First Observation of Single Top Quark Production at DØ

Monica Pangilinan
Brown University
on behalf of
DØ

Pheno Symposium 2009

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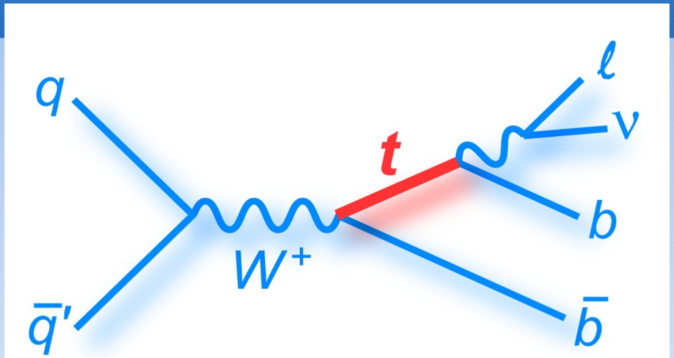
Motivation

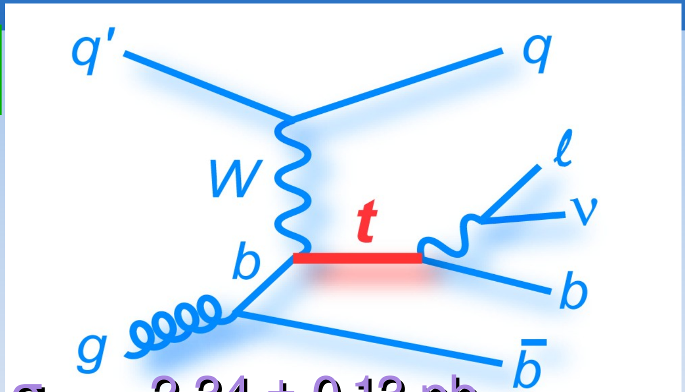
s channel

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



σ_{SM} = 1.12 ± 0.05 pb

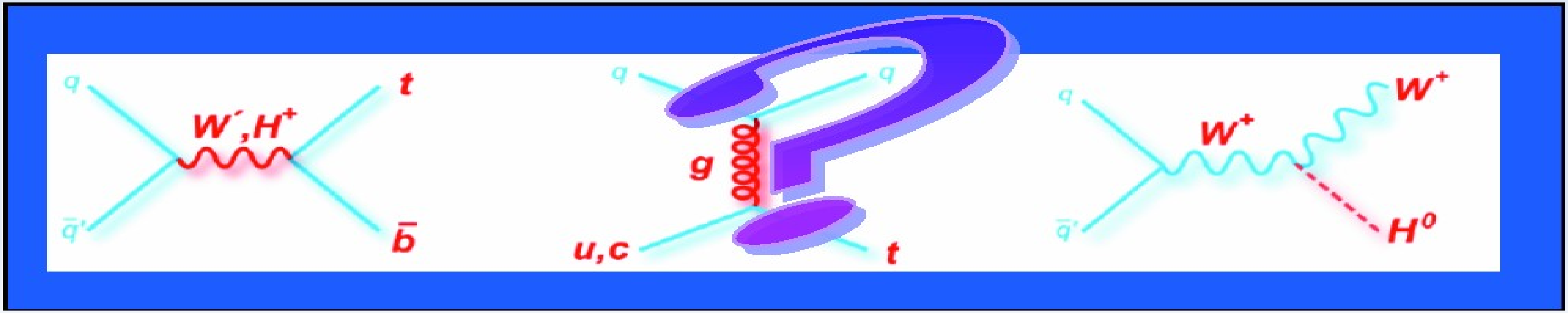
t channel



σ_{SM} = 2.34 ± 0.13 pb

- Investigate Wtb coupling
  - Direct measurement of $|V_{tb}|$
  - Checks unitarity of CKM matrix
  - Anomalous Wtb couplings
- Study top quark properties
  - Polarization, lifetime, decay width

- Window to new physics
  - s channel: charged Higgs, heavy W'
  - s+t channel: flavor changing neutral currents
  - 4^{th} quark generation?



Tevatron and DØ Detector

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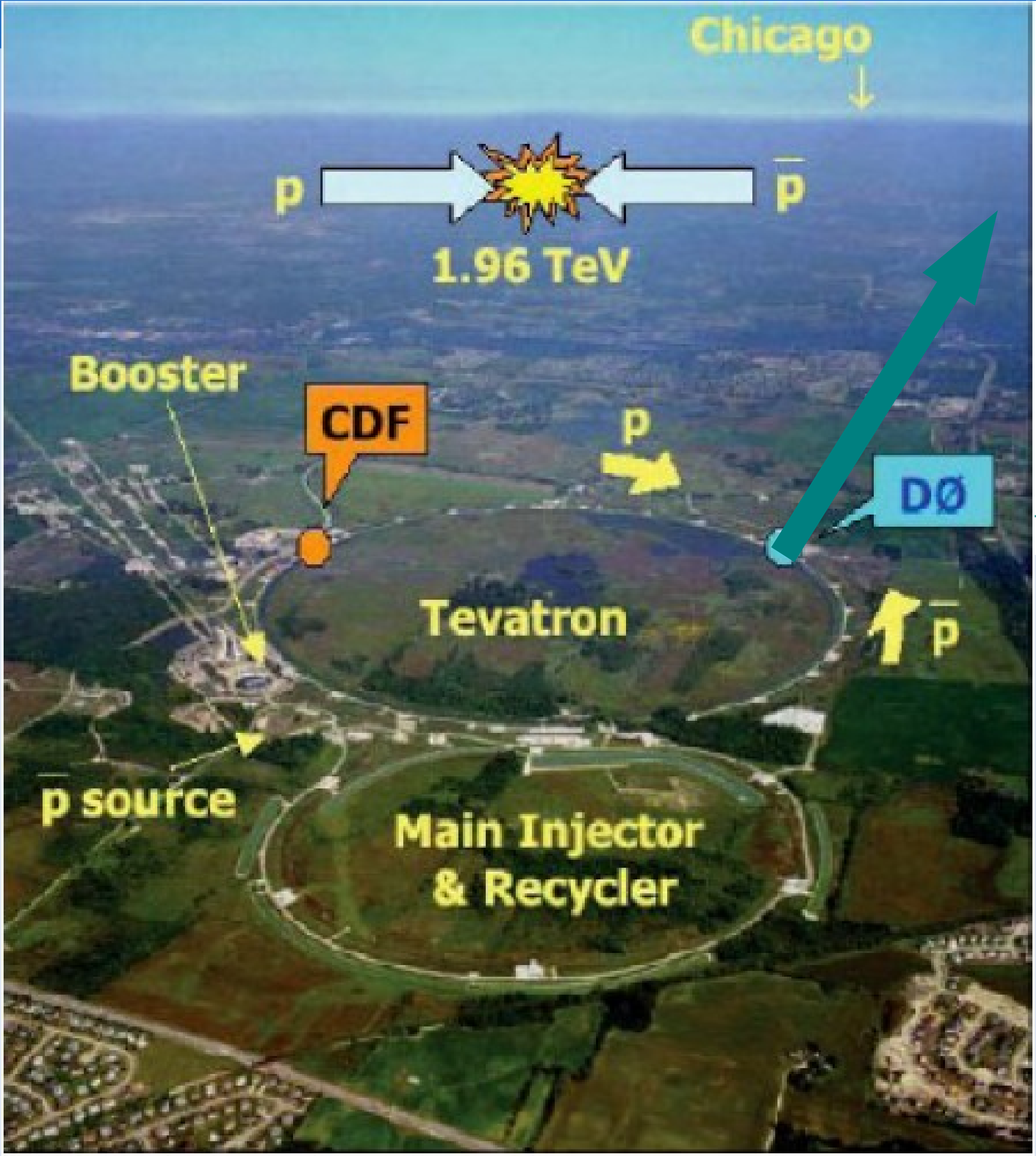

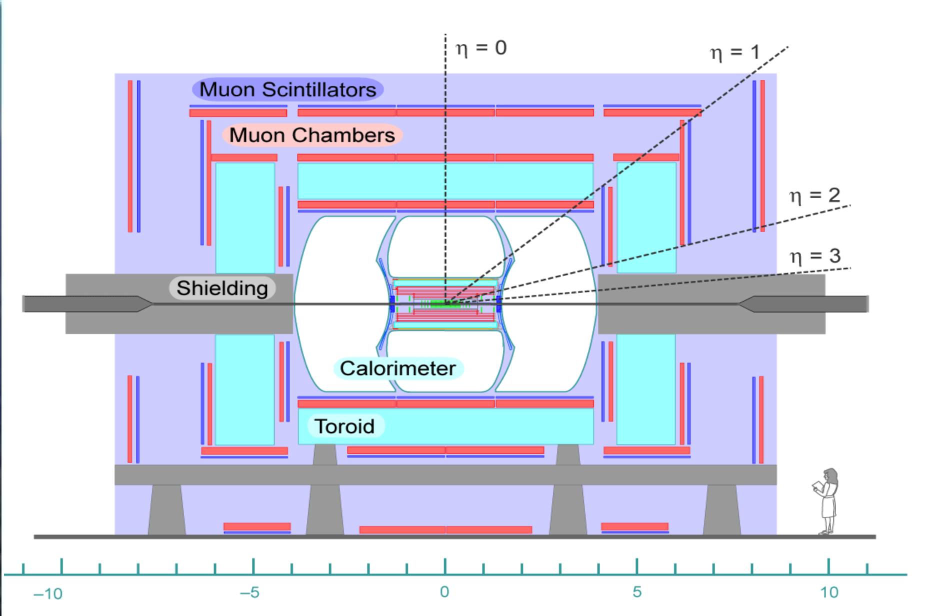

- This analysis uses 2.3 fb^{-1} data
- 5.81 fb^{-1} data on tape thanks to the Tevatron accelerator division
- DØ detector
  - a silicon and fiber tracker in 2T superconducting solenoid
  - Liquid Argon/Uranium calorimeter
  - Muon system in 1.8T toroidal magnetic field

Event Selection

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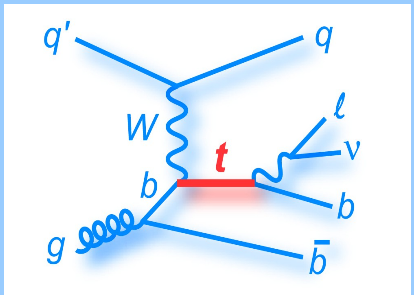
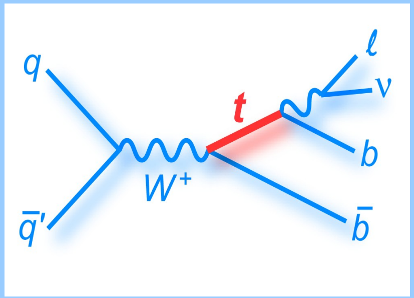
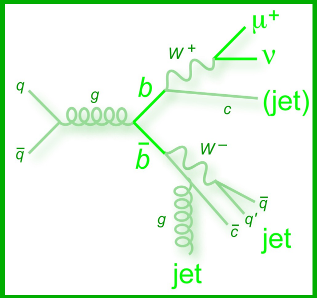
- 1 isolated electron or muon
- Missing transverse energy
- At least one b-tagged jet and at least one more jet
- Sample divided by (RunIIa or IIb), (e or μ), (1 or 2 b-tags), (2,3,4 jets)



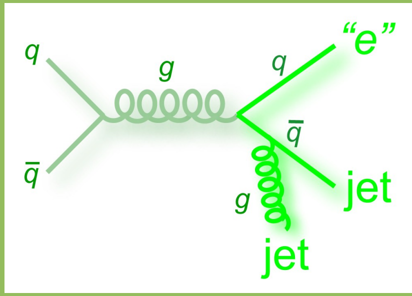


•Single top:
- CompHEP – SingleTop

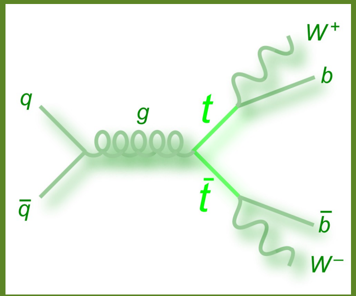


W+jets:
- Shapes from ALPGEN
- Normalization and heavy flavor fractions from data

Multijets:



from data where events have a misidentified lepton



t-tbar:
- Shapes from ALPGEN
- Normalized to σ_{NNLO} = 7.91 pb

Dibosons (Pythia) and Z+jets (ALPGEN) but minor backgrounds

Improvements to Event Selection

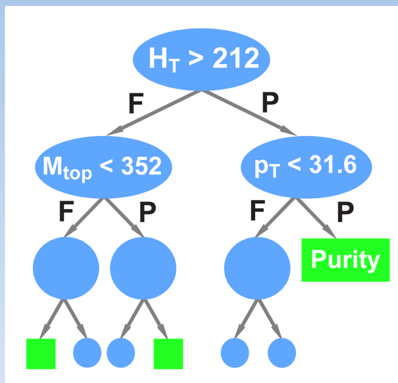
- Signal acceptance increased by 18% compared to 2006 evidence analysis (Phys. Rev. Lett. 98, 181802 (2007), Phys. Rev. D 78, 012005 (2008))
  - Logical OR of many trigger conditions
  - Looser jet eta and p_T cuts
  - Loosened the b-jet identification criteria for the 2 tag case

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

Electron + muon, 1 tag + 2 tags combined

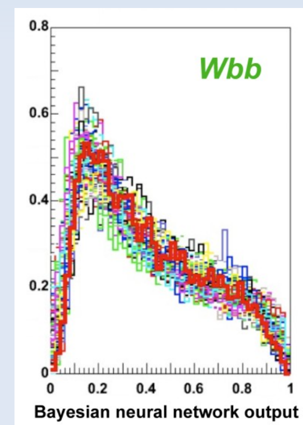
Source	2 jets	3 jets	4 jets
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \rightarrow \ell\ell$	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

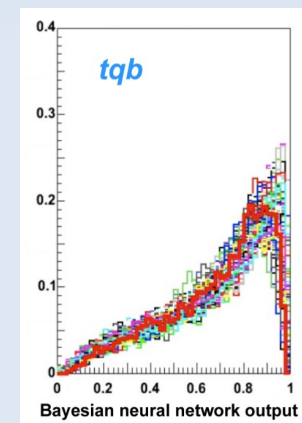
Multivariate Techniques

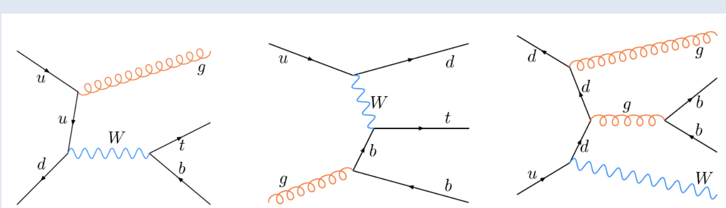


- Boosted Decision Trees (BDT):
  - applies sequential cuts to events but keeps events that fail cuts
  - Cuts continue until not enough events or no more improvement
  - Boosting adds extra weight to misclassified events
  - 64 input variables used

- Bayesian Neural Networks (BNN):
  - A Neural Network is group of interconnected nodes that model complex relationships between inputs and outputs
  - Is an average over many neural networks -> avoids overtraining
  - 18 -28 variables used

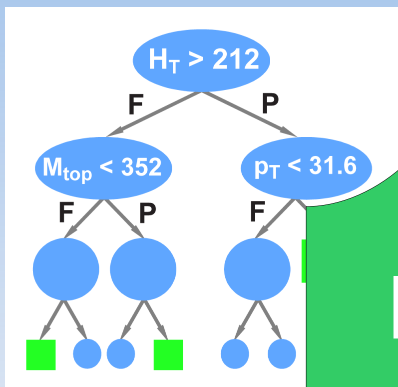






- Matrix Element Analysis
  - Uses parton level information matrix elements to calculate a event probability density for signal and background
  - Uses all event information (4 momenta)

Multivariate Techniques



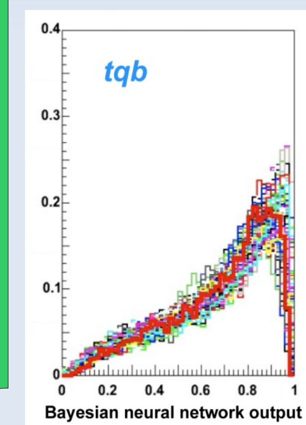
- Boosted Decision Tree (BDT):
  - ents that fail cuts
  - e improvement

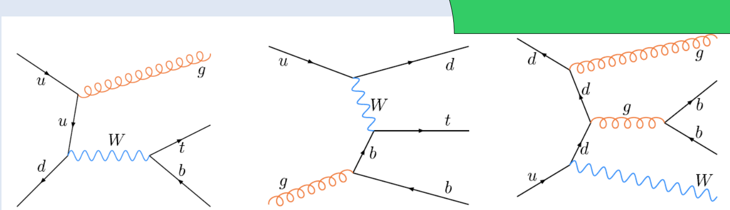
- Bayesian Neur
  - A Neural Ne
    model comp
  - Is an averag
    overtraining
  - 18 -24 variable

Improvements to 2006 Analysis

- BDT/BNN: Added Jet Reconstruction and Top Reconstruction Variables
- ME: Added more ME, $H_T = \Sigma_{lepton,\not{E}_T,jets}|E_T|$ divided sample

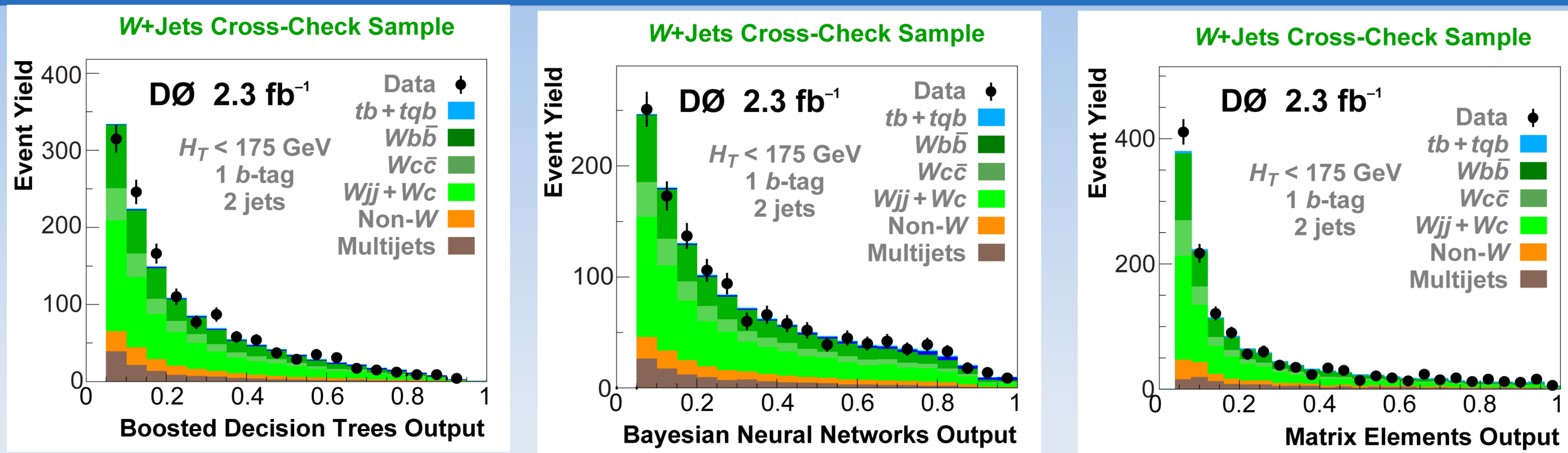
utput



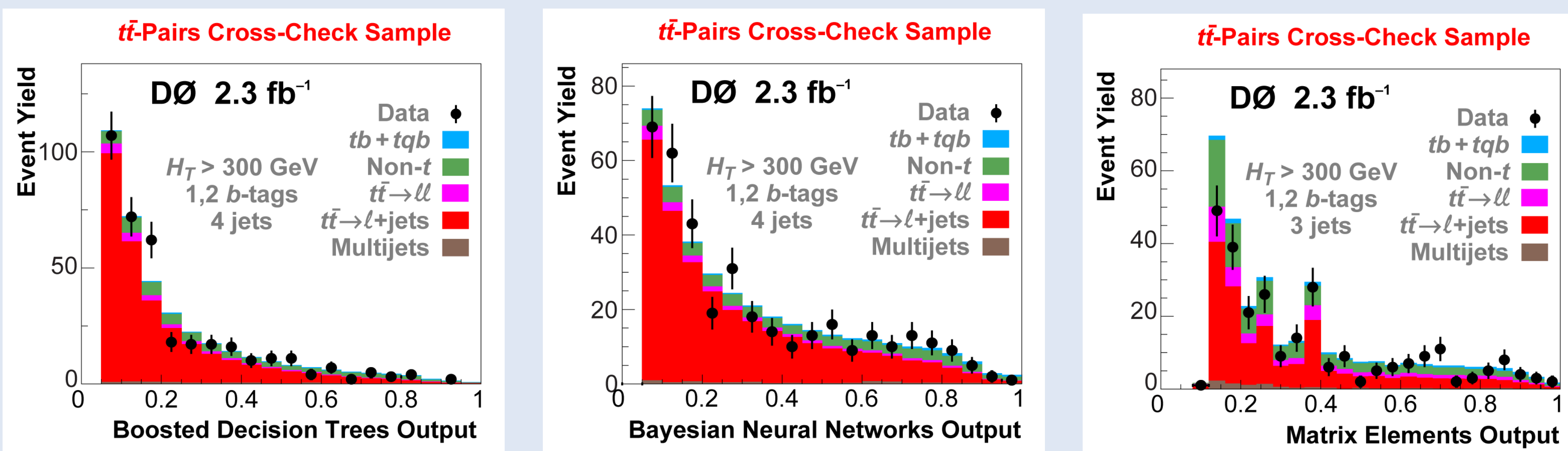


- Uses parton level information matrix elements to calculate a event probability density for signal and background
- Uses all event information (4 momenta)

Cross Check Samples



W+jets enriched sample: H_T < 175 GeV, 1 b-tag with 2 jets



t-tbar enriched sample: H_T > 300 GeV, 1+2-btags 4 jets for BDT/BNN and 3 jets for ME

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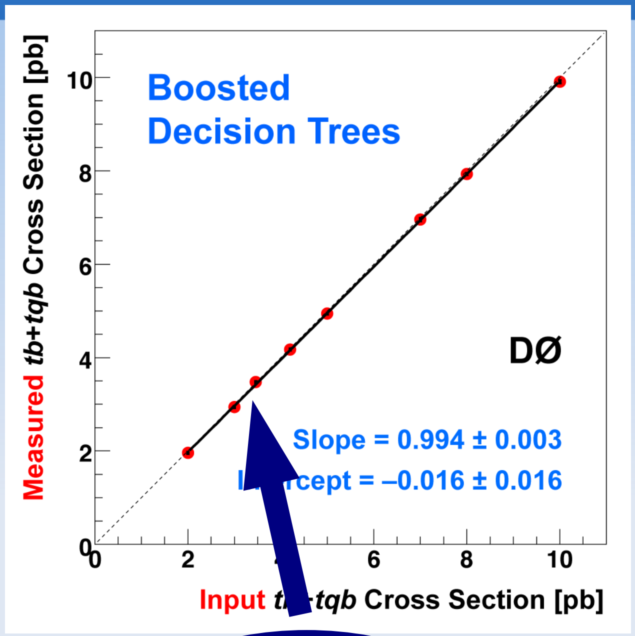
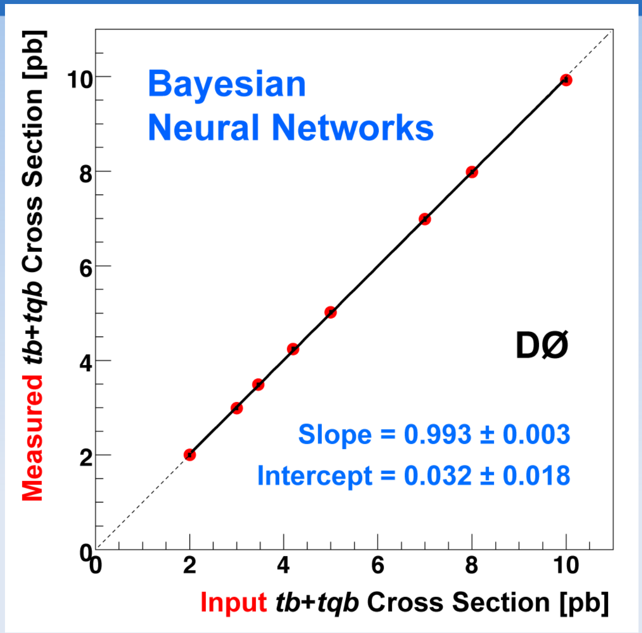
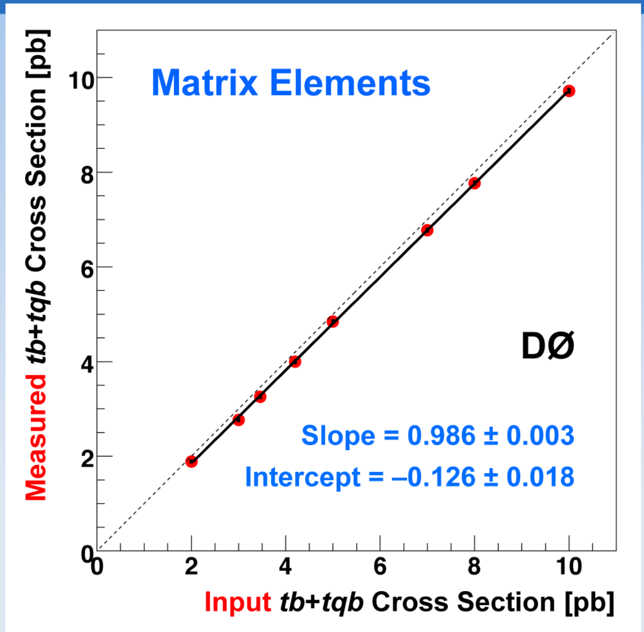
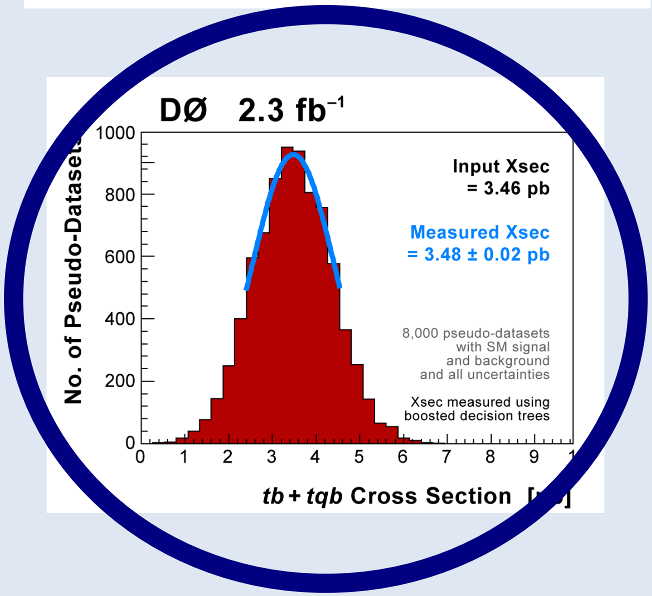
Linearity Performance Check



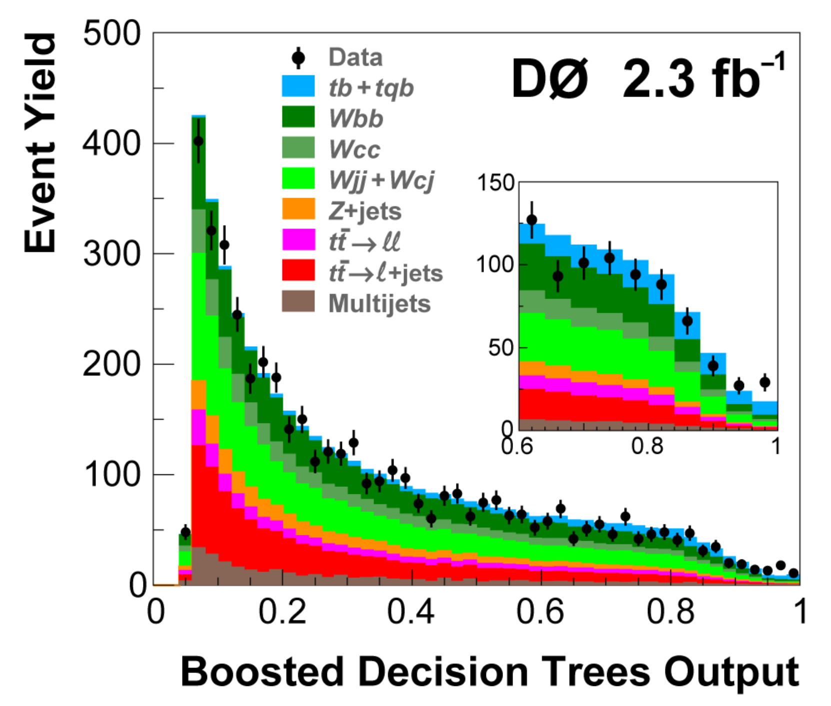


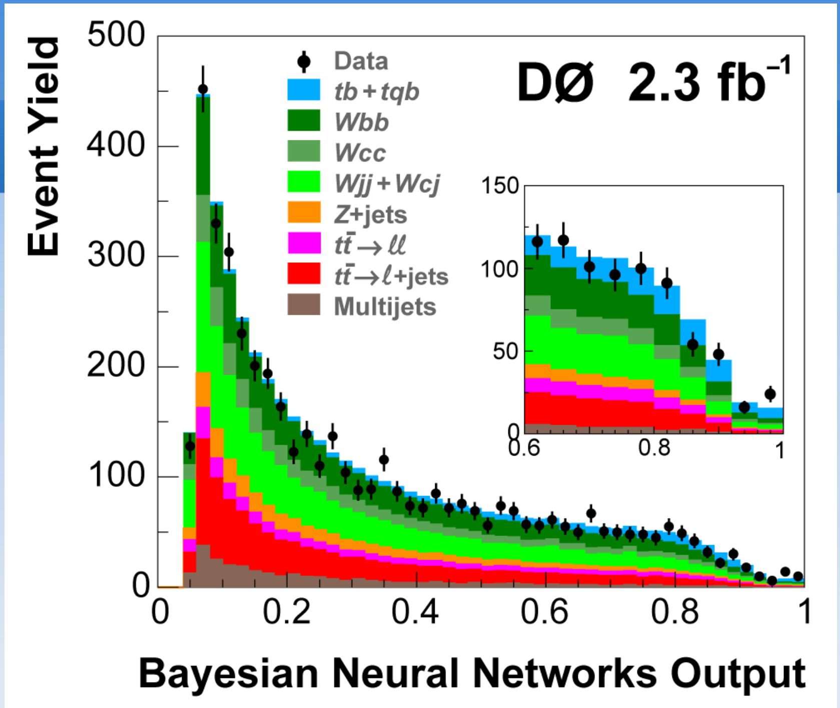


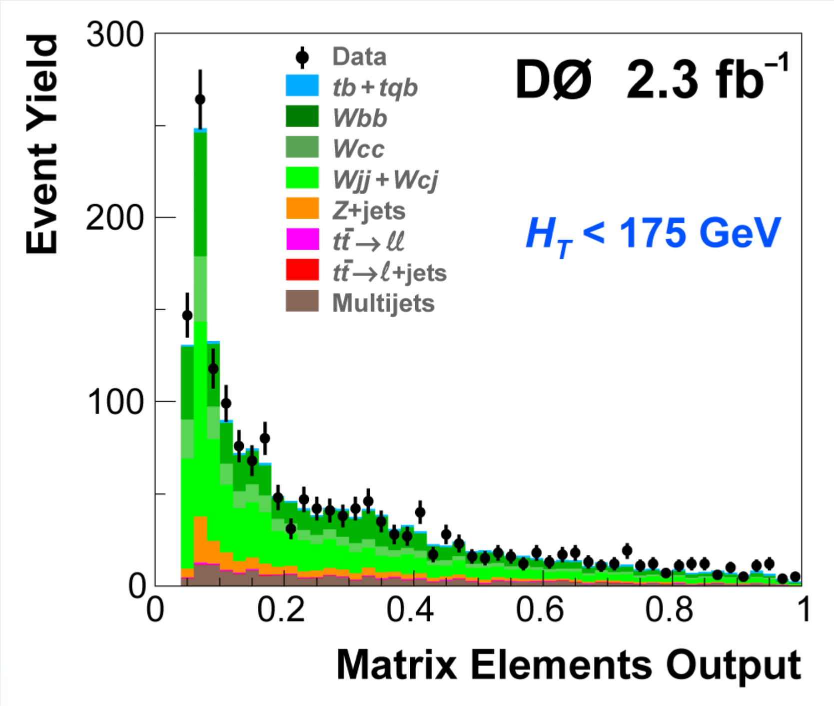


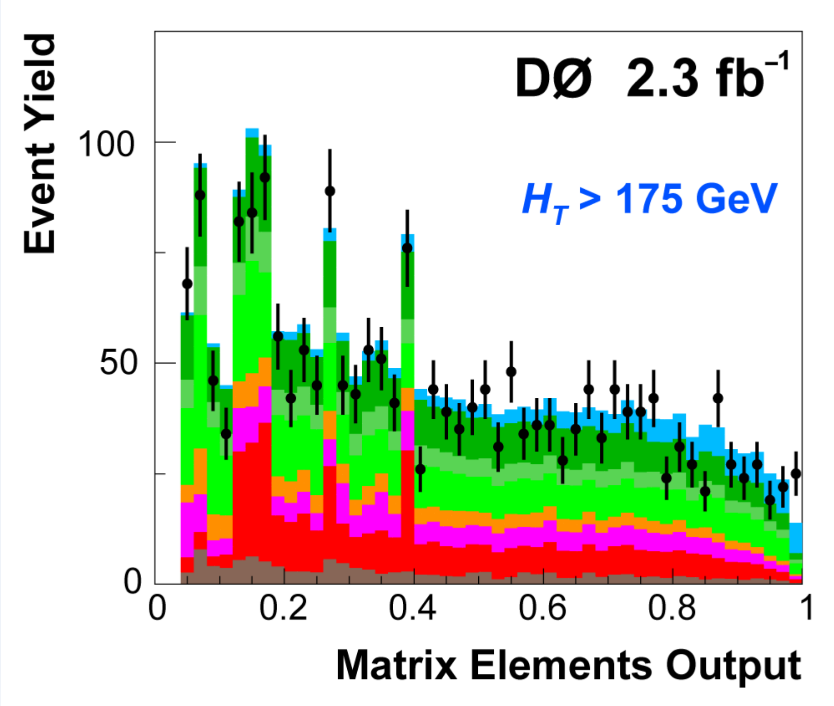
- Many DØ experiments generated with different input single top cross section
- Measure many cross sections with a specific input single top cross section using multivariate technique
- A Gaussian is fit for each input single top cross section and the mean used to generate response curve of the method

Discriminant





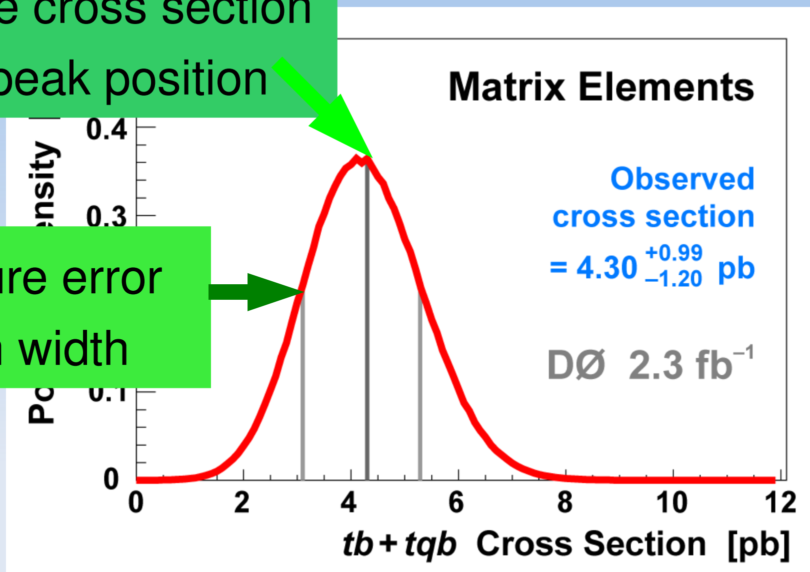


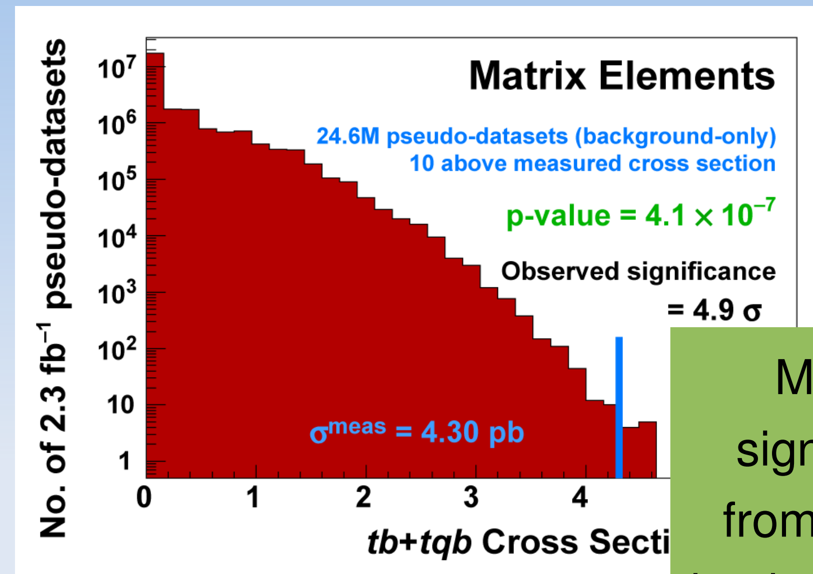


Cross Section Measurements

Measure cross section from peak position

Measure error from width



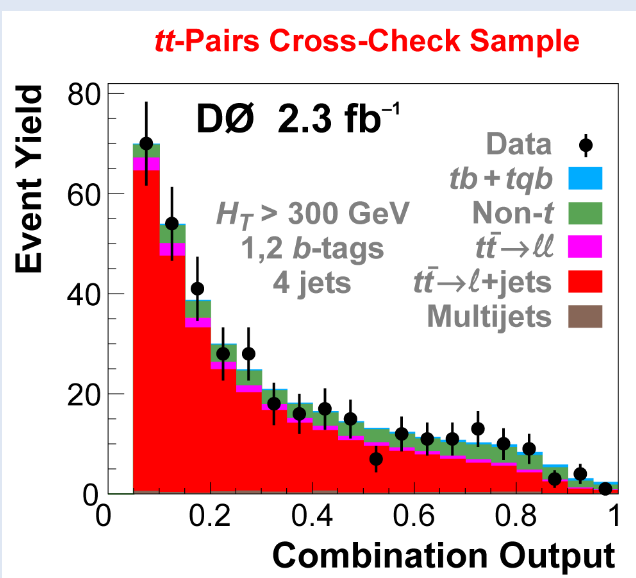


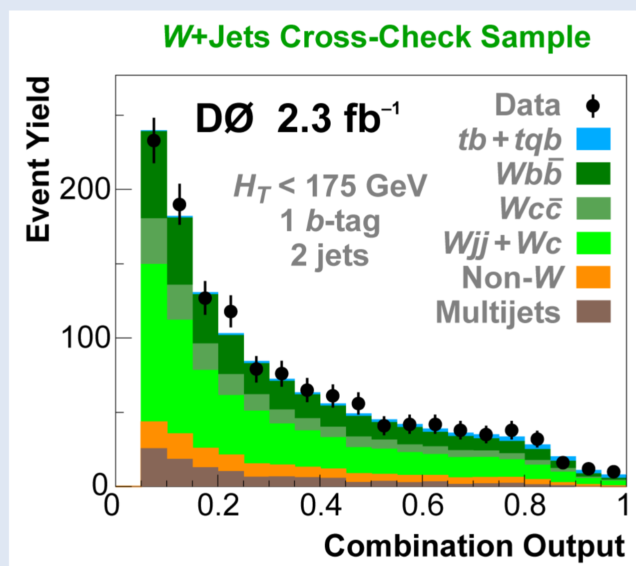
Measure significance from counting background-only cross section measurements

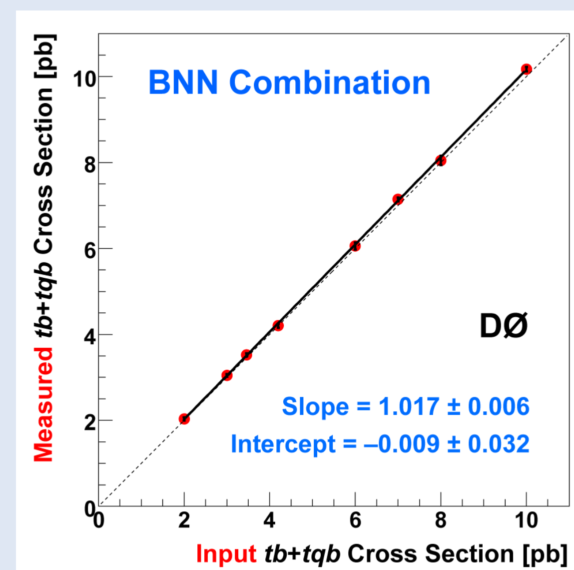
DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance Expected	Significance Measured
Boosted Decision Trees	$3.74\,^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70\,^{+1.18}_{-0.93}$ pb	4.1 σ	5.2 σ
Matrix Elements	$4.30\,^{+0.99}_{-1.20}$ pb	4.1 σ	4.9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

Combination

- Can gain sensitivity by combining the 3 multivariate techniques
  - BNN/BDT correlation: 74%
  - ME/BDT correlation: 60%
  - ME/BNN correlation: 57%
- Another BNN was trained using the 3 multivariate techniques as inputs
- Expected sensitivity: 4.5 σ vs highest multivariate sensitivity (BDT) 4.3 σ







Combination Results

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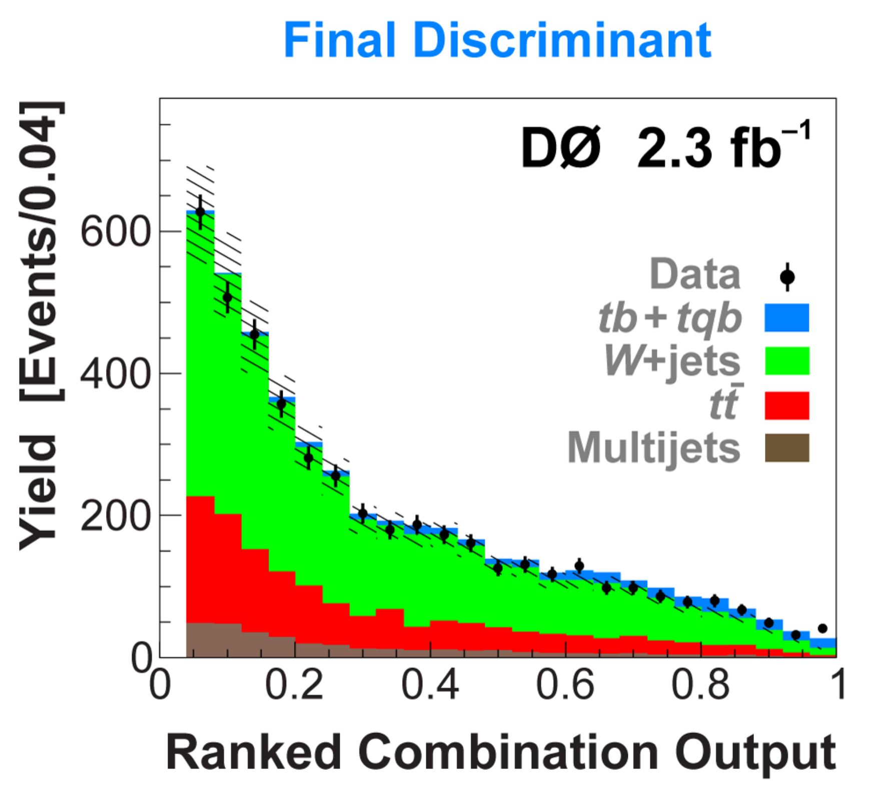

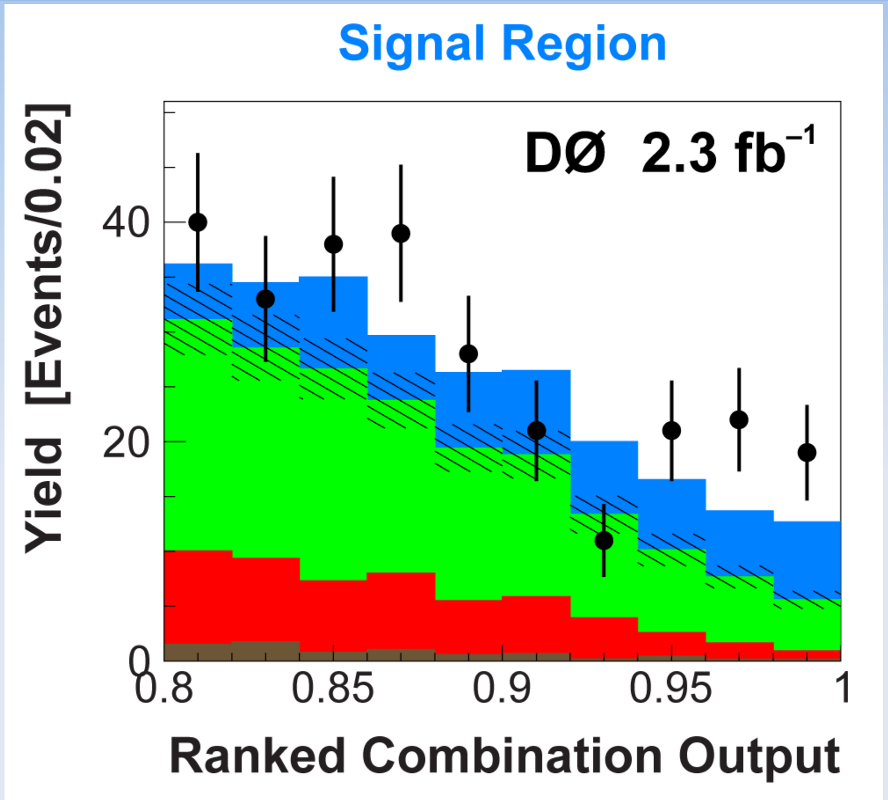

Cross Section: 3.94 ± 0.88 pb

p-value: 2.5 x 10^{-7}

Significance: 5.03 σ

Direct V_{tb} Measurement

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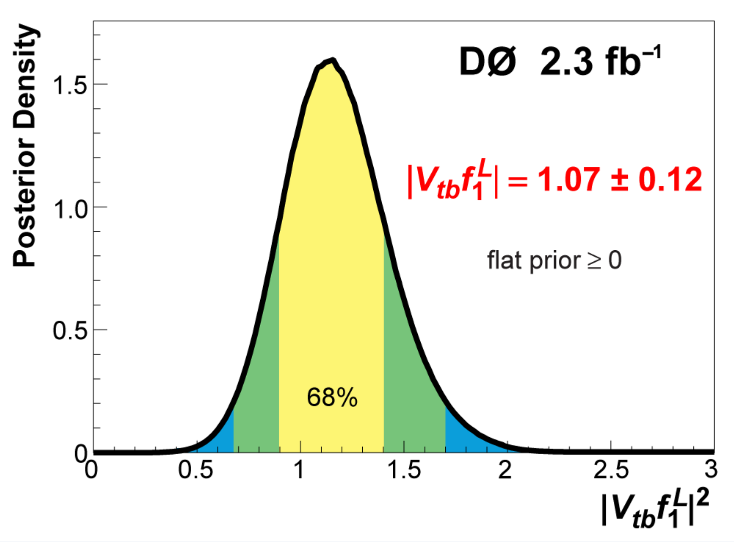
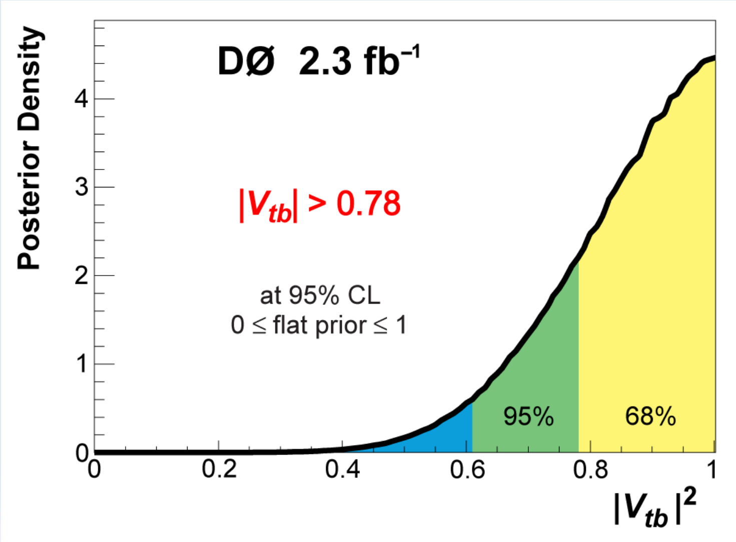
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

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

- V_{tb} can be measured directly without assumptions to number of quark families and CKM unitarity
- Assume $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ and a pure V -A and CP-conserving Wtb interaction ($f_1^R = f_2^L = f_2^R = 0$)
- The single top cross section is proportional to $|V_{tb}|^2$ so $|V_{tb}|$ is essentially measured as $\sqrt{\sigma_{meas} / \sigma_{SM}}$





Conclusion

- "Observation of Single Top Quark Production"

arXiv:0903.0850

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

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

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

Uncertainties

Systematic Uncertainties

Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

Larger terms	
b-ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
W+jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
$t\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
Wbb/*Wcc* correction ratio	5%
Primary vertex selection	1.4%

Systematic Uncertainties

Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%
W+jets and multijets normalization to data	(1.8–3.9)% (*W*+jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen *W*+jets shape corrections	shape only
Trigger	5%

The total uncertainty on the single top cross section measured in this observation analysis is ±22%. When we perform the calculation without including any systematics, it is 18% (i.e., this is the statistical uncertainty). Thus, the systematic component of the total cross section is approximately 13%.

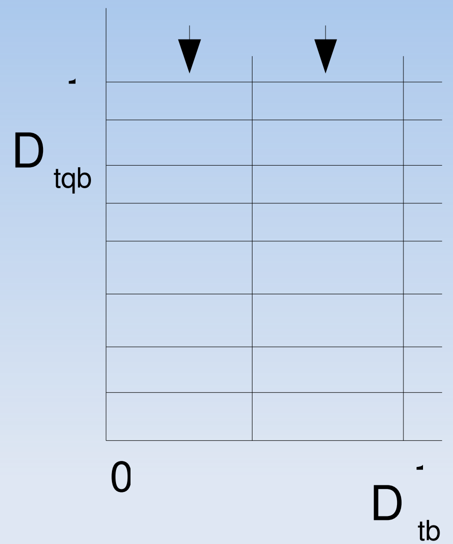
Additional Uncertainties for Vtb

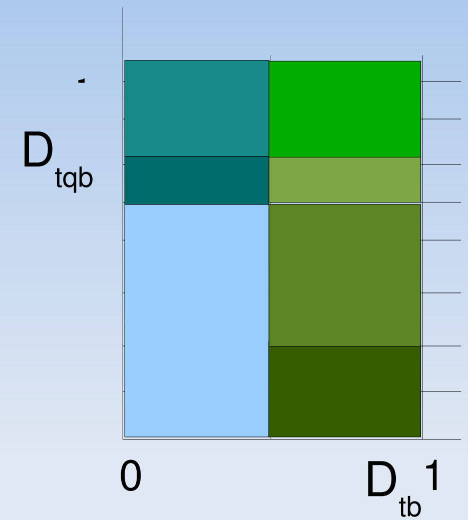
Additional Systematic Uncertainties for the $|V_{tb}|$ Measurement

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%

Presentation of ME Discriminant



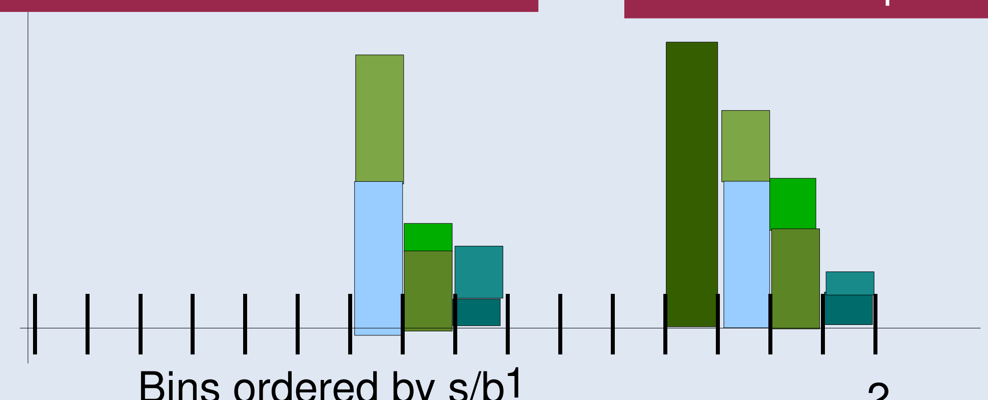


s/b = 0.90
s/b = 0.85
s/b = .80
s/b = .60
s/b = .34
s/b = .16
s/b = .15

Step 1: tb and tqb 2-D discriminant divided into 16 bins total

Step 2: Merge bins so that have sufficient background -> 7 bins total

Step 3: Merged bins s/b computed



Step 4: Merged bins ordered by s/b in 16 bins from 0 to 1. Red line signifies H_T cut where below the red line is yield < 175 GeV and above is yield > 175 GeV

Step 5: Histogram divided into low H_T region [0,1] and high H_T region [1,2]. Also these regions are rebinned to 16 bins from [0,2]

Variables Used

BDT – Jet Reconstruction

$\text{Width}_\eta(\text{jet2})$
$\text{Width}_\eta(\text{jet4})$
$\text{Width}_\phi(\text{jet4})$
$\text{Width}_\eta(\text{tag1})$
$\text{Width}_\eta(\text{light2})$
$\text{Width}_\phi(\text{light2})$

BDT – Object Kinematics

$p_T(\text{jet2})$
$p_T(\text{jet3})$
$p_T(\text{jet4})$
$p_T(\text{tag1})$
$p_T(\text{light2})$
$p_T(\text{notbest2})$
$p_T(\text{lepton})$
$\not\!\!E_T$
$Q(\text{lepton})\times\eta(\text{jet1})$
$Q(\text{lepton})\times\eta(\text{jet2})$
$Q(\text{lepton})\times\eta(\text{best})$
$Q(\text{lepton})\times\eta(\text{light1})$
$Q(\text{lepton})\times\eta(\text{light2})$

BDT – Event Kinematics

$\text{Centrality}(\text{alljets})$
$H_T(\text{alljets})$
$H_T(\text{alljets}-\text{tag1})$
$H_T(\text{alljets}-\text{best})$
$H_T(\text{jet1,jet2})$
$H_T(\text{jet1,jet2,lepton},\not\!\!E_T)$
$H_T(\text{alljets,lepton},\not\!\!E_T)$
$H_T(\not\!\!E_T,\text{lepton})$
$H(\text{alljets}-\text{tag1})$
$M(\text{alljets})$
$M(\text{alljets}-\text{best})$
$M(\text{alljets}-\text{tag1})$
$M(\text{jet1,jet2})$
$M(\text{jet1,jet2},W)$
$M(\text{jet3,jet4})$
$M_T(\text{jet1,jet2})$
$p_T(\text{jet1,jet2})$
$\sqrt{\hat{s}}$
$M_T(W)$

BDT – Top Quark Reconstruction

$M(W,\text{best1})$ ("best" top mass)
$M(W,\text{tag1})$ ("b-tagged" top mass)
$M(W,\text{tag1},S2)$ (with 2nd ν solution)
$M(W,\text{jet1})$
$M(W,\text{jet1},S2)$
$M(W,\text{jet2})$
$M(W,\text{jet2},S2)$
$M(W,\text{notbest2})$
$M(W,\text{notbest2},S2)$
$M_{\text{top}}^{\Delta M^{\min}}$
$M_{\text{top}}^{\text{sig}}$
$\Delta M_{\text{top}}^{\min}$
$\text{Significance}_{\min}(M_{\text{top}})$

BDT – Angular Correlations

$\Delta R(\text{jet1,jet2})$
$\Delta R(\text{jet1,lepton})$
$\Delta R(\text{tag1,lepton})$
$\Delta R(\text{light1,lepton})$
$\Delta\phi(\text{lepton},\not\!\!E_T)$
$\cos(\text{best,lepton})_{\text{besttop}}$
$\cos(\text{best,notbest})_{\text{besttop}}$
$\cos(\text{jet1,lepton})_{\text{btaggedtop}}$
$\cos(\text{tag1,lepton})_{\text{btaggedtop}}$
$\cos(\text{lepton}_{\text{besttop}},\text{besttop}_{\text{CMframe}})$
$\cos(\text{lepton}_{\text{btaggedtop}},\text{btaggedtop}_{\text{CMframe}})$
$\cos(\text{tag1,lepton})_{\text{btaggedtop}}$
$\cos(\text{lepton},Q(\text{lepton})\times z)_{\text{besttop}}$

Best Variables to Separate Single Top from W+Jets
DØ 2.3 fb^{-1} Analysis

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

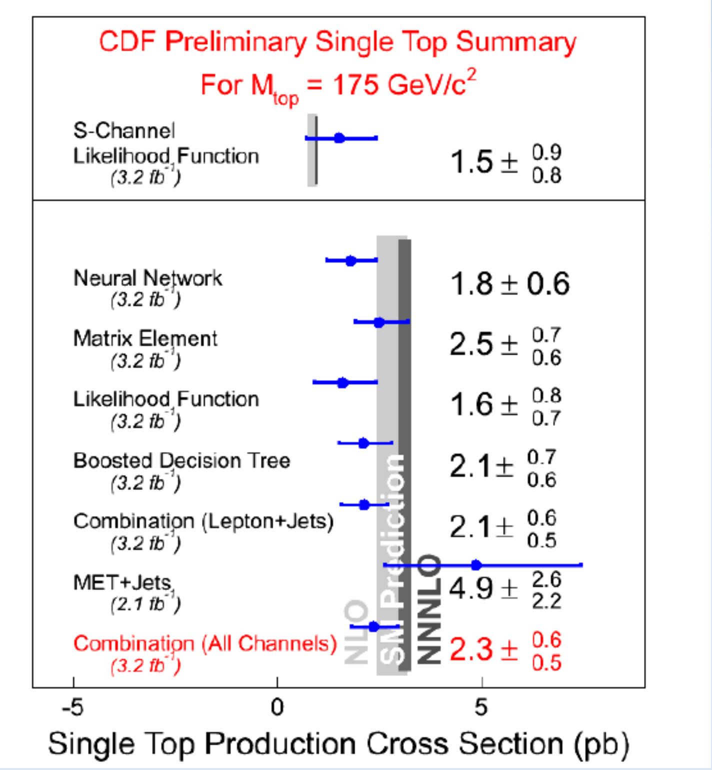
Best Variables to Separate Single Top from Top Pairs
DØ 2.3 fb^{-1} Analysis

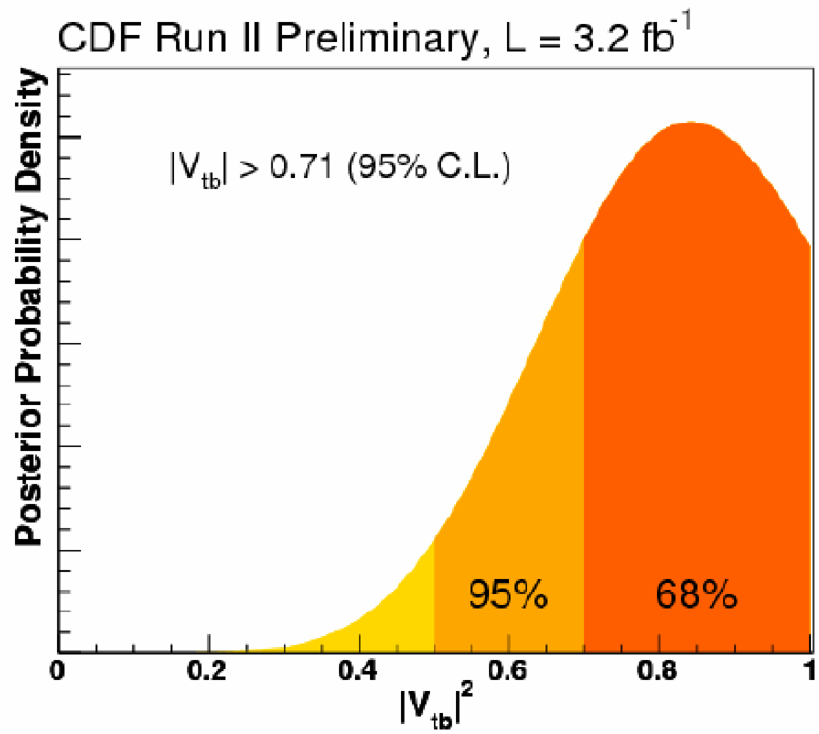
Object kinematics	pT(notbest2)
	pT(jet4)
	pT(light2)
Event kinematics	M(alljets–tag1)
	Centrality(alljets)
	M(alljets–best1)
	H_T(alljets–tag1)
	H_T(lepton,$\not\!\!E_T$,alljets)
	M(alljets)
Jet reconstruction	Width_η(jet4)
	Width_ϕ(jet4)
	Width_ϕ(jet2)
Angular correlations	cos(lepton$_{btaggedtop}$,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

CDF Result

CDF Discovery:

ArXiv:0903.0885





$$|V_{tb}| = 0.91 \pm 0.11,$$
$$|V_{tb}| > 0.71 \text{ at } 95\% \text{ CL}$$

σ_{NLO}[†] 0.88 ± 0.11 pb 1.98 ± 0.25 pb (m_t=175 GeV)

[†] Z. Sullivan, Phys. Rev. D 70, 114012 (2004)