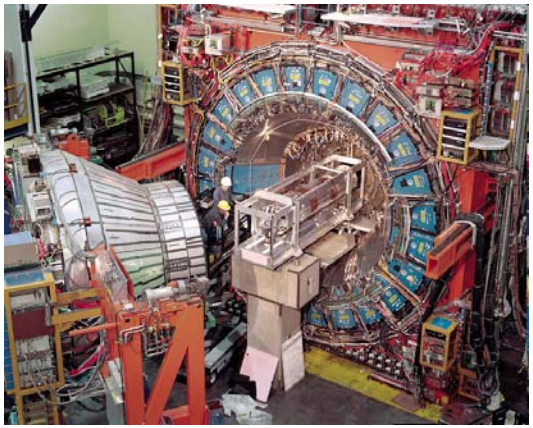
Single Top Physics at the Tevatron



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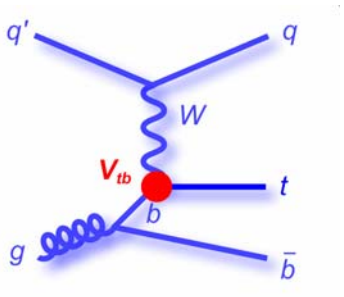
Columbia University

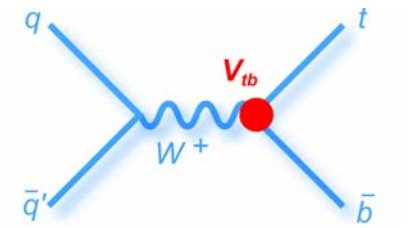
On behalf of the CDF and D∅ Collaborations

DISCRETE'08, Valencia, December 11/2008

Motivations for Studying Single Top

- Cross-section provides direct measurement of $|V_{tb}|$, without assuming unitarity of 3X3 CKM matrix



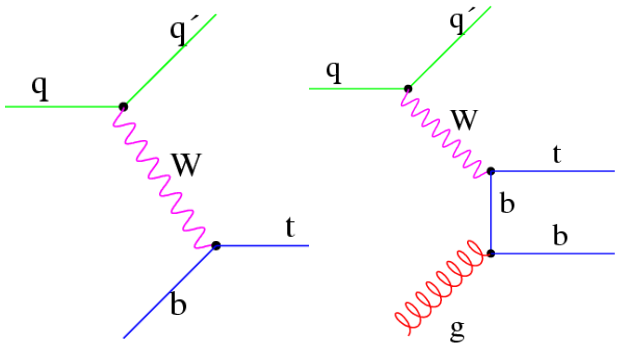


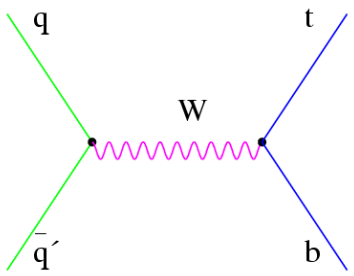
- Single top quark production provides excellent windows onto possible new physics, such as
  - Anomalous Wtb couplings (affecting cross-sections, angular distns, …) eg. V+A
  - New, heavy gauge bosons $W' \rightarrow tb$
  - Heavy charged Higgs $H^+ \rightarrow tb$
  - FCNC couplings of the top quark eg. tgu, tgc
  - …
  - Since the various single top processes are impacted differently by different types of new physics, it is important to measure each process separately

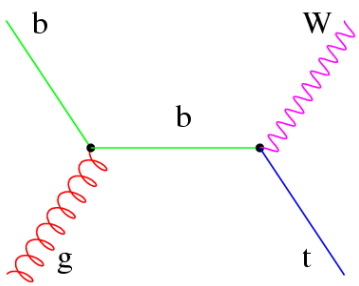
- Signal top analysis is "training ground" for Higgs analyses in similar final states (eg. $WH \rightarrow l\nu bb$)

Single Top Quark Production at the Tevatron

- **In addition to t-tbar production (via strong processes), single top quarks can be produced at hadron colliders via electroweak processes:**







W-gluon fusion (t-channel, or "**tqb**") [σ_{NLO}(tqb)= 2.0±0.3 pb]

W* (s-channel, or "**tb**") [σ_{NLO}(tb) = 0.9±0.1 pb]

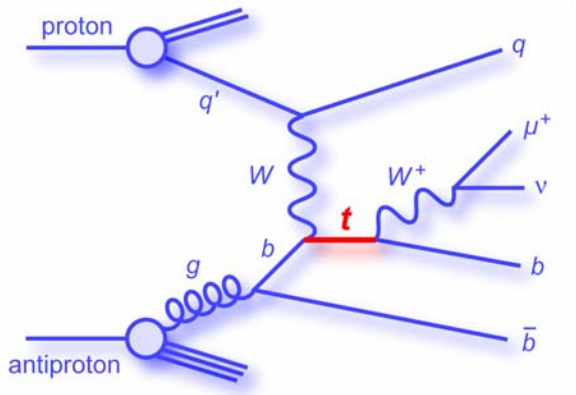
Wt (0.2 pb) **Not used**

- **Single top production is ~40% of the t tbar cross-section at the Tevatron**
- **However, first evidence for single top was not observed until 2006 (more than 10 years after the top quark was discovered via t tbar measurements)**
  - **The less distinctive signal topology, combined with the large and kinematically very similar backgrounds, has made the single top search difficult**
  - **Nevertheless, CDF and D∅ have by now produced an impressive array of results from the study of single top**

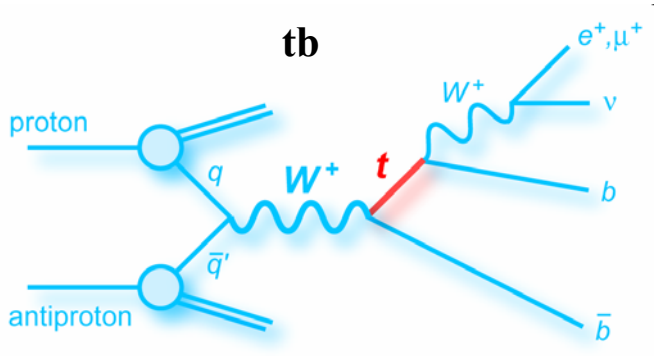
Event Selection

- **Select signal topology with leptonic W decay**

tqb



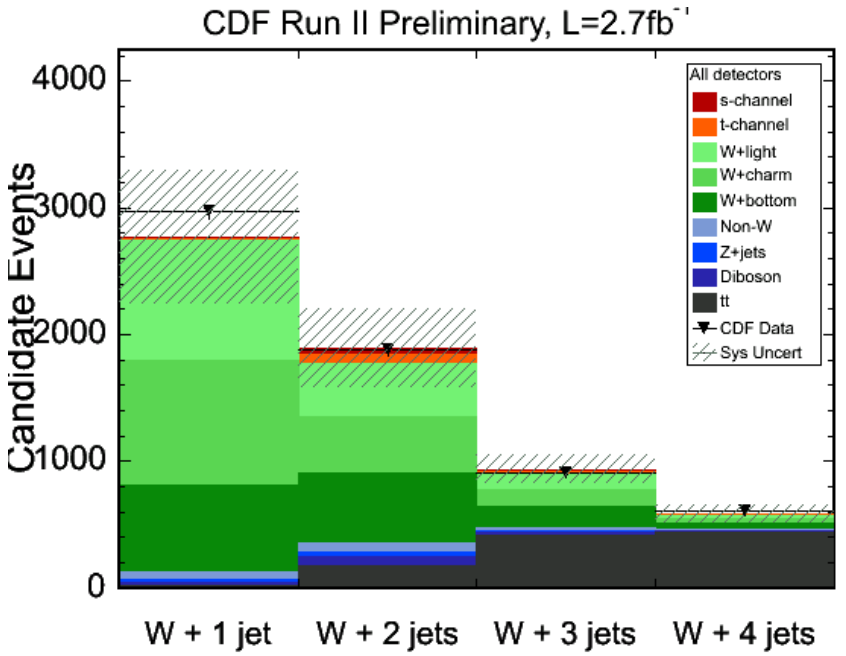
tb



- **Selection cuts**
  - **One isolated electron or muon**
    - ***pT*** **> 20 GeV (CDF); > 15(*e*), 18(μ) GeV (DØ)**
    - **|η| < 1.6 (CDF); < 1.1(*e*), 2.0(μ) (DØ)**
  - **Missing transverse energy**
    - ***MET*** **> 25 GeV (CDF); > 15 GeV (DØ)**
  - **Two, three, or four jets, including one or two *b*-tagged jets**
    - ***pT*** **> 20 GeV (CDF); > 25, 20, 15 GeV (DØ)**
    - **|η| < 2.8 (CDF); < 2.5, 3.4, 3.4 (DØ)**
- **Background is mainly *W*+jets and *tt*, plus some contributions from *Z*+jets, dibosons, and multijets (with fake leptons)**

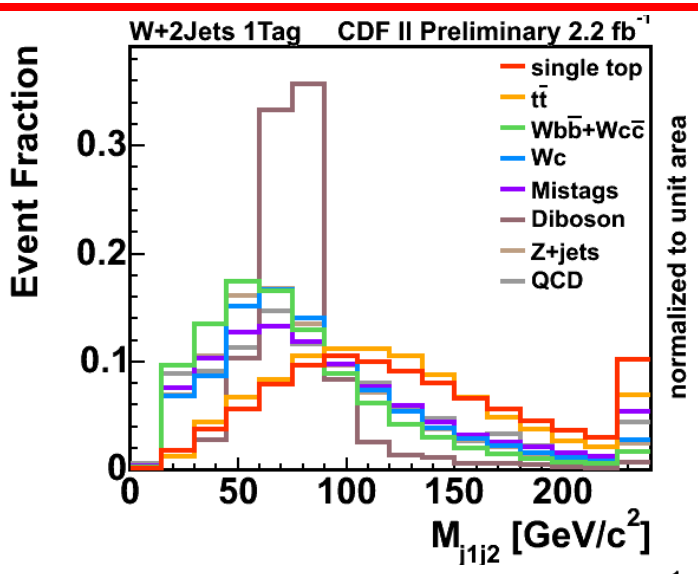
Expected Event Yields

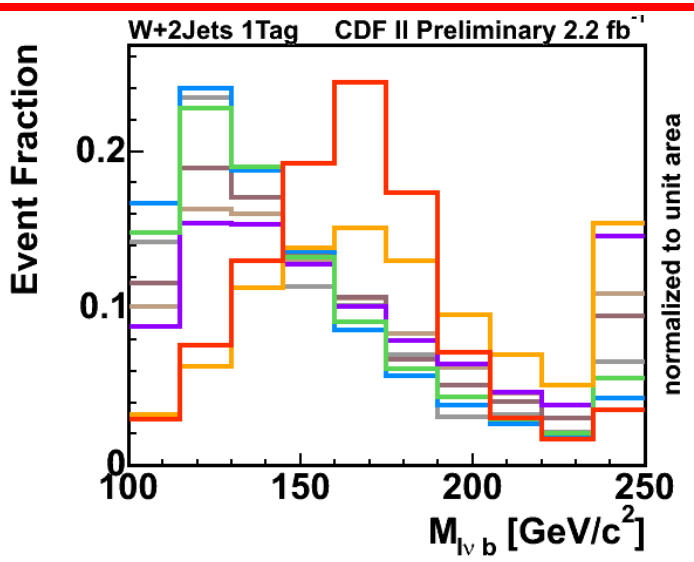
DØ PRD	0.9 fb^{-1}	
1,2 b-tags	2-jets	3-jets
s-channel tb	16	8
t-channel tqb	20	12
W+light-jets	119	43
W+charm	151	85
W+bottom	261	120
$t\bar{t}\rightarrow$dileptons	39	32
$t\bar{t}\rightarrow$lepton+jets	20	103
Multijets	95	77
Total prediction	**721**	**480**
Data	**697**	**455**

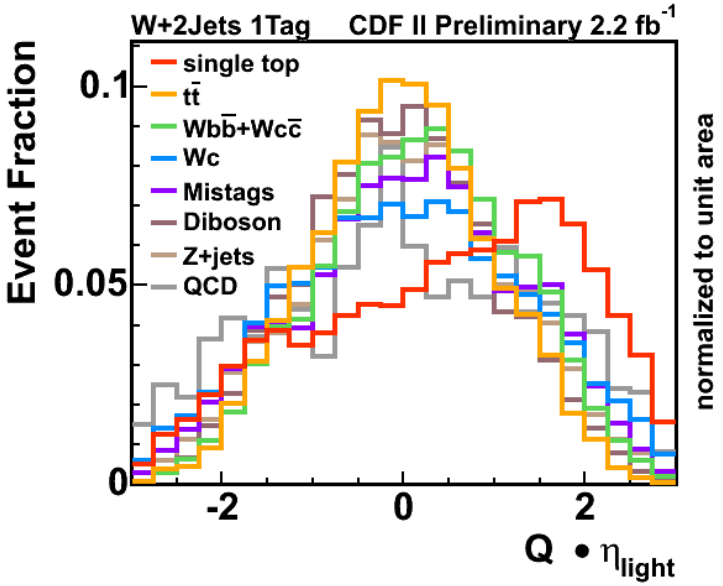


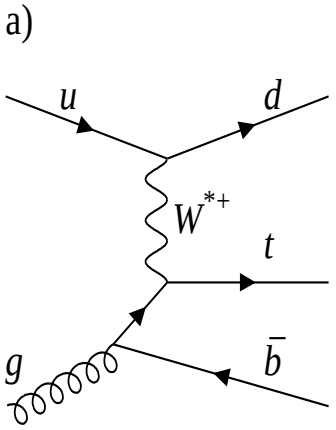
- After selection cuts and b-tagging, still have to find signals within much larger backgrounds
- Uncertainties on N(bkgnd) larger than expected signals
  - Cannot use simple counting experiment ⇒ use multivariate techniques to increase sensitivity
  - Divide into subsamples according to lepton type (e/mu), Njets (2,3,4), Nbjets (1,2), analyze separately, and then combine for maximum sensitivity

Some Discriminating Variables







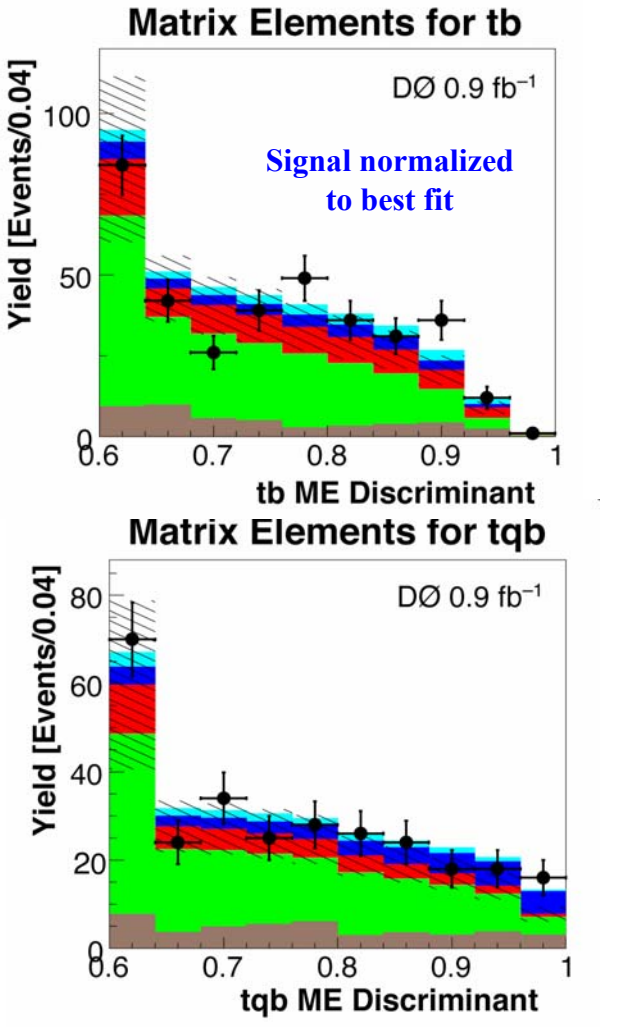


DØ Measurement of tb+tqb Cross-Section

- First evidence for single top production was presented in December 2006, with data corresponding to 0.9 fb^{-1}
  - Published in PRL 98, 181802 (2007), with updated and expanded publication in PRD 78, 012005 (2008)
- Three different multivariate techniques used
  - Boosted decision tree (BDT), using 49 variables
  - Matrix elements
  - Bayesian neural net (BNN), avg. over 100 nets, 18-25 var per channel
- All 3 methods found >3 σ evidence for single top

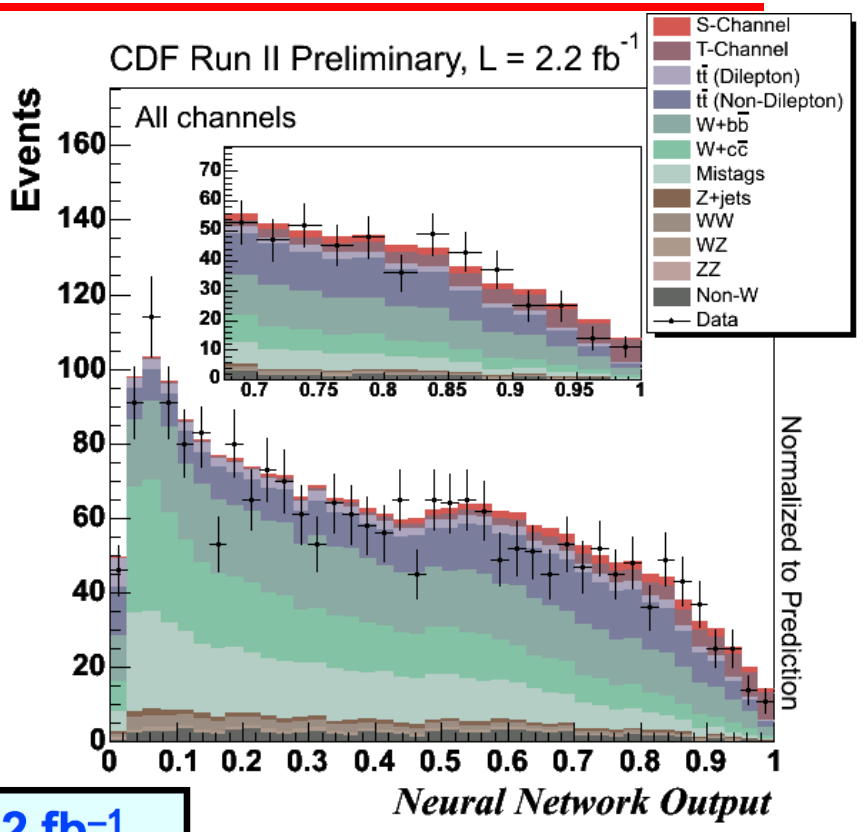
tb+tqb Results DØ PRD 0.9 fb^{-1}	DT	BNN	ME
Expected significance	2.1 σ	2.2 σ	1.9 σ
Observed significance	3.4 σ	3.1 σ	3.2 σ
Cross section	$4.9^{+1.4}_{-1.4}$ pb	$4.4^{+1.6}_{-1.4}$ pb	$4.8^{+1.6}_{-1.4}$ pb

- Data was used to provide first direct measurement of CKM matrix element Vtb



CDF Measurement of tb+tqb Cross-Section

- **CDF used larger dataset (2.2 fb^{-1}) with 3 different multivariate techniques to make a measurement of tb+tqb cross-section**
  - **Likelihood, using 7 (10) variables in 2j (3j) channel**
  - **Neural net (NN), with 11-18 vars per channel**
  - **Matrix element**
- **Results presented in arXiv:0809.2581v2 [hep-ex] (accepted for publication in PRL)**



Signal normalized to SM

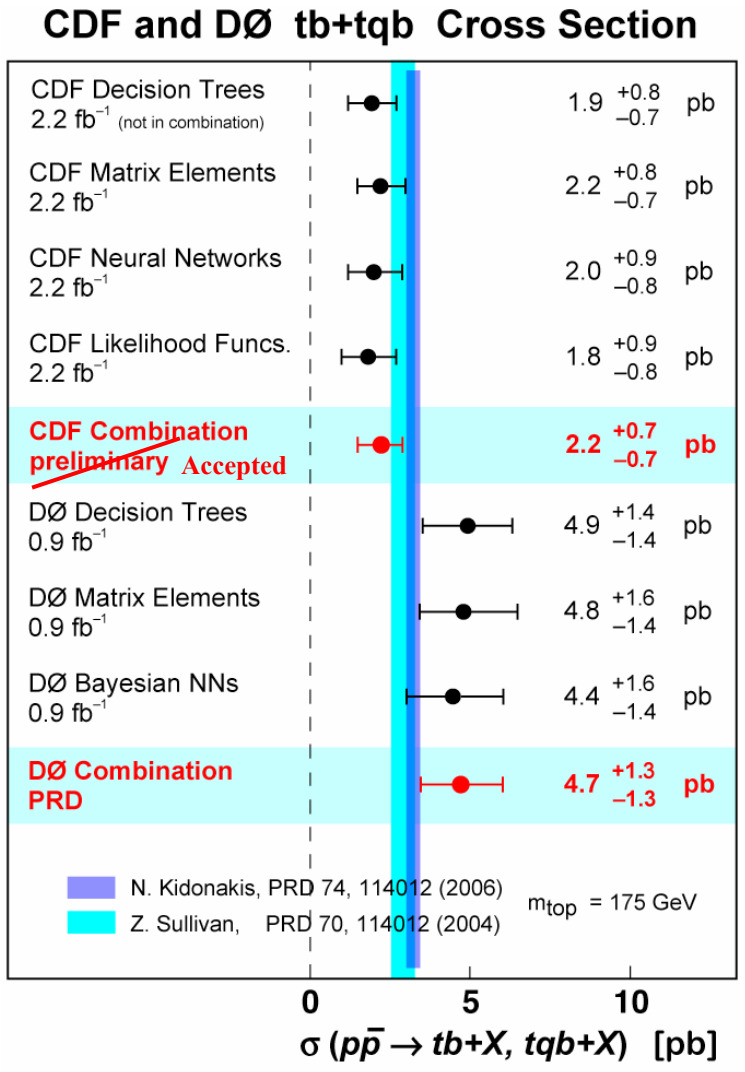
accepted

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

Combination of tb+tqb Cross-Section Measurements

- **Both DØ and CDF have performed combination of analyses, taking properly into account the correlations**
  - **DØ combines using "BLUE" method, while CDF checks this but also uses a "super-discriminant" combining discriminants from the 3 separate analyses**

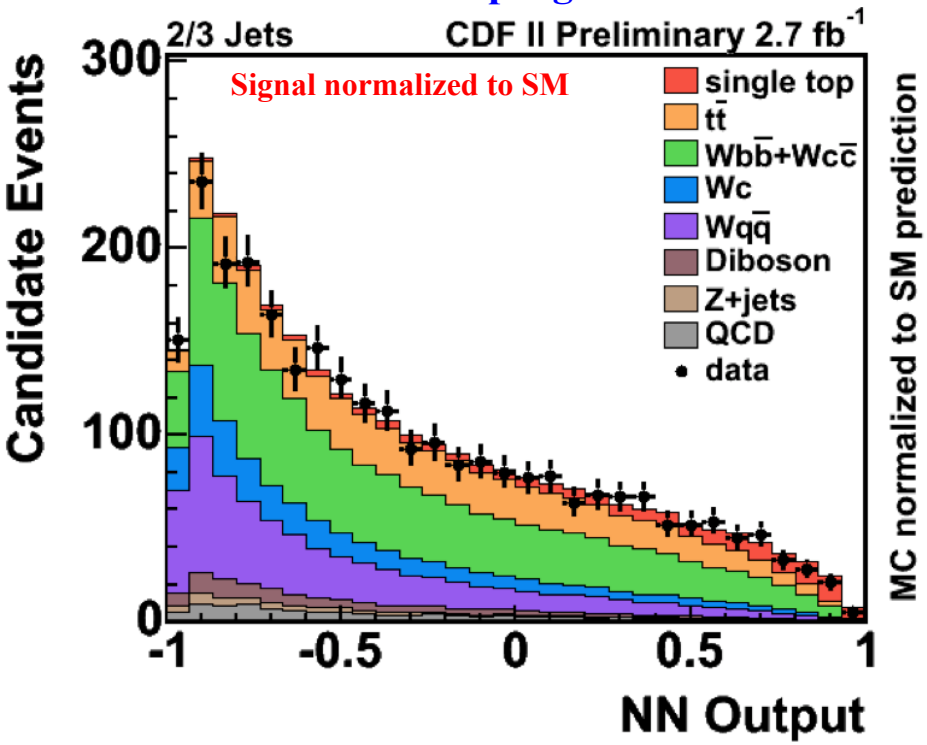
tb+tqb Combined Results	DØ PRD 0.9 fb^{-1}	CDF ~~prelim.~~ Accepted 2.2 fb^{-1}
Expected significance	2.3 σ	5.1 σ
Observed significance	3.6 σ	3.7 σ
Cross section	4.7 ± 1.3 pb	2.2 ± 0.7 pb

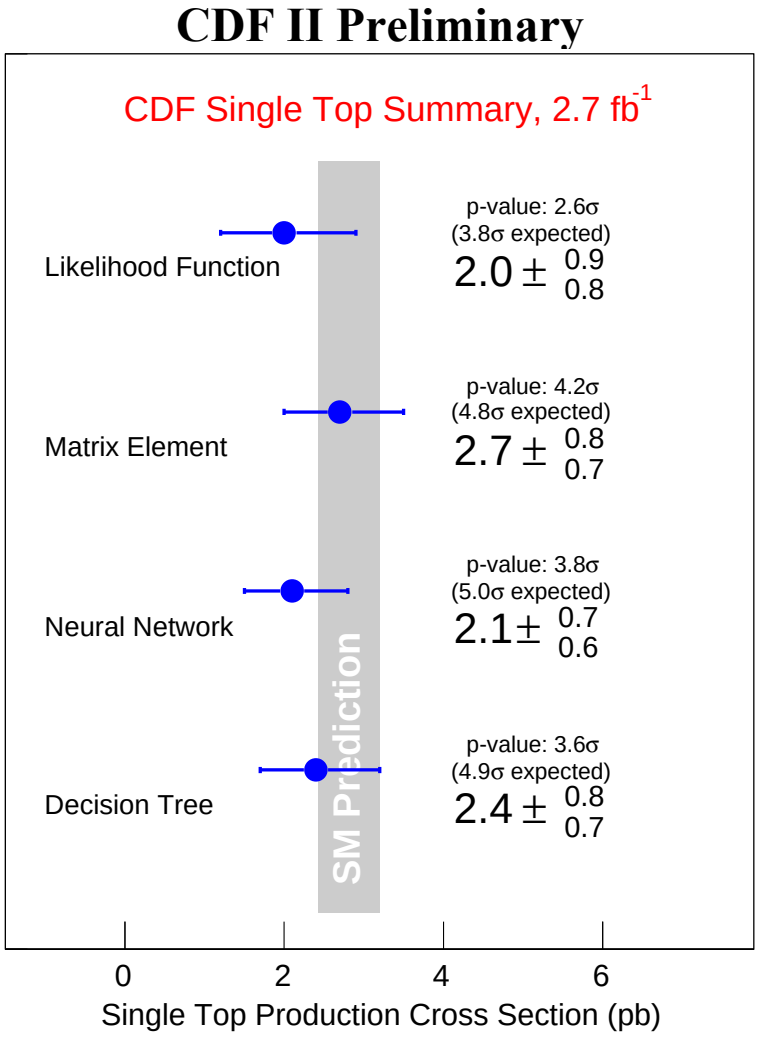


- **Results are in good agreement with each other, and with Standard Model prediction**

New CDF tb+tqb Cross-Section Measurement

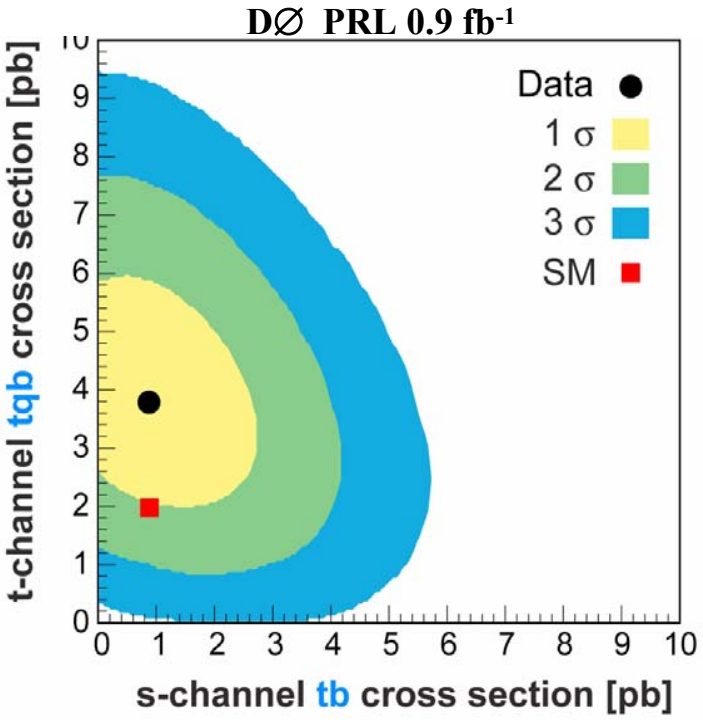
- CDF has recently presented preliminary cross-section results with an even larger data sample (2.7 fb^{-1})
  - Four different multivariate techniques now used (added a new BDT analysis)
  - Most precise single method (NN) has 5.0σ expected significance (3.8 σ observed)
  - Combination in progress

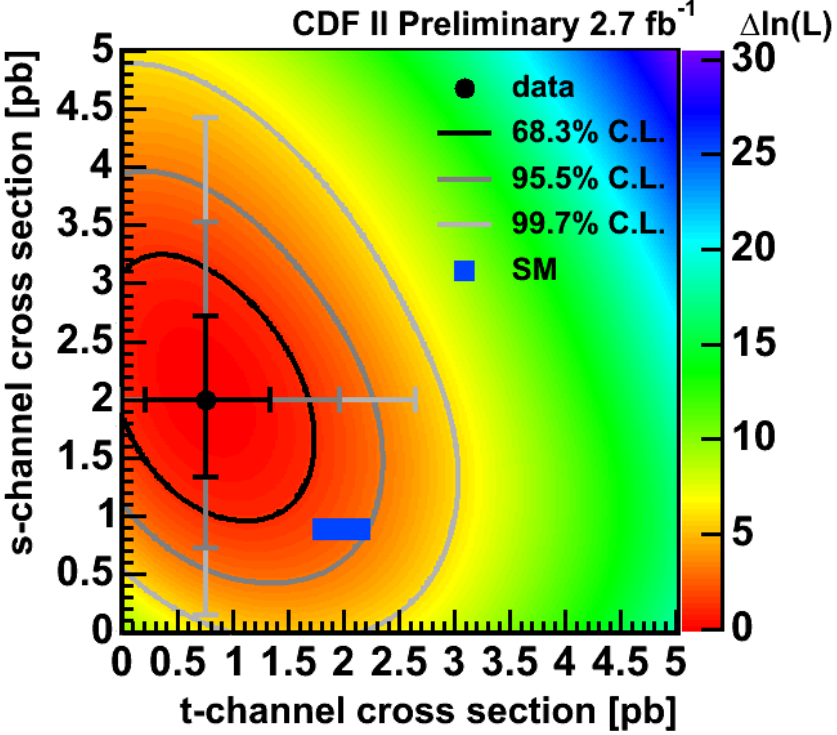




Measuring tb and tqb Separately

- tb and tqb have different sensitivities to new physics, so want to measure them separately
  - Both expts have done so, either by fixing one channel to the SM prediction while fitting the other, or allowing BOTH to float and fitting them both simultaneously
- Results when BOTH cross-sections are fitted simultaneously:





- More data should bring improved measurements of separate processes

Measurement of V_{tb}

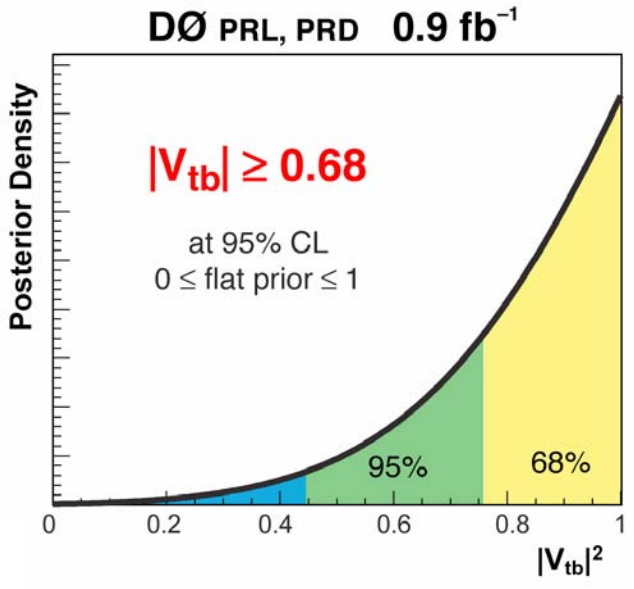
- **Assuming 3 generations, PDG 2008 fit to SM determines a value**

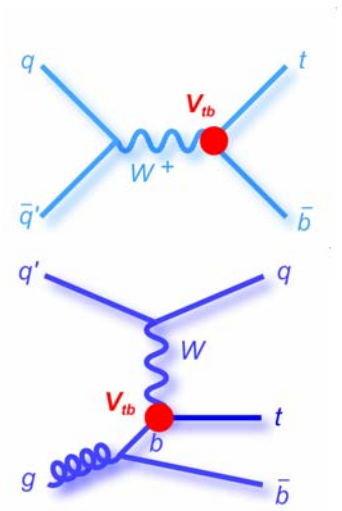
$$|V_{tb}| = 0.999133 \pm 0.000044$$

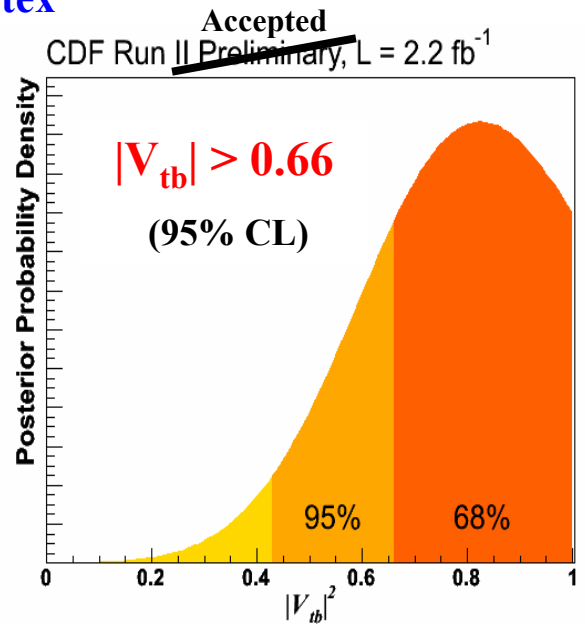
  - **In 3-generation SM, V_{tb} is highly constrained (and only one CP violating phase is present in CKM matrix)**

- **Single top cross-section is proportional to $|V_{tb}|^2$**

- **Use cross-section result to measure $|V_{tb}|$, without having to assume unitarity of 3-generation CKM matrix**
  - **Only need to assume:** $|V_{tb}|^2 >> |V_{ts}|^2 + |V_{td}|^2$ **(ie. SM top quark decay)**
    V-A interaction at Wtb vertex







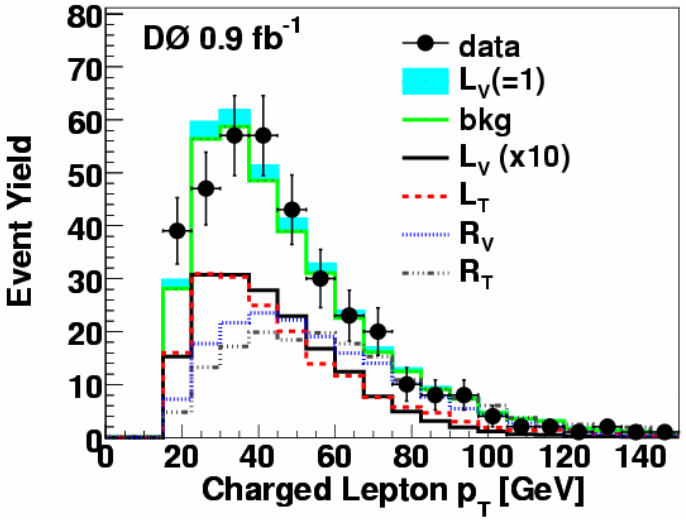
Search for Anomalous Wtb Couplings

- **General CP-conserving form of Wtb vertex:**

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

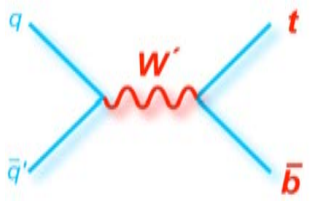
- **Anomalous Wtb couplings can change single top cross-sections as well as kinematics and angular distributions**

- **DØ has performed analyses including, in each case, SM V-A (ie. f_1^L) term plus ONE other term**
  - **Simultaneous limit setting for two signals by calculating 2-dim posterior probability density**
  - **Results favor SM, and provide limits on Wtb anomalous couplings** **PRL 101, 221801 (2008)**

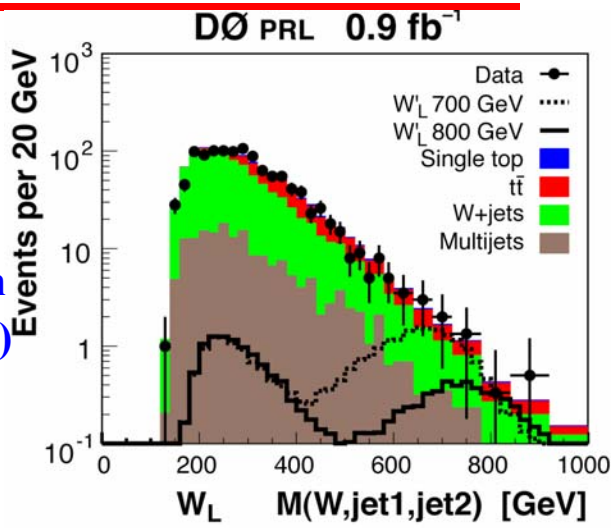


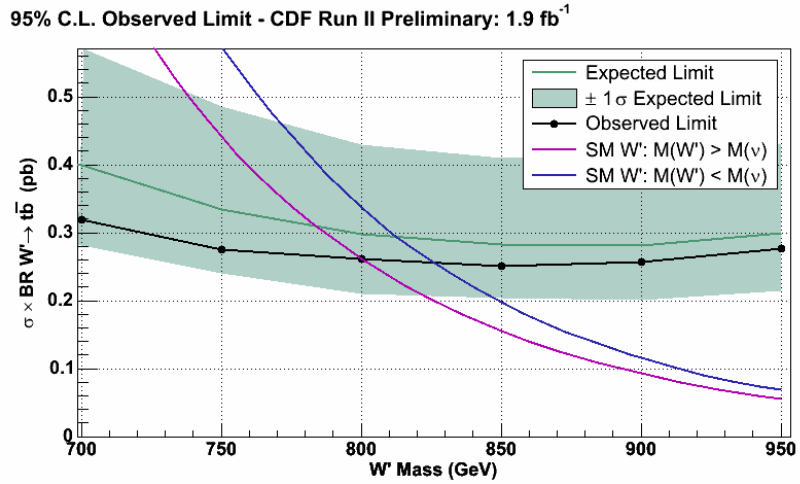
Scenario	Cross section	Coupling
(L_1, L_2)	$4.4^{+2.3}_{-2.5}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.6}_{-0.5}$
		$\lvert f_2^L\rvert^2 < 0.5$ at 95% C.L.
(L_1, R_1)	$5.2^{+2.6}_{-3.5}$ pb	$\lvert f_1^L\rvert^2 = 1.8^{+1.0}_{-1.3}$
		$\lvert f_1^R\rvert^2 < 2.5$ at 95% C.L.
(L_1, R_2)	$4.5^{+2.2}_{-2.2}$ pb	$\lvert f_1^L\rvert^2 = 1.4^{+0.9}_{-0.8}$
		$\lvert f_2^R\rvert^2 < 0.3$ at 95% C.L.

Search for Heavy W'→ tb



- DØ [PRL 100, 211803 (2008)] and CDF (Conf. note) searched for W'→ tb (resonance in s-channel)
- For Left-Handed W', assume SM couplings
  - DØ analysis includes interference with SM W-boson (can reduce total rate by ~16-33%, depending on mass, couplings)
- For Right-Handed W', decays depend on mass of associated RH neutrino (ν_R)
  - $m(\nu_R) < m(W'_R)$ – assume both leptonic and hadronic decays of the W'_R
  - $m(\nu_R) > m(W'_R)$ – only hadronic decays of the W'_R

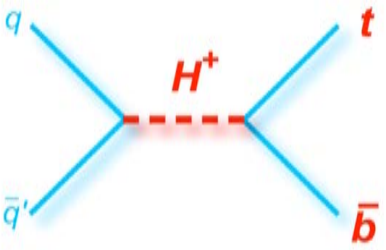




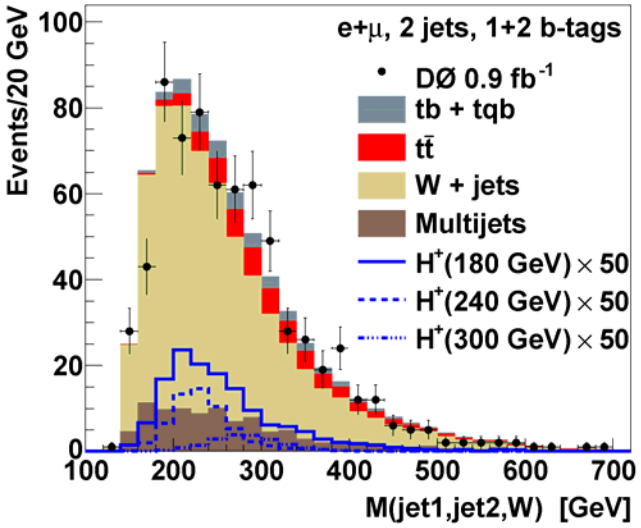
	DØ PRL (0.9 fb^{-1})	CDF Prelim. (1.9 fb^{-1})
W'_L	> 731 GeV (with int.)	> 800 GeV (no int.)
W'_R $[m(\nu_R) < m(W'_R)]$	> 739 GeV	> 800 GeV
W'_R $[m(\nu_R) > m(W'_R)]$	> 768 GeV	> 825 GeV

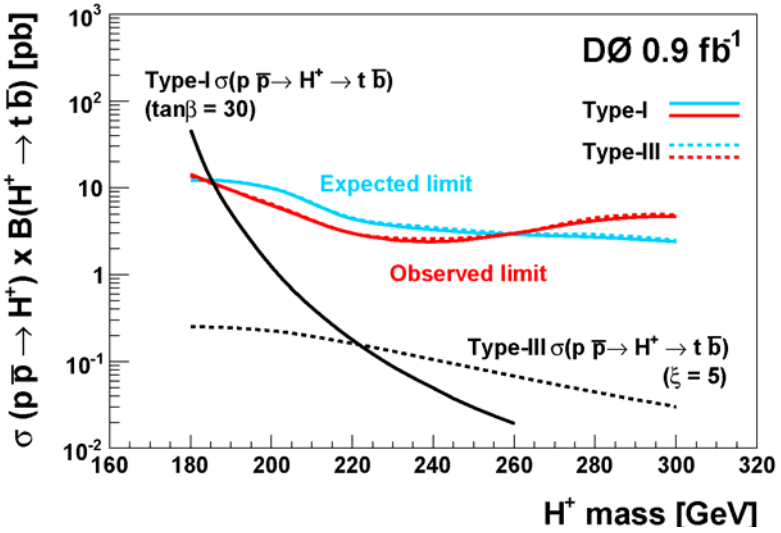
Search for Charged Higgs Via $H^+ \rightarrow tb$

- DØ has performed first search for $H^+ \rightarrow tb$
  - Look for resonance in s-channel (arXiv:0807.0859, submitted to PRL)



- Three different two Higgs doublet models (2HDM) investigated:
  - Type I – only one doublet couples to fermions
  - Type II – one doublet couples to up-type only, and other to down-type only
  - Type III – both doublets couple to fermions (need other sol'n to FCNC)
  - $H^+ \rightarrow tb$ is dominant decay mode for heavy H^+ in much of parameter space

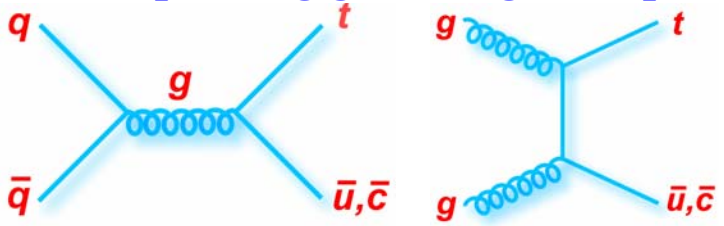




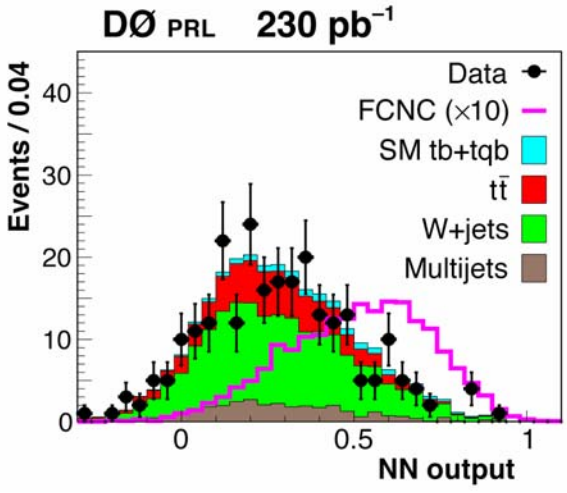
- Excluded parameter region for Type I: $180 < m_{H+} < 184$ GeV with $23 < \tan\beta < 70$
  - More data needed to increase sensitivity, including for other Types

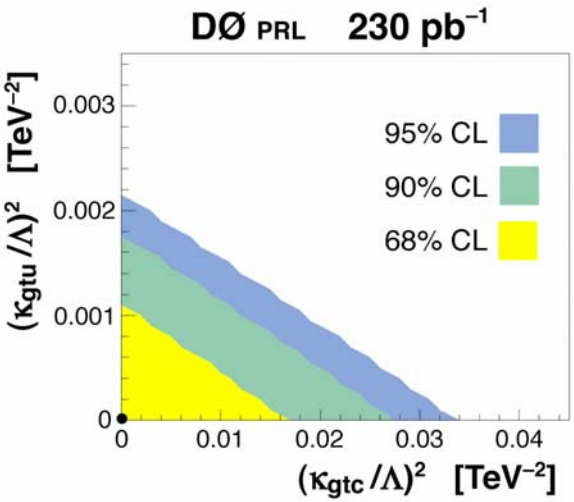
Search for FCNC

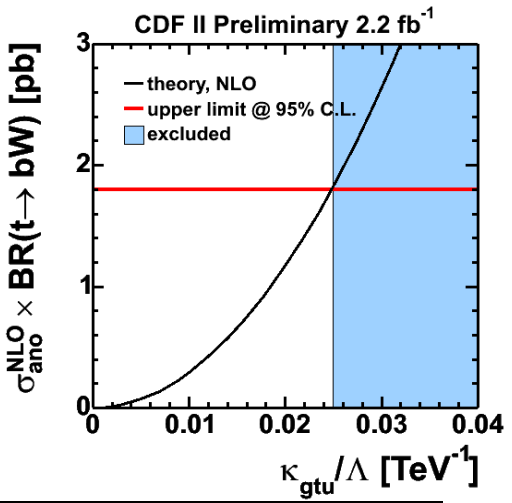
- Can search for single top production via FCNC, probing gtu and gtc couplings
  - Representative Feynman diagrams:



  - Same selection as for single top, except require only bjet from t-decay (ie. no 2nd bjet)







Coupling (95% C.L.)	DØ PRL (230 pb^{-1})	CDF Preliminary (2.2 fb^{-1})
κ_{gtu}/Λ	< 0.037 TeV^{-1}	< 0.025 TeV^{-1}
κ_{gtc}/Λ	< 0.15 TeV^{-1}	< 0.105 TeV^{-1}

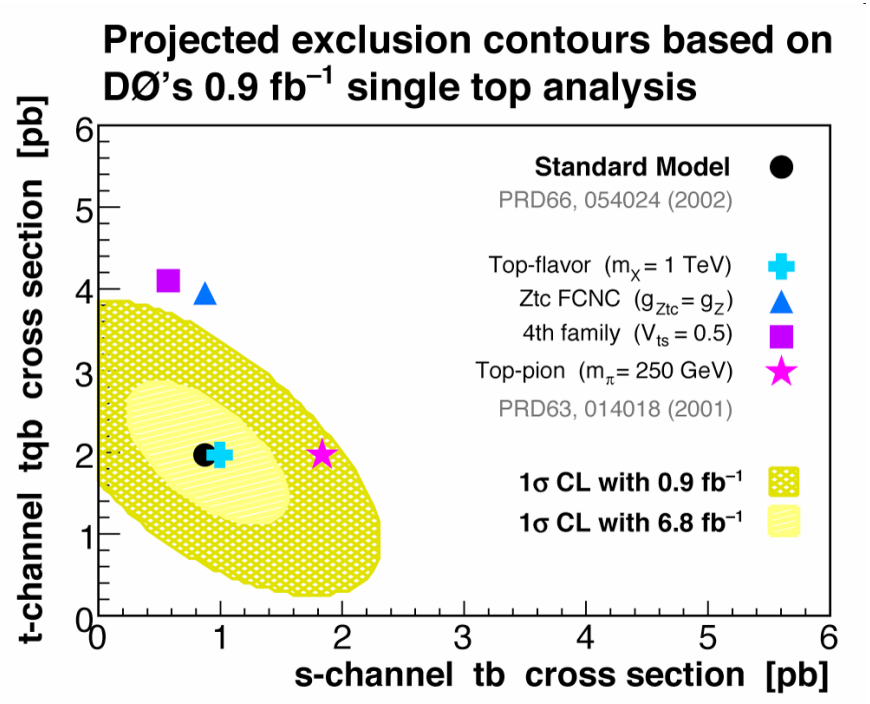
- Limits are significantly better than 0.4 TeV^{-1} derived from HERA data (hep-ph/0604119)

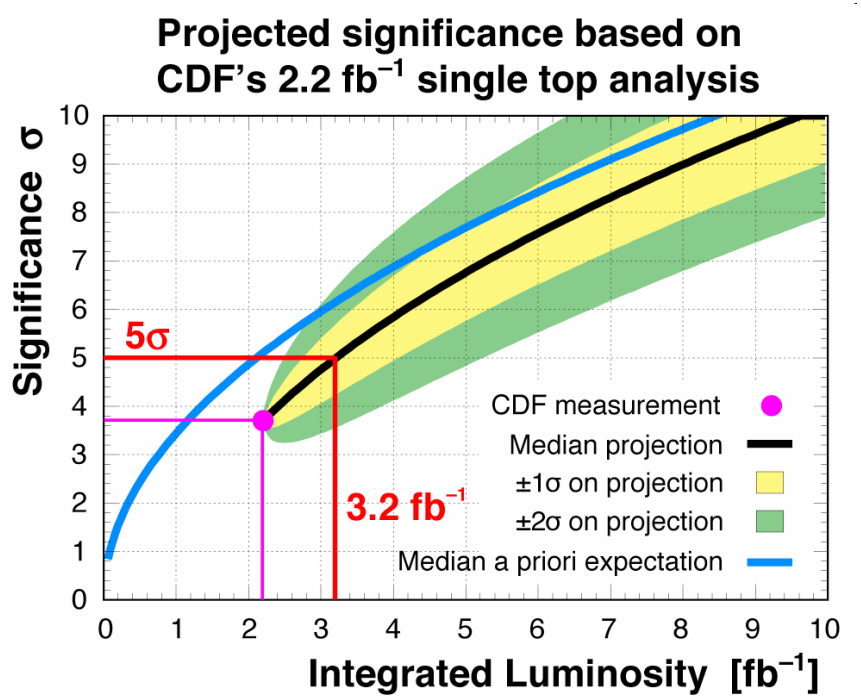
Summary

- **In December 2006, more than 10 years after the top quark was discovered, DØ presented first evidence for electroweak single top production**
  - **CDF has since also presented evidence for single top**
- **Since then, a lot of use has been made of this interesting SM process**
  - **Combined s+t cross-section measurements with significance 3.7σ (CDF), 3.6σ (DØ)**
  - **Recent CDF preliminary result with larger dataset has 5.0σ expected significance for most sensitive analysis (3.8σ observed significance)**
  - **First direct measurements of V_{tb}, with $|V_{tb}| > 0.68$ (DØ), $|V_{tb}| > 0.66$ (CDF)**
  - **Limits on anomalous Wtb couplings**
  - **Limits on heavy W' and H^+ bosons decaying to tb**
  - **Limits on FCNC couplings of the top quark**

Outlook

- **Significant improvements are still coming, using the larger Tevatron data sets**
  - **Most public single top results so far based on 0.9 fb^{-1} (DØ) and 2.2-2.7 fb^{-1} (CDF)**
  - **>5 fb^{-1} delivered so far, with ~8 fb^{-1} expected per expt before the end of running**





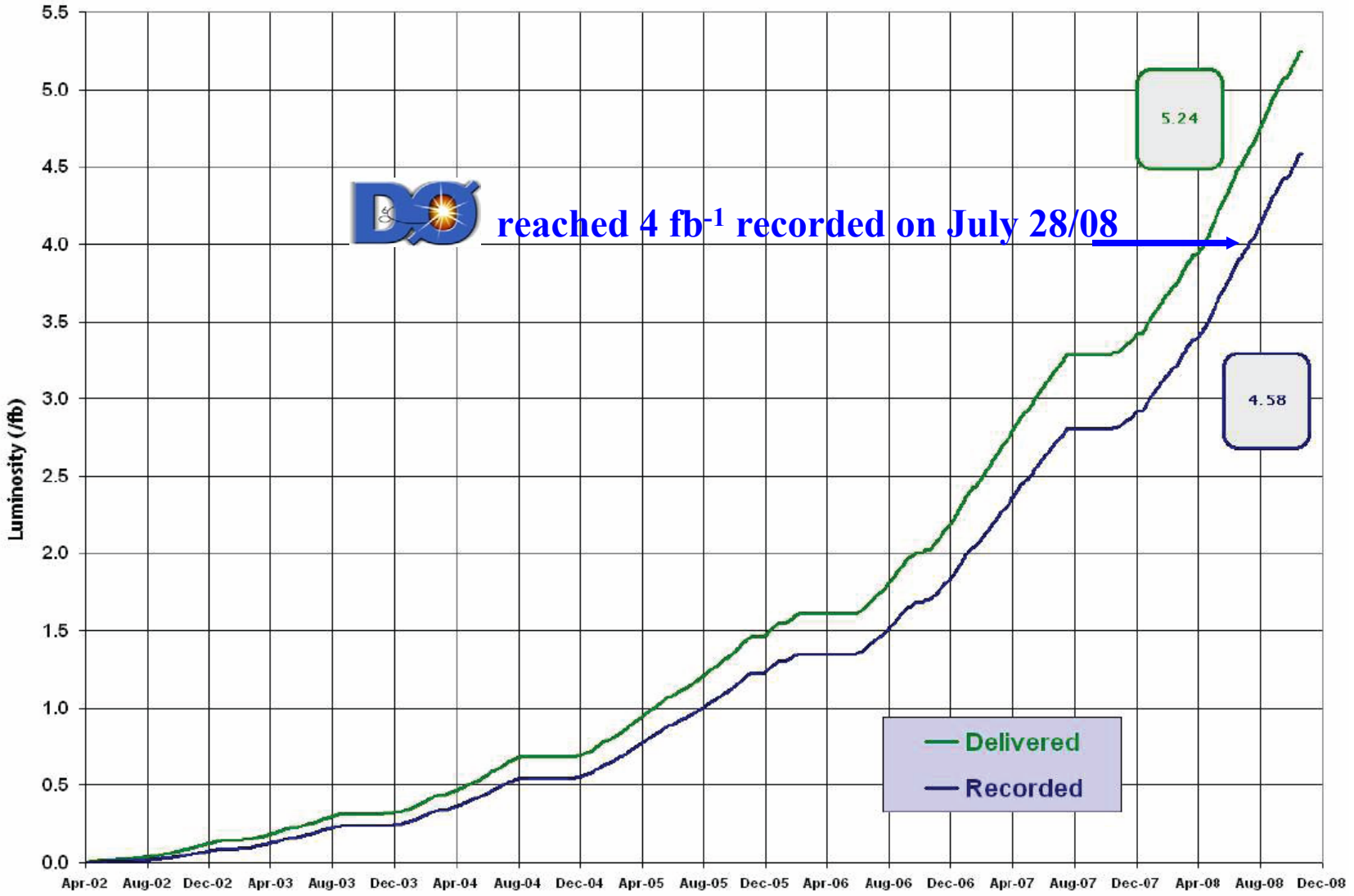
- **Single top studies will continue to yield interesting new physics sensitivity at the Tevatron, and the high statistics make single top very promising at the LHC**

Backup Slides

Bibliography of Single Top Results

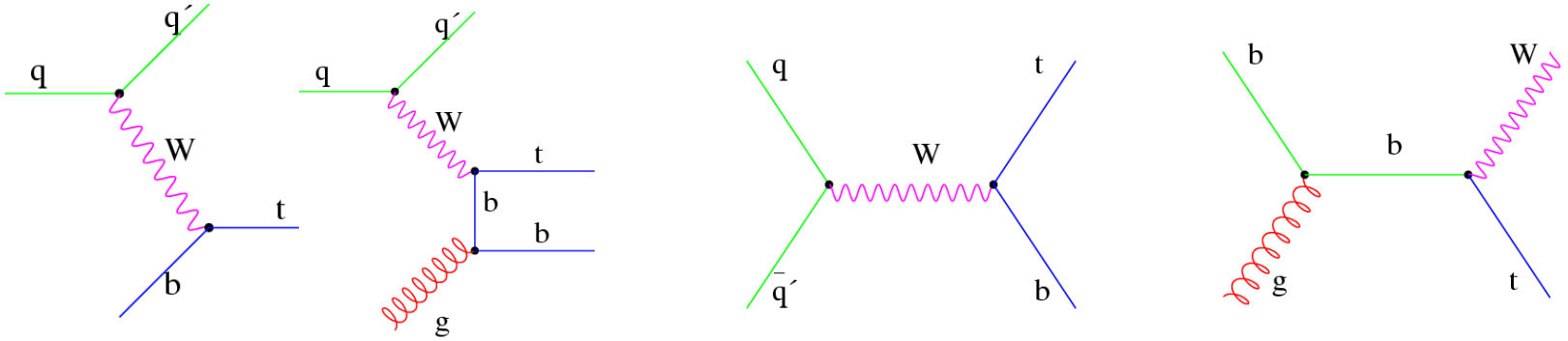
- **DØ**
  - **Evidence for single top and first direct measurement of V_{tb}** — PRL 98, 181802 (2007), PRD 78, 012005 (2008)
  - **Search for anomalous Wtb couplings** — PRL 101, 221801 (2008)
  - **Search for W'** — PRL 101, 221801 (2008)
  - **Search for FCNC** — PRL 99, 191802 (2007)
  - **Search for H^+** — arXiv:0807.0859 (submitted to PRL)
- **CDF**
  - **Measurement of single top cross-section, V_{tb}** — arXiv:0809.2581 (accepted by PRL)
  - **Updated (2.7 fb^{-1}) cross-section** — Conference note (Summer 08)
  - **Search for FCNC** — Conference notes (Winter 07, Winter 08)
  - **Search for W'** — Conference notes (Summer 08)

Tevatron Run II Integrated Luminosity



Single Top Quark Production at the LHC

- **At LHC, need to consider all 3 separate production processes:**



W-gluon fusion (250 pb) W* (s-channel) (10 pb) Wt (60 pb)

$\Rightarrow$ **total LHC single top cross-section > 300 pb !!**

- **Studies have shown that it should be possible to measure each process separately (s-channel will be particularly challenging)**

Summary of Systematic Uncertainties

Source of Uncertainty	Rate	Shape
Jet Energy Scale	0...16%	✓
Initial State Radiation	0...11%	✓
Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓
Non-W Normaliztion	40%	
Non-W Flavor Model		✓

Also:
MC Stats
in each
bin
independently

ISR & FSR
treated as
correlated