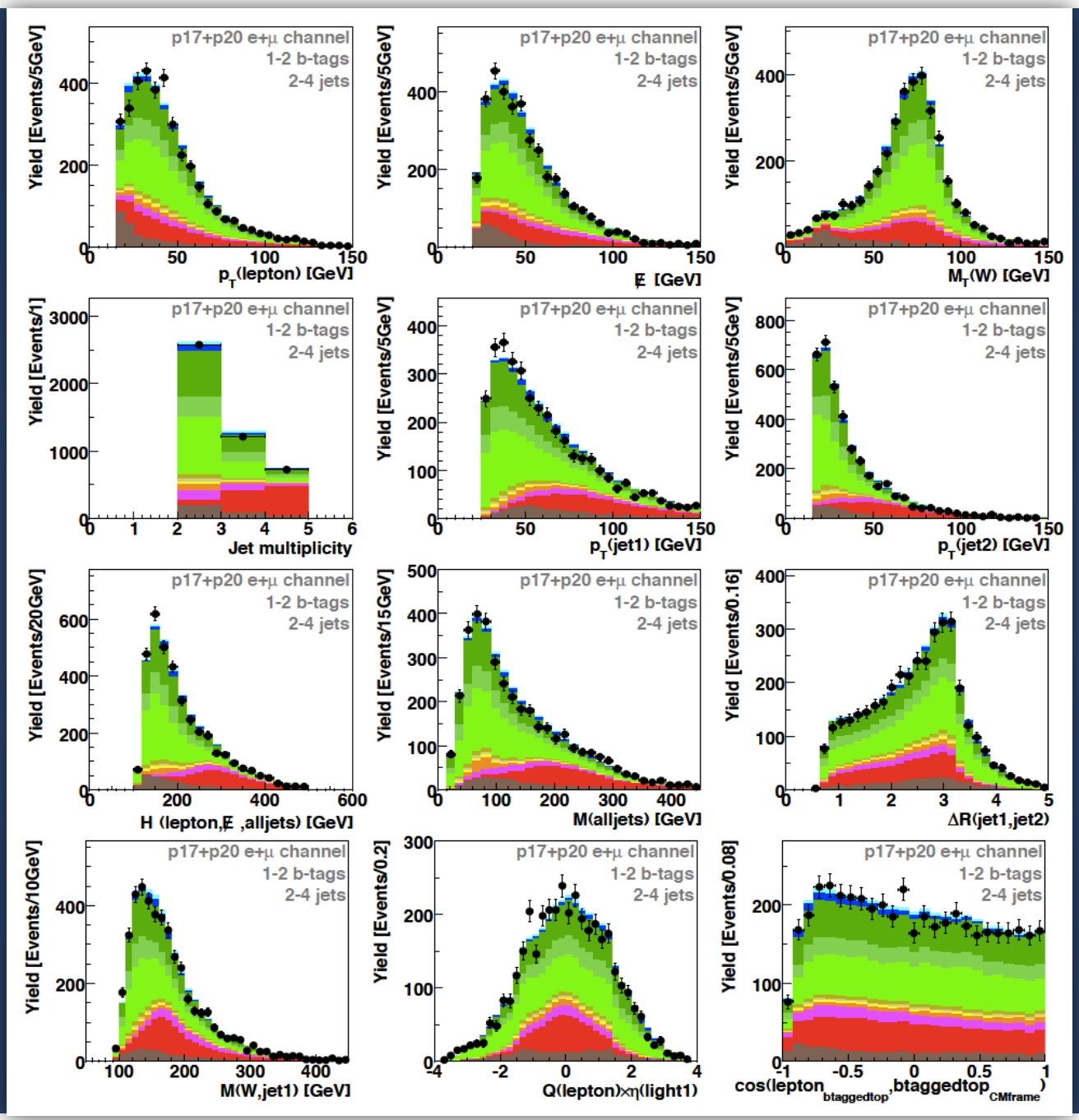
$|V_{tb} f_1^L| = 1.07 \pm 0.12$

flat prior ≥ 0

$0.78 < |V_{tb}| < 1$ @ 95% CL

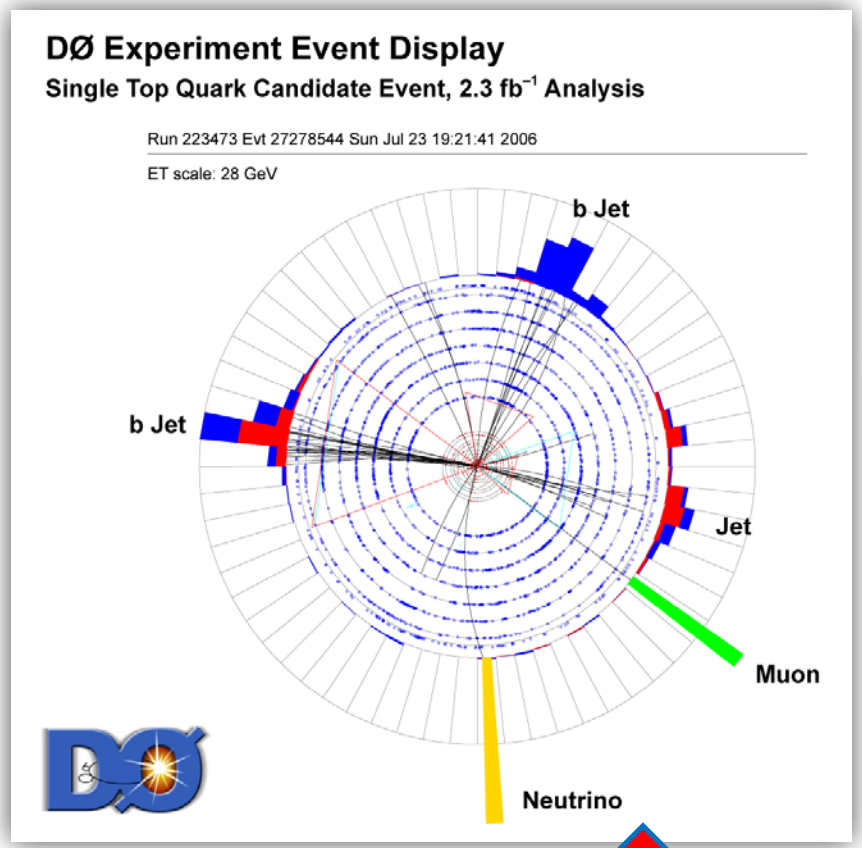
0 ≤ flat prior ≤ 1

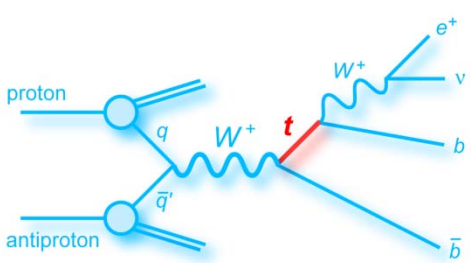


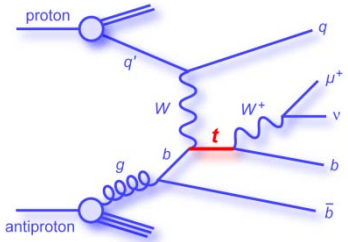


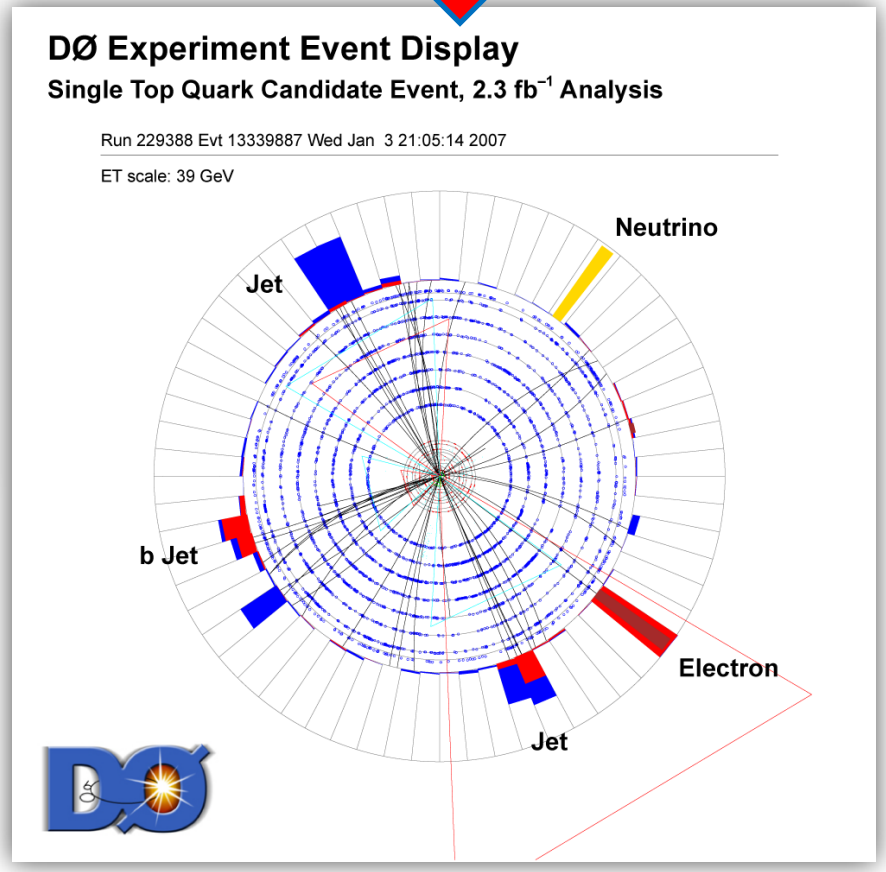
Data/MC agreement (for all channels combined)

- tb
- tqb
- $Wb\bar{b}$
- $Wc\bar{c}$
- Wjj
- $Zb\bar{b}$
- $Zc\bar{c}$
- Zjj
- Dibosons
- $t\bar{t} \to \ell\ell$
- $t\bar{t} \to \ell$+jets
- Multijets


DØ Experiment Event Display
Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis
Run 223473 Evt 27278544 Sun Jul 23 19:21:41 2006
ET scale: 28 GeV
b Jet
b Jet
Jet
Muon
Neutrino

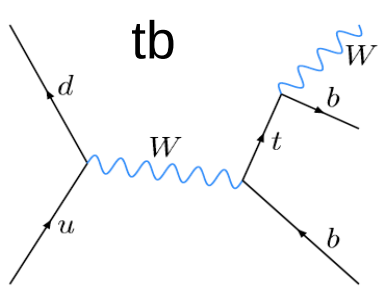

proton
antiproton
q
$\bar{q}'$
W+
t
W+
e+
ν
b
$\bar{b}$

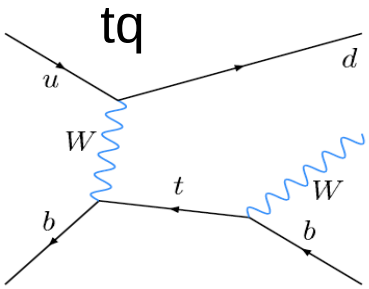

proton
antiproton
q
q'
W
W+
t
b
g
μ+
ν
b
$\bar{b}$

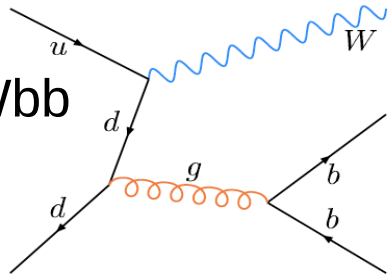

DØ Experiment Event Display
Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis
Run 229388 Evt 13339887 Wed Jan 3 21:05:14 2007
ET scale: 39 GeV
Neutrino
Jet
b Jet
Electron
Jet

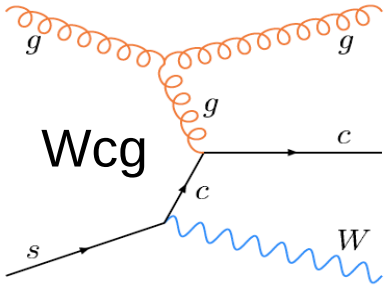
Feynman Diagrams Matrix Elements

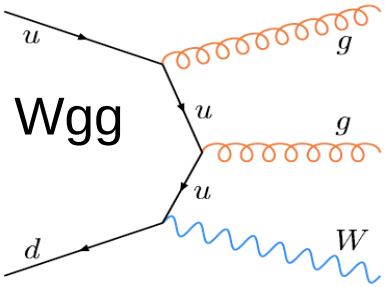
2-jet channels



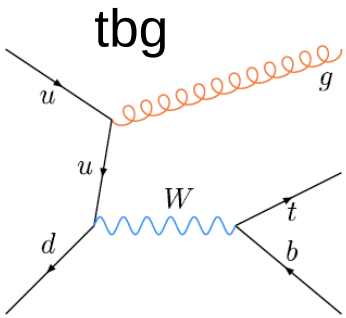


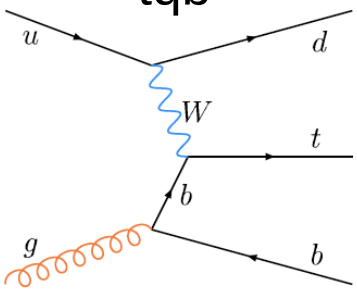


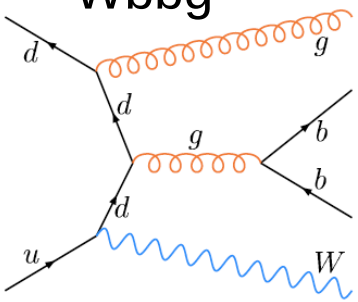




3-jet channels







Added additional Matrix Elements since 2006

2jets: top pair, WW, WZ, ggg; 3jets:top pair, Wugg