Single-Top-Quark Physics at Hadron Colliders

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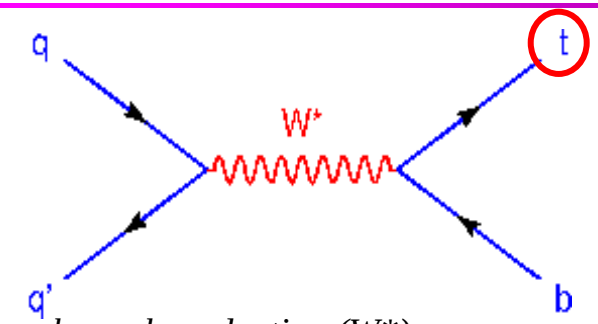
Outline:

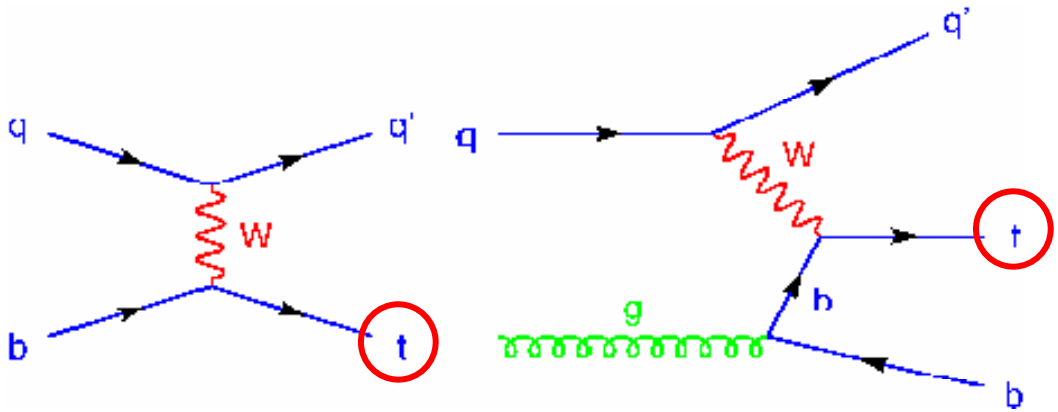
- Introduction
- CDF single-top searches
- D0 single-top searches
- Beyond the SM single-top
- Outlook for the LHC

Single Top Production

- At the Tevatron, top quarks are:
  - Mostly produced in pairs (7pb):
    - qq annihilation (85%)
    - gg fusion (15%)
  - Also electroweak (single-top):
    - s-channel
    - t-channel
    - Wt associated production



s-channel production (W)*



t-channel production (Wg fusion)

$s^{1/2}$ =*1.96TeV*	NLO Cross-sections
t-channel	1.98±0.25 pb
s-channel	0.88±0.11 pb

M_{top} = 175 GeV/c^2

B.W. Harris et al.: Phys. Rev. D 66, 054024, Z. Sullivan hep-ph/0408049

Compatible results: Campbell et al, Phys. Rev. D 70, 094012 (2004).
N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

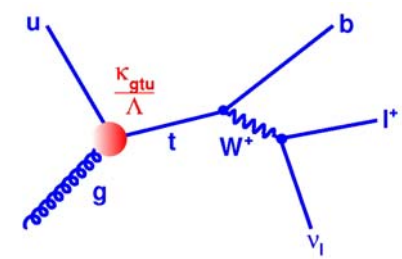
Why Look for Single-Top?

- Predicted by SM – we should observe it:
  - Cross section $\propto |V_{tb}|^2$
  - Test the unitarity of the CKM matrix
    - 4th generation needed?

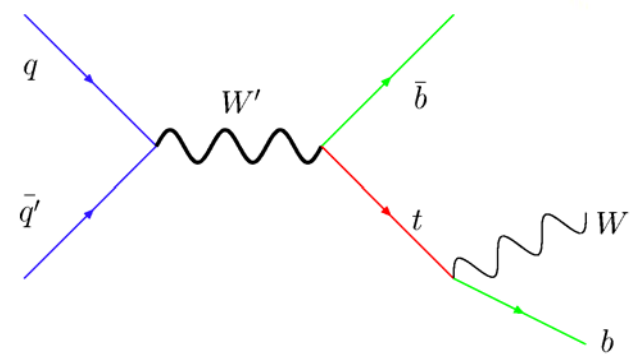
$$V_{ub}^2 + V_{cb}^2 + V_{tb}^2 \stackrel{?}{=} 1$$

  - Source of ~100% polarized top quarks
  - Test of *b* quark structure function: DGLAP evolution

- Prerequisite for an intermediate mass Higgs at the Tevatron
  - *WH* with *H*→*bb* has similar final state
  - Background estimation is crucial

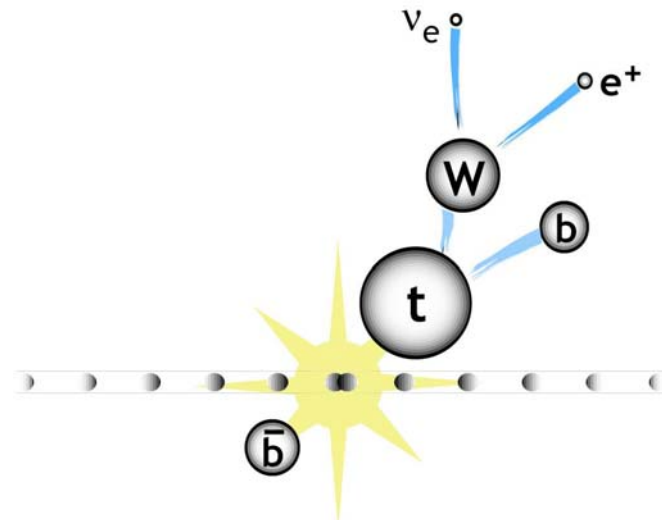


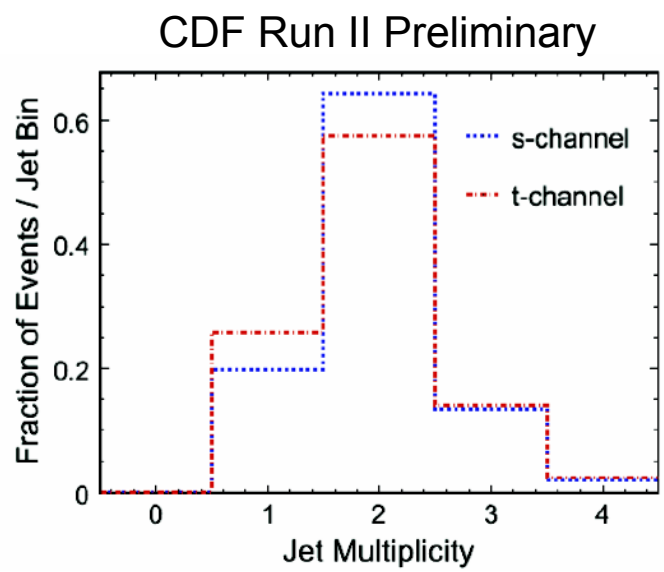
- Test of several new physics phenomena:
  - Flavor-changing neutral currents: *tug*, *Ztc*, etc
  - Heavy *W'* (or charged Higgs) production
  - Anomalous *W-t-b* couplings
  - …



Event Selection

- CDF:
  - 1 lepton with E_T>20 GeV, $|\eta_e|$<2.0, $|\eta_\mu|$<1.0
  - missing transverse energy: MET>25 GeV
  - 2 jets : E_T> 15 GeV, $|\eta|$ < 2.8
  - at least one b-tag (displaced sec. vertex)
  - Acceptance: 1.2% t-chan, 1.8% s-chan
- DØ:
  - 1 electron with E_T>15 GeV, $|\eta_e|$<1,1, or:
  - 1 muon with P_T>18 GeV, $|\eta_\mu|$<2.0
  - missing transverse energy: MET>15 GeV
  - 2, 3, or 4 jets: E_T> 15 GeV, $|\eta|$ < 3.4:
    - Leading jet: P_T>25 GeV, $|\eta_\mu|$<2.5
    - Second leading jet: P_T>20 GeV
  - at least one b-tag
  - Acceptance: 2.1% t-chan, 3.2% s-chan





Event Yield

CDF Predicted event yield with 955 pb^{-1}

t-channel	22.36 ± 3.64
s-channel	15.44 ± 2.23
Single top	37.80 ± 5.87
tt	58.35 ± 13.46
Diboson	13.72 ± 1.85
Z + jets	11.92 ± 4.42
Wbb	170.9 ± 50.7
Wcc	63.5 ± 19.9
Wc	68.6 ± 19.0
Non-*W*	26.2 ± 15.9
Mistags	136.1 ± 19.7
Total background	549.3 ± 95.2
Total prediction	587.1 ± 96.6
Observed	644

Systematic uncertainties

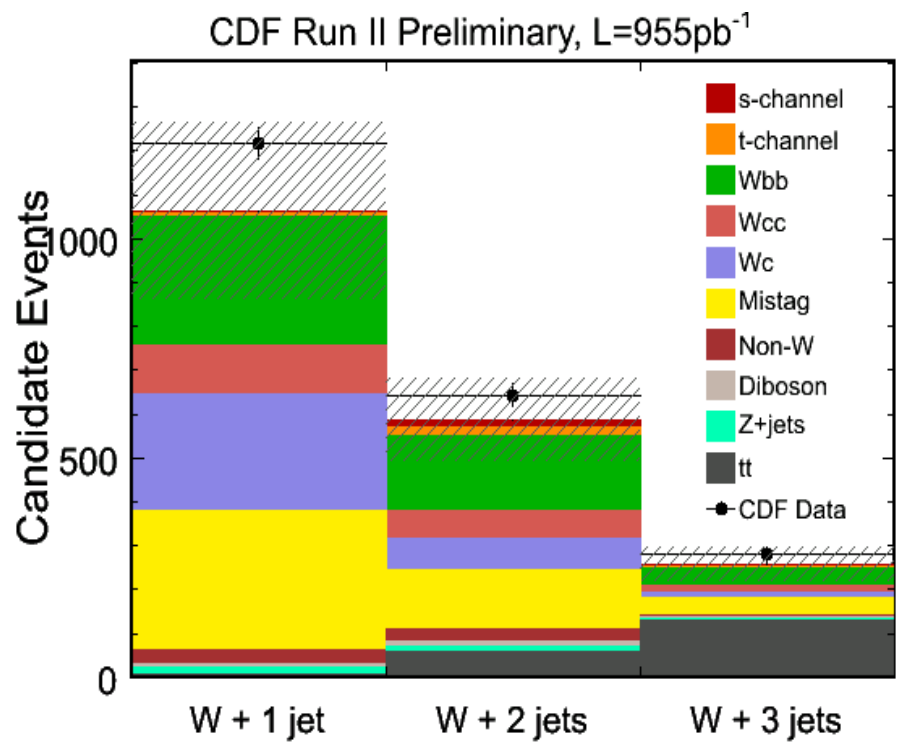
Systematic (-1σ/+1σ)	All single top
Jet energy scale	+1.6% −2.0%
Initial state radiation	+2.0% +0.3%
Final state radiation	+2.6% +1.9%
Parton distribution function	+1.4% −0.4%
Monte Carlo generator	±1.6%
Event detection efficiency	±7.4%
Luminosity	±6%
Total rate uncertainty	±10.5%

Why is it Challenging?

- Small cross section 3 pb – not the main problem!
- Huge backgrounds. In 1 fb^{-1}:
  - $W \to \ell\nu$ + 2 jets — S/B=1/200, S/√B = 0.6
  - $W \to \ell\nu$ + 2 jets +≥1btag: — S/B=1/15, S/ √B = 1.5 (S~40, B~600)
  - *$W \to \ell\nu$ + 2 jets +≥1btag + discrim:* — *S/B=1/3, S/ √B = 2.5*

- Backgrounds:
  - *W*+heavy flavor (*Wbb, Wcc, Wc*)
  - *W*+light flavor (mistags)
  - Diboson, *Z*-decays, non-*W*
  - Top pair production

- Signal MC modeling:
  - Comphep+Pythia (D0) ~NLO
  - MadEvent+Pythia (CDF) ~NLO



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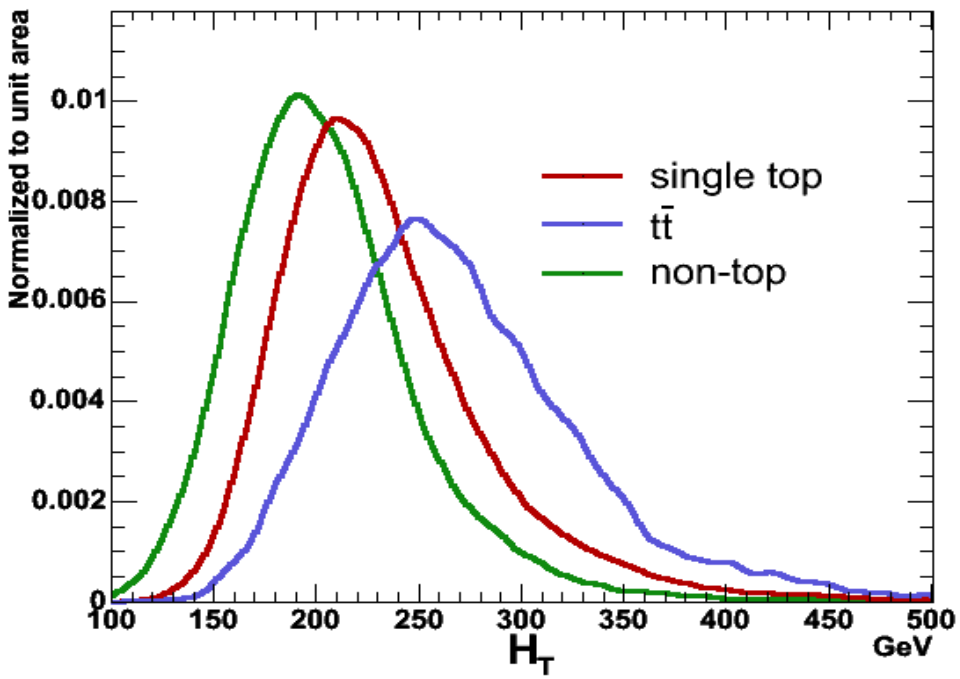


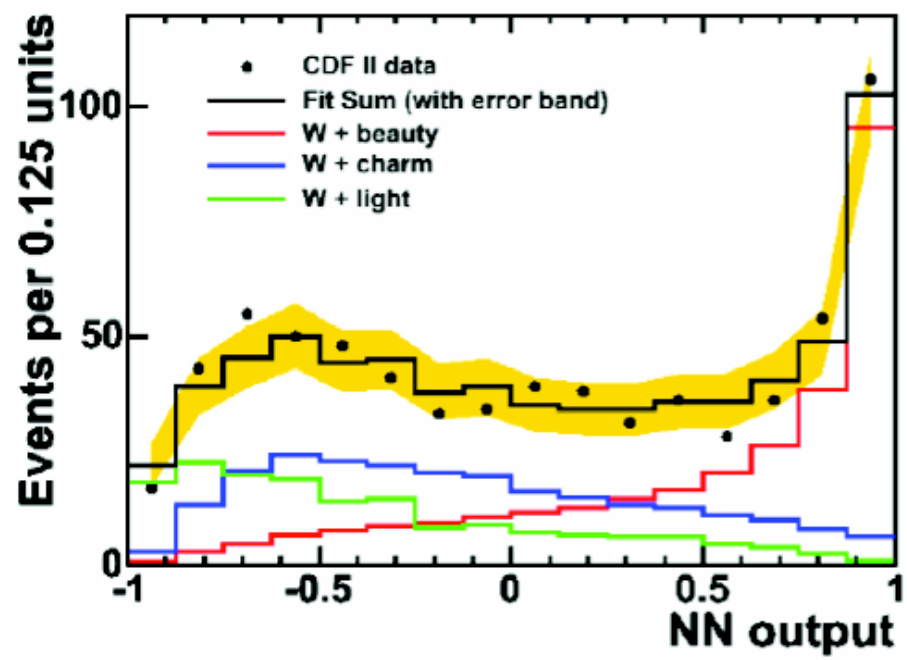
CDF Analyses

- Multivariate analyses using 0.95 fb^{-1}
  - Matrix Element: search for s+t channel signal
  - Likelihood function: search for s- and t-channel signal
  - Neural Networks: search for both s+t and individual s- and t-channel

- All analyses use a neural networks b-tag extension
  - 50% of the *b*-tagged jets do not contain *b*-quarks! NN *b*-tagger constructed to address this

- NN *b*-tagger applies to secondary vertex tags; uses information such as:
  - Vertex mass, decay length, number of tracks, etc.

Fit to NN output for *W* + 2 jets events with one secondary vertex (955 pb^{-1})



Matrix Element Analysis

Idea: Compute an event probability P for signal and background hypotheses

14 degrees of freedom (p_z of incoming quarks and **p** of the outgoing leptons and quarks)

Measured lepton and quark momenta, plus 4momentum conservation => 11 constraints

LO matrix element (MadEvent)

Probability that parton with E_p is measured as jet with E_j.

$$P(p_\ell, p_{j1}, p_{j2}) = \frac{1}{\sigma}\int dE_{p1} dE_{p2} dp_\nu^z \sum_{comb} |M(p_i)|^2 \frac{f(q_1) f(q_2)}{|q_1|\cdot|q_2|} \phi_4 W_j(E_j, E_p)$$

input: lepton and 2 jets 4-vectors!

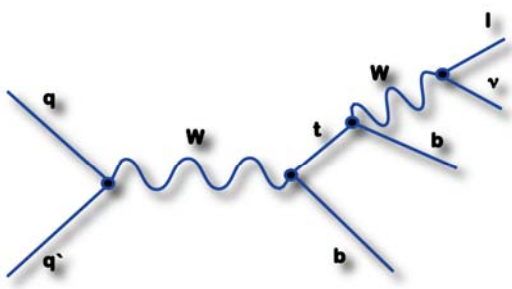
integration over part of the phase space Φ_4

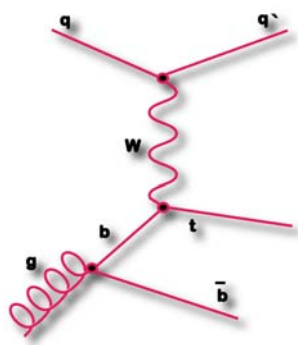
parton distribution functions (CTEQ5)

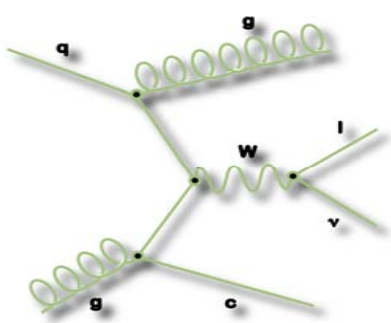
single-top: s-channel and t-channel

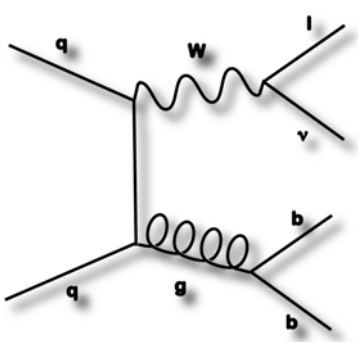
Wcj

Wbb and Wcc







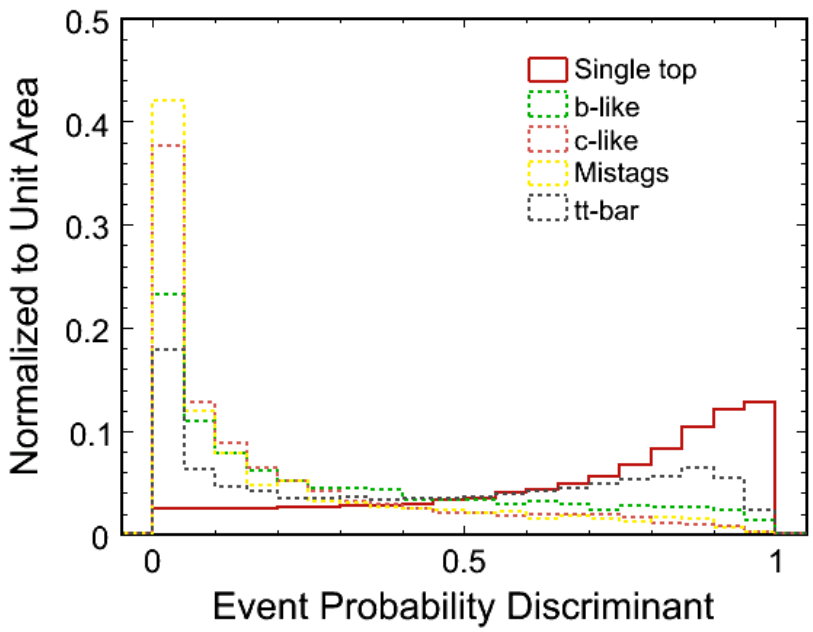


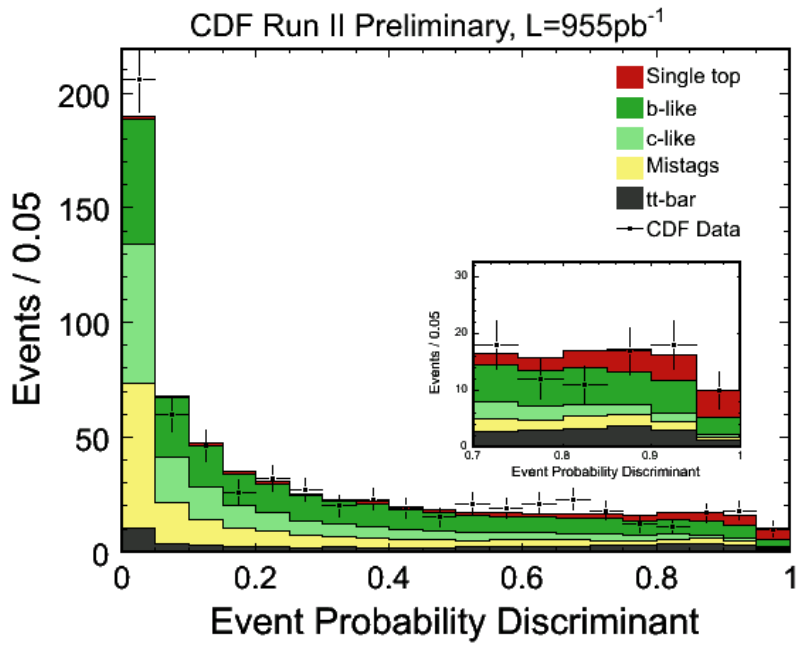
Matrix Element Data Result

- Form an "event probability discriminant" (EPD) by combining the signal and background probabilities as:

$$EPD = \frac{b \cdot P_{\text{single-top}}}{b \cdot P_{\text{single-top}} + b \cdot P_{Wbb} + (1-b) \cdot P_{Wcc} + (1-b) \cdot P_{Wcj}}$$

b = NN tagger output





Expected *p*-value: 0.6% (2.5σ)

p-value: Observed 1.0% (2.3σ)

Fit result: $2.7^{+1.5}_{-1.3}$ pb

Theory cross section: 2.9 pb

Likelihood Function Analysis

- Single Top signature: W(e,μ+$\not{E}_T$) and 2 jets

- Kinematic fitter to address the following
  - Jets' E_T imprecisely measured
  - Ambiguities in:
    - choosing the Pz(ν) solution
    - choosing b quark from top decay (s-channel)
- Build a χ^2 in which we float P_b, $E_T(\nu)$, $\Phi(\nu)$
- Without looking at the b-tag, minimize χ^2 under four scenarios
  - 2 choices of which jet comes from top decay
  - 2 neutrino solutions

- t-channel search – use χ^2 to choose $P_z(\nu)$
- s-channel search – use χ^2 to choose b-jet

<u>Multivariate Likelihoods:</u>

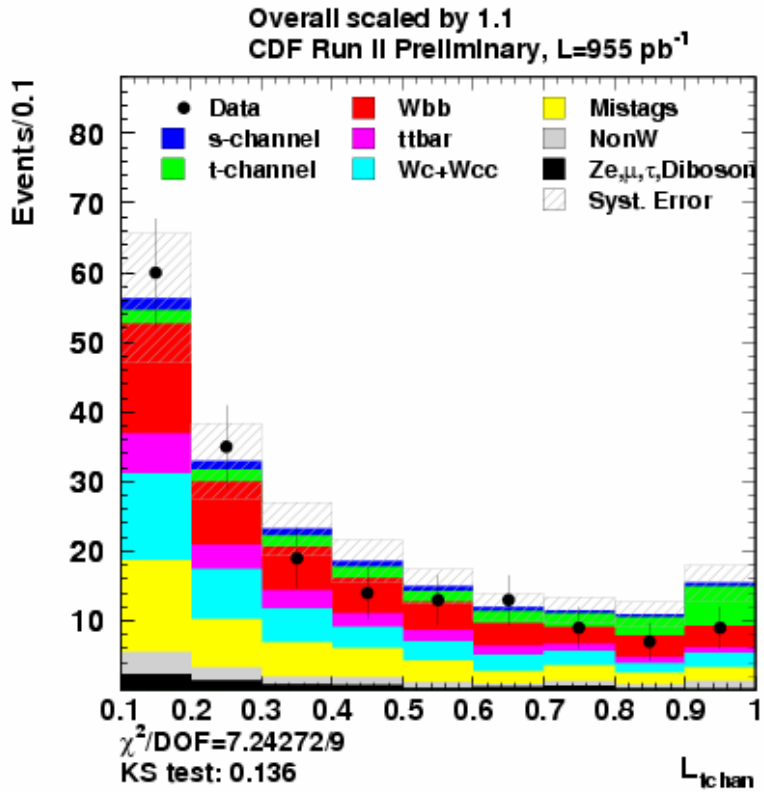
t-channel LF Variables:

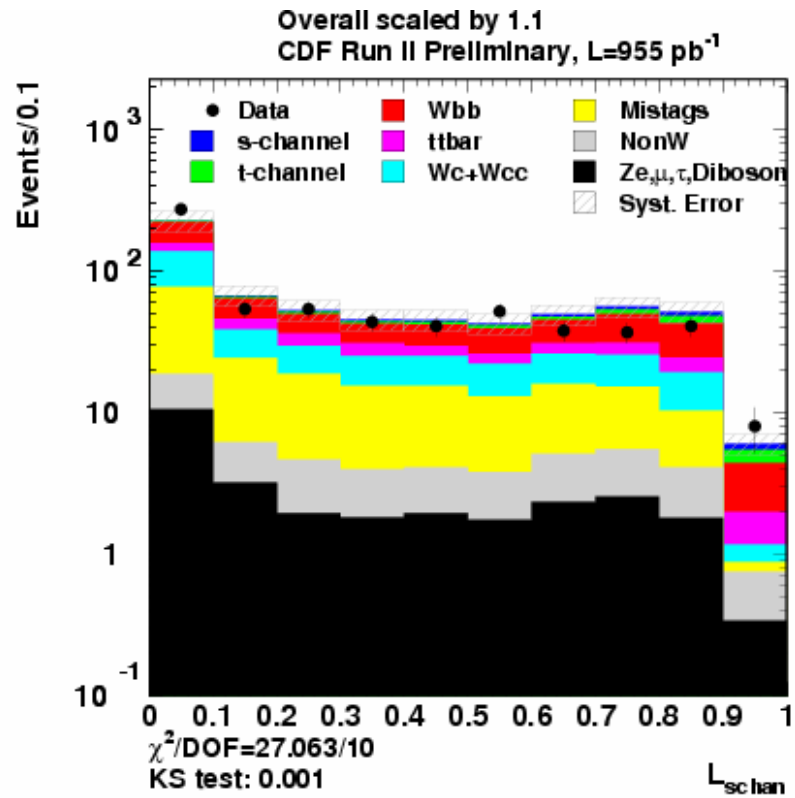
- H_T
- $M_{l\nu b}$ (hybrid, t-chan)
- $\cos\theta_{lepton,other\text{-}jet}$
- $Q_l * \eta_{untagged\text{-}jet}$
- M_{jj}
- $\log(ME_{t\text{-}chan})$ from Madgraph
- b=NN tagger output

s-channel LF Variables:

- $M_{l\nu b}$ (hybrid, s-chan)
- $\log(H_T * M_{l\nu b})$
- E_T(jet 1)
- log(MEt-chan)
- H_T
- b=NN tagger output

Likelihood Function Data Result





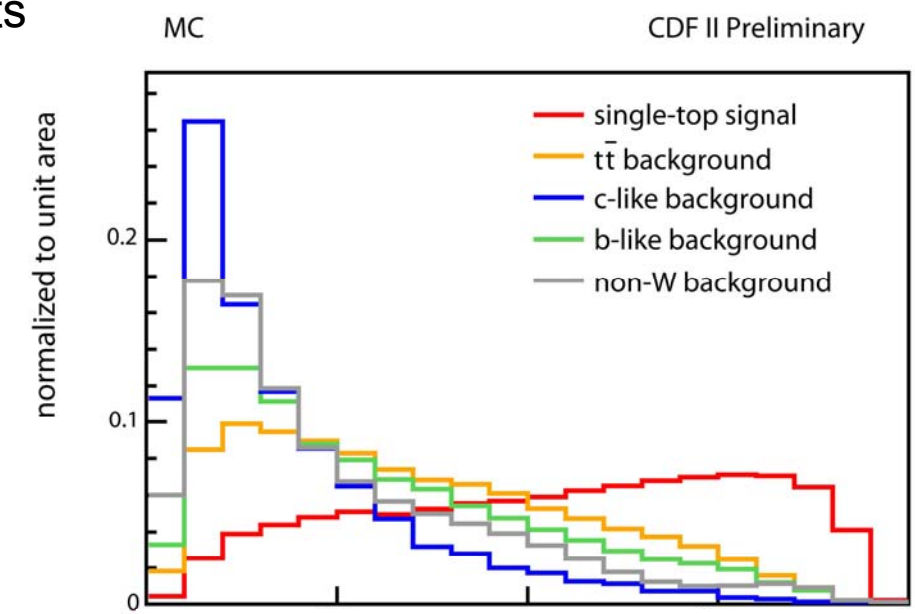
Deficit of candidates in signal region →Data prefer the background-only hypothesis

	p-value	95% C.L. upper limit
expected	2.3% (2.0 σ)	2.9 pb
observed	58% (0 σ)	2.7 pb

Neural Networks Analysis

- Similar to the Likelihood Function:
  - 26 input variables
  - Correlation among input variables accounted for naturally by training
- Construct three networks:
  - s+t channel NN
  - separate s-channel and t-channel NN's
  - get combined and separate results

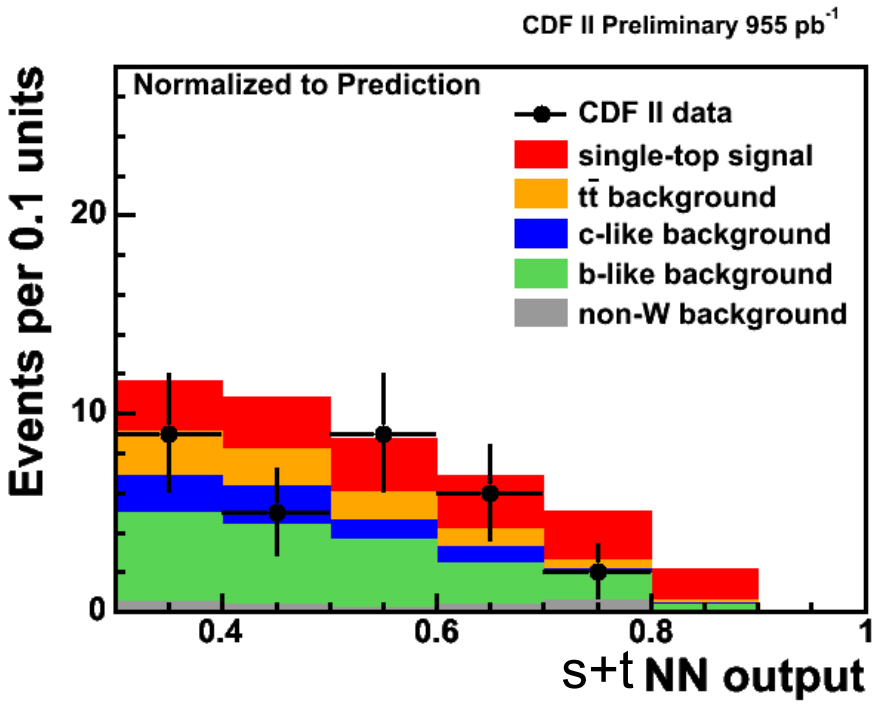
Position	Variable
1	NN b tag
2	$M_{l\nu b}$
3	M_{j_1,j_2}
4	$Q \times \eta$
5	# loose jets
6	H_T
7	$cos\Theta(\text{lep, quark})$
8	$\eta(W)$
9	$\Delta\chi^2_{(1,2)}$
10	$p_T(\text{lep})$
...	...

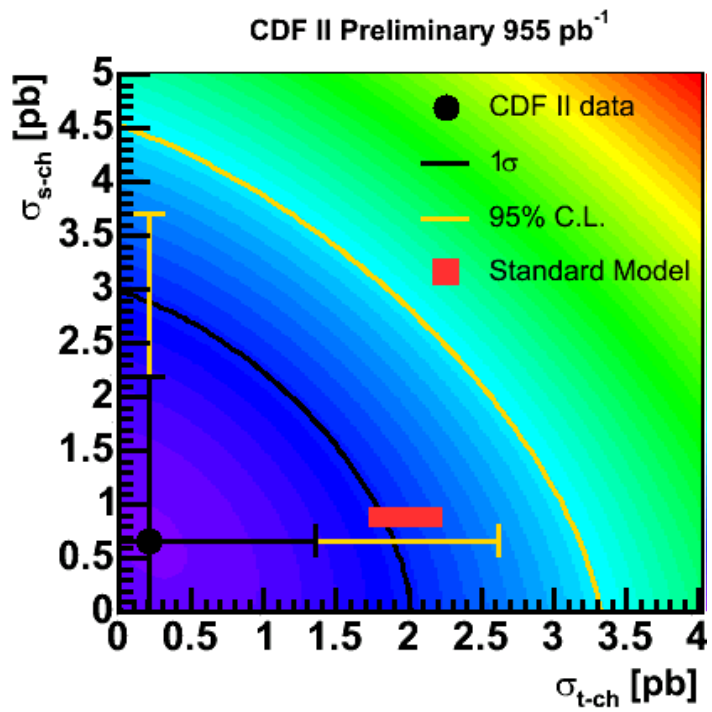


s+t Neural Network Output

NN Comparison to Data

- Deficit of candidates in the signal region for both NN searches
- Combined s + t search P-value is 55% (0 σ):
  - Fit value: $\sigma(s+t) = 0.0^{+1.2}_{-0.0}$ pb
- Separate s-, t-channel search 22% (0.8 σ):
  - Fit value: $\sigma(t) = 0.2^{+1.1}_{-0.2}$ pb and $\sigma(s) = 0.7^{+1.5}_{-0.7}$ pb

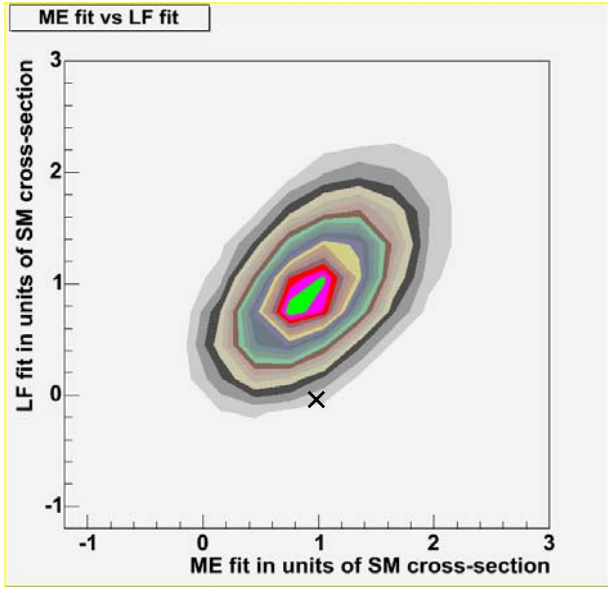




Compatibility?

Method	Neural Networks		Matrix Elements	Likelihood Function
	1D	2D	1D	2D
Expected p-value	0.5% $\cong 2.6\ \sigma$	0.4% $\cong 2.6\ \sigma$	0.6% $\cong 2.5\ \sigma$	2.5% $\cong 2.0\ \sigma$
Observed p-value	54.6%	21.9%	1.0% $\cong 2.3\ \sigma$	58.5%

- Generate pseudo-experiments according to 0.95 fb^{-1} predictions:
  - For each pseudo-experiment, form the ME, NN, and LF distrib.
  - Fit these distributions (separately) as weighted sums of signal/background reference histograms
- For the four analyses (LF, ME, NN1D, NN2D), the compatibility is 1%



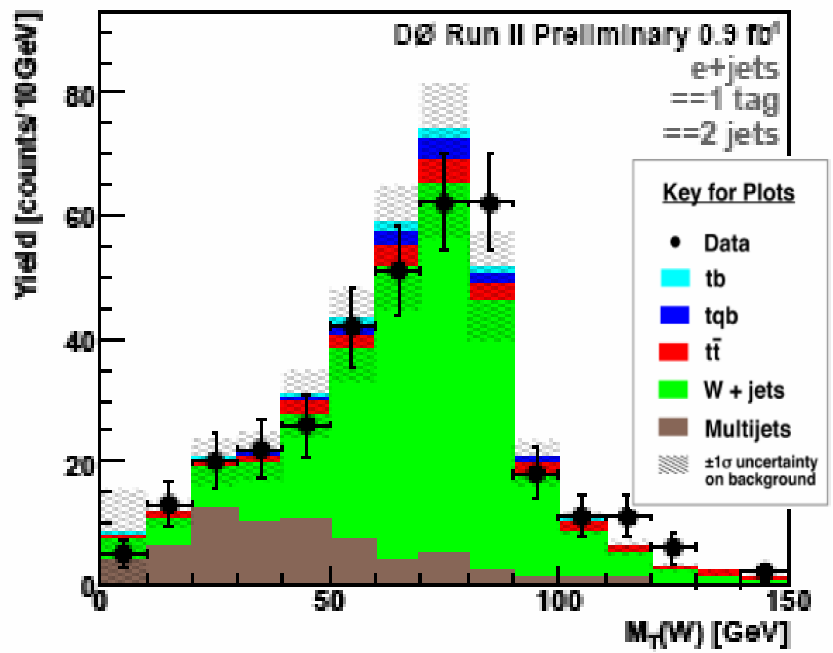
D0 analyses: Event Selection

- **Decision Trees, Matrix Element, NN using same event e,μ+jets selection**
- **Phys. Rev. Lett 98, 181802 (2007), with updated BNN and ME results**
- **62 Signal and 1400 Background events**

Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

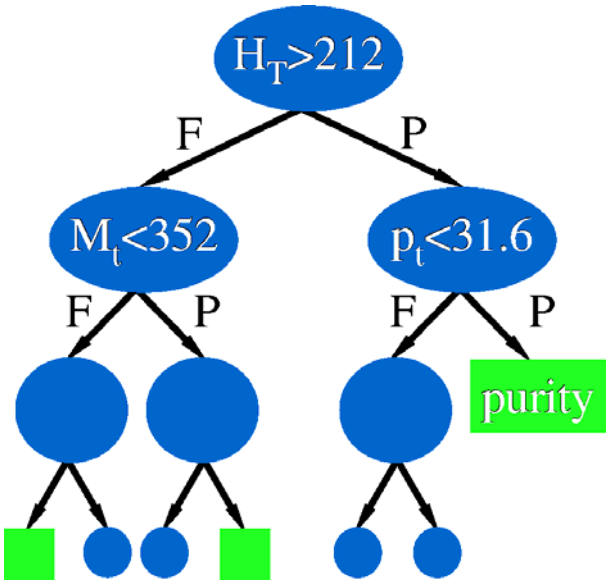
Electron + Muon	1 jet	2 jets	3 jets	4 jets	≥ 5 jets
0 tags	10% 1 : 3,200	25% 1 : 390	12% 1 : 300	3% 1 : 270	1% 1 : 230
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	3% 1 : 40	1% 1 : 53
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

Many control plots like this one..



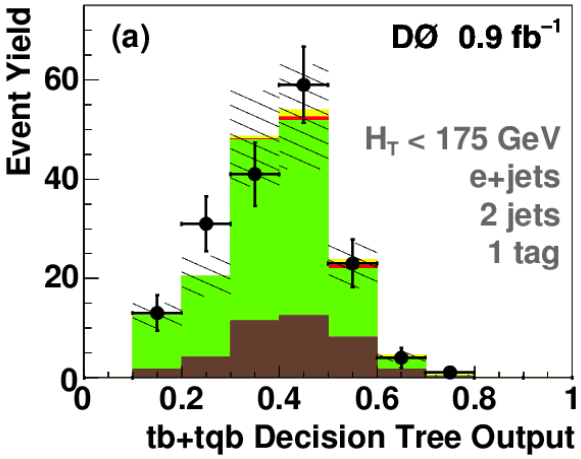
Boosted Decision Trees

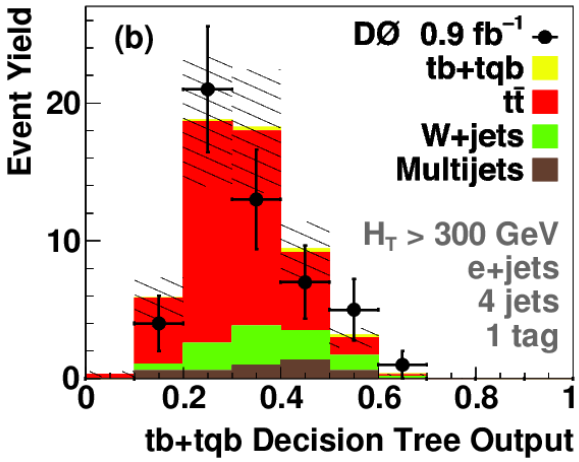
- 49 input variables. Each tree node corresponds to a given cut on a given variable.
- Run signal and background events through, and calculate purity $N_s/(N_s+N_B)$
- Iteratively change the variable and the cut to optimize classification
  - Boosting – take the misclassified events and retrain 20 times



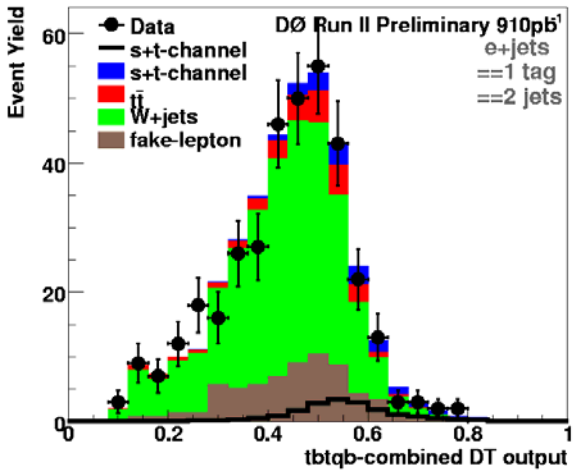
Control samples:

Best variables
M(all jets)
M(*W*, b_1)
cos(b_1,*l*) $_{top}$
Q(*l*)η(untag1)
45 more

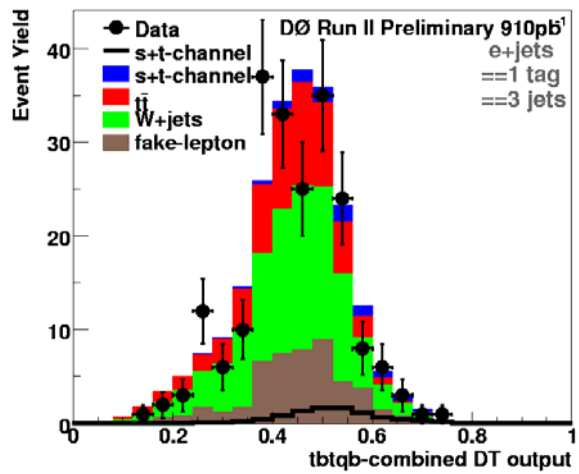




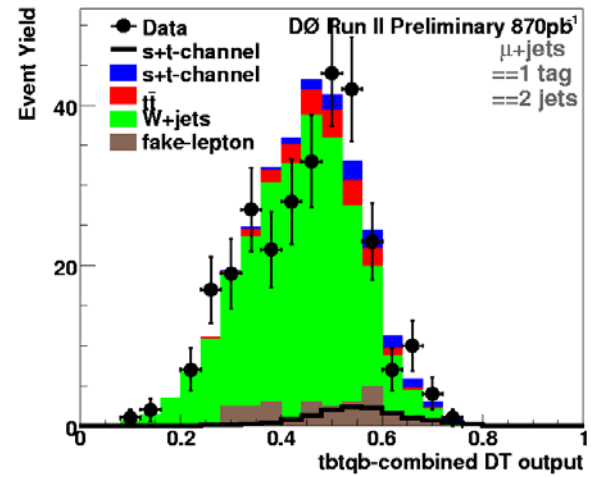
Data results (Decision Trees)



e+2jets (1tag)

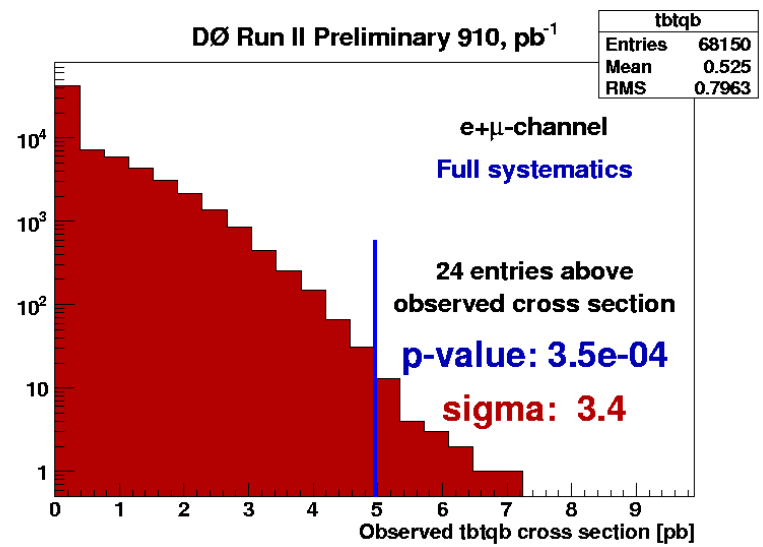


e+3jets (1tag)



μ+2jets (1tag)

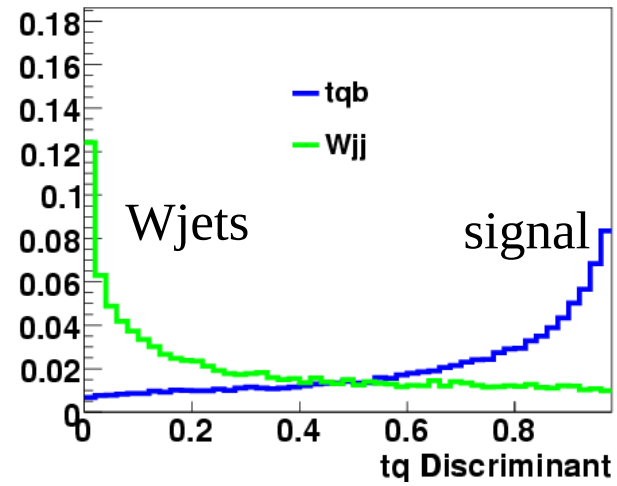
- Expected p-value: 1.9% (2.1 σ)
- Observed p-value: 3.4 σ =>Evidence!
- Data favors S+B hypothesis
- Best fit value: 4.9±1.4 pb (expect 2.9 pb)



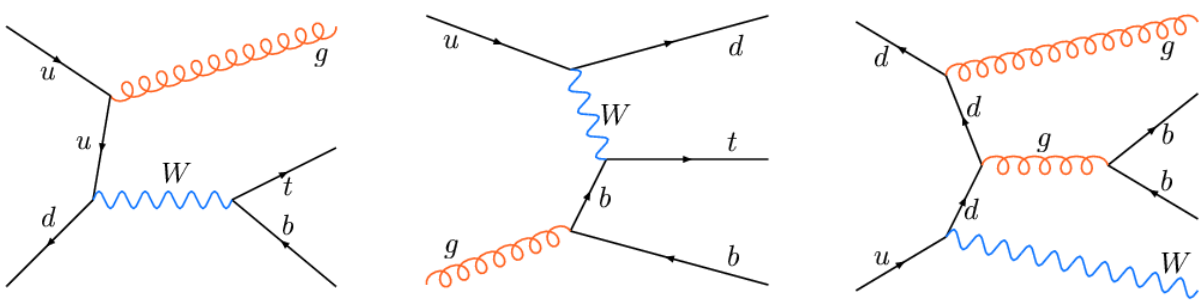
Matrix Element Technique

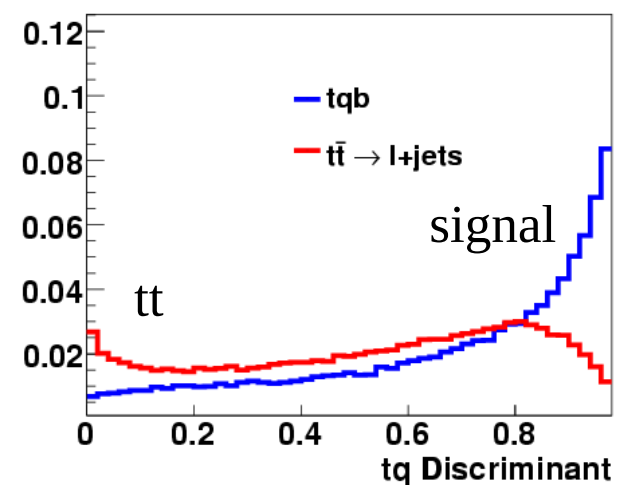
- Similar to CDF technique. However, it includes the 3-jet channel (no 4-jet).
- Recent additions:
  - New tqg, Wcgg, Wggg matrix elements
  - ttbar matrix element for the 3-jet bin

$$D_S(\vec{x}) = P(S|\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_B(\vec{x})}$$



3-jet matrix elements:

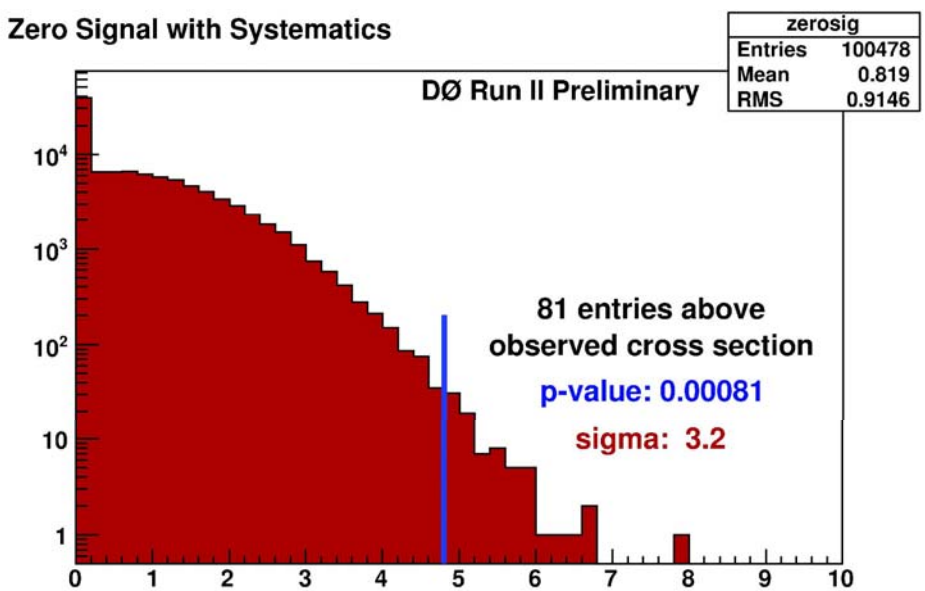




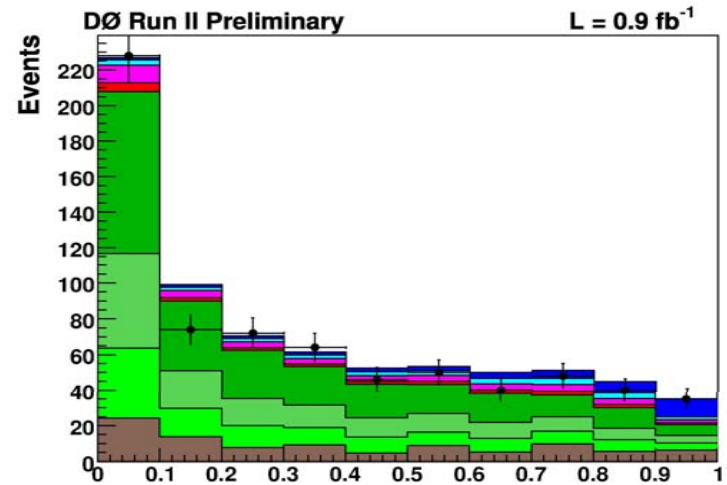
- Expected p-value: 3.1% (1.9 σ)

Data results (ME)

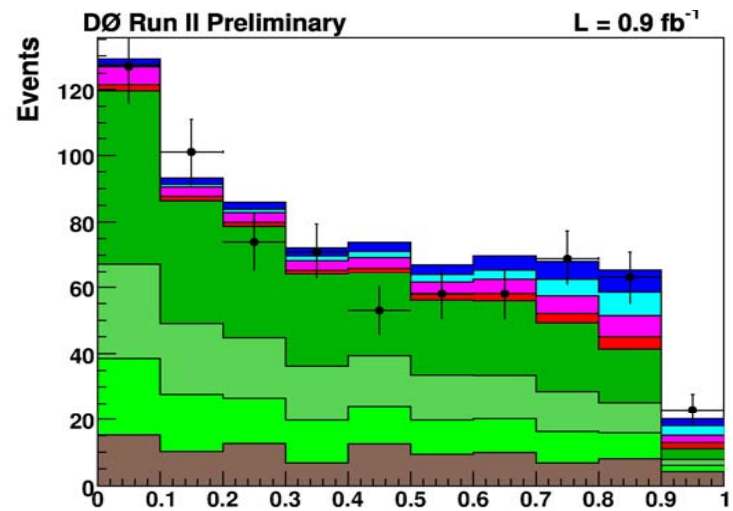
- Observed results favor signal+background hypothesis:
  - **P-value: 3.2 σ (expected 1.9 σ)**
  - **Best fit value: $4.8^{+1.6}_{-1.4}$ pb**



Observed cross section (pb)



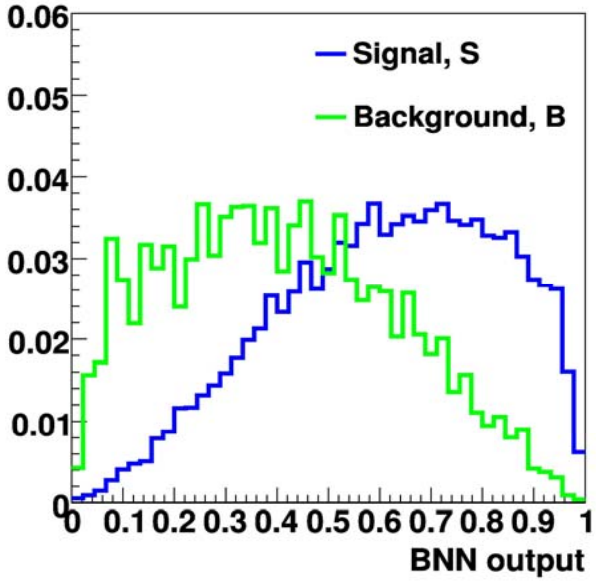
t-channel discr. 2jets

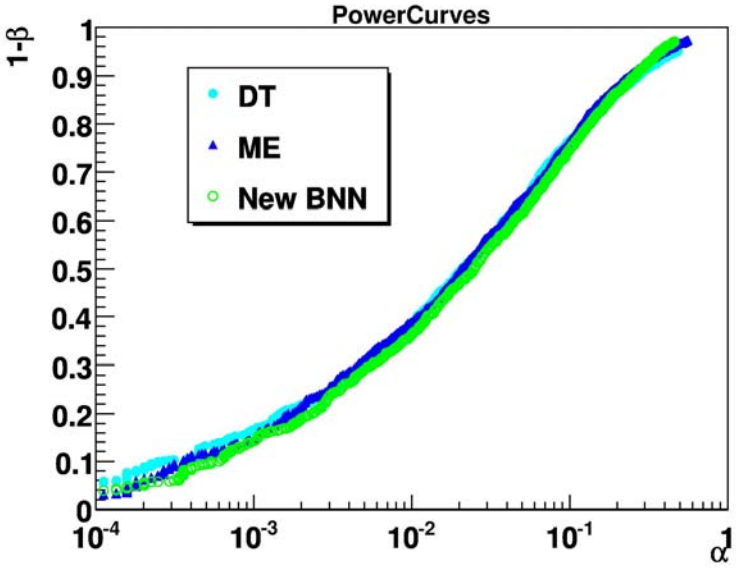


s-channel discr. 2jets

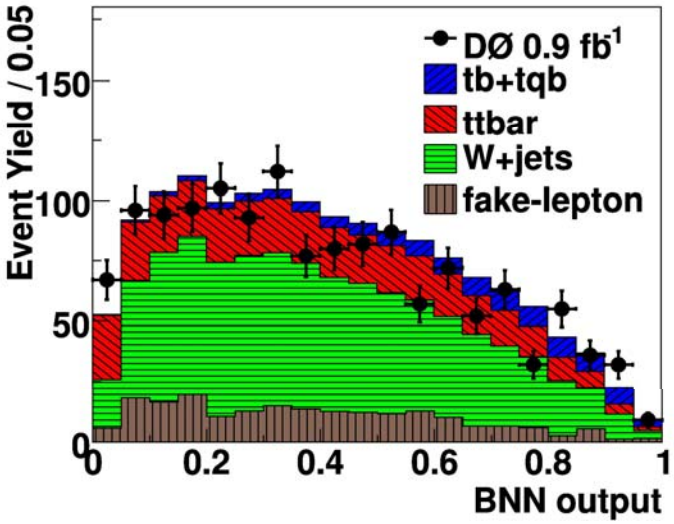
Bayesian Neural Networks

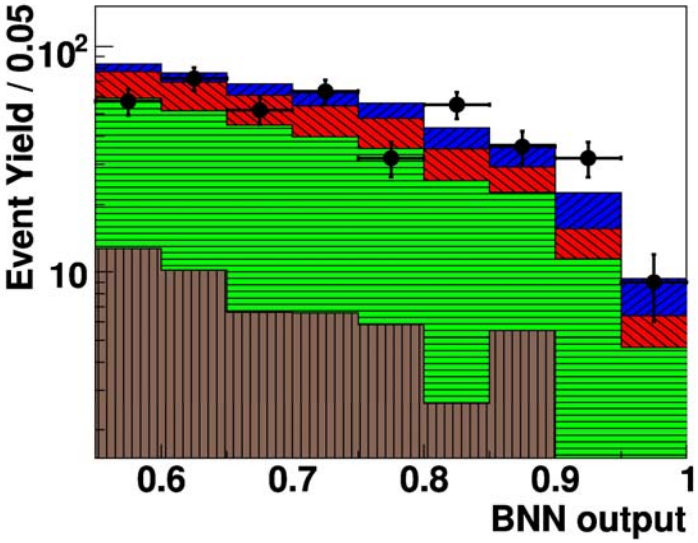
- Between 18-25 variables, depending on channel
- Output approximates the discriminant: $$D(x) = \frac{f(x|S)}{f(x|S) + f(x|B)}$$
- Noise-insensitive, training procedure (improved since the PRL):
  - For training, NN parameters constrained by Gaussian functions of small widths
- Comparison to DT and ME methods:
  - α =p-value for the null (background only hypothesis).
  - 1-β = p-value for the signal+background hypothesis

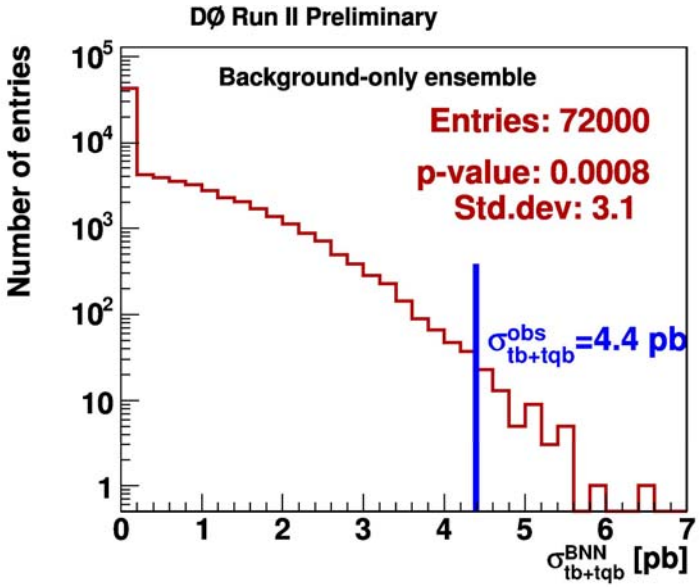




Data results (BNN)







- Again, the data prefer signal +background hypothesis
- Observed P-value = 3.1 σ (expected 2.2 σ)
- Fitted cross-section: $4.4^{+1.6}_{-1.4}$pb

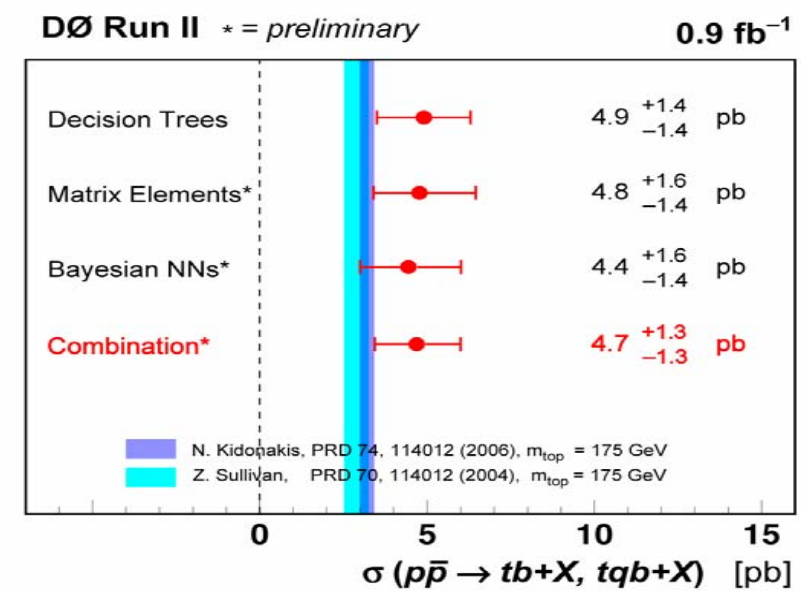
D0 Combination and V_{tb}

- Using the Best Linear Unbiased Estimate (BLUE)
- Properly account for correlations
- Perform common pseudo-experiments

$$\rho = \begin{pmatrix} DT & ME & BNN & \\ 1 & 0.64 & 0.66 & DT \\ 0.64 & 1 & 0.59 & ME \\ 0.66 & 0.59 & 1 & BNN \end{pmatrix}$$

P-value	DT	ME	BNN	Comb
Expect	2.1 σ	1.9 σ	2.2 σ	2.3 σ
Observe	3.4 σ	3.2 σ	3.1 σ	3.6 σ

→ Each analysis excess > 3σ!



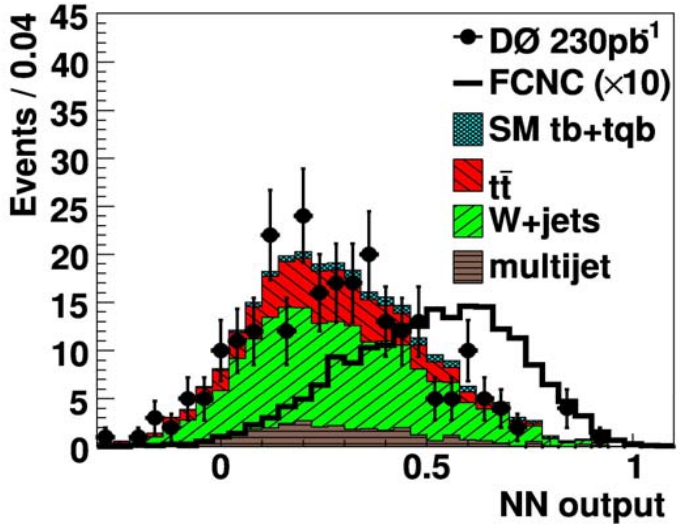
- V_{tb} measurement (using DT):
  - Assume $|Vtd|^2 + |Vts|^2 << |Vtb|^2$, then:
  - Coupling $|V_{tb} f^L| = 1.3 \pm 0.2$
  - Assuming $f^L = 1$, and a flat prior:

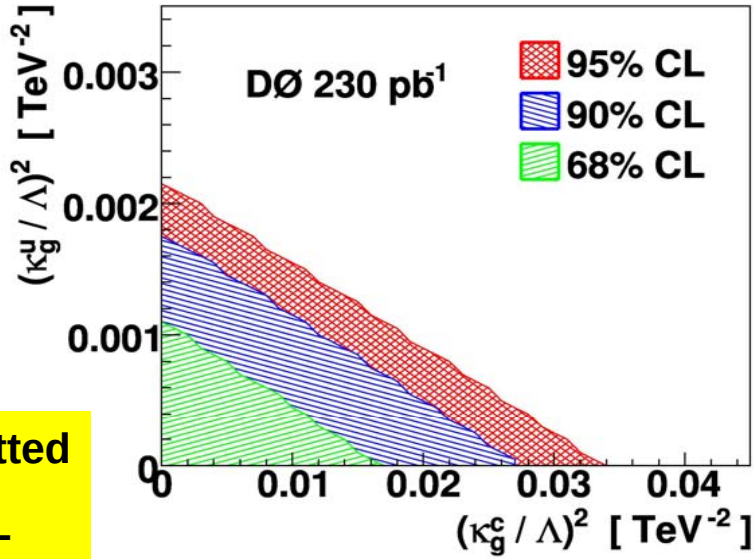
$$0.68 < V_{tb} < 1 \text{ at } 95\% \text{ C.L.}$$

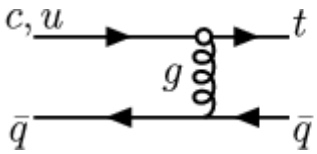
Search for Single-Top-Quarks Produced via FCNC

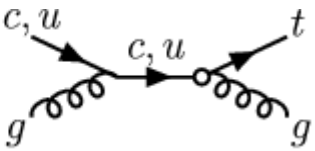
- If present, Flavor Changing Neutral Currents (FCNC) will produce single-top quarks
- DESY constraints: $k_g/\Lambda < 0.4$ TeV^{-1} at 95% C.L.:
  - Λ = new physics cutoff scale
  - k_g is the anomalous coupling we constrain
- First search at a hadron collider; uses 230/pb
- Same event selection, but restrict to 1 b-tag:
  - Single-top is a background!

κ_g/Λ [TeV^{-1}]	$\sigma(t)$ [pb]	
	tcg $(\kappa_g^u = 0)$	tug $(\kappa_g^c = 0)$
0.01	0.05	0.88
0.03	0.45	7.92
0.07	2.40	42.61
0.11	5.86	104.78









Submitted to PRL

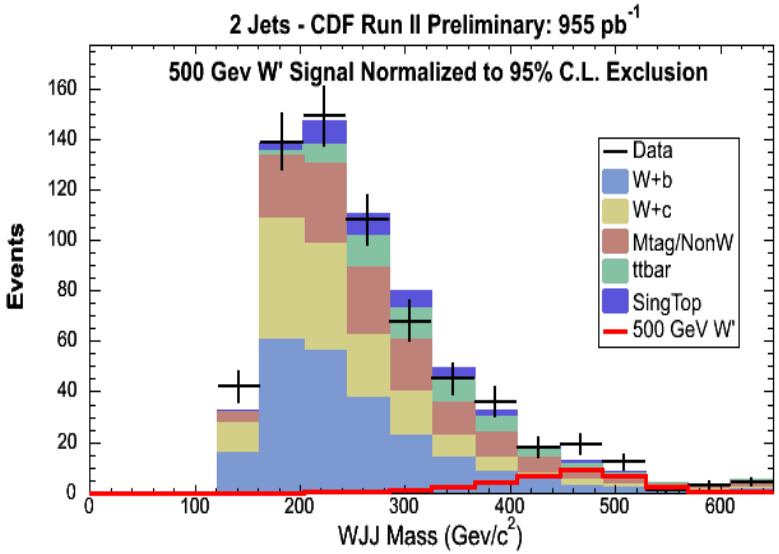
W' $\rightarrow t\bar{b}$ Search

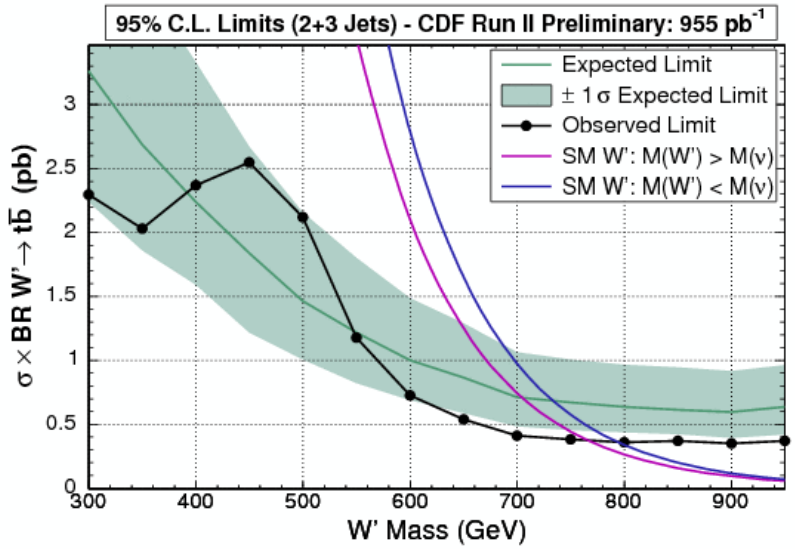
- Heavy W'$\rightarrow$tb resonance search in single-top sample
  - Additional $SU(2)_L$ sector
  - Or lowest KK mode of the W boson
  - Or left-right symmetric model: broken $SU(2)_L \times SU(2)_R$
- No evidence of resonant W' signal – exclude cross sections 0.5~2.5 pb.

Theoretical calculations detailed in Z. Sullivan, Phys. Rev. D 66, 075011, (2006)

- Mass limits: **760-790 GeV**. Improve D0 2005 result 610-630 GeV and previous CDF (560 GeV).

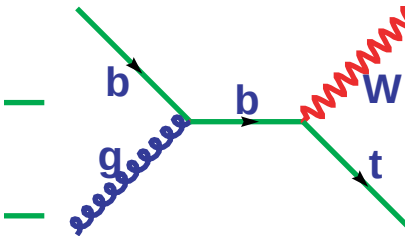
D0: Phys. Lett. B 641, 423 (2006). CDF Run I Rev. Lett. 90, 081802 (2003)





Beyond the Tevatron

- LHC will be a top quark factory:
  - 8 million top pairs per experiment per year (10 fb^{-1} / year)
  - Some cross section values for $\sqrt{s}$ = 14 TeV:
    - top pair production: ~ 800 pb (mostly via gluon-gluon fusion)
    - t-channel single top: 150 (top) and 90 (antitop) ~ **240 pb**
      - **e.g. per day ~6000 events, at $10^{33} cm^{-2} s^{-1}$**
    - s-channel single top: 7 (top) and 5 (antitop) ~ **11 pb**
    - associated Wt production: **~ 60 pb**
      - **Negligible at the Tevatron**



- With 10 fb^{-1}, both experiments should be able to see evidence of t-channel:
  - CMS 10 fb^{-1} : t-channel: $\Delta\sigma/\sigma$ = 10% (reco. top mass $M_{l\nu b}$) from *CMS2006_084*
  - CMS 10 fb^{-1} : s-channel: $\Delta\sigma/\sigma$ = 36 %
  - CMS 10 fb^{-1}: Wt channel: $\Delta\sigma/\sigma$ = 26% (dilepton) 23%(l+jets).
  - ATLAS 30 fb^{-1}: t-channel $\Delta\sigma/\sigma$ = 13 (only 1% stat! rest is almost all bkg. estimate)
  - ATLAS 30 fb^{-1}: s-channel $\Delta\sigma/\sigma$ = 21 %

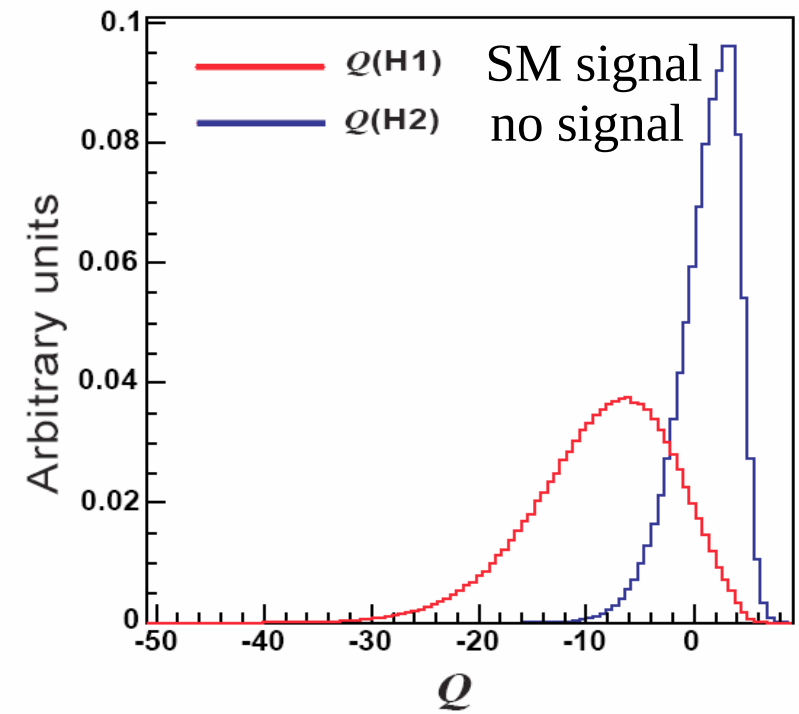
Tevatron for LHC report: arXiv:0705.3251v1

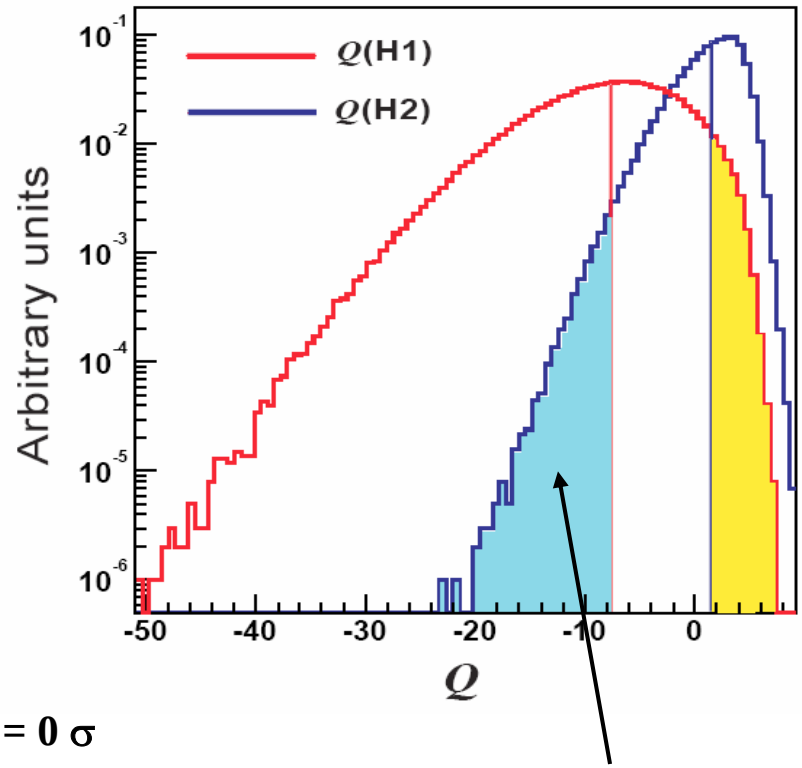
Conclusions

- Tevatron collaborations completed the 1fb^{-1} analyses with exciting results!
  - DØ analyses' p-values (in units of σ):
    - **A priori: 2.2 σ (BNN), 2.1 σ (DT), 1.9 σ (ME). Combined 2.3 σ**
    - **Observe: 3.1 σ (BNN), 3.4 σ (DT), 3.2 σ (ME). Combined 3.6 σ**
  - CDF analyses' p-values (in units of σ):
    - **A priori: 2.6 σ (NN), 2.5 σ (ME), 2.0 σ (LF)**
    - **Observe: 0 σ (NN), 2.3 σ (ME), and 0 σ (LF)**
  - Interesting to see how the results will converge as more data is analysed:
    - Next round of analyses 2 fb^{-1} => each analysis expects a **>3** σ measurement
- Single top searches:
  - step toward Higgs searches – especially WH at the Tevatron
  - small signals at the LHC (including single-top itself!)
  - multivariate methods amount to an unprecedented testing of MC modeling
- Beyond the SM processes (W', FCNC) contributing to single-top rates
  - Especially important with larger datasets!
- Stay tuned for the next round of results!

p-value

Exclusion (yellow) and Discovery (blue)





P-value = 50% = 0 σ

P-value = 5% = 1.6 σ

P-value = 1% = 2.3 σ

P-value = 0.1% = 3.1 σ

p-value: smaller is better