Observation of Single Top Quark Production

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for the DØ collaboration

Wine & Cheese Seminar

Fermilab

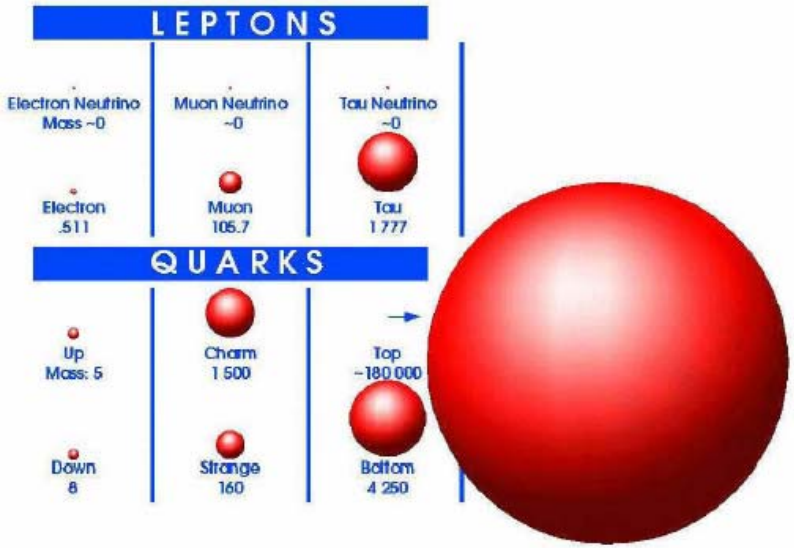
March 10, 2009

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 $|V_{tb}|$
- Conclusions

Why Study the Top Quark?

- Predicted by the SM and discovered in 1995 by CDF and DØ
  - $m_t = 172.4 \pm 1.2$ GeV
- Top-Higgs Yukawa coupling ≈ 1
  - may help identify the mechanism of EWSB and mass generation
  - may serve as a window to new physics that might couple preferentially to top

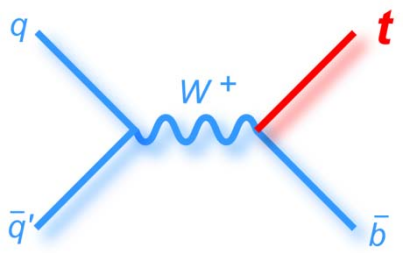


- Successful Tevatron top quark program
  - High precision measurements for the top quark mass, top pair production cross section and decay properties
- Some basic quantities still unmeasured: spin, width, lifetime
- Single top quark production predicted by the SM, had not been observed till now

Single Top Production

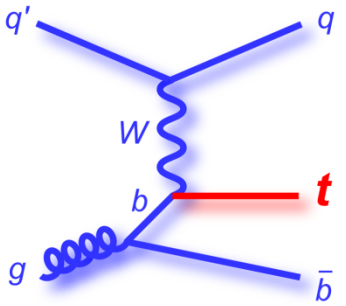
- Probe of the Wtb interaction with no assumption on the number of quark families or unitarity of the CKM matrix

- 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



s-channel

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

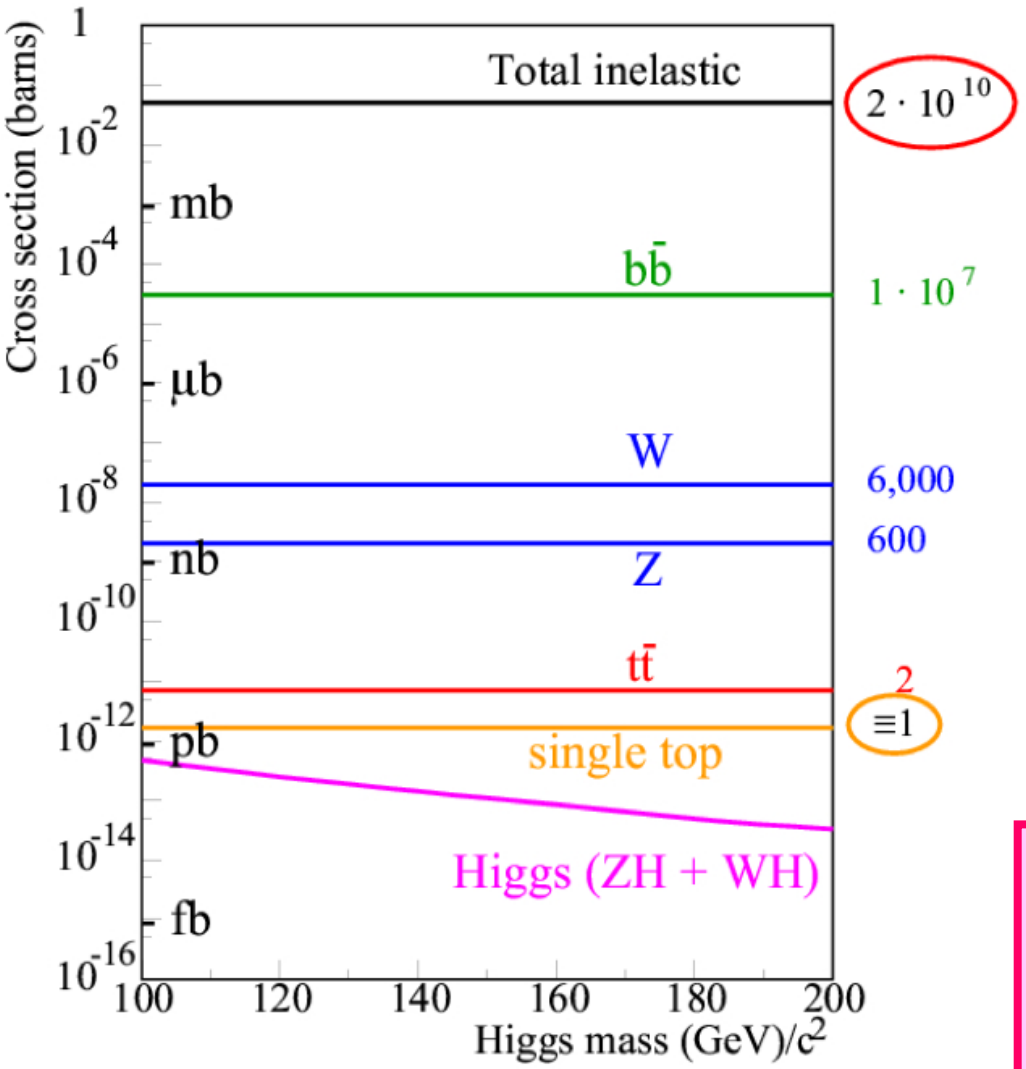


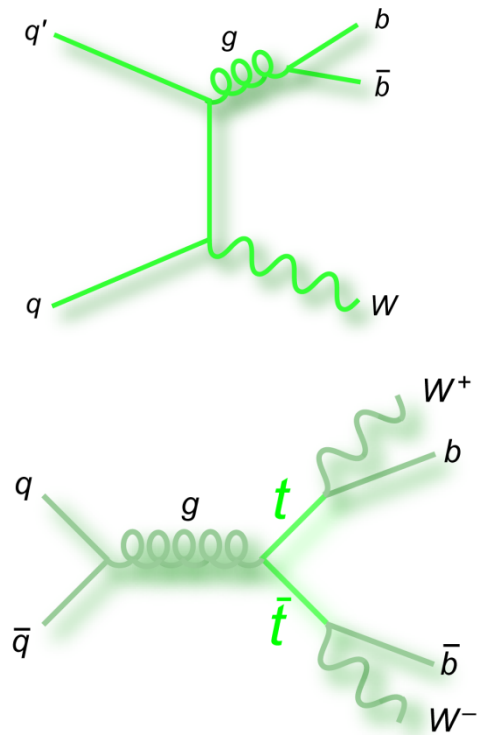
t-channel

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

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

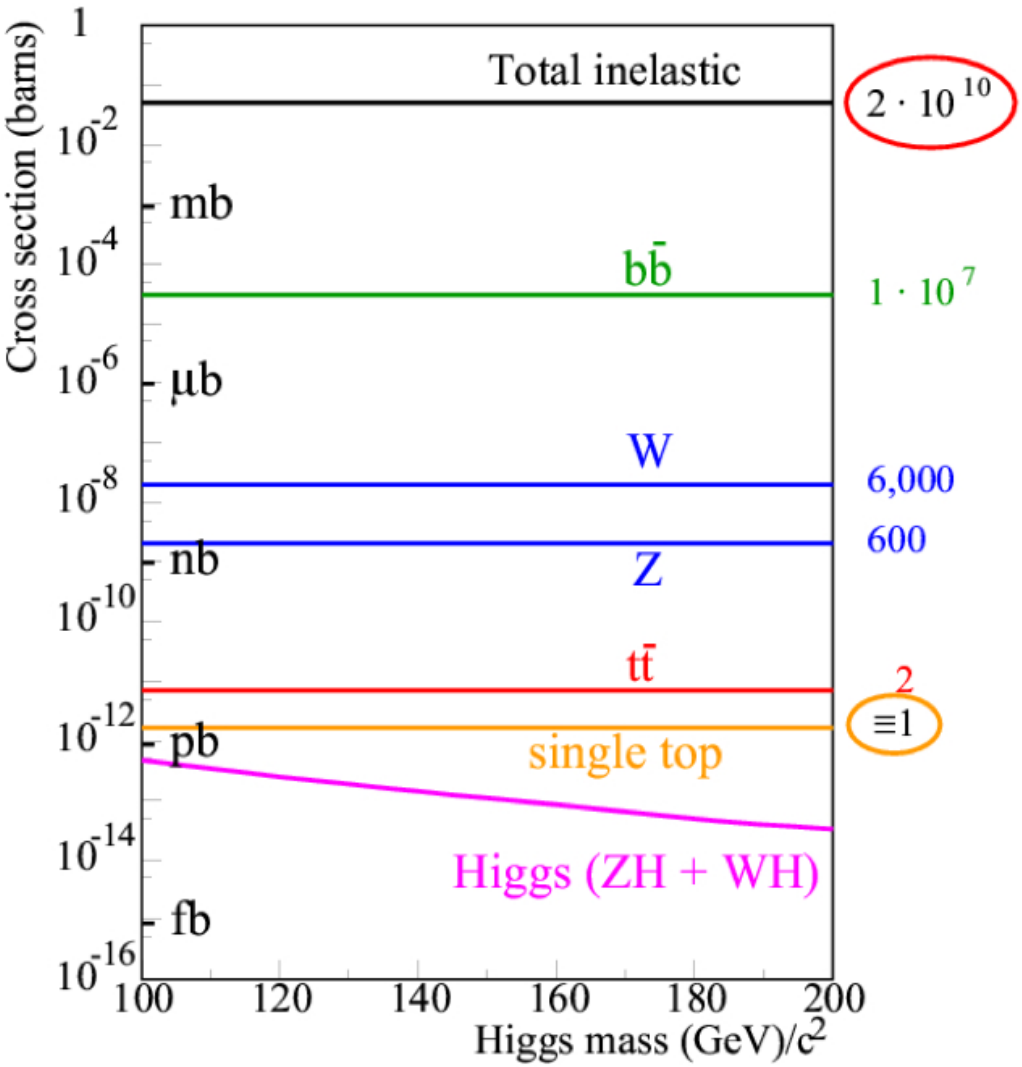
Experimentally very challenging





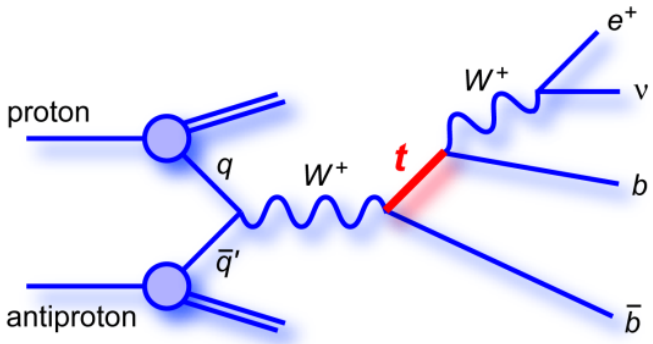
Simple counting experiment cannot extract the signal from the overwhelming background

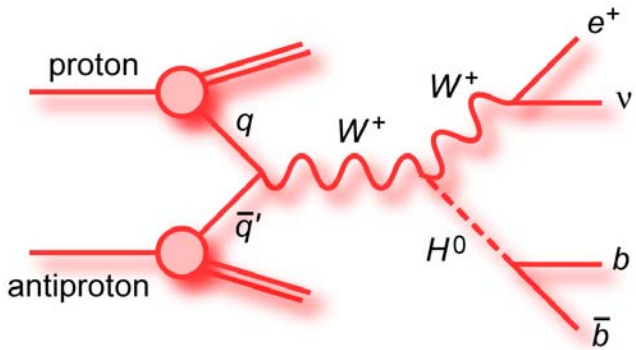
Experimentally very challenging



Same final state as WH

- Backgrounds are the same
- Test of techniques to extract small signal from a large background



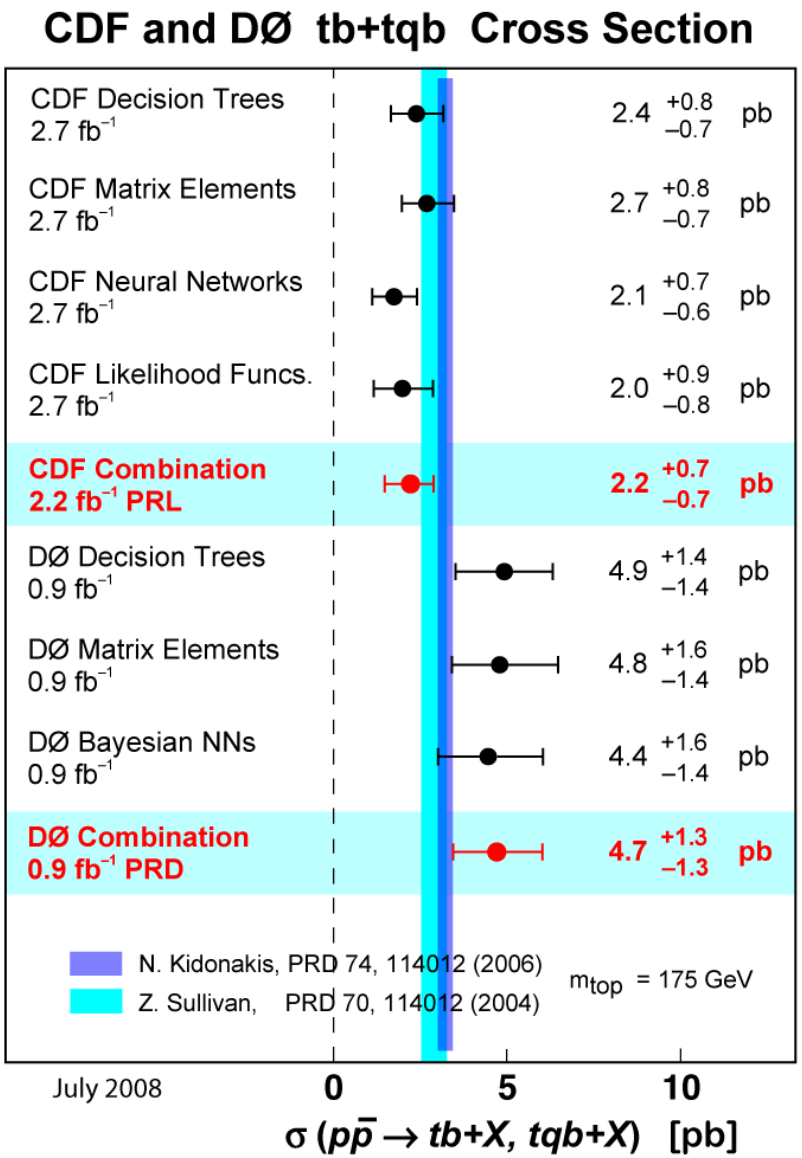


Evidence for Single Top Production

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



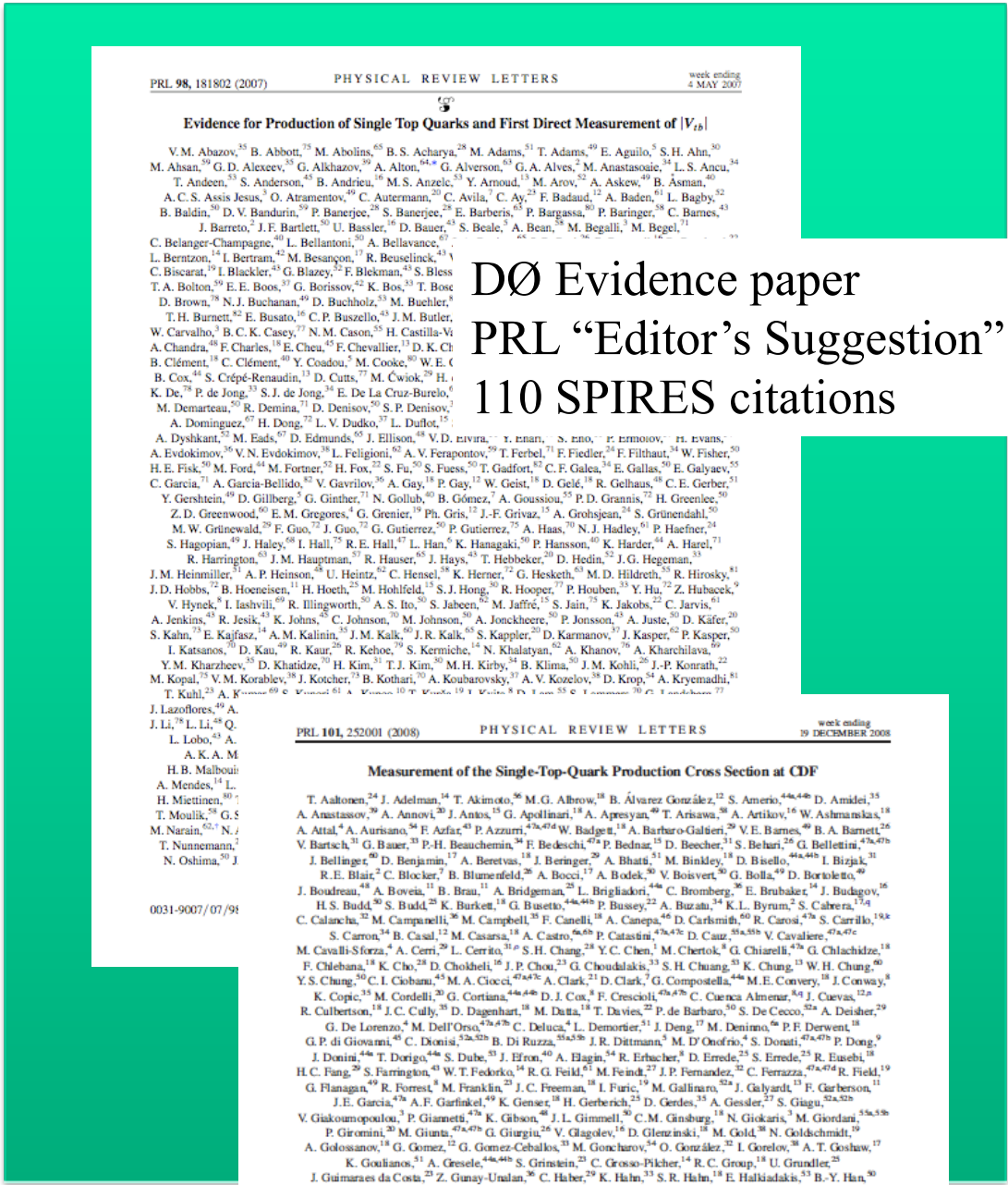
Culmination of a Long History

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**


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,[50] M. Ahsan,[59] G.D. Alexeev,[35] G. Alkhazov,[39] A. Alton,[64,*] G. Alverson,[63] G.A. Alves,[2] M. Anastasoaie,[34] L.S. Ancu,[34] T. Andeen,[53] S. Anderson,[45] B. Andrieu,[16] M.S. Anzelc,[53] Y. Arnoud,[13] M. Arov,[52] A. Askew,[49] B. Åsman,[40] A.C.S. Assis Jesus,[3] O. Atramentov,[49] C. Autermann,[20] C. Avila,[7] C. Ay,[23] F. Badaud,[12] A. Baden,[61] L. Bagby,[52] B. Baldin,[50] D.V. Bandurin,[59] P. Banerjee,[28] S. Banerjee,[28] E. Barberis,[63] P. Bargassa,[80] P. Baringer,[58] C. Barnes,[43] J. Barreto,[2] J.F. Bartlett,[50] U. Bassler,[16] D. Bauer,[43] S. Beale,[5] A. Bean,[58] M. Begalli,[3] M. Begel,[71] C. Belanger-Champagne,[40] L. Bellantoni,[50] A. Bellavance,[67] L. Berntzon,[14] I. Bertram,[42] M. Besançon,[17] R. Beuselinck,[43] C. Biscarat,[19] I. Blackler,[43] G. Blazey,[52] F. Blekman,[43] S. Bless T. A. Bolton,[59] E.E. Boos,[37] G. Borissov,[42] K. Bos,[33] T. Bose D. Brown,[78] N.J. Buchanan,[49] D. Buchholz,[53] M. Buehler,[8] T.H. Burnett,[82] E. Busato,[16] C.P. Buszello,[43] J.M. Butler, W. Carvalho,[3] B.C.K. Casey,[77] N.M. Cason,[55] H. Castilla-Va A. Chandra,[48] F. Charles,[18] E. Cheu,[45] F. Chevallier,[13] D.K. Ch B. Clément,[18] C. Clément,[40] Y. Coadou,[5] M. Cooke,[80] W. E. C B. Cox,[44] S. Crépé-Renaudin,[13] D. Cutts,[77] M. Ćwiok,[29] H. K. De,[78] P. de Jong,[33] S.J. de Jong,[34] E. De La Cruz-Burelo, M. Demarteau,[50] R. Demina,[71] D. Denisov,[50] S.P. Denisov, A. Dominguez,[67] H. Dong,[72] L.V. Dudko,[37] L. Duflot,[15] A. Dyshkant,[52] M. Eads,[67] D. Edmunds,[65] J. Ellison,[48] V.D. Elvira, Y. Enari, S. Eno, P. Ermolov, H. Evans, A. Evdokimov,[38] V.N. Evdokimov,[38] L. Feligioni,[62] A.V. Ferapontov,[59] T. Ferbel,[71] F. Fiedler,[24] F. Filthaut,[34] W. Fisher,[50] H.E. Fisk,[50] M. Ford,[44] M. Fortner,[52] H. Fox,[22] S. Fu,[50] S. Fuess,[50] T. Gadfort,[82] C.F. Galea,[34] E. Gallas,[50] E. Galyaev,[55] C. Garcia,[71] A. Garcia-Bellido,[82] V. Gavrilov,[36] A. Gay,[18] P. Gay,[12] W. Geist,[18] D. Gelé,[18] R. Gelhaus,[48] C.E. Gerber,[51] Y. Gershtein,[49] D. Gillberg,[5] G. Ginther,[71] N. Gollub,[40] B. Gómez,[7] A. Goussiou,[55] P.D. Grannis,[72] H. Greenlee,[50] Z.D. Greenwood,[60] E.M. Gregores,[4] G. Grenier,[19] Ph. Gris,[12] J.-F. Grivaz,[15] A. Grohsjean,[24] S. Grünendahl,[50] M.W. Grünewald,[29] F. Guo,[72] J. Guo,[72] G. Gutierrez,[50] P. Gutierrez,[75] A. Haas,[70] N.J. Hadley,[61] P. Haefner,[24] S. Hagopian,[49] J. Haley,[68] I. Hall,[75] R.E. Hall,[47] L. Han,[6] K. Hanagaki,[50] P. Hansson,[40] K. Harder,[44] A. Harel,[71] R. Harrington,[63] J.M. Hauptman,[57] R. Hauser,[65] J. Hays,[43] T. Hebbeker,[20] D. Hedin,[52] J.G. Hegeman,[33] J.M. Heinmiller,[51] A.P. Heinson,[48] U. Heintz,[62] C. Hensel,[58] K. Herner,[72] G. Hesketh,[63] M.D. Hildreth,[55] R. Hirosky,[81] J.D. Hobbs,[72] B. Hoeneisen,[11] H. Hoeth,[25] M. Hohlfeld,[15] S.J. Hong,[30] R. Hooper,[77] P. Houben,[33] Y. Hu,[72] Z. Hubacek,[9] V. Hynek,[8] I. Iashvili,[69] R. Illingworth,[50] A.S. Ito,[50] S. Jabeen,[62] M. Jaffré,[15] S. Jain,[75] K. Jakobs,[22] C. Jarvis,[61] A. Jenkins,[43] R. Jesik,[43] K. Johns,[45] C. Johnson,[70] M. Johnson,[50] A. Jonckheere,[50] P. Jonsson,[43] A. Juste,[50] D. Käfer,[20] S. Kahn,[73] E. Kajfasz,[14] A.M. Kalinin,[35] J.M. Kalk,[60] J.R. Kalk,[65] S. Kappler,[20] D. Karmanov,[37] J. Kasper,[62] P. Kasper,[50] I. Katsanos,[70] D. Kau,[49] R. Kaur,[26] R. Kehoe,[79] S. Kermiche,[14] N. Khalatyan,[62] A. Khanov,[76] A. Kharchilava,[69] Y.M. Kharzheev,[35] D. Khatidze,[70] H. Kim,[31] T.J. Kim,[30] M.H. Kirby,[34] B. Klima,[50] J.M. Kohli,[26] J.-P. Konrath,[22] M. Kopal,[75] V.M. Korablev,[38] J. Kotcher,[73] B. Kothari,[70] A. Koubarovsky,[37] A.V. Kozelov,[38] D. Krop,[54] A. Kryemadhi,[81] T. Kuhl,[23] A. K J. Lazoflores,[49] A. J. Li,[78] L. Li,[48] Q. L. Lobo,[43] A. A. K. A. M H. B. Malboui A. Mendes,[14] L. H. Miettinen, T. Moulik,[58] G. S M. Narain,[52,*] N. T. Nunnemann, N. Oshima,[50] J.

0031-9007/07/98

PRL 101, 252001 (2008) PHYSICAL REVIEW LETTERS week ending 19 DECEMBER 2008

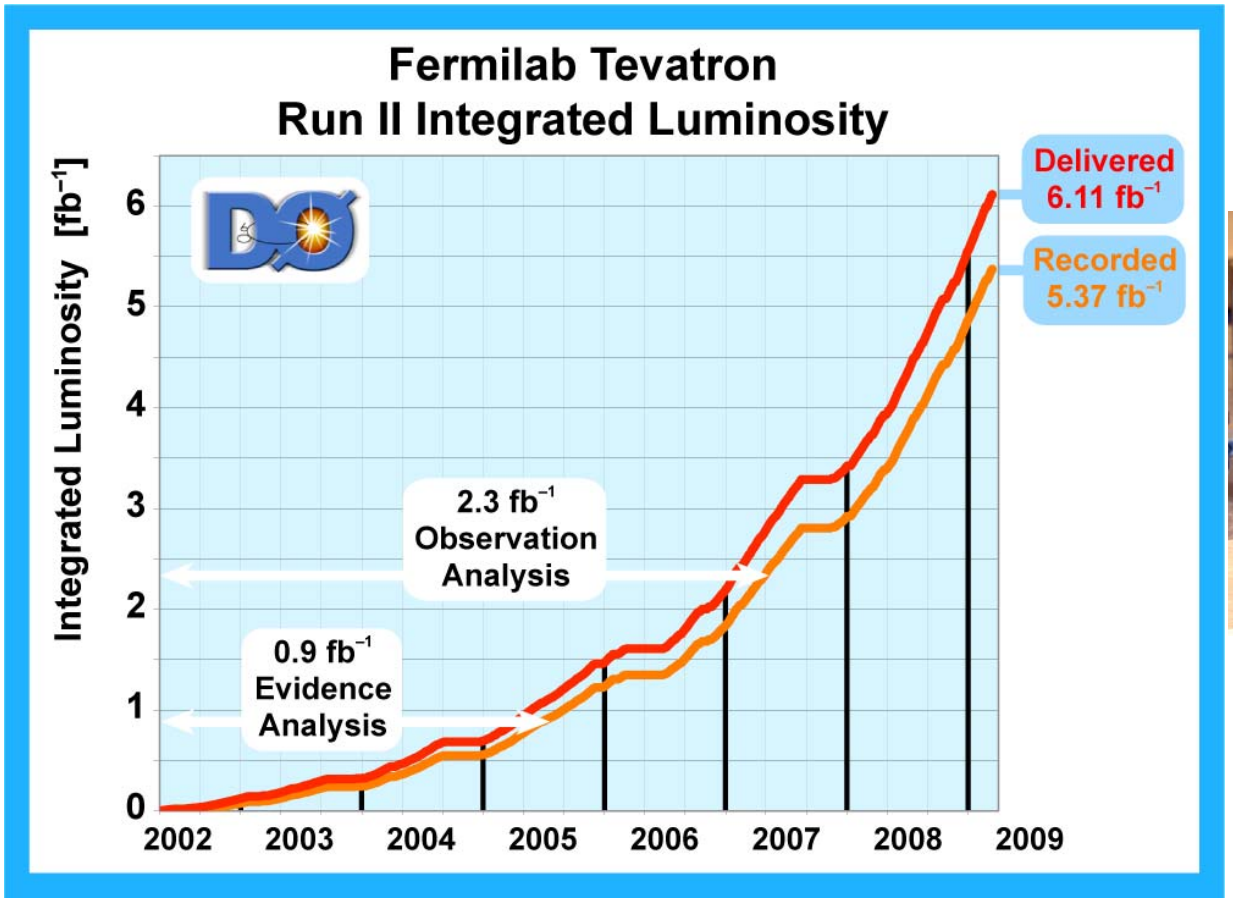
Measurement of the Single-Top-Quark Production Cross Section at CDF

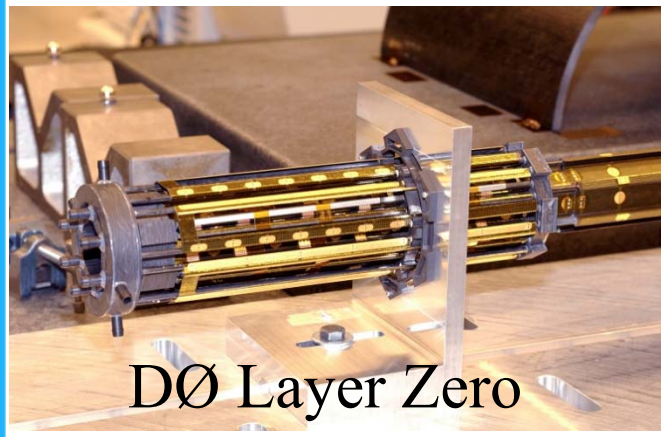
T. Aaltonen,[24] J. Adelman,[14] T. Akimoto,[56] M.G. Albrow,[18] B. Álvarez González,[12] S. Amerio,[44a,44b] D. Amidei,[35] A. Anastassov,[39] A. Annovi,[20] J. Antos,[15] G. Apollinari,[18] A. Apresyan,[46] T. Arisawa,[58] A. Artikov,[16] W. Ashmanskas,[18] A. Attal,[4] A. Aurisano,[54] F. Azfar,[43] P. Azzurri,[47a,47d] W. Badgett,[18] A. Barbaro-Galtieri,[29] V.E. Barnes,[46] B.A. Barnett,[26] V. Bartsch,[31] G. Bauer,[33] P.-H. Beauchemin,[34] F. Bedeschi,[47a] P. Bednar,[15] D. Beecher,[31] S. Behari,[26] G. Bellettini,[47a,47b] J. Bellinger,[60] D. Benjamin,[17] A. Beretvas,[18] J. Beringer,[29] A. Bhatti,[51] M. Binkley,[18] D. Bisello,[44a,44b] I. Bizjak,[31] R.E. Blair,[2] C. Blocker,[7] B. Blumenfeld,[26] A. Bocci,[17] A. Bodek,[50] V. Boisvert,[50] G. Bolla,[49] D. Bortoletto,[46] J. Boudreau,[48] A. Boveia,[11] B. Brau,[11] A. Bridgeman,[25] L. Brigliadori,[44a] C. Bromberg,[36] E. Brubaker,[14] J. Budagov,[16] H.S. Budd,[50] S. Budd,[25] K. Burkett,[18] G. Busetto,[44a,44b] P. Bussey,[22] A. Buzatu,[34] K.L. Byrum,[2] S. Cabrera,[17,q] C. Calancha,[32] M. Campanelli,[36] M. Campbell,[35] F. Canelli,[18] A. Canepa,[46] D. Carlsmith,[60] R. Carosi,[47a] S. Carrillo,[19,k] S. Carron,[34] B. Casal,[12] M. Casarsa,[18] A. Castro,[6a,6b] P. Catastini,[47a,47c] D. Cauz,[55a,55b] V. Cavaliere,[47a,47c] M. Cavalli-Sforza,[4] A. Cerri,[29] L. Cerrito,[31,p] S.H. Chang,[28] Y.C. Chen,[1] M. Chertok,[8] G. Chiarelli,[47a] G. Chlachidze,[18] F. Chlebana,[18] K. Cho,[28] D. Chokheli,[16] J.P. Chou,[23] G. Choudalakis,[33] S.H. Chuang,[53] K. Chung,[13] W.H. Chung,[60] Y.S. Chung,[50] C.I. Ciobanu,[45] M.A. Ciocci,[47a,47c] A. Clark,[21] D. Clark,[7] G. Compostella,[44a] M.E. Convery,[18] J. Conway,[8] K. Copic,[35] M. Cordelli,[20] G. Cortiana,[44a,44b] D.J. Cox,[8] F. Crescioli,[47a,47b] C. Cuenca Almenar,[8,d] J. Cuevas,[12,n] R. Culbertson,[18] J.C. Cully,[35] D. Dagenhart,[18] M. Datta,[18] T. Davies,[22] P. de Barbaro,[50] S. De Cecco,[52a] A. Deisher,[29] G. De Lorenzo,[4] M. Dell'Orso,[47a,47b] C. Deluca,[4] L. Demortier,[51] J. Deng,[17] M. Deninno,[6a] P.F. Derwent,[18] G.P. di Giovanni,[45] C. Dionisi,[52a,52b] B. Di Ruzza,[55a,55b] J.R. Dittmann,[5] M. D'Onofrio,[4] S. Donati,[47a,47b] P. Dong,[9] J. Donini,[44a] T. Dorigo,[44a] S. Dube,[53] J. Efron,[40] A. Elagin,[54] R. Erbacher,[8] D. Errede,[25] S. Errede,[25] R. Eusebi,[18] H.C. Fang,[29] S. Farrington,[43] W.T. Fedorko,[14] R.G. Feild,[61] M. Feindt,[27] J.P. Fernandez,[32] C. Ferrazza,[47a,47d] R. Field,[19] G. Flanagan,[49] R. Forrest,[8] M. Franklin,[23] J.C. Freeman,[18] I. Furic,[19] M. Gallinaro,[52a] J. Galyardt,[13] F. Garberson,[11] J.E. Garcia,[47a] A.F. Garfinkel,[49] K. Genser,[18] H. Gerberich,[25] D. Gerdes,[35] A. Gessler,[27] S. Giagu,[52a,52b] V. Giakoumopoulou,[3] P. Giannetti,[47a] K. Gibson,[48] J.L. Gimmell,[50] C.M. Ginsburg,[18] N. Giokaris,[3] M. Giordani,[55a,55b] P. Giromini,[20] M. Giunta,[47a,47b] G. Giurgiu,[26] V. Glagolev,[16] D. Glenzinski,[18] M. Gold,[38] N. Goldschmidt,[19] A. Golossanov,[18] G. Gomez,[12] G. Gomez-Ceballos,[33] M. Goncharov,[54] O. González,[32] I. Gorelov,[38] A.T. Goshaw,[17] K. Goulianos,[51] A. Gresele,[44a,44b] S. Grinstein,[23] C. Grosso-Pilcher,[14] R.C. Group,[18] U. Grundler,[25] J. Guimaraes da Costa,[23] Z. Gunay-Unalan,[36] C. Haber,[29] K. Hahn,[33] S.R. Hahn,[18] E. Halkiadakis,[53] B.-Y. Han,[50]

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

Dataset

- DØ has >5 fb^{-1} on tape *Many thanks to the Fermilab Accelerator Division!*





This analysis uses 2.3 fb^{-1} of data collected from 2002 to 2007

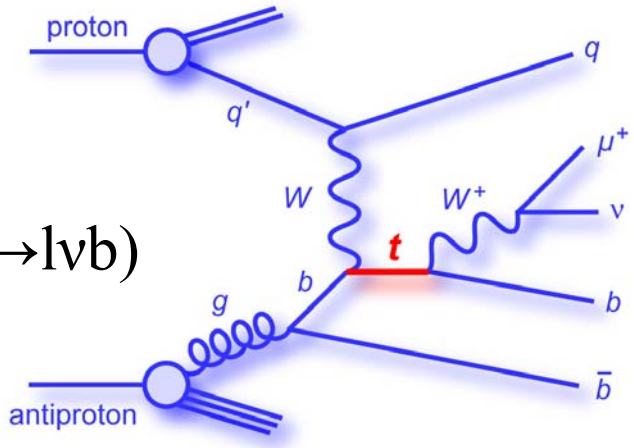
–Full Run IIa dataset, 1.1 fb^{-1} (20% increase w.r.t. 2006 analysis)

–Run IIb dataset, 1.2 fb^{-1}

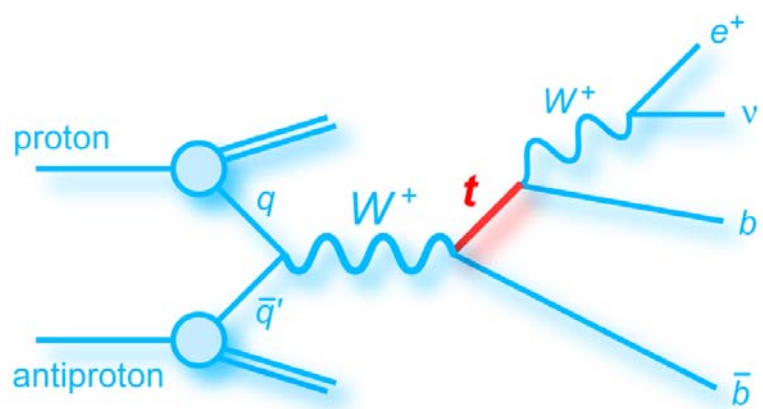
Event Selection

FINAL STATE CONTAINS:

- One high-p_T isolated electron or muon
- Large missing transverse energy $\not{E}_T$
- A b-jet from the top quark decay ($t \rightarrow Wb \rightarrow l\nu b$)
- A second b-jet or a light jet



- Analysis is performed in 24 channels:
  - Run IIa or Run IIb
  - e or mu
  - 2, 3 or 4 jets
  - 1 or 2 b-tags



Changes in Event Selection

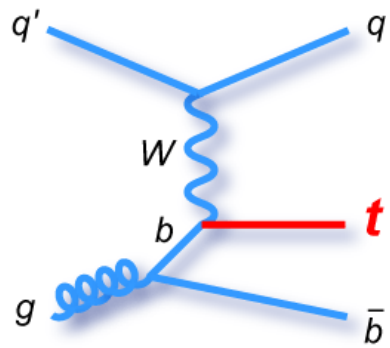
- Logical OR of many trigger conditions (was *lepton + jets*)
- Leading Jet η acceptance increased to 3.4 (was 2.5)
- Non-leading Jet p_T cut reduced to 15 GeV (was 20 GeV)
- Muon p_T cut reduced to 15 GeV (was 18 GeV)
- Loosened the b-jet identification criteria for the 2 tag case
- H_T, $\not{E}_T$ not aligned with lepton or leading jet

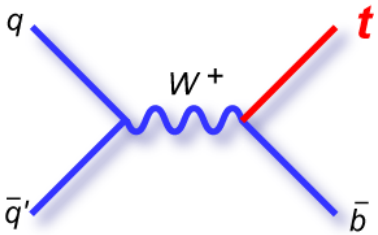
- Signal acceptance
  - s-channel $tb = (3.7 \pm 0.5)$ %
  - t-channel $tqb = (2.5 \pm 0.3)$ %

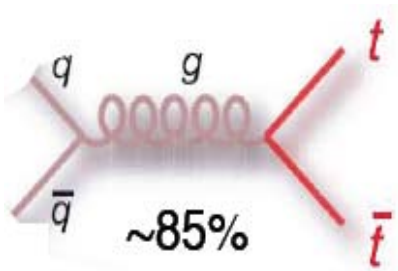
Signal acceptance increased by 18% compared to 2006

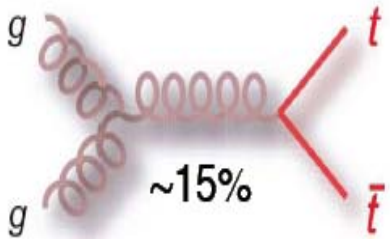
Signal and Background Models

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





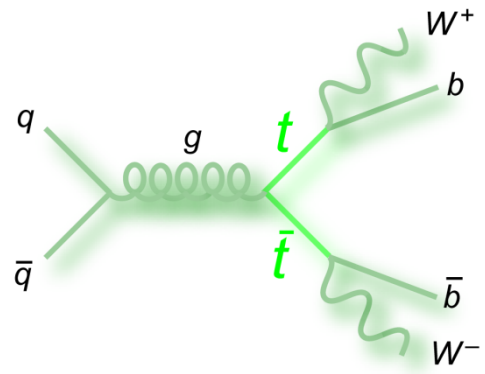




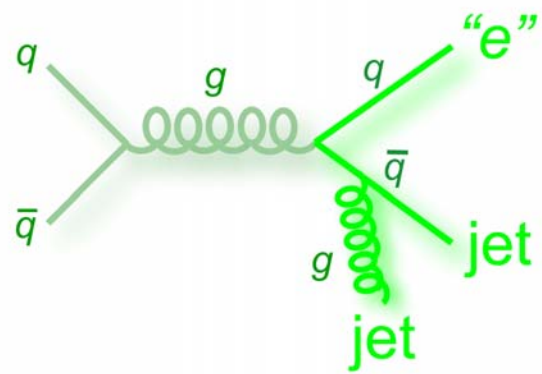
- Top pair backgrounds modeled using ALPGEN
  - PYTHIA for parton hadronization
  - Parton-jet matching algorithm used to avoid double-counting final states
  - Normalized σ = 7.91pb from Kidonakis and Vogt, PRD 68, 114014 (2003) for m_t =170 GeV
  - Uncertainties +7.7% −12.7% includes theory, PDF and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

Signal and Background Models (Cont.)

- W+jets modeled using ALPGEN
  - PYTHIA for parton hadronization
  - MLM parton-jet matching avoids double-counting final states
  - η(jets), Δϕ(jet1,jet2), Δη(jet1,jet2) corrected to match data



- QCD Multijet
  - Misidentified lepton, directly from data
  - Switched to 10x larger background samples compared to 2006
  - Kept small (~5%) with topological selection cuts



- Z+jets modeled using ALPGEN + PYTHIA
  - Z+ heavy flavor corrected to theory, with ±20% uncertainty
- Dibosons modeled using PYTHIA

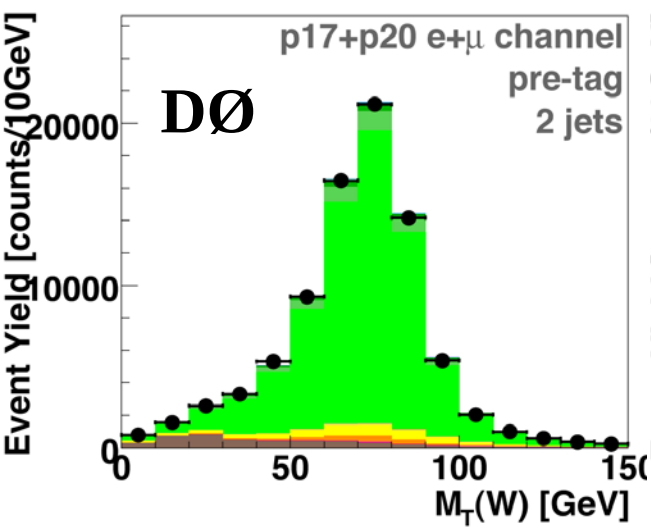
Background Normalization

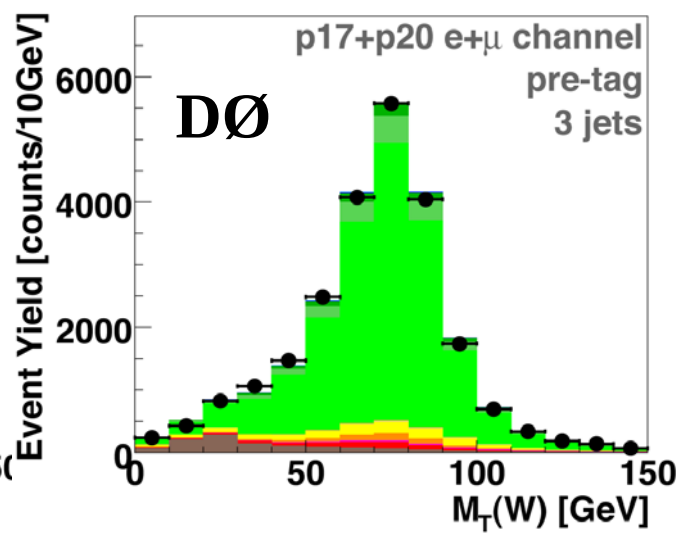
- W+jets and multijet normalized using iterative template fits to data BEFORE TAGGING on three sensitive variables: $p_T(\ell)$, $\not{E}_T$, $M_T(W)$

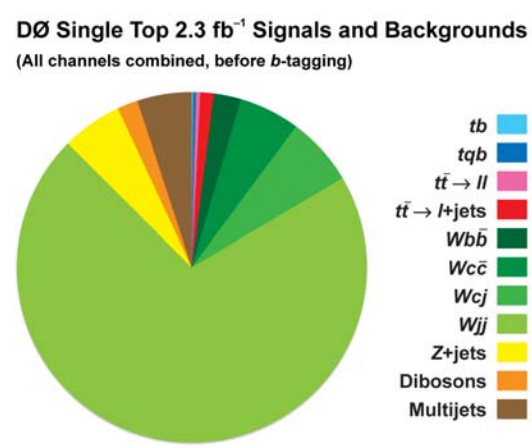
$$N_{\text{pretag}}^{\text{data}} - N_{\text{bkgd}}^{\text{MC}} = S_{\text{W+jets}} N_{\text{W+jets}}^{\text{MC}} + S_{\text{multijet}} N_{\text{multijet}}^{\text{data}}$$

  - Normalization given by KS-weighted average
  - Uncertainty obtained from max. difference with 1-variable result
    - 30 to 54% for multijet, 1.8 to 3.9% for W's

S:B = 1:259

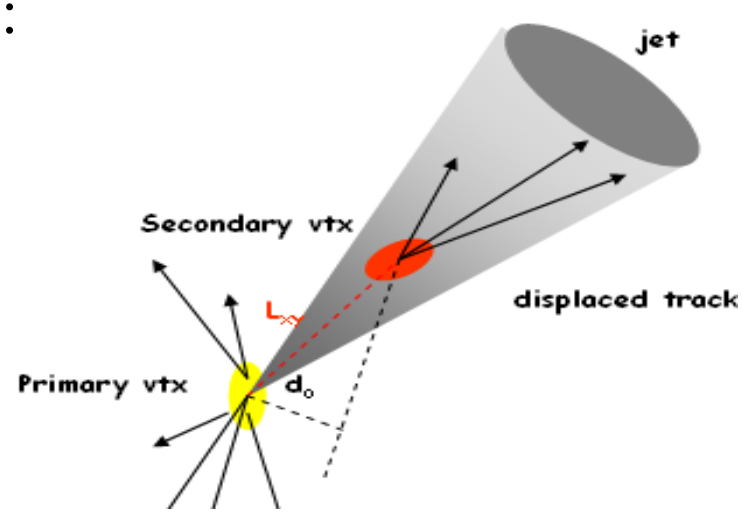






b-Jet Identification

- 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
- Two operating points used in analysis:
  - TIGHT ($\varepsilon_b = 40\%$, $\varepsilon_c = 9\%$, $\varepsilon_\ell = 0.4\%$)
  - LOOSE ($\varepsilon_b = 50\%$, $\varepsilon_c = 14\%$, $\varepsilon_\ell = 1.5\%$)
- Leading *b*-jet $p_T > 20$ GeV
- Define two exclusive samples
  - EqOneTag: 1T, no L
  - EqTwoTag: 2L (was 2T; ≈ 50% gain)

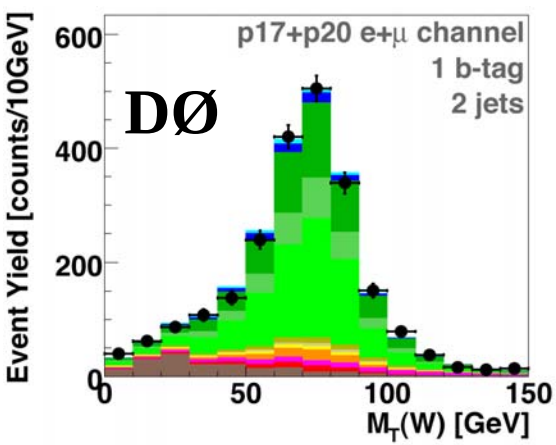


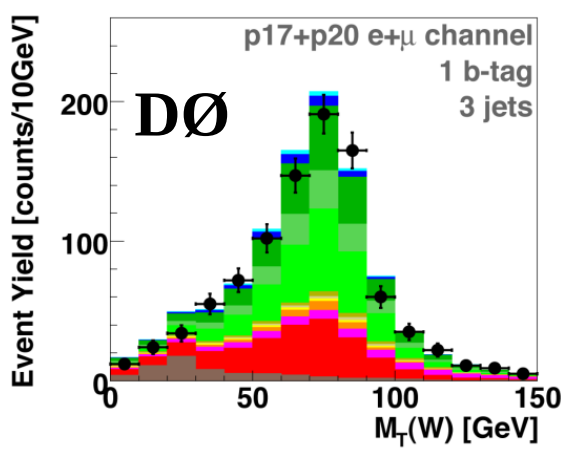
- Uncertainties dominated by variation in data samples used to measure the efficiencies.
- Smaller contribution from MC sample dependence

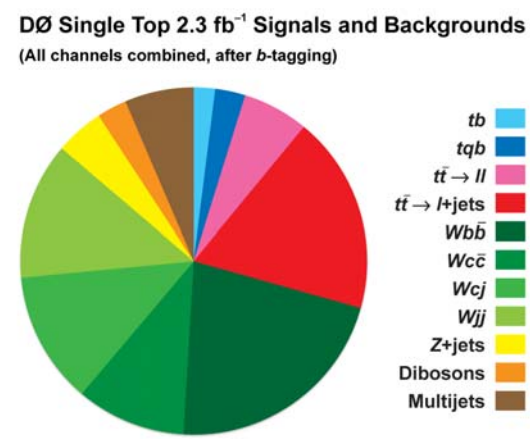
W + Heavy–Flavor Scale Factor

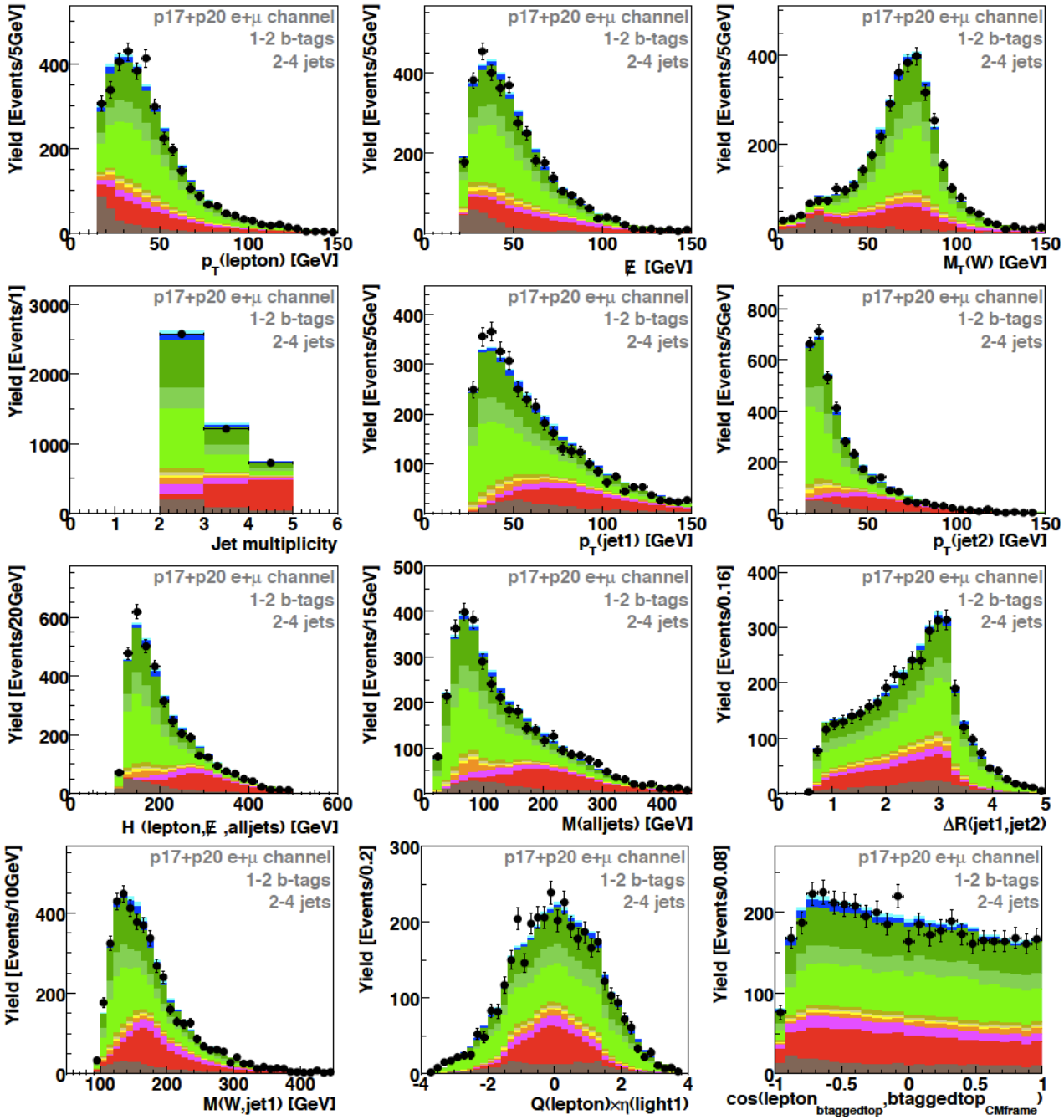
- W + heavy flavor normalized to theory (MCFM-NLO)
  - 1.47 (Wbb,Wcc), 1.38 (Wcj)
- Additional empirical correction
  - derived from two-jet data and simulation: includes zero-tag events
  - 0.95 ± 0.13 (Wbb, Wcc)
- Uncertainties considered
  - Data statistics ± 9%
  - ± 40% single top cross section → ± 7% in SF
  - ± 10% on the Wcj theory SF → ± 8% in SF
  - Additional ± 10% Wbb/Wcc → ± 5% in SF

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









Data/MC agreement (for all channels combined)

Expected and Observed Events

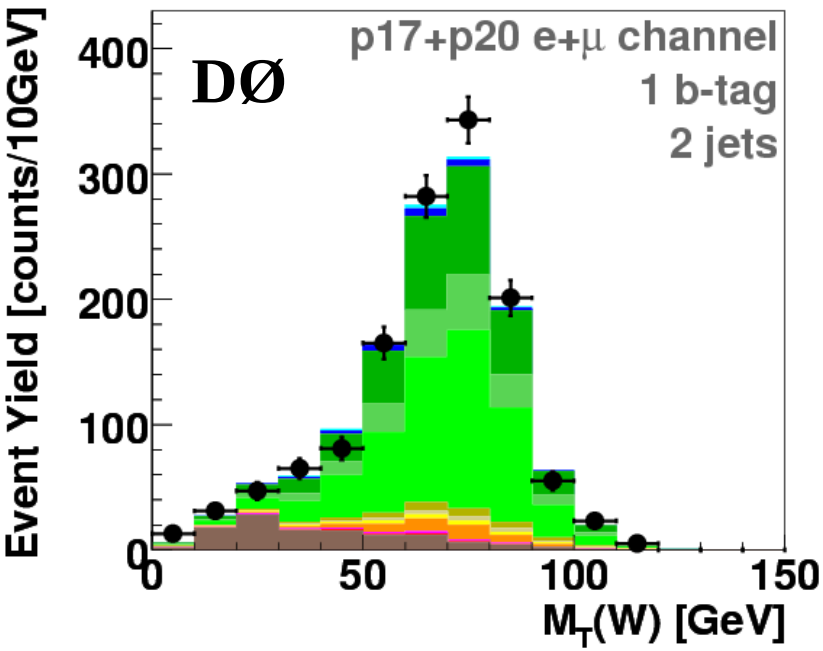
Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
s-channel tb	62 ± 9	24 ± 4	7 ± 2
t-channel tqb	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \rightarrow \ell\ell$	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

Cross Check Samples

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

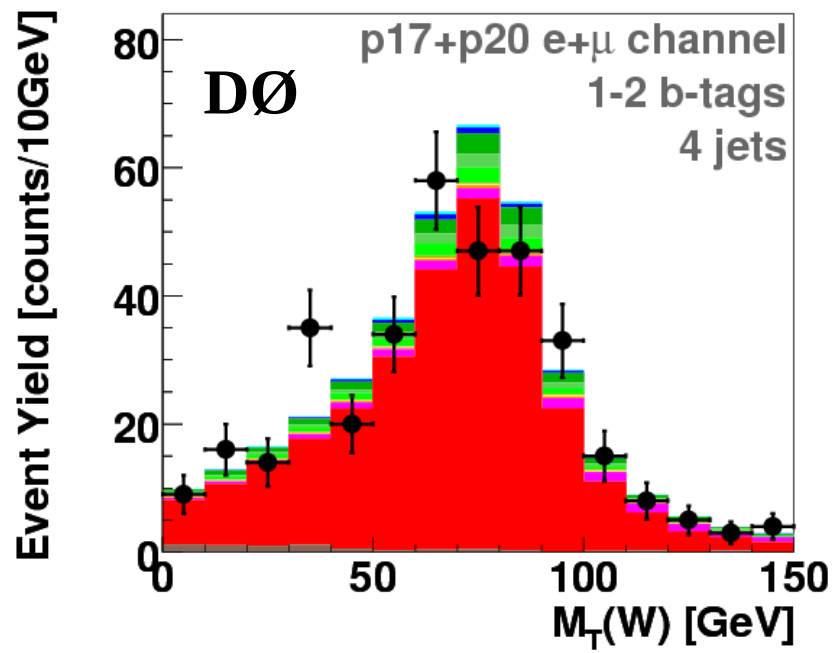
W + JETS

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



Top Pairs

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



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)%

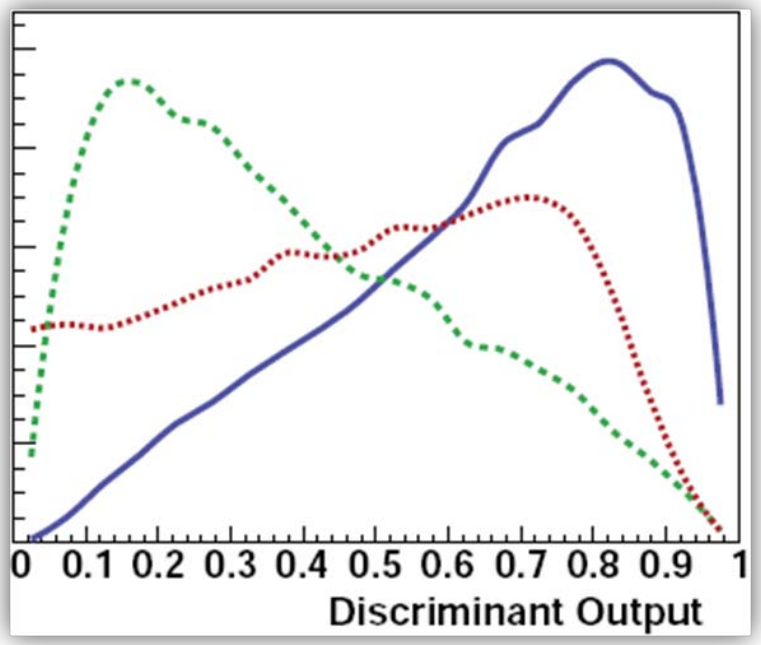
Components for normalization and shape	
Jet energy scale for signal	(1.1–13.1)%
Jet energy scale for total background	(0.1–2.1)%
b tagging for single-tagged	(2.1–7.0)%
b tagging for double-tagged	(9.0–11.4)%
Component for shape only	
ALPGEN reweighting	–

Components that most affect the cross section measurement are shown in *red*

Other important contributions are shown in *pink*

Analysis Strategy

- Maximize signal acceptance
  - Background model gives good representation of data in each of the 24 independent analysis channels



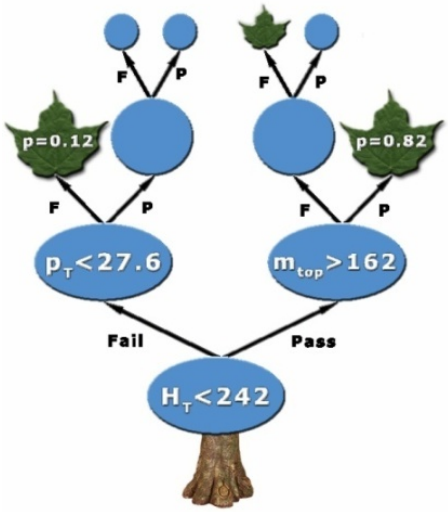
- Calculate discriminant functions that separate signal from background
  - Boosted Decision Trees (BDT)
  - Bayesian Neural Networks (BNN)
  - Matrix Elements (ME)
- Check discriminant performance using data control samples
- Use ensembles of pseudo-data to test validity of methods
- Cross sections measured using binned likelihood calculation of signal + background to data

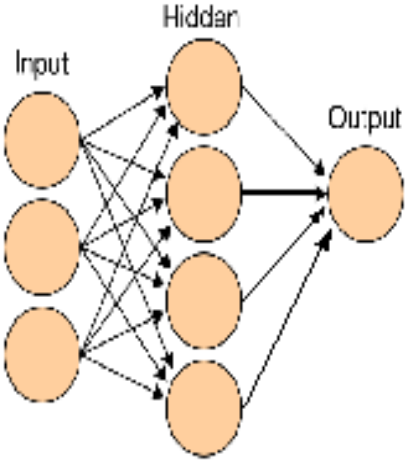
Multivariate Analyses: BDT & BNN

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



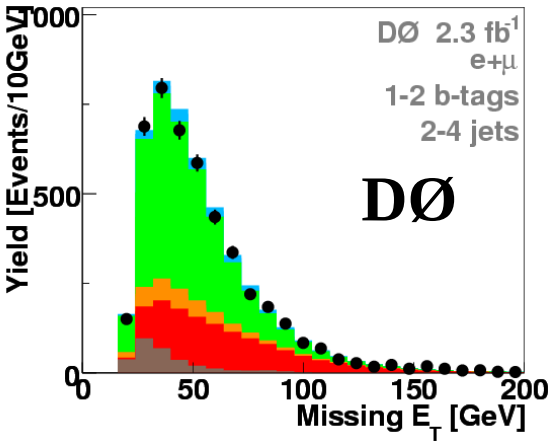


Bayesian Neural Network (BNN)

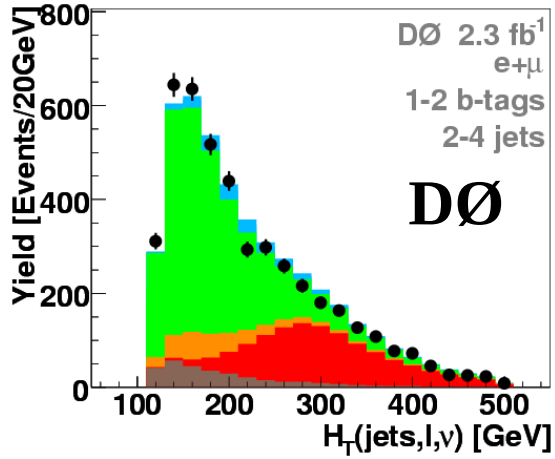
- NN train on signal and background, producing one output discriminant
- Bayesian NN average over many networks, improving the performance
- Uses highest ranked 18-28 variables in each channel

Discriminating Variables – BDT/BNN

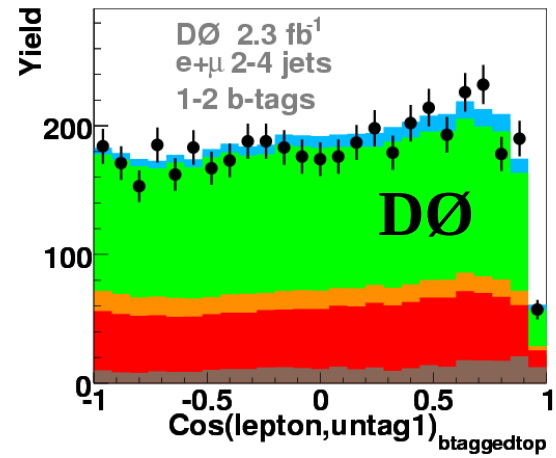
OBJECT KINEMATICS



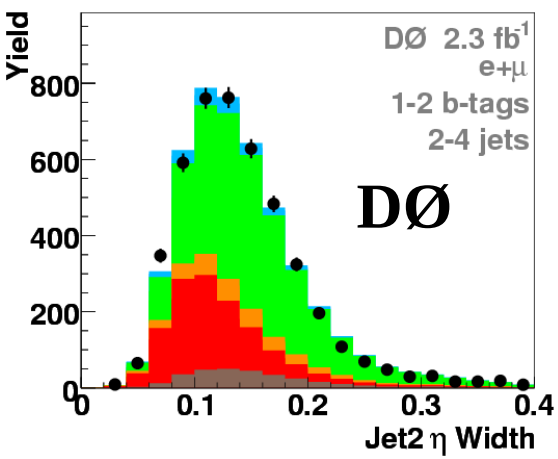
EVENT KINEMATICS



ANGULAR CORRELATIONS

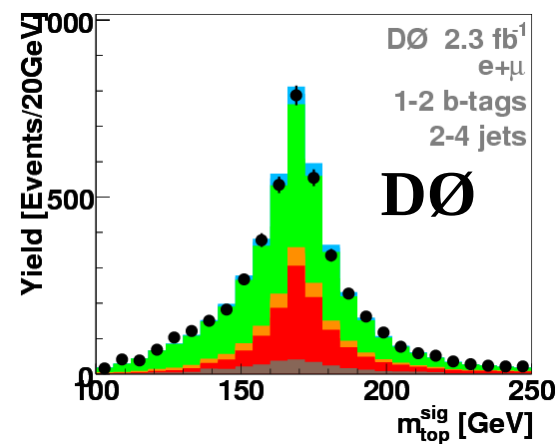


JET RECONSTRUCTION



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

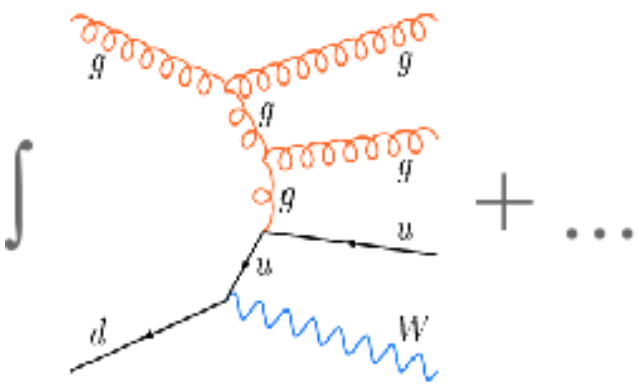
TOP QUARK RECONSTRUCTION



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

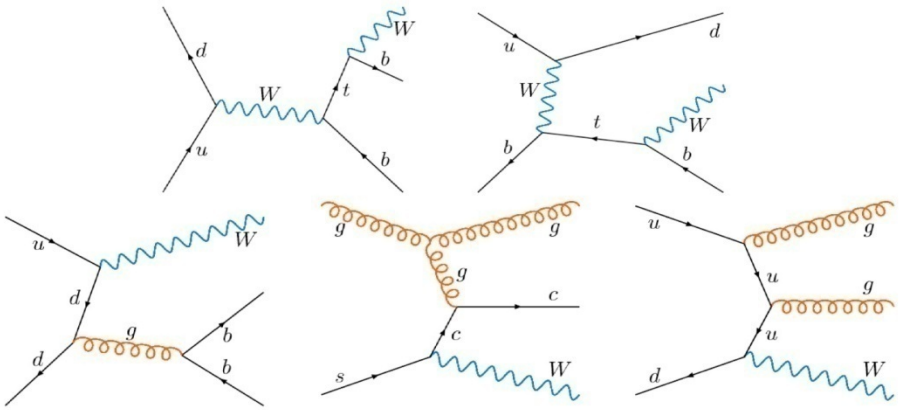
  (W+jets and top quark pair dominated regions) improves the performance

Multivariate Analyses: ME

2-jet channels

tb tq

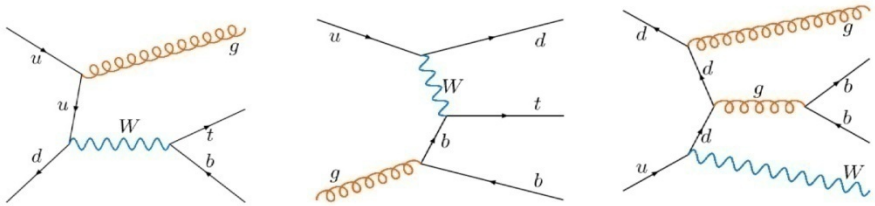
Wbb Wcg Wgg



3-jet channels

tbg tqb tqg

Wbbg

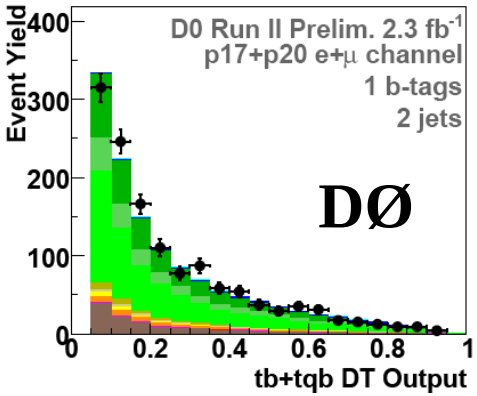


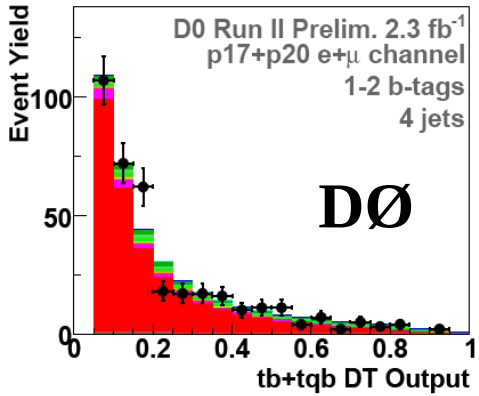
Added additional Matrix Elements since 2006

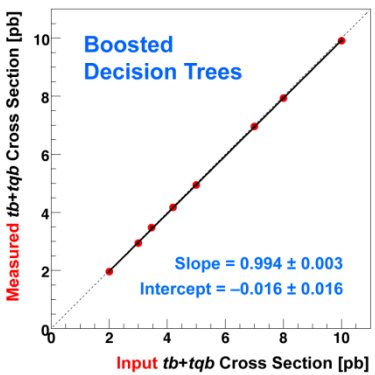
2jets: top pair, WW, WZ, ggg

3jets:top pair, Wugg

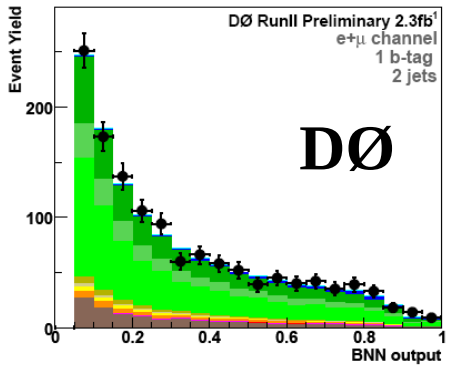
Cross Check Samples and Linearity

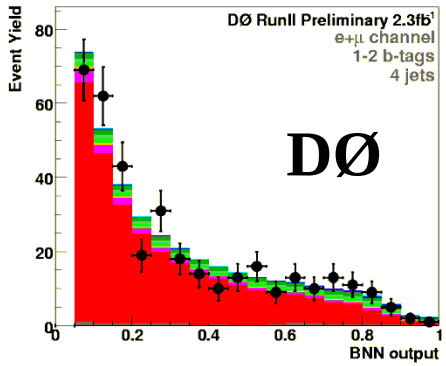


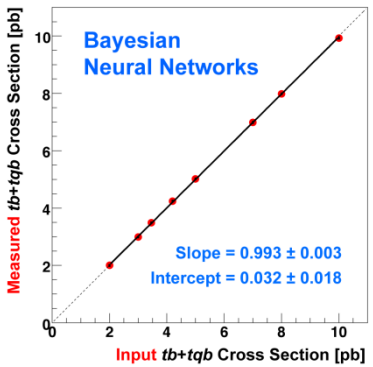




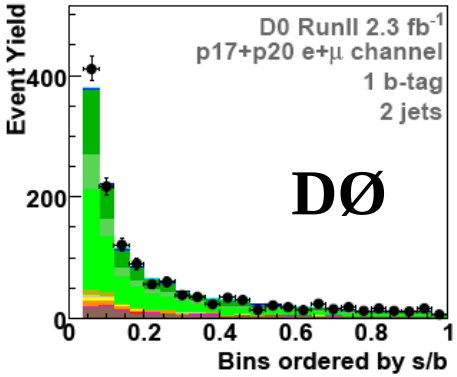
BDT

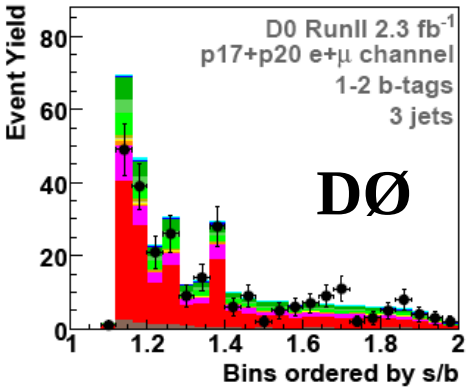


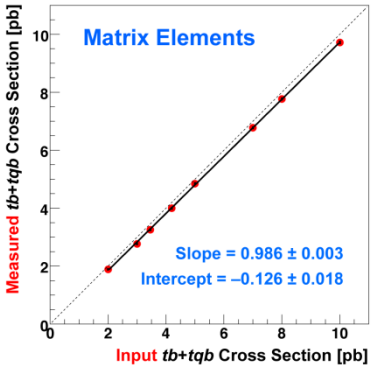




BNN

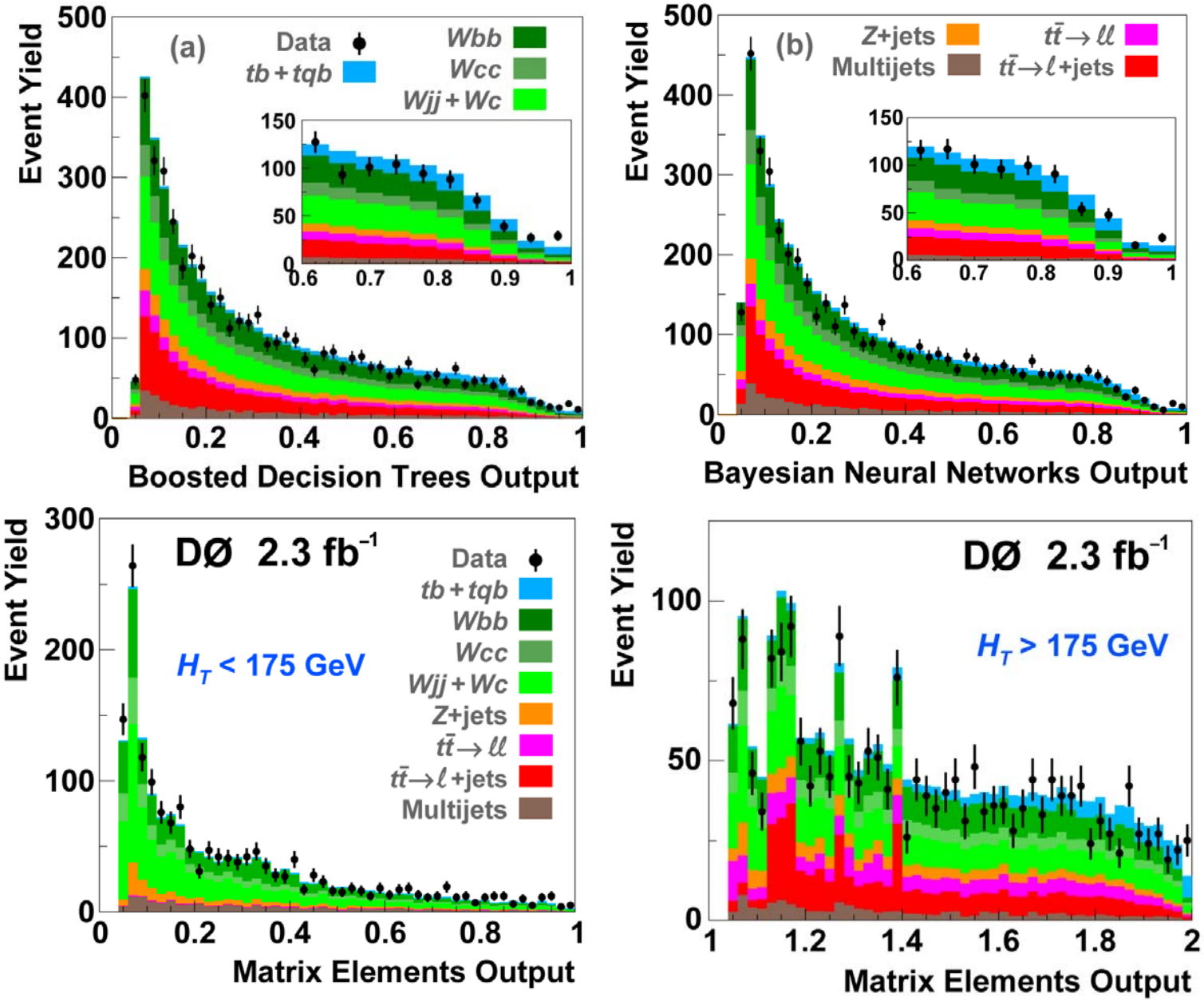






ME

Multivariate Discriminant Outputs



Signal normalized to measured x-sec

Statistical Analysis

Before looking at the data, we can calculate:

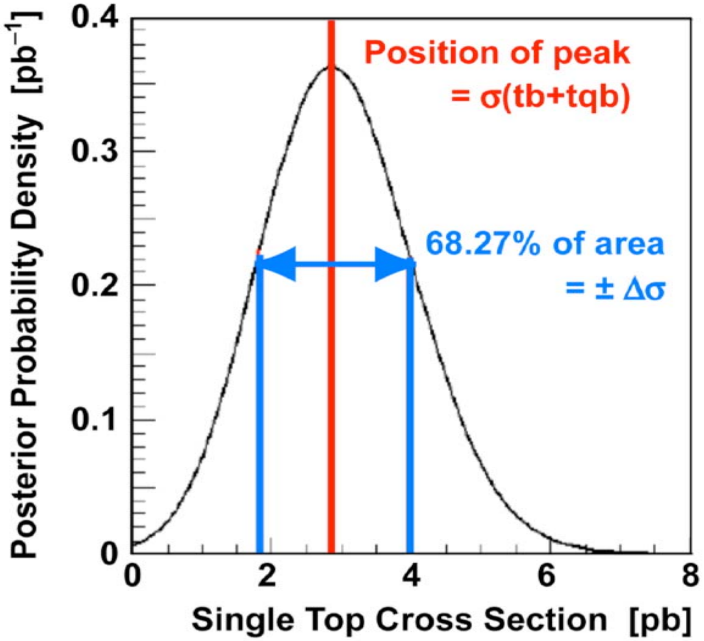
- "expected p-value": fraction of the ensemble of zero-signal pseudo-datasets that give a cross section at least as large as the SM value.
  - For a Gaussian distribution, convert p-value to give "expected significance"

With the data, we can calculate:

- "measured cross section"
- "measured p-value": fraction of the ensemble of zero-signal pseudo-datasets that give a cross section at least as large as the measured value
  - For a Gaussian distribution, convert p-value to give "measured significance"

Cross Section Measurement

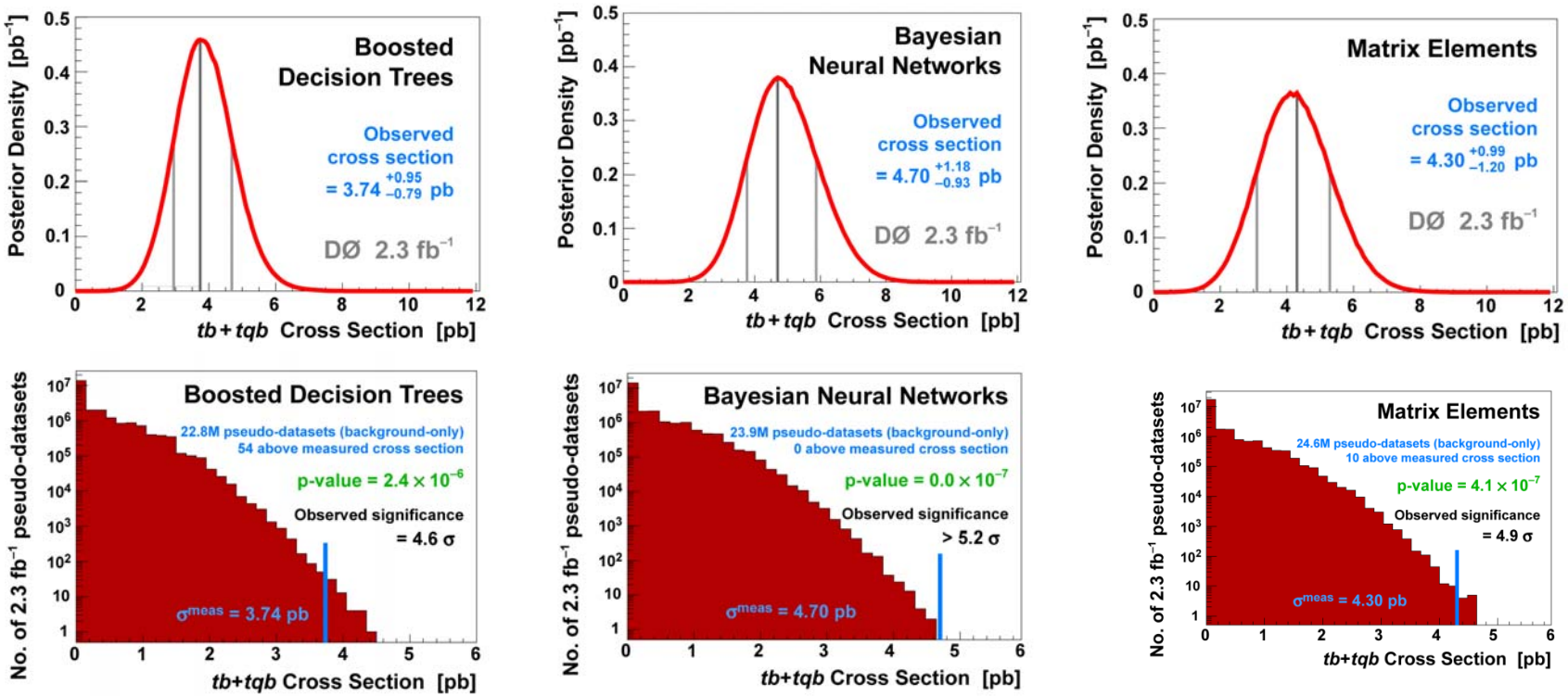
- Cross Sections are measured by building a Bayesian posterior probability density
- For each analysis, the single top cross section is given by the position of the posterior density peak, with 68% asymmetric interval as uncertainty



- 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

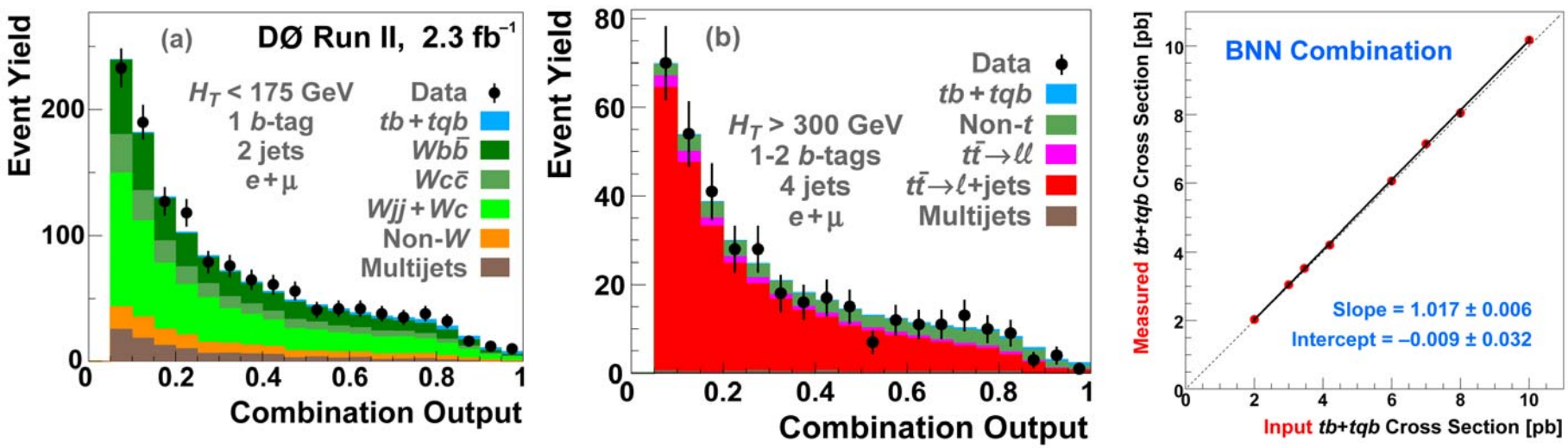
MVA	$\sigma \pm \Delta\sigma$(pb)	Expected Sensitivity	Observed Sensitivity
BDT	$3.74 \pm^{0.95}_{0.79}$	4.3 σ	4.6 σ
BNN	$4.70 \pm^{1.18}_{0.93}$	4.1 σ	5.2 σ
ME	$4.30 \pm^{0.99}_{1.20}$	4.1 σ	4.9 σ



Combination of Results

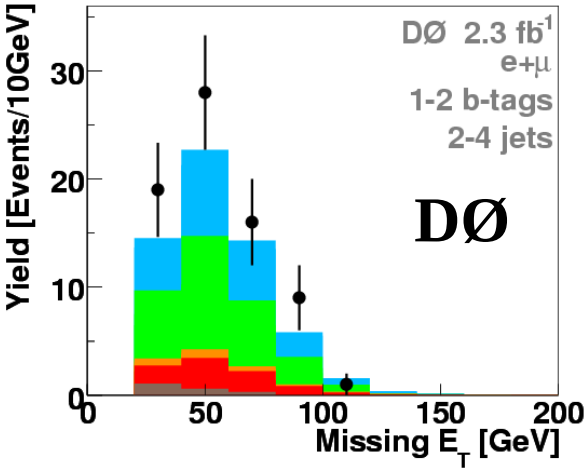
- Even though all MVA analyses use the same data, they are not 100% correlated
  - BNN&BDT are 75% correlated with each other, 60% with ME
- We use a BNN to combine the three methods. The BNN takes as input variables the output discriminants of the individual methods
- Expected sensitivity for the BNN Combination: **4.5 σ**
- BLUE combination (used in 2006) now presented as a cross check

CROSS CHECK SAMPLES AND LINEARITY

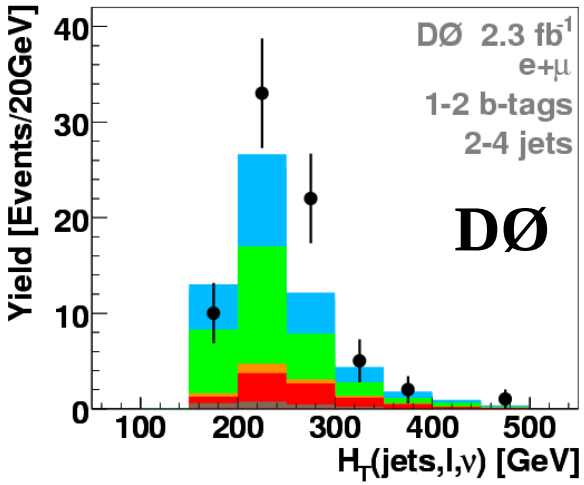


Distributions for BNNComb > 0.9

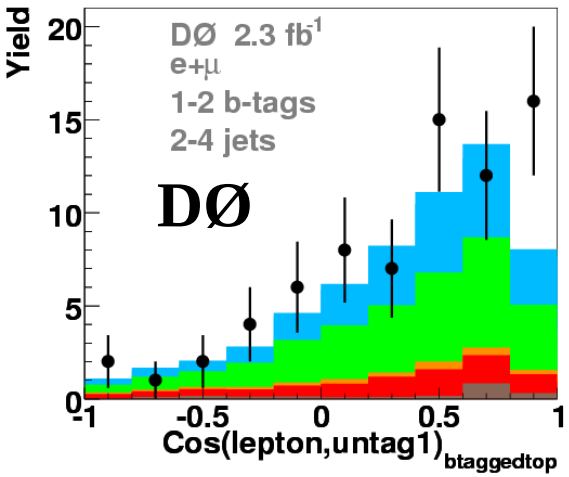
OBJECT KINEMATICS



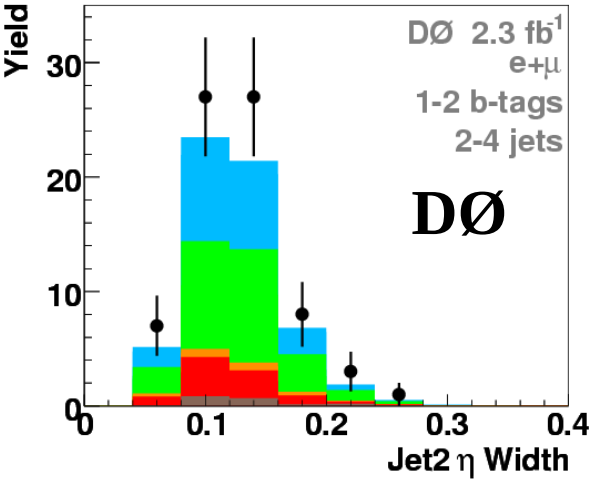
EVENT KINEMATICS



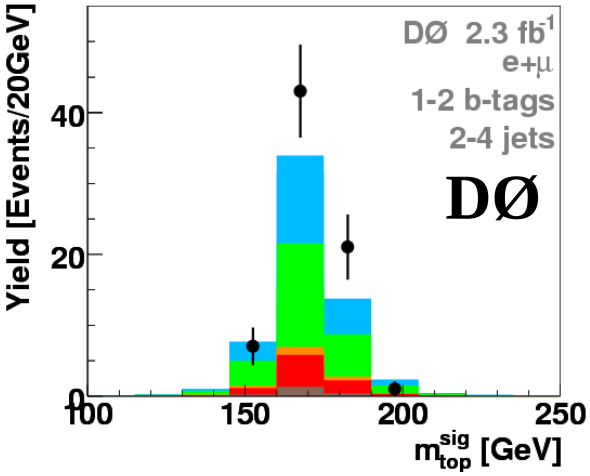
ANGULAR CORRELATIONS



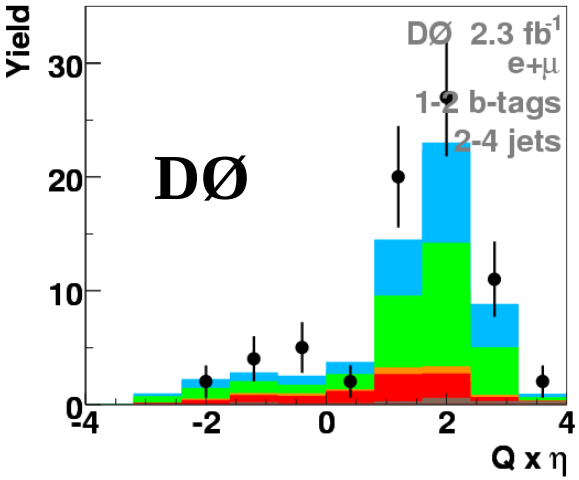
JET RECONSTRUCTION



TOP QUARK RECONSTRUCTION

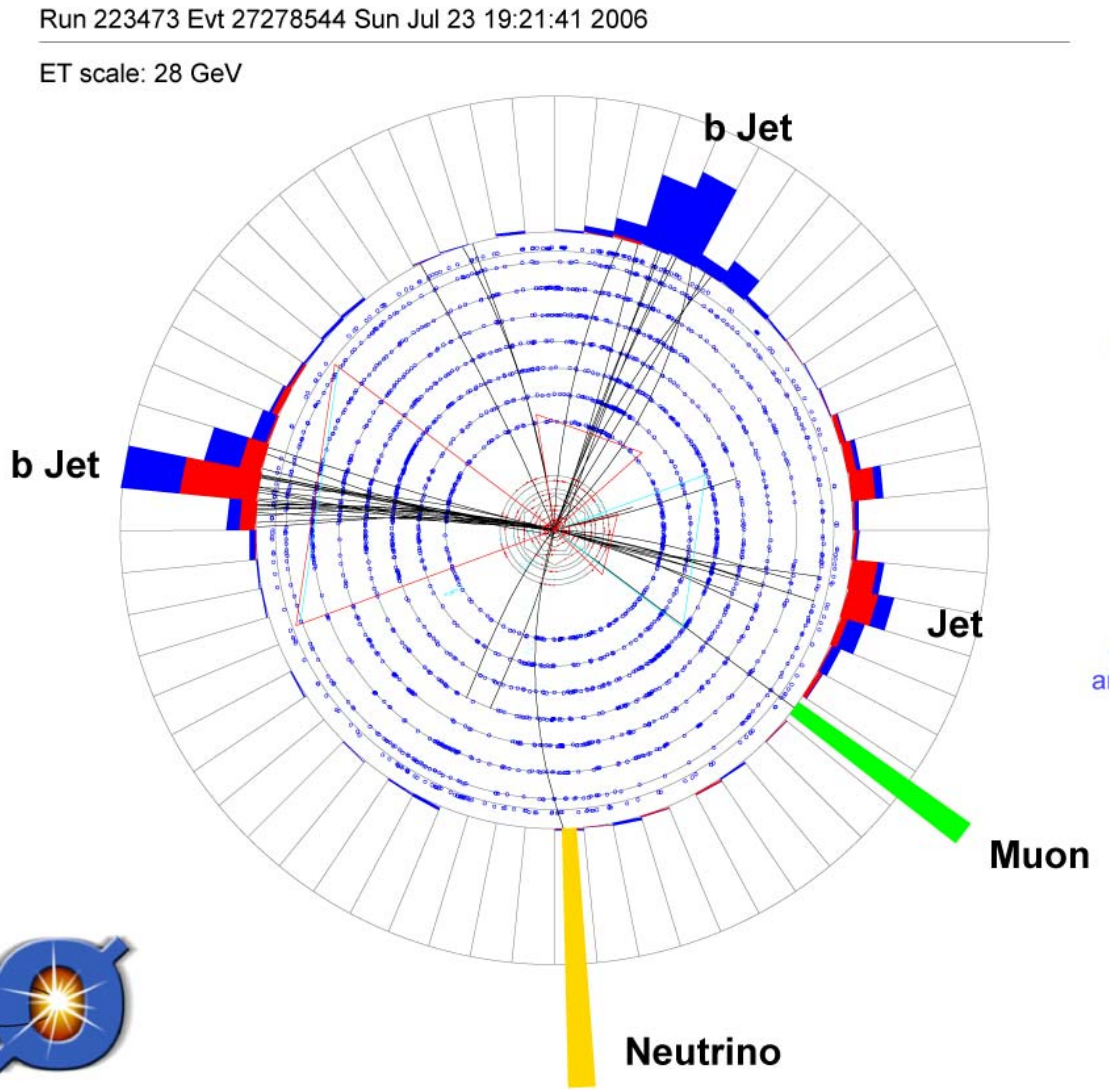


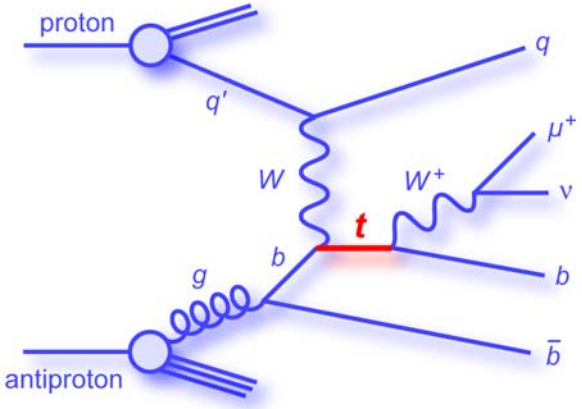
SINGLE TOP FINAL STATE



DØ Experiment Event Display

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



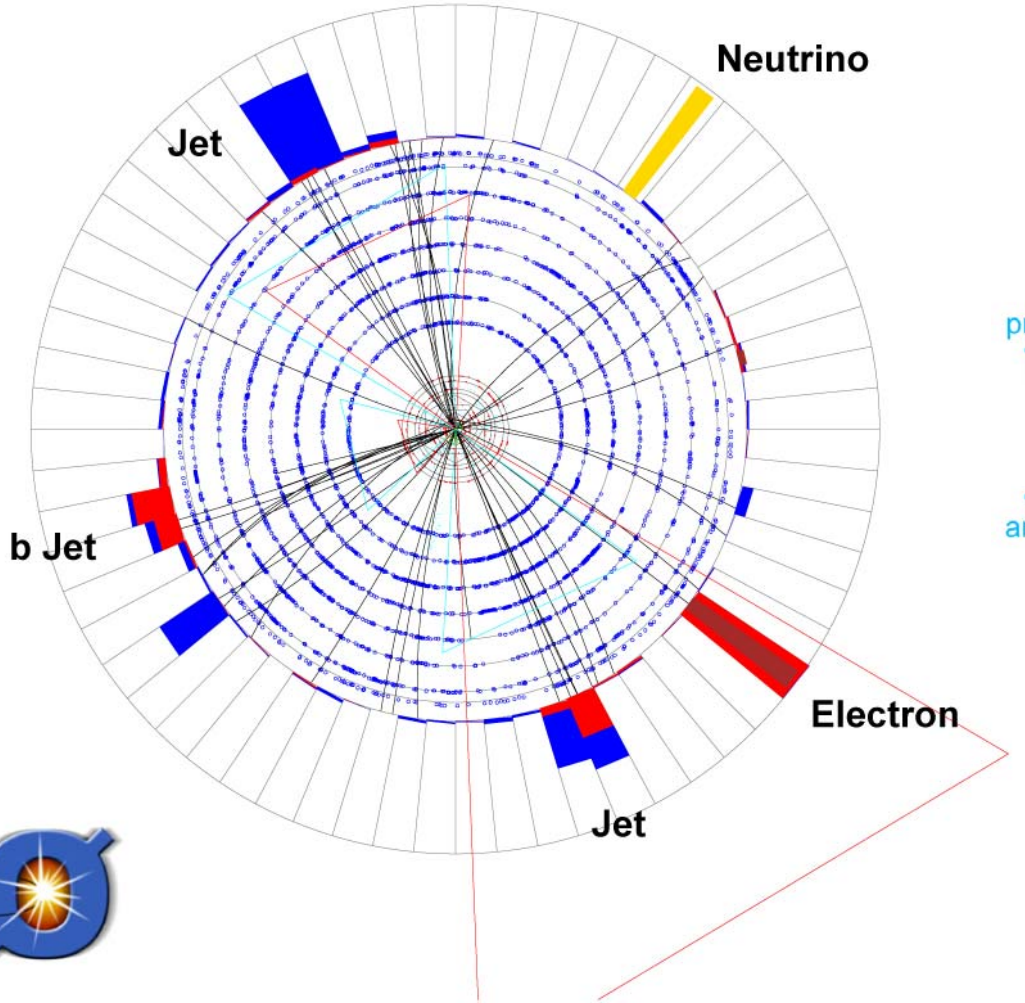


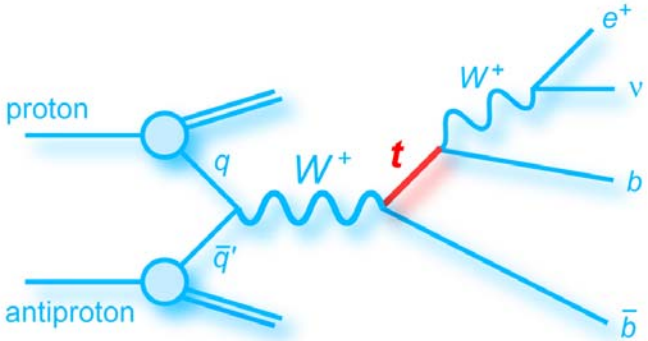
DØ Experiment Event Display

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

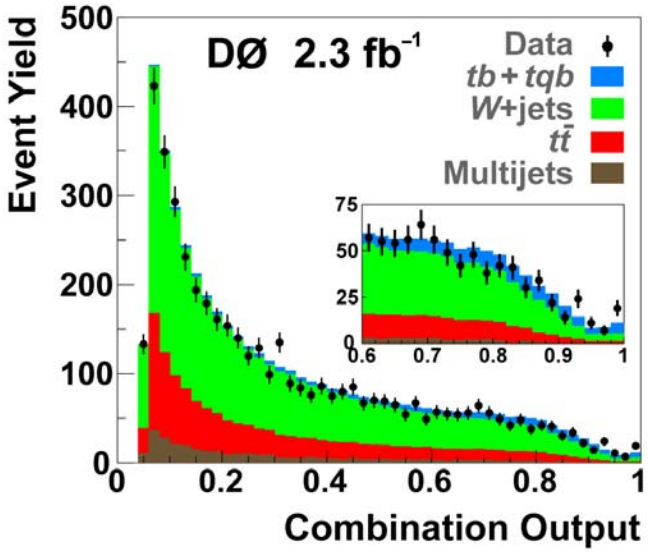


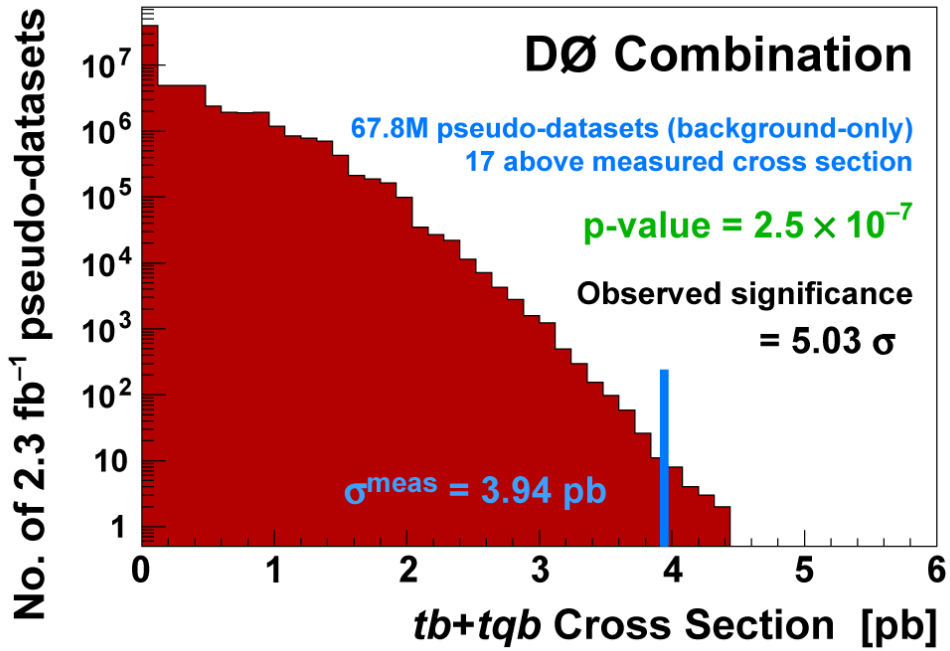


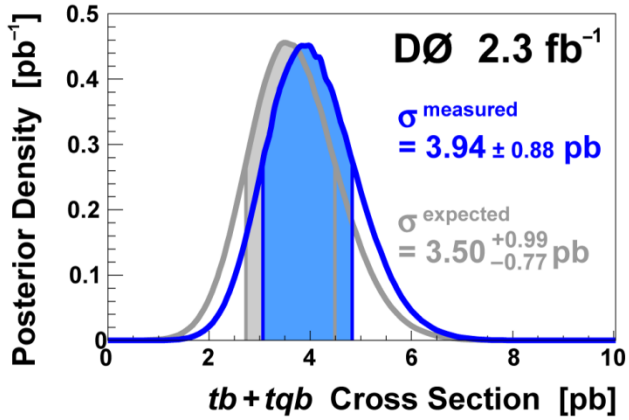
Combined Results

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

(m_t=170GeV)



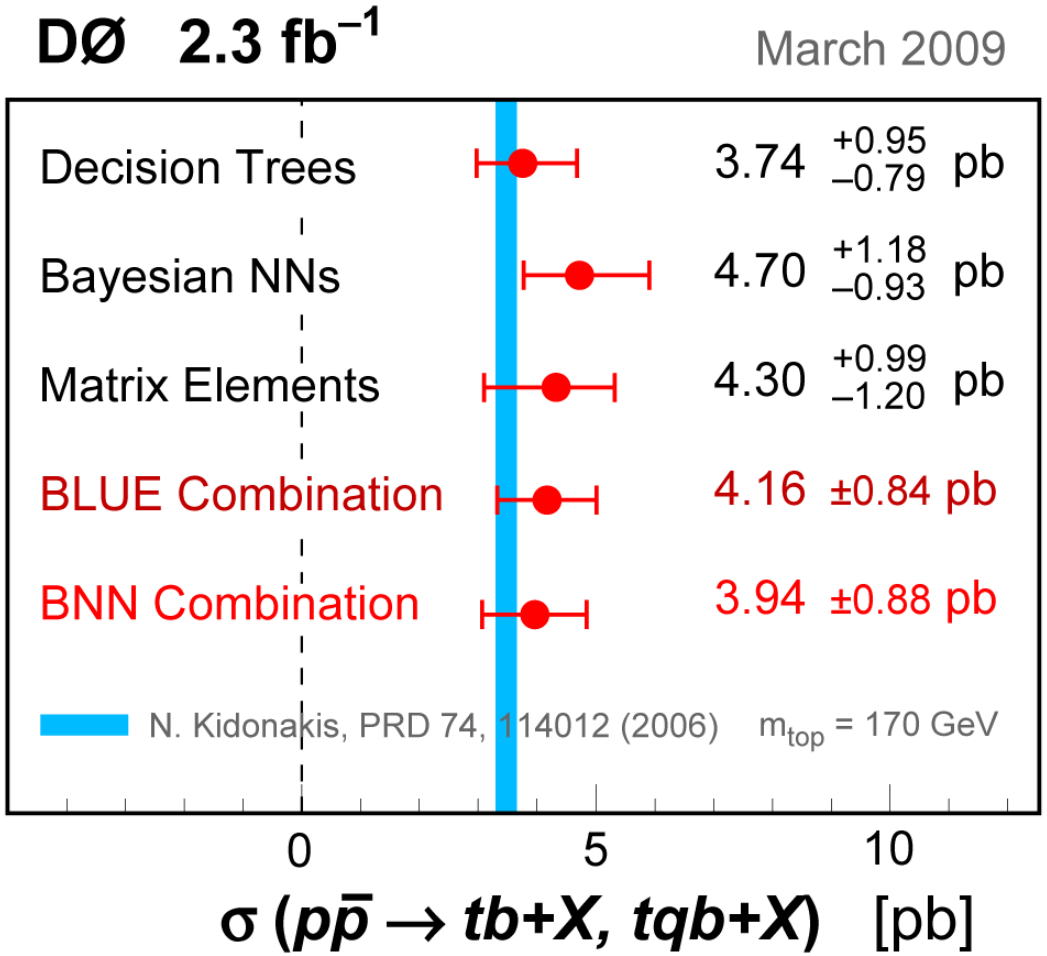




$$p - value = 2.5 \times 10^{-7}$$

Measured Significance = 5.03σ

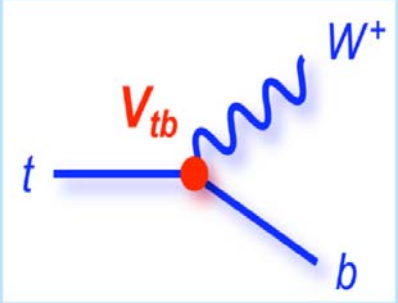
Cross Section Summary



MVA	Expected Signif.	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**

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 the Wtb vertex

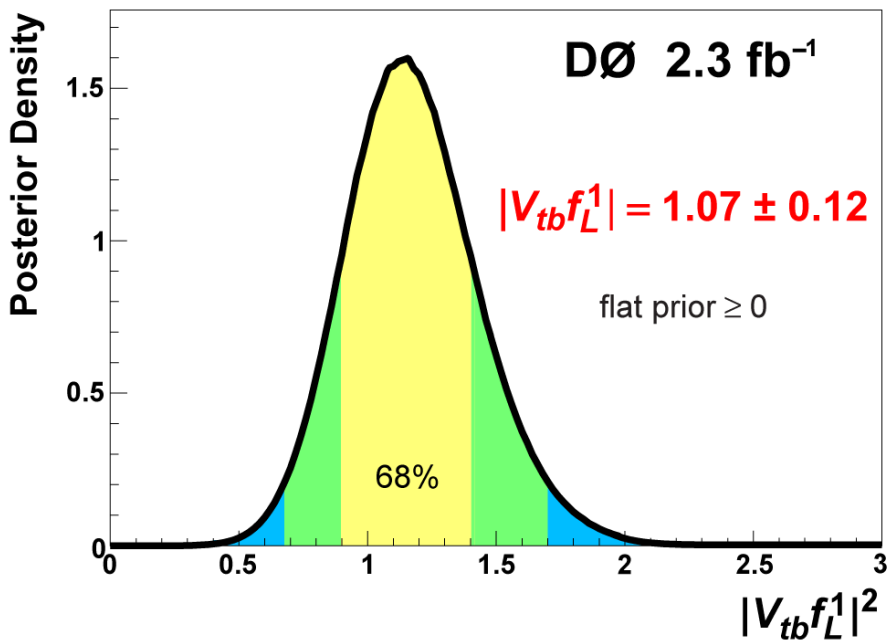
$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

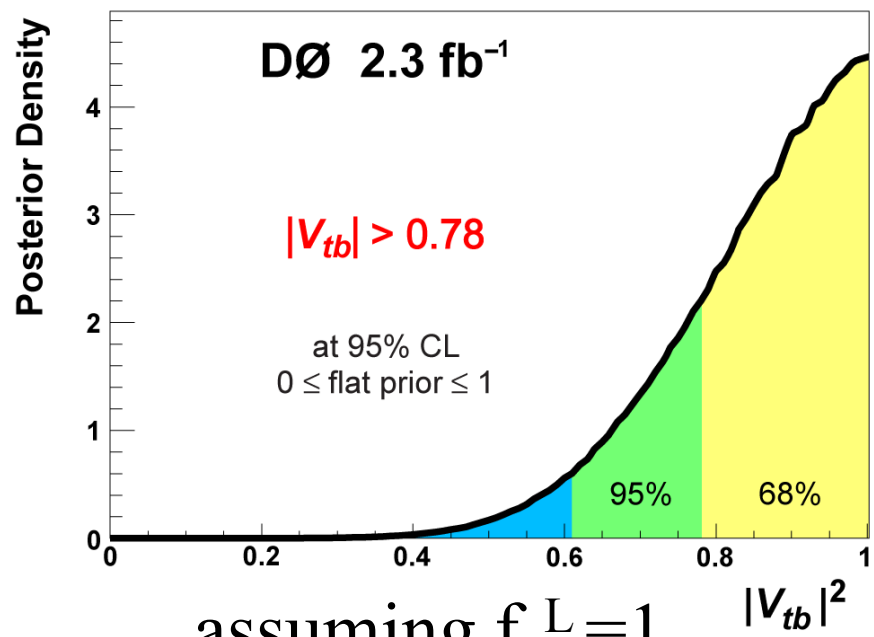
- Measurement assumes SM production mechanisms
  - Pure V–A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)
    - f_1^L : strength of the left-handed Wtb coupling, is allowed to be anomalous
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ (supported by CDF & DØ "ratio" measurements)
- Does not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

Measurement of $|V_{tb}|$

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

Additional theoretical uncertainties (%)	
	tb+tqb
Top quark mass	4.2
Factorization Scale	2.4
PDF	3.0
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
$0 \leq$ flat prior ≤ 1

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