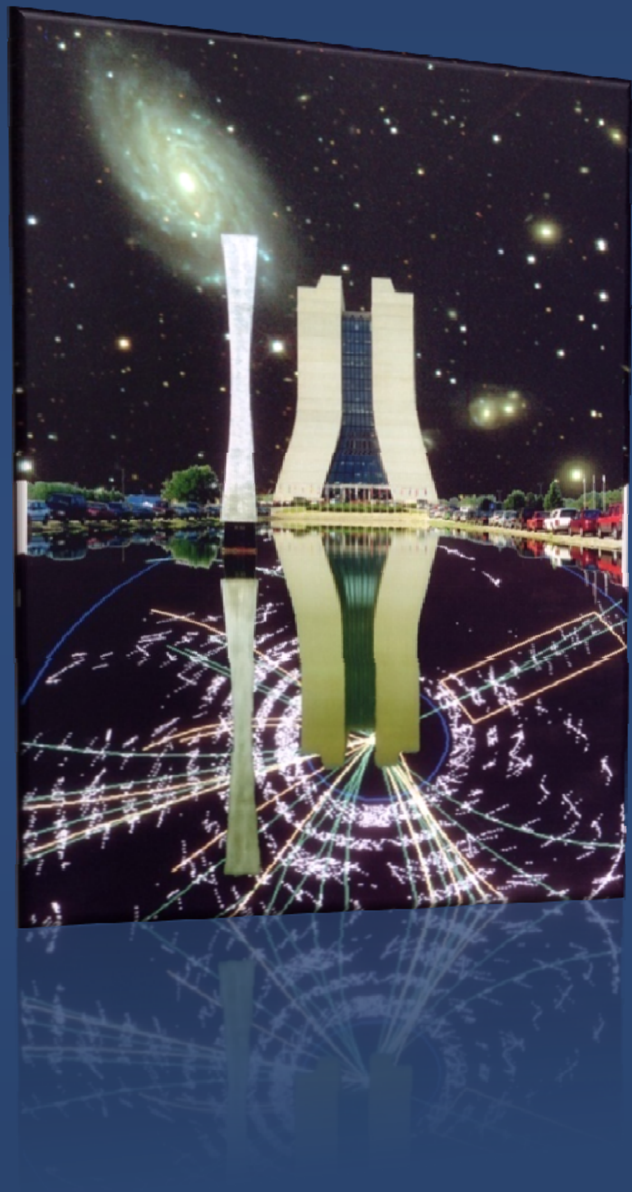


Discovery of Single Top Quark Production at D0

Shabnam Jabeen

Boston University

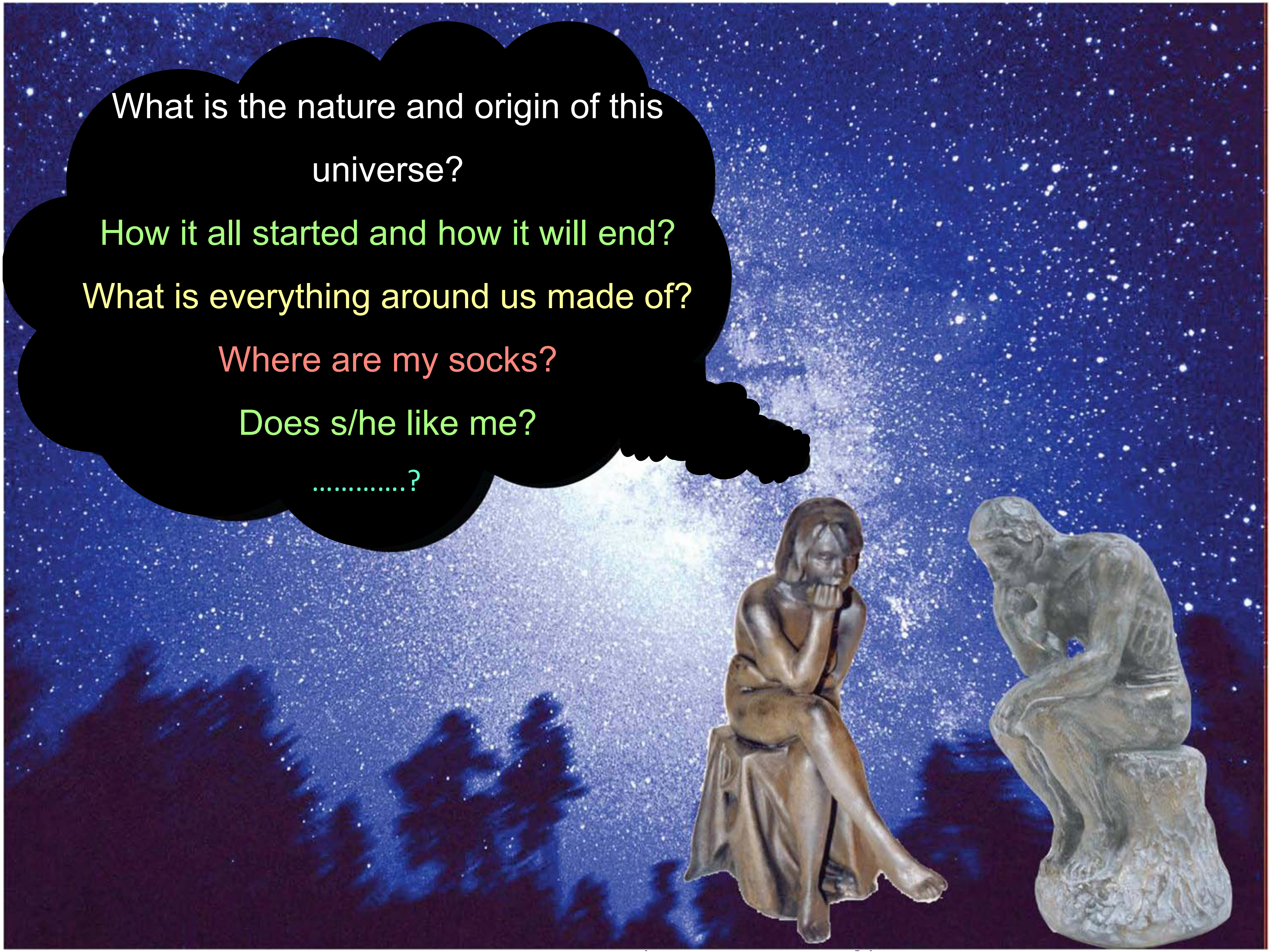
Outline

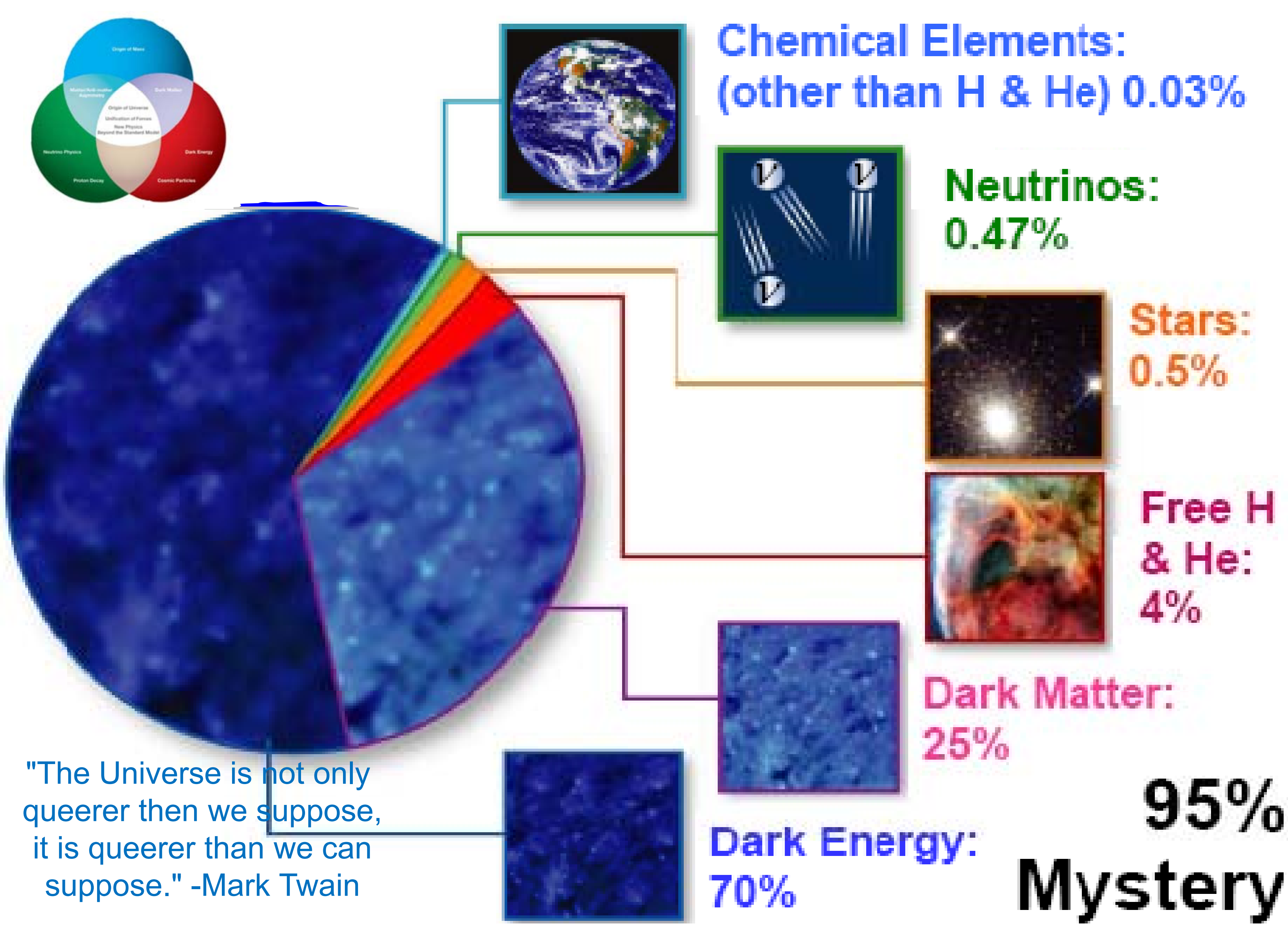
Introduction
- **Motivation**
- **Tools of our Trade**

Analysis Steps
- **Understanding the data**
  - Event Selection
  - Background Modeling
- **Multivariate Analysis**
- **Expected Sensitivity**

Cross Sections and Significance

Direct Measurement of $|V_{tb}|$


What is the nature and origin of this universe?
How it all started and how it will end?
What is everything around us made of?
Where are my socks?
Does s/he like me?
.............?



"The Universe is not only queerer then we suppose, it is queerer than we can suppose." -Mark Twain

The Outstanding Questions

- What is origin of mass?
- Why the values of quark and Lepton masses so different?
- Why are there 3 generations of particles ?

  (everyday matter comprises particles only from first generation)

- What about gravity?
- What is dark matter?
- What is dark energy?
- Matter antimatter asymmetry?

Why Look at the Top Quark

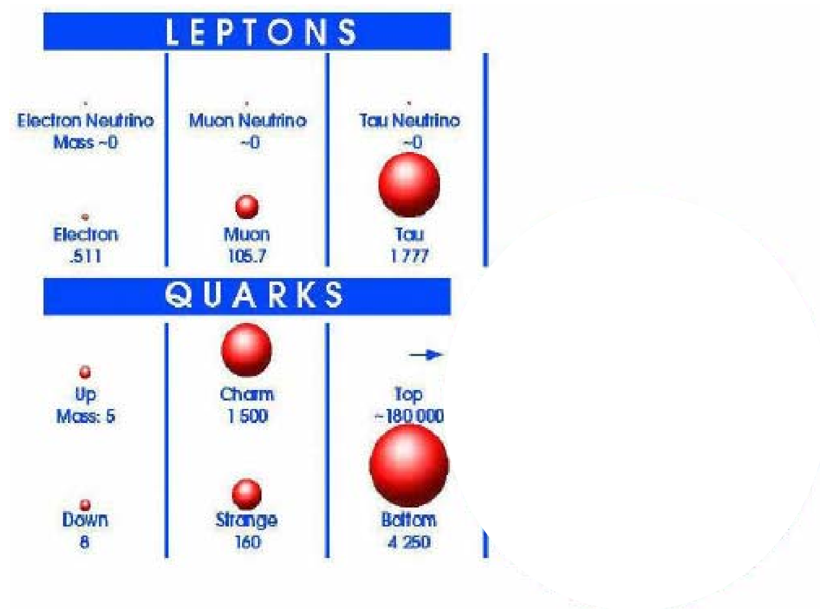
- Was discovered at Fermilab in 1995
- The heaviest known fundamental particle
  - m_t = 172.4 ±1.4 GeV (~1% precision)

    Close to a gold atom

  $\tau = 5\times10^{-25}$ s $<< \Lambda_{QCD}^{-1}$

  Decays before hadronization
- Mass close to scale of electroweak symmetry breaking
  - Only quark for which coupling to Higgs is significant
  - May shed light on EWSB mechanism
- Top quark plays special role in many of the new physics models

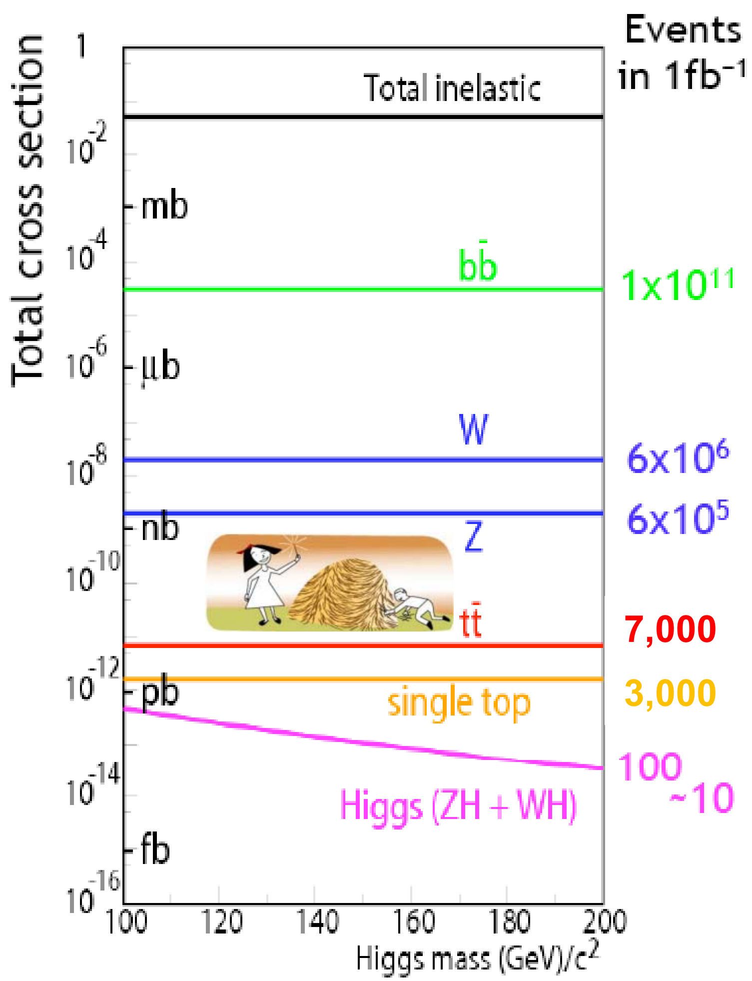
Discovered at Fermilab in1995



Why Keep Looking at the Top?

- Tevatron is the only place (so far) where top quarks can be produced
- Even more than a decade after its discovery, our sample consists of ~ 1000 top quark events

Lot of room for surprises!



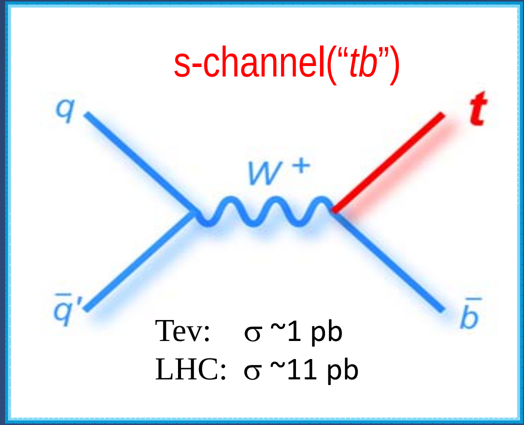
Why Being Single is Good?

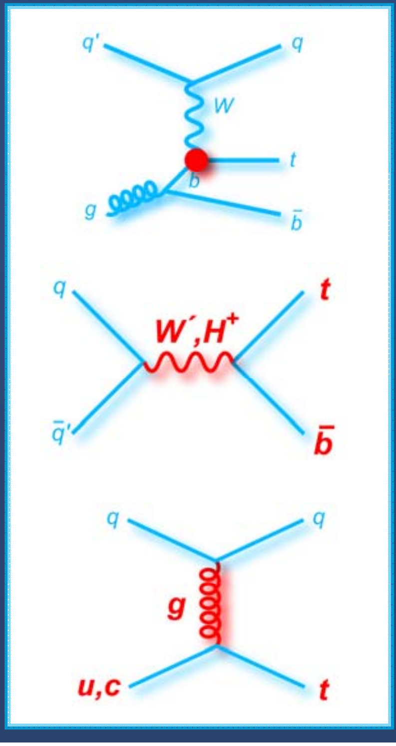
- Study *Wtb* coupling in top production
  - Measure $|V_{tb}|$ directly: $\sigma \propto |V_{tb}|^2$

- Cross sections sensitive to new physics
  - s-channel: resonances (heavy W' boson, charged Higgs boson, Kaluza-Klein excited W_{KK}, technipion, etc.),
  - t-channel: flavor-changing neutral currents ($t - Z / \gamma / g - c / u$ couplings), Fourth generation of quarks

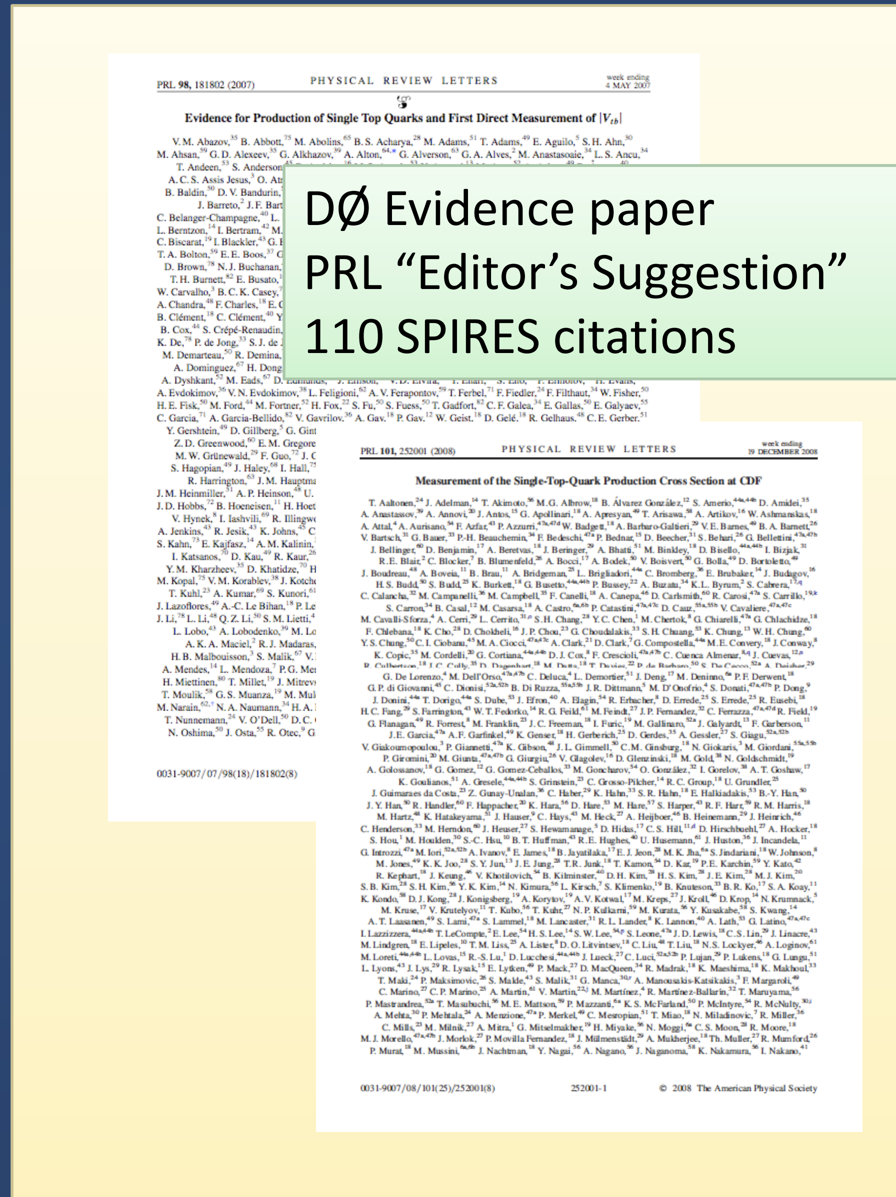
- Top properties

- Similar search for *WH* associated Higgs production





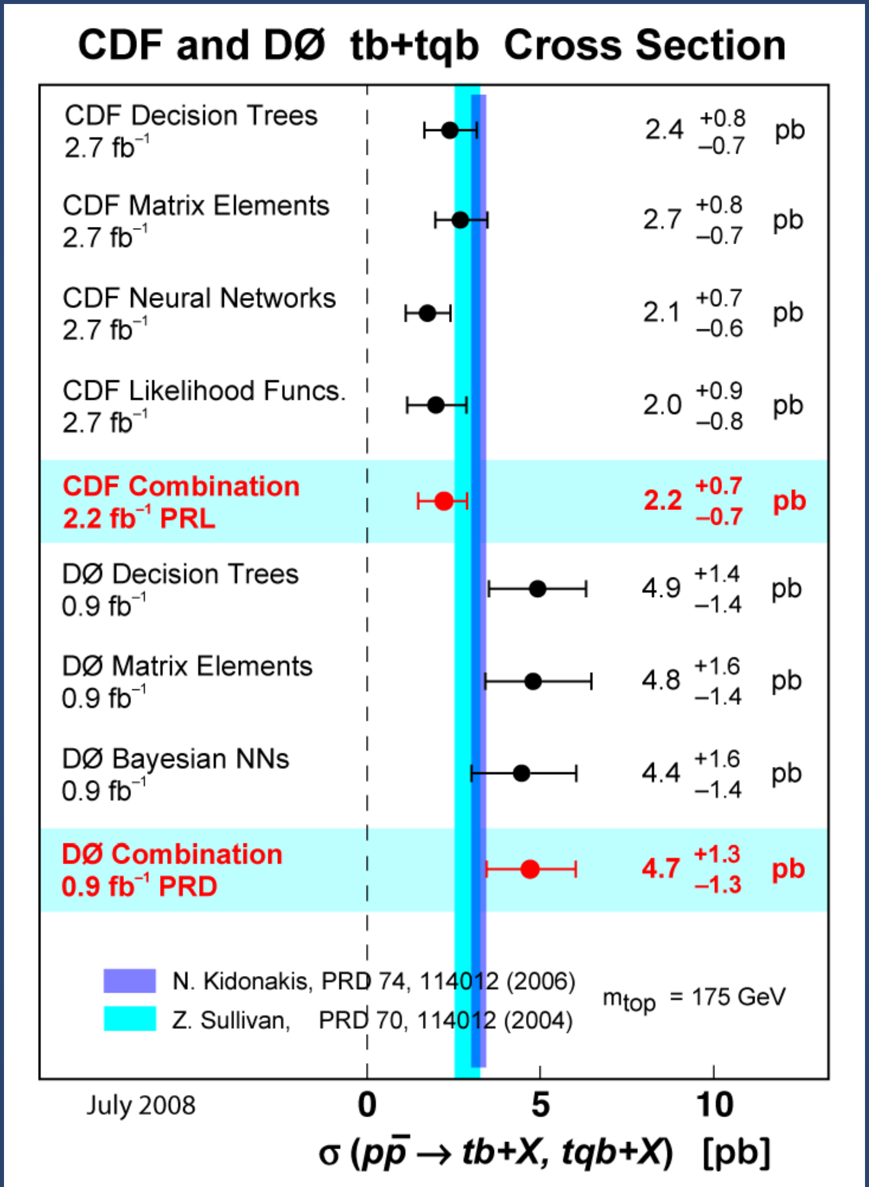
- **DØ**
- Search: PRD 63, 031101 **(2000)**
- Search: PLB 517, 282 **(2001)**
- Search: PLB 622, 265 **(2005)**
- W’: PLB 641, 423 **(2006)**
- Search: PRD 75, 092007 **(2007)**
- **Evidence**: PRL 98, 181802 **(2007)**
- FCNC: PRL 99, 191802 **(2007)**
- W’: PRL 100, 211802 **(2007)**
- Evidence: PRD 78, 012005 **(2008)**
- Wtb: PRL 101, 221801 **(2008)**
- Wtb: PRL 102, 092002 **(2009)**
- H^+: (PRL) arXiv:0807.0859
- **Observation: (PRL) arXiv:0903.0850**
- **CDF**
- Search: PRD 65, 091102 **(2002)**
- W’ PRL 90, 081802 **(2003)**
- Search: PRD 69, 052003 **(2004)**
- Search: PRD 71, 012005 **(2005)**
- **Evidence:** PRL 101, 252001 **(2008)**
- FCNC: (PRL) arXiv:0812.3400
- W’: (PRL) arXiv:0902.3276
- **Observation: (PRL) arXiv:0903.0885**



Evidence for Single Top Production

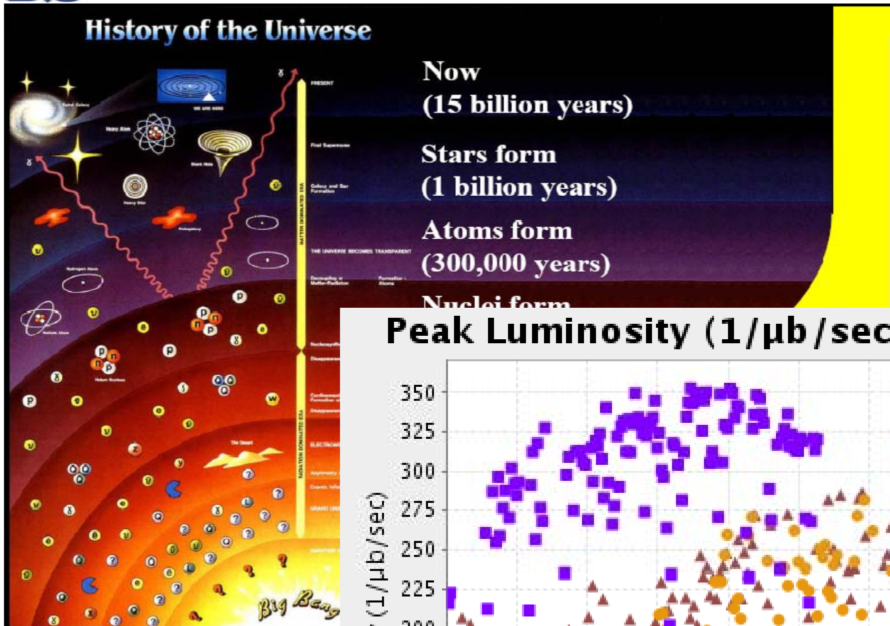
Status as of March 3, 2009

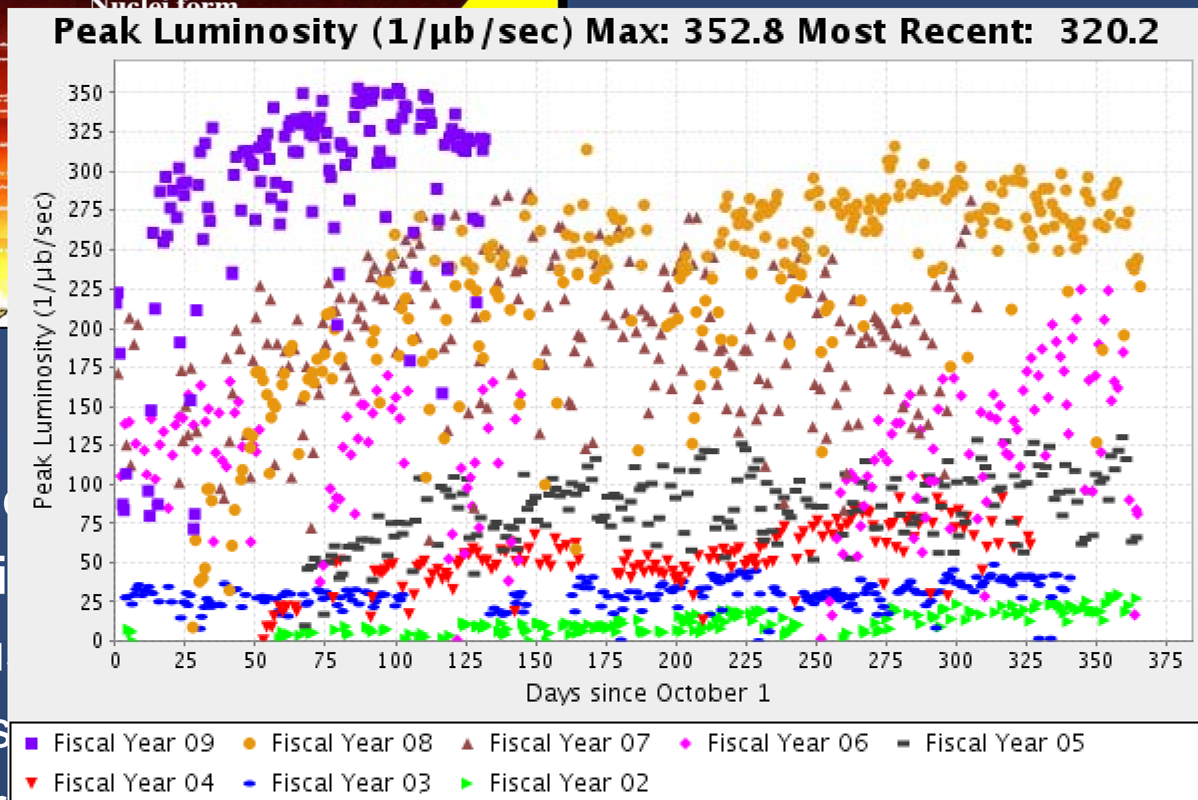
Signal Significance		Cross Section
Expected	Observed	Measured
DØ ($0.9\ fb^{-1}$) PRL 98, 181802 (2007)		
2.3σ	3.6σ	4.7 ± 1.3 pb
$\lvert V_{tb}\rvert = 1.31 + 0.25 - 0.21$		
CDF ($2.2\ fb^{-1}$) PRL 101, 252001 (2008)		
4.9σ	3.7σ	2.2 ± 0.7 pb
$\lvert V_{tb}\rvert = 0.88 \pm 0.12 \pm 0.07$		



Observed significance is a measure of how likely it is to measure the cross section in the absence of signal

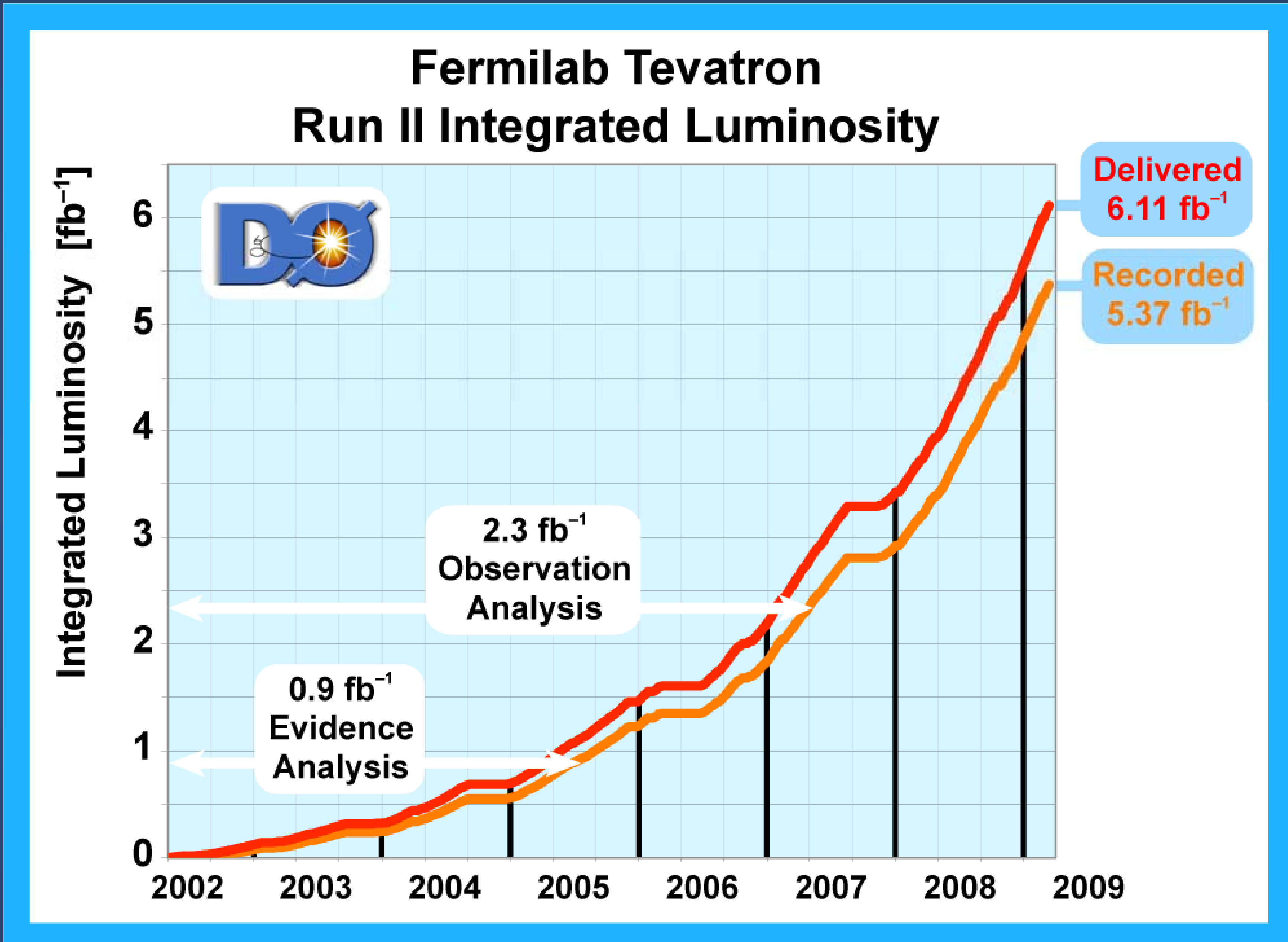
The Tevatron Accelerator



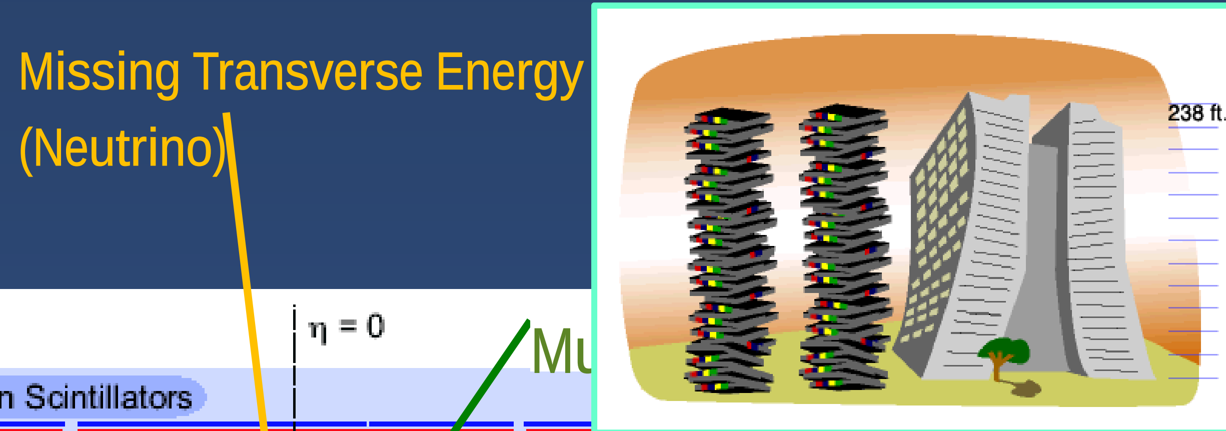


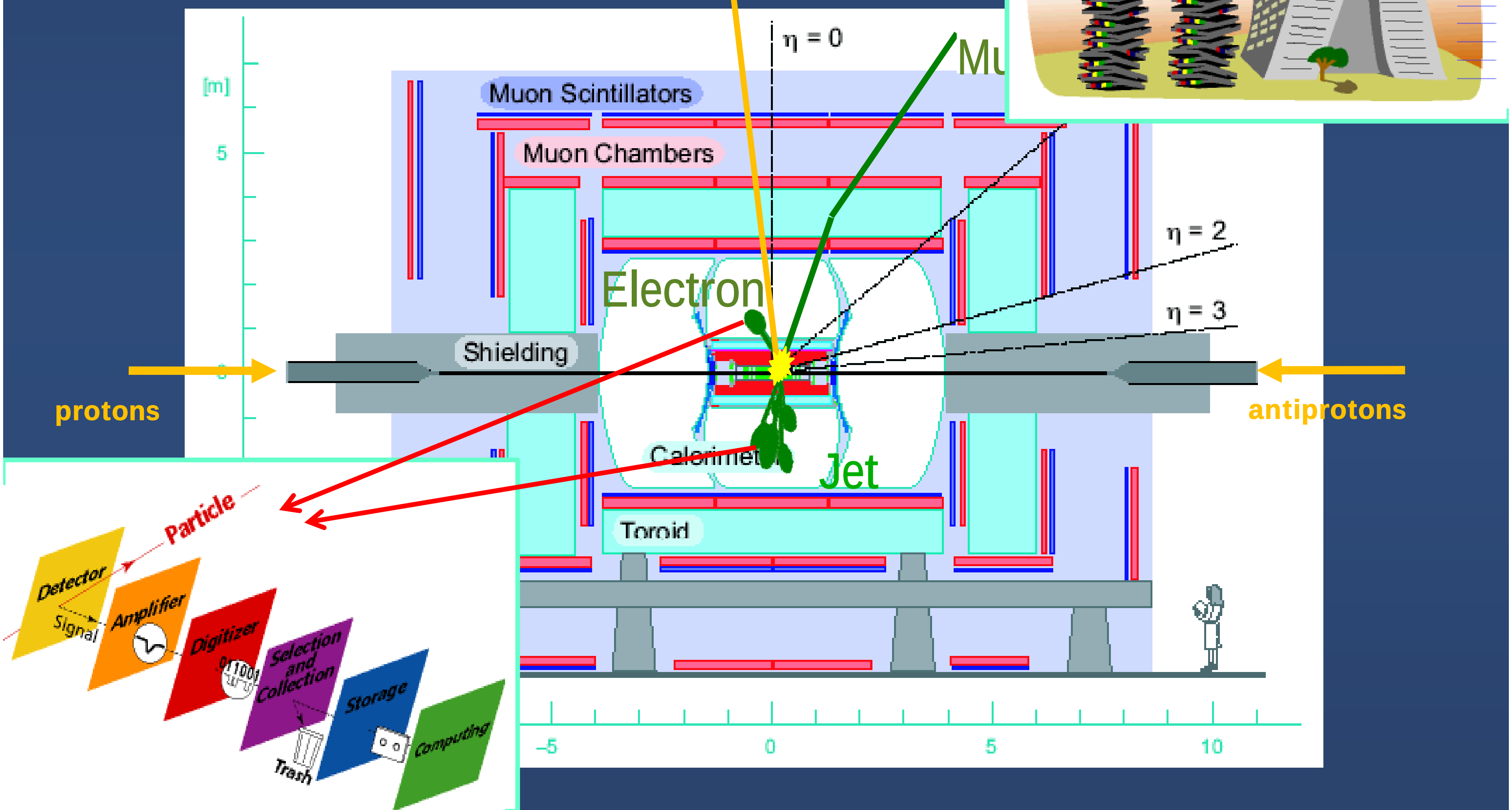
~ 20 countri
~ 80 instituti
~ 700 enthu
physicists
per experiment

The only place where top quarks are produced and measured
(on average, we are collecting more than 400 top pairs per week now)


Fermilab Tevatron
Run II Integrated Luminosity
Integrated Luminosity [fb^{-1}]
0
1
2
3
4
5
6
2002
2003
2004
2005
2006
2007
2008
2009
Delivered
6.11 fb^{-1}
Recorded
5.37 fb^{-1}
2.3 fb^{-1}
Observation
Analysis
0.9 fb^{-1}
Evidence
Analysis

Every 396 ns....

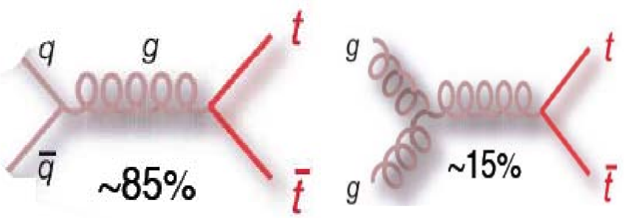

Missing Transverse Energy
(Neutrino)
238 ft.


Muon Scintillators
Muon Chambers
Electron
Shielding
Calorimet
Jet
Toroid
η = 0
η = 2
η = 3
[m]
5
0
-5
0
5
10
protons
antiprotons
Particle
Detector
Signal
Amplifier
Digitizer
Selection and Collection
Trash
Storage
Computing

Production

Top quark pair production

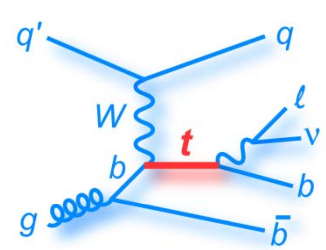
σ_{tt} ~7 pb



Single Top quark production

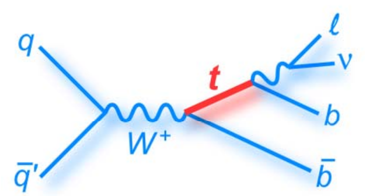
***t*-channel**

σ ~2 pb



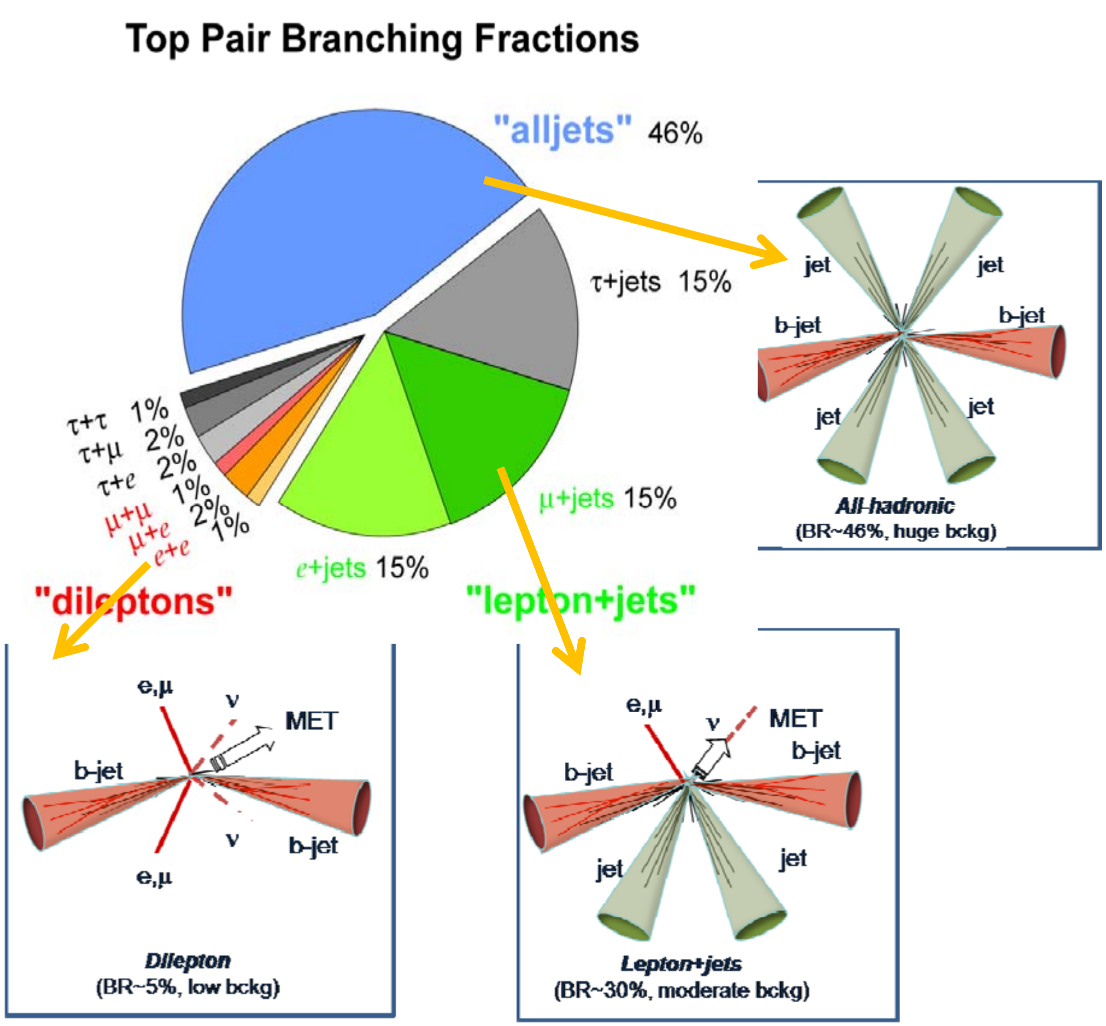
***s*-channel**

σ ~1 pb

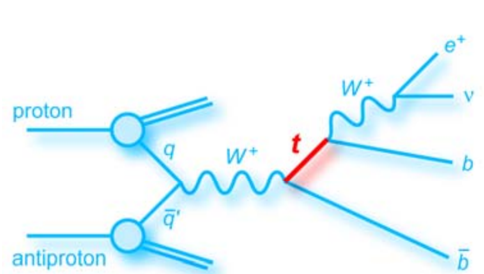


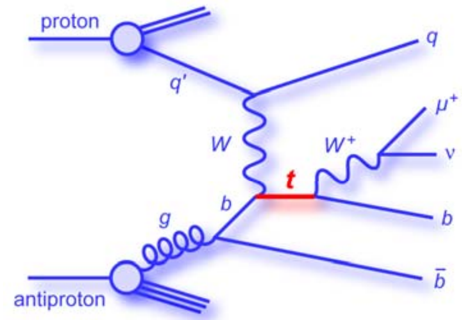
Decay

Within Standard Model t→Wb ~ 100%



Event Signatures and Event Selection





$e:\quad p_T > 15\,GeV, |\eta| < 1.1$

$\mu:\quad p_T > 18\,GeV, |\eta| < 2.0$

Missinng E_T $\quad 15 < MET < 200\,GeV$

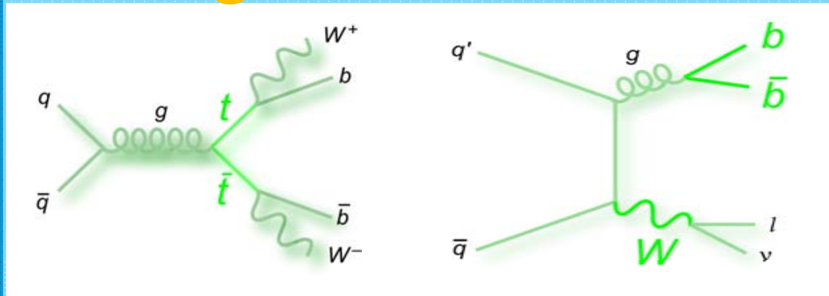
Jets $\quad 2-4,\ p_T > 15\,GeV, |\eta| < 3.0$

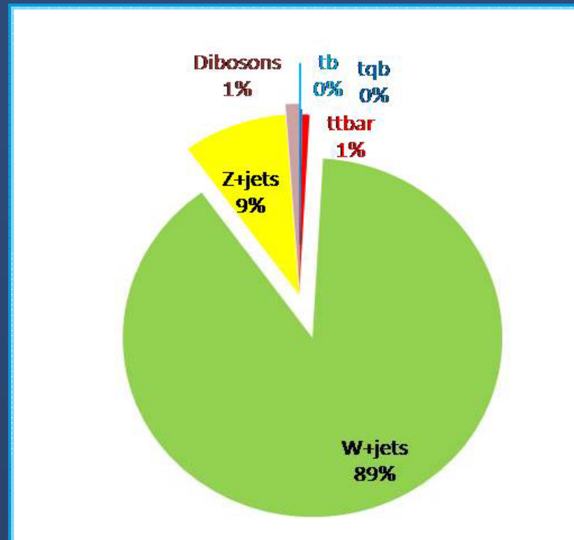
$p_{T,1} > 25\,GeV, |\eta| < 2.5$

$p_{T,2} > 20\,GeV$

B − jet $\quad$ 1 or 2

Backgrounds





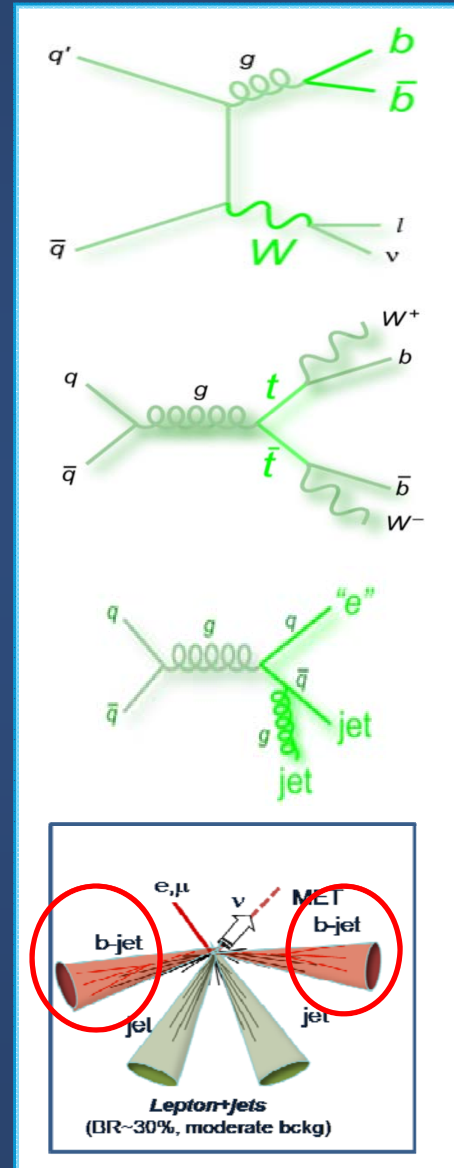
- Top pairs W+jets, and Multijets are the main processes that can mimic these signatures
- Single top signal is negligible compared to these backgrounds

Background Modeling

- Single top signal

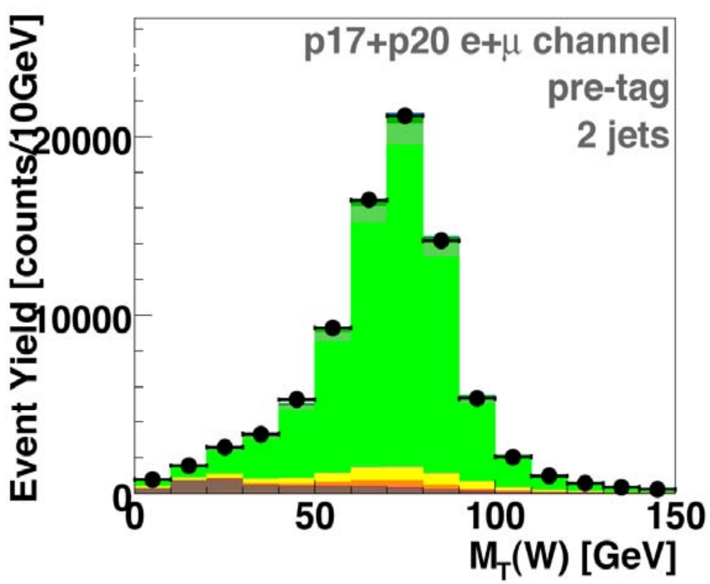
  Modeled using SINGLETOP based on COMPHEP

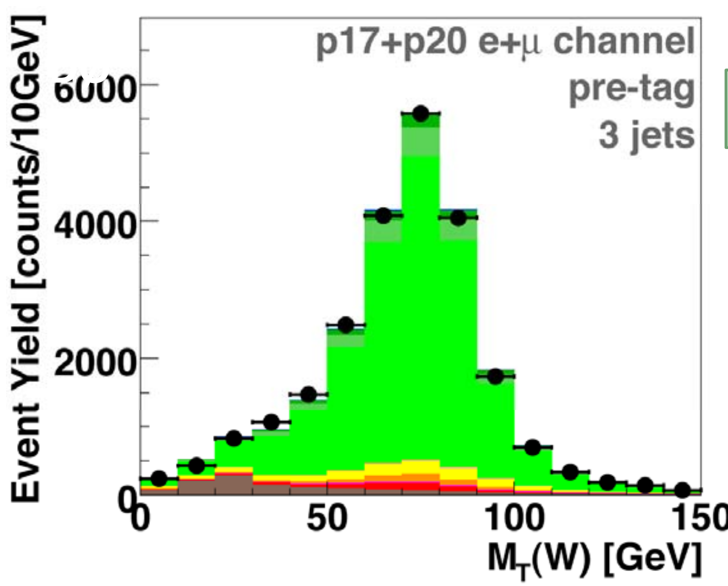
- W+jets background
  - Event kinematics and flavor composition modeled using Alpgen generator and PYTHIA for parton hadronization
  - η(jets), $\Delta\phi$(jet1,jet2), $\Delta\eta$(jet1,jet2) corrected to match data
  - Normalized to data before b tagging and after subtracting other backgrounds
- Multijet background
  - Modeled using data with a non-isolated lepton and jets
  - Kept small (~5%) with topological selection cut
- Top pair backgrounds modeled using ALPGEN +PYTHIA
- Z+jets modeled using ALPGEN + PYTHIA
- Dibosons modeled using PYTHIA



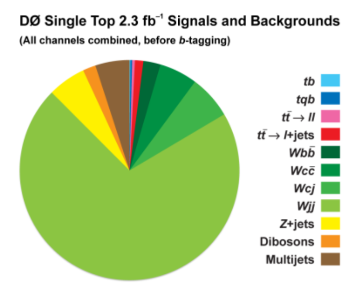
Background Normalization

- W+jets and multijet normalized using iterative template fits to data BEFORE TAGGING on three sensitive variables: $p_T(\ell)$, $\not{E}_T$, $M_T(W)$



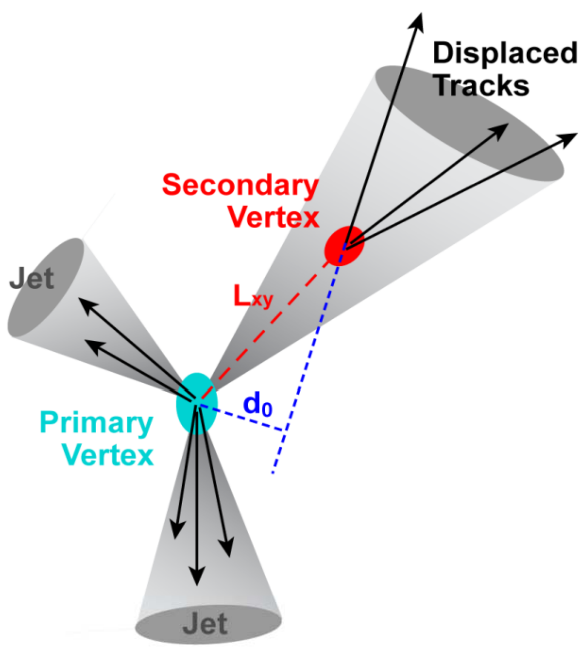


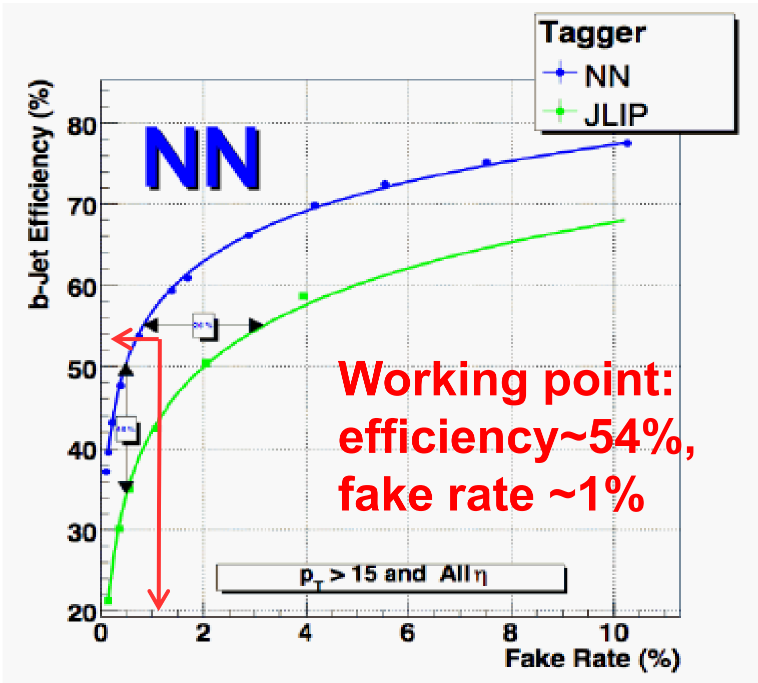
S:B = 1:259



B-jet Identification (aka b-tagging)

- Separate *b*-jets from light-quark and gluon jets to reject most W+jets background
- DØ uses a neural network algorithm with seven input variables based on impact parameter and reconstructed vertex

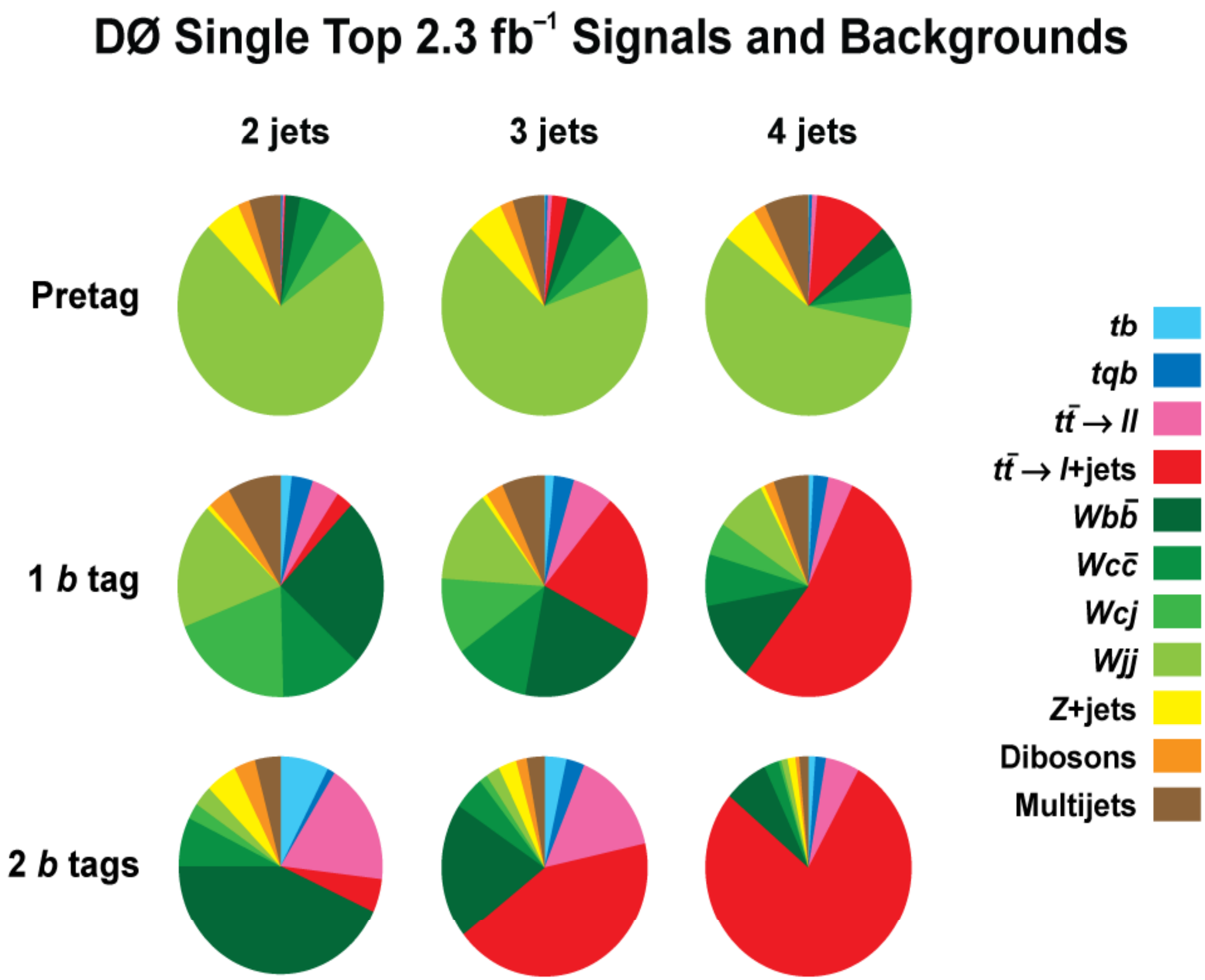




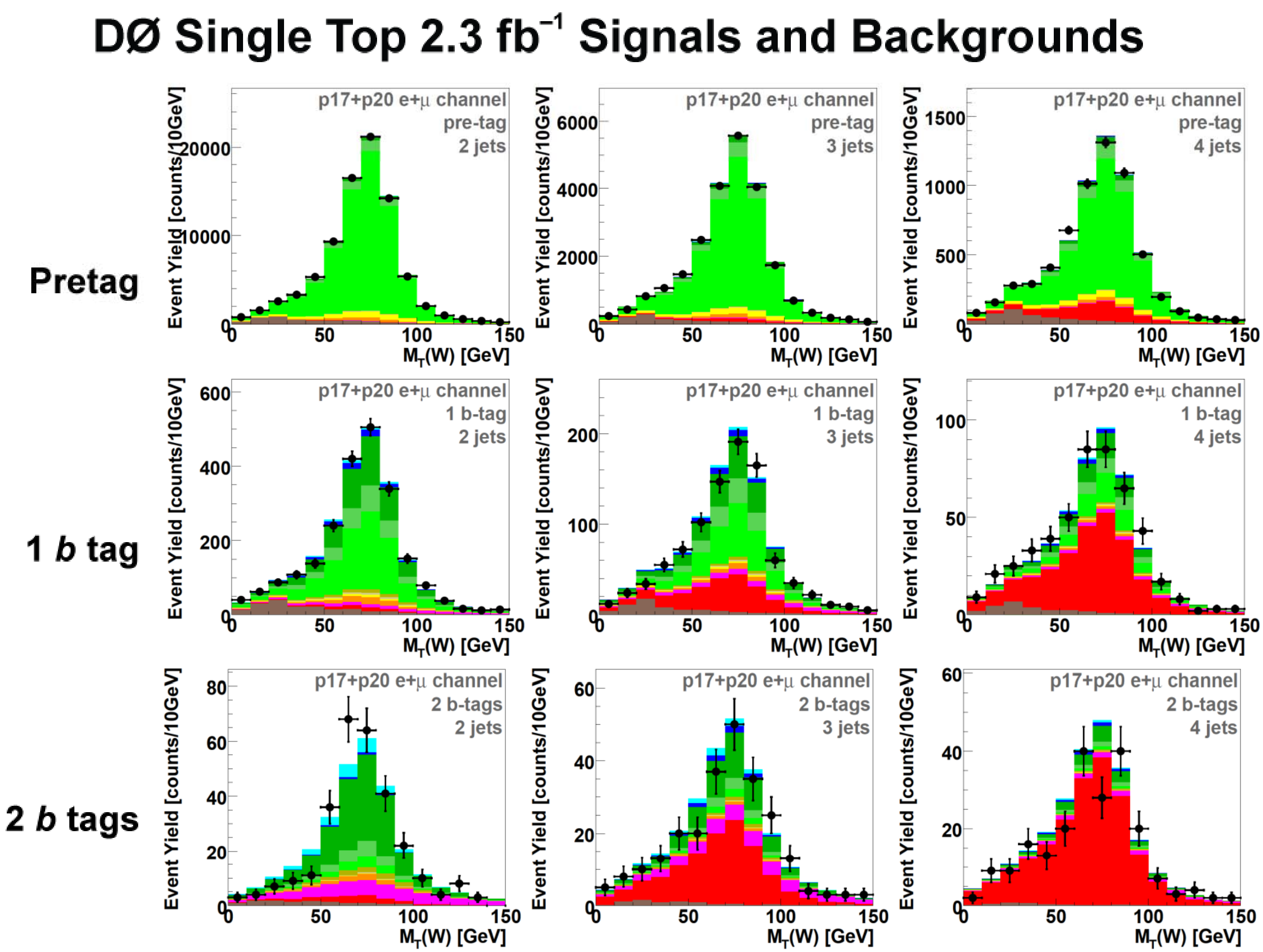
Before and After .....

~100,000 Evts

~5000 Evts

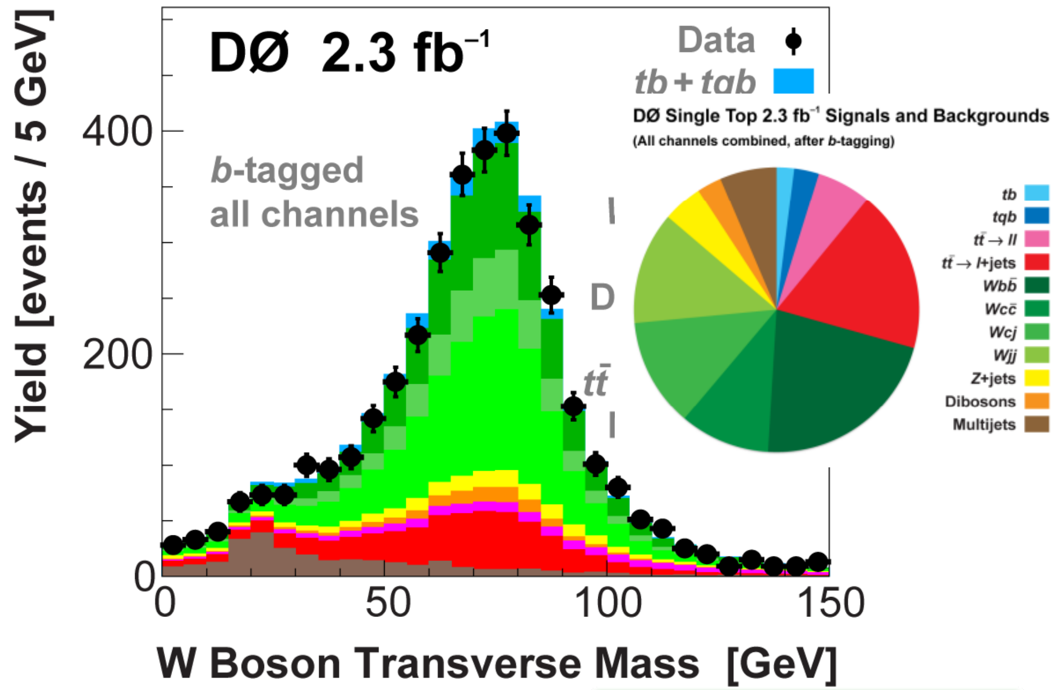


Before and After …..



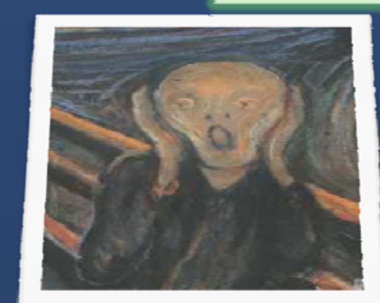
Event Yields After B-Tagging

Event Yields in 2.3 fb^{-1} of DØ Data	
e,μ, 2,3,4-jets, 1,2-tags combined	
tb + *tqb*	223 ± 30
W+jets	2,647 ± 241
Z+jets, dibosons	340 ± 61
$t\bar{t}$ pairs	1,142 ± 168
Multijets	300 ± 52
Total prediction	4,652 ± 352
Data	4,519



S:B = 1:21 in 1Tag
S:B = 1:15 in 2Tag

- Single top signal is smaller than total background uncertainty
- Counting events is not a sensitive enough method

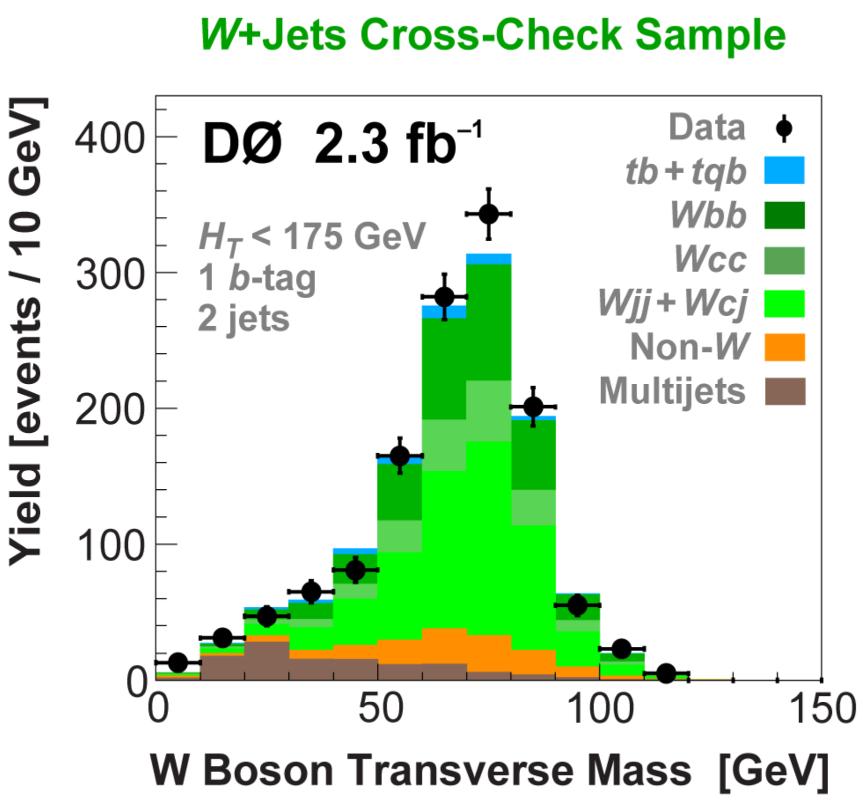


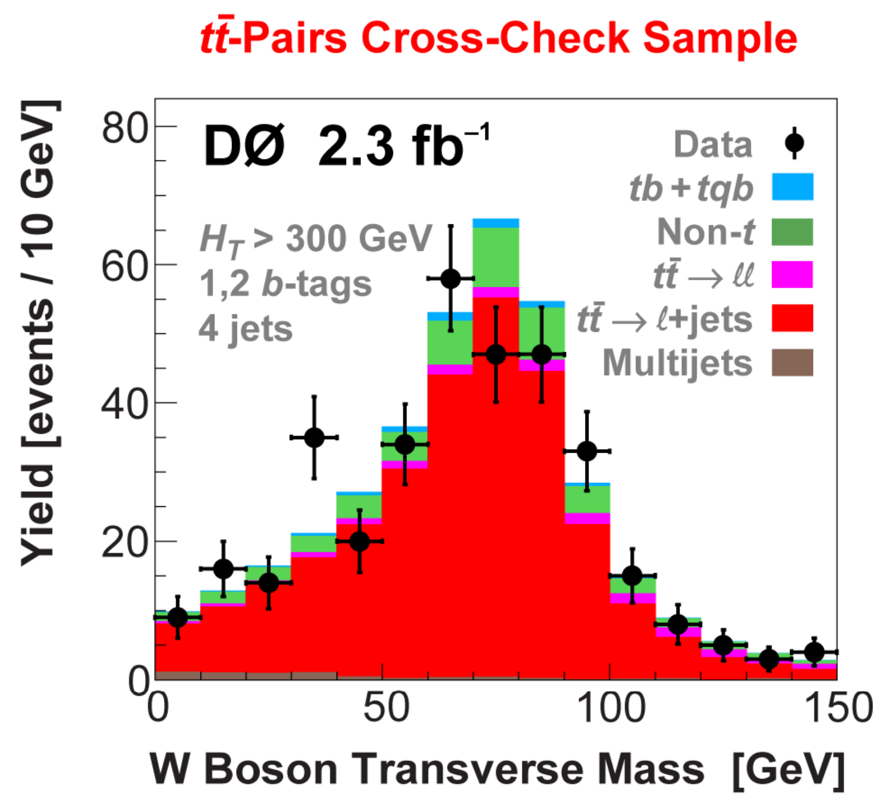
Cross Check Samples

Validate a background model in side-band regions

a) An enriched W+jets background

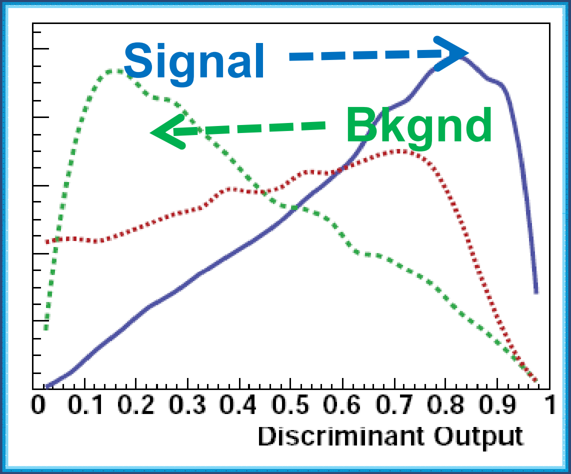
b) An enriched top pair background





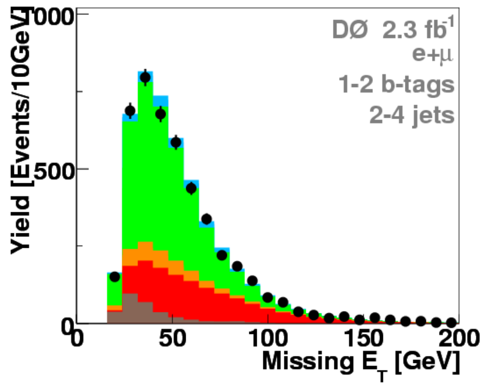
Search Strategy

- **Maximize the signal acceptance**
  - Particle ID definitions set as loose as possible
  - Transverse momentum thresholds set low, pseudo-rapidities wide
  - As many decay channels used as possible
  - All channels analyzed separately since S:B and background compositions differ
- **Use multivariate techniques**
- **Three techniques used for this analysis**
  - Boosted Decision Trees
  - Matrix Elements
  - Bayesian Neural Networks
- Check discriminant Performance using data control samples
- **Use ensembles of pseudo-data to test validity of methods**
- **Cross sections measured using binned likelihood calculation of signal + background to data**

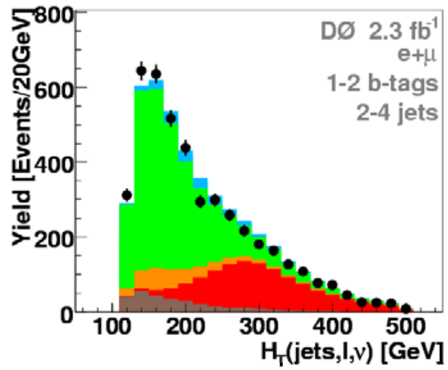


Discriminating Variables–BDT/BNN

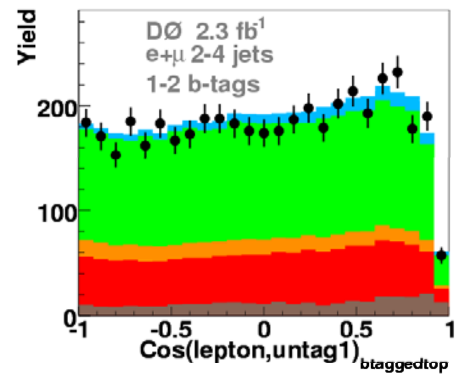
OBJECT KINEMATICS



EVENT KINEMATICS



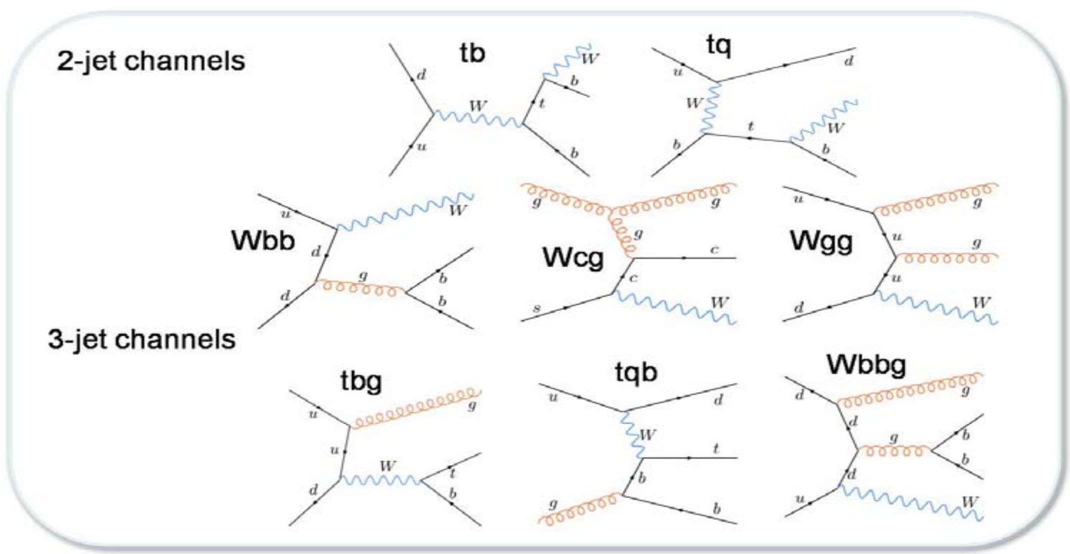
ANGULAR CORRELATIONS



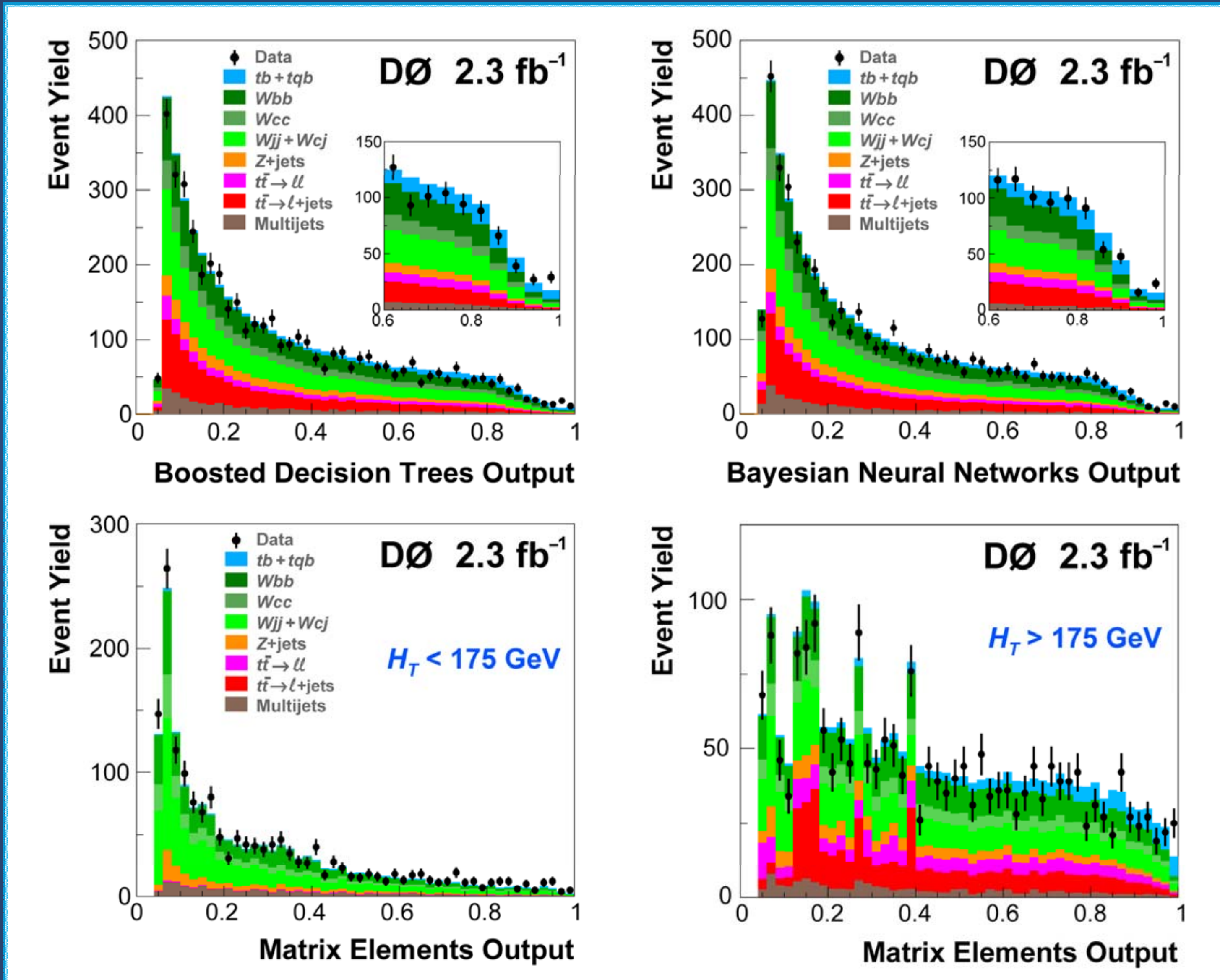
Feynman Diagrams Matrix Elements

Added additional Matrix Elements since 2006

2jets: top pair, WW, WZ, ggg;
3jets:top pair, Wugg



Multivariate Discriminant Output



Systematic Uncertainties

Systematic Uncertainties

Components for normalization	
Integrated luminosity	6.1%
$t\bar{t}$ 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	–

Components that most affect the cross section measurement are shown in yellow

Other important contributions are shown in *pink*

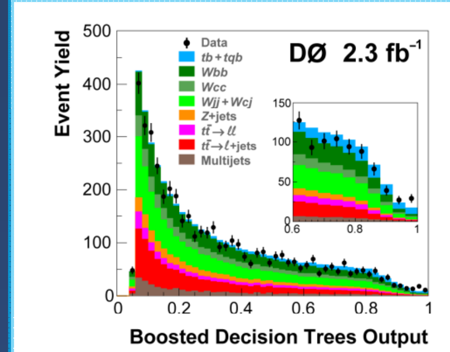
Statistical Analysis

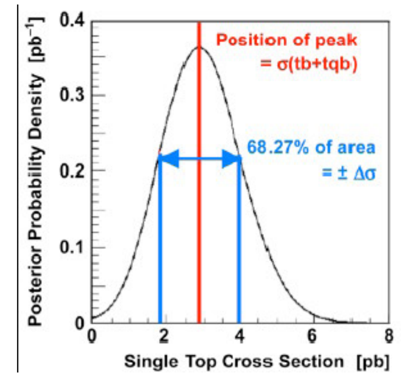
Cross Section Measurement

– Calculate cross sections using binned likelihood fits of (floating) signal + (fixed) background to data

– Compute posterior probability density of tb+tqb using Bayes' theorem:

- Flat positive-defined prior for the cross section
- Systematic uncertainties are treated as Gaussian nuisance parameters

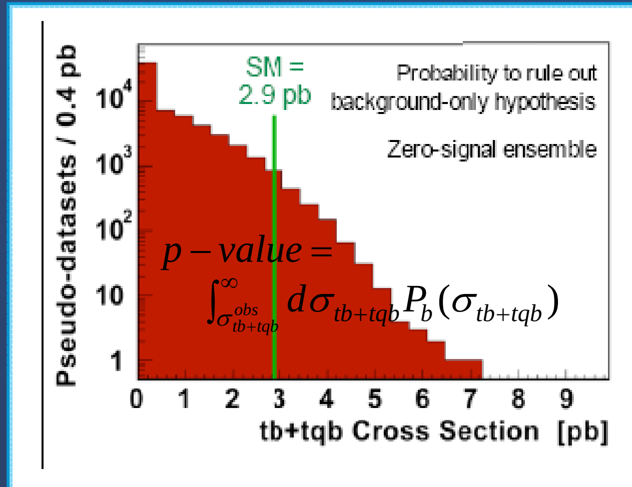




Significance

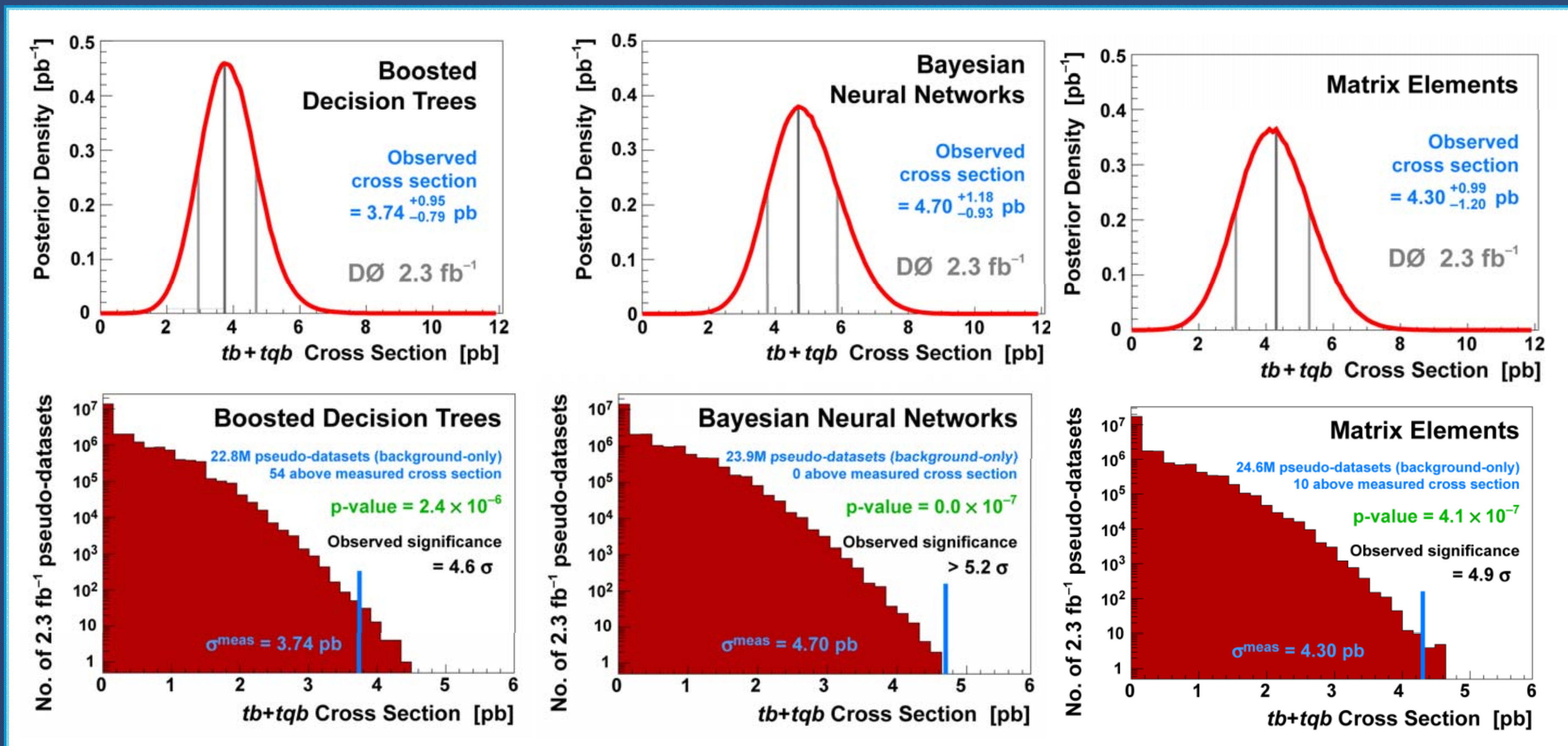
– Use the ensemble of zero-signal pseudo-datasets to find what fraction give a cross section at least as large as the measured value: the "measured p-value"

– Convert p-value to "measured significance



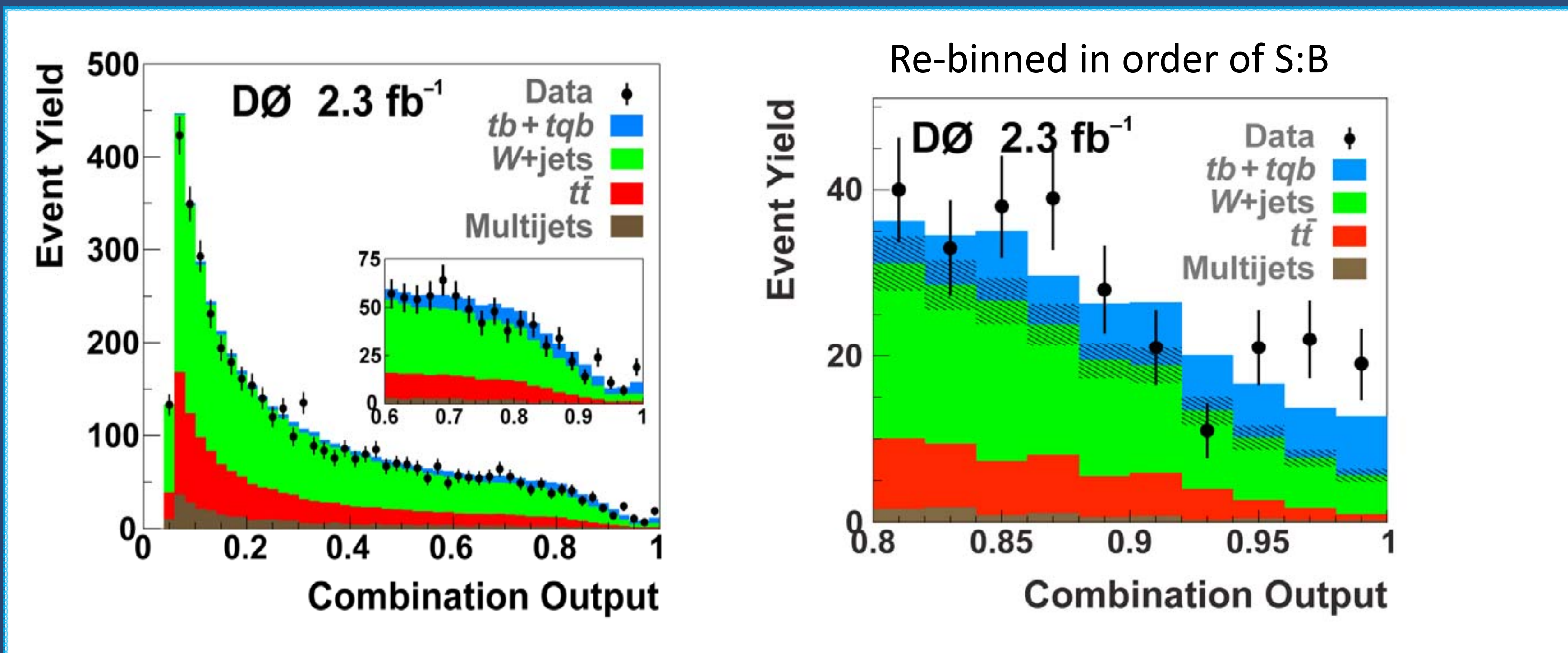
Results

DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance Expected	Significance Measured
Boosted Decision Trees	$3.74\ ^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70\ ^{+1.18}_{-0.93}$ pb	4.1 σ	5.2 σ
Matrix Elements	$4.30\ ^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ



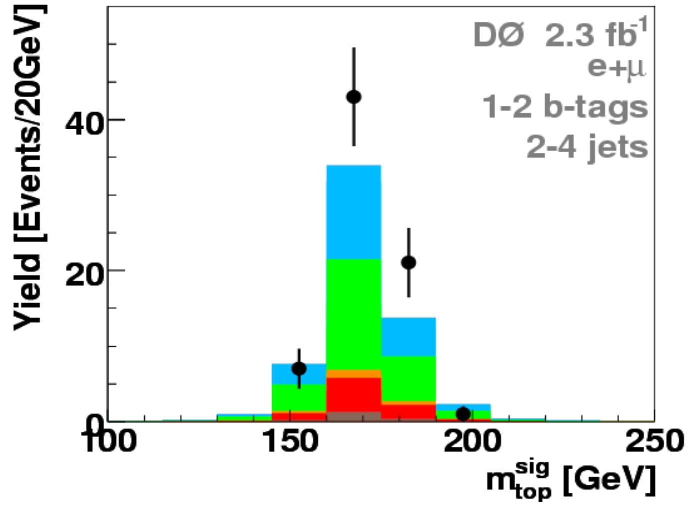
Combination of Results

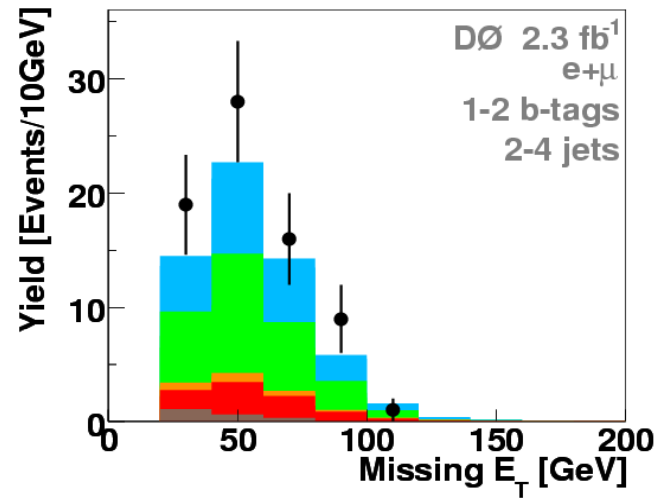
- All MVA analyses use the same data, but they are not 100% correlated
- We use a BNN to combine the three methods. The BNN takes as input variables the output discriminants of the individual methods
- Expected sensitivity for the BNN Combination:**4.5σ**

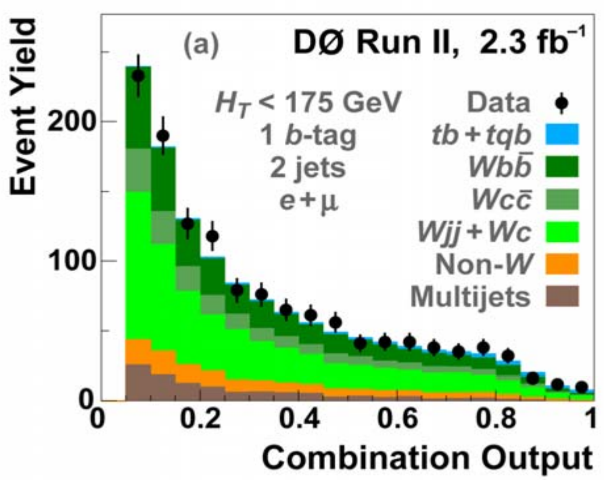


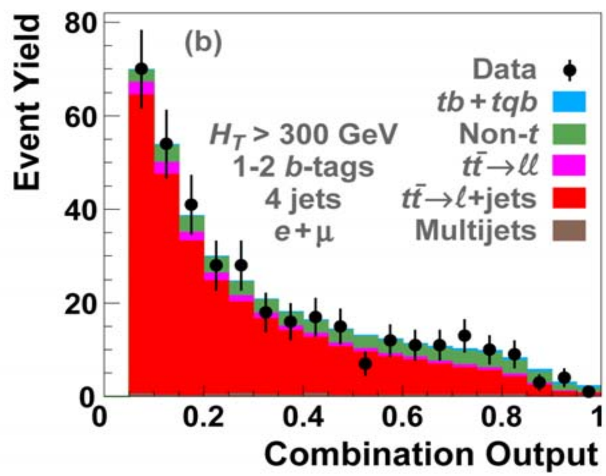
Combination of Results

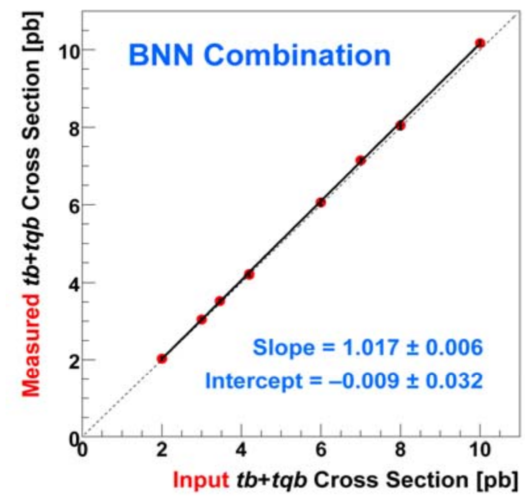
Distributions for BNN Comb > 0.9









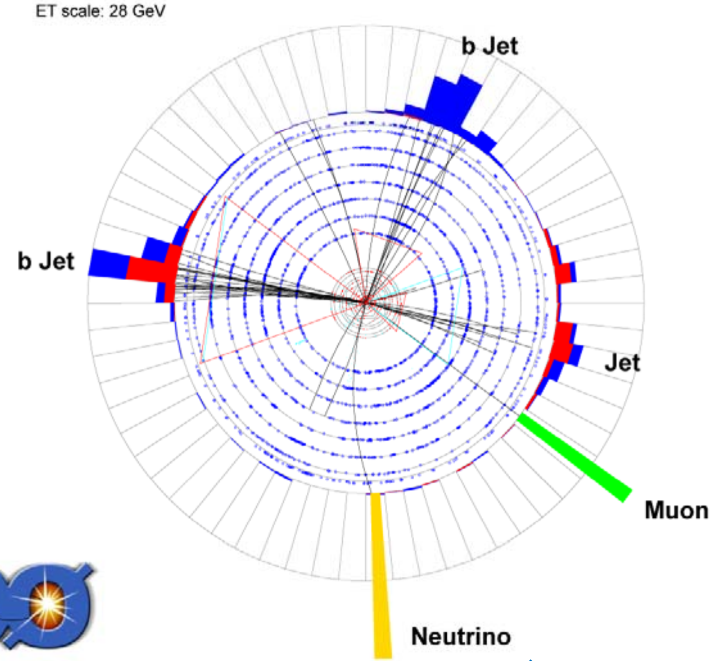


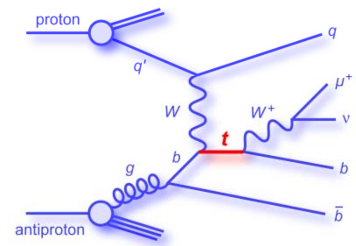
DØ Experiment Event Display

Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis

Run 223473 Evt 27278544 Sun Jul 23 19:21:41 2006

ET scale: 28 GeV



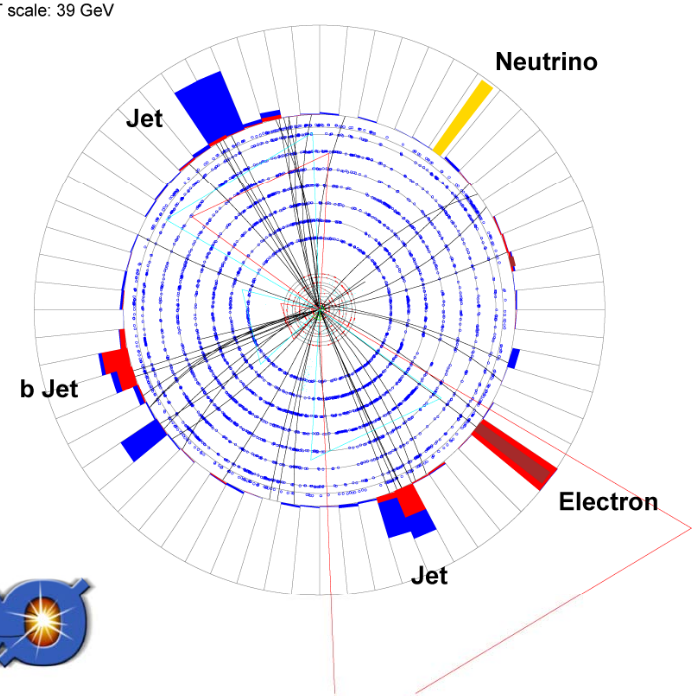


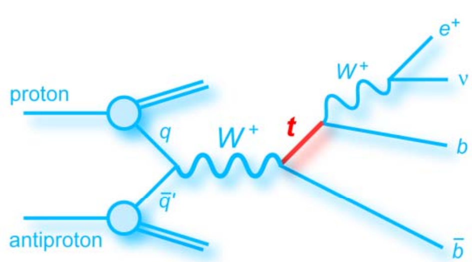
DØ Experiment Event Display

Single Top Quark Candidate Event, 2.3 fb^{-1} Analysis

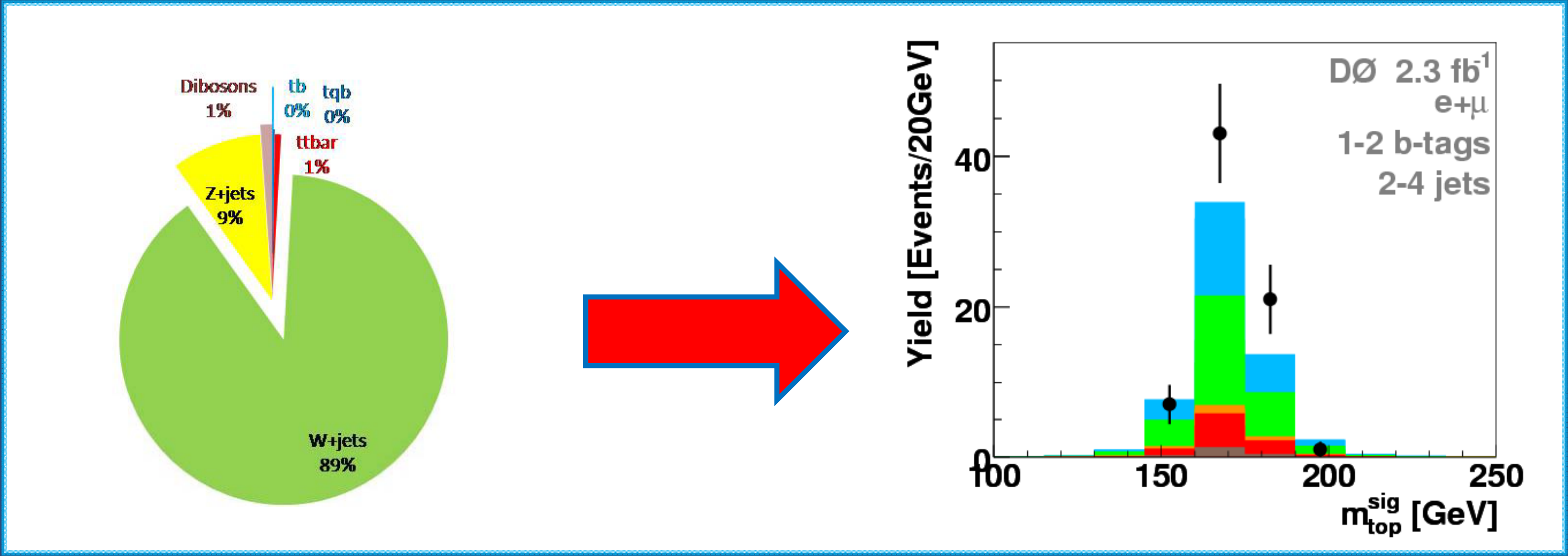
Run 229388 Evt 13339887 Wed Jan 3 21:05:14 2007

ET scale: 39 GeV





Combined Results



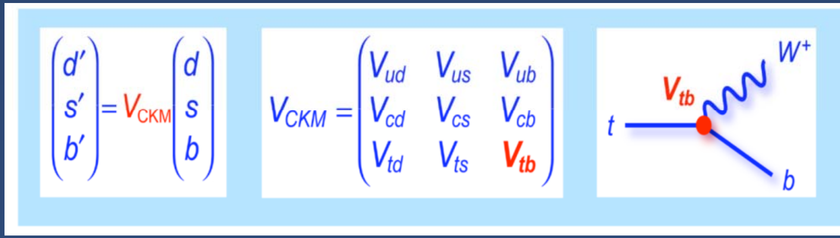
$$\sigma(p\bar{p} \to tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

Measured Significance = **5.03σ**

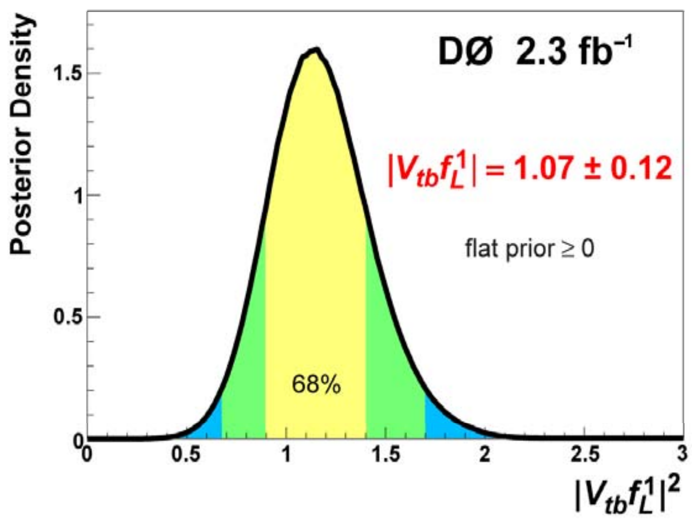
Discovery of single top production!!

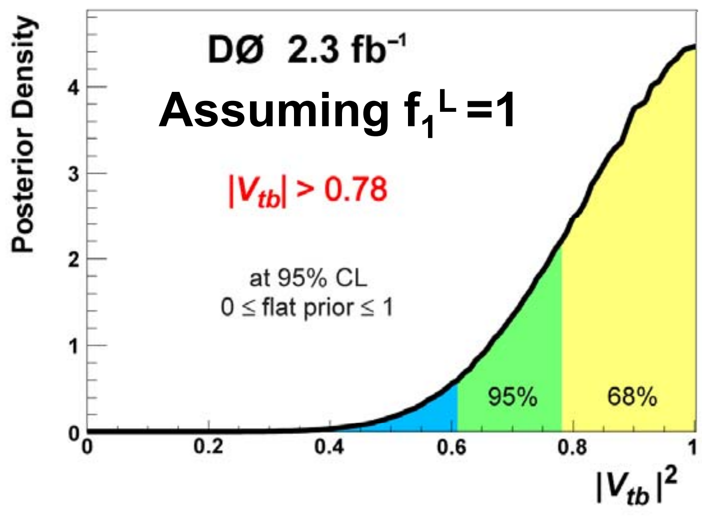
Measurement of $|V_{tb}|$

- Use the measurement of the single top cross section to make a direct measurement of $|V_{tb}|$:
  - Calculate a posterior in $|V_{tb}|^2$
  - Measure the strength of the V–A



$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$





Conclusions

- Both DØ and CDF collaborations at Tevatron have observes single top quark production in Run II data (I have presented only DØ analysis)

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.94 \pm 0.88 \text{ pb}$$

Measured Significance 5.03σ

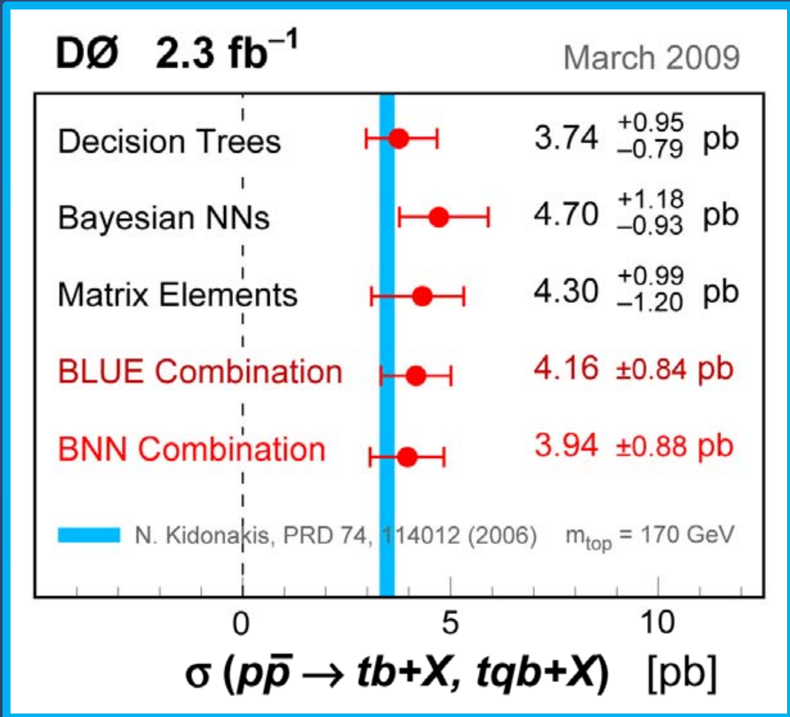
- Direct measurement of $|V_{tb}|$

$|V_{tb}\, f_1^L| = 1.07 \pm 0.12$

flat prior ≥ 0

$0.78 < |V_{tb}| < 1$ @ 95% CL

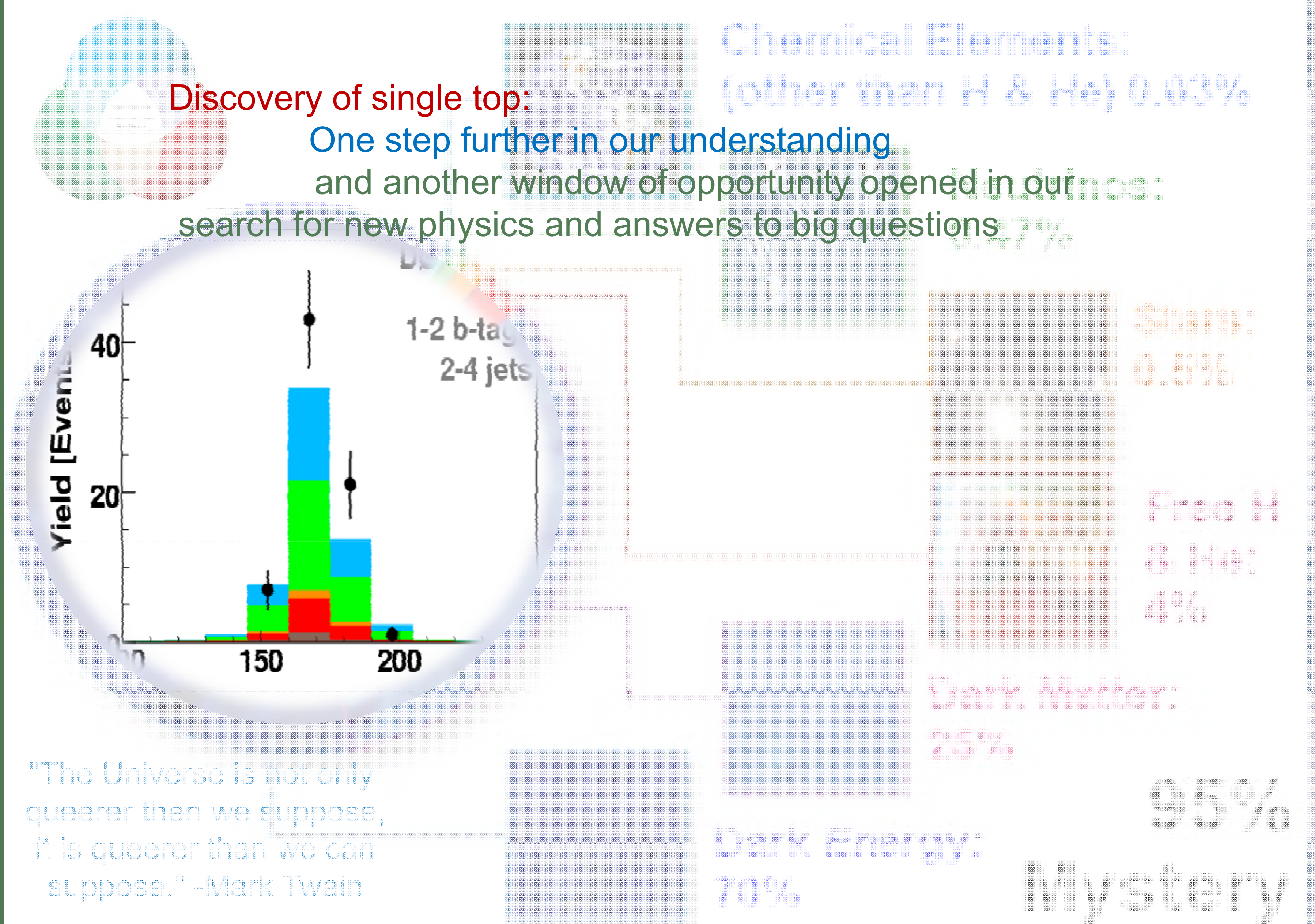
0 ≤ flat prior ≤ 1

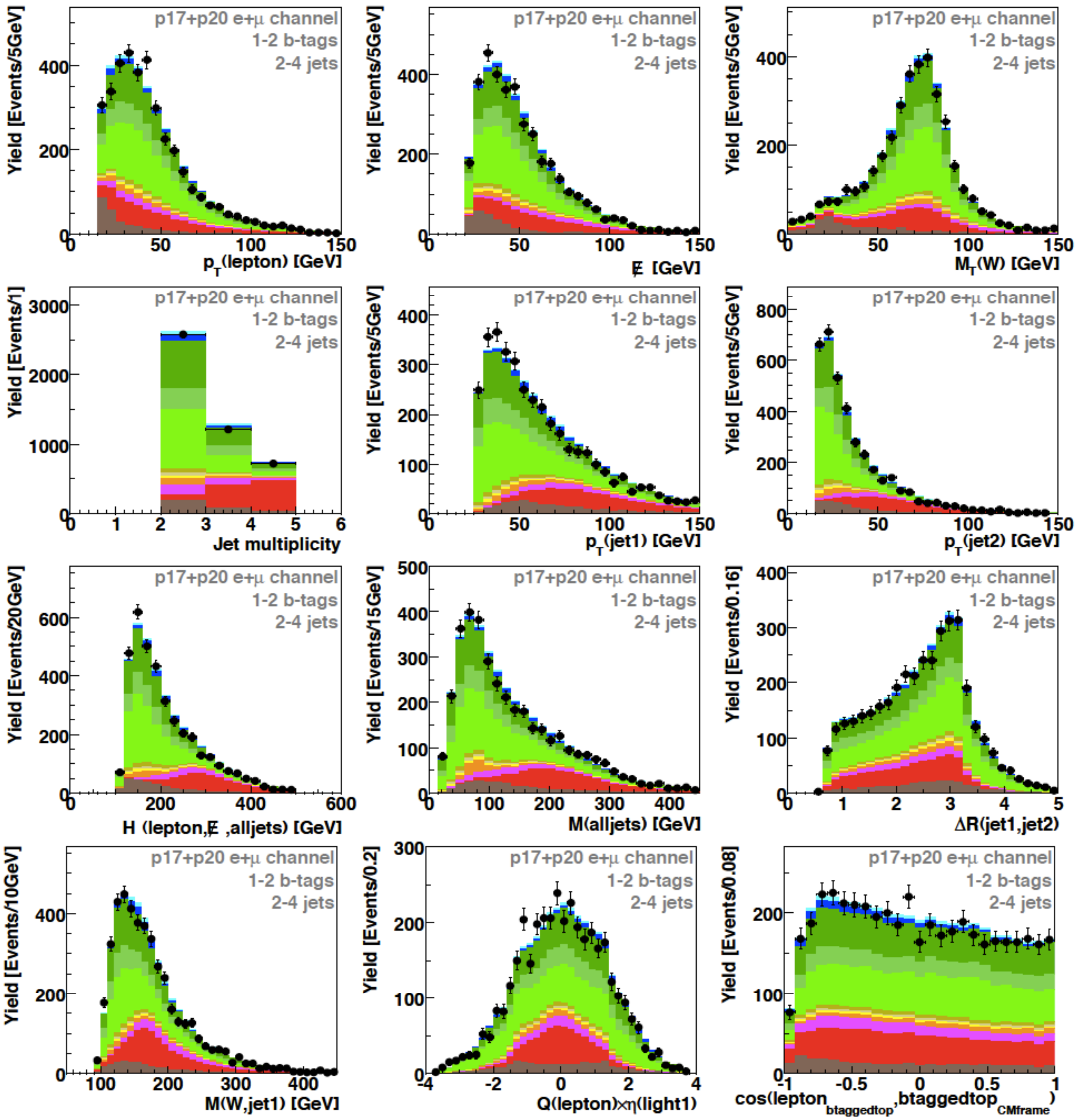


Discovery of single top:

One step further in our understanding

and another window of opportunity opened in our search for new physics and answers to big questions

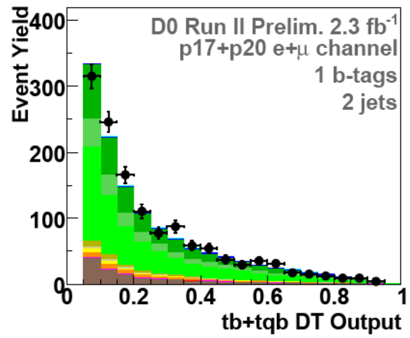


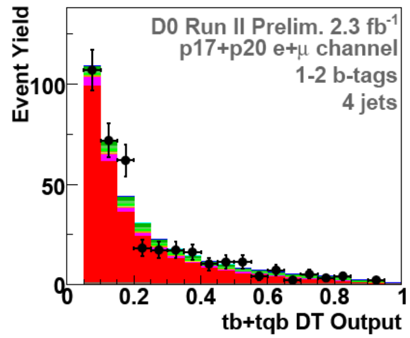


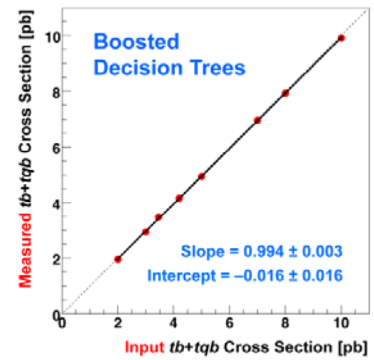
Data/MC agreement (for all channels combined)

Seprating Signal from Background

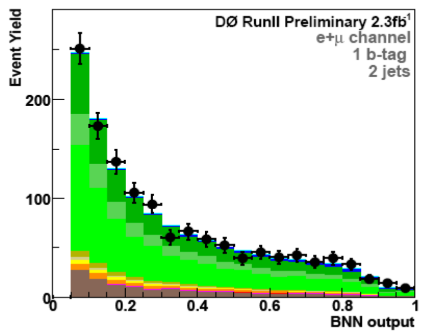
Cross Check Samples and Linearity

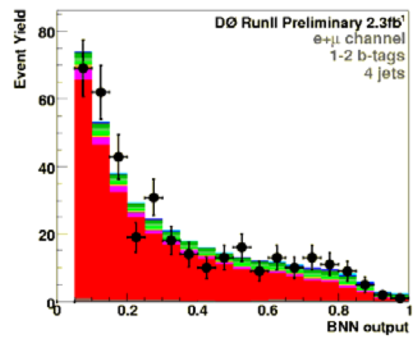


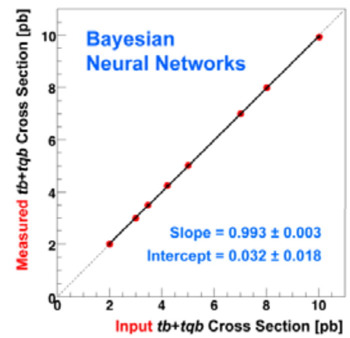




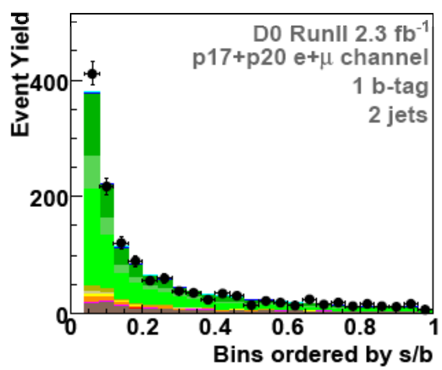
BDT

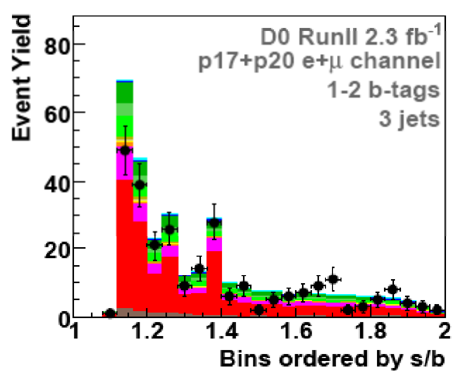


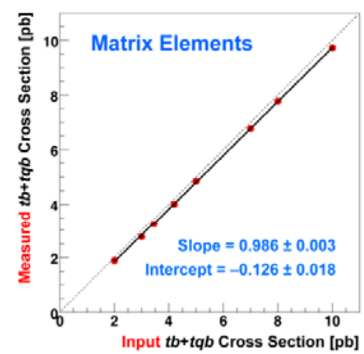




BNN



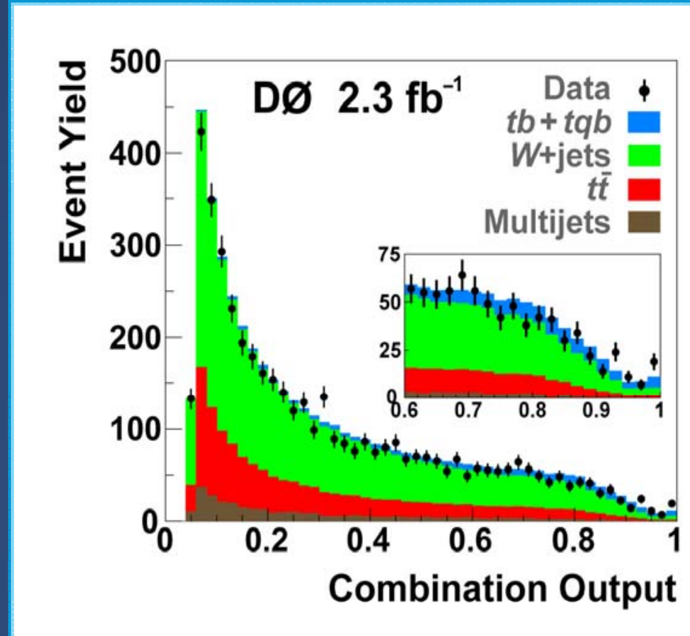


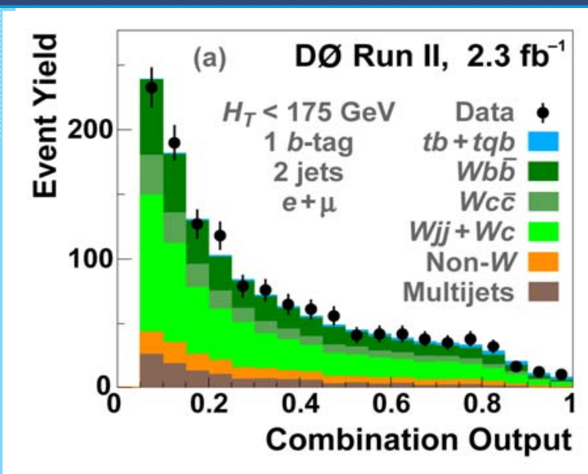


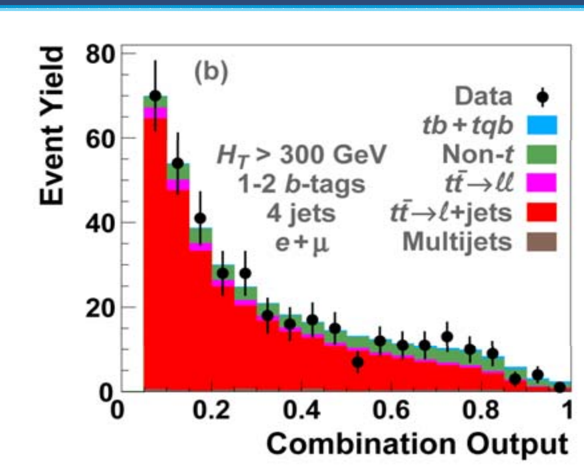
ME

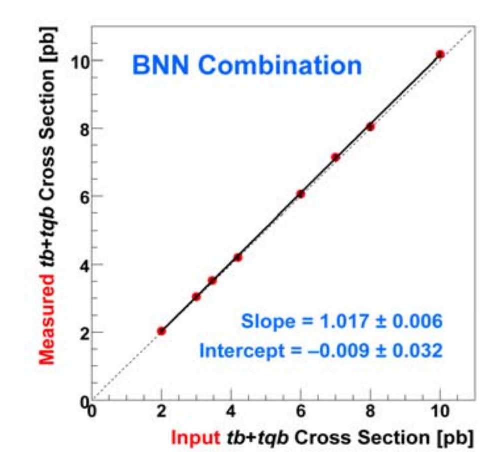
Combination of Results

- All MVA analyses use the same data, but they are not 100% correlated
- We use a BNN to combine the three methods. The BNN takes as input variables the output discriminants of the individual methods
- Expected sensitivity for the BNN Combination:**4.5σ**

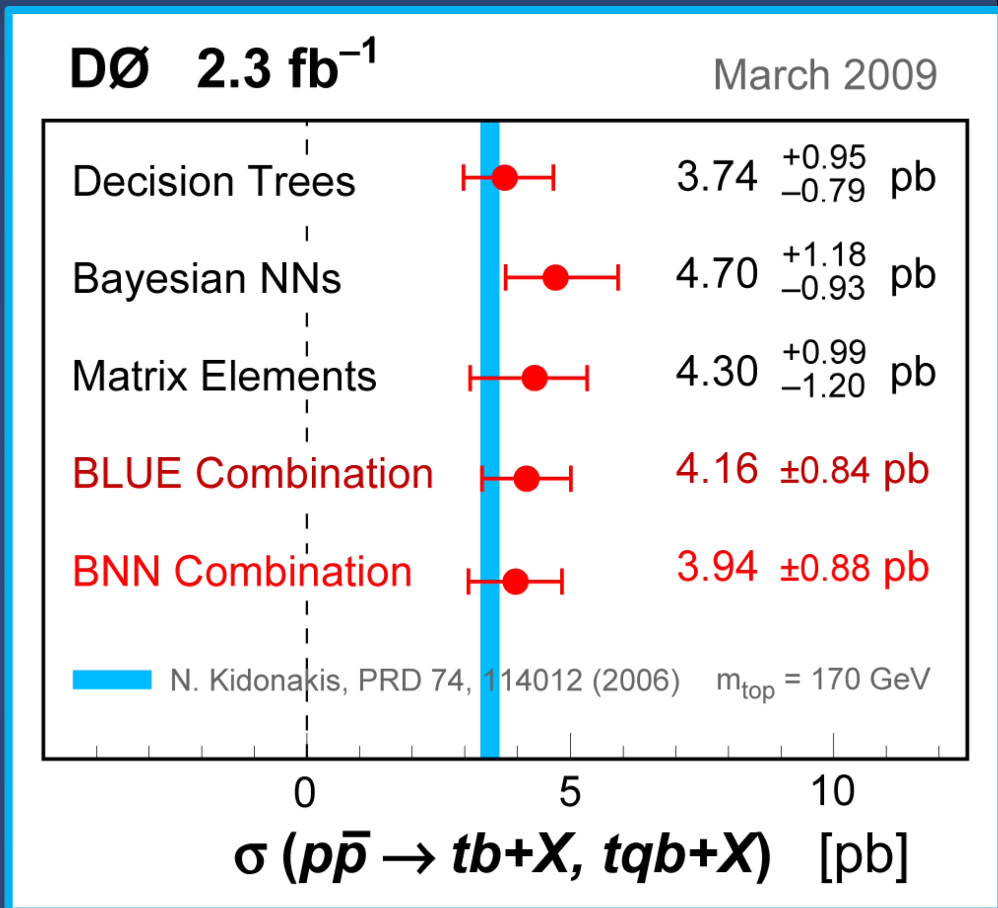




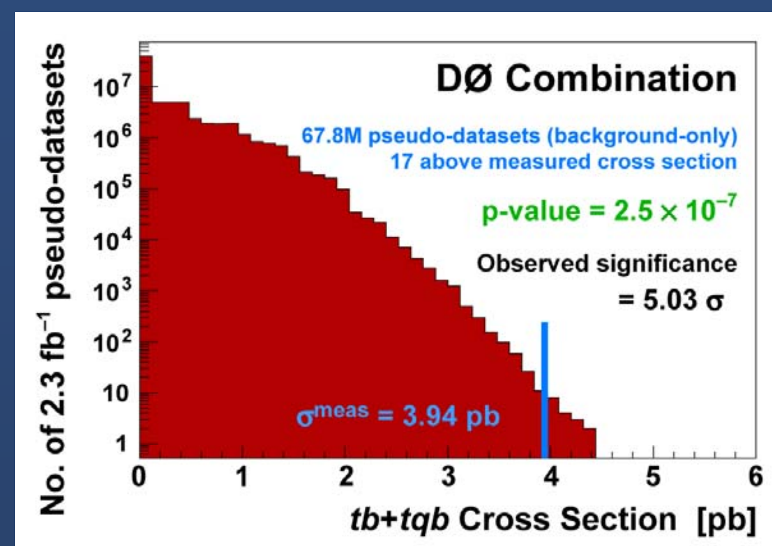




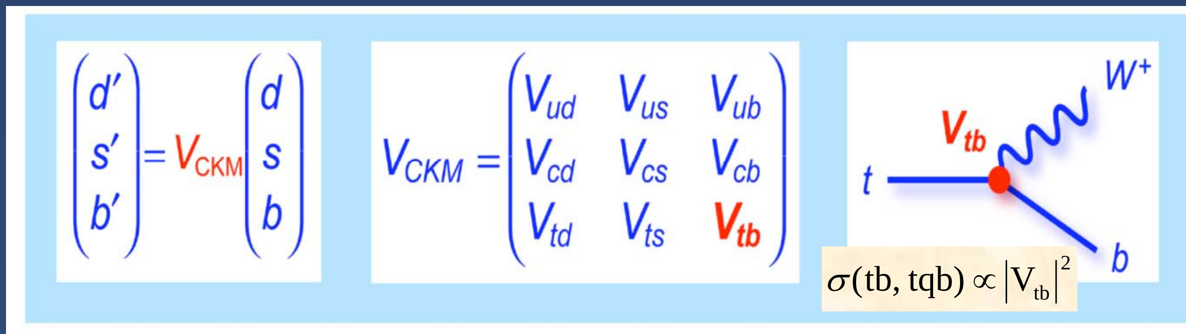
Cross Section Summary



MVA	ExpectedSignif.	Observed Signif.
BDT	4.3σ	4.6 σ
BNN	4.1σ	5.2 σ
ME	4.1σ	4.9 σ
BNNComb	4.5σ	5.0 σ



CKM Matrix Element Vtb



Additional Systematic Uncertainties for the $|V_{tb}|$ Measurement

DØ 2.3 fb^{-1}

For the *tb+tqb* theory cross section	
Top quark mass	4.2%
Parton distribution functions	3.0%
Factorization scale	2.4%
Strong coupling α_s	0.5%

- Weak interaction eigenstates and mass eigenstates are not the same: there is mixing between quarks, described by CKM matrix
- General form of the Wtb vertex

$$\Gamma^{\mu}_{Wtb} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \left[f_1^L P_L + f_1^R P_R \right] - \frac{i\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \left[f_2^L P_L + f_2^R P_R \right] \right\}$$

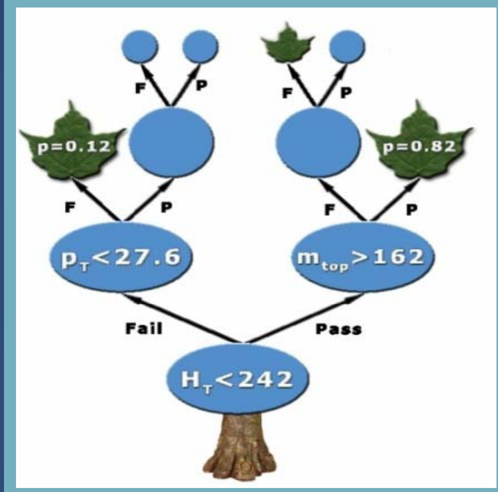
- Measurement assumes SM production mechanisms
- Pure V–A and CP-conserving interaction ($f_1^R = f_2^L = f_2^R = 0$)
- f_1^L : strength of the left-handed Wtb coupling, is allowed to be anomalous
- $|V_{td}|^2 + |V_{ts}|^2 << |V_{tb}|^2$ (supported by CDF & DØ “ratio” measurements)
- Does not assume 3 generations or unitarity of the CKM matrix

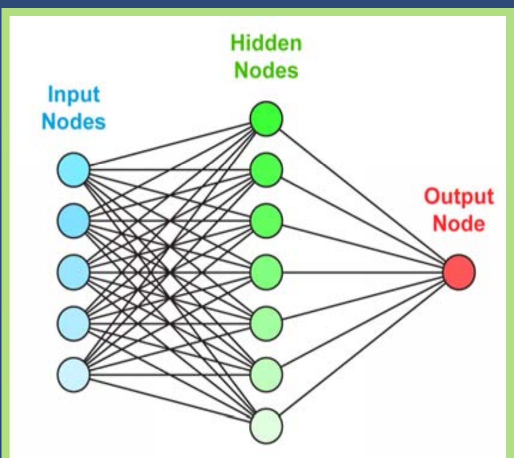
Multivariate Analyses: BDT & BNN

Use common Object and Event Kinematics, Angular Correlations, Jet Reconstruction and Top Quark Reconstruction variables

Boosted Decision Trees (BDT)

- Recover events that fail criteria in cut-based analysis
- Boosting averages the results over many trees, improving the performance
- Uses highest ranked common 64 variables





Bayesian Neural Network (BNN)

- NN train on signal and background, producing one output discriminant
- Bayesian NN average over many networks, improving the performance
- Uses highest ranked 18-28 variables in each channel

Matrix Element (ME)

- Method pioneered by DØ for the top quark mass measurement in Run I
- Use the 4-vectors of all reconstructed leptons and jets
- Use Feynman diagrams to compute an event probability density for signal and background hypotheses

differential cross section (LO matrix element)

parton distribution functions

transfer function: mapping from parton-level variables (y) to reconstruction-level variables (x)

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

Calculate a discriminant using above probability:

$$D_S(\vec{x}) = \frac{P_S(\vec{x})}{P_S(\vec{x}) + P_{bckg}(\vec{x})}; \qquad S = tb \text{ or } tqb$$

- Uses events with 2 and 3 jets only
- Split the sample in high and low H_T