Observation of Single Top Production at DØ

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at Chicago
(on behalf of the DØ Collaboration)

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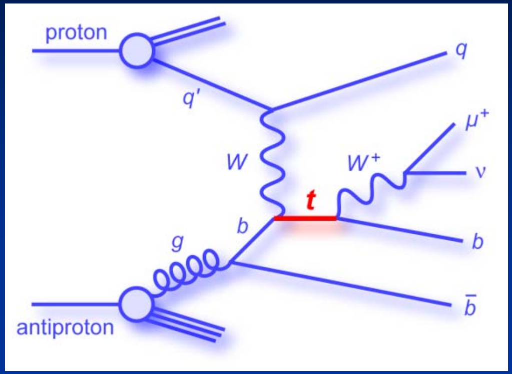
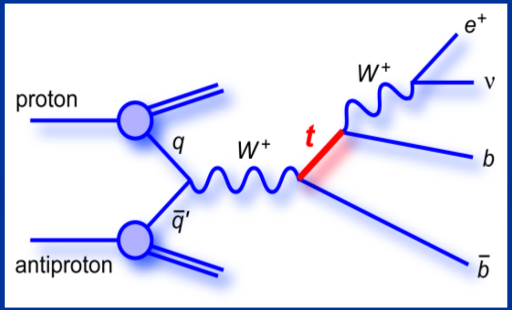
Outline

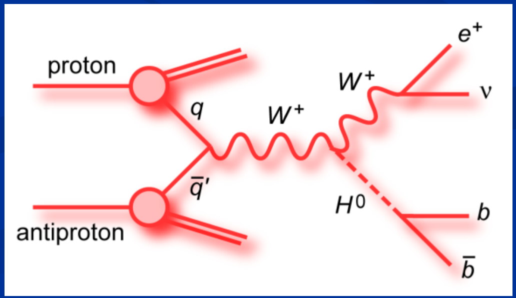
- Introduction
- Understanding the data
  - Event Selection
  - Background Modeling
- Multivariate Analysis Techniques
  - Boosted Decision Trees
  - Bayesian Neural Networks
  - Matrix Elements Method
  - Combination
- Expected Sensitivity
- Cross Sections and Significance
- Direct Measurement of $|V_{tb}|$
- Evidence for t-channel production
- Conclusions

Single Top Production

- Predicted by the Standard Model, and observed for the first time in May 2009, 14 years after the observation of the top quark pair production
- Probe of the Wtb interaction with no assumption on the number of quark families or unitarity of the CKM matrix
- Cross sections sensitive to beyond-the-SM processes
  - s-channel:
    - Resonances: heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.
  - t-channel
    - flavor-changing neutral currents
  - Fourth generation of quarks
- Same final state as WH
  - Same backgrounds
  - Test techniques to extract small signal

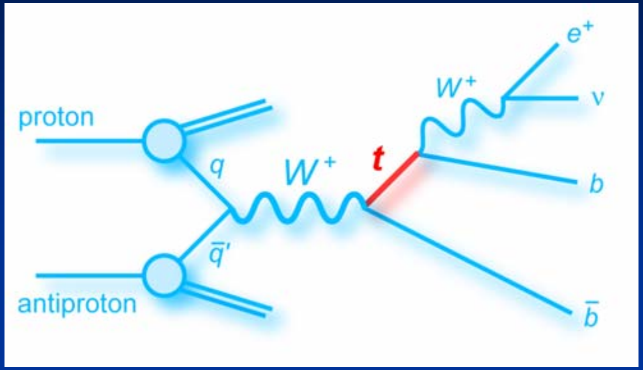






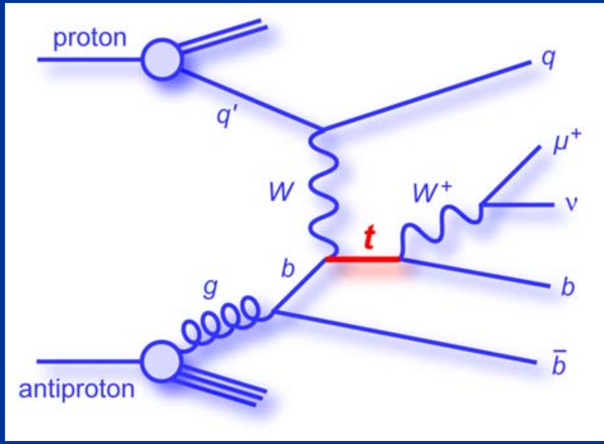
Experimentally Very Challenging

_s_-channel ("tb")

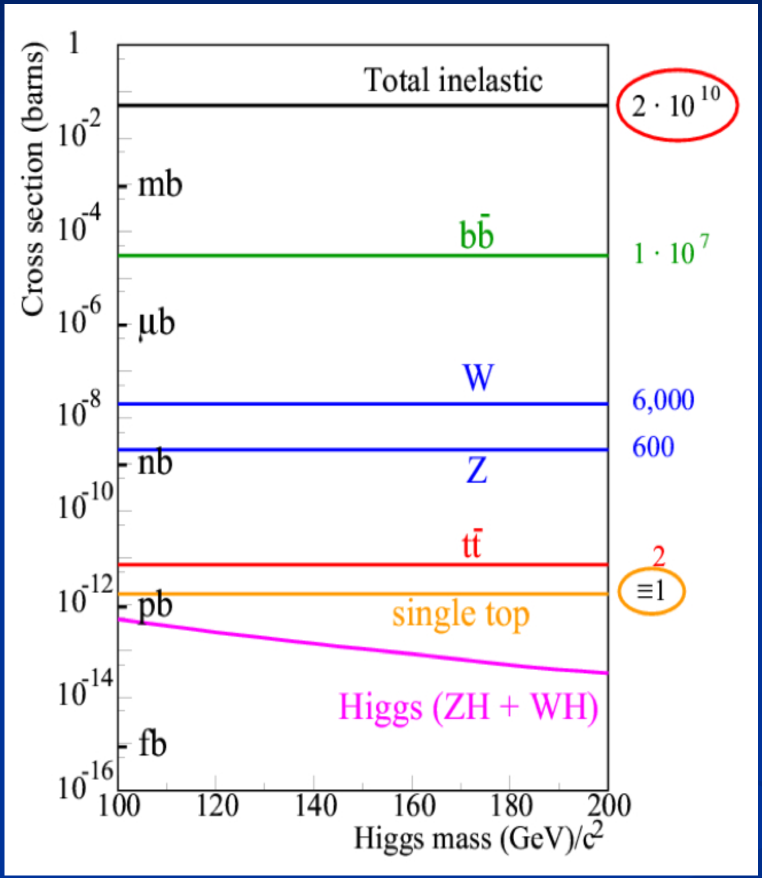


$\sigma_{SM} = 1.12 \pm 0.05$ pb

_t_-channel ("tqb")

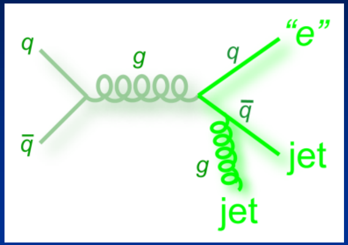


$\sigma_{SM} = 2.34 \pm 0.13$ pb

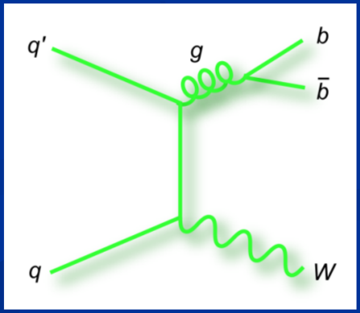


Single top cross sections: Kidonakis and Vogt, PRD 68, 114014 (2003) for m_t =170 GeV

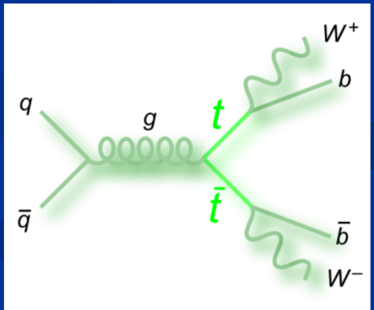
Multijets



W+jets

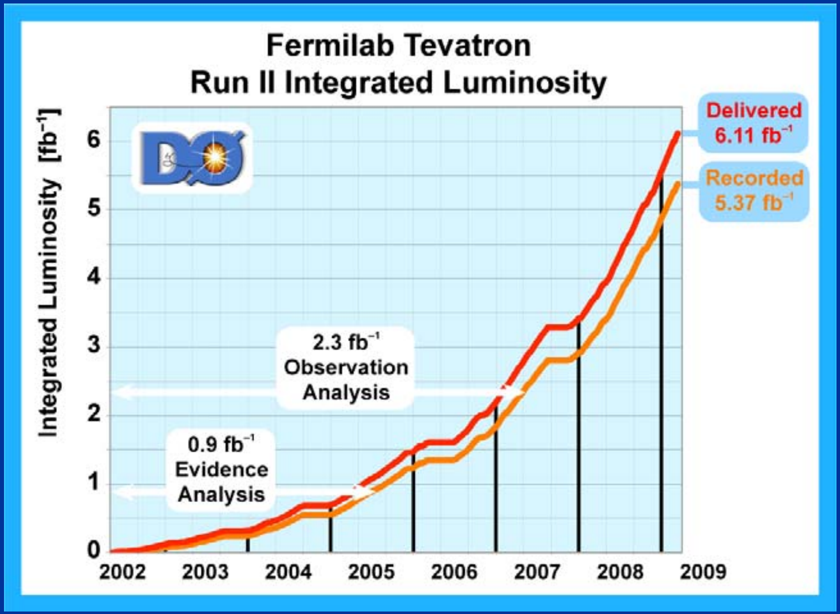


Top pairs

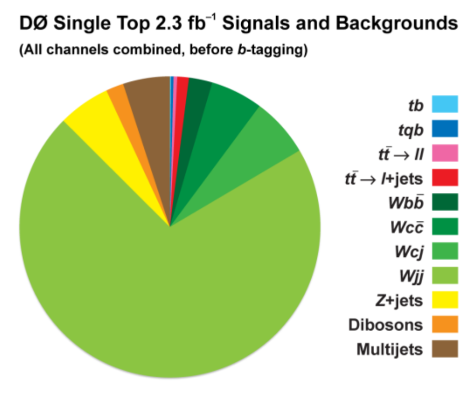


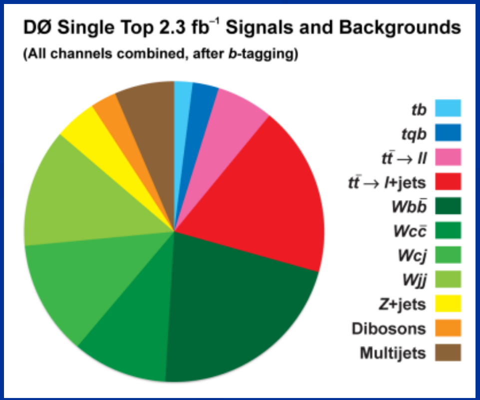
Data Set and Event Selection

- Analysis uses 2.3 fb^{-1} of data collected from 2002 to 2007
  - Full Run IIa dataset, 1.1 fb-1 (20% increase w.r.t. 2006 evidence analysis)
  - Run IIb dataset, 1.2 fb-1



- Event Selection
  - One high-p_T isolated electron or muon
  - Large missing transverse energy
  - A b-jet from the top quark decay
  - A second b-jet or a light jet

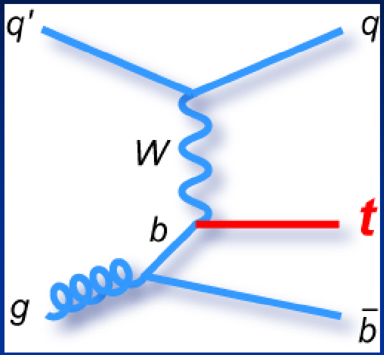


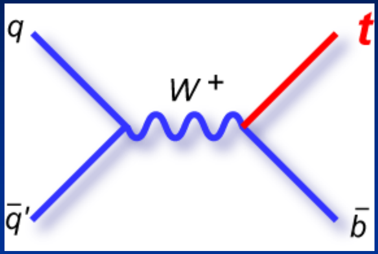


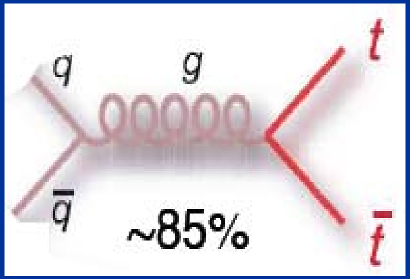
S:B = 1:259 PreTag
S:B = 1:21 in 1Tag
S:B = 1:15 in 2Tag

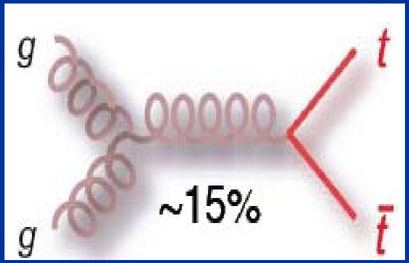
Signal and Background Models

- Single top quark signals modeled using SINGLETOP
  - Based on COMPHEP
  - Reproduces NLO kinematic distributions
  - PYTHIA for parton hadronization





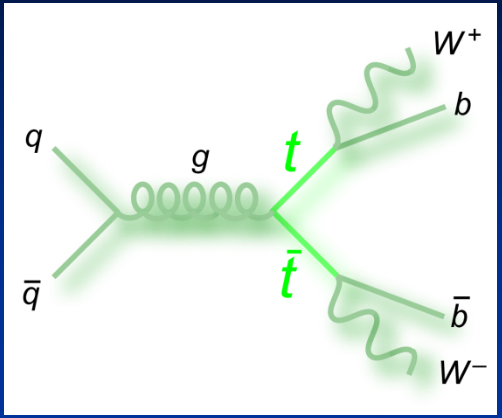


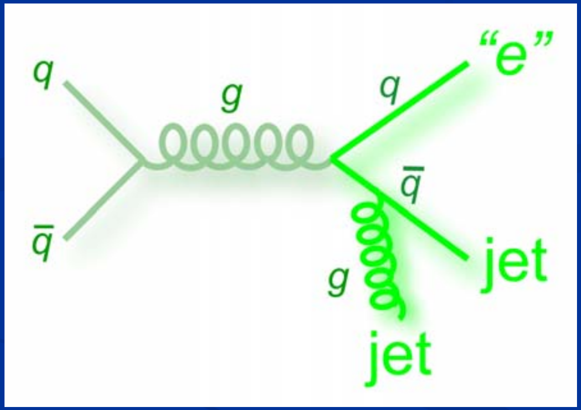


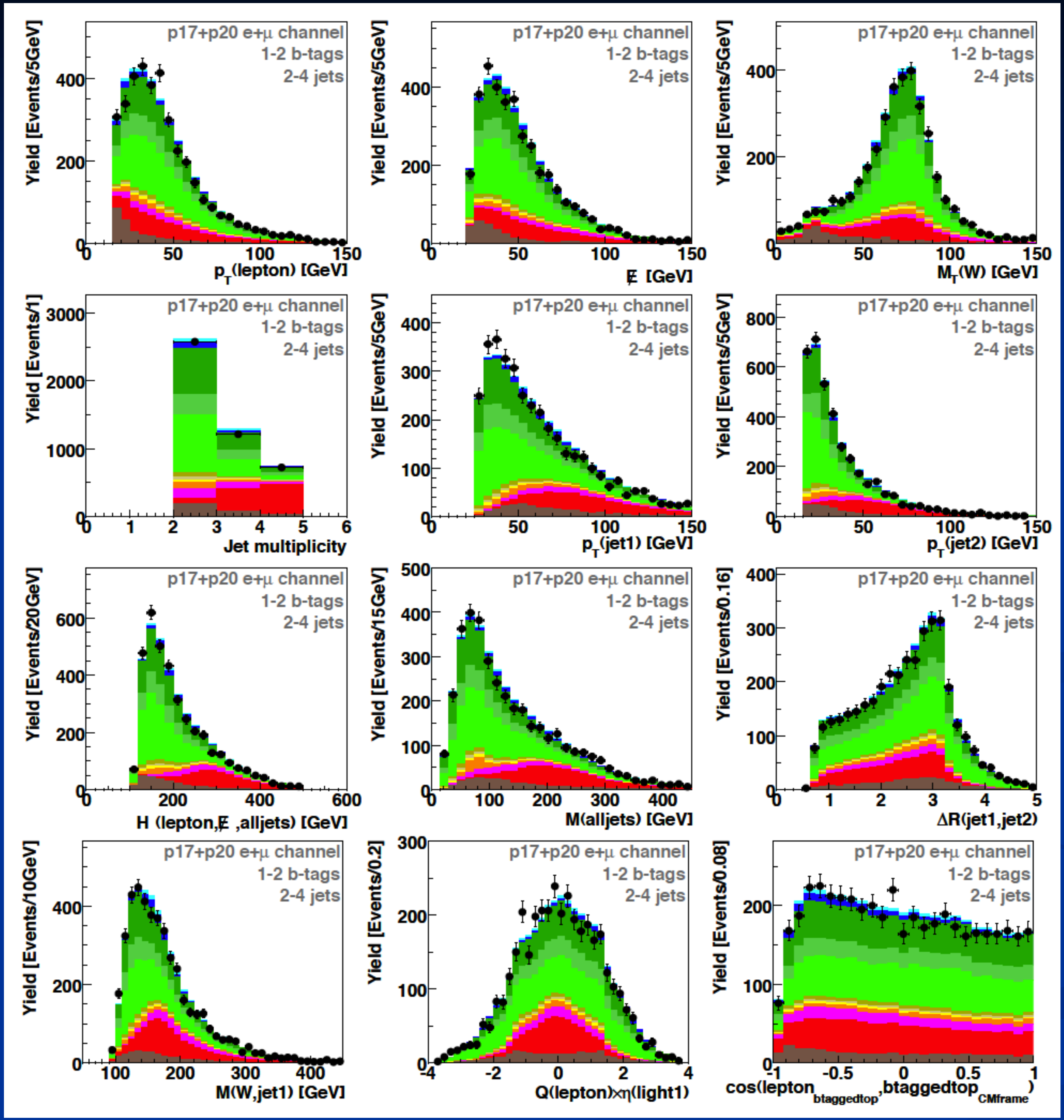
- Top pair backgrounds modeled using ALPGEN
  - PYTHIA for parton hadronization
  - Parton-jet matching algorithm used to avoid double-counting final states
  - Normalized σ = 7.91pb from Kidonakis and Vogt, PRD 68, 114014 (2003) for m_t =170 GeV
  - Uncertainties +7.7% −12.7% includes theory, PDF and mass shift to (172.4±1.2) GeV

Signal and Background Models

- W+jets modeled using ALPGEN + PYTHIA
  - MLM parton-jet matching avoids double-counting final states
  - η(jets), $\Delta\phi$(jet1,jet2), $\Delta\eta$(jet1,jet2) corrected to match data
  - Normalized to data before tagging
  - W+ heavy flavor corrected to NLO theory, with additional empirical factor derived from data
- QCD Multijet (misidentified lepton)
  - Taken directly from data
  - Kept small (~5%) with topological cuts
  - Normalized to data before tagging
- Z+jets modeled using ALPGEN + PYTHIA
  - Z+ heavy flavor corrected to theory, with ±20% uncertainty
- Dibosons modeled using PYTHIA



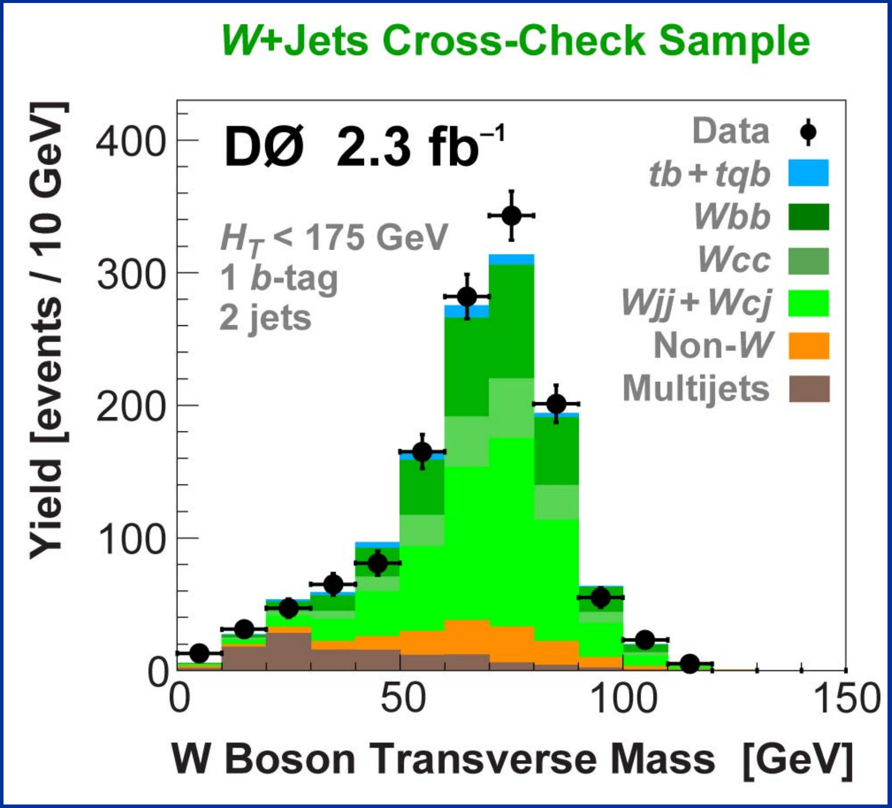


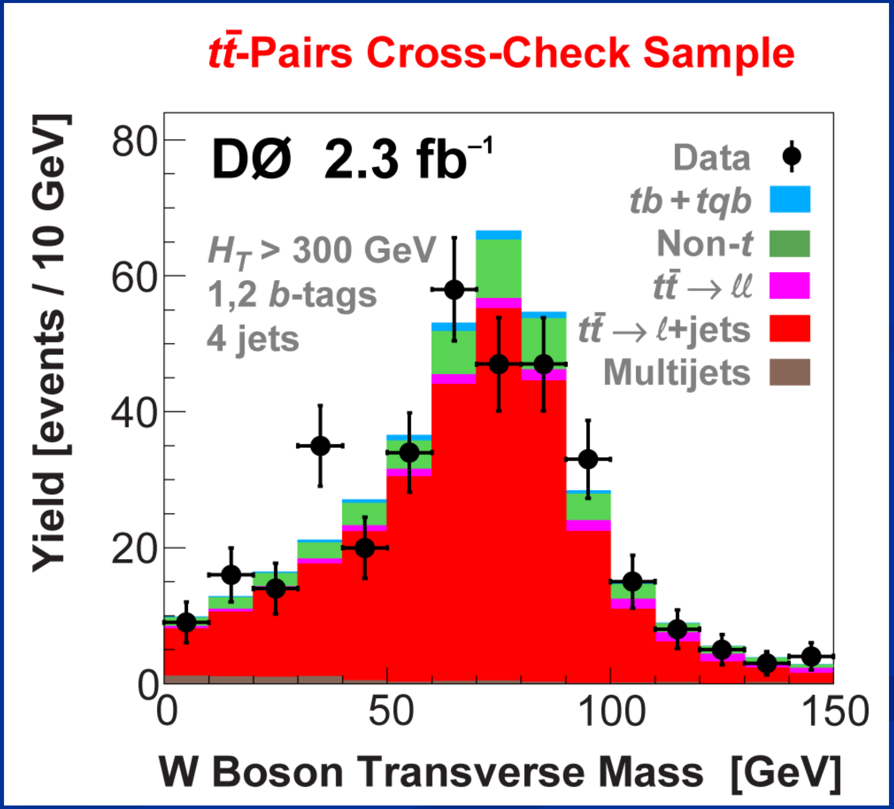


- Analysis is performed in 24 individual channels:
  - Run IIA, Run IIb
  - Electron, muon
  - 2, 3 or 4 jets
  - 1 or 2 b-tags
- Good data/MC agreement (shown here for all channels combined)

Cross Check Samples

- Selected to test background model in regions dominated by one type of background: W+jets or Top Pairs





Systematic Uncertainties

- Considered components for normalization and or shape.
  - Largest contribution is still from statistics

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}

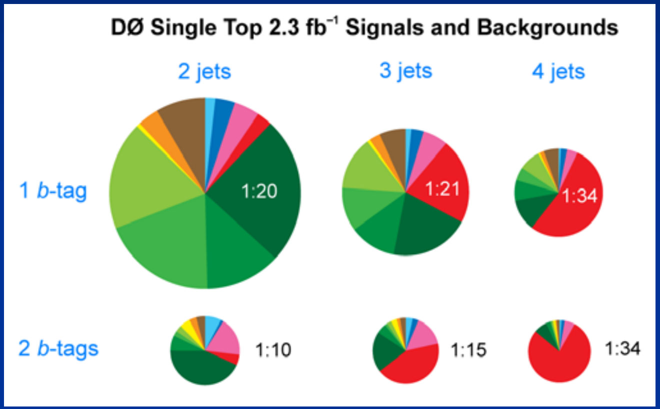
Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%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

Expected and Observed Events

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

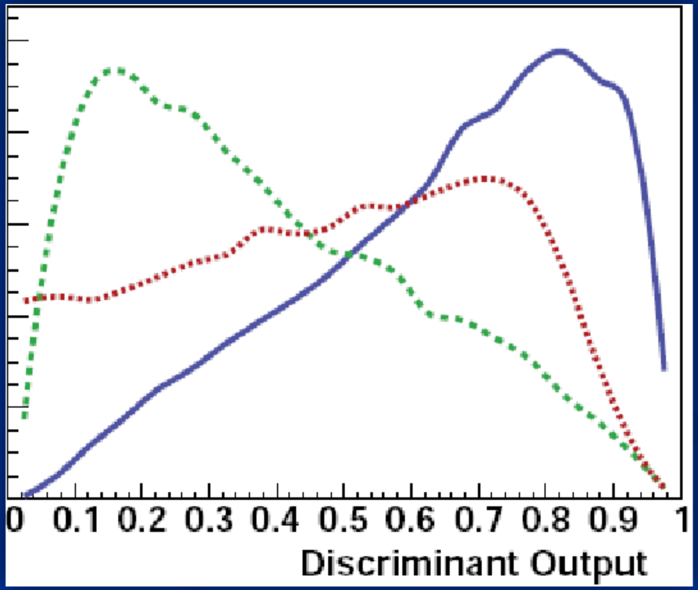
Electron + muon, 1 tag + 2 tags combined

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



Analysis Strategy

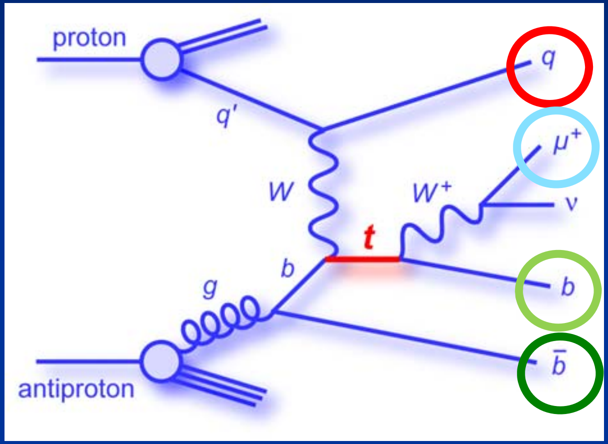
- Maximize signal acceptance.
  - Background model gives good representation of data in each of the 24 independent analysis channels
- Calculate discriminant functions that separate signal from background
  - Boosted Decision Trees (BDT)
  - Bayesian Neural Networks (BNN)
  - Matrix Elements (ME)

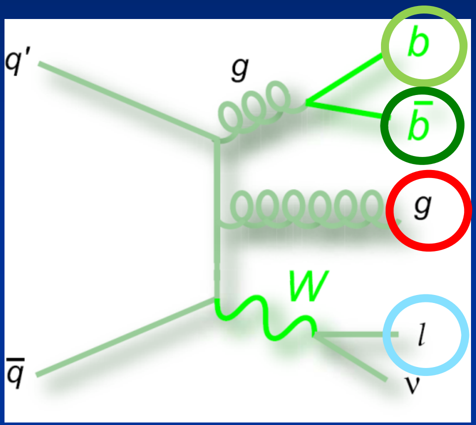


- Check discriminant performance using data control samples
- Use ensembles of pseudo-data to test validity of methods
- Calculate cross sections using binned likelihood fits of signal + background to data

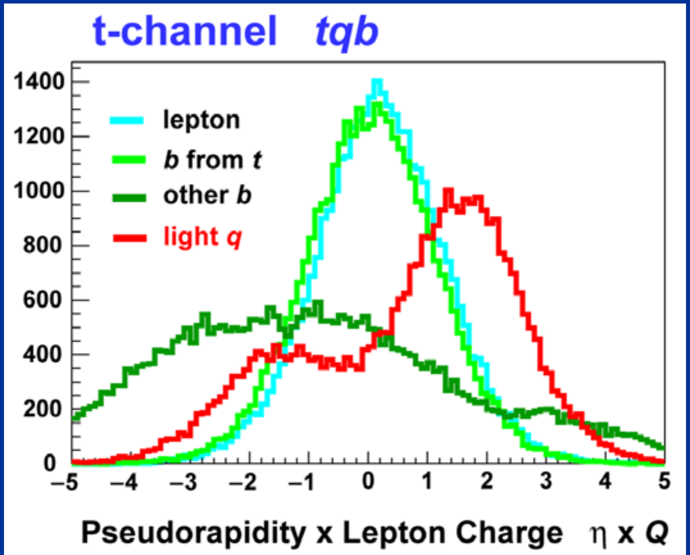
Multivariate Analysis

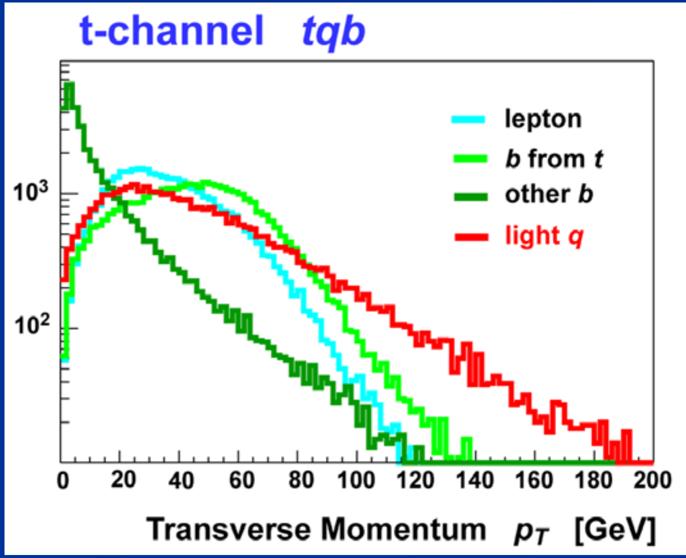
- Exploit kinematic differences between signal and background





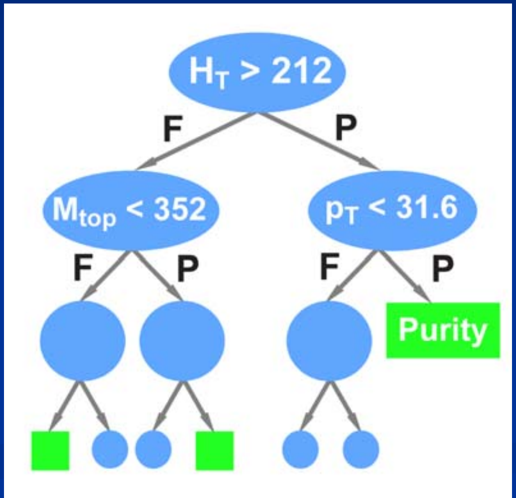
Even though final state is identical, MVA can extract the signal due to characteristic shape of variables with high discriminating power





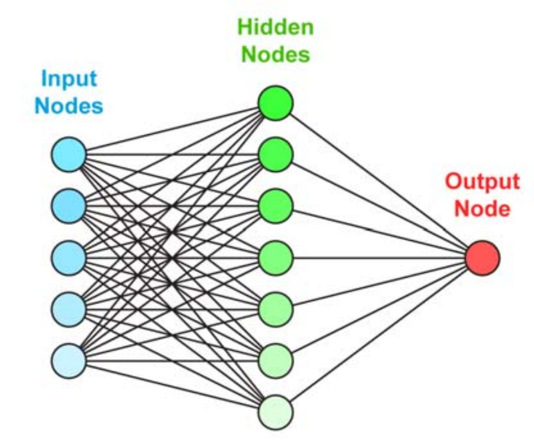
Multivariate Analyses: BDT & BNN

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

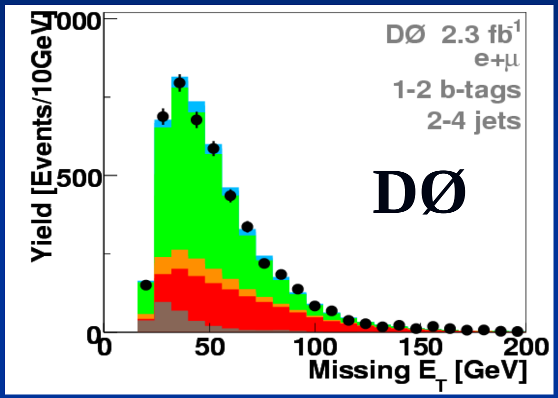


Bayesian Neural Network (BNN)

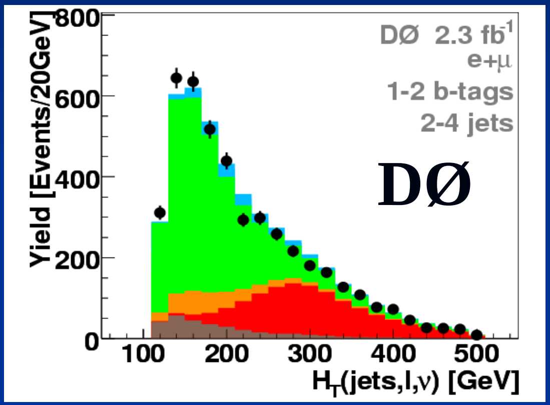
- NN train on signal and background, producing one output discriminant
- Bayesian NN average over many networks, improving the performance
- Uses highest ranked 18-28 variables in each channel

Discriminating Variables – BDT/BNN

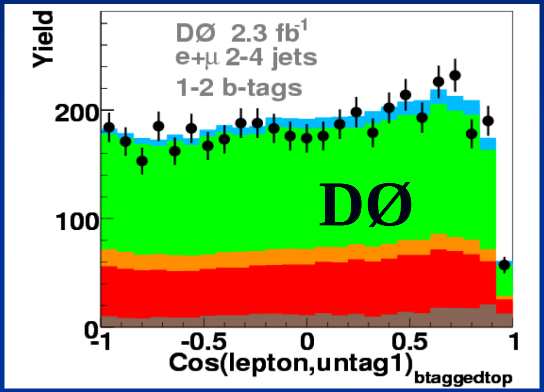
OBJECT KINEMATICS



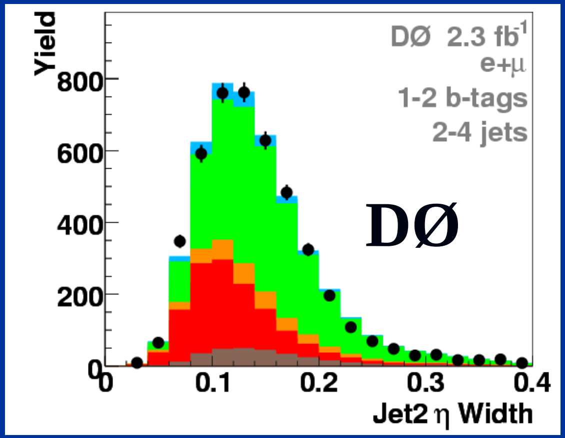
EVENT KINEMATICS



ANGULAR CORRELATIONS

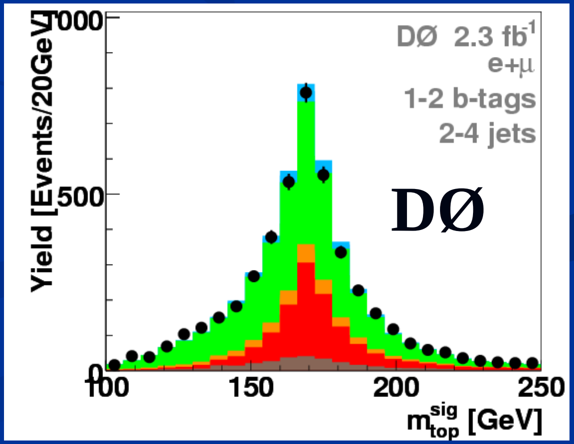


JET RECONSTRUCTION



New categories of variables added since 2006 improve BDT & BNN performance

TOP QUARK RECONSTRUCTION



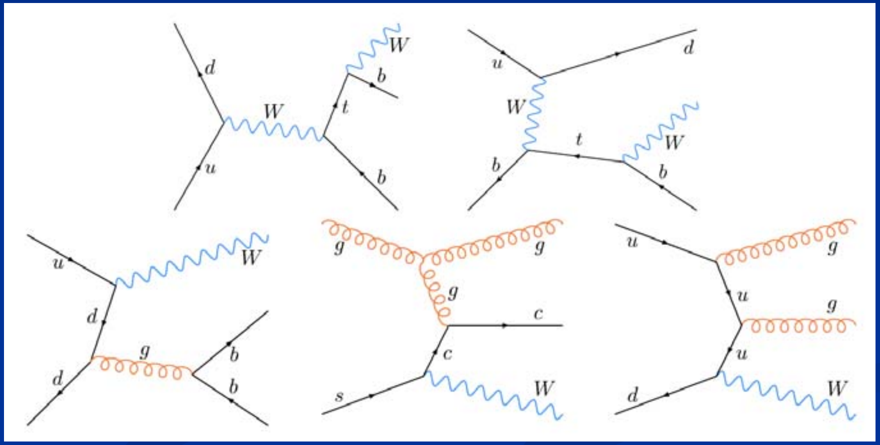
Multivariate Analyses: ME

Matrix Element (ME)

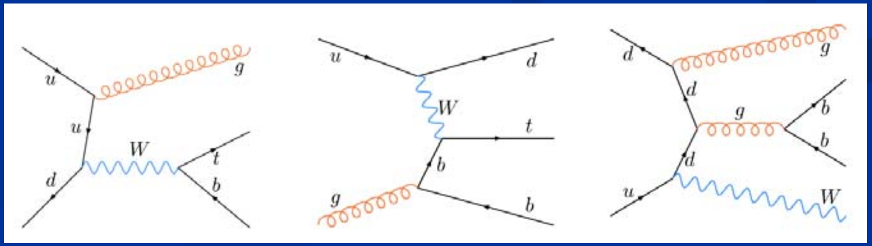
- Method pioneered by DØ for the top quark mass measurement in Run I
- Use the 4-vectors of all reconstructed leptons and jets
- Use Feynman diagrams to compute an event probability density for signal and background hypotheses

- Uses events with 2 and 3 jets only
- ME for signal (tb & tqb) and background
- Split the sample in high and low H_T (W+jets and top quark pair dominated regions) improves the performance

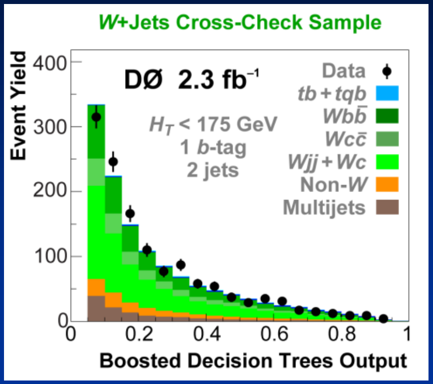
2 JET CHANNEL
tb, tq
Wbb, Wcg, Wgg

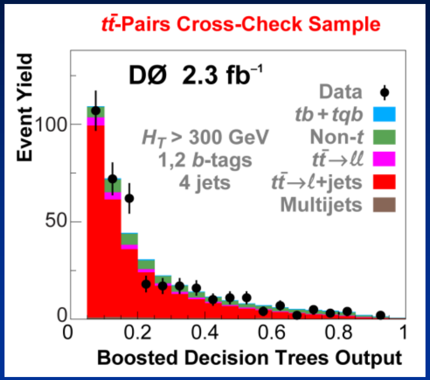


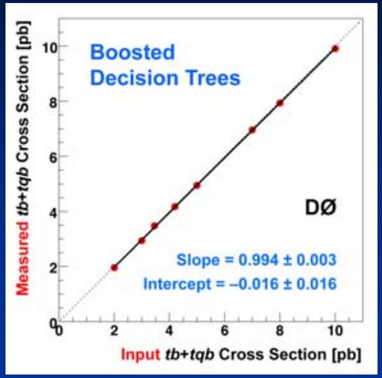
3 JET CHANNEL
tbg, tqb, tqg
Wbbg



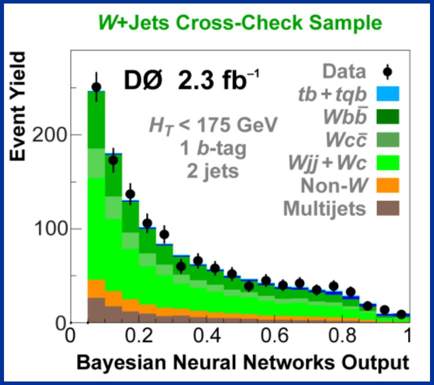
Cross Check Samples and Linearity

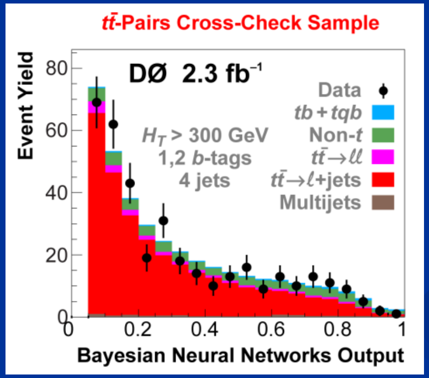


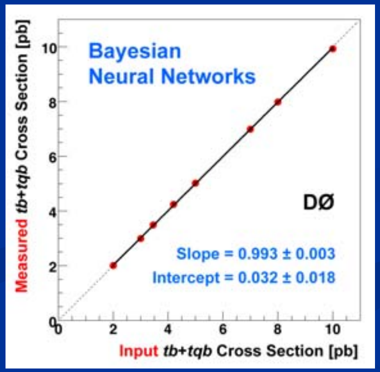




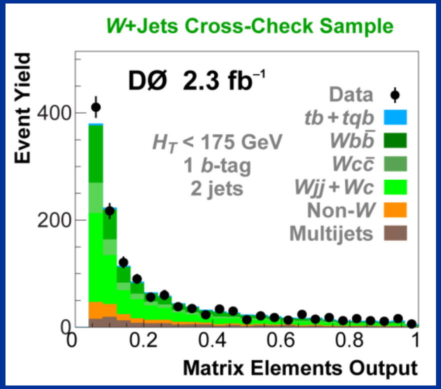
BDT

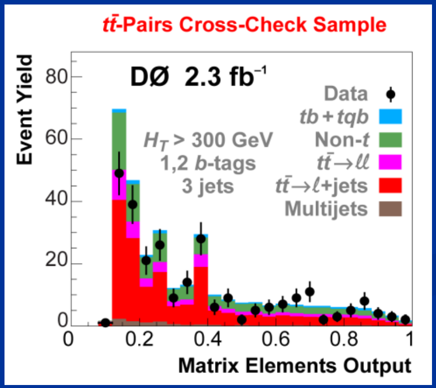


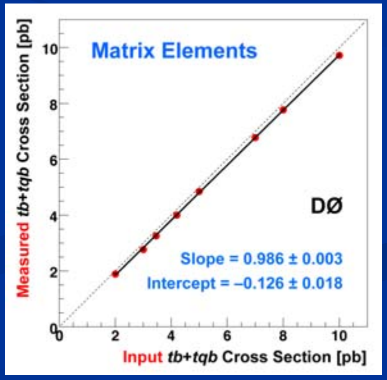




BNN

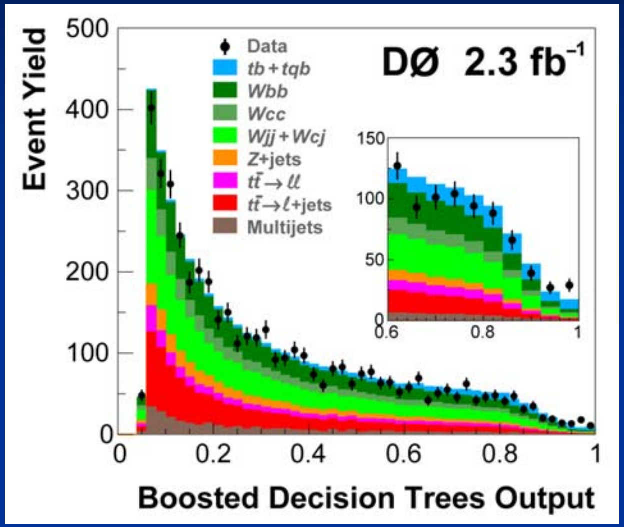


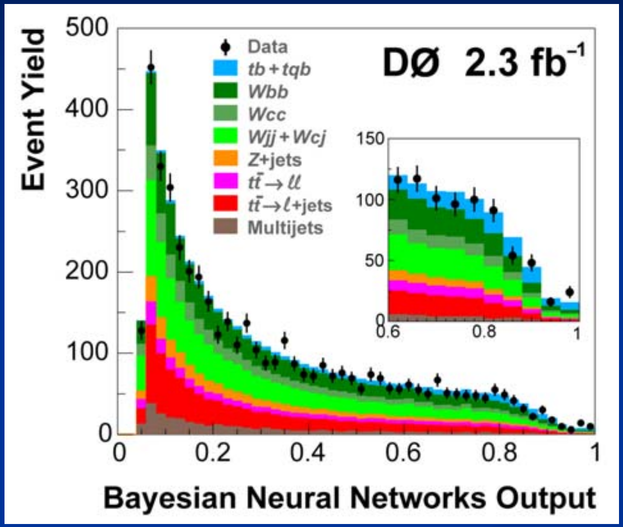


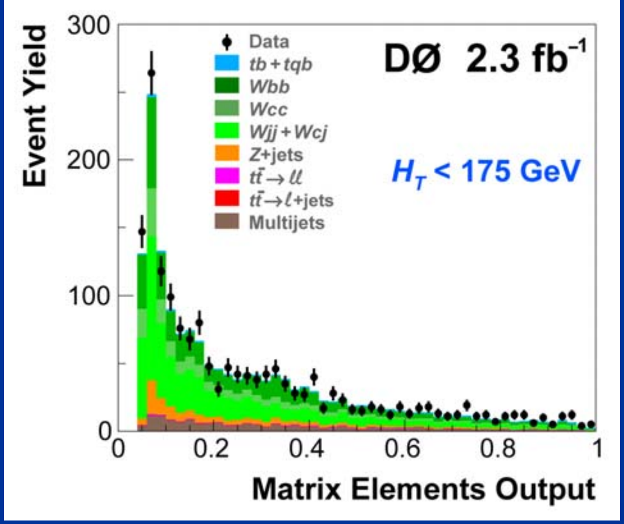


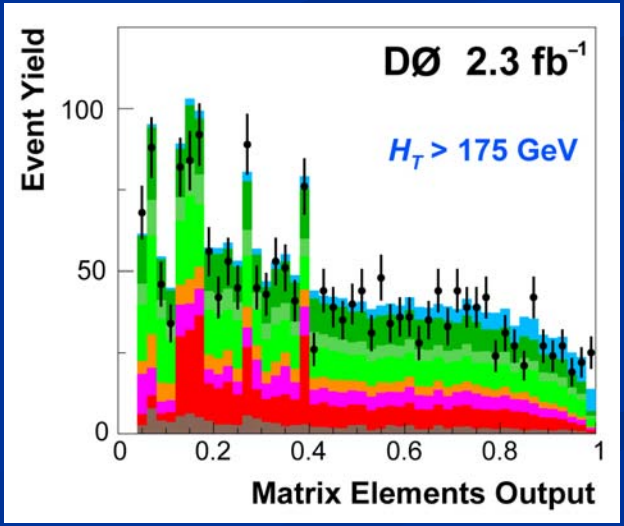
ME

Multivariate Discriminant Outputs





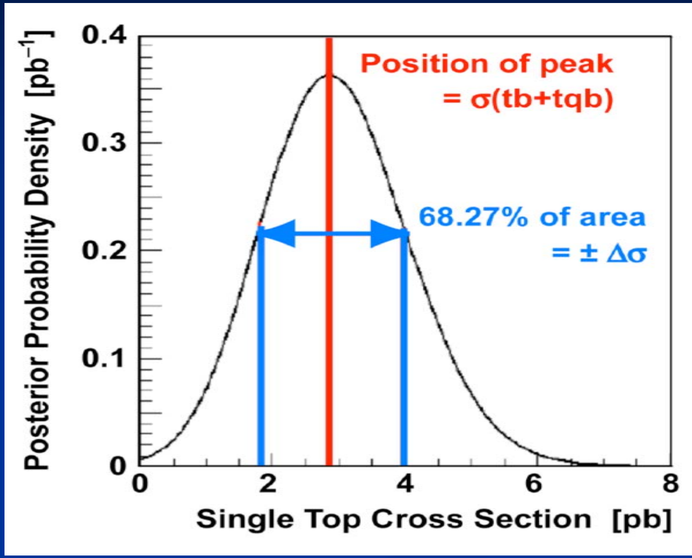


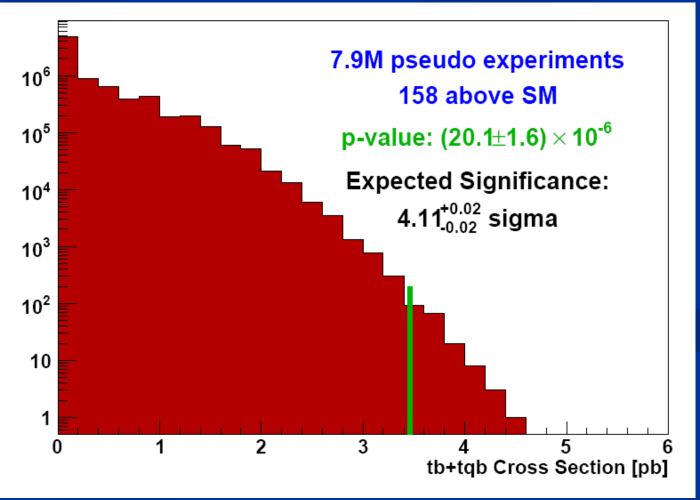


Signal normalized to measured x-sec

Cross Section & Significance

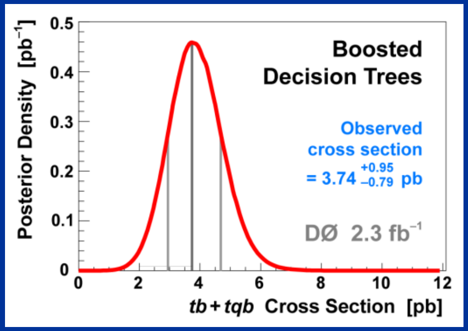
- Cross sections are measured by building a Bayesian posterior probability density
- For each analysis, the single top cross section is given by the position of the posterior density peak, with 68% asymmetric interval as uncertainty
- Gaussian prior for systematic uncertainties
  - Correlations of uncertainties properly taken into account
  - Flat prior in signal cross sections
- Significance derived from background-only pseudo-datasets
  - Expected/Observed: SM/Measured x-sec

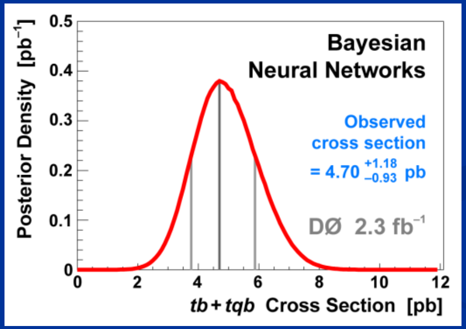


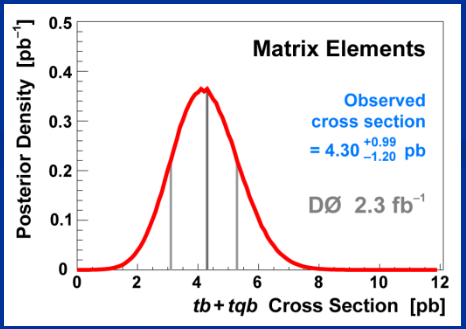


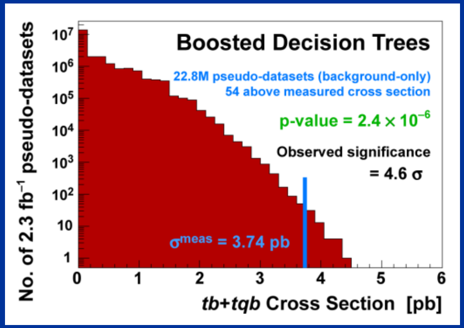
Cross Section Results

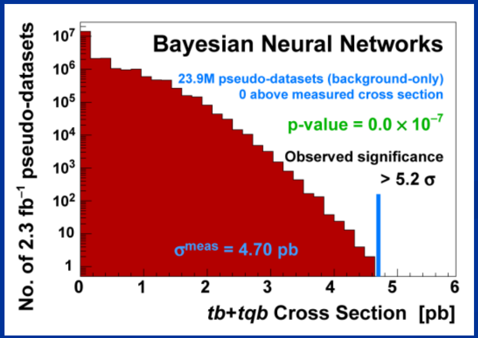
MVA	σ±Δσ(pb)	Expected Significance	Observed Significance
BDT	3.74+0.95–0.79	4.3 SD	4.6 SD
BNN	4.70+1.18–0.93	4.1 SD	5.2 SD
ME	4.30+0.99–1.20	4.1 SD	4.9 SD

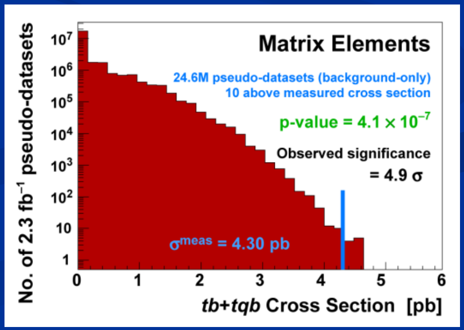








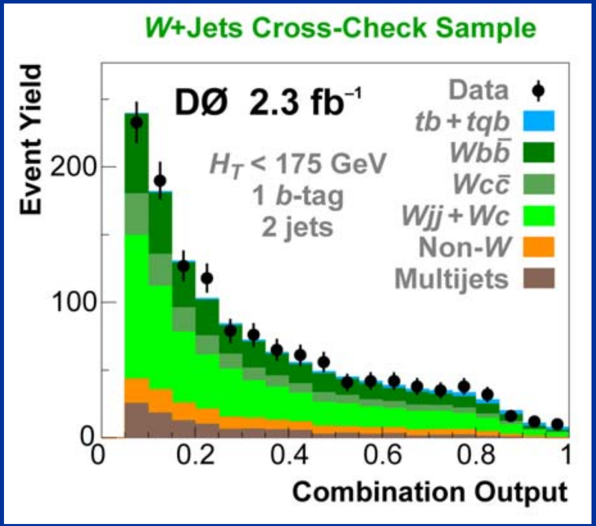


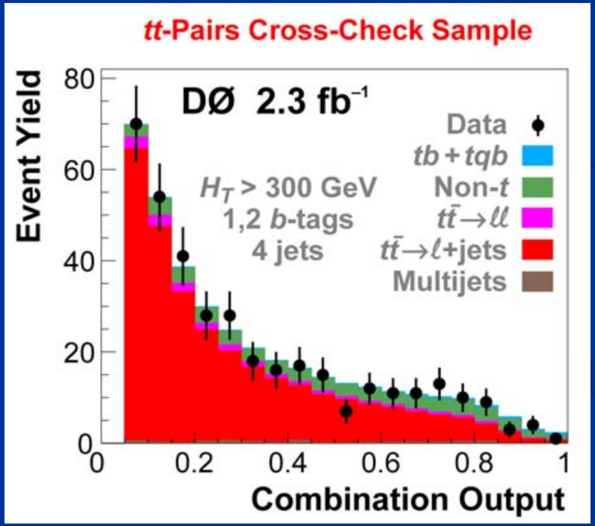


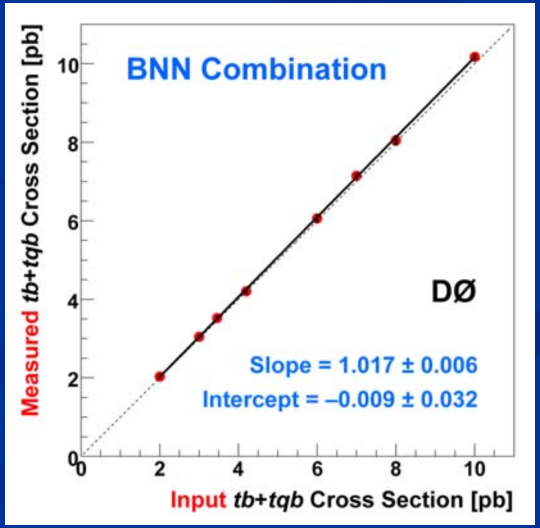
Combination of Results

- Even though all MVA analyses use the same data, they are not 100% correlated
  - BNN&BDT are 75% correlated with each other, 60% with ME
- 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: **4.5 σ**

CROSS CHECK SAMPLES AND LINEARITY

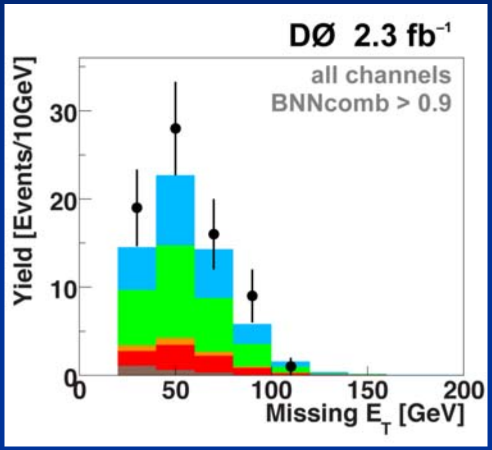




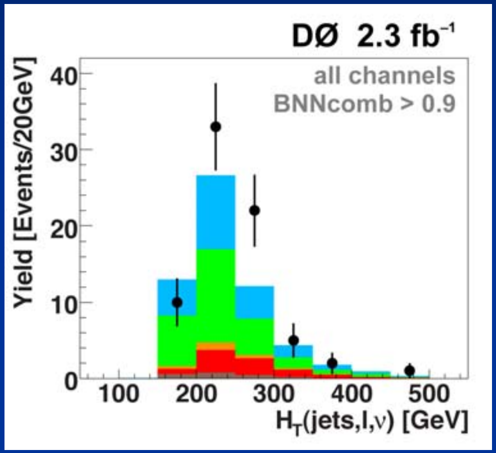


Discriminating Variables

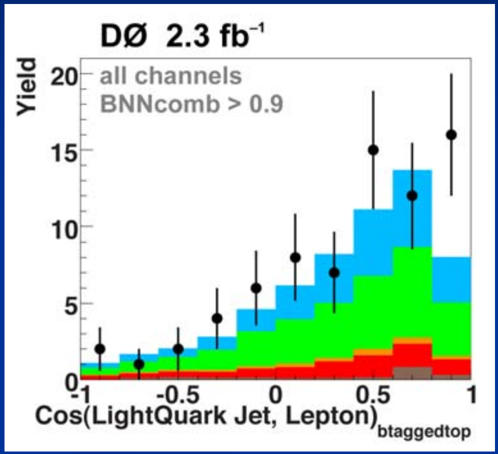
OBJECT KINEMATICS



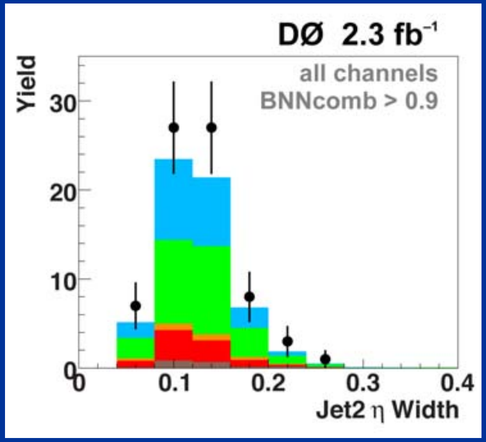
EVENT KINEMATICS



ANGULAR CORRELATIONS

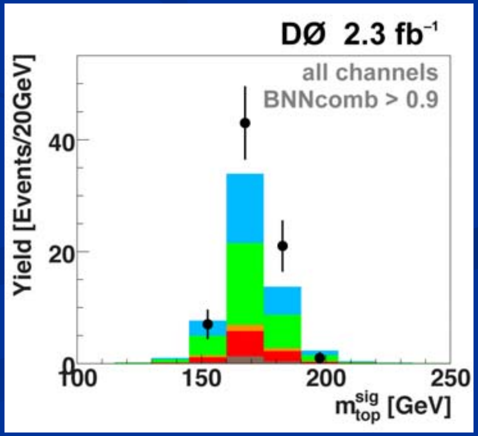


JET RECONSTRUCTION



Examples of discriminating variables in the high S:B region

TOP QUARK RECONSTRUCTION

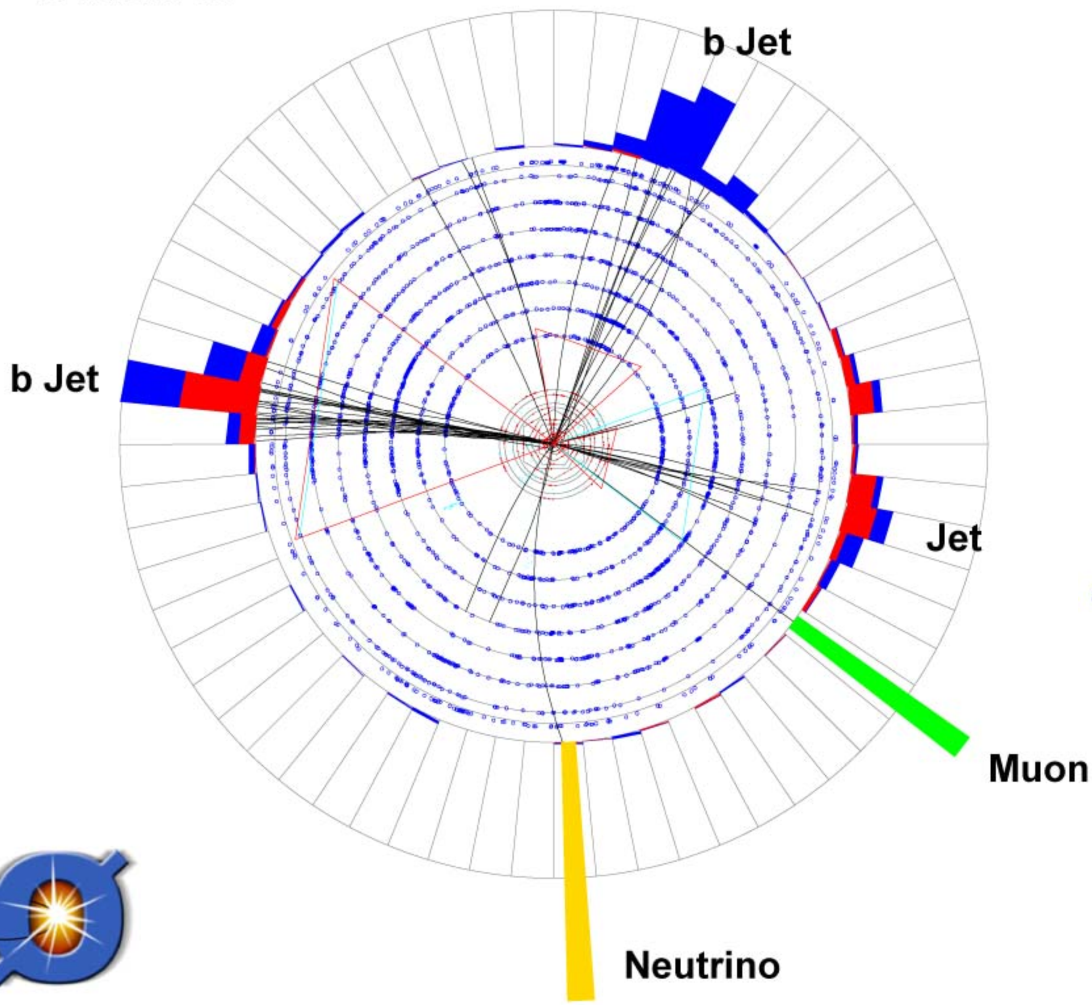


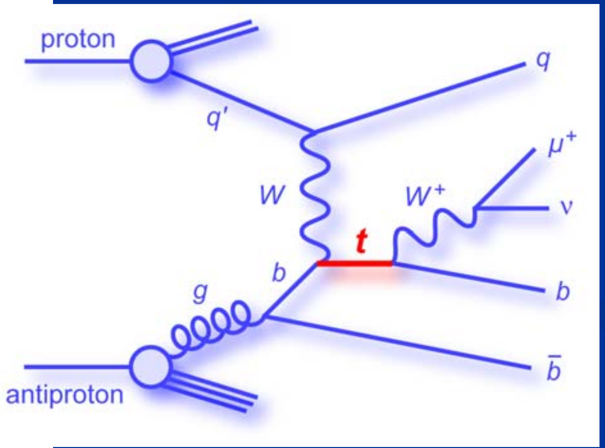
DØ Experiment Event Display

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

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

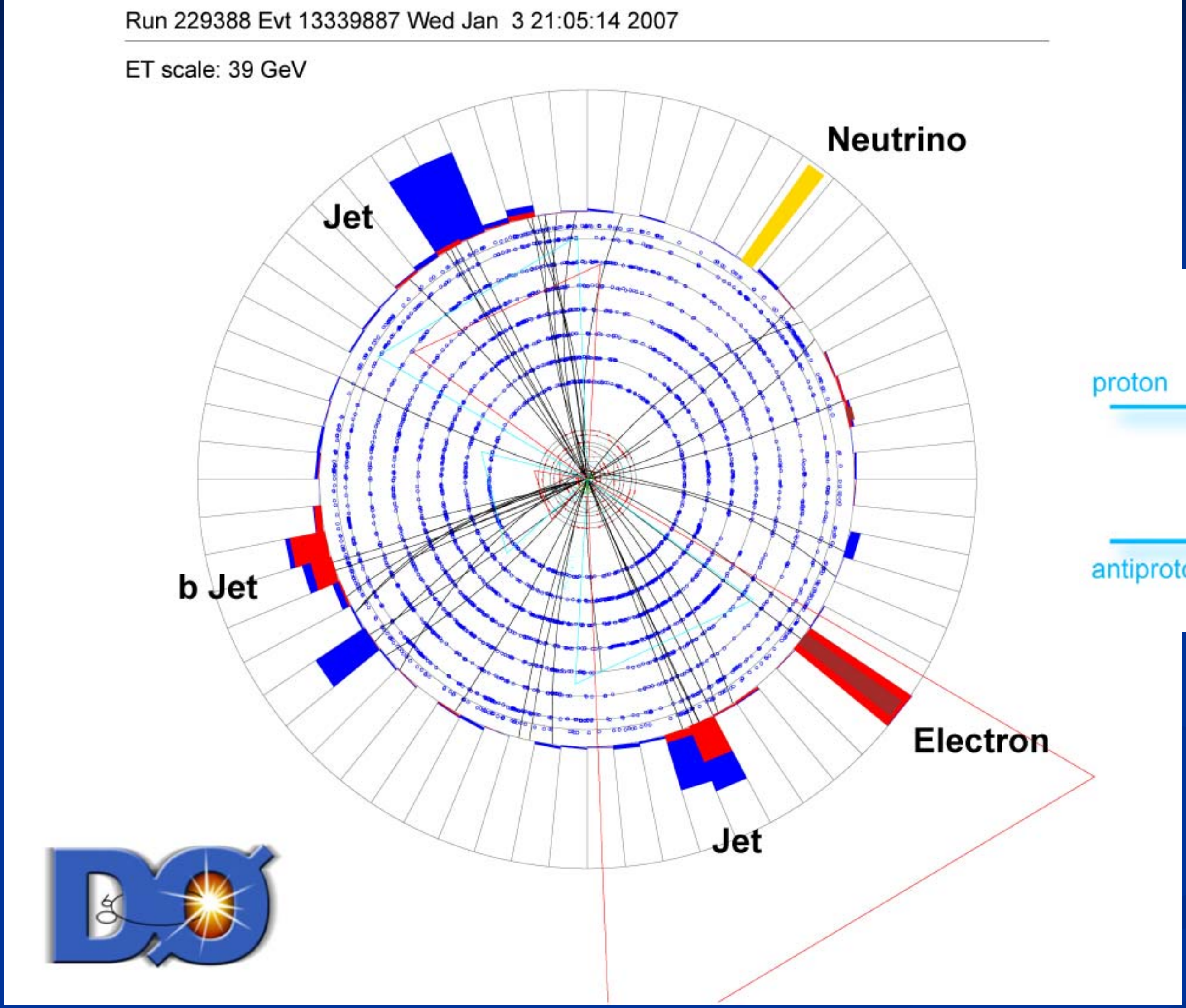
ET scale: 28 GeV

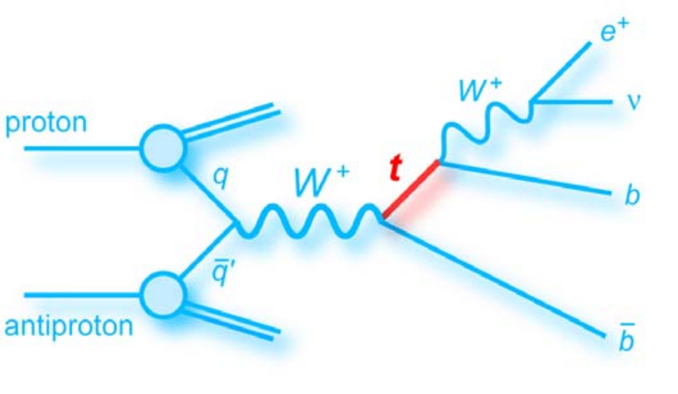




DØ Experiment Event Display

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

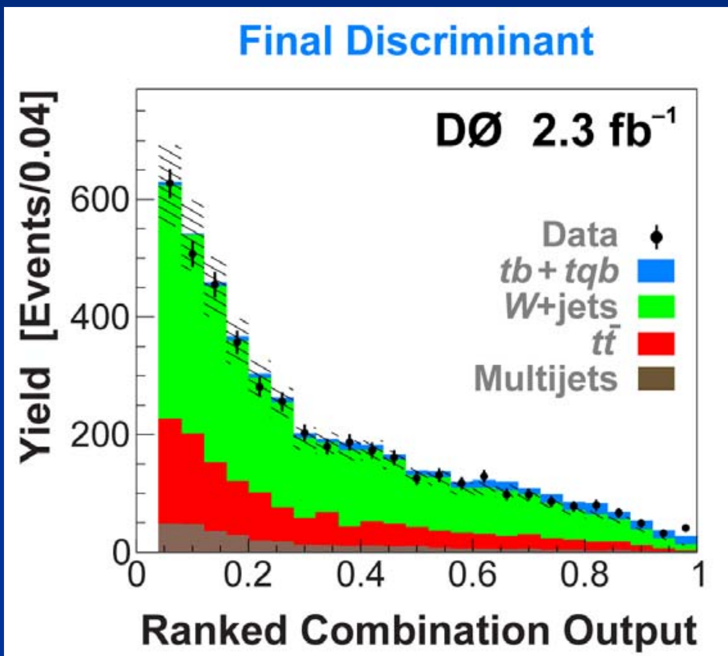


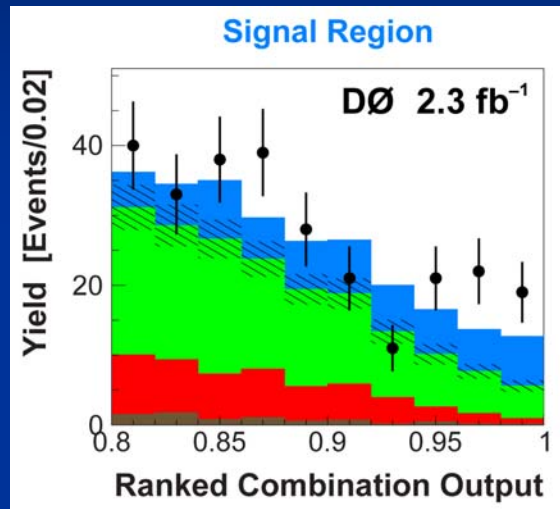


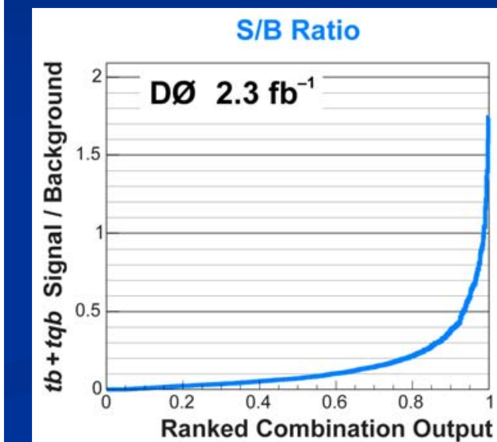
Combined Results

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

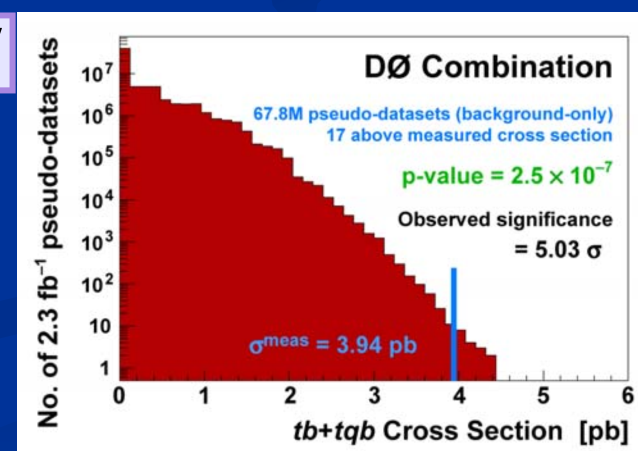
$(m_t = 170\text{GeV})$

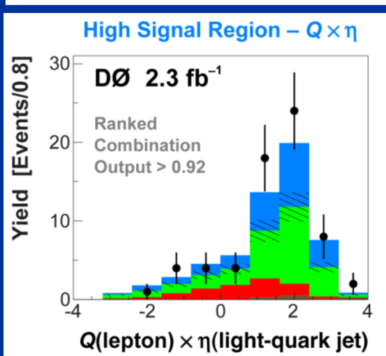


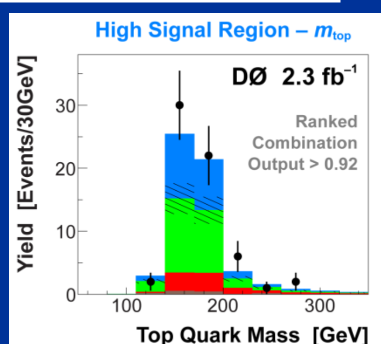




$$p - value = 2.5 \times 10^{-7}$$

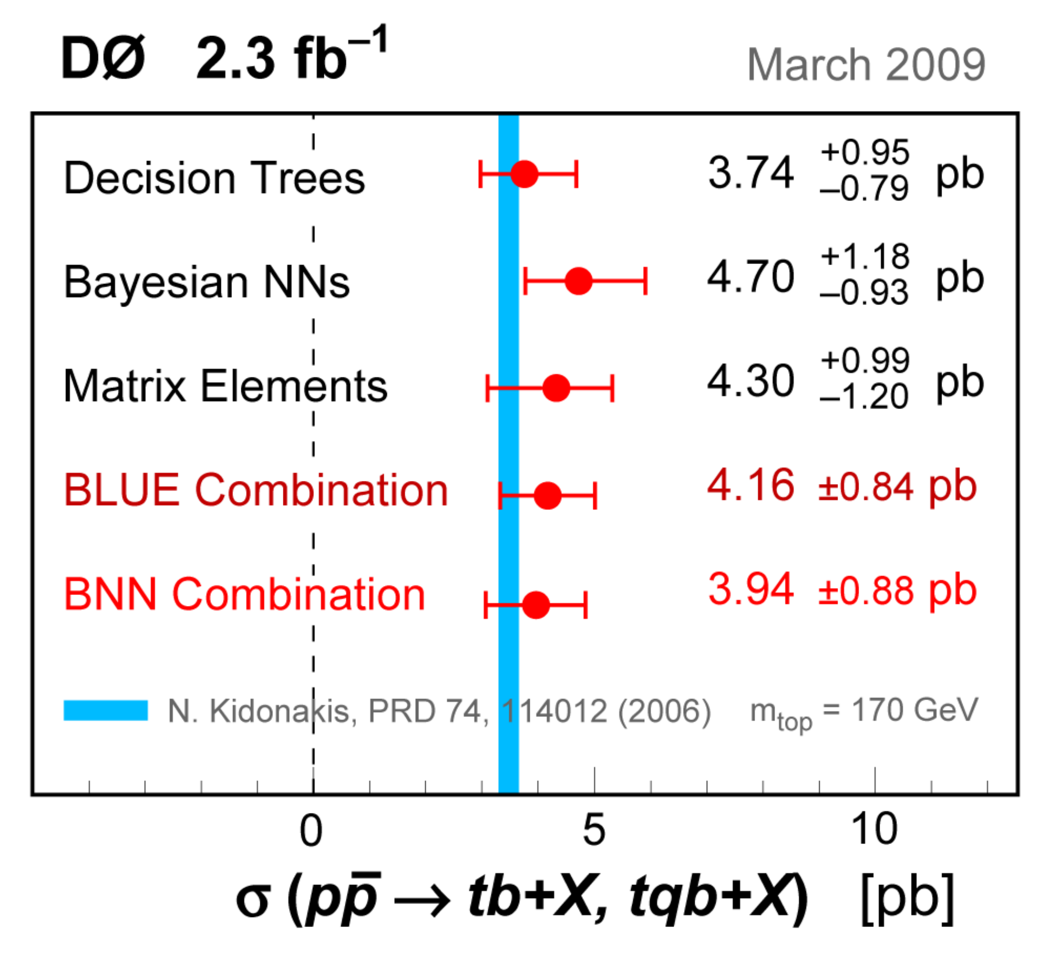






Measured Significance = 5.03 SD

Cross Section Summary

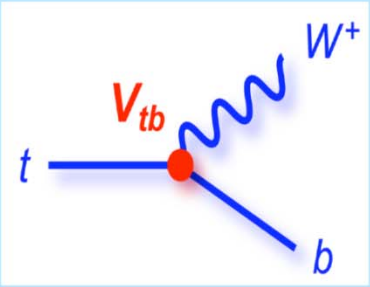


MVA	Expected Signif.	Obs. Signif.
BDT	4.3 SD	4.6 SD
BNN	4.1 SD	5.2 SD
ME	4.1 SD	4.9 SD
BNN Comb	4.5 SD	5.0 SD

CKM Matrix Element Vtb

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

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



- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- 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
  - $|Vtd|^2 + |Vts|^2 << |Vtb|^2$ (supported by CDF & DØ "ratio" measurements)
- Does not assume 3 generations or unitarity of the CKM matrix

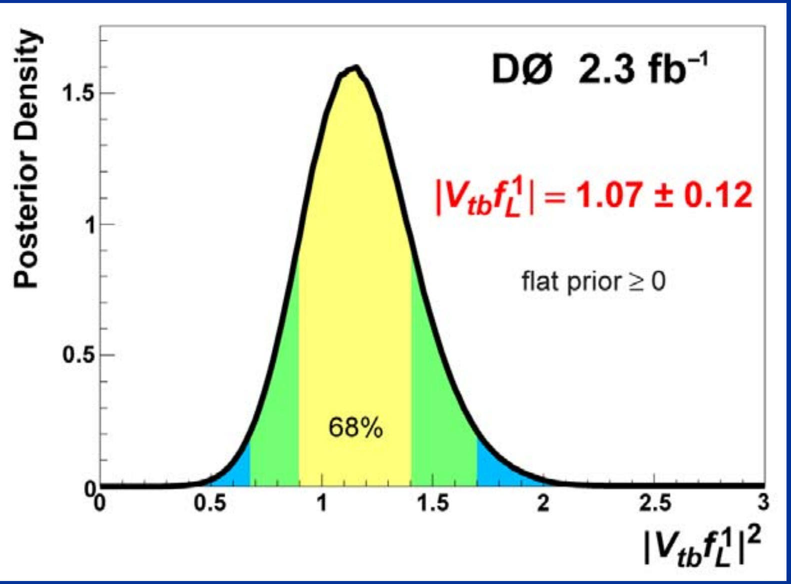
Measurement of $|V_{tb}|$

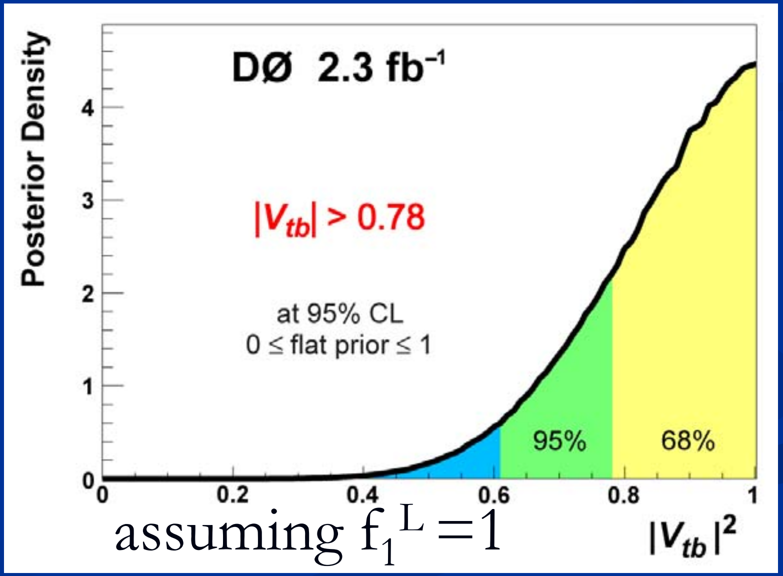
- Use the measurement of the single top cross section to make a direct measurement of $|V_{tb}|$: $\sigma(tb,tqb) \sim |V_{tb}|^2$
  - Calculate a posterior in $|V_{tb}|^2$
  - Measure the strength of the V–A coupling.

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%

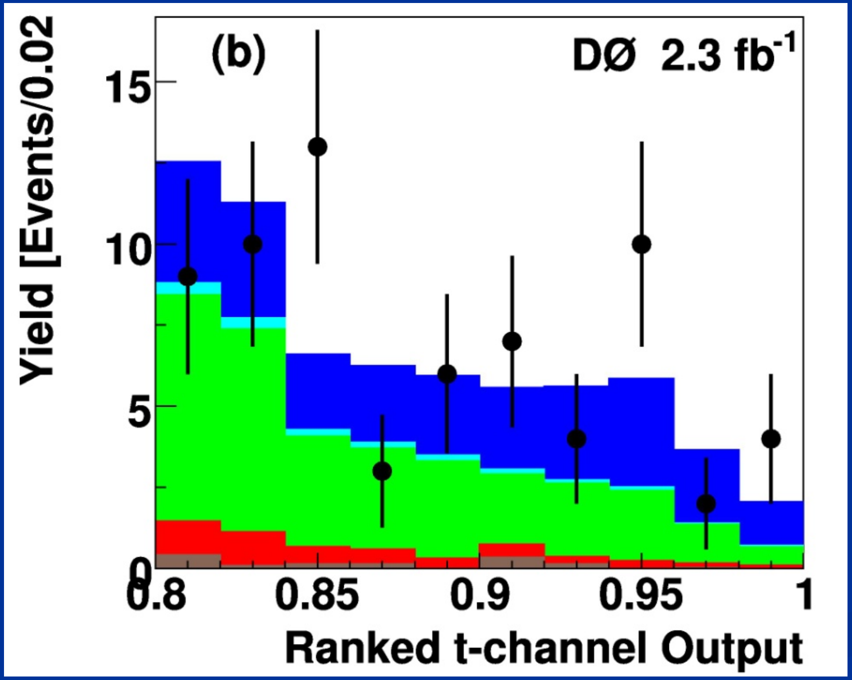


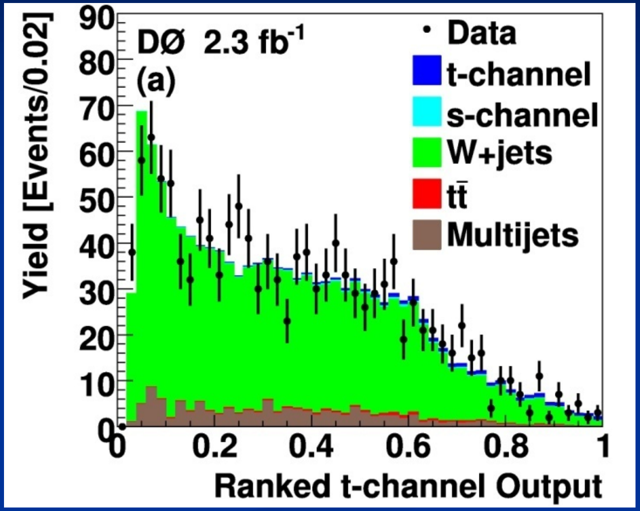


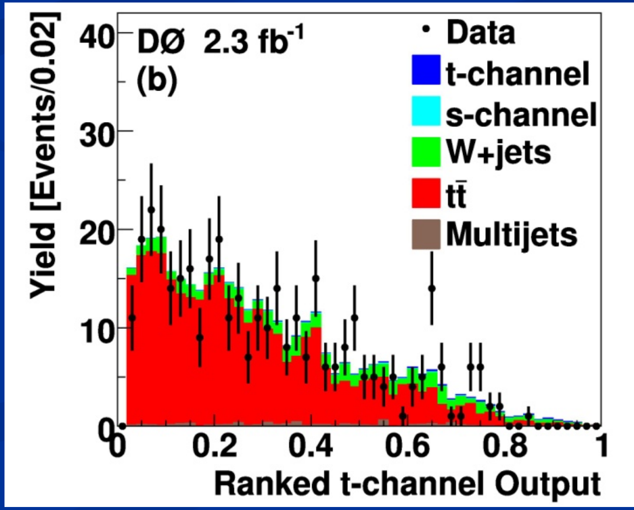
New!

First evidence for t-channel production

- Using the same dataset and event selection, train MVA filters with t-channel as signal, s-channel as bkgd.
- Measure t- and s-channel simultaneously, removing the SM constraint on s:t rate

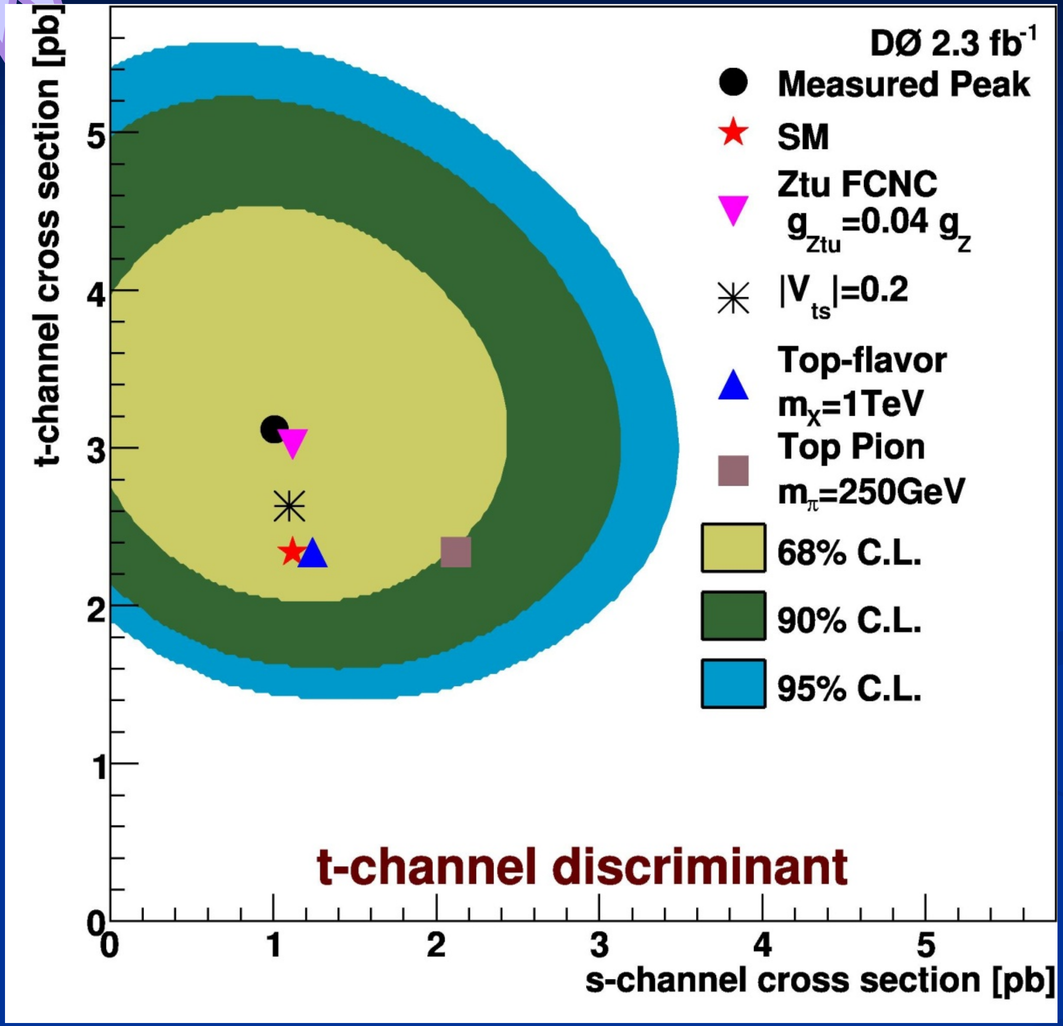






New!

First evidence for t-channel production



$\sigma(t) = 3.14{+0.94}{-0.81}$ pb

$\sigma(s) = 1.05 \pm 0.81$ pb

Expected/ Measured Significance for t-channel production = 3.7/4.8 SD

http://arxiv.org/abs/0907.4259 submitted to PLB

Conclusions

- The DØ collaboration observes single top quark production in 2.3 fb^{-1} of Run II data

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

Measured Significance 5.03 SD

$|V_{tb}\, f_1^L| = 1.07 \pm 0.12$
flat prior ≥ 0

$0.78 < |V_{tb}| < 1$ @ 95% CL
$0 \leq$ flat prior ≤ 1

http://arxiv.org/abs/0903.0850 accepted by PRL

New!

$$\sigma(p\bar{p} \rightarrow tqb + X) = 3.14 \pm^{0.94}_{0.81} \text{ pb}$$

Measured Significance 4.8 SD

http://arxiv.org/abs/0907.4259 submitted to PLB