



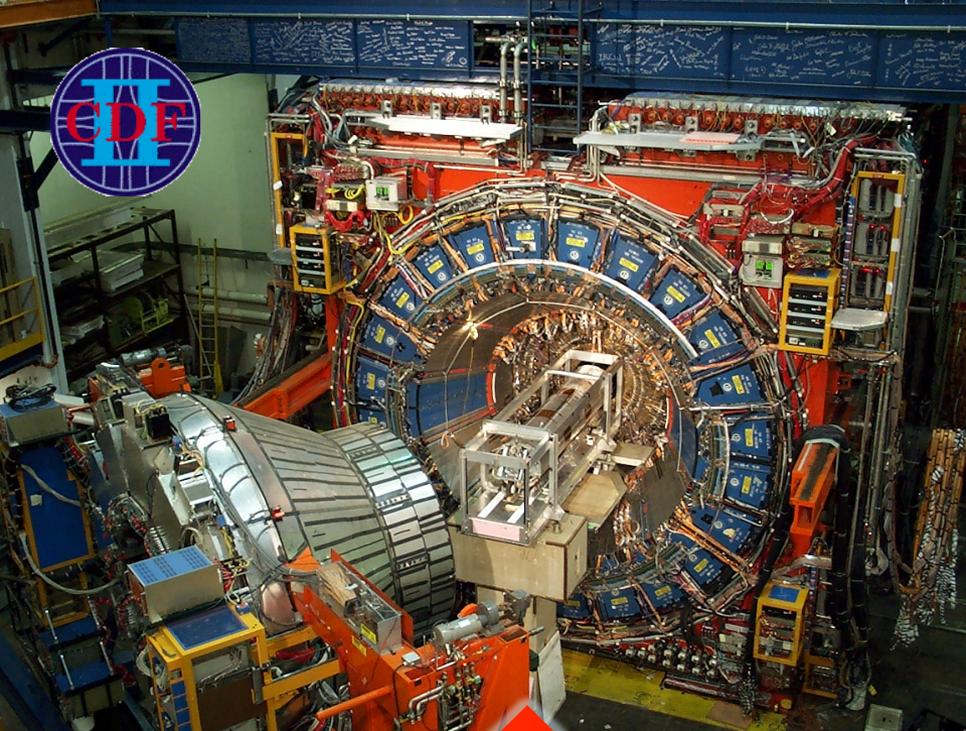
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DE GENÈVE

FACULTÉ DES SCIENCES

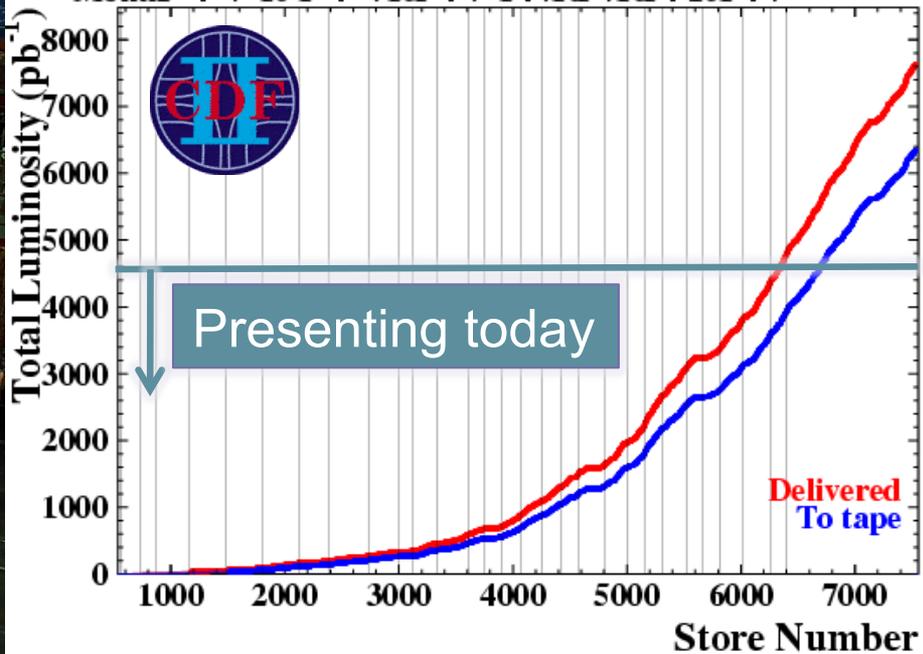
# LATEST RESULTS FROM TOP PRODUCTION AT THE TEVATRON



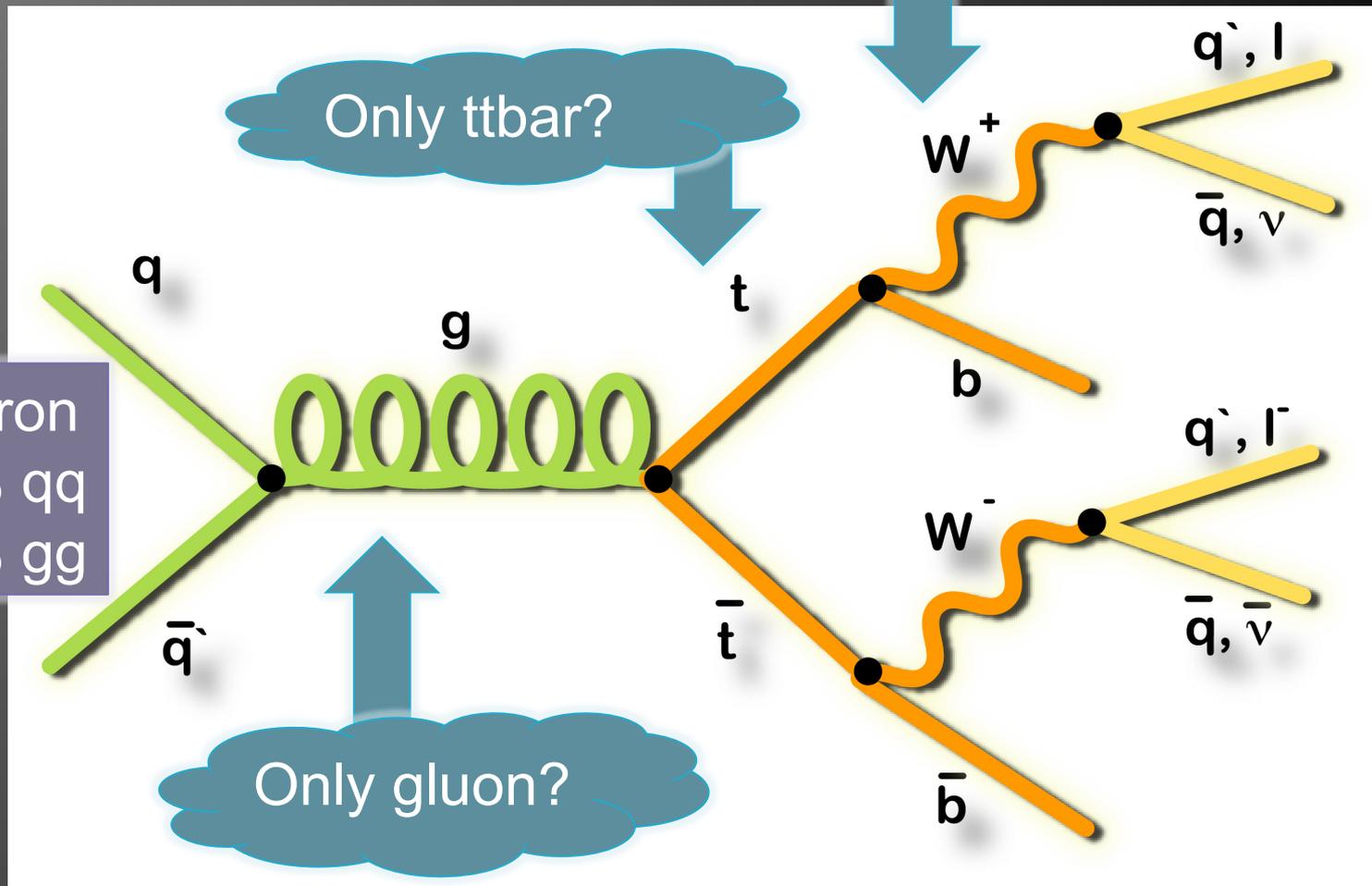
Alison Lister  
Université de Genève  
On behalf of the D0 and CDF collaborations



Year 2002 2003 2004 2005 2006 2007 2008 2009  
 Month 4 7 10 1 4 7 10 1 4 7 10 1 4 7 10 1 4 7



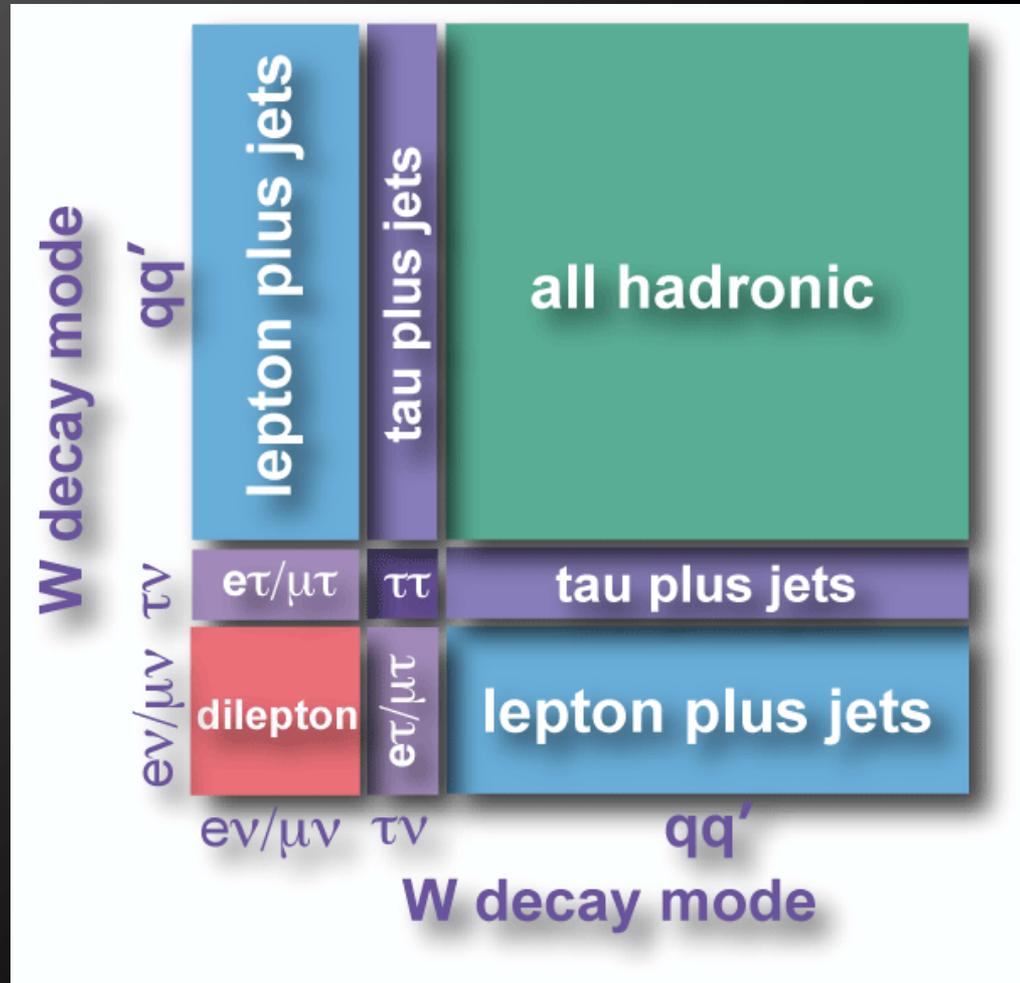
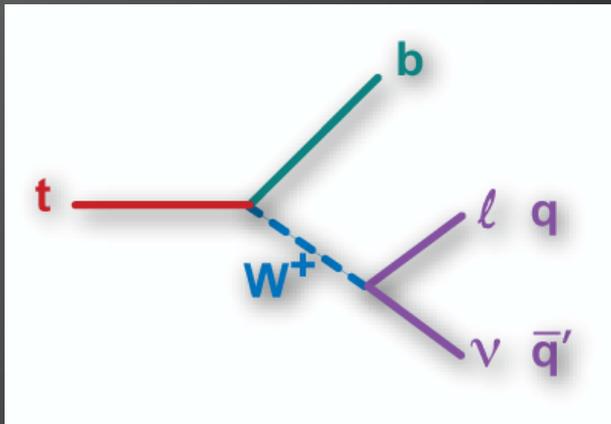
# Top Physics



Goal is to measure the top quark as precisely as possible at the Tevatron  
Get a complete a picture of the heaviest quark?  
Signs of weakness of the SM?

# Top Event Decays

- Standard Model  
BR( $t \rightarrow Wb$ )  $\sim 100\%$
- Top events are characterised by the decay of the W boson



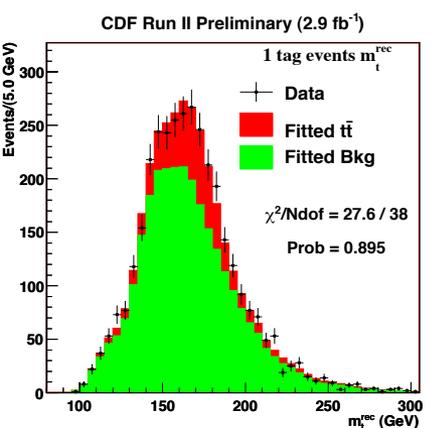
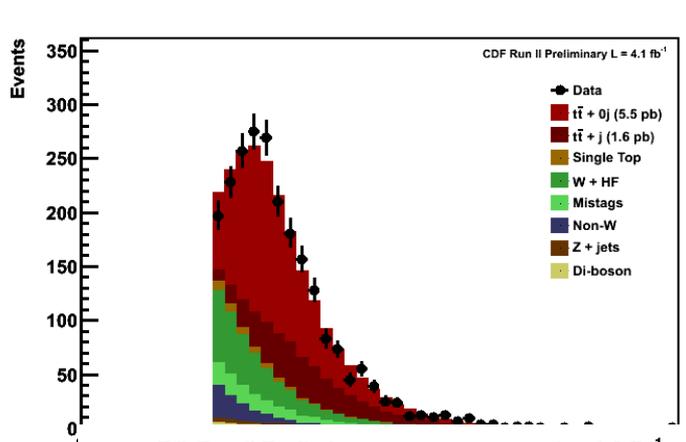
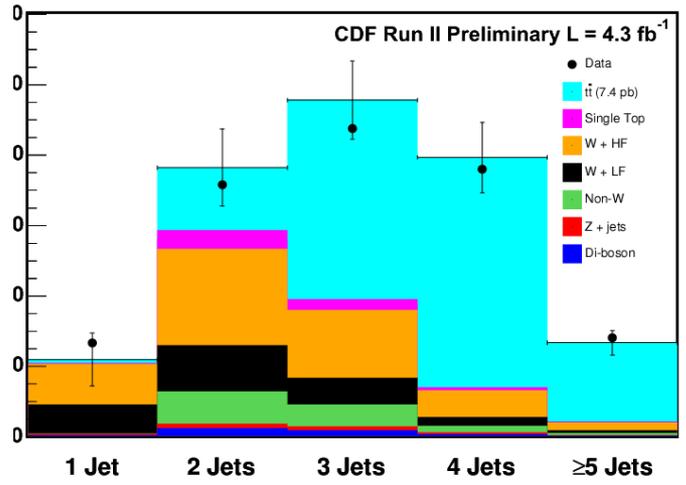
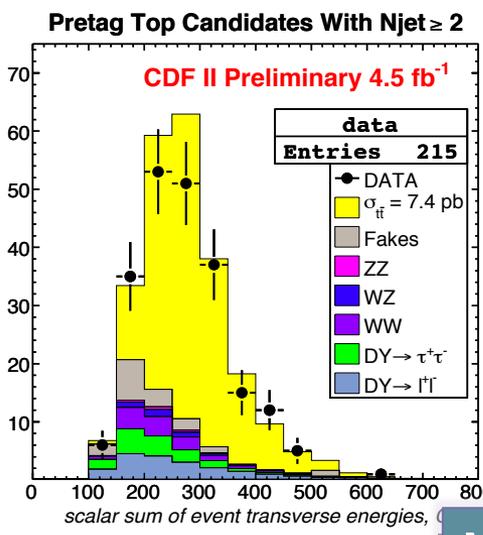
“Leptons” are only electrons and muons

# TOP QUARK PAIR PRODUCTION CROSS SECTION

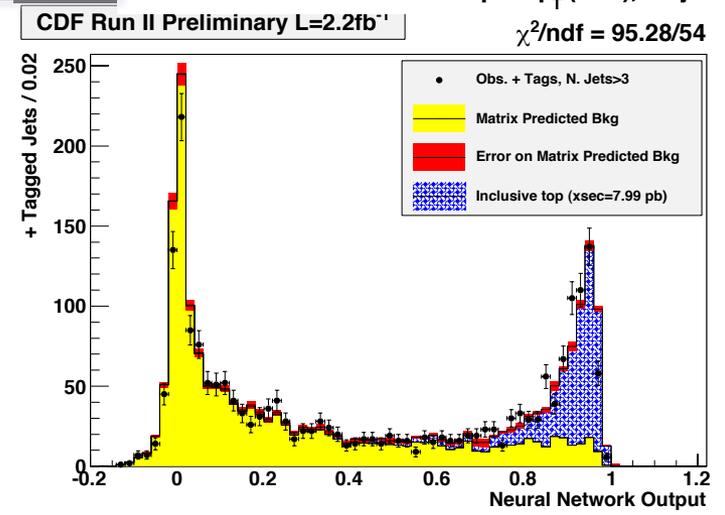
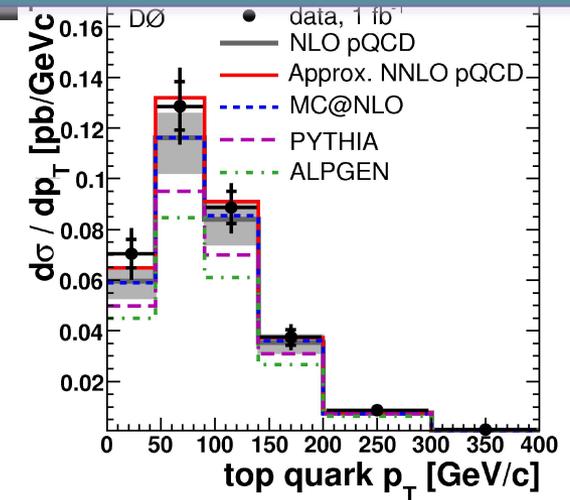
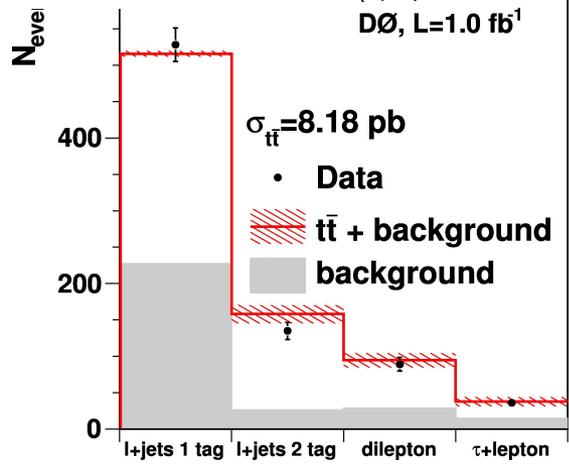
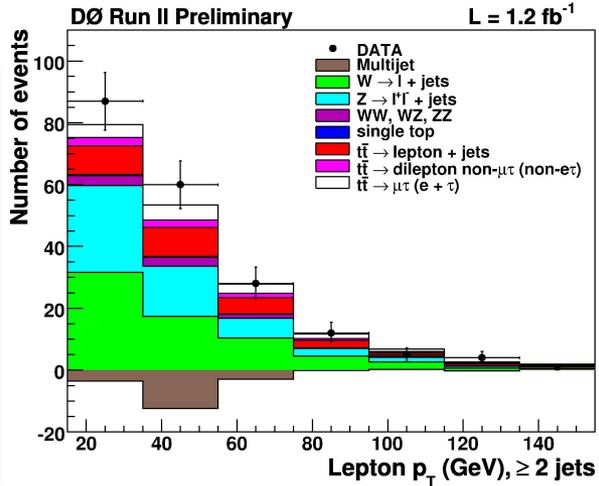
$$\sigma_{t\bar{t}} = \frac{N_{data} - N_{bck}}{\epsilon \cdot A \cdot L}$$

Measurements differ in

- W-decay channel
- Analysis cuts
- Background composition
- Background estimation methods
- Luminosity determination



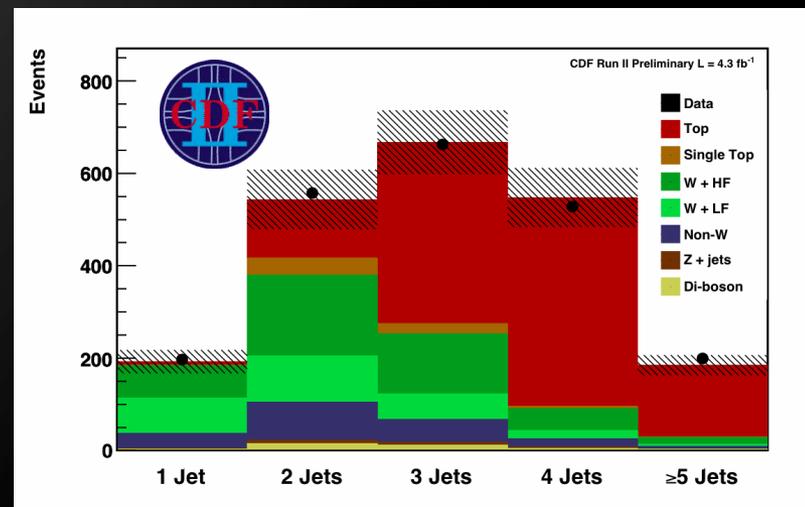
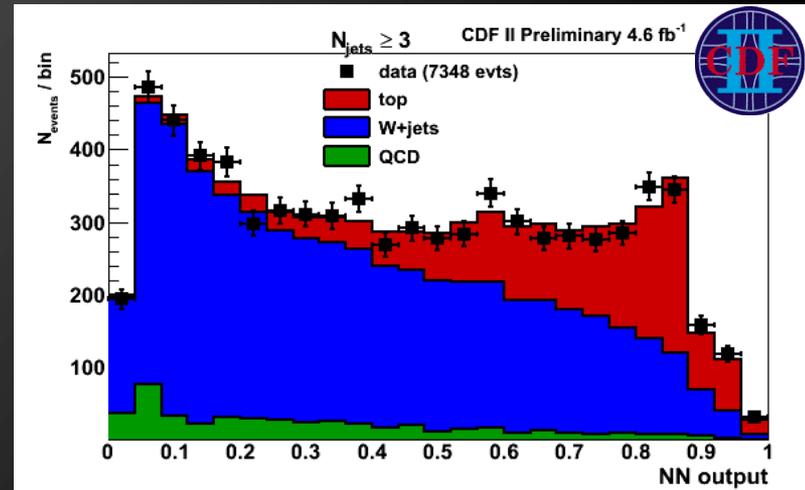
Many more new analyses than I have the time to present...  
18 CDF top publications in 2009 (60 total)  
33 analyses to conferences...  
Similar numbers for D0



# Lepton+Jets 4.3 fb<sup>-1</sup>

- 2 CDF analyses
  - Kinematic Neural Network (NN) fit
  - ≥1 b-tagged jet
- Luminosity determination is dominant uncertainty (~ 6%)
- Take ratio of  $\sigma_{t\bar{t}} / \sigma_Z$ 
  - Z measured using same runs, lepton ID, trigger as tbar
- Multiply by theoretical  $\sigma_Z^{\text{theory}}$ 
  - 2% uncertainty

Total uncertainty: 7.9% / 9.5%



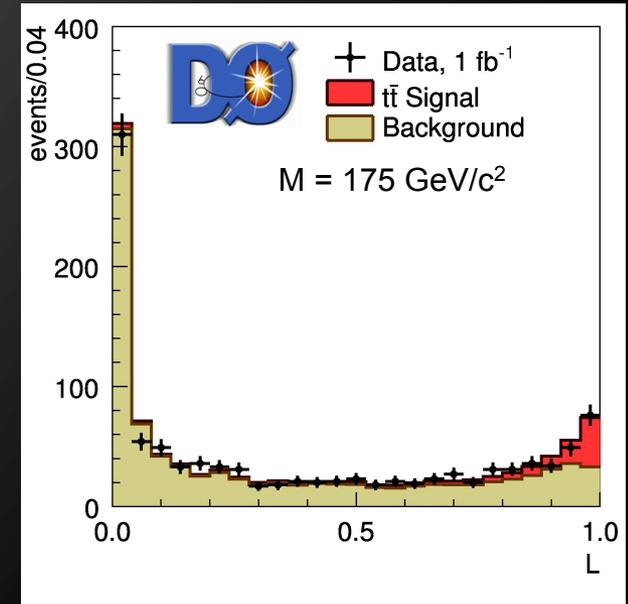
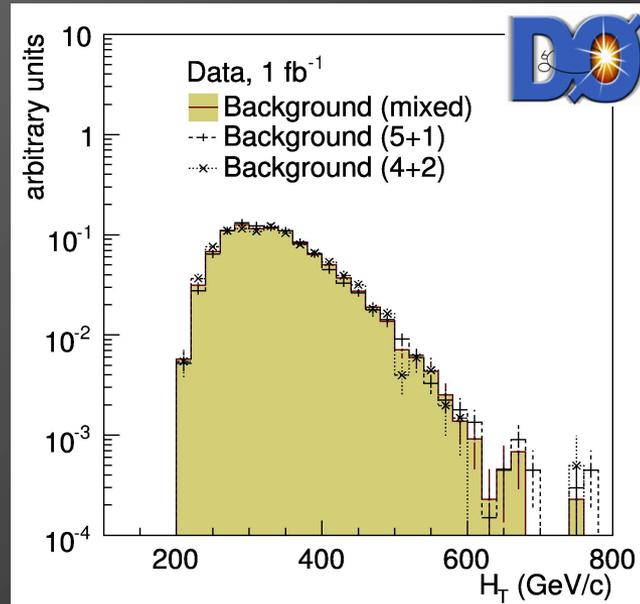
$$\sigma_{t\bar{t}}^{\text{kin}} (172.5 \text{ GeV}/c^2) = 7.6 \pm 0.4(\text{stat}) \pm 0.4(\text{syst}) \pm 0.2(\text{z theory}) \text{ pb}$$

$$\sigma_{t\bar{t}}^{\text{btag}} (172.5 \text{ GeV}/c^2) = 7.1 \pm 0.3(\text{stat}) \pm 0.6(\text{syst}) \pm 0.1(\text{z theory}) \text{ pb}$$

# All Jets 1 fb<sup>-1</sup>

- $\geq 6$  high  $p_T$  jets

- 2 identified b-jets
- S:B ~ 1:7



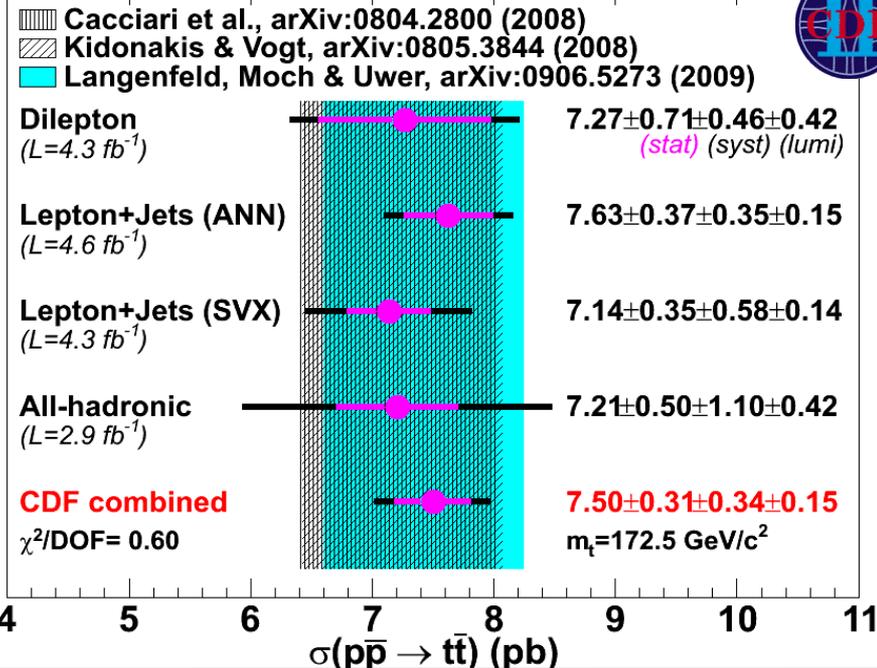
- Main background: multijet events

- Estimated from data with events with 4 jets (2 tags) + attach low  $p_T$  jets from events with 4-5 jets to match data

- Fit likelihood discriminant

$$\sigma_{tt}^{170 \text{ GeV}/c^2} = 7.9 \pm 1.5(\text{stat}) \pm 1.6(\text{syst}) \pm 0.5(\text{lumi}) \text{ pb}$$
$$\sigma_{tt}^{175 \text{ GeV}/c^2} = 6.9 \pm 1.3(\text{stat}) \pm 1.4(\text{syst}) \pm 0.4(\text{lumi}) \text{ pb}$$

$$M_t = 172.5 \text{ GeV}/c^2$$



- Account for statistical and systematic correlations between results

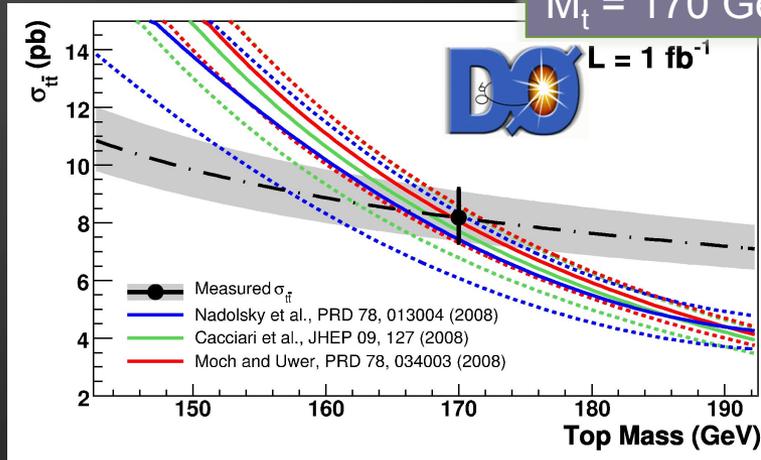
Relative uncertainty 6.4%

$$\sigma_{tt}^{\text{CDF}} = 7.50 \pm 0.48 \text{ pb}$$

All measurements compatible with each other and with SM

# Combinations

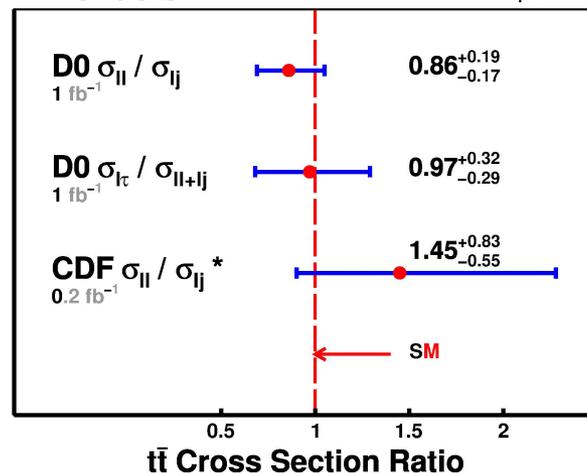
$$M_t = 170 \text{ GeV}/c^2$$



- Combine lj, ll, lt in 1 fb<sup>-1</sup>

$$\sigma_{tt}^{\text{D0}} = 8.18^{+0.98}_{-0.87} \text{ pb}$$

Tevatron



# SINGLE TOP QUARK PRODUCTION

# Why Only Now?

## Timeline

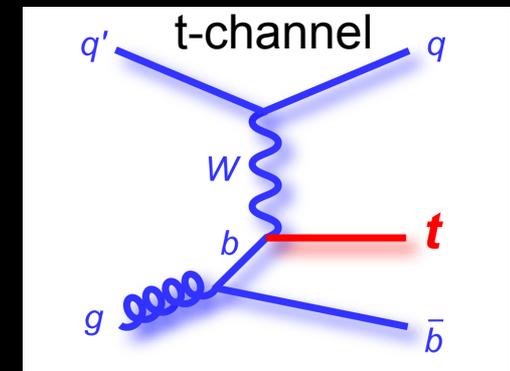
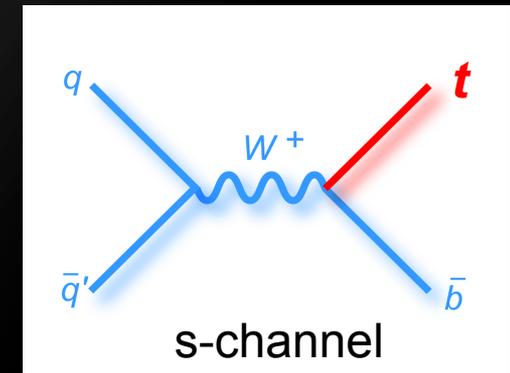
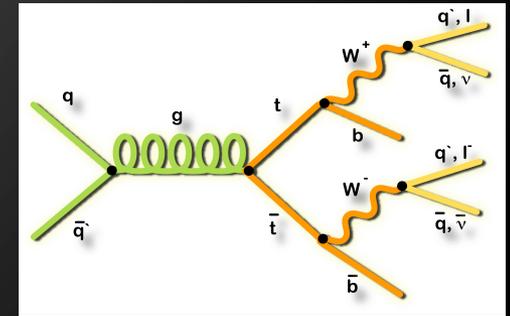
- 1995: top quark discovered
- 2007: evidence for single top ( $0.9-2.2 \text{ fb}^{-1}$ )
- 2009: observation of single top ( $2.3-3.2 \text{ fb}^{-1}$ )

## $t\bar{t}$ pairs

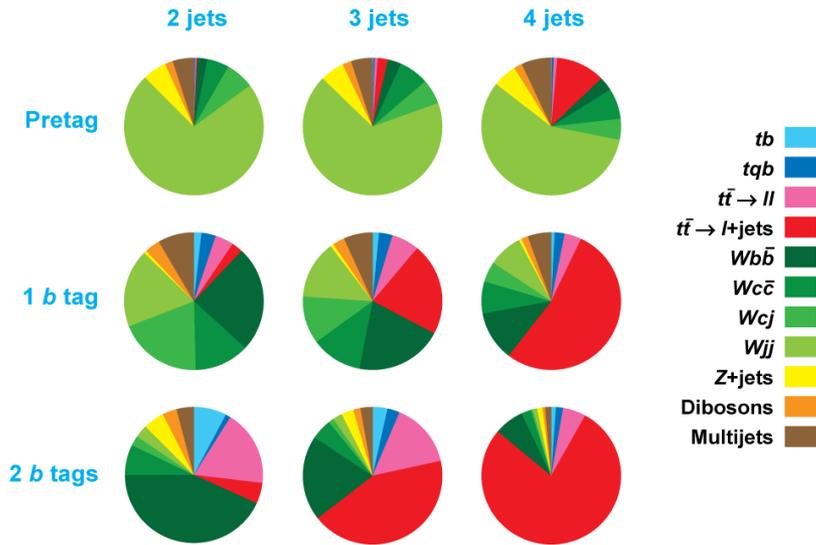
- $\sigma_{t\bar{t}} = 7.5 \text{ pb}$  (@  $M_t = 172.5 \text{ GeV}/c^2$ )
- Strong production
- Signal to background  $\sim 1:3$  using b-tagging

## single top

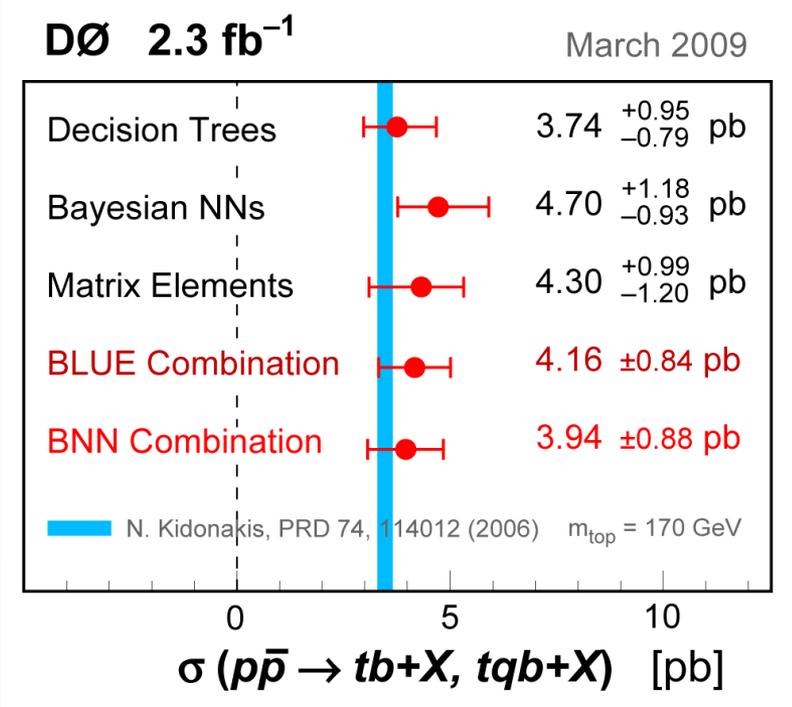
- $\sigma_{\text{tt}} = 3.5 \text{ pb}$  (@  $M_t = 170 \text{ GeV}/c^2$ )
- Charged electroweak production only
- Large backgrounds
  - W+jets
  - $t\bar{t}$
  - Multijet
- Signal to background  $\sim 1:20$



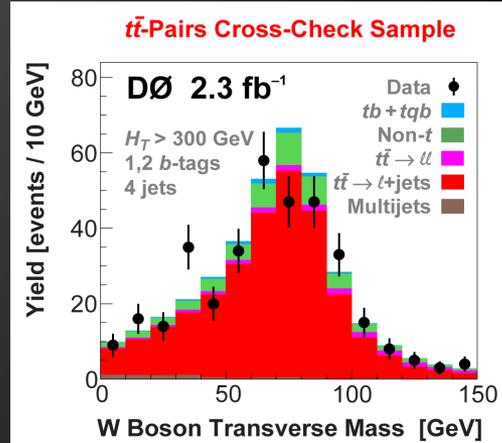
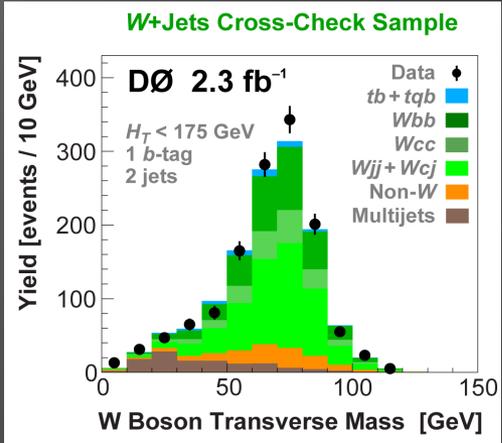
# DØ Single Top 2.3 fb<sup>-1</sup> Signals and Backgrounds



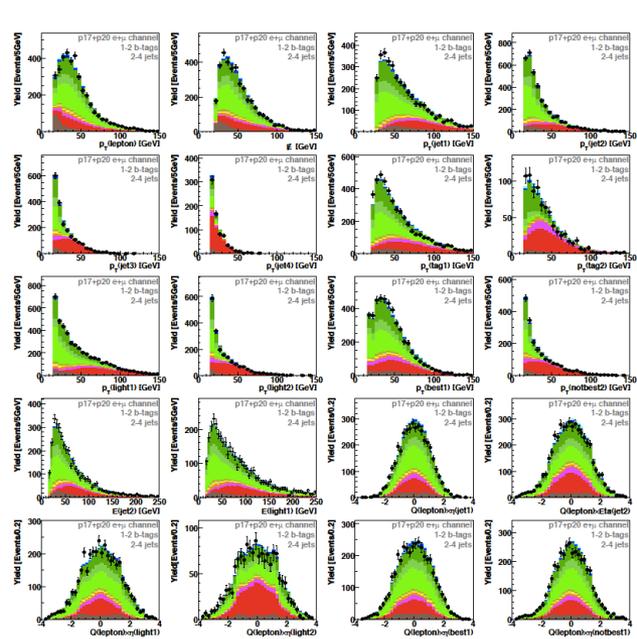
24 independent analysis channels



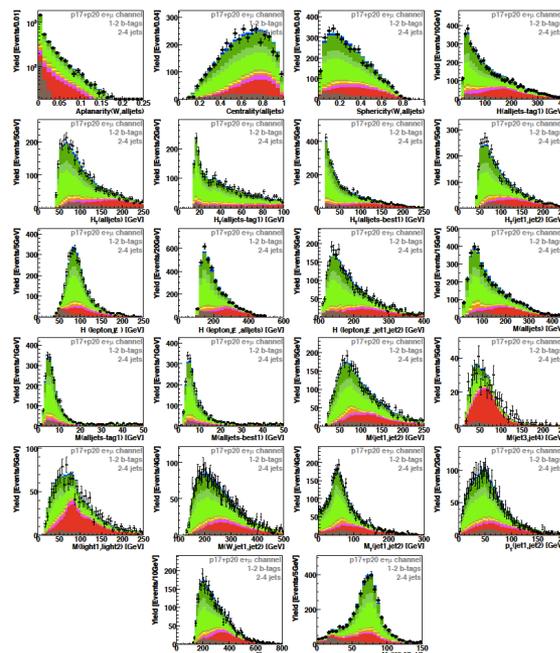
Many many cross-checks...



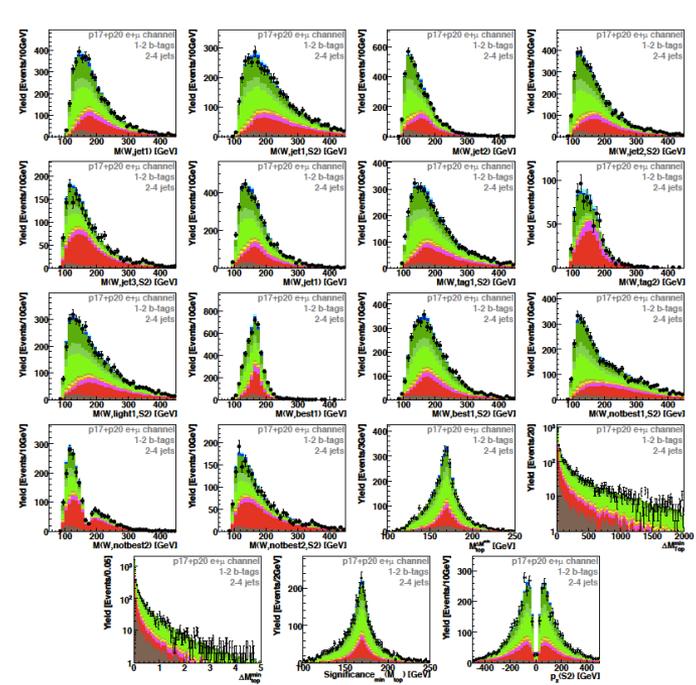
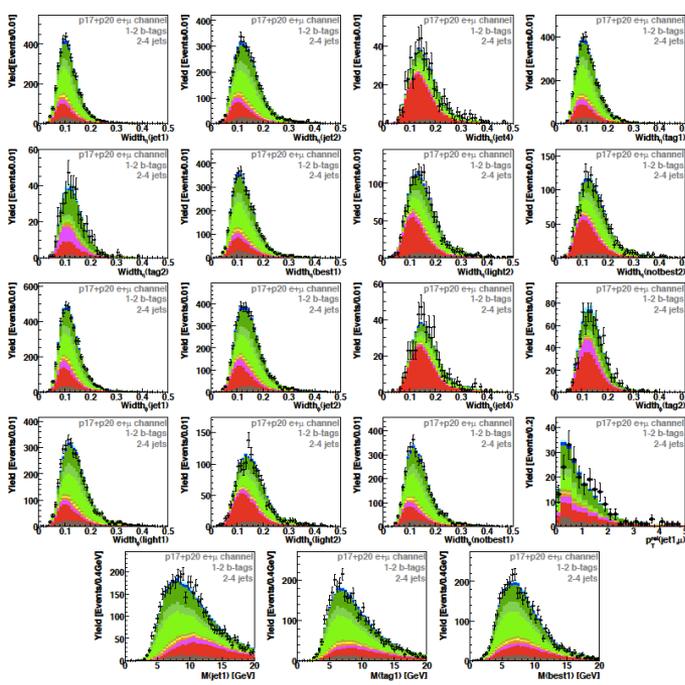
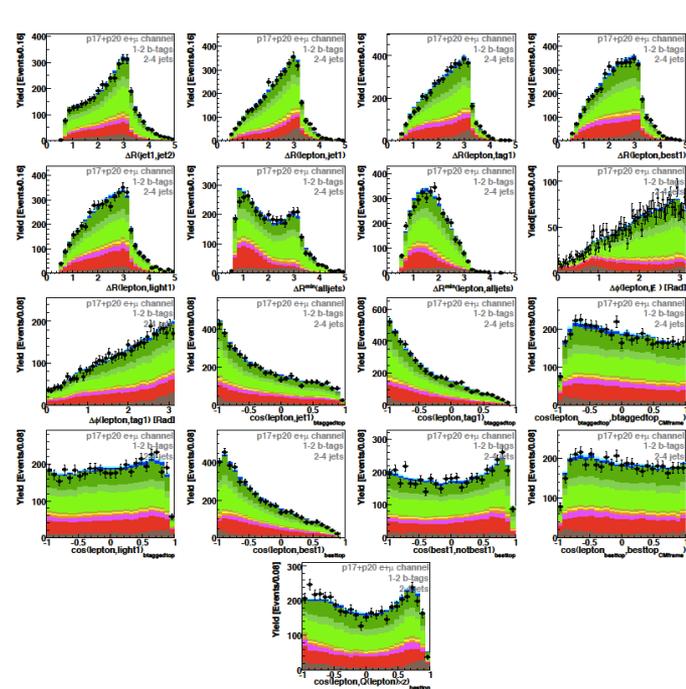
Even one analysis looking at τ + jets channel



JET RECONSTRUCTION

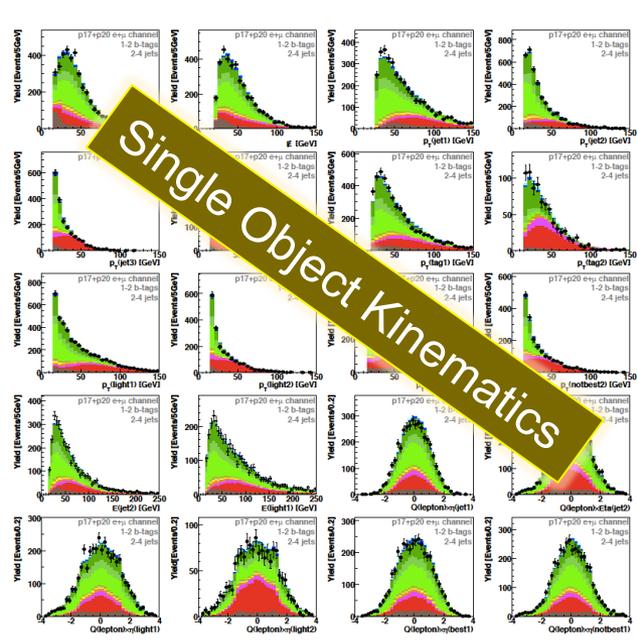


TOP QUARK RECONSTRUCTION

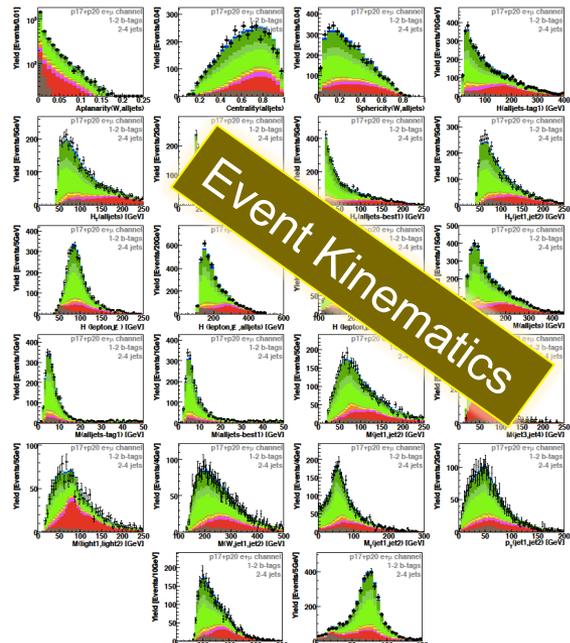


- $tb$
- $tqb$
- $Wb\bar{b}$
- $Wc\bar{c}$
- $Wjj$
- $Zb\bar{b}$
- $Zc\bar{c}$
- $Zjj$
- Dibosons
- $t\bar{t} \rightarrow \mu\mu$

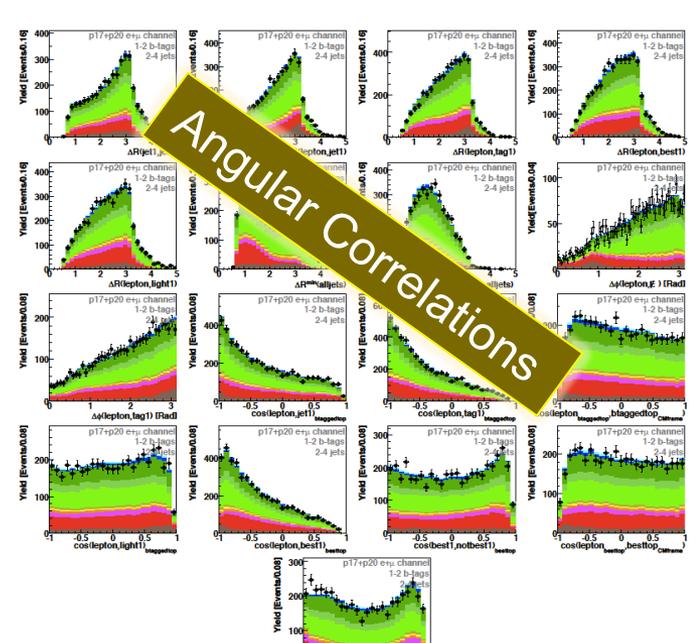
97 Variables  
used in Boosted  
Decision Tree  
and Bayesian  
NN



Single Object Kinematics

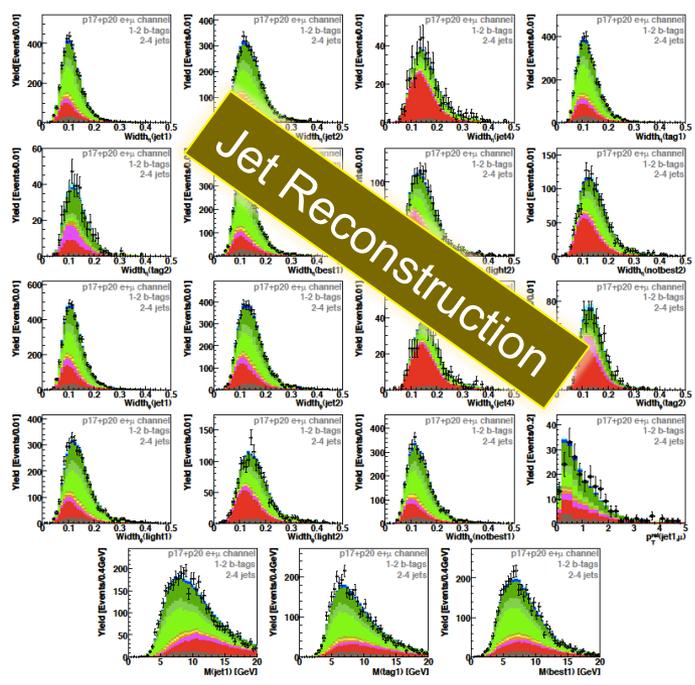


Event Kinematics



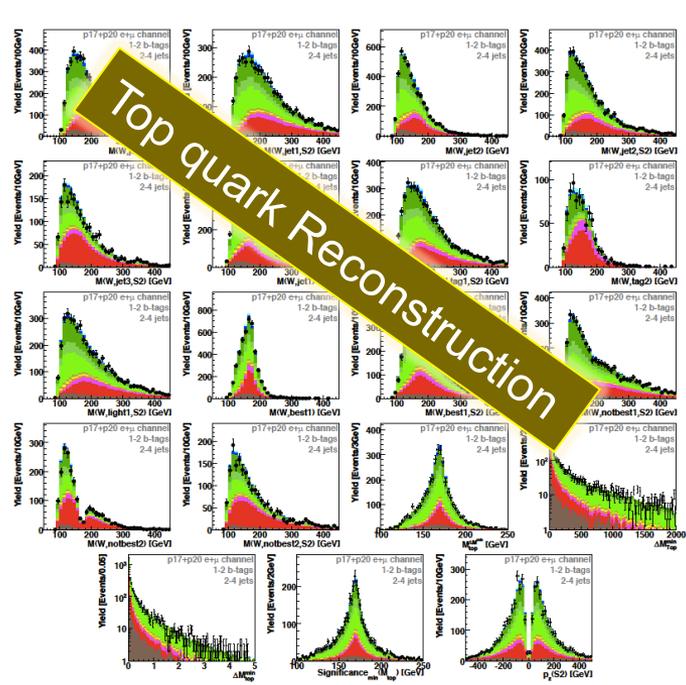
Angular Correlations

JET RECONSTRUCTION



Jet Reconstruction

TOP QUARK RECONSTRUCTION



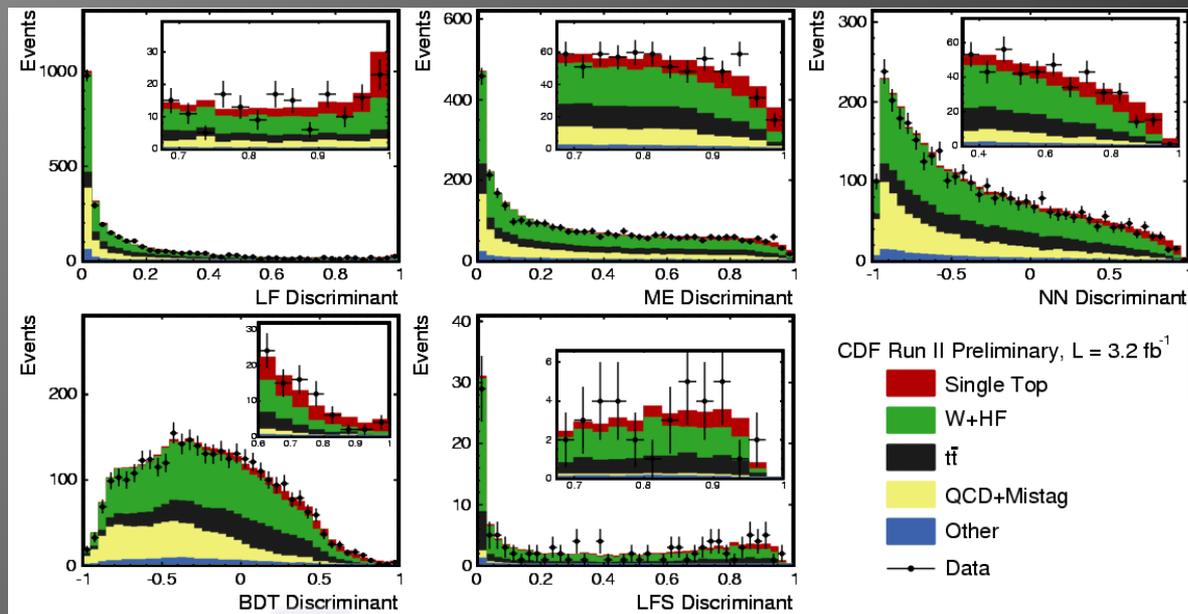
Top quark Reconstruction

- $tb$
- $tqb$
- $Wb\bar{b}$
- $Wc\bar{c}$
- $Wjj$
- $Zb\bar{b}$
- $Zc\bar{c}$
- $Zjj$
- Dibosons
- $t\bar{t} \rightarrow ll$
- $t\bar{t} \rightarrow l+jets$
- Multijets



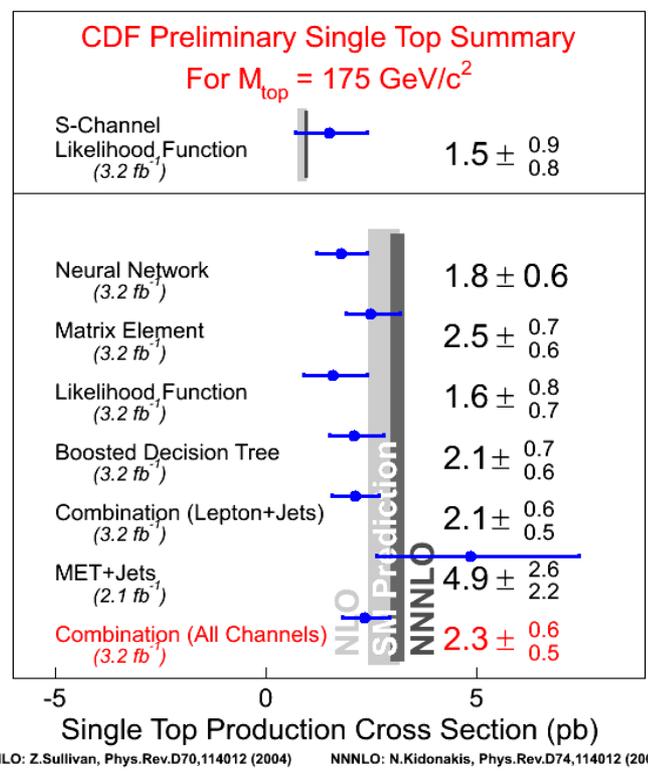
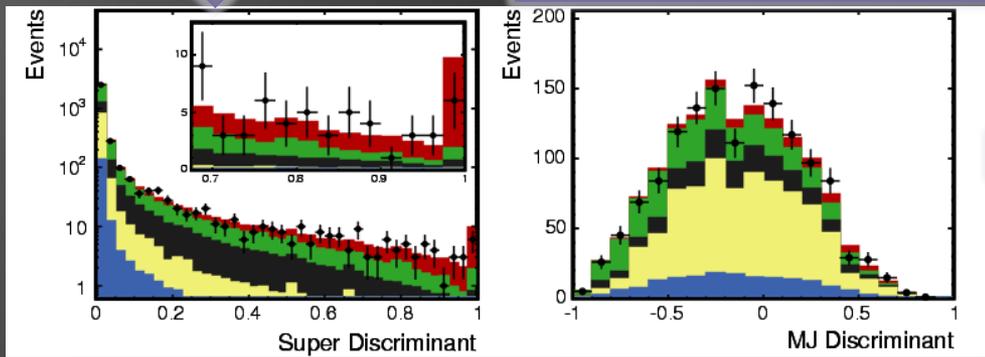


16% better significance than single best analysis



5 Lepton+jets analyses combined

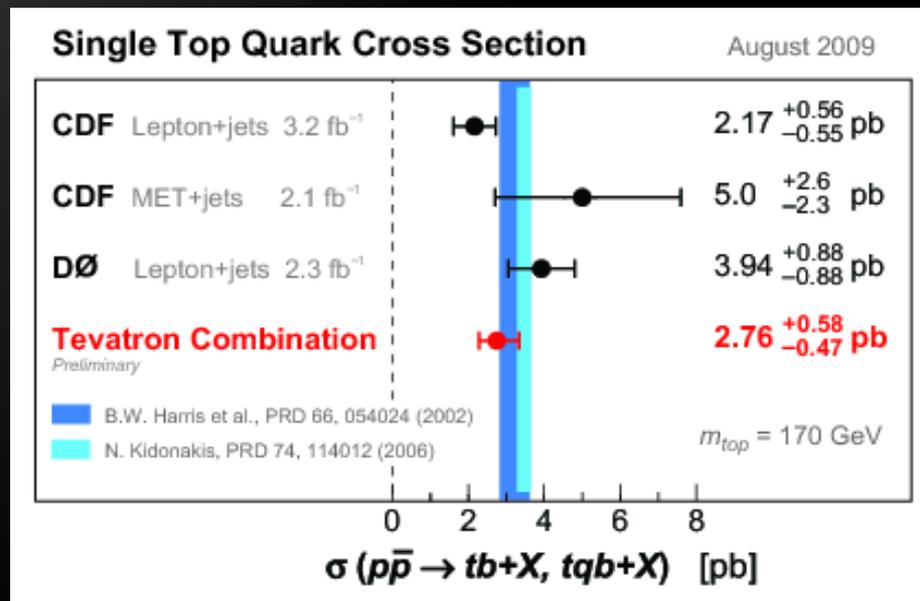
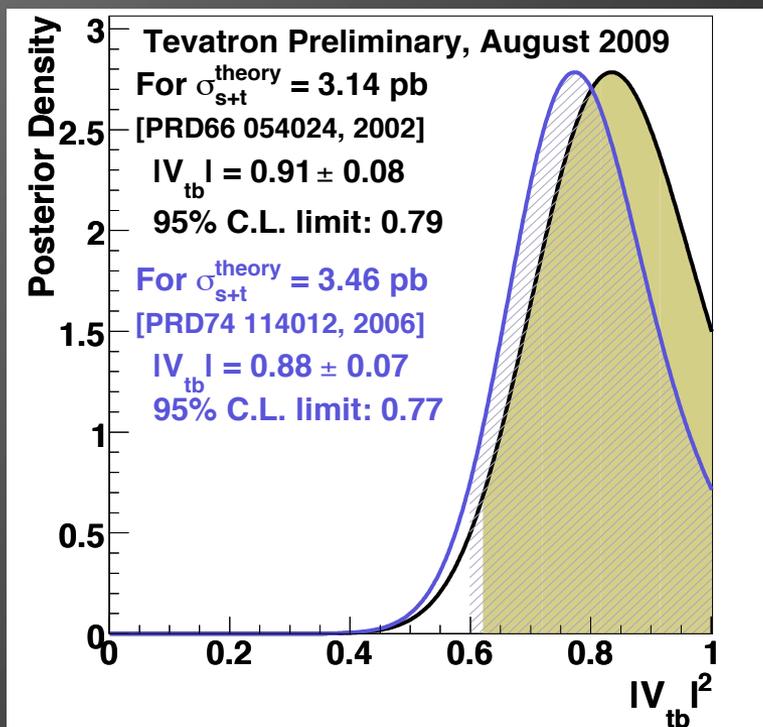
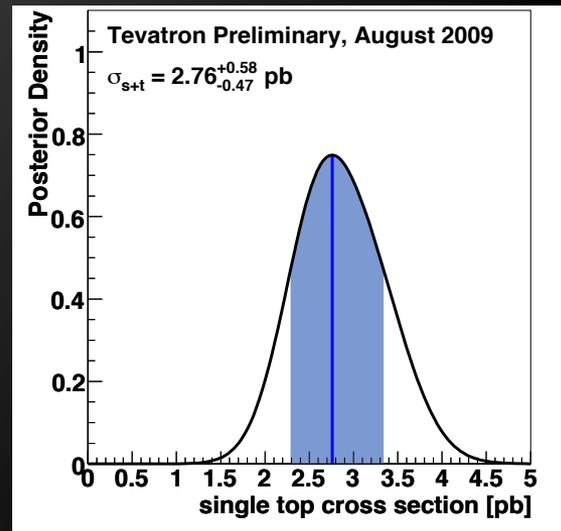
add Missing E<sub>T</sub> + jets



$|V_{tb}| = 0.91 \pm 0.11$  (exp.)  $\pm 0.07$  (theory)

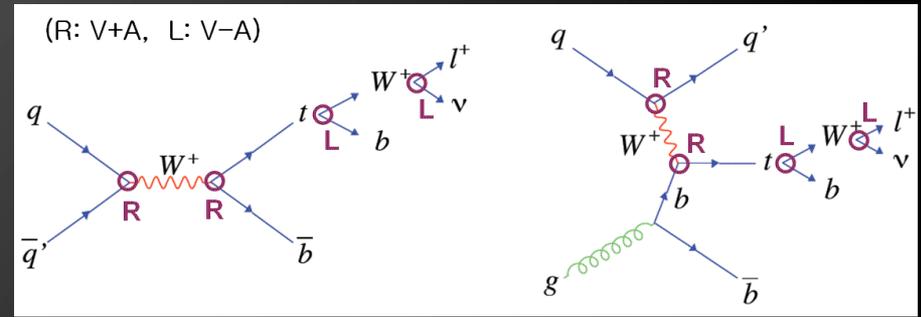
# First Tevatron Single Top Combination

- Bayesian analysis from distributions of multivariate discriminants from each collaboration
- Results compatible with SM predictions



# Single Top Polarization 3.2 fb<sup>-1</sup>

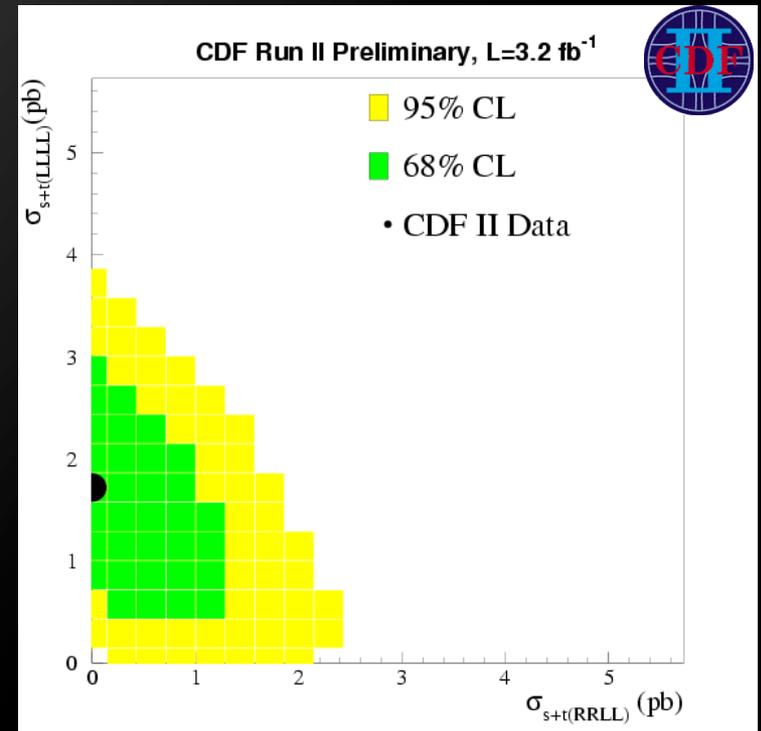
- Weak charged current maximally violates parity (V-A)
  - Top quarks produced almost 100% polarized
  - Remain polarized when they decay
- Measure polarization of single top to study de-polarization effects and non-SM mechanisms
- Use  $\cos\theta_{ij}$  in top quark reference frame for fit to cross sections for SM and RRLL



$$\sigma_t^{\text{SM}} = 1.72 \text{ pb}$$

$$\sigma_{tt}^{\text{RRLL}} = 0.00 \text{ pb}$$

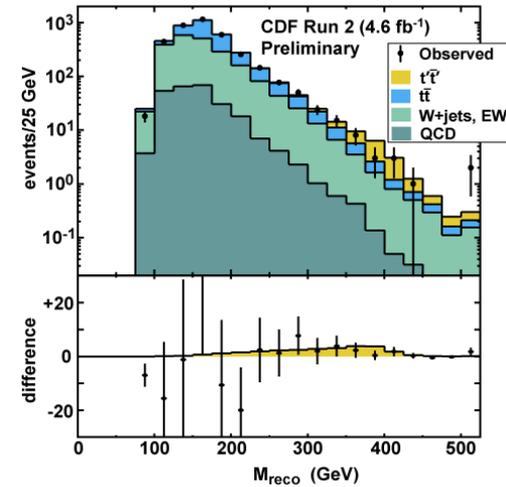
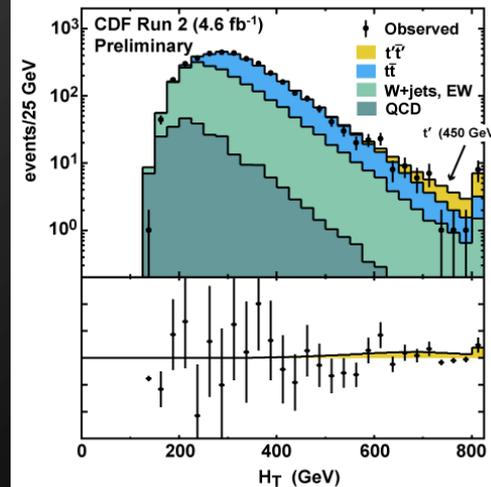
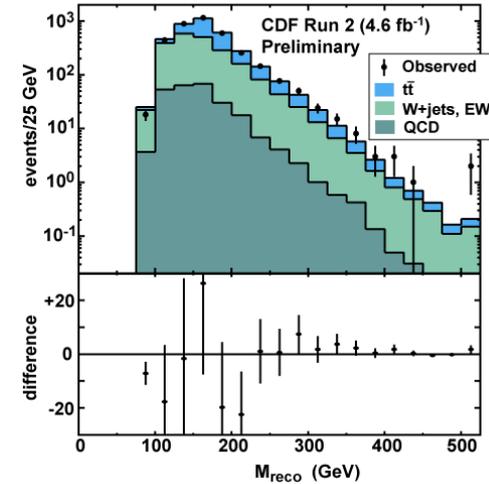
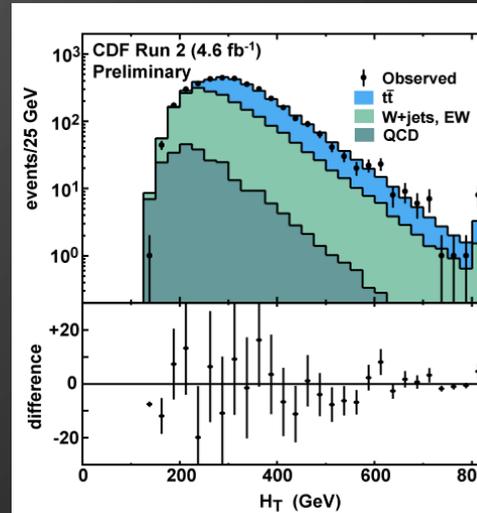
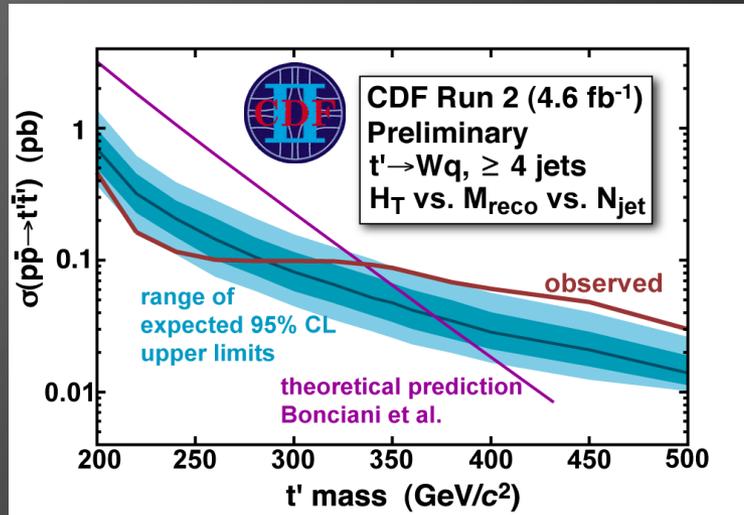
$$P = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -1_{-0}^{+1.5}$$



# SEARCHES IN THE TOP SECTOR

# Search for 4<sup>th</sup> Generation Top-Like Quark

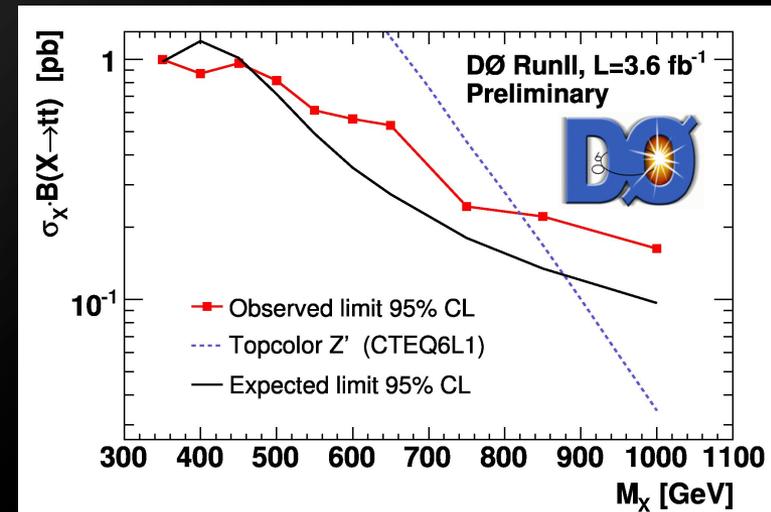
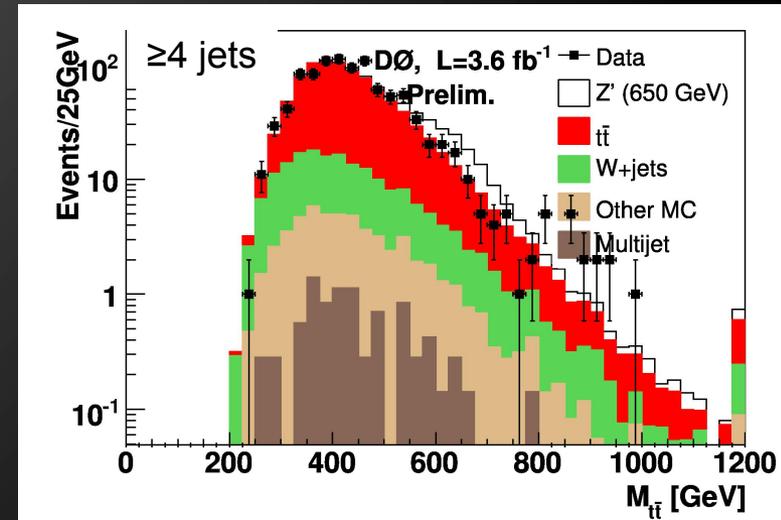
- $t'$  strong pair production
- Small mass splitting  $t'$  to  $b'$ 
  - $t'$  decays mostly to  $Wb$
- Lepton + jets channel
- 2D likelihood fit
  - Total reconstructed Energy ( $H_T$ )
  - Reconstructed top Mass ( $M_{reco}$ )



Assuming 100% BR to  $Wq$ : Exclude  $M_{t'} < 335 \text{ GeV}/c^2$

# ttbar Resonance Searches

- Lepton + jets channel
  - $\geq 1$  b-tagged jet
- Search for narrow resonances
  - Less than D0 detector resolution
- Reconstruct invariant mass of ttbar pair
- No significant deviation from Standard Model observed
- Use Bayesian flat priors to calculate 95% CL on  $\sigma \cdot \text{BR}(X \rightarrow \text{ttbar})$
- Place limits on top-color assisted technicolor [*hep-th/9911288*]
  - Leptophobic  $Z'$



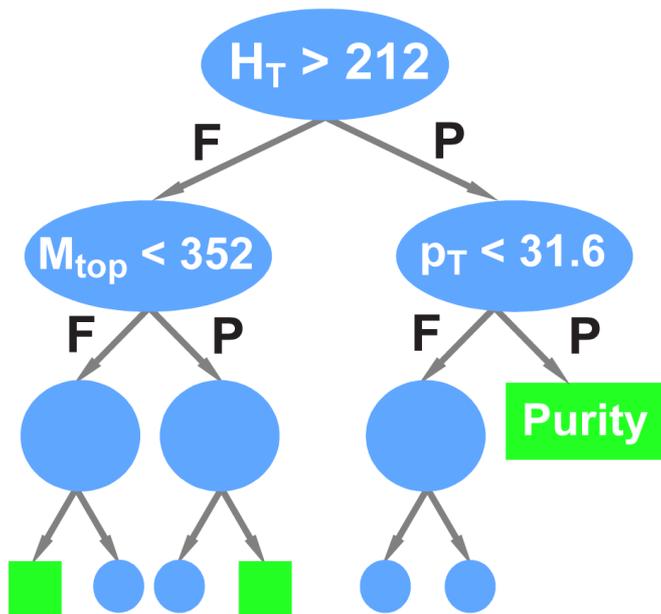
Exclude  $M_{Z'} < 820 \text{ GeV}/c^2$

# Conclusions And Outlook

- Many precision top quark measurements being carried out at the Tevatron
- All measurements are consistent with the Standard Model ... so far...
- Some of these measurements will be hard to beat at the LHC
  - Don't want to make their life too easy ☺
  - $V_{tb}$  and mass in particular...
- More exciting top results in next talk...

# BACKUP

## Boosted Decision Trees

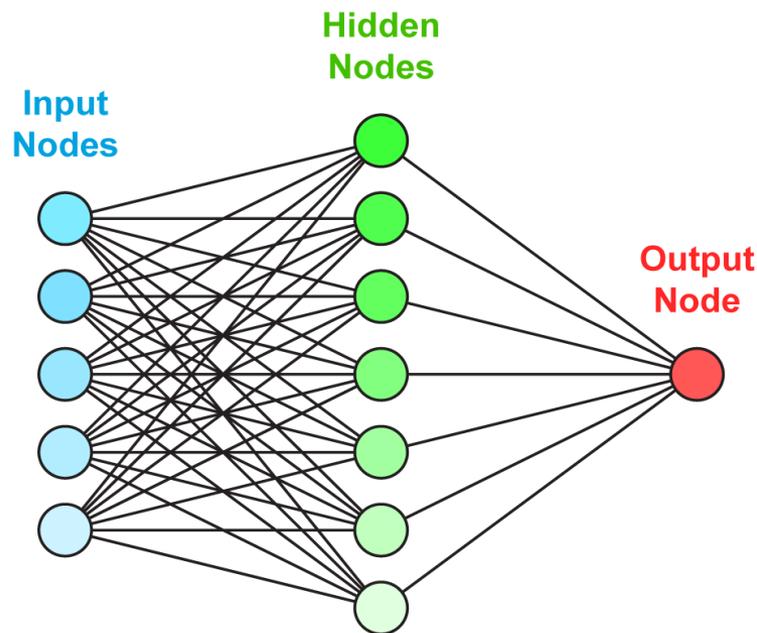


A decision tree applies sequential cuts to the events but does not reject events that fail the cuts. Boosting averages the results over many trees.

The most important part of a boosted decision tree analysis is the choice of variables.

D0: Uses 64 Variables

## Bayesian (or Artificial) Neural Networks



A neural network is trained on signal and background samples to obtain weights between the network nodes and thresholds at the nodes. Bayesian neural networks average over a large number of such networks to improve the performance. The most important part of a Bayesian neural network analysis is the choice of variables.

D0: Uses 18-28 Variables

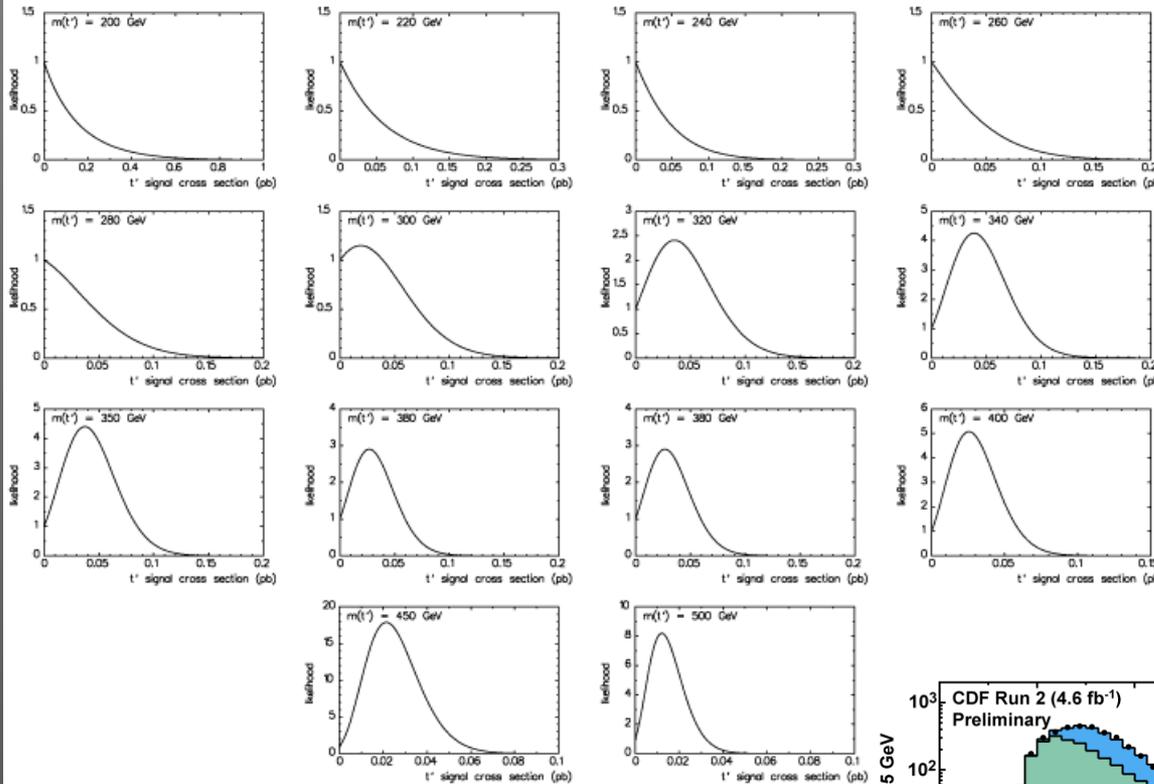
# Matrix Elements

Matrix Elements used to Separate Single Top Signal from Background DØ 2.3 fb <sup>-1</sup>			
2 Jets		3 Jets	
$t\bar{b}$	$u\bar{d} \rightarrow t\bar{b}$	$t\bar{b}g$	$u\bar{d} \rightarrow t\bar{b}g$
$tq$	$ub \rightarrow td$ $d\bar{b} \rightarrow t\bar{u}$	$tqg$	$ub \rightarrow tdg$ $d\bar{b} \rightarrow t\bar{u}g$
		$tq\bar{b}$	$ug \rightarrow t\bar{d}\bar{b}$ $\bar{d}g \rightarrow t\bar{u}\bar{b}$
$Wb\bar{b}$	$u\bar{d} \rightarrow Wb\bar{b}$	$Wb\bar{b}g$	$u\bar{d} \rightarrow Wb\bar{b}g$
$W\bar{c}g$	$\bar{s}g \rightarrow W\bar{c}g$		
$Wgg$	$u\bar{d} \rightarrow Wgg$	$W\bar{u}gg$	$\bar{u}g \rightarrow W\bar{u}gg$
$WW$	$q\bar{q} \rightarrow WW$		
$WZ$	$q\bar{q} \rightarrow WZ$		
$ggg$	$gg \rightarrow ggg$		
$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ v b \ell^- v \bar{b}$		
$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ v b \bar{u} d \bar{b}$	$t\bar{t}$	$q\bar{q} \rightarrow t\bar{t} \rightarrow \ell^+ v b \bar{u} d \bar{b}$

It uses the 4-vectors of the reconstructed lepton and jets (including the jet flavor information) and the Feynman diagrams for 2-jet and 3-jet events to compute an event probability density for the signal and background hypotheses.

# Search for 4<sup>th</sup> Generation Top-Like Quark

CDF Run 2 (4.6 fb<sup>-1</sup>) - t' Search Likelihoods - Preliminary



Likelihoods well behaved for all t' masses

Improvements from 2.8 fb<sup>-1</sup>

QCD veto cuts similar to single top

Separate into 4 sub-samples

4 jets

>=5 jets

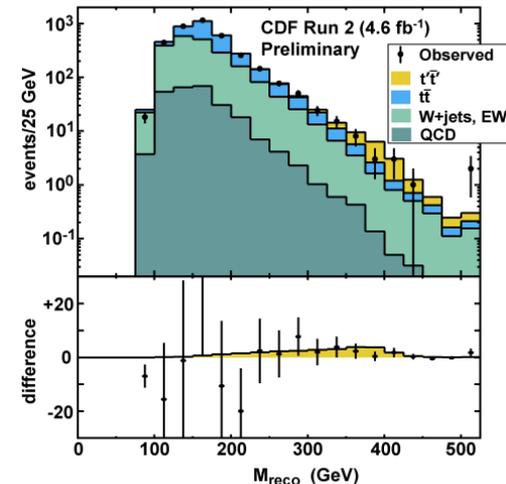
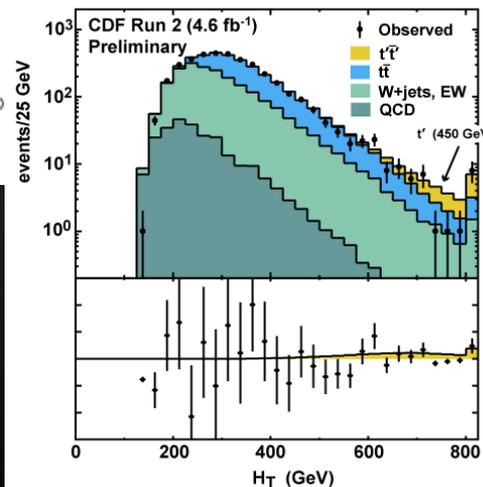
Good  $\chi^2$  from Mass Fit

Poor  $\chi^2$  from Mass Fit

Require minimum MC

statistical uncertainty of 0.4 in each bin

Bin Merging algorithm

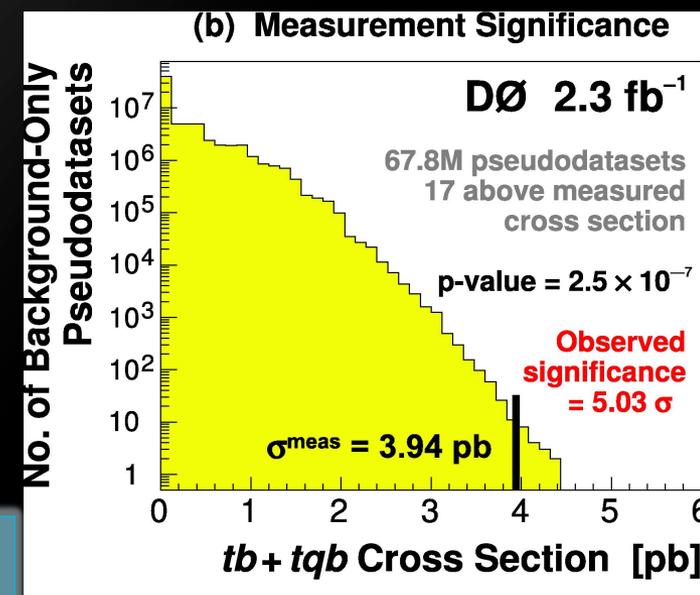
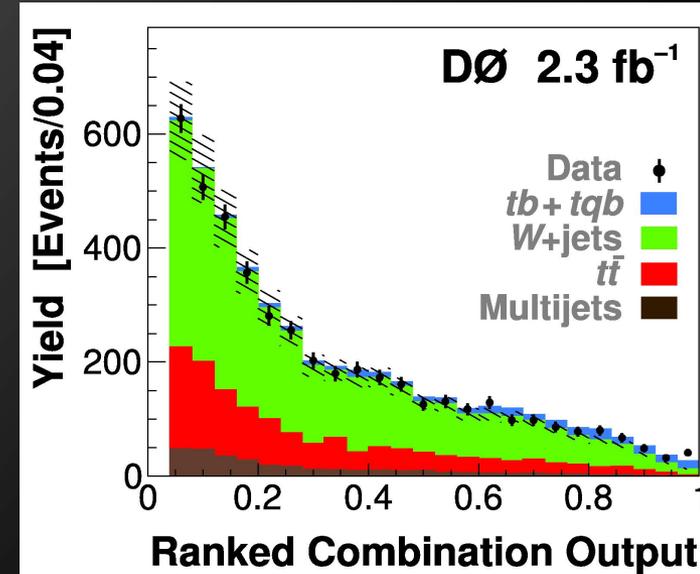


# D0 Single Top Observation

- s+t channel together
  - Assume SM prediction for ratio
- Several offline selection loosened wrt previous
  - B-tagging for double-tagged events
  - Increase signal acceptance by 18%
- Selection
  - 2,3,4 jets
    - 1,2 b-tagged
  - 1 lepton (electron or muon)
  - Missing transverse energy
  - Multijet background reduction
- 4519 events
  - $223 \pm 30$  expected from single top
- Systematics
  - Most only normalisation
  - Some also shape
    - Jet Energy Scale
    - Tag-rate function
- Uncertainty on background (8-16%) larger than expected signal ( $\sim 3-9\%$ )

# D0 Single Top Observation

- Need to use multivariate analysis techniques
  - Boosted Decision Trees
  - Bayesian Neural Networks
  - Matrix Element Method
- Use ensembles of pseudo-data from background + signal at different cross sections
  - Confirm linear behaviour
- For each multivariate discriminant
  - Form binned likelihood as a product over all bins and channels
  - Extract the single top cross section
  - Measure significance in each channel (4.6, 5.2, 4.9 sigma)
- Measurements not completely correlated
  - Combination leads to increased sensitivity
  - Use second set of Bayesian Neural Networks



$$\sigma_t^{\text{D0 obs}} = 3.49 \pm 0.88 \text{ pb}$$

$$|V_{tb}| > 0.78 \text{ @ 95\% CL}$$