Measurement of Single Top Production at the Tevatron

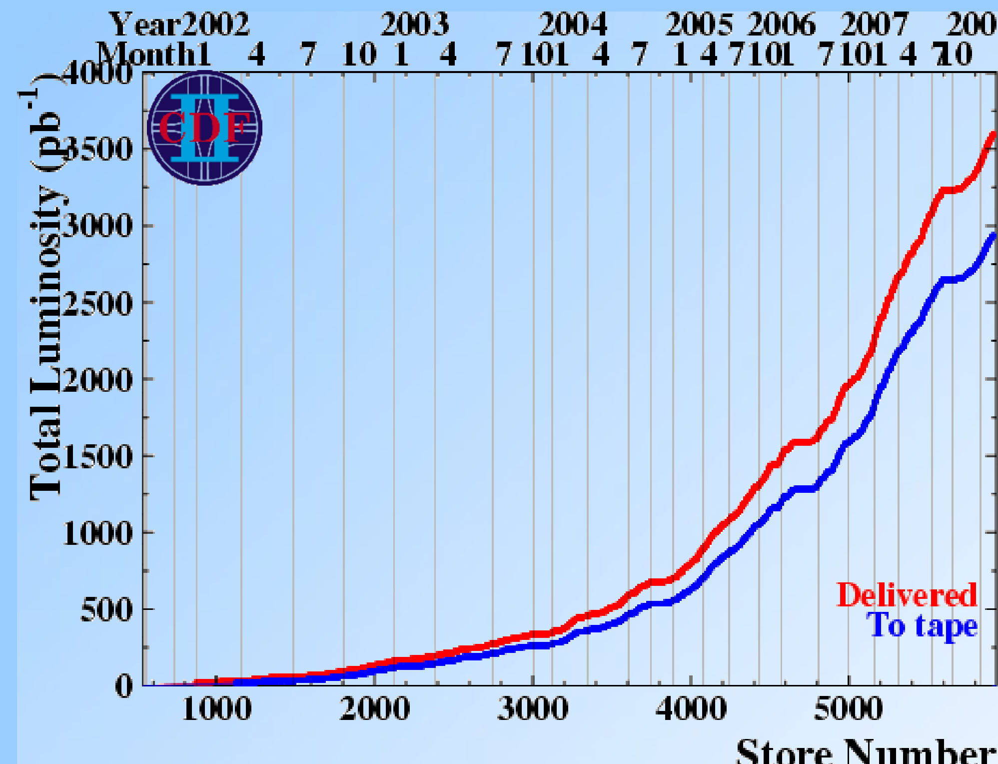
Dominic Hirschbühl

University of Karlsruhe

On behalf of the CDF and DØ Collaborations

DIS08 09.04.2008 London

Tevatron



Proton-Antiproton-Collisions with
a rate of 1.7 MHz
Center-of-mass energy: $\sqrt{\hat{s}} = 1.96\,\mathrm{TeV}$

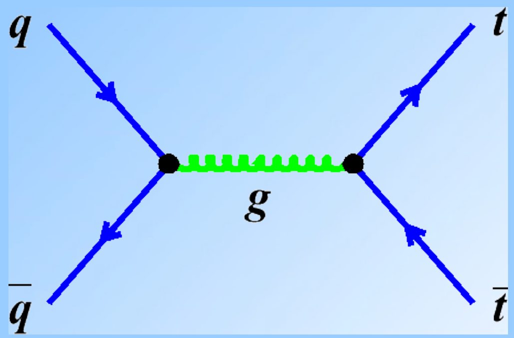
Record luminosity: $\mathcal{L} = 3.2 * 10^{32}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

World Record for hadron colliders!

Top quark production – Standard Model

At the Tevatron, top quarks are

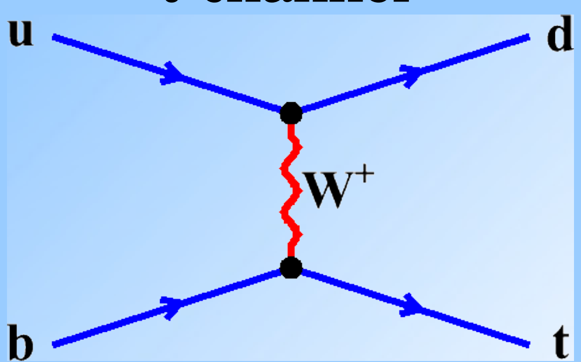
primarily produced in pairs via the strong interaction



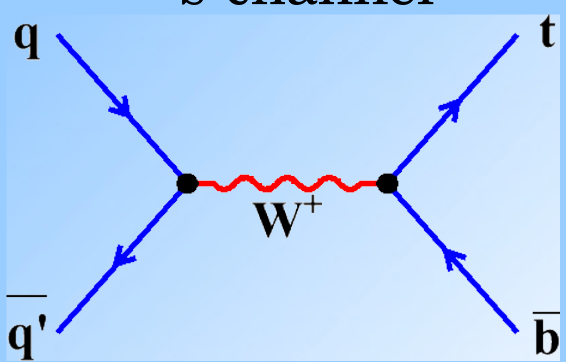
$\sigma_{tt} = 6.7 \pm 0.8$ pb

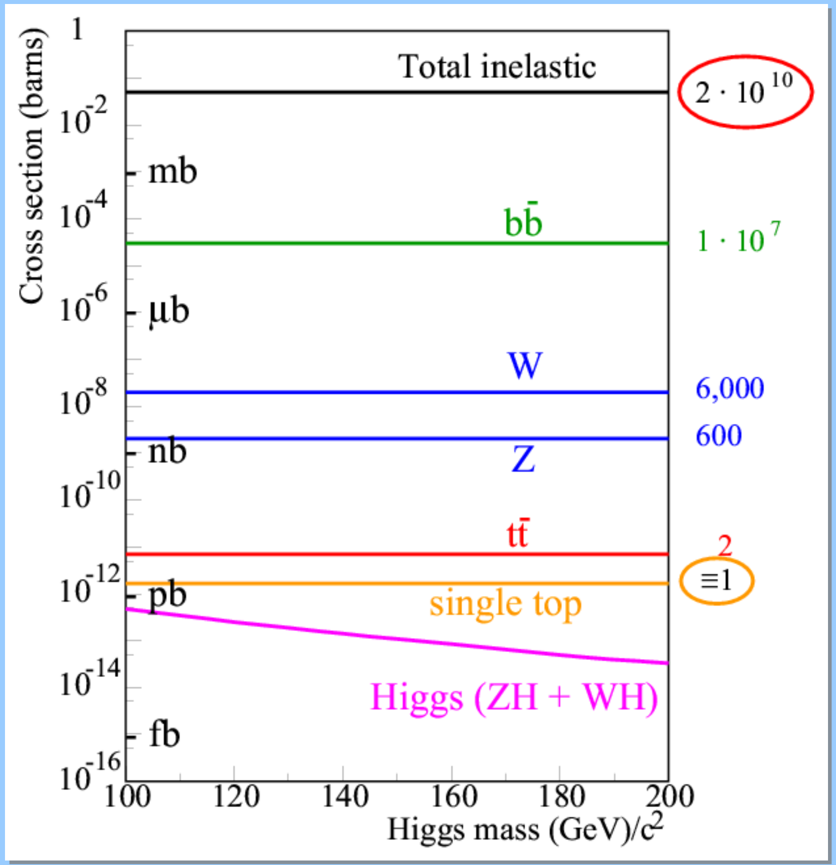
Top quark production via the weak interaction

t-channel



s-channel





$\sigma_t = 2.0 \pm 0.3$ pb $\sigma_s = 0.9 \pm 0.1$ pb

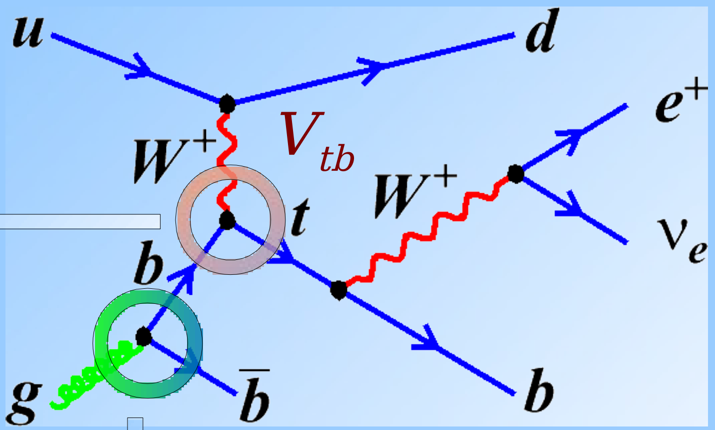
assumed top quark mass
m_{top} = 175 GeV

B.W. Harris et al. Phys. Rev. D 66, 054024 (2002), Z. Sullivan, Phys. Rev. D 70, 114012 (2004)
compatible results: Campbell/Ellis/Tramontano, Phys. Rev. D 70, 094012 (2004)
N. Kidonakis, Phys.Rev. D 74, 114012 (2006)

Why measure single top ?

- Source of single ~100% polarized top quarks:
  - Test V-A structure of Wtb vertex
  - Access to the top quark spin

- Test of the SM prediction. Does it exist?
  - Cross section $\propto |V_{tb}|^2$
    ➔ allows direct measurement of $|V_{tb}|$
  - Test unitarity of the CKM matrix
    - Hints for existence of a 4th generation ?
    - Vector t' is also a possibility

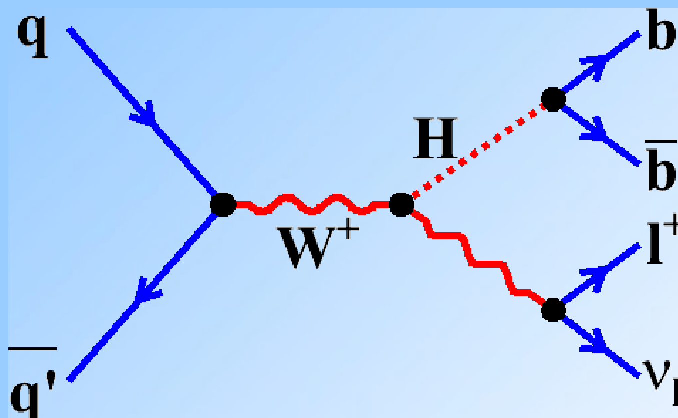


J. Alwall et. al., "Is $|V_{tb}| \sim 1$?", Eur. Phys. J. C49 791-801 (2007).

- Test of *b* quark structure function: DGLAP evolution
- Can test CP-violation – single t vs. single tbar

Sensitivity to new physics

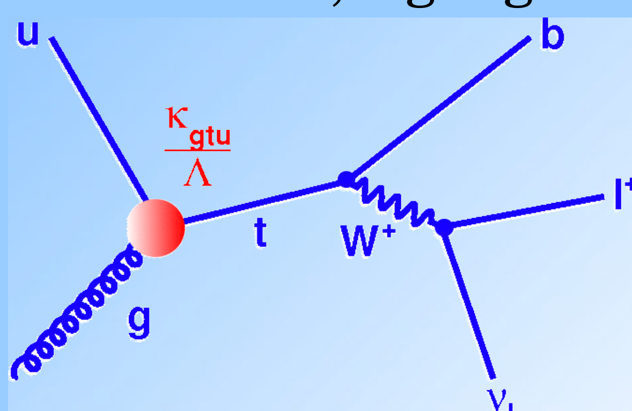
- Same final state signature as Higgs: WH, H →bbbar. Understanding single-top backgrounds is a prerequisite for Higgs searches at the Tevatron. Same tools can be applied for Higgs searches.

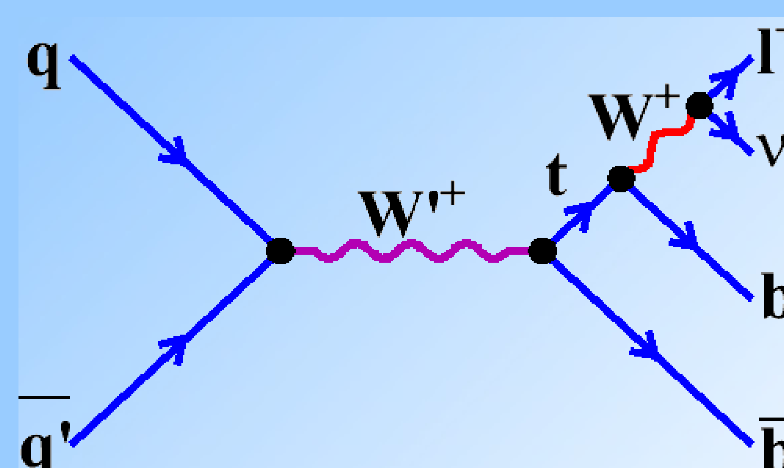


$$\sigma_{WH} \sim \frac{1}{10}\,\sigma_{\text{single top}}$$

Test non-SM phenomena

- Search W´ or H⁺ (s-channel signature)
- Search for FCNC, e.g. ug → t
- …

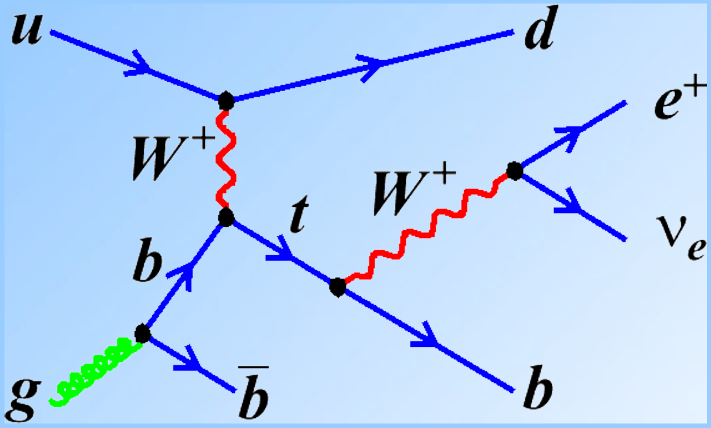




Event signature and selection

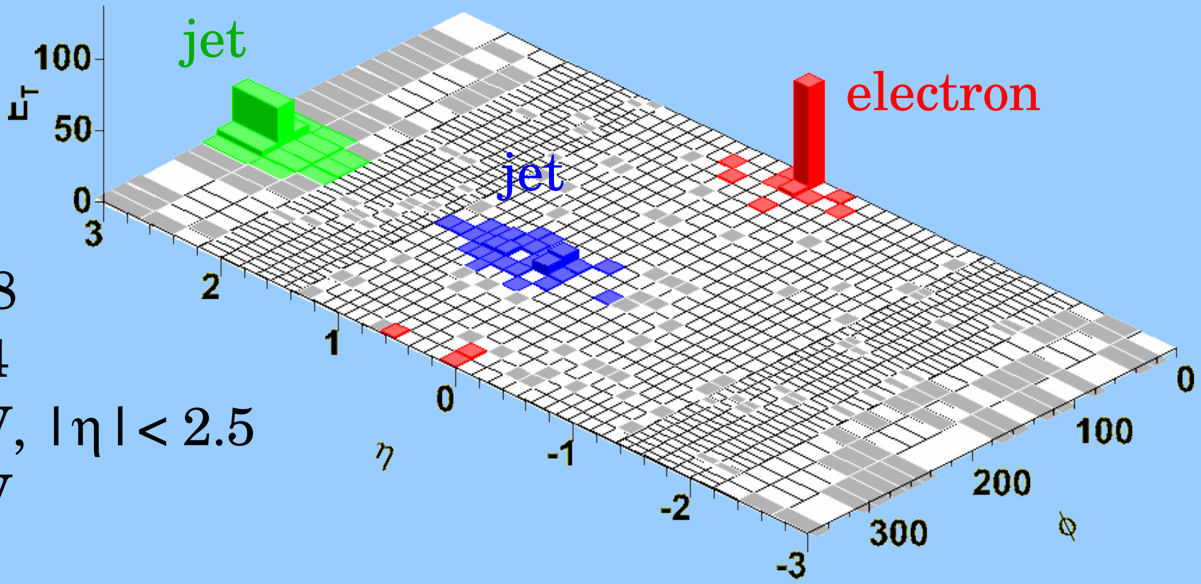
Event Selection:

- 1 lepton (electron / muon)
  - CDF: $E_T > 20$ GeV, $|\eta| < 2.0$
  - DØ: electron: $E_T > 15$ GeV, $|\eta_e| < 1.1$
  - muon: $p_T > 18$ GeV, $|\eta_\mu| < 2.0$



- Missing E_T
  - CDF: MET > 25 GeV
  - DØ: MET > 15 GeV

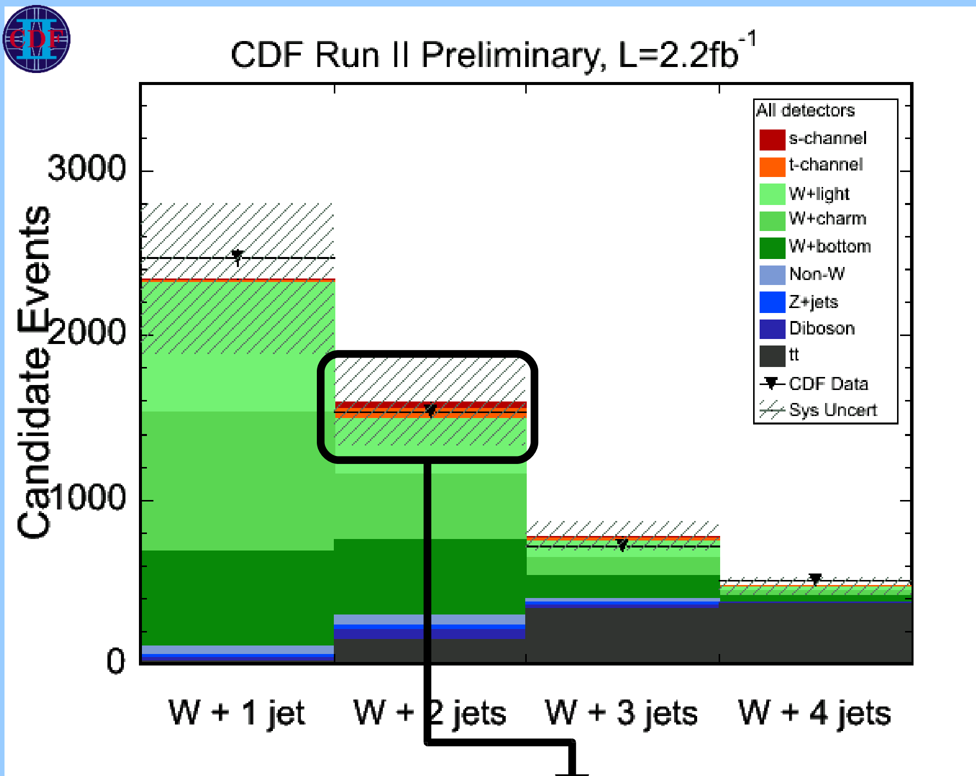
- 2 - 4 jets
  - CDF: $E_T > 20$ GeV, $|\eta| < 2.8$
  - DØ: $p_T > 15$ GeV, $|\eta| < 3.4$
    1. jet: $p_T > 25$ GeV, $|\eta| < 2.5$
    2. jet: $p_T > 20$ GeV



Main Backgrounds:

W/Z+heavy flavor jets, Mistags, ttbar, Multijet events

Why it is challenging ?



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

Single top hidden behind background uncertainty! ($s \ll \sigma_{bkg,syst}$)

➔ Makes counting experiment impossible!

➔ S/√B is an inadequate estimate of sensitivity

Improved b jet identification

About 50% of the background in the W + 2 jets sample do **NOT** contain **b quarks** even though a secondary vertex was required!

Fit to NN output for W + 2 jets events with one secondary vertex

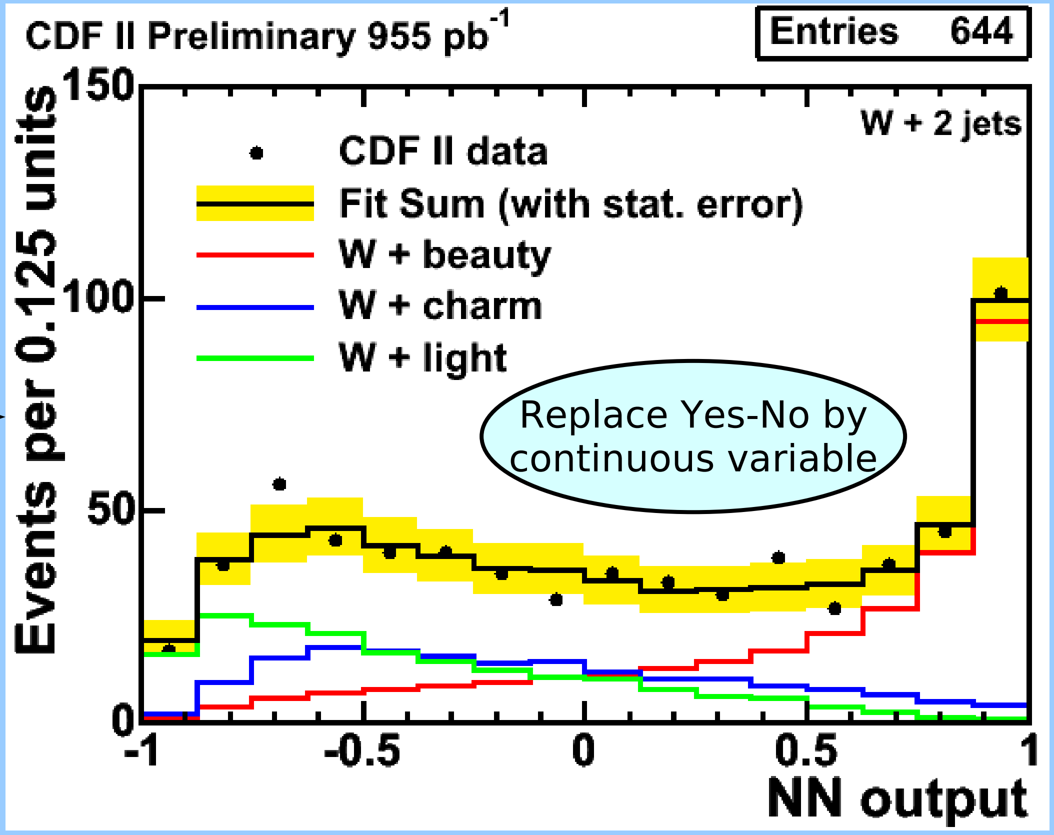
Jet and track variables, e.g. vertex mass, decay length, track multiplicity, …

⊕

neural network

↓

powerful discriminant



mistags / charm beauty

~20 % gain in sensitivity for all three analyses

Search strategy

Combined Search

t-channel and s-channel regarded as one single top signal.

Cross section ratio is fixed to SM value.

Signal Model
MadEvent + Pythia
CompHep + Pythia

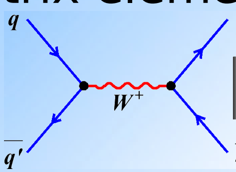
Background Model
MC & Data

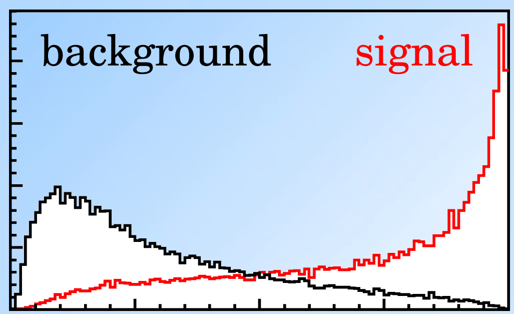
Data

Event Selection

Multivariate Analysis

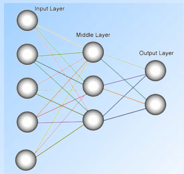
Matrix elements





Boosted Decision Trees

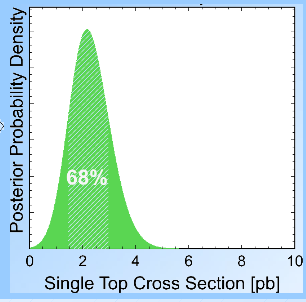
Neural Networks

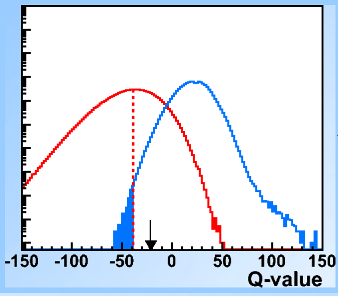


Likelihood discriminants

$$\mathcal{L}_k(\{x_i\}) = \frac{\prod_{i=1}^{n_{var}} p_{ik}}{\sum_{m=1}^{5} \prod_{i=1}^{n_{var}} p_{im}}$$

Extraction of cross section





Ensemble tests

Matrix Element Analysis

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

input: lepton and jet 4-vectors!

Integration over part of the phase space Φ_4

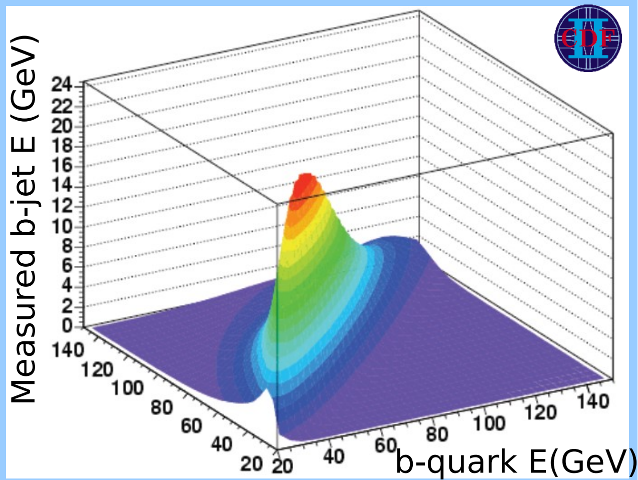
Parton distribution functions (CTEQ6)

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

Leading Order matrix elements

Probability of measuring a jet energy E_j if E_p was produced.

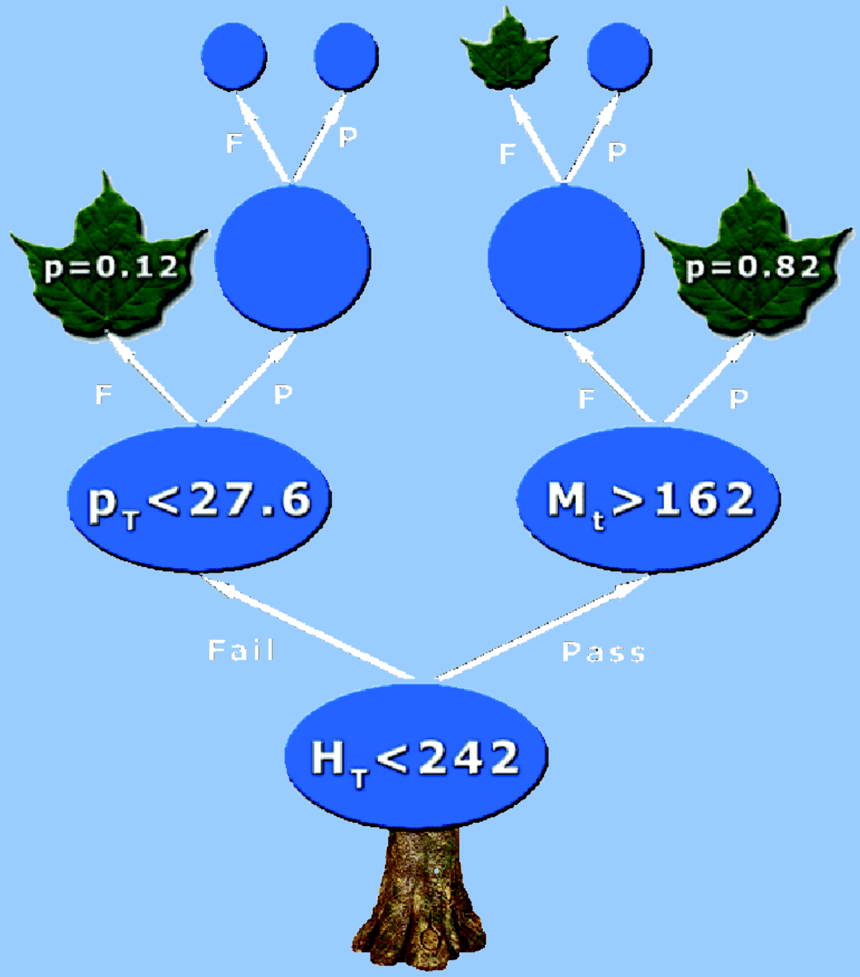
- Use full kinematic information of an event
- Calculate probability densities for
  - s- and t-channel single top production
  - Main background contributions
- Create Discriminant
  - CDF: $$EPD = \frac{b \cdot P_{signal}(\vec{x})}{b \cdot P_{signal}(\vec{x}) + b \cdot P_{b-bkg}(\vec{x}) + (1-b) P_{nonb-bkg}(\vec{x})}$$
  - DØ: $$D(\vec{x}) = \frac{P_{signal}(\vec{x})}{P_{signal}(\vec{x}) + P_{background}(\vec{x})}$$



Boosted Decision Tree

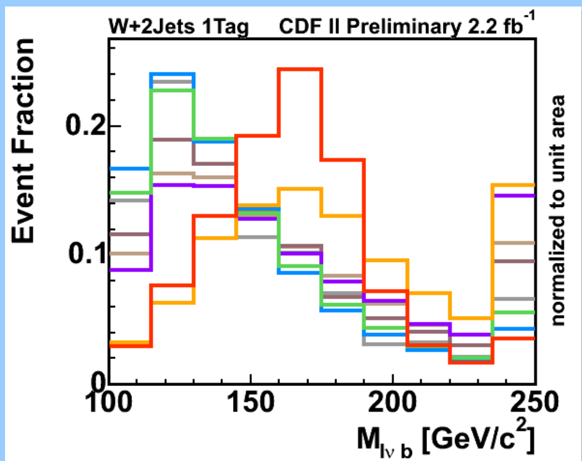
Idea: Effective extension of a cut-based analysis

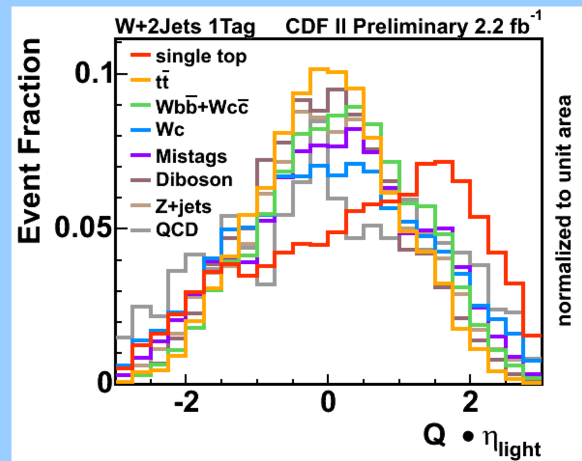
- Use large number of input variables (49)
- Non-discriminating variables are automatically ignored, but don't degrade the performance
- Optimize series of binary cuts with training sample
- Calculate for each leaf purity p = s/(s+b)
- Sort events by output purity
- Create series of “boosted“ trees by reweighting based on value of misclassification

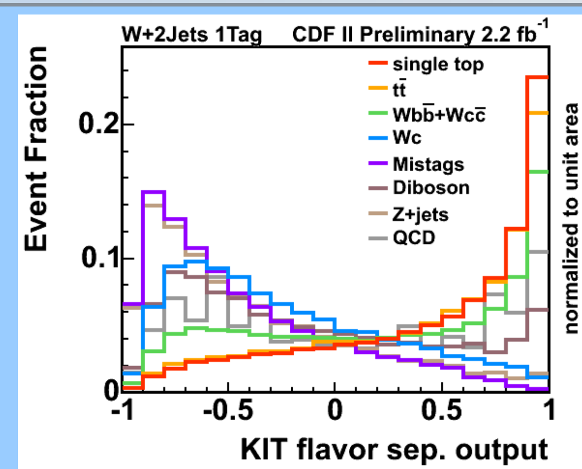


Neural Network Analysis

Idea: Combine many variables into one more powerful discriminant



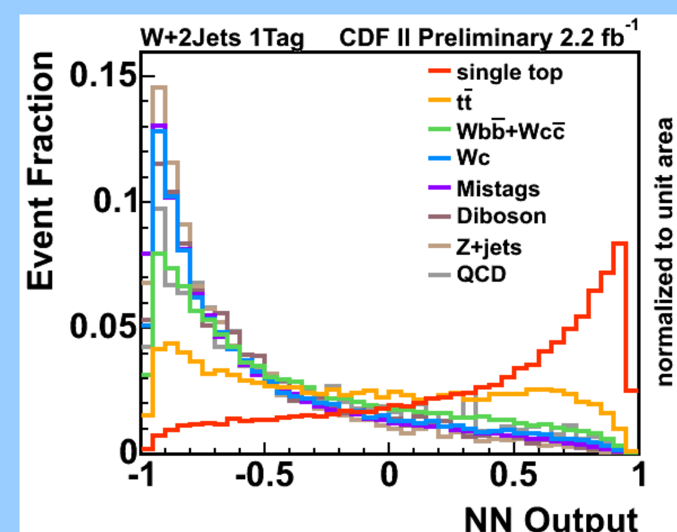




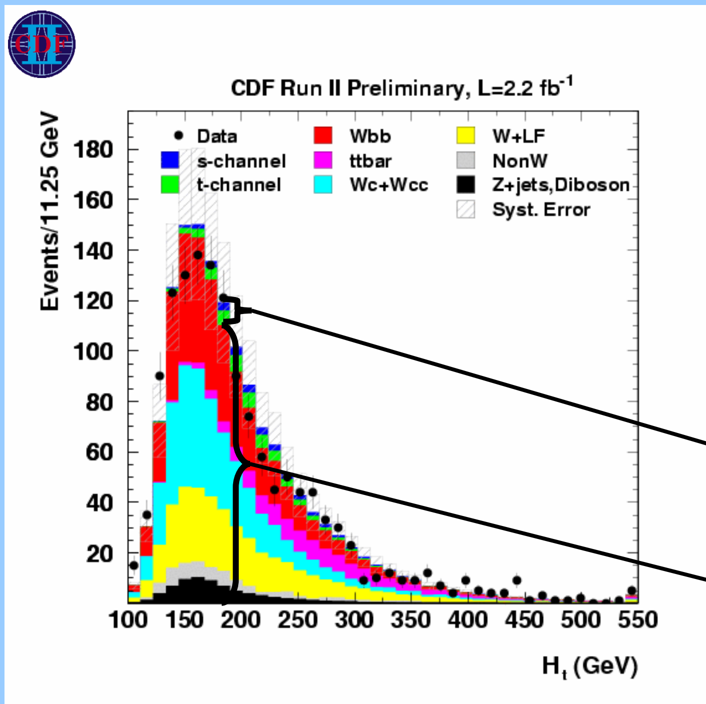
...

- uses 10-15 variables
- Network: NeuroBayes

- uses 18-25 variables (subset of those in the Decision Tree analysis)
- Bayesian Neural Network
  → weighted average over many networks



Multivariate Likelihood Analysis

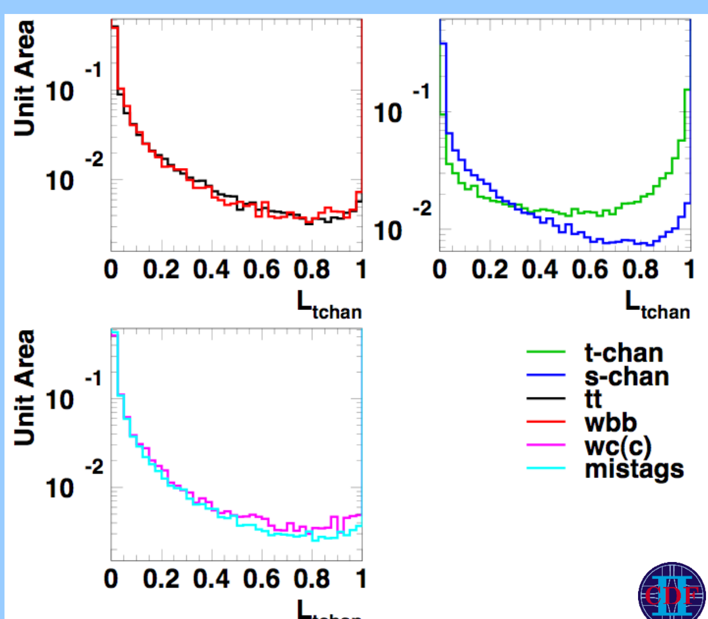


- Multivariate binned likelihood combines several sensitive variables into a single variable
- Pioneered at LEP
- Seven variables used in the 2 jet bin
- Ten variables used in the 3 jet bin

N_i^{sig}, N_i^{bkg} →

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

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

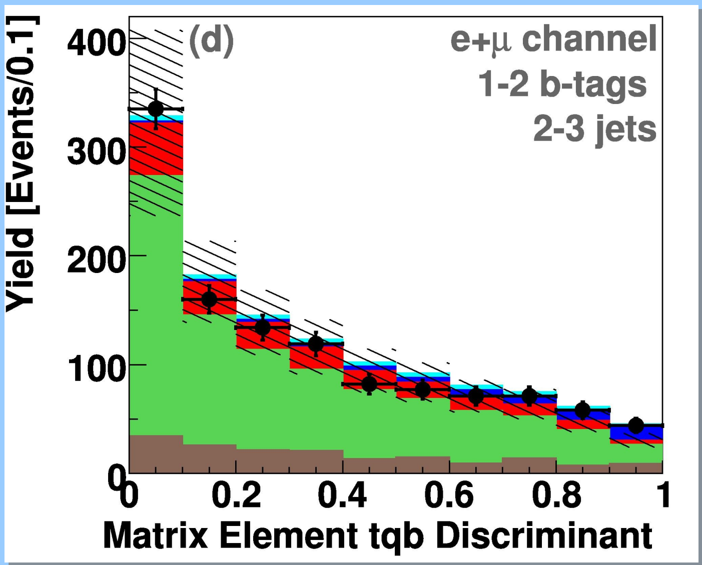


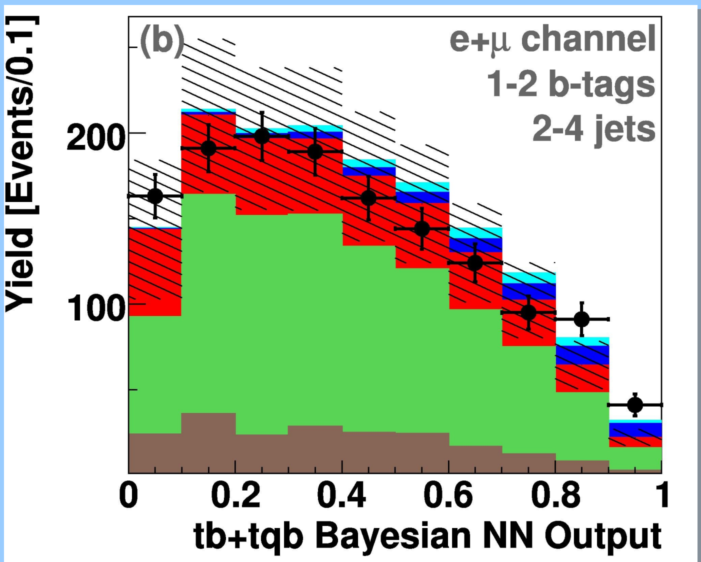
Results from DØ

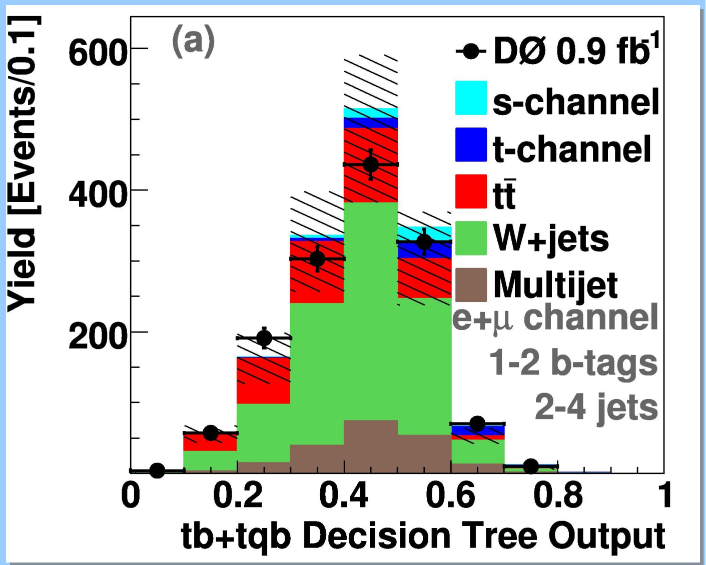
Measured cross sections

Matrix element method | Bayesian neural network | Boosted decision tree

Measured using a Bayesian binned likelihood calculation







$\sigma_{t+s} = 4.8^{+1.6}_{-1.4}$ pb

$\sigma_{t+s} = 4.4^{+1.6}_{-1.4}$ pb

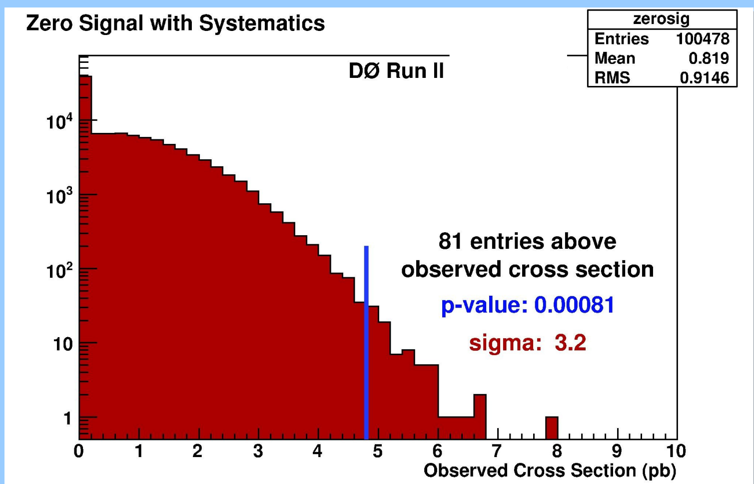
$\sigma_{t+s} = 4.9^{+1.4}_{-1.4}$ pb

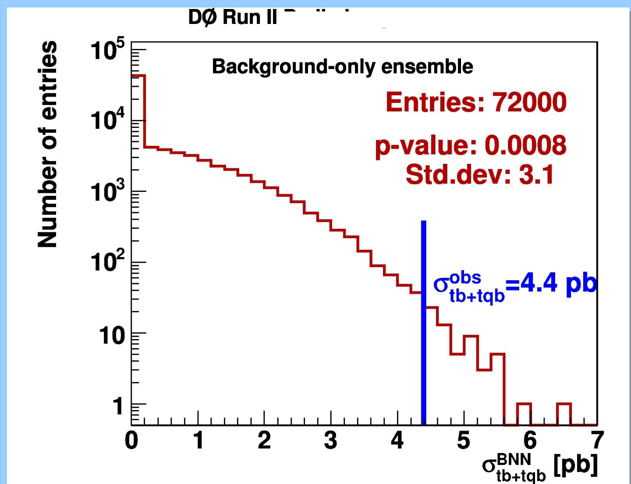
SM prediction : $\sigma_{t+s} = 2.9 \pm 0.4$ pb

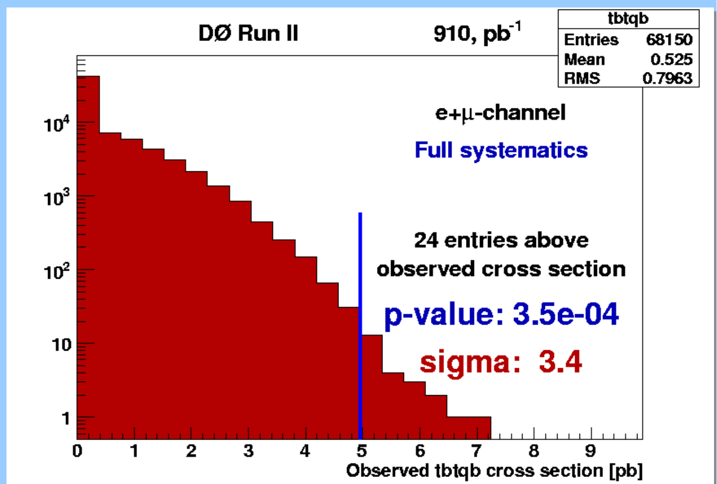
Sensitivity

Matrix element method | Bayesian neural networks | Boosted decision trees

Determined using ensemble tests without signal contribution





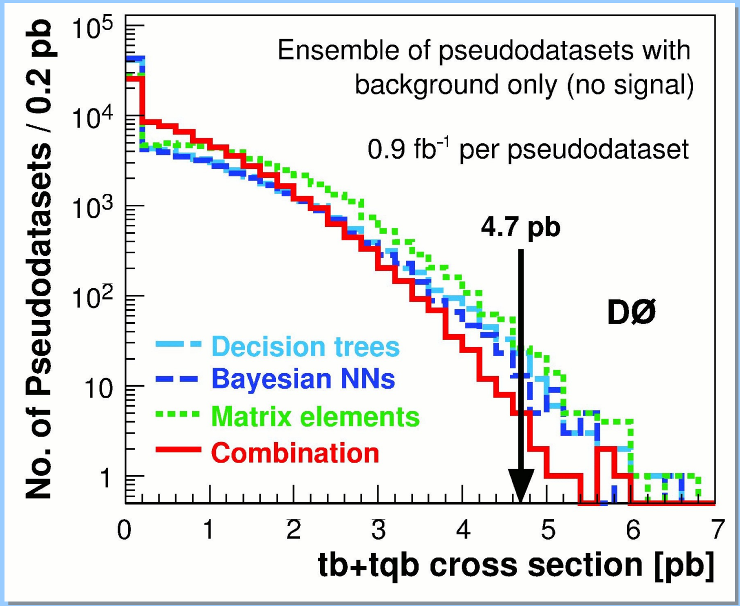


Matrix element method	Bayesian neural networks	Boosted decision trees
Expected p-value: 3% (1.9 σ)	Expected p-value: 1.6% (2.2 σ)	Expected p-value: 1.9% (2.1 σ)
Observed p-value: 0.081% (3.2 σ)	Observed p-value: 0.08% (3.1 σ)	Observed p-value: 0.035% (3.4 σ)

Combination & Limit on $|V_{tb}|$

Combine results with best linear unbiased estimator (BLUE) method

Correlations ~60%



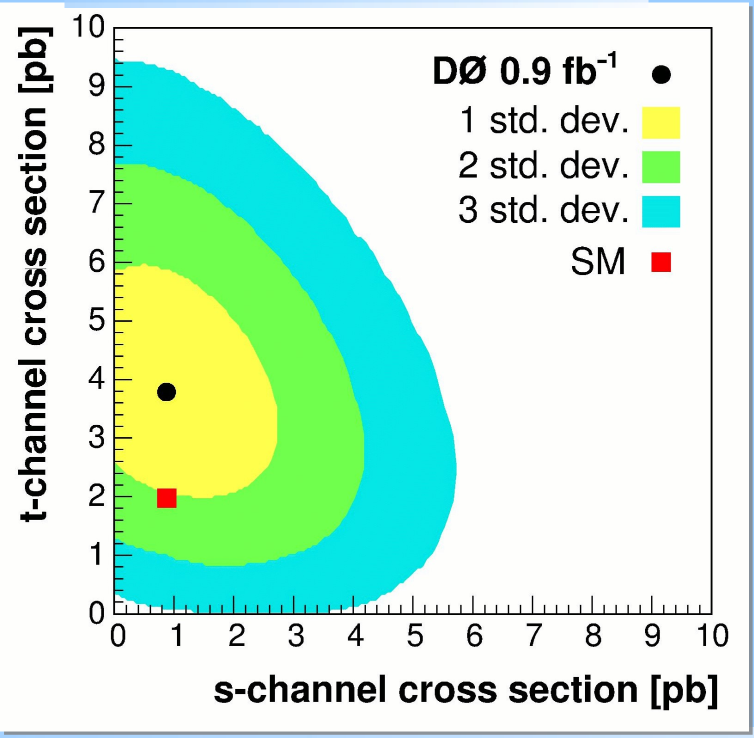
Measured cross section:

$$\sigma_{t+s} = 4.7 \pm 1.3 \text{ pb}$$

Expected p-value: 1.1% (2.3 σ)

Observed p-value: 0.014% (3.6 σ)

Seperate search result



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

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

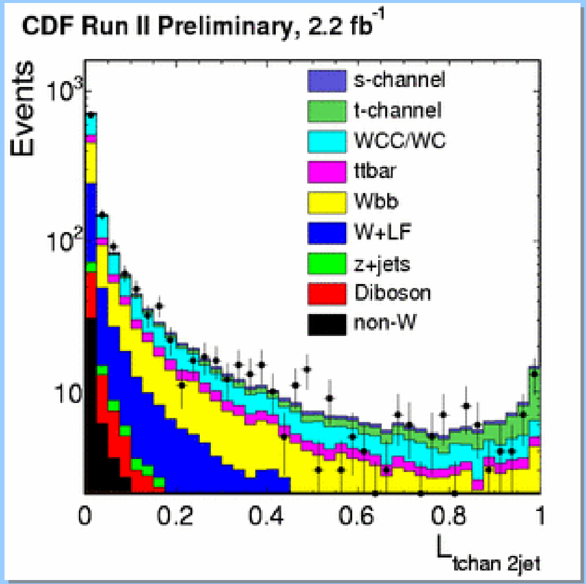
Phys. Rev. Lett. 98, 181802 (2007), and arXiv.org:0803.0739 (submitted to Phys. Rev. D)

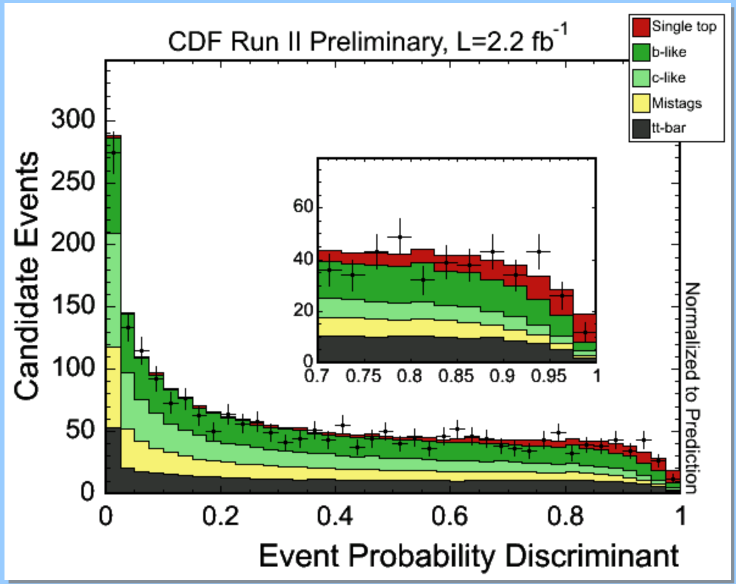
Results from CDF II

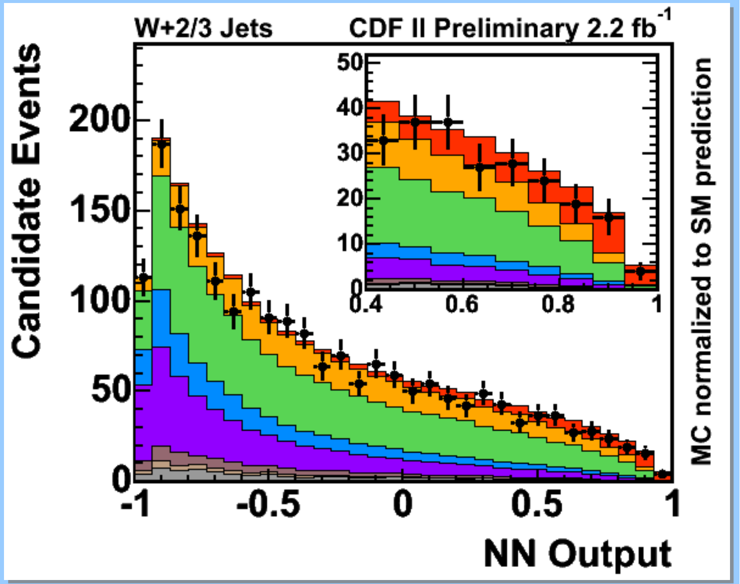
Measured cross sections

Likelihood Discriminant | Matrix element method | Neural networks

Measured using a binned likelihood fit







$\sigma_{t+s}=1.8^{+0.9}_{-0.8}$ pb

$\sigma_{t+s}=2.2^{+0.8}_{-0.7}$ pb

$\sigma_{t+s}=2.0^{+0.9}_{-0.8}$ pb

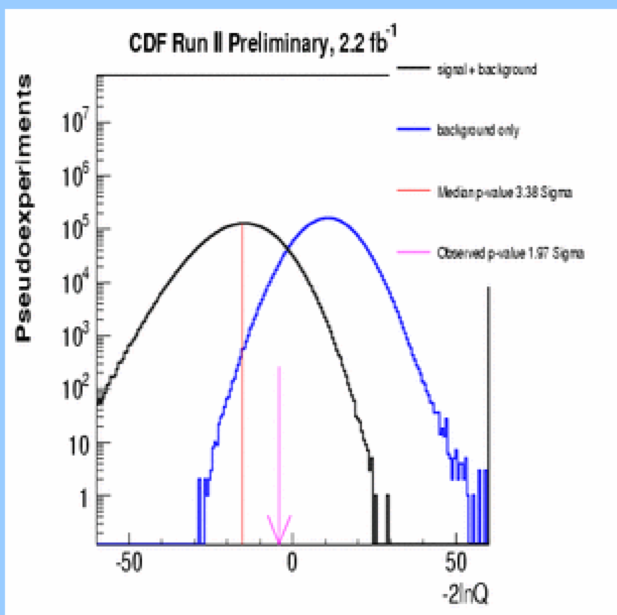
SM prediction : $\sigma_{t+s}=2.9\pm0.4$ pb

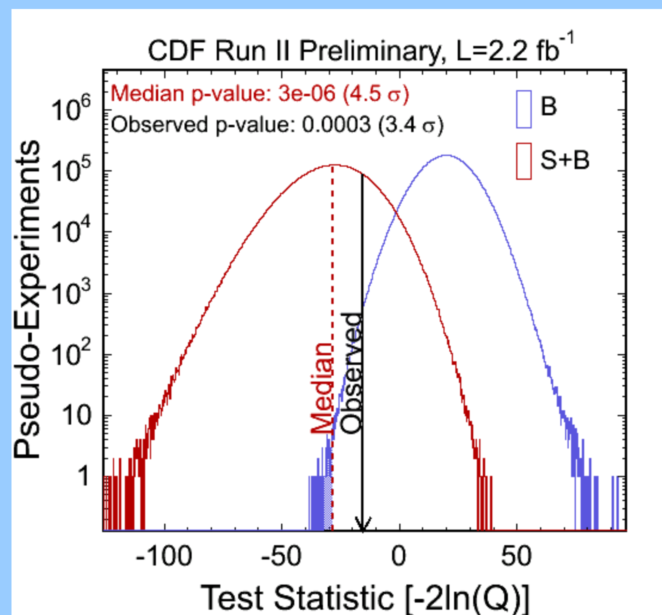
Sensitivity

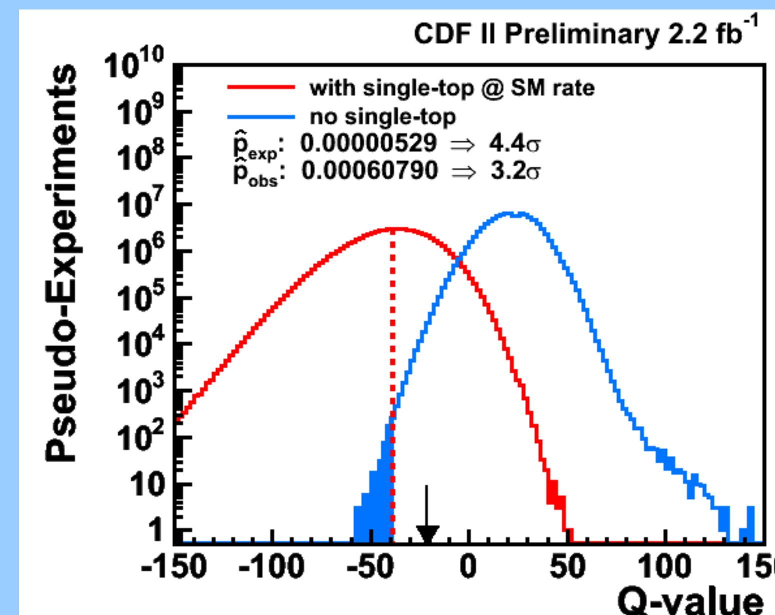
Likelihood Discriminant | Matrix element method | Neural networks

Determined using a hypothesis test

$$Q = -2\left(\ln L_{red.}(\beta_1=1) - \ln L_{red.}(\beta_1=0) \right)$$







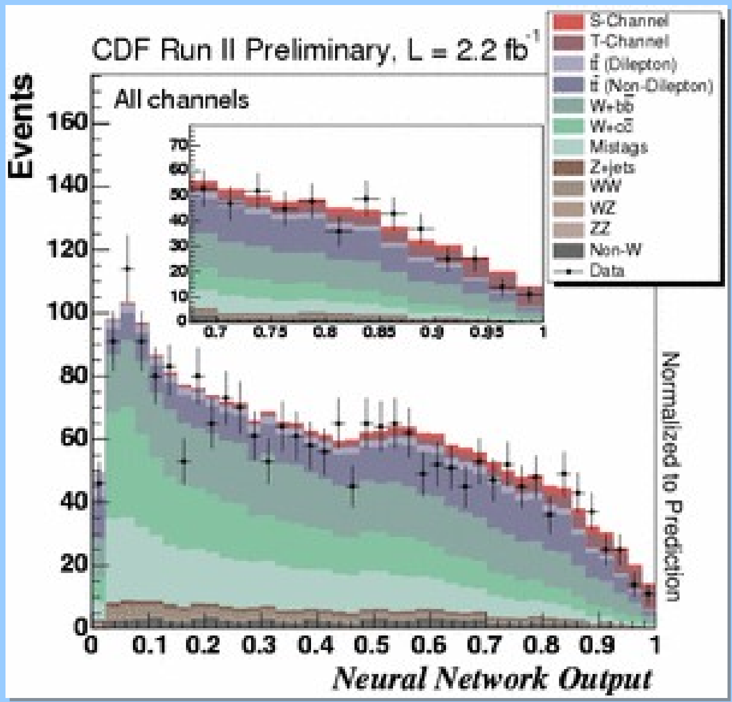
Expected p-value:
0.03% (3.4 σ)
Observed p-value:
2.5% (2.0 σ)

Expected p-value:
0.0003% (4.5 σ)
Observed p-value:
0.03% (3.4 σ)

Expected p-value:
0.0005% (4.4 σ)
Observed p-value:
0.06% (3.2 σ)

Combination & Limit on $|V_{tb}|$

- Two approaches to combine results:
  - Extended BLUE method
    - Uses results and correlations as input
    - Correlations ~60-70%
  - Superdiscriminant (NEAT neural network) (“Neuro-Evolution of Augmenting Topologies”)
    - Uses output of individual analysis as input
    - Candidate networks compete against each other.
    - Automatically optimizes
      - Network topology, weights, output histogram binning, includes systematic errors in optimization procedure



BLUE

Measured cross section

$\sigma_{t+s} = 2.2 \pm 0.7$ pb

Expected p-value: 4.7 σ

Observed p-value: 3.7 σ

NEAT

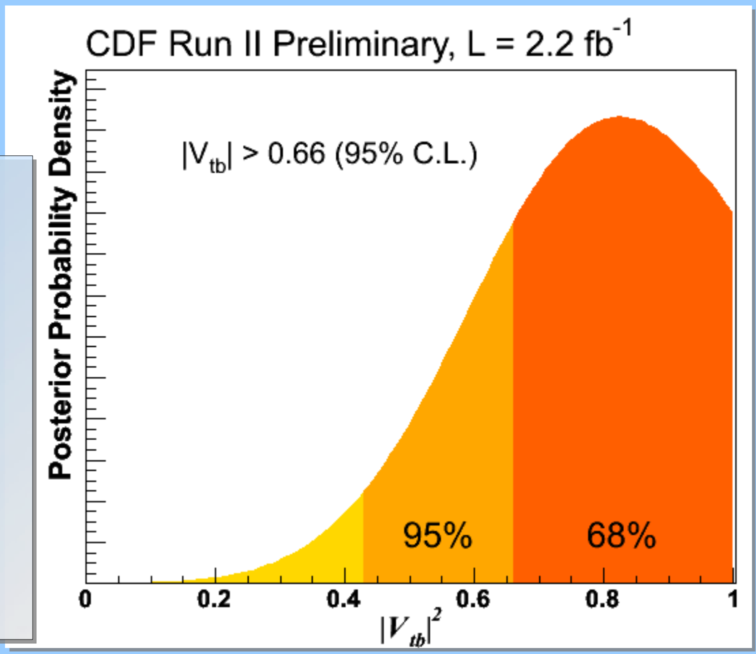
Measured cross section

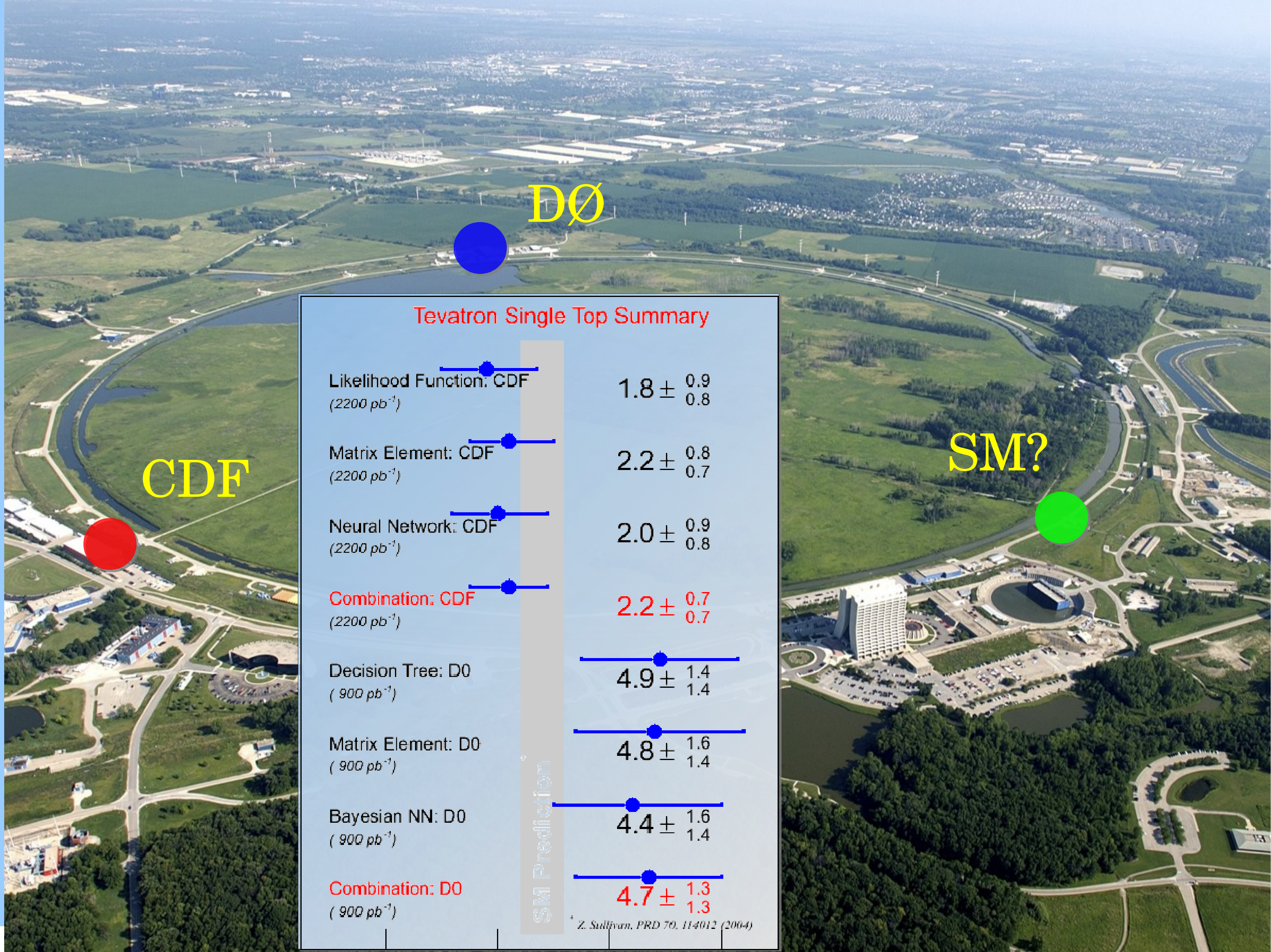
$\sigma_{t+s} = 2.1^{+0.7}_{-0.6}$ pb

Expected p-value: 5.1 σ

Observed p-value: 3.7 σ

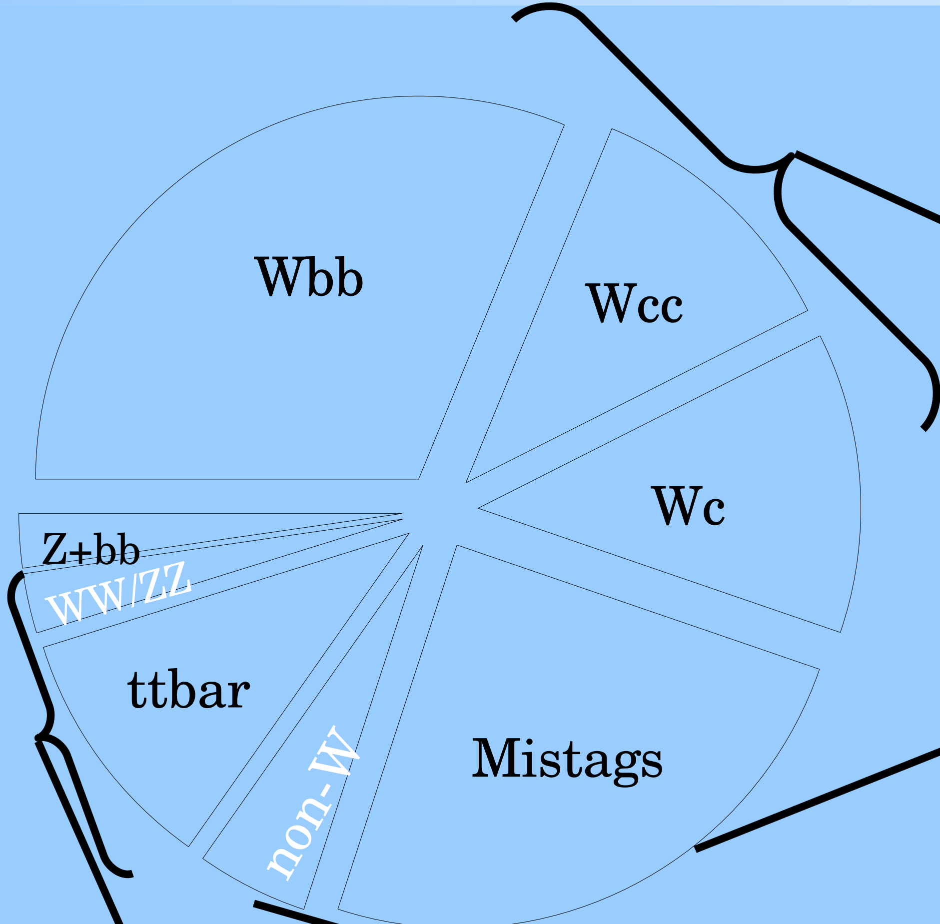
$|V_{tb}| > 0.66 @ 95\ C.L.$





DØ
CDF
SM?
Tevatron Single Top Summary
Likelihood Function: CDF
(2200 pb⁻¹)
1.8 ± 0.9 0.8
Matrix Element: CDF
(2200 pb⁻¹)
2.2 ± 0.8 0.7
Neural Network: CDF
(2200 pb⁻¹)
2.0 ± 0.9 0.8
Combination: CDF
(2200 pb⁻¹)
2.2 ± 0.7 0.7
Decision Tree: D0
(900 pb⁻¹)
4.9 ± 1.4 1.4
Matrix Element: D0
(900 pb⁻¹)
4.8 ± 1.6 1.4
Bayesian NN: D0
(900 pb⁻¹)
4.4 ± 1.6 1.4
Combination: D0
(900 pb⁻¹)
4.7 ± 1.3 1.3
SM Prediction
Z. Sullivan, PRD 70, 114012 (2004)

Background composition



W+HF jets (Wbb/Wcc/Wc)

W+jets normalization from data and heavy flavor (HF) fractions from ALPGEN Monte Carlo, calibrated in generic multijet data

Mistags (W+2jets)

- Falsely tagged light quark or gluon jets
- Mistag probability parameterization obtained from inclusive jet data

Non-*W (QCD)*

- Multijet events with semileptonic *b*-decays or mismeasured jets
- Fit low missing E_T data and extrapolate into signal region

Top/EWK (WW/WZ/Z→bb, ttbar)

- MC normalized to theoretical cross-section

Event Yield

CDF Run II Preliminary Predicted 2-jet event yield with 2.2 fb^{-1}	
s-channel	41.2 ± 5.9
t-channel	62.1 ± 9.1
Single top	103.3 ± 15.0
$t\bar{t}$	146.0 ± 20.9
Diboson	63.2 ± 6.3
Z + jets	26.7 ± 3.9
W + bottom	461.6 ± 139.1
W + charm	395.0 ± 121.8
W + light	339.8 ± 56.1
Non-*W*	59.5 ± 23.8
Total background	1491.8 ± 268.6
Total prediction	1595.1 ± 269.0
Observed	1535

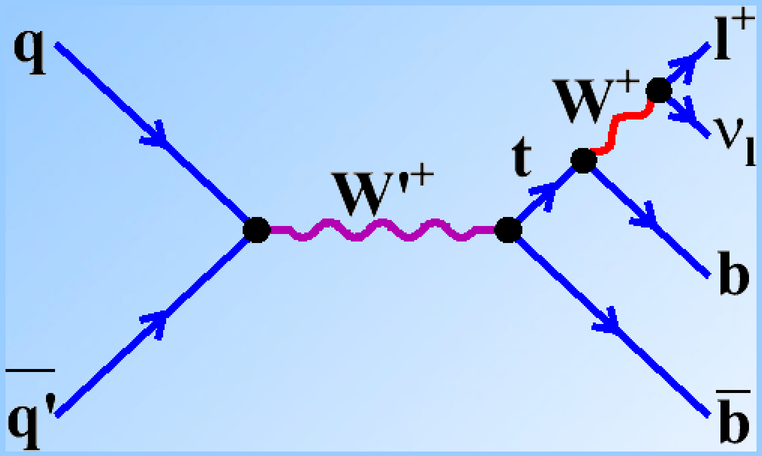
CDF Run II Preliminary Predicted 3-jet event yield with 2.2 fb^{-1}	
s-channel	13.5 ± 1.9
t-channel	18.3 ± 2.7
Single top	31.8 ± 4.6
$t\bar{t}$	338.7 ± 48.2
Diboson	21.5 ± 2.2
Z + jets	11.0 ± 1.6
W + bottom	141.1 ± 42.6
W + charm	108.8 ± 33.5
W + light	101.8 ± 16.9
Non-*W*	21.3 ± 8.5
Total background	744.8 ± 91.3
Total prediction	776.6 ± 91.4
Observed	712

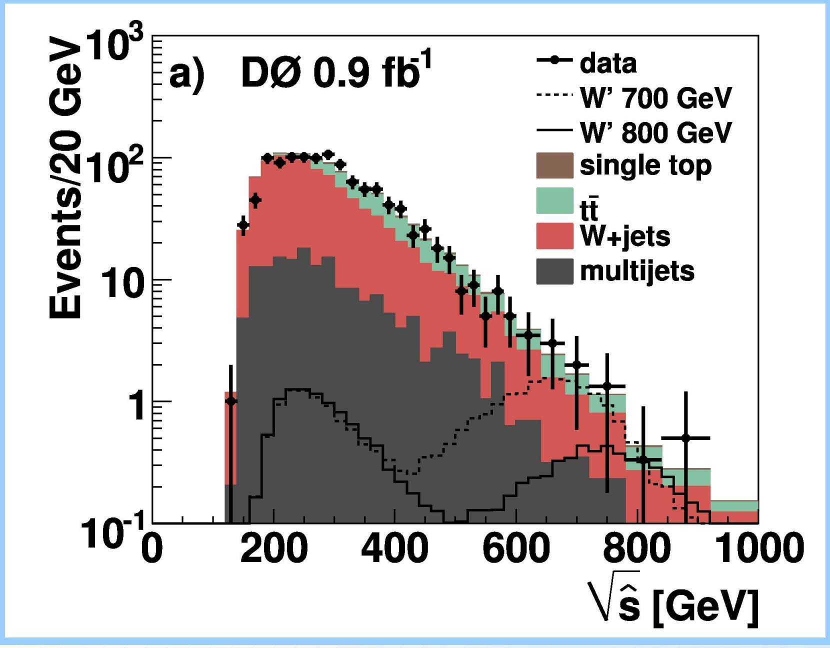
Event Yield

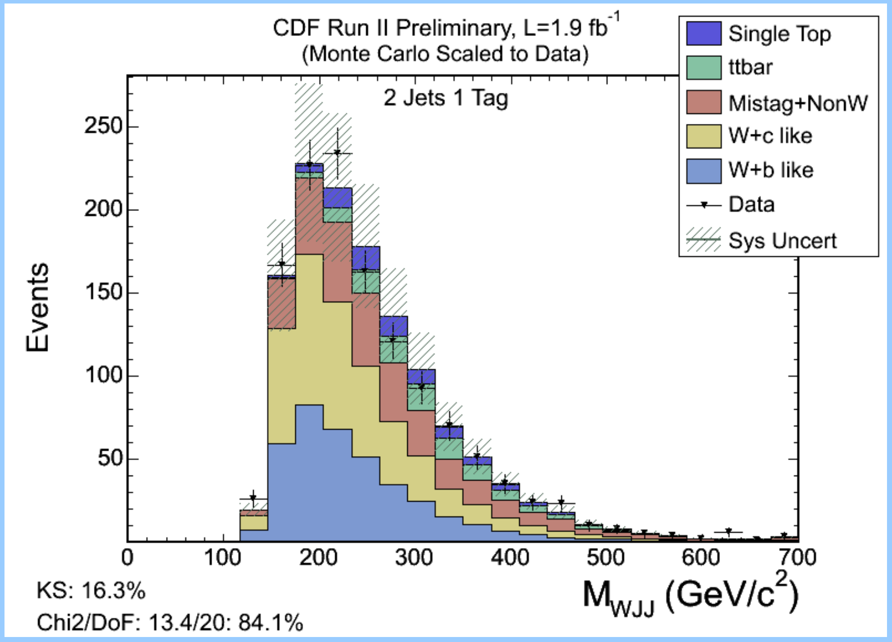
Source	Event Yields in 0.9 fb^{-1} Data Electron+muon, 1tag+2tags combined 2 jets	3 jets	4 jets
tb	16 ± 3	8 ± 2	2 ± 1
tqb	20 ± 4	12 ± 3	4 ± 1
$t\bar{t} \rightarrow ll$	39 ± 9	32 ± 7	11 ± 3
$t\bar{t} \rightarrow l$+jets	20 ± 5	103 ± 25	143 ± 33
$W+b\bar{b}$	261 ± 55	120 ± 24	35 ± 7
$W+c\bar{c}$	151 ± 31	85 ± 17	23 ± 5
$W+jj$	119 ± 25	43 ± 9	12 ± 2
Multijets	95 ± 19	77 ± 15	29 ± 6
Total background	686 ± 41	460 ± 39	253 ± 38
Data	697	455	246

Search for W' → tb events

- W' occurs in some extensions of the SM with higher symmetry.
- Complementary to searches in W'→ eν / μν (e.g. W' of leptophobic nature).
- Same event selection ans background estimate as single top analysis.
- Use M(lνjj) as discriminant
- Neglect interference with SM W boson.

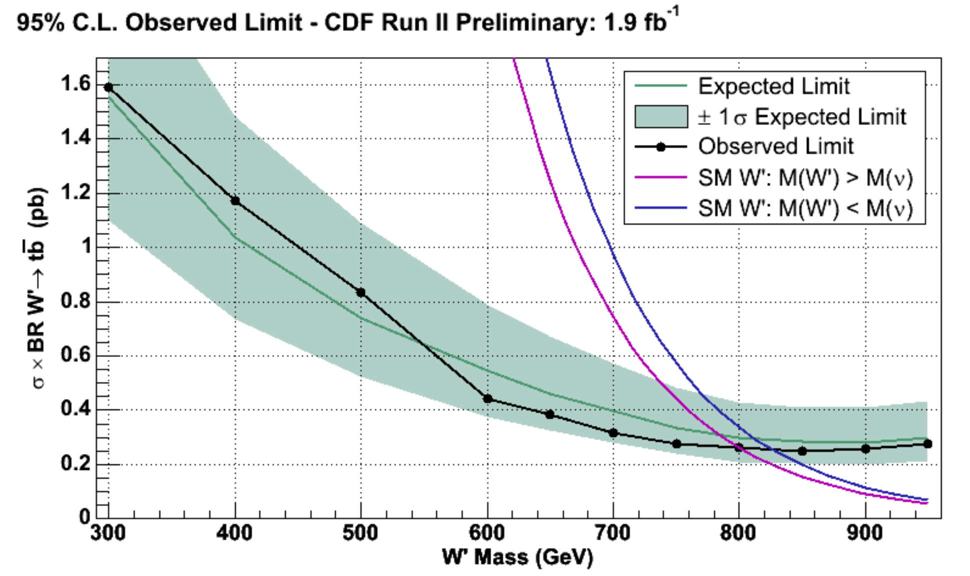


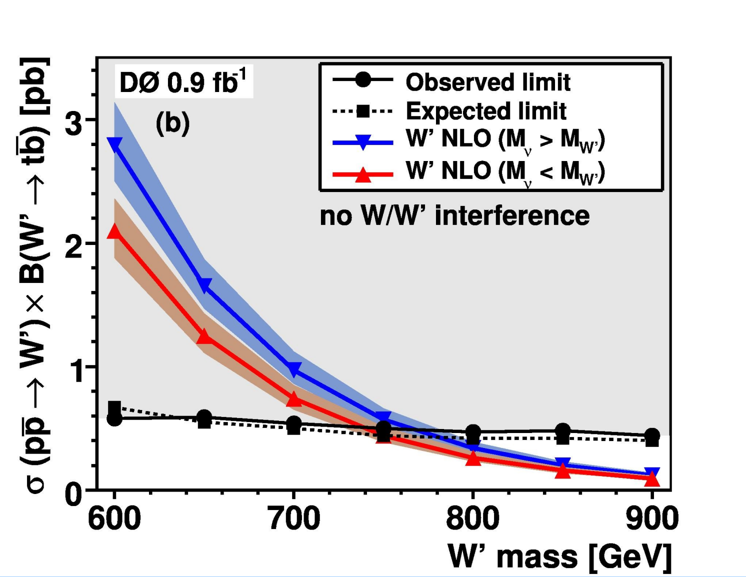




Mass limits on W'

Observe no evidence for resonant W‘ production.
Mass limits: Based on the theoretical cross section prediction
(Z. Sullivan, Phys. Rev. D 66, 075011, 2006)





Mass limits

CDF:

$M(W') > 800$ GeV if $M(W'_R) > M(\nu_R)$

$M(W') > 825$ GeV if $M(W'_R) < M(\nu_R)$

DØ:

$M(W') > 731$ GeV if $M(W'_R) > M(\nu_R)$

$M(W') > 739$ GeV if $M(W'_R) < M(\nu_R)$