Single Top Quark Production at the Tevatron

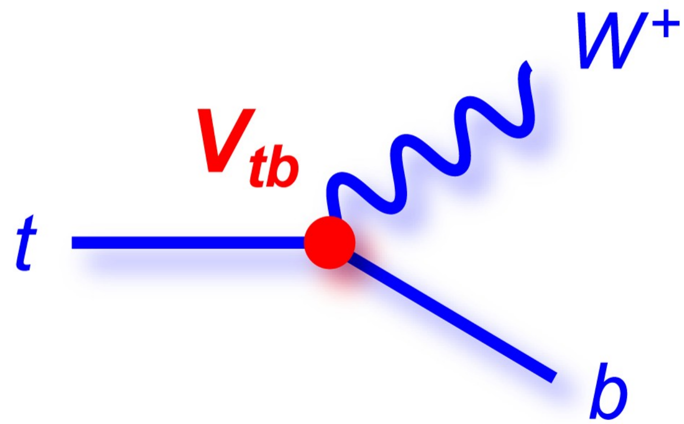
Reinhild Yvonne Peters

Georg-August University Göttingen & DESY

on behalf of the CDF & DØ Collaborations

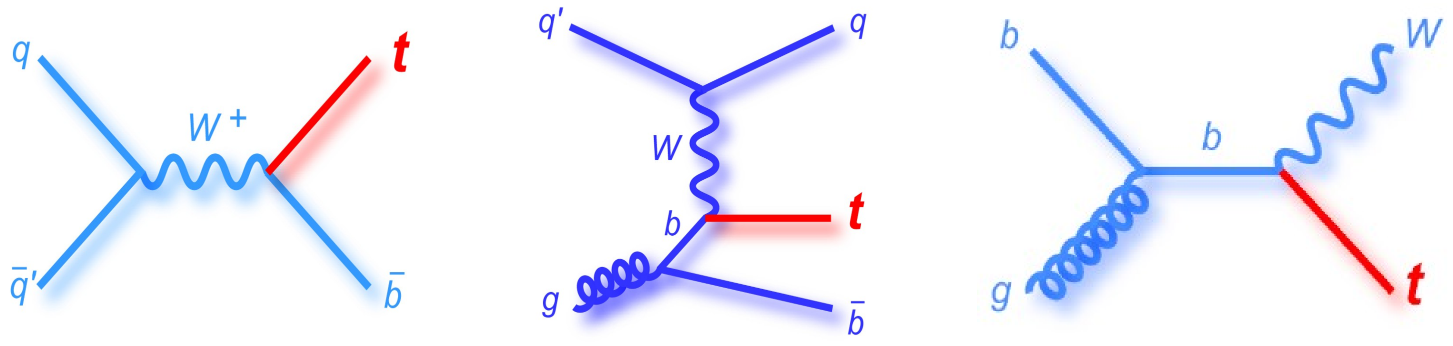
Motivation: Why study Single Top Quarks?

- Measure the production rate and compare to SM predictions
  - Test of EW interaction
  - Probe for new physics
- Physics beyond the SM could look similar to single top processes
  - Various models look similar to s- or t-channel production
- Direct probe of Wtb interaction
  - Direct measurement of CKM matrix element $|V_{tb}|$
- Single top similar to WH → testing ground for methods to extract a small signal



Single Top Cross Sections

- Single top quark production via electroweak interaction



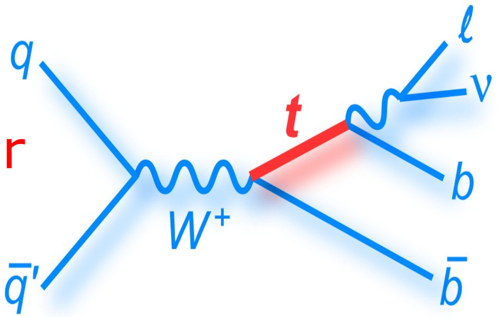
Collider	s-channel: σ_{tb}	t-channel: σ_{tqb}	Wt-channel: σ_{tW}
Tevatron: $p\bar{p}$ (1.96 TeV)	1.04 pb	2.26 pb	0.28 pb
LHC: pp (7 TeV)	4.6 pb	64.6 pb	15.7 pb

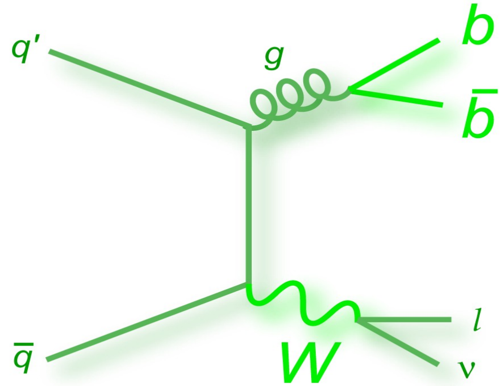
- Wt-channel: negligible at the Tevatron
- s-channel: challenging at the LHC

The Challenge

- (s+t) production cross section about ½ of $t\bar{t}$
- Single top signature similar to W+jets background

Simulated with Comphep (DØ) or POWHEG (CDF) +Pythia





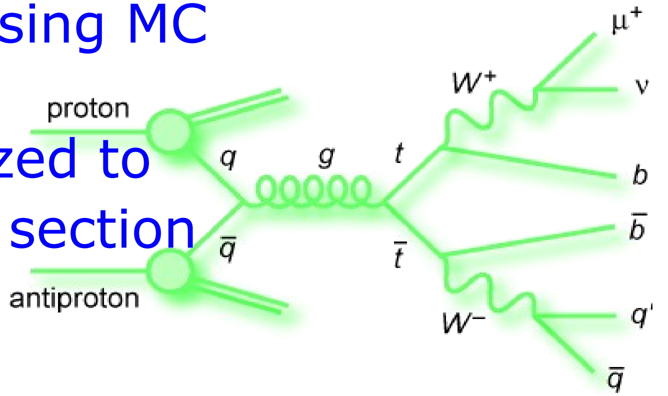
Modeled using Alpgen+Pythia/ Herwig

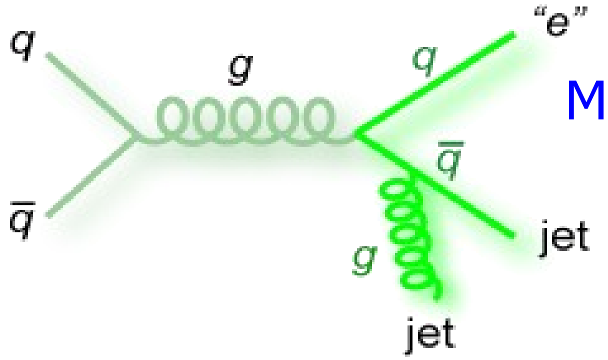
Normalized to Data

- Other important backgrounds: $t\bar{t}$ and multijet

Modeled using MC

Normalized to SM cross section

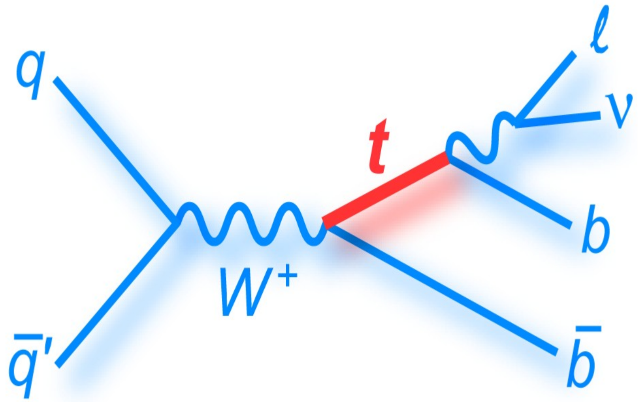




Modeled using Data

Event Selection

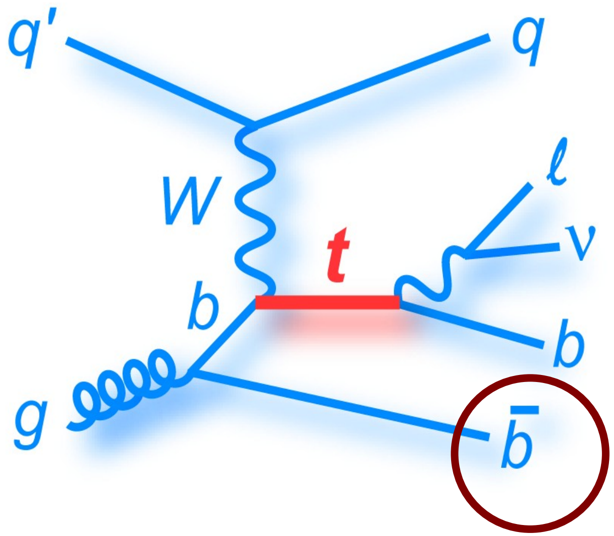
- Enrich data sample in single top-like events:



Exactly one high p_T
isolated electron or muon

Large $\not{E}_T$ for the neutrino

2, 3 (and 4) jets with high p_T



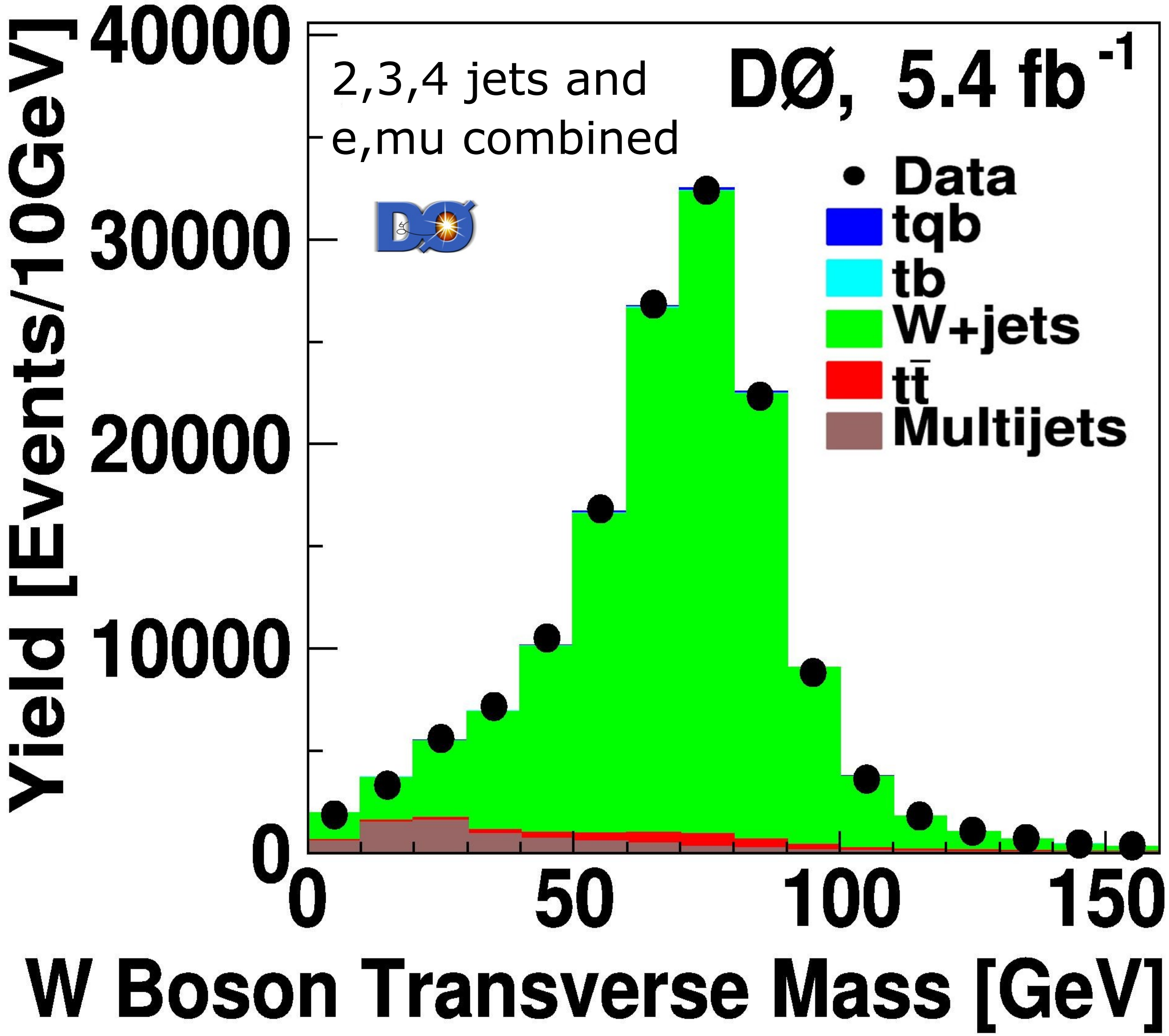
Angular and total energy cuts to reject multijet background

Very challenging to understand: high $|\eta|$ and low p_T

- Important tool to reject background: b-jet identification

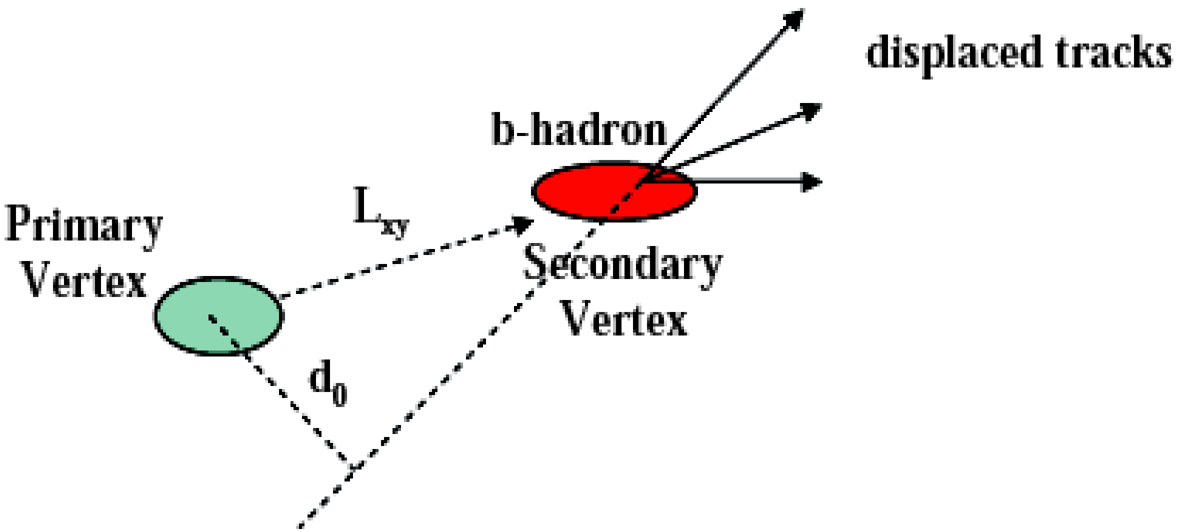
After Event Selection and before b-jet identification

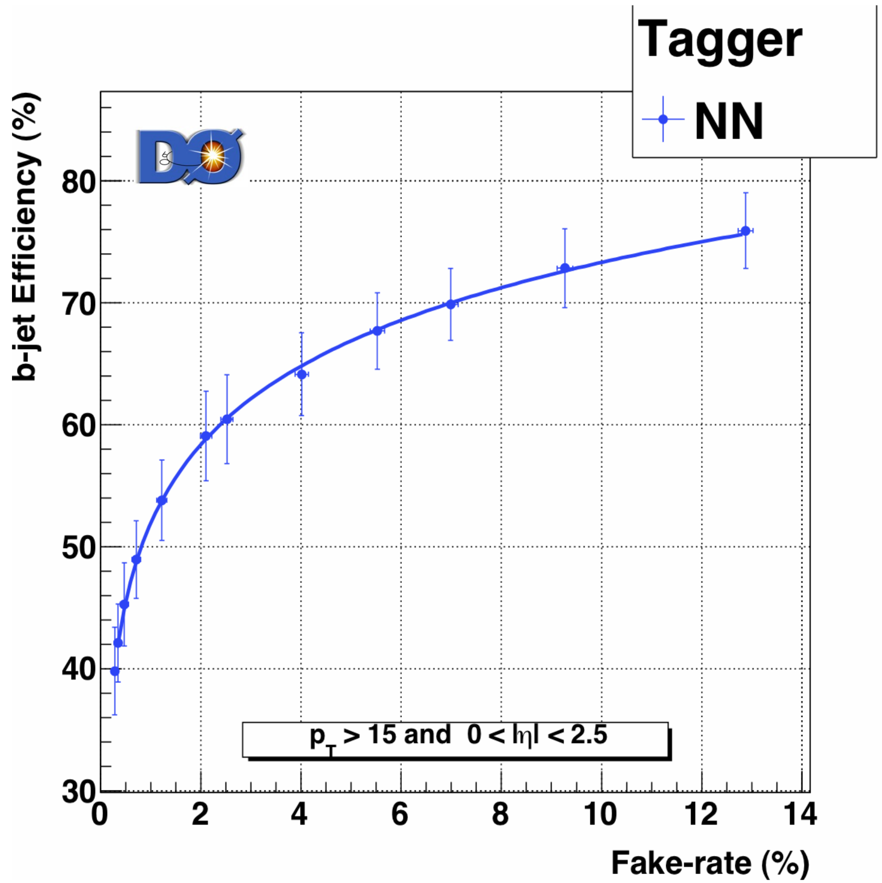
- Before b-jet identification: single top signal hardly visible!
  - S/B of about 1:185
- W+jets normalized to data before b-jet identification



Identification of b-Jets

- Important to increase $t\bar{t}$ purity
- b-hadron: travels some millimeters before it decays
- Neural Network (DØ)
  combines properties of displaced tracks and displaced vertices



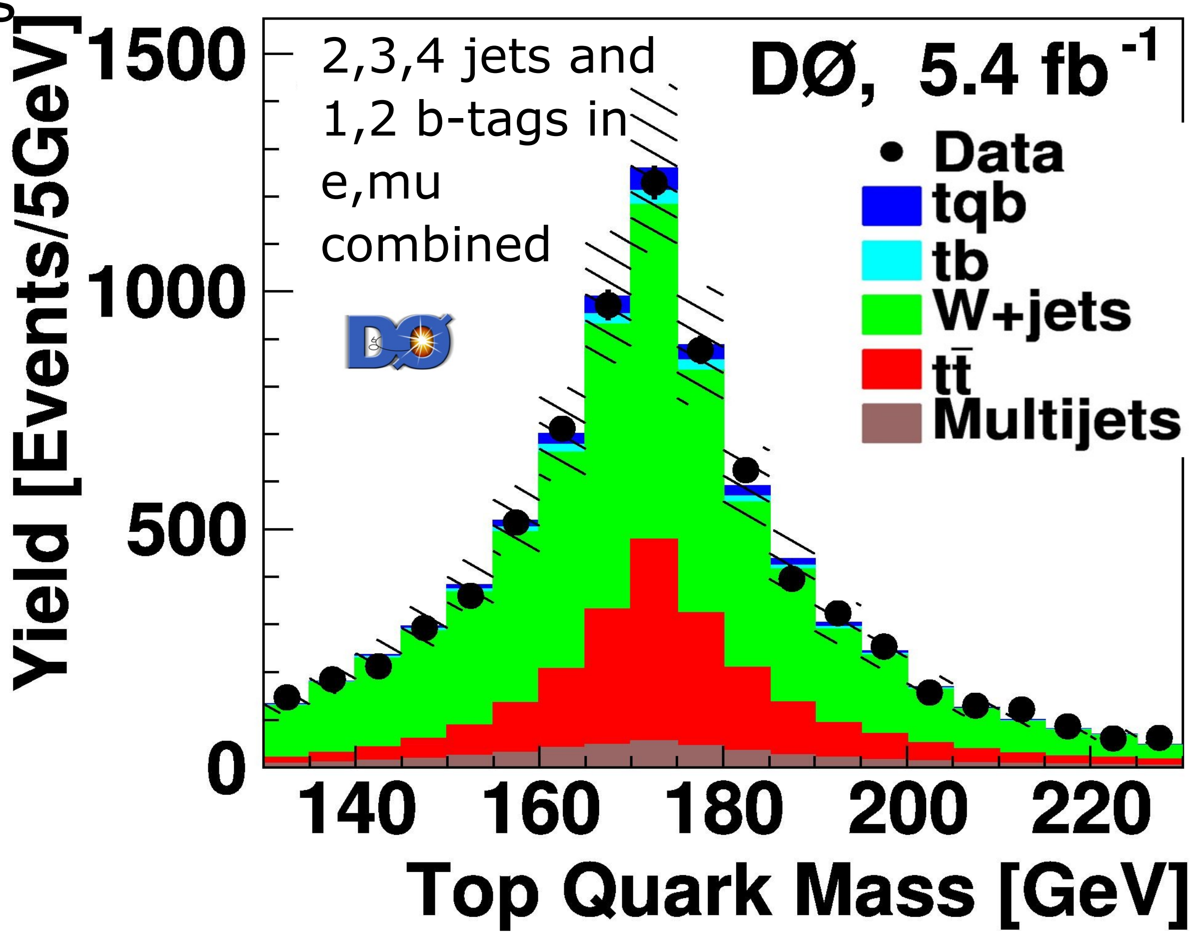


After Event Selection and after b-jet Identification

- Require 1 or 2 identified b-jets
  - S:B about 1:20

- Background enriched samples ($t\bar{t}$ and W+jets enriched) to check background modeling

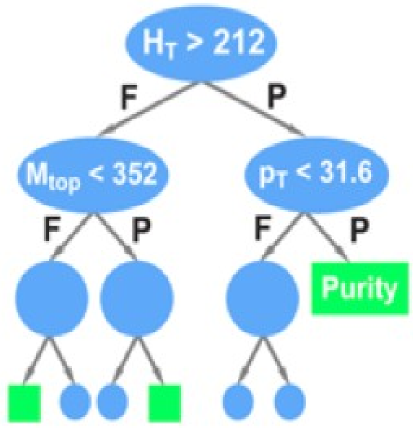
- Using counting-only: Systematic uncertainty on background larger than signal

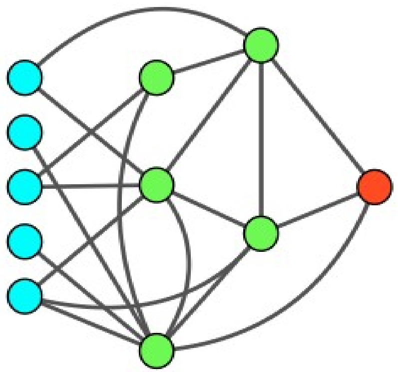


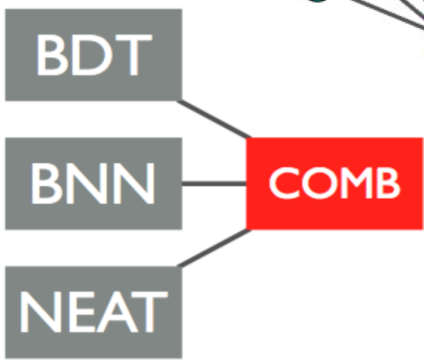
- Use multivariate discriminant techniques to separate signal from background

Further Signal Enhancement: Multivariate Discriminants

- Several techniques used for MVAs
  - Boosted Decision Trees (BDTs)
    - Application of sequential cuts
  - (Bayesian) Neural Networks
  - NEAT
    - Generic algorithms evolving a population of NNs
  - Matrix Elements
    - Use the full event kinematics
- Combination of different techniques
  - BLUE
  - For observation and now:
    use the outputs of the discriminants
    as input to a super-discriminant



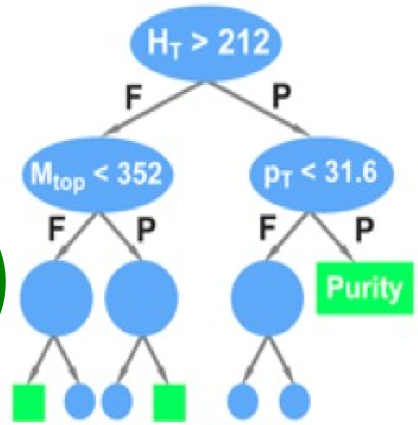


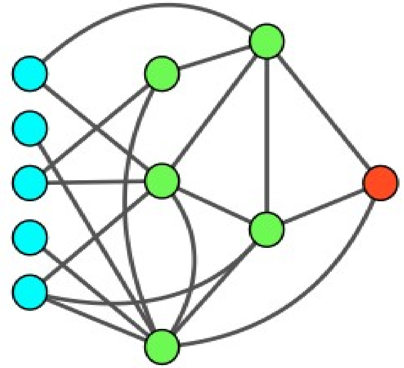


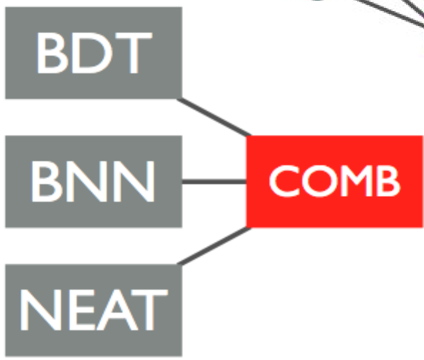
Further Signal Enhancement: Multivariate Discriminants

- Several techniques used for MVAs
  - Boosted Decision Trees (BDTs)
    - Application of sequential cuts
  - (Bayesian) Neural Networks
  - NEAT
    - Generic algorithms evolving a population of NNs
  - Matrix Elements
    - Use the full event kinematics
- Combination of different techniques
  - BLUE
  - For observation and now:
    use the outputs of the discriminants
    as input to a super-discriminant

Used by CDF in new 7.5fb^{-1} analysis



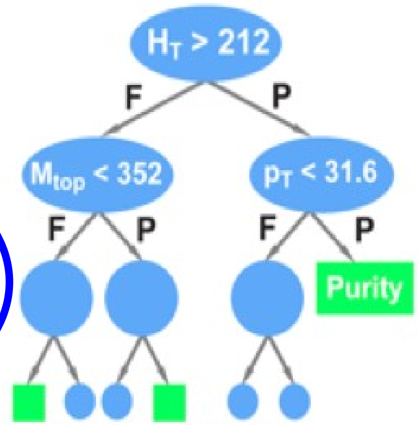


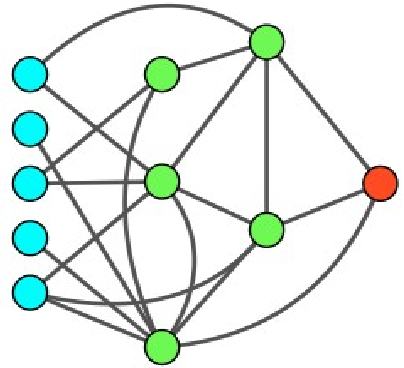


Further Signal Enhancement: Multivariate Discriminants

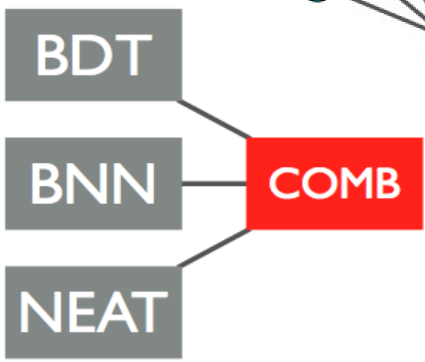
- Several techniques used for MVAs
  - Boosted Decision Trees (BDTs)
    - Application of sequential cuts
  - (Bayesian) Neural Networks
  - NEAT
    - Generic algorithms evolving a population of NNs
  - Matrix Elements
    - Use the full event kinematics

Used by DØ in new 5.4fb^{-1} analysis



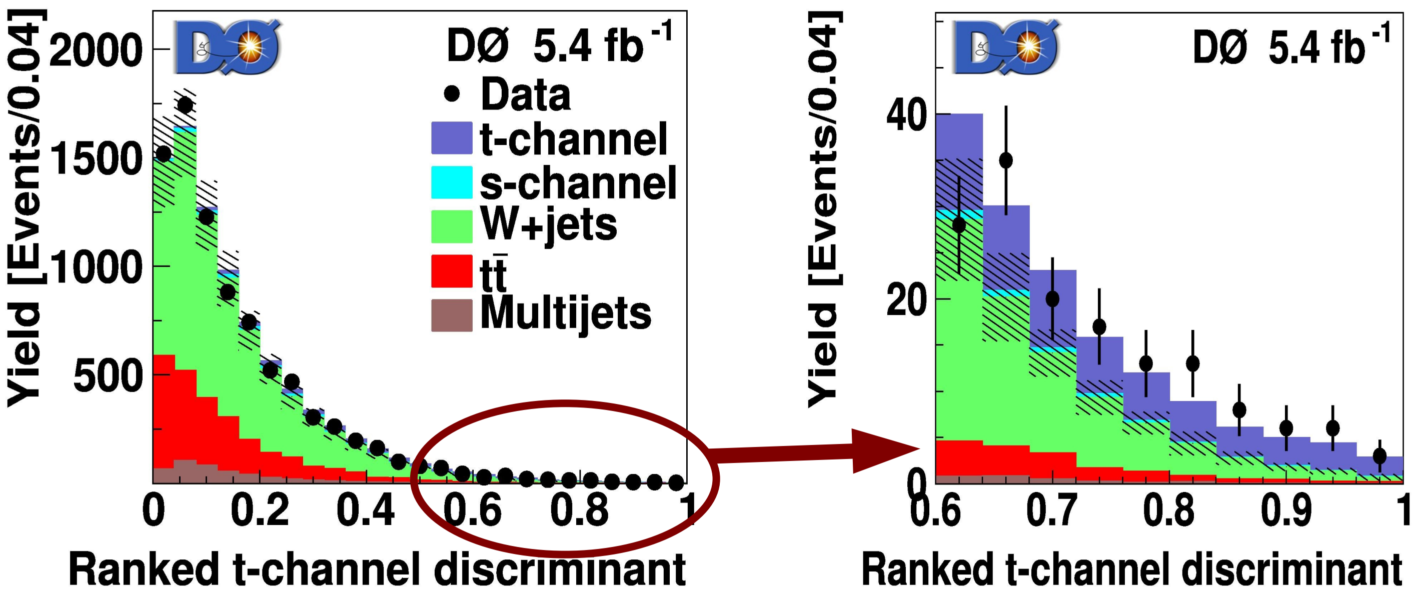


- Combination of different techniques
  - BLUE
  - For observation and now: use the outputs of the discriminants as input to a super-discriminant (BNN)



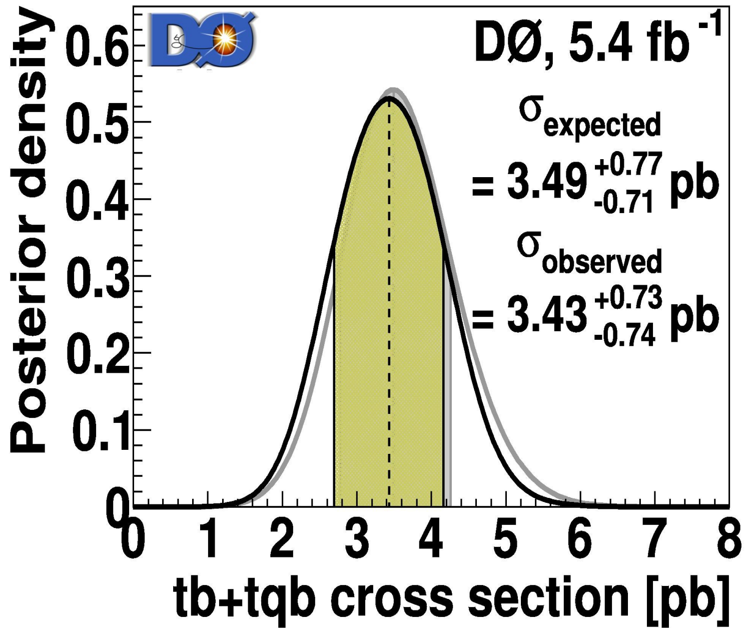
Training and cross section extraction

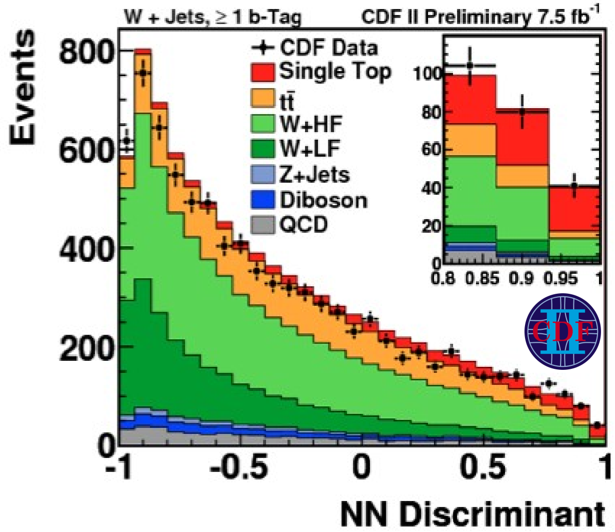
- Train MVA on
  - s+t channel using SM ratio between s- and t-channel
  - t-channel with s-channel as background in training (not in fit)
  - s-channel with t-channel as background in training (not in fit)
- Bayesian method to extract cross section results
  - Integration over systematic uncertainties (modeled as Gaussian priors)
- Example: t-channel trained discriminant

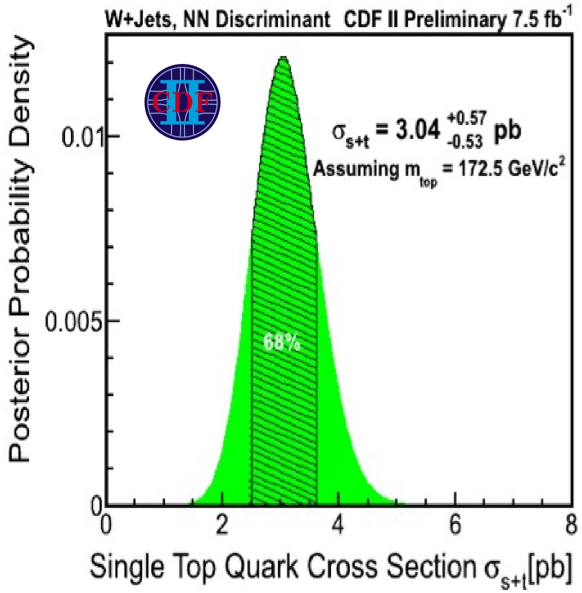


Results: (s+t)-Channel

- Trained discriminants on s+t channel







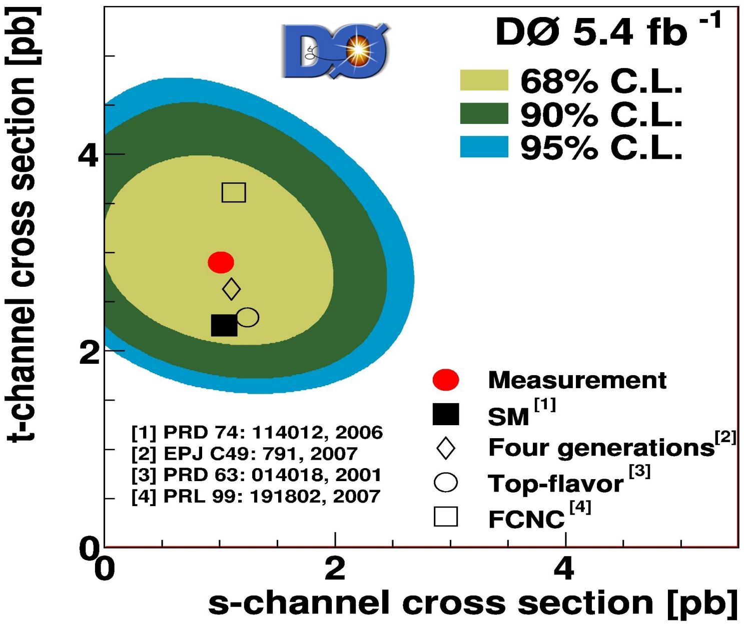
$$\sigma_{s+t} = 3.43^{+0.73}_{-0.74}\, pb$$ PRD 84, 112001 (2011)

$$\sigma_{s+t} = 3.04^{+0.57}_{-0.53}\, pb$$ for m_t=172.5GeV

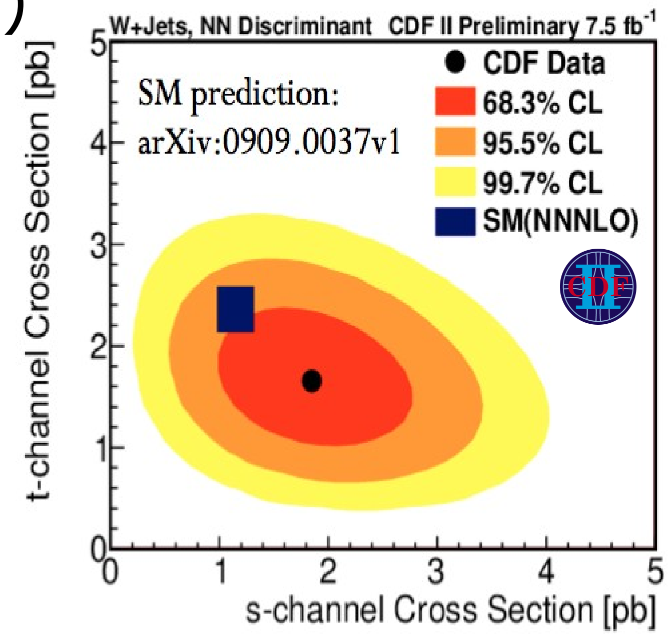
- Main systematic uncertainties from
  - Luminosity
  - Jet-energy related uncertainties
  - Uncertainties on b-jet identification scale factors

2D Single Top

- s- and t-channel are differently sensitive to new physics
  - Measure both channels simultaneously
- Train on t-channel (DØ) or s-channel (CDF)



In agreement with SM prediction



$$\sigma_s = 0.98 \pm 0.63\ pb$$

$$\sigma_t = 2.90 \pm 0.59\ pb$$

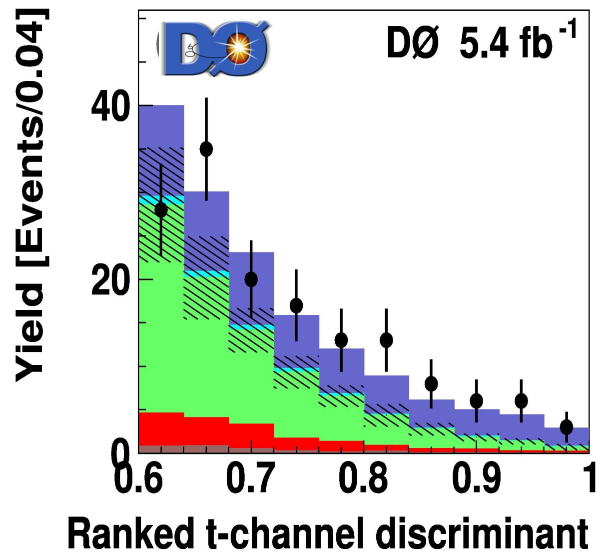
PLB 705, 313 (2011)

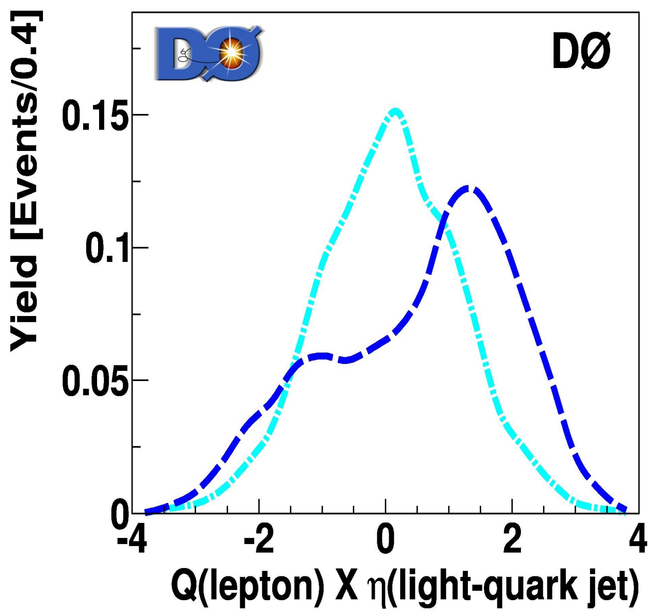
$$\sigma_s = 1.81^{+0.63}_{-0.58}\ pb$$

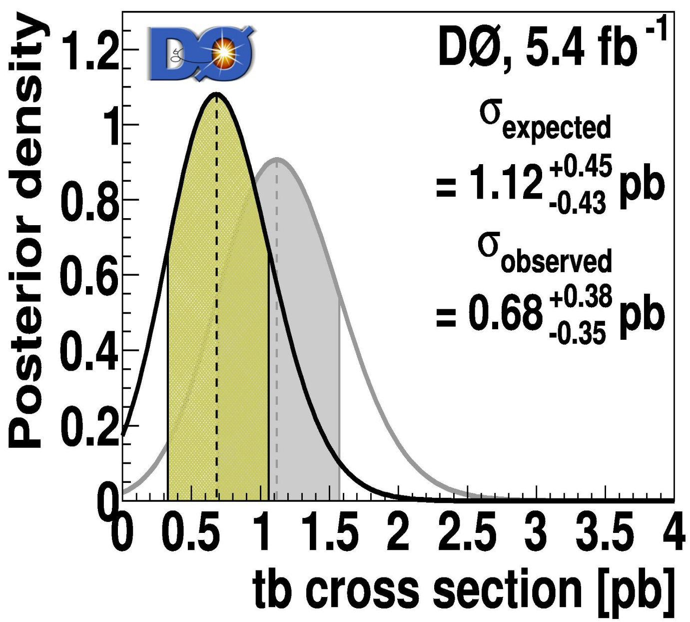
$$\sigma_t = 1.49^{+0.47}_{-0.42}\ pb$$

t-Channel and s-channel

- In 2D: Integrate over s-channel → t-channel cross section
- Result: $\sigma_t = 2.90 \pm 0.59\ pb$
- First observation of t-channel with 5.5 standard deviations (SDs) significance
- s-channel trained MVA → not yet significant at DØ





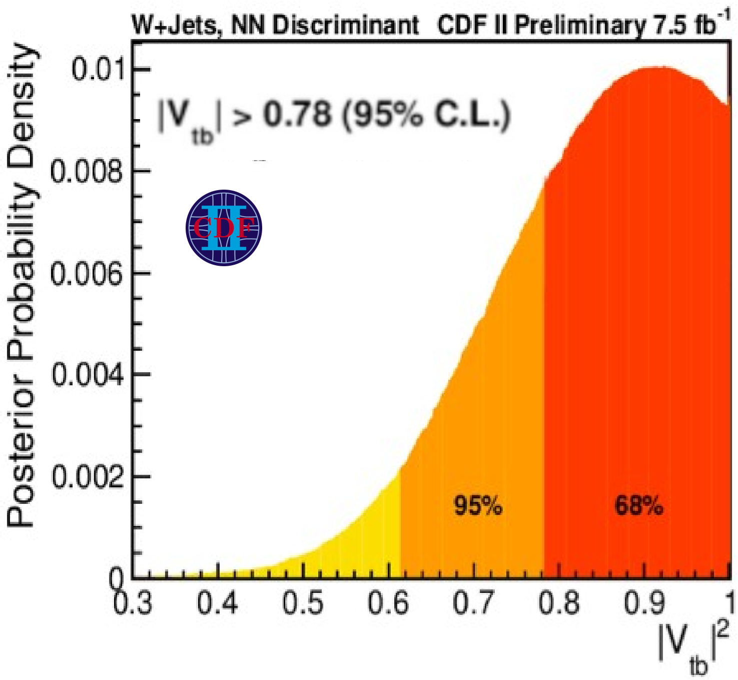


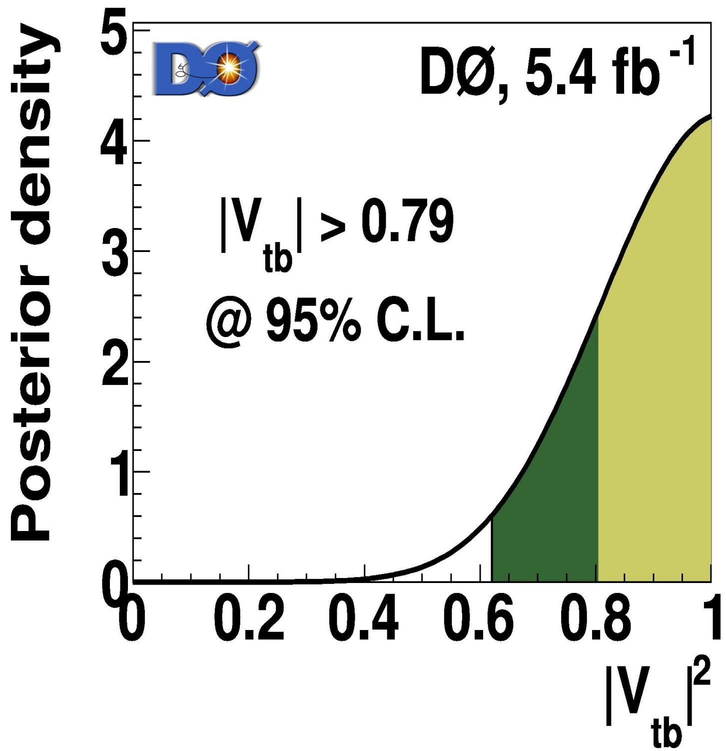
PLB 705, 313 (2011)

$|V_{tb}|$

- Direct extraction of V_{tb} from single top cross section $|V_{tb}|^2 \propto \sigma(s+t)$
  - No assumption about number of generations
  - Assumption: $|V_{ts}|^2+|V_{td}|^2 << |V_{tb}|^2$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



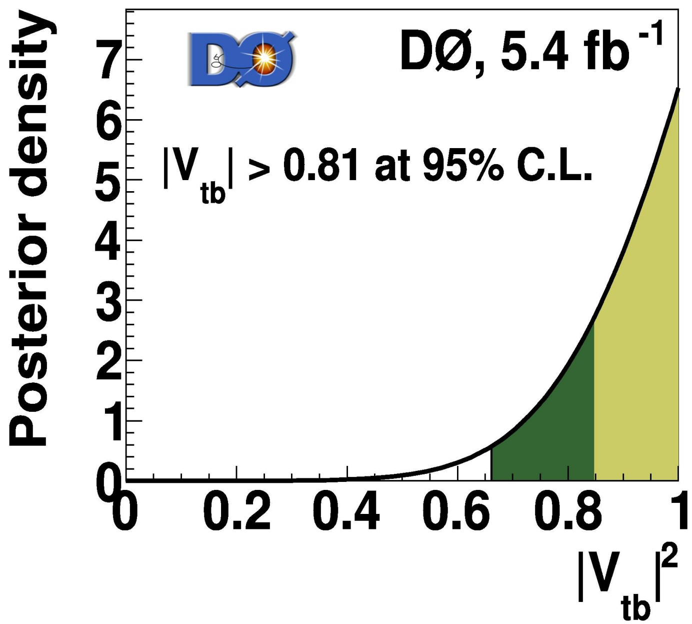


PRD 84, 112001 (2011)

$|V_{tb}|$ revisited

- Direct extraction of V_{tb} from partial top width $|V_{tb}|^2 \propto \Gamma(t \to b)$
  - No assumption about number of generations
  - NOT assuming $|V_{ts}|^2+|V_{td}|^2 << |V_{tb}|^2$
  - NOT assuming SM ratio between s- and t-channel cross sections

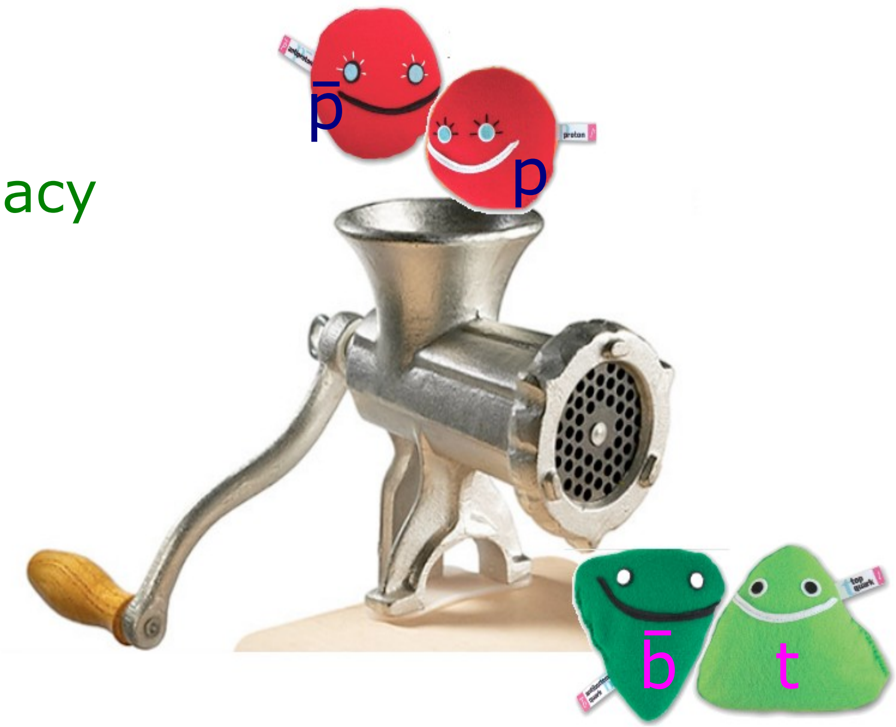
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



PRD 85, 091104 (2012)

Summary

- Single Top at Tevatron: A real challenge!
  - Ideas and methods were developed and established
  - From cross section measurements
    to searches and properties studies
  - s-channel single top: A Tevatron Legacy



- More details on the results:

DØ: http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

CDF: http://www-cdf.fnal.gov/physics/new/top/top.html

BACKUP

The Top Quark

- Heaviest known elementary particle:

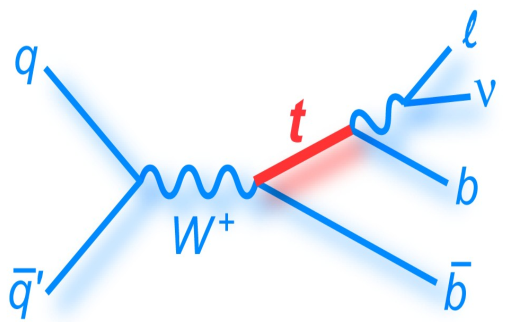
  m_t=173.3±1.1GeV

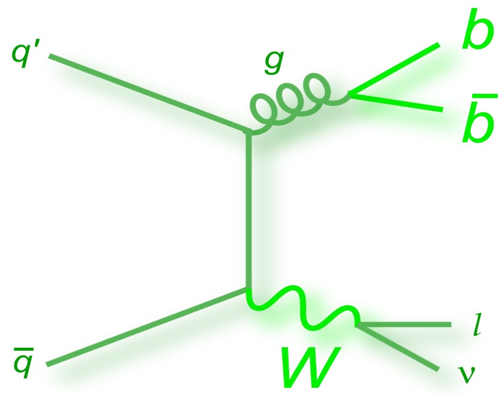
  arXiv:1007.3178

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

The Challenge

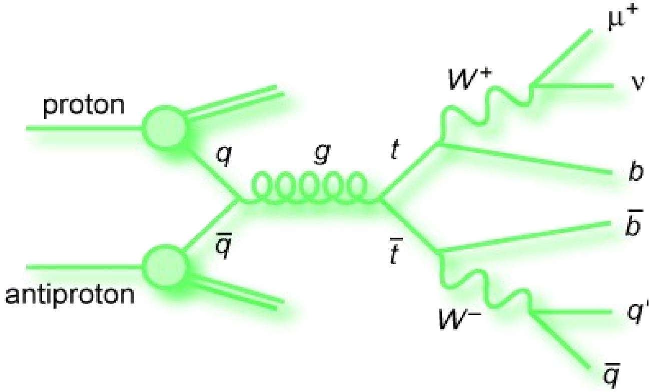
- Production cross section about ½ of $t\bar{t}$
- Single top signature similar to W+jets background



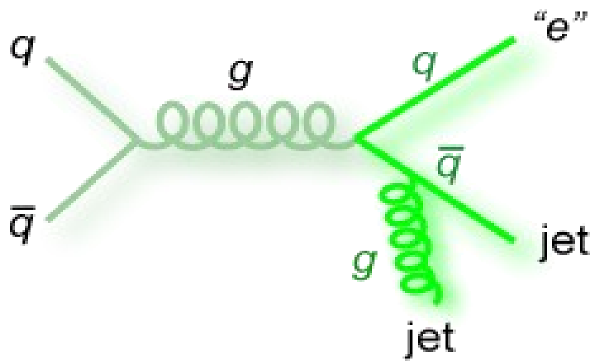


- Other important backgrounds:

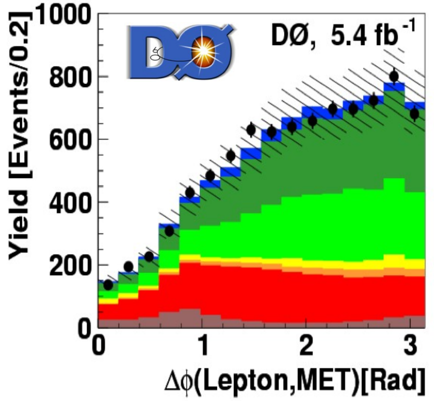
$t\bar{t}$

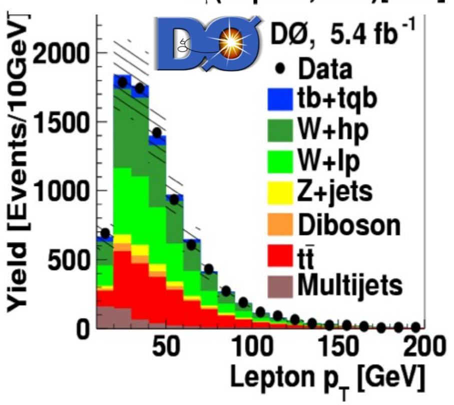


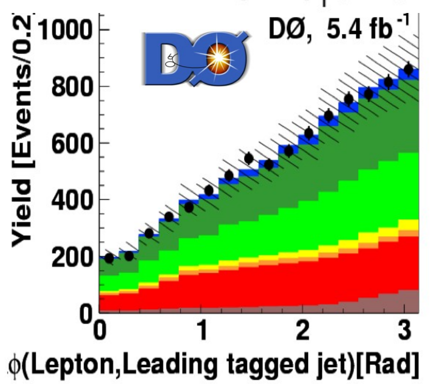
and multijet



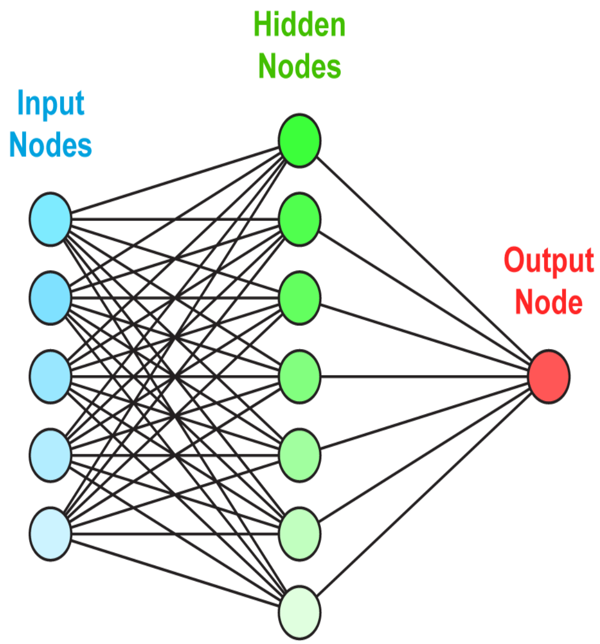
Further Signal Enhancement: Multivariate techniques

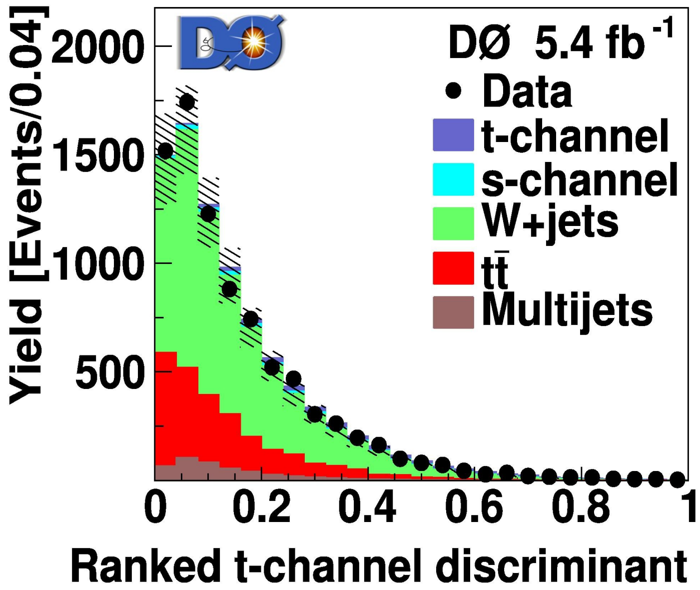






- 1. Select variables discriminating signal and background
- 2. Combination via a multivariate analysis (MVA) tool
- 3. Fit the distribution

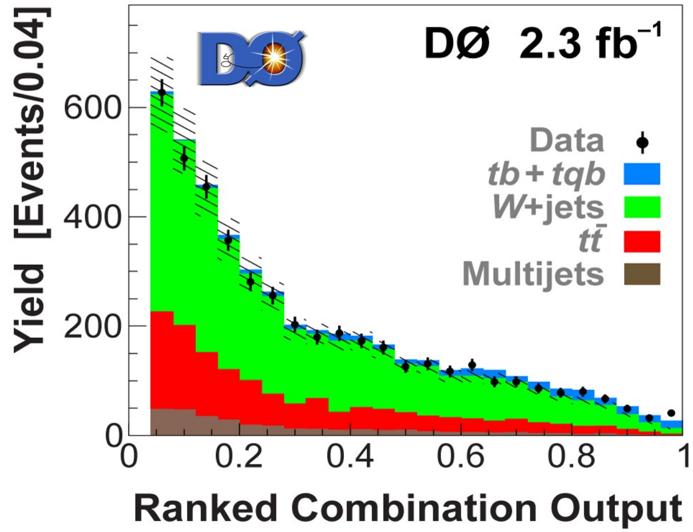




Results: Single Top Observation 2009

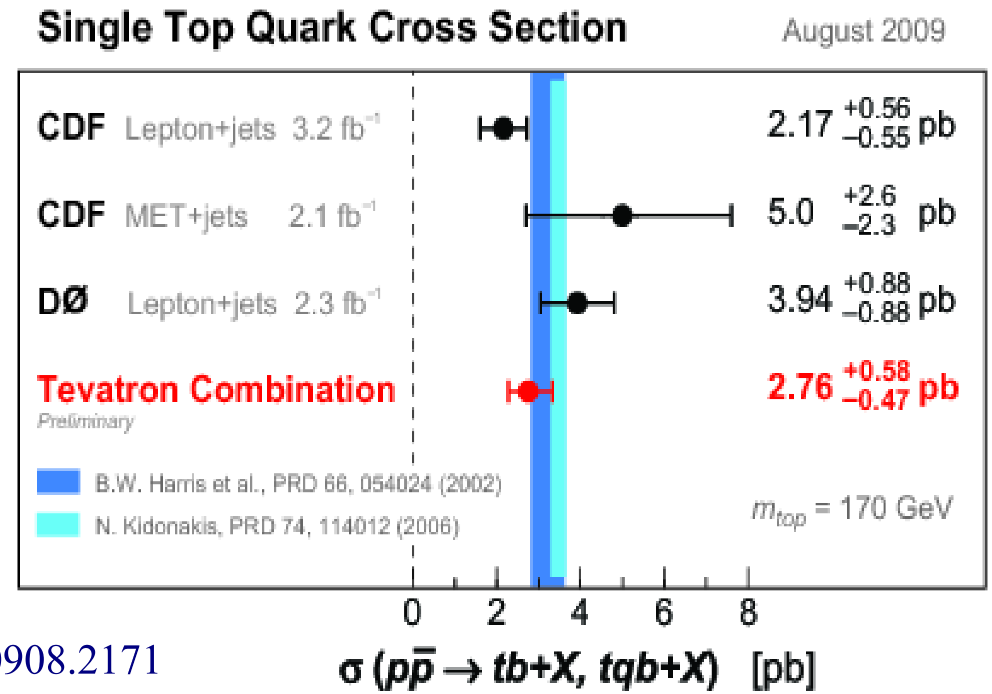
- Observation 14 years after top discovery
- Usage of multiple multivariate techniques by CDF and D0
  - BDT, Matrix Element, (B)NN, NEAT

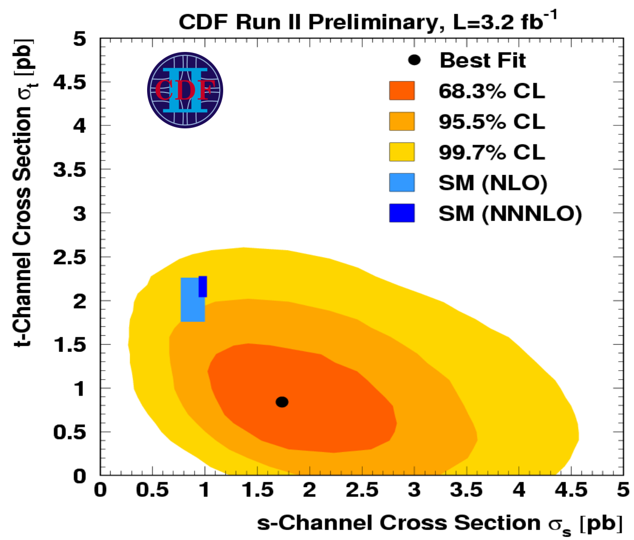
Final Discriminant



5σ

5σ

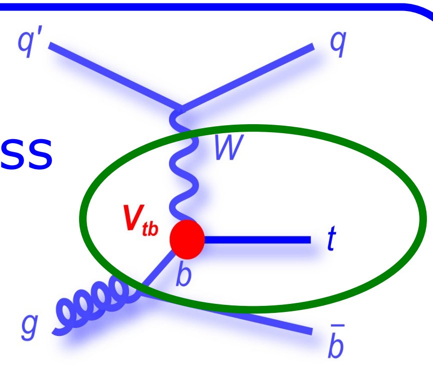


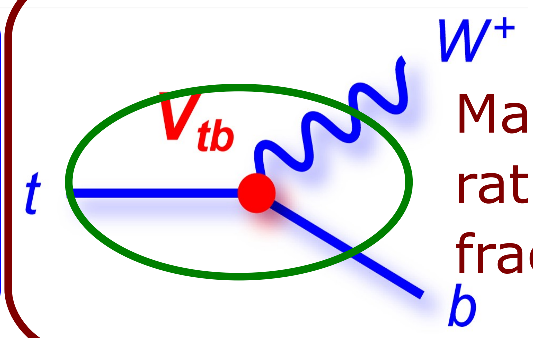


arXiv:0908.2171

Top Quark Width

Main ingredient:
t-channel single top cross section measurement





Main ingredient:
ratio of branching fractions measurement

$$\Gamma_t = \frac{\Gamma(t \to Wb)}{B(t \to Wb)}$$

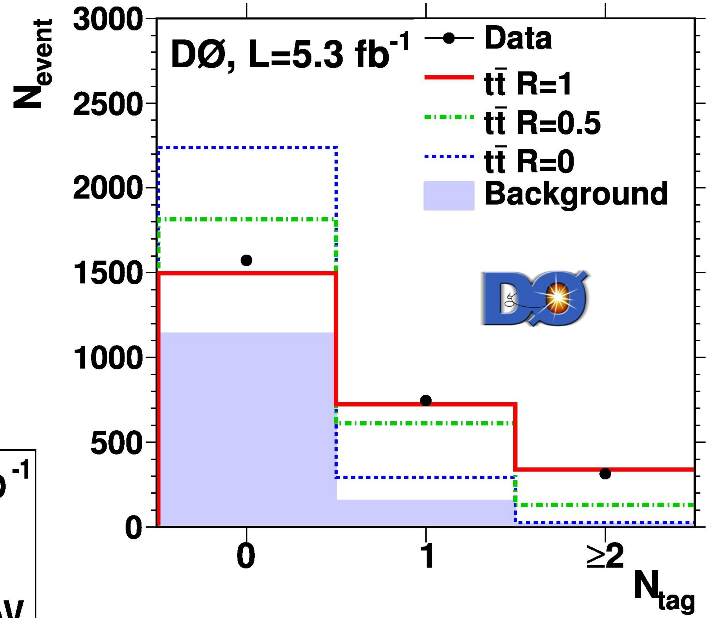
- Partial width:

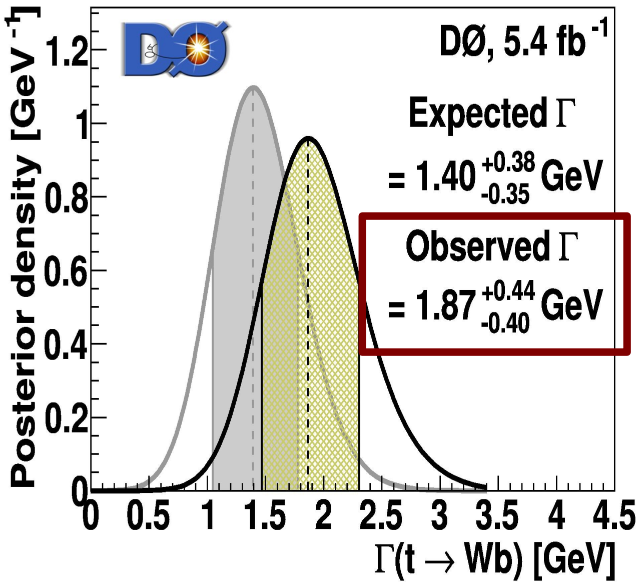
$$\Gamma(t \to Wb) = \sigma(t-channel) \times \frac{\Gamma(t \to Wb)_{SM}}{\sigma(t-channel)_{SM}}$$

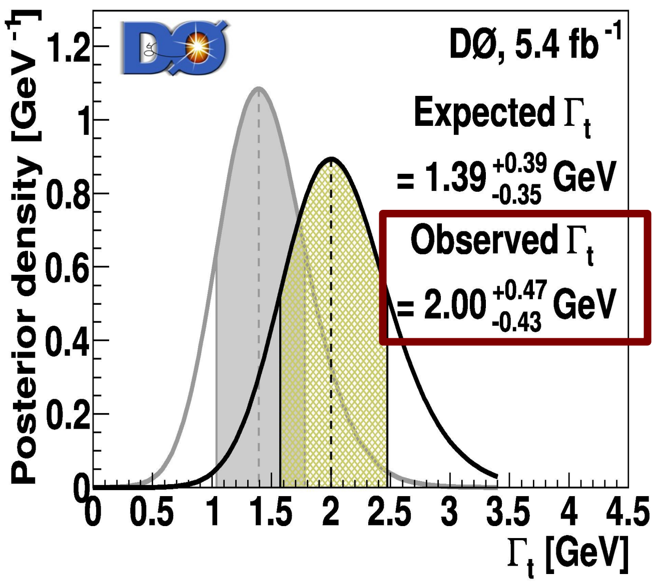
- Extract partial and total width from combination of R measurement and t-channel cross section
- Correlations of systematics fully taken into account

Top Quark Width

- Definition of R: $$R = \frac{B(t \rightarrow Wb)}{B(t \rightarrow \{Wd + Ws + Wb\})}$$ $B(t \rightarrow \{Wd+Ws+Wb\})=1$
- Using dilepton and lepton+jets $t\bar{t}$ events
- Measure: $B(t \rightarrow Wb) = 0.90 \pm 0.04$
- Extract partial and total top width







arXiv:1201.4156 [hep-ex]