Single Top Quark Production at the Tevatron

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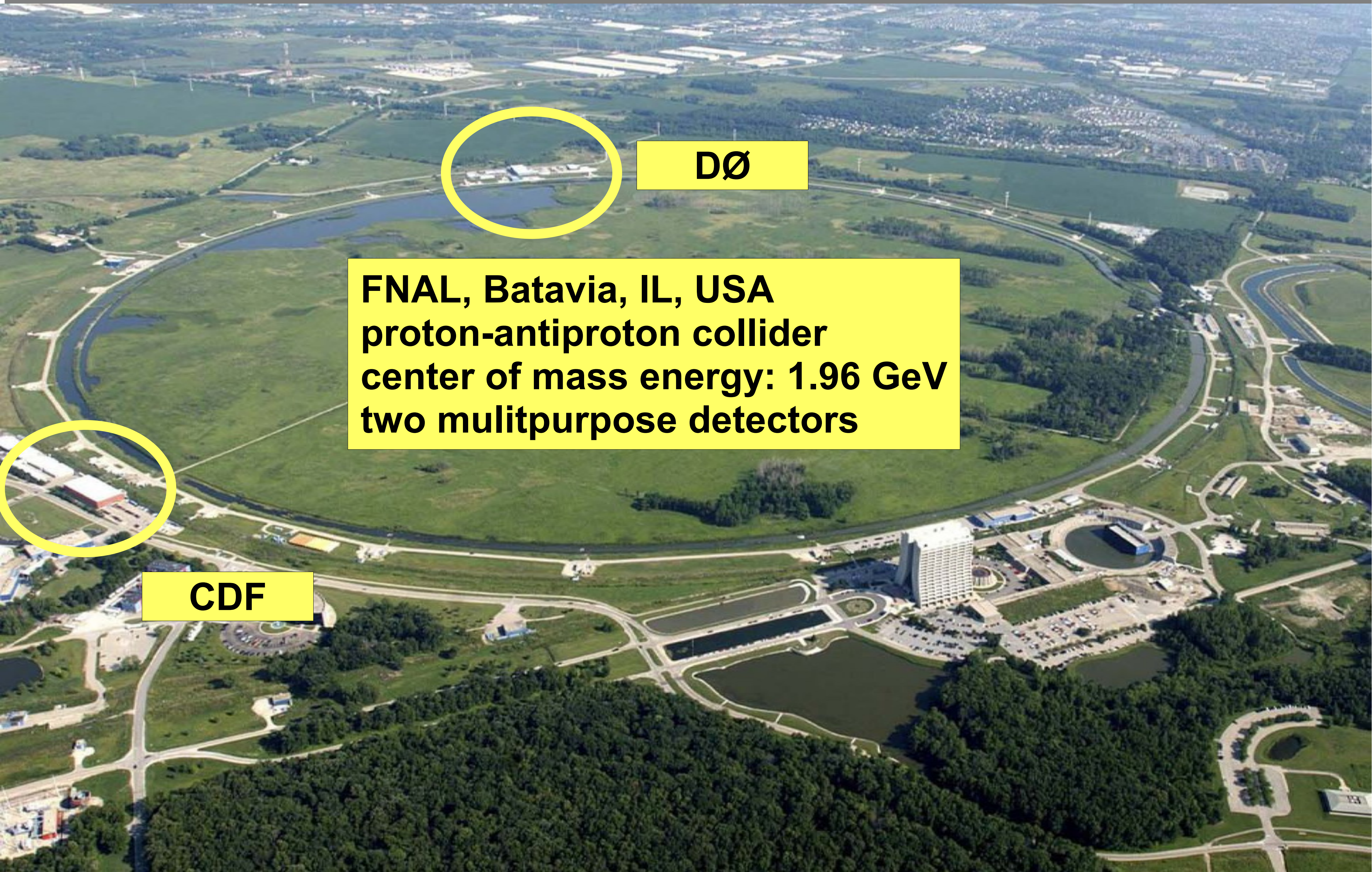
on behalf of the DØ and CDF collaborations

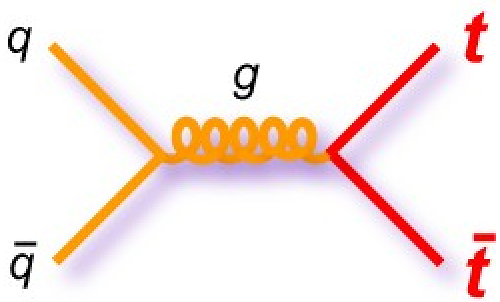
Heavy Quarks and Leptons 2008, Melbourne, Australia

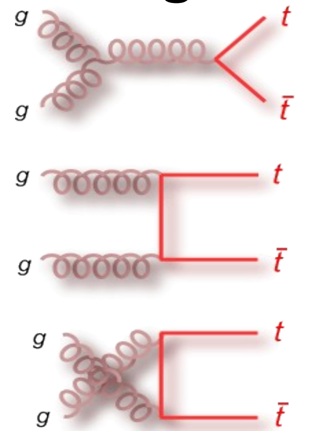
Experimental setup



Top quark production @ Tevatron

• **top pair production via strong interaction:**

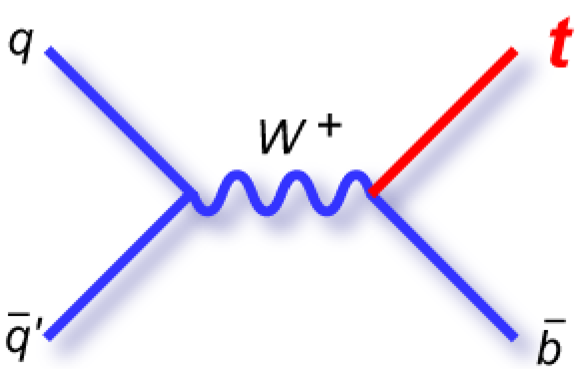


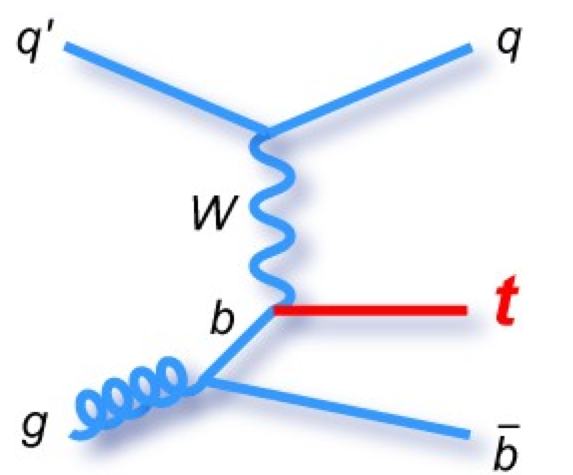


$$\sigma_{t\bar{t}} = 6.77 \pm 0.42 \ pb$$

[N. Kidonakis, R. Vogt, Phys. Rev. D **68** 114014 (2003)]

• **single top production via electroweak interaction:**





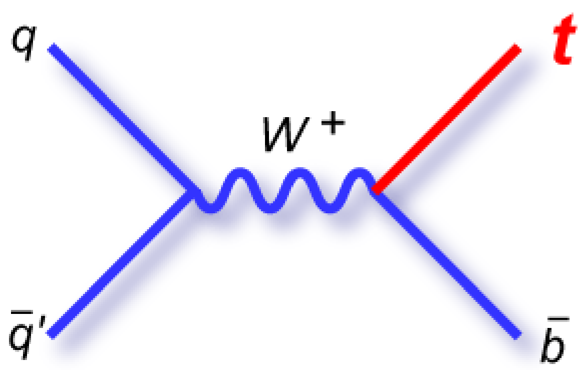
Every 3rd top quark event is a single top event!

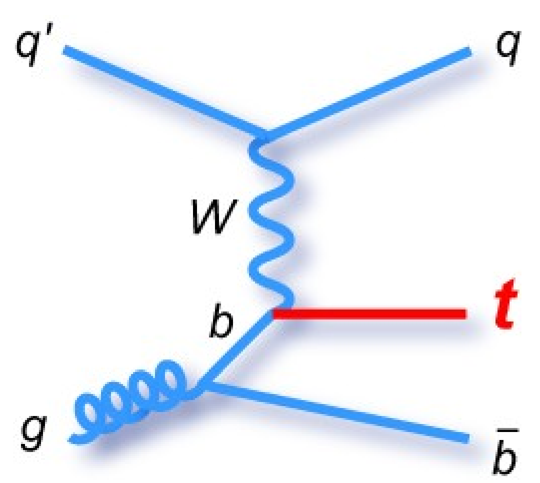
$$\sigma_{s-channel} = 0.88 \pm 0.14 \ pb \qquad \sigma_{t-channel} = 1.98 \pm 0.30 \ pb$$

[Z. Sullivan, Phys. Rev. D **70** 114012 (2004)]

All cross sections for m(top) = 175 GeV

Physics with single top quark events



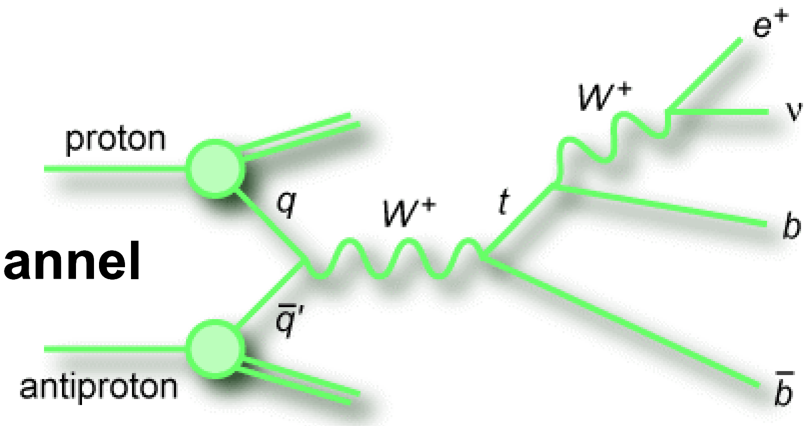


- Measurement of the production cross sections:
  - σ_{s+t} combined
  - σ_s, σ_t individually
- Direct measurement of CKM matrix element $|V_{tb}|$
- Study top quark spin polarization
- Understand single top as background process
- Establish analysis techniques for small signals
- Search for new physics:
  - Heavy gauge bosons
  - Anomalous Wtb couplings
  - Charged Higgs production
  - ...

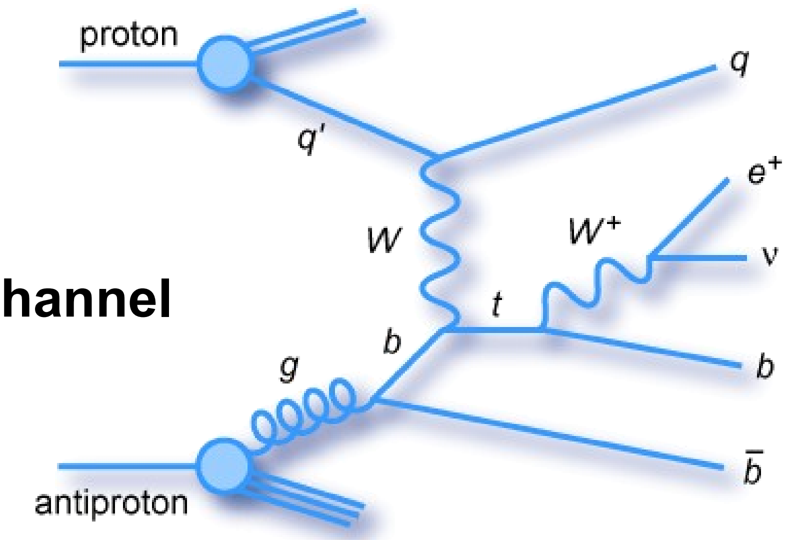
Single top is an exciting field!

Event selection

s-channel



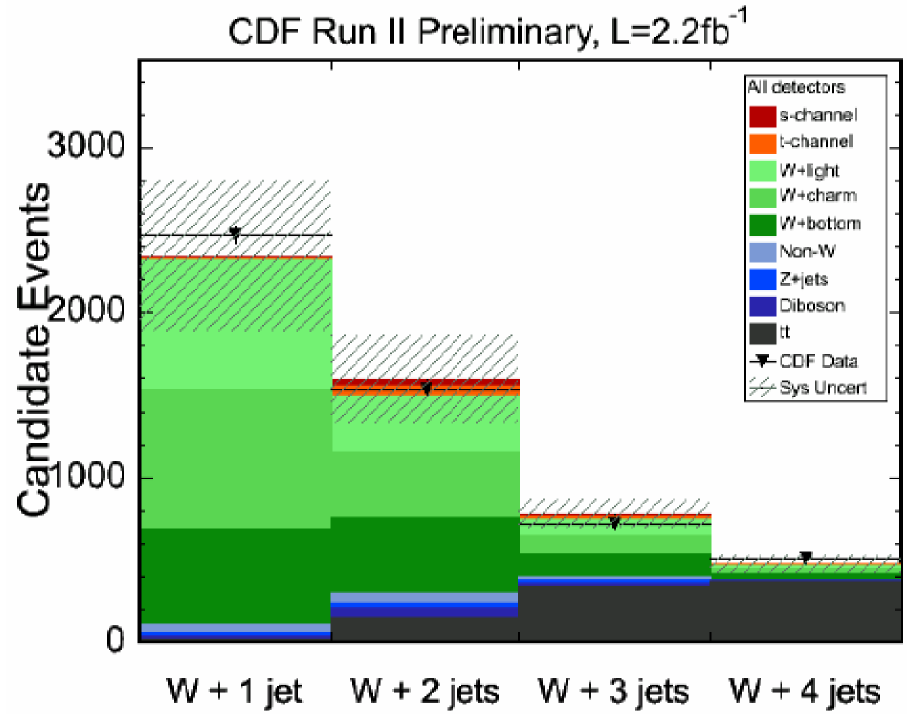
t-channel



- One isolated high-E_T lepton (electron or muon)
- Missing transverse energy (from the neutrino)
- 2-4 jets
- at least one b-tagged jet (to reduce multijet background)

Challenge of single top

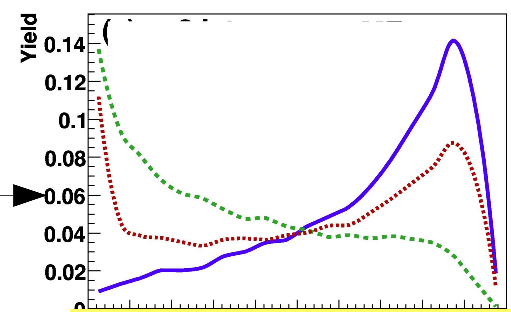
- We expect ~50 signal events per fb^{-1}
- Still, signal is lower than background uncertainty
  - Counting experiment not possible
  - Use multivariate analysis techniques



Event selection

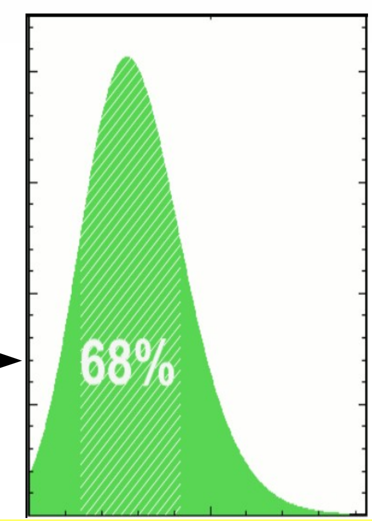
↓

discriminating variables → Multivariate analysis →



Discriminant

→

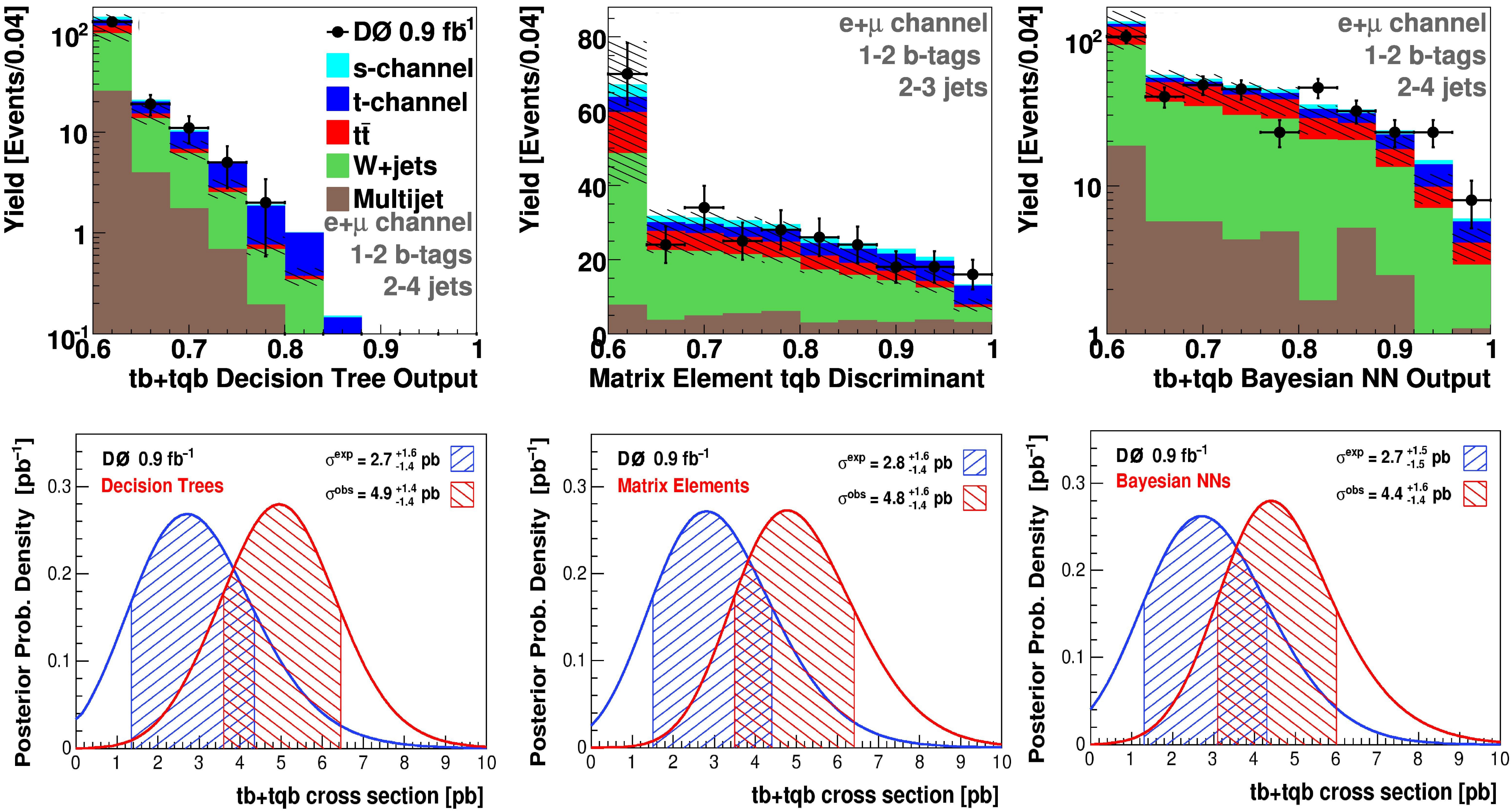


cross section

- Based on 0.9 fb^{-1} of Tevatron RunII data
- Using (up to) 24 analysis channels
- Three different multivariate analysis techniques:
  - Boosted decision trees
  - Bayesian neural networks
  - Matrix element method

[Phys. Rev. Lett. 98, 181802 (2007)]

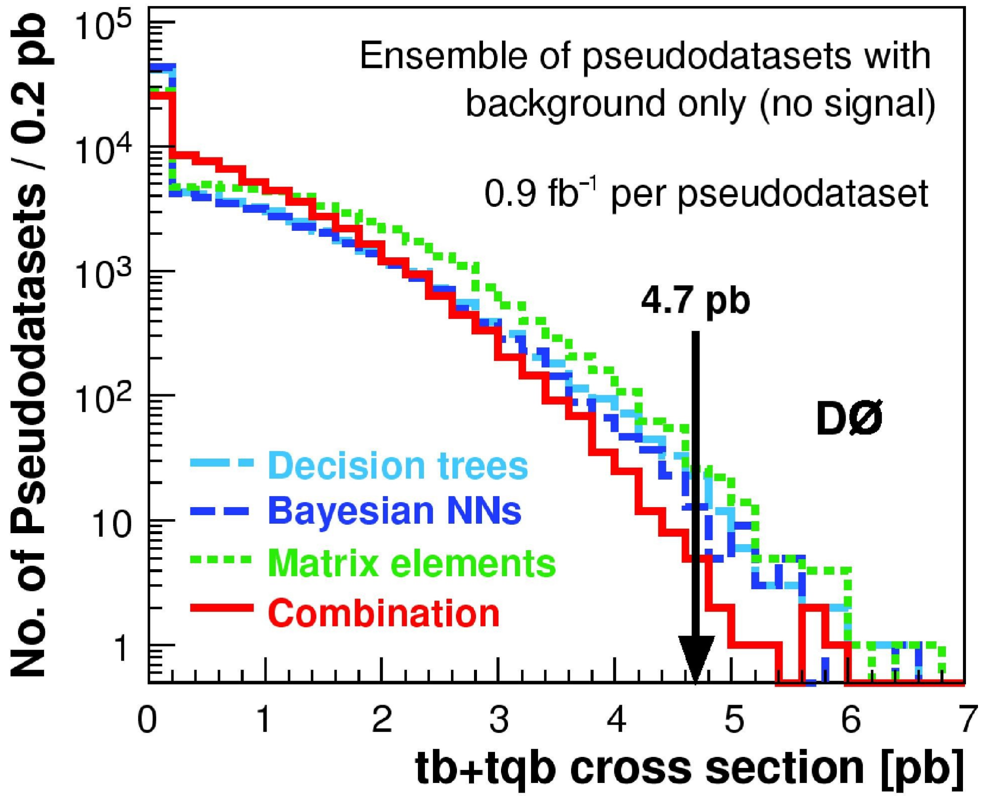
s+t cross section measurements



Single top quark production describes high discriminant distributions!
Consistent results with three different multivariate classifiers

Combining the three analyses

- Use the BLUE method (*B*est *L*inear *U*nbiased *E*stimator) to combine the results
- Determine correlations and weights from ensembles



Correlation matrix

	BDT	BNN	ME
BDT	1	0.66	0.64
BNN	0.66	1	0.59
ME	0.64	0.59	1

- **Expected** σ_{s+t} : $3.0 \pm 1.3\ pb$
- **Measured** σ_{s+t} : $4.7 \pm 1.3\ pb$

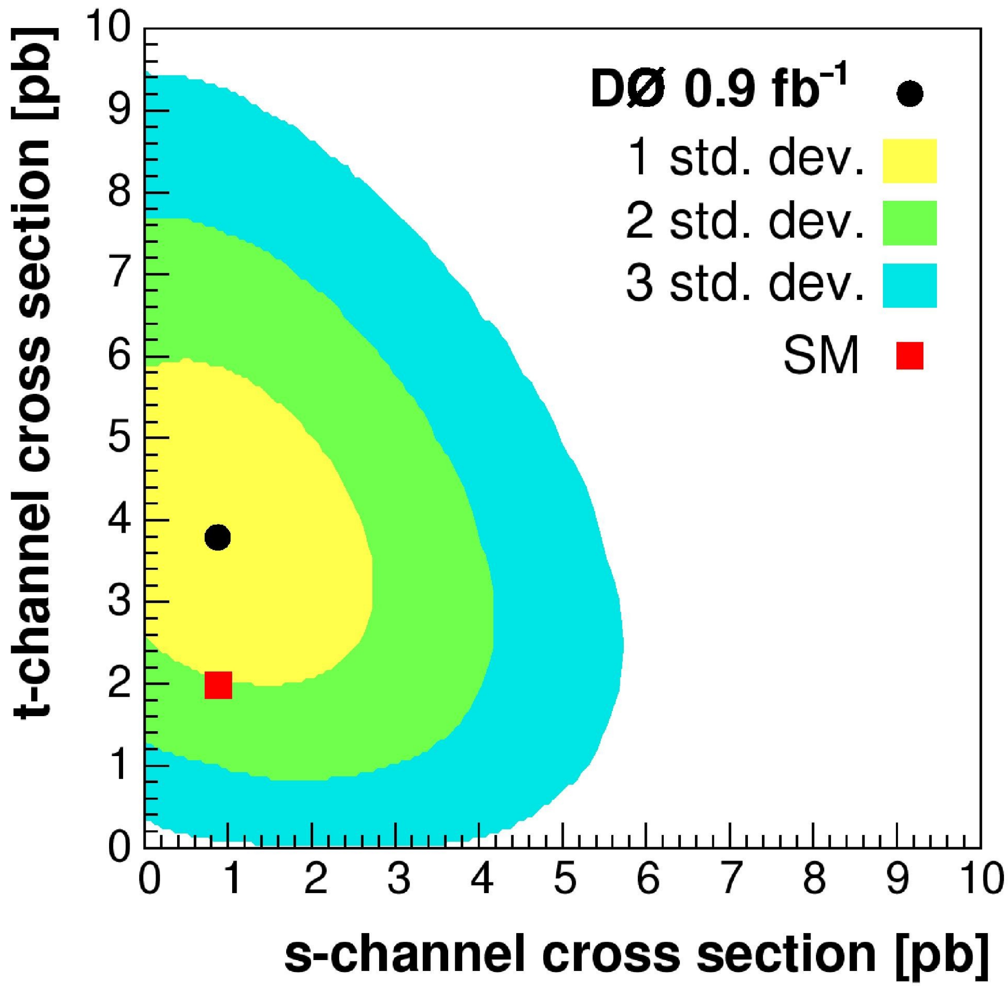
- **Expected sensitivity:** $2.3\,\sigma$
- **Observed significance:** $3.6\,\sigma$

Evidence for single top quark production!

[arXiv.org:0803.0739, accepted by PRD]

s- vs. t-channel

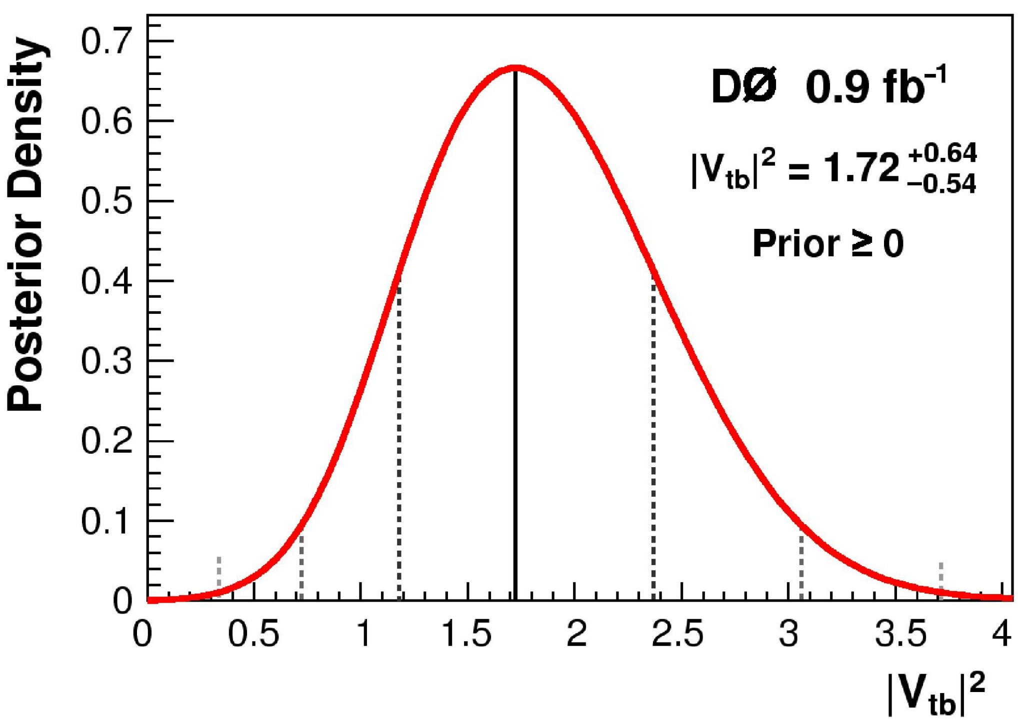
- Calculate contours for different levels of confidence in the t-channel vs. s-channel plane
- Analysis based on Boosted Decision Tree analysis (optimised for s+t channel)

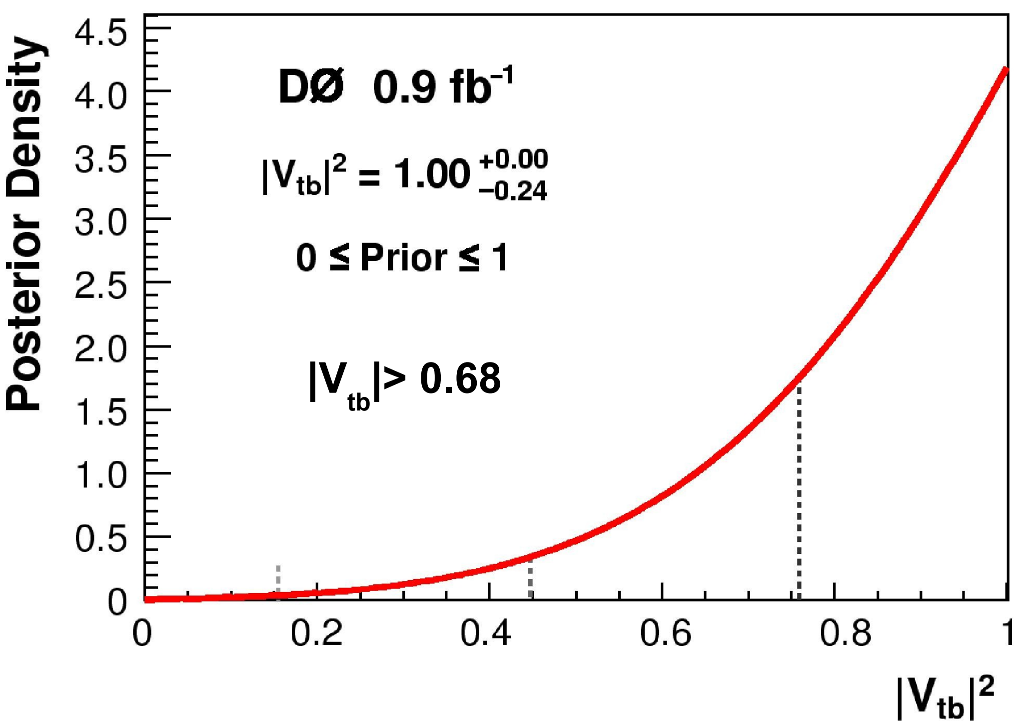


Measurement is in good agreement with the SM prediction

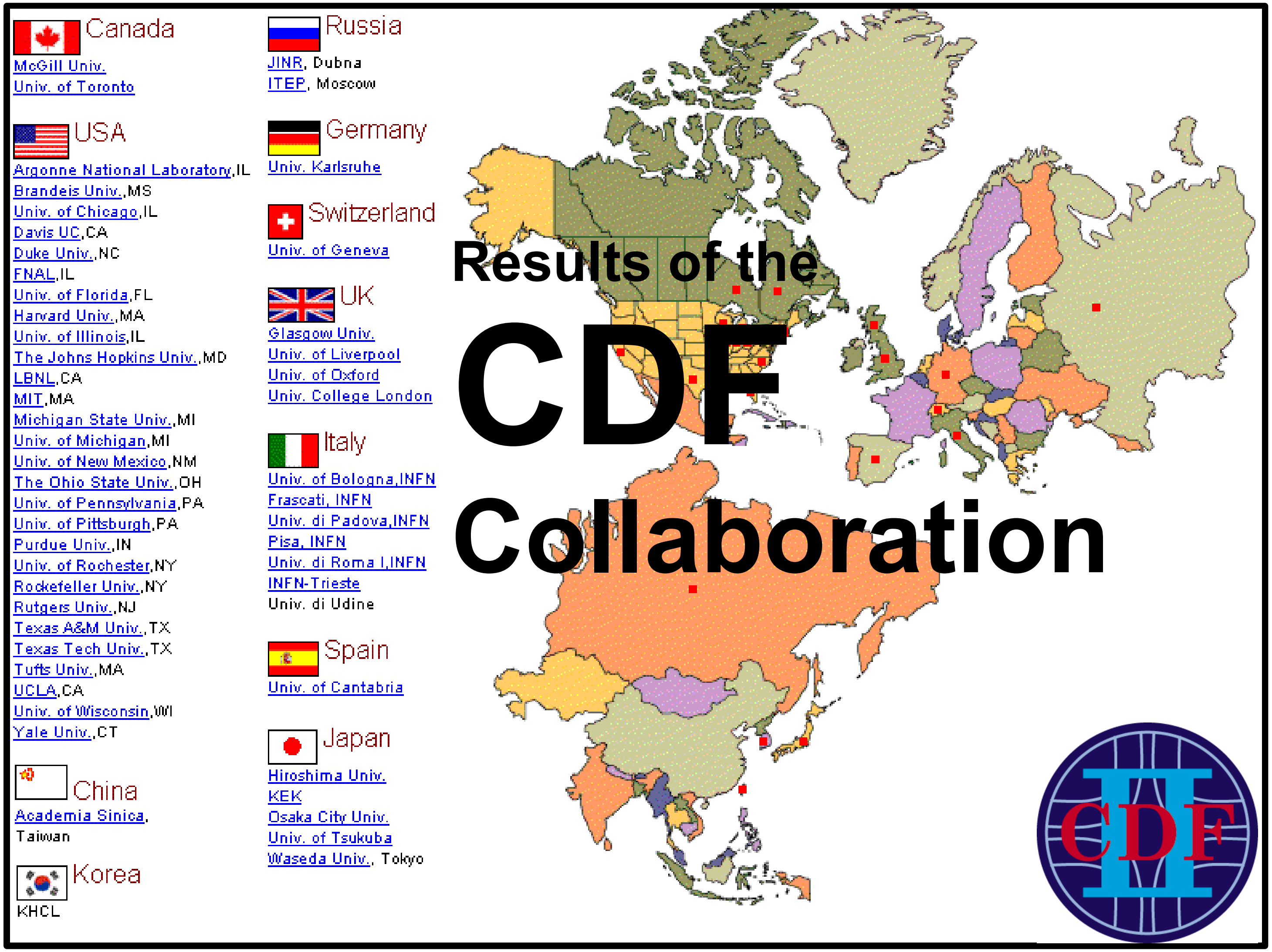
Measurement of $|V_{tb} \times f_1^L|$

- **Based on result of Boosted Decision Tree analysis**
- **Assumptions:**
  - $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$
  - **left-handed form factor $f_1^L = 1$**
  - **No constraint on number of generations**



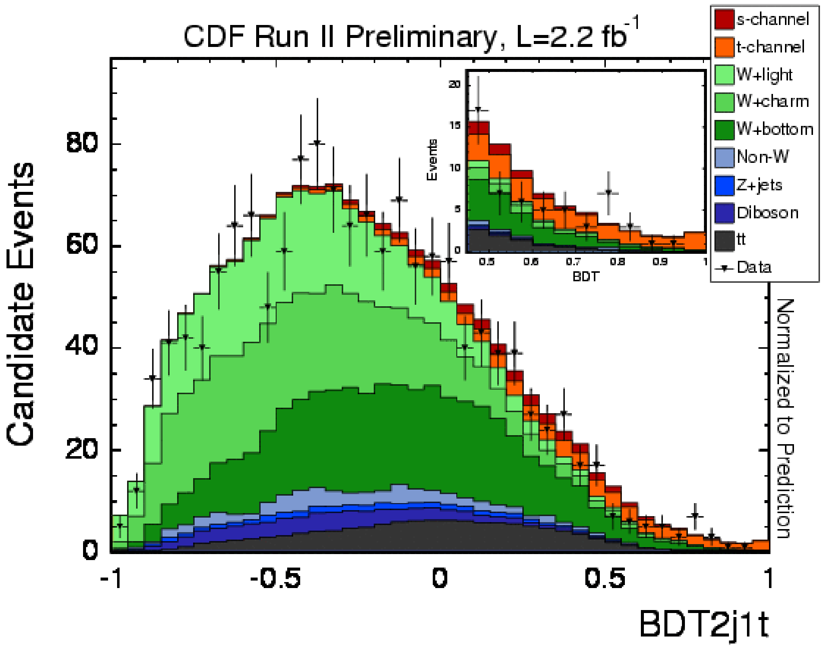


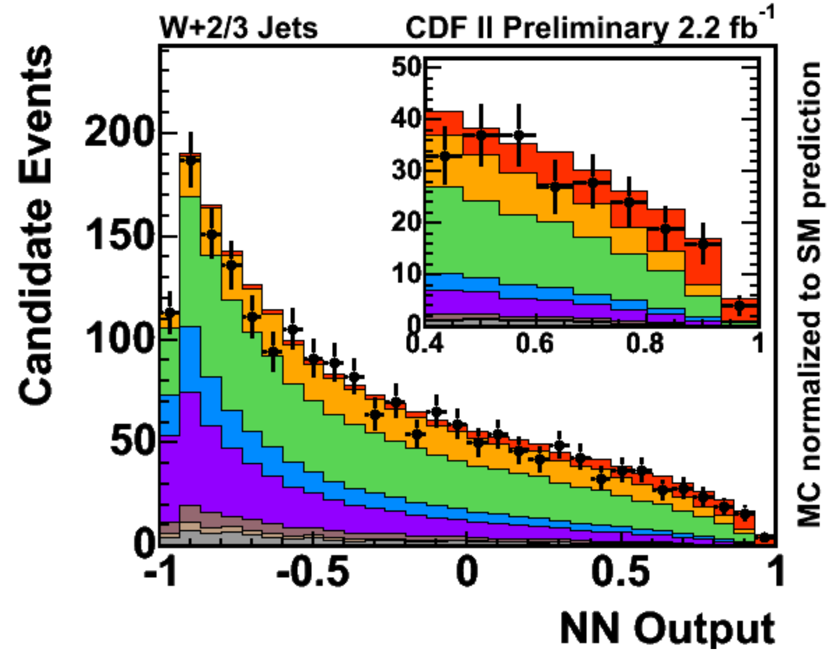
Results of the CDF Collaboration



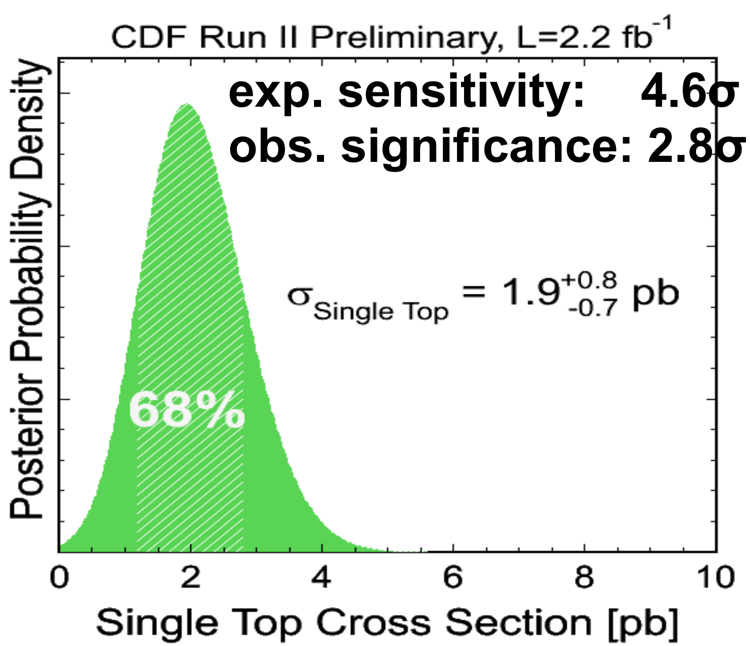
- Based on 2.2 fb^{-1} of Tevatron RunII data
- Four different multivariate analysis techniques:
  - Boosted decision trees
  - Neural networks
  - Matrix element method
  - Multivariate likelihood function

s+t cross section measurements (I)

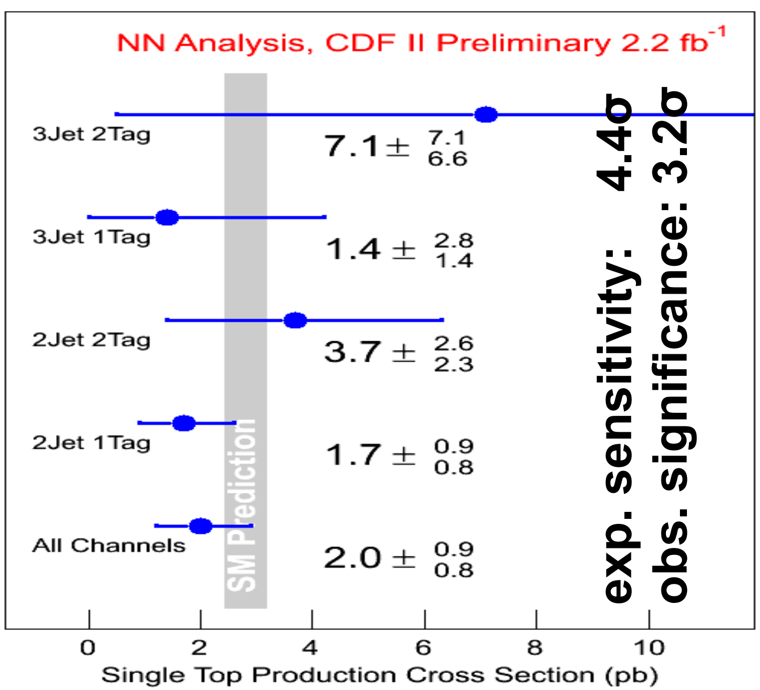




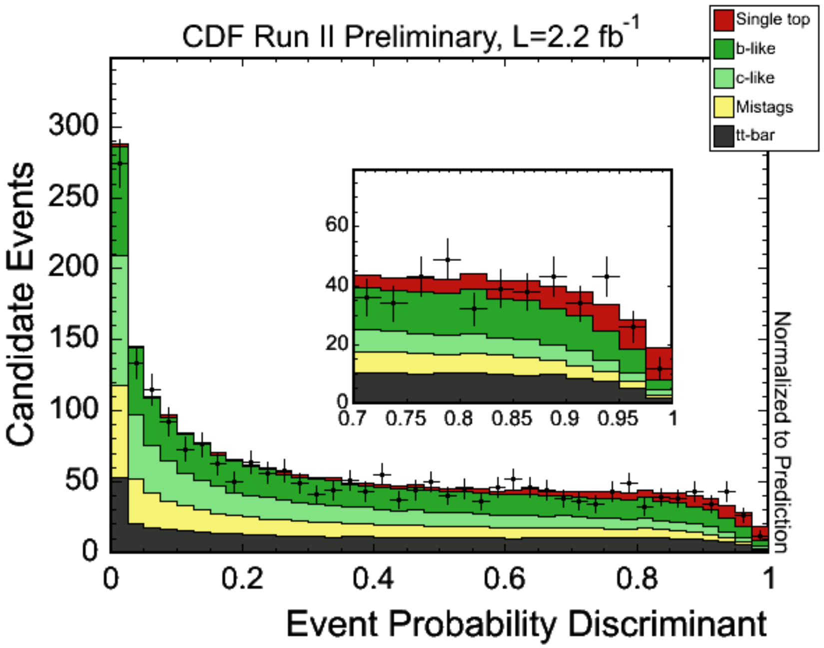
Boosted Decision Trees



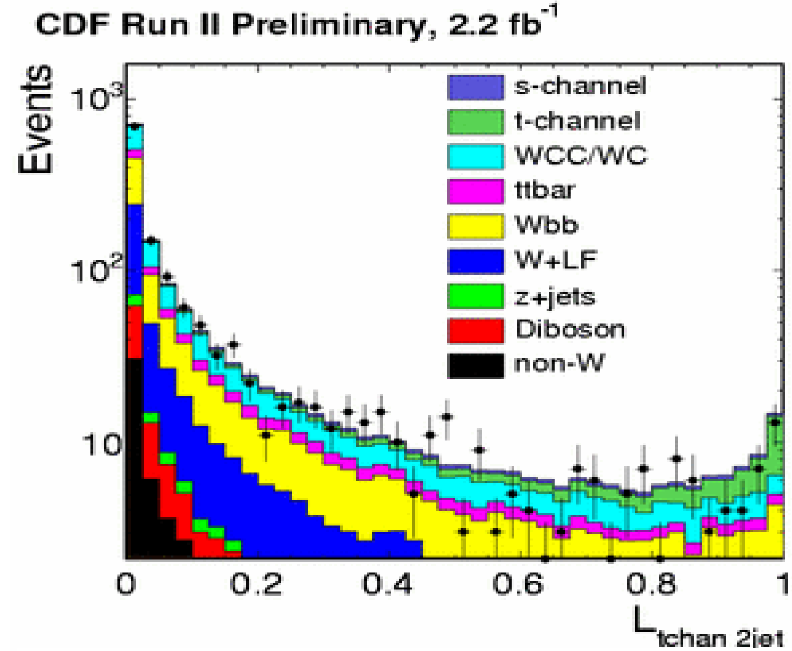
Neural Networks

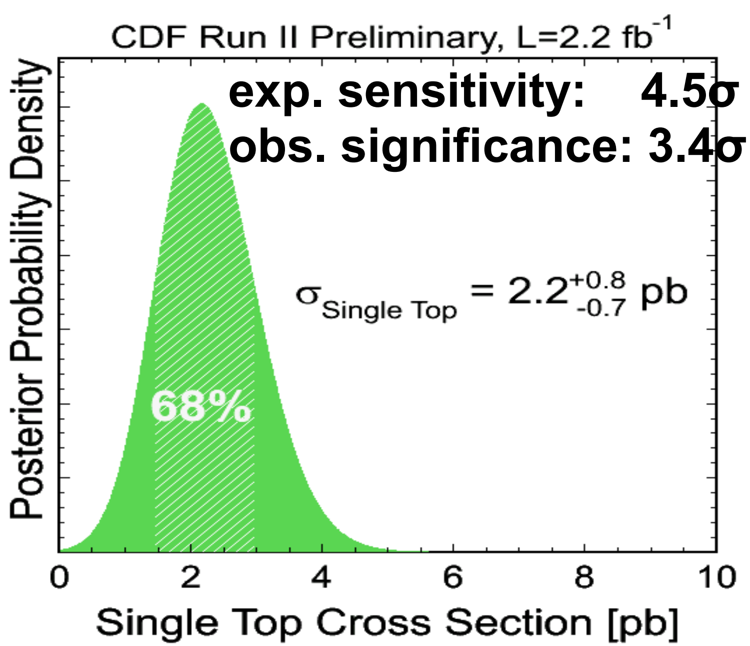


s+t cross section measurements (II)

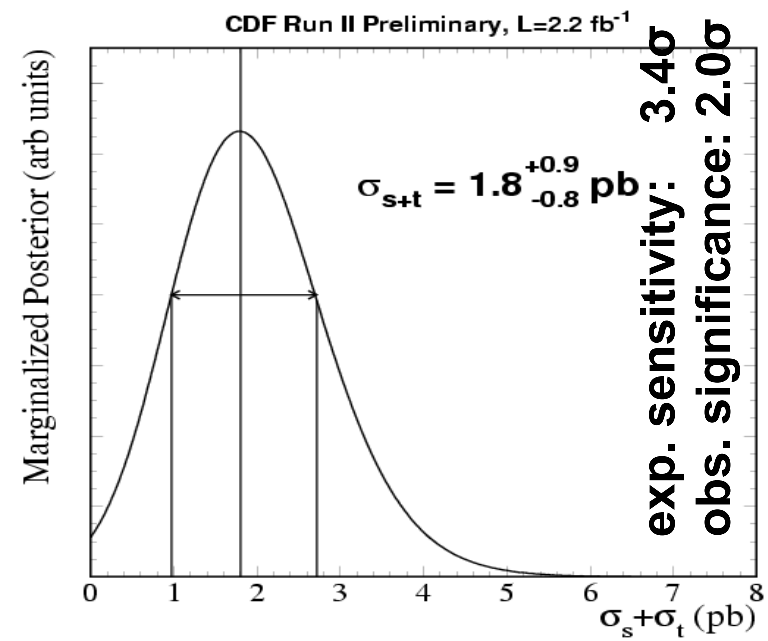


Matrix Elements



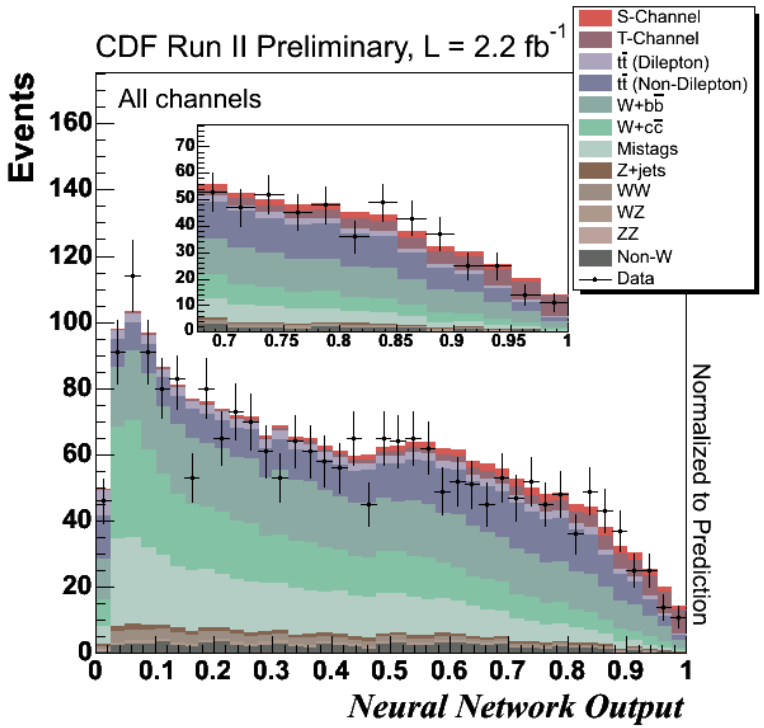


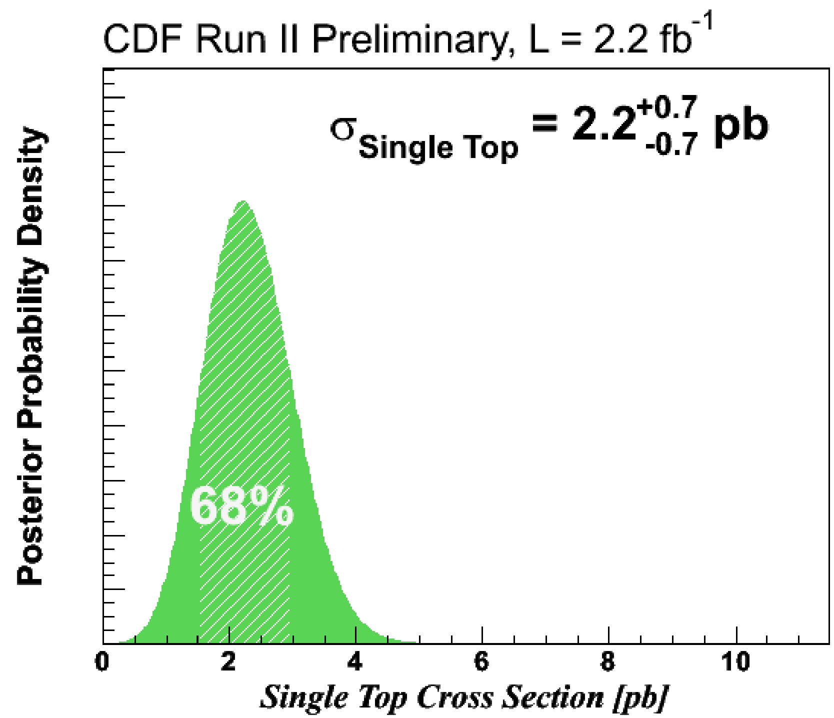
Likelihood Function



Combining three analyses

- Use another Neural Network to combine Neural Network, Likelihood Function and Matrix Element analyses
- Cross check with BLUE method gives similar result





Correlation matrix

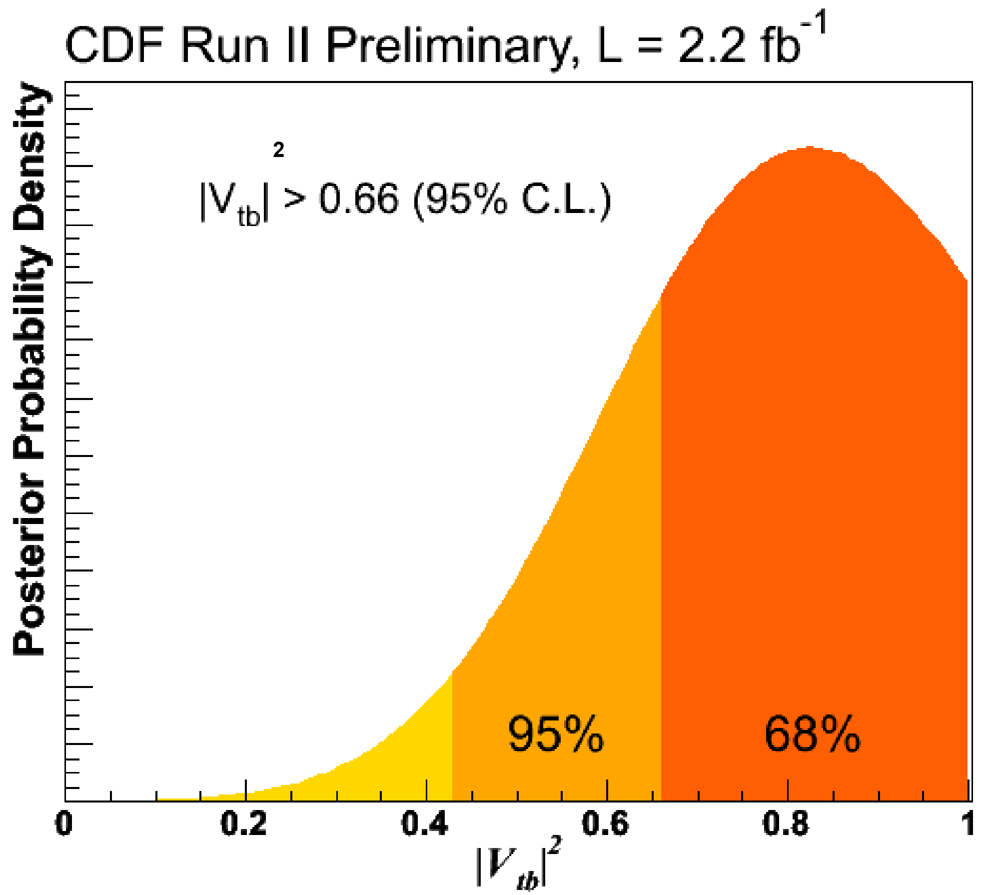
	LF	ME	NN
LF	1	0.60	0.74
ME		1	0.61
NN			1

exp. sensitivity: 5.1σ
obs. significance: 3.7σ

A 5σ oberservation of single top is around the corner!

Measurement of $|V_{tb}|$

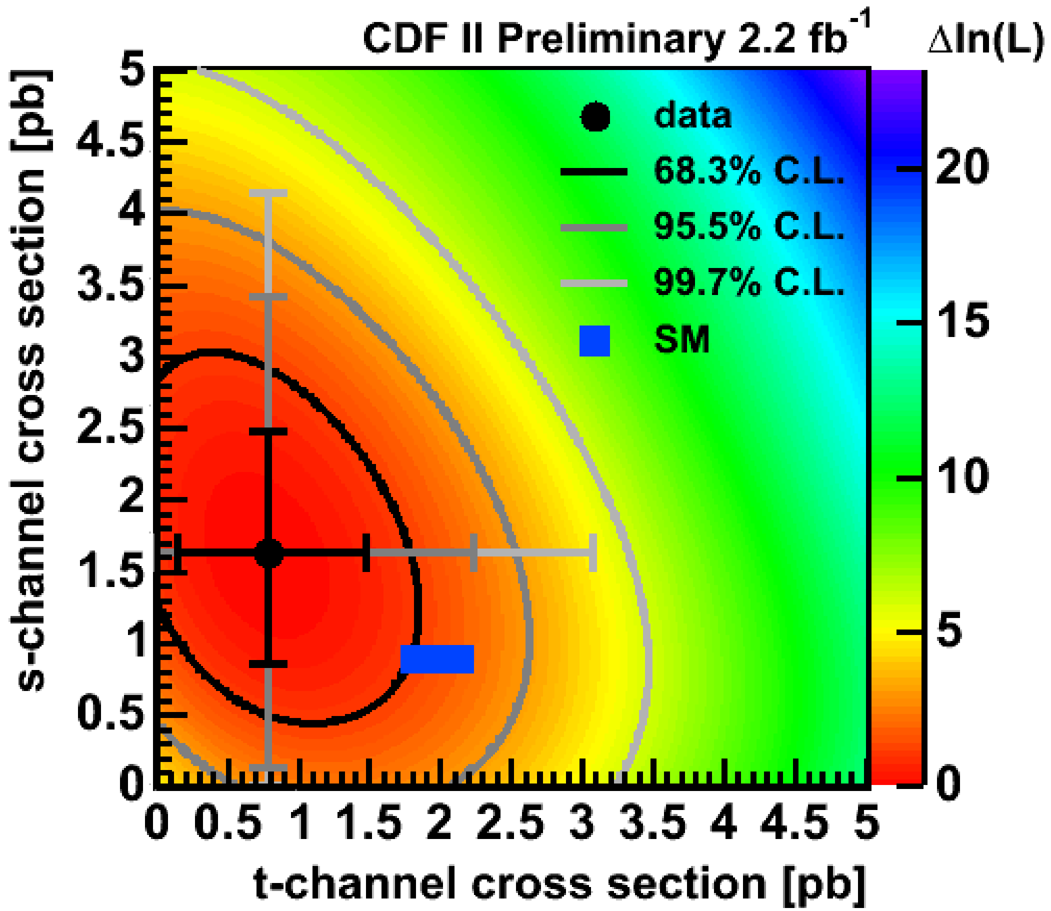
- Extract $|V_{tb}|$ from combined analysis
- Assuming a flat prior on $|V_{tb}|^2$



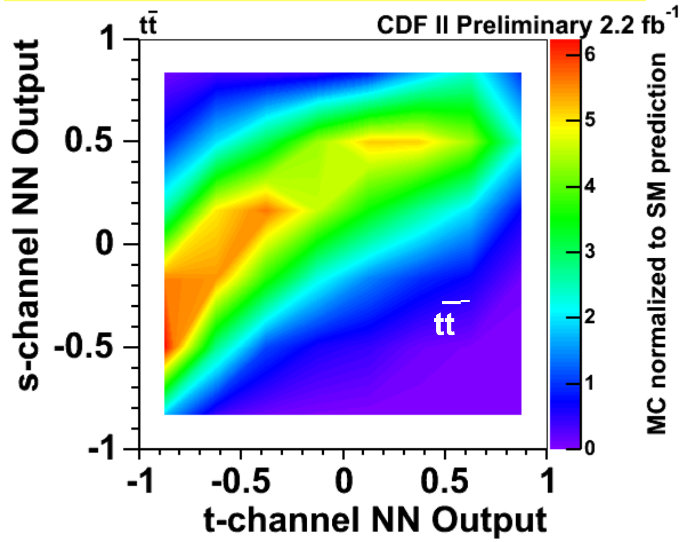
$|V_{tb}| = 0.89 \pm 0.14$ (exp.) ± 0.07 (theory)

s- and t-channel search

- Use Neural Networks from the combined analysis
- Adding an additional s-channel Neural Network for 2 jets and 1 b-tag
- Perform a 2 parameter likelihood fit to data



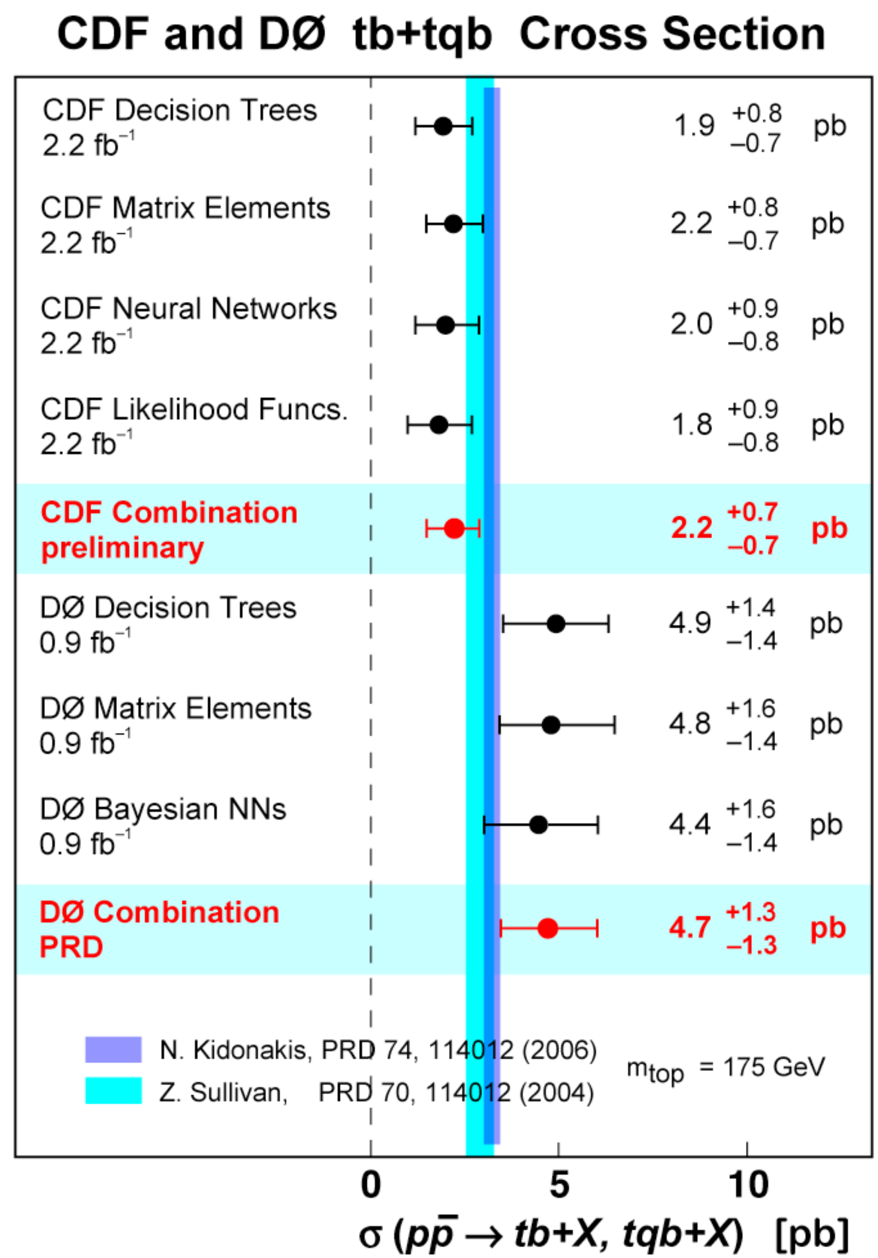
Example for ttbar Neural Network template



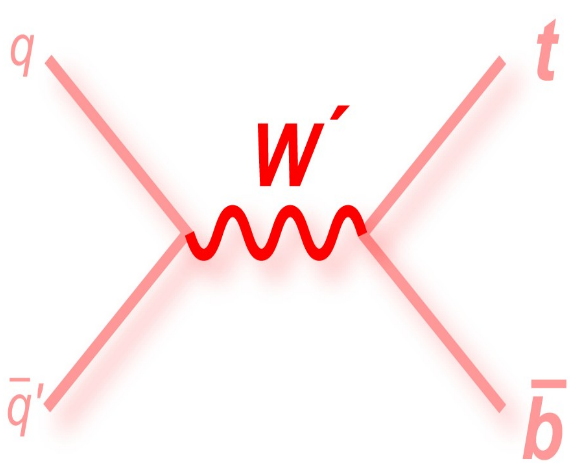
$$\sigma_{\mathrm{t-channel}} = 0.8^{+0.7}_{-0.6}\,(\mathrm{stat.} + \mathrm{syst.})\ \mathrm{pb}$$
$$\sigma_{\mathrm{s-channel}} = 1.6^{+0.9}_{-0.8}\,(\mathrm{stat.} + \mathrm{syst.})\ \mathrm{pb}$$

SM single top summary

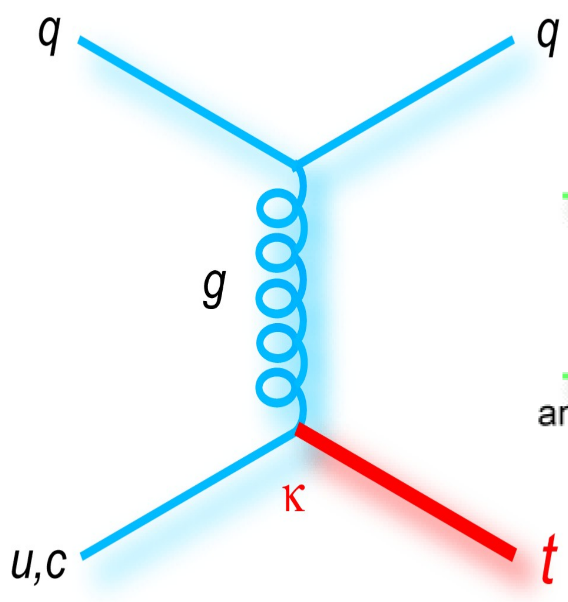
- **Both CDF and DØ perform several analyses searching for the production of single top quarks**
- **Individual analyses and the combinations are in good agreement with the SM predictions**



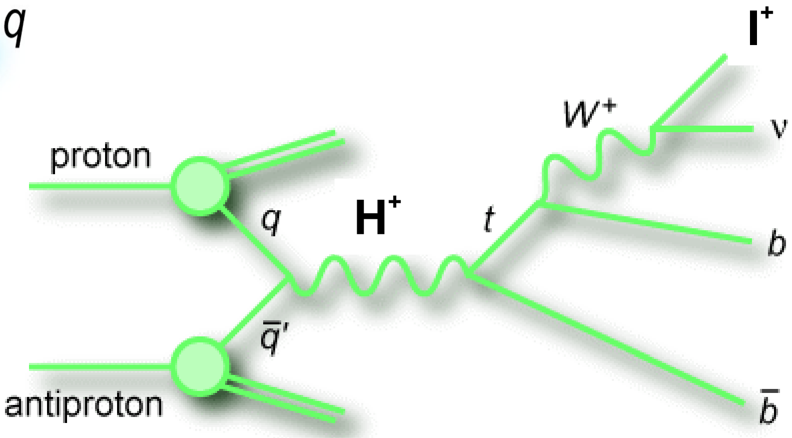
Searches for New Physics



W'



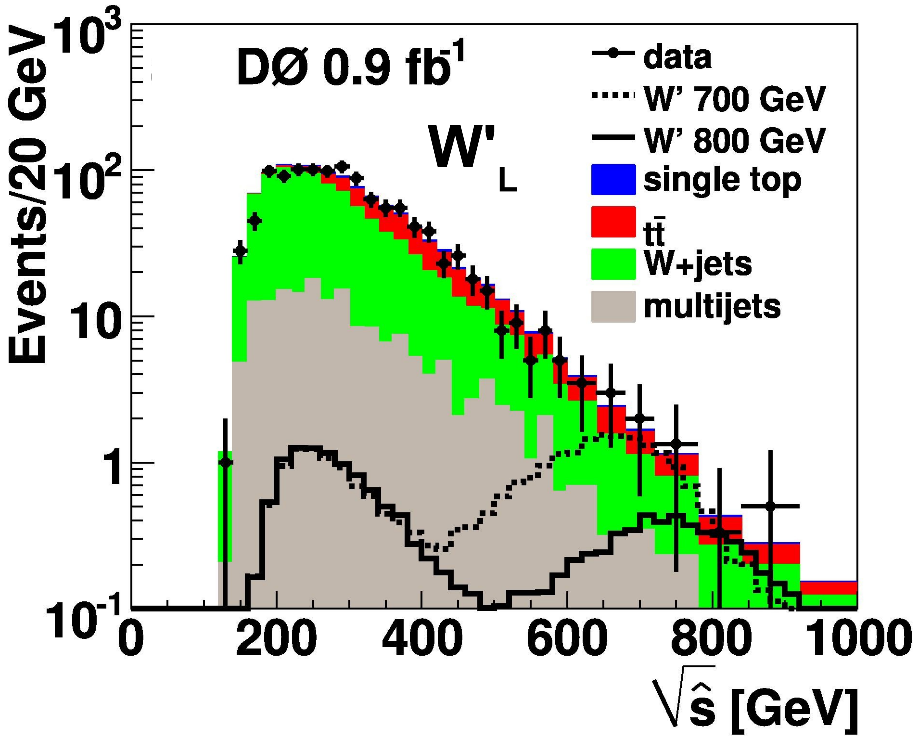
FCNC
DØ [PRL 99:191802 (2007)

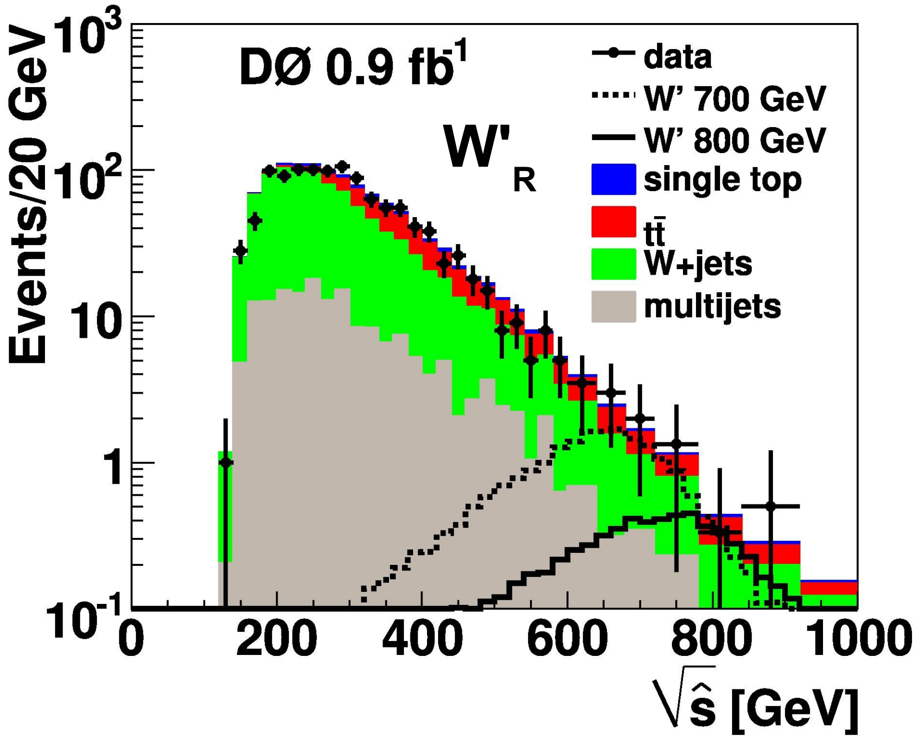


charged Higgs

Search for W'

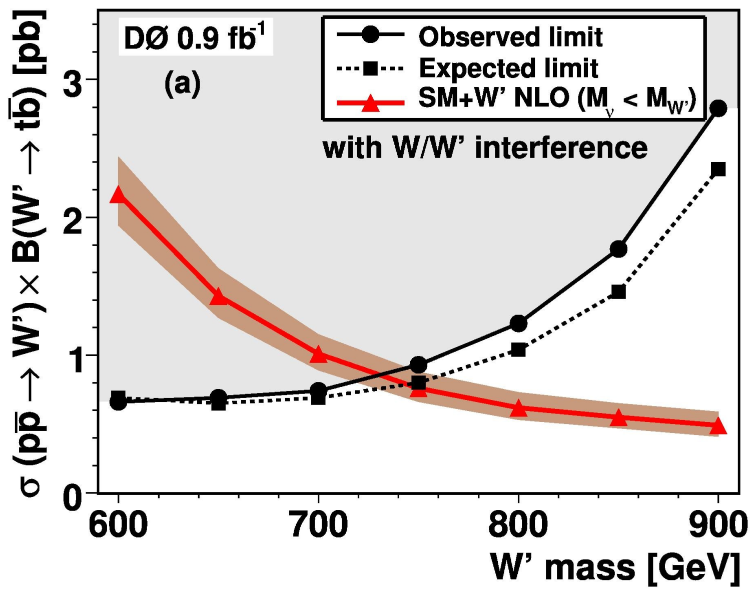
- Analysis performed in 0.9 fb^{-1}
- Search for W'_R and W'_L seperately
- Selection similar to single top analyses
- Binned likelihood analysis using $\sqrt{\hat{s}}$

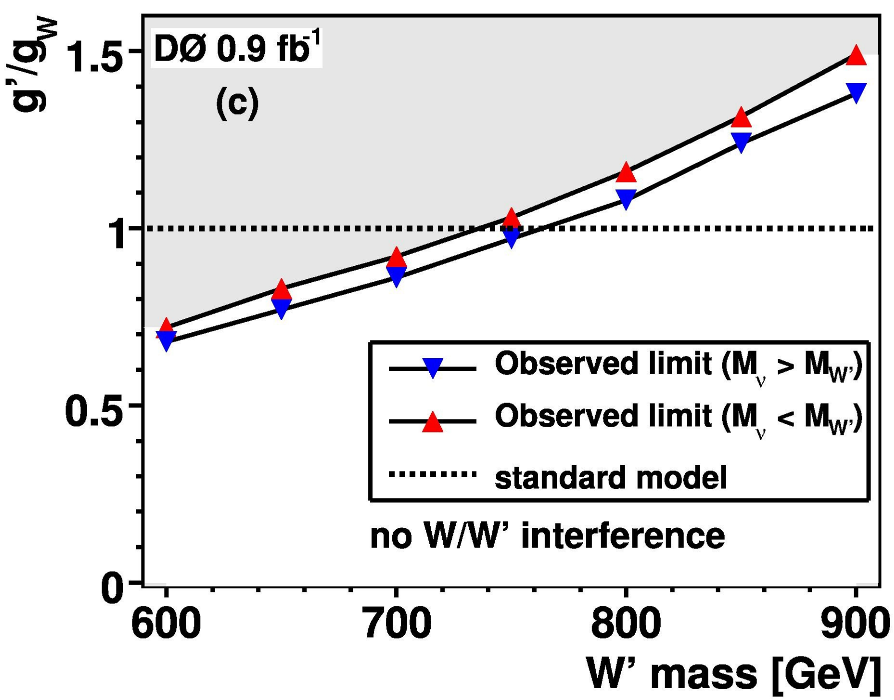


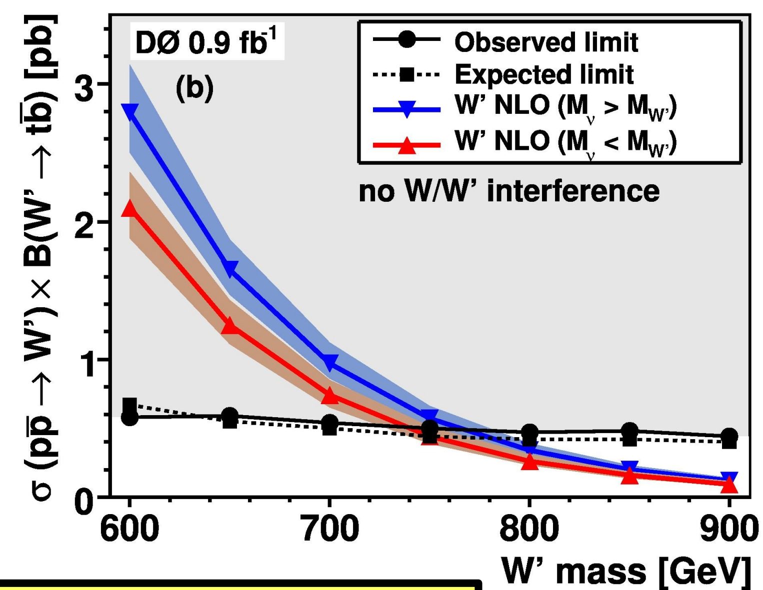


Search for W'

- Fit region with $\sqrt{\hat{S}} > 400\,GeV$
- Set 95% C.L for W'_L and W'_R masses and couplings:
  - $M(W'_L) > 731$ GeV
  - $M(W'_R;l,q) > 739$ GeV
  - $M(W'_R;q,q) > 768$ GeV



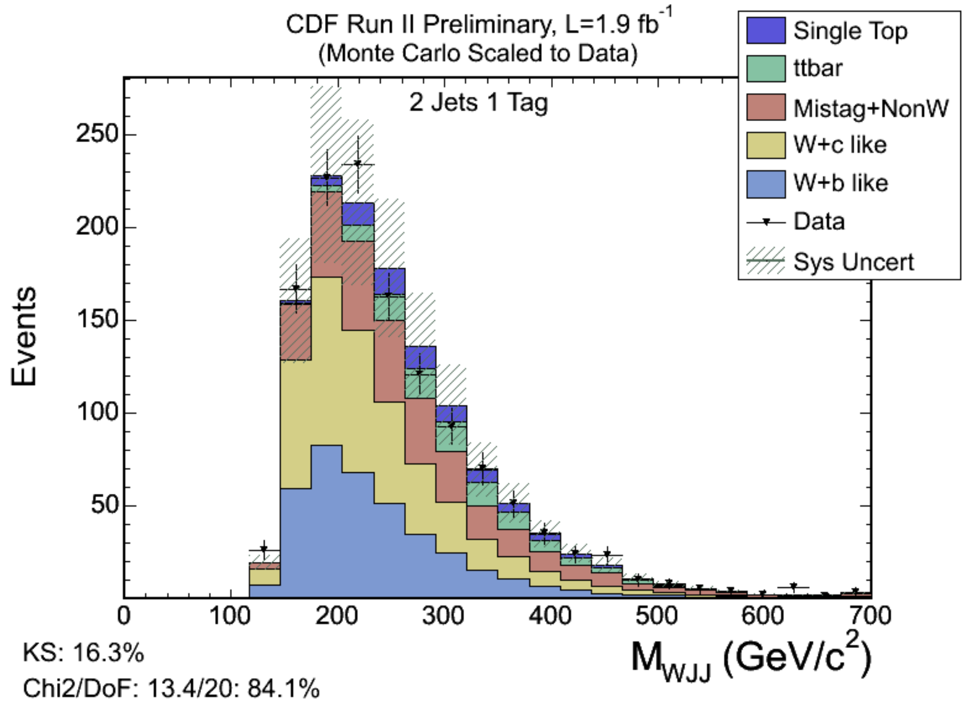


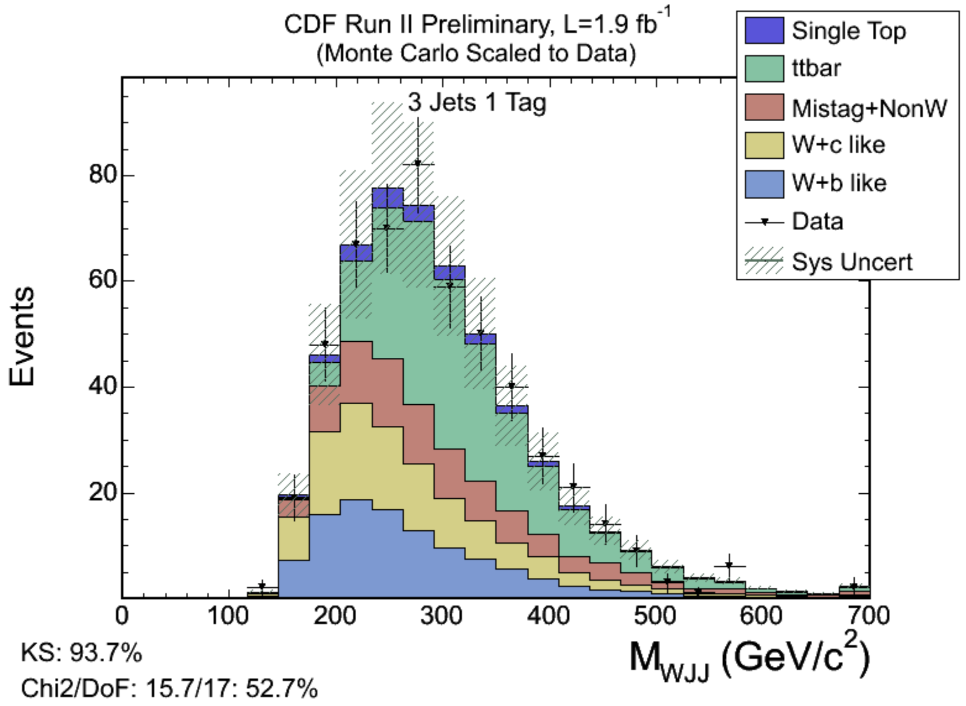


Phys. Rev. Lett. 100, 211803 (2008)

Search for W'

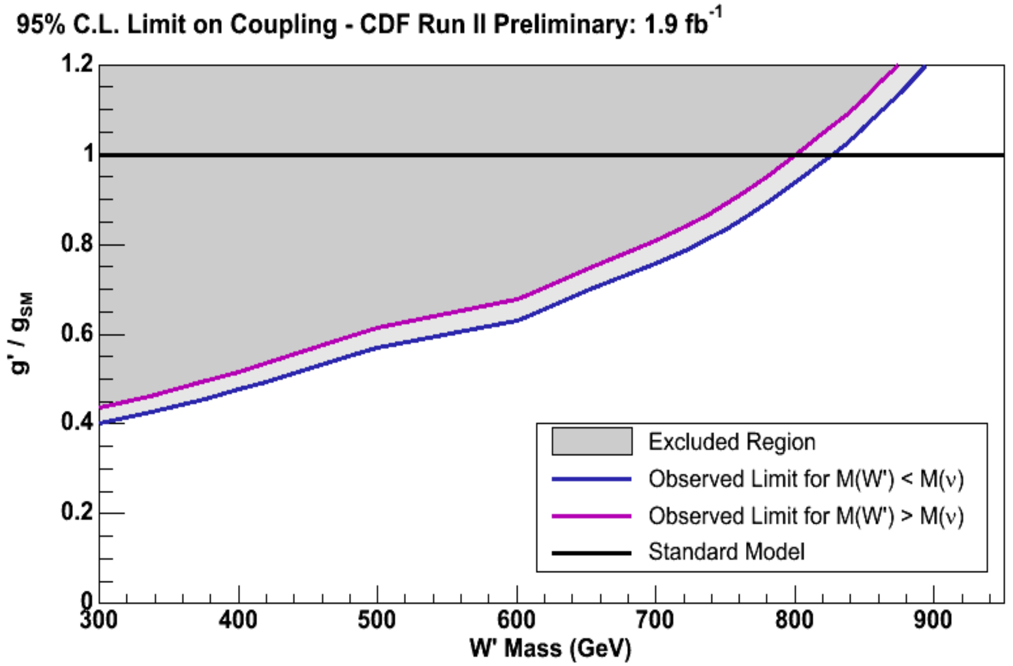
- Analysis of 1.9 fb^{-1} of RunII data using single top selection
- Assume SM-like couplings to fermions for mass analysis
- Use b-tagged events with 2 or 3 jets
- Fit invariant mass of reconstructed W and the two leading jets

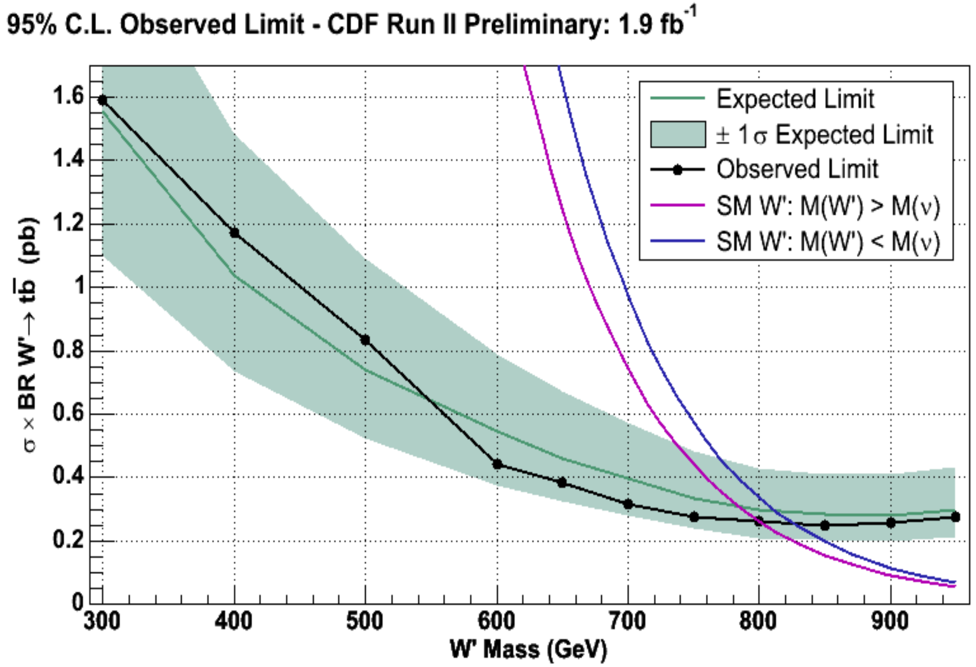




Search for W'

- **Set 95% C.L. on W' mass and couplings**
- **Result:**
  - **M(W') > 800 GeV (M(W') > M(ν_R))**
  - **M(W') > 825 GeV (M(W') < M(ν_R))**

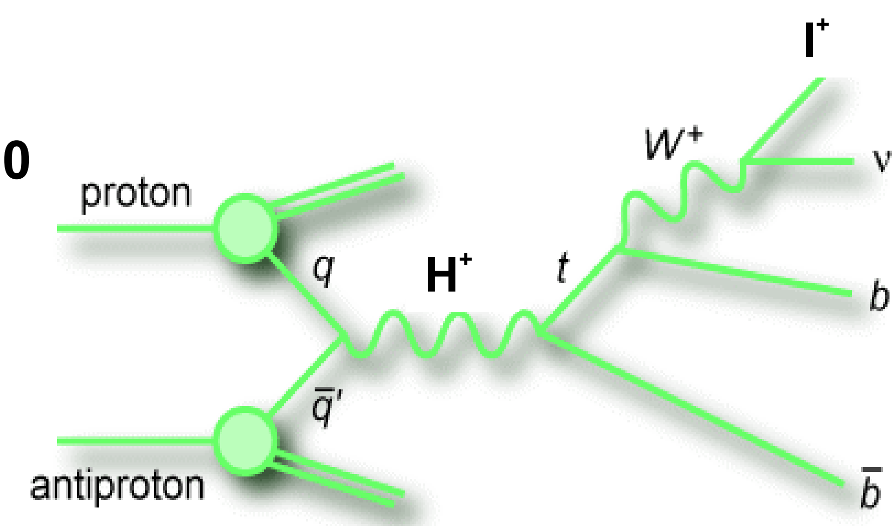




Limits on heavy gauge boson production in single top final state!

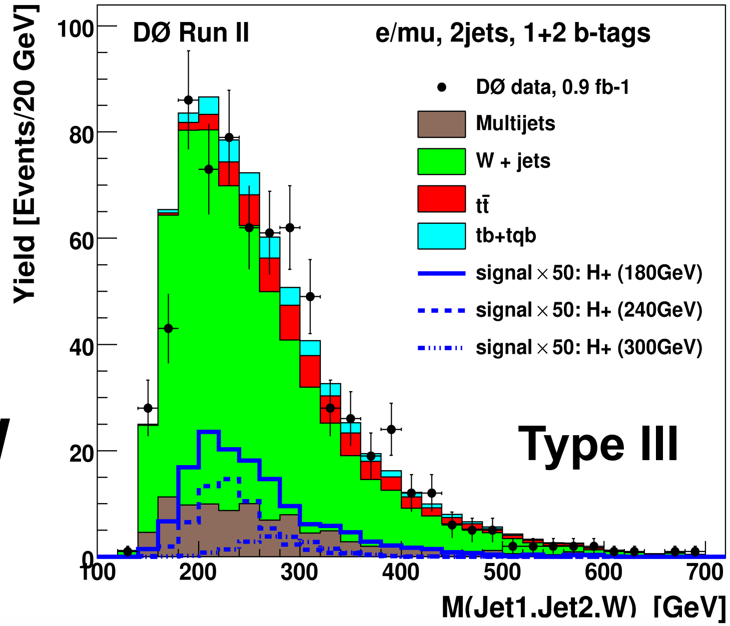
Search for charged Higgs

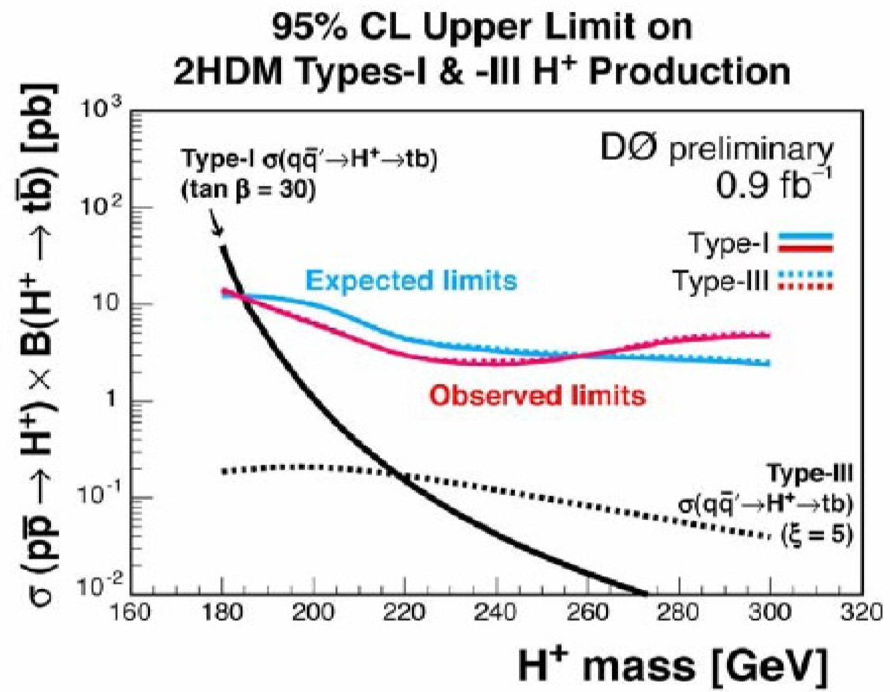
- Two-Higgs Doublet Model (2HDM) extension to the SM predicts five Higgs bosons, two carry electric charge (H^+, H^-)
- Three types of 2HDMs in order to avoid FCNCs:
  - Type I: One doublet gives mass to all quarks and leptons
  - Type II: One doublet gives mass to up-type quarks and neutrinos, other doublet gives mass to down-type quarks and charged leptons
  - Type III: Two doublets contribute to quark and lepton masses. Top-charm mixing parameter ξ [H.-H. He and C.-P. Yuan, PRL 83 (1999) 28]
- Cross sections up to:
  - Type I: ~10pb (Type I)
  - Type II: ~0.5pb (Type II) with tanβ = 100
  - Type III: ~0.1 pb (Type III) with ξ=5

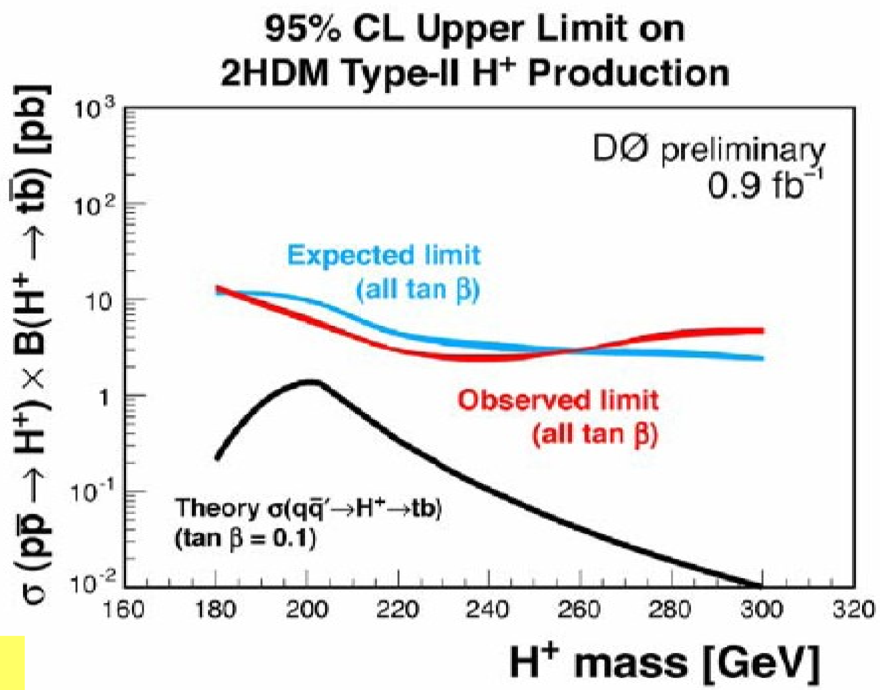


Search for charged Higgs

- **Analyse events with 2 jets, one or two b-tags, and an electron or a muon (4 channels)**
- **Binned likelihood fit on reconstructed invariant mass of jets and reconstructed W**







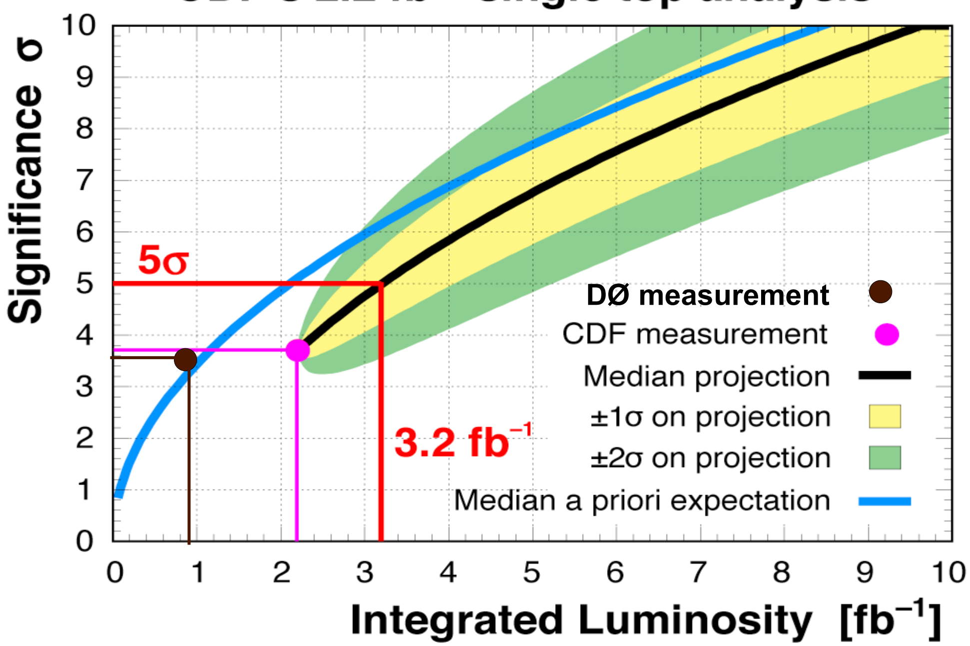
Limits on 2HDM cross sections!

Summary & Outlook

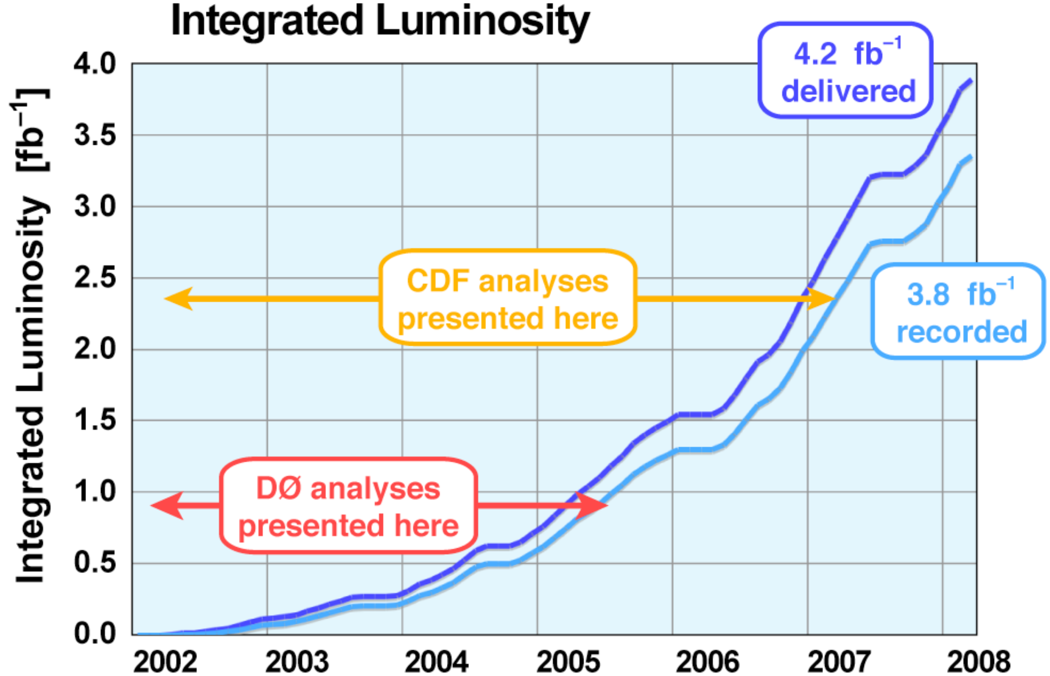
- Both DØ and CDF see 3σ evidence for single top quark production
- First direct measurements of $|V_{tb}|$
- Transfer of analysis techniques to signal processes beyond Standard Model in progress

- Excellent Tevatron performance combined with high efficiency data taking promises interesting measurements in the single top final state in the (near) future!

Projected significance based on CDF's 2.2 fb^{-1} single top analysis



Tevatron Run II Integrated Luminosity



Backup

Systematic uncertainties

DØ

Source of Uncertainty	Size
Top pairs normalization	18%
W+jets & multijets normalization	18–28%
Integrated luminosity	6%
Trigger modeling	3–6%
Lepton ID corrections	2–7%
Jet modeling	2–7%
Other small components	Few %
Jet energy scale ✚	1–20%
Tag rate functions ✚	2–16%

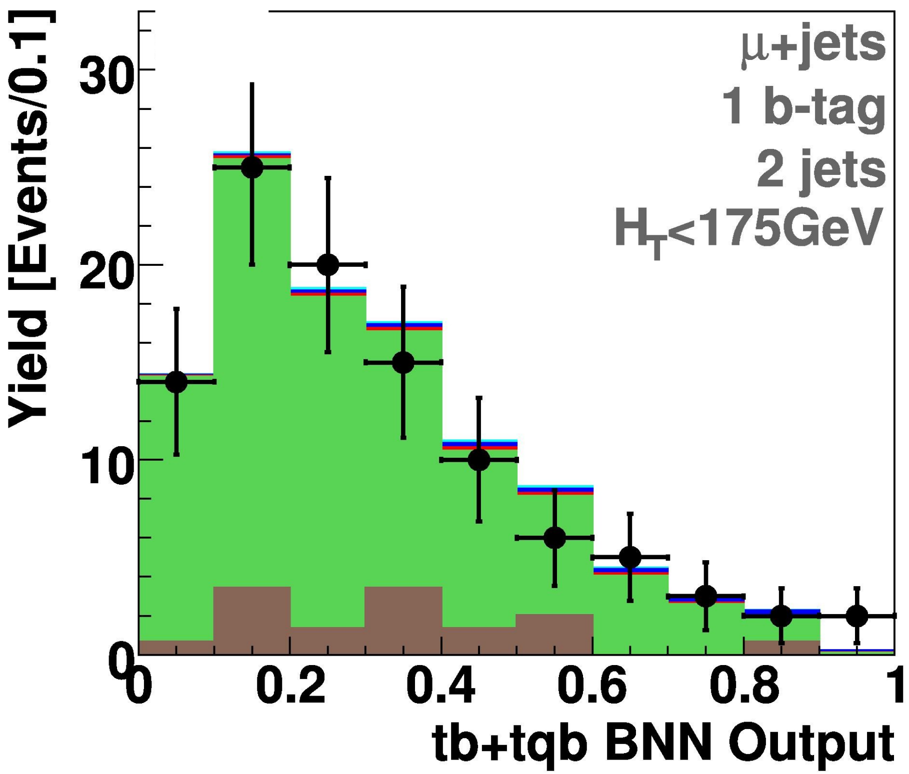
✚ **systematics affecting shape**

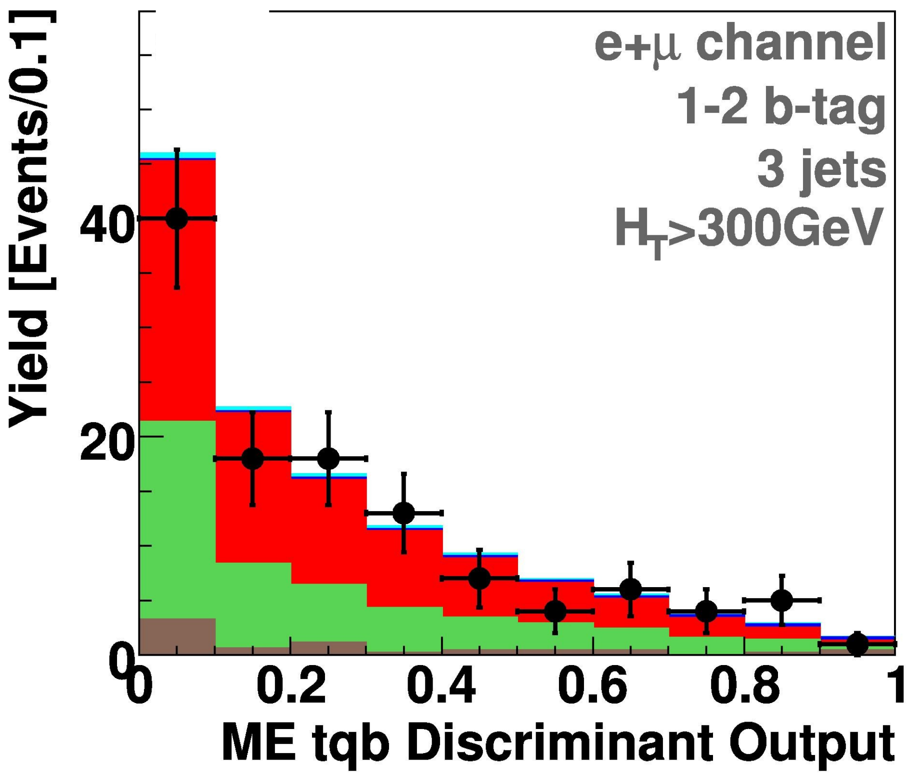
CDF

Syst. Uncertainty	Rate	Shape
Jet Energy Scale	0...16%	☑
Initial state radiation	0...11%	☑
Final state radiation	0...15%	☑
Parton Distribution Function	2...3%	☑
MC Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
NN Flavor-Separator		☑
Mistag model		☑
Q2 scale in ALPGEN MC		☑
Input variable mismodeling		☑
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
Top-pair normalization & mtop	23%	☑

Cross checks

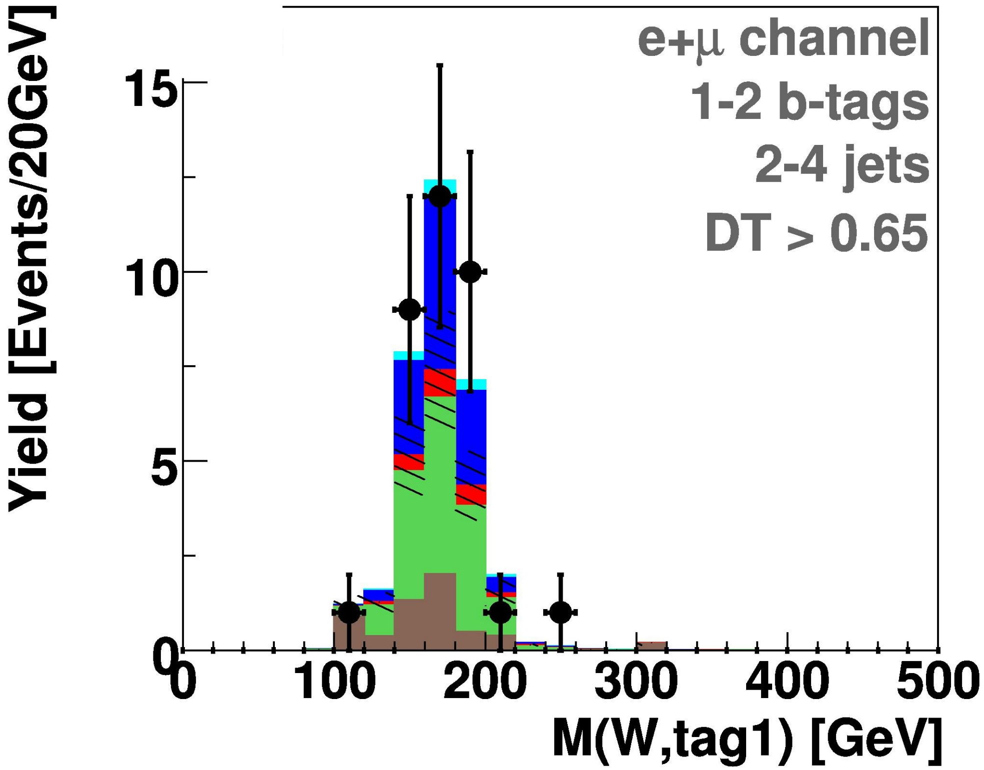
- Check background modelling in
  - W+jets dominated region (H_T < 175 GeV)
  - Region dominated by top pair production (H_T > 300 GeV)

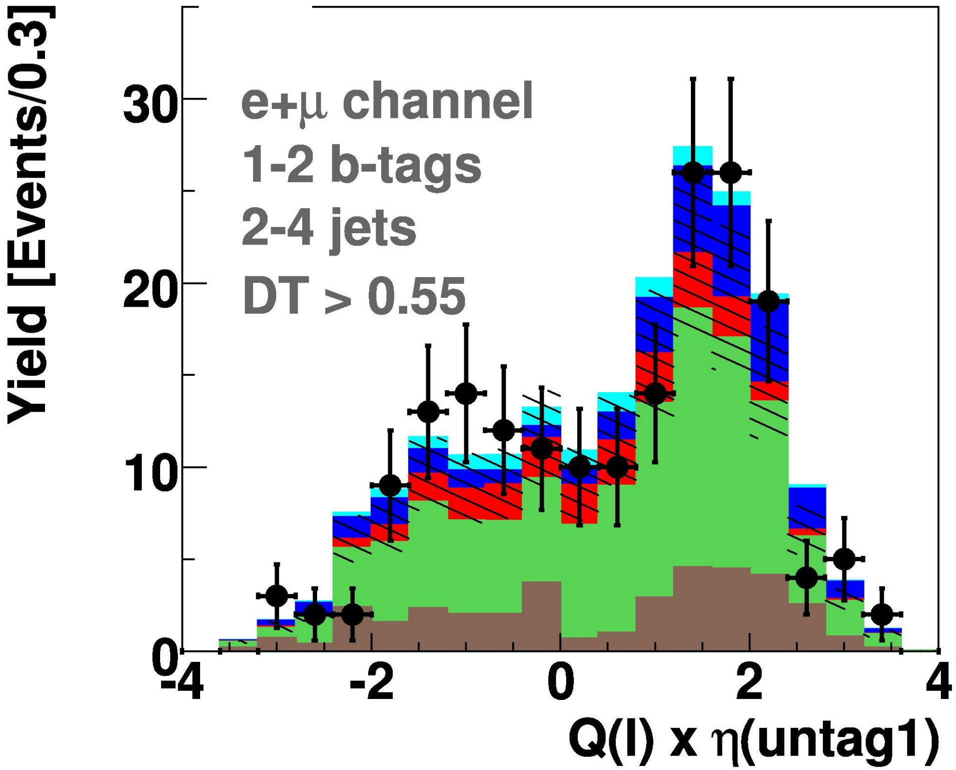




Do we see single tops?

- Look at high BDT output
- Looking at reconstructed top quark mass and q(lepton) * η(untagged jet) distribution (Tevatron specific t-channel variable)

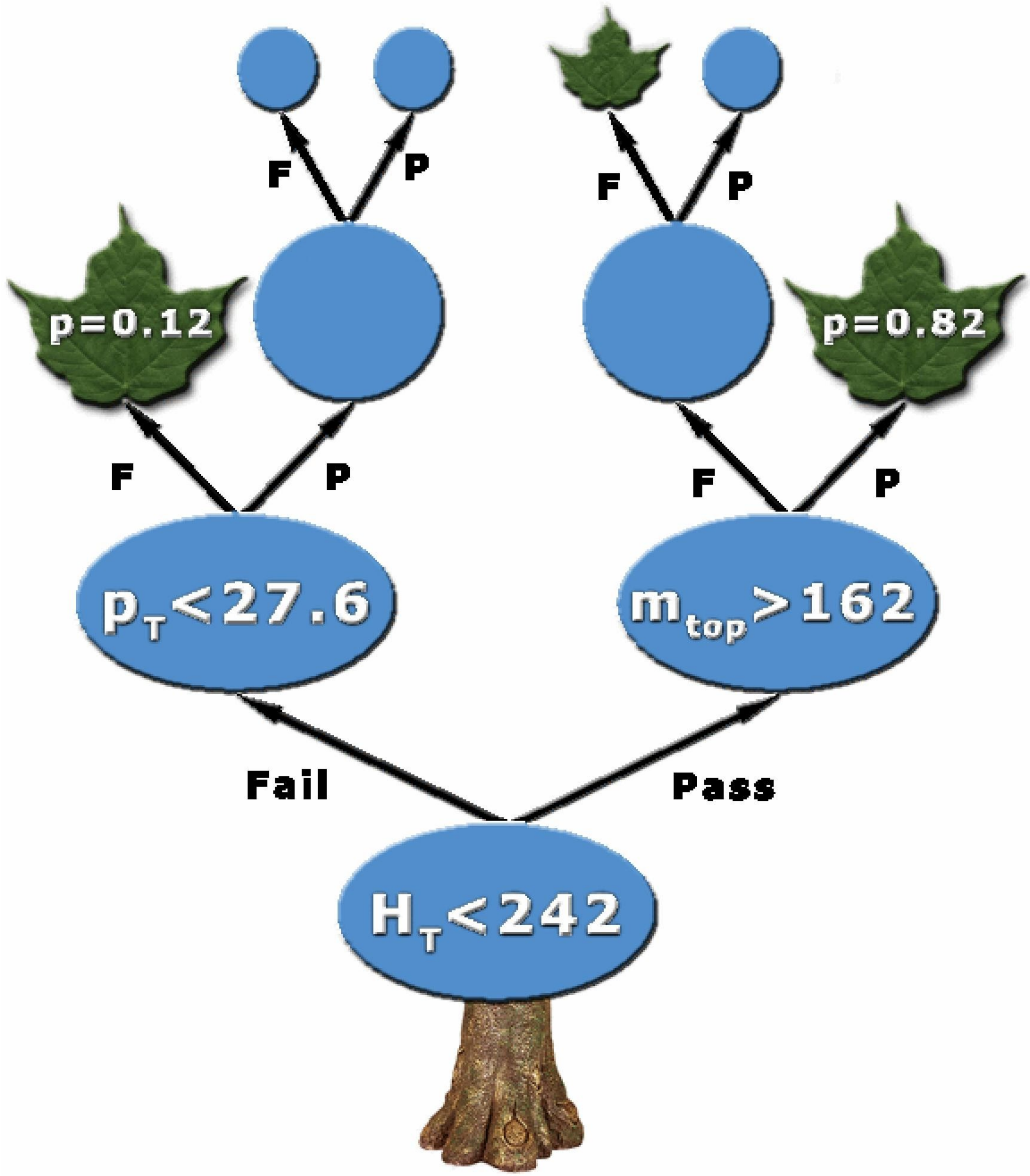




Distributions in good agreement with SM single top hypothesis

Boosted Decision Trees

- Machine learning technique, widely used in social sciences
- Extension to a cut-based analysis
- Cut at each node on variable giving the best separation
- Use adaptive boosting to dilute the discrete output of a single decision tree
- Reweight missclassified events
- Calculate purity p in each final leaf (discriminant)



Matrix method

- Uses the 4-vectors of reconstructed leptons and jets
- Use matrix elements of main signal and background Feynman diagrams to compute an event probability density for signal and background hypotheses

differential cross section (LO matrix element)

parton distribution functions

$$P_i(\vec{x}) = \frac{1}{\sigma} \int \dots \int \sum_{comb} d^n \sigma_i(\vec{y})\, dq_1\, dq_2\, f(q_1)\, f(q_2)\, W(\vec{x};\vec{y})$$

transfer fuctions

- Calculate discriminant D (S = s- or t-channel):

$$D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bkgd}(\vec{x})}$$