Single Top Quark at the Tevatron

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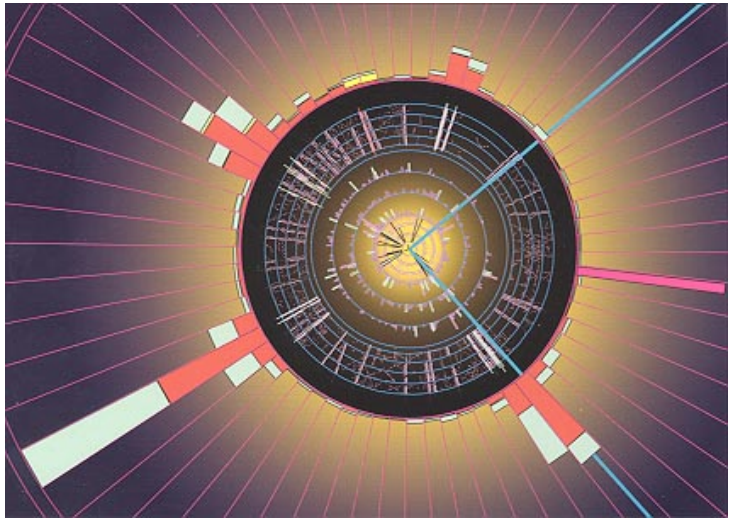
Top 2011 Workshop
Sant Feliu de Guixols
25-30 Sept. 2011

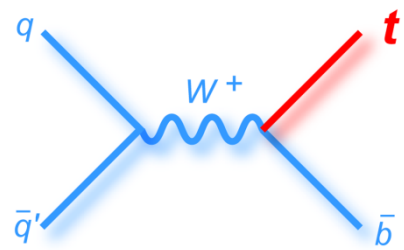
Outline

- Introduction
- Refresher of Observation Analyses
- Details of new 5.4fb^{-1} DØ results
- Understanding the data
  - Event Selection
  - Background Modeling
- Multivariate Analysis Techniques
- Cross Sections
- Direct Measurement of $|V_{tb}|$
- Anomalous Couplings
- Conclusions & Outlook



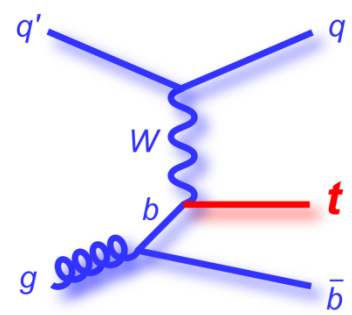
Why Study Single Top Production?

- Probe of the Wtb interaction with no assumption on the number of quark families or unitarity of the CKM matrix
- Allows for indirect measurement of the top quark width
- Cross sections sensitive to beyond-the-SM processes
  - Resonances
    - heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.
  - flavor-changing neutral currents
  - Fourth generation of quarks



s-channel

$\sigma_{SM} = 0.88 \pm 0.11$ pb

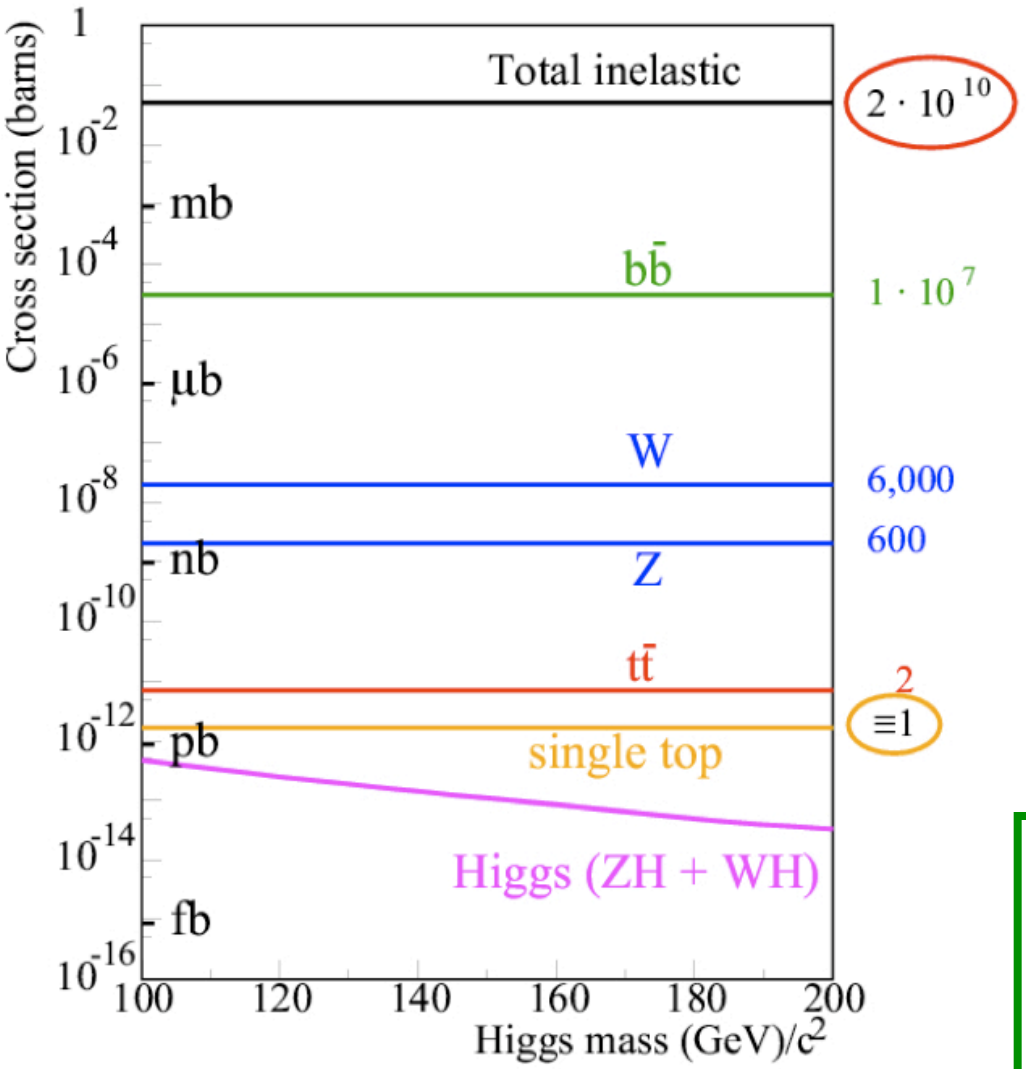


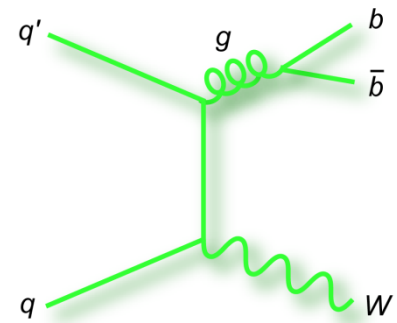
t-channel

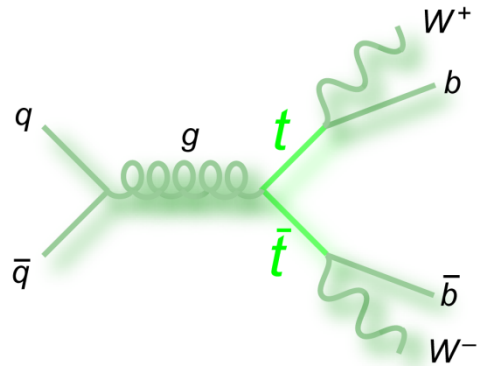
$\sigma_{SM} = 1.98 \pm 0.25$ pb

Single top cross sections from Kidonakis PRD 74, 114012 (2006) for m_t =172.5 GeV

Experimentally very challenging

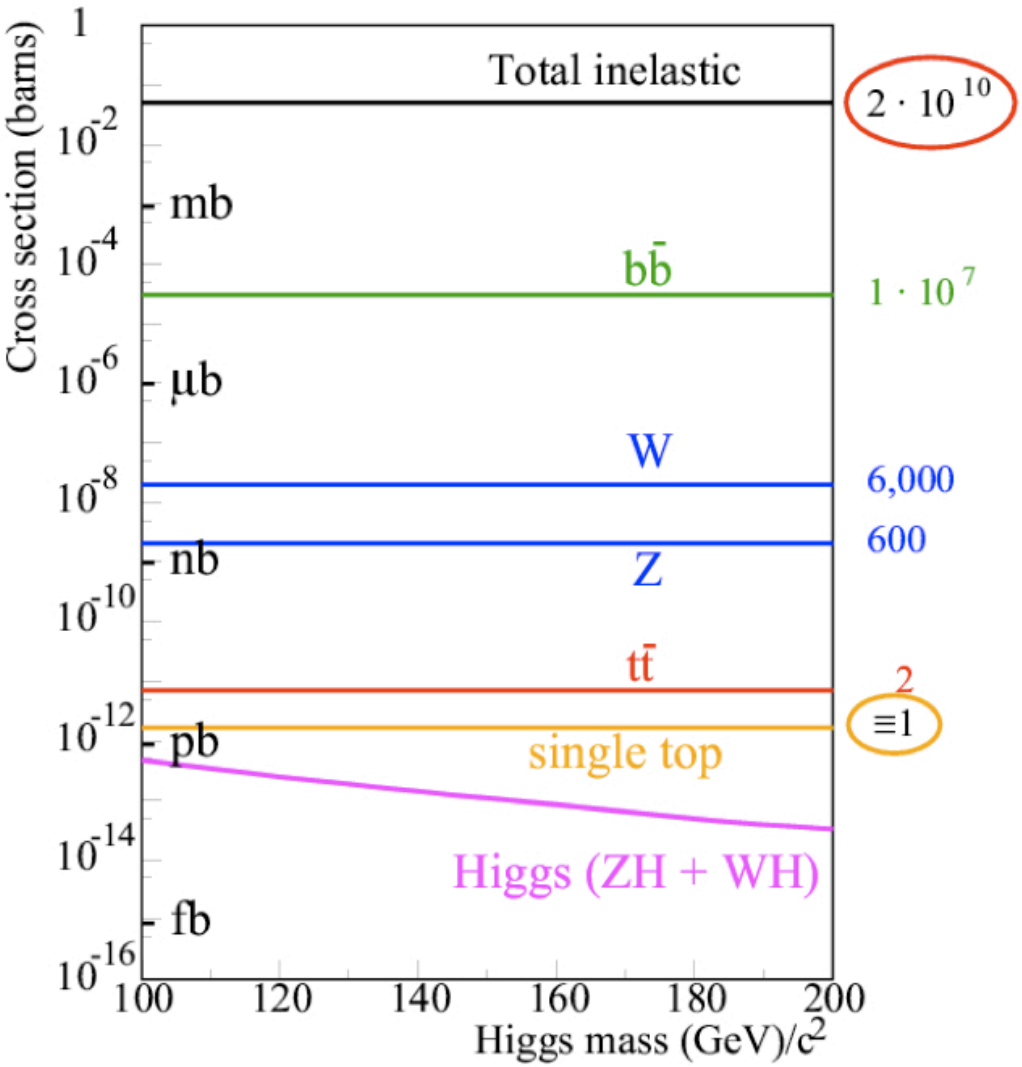






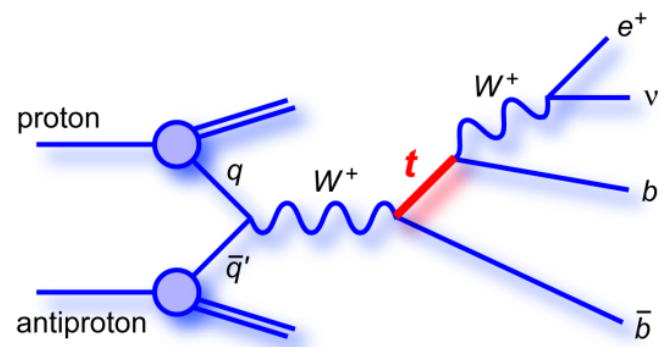
Simple counting experiment cannot extract the signal from the overwhelming background

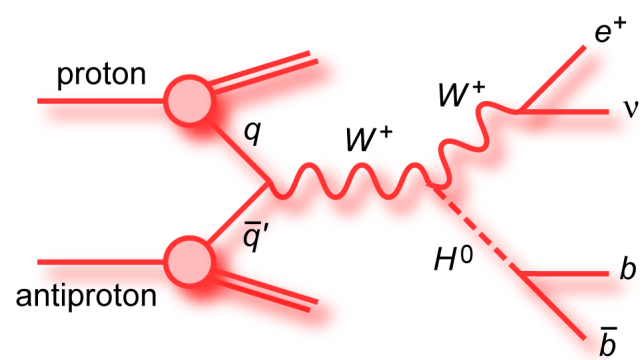
Experimentally very challenging



Same final state as WH

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





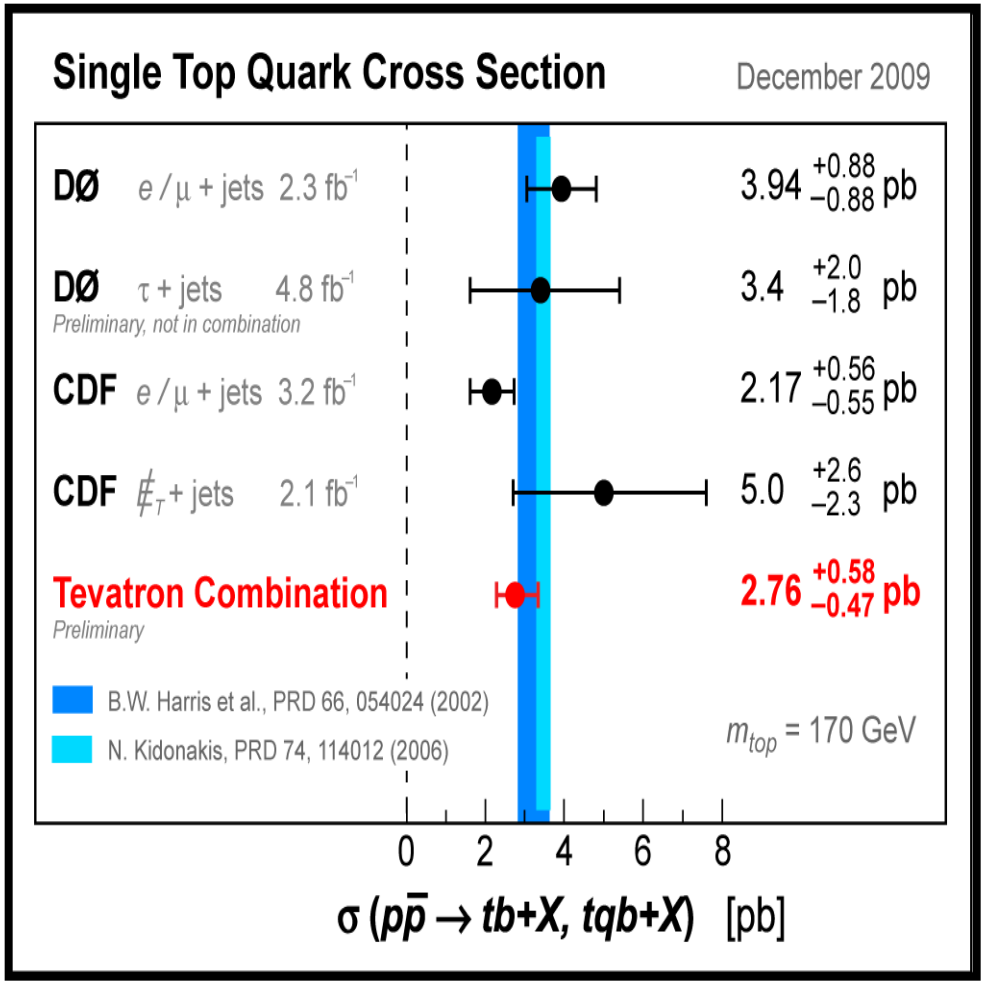
Observation of Single Top Production

March 2009, 14 years after pair production, 50 times more data

Signal Significance	
Expected	**Observed**
DØ (2.3 fb^{-1}) PRL 103, 092001 (2009)	
4.5 σ	**5.0 σ**
CDF (3.2 fb^{-1}) PRL 103, 092002 (2009)	
> 5.9 σ	**5.0 σ**

$$|V_{tb}| = 0.88 \pm 0.07$$

$$|V_{tb}| > 0.77 @ 95\% C.L.$$



http://arxiv.org/abs/0908.2171

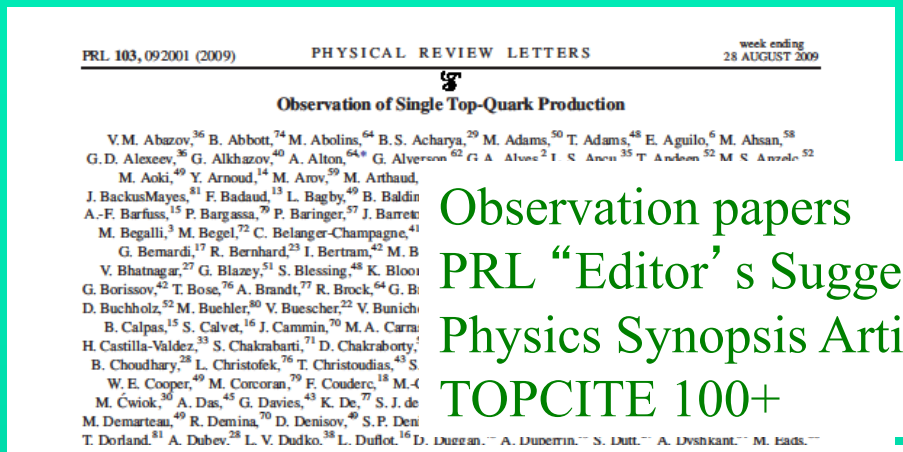
Culmination of a Long History

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 102, 191802 (2009)
- **Observation: PRL 103, 092001 (2009)**

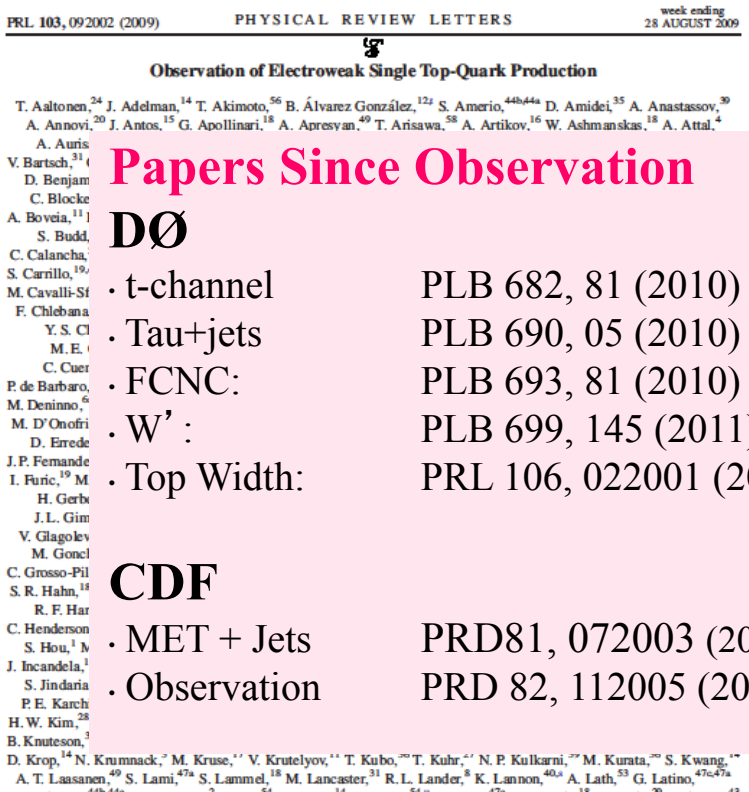
CDF

- 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 102, 151801 (2009)
- W' : PRL 103 091801 (2009)
- **Observation: PRL 103, 092002 (2009)**


PRL 103, 092001 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Observation of Single Top-Quark Production

Observation papers
PRL "Editor's Suggestion"
Physics Synopsis Article
TOPCITE 100+


PRL 103, 092002 (2009) PHYSICAL REVIEW LETTERS week ending 28 AUGUST 2009

Observation of Electroweak Single Top-Quark Production

Papers Since Observation

DØ

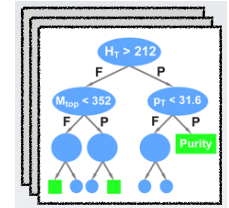
- t-channel PLB 682, 81 (2010)
- Tau+jets PLB 690, 05 (2010)
- FCNC: PLB 693, 81 (2010)
- W' : PLB 699, 145 (2011)
- Top Width: PRL 106, 022001 (2011)

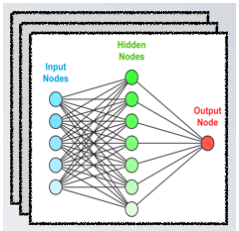
CDF

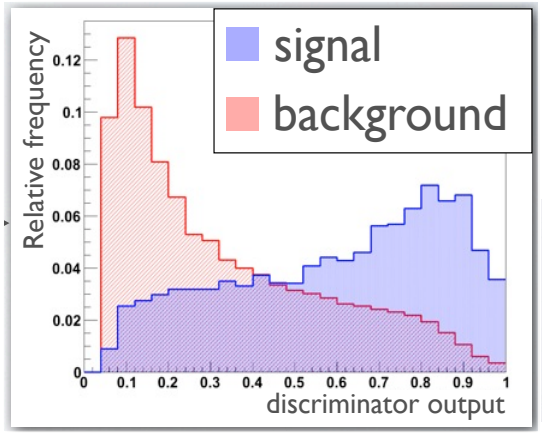
- MET + Jets PRD81, 072003 (2010)
- Observation PRD 82, 112005 (2010)

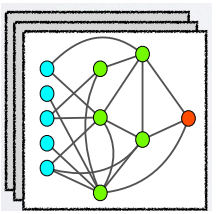
Variety of Published Results

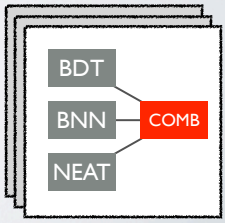
- Different Final States
  - Electron/Muon + Jets
  - Tau + jets (DØ)
  - MET + jets (CDF)
  - Crucial for all the channels
    - b-jets identification





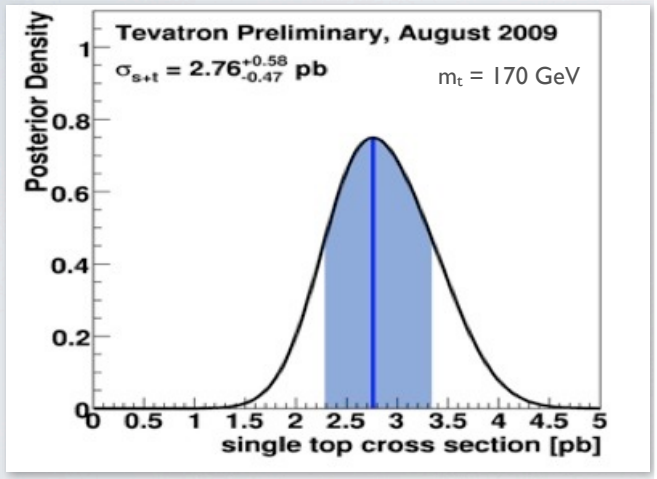




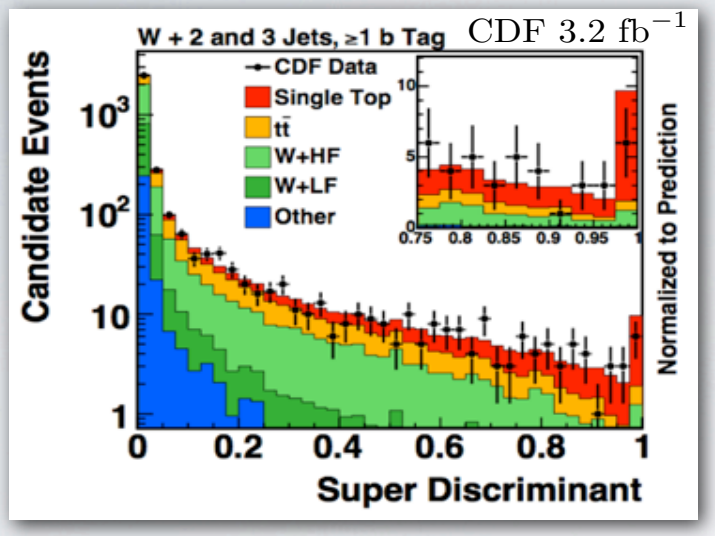


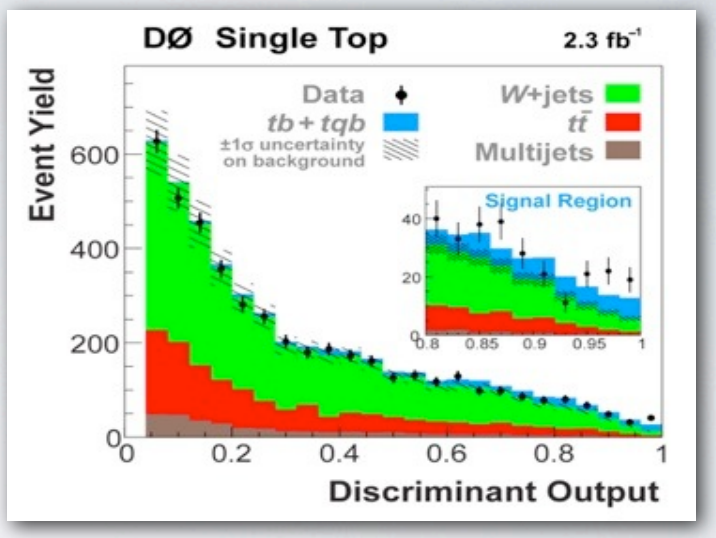
- S:B ~ 1:20 at best
  - Uncertainties in background larger than expected signal
- Use MVAs
  - BNN, BDT, ME, NEAT
  - Both CDF and DØ used a second MVA to increase sensitivity

- Bayesian posterior probability density to extract cross section

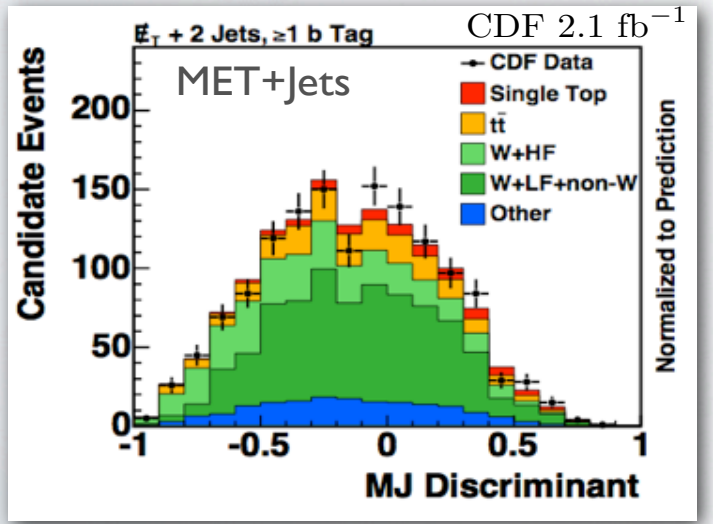


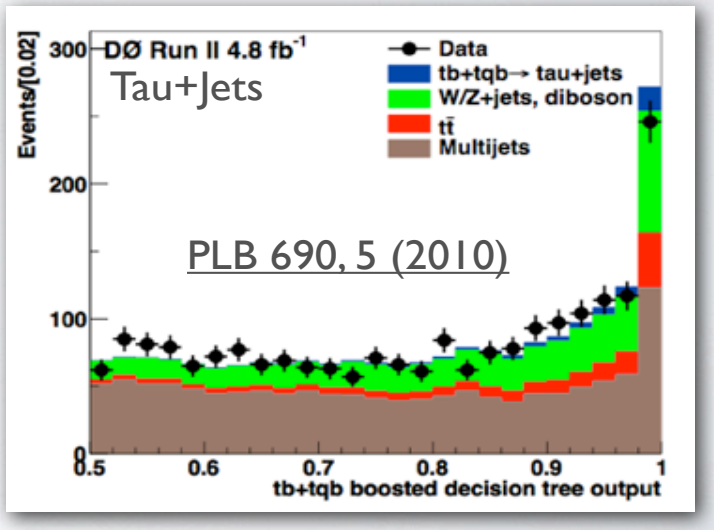
MVA Outputs





arXiv:1101.1275

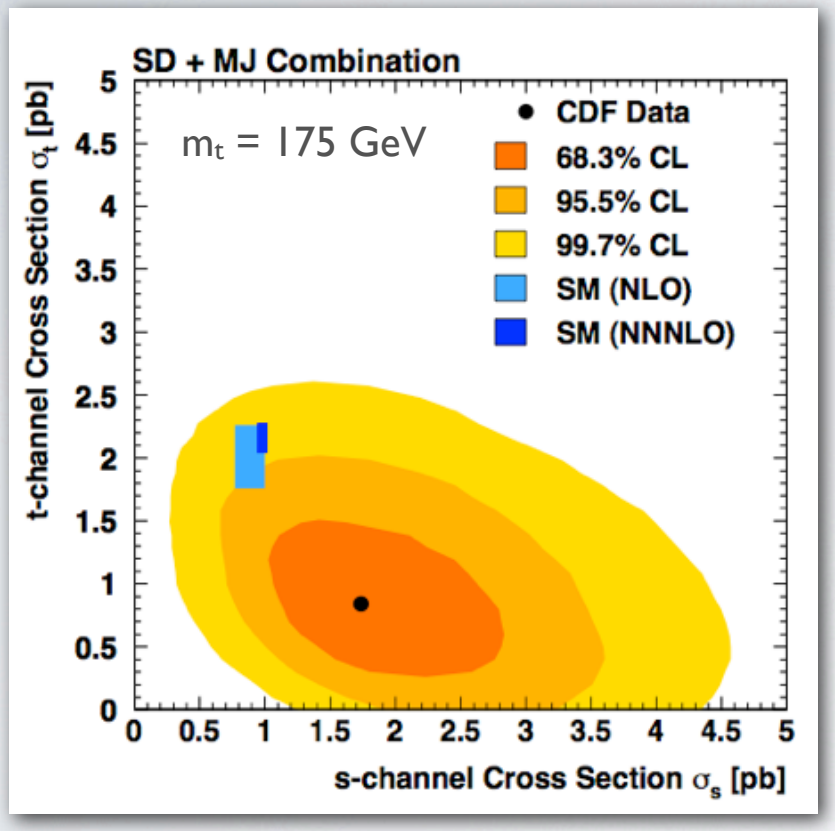




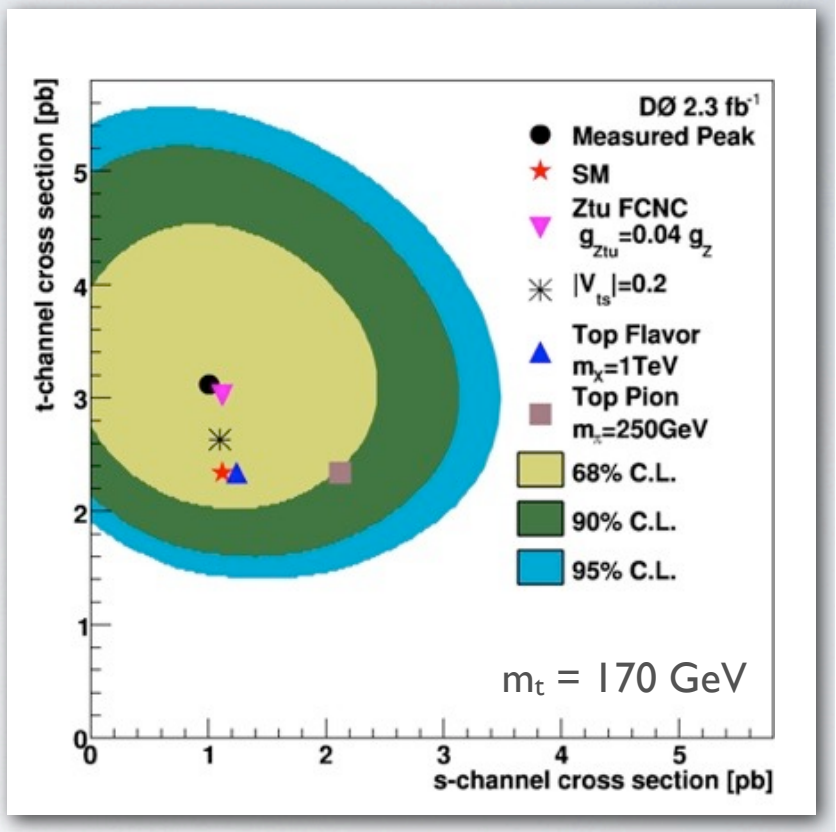
PLB 690, 5 (2010)

2D measurements (2010)

Phys. Rev. D82,112005 (2010)



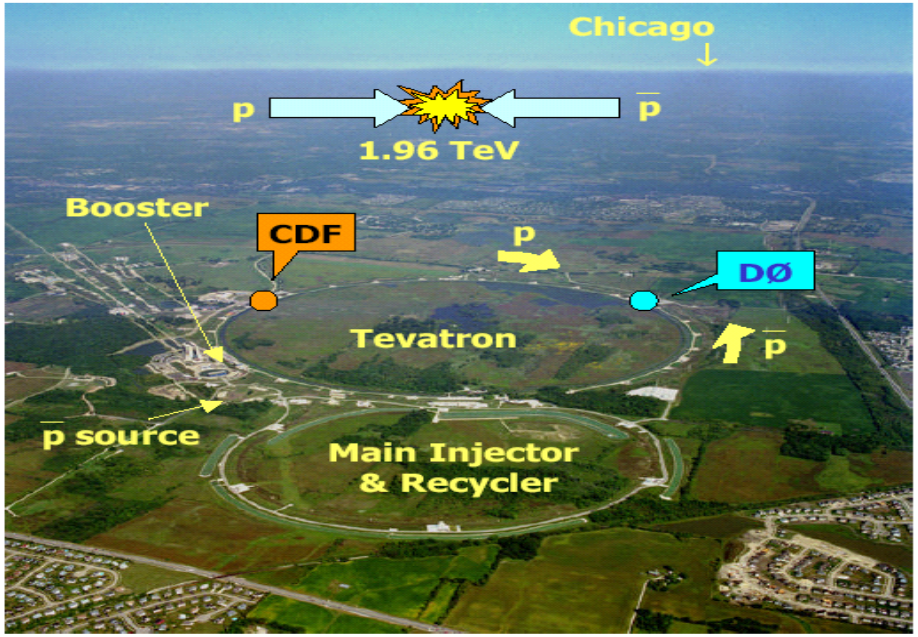
PLB 682, 363 (2010)



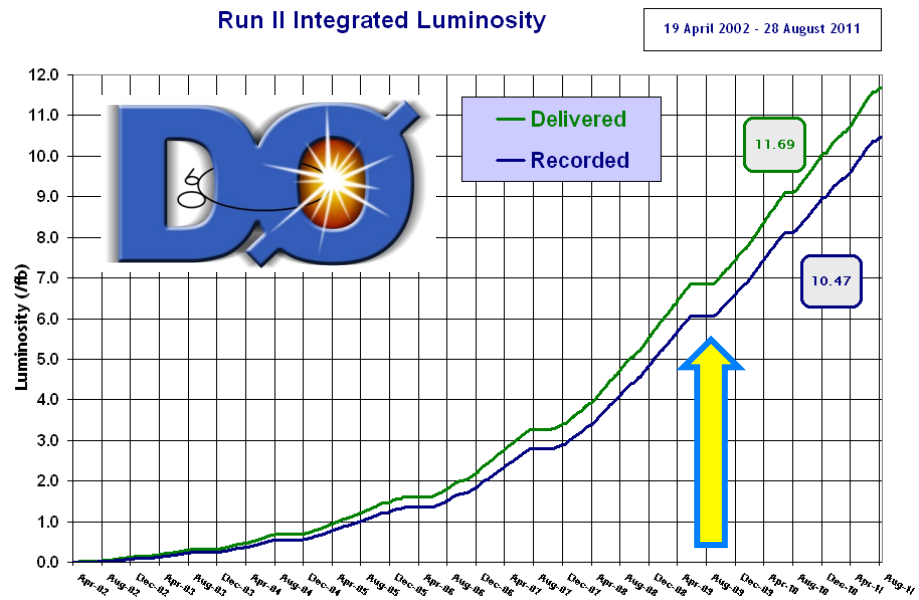
- Simultaneous measurements of s- and t-channel cross sections.
- No standard model cross section is assumed for either of the signals.

New 5.4fb^{-1} DØ analyses as a detailed example

The Fermilab Tevatron



- proton anti-proton collider
  - Until recently, only place where top quarks had been studied
- Data delivered ~12fb^{-1}
  - Recorded ~10.5 fb^{-1}



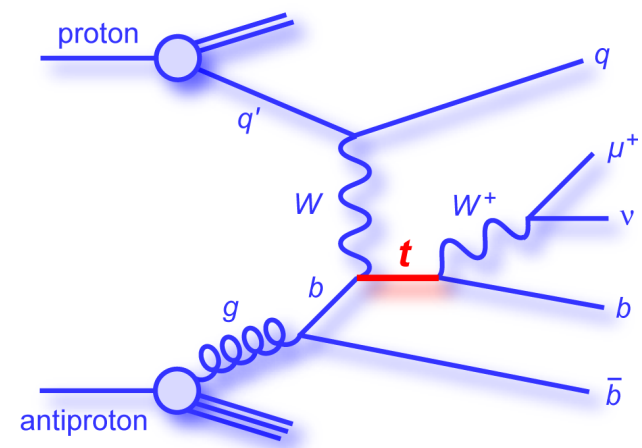
	Run I	Run IIa	Run IIb
Bunches in Turn	6 × 6	36 × 36	36 ×36
√s (TeV)	1.8	1.96	1.96
Peak L (cm^{-2}s^{-1})	1.6 ×10^{30}	9 ×10^{31}	3 ×10^{32}
∫ Ldt (pb^{-1}/week)	3	17	50
Bunch crossing (ns)	3500	396	396
Interactions/ crossing	2.5	2.3	8

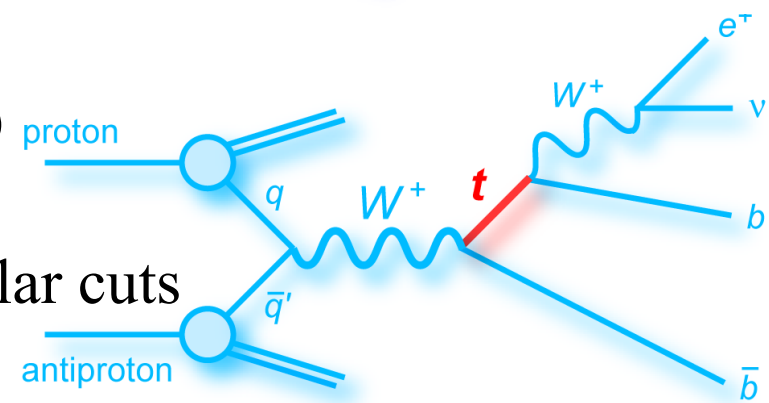
Results based on ~5.5 fb^{-1}

Event Selection

FINAL STATE CONTAINS:

- One high-p_T isolated electron or muon
  - $p_T > 15$GeV, $|\eta| < 1.1(e) < 2.0(\mu)$
- Large missing transverse energy
  - $\not{E}_T > 20$GeV
- 2, 3 or 4 jets
  - $p_T > 25$ GeV (jet1), > 15 GeV (other jets)
  - $|\eta| < 3.4$
- Total Transverse Energy and Triangular cuts
  - $H_T > 110 - 160$ GeV
  - $|\Delta\varphi(\text{jet1}, ME_T)|$ vs ME_T
  - $|\Delta\varphi(\text{lepton}, ME_T)|$ vs ME_T
- At least one b-tagged jet





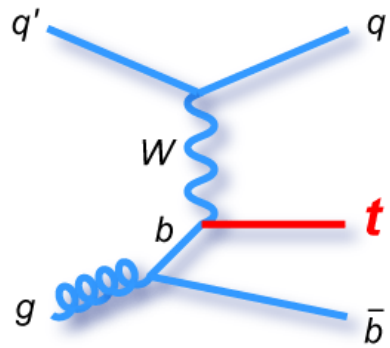
Signal acceptance

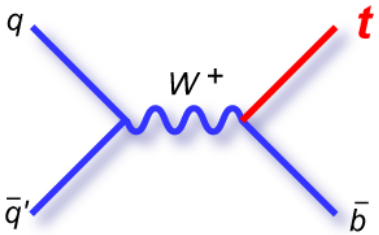
tb = (2.9 ± 0.4) %

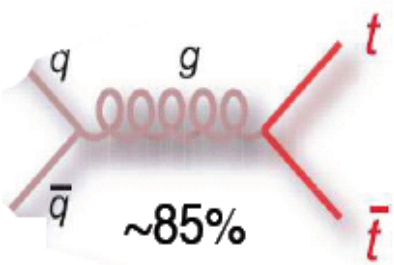
tqb = (2.0 ± 0.3) %

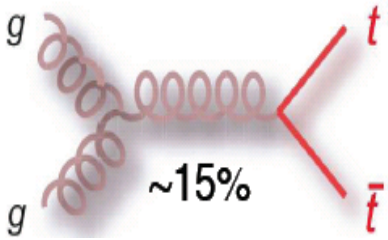
Signal and Background Models

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





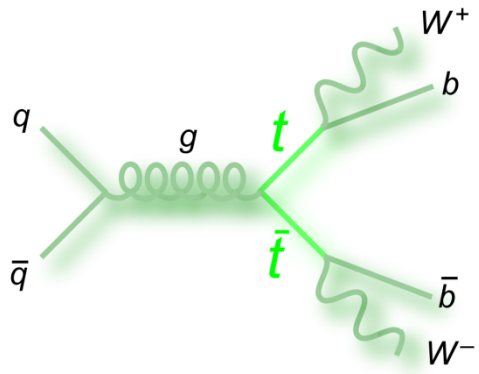




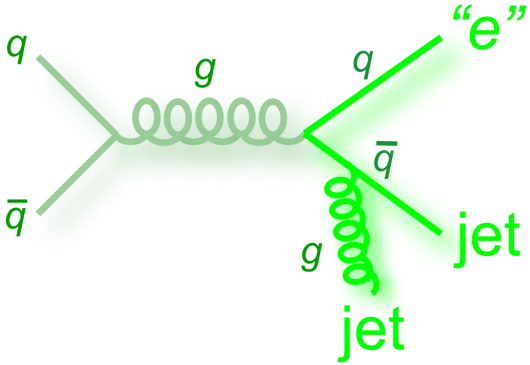
- Top pair backgrounds modeled using ALPGEN
  - PYTHIA for parton hadronization
  - Parton-jet matching algorithm used to avoid double-counting final states
  - Normalized σ = 7.46+0.48-0.67 pb from Moch and Uwer, PRD 78, 034003 (2008) for m_t =172.5 GeV
  - Additional uncertainties include color reconnection (1%), jet fragmentation and higher order effects (1.6%-7%), ISR/FSR (0.8%-11%), and b-jet fragmentation (2%).

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
  - Kept small (~5%) with topological selection cuts



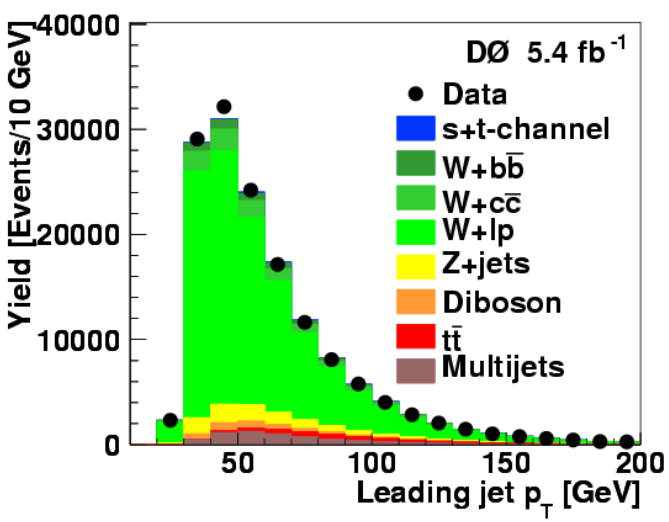
- Z+jets modeled using ALPGEN + PYTHIA
  - Normalized to NNLO given by FEWZ, with 3.3% uncertainty
- Dibosons modeled using PYTHIA
  - Normalized to NLO given by MCFM, with 7% uncertainty

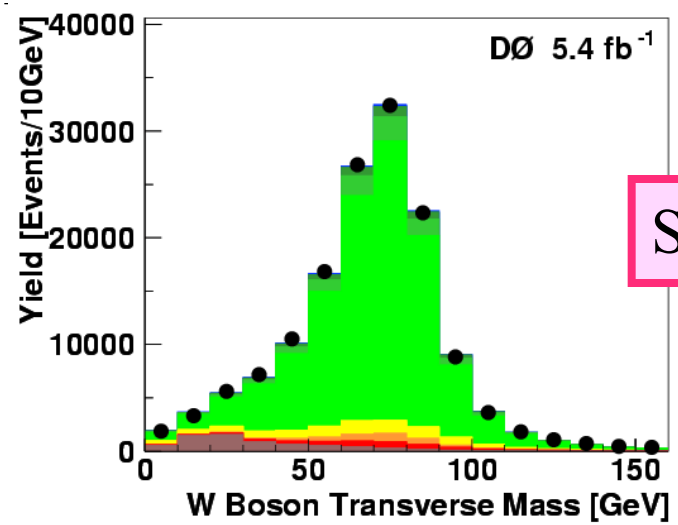
Background Normalization

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

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

- $\lambda_{\text{W+jets}}$ & $\lambda_{\text{multijet}}$ are varied to maximize the product of the KS values for the three sensitive variables.
- Uncertainties are 30%-40% for multijet, 1.8% for W's

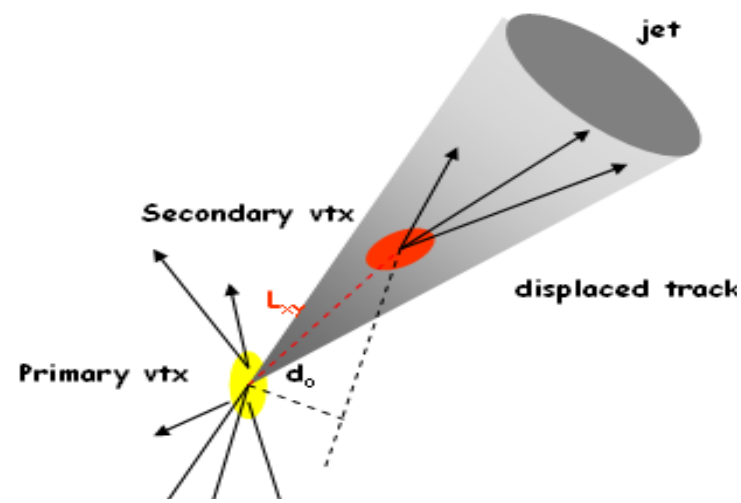




S:B = 1:224

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 ($\varepsilon_b = 40\%$, $\varepsilon_c = 9\%$, $\varepsilon_l = 0.4\%$)
  - LOOSE ($\varepsilon_b = 50\%$, $\varepsilon_c = 14\%$, $\varepsilon_l = 1.5\%$)
- Leading b-jet $p_T > 20$ GeV
- Define two exclusive samples
  - EqOneTag: 1T, no L
  - EqTwoTag: 2L



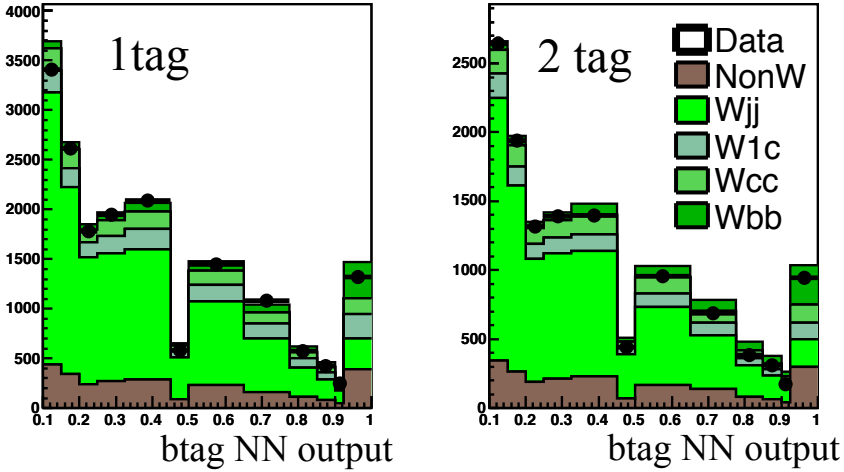
- b-tagging uncertainties dominated by variation in data samples used to measure the efficiencies.
- Smaller contribution from MC sample dependence

W + Heavy Flavor Normalization

- W/Z + heavy flavor normalized to theory (MCFM-NLO)
  - 1.47 (Wbb,Wcc), 1.32 (Wcj), 1.52 (Zbb), 1.67 (Zcc)
- Normalization checked in 2 jets/0 tag sample

$$N^{(0)} = N^{(0)}_{\mathrm{Wlp}} + \lambda_{\mathrm{HF}} N^{(0)}_{\mathrm{Whp}}$$

  - λ_{HF} found to be consistent with 1
- Uncertainties considered
  - ± 40% single top cross section
    - ± 1% in λ_{HF}
  - ± 10% on the Wcj theory SF
    - ± 7% in λ_{HF}
  - Additional ± 10% Wbb/Wcc
    - ± 8% in λ_{HF}
  - For a total uncertainty of 12%



Systematic Uncertainties

Relative Systematic Uncertainties

Components for Normalization	
Integrated luminosity	6.1%
$t\bar{t}$ cross section	9.0%
Z+jets cross section	3.3%
Diboson cross sections	7.0%
Branching fractions	1.5%
Parton distribution functions (signal acceptances only)	2.0%
Triggers	5.0%
Instantaneous luminosity reweighting	1.0%
Primary vertex selection	1.4%
Color reconnection	1.0%
b/light jet response	(0.3-1.0)%
Electron identification	(2.8-3.8)%
Muon identification	2.1%
Jet fragmentation and higher order effects	(0.7-7.0)%
Initial-and final-state radiation	(0.8-10.9)%
b-jet fragmentation	2.0%
Taggability	(3.1-21.5)%
W+jets heavy-flavor correction	12.0%
Z+jets heavy-flavor correction	12.0%
W+jets normalization to data	1.8%
Multijets normalization to data	(30-40)%
MC and multijets statistics	(0.2-16)%

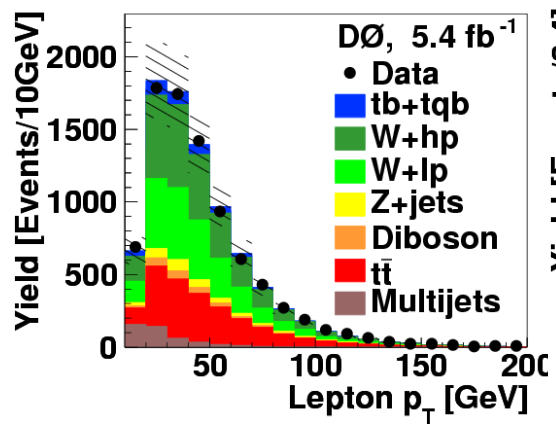
Components for Normalization and Shape	
Jet reconstruction and identification	(0.04-3.7)%
Jet energy resolution	(0.2-11.6)%
Jet energy scale	(0.3-14.6)%
Vertex confirmation	(0.1-9.6)%
b tagging, single-tagged	(4.3-14.0)%
b tagging, double-tagged	(5.8-11.2)%
Angular correction	0.3%

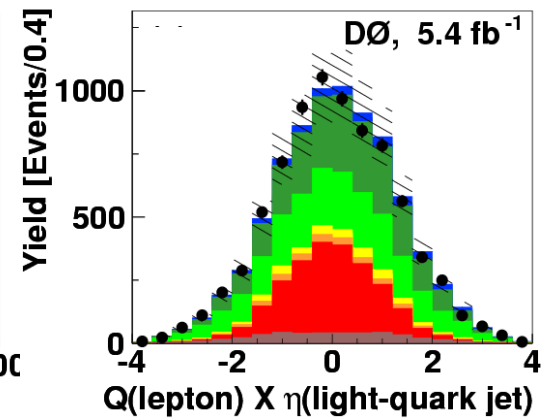
Components that most affect the cross section measurement are shown in *red*

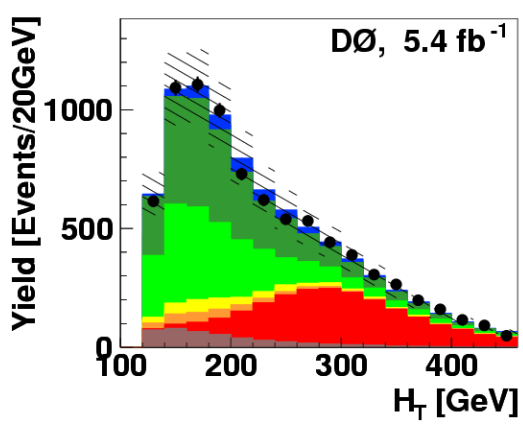
Other important contributions are shown in *pink*

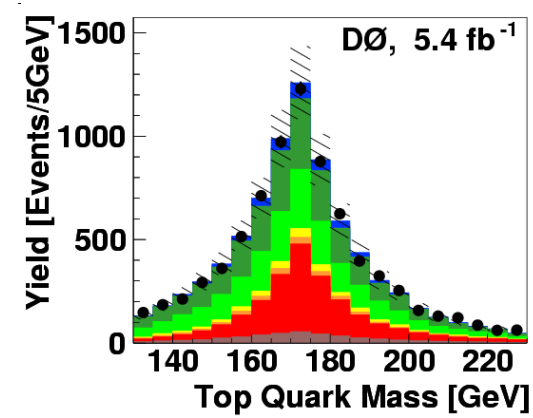
Event yields & Background Modeling

Event yields in 5.4/fb DØ data	
e,μ, 2,3,4-jets 1,2-tags combined	
t-channel	239 ± 28
s-channel	160 ± 27
W+jets	4943 ± 598
Z+jet, dibosons	576 ± 113
tt	2124 ± 383
Multijets	451 ± 56
Total prediction	8492 ± 987
Data	8471 ± 92









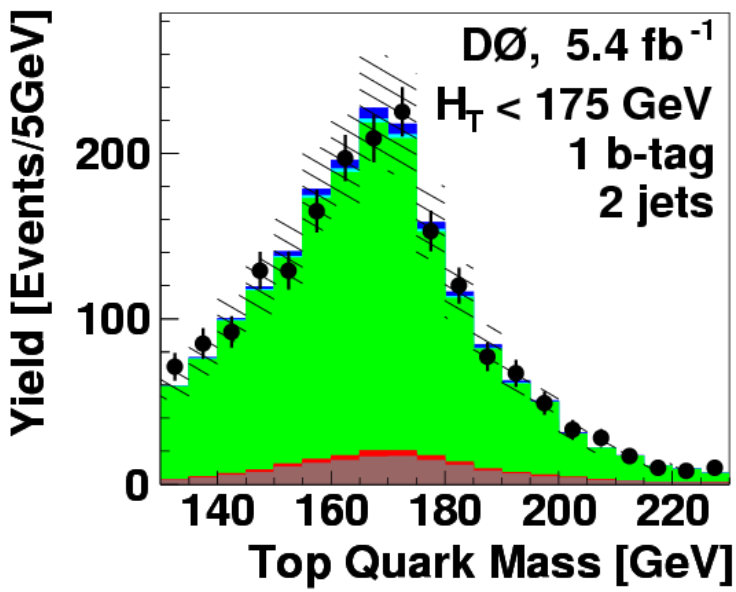
S:B = 1:22 in 1Tag
S:B = 1:16 in 2Tag

Cross Check Samples

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

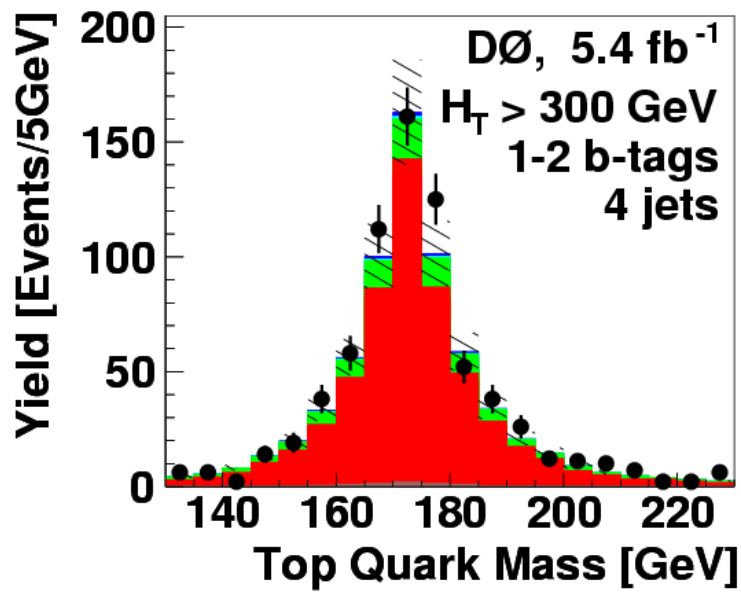
W + JETS

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



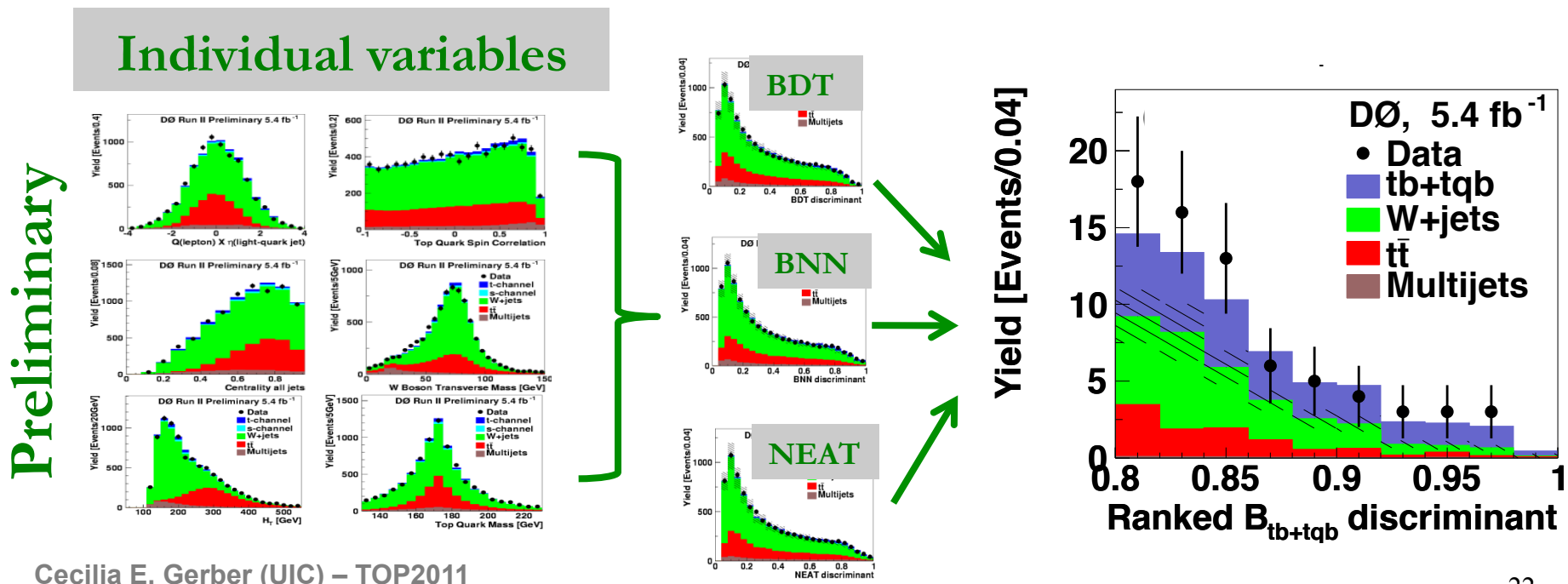
Top Pairs

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



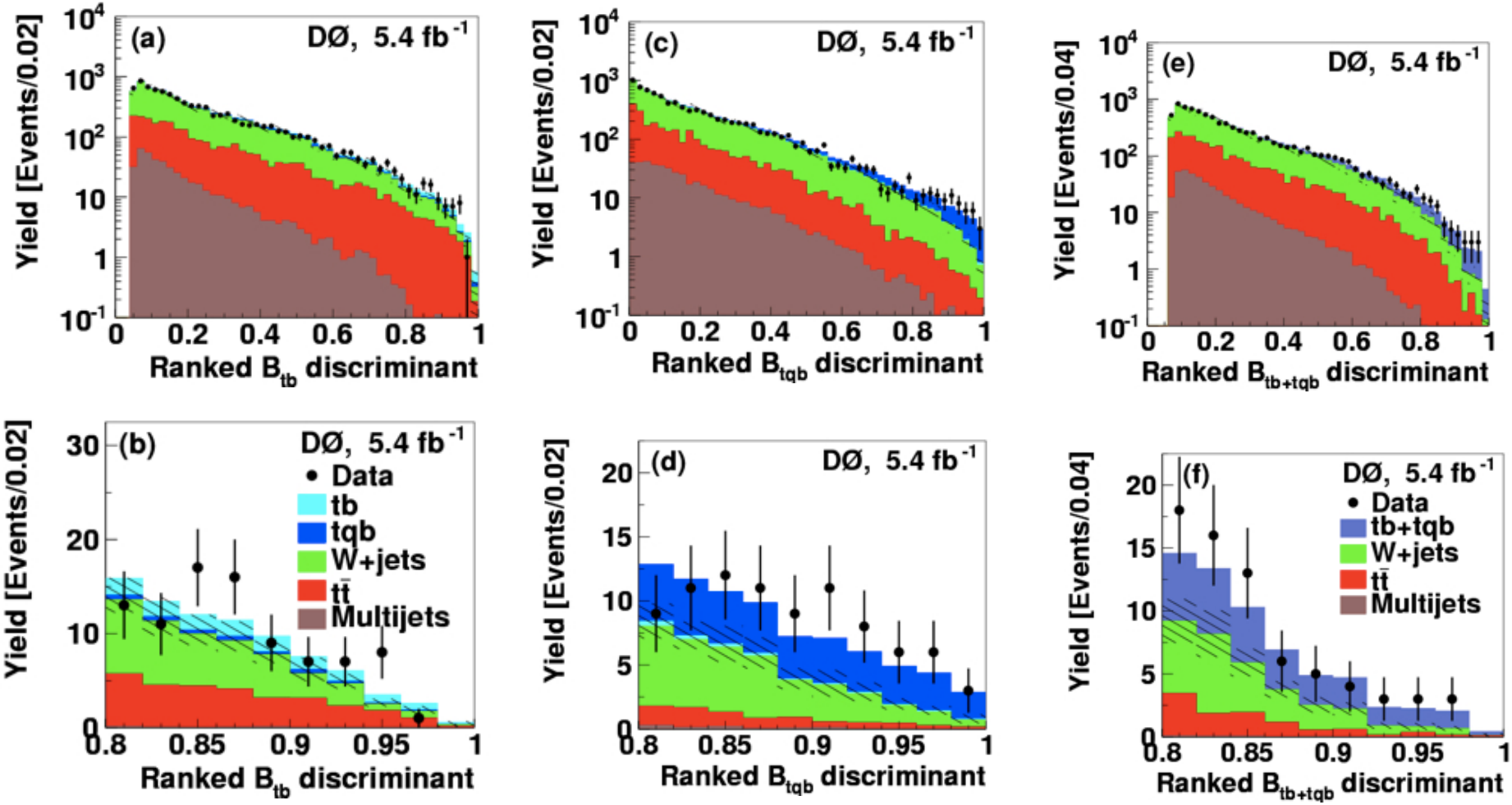
Analysis Strategy

- Combine variables with large discriminating power into discriminant functions that separate signal from background
  - Boosted Decision Tree (BDT)
  - Bayesian Neural Network (BNN)
  - Neuroevolution of Augmented Topologies (NEAT)
- Correlation between methods ~70%, gain by combining them



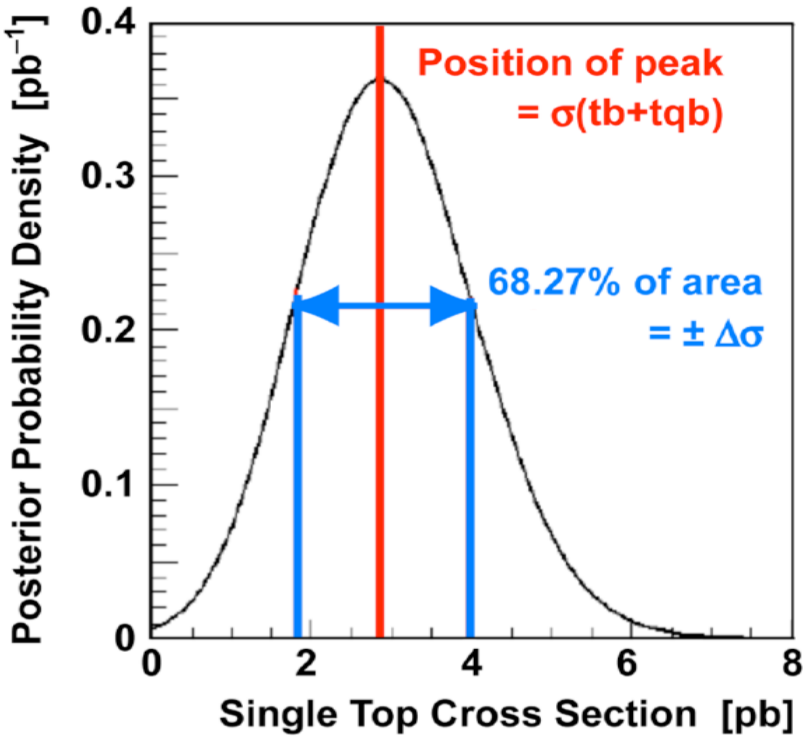
Multivariate Discriminant Outputs

tb discriminant | tqb discriminant | tb+tqb discriminant



Cross Section Measurement

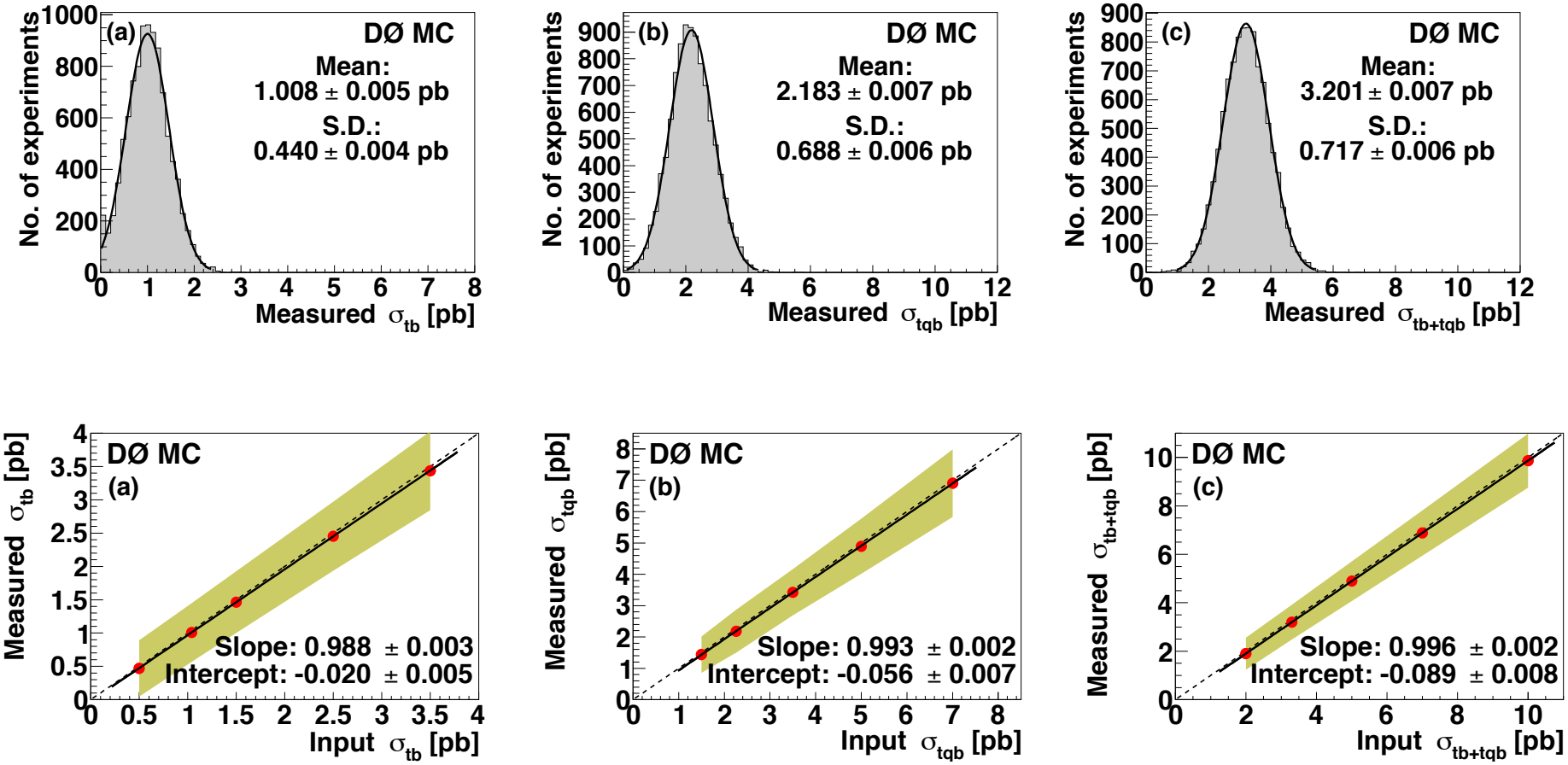
- Cross Sections are measured by building a Bayesian posterior probability density
- For each analysis, the single top cross section is given by the position of the posterior density peak, with 68% asymmetric interval as uncertainty



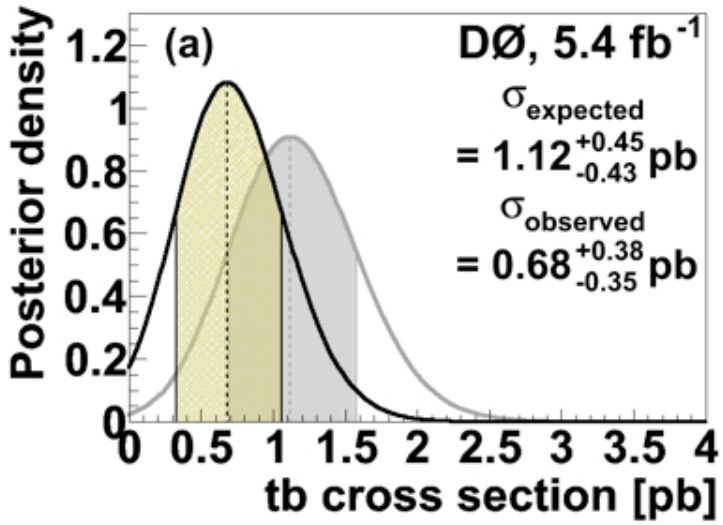
- Gaussian prior for systematic uncertainties
  - Correlations of uncertainties properly taken into account
- Flat prior in signal cross sections

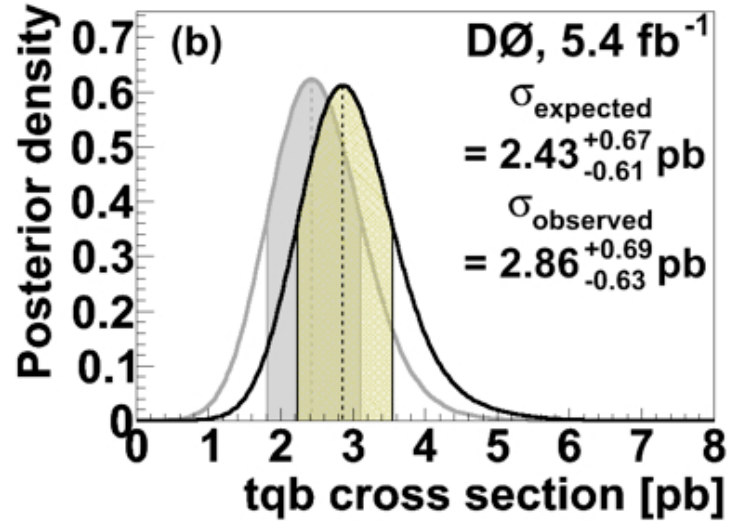
Linearity Tests

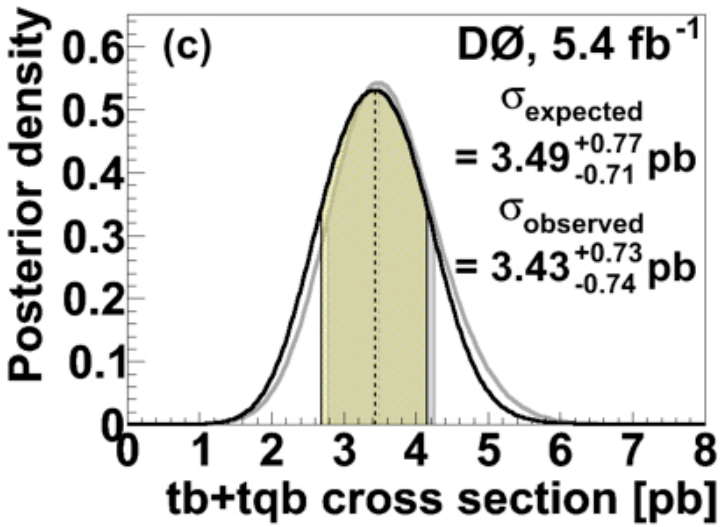
Use ensembles of pseudo-data to test validity of x-sec extraction method



Measured Cross Sections



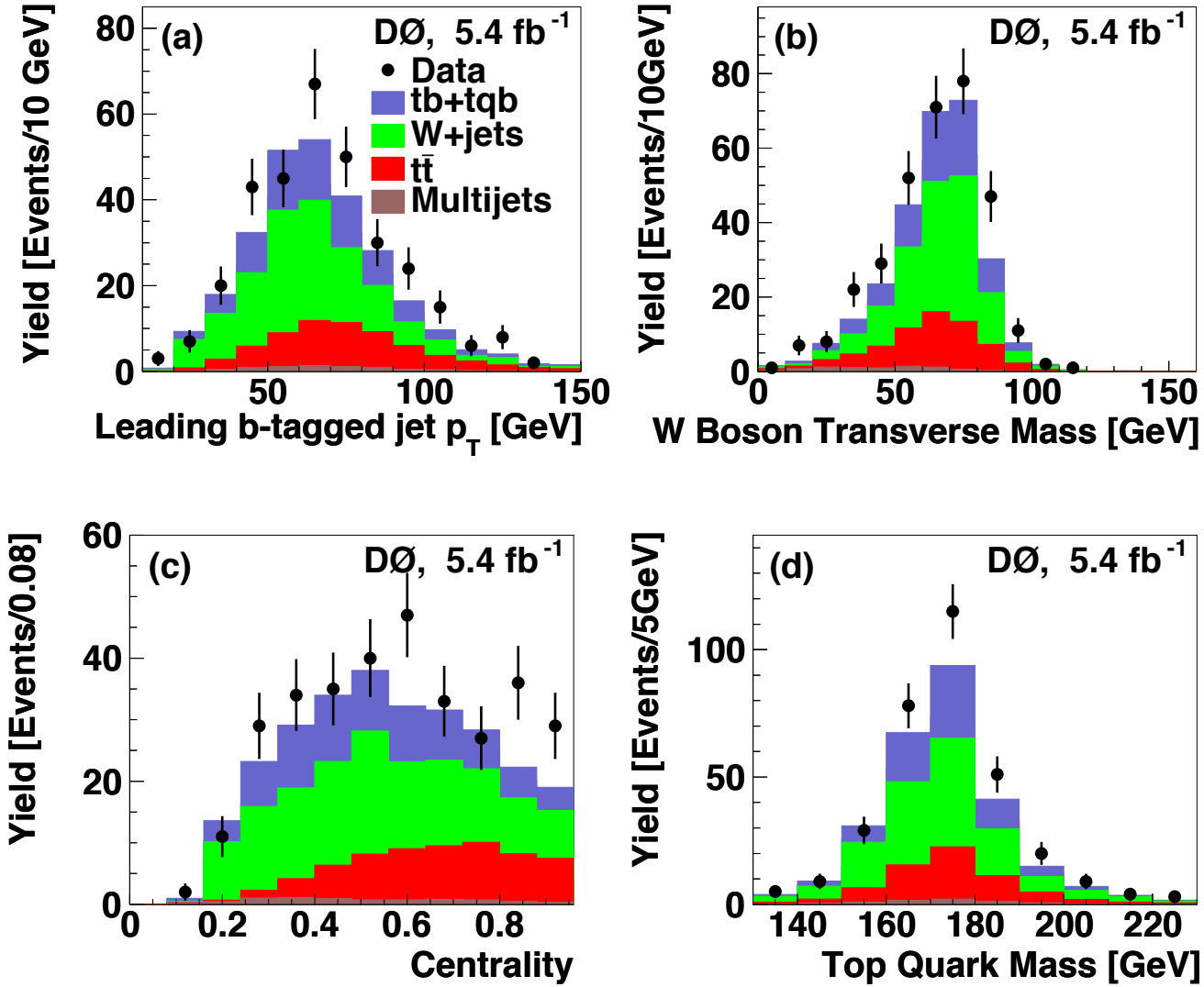




m_t	170 GeV	172.5 GeV	175 GeV
tb	$1.20^{+0.62}_{-0.56}$	$0.68^{+0.38}_{-0.35}$	$0.53^{+0.36}_{-0.34}$
SM	$1.12^{+0.04}_{-0.04}$	$1.04^{+0.04}_{-0.04}$	$0.98^{+0.04}_{-0.04}$
tqb	$2.65^{+0.65}_{-0.59}$	$2.86^{+0.69}_{-0.63}$	$2.45^{+0.60}_{-0.57}$
SM	$2.34^{+0.12}_{-0.12}$	$2.26^{+0.12}_{-0.12}$	$2.16^{+0.12}_{-0.12}$
tb+tqb	$3.70^{+0.78}_{-0.80}$	$3.43^{+0.73}_{-0.74}$	$2.56^{+0.69}_{-0.61}$
SM	$3.46^{+0.16}_{-0.16}$	$3.30^{+0.16}_{-0.16}$	$3.14^{+0.16}_{-0.16}$

arXiv:1108.3091 submitted to Phys. Rev. D

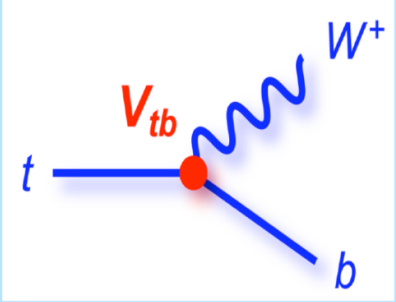
Distributions for S:B > 0.24



CKM Matrix Element Vtb

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

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



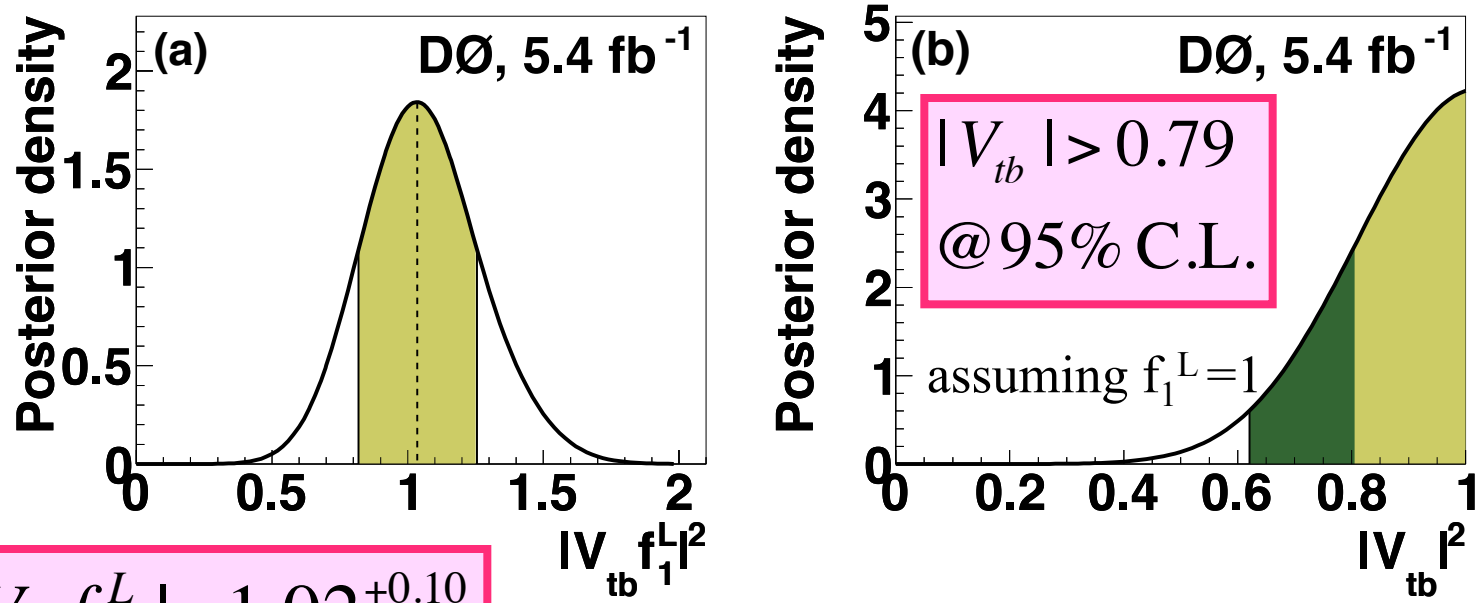
- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- General form of the Wtb vertex

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

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

Measurement of $|V_{tb}|$

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

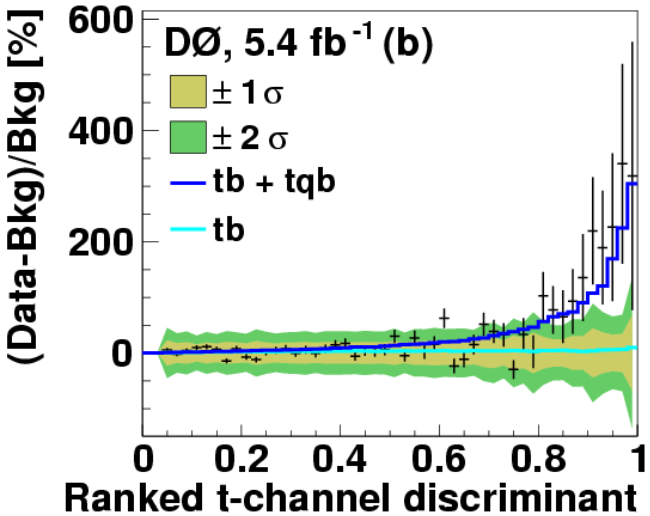


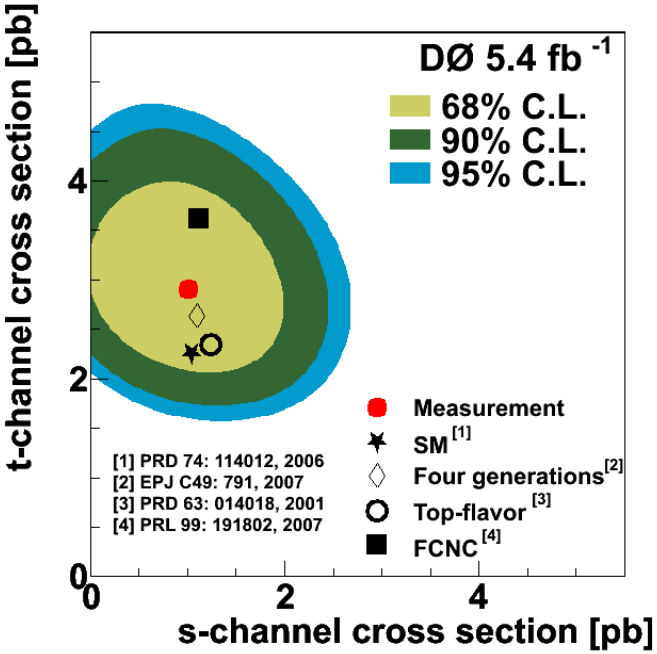
$$|V_{tb} f_1^L| = 1.02^{+0.10}_{-0.11}$$

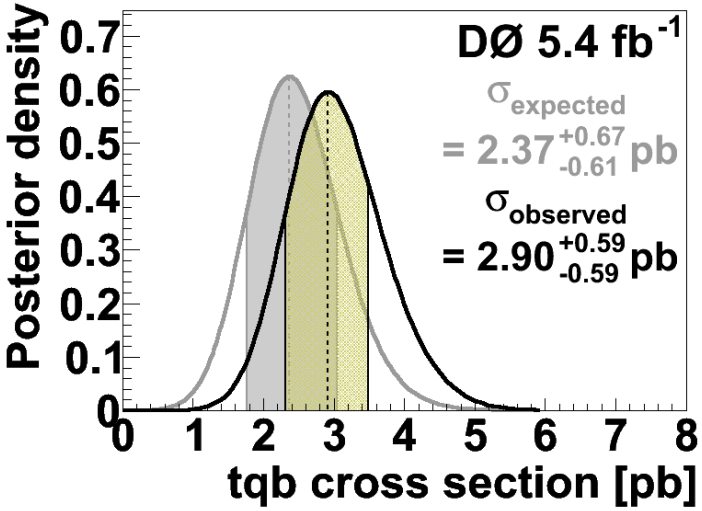
arXiv:1108.3091 submitted to Phys. Rev. D

Model-independent t-channel Cross Section

- Construct a 2D posterior probability density for tqb vs tb cross sections
  - No constraint is imposed on the relative rates of tb and tqb production
- Extract the tqb cross section from a 1D posterior obtained by integrating over the tb axis, with no assumption on the tb rate







Observed significance > 5SD

arXiv:1105.2788 submitted to Phys Lett B

Anomalous Wtb Couplings

- Most general, lowest dimension Wtb vertex:

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}(L_V P_L + R_V P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}(L_T P_L + R_T P_R)tW_{\mu}^{-} + h.c.$$

Left-handed vector $L_V = V_{tb} \cdot f_{L_V}$

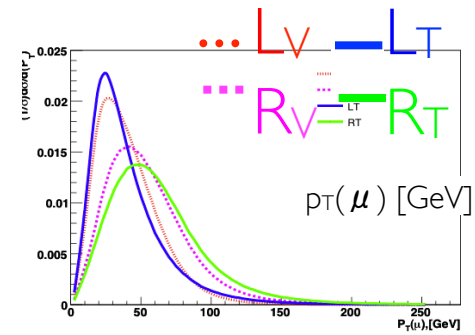
Right-handed vector $R_V = V_{tb} \cdot f_{R_V}$

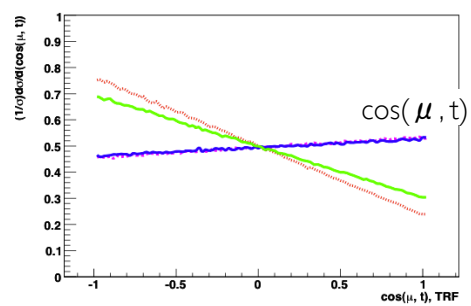
Left-handed tensor $L_T = V_{tb} \cdot f_{L_T}$

Right-handed tensor $R_T = V_{tb} \cdot f_{R_T}$

$$\text{SM}: L_V \equiv |V_{tb}| \simeq 1 \text{ and } R_V = L_T = R_T = 0$$

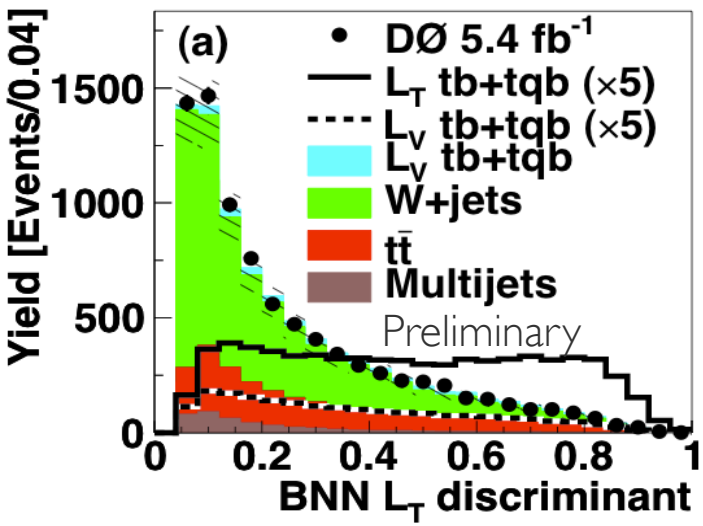
- Assumptions:
  - Production (SM & Anom.) only via W boson exchange
  - $|V_{td}|^2+|V_{ts}|^2 << |V_{tb}|^2$
  - CP-conserving Wtb vertex
  - Anomalous couplings in both production and decay
- Event kinematics and angular distributions sensitive to anomalous couplings





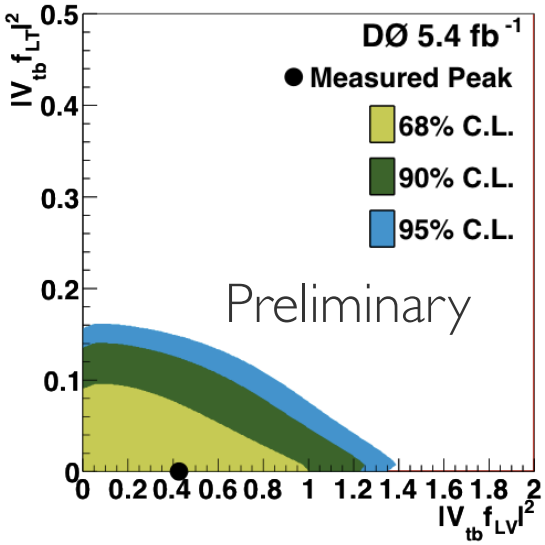
Analysis Strategy: Three Scenarios

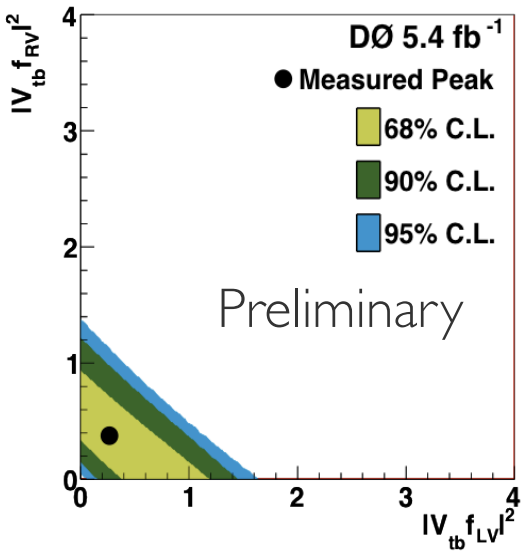
- Pair the L_V coupling with one non-SM coupling and assume the other two are negligible
  - (L_V, L_T); L_V=L_T=1; R_V = R_T = 0
    - includes the interference L_V+L_T
  - (L_V, R_V); L_V= R_V=1; L_T = R_T = 0
  - (L_V, R_T); L_V=R_T=1; R_V = L_T = 0
- Use BNN. For each Scenario:
  - Signal: one of L_T/R_V/R_T
  - Background includes SM L_V
- Additional systematics:
  - tb (3.8%), tqb (5.3%), mixed couplings in prod and decay (15%)

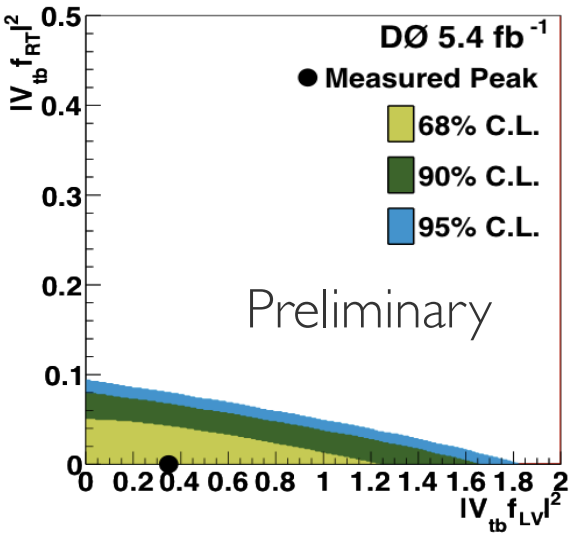


- Build 2D posterior of $|V_{tb}\, f_{LV}|^2$ vs $|V_{tb}\, f_X|^2$
  - Obtain 1D posterior for $|V_{tb}\, f_X|^2$ by integrating over $|V_{tb}\, f_{LV}|^2$

Results





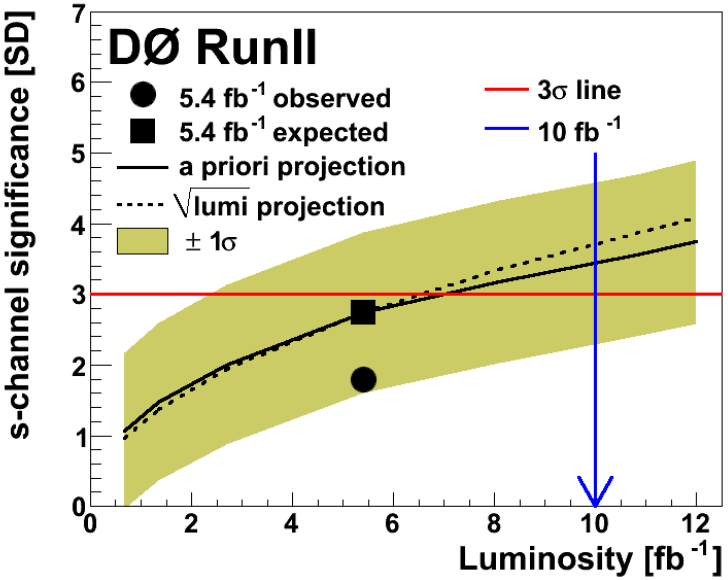


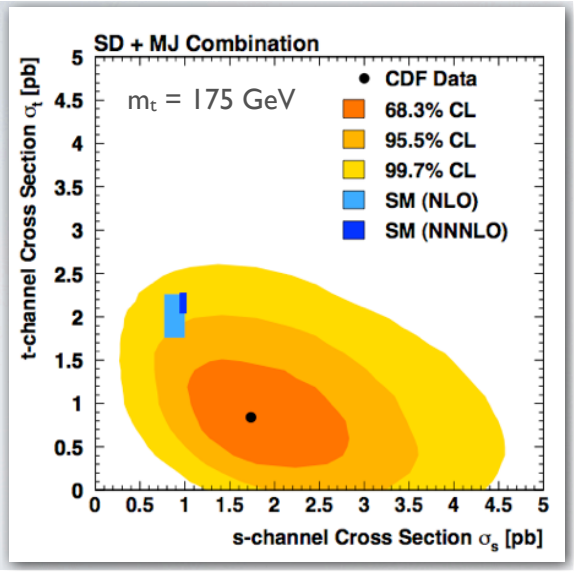
No evidence for anomalous couplings, set 95% C.L upper limits

Anomalous couplings	(L_V, L_T)	(L_V, R_V)	(L_V, R_T)
Cross Section	< 1.21 pb	< 2.81 pb	< 0.60 pb
Coupling $\lvert V_{tb} \cdot f_X \rvert^2$	< 0.13	< 0.93	< 0.06

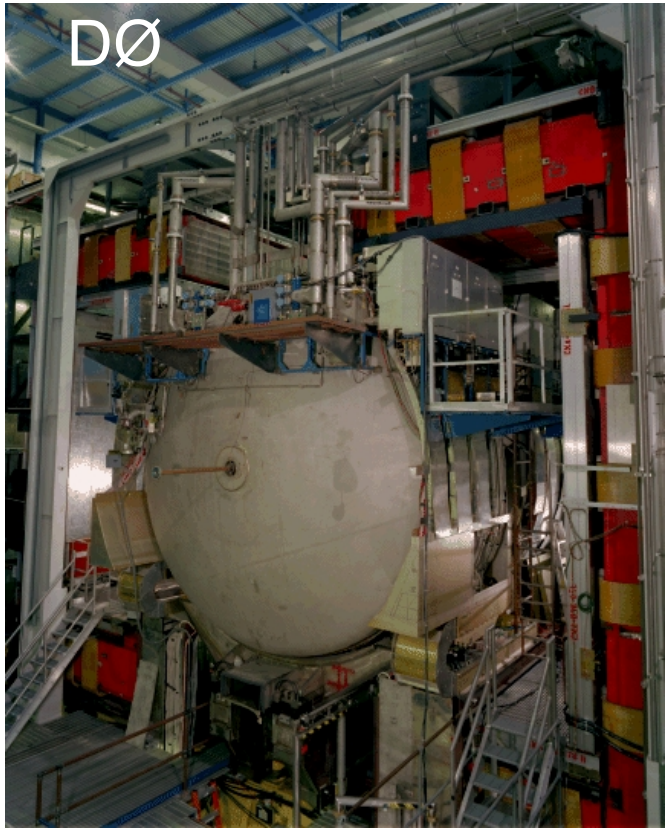
Conclusions and Plans

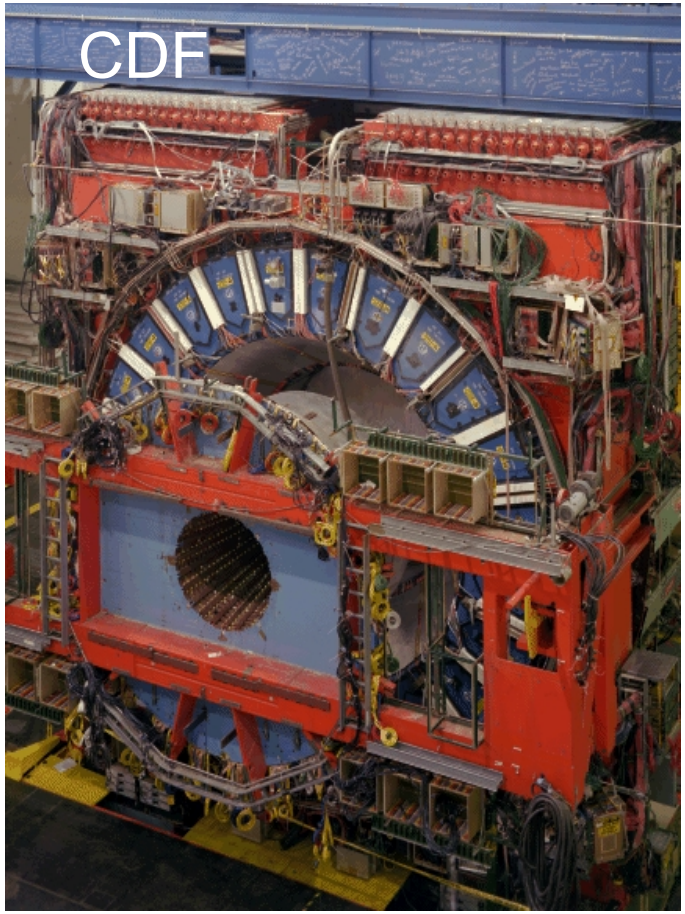
- Vibrant Single Top Program after 2009 observation
- With half the available luminosity analyzed:
  - New cross section measurements with precision of ~20%
  - Observation of t-channel production
  - Measurements and limits on Vtb
    - No departures from the SM observed
- Going after s-channel with full dataset





Latest measurements and discoveries



http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html#singletop

http://www-cdf.fnal.gov/physics/new/top/public_singletop.html