

Single Top Quarks at the Tevatron

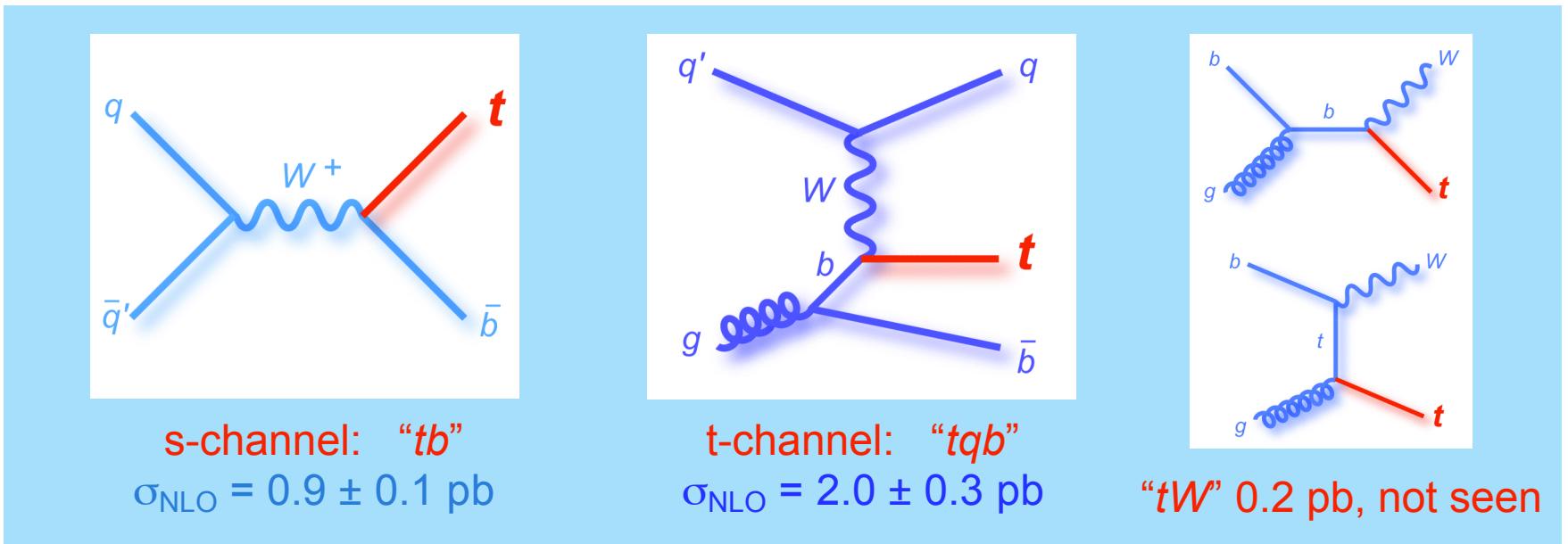
Ann Heinson
University of California, Riverside
for the CDF and DØ Collaborations

Hadron Collider Physics Symposium
Tuesday May 27, 2008

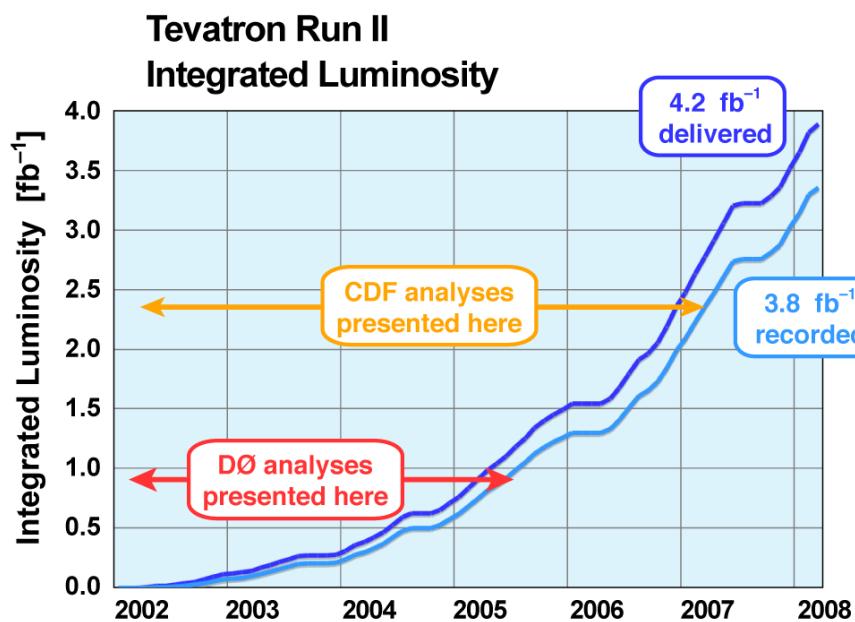
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Single Top Quark Production



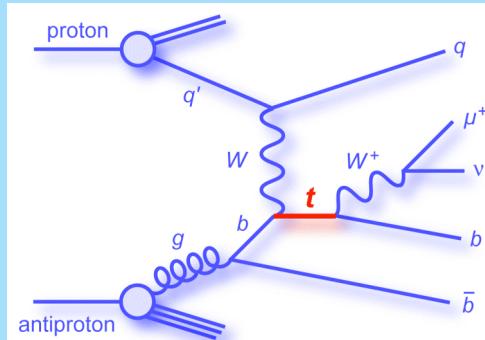
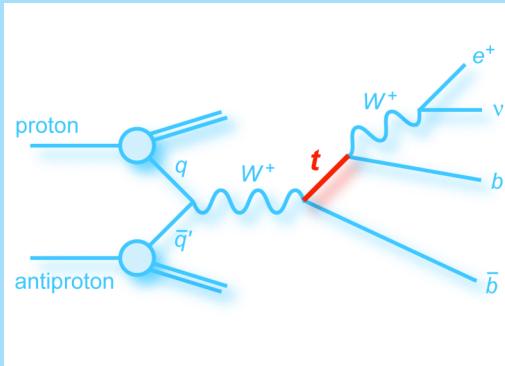
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- Search started in 1994
- Signals are small, backgrounds huge – search proved more difficult than anticipated
- **First evidence for single top presented in 2006**
- Rich program of measurements now underway

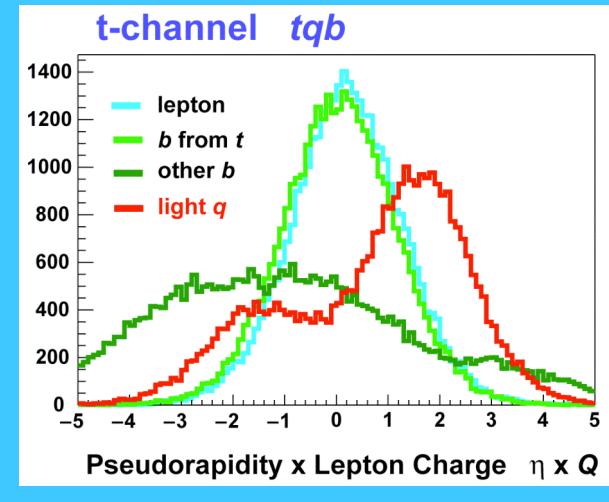
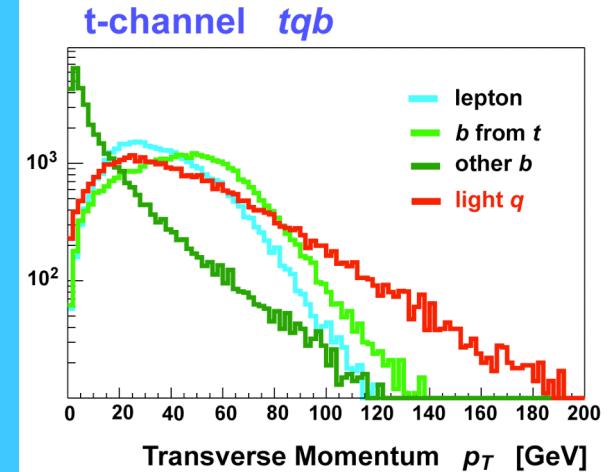
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Event Selection



- One isolated electron or muon
 - $p_T > 20$ GeV (CDF), $> 15(e)$, $18(\mu)$ GeV (DØ)
 - $|\eta| < 1.6$ (CDF), $> 1.1(e)$, $2.0(\mu)$ (DØ)
- Missing transverse energy
 - $\cancel{E}_T > 25$ GeV (CDF)
 - $\cancel{E}_T > 15$ GeV (DØ)
- Two, three, four jets, one or two b -tagged
 - $p_T > 20$ GeV (CDF) $> 25, 20, 15$ GeV (DØ)
 - $|\eta| < 2.8$ (CDF), $< 2.5, 3.4, 3.4$ (DØ)
- Backgrounds are mainly W +jets and $t\bar{t}$, also Z +jets, dibosons, and multijets

Parton-level distributions



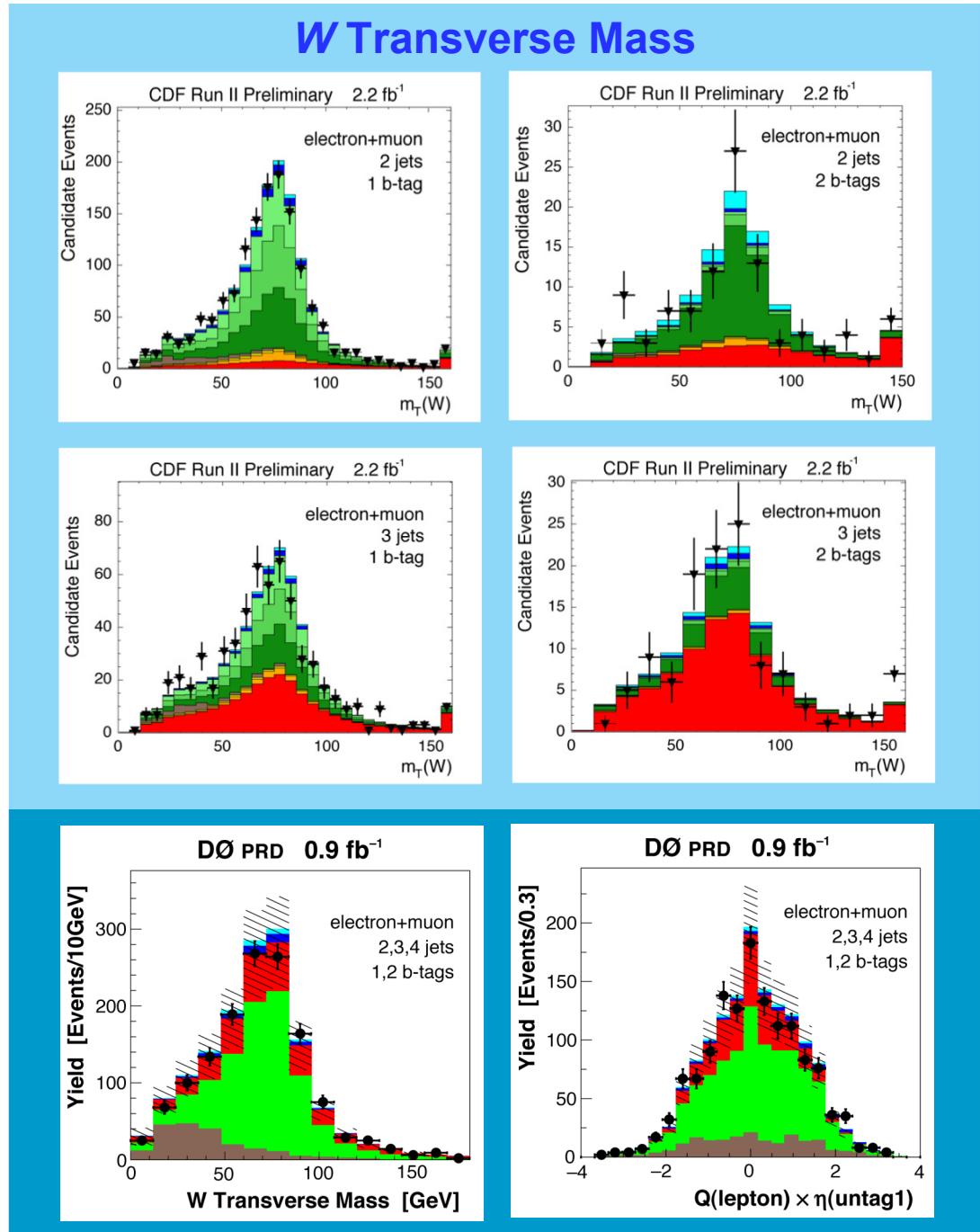
Event Yields

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CDF preliminary 2.2 fb^{-1}		
	1,2 b-tags	2-jets 3-jets
s-channel tb	41	14
t-channel tqb	62	18
W+light-jets	340	102
W+charm	395	109
W+bottom	462	141
Z+jets	27	11
Dibosons	63	22
t̄t	146	339
Multijets	60	21
Total prediction	1,595	777
↓ Data	1,535	712

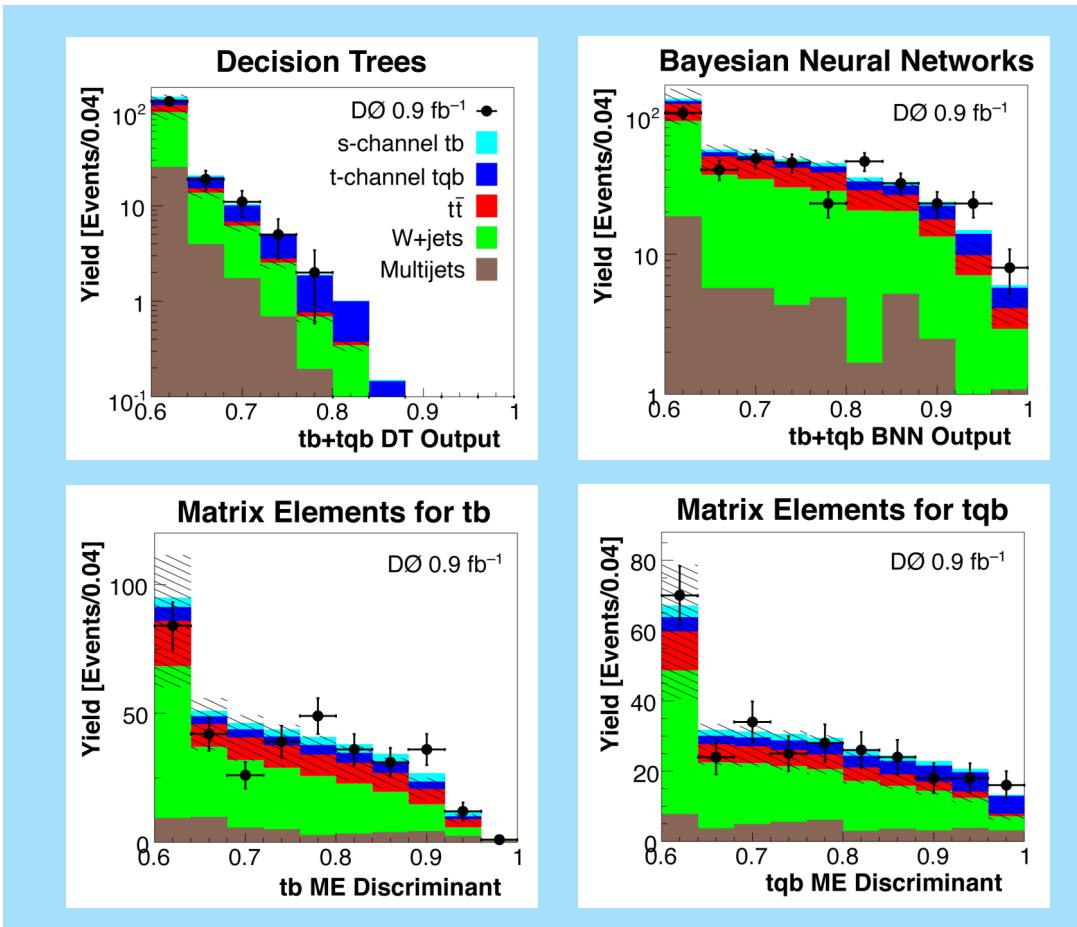
- Signal:background ranges from 1:9 (2-jets/2-tags) to 1:25 (3-jets/1-tag) (1:180 before tagging)

Signal Acceptances		
	CDF	DØ
s-channel tb	2.8%	3.2%
t-channel tqb	1.8%	2.1%



DØ's $tb+tqb$ Analysis and Results

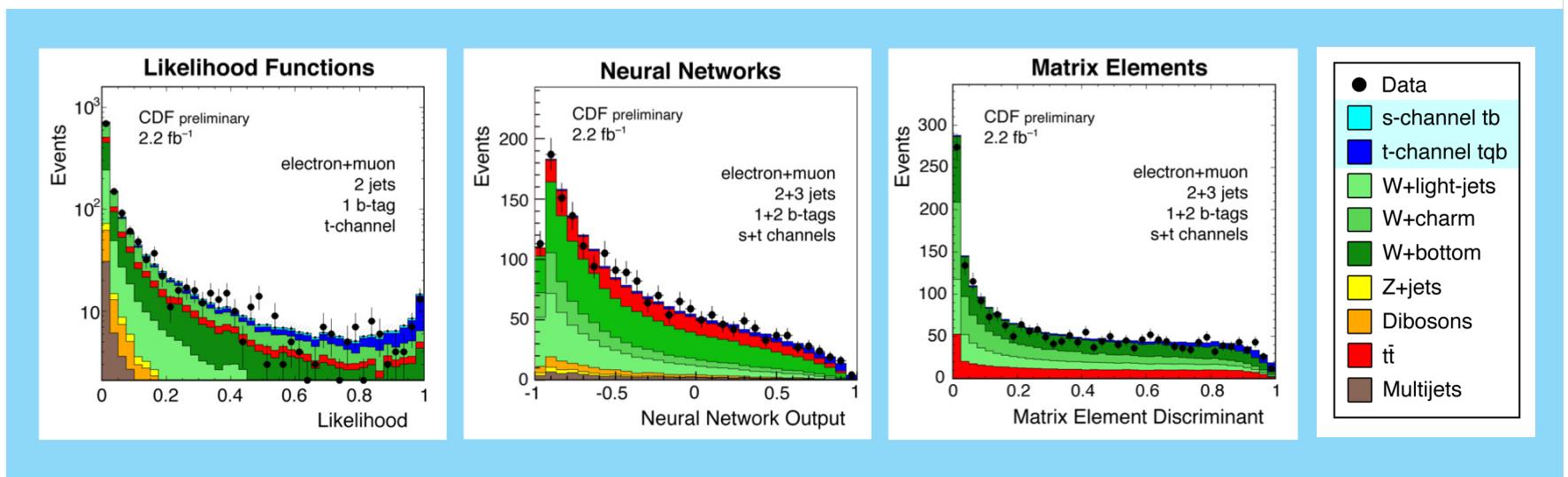
- First evidence ($>3\sigma$) for single top quark production, December 2006
- Three types of discriminants separate $tb+tqb$ signal from background
 - Boosted decision trees – 49 variables: object and event kinematics, angular correlations
 - Bayesian neural networks – average over 100 networks, 18-25 input variables per channel
 - Matrix elements – include many Feynman diagrams for signals and backgrounds



- Excess of data over background observed
- Combined significance
 - 2.3 σ (expected)
 - 3.6 σ (observed)
- Cross section from 0.9 fb⁻¹ of data
 - 4.7 ± 1.3 pb
- Phys. Rev. Lett. 98, 181802 (2007)
- Phys. Rev. D (accepted)

CDF's $tb+tbq$ Analyses and Results

- Large dataset analyzed – 2.2 fb^{-1}
- Three types of discriminants separate $tb+tbq$ signal from background
 - Likelihood functions – combine 7 (10) variables in 2- (3-) jet channels
 - Neural networks – 11-18 inputs per network for each channel
 - Matrix elements – many Feynman diagrams, with b -tagging information included

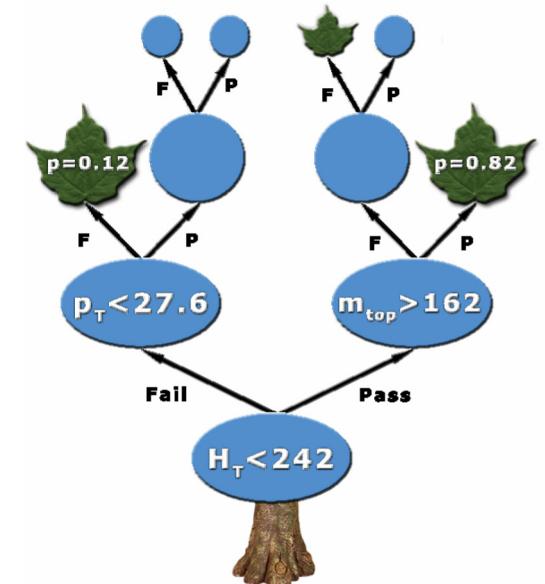
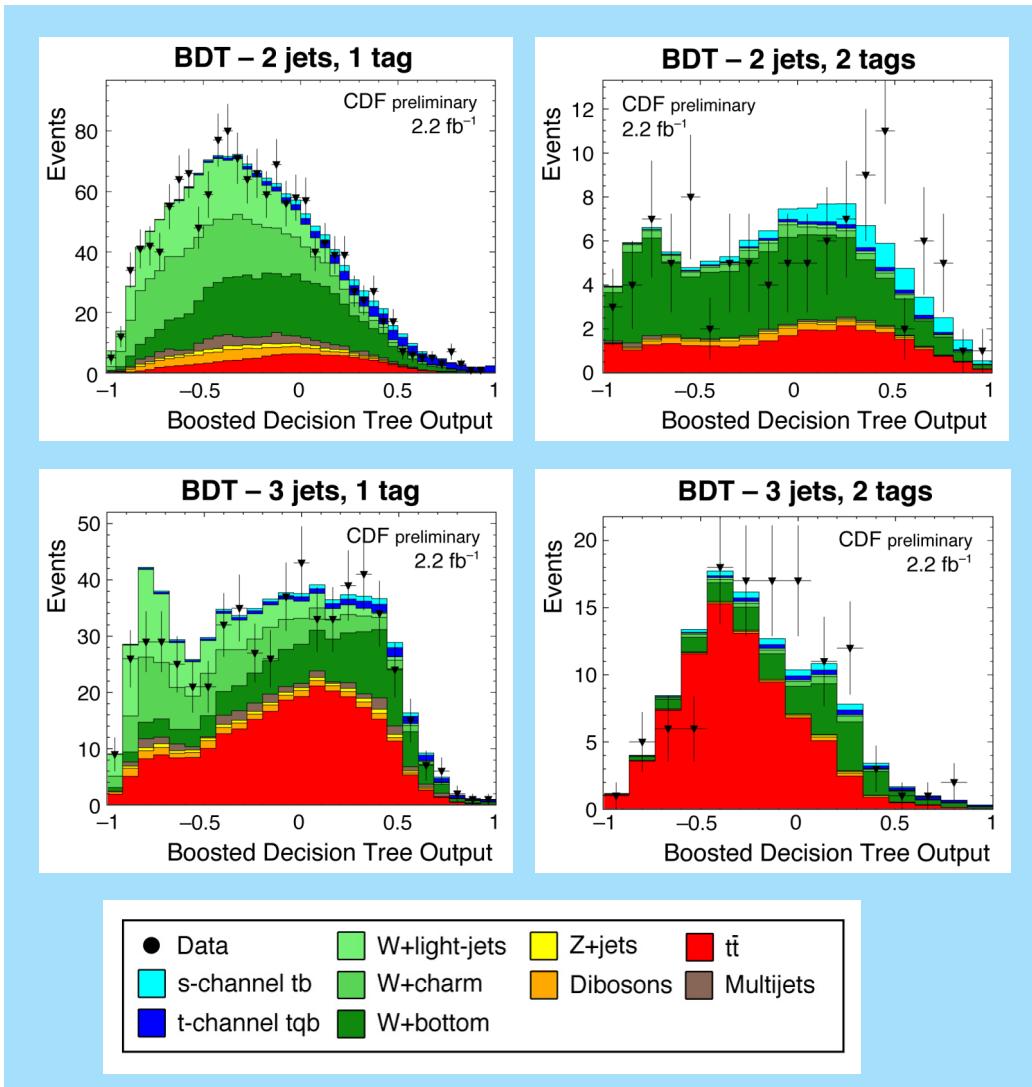


$tb+tbq$ Results CDF preliminary 2.2 fb^{-1}			
	LF	NN	ME
Expected significance	3.4σ	4.4σ	4.5σ
Observed significance	2.0σ	3.2σ	3.4σ
Cross section	$1.8^{+0.9}_{-0.8} \text{ pb}$	$2.0^{+0.9}_{-0.8} \text{ pb}$	$2.2^{+0.8}_{-0.7} \text{ pb}$

New CDF $t\bar{t}+tqb$ Analysis

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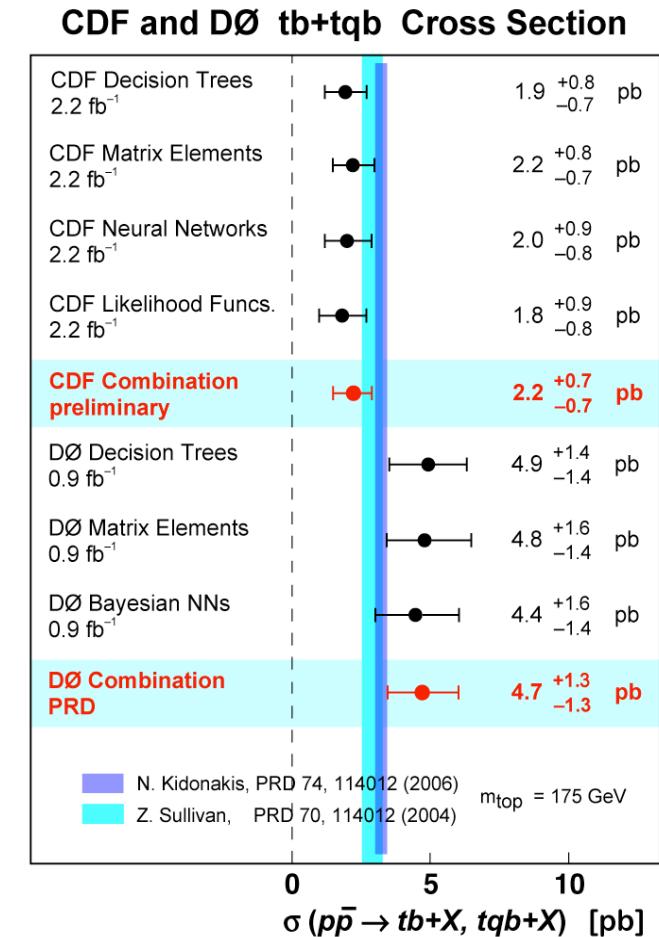
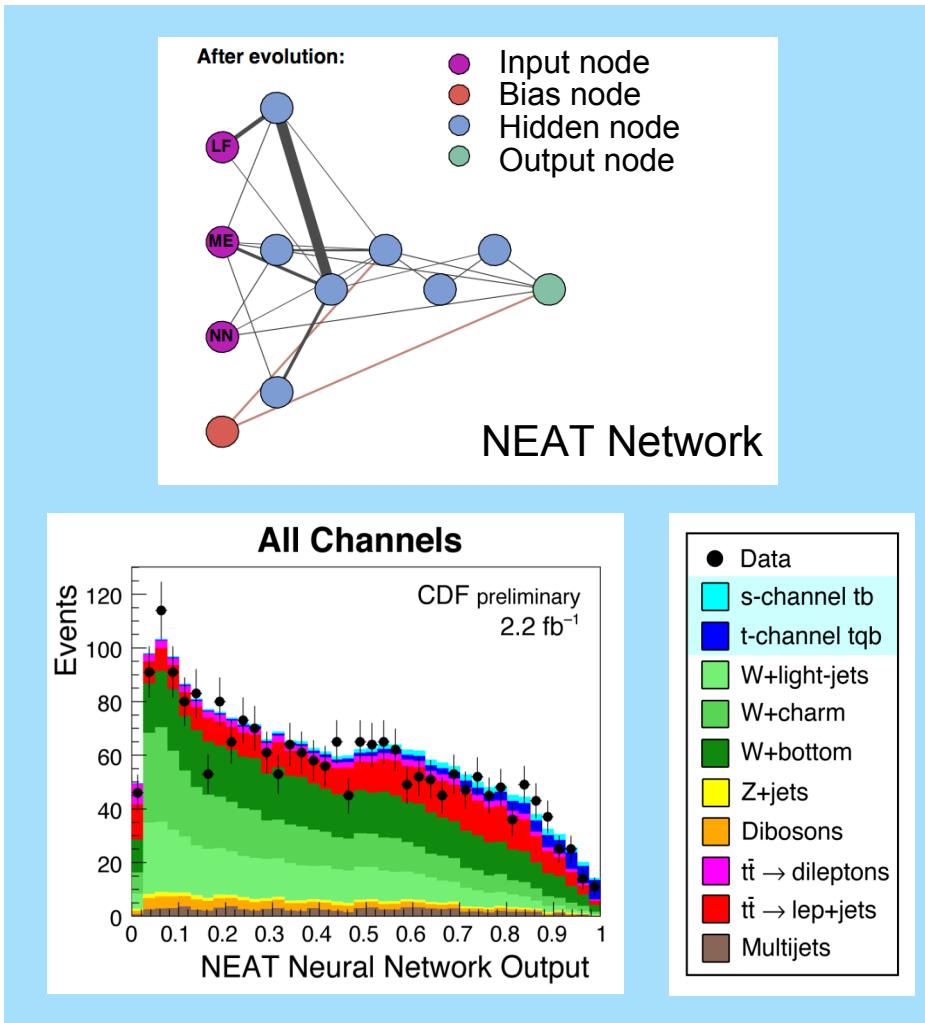
- Boosted decision trees for signal-background separation
- Result consistent with previous three measurements



- 22, 29, 21 input variables for 2-, 3-, 4-jets events
- Most sensitive method
- Significance
 - 4.6σ (expected)
 - 2.8σ (observed)
- Cross section
 - $1.9^{+0.8}_{-0.7} \text{ pb}$

Combining the Results

- CDF combine first three measurements with a *neural network*, optimized using *neuro-evolution of augmenting topologies* (NEAT)
 - Expected significance improves: 4.5σ (ME-only), 4.7σ (BLUE combination of LF, NN, ME), 5.1σ (NEAT combination of LF, NN, ME). Measured significance = 3.7σ
- DØ combine measurements using *best linear unbiased estimate* (BLUE) method



Separate Measurements of tb and tqb

tb

tqb

tb

tqb

tb

tqb

tb

tqb

tb

tqb

tb

DØ decision tree analysis

- Boosted decision trees trained in 2-, 3-, 4-jets, 1,2 b -tags channels for tb and tqb separately
- 49 input variables
- SM cross section assumed for single top process not being measured
- Phys. Rev. Lett. 98, 181802 (2007)**

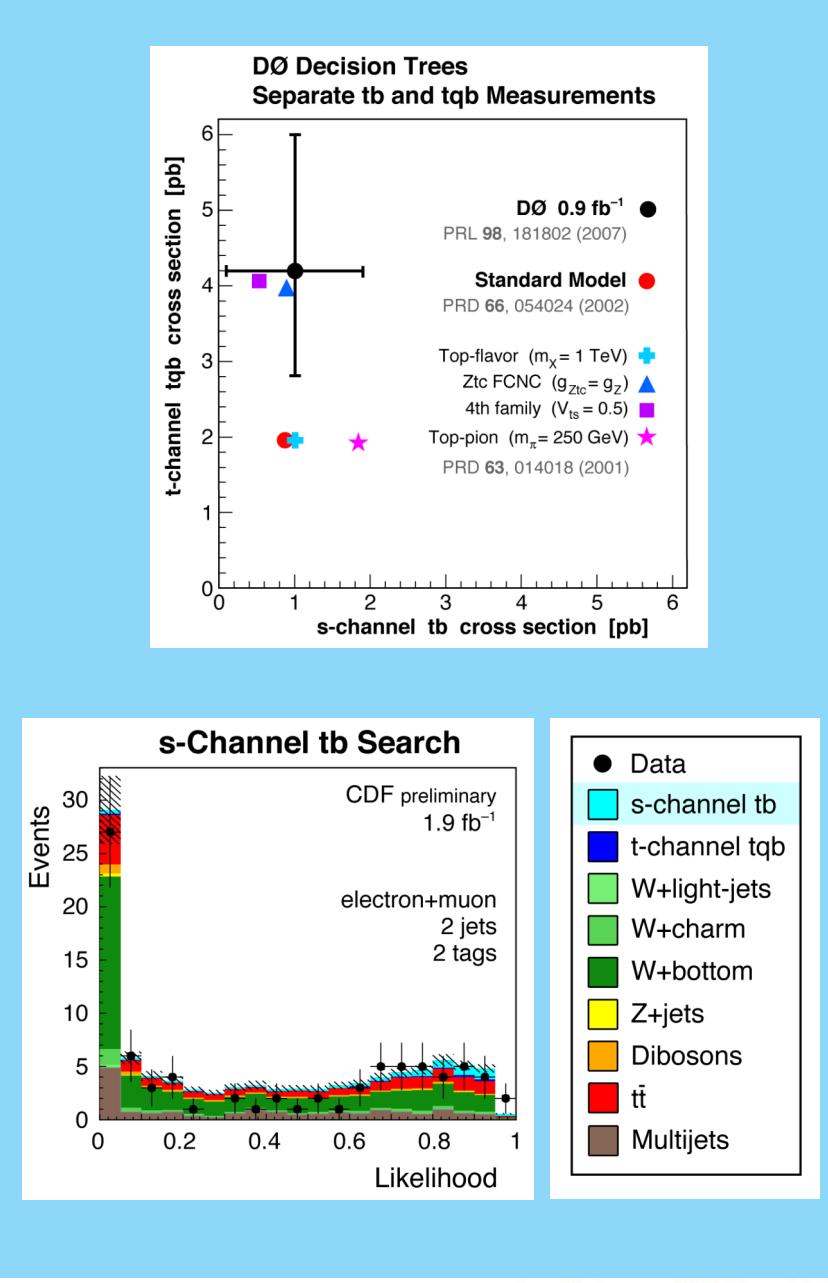
$$s\text{-channel } \sigma(tb) = 1.0 \pm 0.9 \text{ pb}$$

$$t\text{-channel } \sigma(tqb) = 4.2^{+1.8}_{-1.4} \text{ pb}$$

CDF likelihood function – tb -only

- Search 1.9 fb^{-1} of data in the 2-jets, 2-tag channel
- $M(\ell\nu b)$, $M(bb)$, $H_T(\text{all})$, \cancel{E}_T , $p_T(bb)$, $p_T(\text{jet1})$, kinematic fit
- Small excess of data over background

$$\sigma(tb) < 2.8 \text{ pb at 95% CL}$$



More Measurements of tb and tqb

tb

tqb

tb

tqb

tb

tqb

tb

tqb

tb

tqb

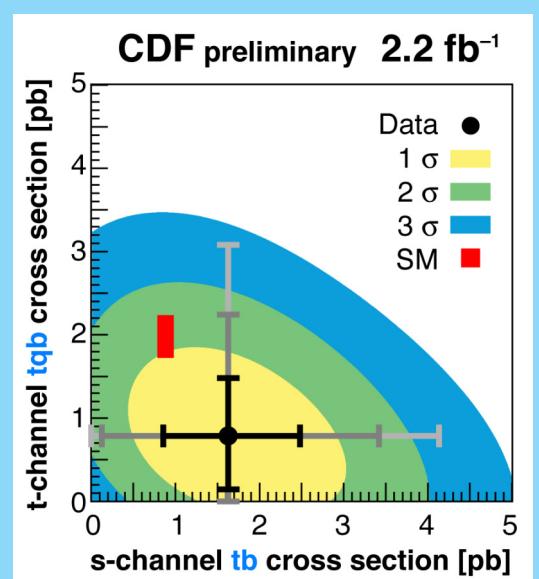
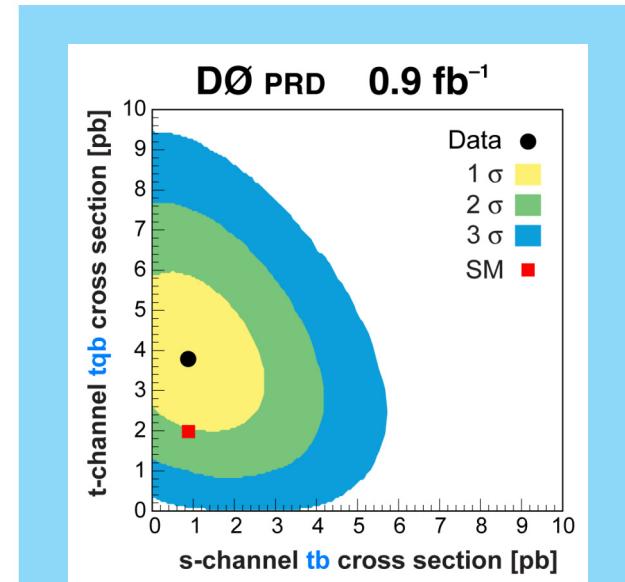
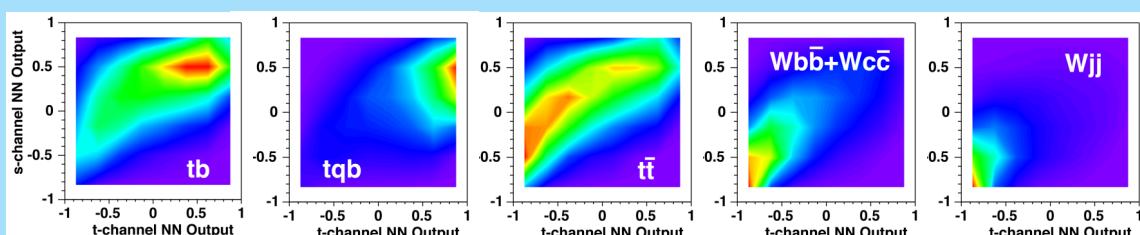
tb

- DØ $tb+tqb$ decision trees 2-d fit
 - Allow tb and tqb cross sections to float
 - Fit cross sections simultaneously
 - arXiv.org:0803.0739, accepted in PRD

$$\begin{aligned} \text{s-channel } \sigma(tb) &= 0.9 \text{ pb} \\ \text{t-channel } \sigma(tqb) &= 3.8 \text{ pb} \end{aligned}$$

- CDF neural networks 2-d fit – **NEW**
 - Search 2.2 fb^{-1} of data in the 2-, 3-jets 1-, 2-tag channels
 - Fit to tb and tqb templates

$$\begin{aligned} \text{s-channel } \sigma(tb) &= 1.6 {}^{+0.9}_{-0.8} \text{ pb} \\ \text{t-channel } \sigma(tqb) &= 0.8 {}^{+0.7}_{-0.8} \text{ pb} \end{aligned}$$

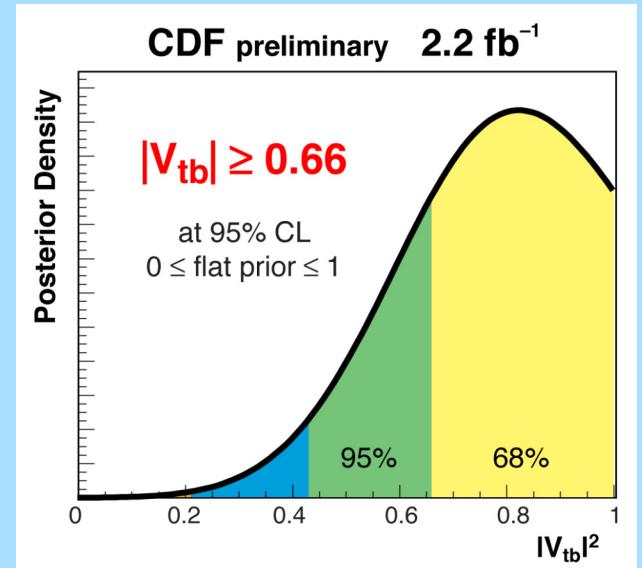
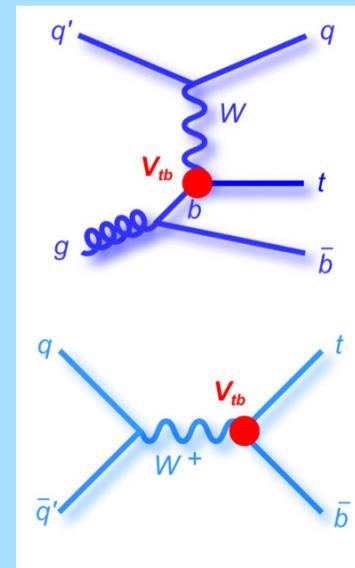
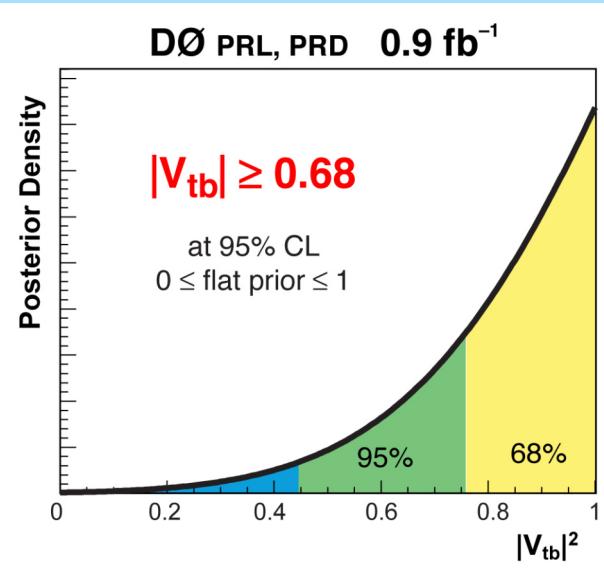


CKM Matrix Element V_{tb}

- General form of Wtb vertex:

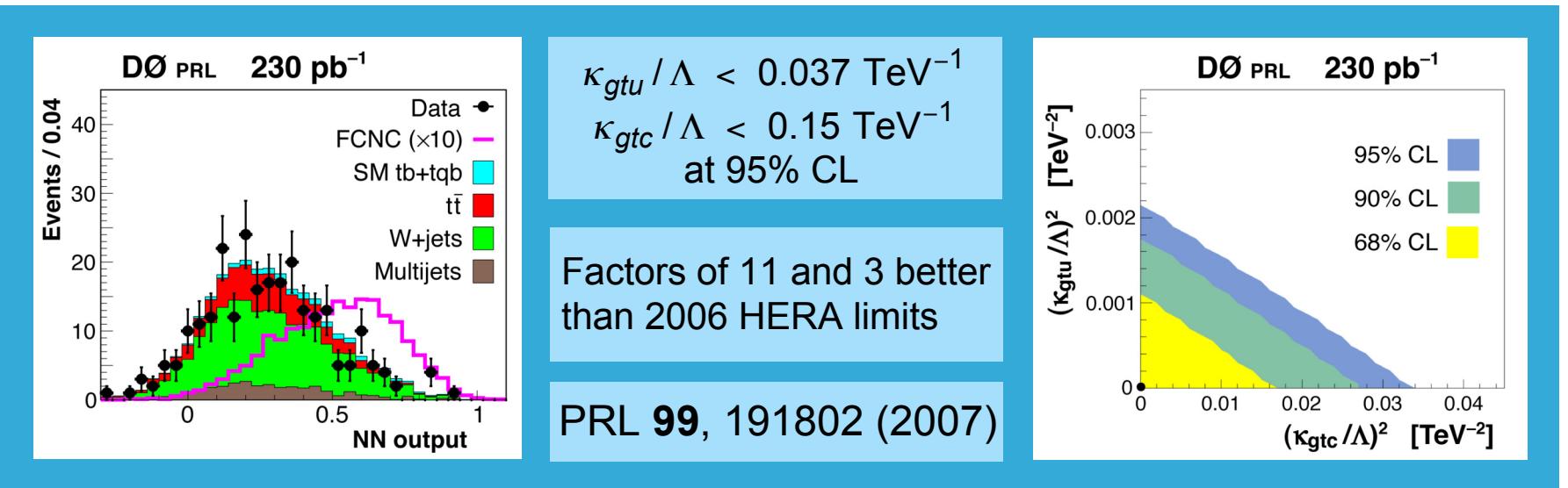
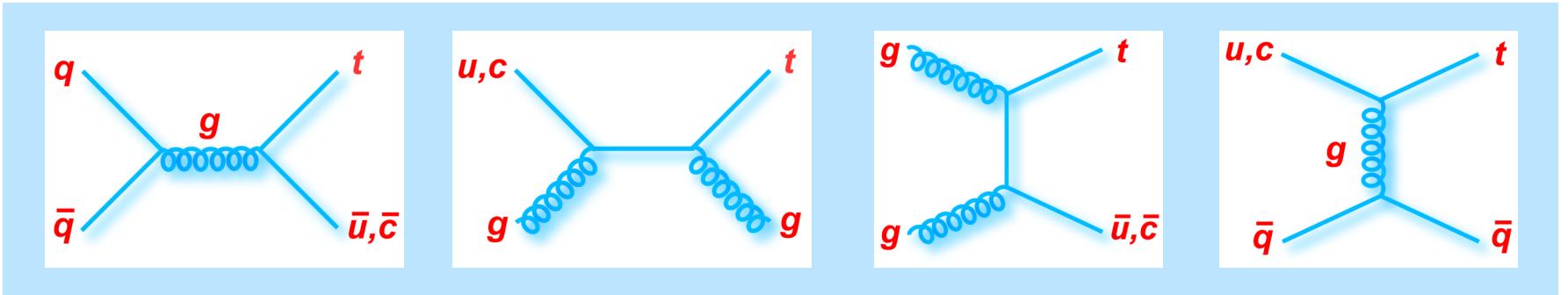
$$\Gamma_{Wtb}^\mu = -\frac{g}{\sqrt{2}} \textcolor{red}{V_{tb}} \left\{ \gamma^\mu [f_1^L P_L + f_1^R P_R] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_\nu [f_2^L P_L + f_2^R P_R] \right\}$$

- $\sigma(tb, tqb) \propto |V_{tb}|^2 \Rightarrow$ calculate a posterior in $|V_{tb}|^2$
- Assume**
 - SM top quark decay : $V_{td}^2 + V_{ts}^2 \ll V_{tb}^2$
 - Pure V-A : $f_1^R = 0$
 - CP conservation : $f_2^L = f_2^R = 0$
- No need to assume only three quark families or CKM matrix unitarity



Flavor-Changing Neutral Currents

- **DØ analysis**, same selection as for single top, except:
 - require only one *b*-tagged jet (from decay of the top) – no second *b* present
- Use neural network to combine 10 kinematic variables
- **Cross sections scale with** $(\kappa_{gtu}/\Lambda)^4$ and $(\kappa_{gtc}/\Lambda)^4$

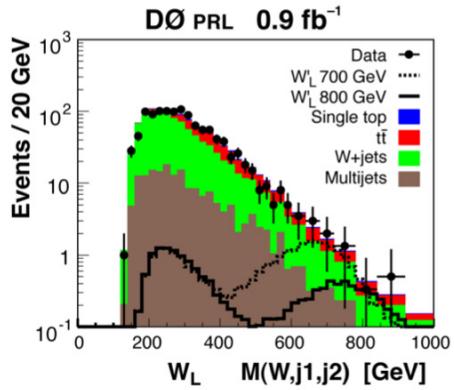
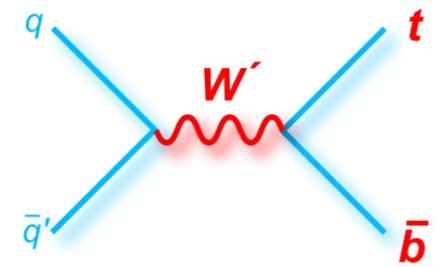


Heavy W' Resonances

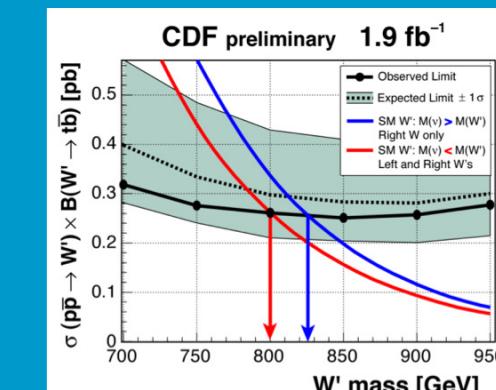
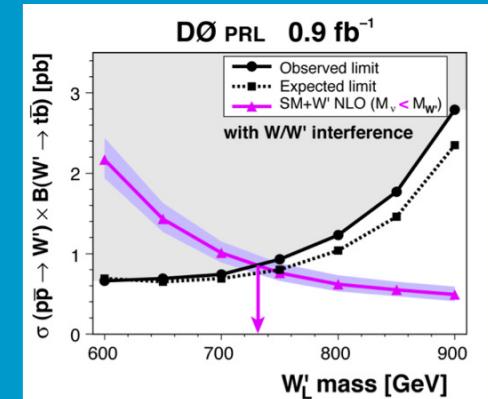
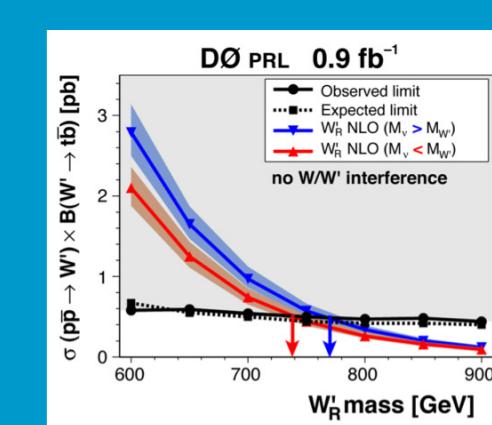
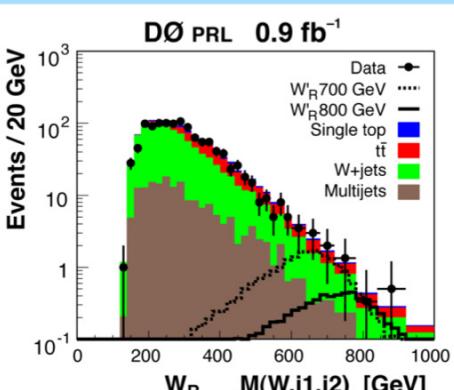
W' W' W' W' W' W' W' W' W'

- DØ and CDF search for s-channel $t\bar{b}$ resonance

- left-handed W'_L with SM couplings
(DØ includes interference with SM W in signal model)
- right-handed W'_R that decays to $\ell\nu$ and $q\bar{q}'$ ($M(v_R) < M(W'_R)$)
- right-handed W'_R that decays only to $q\bar{q}'$ ($M(v_R) > M(W'_R)$)



[arXiv.org:0803.3256](https://arxiv.org/abs/0803.3256) (accepted in PRL)

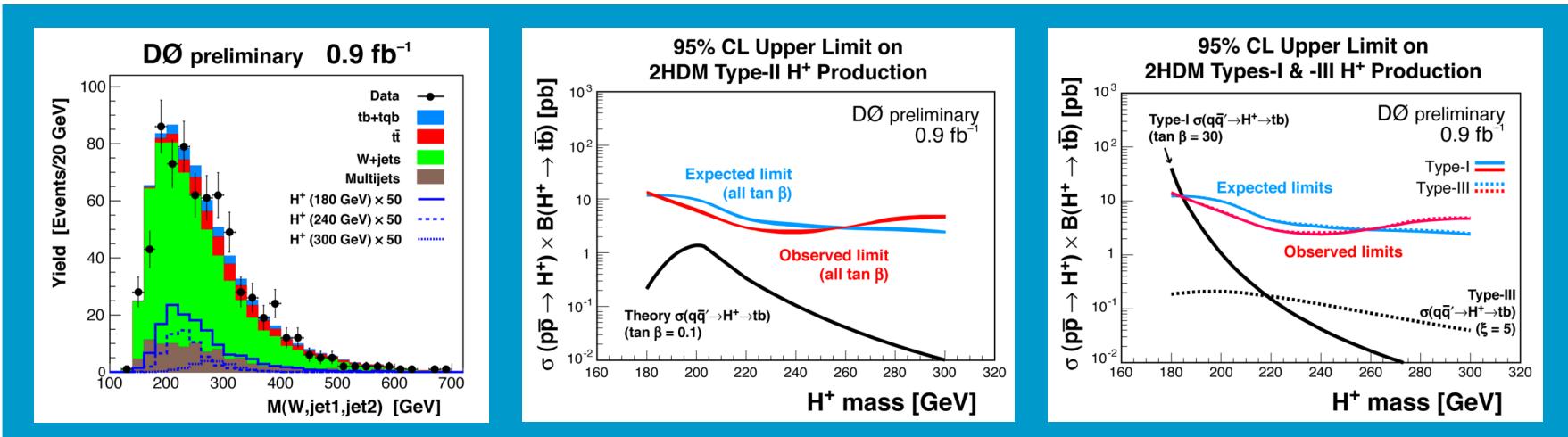
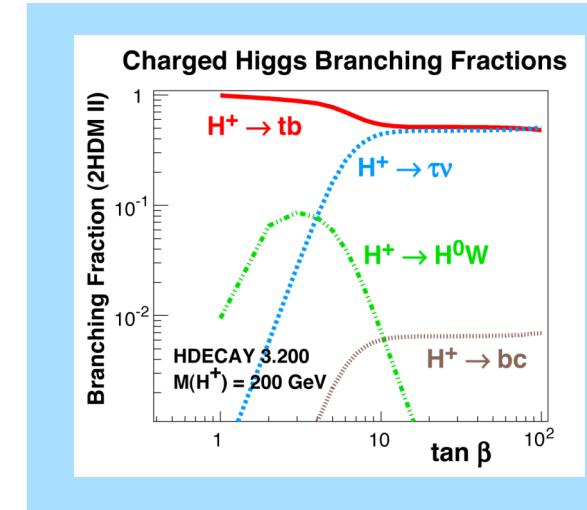
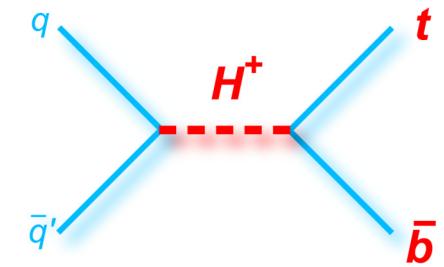


$M(W'_L) > 731 \text{ GeV}$ (DØ)
 $> 800 \text{ GeV}$ (CDF prelim.)
 $M(v_R) < M(W'_R)$
 $M(W'_R) > 739 \text{ GeV}$ (DØ)
 $> 800 \text{ GeV}$ (CDF prelim.)
 $M(v_R) > M(W'_R)$
 $M(W'_R) > 768 \text{ GeV}$ (DØ)
 $> 825 \text{ GeV}$ (CDF prelim.)

Charged Higgs Resonance

H⁺
H⁺
H⁺
H⁺
H⁺
H⁺
H⁺
H⁺
H⁺

- DØ analysis - first search for heavy H^+ decaying to top
 - Search for s-channel tb resonance, use 2-jets, 1,2 b -tags
 - Binned likelihood calculation in $M(W, \text{jet1}, \text{jet2},)$
- Three two-Higgs-doublet models (2HDM) studied
 - Type I – only one doublet couples to fermions
 - Type II – one doublet couples to up-type fermions, the other to down-type fermions
 - Type III – both doublets couple to fermions
- Upper limits set close to predicted cross sections
 - Small region excluded for 2HDM Type-I H^+ between 180 and 184 GeV with $23 < \tan \beta < 70$
- NEW – Results to be submitted for publication soon



Summary: Single Top Quark Physics at the Tevatron

- Challenging measurements – small signal hidden in large complex background
- Seven multivariate techniques applied to separate signal from background
- DØ's combined analysis has 3.6σ significance, published in PRL and PRD

$D\bar{\Omega} \quad \sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 4.7 \pm 1.3 \text{ pb}$
- CDF's combined analysis has 3.7σ significance, uses 2.2 fb^{-1} of data

$CDF \quad \sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 2.2 \pm 0.7 \text{ pb}$
- Four studies so far: $|V_{tb}|$, FCNC production, $W' \rightarrow tb$, and $H^+ \rightarrow tb$ resonances
- More data and studies in the pipeline, stay tuned!

