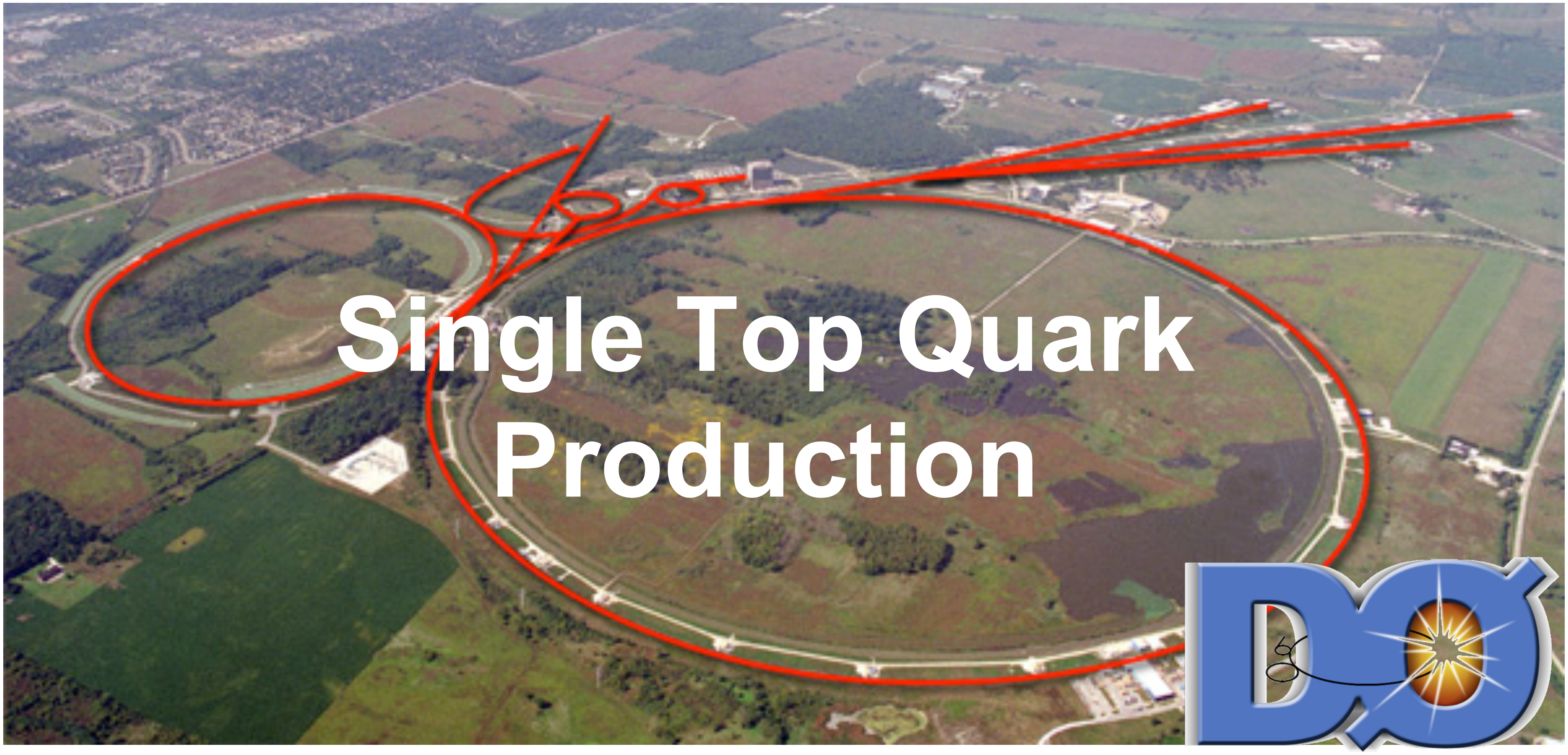
Single Top Quark Production



Meenakshi Narain

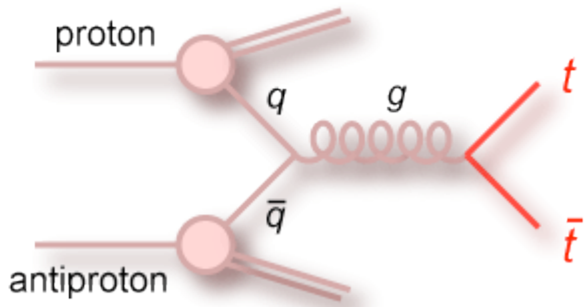
Brown University

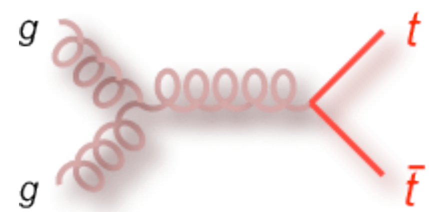
outline

- the top quark
- event selection
- understanding the background model
- multivariate analysis techniques
- combination
- implications
- summary

the top quark

- dominant production mechanism



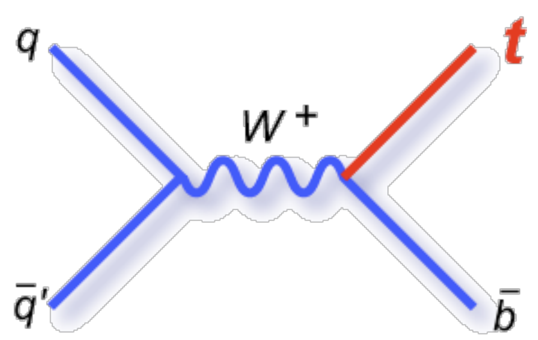


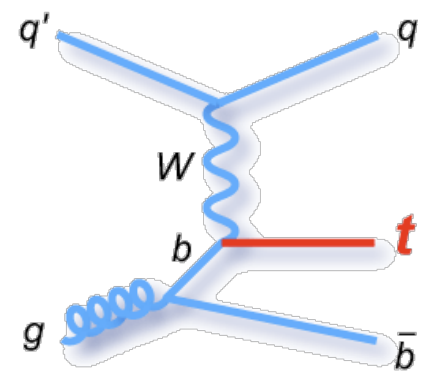
  - σ_{ttbar} = 7.62 ± 0.85 pb
  - m_{top} = 173.1±0.6 (stat) ±1.1 (syst) GeV
  - cannot measure electroweak coupling
    - B(t→Wb) ∝ $|V_{tb}|$ >0.89 @ 95% CL, assuming unitarity of 3×3 CKM matrix
    - from B decays
      - $|V_{ub}|$ = 0.00393 and $|V_{cb}|$ = 0.0412 → $|V_{tb}|$ = 0.9991
    - Γ_{top} << experimental resolution; <12.7 GeV @95% C.L.

the top quark

- electroweak production of top quarks

s channel (tb) t channel (tqb)





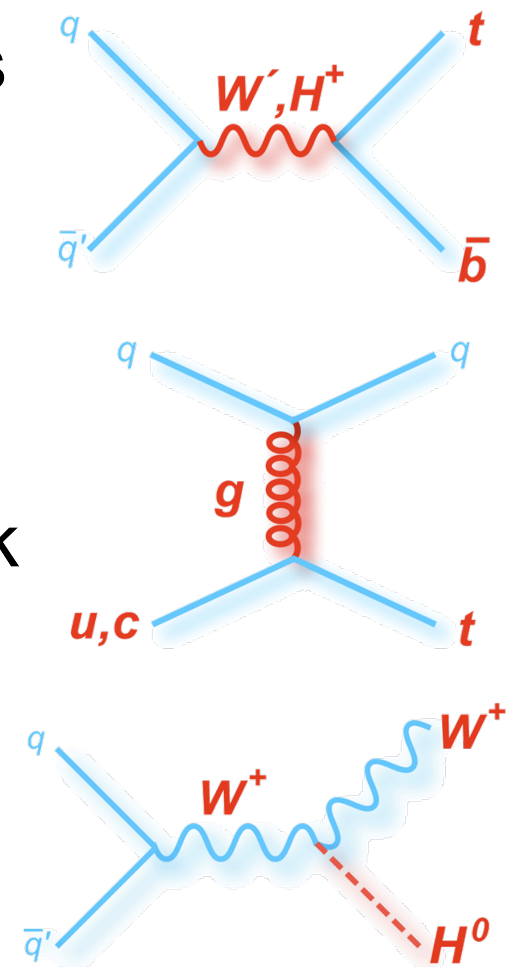
NLO σ = 1.12±0.05 pb σ = 2.34±0.13 pb

N. Kidonakis , PRD 74, 114012 (2006), for m_t =170 GeV

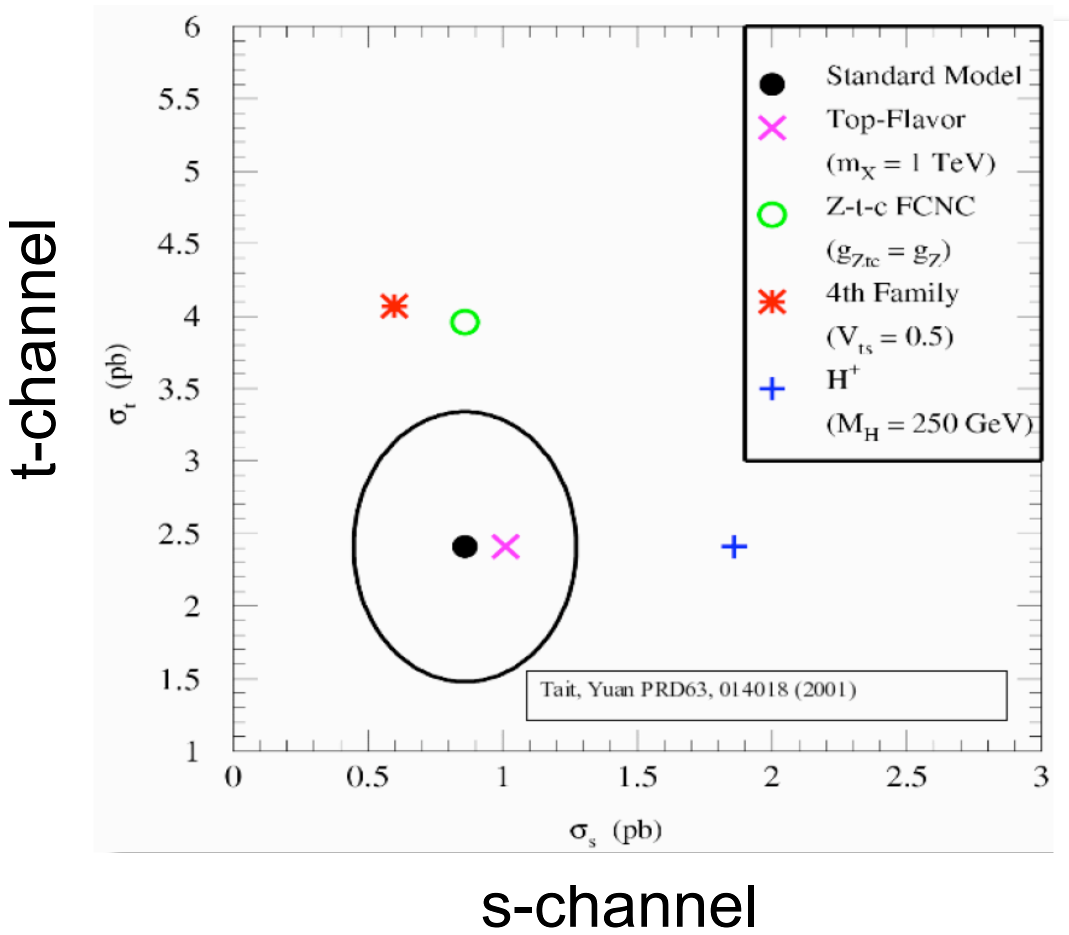
- $\sigma \propto |V_{tb}|^2$
  - no assumption on number generations or unitarity of CKM matrix
- measure $\Gamma(t \rightarrow Wb)$

the top quark

- electroweak production of top quarks
  - sensitive to non-standard physics
    - 4th quark generation
    - anomalous Wtb vertex
    - new particles (H^+, W')
    - FCNC
  - Provides an important benchmark in understanding the backgrounds to Higgs search in WH channel



the top quark



the top quark

2006

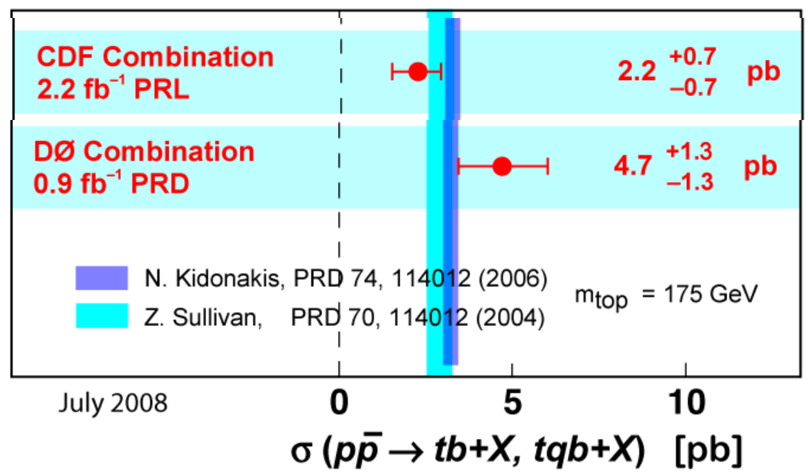
- D0 announces evidence for single top production

PRL **98,** 181802 (2007) PHYSICAL REVIEW LETTERS week ending 4 MAY 2007

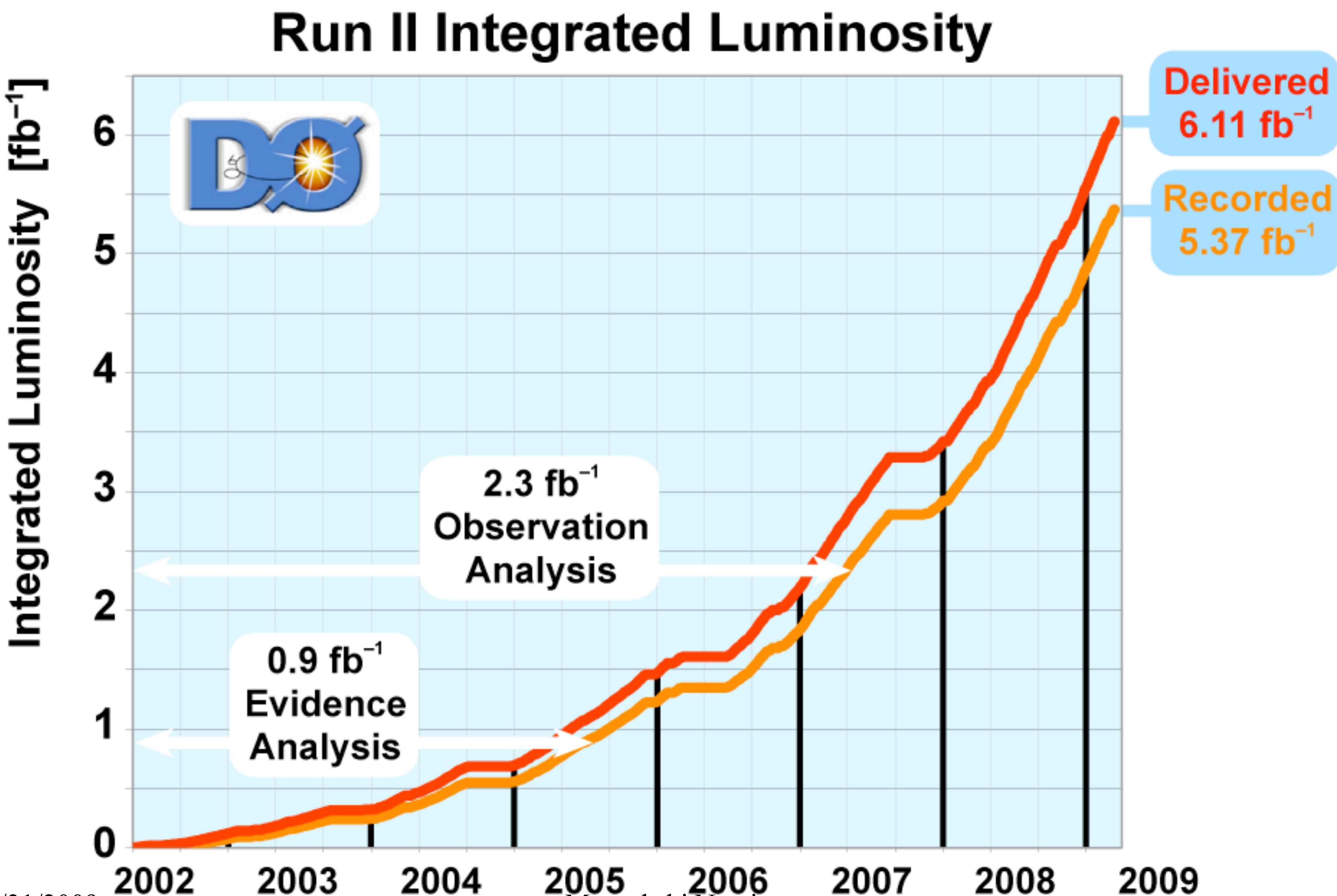
Evidence for Production of Single Top Quarks and First Direct Measurement of $|V_{tb}|$

V. M. Abazov,[35] B. Abbott,[75] M. Abolins,[65] B. S. Acharya,[28] M. Adams,[51] T. Adams,[49] E. Aguilo,[5] S. H. Ahn,[30] M. Ahsan,[59] G. D. Alexeev,[35] G. Alkhazov,[39] A. Alton,[64,*] ... T. Andeen,[53] S. Anderson,[45] B. Andrieu,[16] M. S. An... C. Autermann, ... S. Banerje... D. Bau... A. Bellavance... R. Beuselinck... C. Biscarat,[19] I. Blackler,[43] G. Blazey,[52] F. Blekman,[43] S. B... T. A. Bolton,[59] E. E. Boos,[37] G. Borissov,[42] K. Bos,[33] T. ... D. Brown,[78] N. J. Buchanan,[49] D. Buchholz,[53] M. Bueh... T. H. Burnett,[82] E. Busato,[16] C. P. Buszello,[43] J. M. Bu... W. Carvalho,[3] B. C. K. Casey,[77] N. M. Cason,[55] H. Castill... A. Chandra,[48] F. Charles,[18] E. Cheu,[45] F. Chevallier,[13] D. K. ... B. Clément,[18] C. Clément,[40] Y. Coadou,[5] M. Cooke,[80] W. E. Cooper,[50] M. Corcoran,[80] F. Couderc,[17] M.-C. Cousinou,[14] B. Cox,[44] S. Crépé-Renaudin,[13] D. Cutts,[77] M. Ćwiok,[29] H. da Motta,[2] A. Das,[62] M. Das,[60] B. Davies,[42] G. Davies,[43] K. De,[78] P. de Jong,[33] S. J. de Jong,[34] E. De La Cruz-Burelo,[64] C. De Oliveira Martins,[3] J. D. Degenhardt,[64] F. Déliot,[17] M. Demarteau,[50] R. Demina,[71] D. Denisov,[50] S. ... H. T. Diehl,[50] M. Diesburg,[50] M. Doidge,[42] A. Dominguez,[67] H. Dong,[72] L. V. Dudko,[37] L. Duflot,[15] S. R. Dugad,[28] D. Duggan,[49] A. Duperrin,[14] J. Dyer,[65]

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

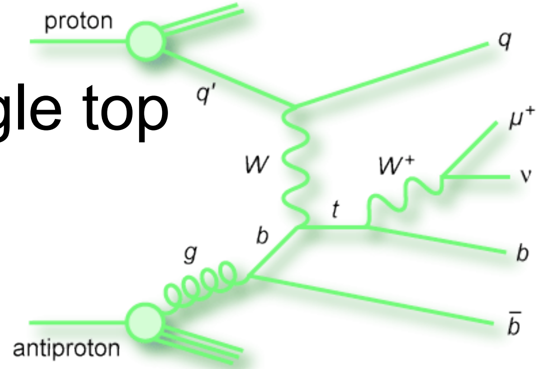


event selection

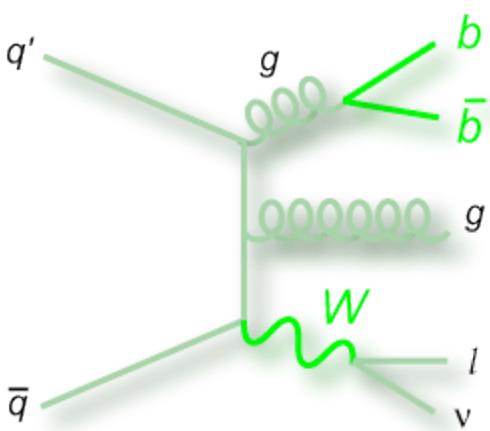


event selection

single top

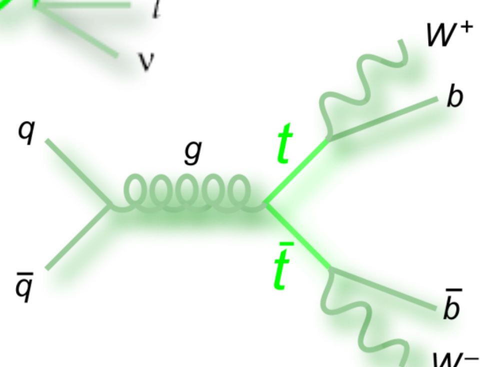


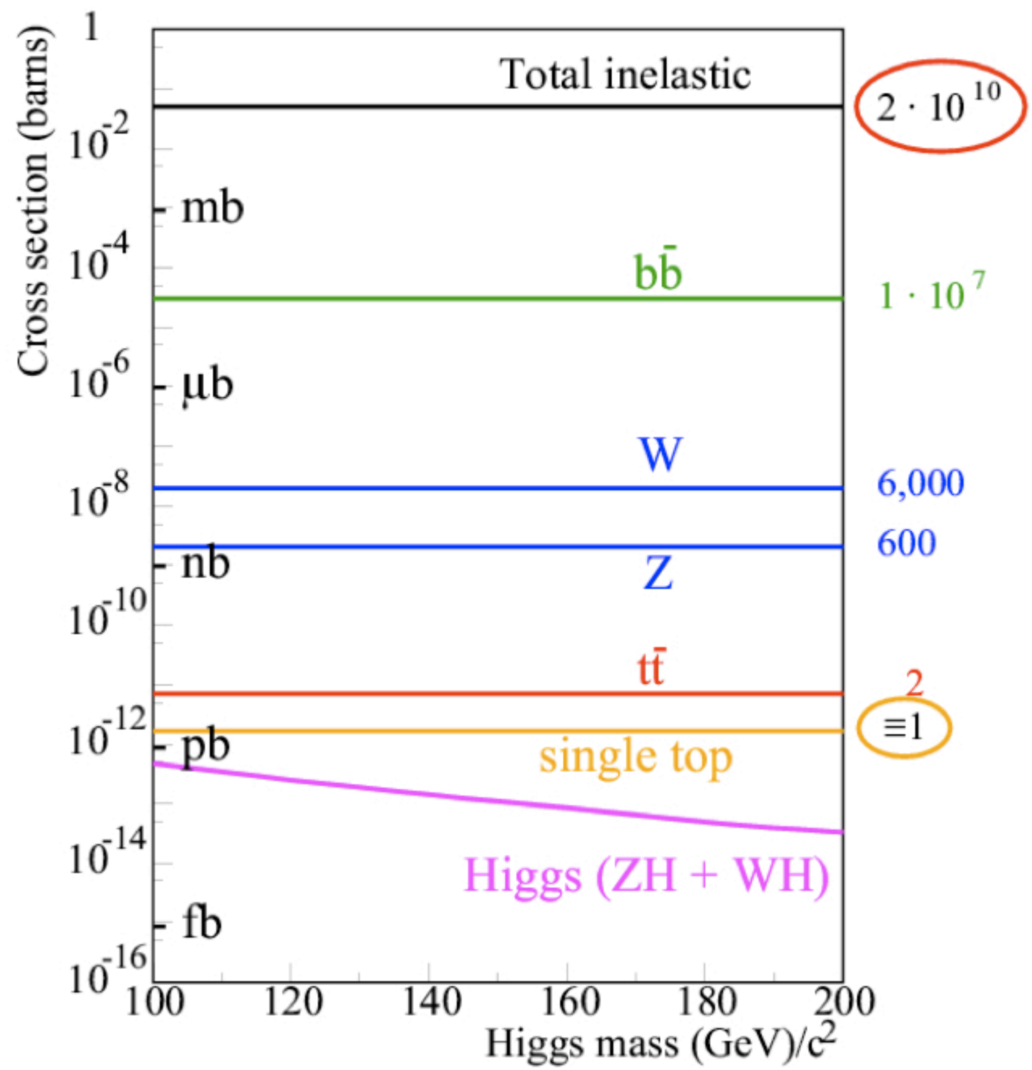
dominant backgrounds



W+jets

top pairs



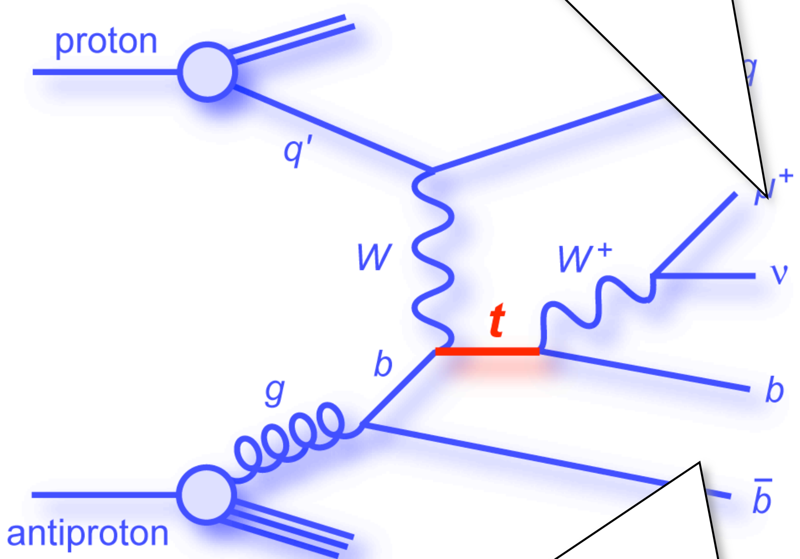


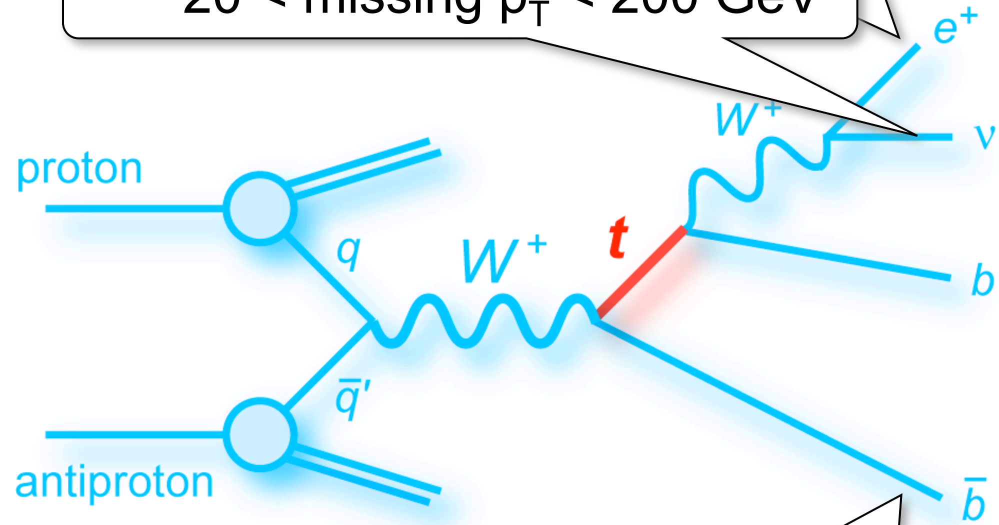
event selection

muon $p_T > 15$ GeV, $|\eta| < 2.0$

electron $p_T > 15$ GeV, $|\eta| < 1.1$

$20 <$ missing $p_T < 200$ GeV





2-4 jets
leading jet $p_T > 25$ GeV, $|\eta| < 3.4$
other jets $p_T > 15$ GeV, $|\eta| < 3.4$

≥1 b-tagged jet
leading b-jet $p_T > 25$ GeV, $|\eta| < 3.4$

24 channels:

2 running periods × 2 lepton flavors × 3 jet multiplicities × 2 b-tag multiplicities

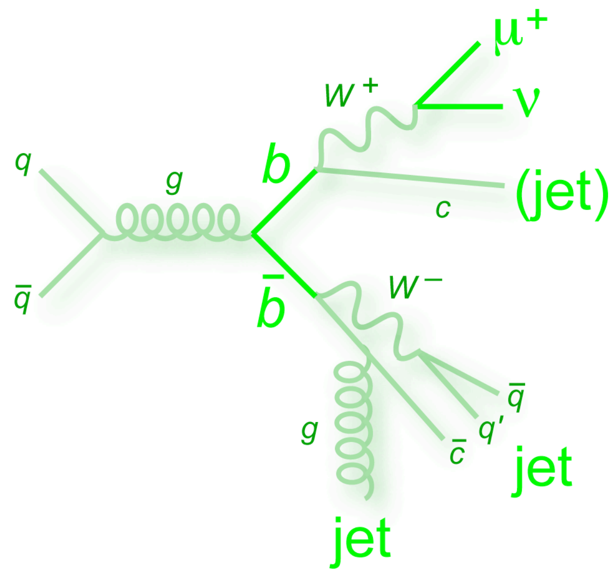
event counts – first selection

- All object level selection cuts
- No btagging.
  - expected signal
  - backgrounds
  - observed

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

modeling of backgrounds:

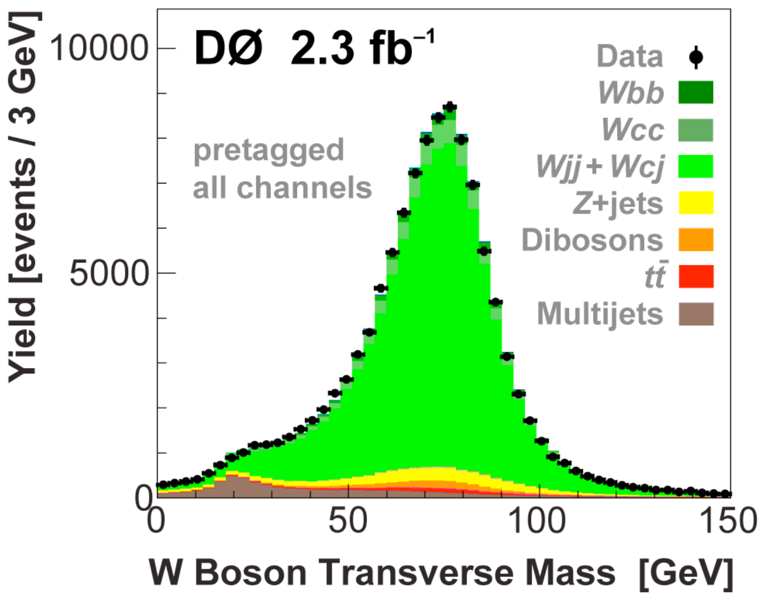
- W+jets:

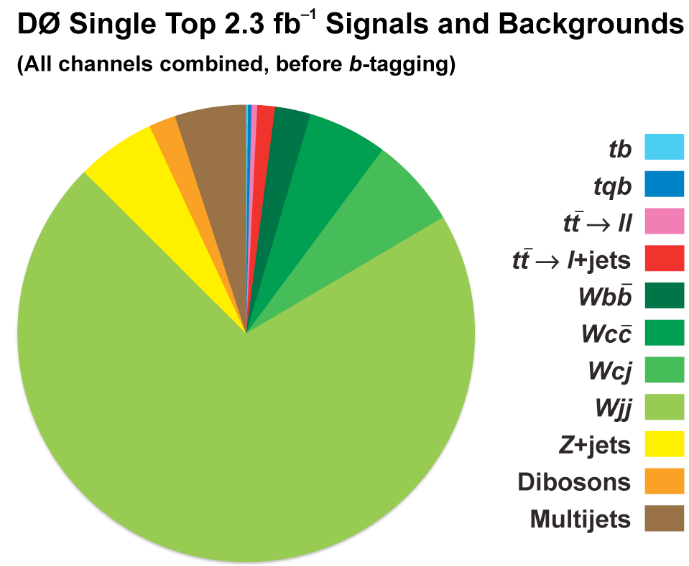


- modeled using ALPGEN
  - PYTHIA for parton hadronization
  - MLM parton-jet matching avoids double-counting final states
- η(jets), $\Delta\phi$(jet1,jet2), $\Delta\eta$(jet1,jet2) corrected to match data

1. bkg normalization pre b-tagging

- dominant background: W+jets





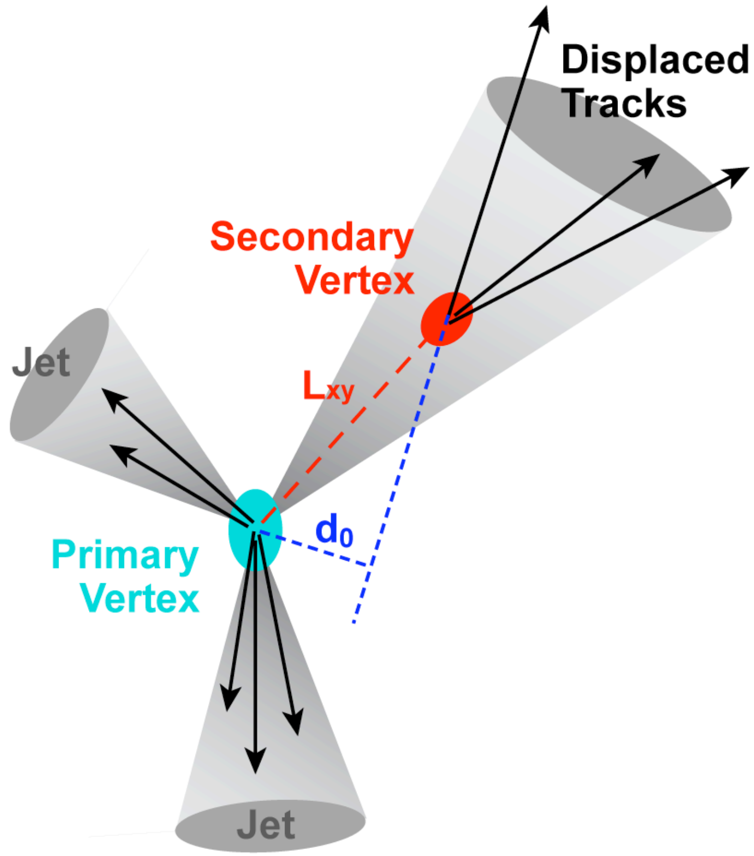
S:B = 1:259

- Overall normalization for Wjets/mis-id determined by using iterative template fits to data using three sensitive variables: $p_T(l)$, $M_T(W)$ and missing E_T

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

b-Jet Identification

- separate *b*-jets from light-quark and gluon jets to reject most W +jets background
- use neural network algorithm
  - based on impact parameter and reconstructed vertex variables
- uncertainties dominated by variation in data samples used to measure the efficiencies.
  - smaller contribution from MC sample dependence



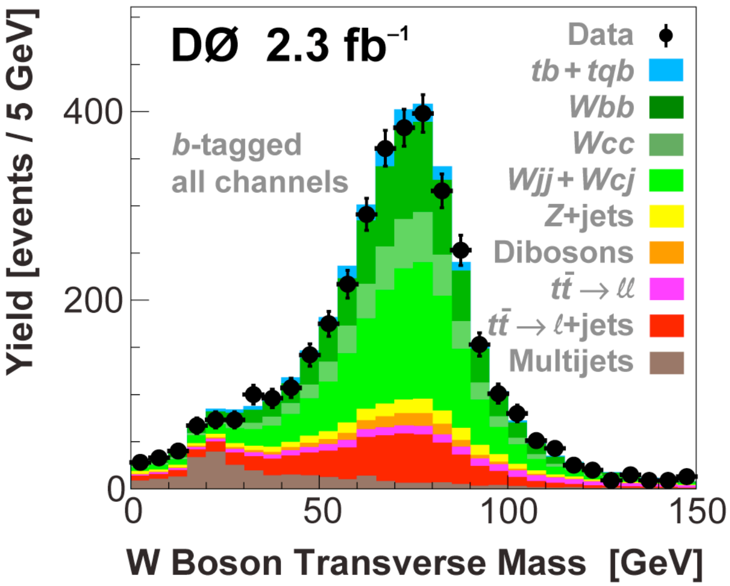
event counts – final selection:

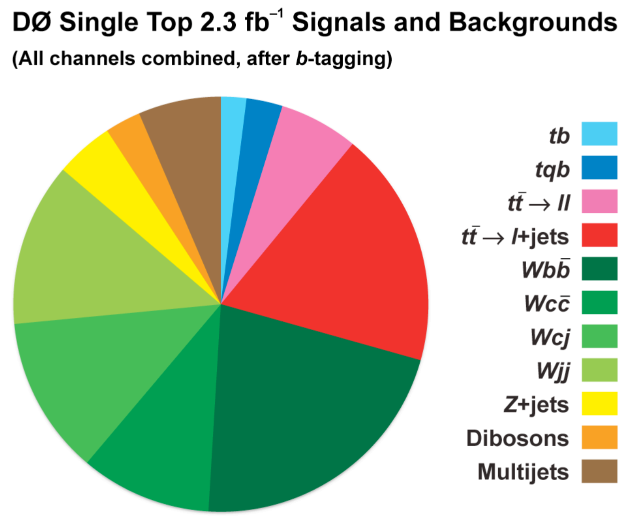
- expected signal
- backgrounds
- observed

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

2. bkg norm. post b-tagging

- W+HF (Wbb, Wcc, Wcj), top pair backgrounds are dominant





S:B

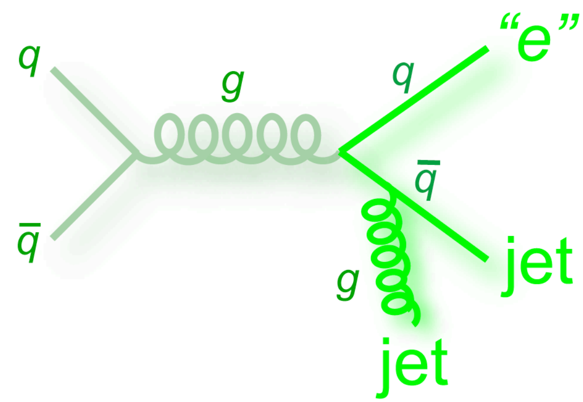
1:21 in 1Tag

1:15 in 2Tag

- W+heavy flavor correction factors
  - normalized to theory (use MCFM @ NLO)
    - 1.47 (Wbb,Wcc), 1.38 (Wcj)
  - additional empirical correction derived from two-jet data and simulation: includes zero-tag events
    - 0.95 ± 0.13 (Wbb, Wcc)

modeling of backgrounds:

- multijet instrumental background

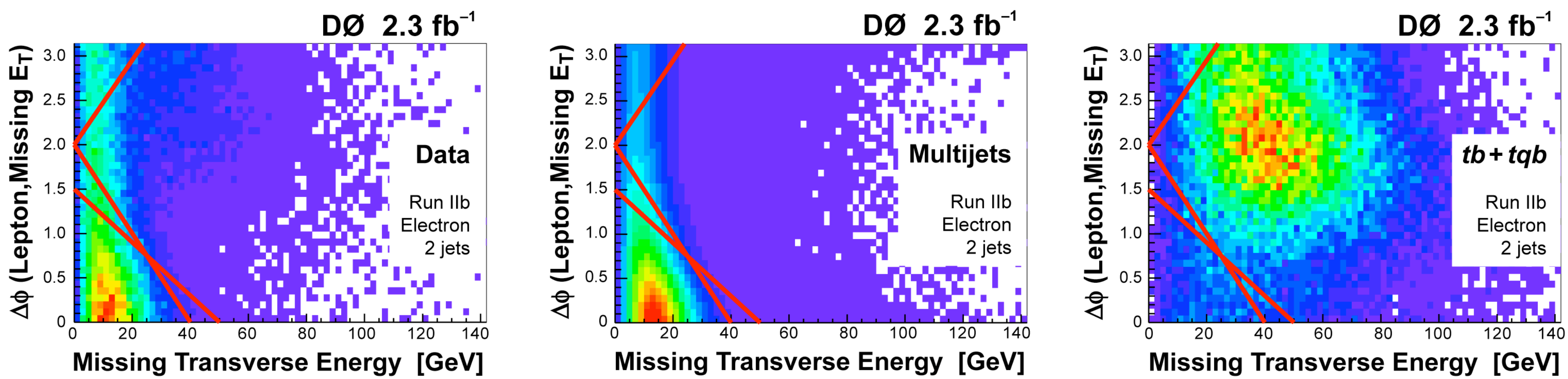


  - misidentified leptons, events with semileptonic b-decays
  - Estimates are data driven
  - Kept small (~5%) with topological selection cuts

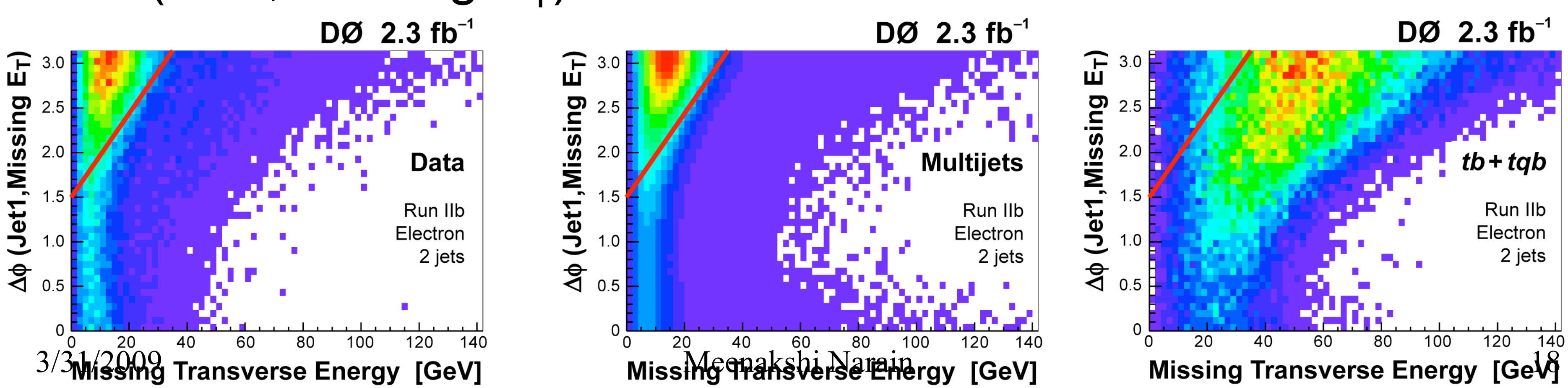
Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
Multijets	196 ± 50	73 ± 17	30 ± 6

reducing multijet background

- employ cut on H_T. Exploit correlations between missing E_T and the directions of leptons, jets in the event.
- $\Delta\Phi$(Lepton, Missing E_T)

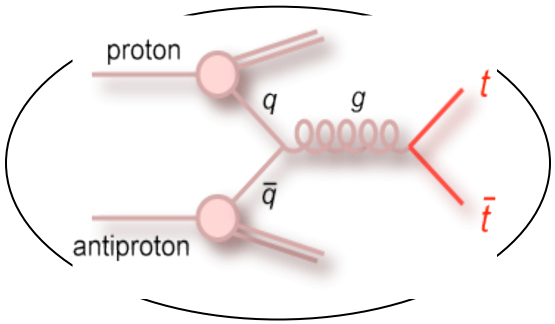


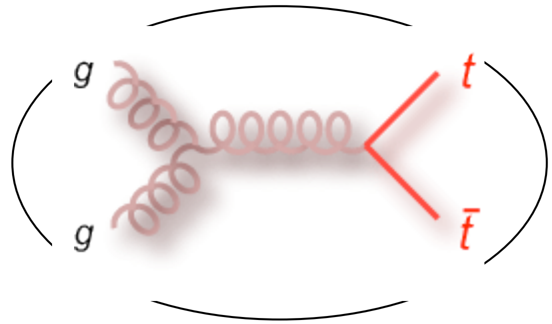
- $\Delta\Phi$(Jet1, Missing E_T)



modeling of backgrounds:

- top pair production:





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Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
$t\bar{t} \rightarrow \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \rightarrow \ell$+jets	72 ± 13	331 ± 51	452 ± 66

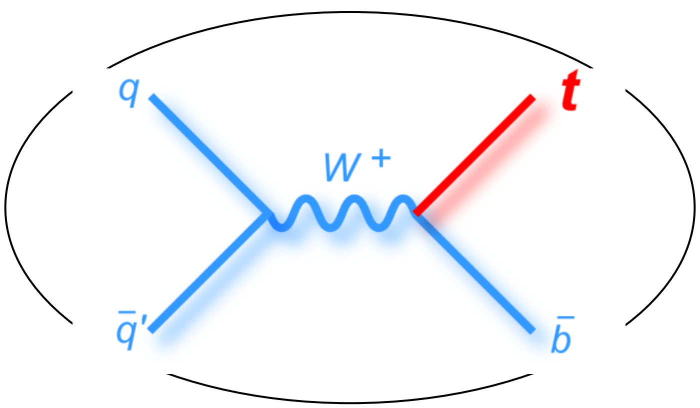
modeling of backgrounds:

- Z+jets:
  - modeled using ALPGEN + PYTHIA hadronization
  - Z+ heavy flavor corrected to theory, with ±14% uncertainty
- Dibosons
  - modeled using PYTHIA
  - Normalized to theory cross sections

Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2

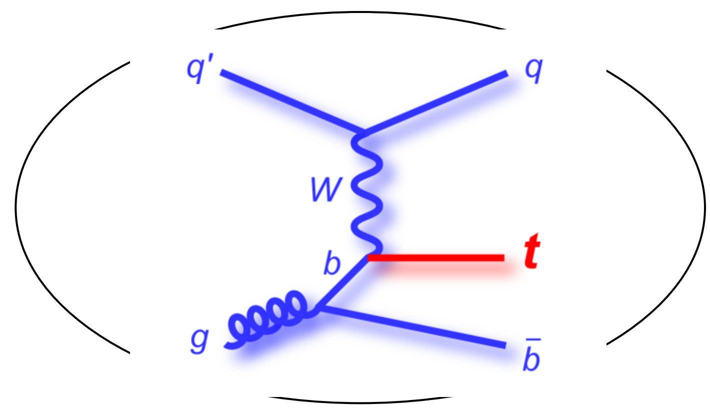
modeling of signal

- Single top production:
  - Use SINGLETOP MC, based on COMPHEP
  - Reproduces NLO kinematic distributions
  - Use PYTHIA for parton hadronization



***s*-channel**

σ_{SM} = 1.12 ± 0.05 pb



***t*-channel**

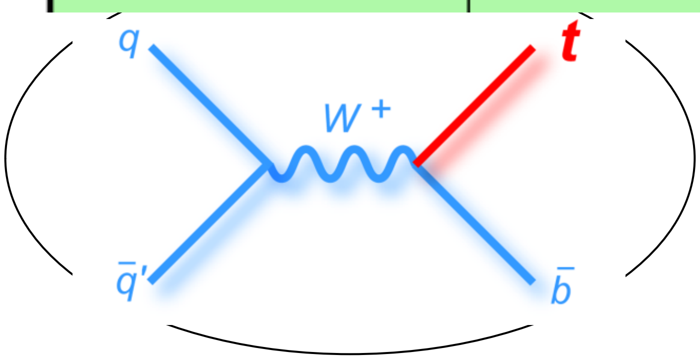
σ_{SM} = 2.34 ± 0.13 pb

cross sections from N. Kidonakis , PRD 74, 114012 (2006), for m_t =170 GeV

modeling of signal

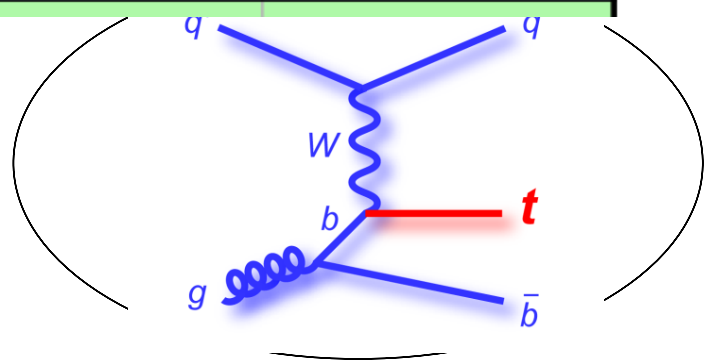
- Single top production:

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



***s*-channel**

σ_{SM} = 1.12 ± 0.05 pb

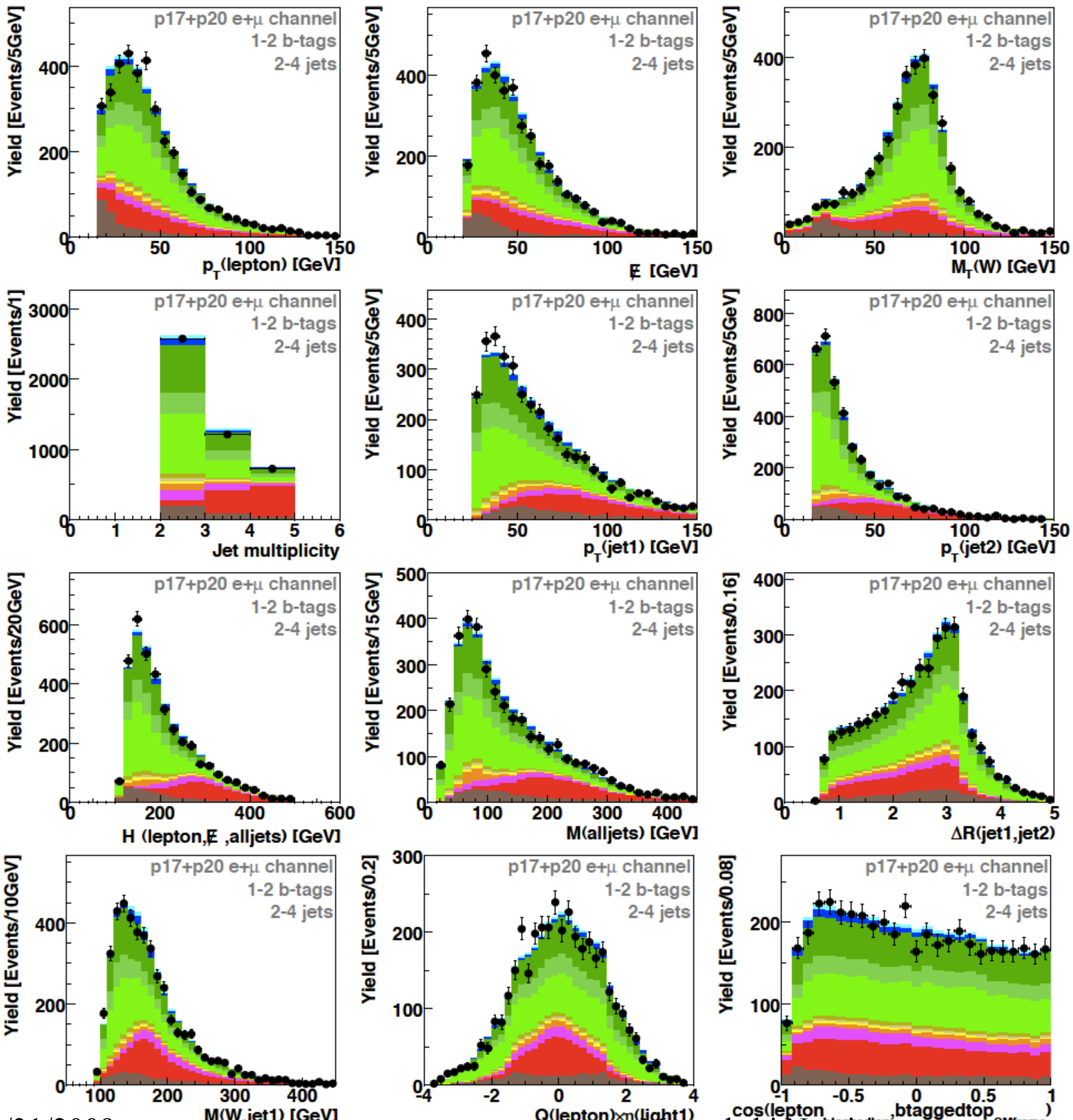


***t*-channel**

σ_{SM} = 2.34 ± 0.13 pb

cross sections from N. Kidonakis , PRD 74, 114012 (2006), for m_t =170 GeV

Data/MC agreement (for all channels combined)



background model validation

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

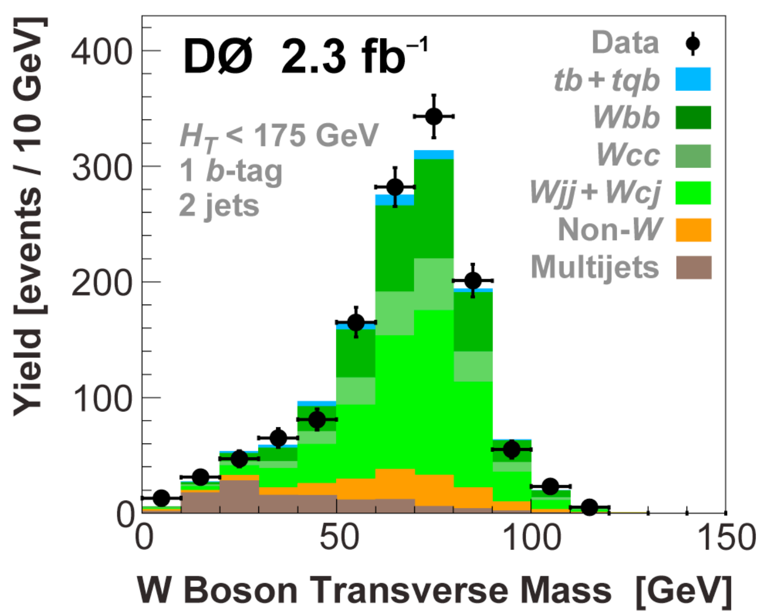
W + JETS

- 2 jets, 1 *b*-tagged jet
- $H_T(l, \not{E}_T, \text{allJets}) < 175$ GeV

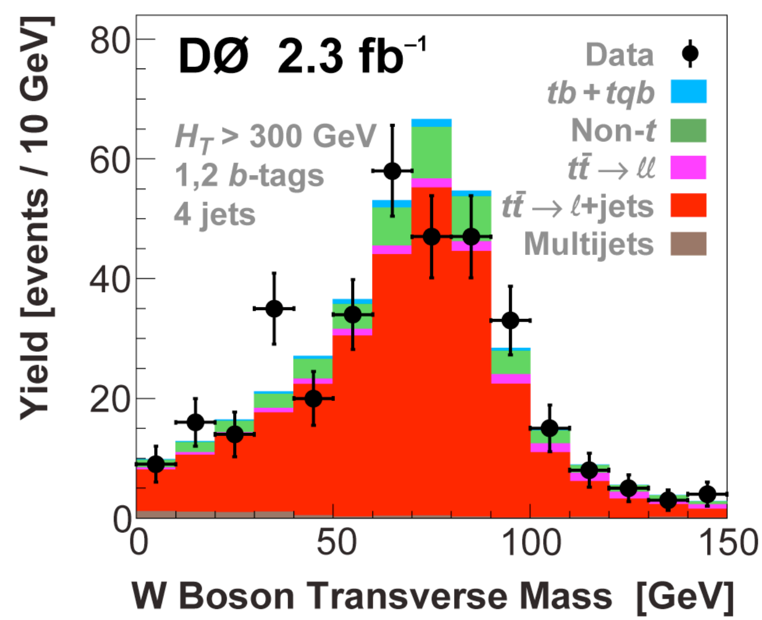
Top Pairs

- 4 jets, 1 or 2 *b*-tagged jets
- $H_T(l, \not{E}_T, \text{allJets}) > 300$ GeV

W+Jets Cross-Check Sample



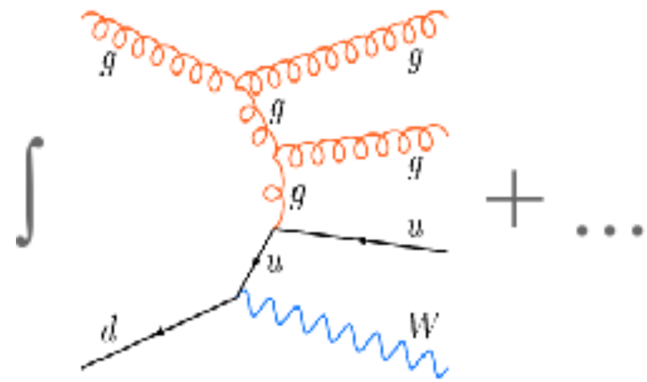
$t\bar{t}$-Pairs Cross-Check Sample



matrix elements

- method pioneered by DØ for top quark mass measurement
- use 4-vectors of all reconstructed leptons and jets
- use matrix elements of main signal and background processes
- compute 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 a normalized differential cross section:

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

- performed in 2-jets and 3-jets channels only
- split the sample in high and low H_T

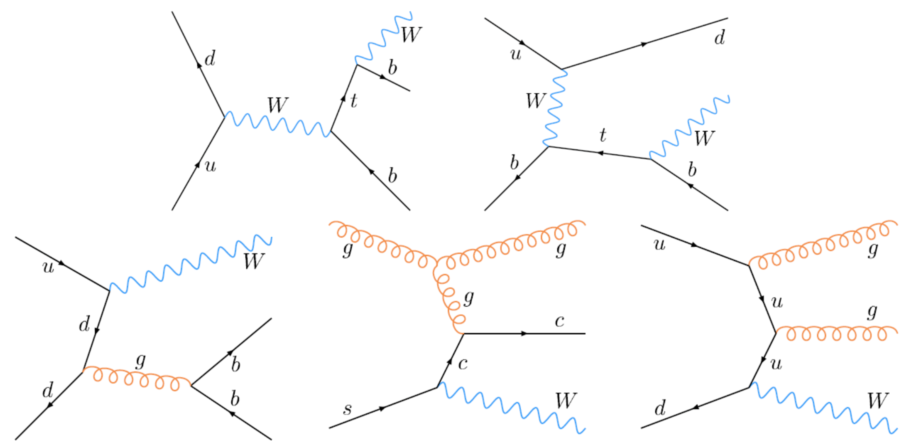
  (W+jets and top quark pair dominated regions) improves the performance
- response verified with ensembles
  - linearity, unit slope, near-zero intercept

matrix elements

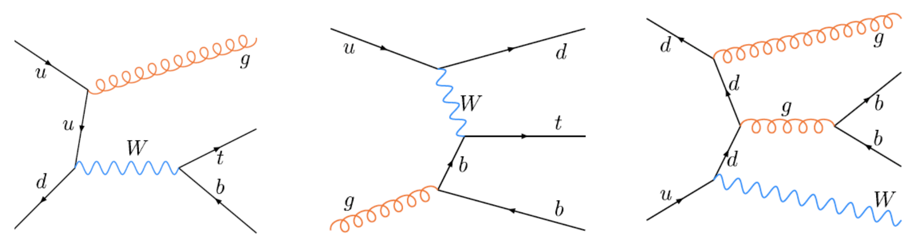
Matrix Elements used to Separate Single Top Signal from Background
DØ 2.3 fb^{-1}

2 Jets		3 Jets	
$t\bar{b}$	$u\bar{d} \to t\bar{b}$	$t\bar{b}g$	$u\bar{d} \to t\bar{b}g$
tq	$ub \to td$ $\bar{d}b \to t\bar{u}$	tqg	$ub \to tdg$ $\bar{d}b \to t\bar{u}g$
		$tq\bar{b}$	$ug \to td\bar{b}$ $\bar{d}g \to t\bar{u}\bar{b}$
$Wb\bar{b}$	$u\bar{d} \to Wb\bar{b}$	$Wb\bar{b}g$	$u\bar{d} \to Wb\bar{b}g$
$W\bar{c}g$	$\bar{s}g \to W\bar{c}g$		
Wgg	$u\bar{d} \to Wgg$	$W\bar{u}gg$	$\bar{u}g \to W\bar{u}gg$
WW	$q\bar{q} \to WW$		
WZ	$q\bar{q} \to WZ$		
ggg	$gg \to ggg$		
$t\bar{t}$	$q\bar{q} \to t\bar{t} \to \ell^+ \nu b \ell^- \nu \bar{b}$		
$t\bar{t}$	$q\bar{q} \to t\bar{t} \to \ell^+ \nu b \bar{u} d \bar{b}$	$t\bar{t}$	$q\bar{q} \to t\bar{t} \to \ell^+ \nu b \bar{u} d \bar{b}$

2-jet channels

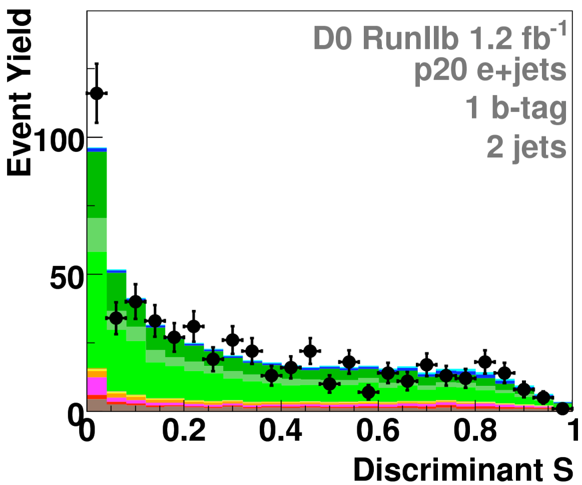


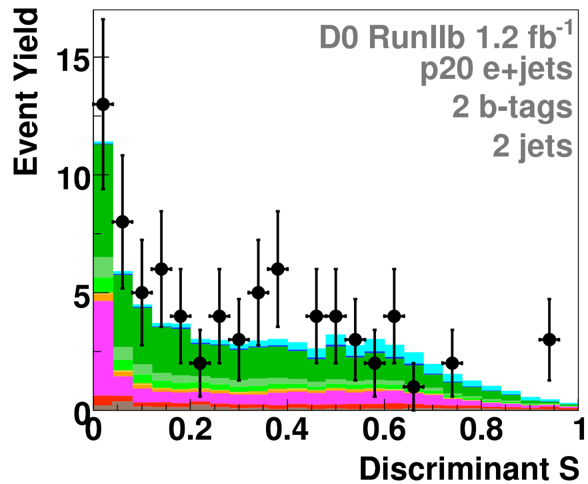
3-jet channels



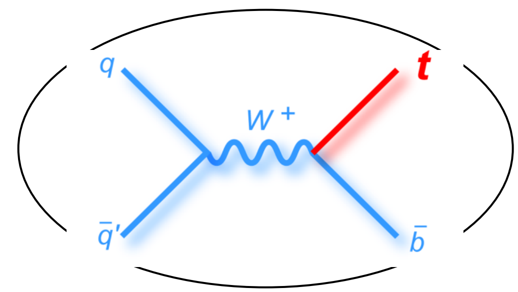
matrix elements

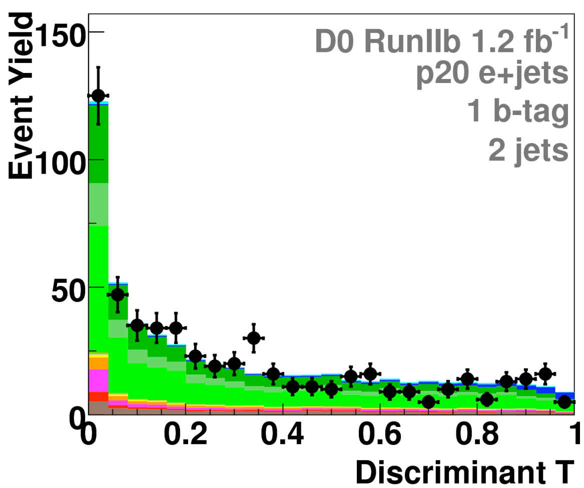
2-jet channels

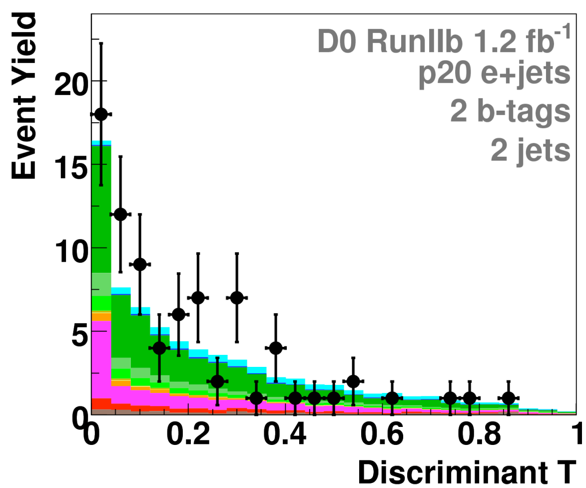




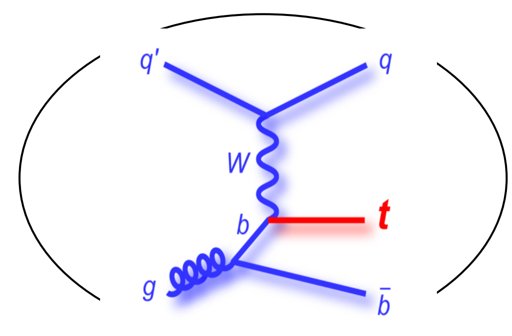
tb discriminant





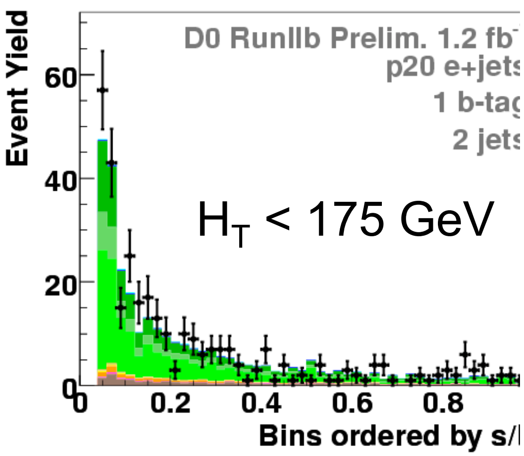


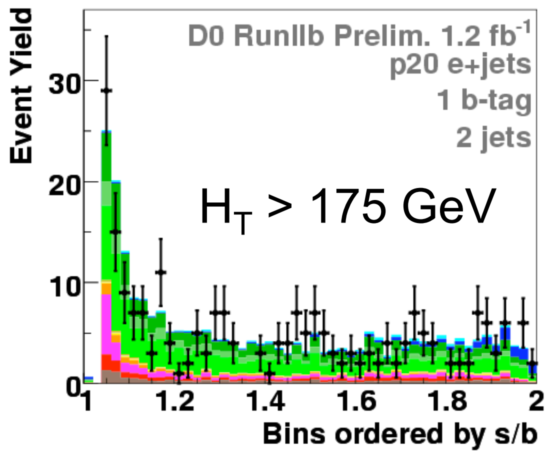
tq discriminant

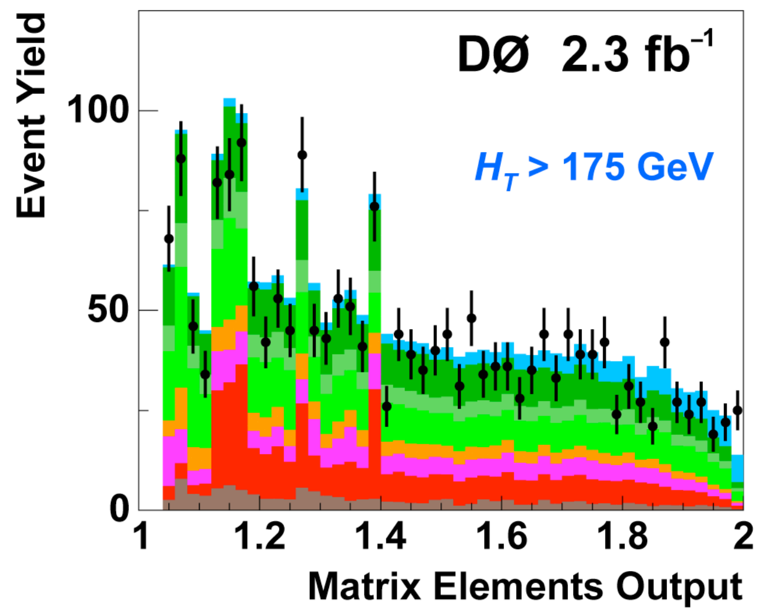


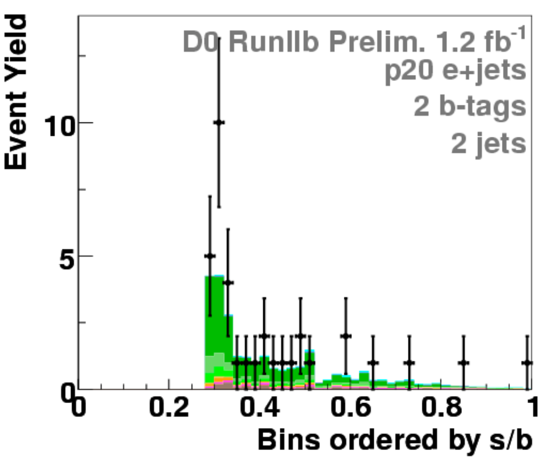
matrix elements

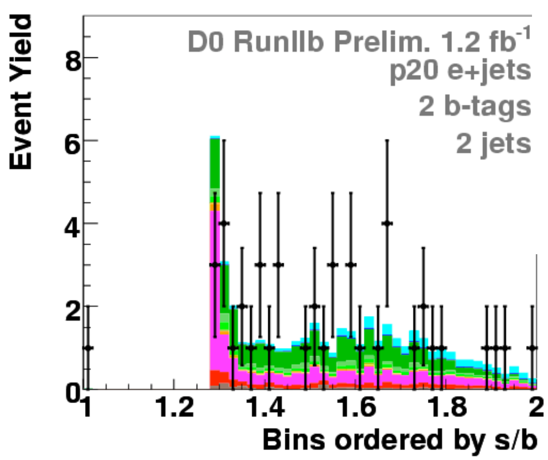
- starting from 2dim S vs T discriminant,
  - rebin to ensure enough background evts in each bin
  - re-order bins according to highest-to-lowest signal:background to obtain the 1dim tb+tqb discriminant; split according to H_T.





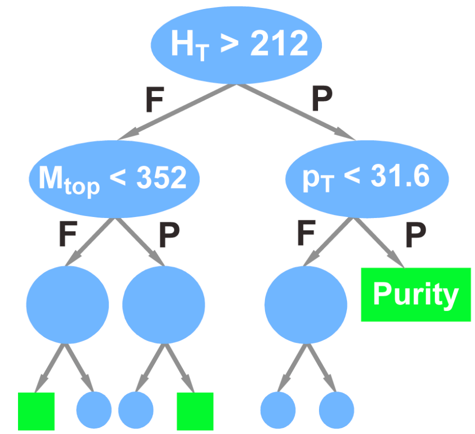






boosted decision trees

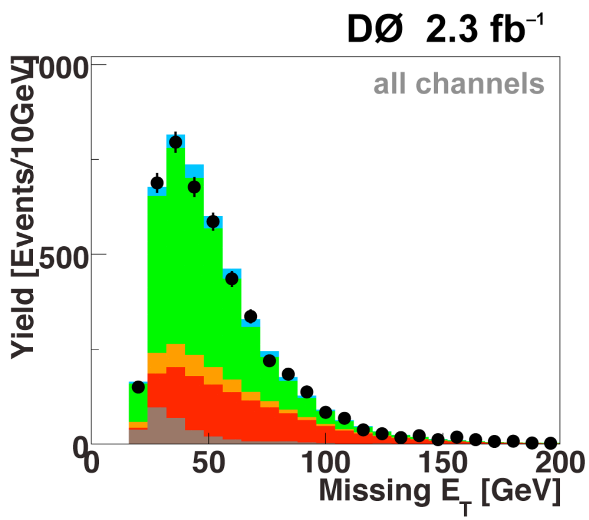
- decision trees
  - idea: recover events that fail a cut
  - successively find cuts with best separation between signal and background
  - repeat recursively on each branch
  - stop when no further improvement or when too few events are left
  - terminal node is called a “leaf”
  - decision tree output = leaf purity



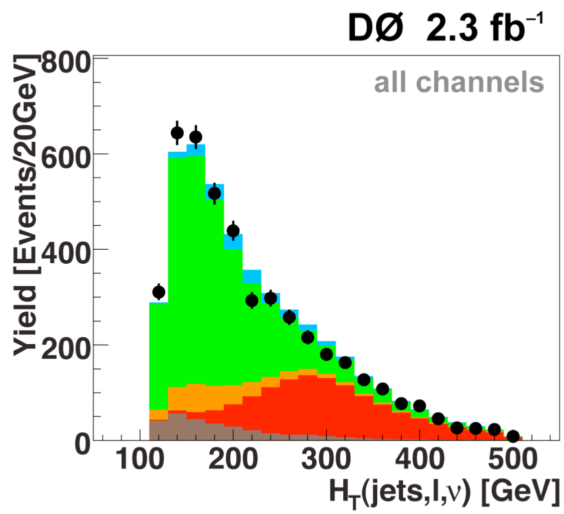
- adaptive boosting
  - technique to improve any weak classifier
  - used with decision trees by GLAST and MiniBooNE
  - train a tree
  - increase weight of misclassified events
  - train again
  - average over 50 boosting cycles
  - dilutes the discrete nature of the output and improves the performance

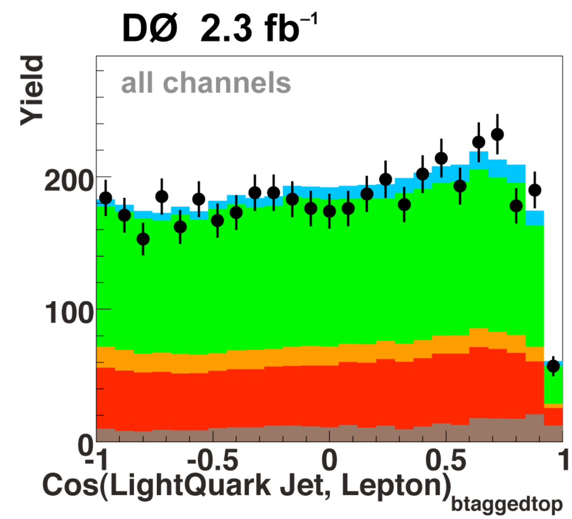
discriminating variable categories

OBJECT KINEMATICS

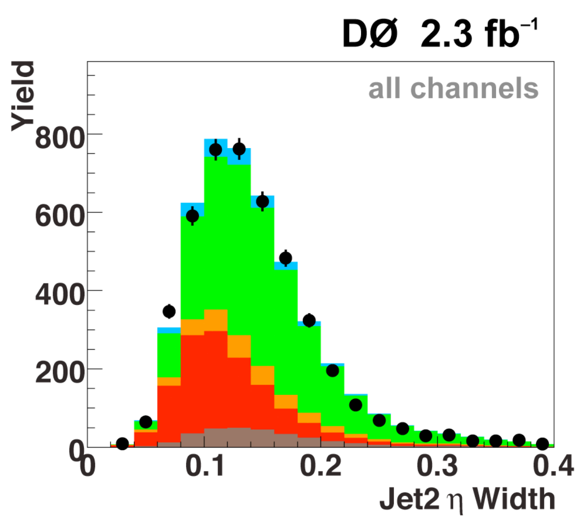


EVENT KINEMATICS

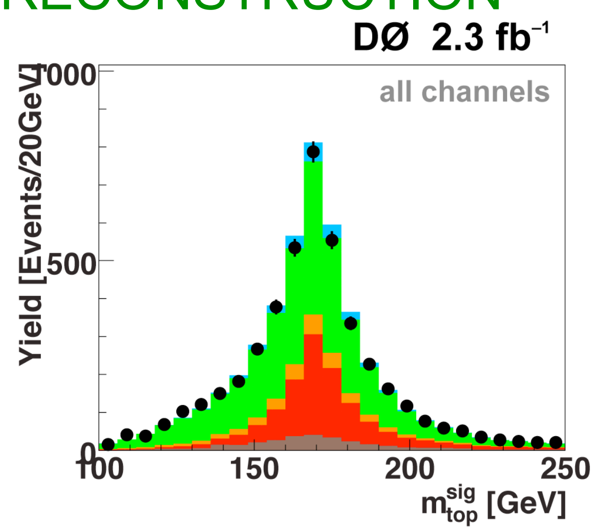




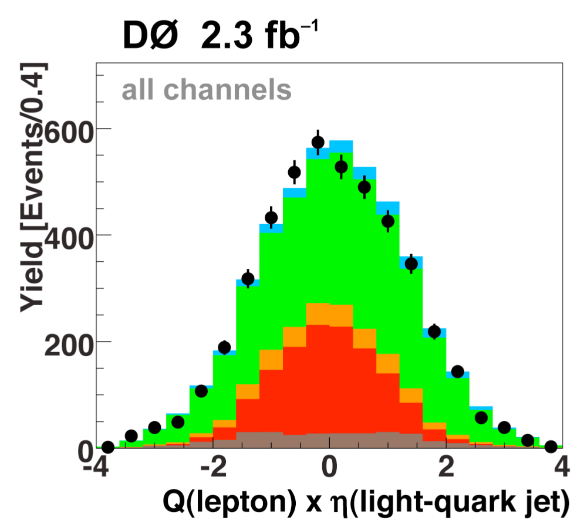
JET RECONSTRUCTION



TOP QUARK RECONSTRUCTION



ANGULAR CORRELATIONS



boosted decision trees

- 64 input variables
  - reducing the number of variables reduces the sensitivity of the analysis
  - start from a list of a few hundred well modeled variables
    - Use ranking to select the at most top 50 variables for each channel and eliminate duplicates to form the final list.

- use 1/3 of all signal and background events as training sample
- Train 24 trees
  - tb+tqb; e,μ
  - 2,3,4 jets; 1,2 b-tags
  - pre/post Silicon layer0 det configuration

- search for combined tb+tqb

boosted decision trees

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)

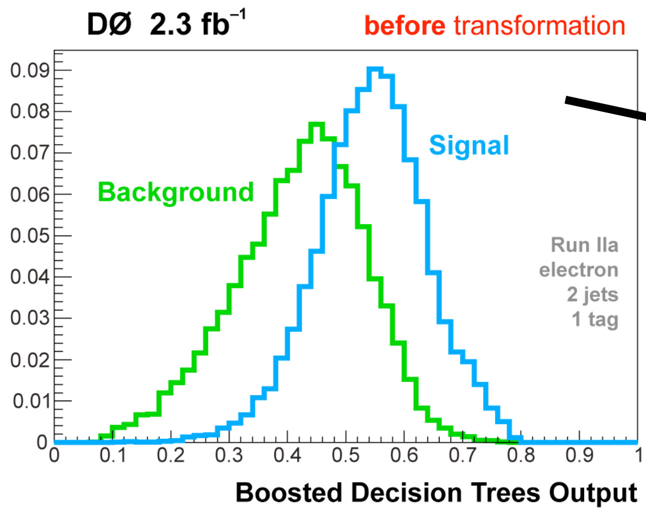
Best Variables to Separate
Single Top from Top Pairs

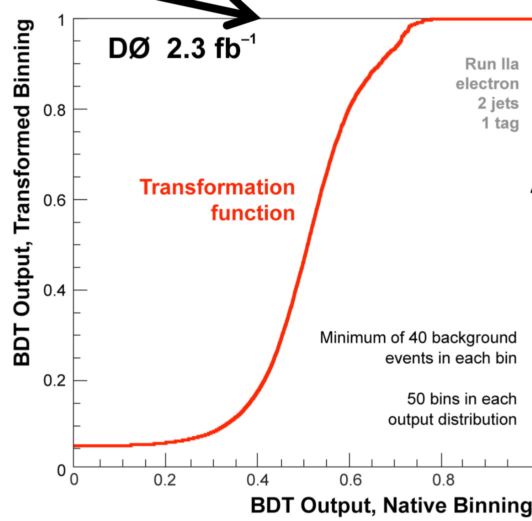
DØ 2.3 fb^{-1} Analysis

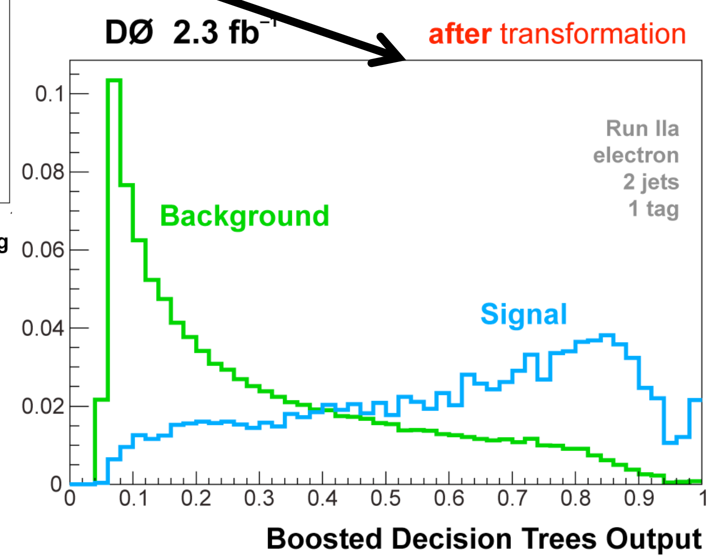
Object kinematics	pT(notbest2)
	pT(jet4)
	pT(light2)
Event kinematics	M(alljets–tag1)
	Centrality(alljets)
	M(alljets–best1)
	H_T(alljets–tag1)
	H_T(lepton,$\not\!\!E_T$,alljets)
	M(alljets)
Jet reconstruction	Width_η(jet4)
	Width_ϕ(jet4)
	Width_ϕ(jet2)
Angular correlations	cos(lepton$_{btaggedtop}$,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

boosted decision trees

- Apply a transformation to the raw discriminant in order to ensure sufficient number of background events in each bin.
  – provides stability in the final cross section measurement calculation.

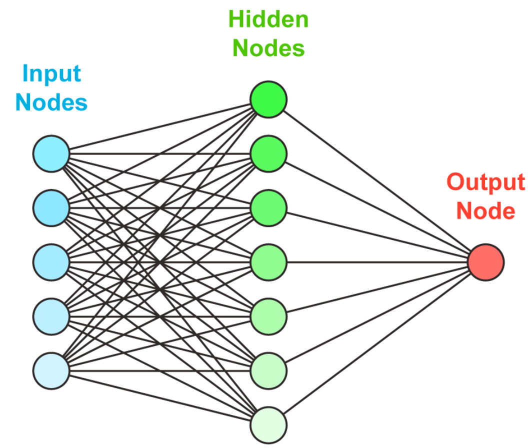


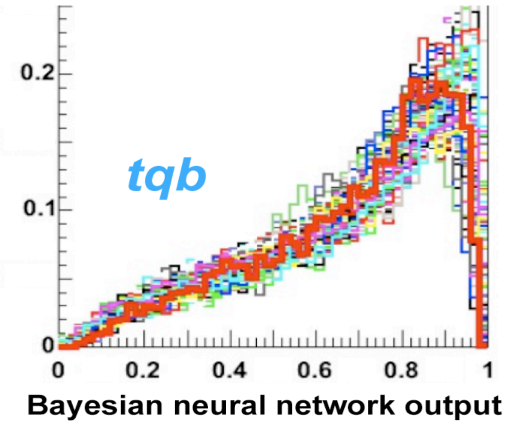


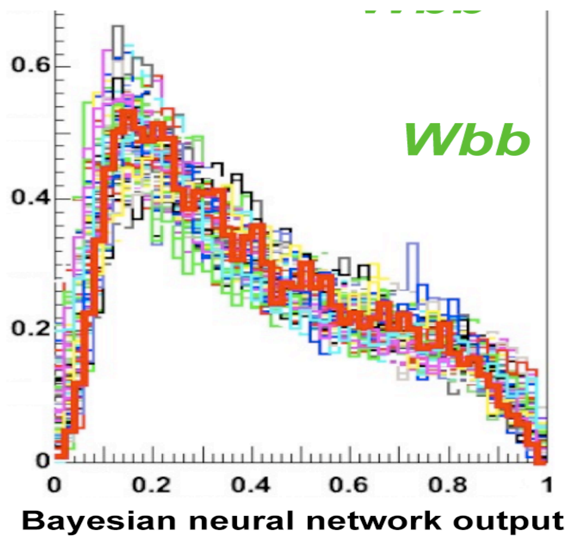


bayesian neural networks

- Neural networks are nonlinear functions
  - defined by weights associated with each node
  - weights are determined by training on signal and background samples
- Bayesian neural networks improve on this technique
  - average over many networks weighted by the probability of each network given the training samples
  - Less prone to over-training
  - Network structure is less important – can use larger numbers of variables and hidden nodes
- For this analysis:
  - Uses highest ranked 18-28 variables in each channel
    - Selected from 600 variables based on KS values and importance ranking
  - 20 hidden nodes
  - 100 training iterations
  - each iteration is the average of 20 training cycles
  - Backgrounds are combined for training
- response verified with ensembles
  - linearity, unit slope, near-zero intercept



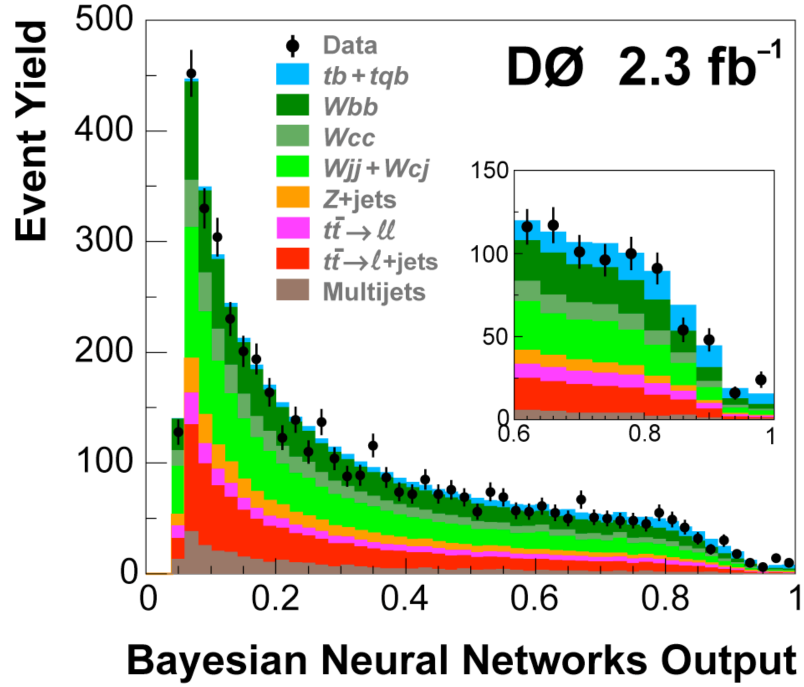




bayesian neural networks

- list of variables
  - example from one channel.

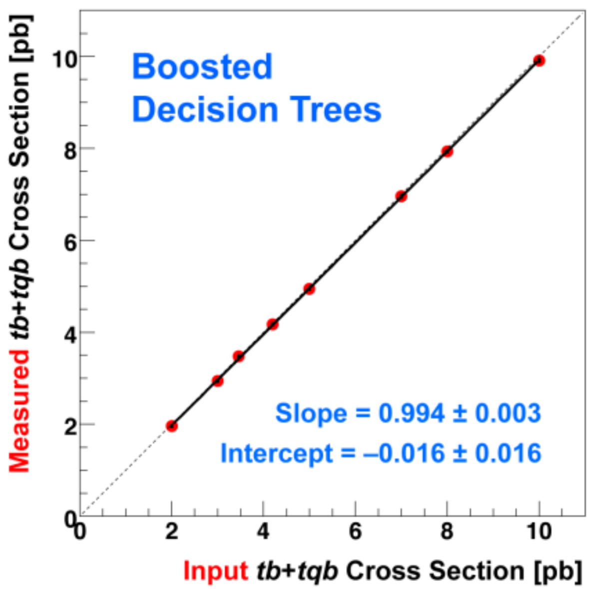
Rank	Variable
1	$M(\text{jet1},\text{jet2})$
2	$M_T(W)$
3	$M_{top}(W,\text{tag1})$
4	$\Delta\ \mathrm{M}_{top}^{min}$
5	$H_T(\text{lepton},\not{E}_T,\text{jet1},\text{jet2})$
6	$M_{top}(W,\text{tag1},S2)$
7	$\not{E}_T$
8	$Q(\text{lepton})\times\eta(\text{light1})$
9	$\cos(\text{lepton}_{\text{btaggedtop}},\text{btaggedtop}_{\text{CMframe}})$
10	$\cos(\text{tag1},\text{lepton})_{\text{btaggedtop}}$
11	$p_T(\text{jet1})$
12	$\text{Width}_\eta(\text{jet2})$
13	$\Delta\phi(\text{lepton},\not{E}_T)$
14	$\text{Width}_\phi(\text{jet2})$
15	$p_T(\text{jet2})$
16	$Q(\text{lepton})\times\eta(\text{best1})$
17	$E(\text{jet2})$
18	$p_T(\text{best1})$
19	$p_T^{rel}(\text{jet1},\mu)$
20	$\cos(\text{light1},\text{lepton})_{\text{btaggedtop}}$
21	$\cos(\text{lepton},Q(\text{lepton})\times z)_{\text{besttop}}$



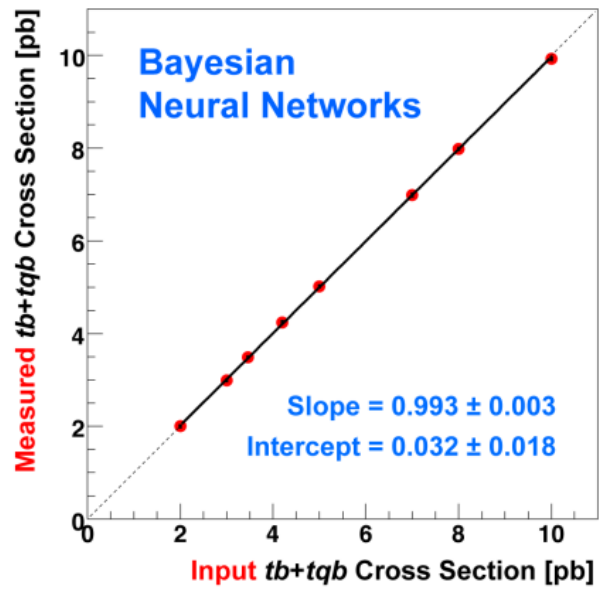
- final discriminant
  - after binning transformation similar to BDT

response validation

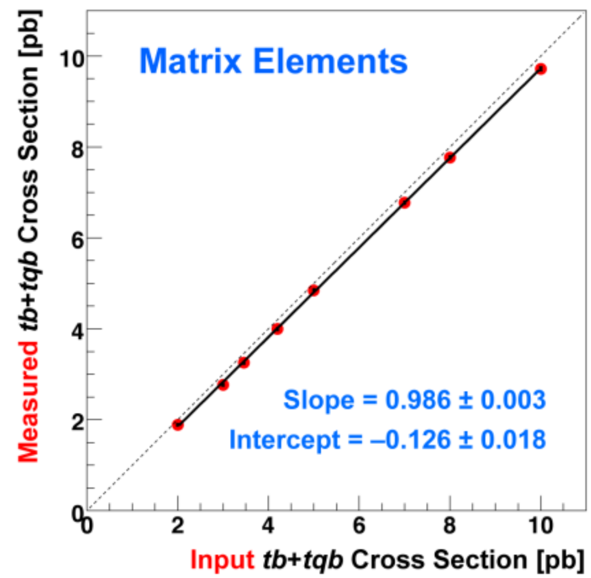
- measure response using ensembles of pseudo data experiments



BDT



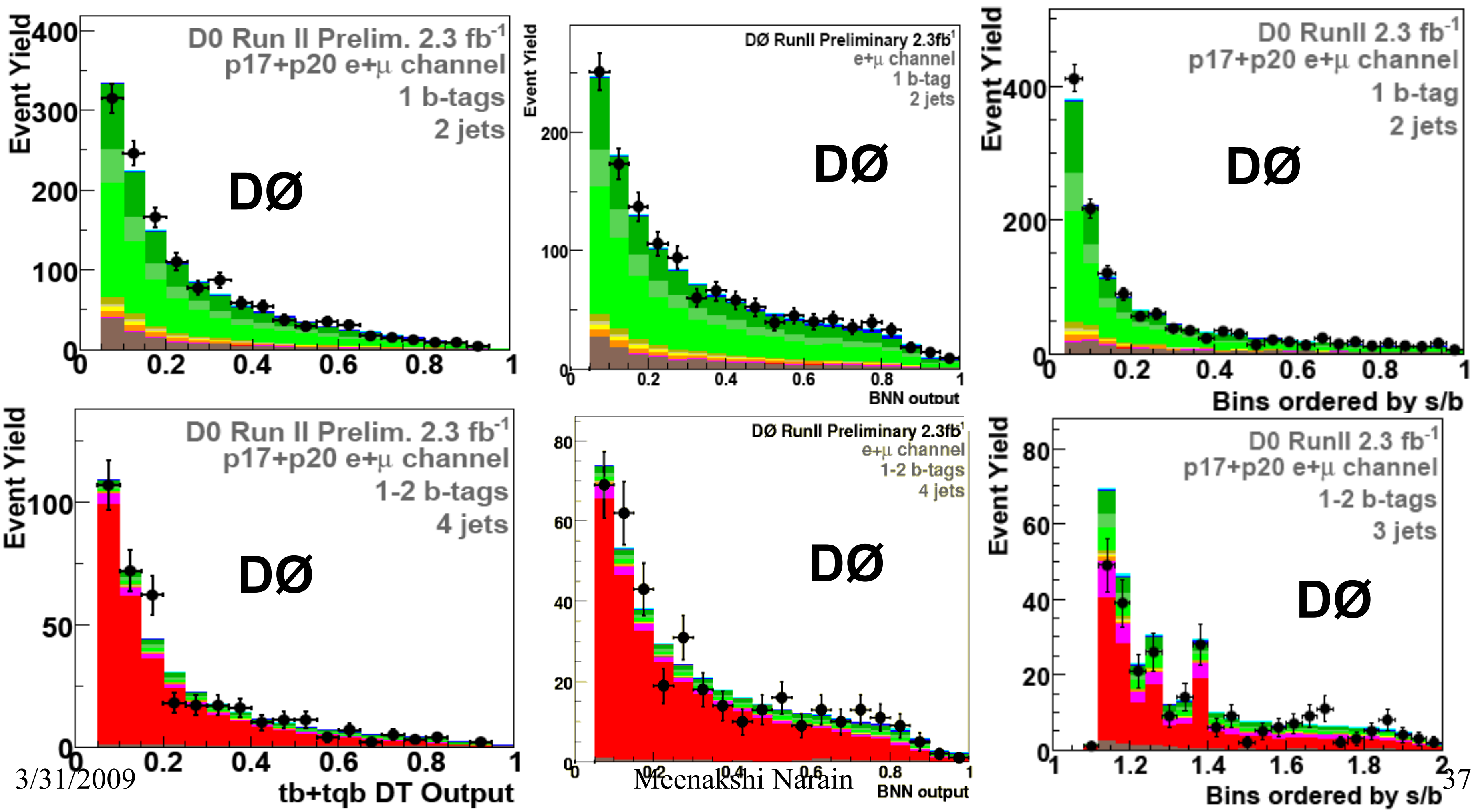
BNN



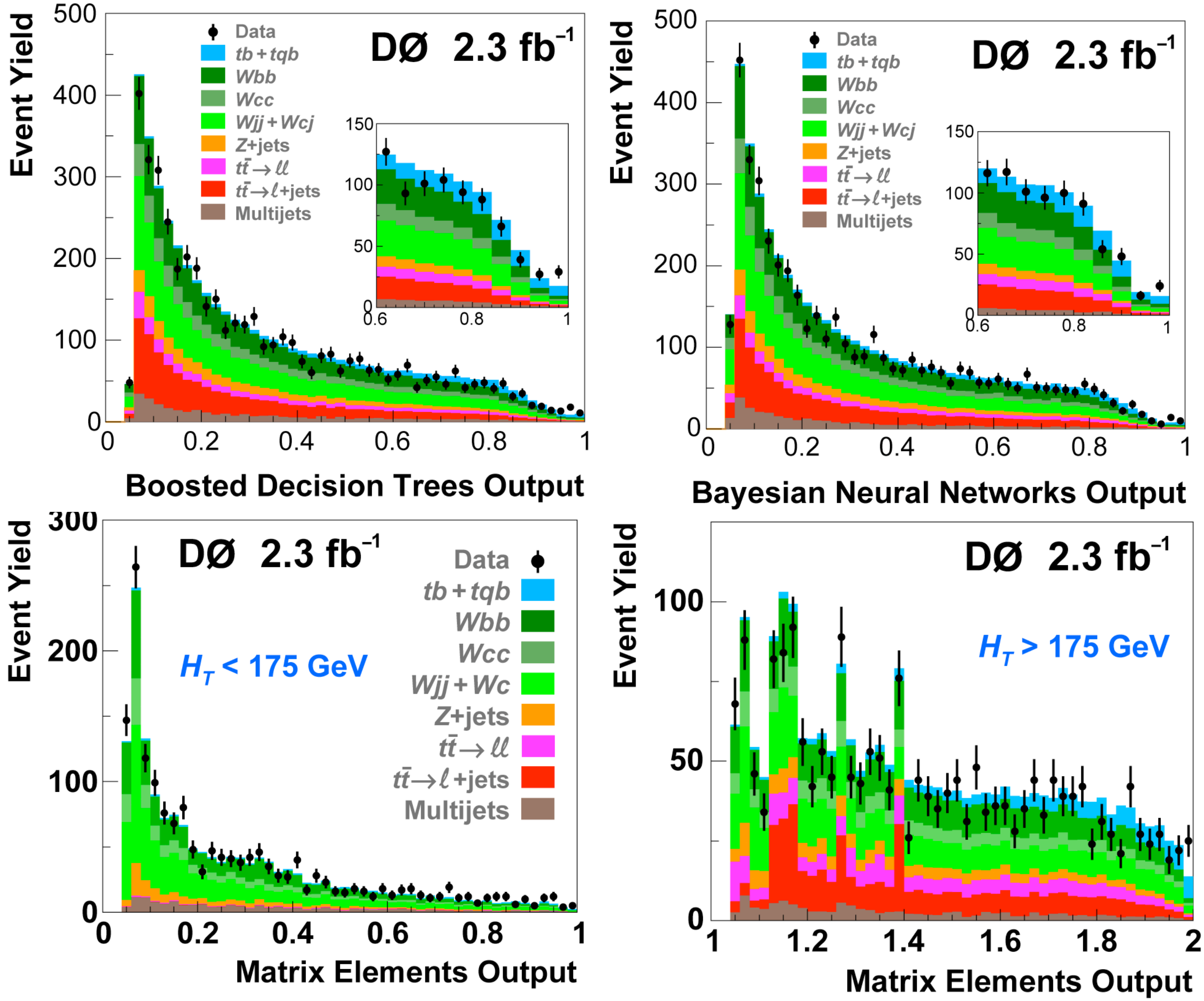
ME

discriminant validation

- Cross check performance in background dominated regions.
  - soft W+jets: 2 jets, 1 b-tag, H_T < 175 GeV
  - ttbar samples/hard W+jets: 4 jets, 1-2 b-tags, H_T > 300 GeV



final discriminant for the 3 methods



Signal normalized to measured x-sec

Systematic uncertainties

Systematic Uncertainties

Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

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

Systematic Uncertainties

Ranked from Largest to Smallest Effect on Single Top Cross Section

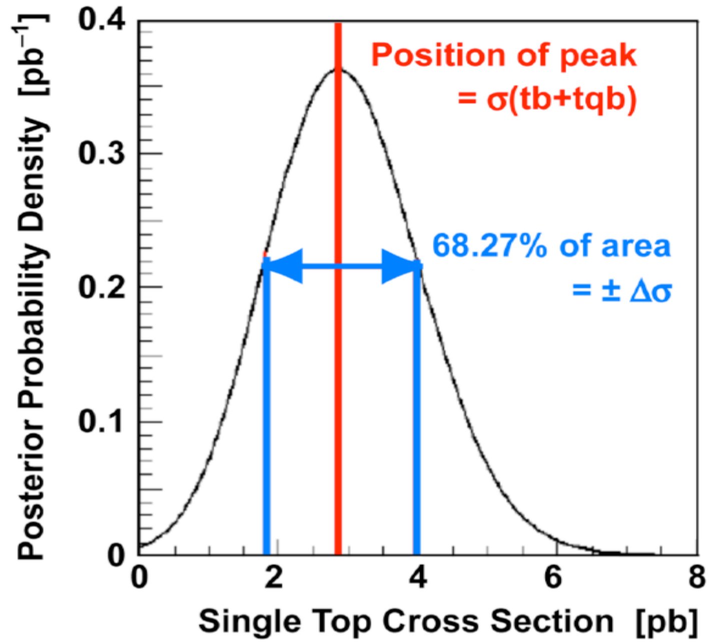
DØ 2.3 fb^{-1}

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

cross section measurement

• Cross Sections are measured by building a Bayesian posterior probability density

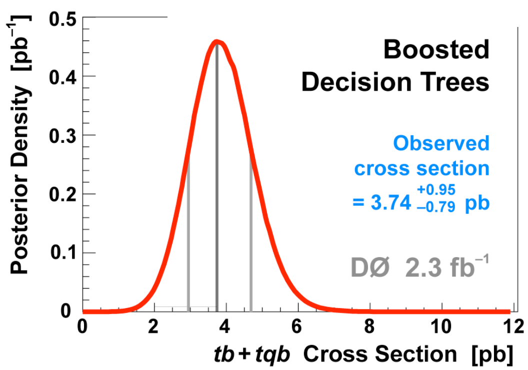
• For each analysis, the single top cross section is given by the position of the posterior density peak, with 68% asymmetric interval as uncertainty

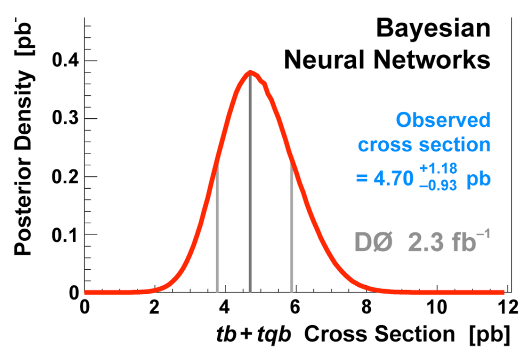


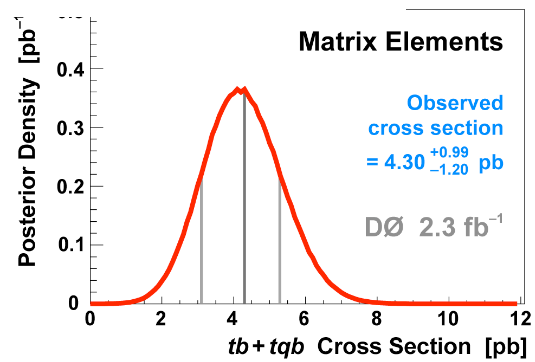
- Gaussian prior for systematic uncertainties
  - Correlations of uncertainties properly taken into account
- Flat prior in signal cross sections
- Significance derived from background-only pseudo-datasets

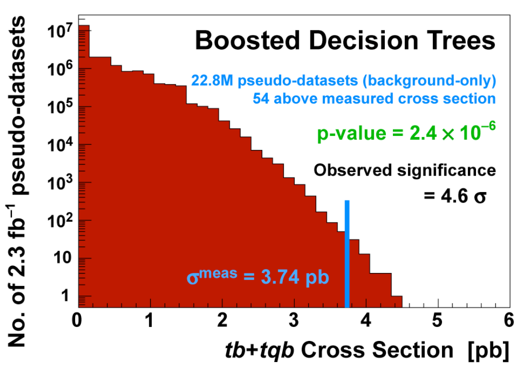
cross section results

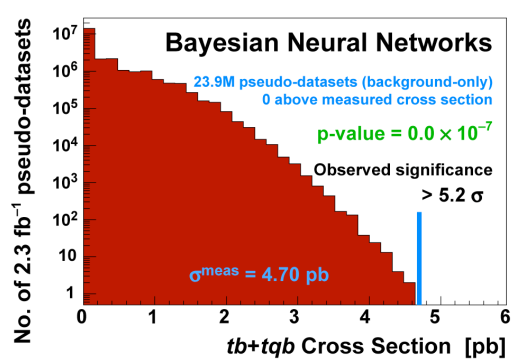
DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	$3.74^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70^{+1.18}_{-0.93}$ pb	4.1 σ	5.2 σ
Matrix Elements	$4.30^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ

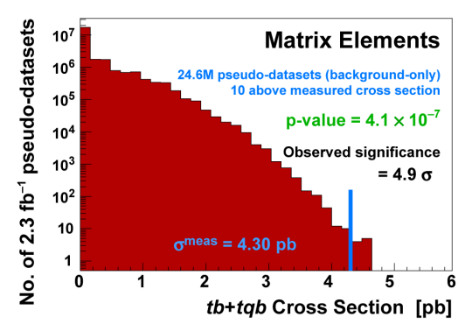






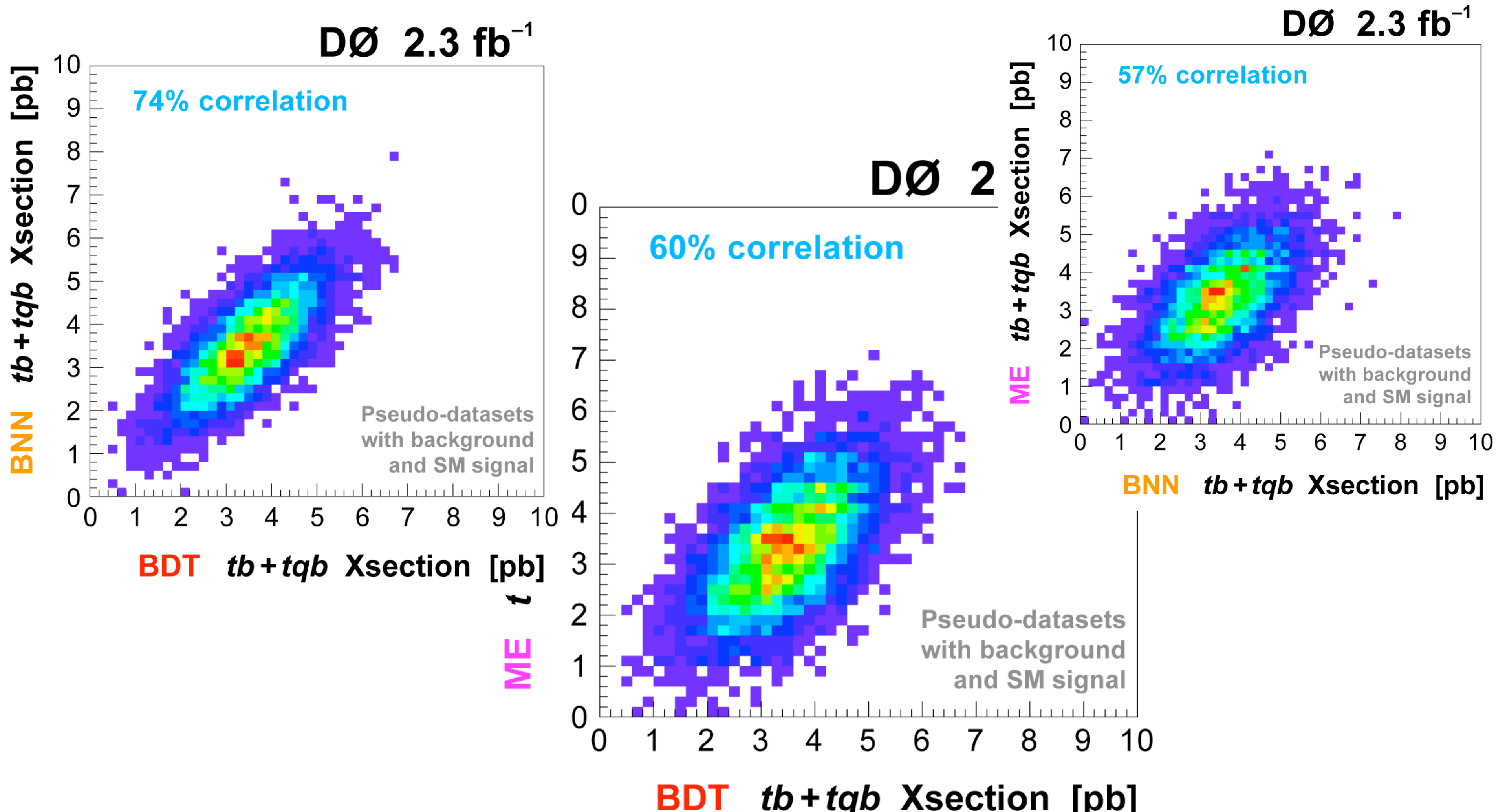






correlations between methods

- Even though all MVA analyses use the same data, they are not 100% correlated

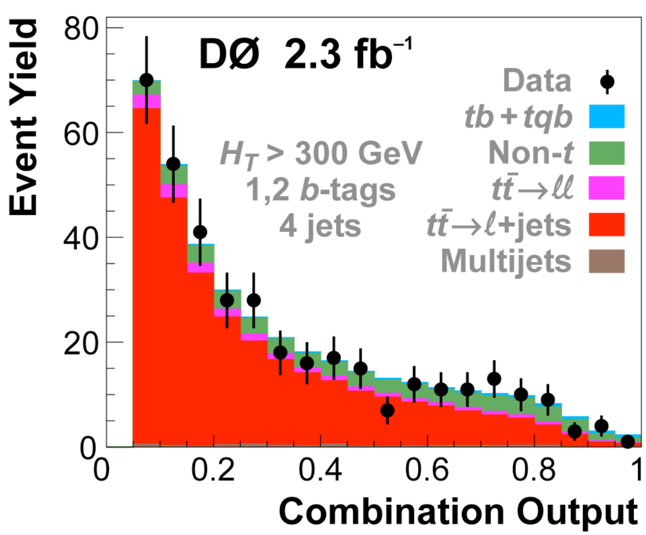


combination of results

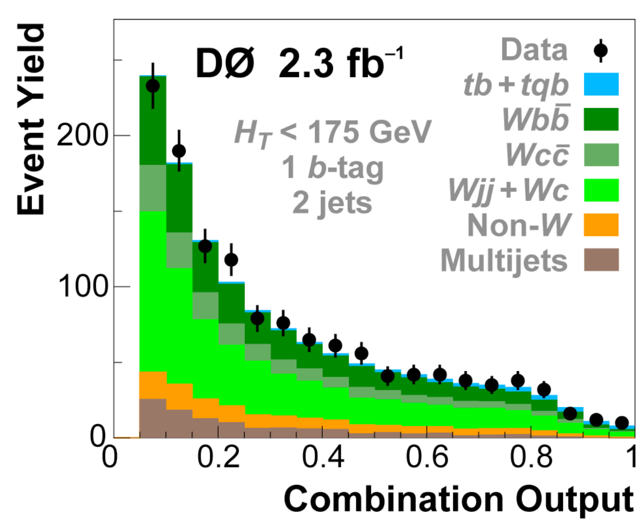
- We use a BNN to combine the three methods. The BNN takes as input variables the output discriminants of the individual methods
- Expected sensitivity for the BNN Combination: **4.5 σ**
- BLUE combination (used in 2006) now presented as a cross check

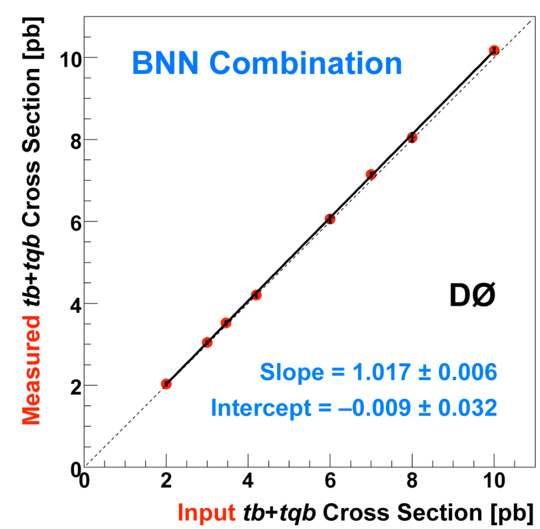
CROSS CHECK SAMPLES AND LINEARITY

***tt*-Pairs Cross-Check Sample**



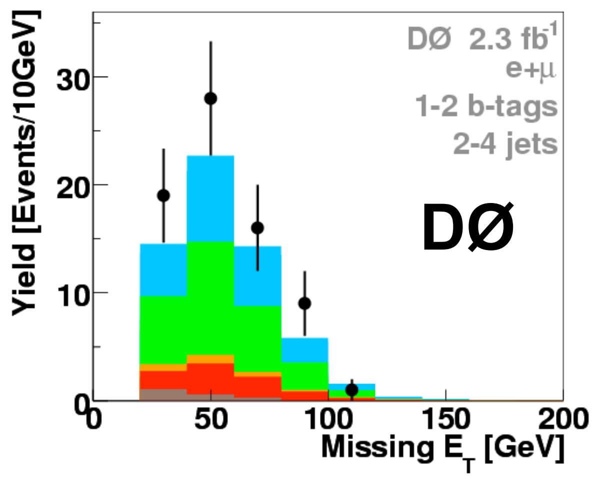
***W*+Jets Cross-Check Sample**



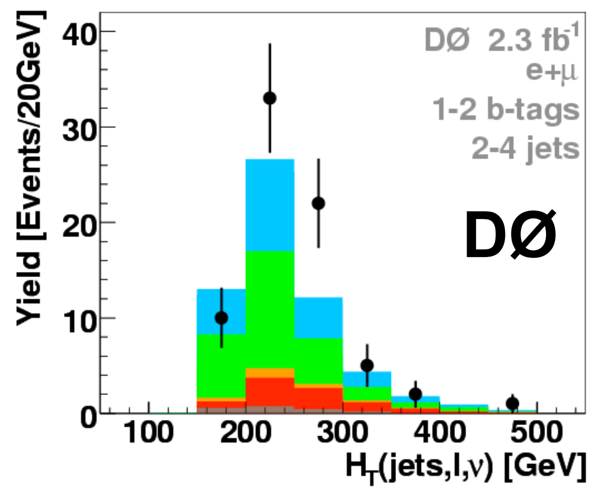


distributions for comb > 0.9

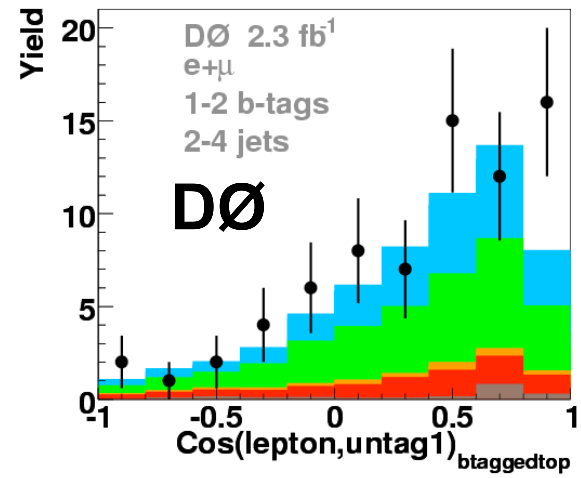
OBJECT KINEMATICS



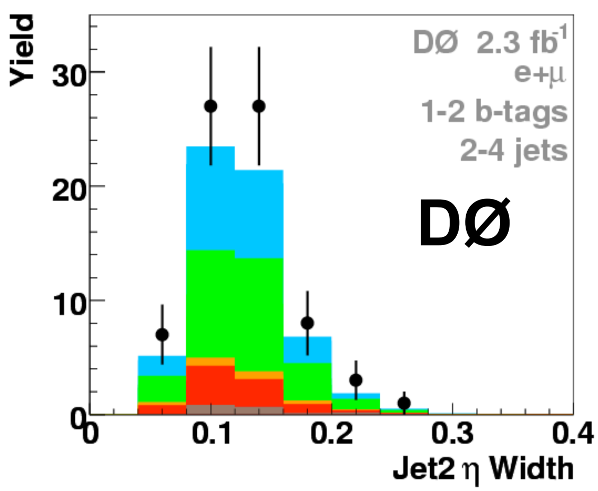
EVENT KINEMATICS



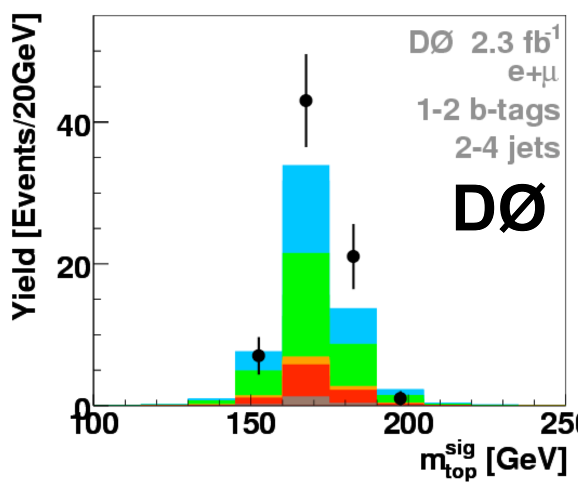
ANGULAR CORRELATIONS



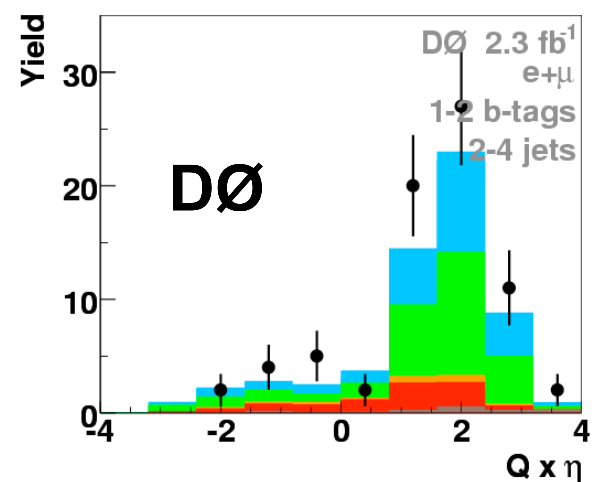
JET RECONSTRUCTION



TOP QUARK RECONSTRUCTION

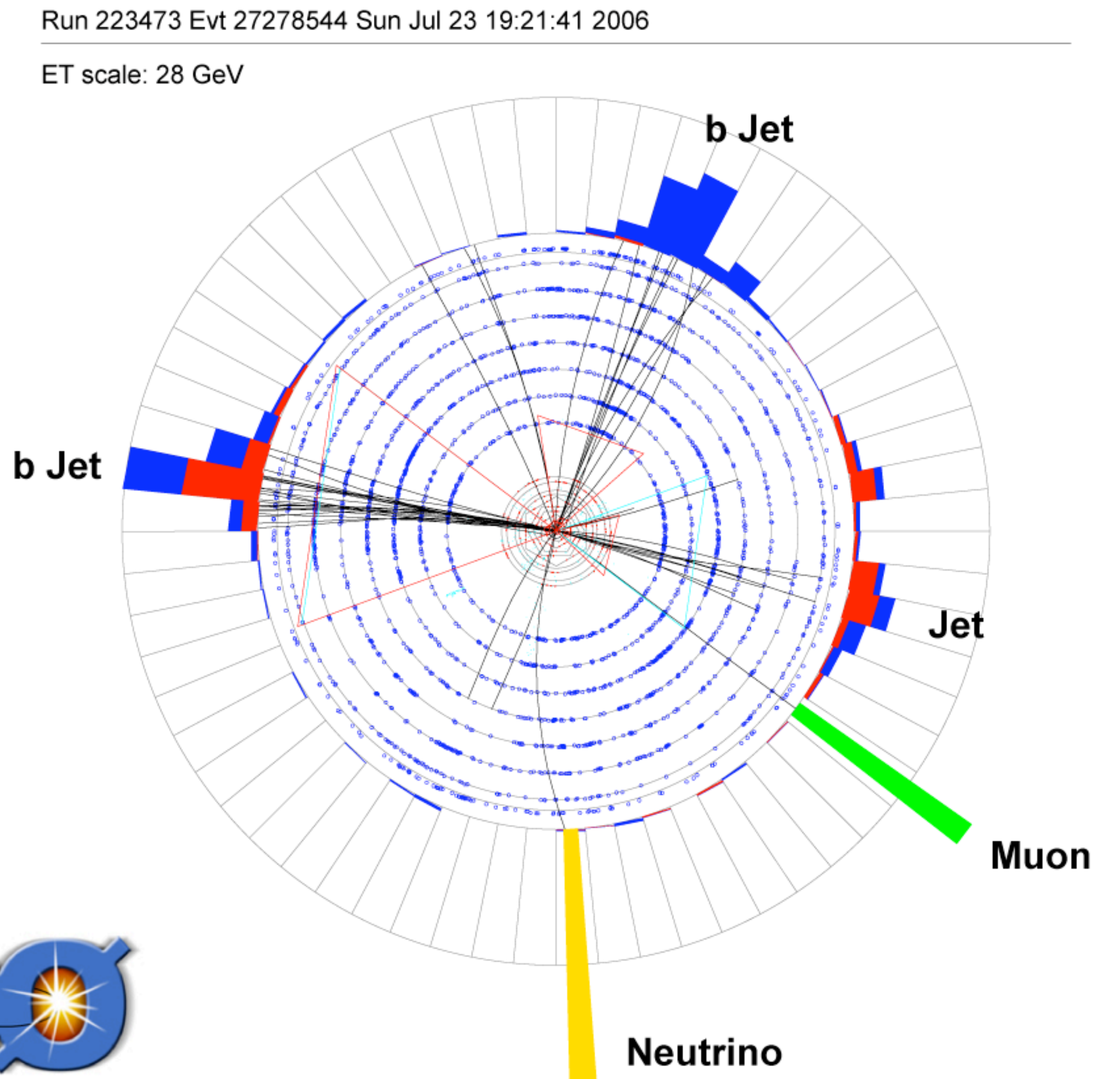


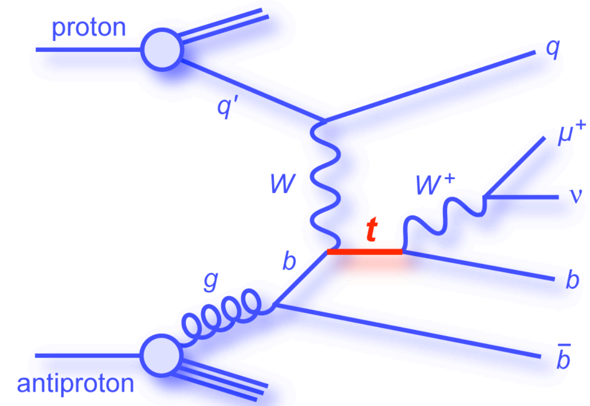
SINGLE TOP FINAL STATE



DØ Experiment Event Display

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

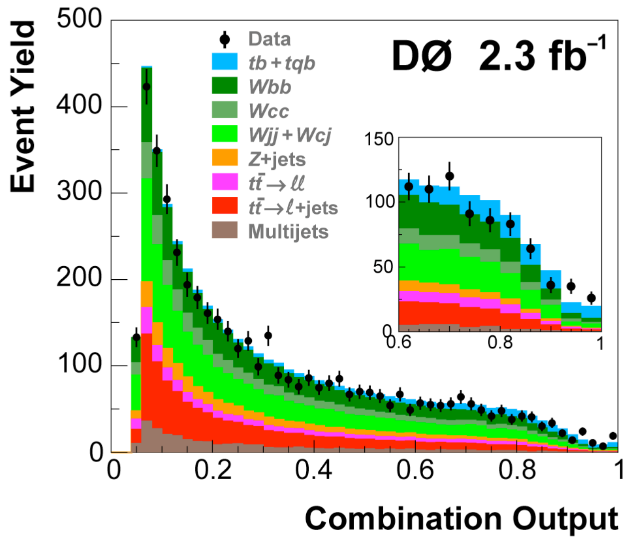


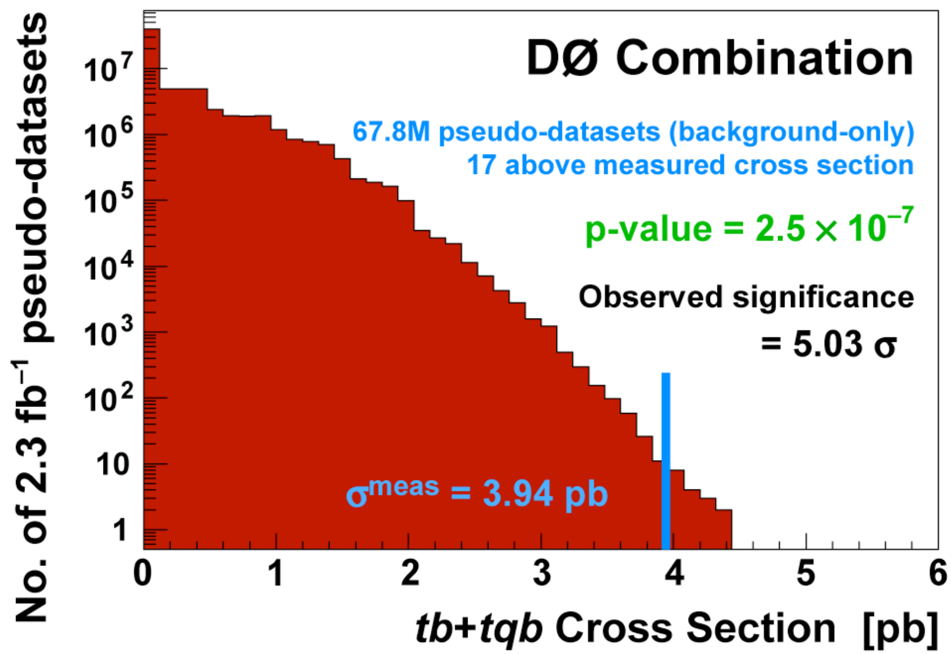


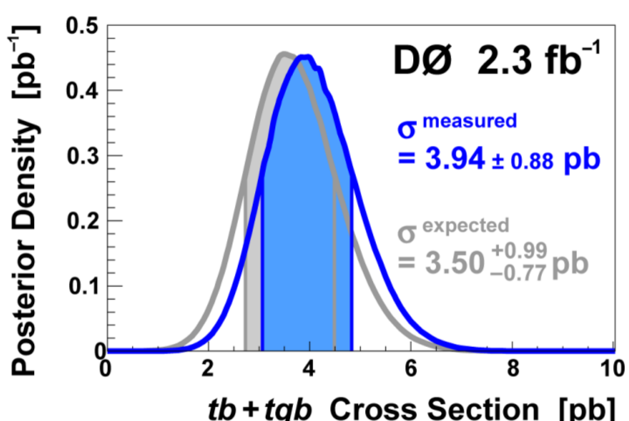
Combined results

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

(m_t=170GeV)



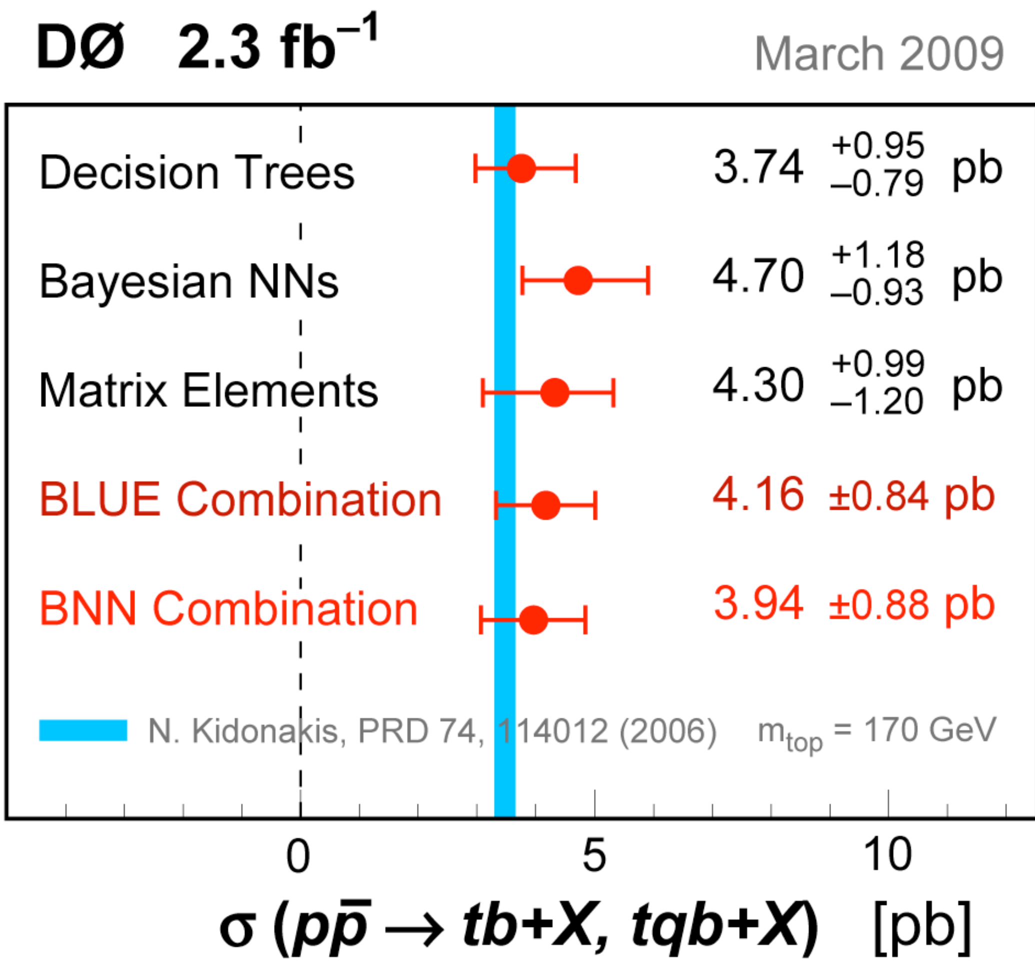




$$p - value = 2.5 \times 10^{-7}$$

Measured Significance = 5.03σ

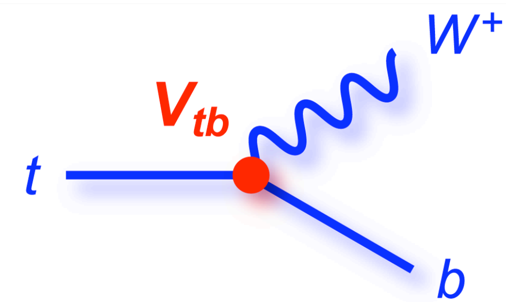
cross section summary



Significance	
Expected	Measured
4.3 σ	4.6 σ
4.1 σ	5.2 σ
4.1 σ	4.9 σ
4.5 σ	**5.0 σ**

CKM matrix element Vtb

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



- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- general form of Wtb vertex:

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

- assume
  - sm top quark decay : $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
  - pure V–A : $f_1^R = 0$
  - CP conservation : $f_2^L = f_2^R = 0$
- do not assume
  - three quark families
  - CKM matrix unitarity
  - (unlike for measurements using tt decays)

measurement of $|V_{tb}|$

- Use the measurement of the single top cross section to make a direct measurement of $|V_{tb}|$:

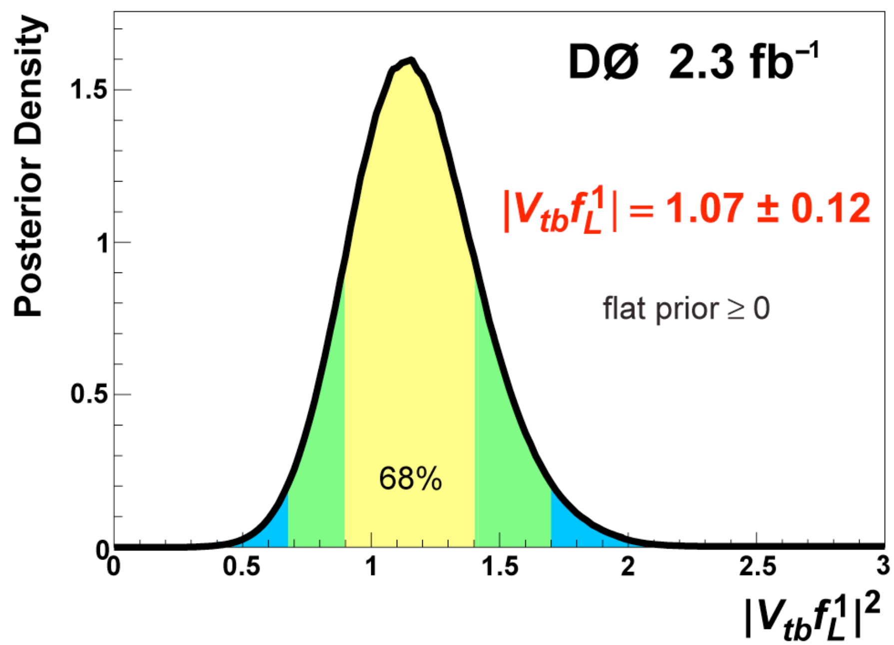
$$\sigma(\mathrm{tb,\ tqb}) \propto \left|V_{tb} f_1^{\,L}\right|^2$$

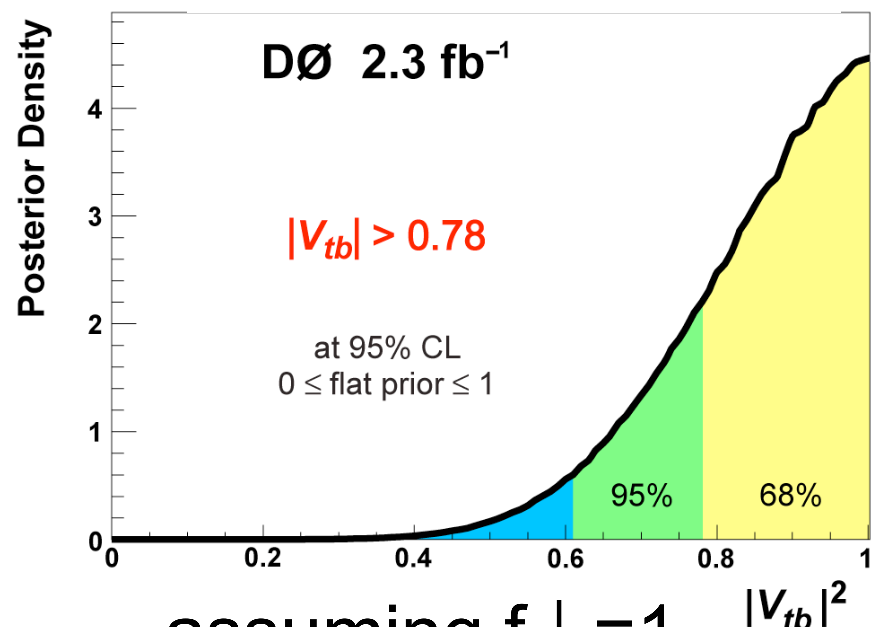
  – Calculate a posterior in $|V_{tb} f_1^L|^2$
  – Measure the strength of the V–A coupling, which can be > 1

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%





assuming $f_1^L = 1$

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 5.03σ

- 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

http://arxiv.org/abs/0903.0850 submitted to PRL