Single Top Quark Production at the Tevatron

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On behalf of the CDF and DØ Collaborations

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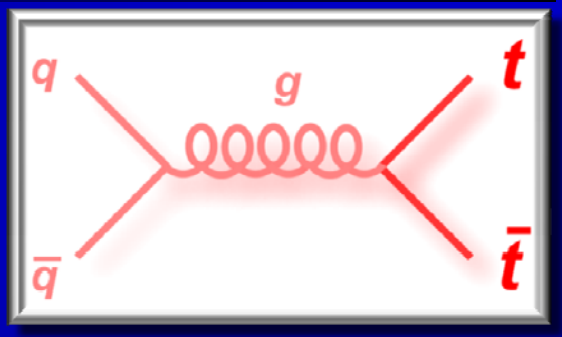
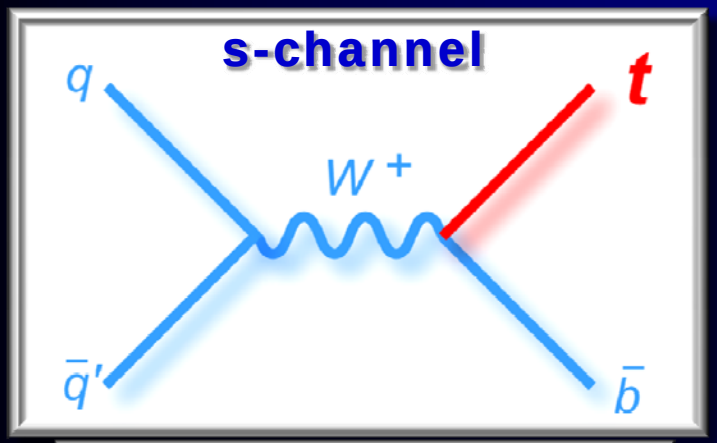
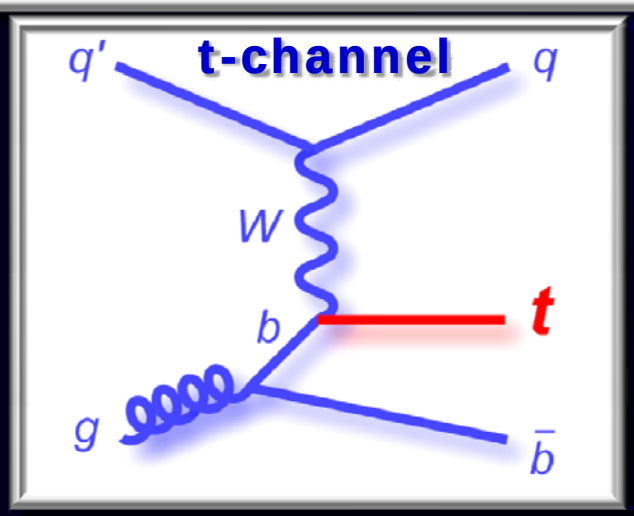
Single Top Production

- Top quarks are most commonly produced in pairs through the strong interaction.
  - $\sigma(t\bar{t}) = 7.46^{+0.48}_{-0.67}$ pb @ m_t=172.5 GeV/c^2
    Moch, Uwer: PRD 78, 034003 (2008)



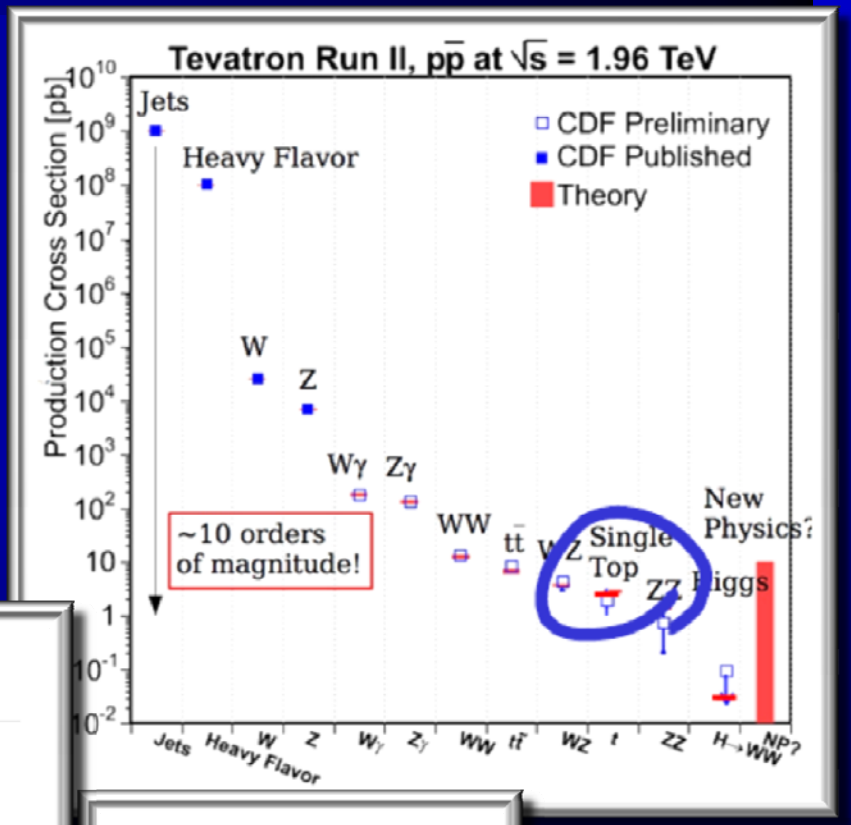


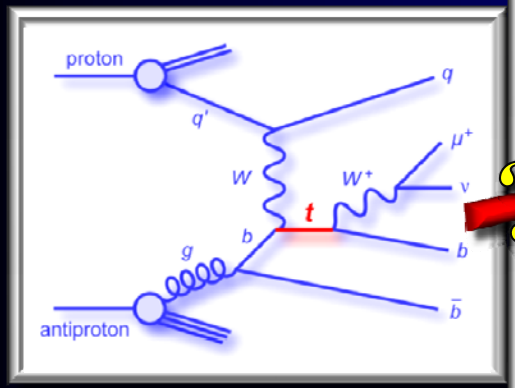


- EW processes can produce single top quarks in association with b quarks.
  - s-channel: σ = 1.12±0.05 pb
  - t-channel: σ = 2.34±0.13 pb
    @ m_t=170 GeV/c^2, Kidonakis PRD **74**, 114012 (2006)
- SM measurements
  - CKM: $|V_{tb}|$
  - top width and polarization…
    - Width: Grohsjean, TRK02, 7/23 11:25
- New Physics
  - Anomalous couplings, FCNC
    - Anomalous couplings: Sharyy, TRK02, 7/23 9:20
  - Resonance searches (W', H^+)
    - W': Scodellaro, TRK10, 7/24 15:20

Why It's Been So Hard To Find

- Single *t* production predicted 10 years before *t* discovered in pair production, but no evidence until 12 years after!
- Half the cross section of $t\bar{t}$, but much more difficult background situation.
  - S:B after event selection 1:20 for Single *t*
    5:1 for $t\bar{t}$
  - Backgrounds:
    QCD, W+jets, Z+jets, Diboson, $t\bar{t}$





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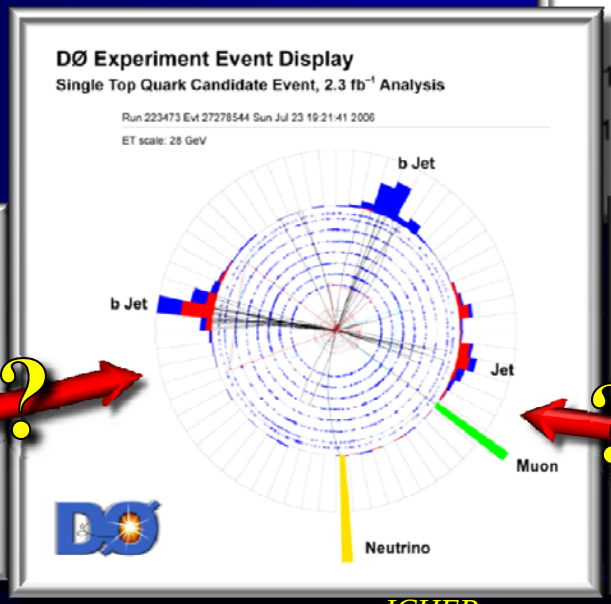

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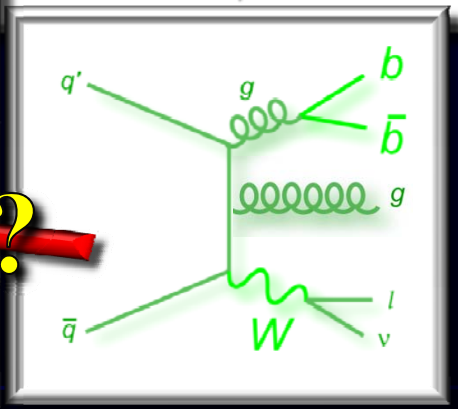
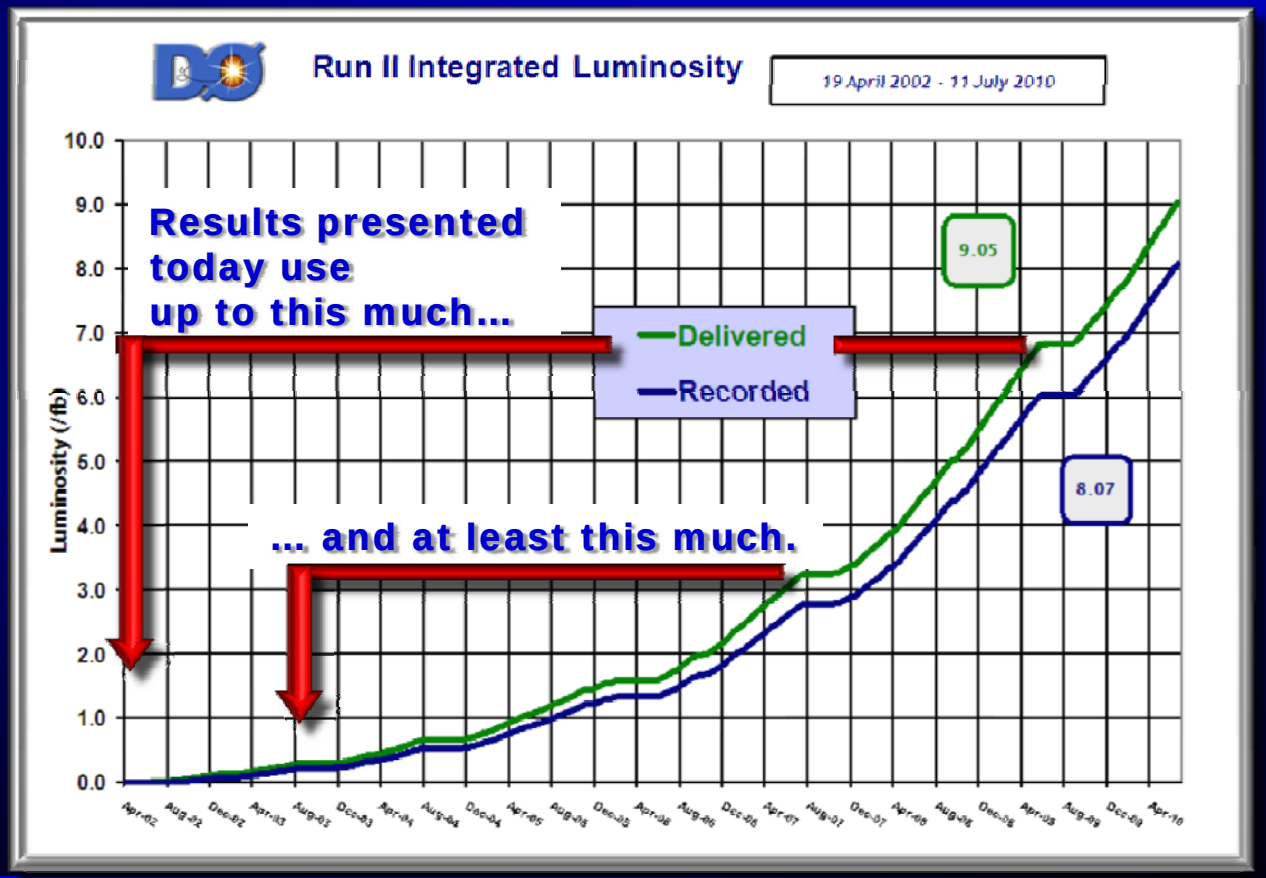


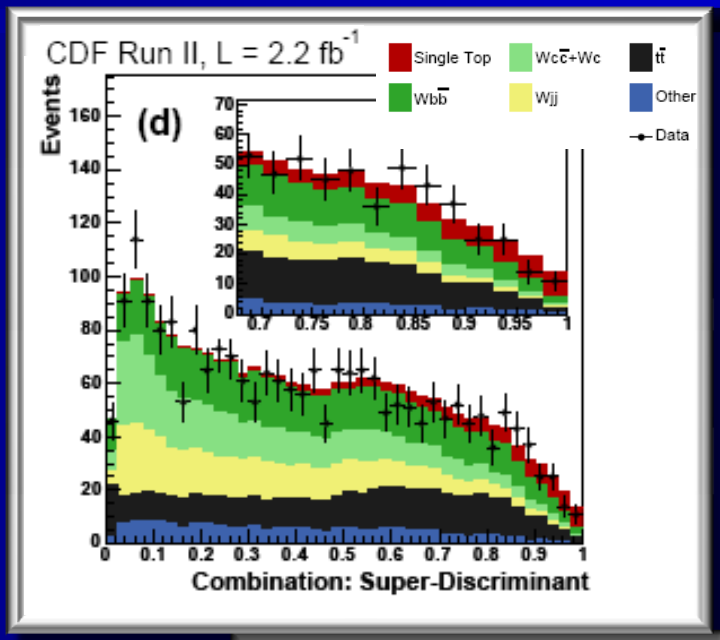
The Data

- **2002-2005**
  - Lower instantaneous luminosities (typical peak ~1E32)
  - ~1.5 fb^{-1} integrated luminosity delivered
- **2006-2010**
  - Higher instantaneous luminosities (typical peak ~3E32)
  - Upgraded detectors
  - ~7.5 fb^{-1} delivered
  - All results described in this talk have been published within the past year, and are based on 2.3-4.8 fb^{-1} of 'good' data.



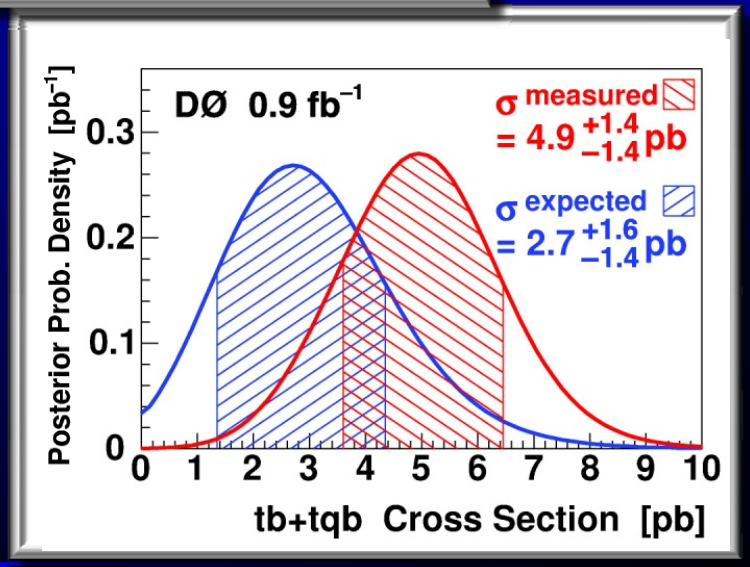
Results Prior to 8/09

- **Evidence, DØ & CDF**
  - DØ: $\sigma = 4.9 \pm 1.4$ pb
    - 3.6 σ, 0.9 fb $^{-1}$
    - PRL **98**, 181802 (2007)
  - CDF: $\sigma = 2.2^{+0.7}_{-0.6}$ pb
    - 3.7 σ, 2.2 fb^{-1}
    - PRL **101**, 252001 (2007)



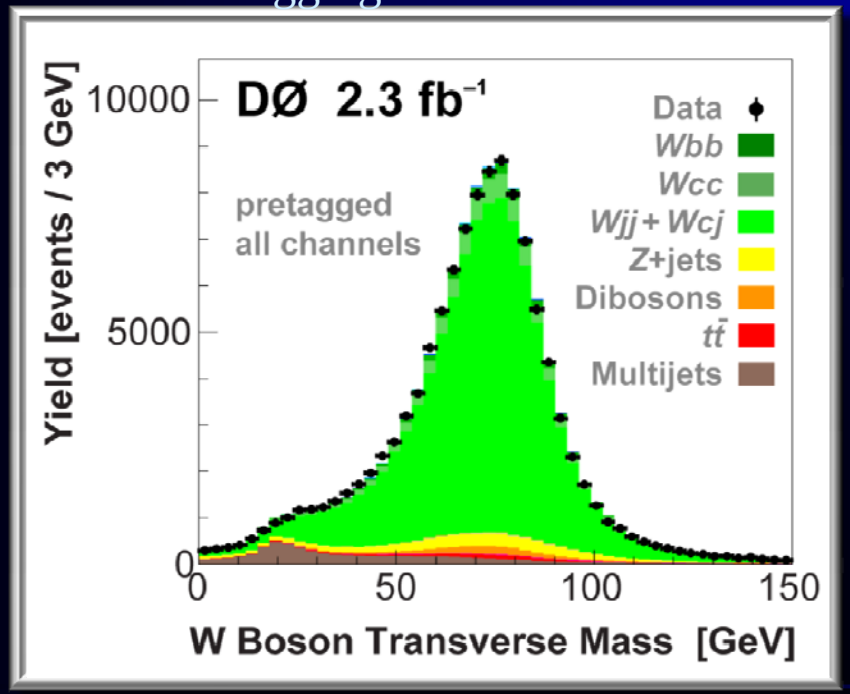
- **FCNC Production, DØ & CDF**
  - Search for $u(c) + g \rightarrow t$ processes
  - CDF: $\sigma < 1.8$ pb PRL **102**, 151801 (2008)
    - $\kappa_{tug}/\Lambda < 0.018$ TeV^{-1}, $\kappa_{tcg}/\Lambda < 0.069$ TeV^{-1}

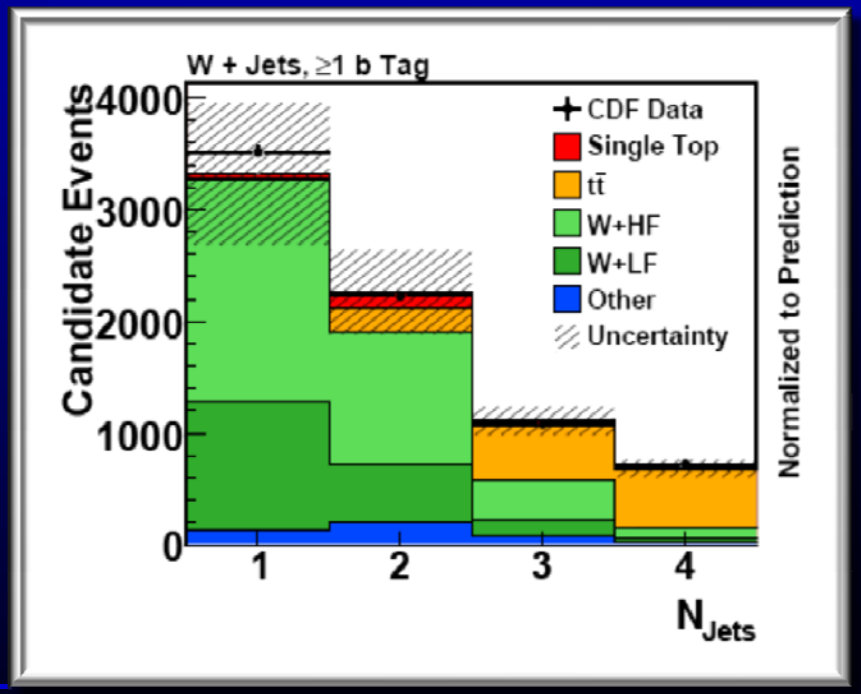
- **Anomalous Wtb Couplings, DØ**
- **Resonance searches, DØ & CDF**



Modeling and BG Normalization

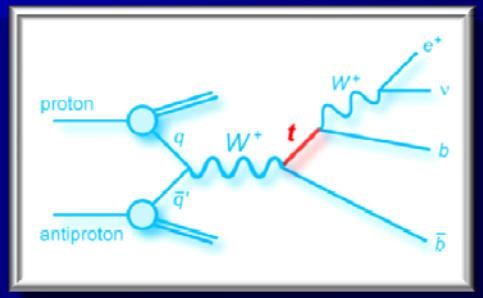
- Signal is modeled using SINGLETOP (DØ) and MADEVENT (CDF).
- Most backgrounds modeled using ALPGEN, with PYTHIA parton hadronization. W+Heavy Flavor jets are underestimated , so are scaled up by a factor of ~1.4, which is obtained from data/MC comparisons.
- QCD background is obtained from data, using orthogonal samples (non-isolated leptons for DØ, extrapolation from low missing transverse energy for CDF).
- W+jets and QCD are normalized to data, all others to SM NNLO cross sections before b-tagging.

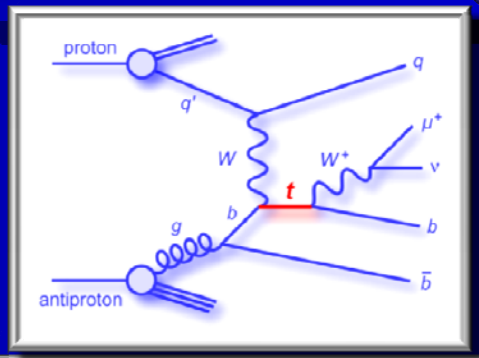


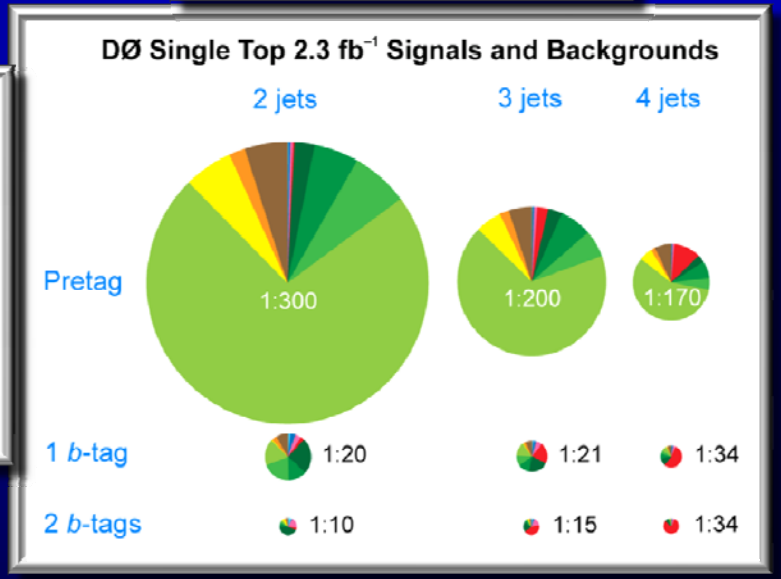


Event Selection

- **Lepton + jets selection**
  - 2 or 3 (or 4 for DØ) jets
  - 1 or 2 jets *b*-tagged
  - High p_T isolated e or μ
  - Large missing transverse energy, $\not\!\!E_T$
- **Still big background problem**
  - S:B ~1:20, Signal acceptance ~3%
  - Need multivariate analysis (MVA) techniques to discriminate







Event Yields	DØ 2.3 fb^{-1}	CDF 3.2 fb^{-1}
	Lepton+$\not\!\!E_T$+jets / *b*-tagged	
tb + *tqb* signal *1,*2	223 ± 30	191 ± 28
W+jets	2,647 ± 241	2,204 ± 542
Z+jets, dibosons	340 ± 61	171 ± 15
$t\bar{t}$ pairs *1,*2, *3	1,142 ± 168	686 ± 99
Multijets	300 ± 52	125 ± 50
Total prediction	4,652 ± 352	3,377 ± 505
Data	4,519	3,315

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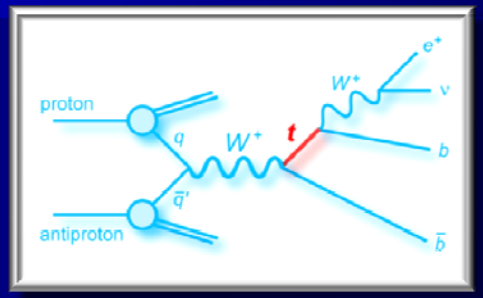

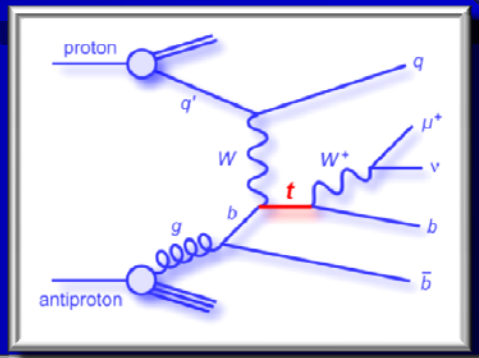

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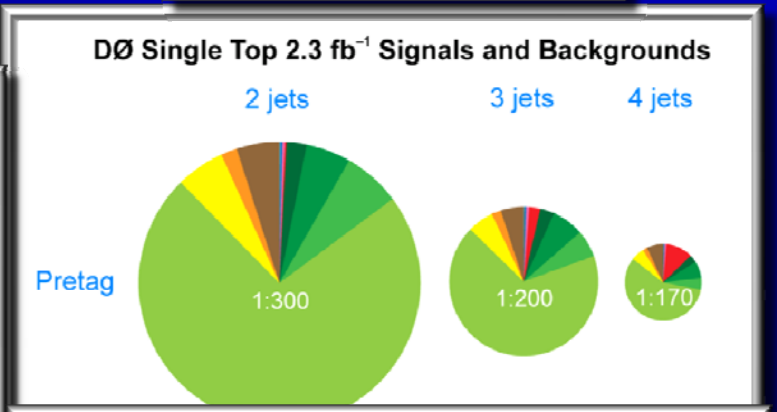
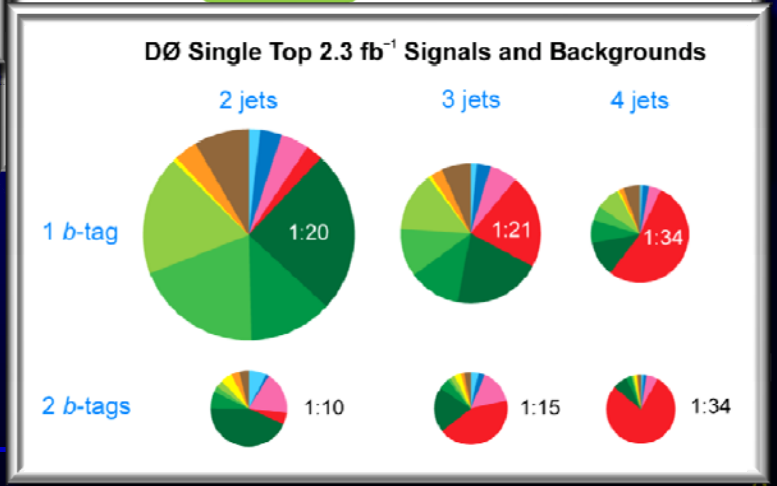




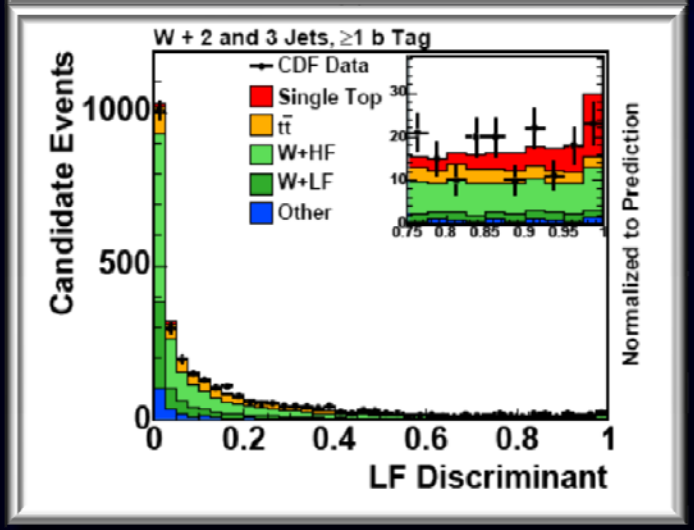
Multivariate Methods

- Combine the modest discriminating power of many separate variables into one very effective discriminant.
- Data is separated into several individual analysis channels based on N_{jet}, $N_{b\text{-}tag}$, and lepton type (DØ only). MVAs are performed on each channel separately, then combined.

Likelihood Functions (CDF only)

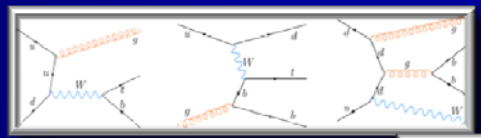
- Combine 7-10 variables into a single likelihood function

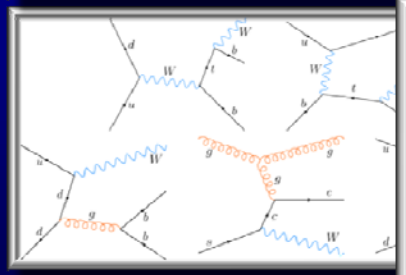
$$L = \frac{\Pi_{i=1}^{nvar} p_i^{sig}(x_i)}{\Pi_{i=1}^{nvar} p_i^{sig}(x_i) + \Pi_{i=1}^{nvar} p_i^{bkg}(x_i)}$$



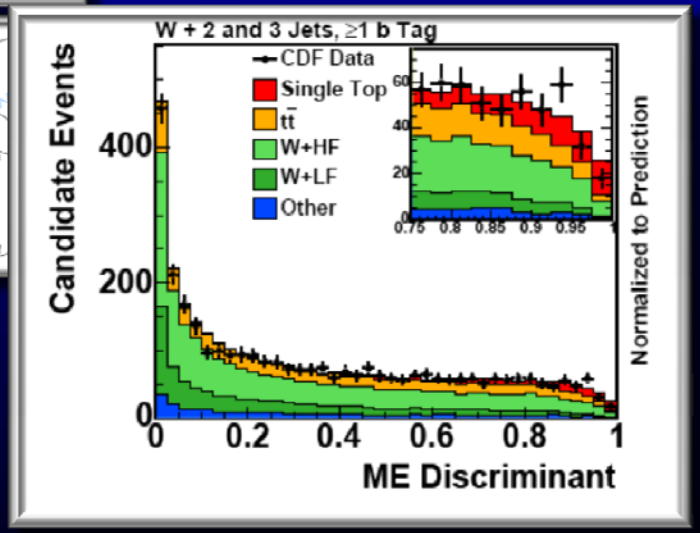
Matrix Elements

- Using full event kinematics from reconstructed 4-momenta, calculate probability for S and B hypotheses





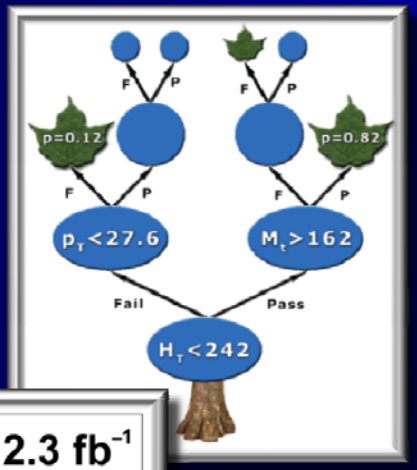
- Include all parton level matrix elements



Multivariate Methods

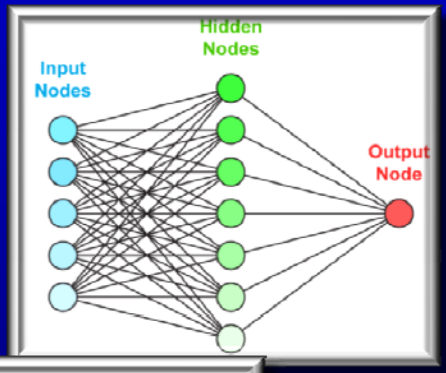
Boosted Decision Trees

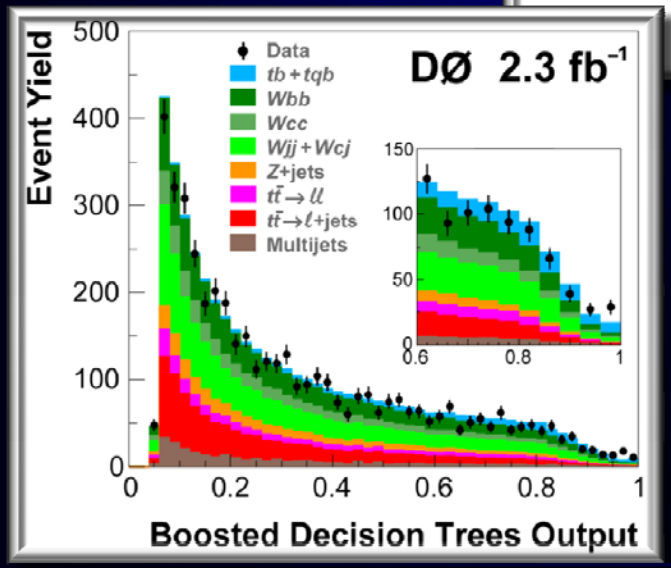
- Sequence of binary split cuts for S/B separation
- Pass or fail, events continue to be analyzed, terminating in leaf nodes classified as S or B based on signal purity
- Boosting: performance and stability improved by averaging over many trees
- Many variables (DØ: 64, CDF: 20), adding more does not degrade performance

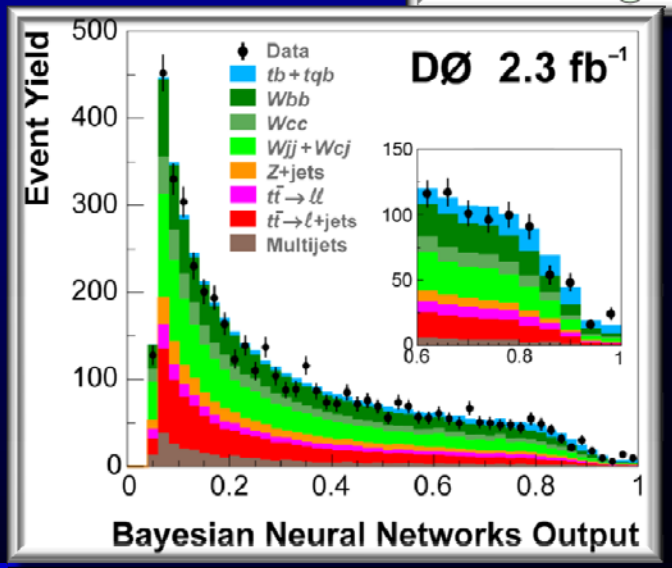


Neural Networks

- Combine variables using node-to-node weights and thresholds
- Fewer variables (DØ: 18-28, CDF: 11-18), adding too many degrades performance
- DØ: Bayesian NN – average over many NN, avoid overtraining
- CDF: NeuroBayes – incl. jet flavor separation





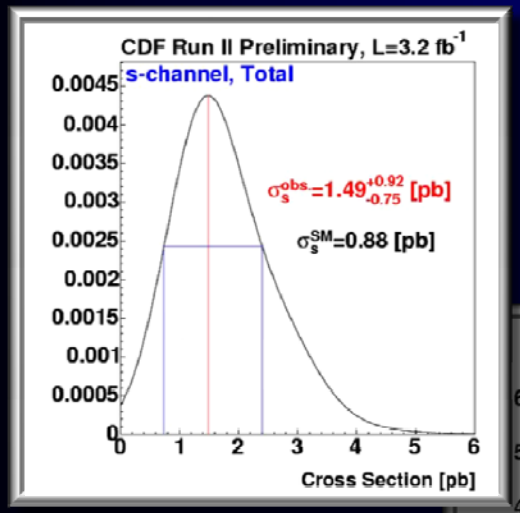


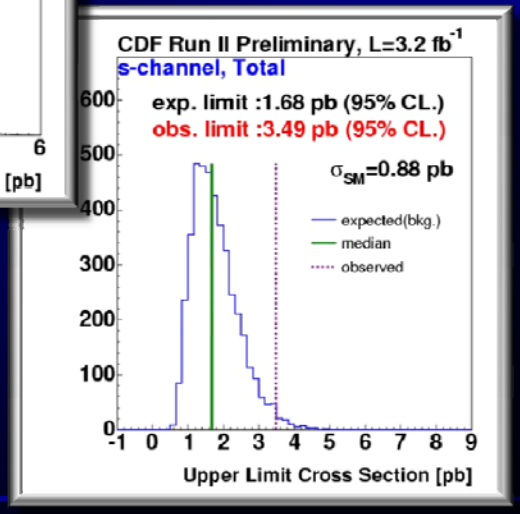
Other Methods (CDF)

Separate s-channel search

- s-channel sensitive to W', H^+
- Likelihood function analysis optimized for s-channel only in lepton+jets
- Double *b*-tagged events only
  - $\sigma_s < 3.49$ pb at 95% CL

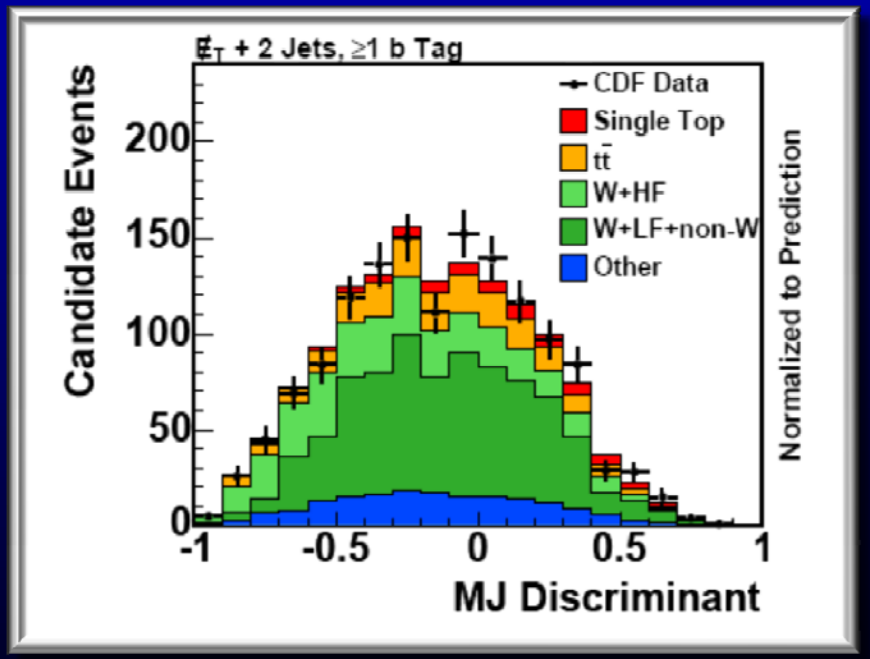
CDF Conf. Note 9712





$\not\!\!E_T$ + Jets

- Performed on a sample orthogonal to lepton+jets, with un-reconstructed leptons
- Recover hadronic taus from W decay
- Neural net based
- Combined with 3.2 fb^{-1} lepton+jets analyses
  - PRD **81**, 072003 (2010)



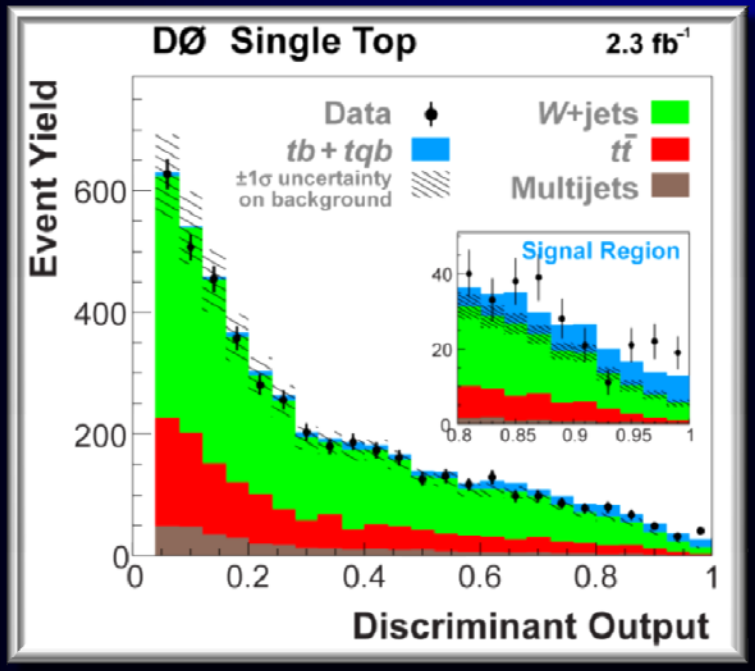
Combinations

Combine the separate MVAs into one, more powerful discriminant

- Individual analyses are ~60-90% correlated

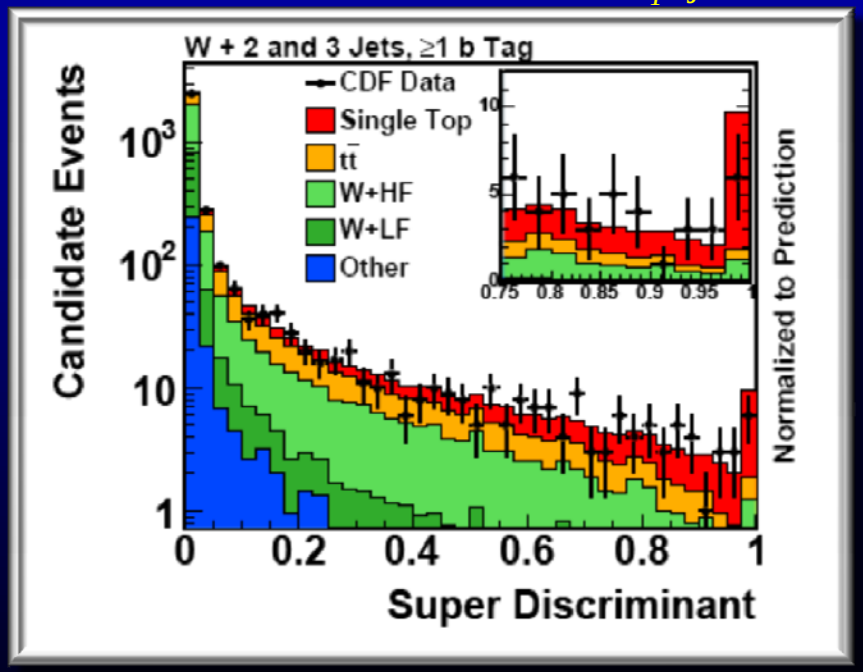
DØ: Bayesian Neural Network

- Similar to individual BNN analysis, but with the three MVA results as inputs
- Cross-checked with BLUE (Best Linear Unbiased Estimator)

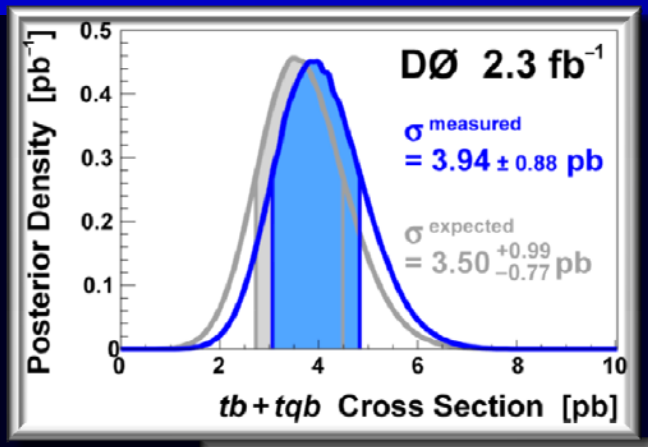


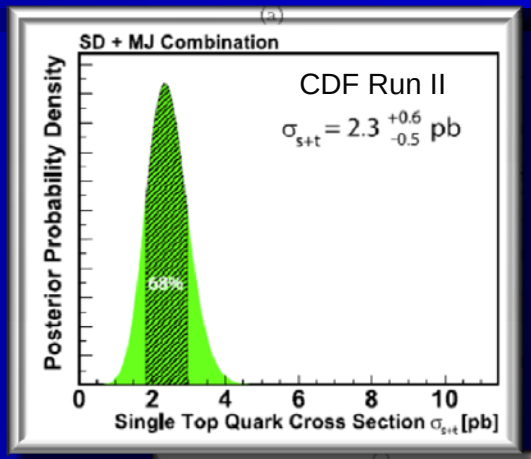
CDF: NeuroEvolution of Augmenting Topologies (NEAT)

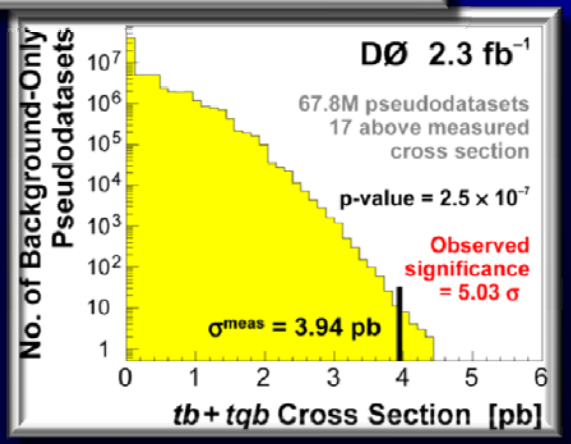
- Competition of NNs that includes binning, systematics, etc. using 5 lepton+jets inputs
- Choose the NN that optimizes expected p-value
- Then do simultaneous fit with $\not\!\!E_T$+jets

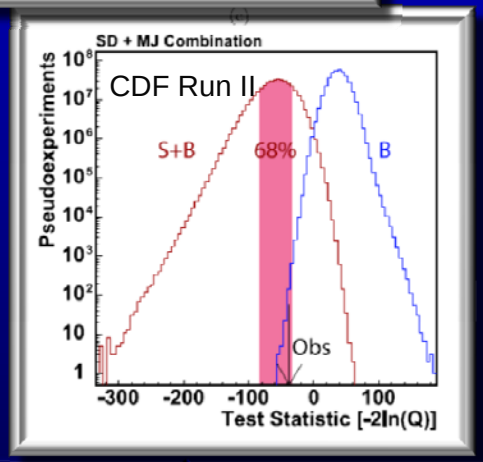


Observation!









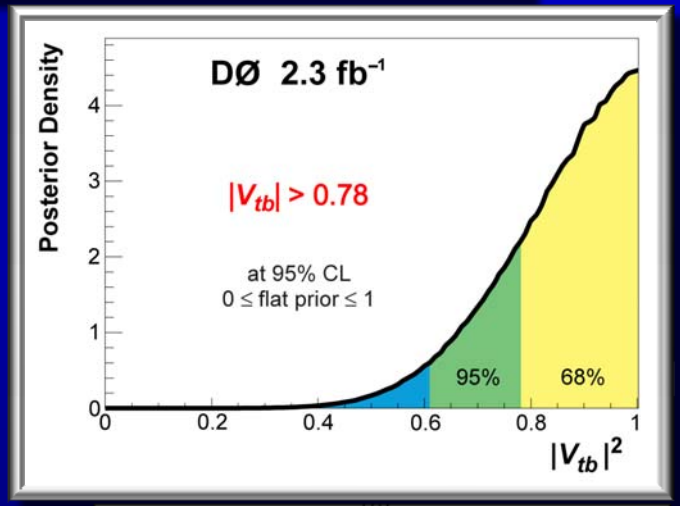
	Lumi (fb^{-1})	Cross Section (pb)	Expected Significance	Observed Significance	Publication
DØ	2.3	3.94±0.88	4.5σ	5.0σ	PRL 103, 092001 (2009)
CDF	3.2	$2.3^{+0.6}_{-0.5}$	5.9σ	5.0σ	PRL 103, 092002 (2009)

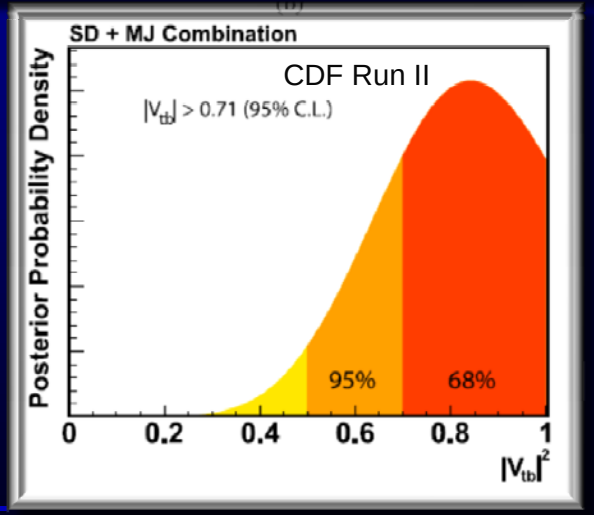
V_{tb} Extraction

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

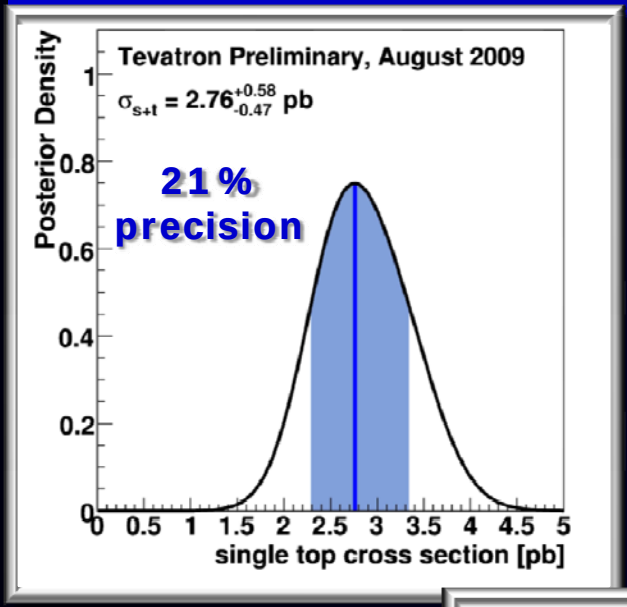
- $|V_{tb}|^2 \alpha \sigma(s+t)_{meas} / \sigma(s+t)_{SM}$
- Need to make some assumptions:
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
  - Pure V-A, CP conserving interaction: $f_1^R = f_2^L = f_2^R = 0$
- Does not assume 3 generations or CKM unitarity

$\|V_{tb}\|$	Measurement	Lower Limit ($0 \le \|V_{tb}\|^2 \le 1$)
DØ	1.07±0.12	0.78
CDF	0.91±0.13	0.71



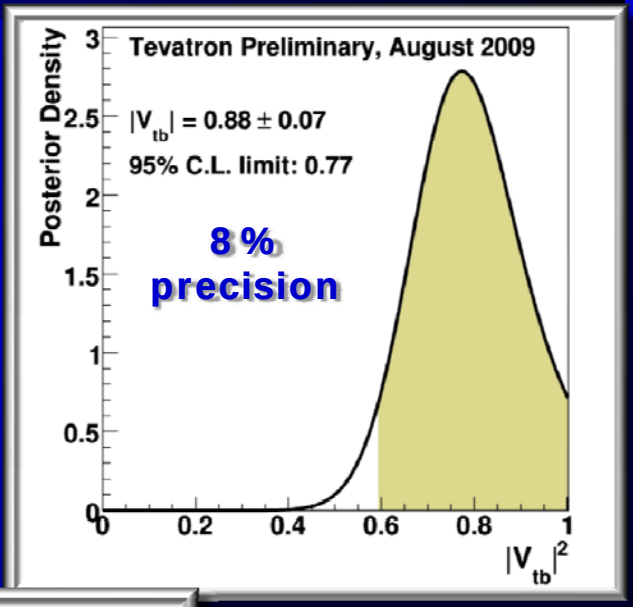


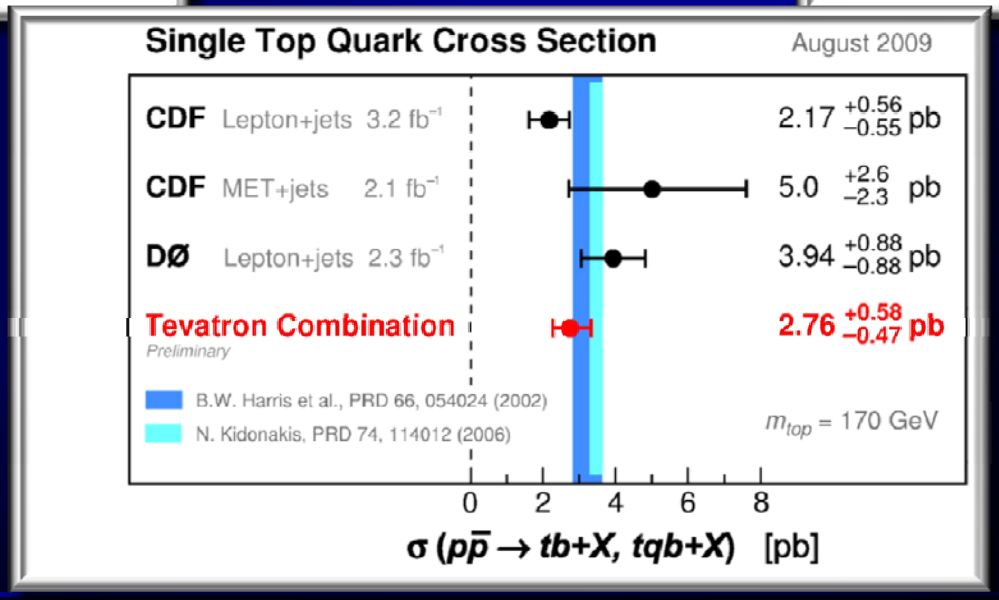
Tevatron Combination



- Bayesian analysis using discriminants from all 9 DØ and CDF MVA outputs.
- Compatible with SM
  - Compatible with each other at 1.6σ

arXiv: 0908.2171

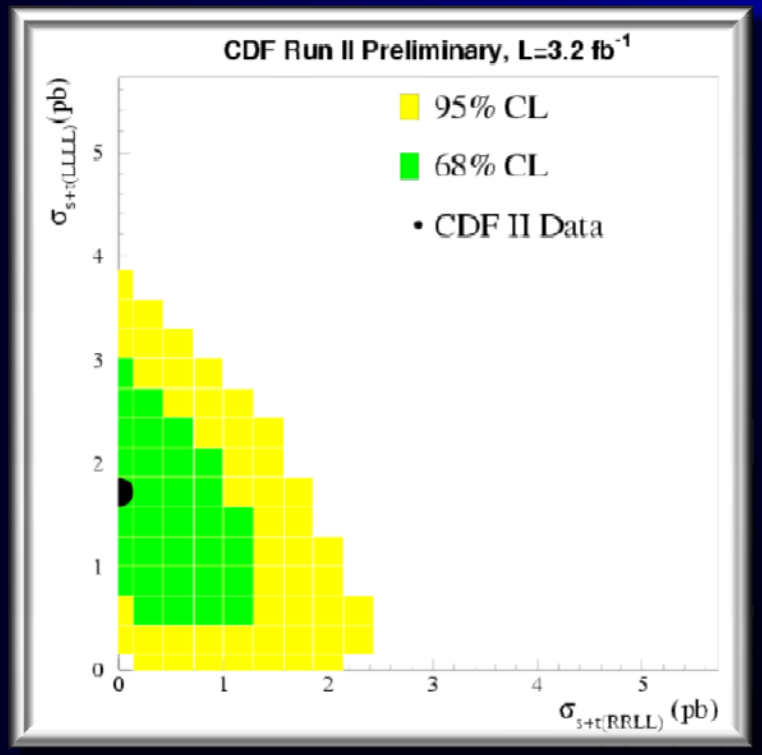


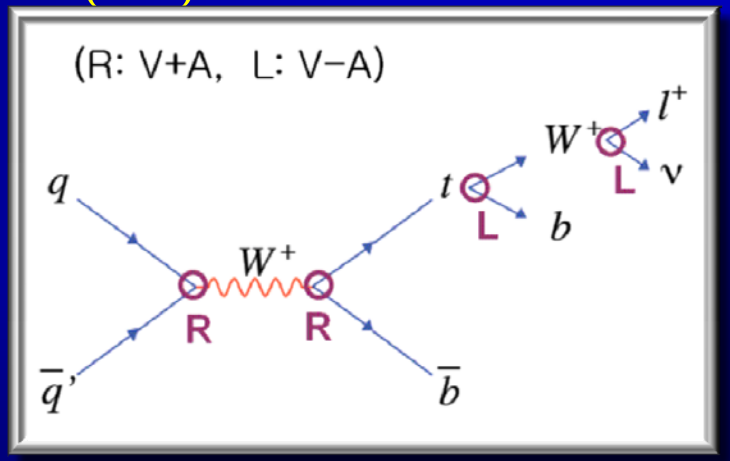


Top Quark Polarization: CDF

- SM single *t* production is almost pure V-A, i.e. 100% left-handed polarization
- Non-SM production can introduce V+A, right-handed couplings
- 2D Likelihood analysis with separate LLLL (SM) and RRLL discriminants

CDF Conf. Note 9920

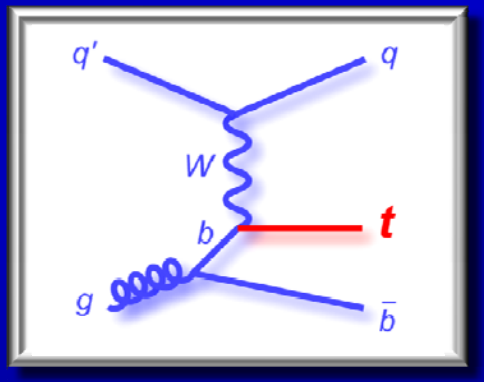




V-A Production	$\sigma_{LLLL} = 1.72$ pb
V+A Production	$\sigma_{RRLL} = 0$ pb
Polarization	$\frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1^{+1.5}_{-0}$

First t-channel Evidence: DØ

- Sensitive to FCNC, anomalous couplings
- Train the MVAs to select t-channel events only
- Measure s- and t-channel cross sections simultaneously
  - s/t is not constrained to SM value



	σ (pb)	Exp. Sig.	Obs. Sig.
t-channel	**3.1±0.9**	**3.7σ**	**4.8σ**
s-channel	**1.0±0.8**		

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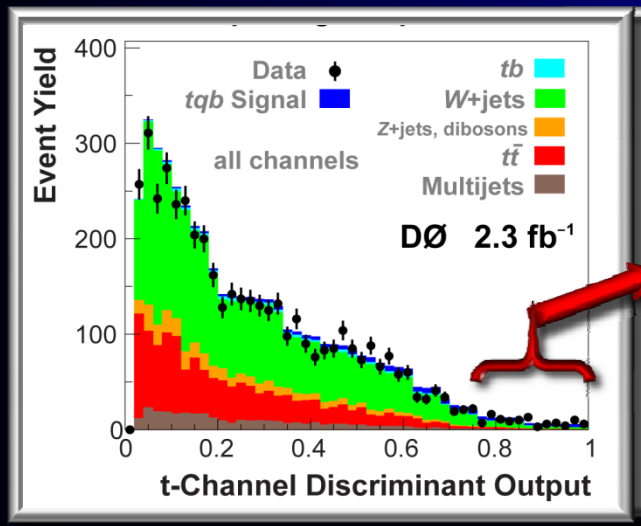

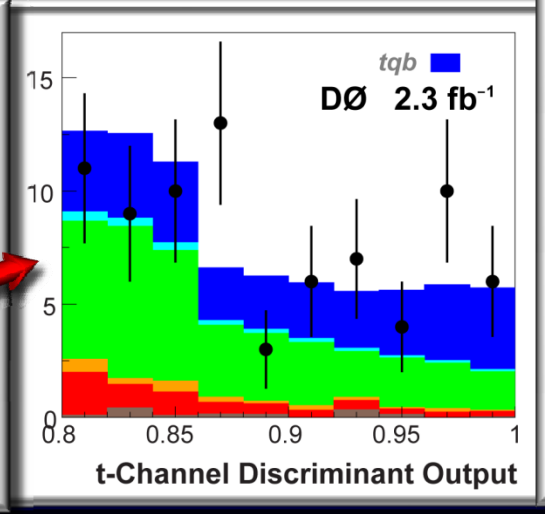

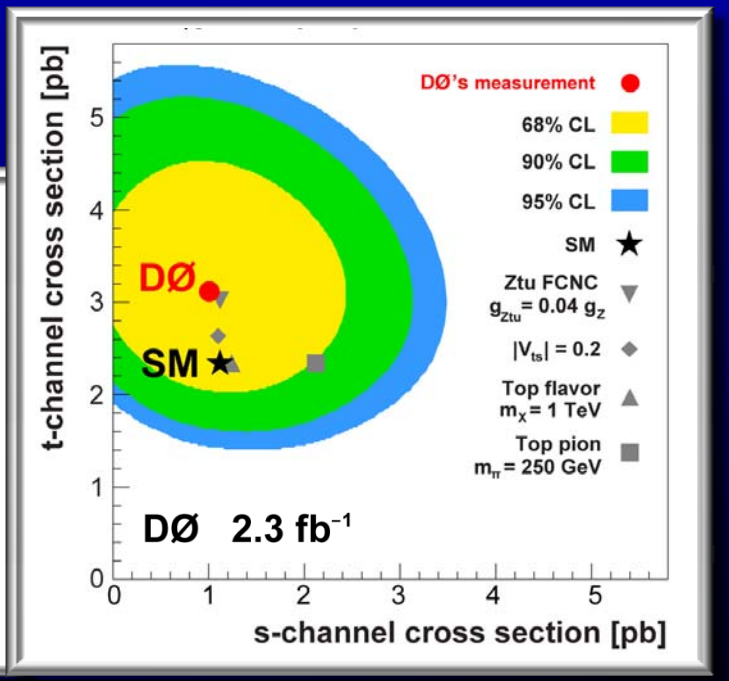

τ +jets: DØ

- Reconstruct hadronically decaying taus
  - 1 and 3 prong, with and without π^0s
- Use Boosted Decision Trees for tau ID
- Use Boosted Decision Trees for signal discrimination
  - 44-70 variables

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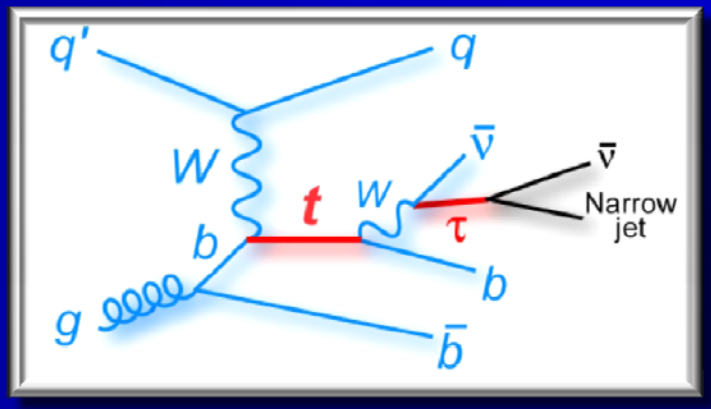
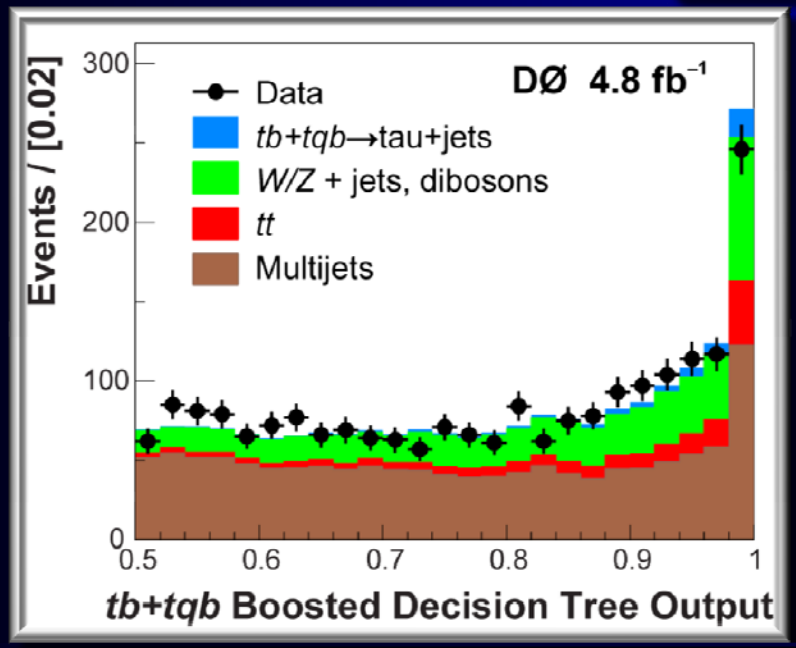
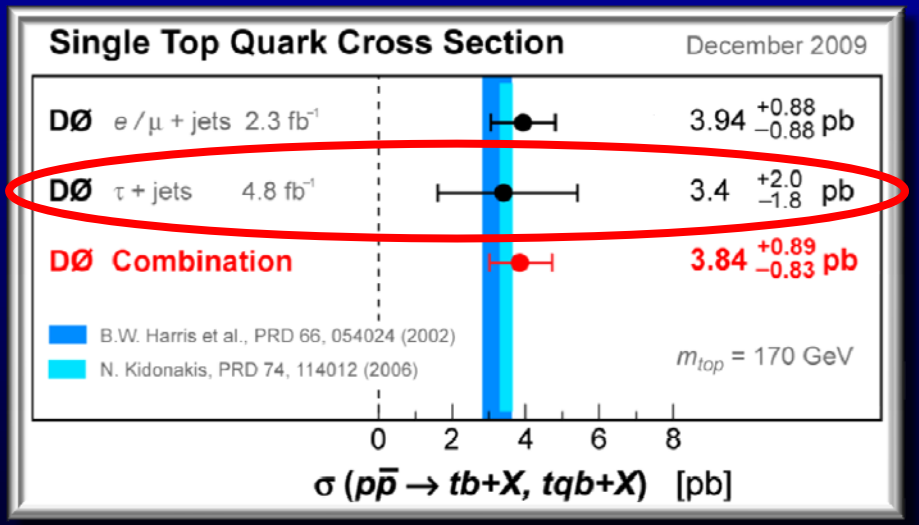
Published 6/7/10!





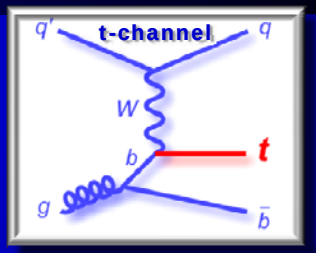


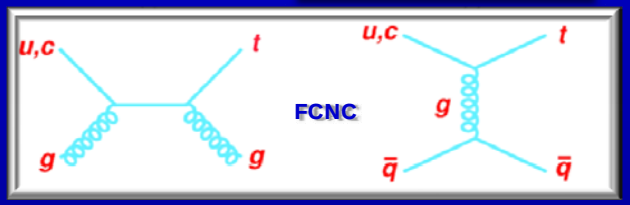
Gluon FCNC Production: DØ

- Gluon mediated flavor-changing neutral currents can produce single *t*
- Negligible in SM, large in BSM (SUSY, composite,…)
- Topology similar to EW t-channel production
  - Same selection except require one and only one *b*-tag
- BNN analysis

  arXiv: 1006.3575

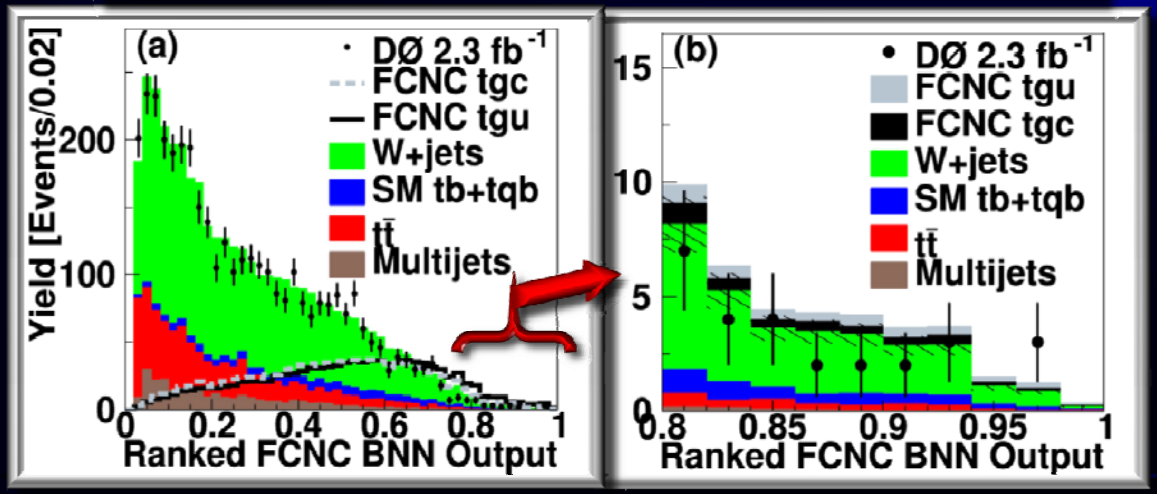
Submitted to PLB 6/18/10!

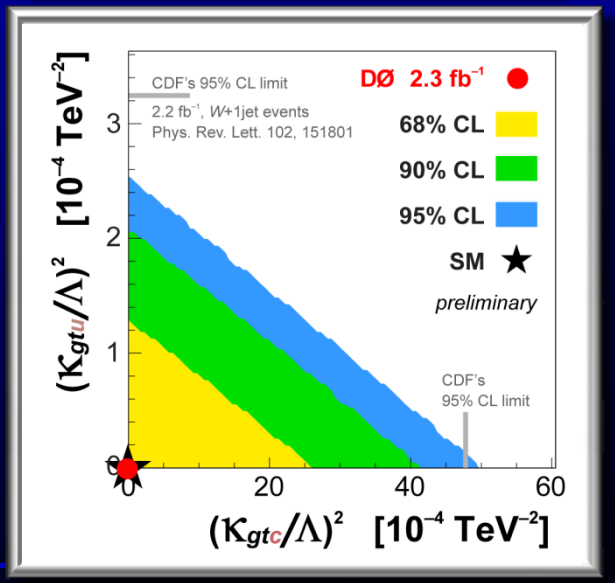




$$\mathcal{L}_{\mathrm{FCNC}} = \frac{\kappa_{tgf}}{\Lambda} g_s \bar{f} \sigma^{\mu\nu} \frac{\lambda^a}{2} t G^a_{\mu\nu},$$

	σ_{tgf} (pb)	κ_{tgf}/Λ (TeV^{-1})	$\mathcal{B}(t\to qg)$
tgu	0.2	0.013	2.0×10^{-4}
tgc	0.27	0.057	3.9×10^{-3}





Summary

- **The study of single top quark physics at the Tevatron has been extremely rich and productive.**
- **In the past year, we've published**
  - Observation of single top production
  - Evidence for t-channel production
  - Top quark polarization
  - New limits on FCNC
  - New W' search (Scodellaro, 7/24 15:20)
  - Top width measurement (Grohsjean, 7/23 11:25)
- **Established single *t* analysis methods now being used to search for Higgs, …**
- **New analyses with more than twice the data *very* soon, 10 fb^{-1} by next year, possibly running 3 more years!**