EPS Conference on High Energy Physics

KTH Stockholm, July 19, 2013

Single top production at the Tevatron

- Electroweak production of top quarks
- Signal and selection
- Recent DØ and CDF results
  - CDF s+t measurement (7.5 fb^{-1})
  - DØ s-channel evidence (9.7 fb^{-1}) NEW
  - CDF s+t measurement in MET+jets (9.1 fb^{-1})
- Searches for anomalous Wtb couplings DØ (5.4 fb^{-1})
- Summary

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On behalf of CDF and DØ

Electroweak top quark production

Main production mechanism is $t\bar{t}$ via the strong interaction:

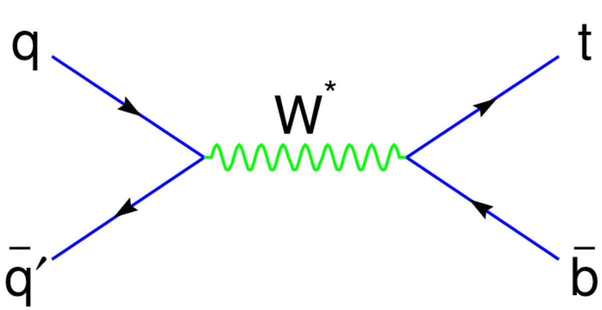
σ(tt) ~ 7.1 pb @ TeV	σ(tt) ~ 234 pb @ LHC8

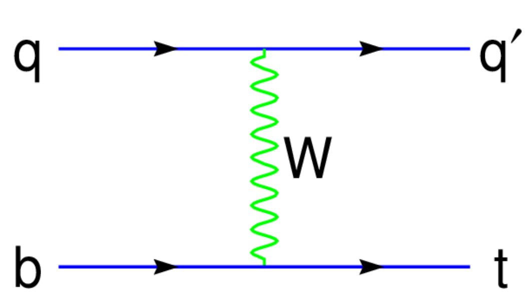
Top quarks can be produced alone via the weak interaction:

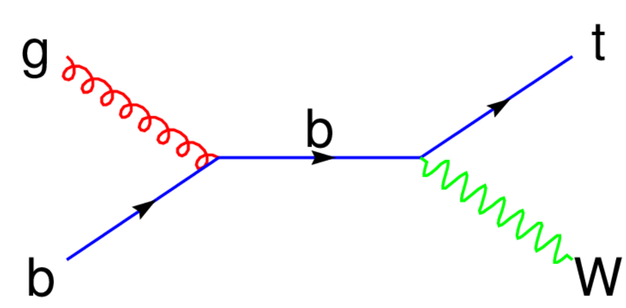
σ(t) ~ 3.2 pb @ TeV	σ(t) ~ 115 pb @ LHC8

- 3 production processes: different topologies and properties
- Offers direct access to $|V_{tb}|$, test V-A nature of SM, probes b PDF
- Window to new physics: new particles, anomalous couplings
- LHC w.r.t TeV: s-channel x5, t-channel x40, tW x100, $t\bar{t}$ x30

	s-channel	t-channel	tW
TeV:	**1.04±0.06 pb**	**2.1±0.1 pb**	**0.22±0.08 pb**
LHC8:	**5.6±0.2pb**	**87±3 pb**	**22±2 pb**







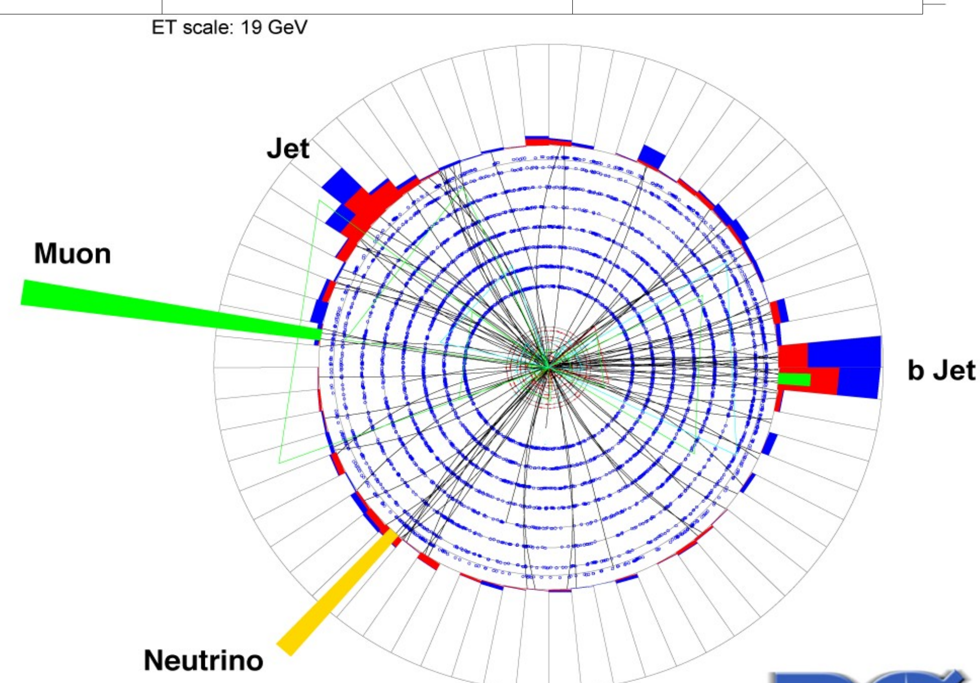
Kidonakis, MSTW2008, NNLO approximation, for m_t=173 GeV

Experimental status

σ (NNLO) [pb]	tb	tqb	tW
TeV prediction	1.04	2.26	0.28
CDF (7.5 fb^{-1})	1.8 ± 0.6	1.49 ± 0.45	-
DØ (9.7 fb^{-1})	1.10 ± 0.33	**3.07 ± 0.53**	-
LHC prediction (7 TeV)	4.6	64.6	15.7
ATLAS (0.7-2.1 fb^{-1})	<20.5 (95%CL)	**83 ± 20**	17 ± 6
CMS (1.2-4.9 fb^{-1})	-	**67 ± 6**	16 ± 5

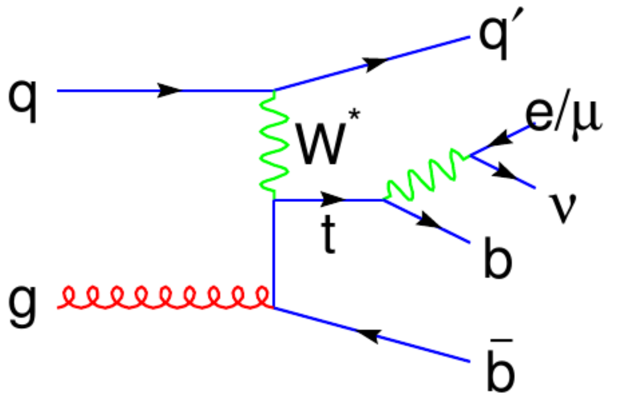
Challenging measurement

- Extract small signal out of a large background with large uncertainties
- Lower cross section: $\sigma_t \sim 1/2\ \sigma_{tt}$
- ℓ+MET+2 jets (harder environment)
- Test bed for Higgs searches
- Want to measure separate channels



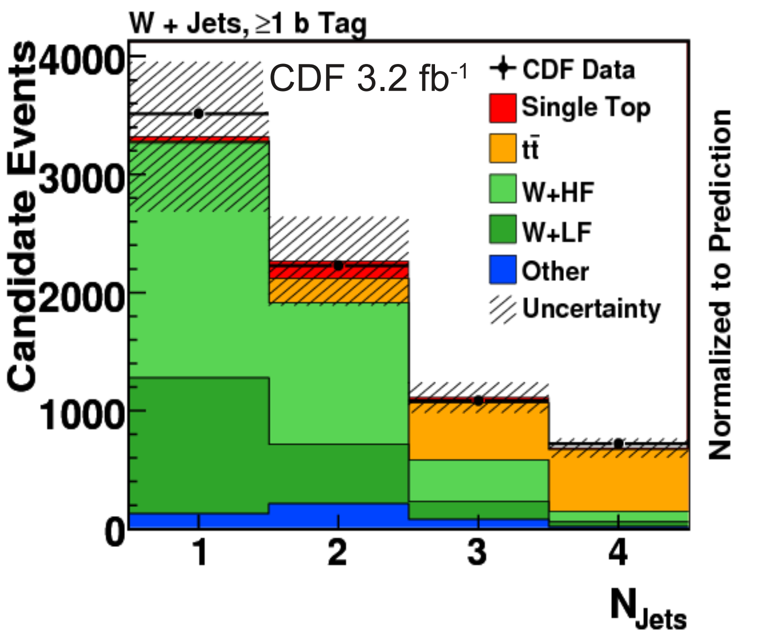
Signal selection

- Selection designed to be as open as possible: describe backgrounds well
  - Only one isolated ℓ; 2, 3 (4) jets; 1,2 b-tags; MET
- S/B~1/200 before b-tagging
- Best S/B~1/10 after b-tagging
- Dominated by W+jets backgrounds
  - 2 jet: $Wb\bar{b}$ 27%, $Wc\bar{c}$+cj 23%, W+lf 24% of total yield
  - 3 jet: $Wb\bar{b}$ 16%, $Wc\bar{c}$+cj 12%, W+lf 14% of total yield

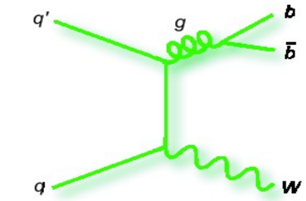


CDF 7.5 fb^{-1}

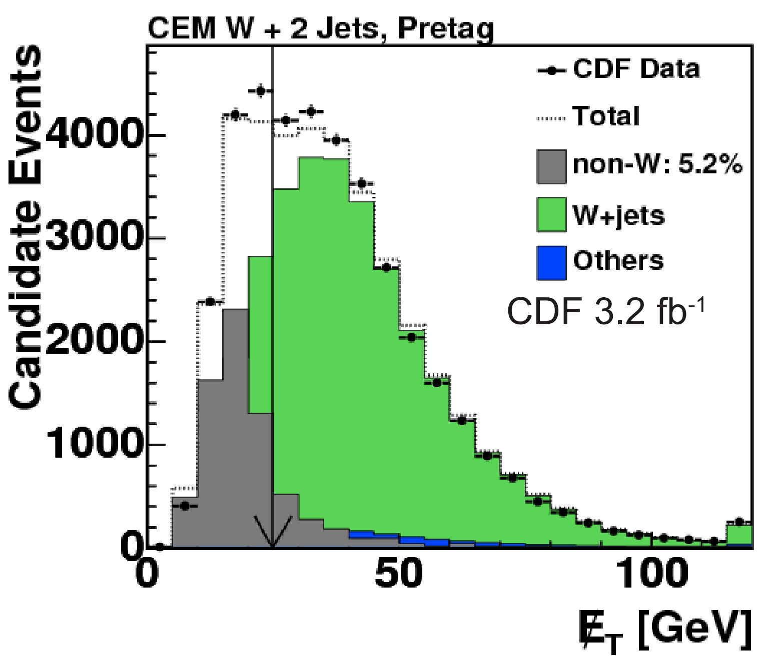
Process	2 jets 1 b-tag	3 jets 1 b-tag	2 jets 2 b-tags	3 jets 2 b-tags
W/Z+jets	4378 ± 547	1295 ± 164	213 ± 56	84 ± 20
tt	474 ± 49	1067 ± 109	98 ± 14	284 ± 42
Diboson	203 ± 22	62.7 ± 7	10 ± 1	4 ± 1
Non-W	316 ± 126	141 ± 57	7 ± 4	3 ± 3
t-channel	193 ± 25	84 ± 11	6 ± 1	15 ± 2
s-channel	128 ± 11	43 ± 4	32 ± 4	12 ± 2
Wt-channel	16 ± 4	26 ± 7	1 ± 0	2 ± 1
Total	5707 ± 877	2719 ± 293	367 ± 66	403 ± 53
Observed	5533	2432	335	355

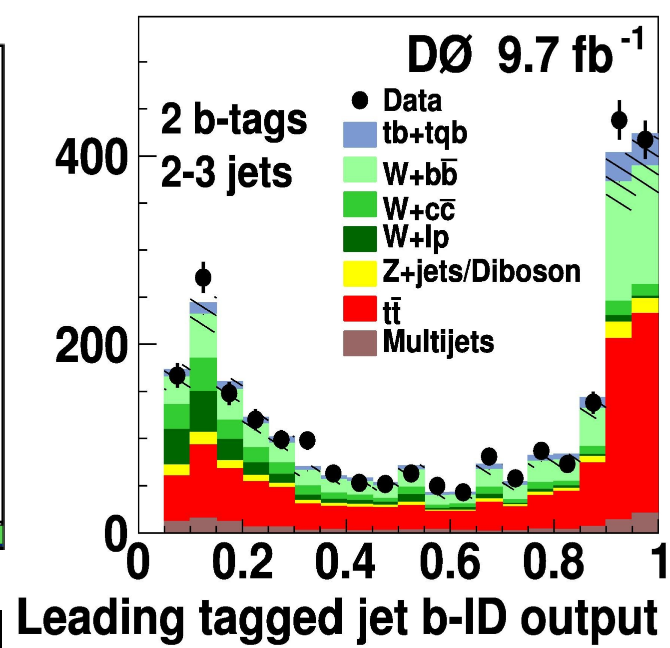


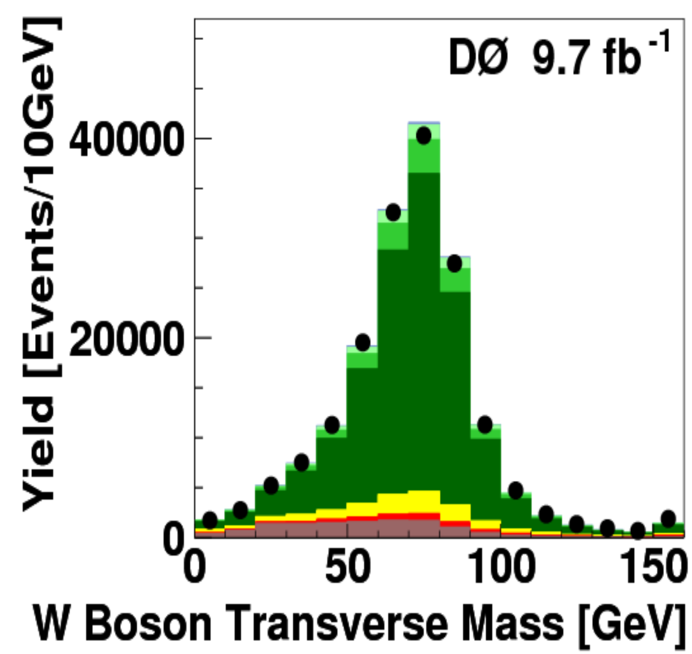
Background modeling



- Diboson, Z+jets, $t\bar{t}$ normalized to SM (NLO) cross section
- Multijets from data with non-isolated lepton (DØ) or “sideband” ℓ (CDF)
- W+jets from Alpgen (Wjj, $Wb\bar{b}$, $Wc\bar{c}$, Wcj)
  - Correct angular distributions jet η and $\Delta R(j_1,j_2)$ before b-tagging
- W+jets and multijets (QCD) are normalized to data before b-tagging
  - CDF fits templates of W+jets and non-W in MET distribution
    - W+light and W+hf from tag rates in control data
  - DØ uses Matrix Method for overall scale, and MCFM for W+hf
    - Crosscheck W+hf fraction in 0-tag sample and b-ID output fits

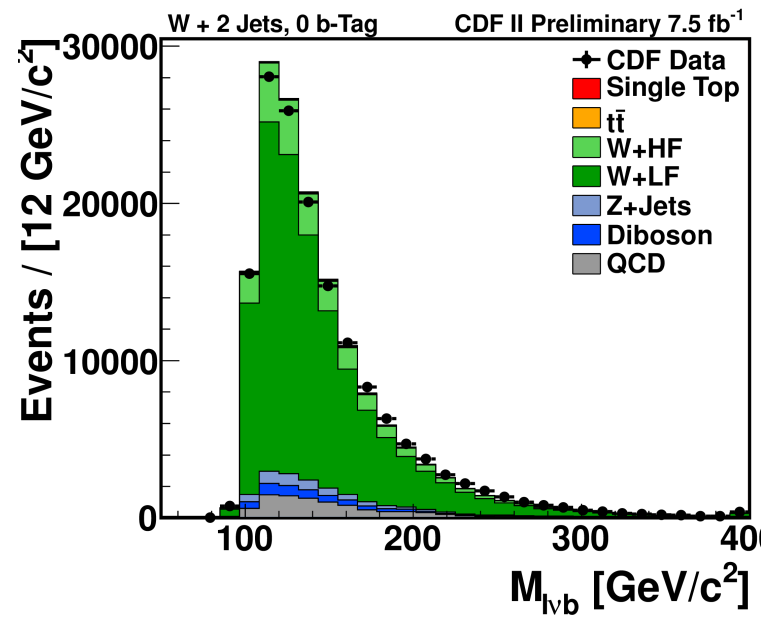


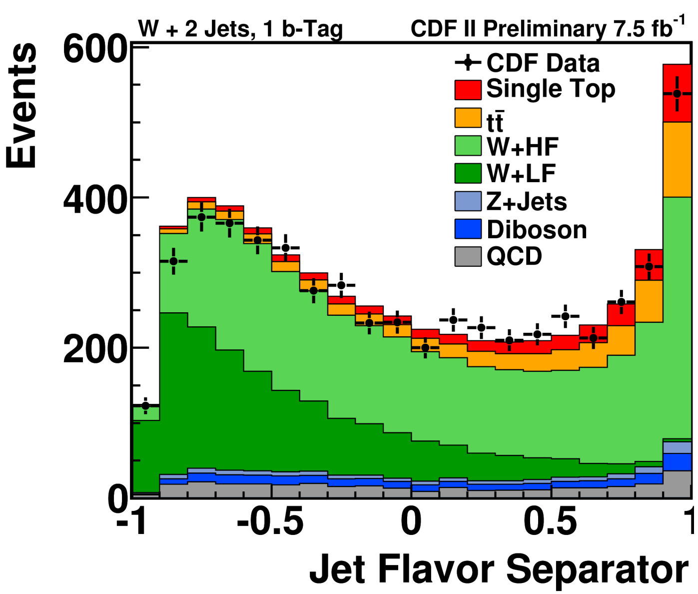


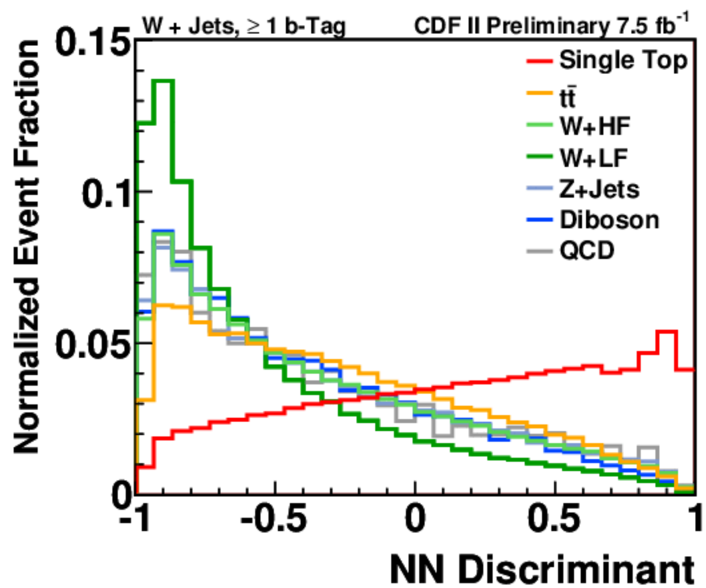


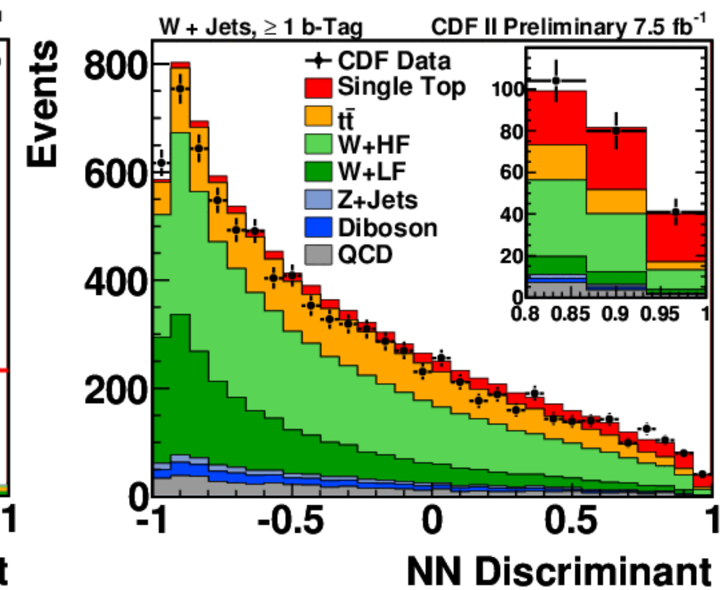
CDF NN analysis 7.5 fb^{-1}

- Added new lepton category
  - ISOTRK → 15% gain in acceptance
- Train NN with 11-14 variables
  - Use s-channel only in 2 jet 2 tag, t-channel for the rest
  - Use admixture of systematics shifted samples → 3% improvement
  - Validate data-background agreement in 0-tag sample





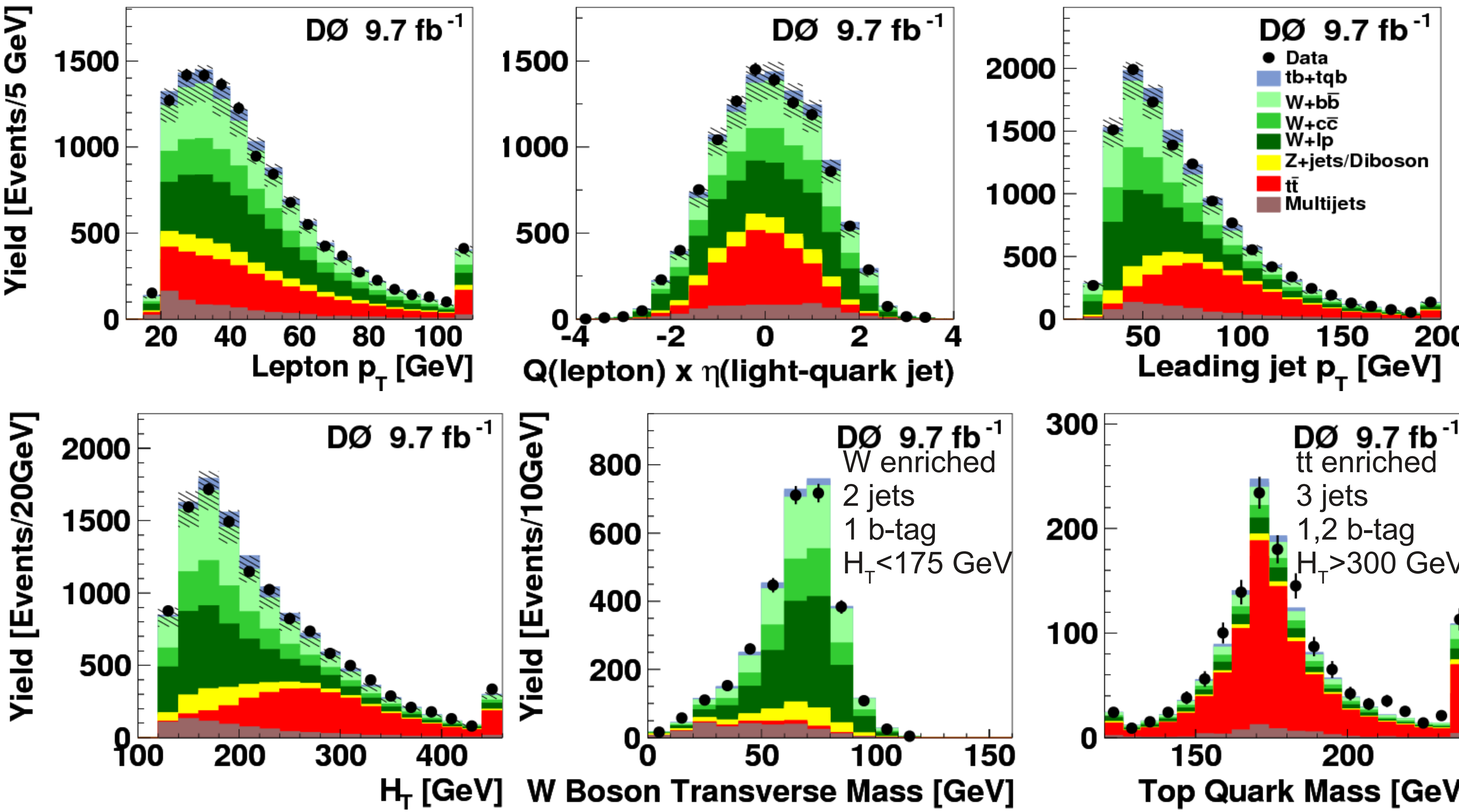




DØ multivariate analysis 9.7 fb^{-1}

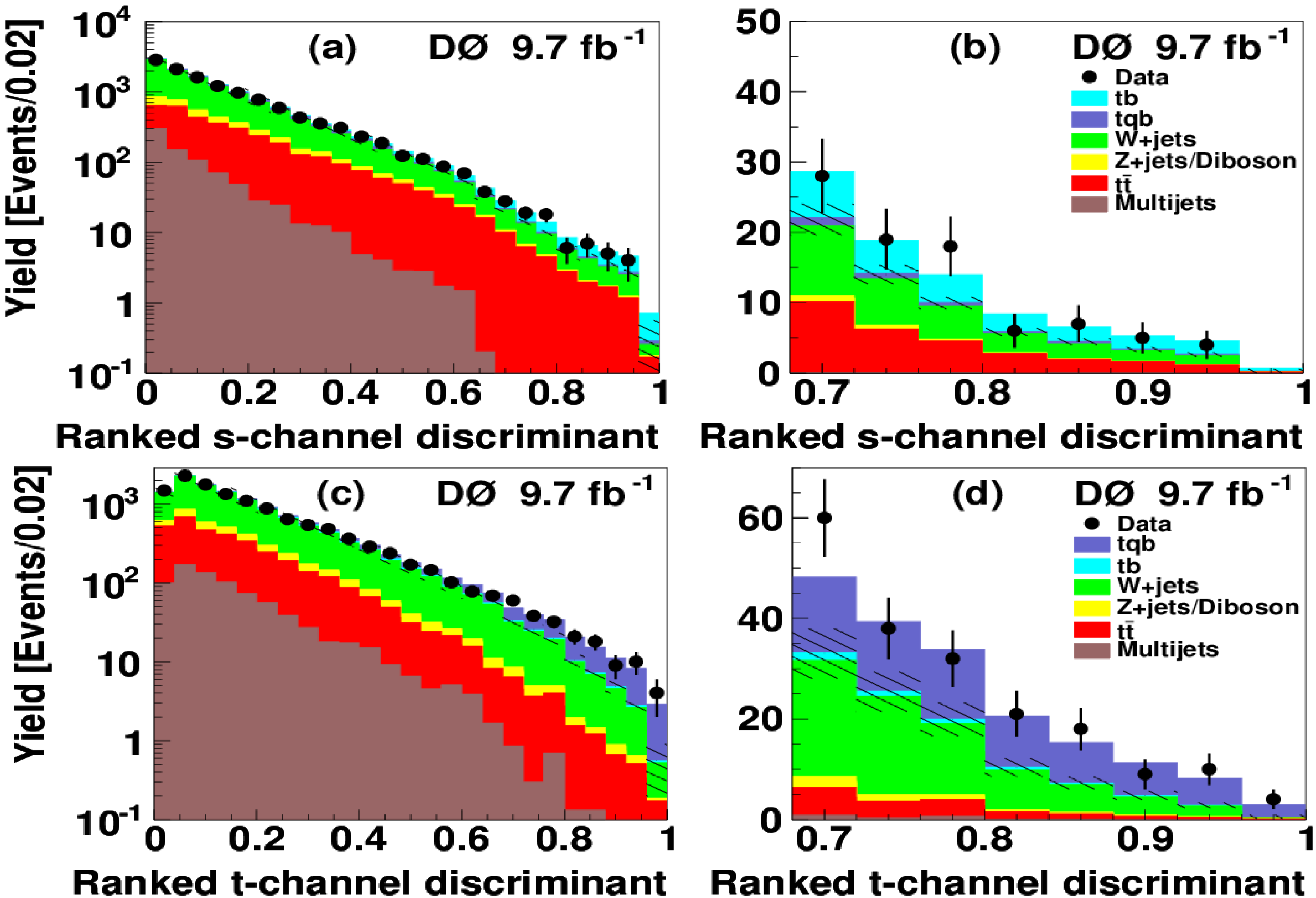
NEW

- Optimized selection for s-channel sensitivity
- DØ has used three different techniques: BDT, BNN, ME
  - BDT uses 30 well-modeled variables, BNN uses 4-vectors
  - Improved ME, better $t\bar{t}$ model, and b-tag weights for discriminants



DØ combined discriminants

- Obtain separate cross section measurements on same data
- Each method selects different event kinematics
- Around 75% correlation → Combination improves significance



s+t cross section results

- CDF 7.5 fb^{-1} (m_t=172.5 GeV) Note 10793

  σ(s+t) = 3.0 $^{+0.6}_{-0.5}$ pb (± 19%)

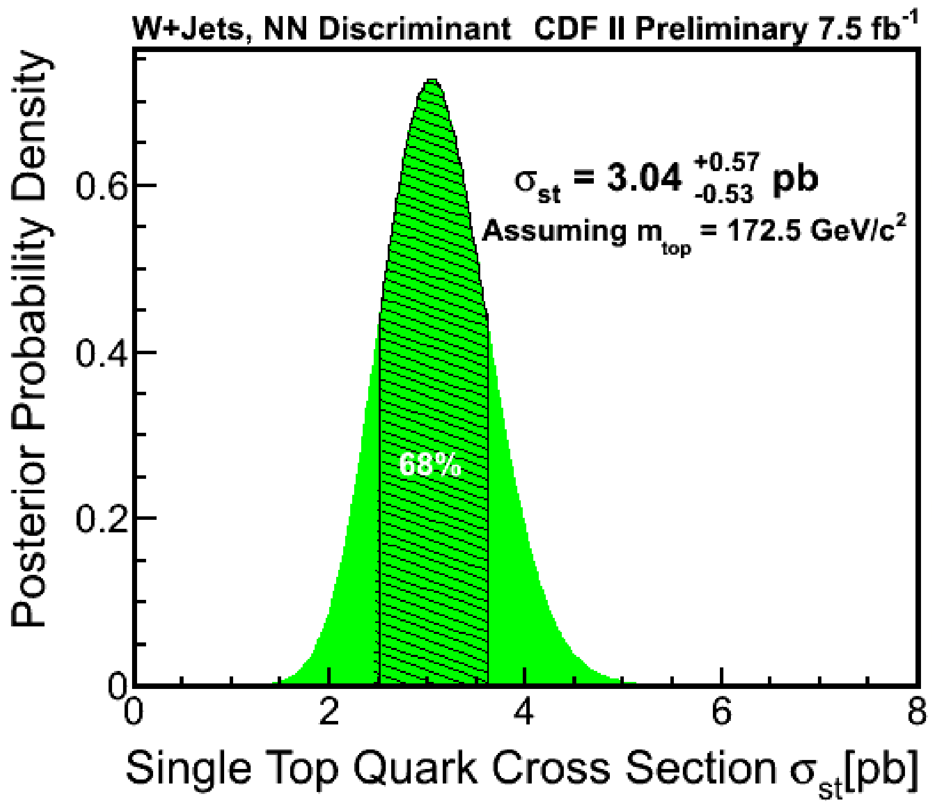
- DØ 9.7 fb^{-1} (m_t=172.5 GeV) arXiv: 1307.0731

  σ(s+t) = 4.1±0.6 pb (± 14%)

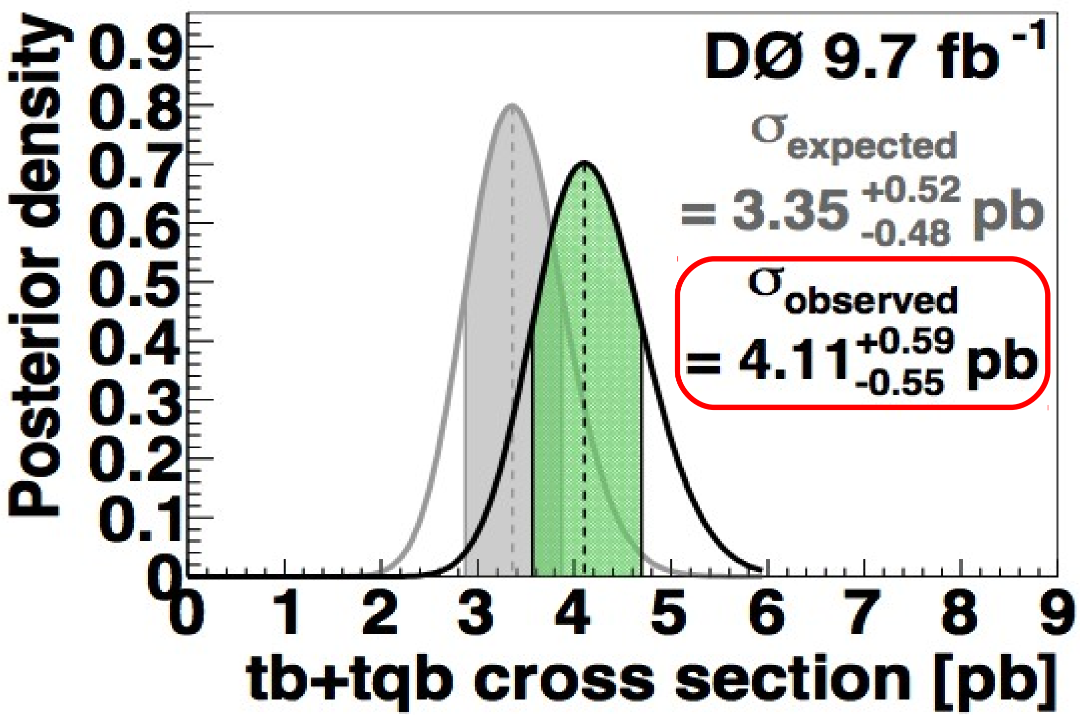
- Previous Tevatron combination (3.2+2.3 fb^{-1}):

  σ(s+t) = 2.76 $^{+0.58}_{-0.47}$ pb (±21%, m_t=170 GeV)

Main systematics:
- B-tagging
- W+jets normalization
- Jet energy scale / resolution

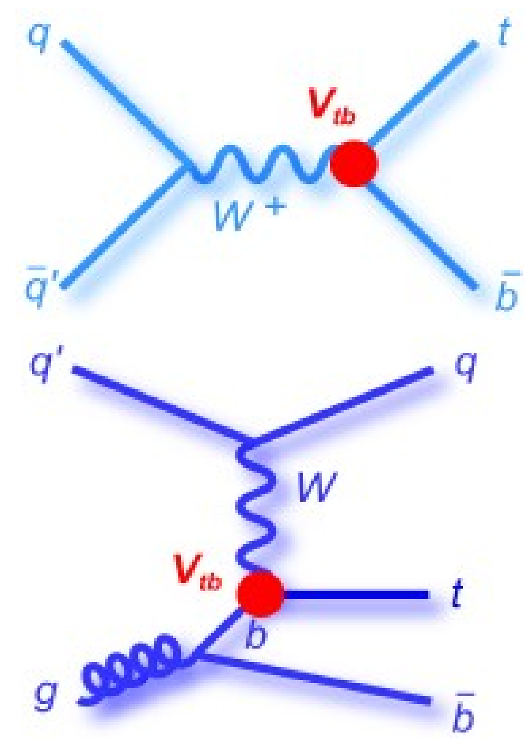


Does not assume SM σ_{tb}/σ_{tqb} ratio



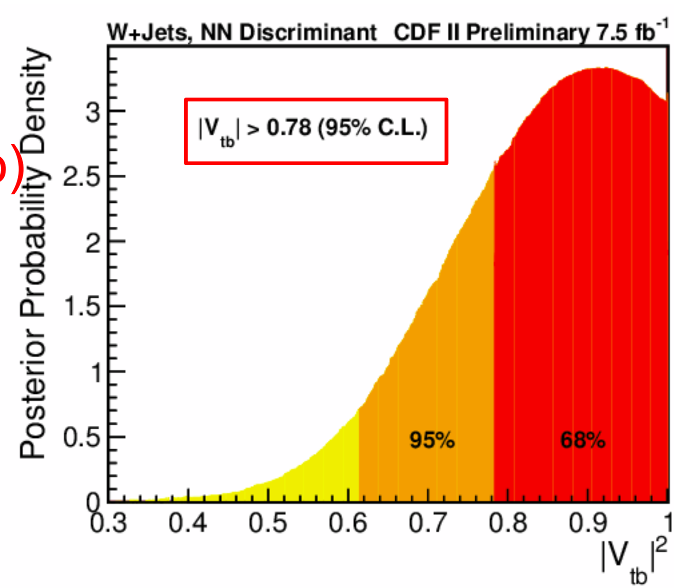
Constraining V_{tb}

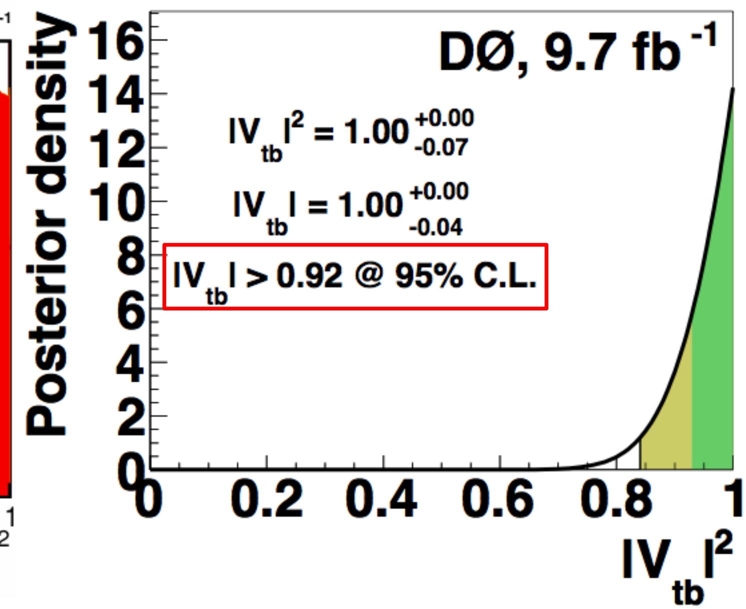
- Single top allows to study V_{tb} at production
- $\sigma(s,t) \propto |V_{tb}|^2 \rightarrow$ calculate posterior pdf in terms of $|V_{tb}|^2$
- To transform $\sigma(s+t)$ measurement into V_{tb}, assume:
  - SM top quark decay: $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - Pure V-A and CP conserving Wtb vertex
- No assumption on number of families or CKM unitarity (DØ doesn't assume SM σ_s/σ_t ratio either)
- Complementary with $t\bar{t}$ decay measurements of R and W helicity



CDF 7.5 fb^{-1}:
$|V_{tb}| = 0.92^{+0.10}_{-0.08} \pm 0.05(\text{theo})$

DØ 9.7 fb^{-1}:
$|V_{tb} f^L_V| = 1.12^{+0.09}_{-0.08}$





SM-independent 2D measurements

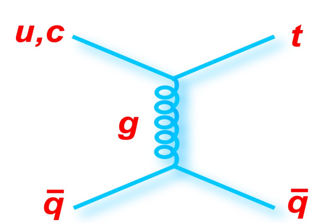
- Relax s:t SM ratio in posterior
  - DØ 9.7 fb^{-1}:

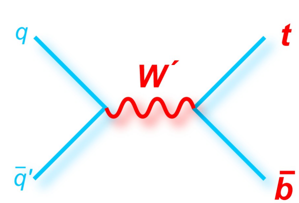
    σ_s = 1.10 ± 0.33 pb (±29%)

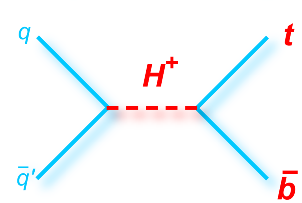
    σ_t = 3.07 ± 0.53 pb (±17%)
  - CDF 7.5 fb^{-1}:

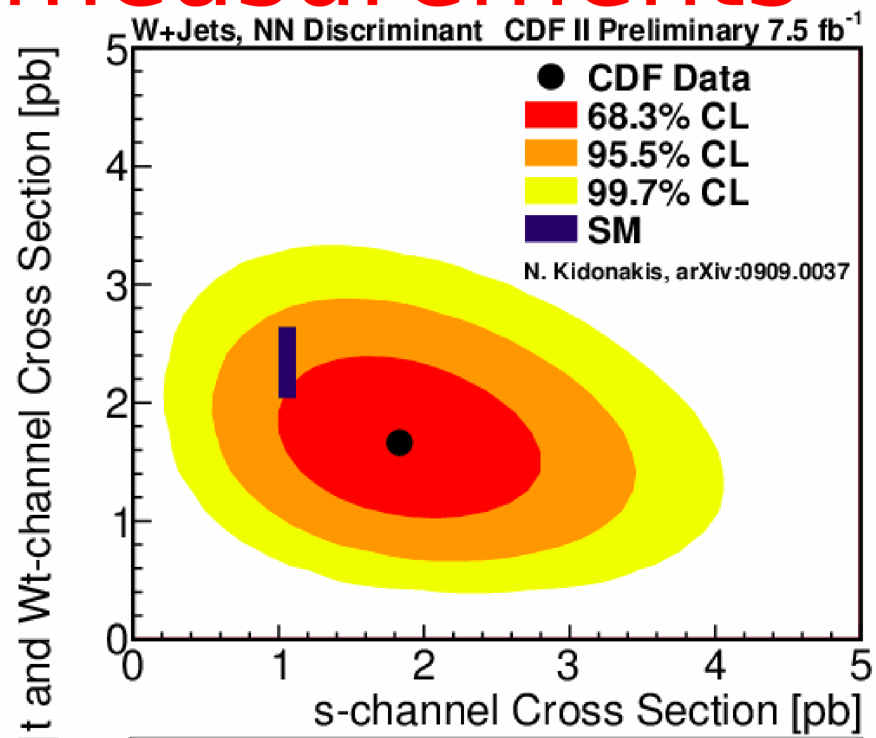
    σ_s = 1.81 ± 0.63 pb (±33%)

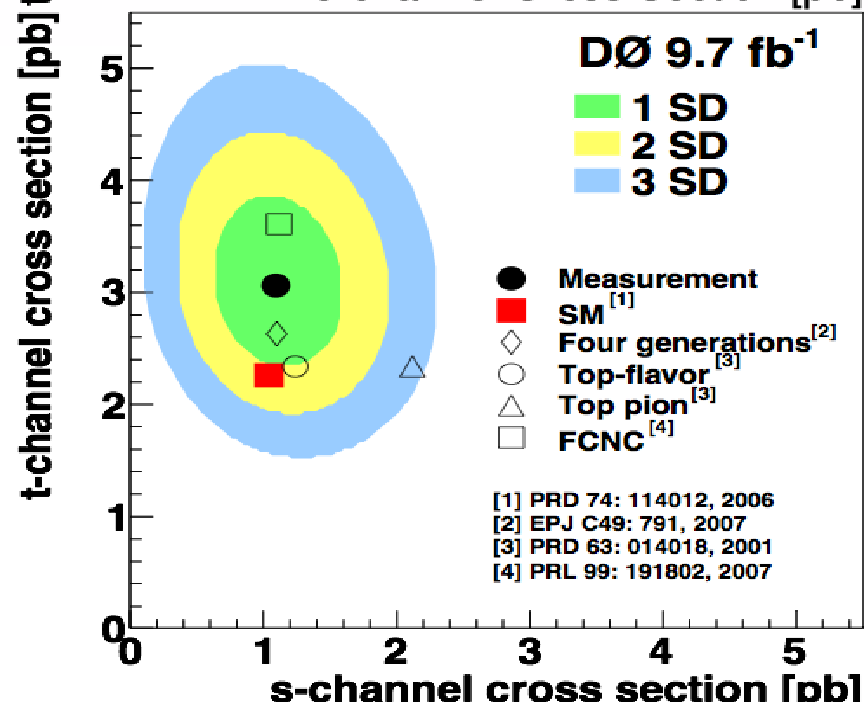
    σ_t = 1.49 ± 0.47 pb (±30%)
- New physics can alter ratio
- Specialized searches in single top by DØ and CDF:
  - Anomalous couplings
  - FCNC
  - W'
  - H±



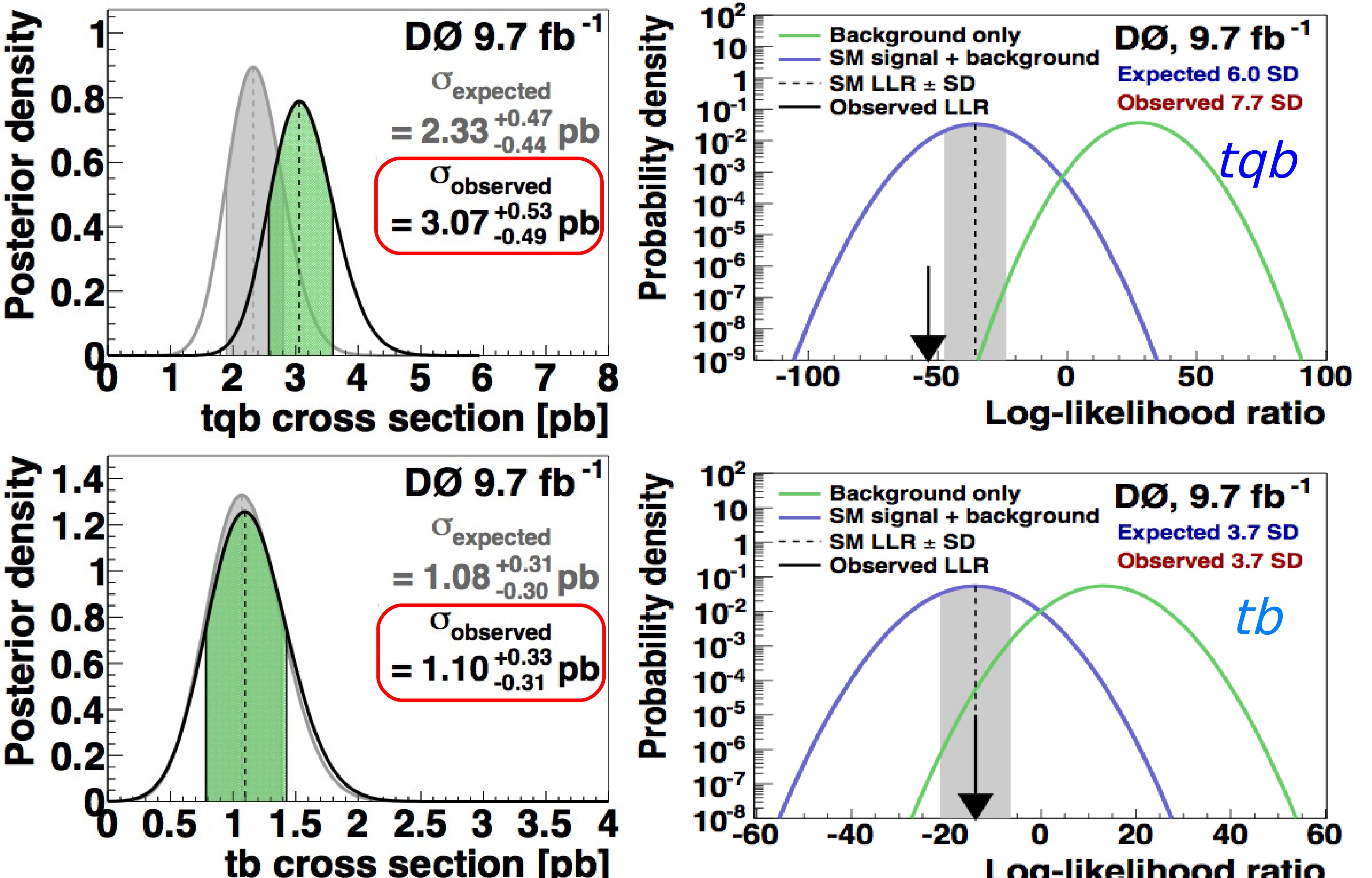








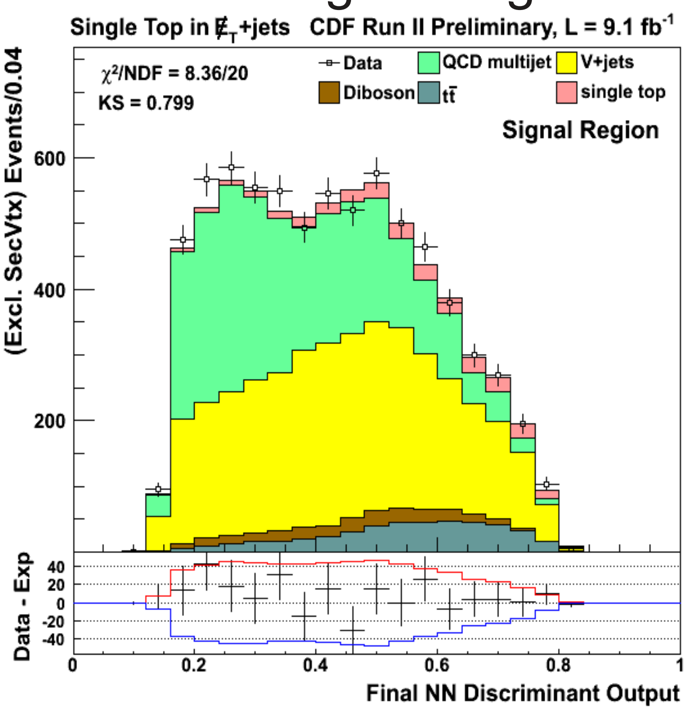
DØ first evidence for s-channel



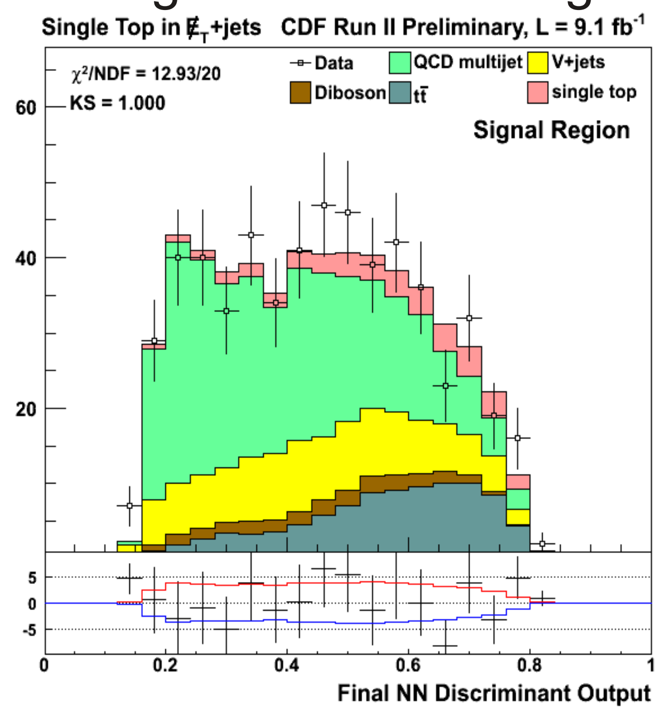
CDF 9.1 fb^{-1} MET+jets analysis

- MET+jets selection only — CDF Note 10979
  - Recover partially reconstructed electrons and muons
  - Include $W \to \tau\nu$ (hadronically-decaying taus as jets)
  - Completely orthogonal dataset to ℓ+jets selection
  - Train several MVA against QCD and $t\bar{t}$, then combine with NN

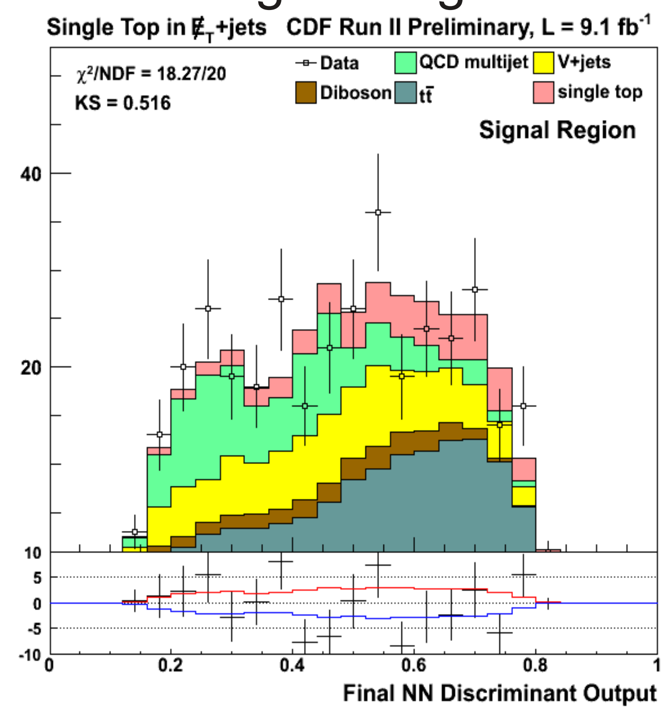
1 tight b-tag



1 tight + 1 loose b-tag



2 tight b-tags

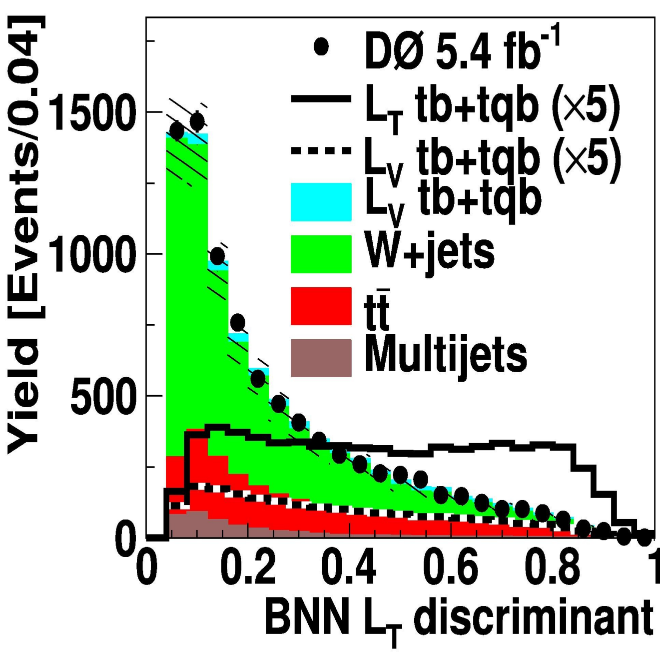


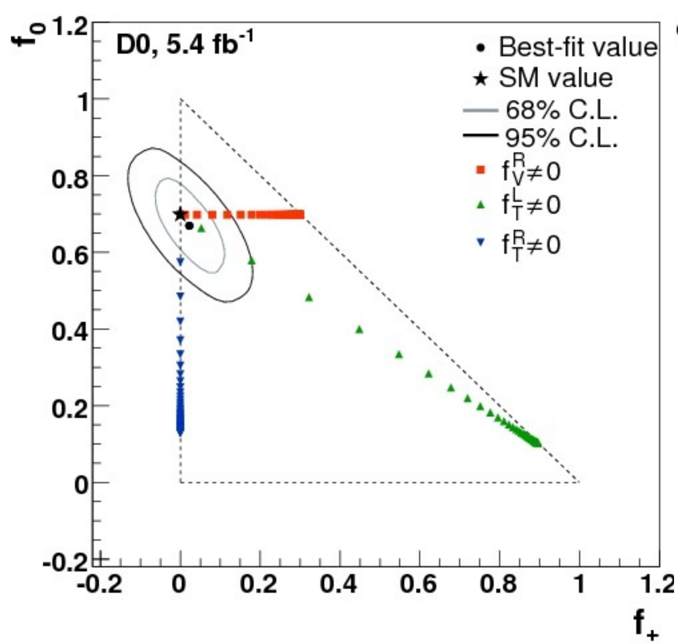
$$\sigma_{s+t} = 3.0\,^{+1.5}_{-1.4}\ \text{pb} \qquad (\pm 50\%)$$

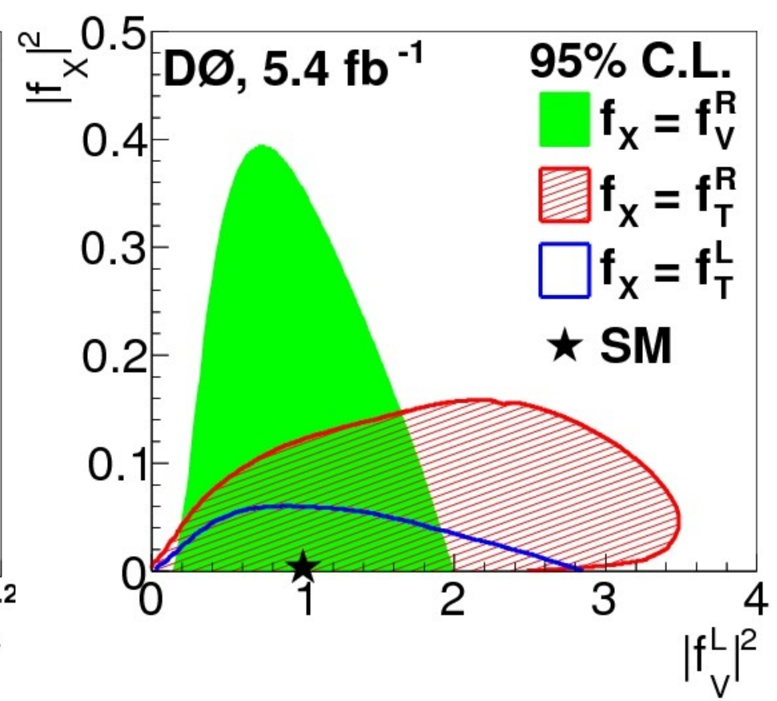
W helicity and anomalous Wtb couplings

$$\mathcal{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_V^L P_L + f_V^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_T^L P_L + f_T^R P_R)tW_{\mu}^{-}$$

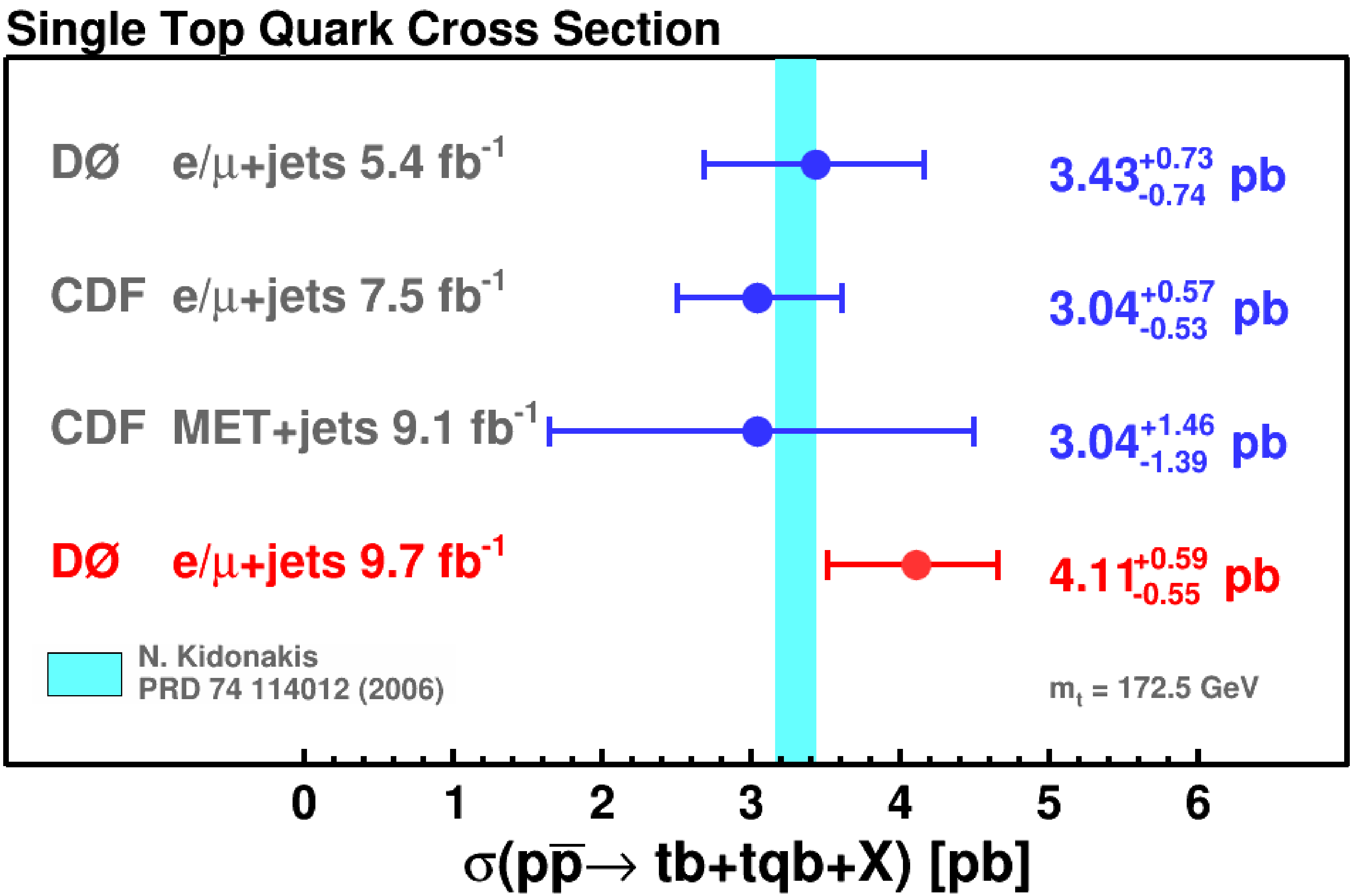
- In SM: $f^L_V=1$ and $f^R_V=f^L_T=f^R_T=0$
- Change rate and kinematics of single top production
  - Assume Wtb production and $|V_{td}|^2+|V_{ts}|^2 \ll |V_{tb}|^2$
  - Train BNN discriminant against each separate signal
- Change f_-(30%), f_0(70%), f_+(0%) rates in W helicity from $t\bar{t}$ decays
  - Use cosθ* as discriminant (angle between ℓ and t in W rest frame)

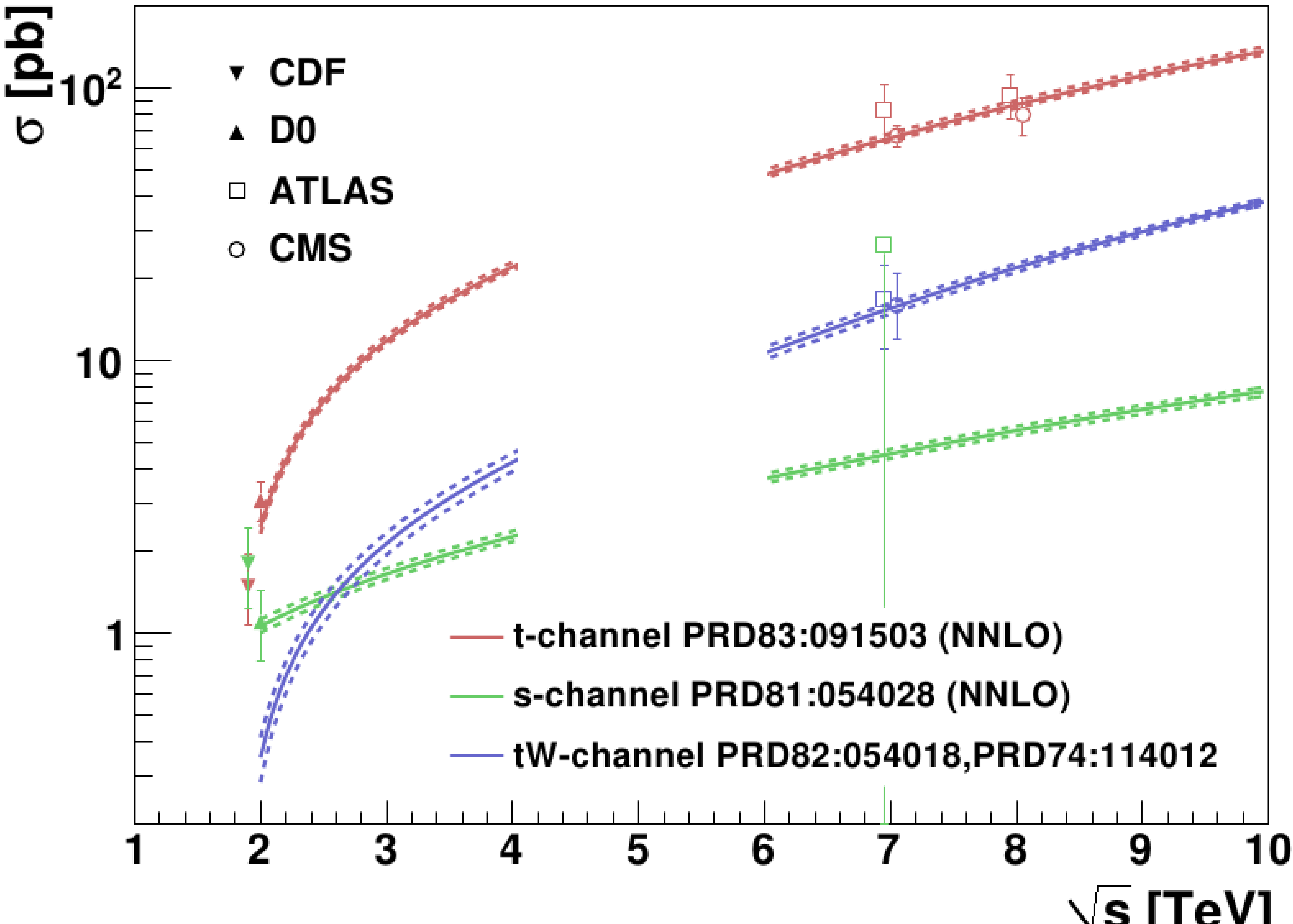






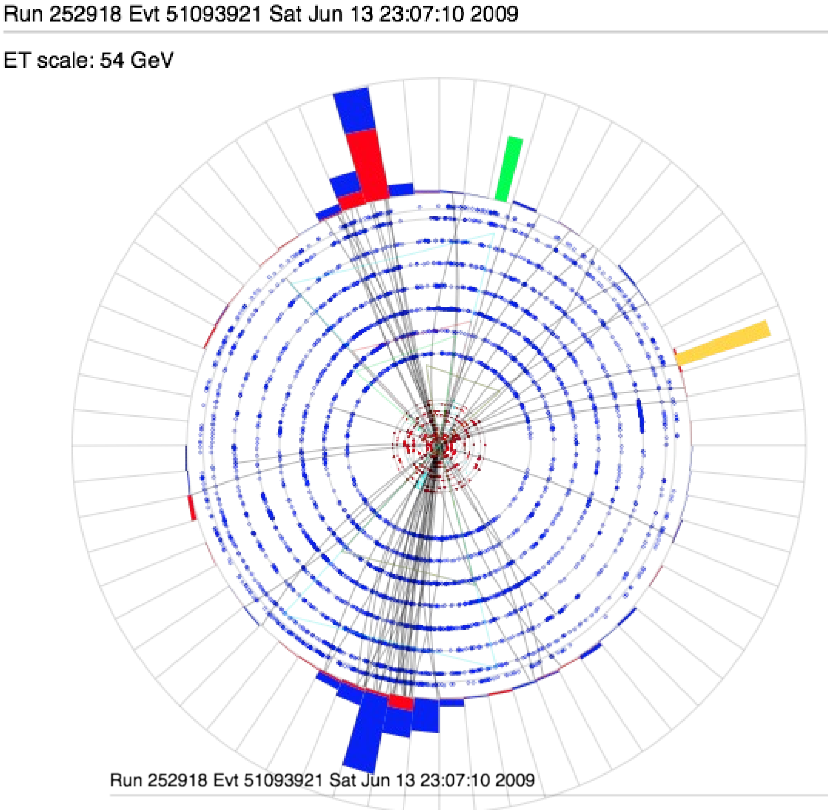
Summary of s+t measurements

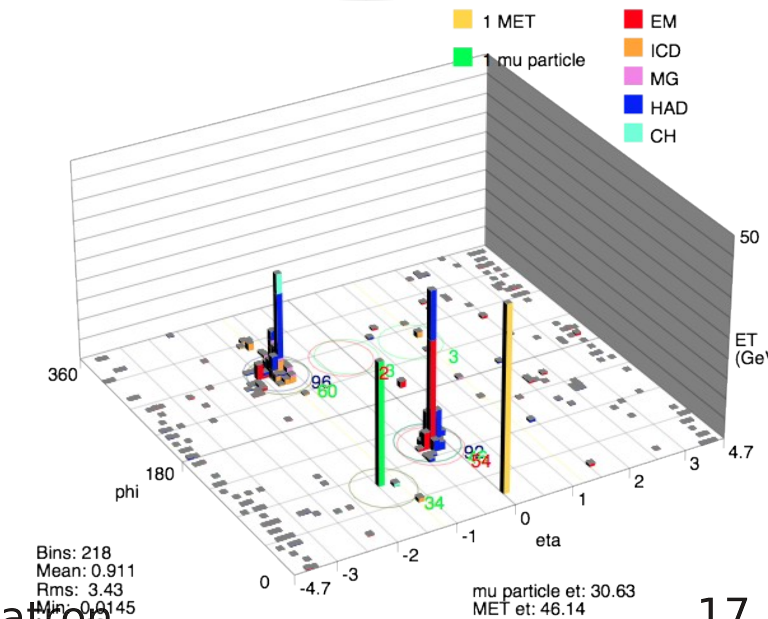



σ [pb]
10^2
10
1
CDF
D0
ATLAS
CMS
t-channel PRD83:091503 (NNLO)
s-channel PRD81:054028 (NNLO)
tW-channel PRD82:054018,PRD74:114012
1
2
3
4
5
6
7
8
9
10
√s [TeV]

Conclusions

- Very rich single top physics program
  - Top width: $\Gamma_t = 2.0\ ^{+0.5}_{-0.4}$ GeV
  - Polarization: consistent with -1
  - W': W'_L > 863 GeV @ 95% C.L.
  - FCNC: $B(t \rightarrow gu) < 2.0 \times 10^{-4}$
  - H^+: Type I 2HDM (m_H,tanβ) exclusion
  - Anomalous couplings
- Important to measure s and t separately
- DØ shows evidence for s-channel (3.7 SD)
- $\sigma(s+t)$ measured with 14% precision
- $\sigma(t)$ measured with 17% precision
- $|V_{tb}|$ measured to ~8% precision (DØ+CDF)
- Single top observation is a legacy measurement from the Tevatron
  - Planning CDF+DØ combination with full dataset in the fall

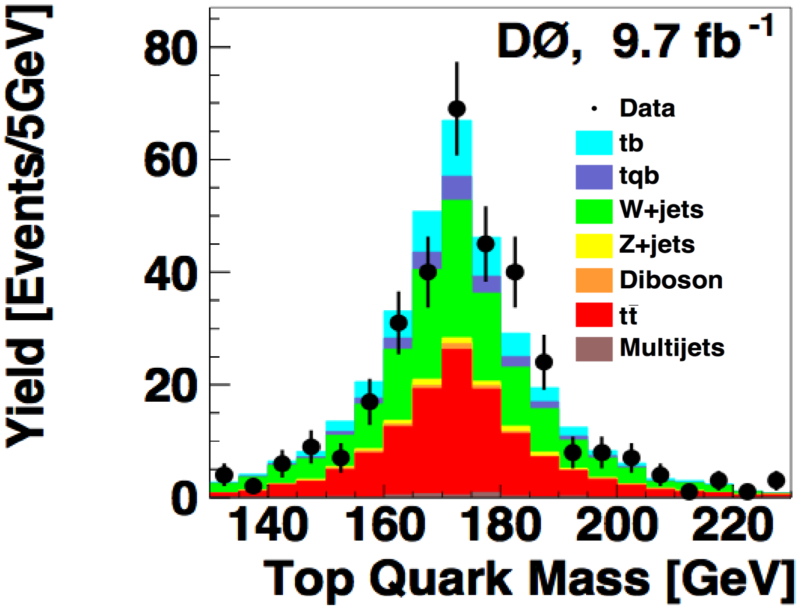


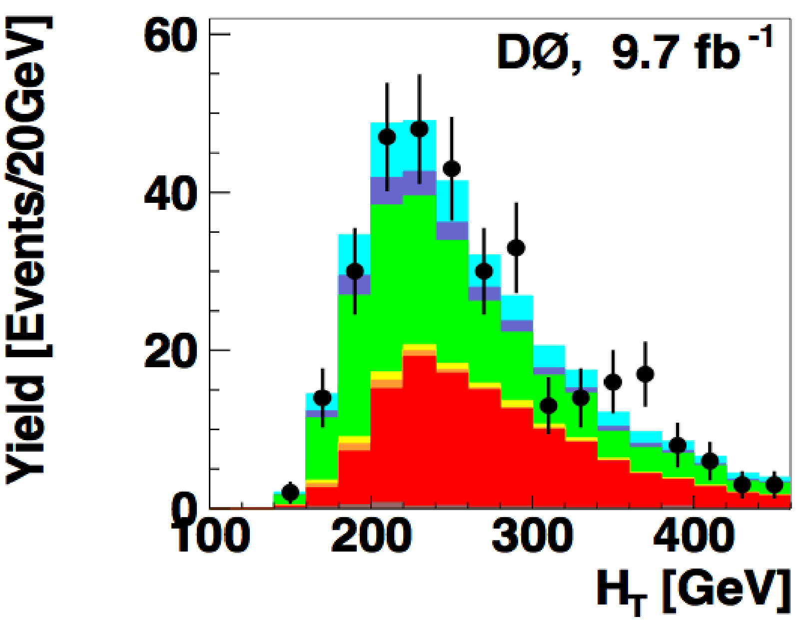


Extras

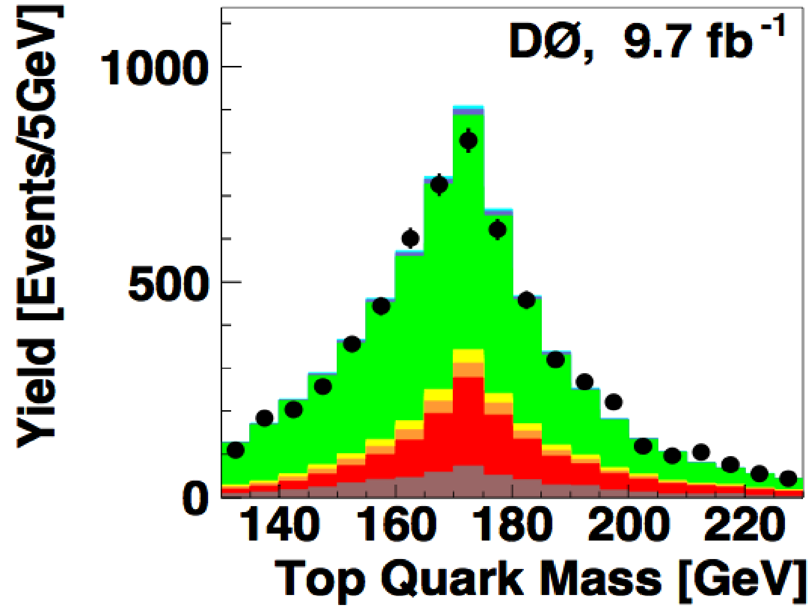
Event characteristics

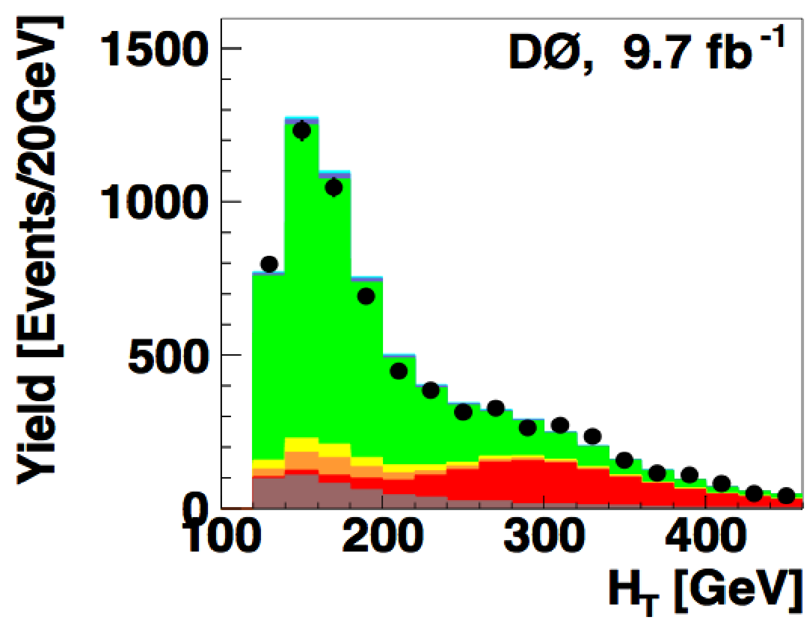
tb Category: $D_{tb} > 0.8$





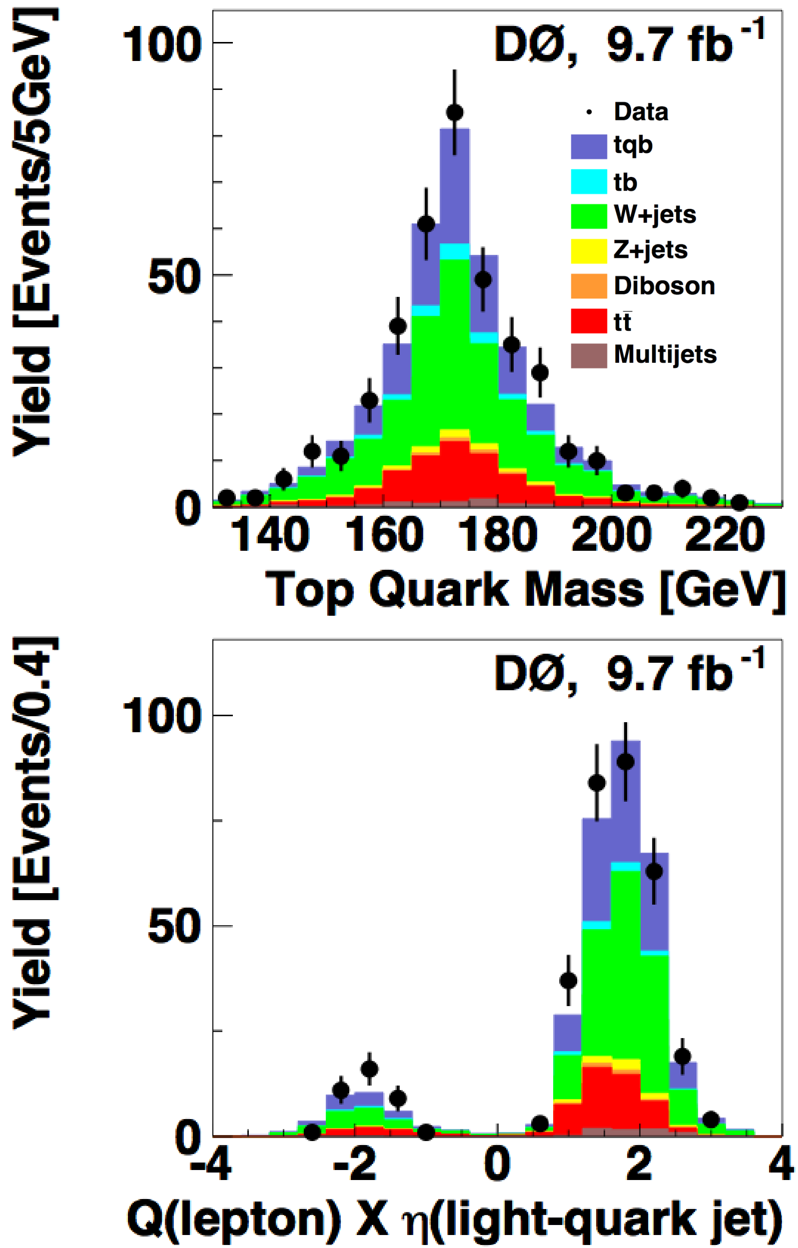
tb & *tqb* Depleted Region



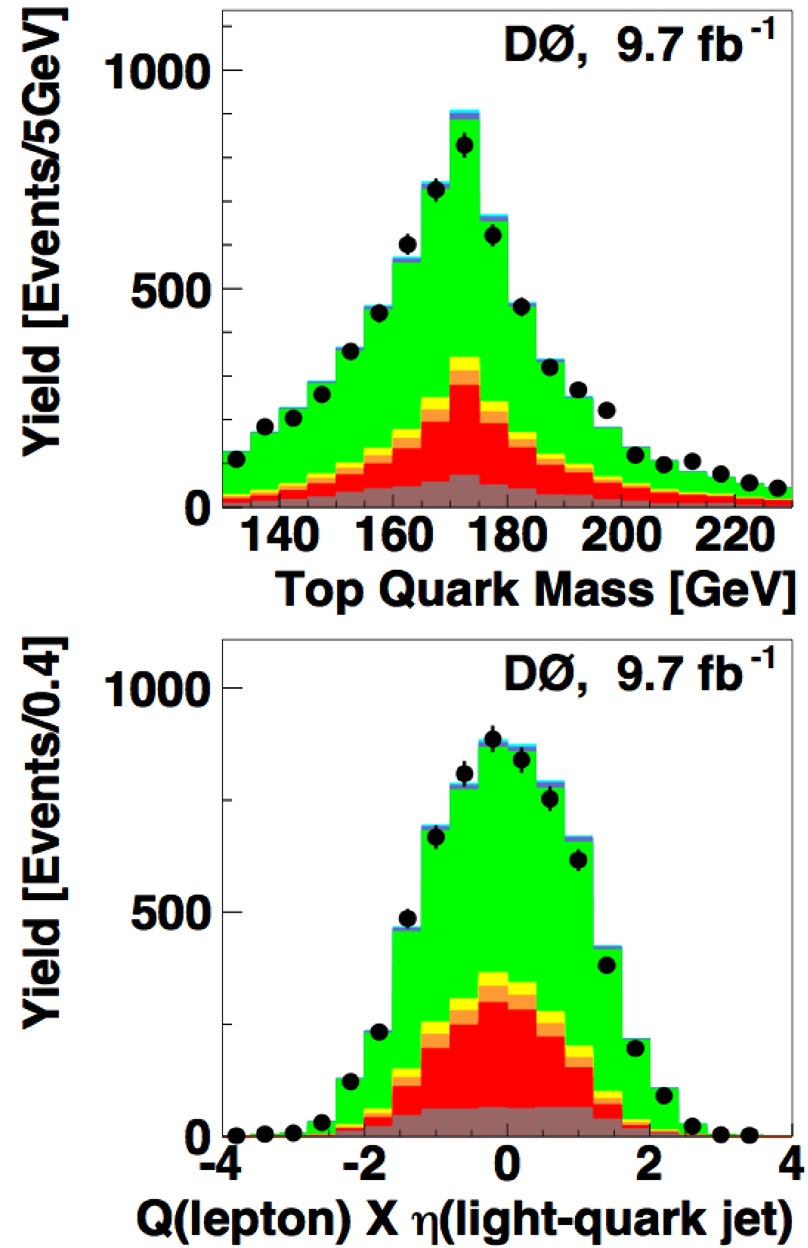


Event characteristics

tqb Category: D_{tqb} > 0.8



tb & *tqb* Depleted Region



Source of Uncertainty	Rate	Shape	Processes affected
Jet energy scale	0–8%	X	all
Initial and final state radiation	0–6%	X	single top, $t\bar{t}$
Parton distribution functions	0–1%	X	single top, $t\bar{t}$
Acceptance and efficiency scale	1–7%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Luminosity	6%		single top, $t\bar{t}$, diboson, Z/γ^*+jets
Jet flavor separator		X	all
Mistag model		X	W+light
Non-W model		X	Non-W
Factorization and renormalizatio		X	$Wb\bar{b}$
Jet η and ΔR distribution		X	W+light
Non-W normalization	40%		Non-W
$Wb\bar{b}$ and $Wc\bar{c}$ norm	30%		$Wb\bar{b}$, $Wc\bar{c}$
Wc normalization	30%		Wc
Mistag normalization	10–20%		W+light
$t\bar{t}$ normalization	8%		$t\bar{t}$
Monte Carlo generator	3–7%		single top, $t\bar{t}$
Single top normalization	7%		single top
Top mass	2-12%	X	single top, $t\bar{t}$

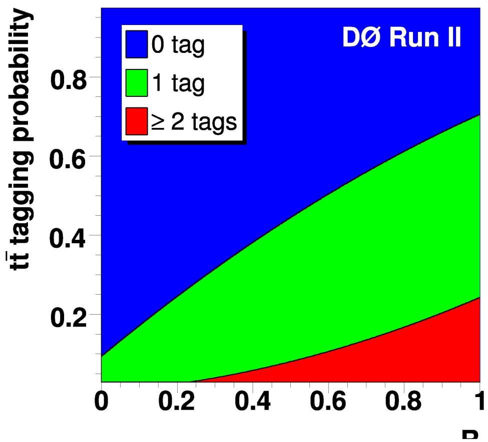
∗ X indicates the sources of uncertainty from shape variation

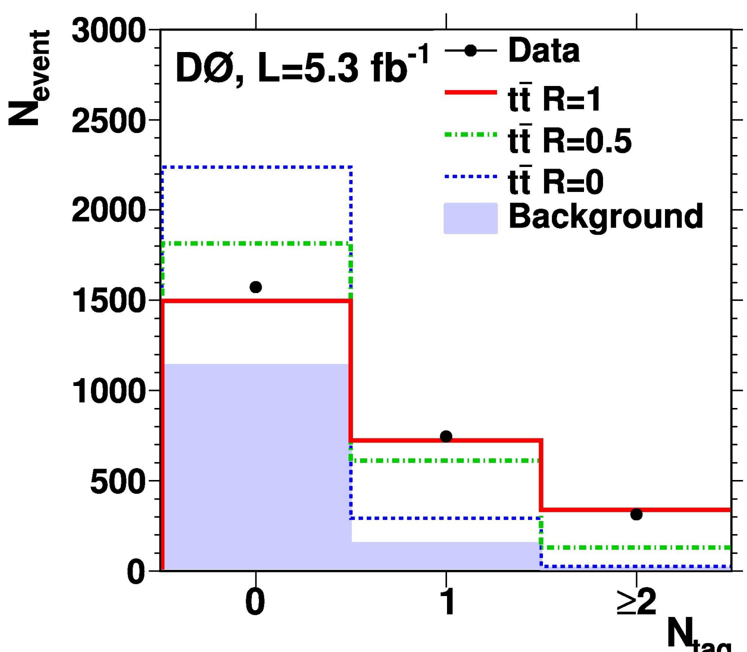
∗ Sources listed below double line are used only in $|V_{tb}|$ measurement

Top mass [GeV]	cross sections [pb]	
	t-channel	s-channel
170	$2.80^{+0.57}_{-0.61}$	$1.31^{+0.77}_{-0.74}$
172.5	$2.90^{+0.59}_{-0.59}$	$0.98^{+0.62}_{-0.63}$
175	$2.53^{+0.58}_{-0.57}$	$0.65^{+0.51}_{-0.50}$

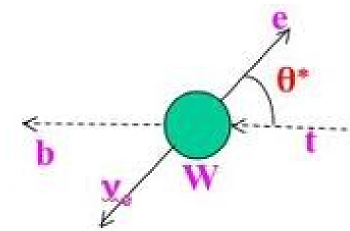
R measurement

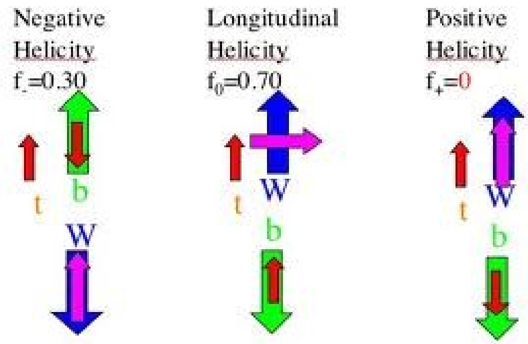
$$P^n_{total}(t\bar{t}) = R^2 A(bb) P^n_t(bb) + 2R(1-R) A(bq_l) P^n_t(bq_l) + (1-R)^2 A(q_l q_l) P^n_t(q_l q_l),$$

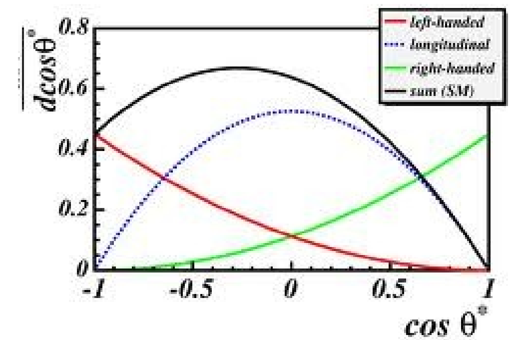




W helicity







$$|f_V^L| = 1 + |C_{\phi q}^{(3,3+3)}| \frac{v^2}{V_{tb}\Lambda^2},$$

$$|f_V^R| = \frac{1}{2} |C_{\phi\phi}^{33}| \frac{v^2}{V_{tb}\Lambda^2},$$

$$|f_T^L| = \sqrt{2} |C_{dW}^{33}| \frac{v^2}{V_{tb}\Lambda^2},$$

$$|f_T^R| = \sqrt{2} |C_{uW}^{33}| \frac{v^2}{V_{tb}\Lambda^2},$$

$$f_- = \frac{2(1+x_m)}{a_t^2(1+x_0) + 2(1+x_m+x_p)}$$

$$f_0 = \frac{a_t^2(1+x_0)}{a_t^2(1+x_0) + 2(1+x_m+x_p)}$$

$$f_+ = \frac{2x_p}{a_t^2(1+x_0) + 2(1+x_m+x_p)}$$

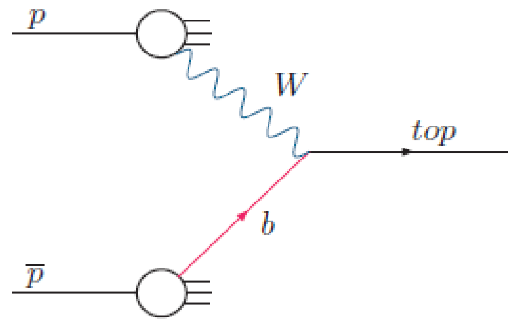
$$a_t = m_t/m_W$$

$$x_m = (f_1^L + a_t f_2^R)^2 - 1$$

$$x_o = (f_1^L + f_2^R/a_t)^2 + (f_1^R + f_2^L/a_t)^2 - 1$$

$$x_p = (f_1^R + a_t f_2^L)^2 .$$

Top quark width



- Direct measurements limited by m_t resolution
- Suggested by C.P. Yuan in 1995 (hep-ph/9509208)

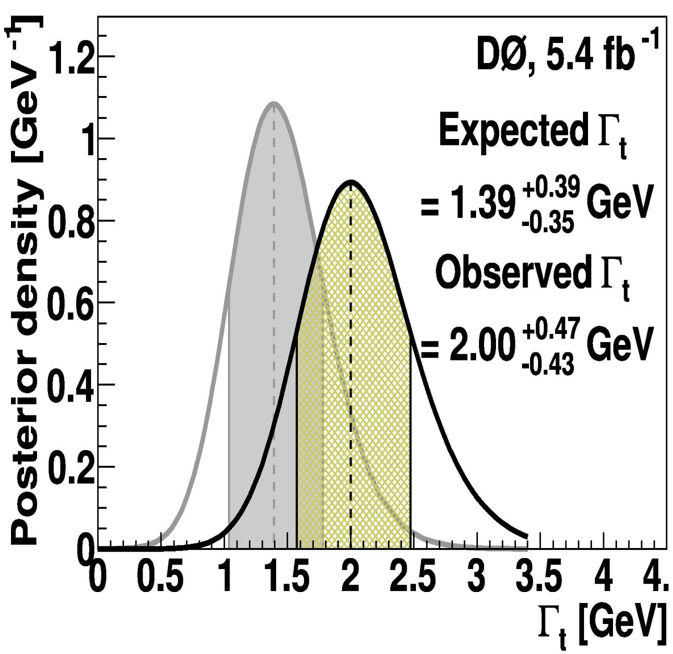
$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)} = \frac{\sigma(t\text{-channel}) \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t\text{-channel})_{SM}}}{B(t \to Wb)}$$

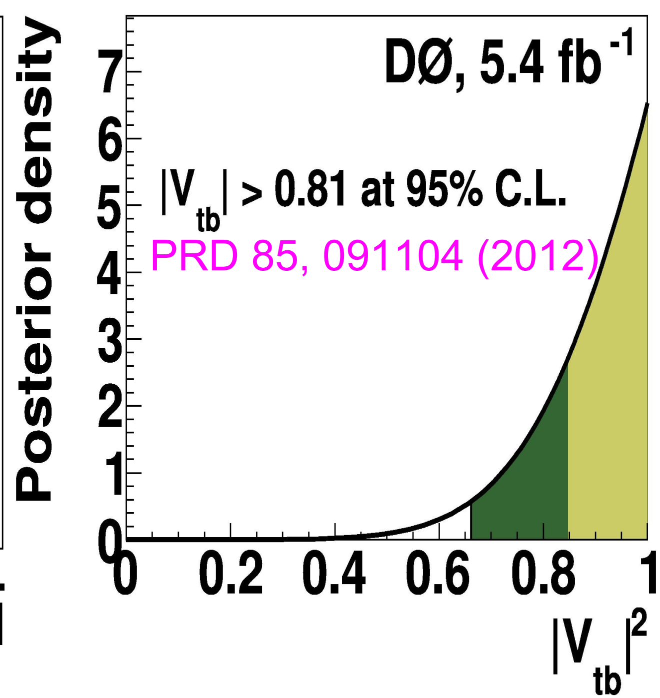
$$\sigma(t)B(t \to Wb) = 2.90 \pm 0.59\,\text{pb}$$

PLB 705, 313 (2011)

$$R = \frac{B(t \to Wb)}{B(t \to Wq)} = 0.90 \pm 0.04$$

PRL 107, 121802 (2011)





SM NLO: Γ_t=1.3 GeV

For m_t=172.5 GeV:

$\Gamma_t = 2.0^{+0.5}_{-0.4}$ GeV

$\tau_t = (3.3^{+0.9}_{-0.6}) \cdot 10^{-25}$ s

Assumes:

- production by W-b fusion
- top decays into any Wq
- $B(t \to Wq) = 1$

Most precise determination