Single top quark physics

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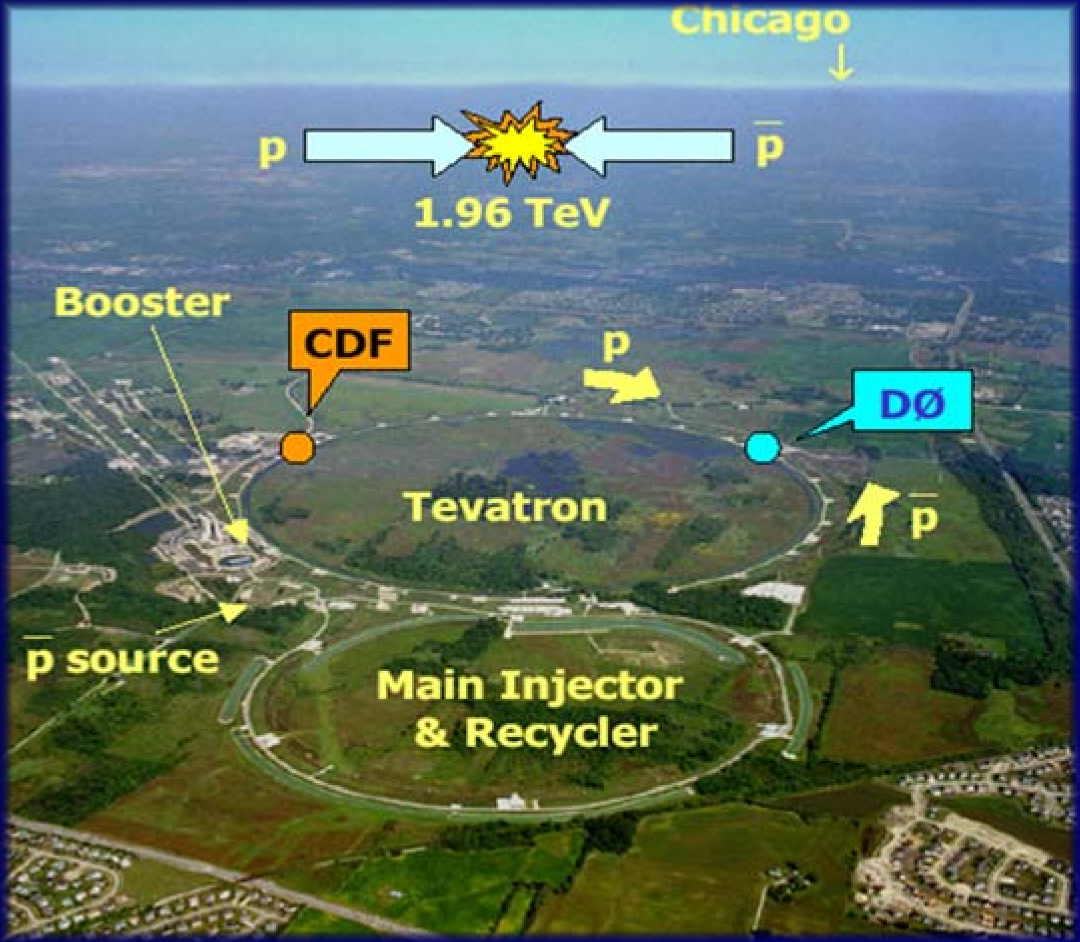
on behalf of the CDF and D0 collaborations

Les Rencontres de Physique de la Vallee d'Aoste

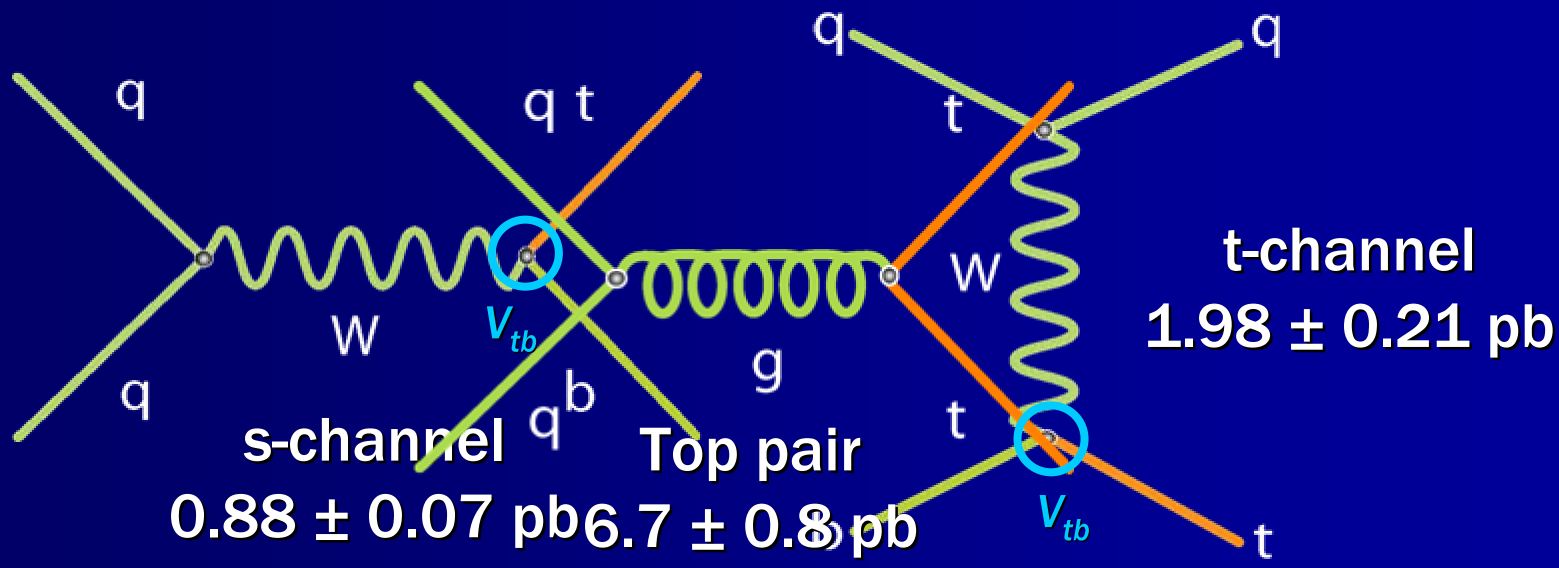
Wednesday, February 27, 2008

The Tevatron

- World's highest-energy operational particle accelerator
- Two multi-purpose particle detectors, CDF and DO
- The only place in the world to study top quarks (for now)



Electroweak single top production

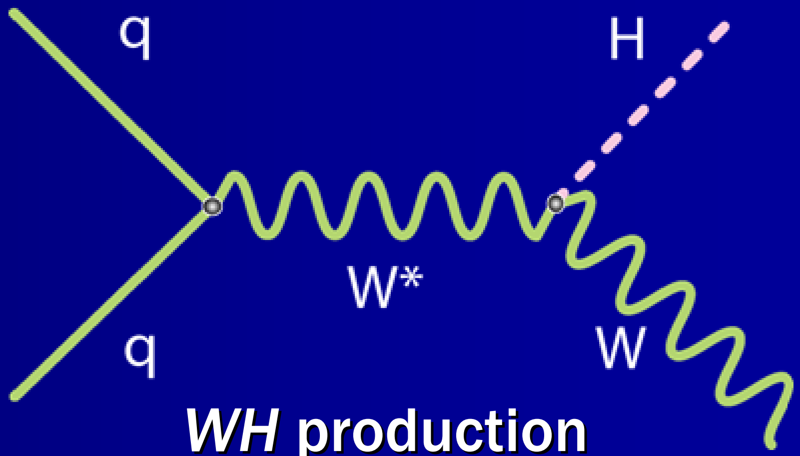


- Electroweak single top production allows
  … in pairs by the strong force
  - Direct measurement of CKM matrix element $|V_{tb}|$
  - Chance to measure polarized top quarks
  - Can study properties like mass, charge, W helicity

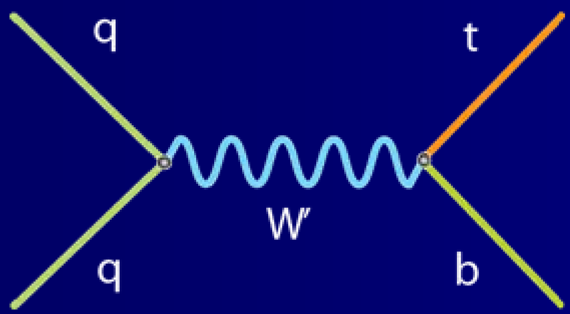
Quoted cross-sections at M_{top}=175 GeV/c^2 — Cacciari et al. JHEP 0404:068; Z. Sullivan, hep-ph/0408049

Sensitivity to new physics

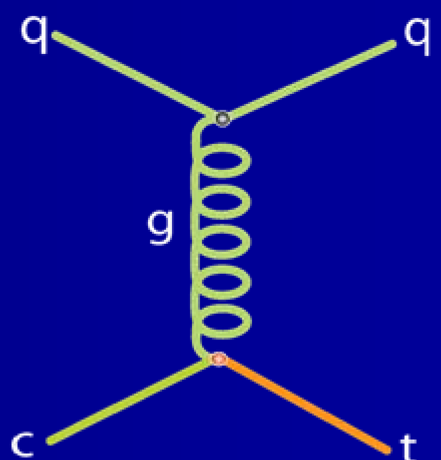
- Single top has similar experimental challenges to *WH*
  - *WH* is preferred channel for low-mass Higgs production at the Tevatron
  - Have to find single top to find Higgs in this channel!



WH production
~0.2 pb at 120 GeV

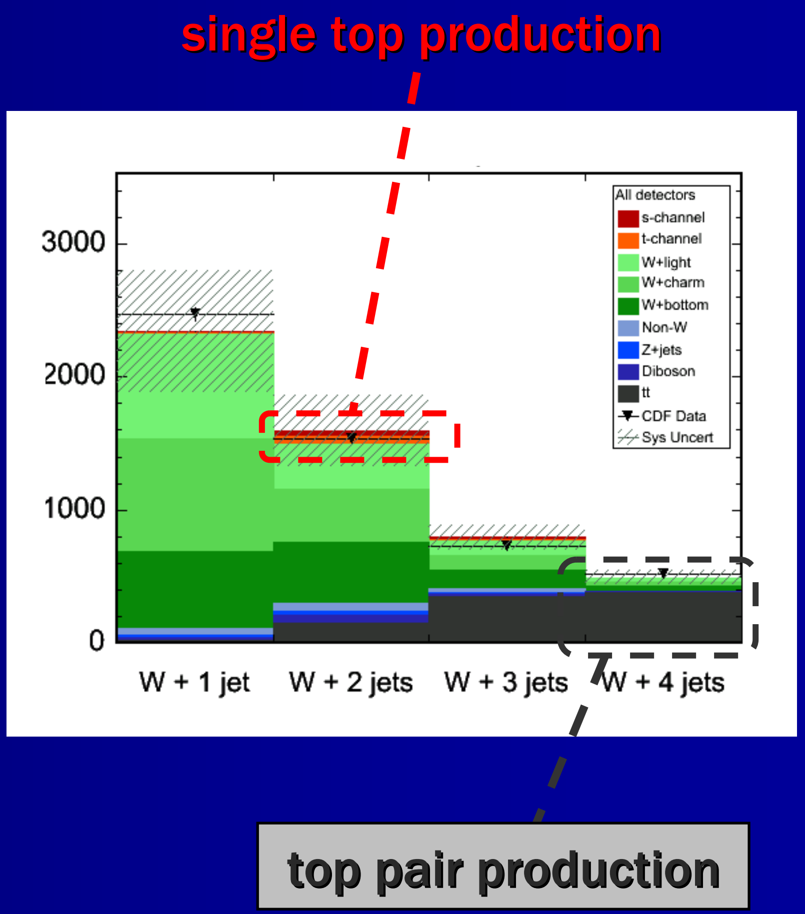


Also sensitive to heavy *W′*, flavor-changing neutral currents, Kaluza-Klein heavy W^{kk}, ...

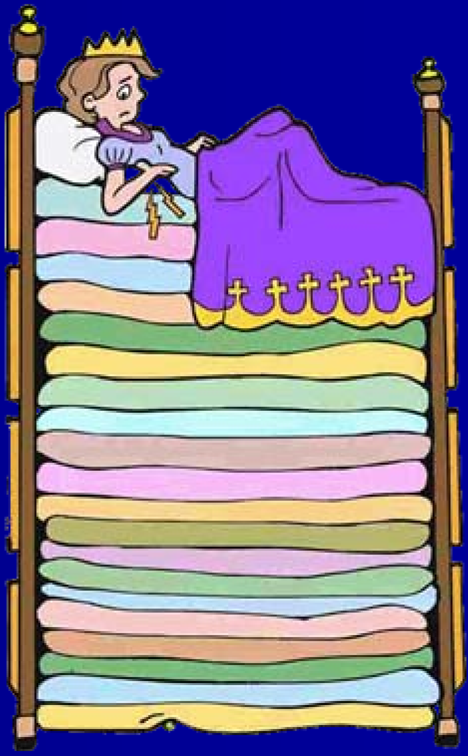


Experimental challenge

- Top quark pairs produce a final state with a lepton, missing transverse energy, and four jets — a distinct signature
  - Signal : background of about 3.4 : 1
- Single top production, with a smaller cross section and two fewer jets, is much harder to find
  - Signal : background of about 1 : 15
  - A simple counting experiment is impossible!

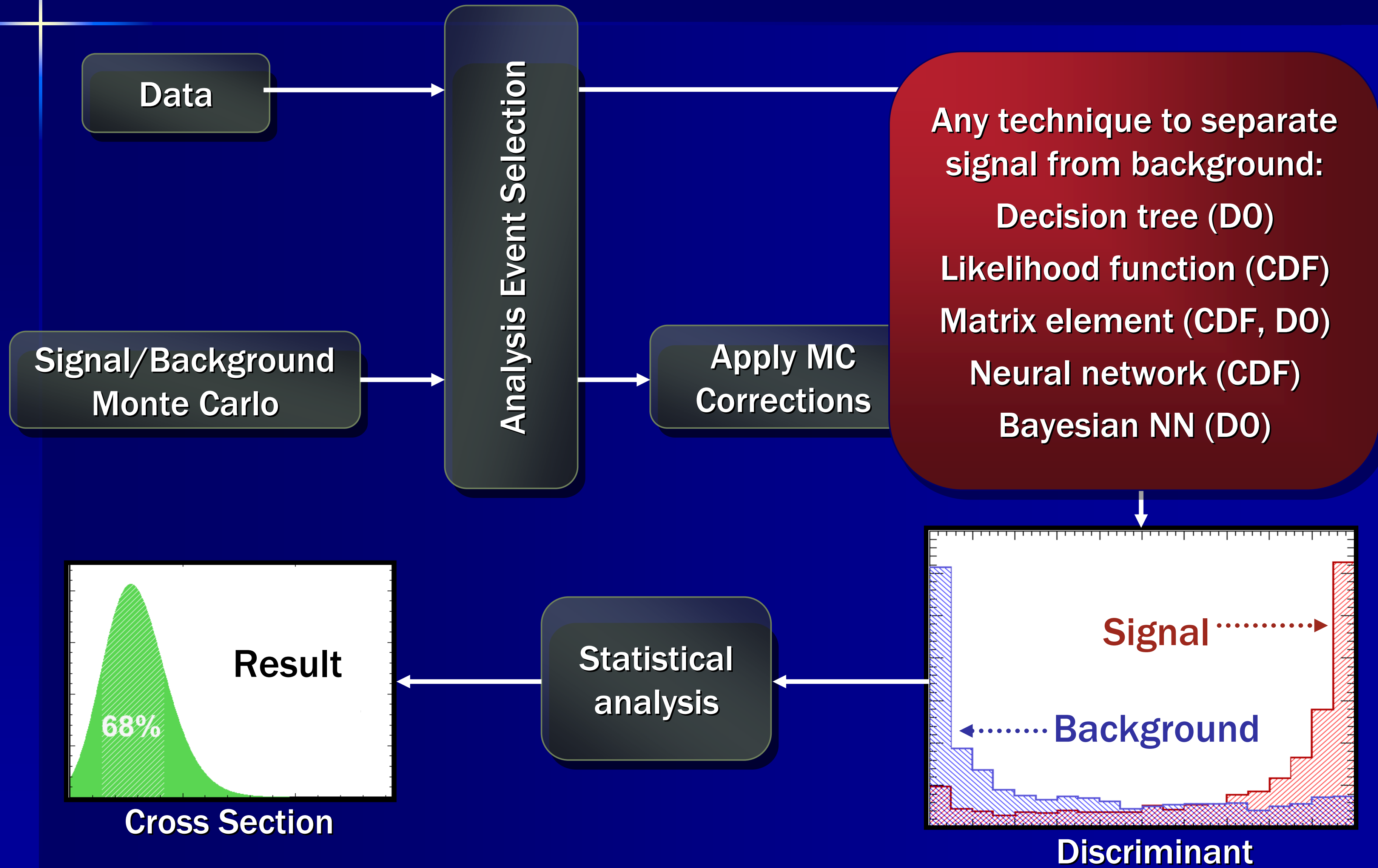


Although searching for something so tiny may seem hopeless…

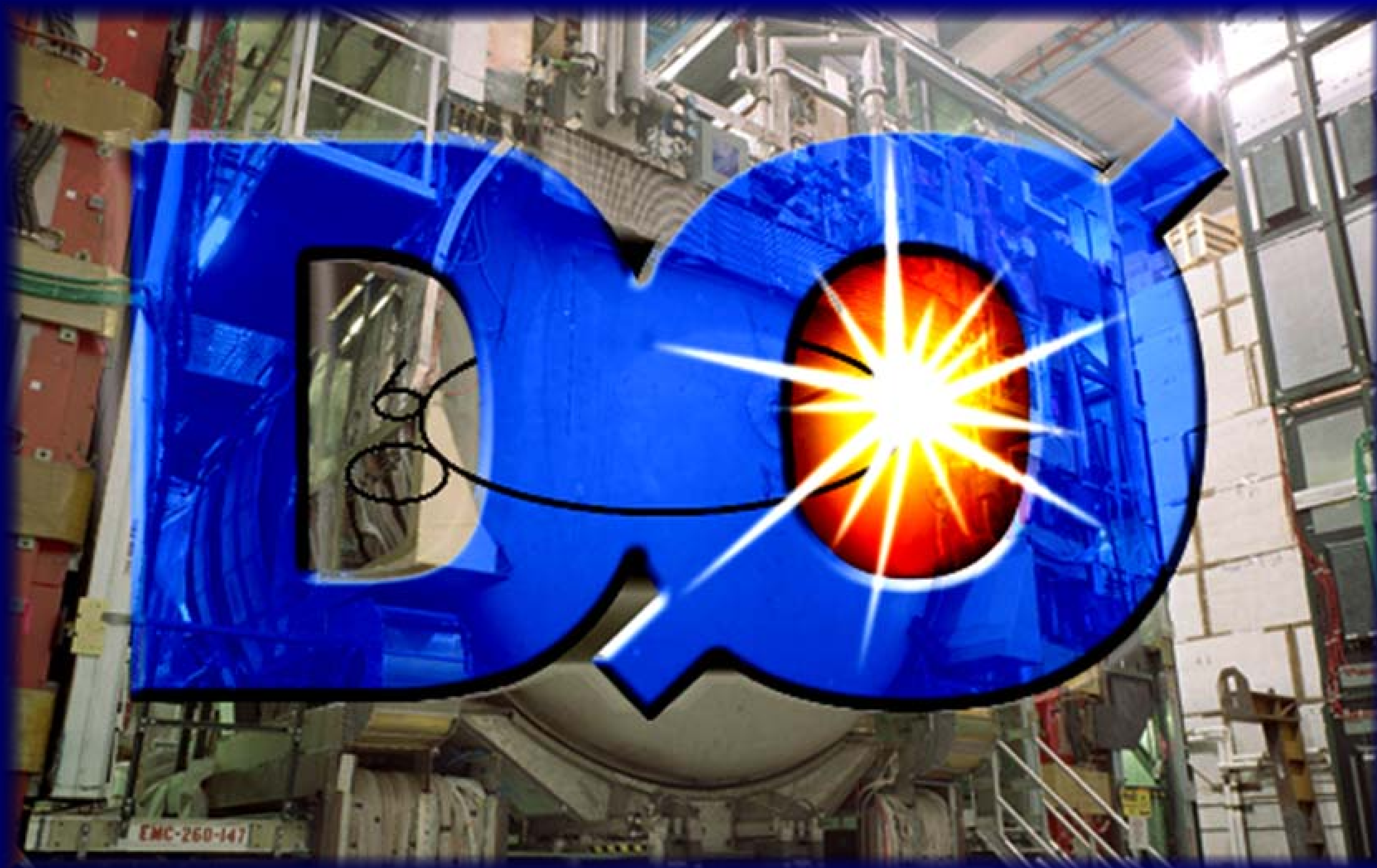


…We are still sensitive to the effects if we know what to look for

General analysis method



D0 single top search in 910 pb^{-1}



Event selection and background estimate

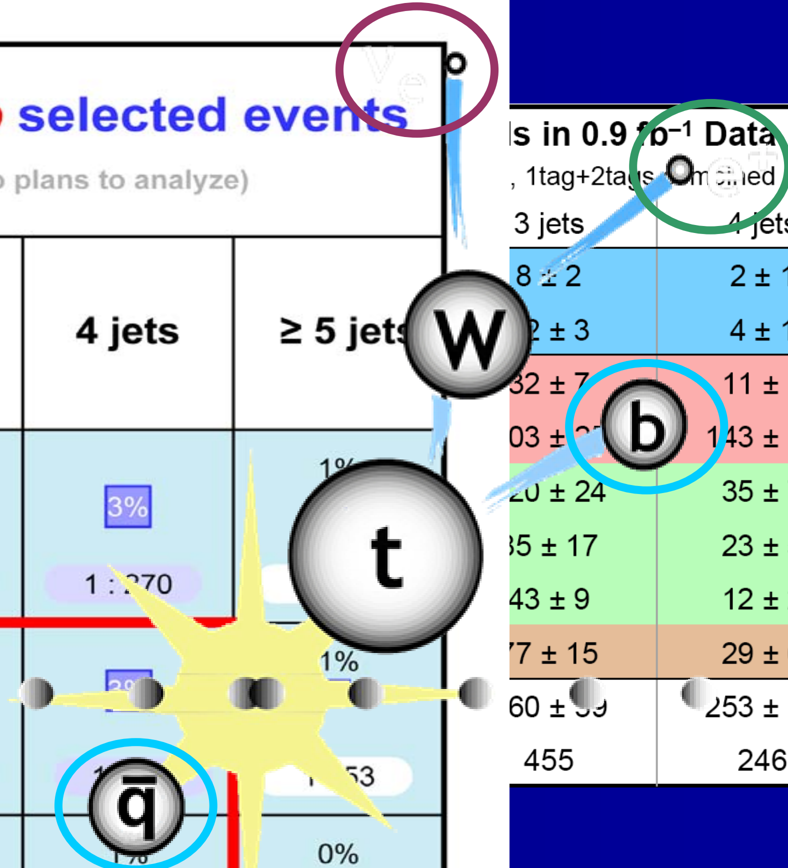
Percentage of single top *tb+tqb* selected events and S:B ratio (white squares = no plans to analyze)

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 : [illegible]70	1% [illegible]
1 tag	6% 1 : 100	21% 1 : 20	11% 1 : 25	[illegible]	1% [illegible]
2 tags		3% 1 : 11	2% 1 : 15	1% 1 : 38	0% 1 : 43

s in 0.9 fb^{-1} Data

, 1tag+2tags combined

3 jets	4 jets
8 ± 2	2 ± 1
2 ± 3	4 ± 1
32 ± 7	11 ± 3
03 ± [illegible]	143 ± 33
20 ± 24	35 ± 7
35 ± 17	23 ± 5
43 ± 9	12 ± 2
7 ± 15	29 ± 6
60 ± [illegible]	253 ± 38
455	246



Matrix element method

- Calculate probability density of an event resulting from a given process

Integrate over parton-level quantities

Parton distribution functions

$$P(p_l^\mu, p_{j1}^\mu, p_{j2}^\mu) = \frac{1}{\sigma} \int d\rho_{j1} d\rho_{j2} dp_\nu^z \sum_{comb} \phi_4 \, |M(p_i^\mu)|^2 \frac{f(q_1) f(q_2)}{|q_1||q_2|} W_{jet}(E_{jet}, E_{part})$$

Inputs:
lepton and jet 4-vectors – no other information needed!

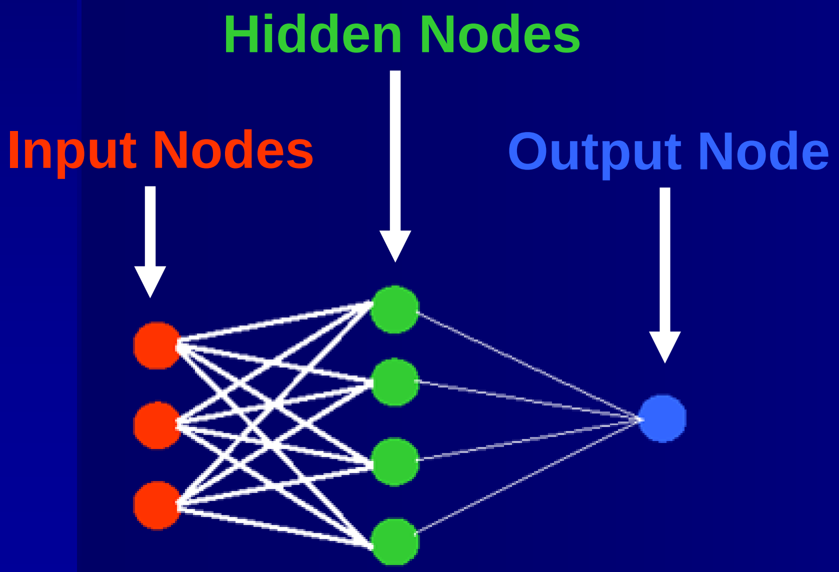
Matrix element:
Different for each process.
Leading order, obtained from MadGraph

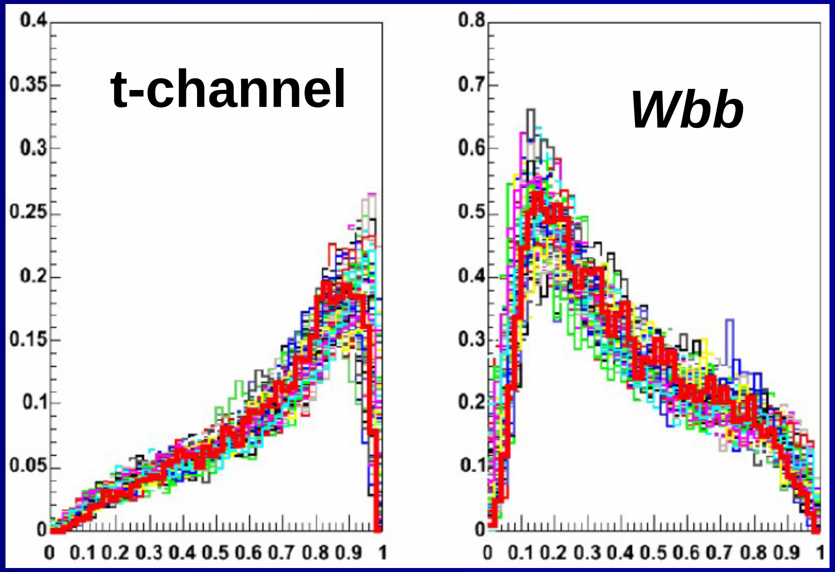
Transfer functions:
Account for detector effects in measurement of jet energy

- Uses full kinematic information of an event to discriminate signal events from background events
- Calculate probabilities for s- and t-channel, *Wbb*, *Wcj*, *Wgg*, and *tt*-bar (for three-jet events)
- Use matrix element probability densities to create a discriminant: signal / (signal + background)

Bayesian neural network

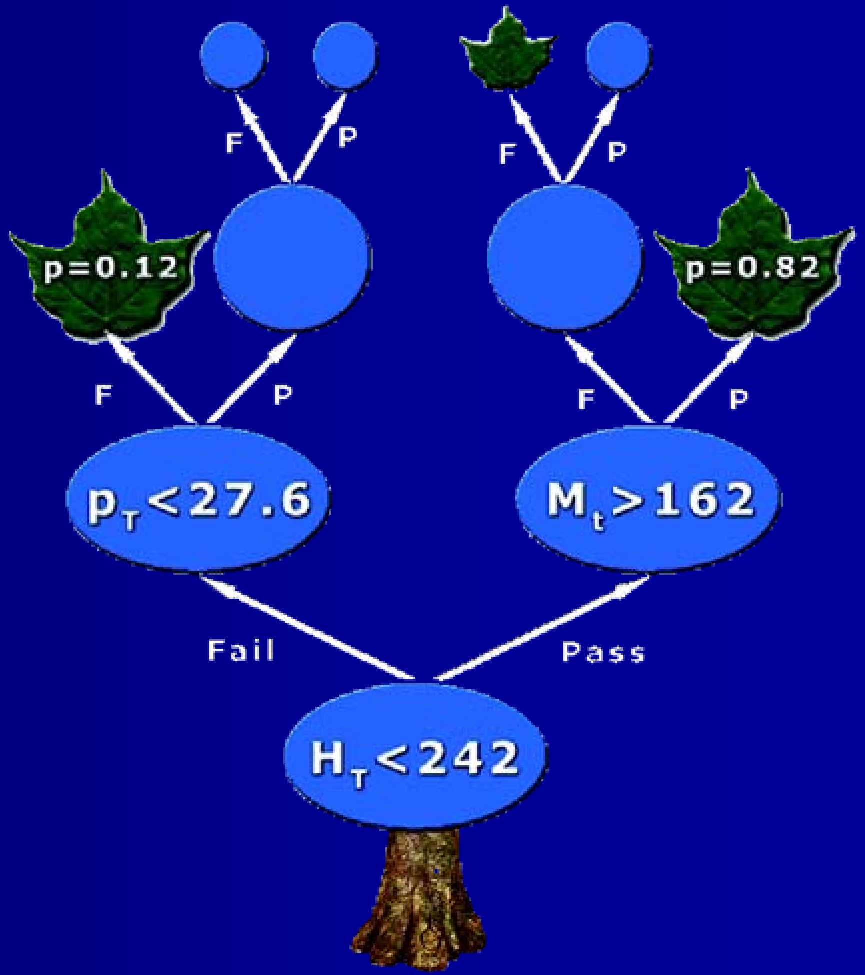
- Neural networks are trained on Monte Carlo to discriminate signal from background
- A Bayesian neural network is a weighted average of many networks
- Protected against overtraining





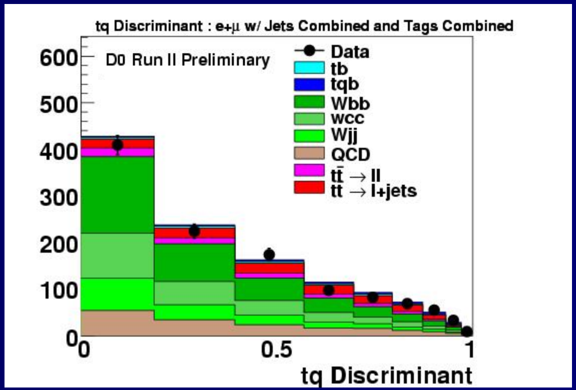
Boosted decision tree

- Start with large number of input variables (49)
- Optimize series of binary cuts in Monte Carlo
  - Automatically finds "interesting" variables
- Sort events by output purity
- Create series of "boosted" trees by reweighting based on misclassified events



D0 results

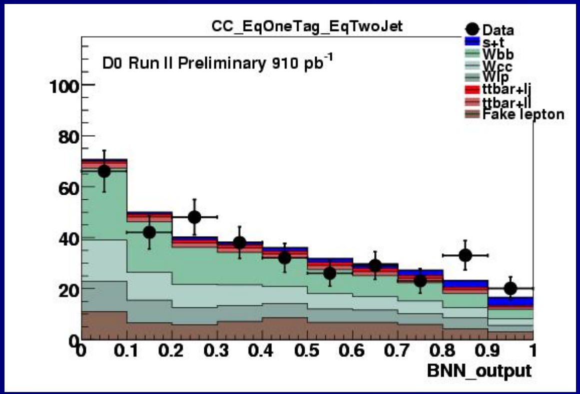
Matrix element method



Measured cross section:

$4.8^{+1.6}_{-1.4}$ pb

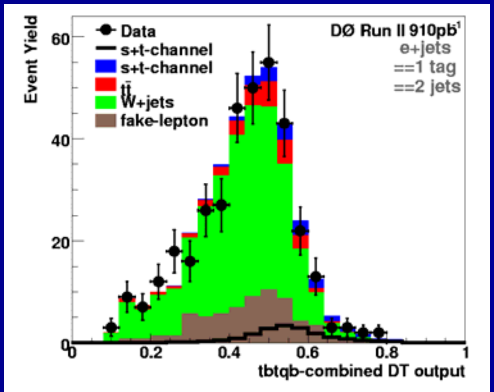
Bayesian neural network



Measured cross section:

$4.4^{+1.6}_{-1.4}$ pb

Boosted decision tree

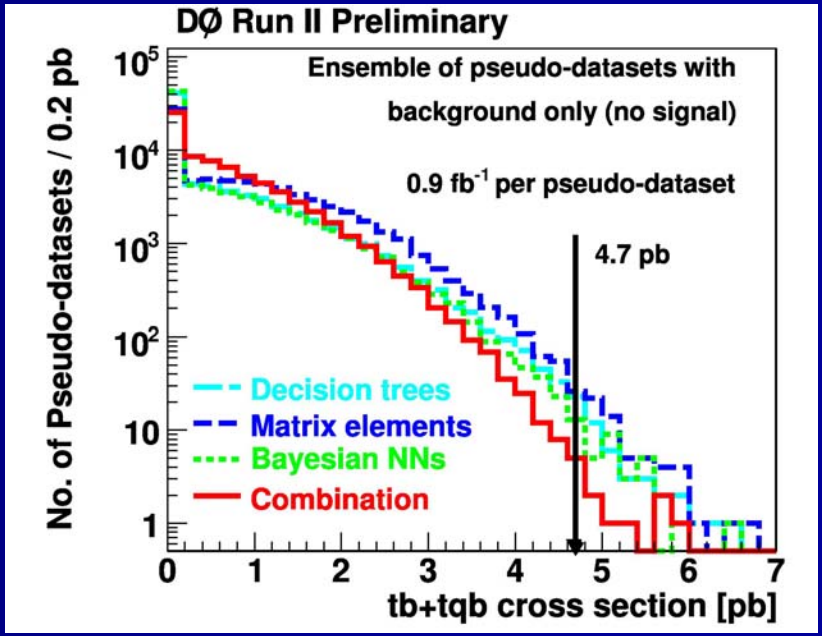


Measured cross section:

$4.9^{+1.4}_{-1.4}$ pb

D0 combination

- Results are not fully correlated — can gain sensitivity by combining
- Combine results with best linear unbiased estimator (BLUE) method



Measured cross section:

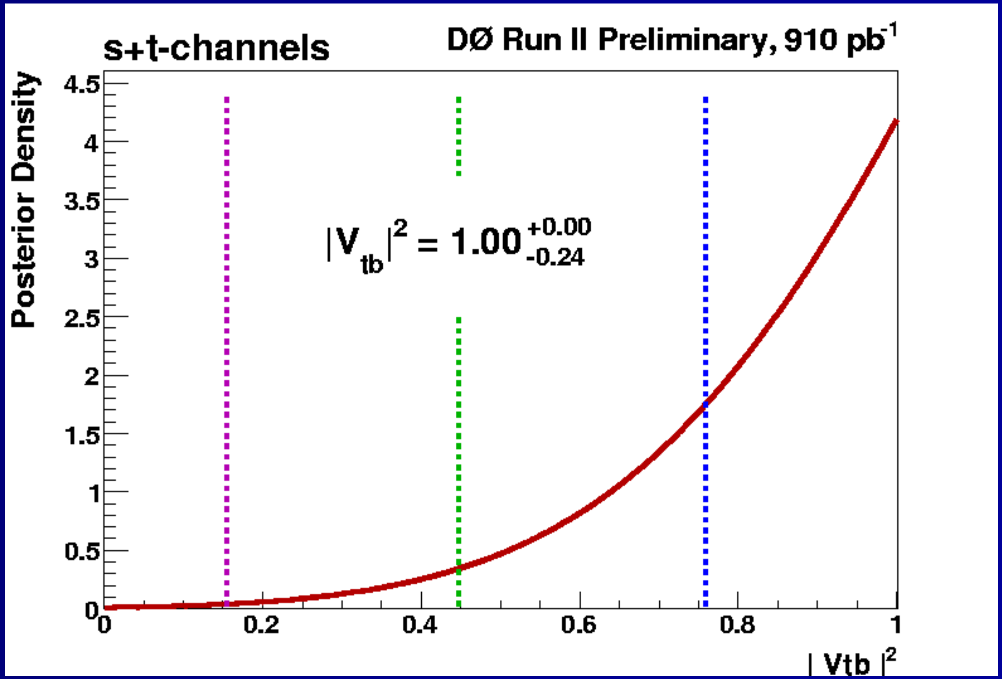
4.7 ± 1.3 pb

Expected sensitivity:
0.011 (2.3σ)

Observed p-value:
0.00014 (3.6σ)

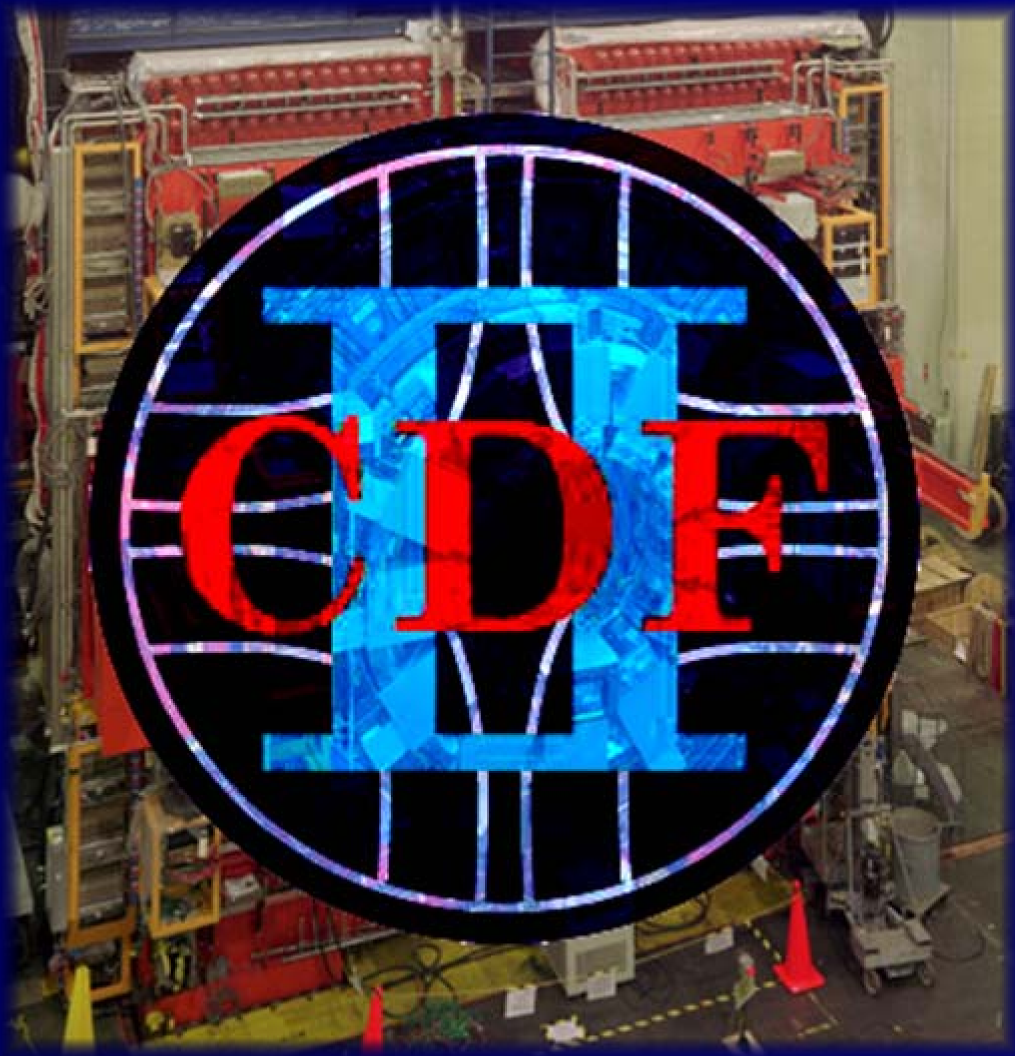
D0 $|V_{tb}|$ measurement

- Derive a limit on $|V_{tb}|$ based on boosted decision tree result
- Assume that $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$



$|V_{tb}|$ > 0.68 at 95% C.L.

CDF single top search

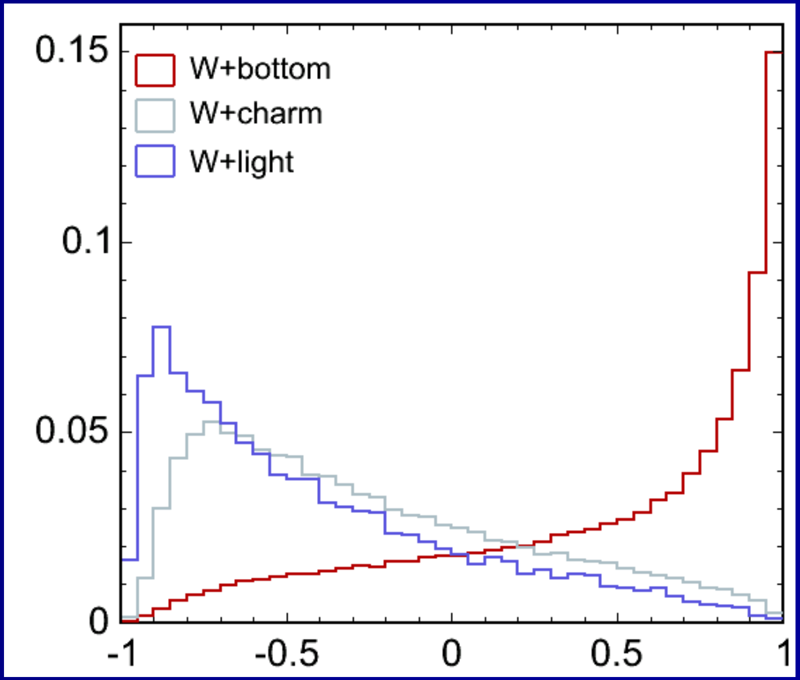


CDF search in 1.5 fb^{-1}

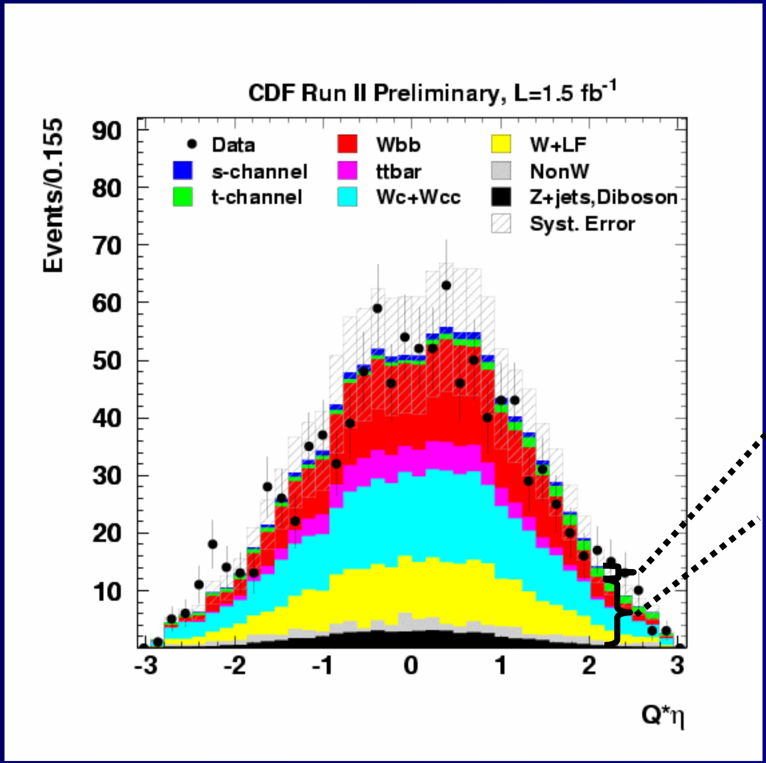
- In summer 2007, CDF also reported evidence for single top production with a two analysis methods: a matrix element method and a multivariate likelihood function
- D0 and CDF use similar approaches for the matrix element
- Expected sensitivity of 3.0σ; observed significance of 3.1σ

Jet flavor separator

- CDF analyses use a neural net to separate jets from *b*-quarks from light-quark jets
- Produces a continuous output – not a cut
- Improves sensitivity by 10–20%!



Multivariate likelihood function



- Multivariate binned likelihood combines several sensitive variables into a single discriminant
- Pioneered at LEP
- Seven variables in this analysis

N^{sig}

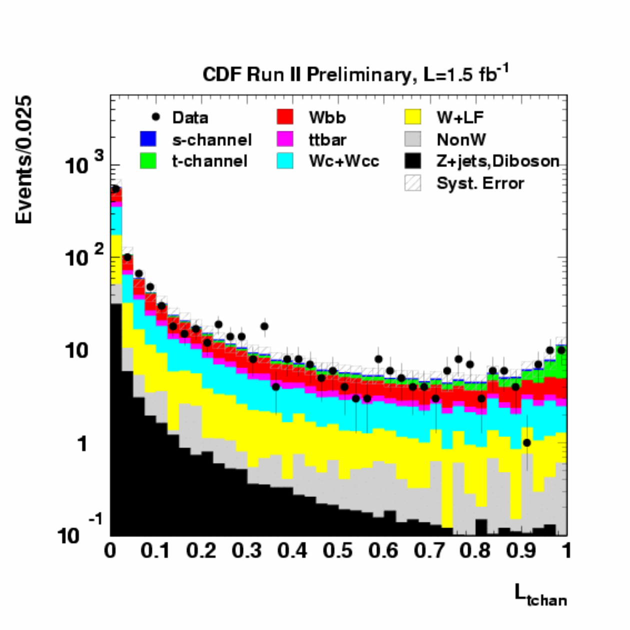
N^{bkg}

$$p_i^{sig} = \frac{N_i^{sig}}{N_i^{sig} + N_i^{bkg}}$$

$$L(\vec{x}) = \frac{\prod_{i=1}^{n_{\text{var}}} p_i^{sig}(x_i)}{\prod_{i=1}^{n_{\text{var}}} p_i^{sig}(x_i) + \prod_{i=1}^{n_{\text{var}}} p_i^{bkg}(x_i)}$$

CDF results with 1.5 fb^{-1}

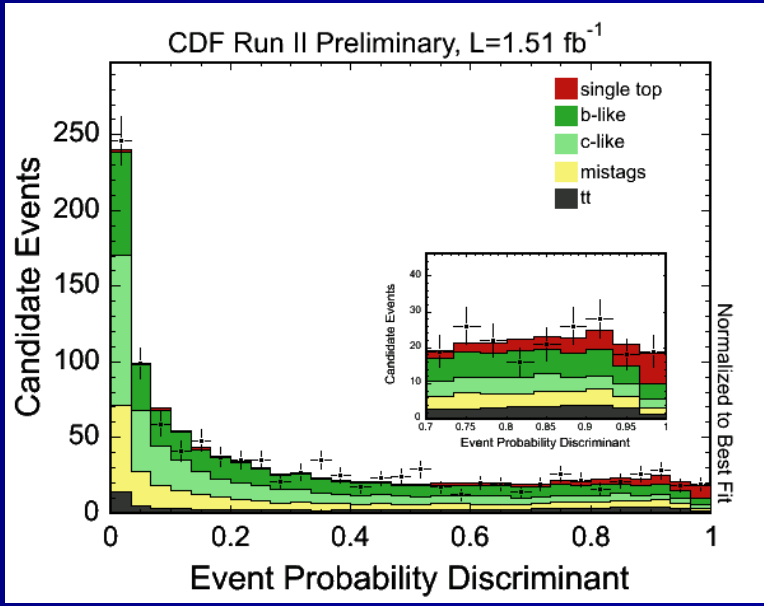
Likelihood function



Measured cross section:

$2.7^{+1.3}_{-1.1}$ pb

Matrix element



Measured cross section:

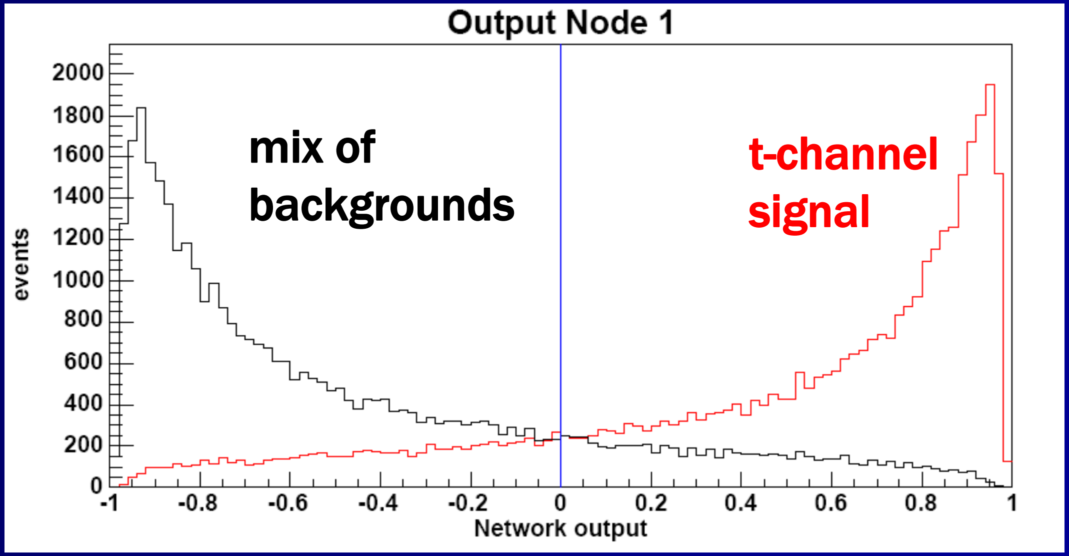
$3.0^{+1.2}_{-1.1}$ pb

More improvements

- Want to improve precision of measurement as much as possible
  - Add more data (another 700 pb^{-1})
  - Update neural network analysis
  - Increase acceptance
  - Improve separation of signal and background
- These will reduce expected uncertainty on the single top cross section, and thus $|V_{tb}|$

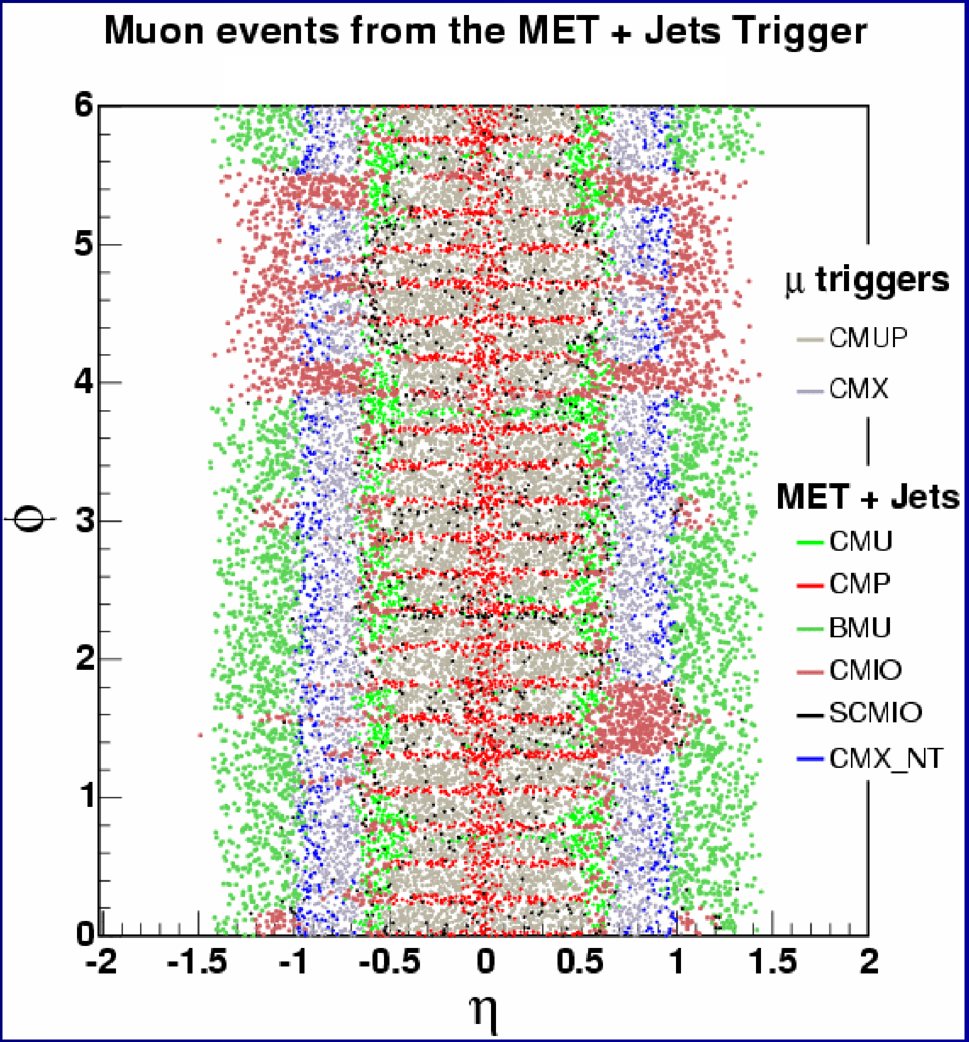
Neural network

- Update neural network measurement last used for 955 pb^{-1}
- Train separate networks for different tag multiplicities, based on the *b*-quark composition of each signal sample:
  - Train for t-channel for single-tagged events
  - Train for s-channel for double-tagged events



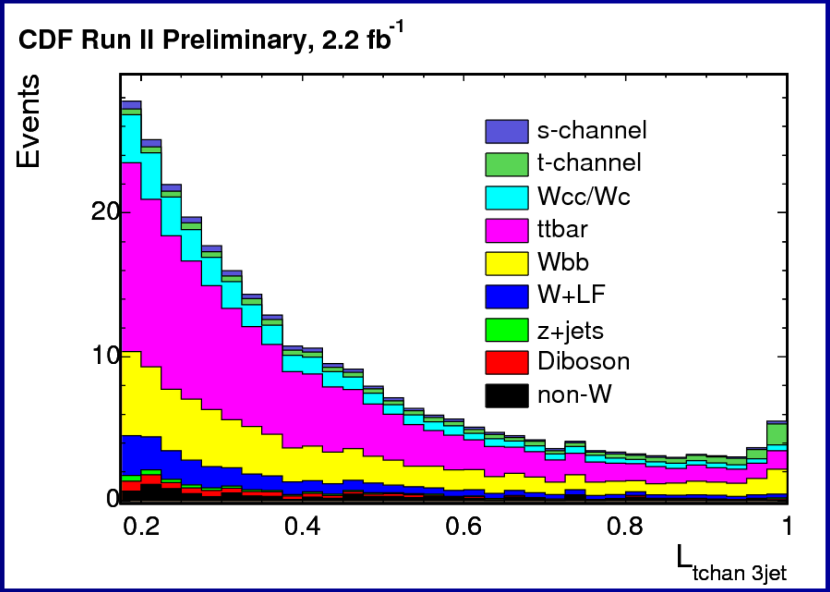
Extended muon coverage

- Increase acceptance by taking muons from complementary trigger (missing E_T plus two jets)
- New muons “fill in the cracks” left by triggered muons
- Improve overall sensitivity by 7%!



Three-jet events

- Can recover another ~20% of signal from three-jet events
- Three-jet events have large tt-bar background — much more difficult to separate signal from background
- Sensitivity improvement of ~3%



Acceptance improvement

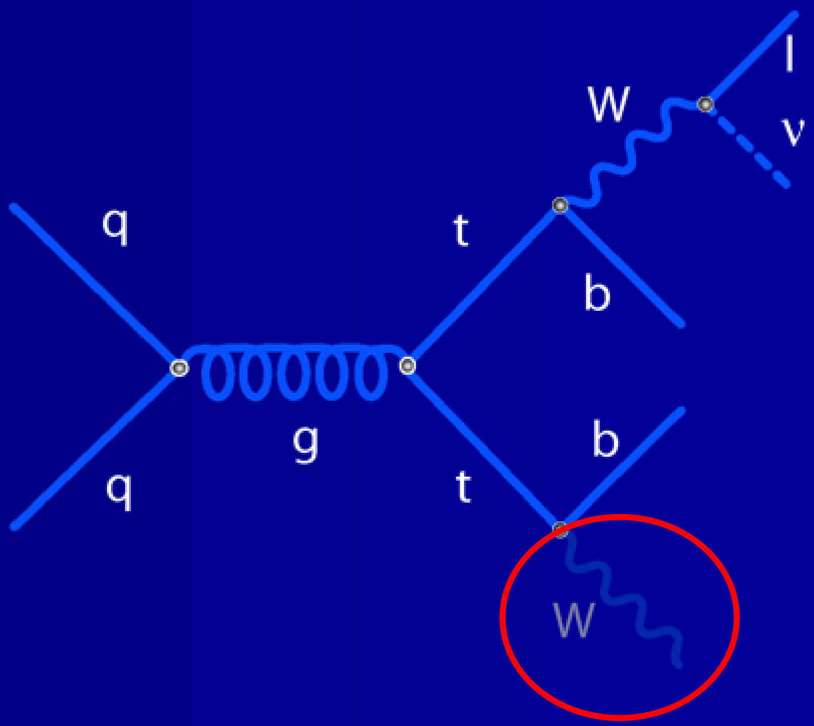
- Acceptance increases gives us more signal
- Luminosity scaling would give 88 expected events
- Now 125 single top events expected – 40% gain in signal acceptance!

CDF Run II Preliminary
Predicted event yield with 2.2 fb^{-1}

Process	2 jets			3 jets		
s-channel	41.2	±	5.9	13.5	±	1.9
t-channel	62.1	±	9.1	18.3	±	2.7
Single top	103.3	±	15.0	21.8	±	4.6
tt	146.0	±	20.9	338.7	±	48.2
Diboson	63.2	±	6.3	21.5	±	2.2
Z + jets	26.7	±	3.9	11.0	±	1.6
W + bottom	461.6	±	139.1	141.1	±	42.6
W + charm	395.0	±	121.8	108.8	±	33.5
W + light	339.8	±	56.1	101.8	±	16.9
Multijet	59.5	±	23.8	21.3	±	8.5
Total background	1491.8	±	268.6	754.8	±	91.3
Total prediction	1595.1	±	269.0	776.6	±	91.4
Observed	1535			712		

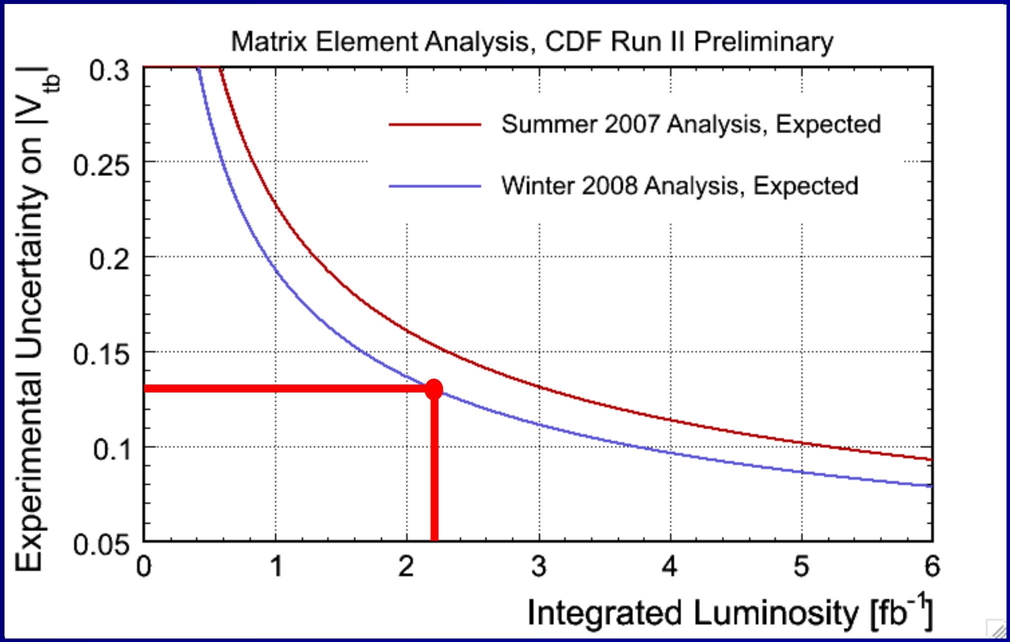
tt-bar matrix element

- Added *tt*-bar matrix element to matrix element method
- Assume a final-state *W* that has been missed (whether it decays leptonically or hadronically)
- Integrate over the unmeasured *W* particle to extract *tt*-bar probability
- Improves sensitivity by about 10%!

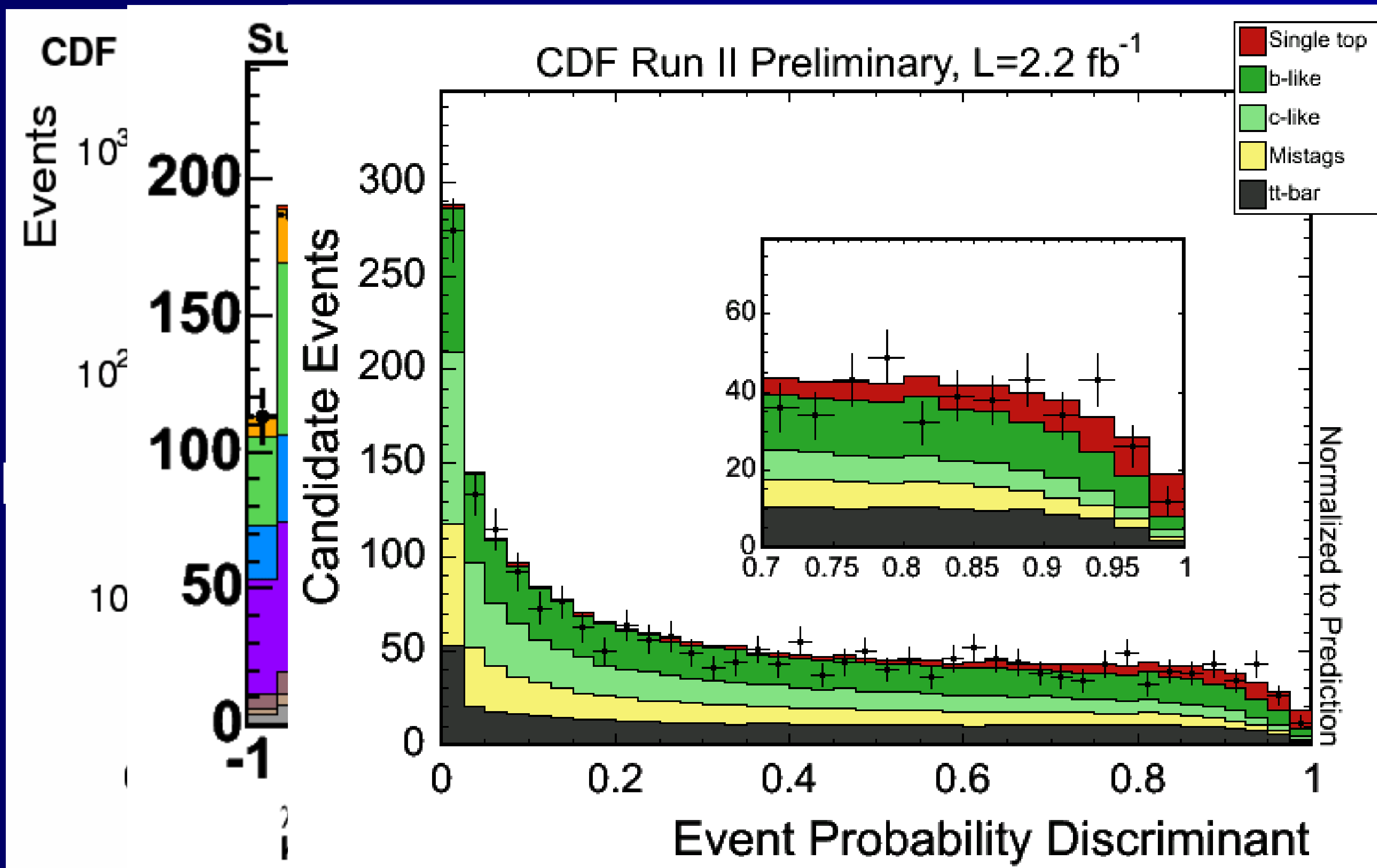


Sensitivity improvement

- Several small improvements add up
- Expected uncertainty on $|V_{tb}|$ for matrix element analysis increases by ~12% compared to simple luminosity scaling
- Equivalent to a 56% increase in data!

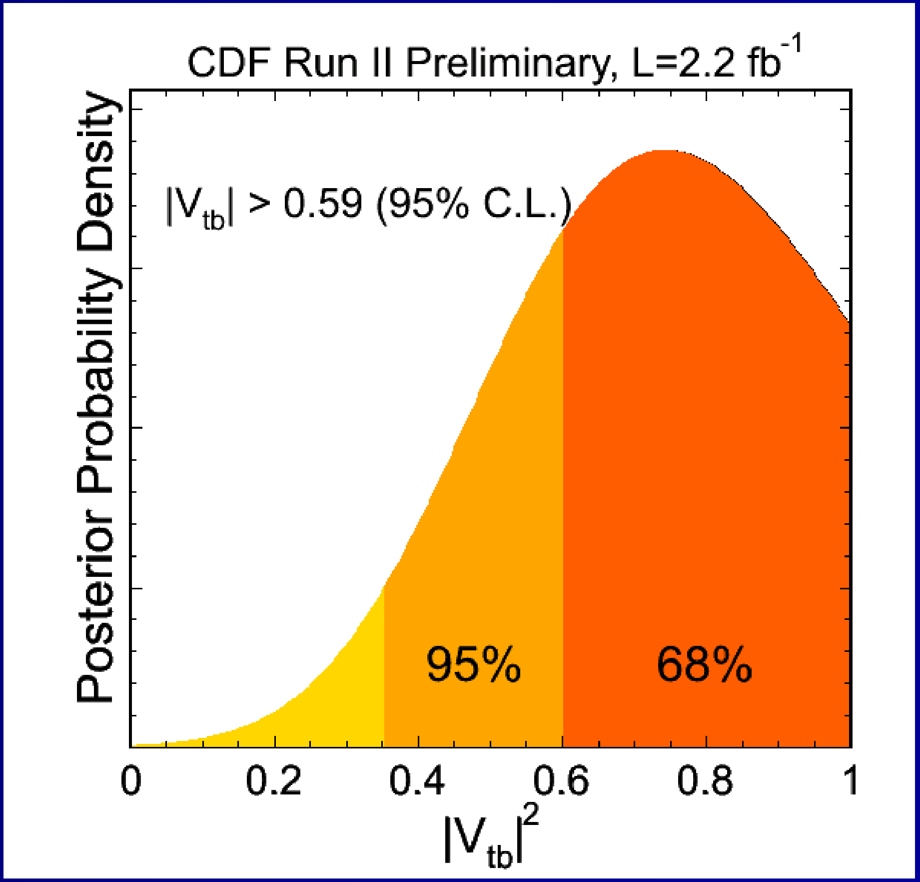


CDF results


CDF
Events
10^3
10^2
10
200
150
100
50
0
-1
CDF Run II Preliminary, L=2.2 fb^{-1}
Single top
b-like
c-like
Mistags
tt-bar
Candidate Events
300
250
200
150
100
50
0
0.2
0.4
0.6
0.8
1
60
40
20
0.7
0.75
0.8
0.85
0.9
0.95
Normalized to Prediction
Event Probability Discriminant

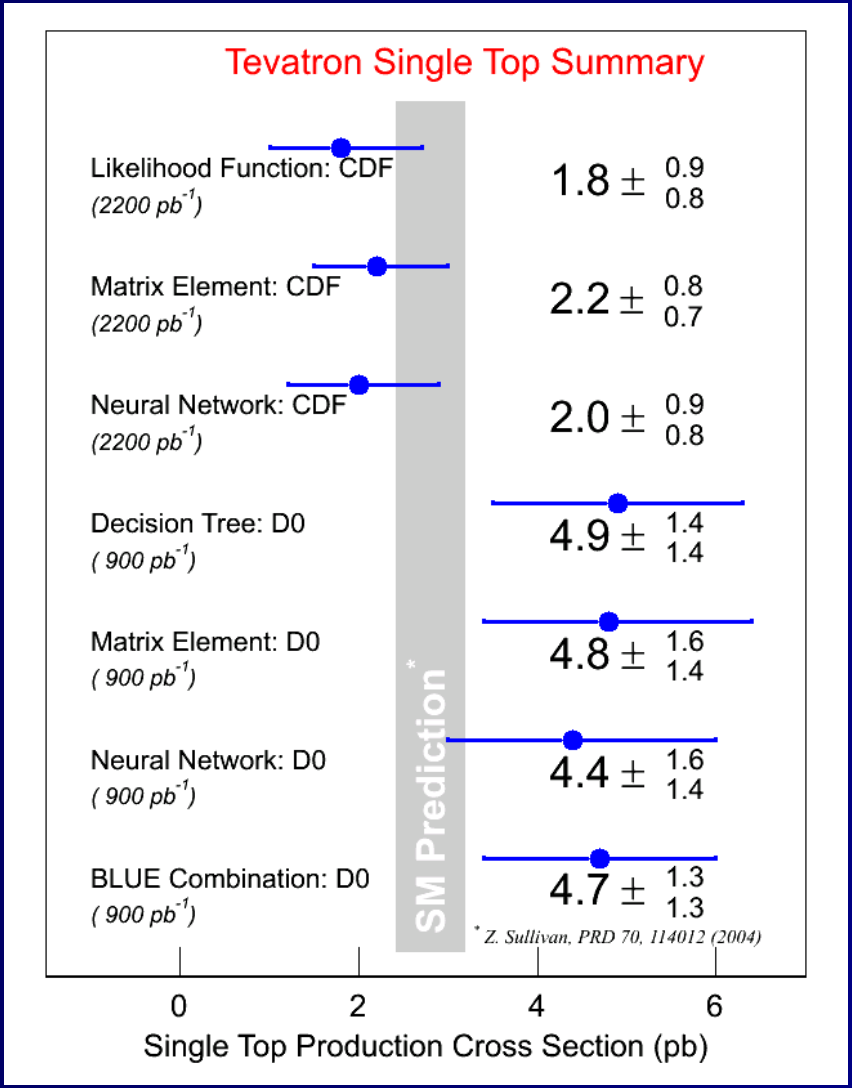
CDF measurement of $|V_{tb}|$

- Assume:
  - Flat prior in $|V_{tb}|^2$
  - $0 < |V_{tb}|^2 \leq 1$
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
- Combined measurement and limit in preparation



$$|V_{tb}| = 0.88^{+0.14}_{-0.12}\text{ (experiment)} \pm 0.07\text{ (theory)}$$

Tevatron summary



- CDF combination in preparation

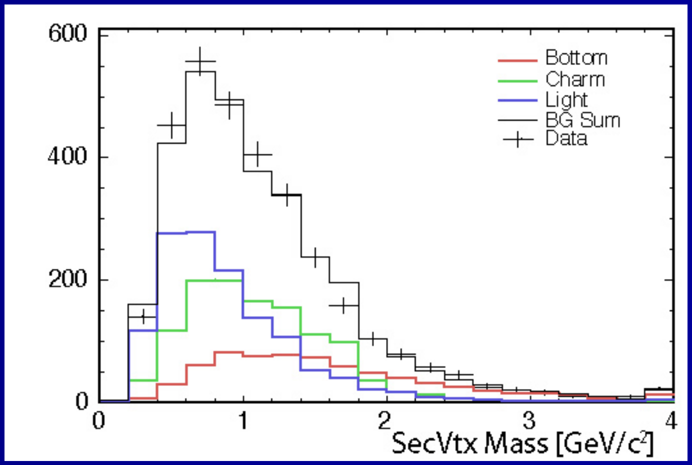
Conclusion

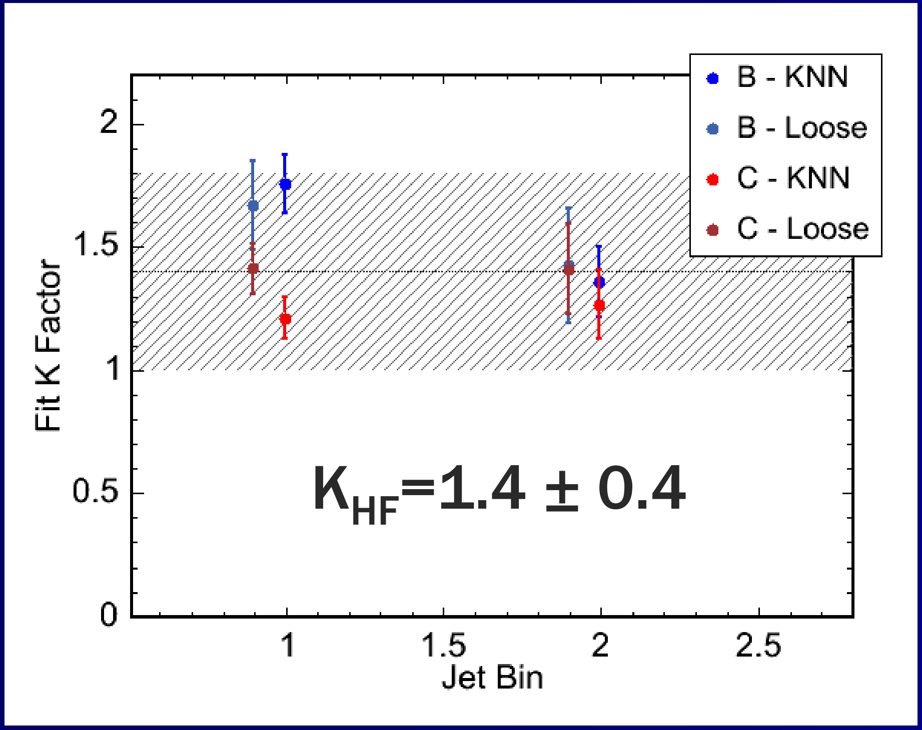
- Measuring the single top cross section is very challenging!
- Multivariate analysis techniques are essential to increase sensitivity
- Both CDF and D0 have seen evidence of single top quark production
- We are able to directly measure $|V_{tb}|$
- Now we enter the next stage:
  - Evidence for s- and t-channel production separately
  - Top quark polarization measurement
  - And, of course, onward to the Higgs!

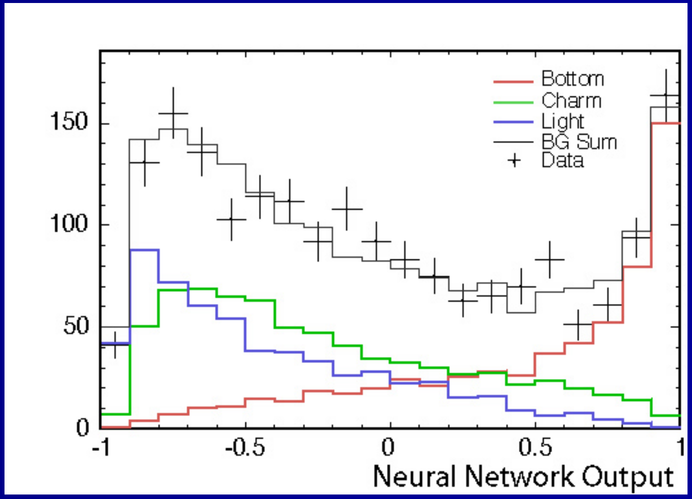
Backup slides

Heavy flavor calibration

- Calibrate *W* + heavy flavor in *W* + 1 jet data
- Three-parameter fit to bottom/charm/light templates of jet-flavor- separating distributions
- Correct for EWK/Top contributions
- Cross-check light flavor yield with prediction from mistag matrix



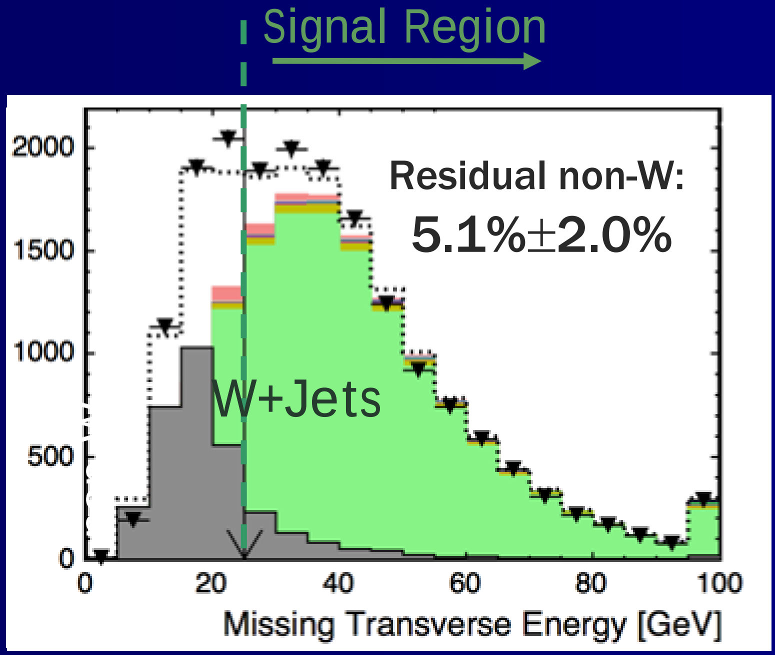




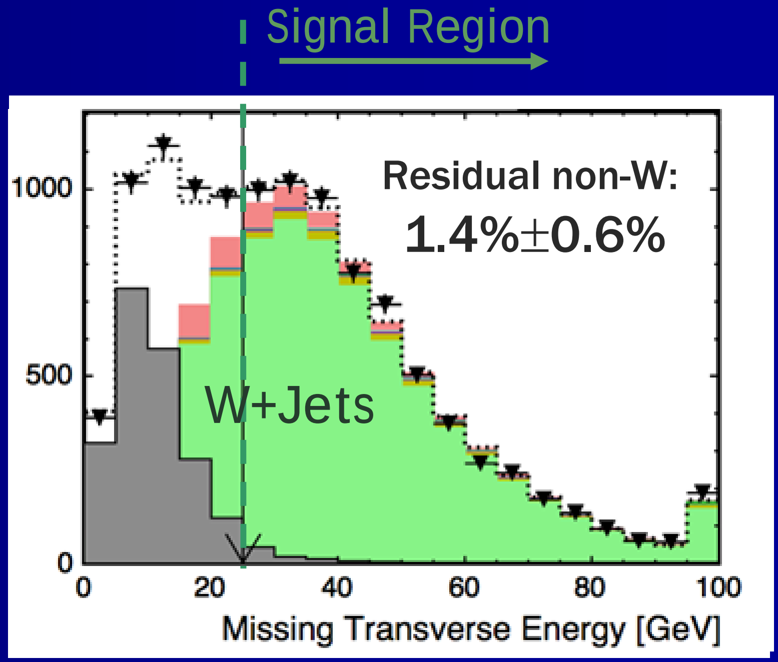
Non-W background

- Build non-*W* model from data
- Invert non-kinematic lepton identification cuts
- Data is superposition of non-*W* and *W*+jets contribution
- Do likelihood fit to data

Electrons + 2 Jets

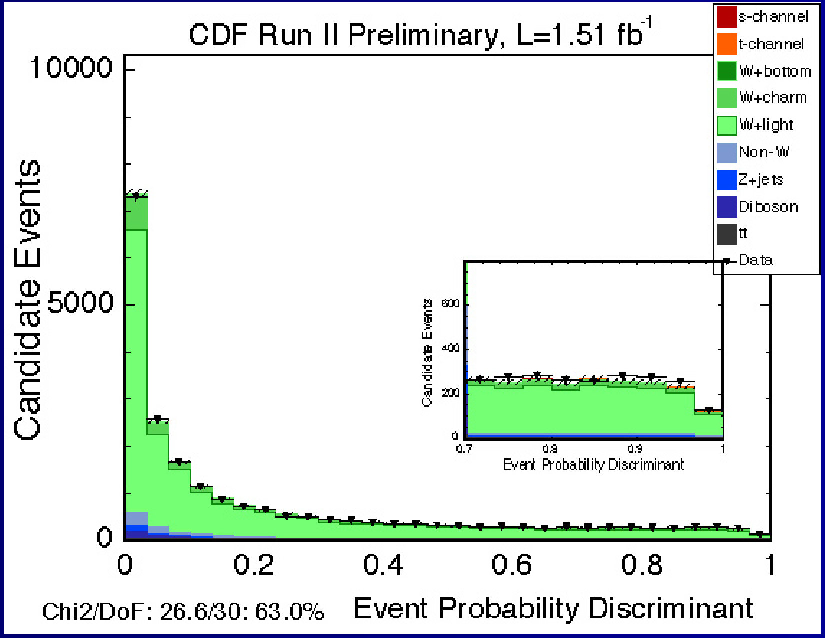


Muons + 2 Jets



Matrix element cross-check

- Check the discriminant in the orthogonal untagged region to show that we model the data well
- Region is dominated by light jets — validates our modeling of *W* + jet kinematics



Matrix element method

- Similar approach for both experiments
- CDF also includes jet flavor separator in discriminant to reduce contamination from light flavor jets:

$$EPD = \frac{b \cdot P_{Singletop}}{b \cdot P_{Singletop} + b \cdot P_{Wbb} + (1-b) \cdot P_{W+charm}}$$

Systematic errors

CDF Run II Preliminary

Systematic uncertainty	Range of Effect	Shape variations
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 jet flavor separator		✓
Mistag model		✓
Non-*W* model		✓
Q^2 scale in Alpgen Monte Carlo		✓
Monte Carlo mismodeling		✓