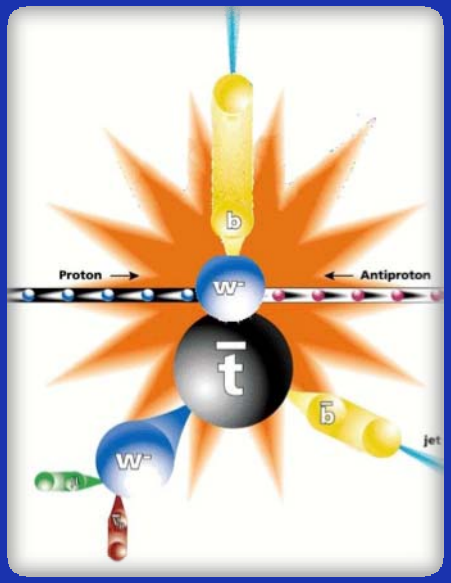
First Observation of Single Top Quark Production



1. Single Top Physics
2. Samples, Event Selection and Analysis Strategy
3. DØ's Results
4. CDF's Results
5. Conclusion

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for the DØ and CDF Collaborations

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Disclaimer

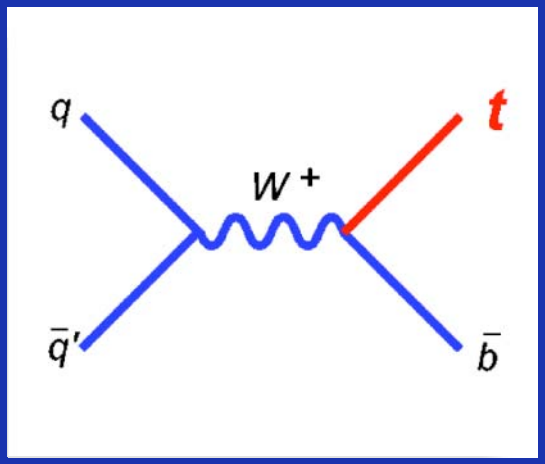
- You are about to see very recent results
  - DØ submitted its latest result to PRL yesterday (arXiv:0903.0850 [hep-ex])
  - CDF also submitted its latest result to PRL yesterday (arXiv:0903.0885 [hep-ex])

  - I had a chance to see this a few hours ago for the first time so bear with your speaker…

Single Top quark production. Why do we care?

- The top quark has been **discovered in 1995** by CDF and DØ **through strong interactions** at the Tevatron
- **Electroweak production** predicted by the Standard Model but **not observed yet**
- The measurement of the cross section is a **test of the SM**
- Dominant production channels at the Tevatron:

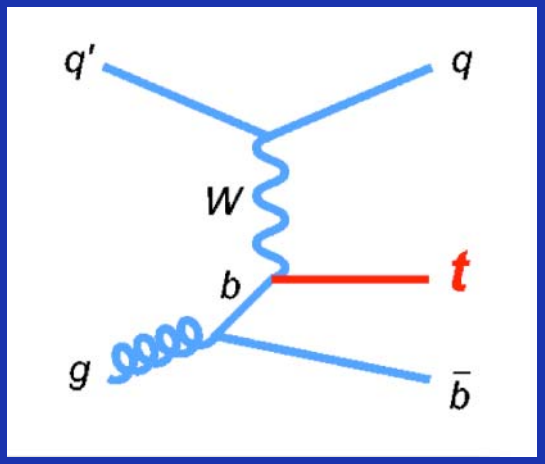
s-channel (*tb*)



$\sigma_{NLO} = 0.88 \pm 0.11$ pb ($m_t = 175$ GeV)†

$\sigma_{NLO} = 1.12 \pm 0.05$ pb ($m_t = 170$ GeV)‡

t-channel (*tqb*)



$\sigma_{NLO} = 1.98 \pm 0.25$ pb ($m_t = 175$ GeV)†

$\sigma_{NLO} = 2.34 \pm 0.13$ pb ($m_t = 170$ GeV)‡

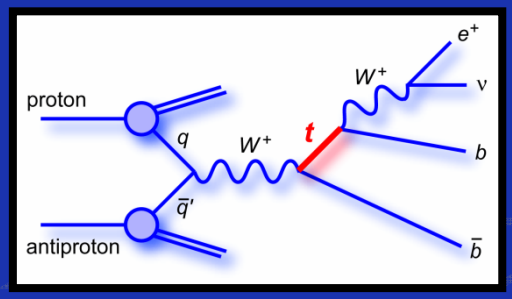
- **Study of the Wtb coupling**
  - Direct $|V_{tb}|$ measurement
  - Unitarity test of CKM matrix
  - Anomalous Wtb couplings
- Measurement of top quark properties (polarization, lifetime, mass, …)
- Chance to explore **New Physics** (different model sensitivities for *s* and *t*)

(†) Z. Sullivan, Phys. Rev. D 70 (2004) 114012

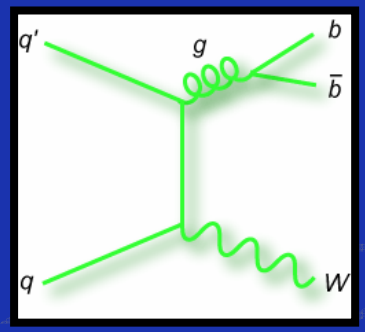
(‡) N. Kidonakis, Phys. Rev. D 74 (2006) 114012

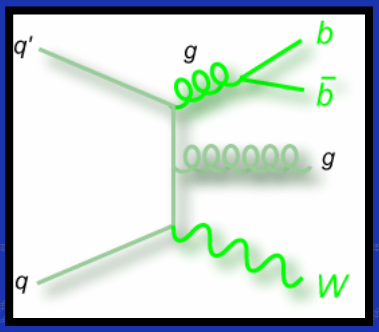
Signal and Background Samples

- **Single Top** signal
  - CompHEP - SingleTop - MadEvent

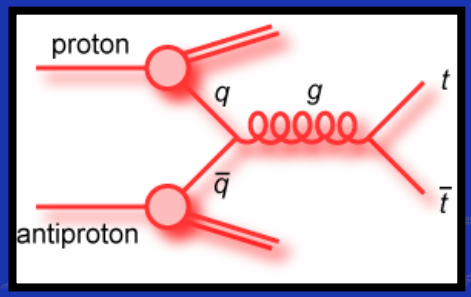


- **W+Jets**
  - Dominant and most difficult background
  - Shapes from ALPGEN
  - Normalization and Heavy Flavor fractions from data

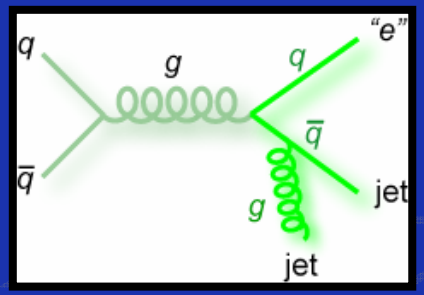




- **t-tbar**
  - ALPGEN
  - Normalized to σ_{NNLO} = 6.8pb



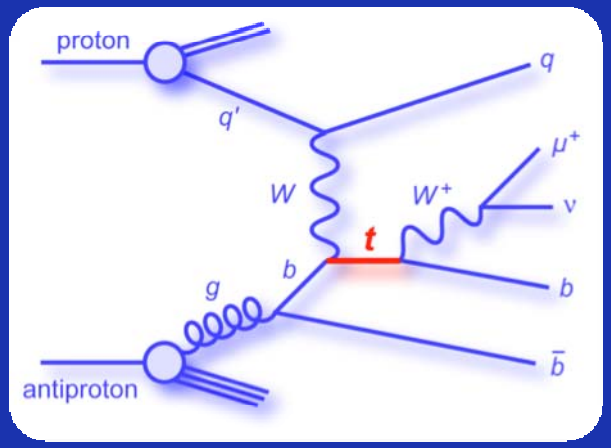
- **Multijets**
  - Misidentified lepton, from data

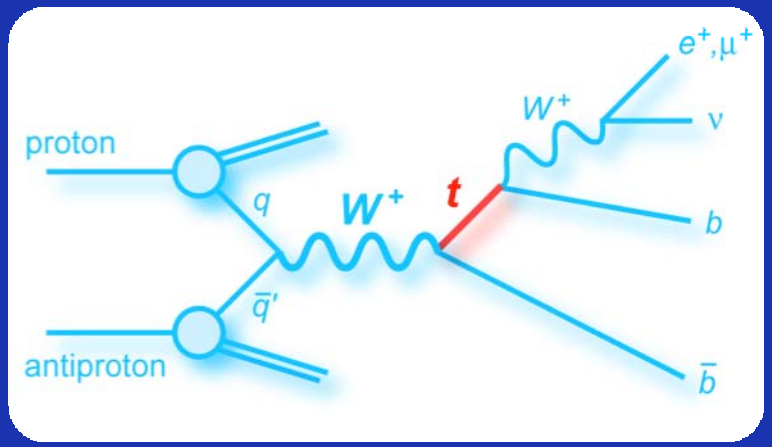


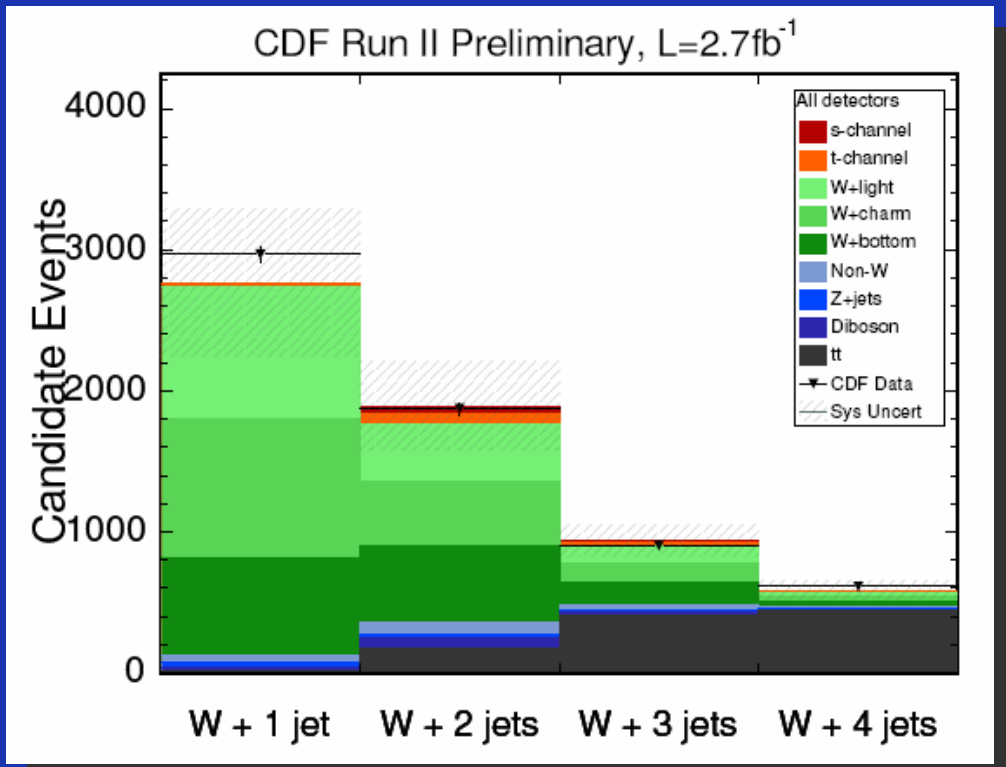
- **Other minor backgrounds**
  - Z+jets (ALPGEN)
  - Diboson (PYTHIA)

Single Top Event Selection

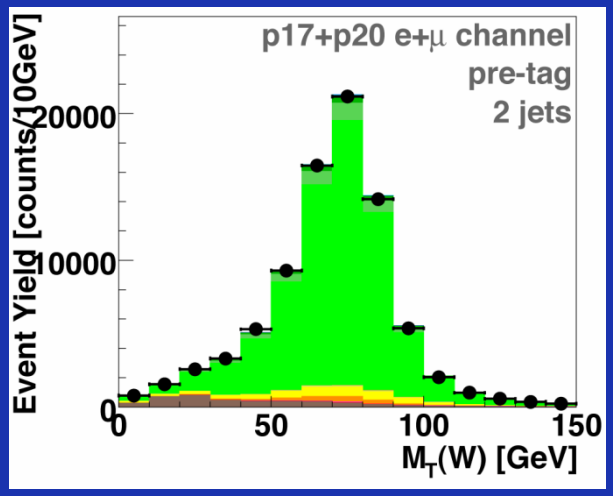
- Crucial to **maximize the signal acceptance**
- Basic event signature (*e* or μ)
  - Single lepton / lepton+jets / MET triggers
  - One high p_T lepton
  - MET
  - 2 - 4 high E_T jets
  - At least one b-tagged jet
- Expect ~ 50 signal events per fb^{-1}
  - **S:B ~ 1:20** after b-tagging
  - Signal acceptances range from 2 to 4%

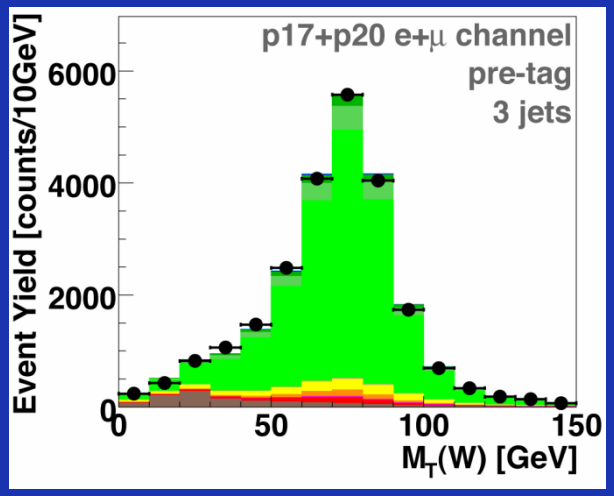


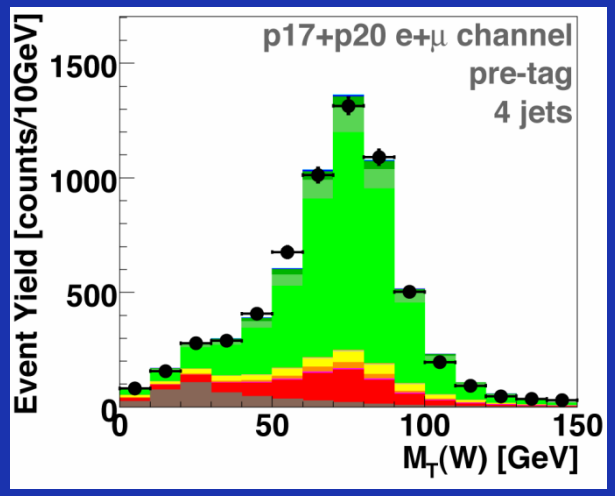


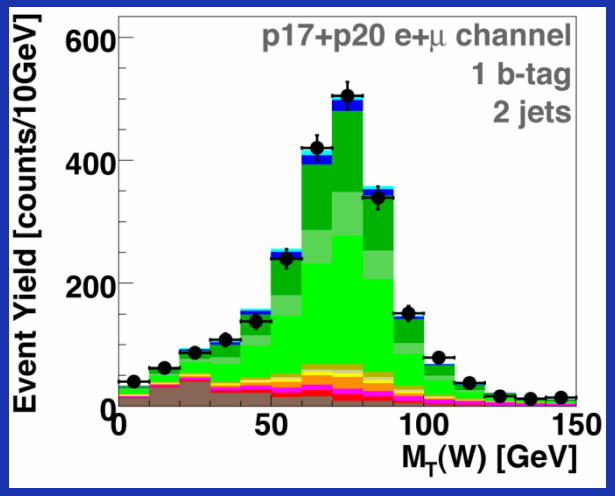


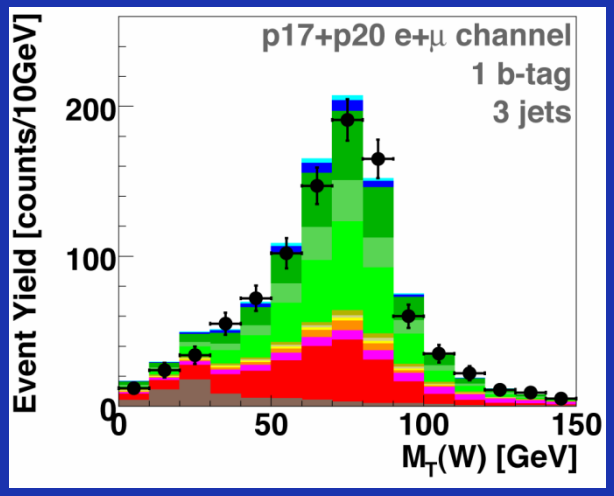
Data-MC agreement

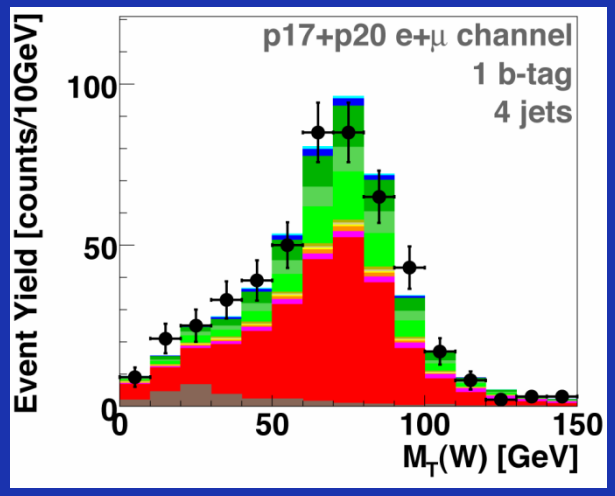


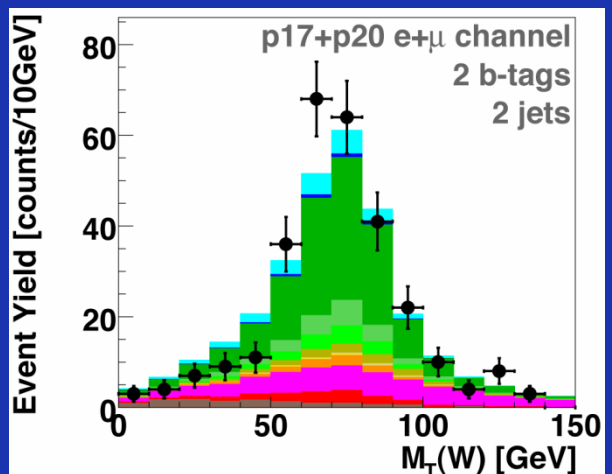


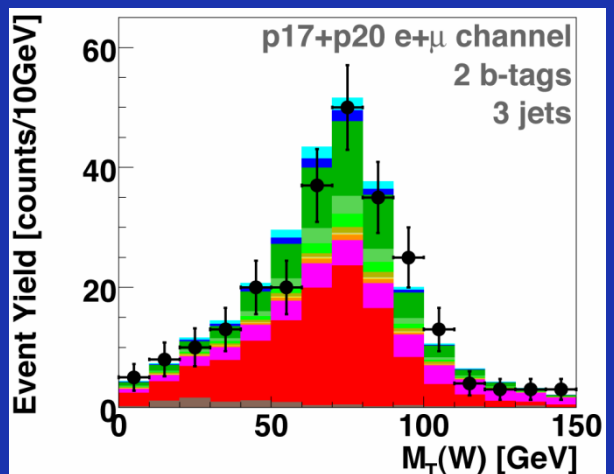


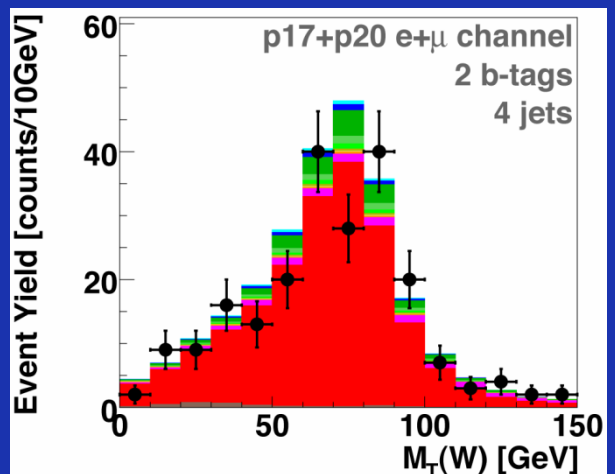












Analysis Strategy

Discriminating variables ➧ **Multivariate Classifier** ➧ **Signal Likelihood** ➧ **Statistical Analysis**

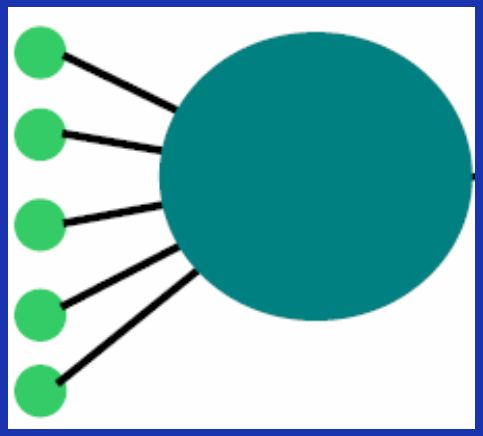
Event kinematics

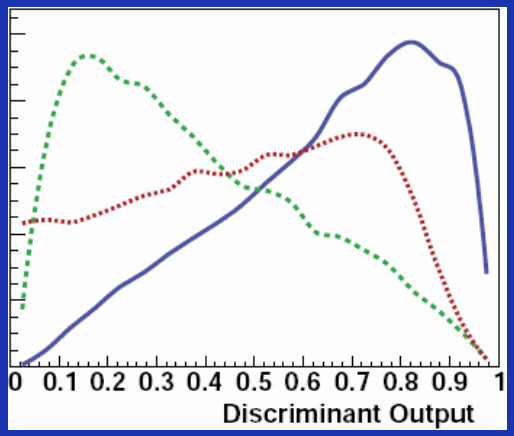
Object kinematics

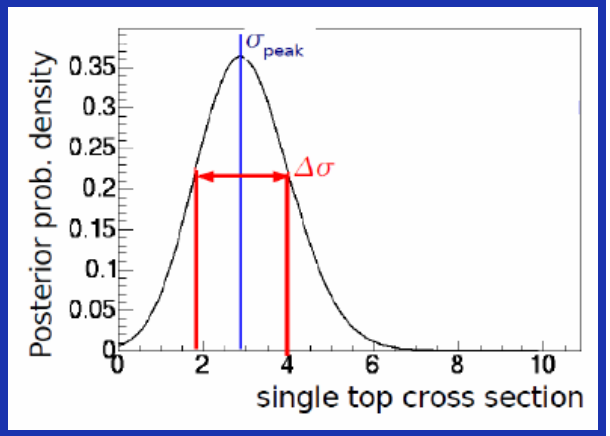
econstructed masses

Angular correlations

…







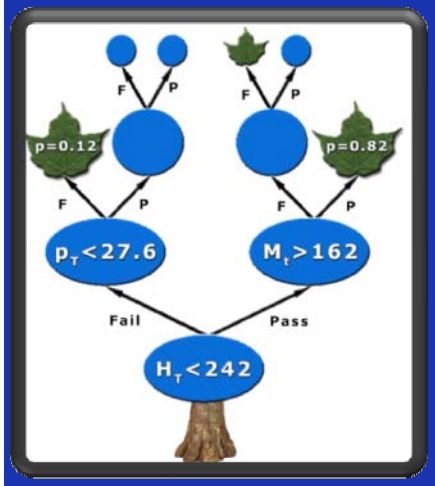
Classifiers

- Likelihood Function (LF)
- Neural Network (NN)
- Bayesian Neural Networks(BNN)
- Boosted Decision Trees (BDT)
- Matrix Element (ME)

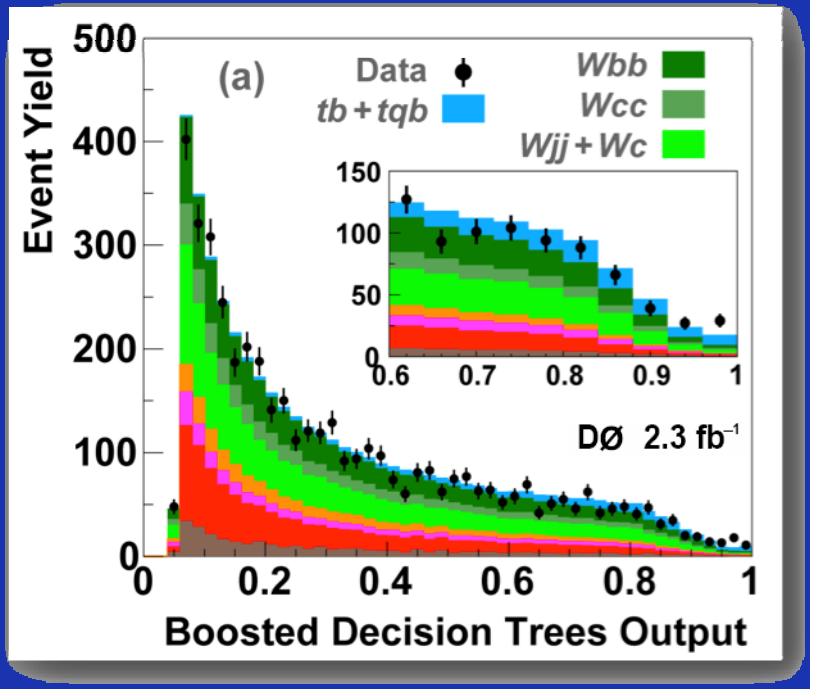
Build Bayesian posterior probability density to measure cross section

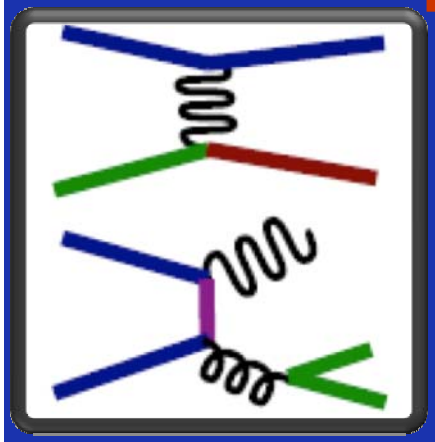
- Shape normalization and systematics treated as nuisance parameters
- Correlations between uncertainties properly accounted for
- Flat prior in signal cross section

Decision Tree and Matrix Elements Analyses

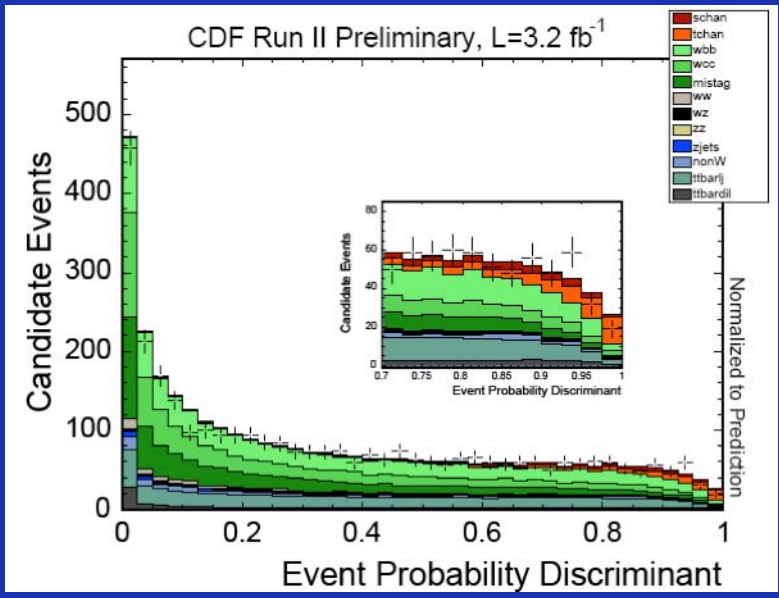


- **Decision Trees:**
  - Single Top signal samples trained against background samples from a large number of input variables
  - Sort events by output purity
  - Used misclassified events to create series of boosted trees



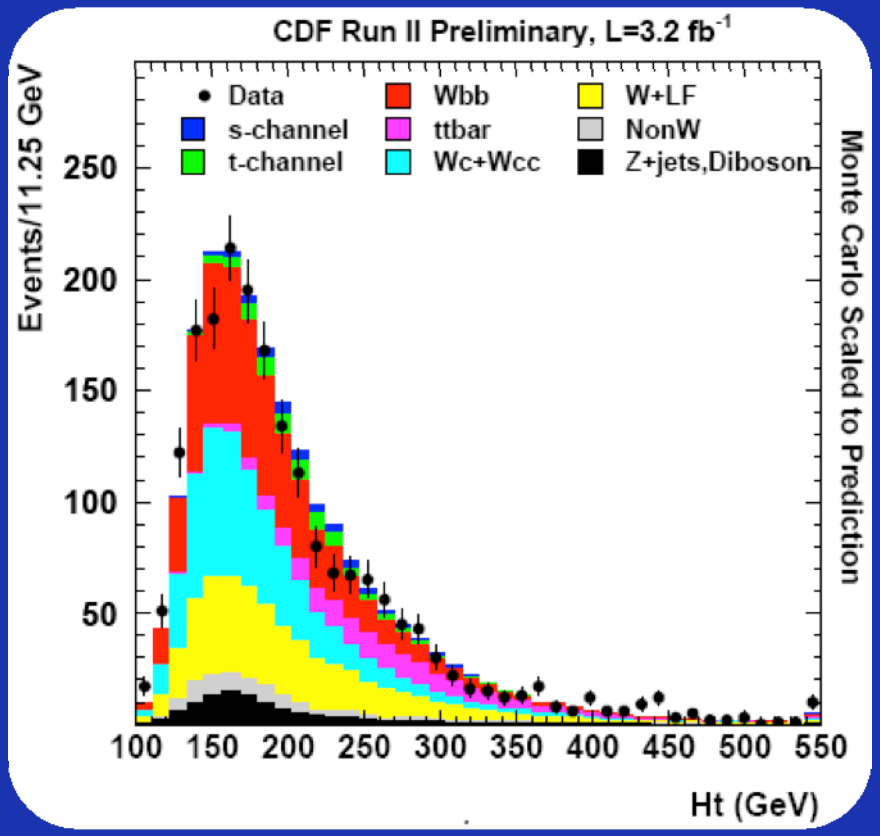


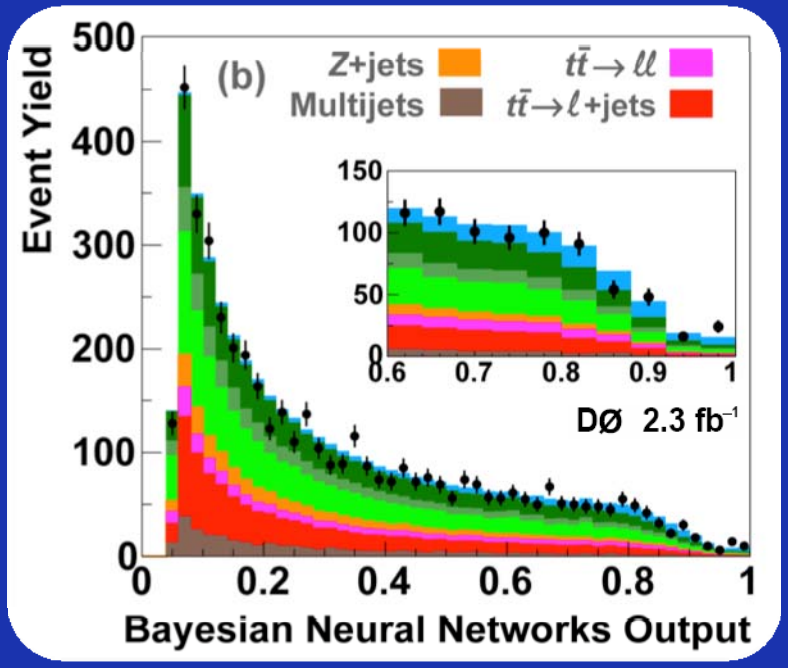
- **Matrix Elements:**
  - Use parton level matrix elements [*s*, *t*, Wbb, Wcg, Wgg, ttbar, DØ also added (2Jet: tt, WW, WZ, ggg; 3Jet: Wugg)]
  - Look at 2 and 3 jet events
  - integrate to calculate event probability densities for signal and background



Likelihood Functions and Neural Networks

- **Likelihood Function (CDF):**
  - Multivariate likelihood function combines 7(10) sensitive variables into a single discriminant for events with 2(3) jets

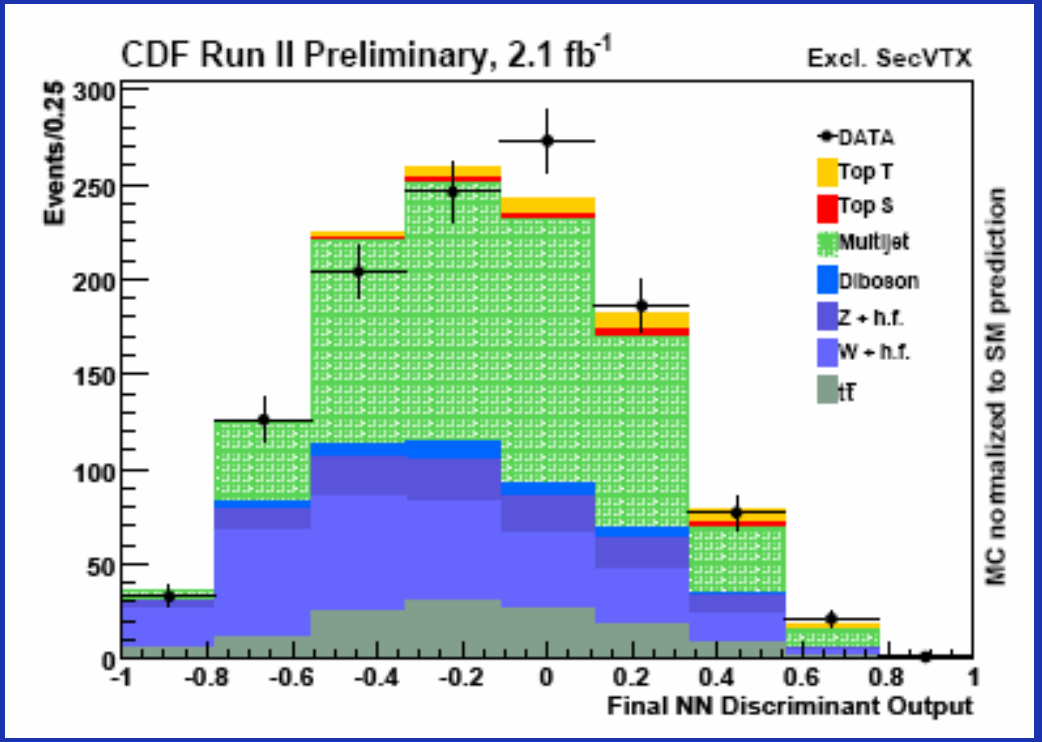




- **Neural Networks:**
  - CDF: Build 4 separate neural networks including btagNN, kinematic variables and angular distributions
  - D0: build a Bayesian Neural Network by tuning parameters and averaging hundreds of networks

New analysis from CDF

- **Brand new MET + Jets analysis**
  - Use discarded events from previous analyses
    - Orthogonal sample compared to other analyses (undetected leptons or hadronically decacying τ from W)
  - Split in 3 samples using 2 b-taggers
  - Separate signal from background with the aid of a dedicated NN



DØ's Results

New result based on 2.3 fb^{-1}

arXiv:0903.0850 [hep-ex]

Selection Improvements

- **2.6 times more data**
  - 2.3 fb^{-1} of RunII data (0.9fb^{-1} in previous analyses)
- **18% acceptance gain compared to 2007 PRL analysis**
  - increased logical OR of many trigger conditions
  - Second leading jet p_T > 15 GeV (20 GeV) |jet 1η| < 3.4 (2.5)
  - Muon p_T > 15 GeV (18 GeV)
  - Looser b-tagging for events with 2 tags
  - Added topological cuts to reduce background
- **Improvement in background modeling**
  - top MC samples @ m_t = 170 GeV
  - Theoretical W-Z+jets K factors
  - Wbb/Wcc SF derived from untagged and tagged 2-jet samples.
  - Reweight ALPGEN jet quantities
  - Improved multijet background modeling

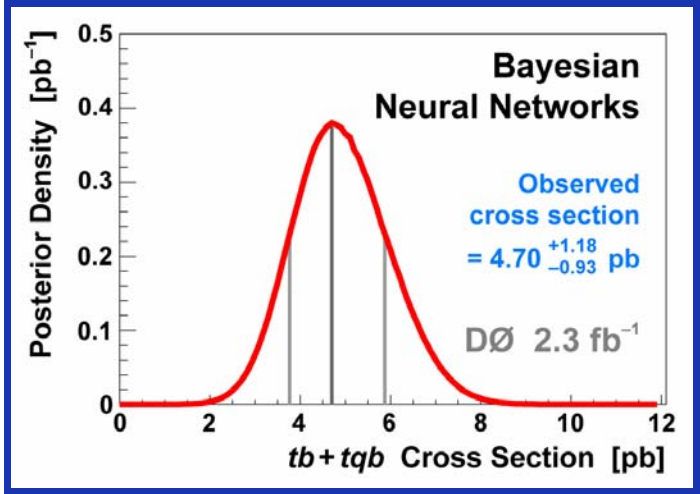
Event Yields in 2.3 fb^{-1} of DØ Data

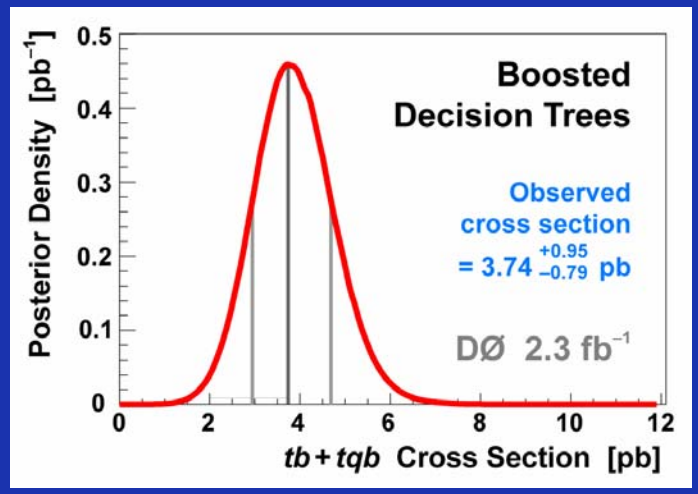
Electron + muon, 1 tag + 2 tags combined

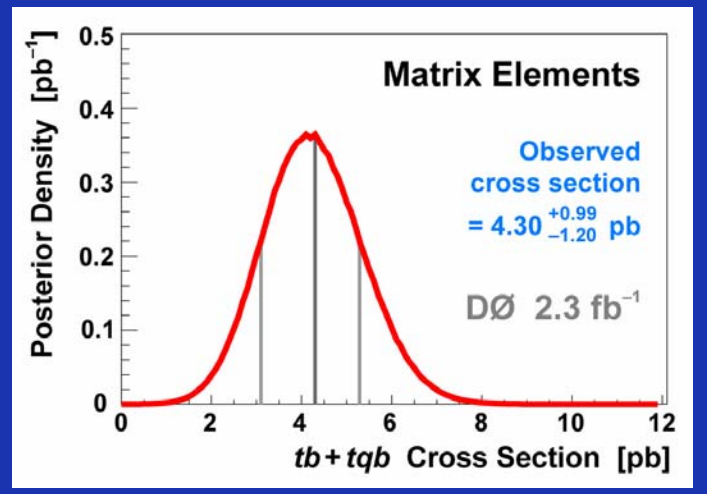
Source	2 jets	3 jets	4 jets
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \to \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \to \ell$+jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724

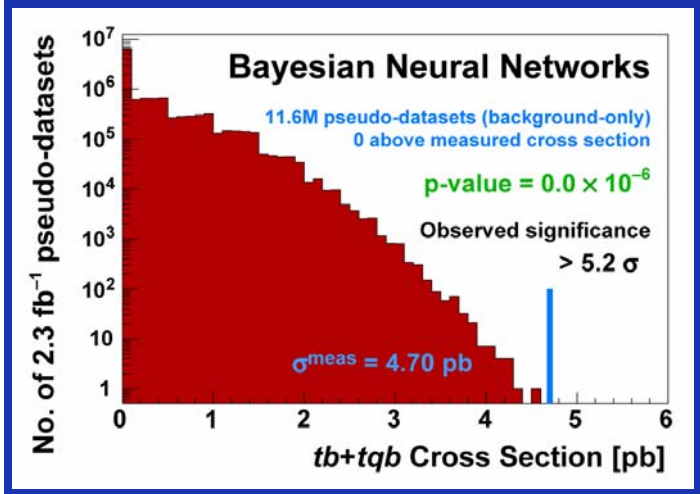
Expected and Observed Results

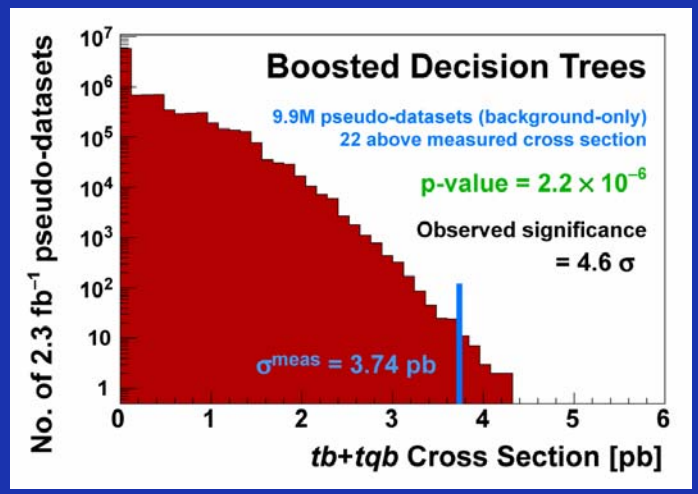
	BNN		BDT		ME	
	Exp.	Obs.	Exp.	Obs.	Exp.	Obs.
$\sigma(s+t)$[pb]	$3.6^{+1.0}_{-0.9}$	$4.7^{+1.2}_{-0.9}$	$3.6^{+1.0}_{-0.9}$	$3.7^{+1.0}_{-0.8}$	$3.6^{+1.1}_{-1.0}$	$4.3^{+1.0}_{-1.2}$
significance	4.1	5.2	4.3	4.6	4.1	5.0

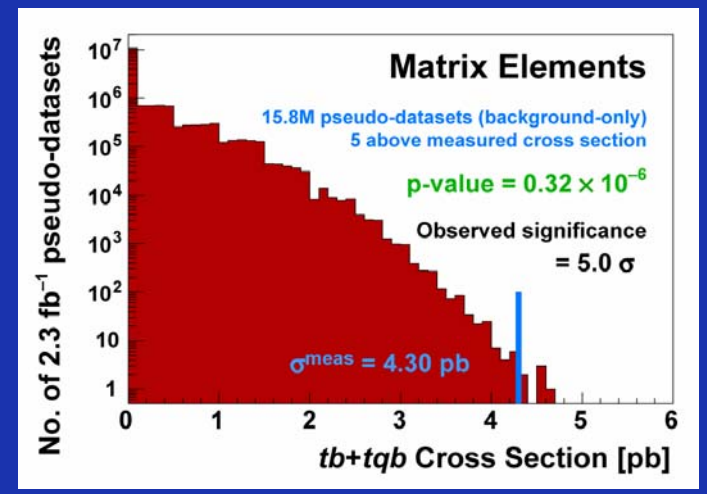






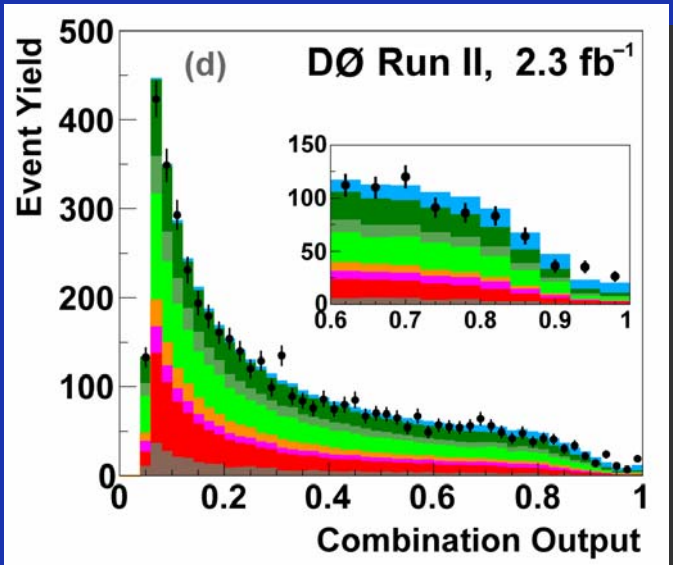


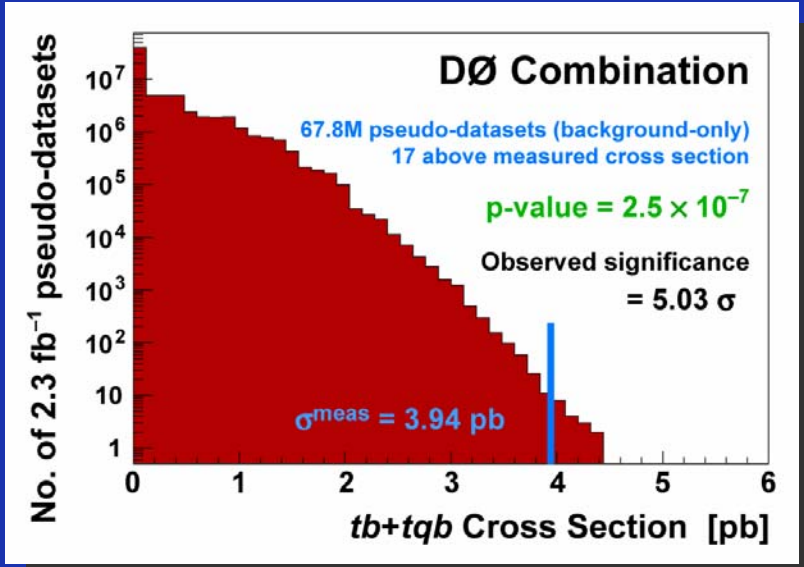




Combination

- Three MV analyses give consistent results and are not fully correlated
- Use BNN, BDT and ME discriminant outputs to build a second layer combination BNN discriminant
- Cross checked with a BLUE method combination



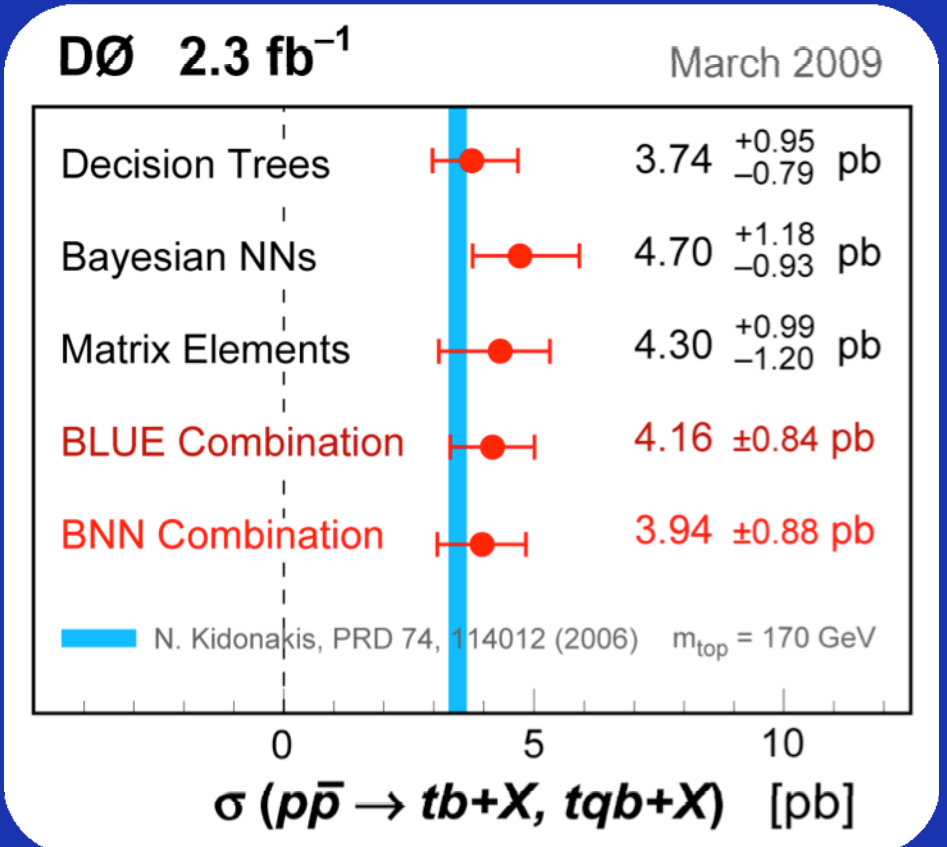


$\sigma(s+t) = 3.94 \pm 0.88$ pb

with 5.0 σ significance

$|V_{tb} f_1^L| = 1.07^{+0.12}_{-0.12}$

$0.78 < |V_{tb}| < 1$ @ 95% CL assuming $f_1^L = 1$



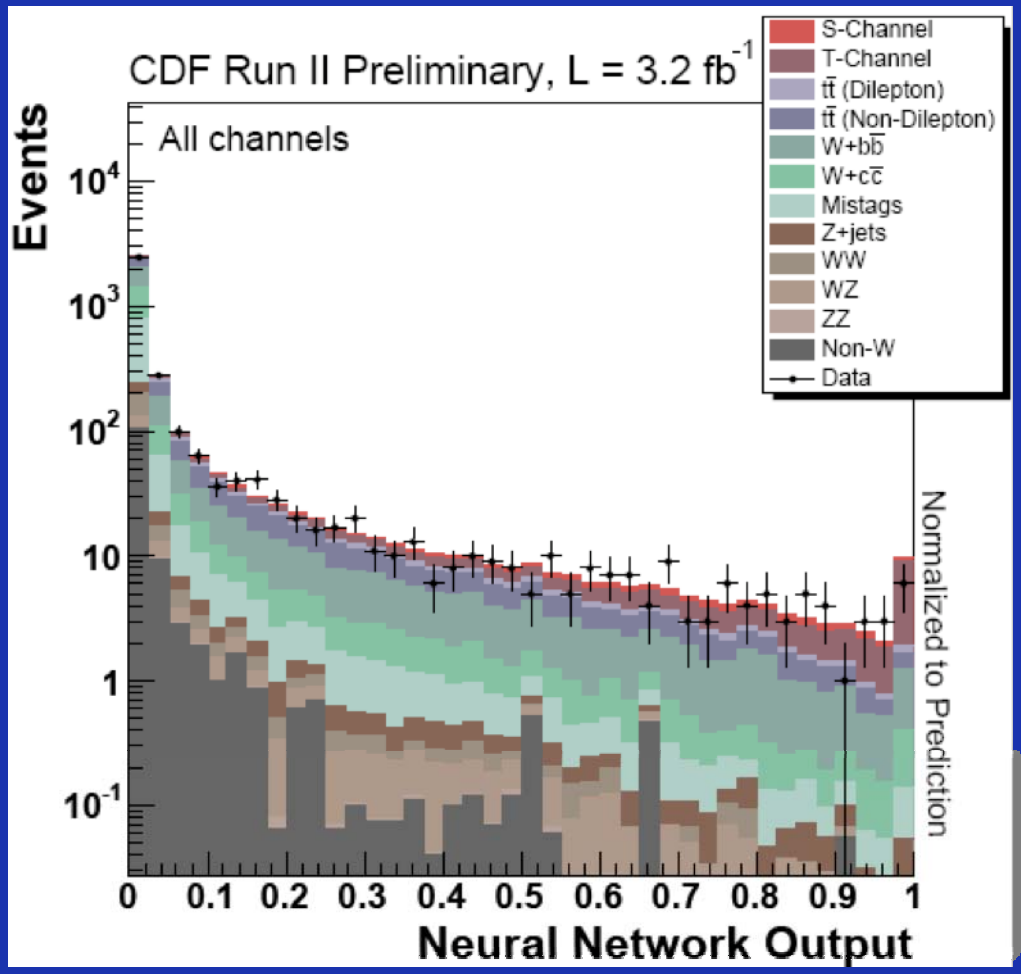
CDF's Results

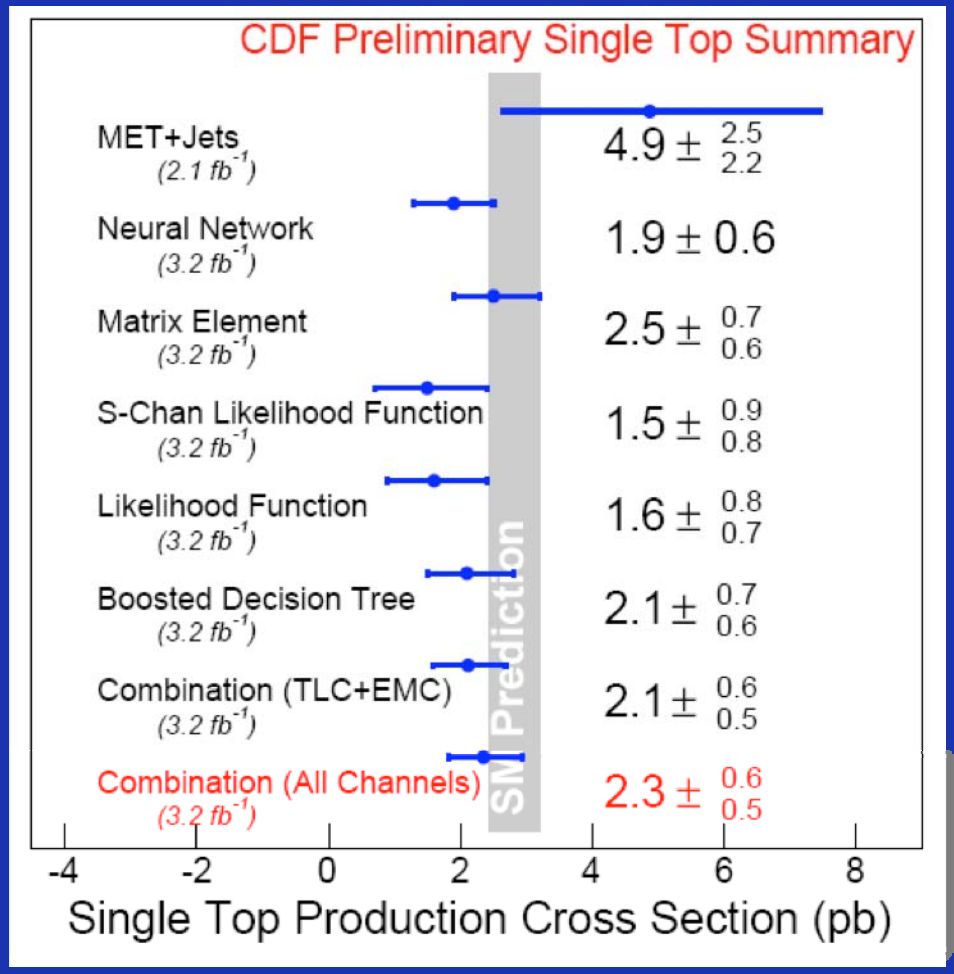
New result based on 3.2 fb^{-1}

arXiv:0903.0855 [hep-ex]

Combination

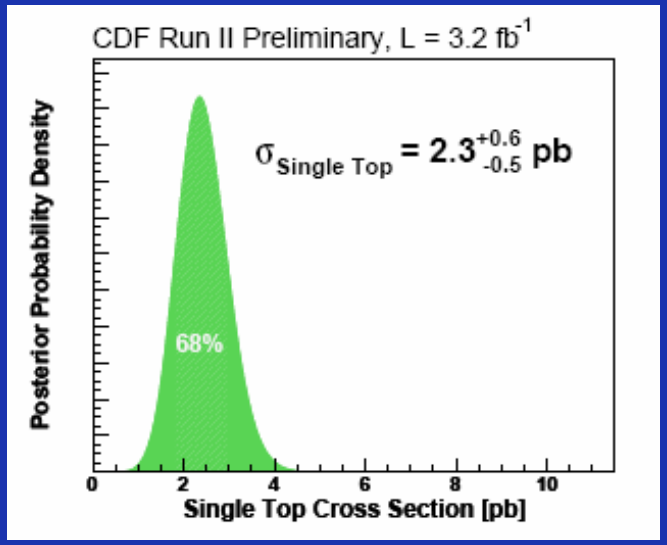
- **Combined results** using evolved NEAT (Neuro Evolution of Argumenting Topologies) taking the output of different multivariate analyses as inputs

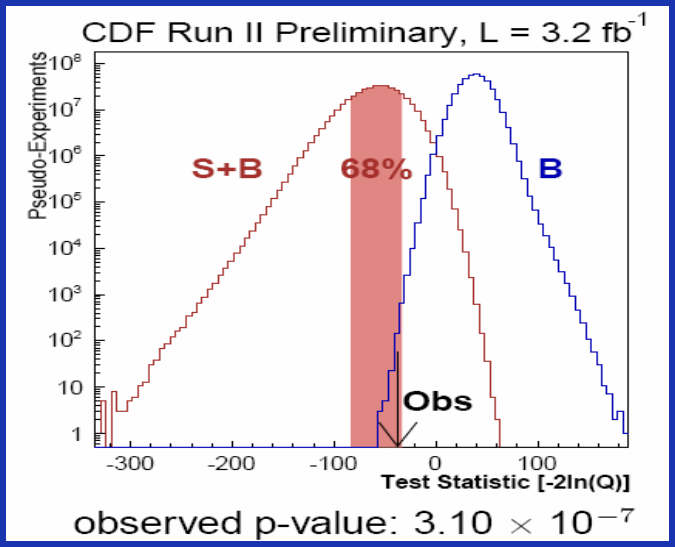


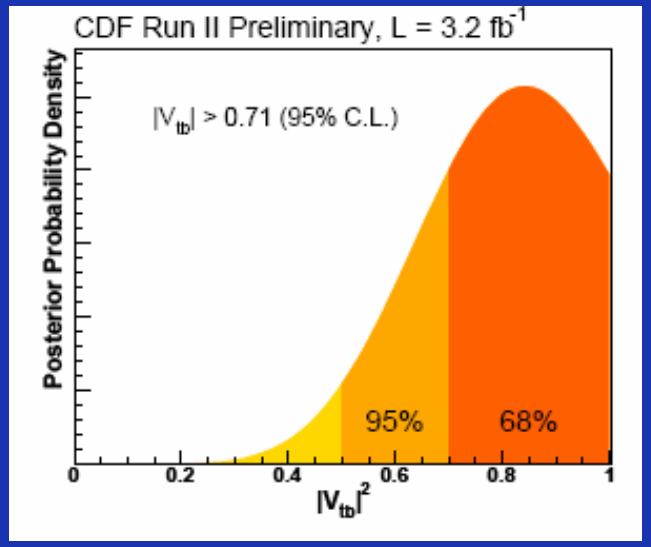


Results

	CDF (3.2 fb^{-1})	
	Exp.	Obs.
ME	4.9	4.3
BDT	5.2	3.5
NN	5.2	3.5
LF	4.0	2.4
$\not\!\!E_T$+jets	1.4	2.1
Comb	**5.9**	**5.0**



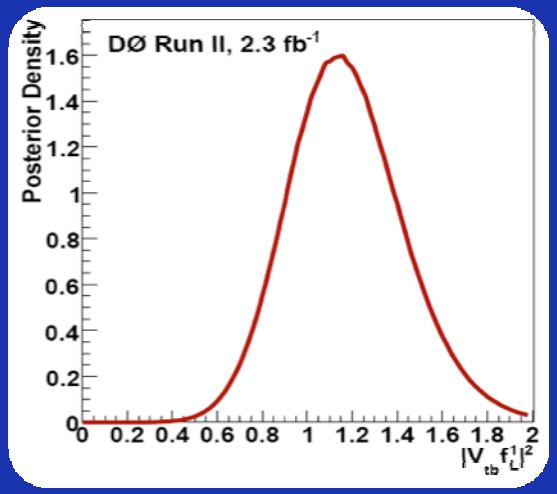


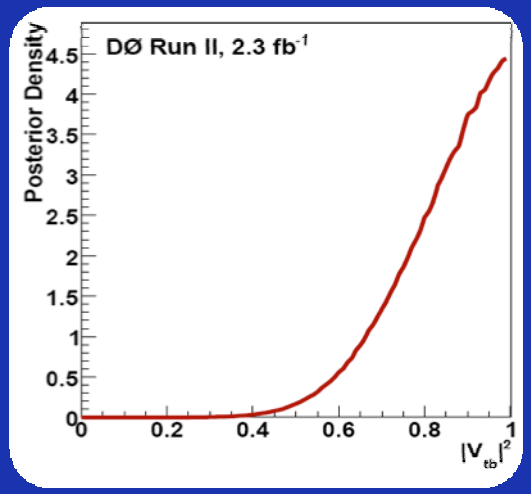


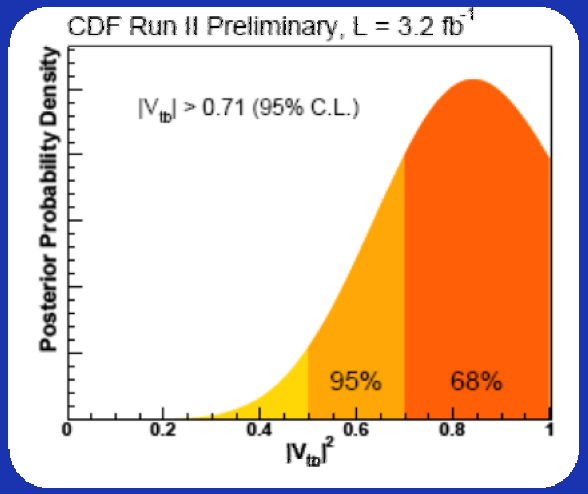
Comb	Lum. (fb^{-1})	Exp. sign.	Obs. sign.	σ (pb)	$\lvert V_{tb}\rvert$
	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$	0.91 $\pm$0.11(exp) $\pm$ 0.07(th)

Direct Measurement of $|V_{tb}|$

- Calculate **posterior probability density for $|V_{tb}|^2$**
  - proportional to the single top cross section
- **Assume Standard Model production**
  - Pure V-A and CP conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)
  - $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$
  - Additional theoretical errors (top mass, scale, PDF, etc…)
- Measurement **does not assume 3 generations or unitarity**







$|V_{tb} f_1^L| = 1.07^{+0.12}_{-0.12}$

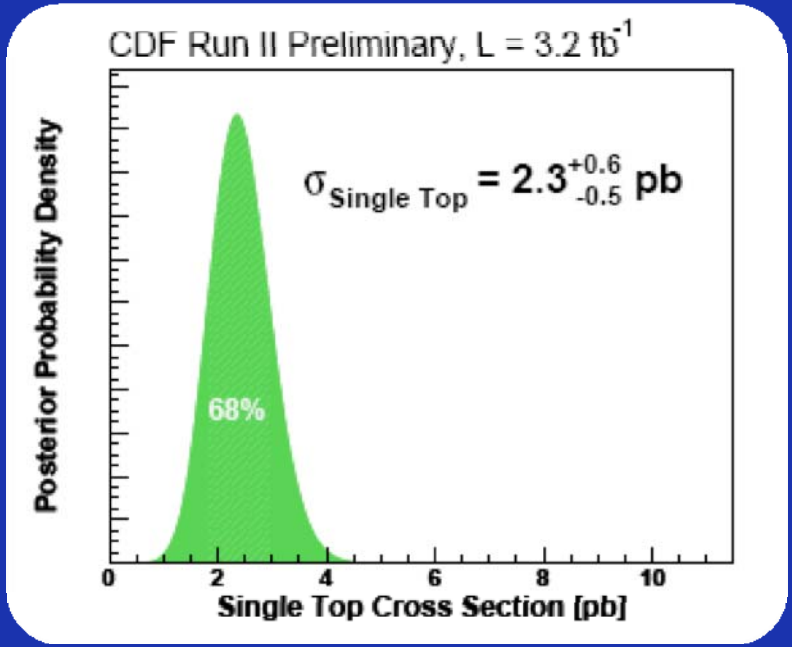
$0.78 < |V_{tb}| < 1$ @ 95% CL assuming $f_1^L = 1$

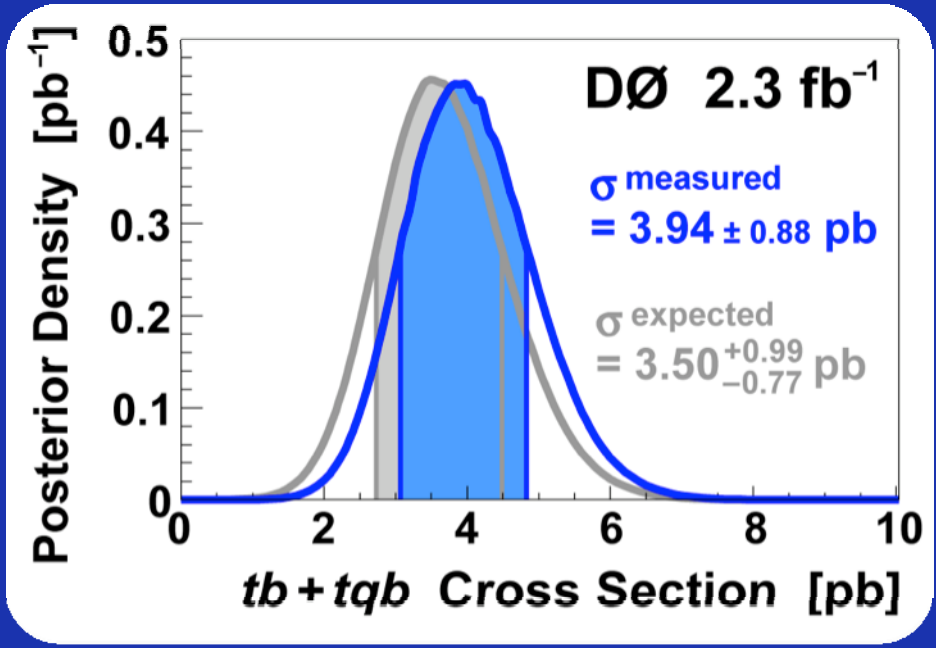
$|V_{tb} f_1^L| = 0.91 \pm 0.11(\text{exp}) \pm$ (th)

Conclusion

- DØ and CDF published 3σ evidence in 2007 and 2008 respectively
- Thanks to the efforts of plenty of people at Fermilab we are pleased to announce a major Tevatron accomplishment

- **Single top production observation at DØ & CDF !**
  - Both DØ and CDF announce here for the first time 5σ observation in their latest results recently submitted to PRL
  - Precise direct measurement of $|V_{tb}|$
  - Results are in agreement with SM





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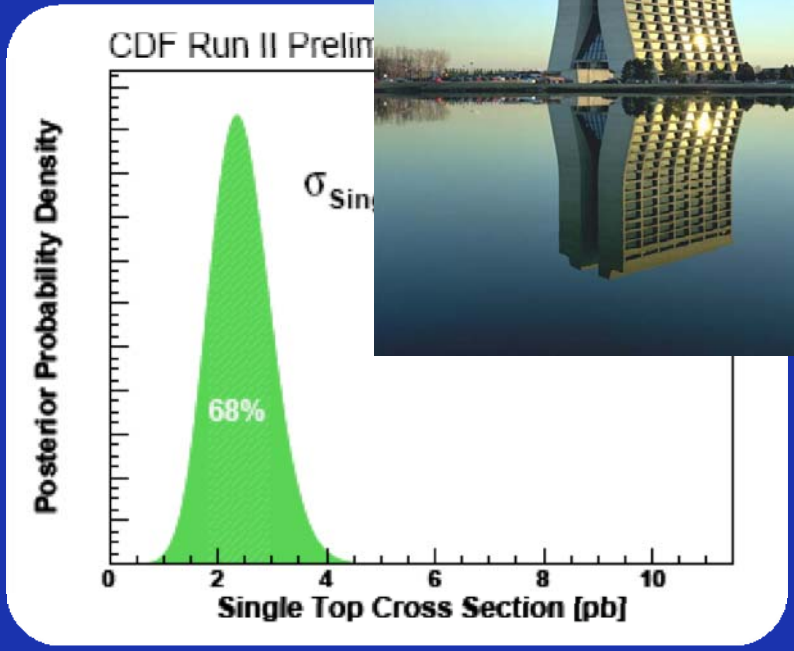

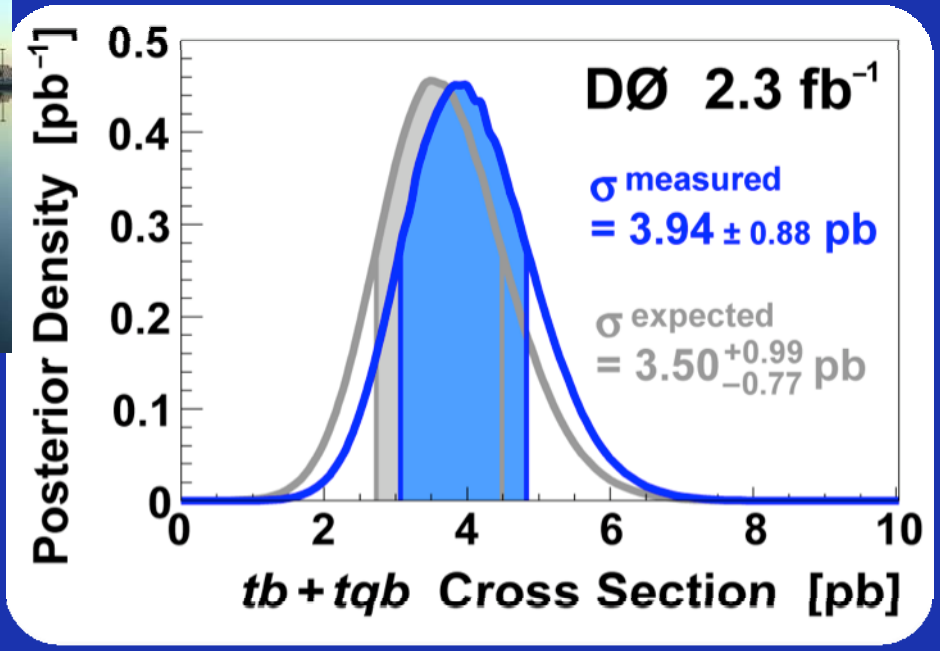

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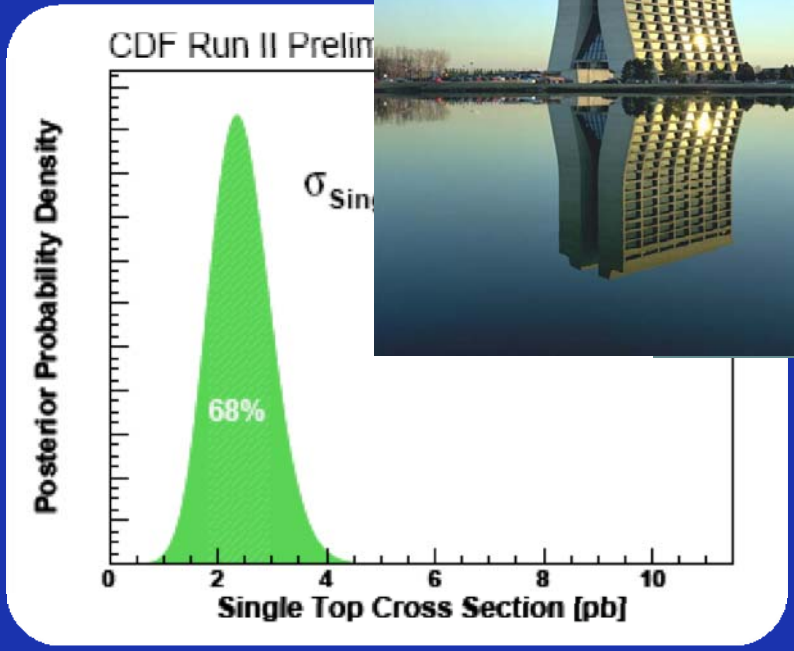
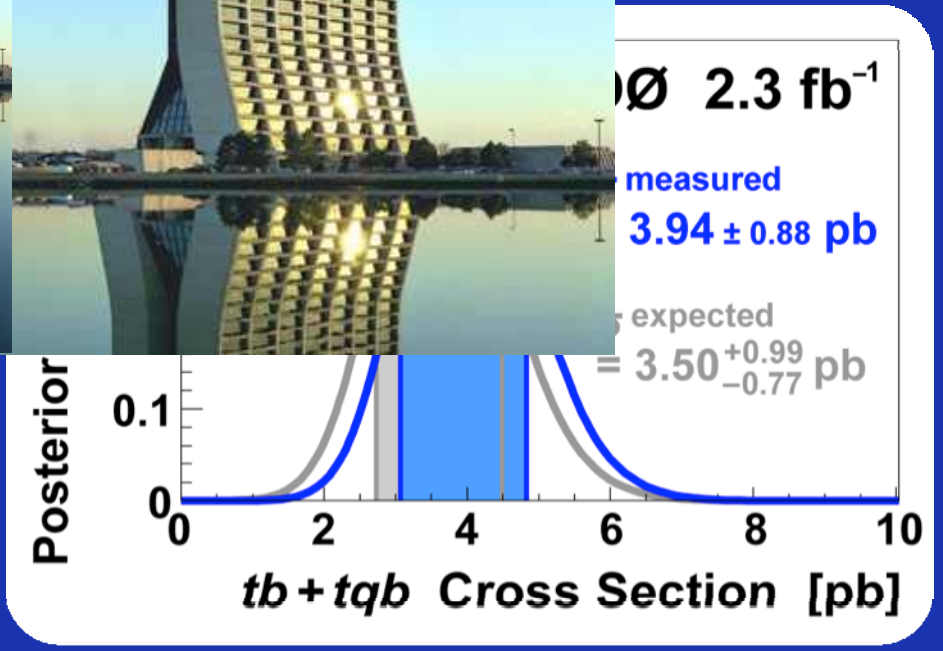




Back up slides

Systematic Uncertainties	
Components for normalization	
Integrated luminosity	6.1%
tt cross section	12.7%
Z+jets and dibosons cross section	5.8%
Branching fractions	1.5%
Parton distribution functions (signal only)	3.0%
Triggers	5.0%
Instantaneous luminosity reweighting	1.0%
Primary vertex selection	1.4%
Lepton identification	2.5%
Jet fragmentation	(0.7–4.0)%
Initial-state and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
Jet reconstruction and identification	1.0%
Jet energy resolution	4.0%
W+jets and *Z*+jets heavy flavor correction	13.7%
Multijets normalization to data	(30–54)%
Monte Carlo and multijets statistics	(0.5–16)%
Components for normalization and shape	
Jet energy scale for signal	(1.1–13.1)%
Jet energy scale for total background	(0.1–2.1)%
b tagging for single-tagged	(2.1–7.0)%
b tagging for double-tagged	(9.0–11.4)%
Component for shape only	
ALPGEN reweighting	–

Systematic Uncertainties

Systematic	Rate	Shape
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%	—
NN flavor separator	—	✓
Mistag model	—	✓
Non-W model	—	✓
ALPGEN Q^2	—	✓
MC Modeling $(\Delta R, \eta(j_2))$	—	✓
$Wb\bar{b}$+$Wc\bar{c}$ normalization	30%	—
Wc normalization	30%	—
Mistag normalization	17...29%	—
Top Mass - top-pair normalization	23%	✓

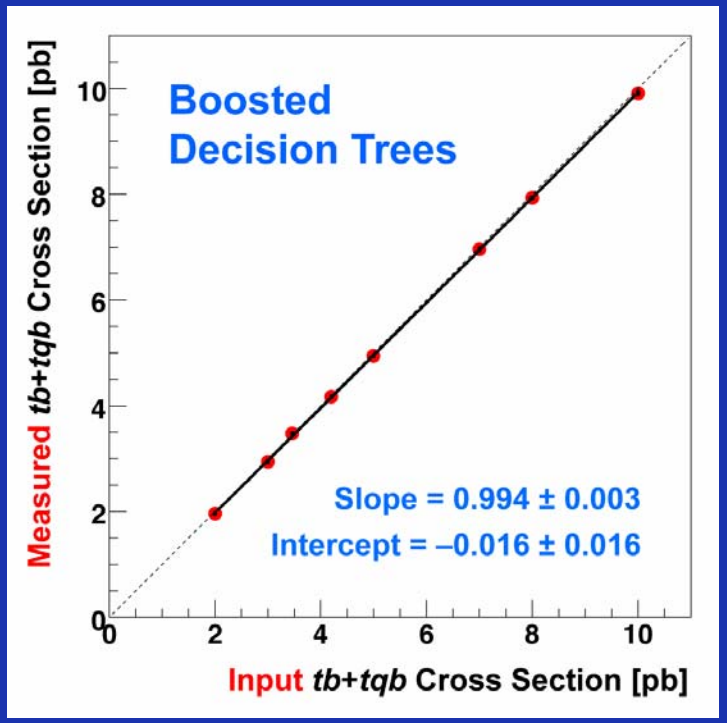
Event Yields

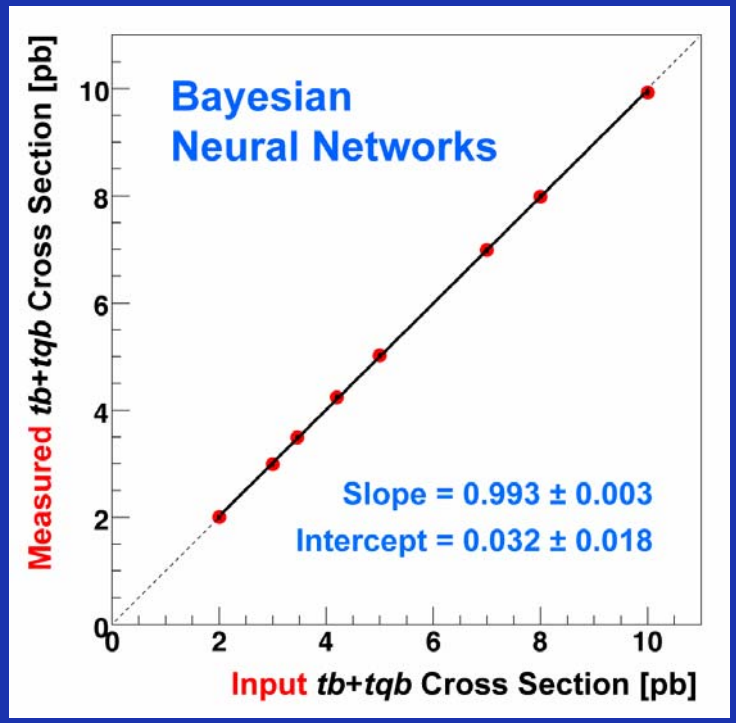
Process	ℓ + $\not\!\!E_T$ + jets	$\not\!\!E_T$ + jets
s-channel signal	77.3 ± 11.2	29.6 ± 3.7
t-channel signal	113.8 ± 16.9	34.5 ± 6.1
$W + HF$	1551.0 ± 472.3	304.4 ± 115.5
$t\bar{t}$	686.1 ± 99.4	184.5 ± 30.2
Z+jets	52.1 ± 8.0	128.6 ± 53.7
Diboson	118.4 ± 12.2	42.1 ± 6.7
QCD+mistags	777.9 ± 103.7	679.4 ± 27.9
Total prediction	3376.5 ± 504.9	1404 ± 172
Observed	3315	1411

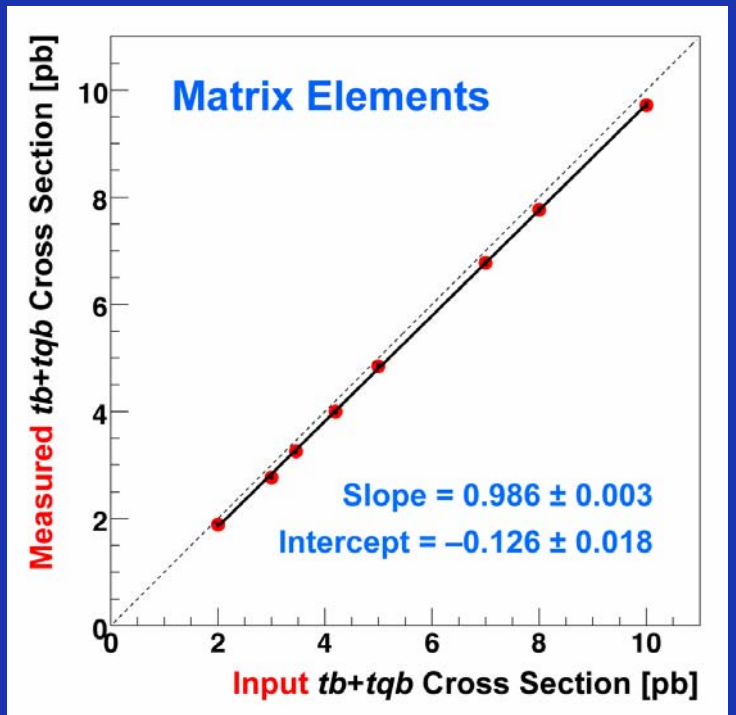
Significance

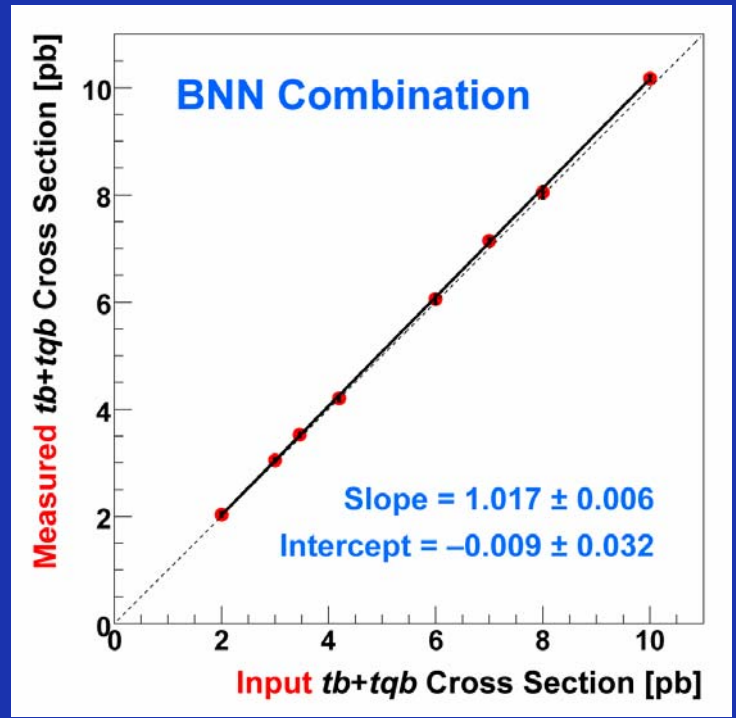
- Quantify the “excess in data over background”
- p-value: assuming a null hypothesis, what’s the probability to get a value equal or greater than the value observed
- Used a large ensemble of zero-signal pseudo-datasets, each corresponding to 2.3 fb^{-1} of data without signal
- Measure cross section for each pseudo-experiment in the same way we measure in our real data
- Measure the fraction of zero-signal datasets in which we derive at least the SM cross section (expected significance), or at least the observed cross section (observed significance)

Cross Checks









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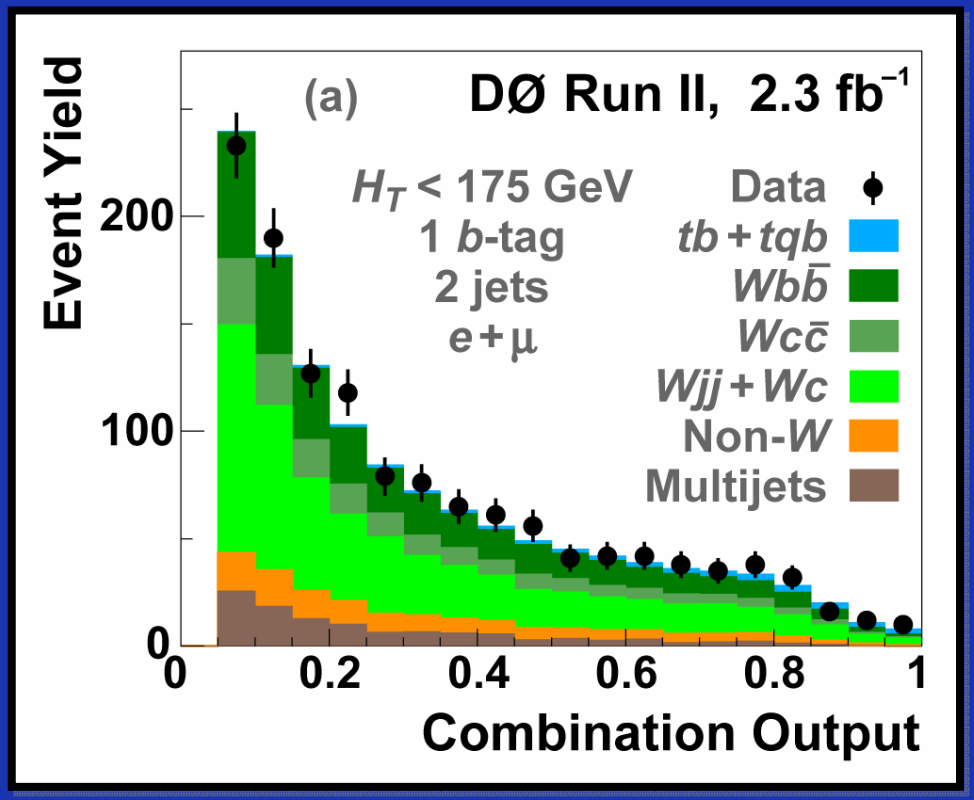
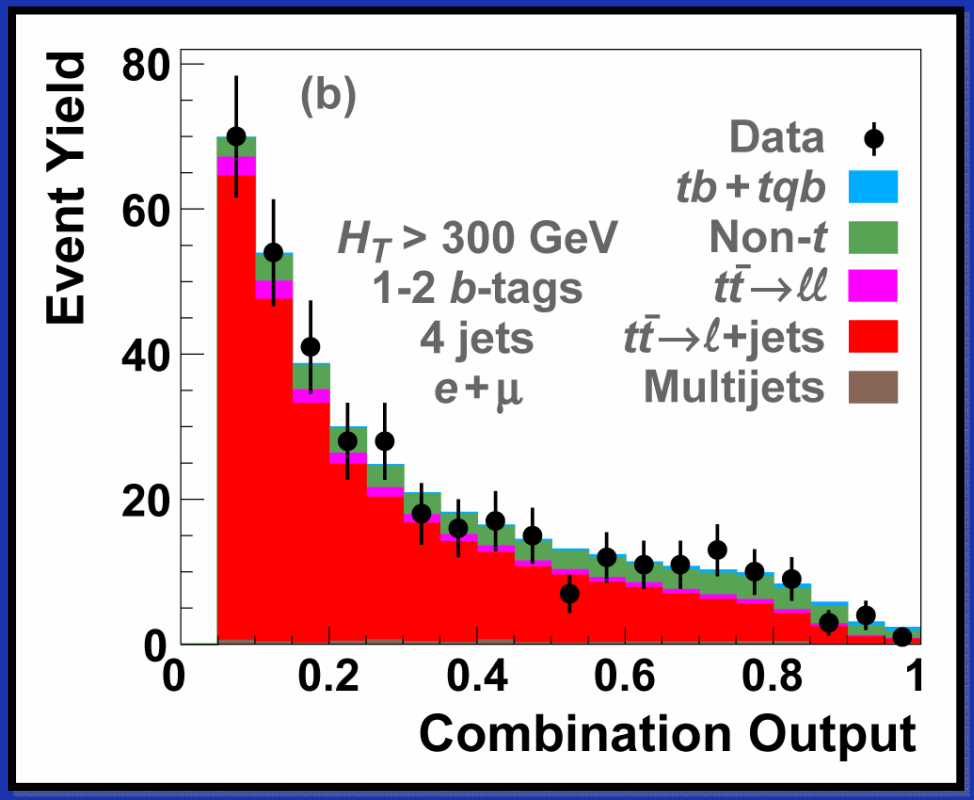
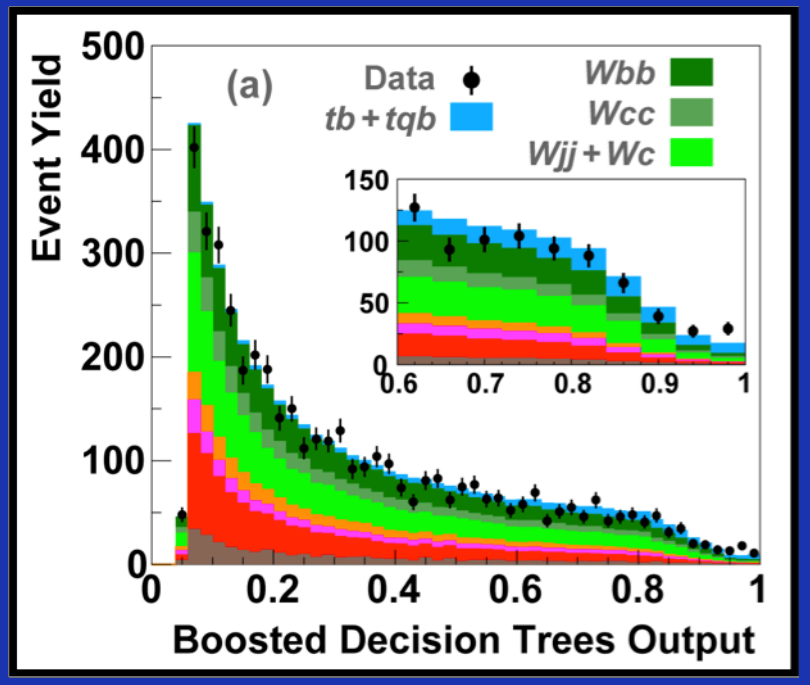
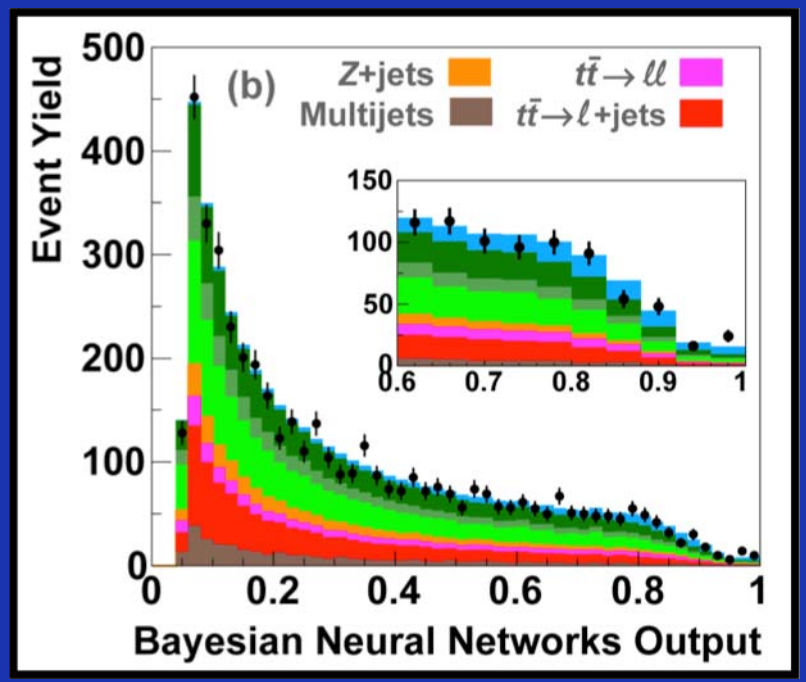


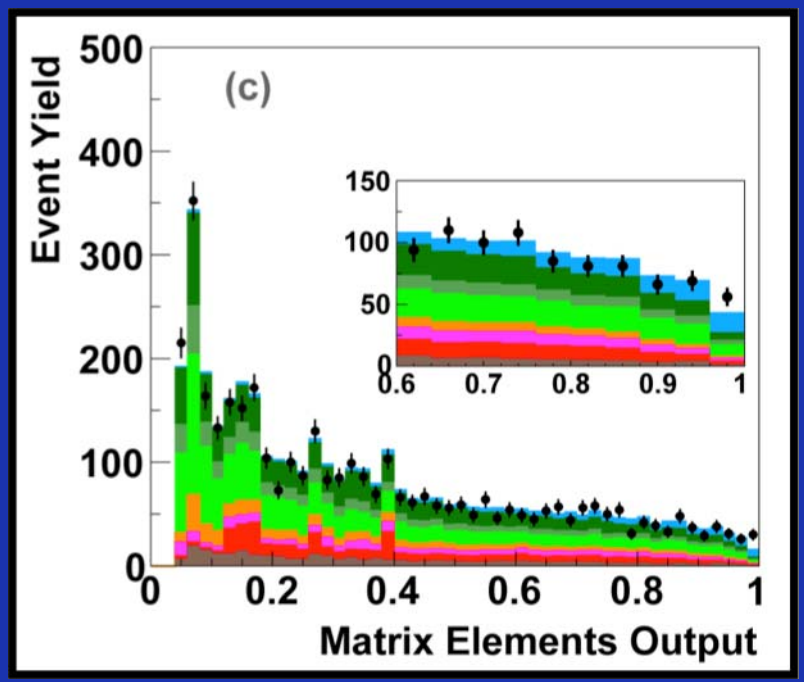


Multivariate Analyses

- Three improved MVA methods
  - **Boosted Decision Trees** (BDT)
    - Improved tuning of parameters
    - Added object and top reconstruction variables
  - **Bayesian Neural Networks** (BNN)
    - First two improvements as BDT
    - Use RuleFitJF to select highest ranked variables
  - **Matrix Elements** (ME)
    - Added MEs (2Jet: tt, WW, WZ, ggg; 3Jet: Wugg)
    - Split sample in low and high HT







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