Search for Single Top Quark Production at DØ in Run II

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for the DØ Collaboration

Fermilab Wine&Cheese Seminar, 4/1/2005

Outline

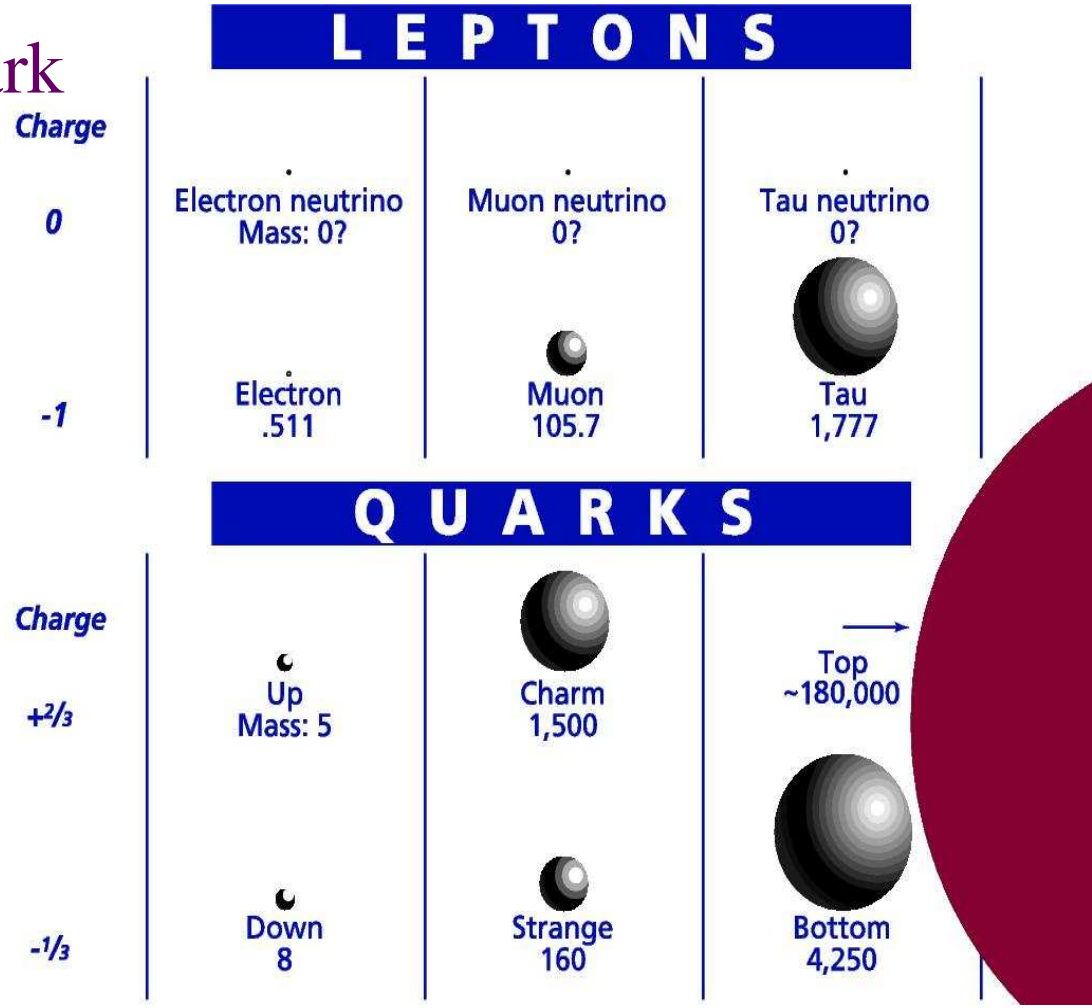
- Introduction
  - The Top Quark
  - Top Quark Electroweak Interactions
- The DØ Experiment at the Tevatron
- Search for Single Top at DØ
  - Event Selection
  - Discriminating Variables
  - Final Analysis Method
    - Cut-based Analysis
    - Neural Network Analysis
    - Decision Tree Analysis
- Conclusions/Outlook

http://www-d0.fnal.gov/Run2Physics/top/public/winter05/singletop/

Top Quark

KING OF FERMIONS

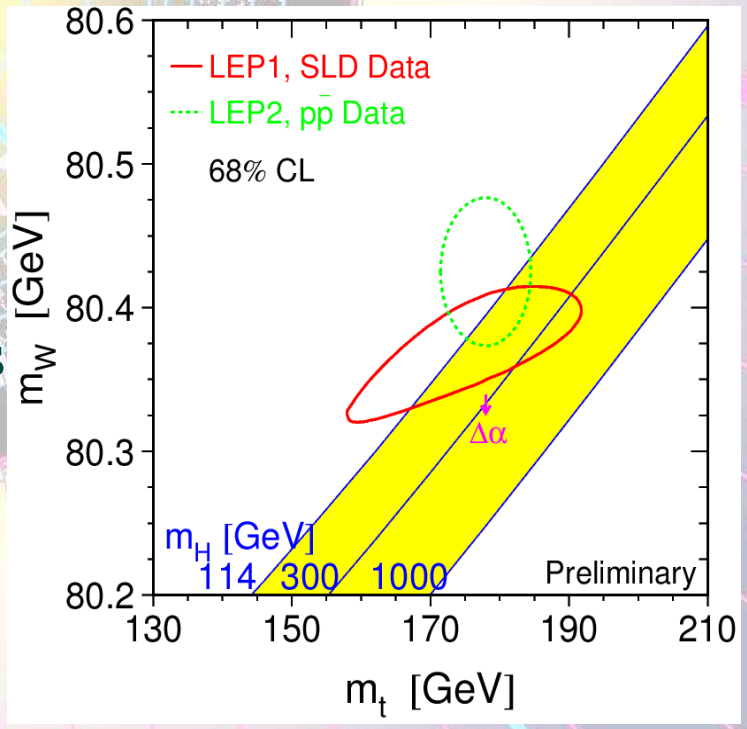
- Discovered in 1995 by CDF and DØ at the Tevatron
- Heaviest of all fermions
  - 40 times heavier than b quark
- Only quark that decays before it hadronizes
  - Clean laboratory to study quark properties
- Couples strongly to SM Higgs boson
  - Electroweak symmetry breaking



Tevatron Top Physics

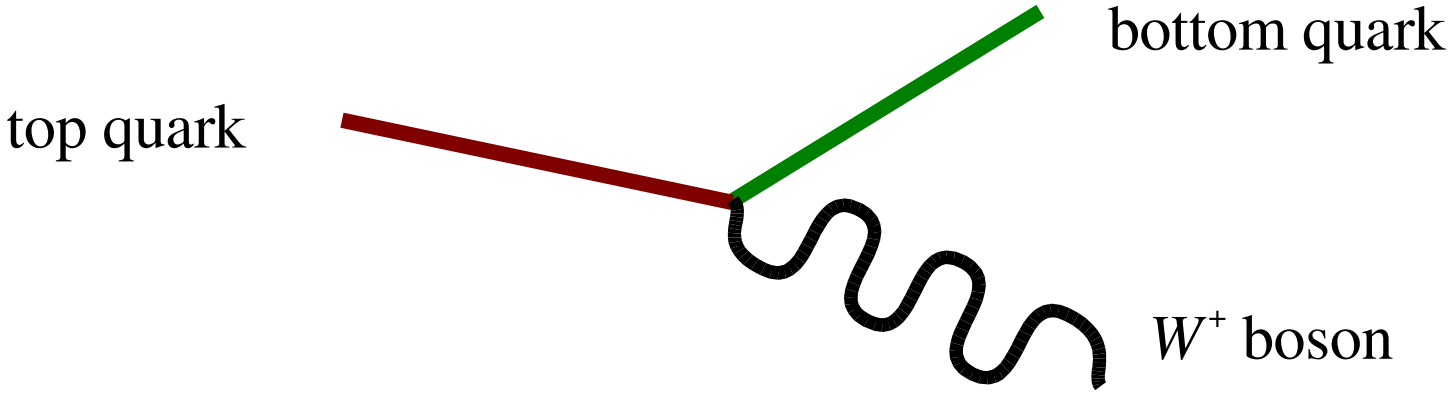
- Top Pair Production at a Proton-Antiproton collider

- Top Pair Studies at the Tevatron
  - Production cross section
  - Top mass
    - Implications for Standard Model Higgs
  - Look for new Physics
    - In top production and decay
  - Many more

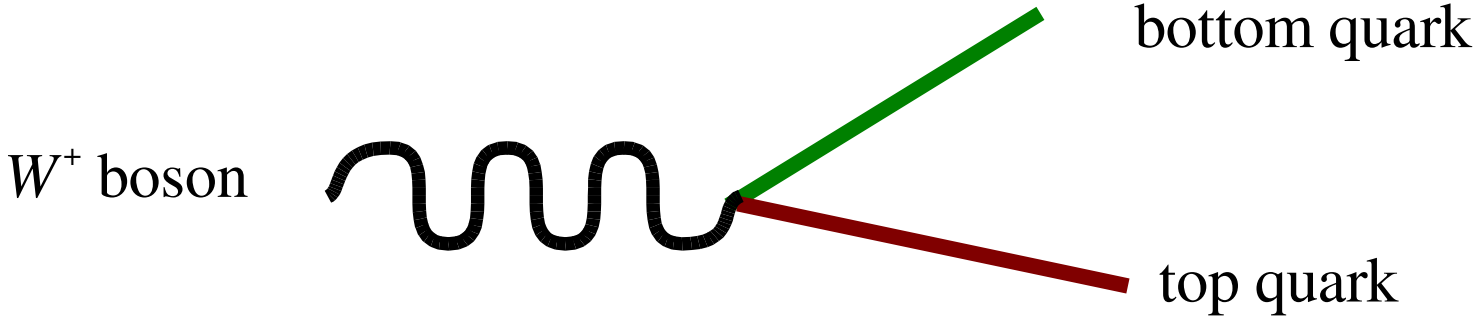


Top Quark Electroweak Interaction

- Charged Current interaction
- Responsible for top quark decay:

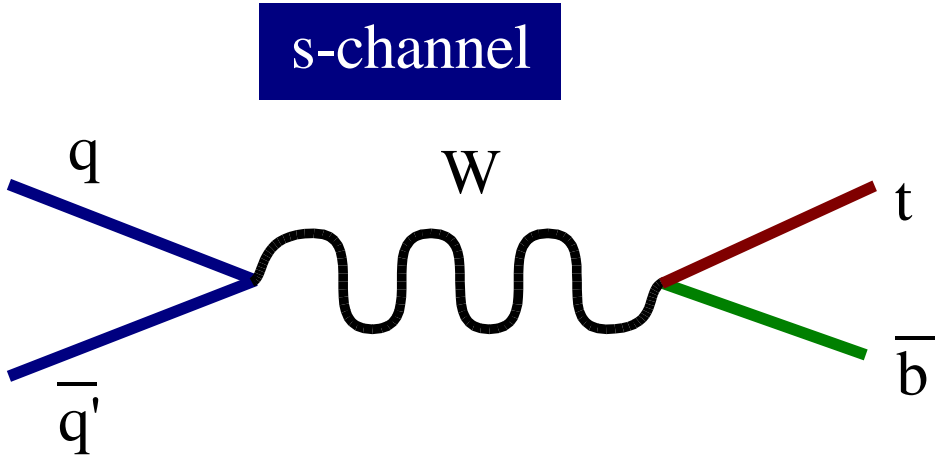


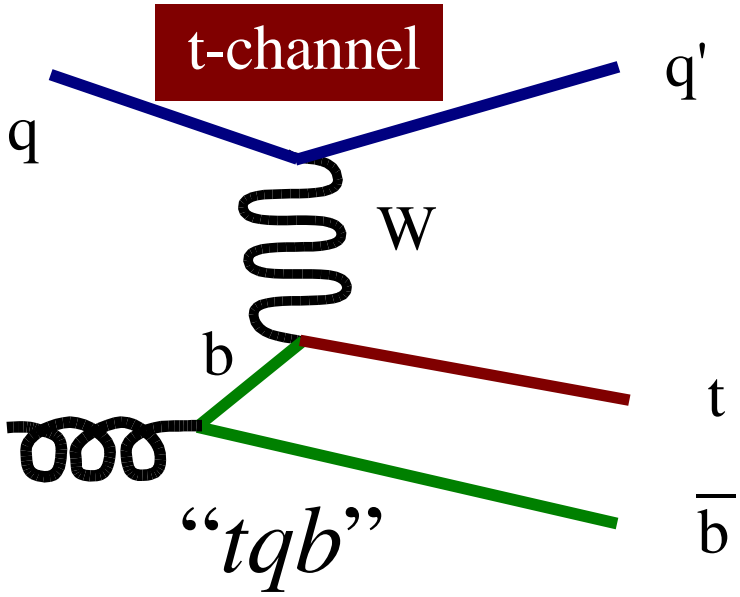
- Possible top quark production mode "*Single Top*":



Tevatron Single Top

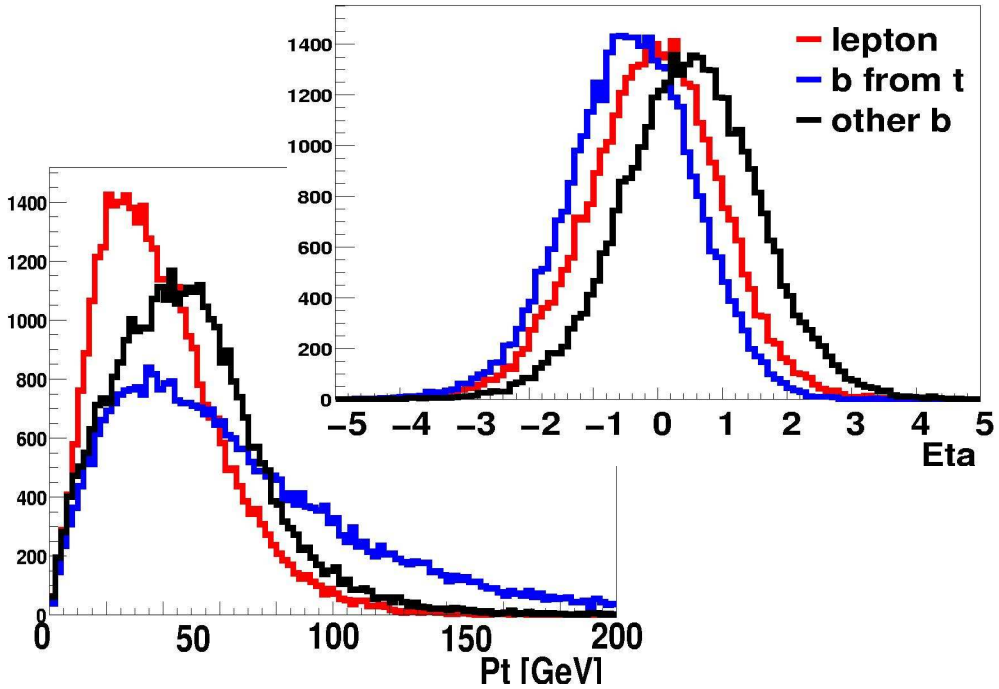
- Electroweak Production of Single Top Quarks

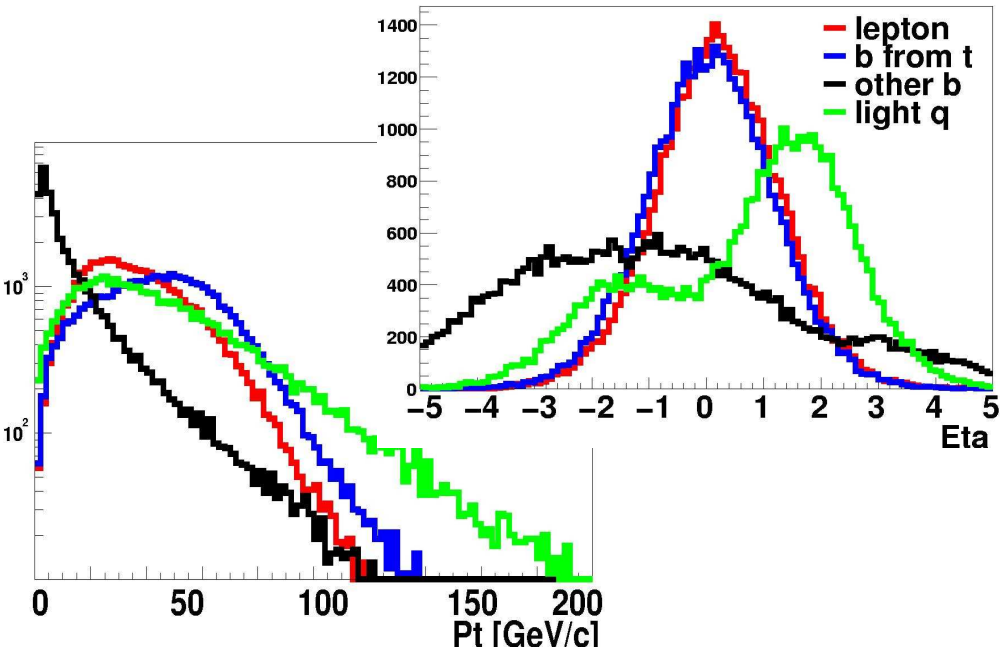




"*tb*"

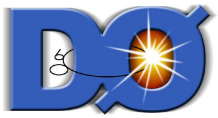
"*tqb*"



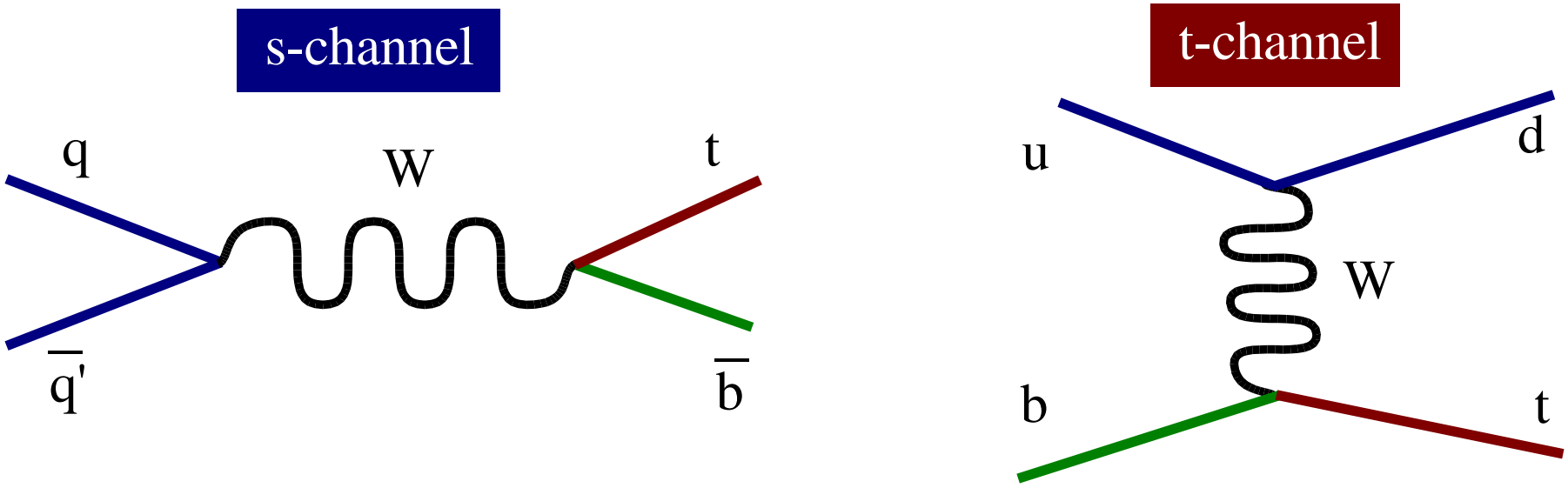


Phenomenology of Tevatron Single Top

- Several differential NLO calculations
  - Single Top at NLO — Harris, Laenen, Phaf, Sullivan, Weinzierl, PRD66:054024,2002; Sullivan, PRD70:114012,2004
    - Full NLO calculation of differential distributions
  - Single Top at NLO including top decay
    - Implemented in MCFM — Campbell, Ellis, Tramontano, PRD70:094012,2004
  - Single Top at NLO including decay and full spin correlations
    - Fully differential distributions — Cao, Yuan, hep-ph/0408180; Cao, RS, Yuan, PRD74:054023,2005
- New Phenomenological Studies
  - LO study using Madgraph and Pythia — Bowen, Ellis, Strassler, Acta.Phys.PolonB36:271,2005
    - Exploit initial state CP symmetry ($p - \bar{p}$ *collider*)
  - Effective tb*W* coupling — Chen, Larios, Yuan, hep-ph/0503040



Single Top Status



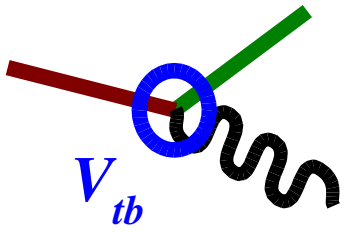
- Production cross section:

	s-channel	*t-channel*	*s+t*
– NLO calculation:	**0.88pb (±8%)**	**1.98pb (±11%)**	
– Run I 95% CL limits, DØ:	< 17pb	< 22pb	
CDF:	< 18pb	< 13pb	< 14pb
– Run II CDF 95% CL limits:	< 14pb	< 10pb	< 18pb

- Other Standard Model production mode (*Wt*) negligible

Tevatron Single Top Goals

- Observe Single Top Production
- Measure Production cross section → *Wtb* vertex
  - CKM matrix element V_{tb}



CKM Matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Weak Interaction Eigenstates are not Mass Eigenstates

Top quark must decay to a *W* plus a *d*, *s*, or *b* quark

$$V_{td}^2 + V_{ts}^2 + V_{tb}^2 = 1 \quad \rightarrow \quad V_{tb} > 0.999$$

Or: new Physics that couples to the top quark:

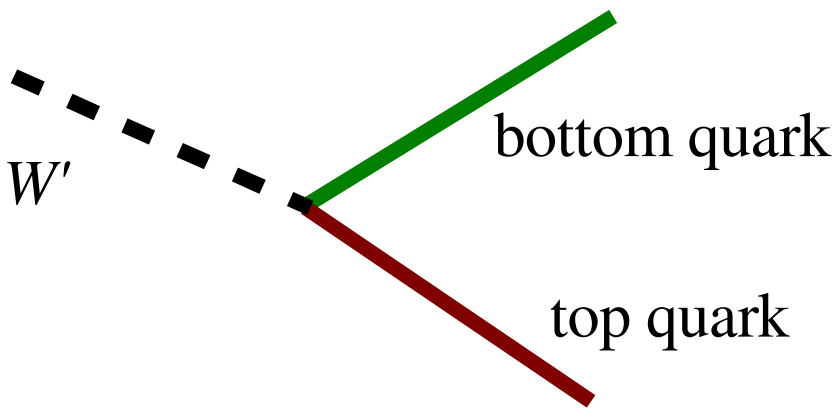
$$V_{td}^2 + V_{ts}^2 + V_{tb}^2 + V_{tx}^2 = 1$$

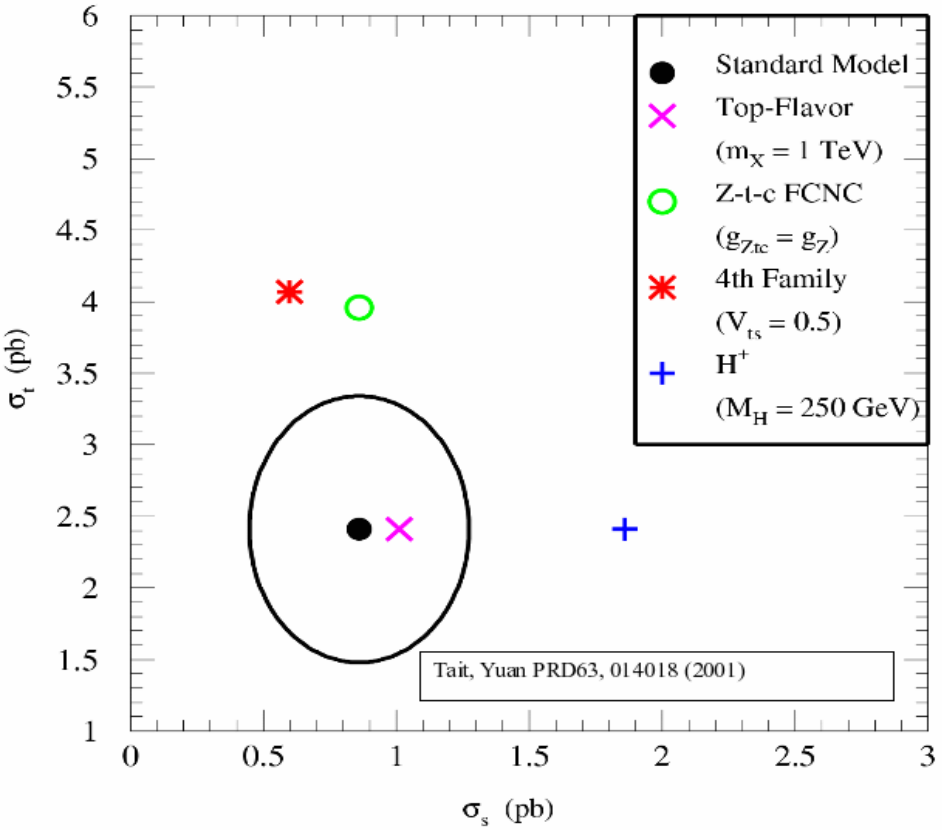
Only weak constraints on V_{tb}

Tevatron Single Top Goals

- Observe Single Top Production
- Measure Production cross section
  - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model
  - Different sensitivity for s-channel and t-channel

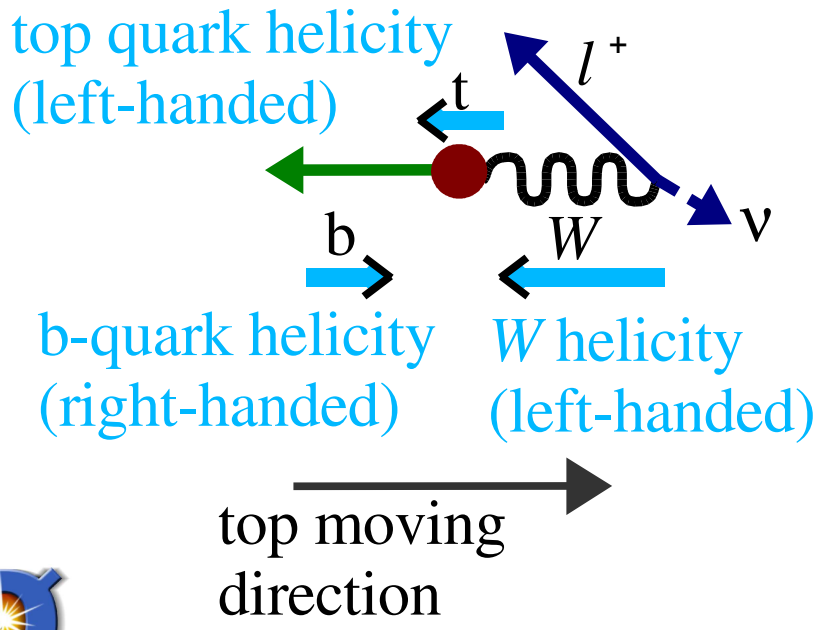
Example:Top-Flavor

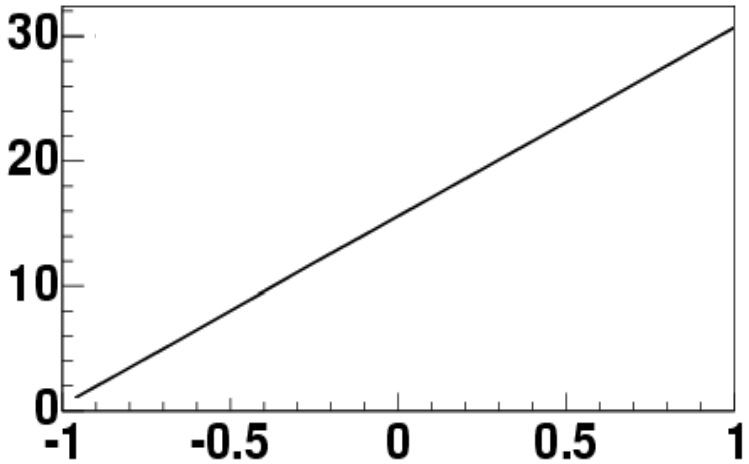




Tevatron Single Top Goals

- Observe Single Top Production
- Measure Production cross section
  - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model
- Study top quark spin correlations
  - Physics with ~100% polarized top quarks

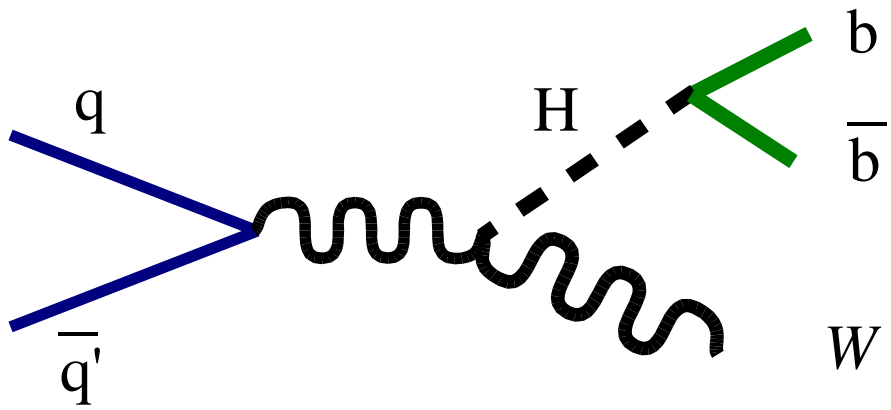


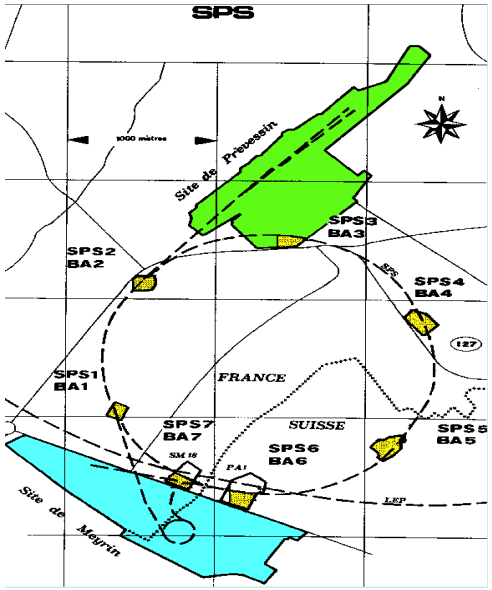


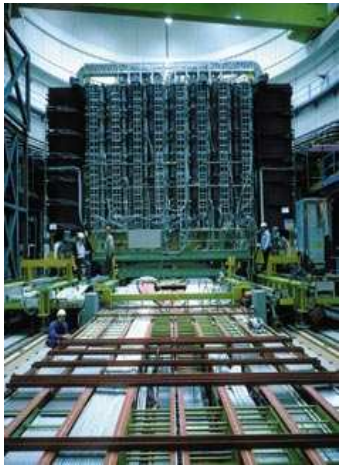
Angle between light quark and lepton

Tevatron Single Top Goals

- Observe Single Top Production
- Measure Production cross section
  - CKM matrix element V_{tb}
- Look for Physics beyond the Standard Model
- Study top quark spin correlations
- Irreducible background to associated Higgs production



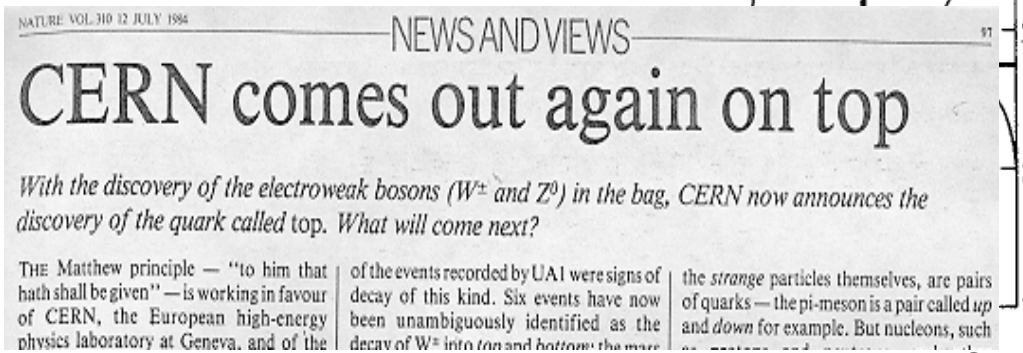




Where in the World is *Single Top?*

Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
  - SPS: $\sqrt{s}$=540GeV
- $M_{top} \approx 40$GeV



NATURE VOL 310 12 JULY 1984

NEWS AND VIEWS

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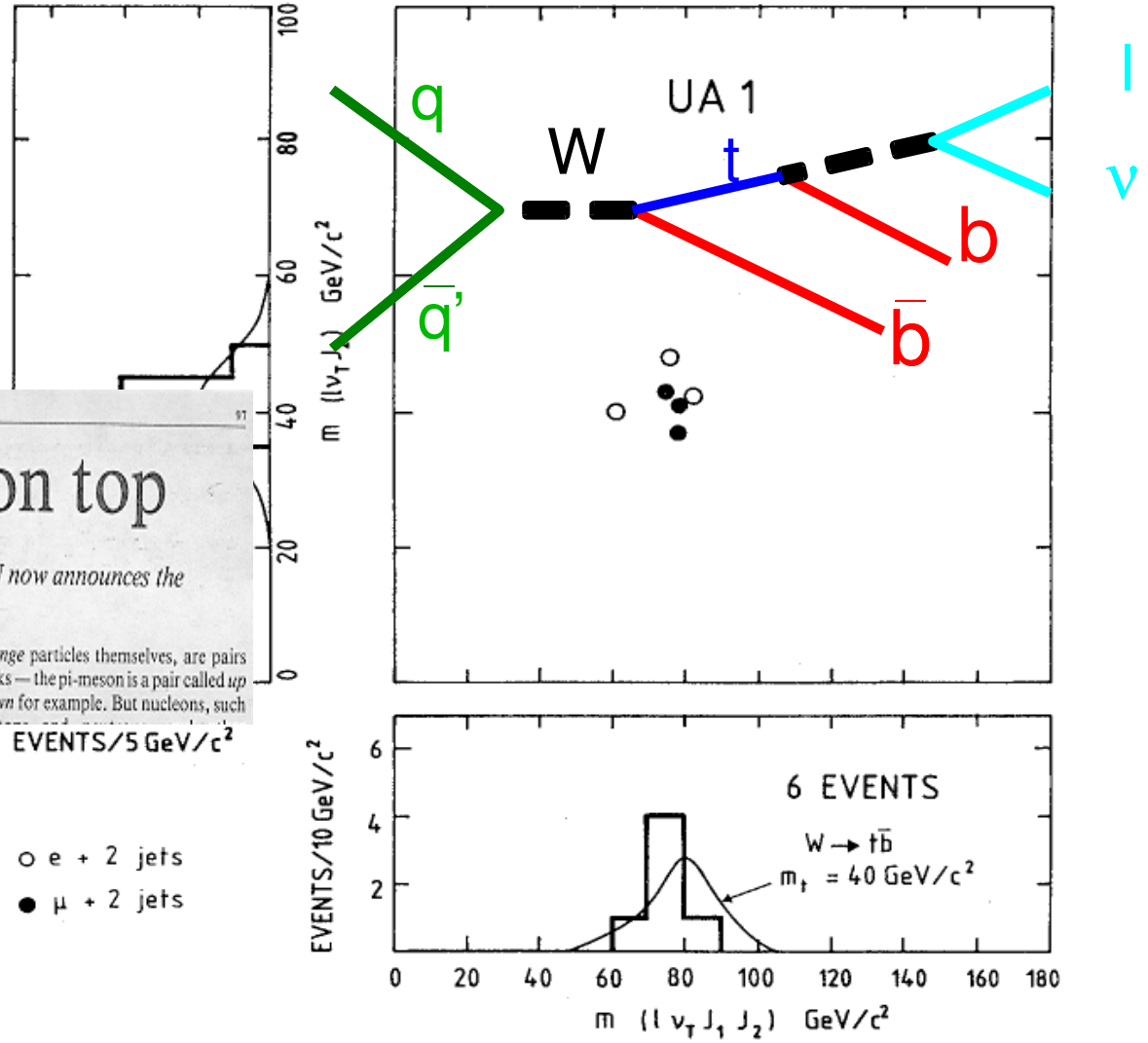
CERN comes out again on top

With the discovery of the electroweak bosons ($W^{\pm}$ and Z^0) in the bag, CERN now announces the discovery of the quark called top. *What will come next?*

THE Matthew principle — "to him that hath shall be given" — is working in favour of CERN, the European high-energy physics laboratory at Geneva, and of the

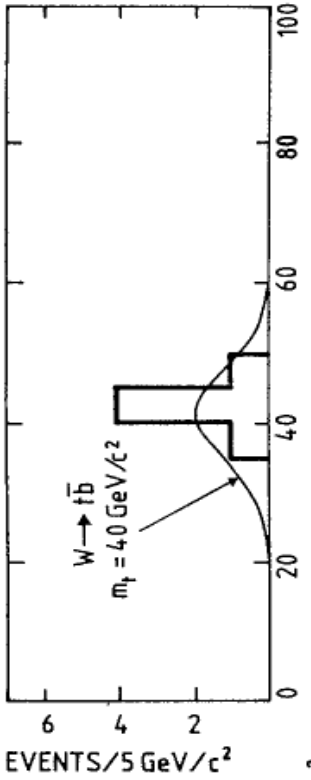
of the events recorded by UA1 were signs of decay of this kind. Six events have now been unambiguously identified as the decay of $W^{\pm}$ into *top* and *bottom*; the mass

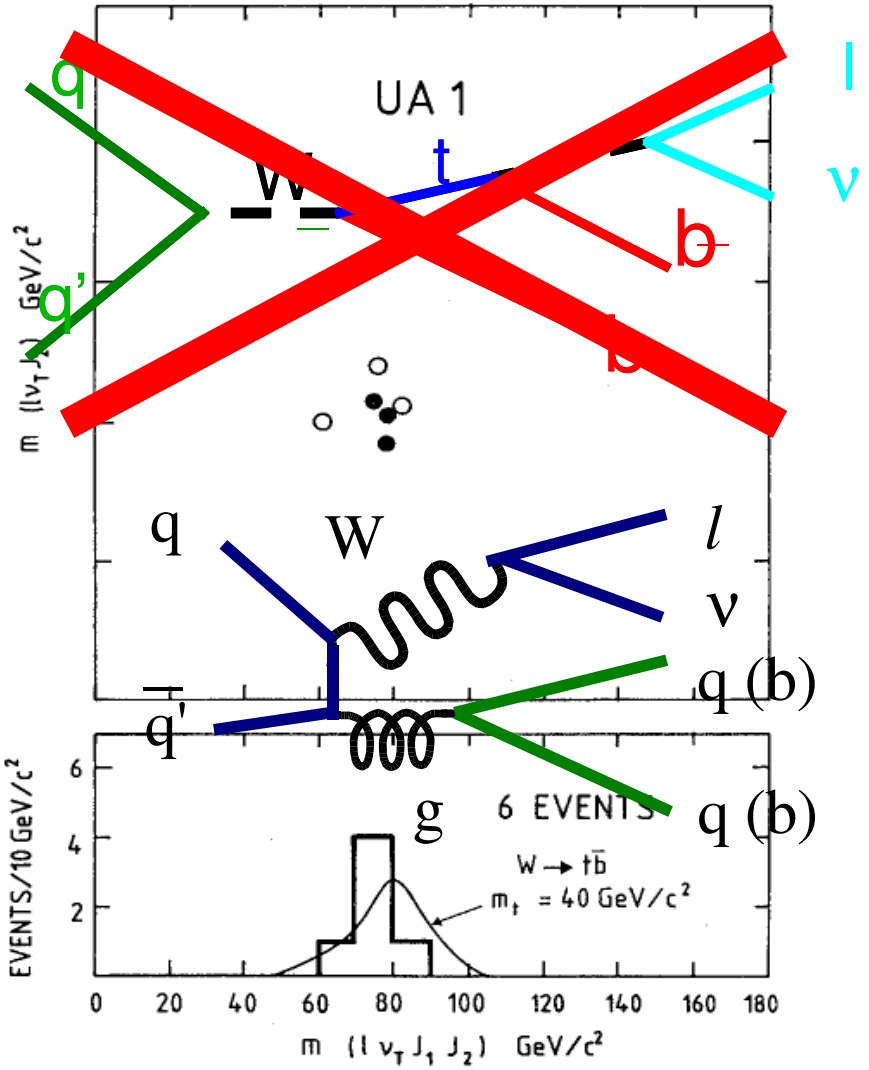
the *strange* particles themselves, are pairs of quarks — the pi-meson is a pair called *up* and *down* for example. But nucleons, such



Discovery of Single Top?

- Excess of lepton+MET+2jet events at UA1 in 1984
  - Consistent with production of single top quark and bottom quark
    - $M_{top} \approx 40GeV$
  - Not confirmed after more data and better background estimation
    - W+jets production!

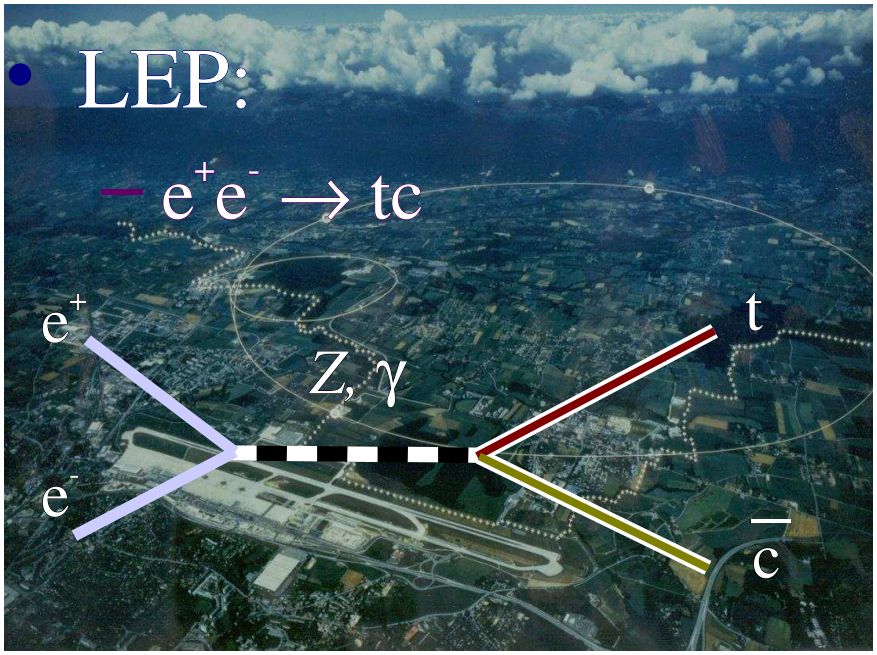




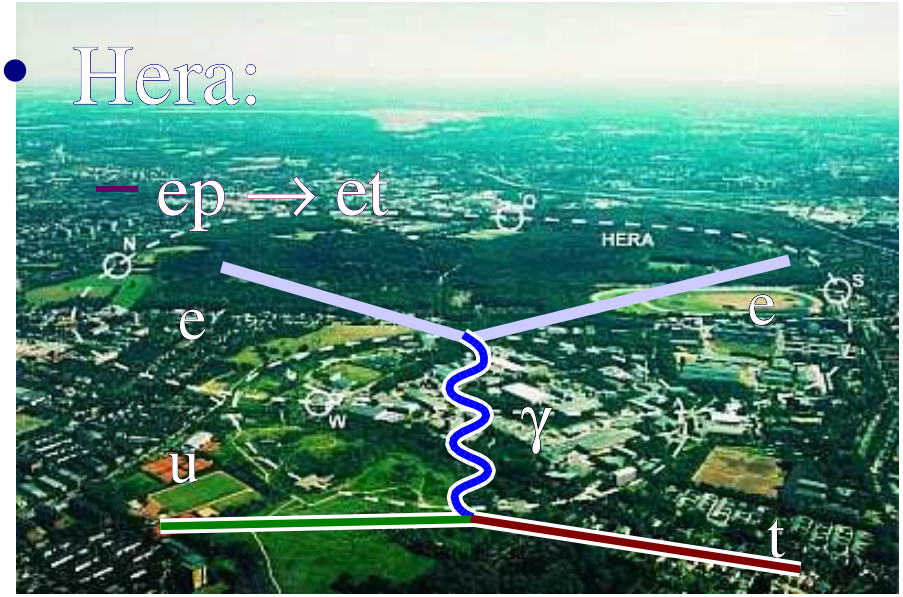
!

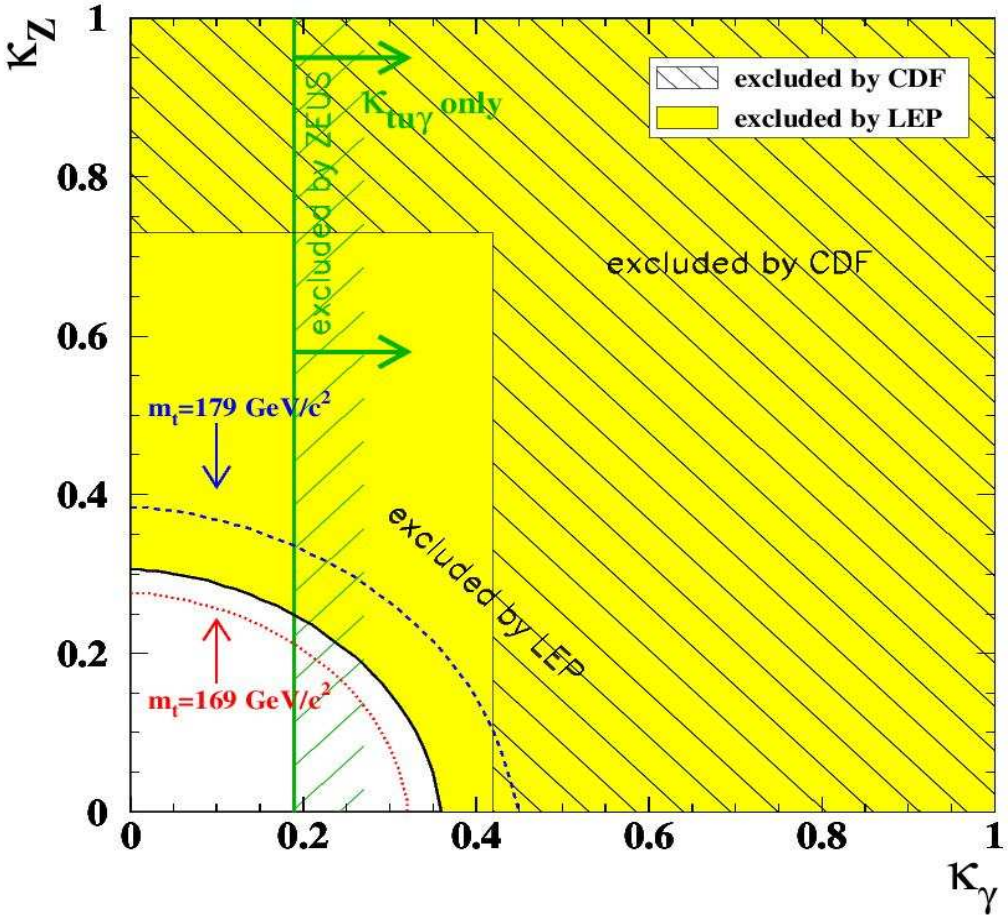
Single Top at LEP and Hera: FCNC

- LEP:
  - $e^+e^- \rightarrow tc$

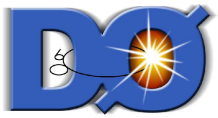


- Hera:
  - $ep \rightarrow et$





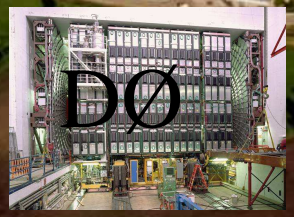
Experimental Detection of Single Top Events



Experimental Setup: Fermilab Tevatron in Run II

Proton-Antiproton Collider
CM Energy 1.96TeV
→ ***Energy Frontier***

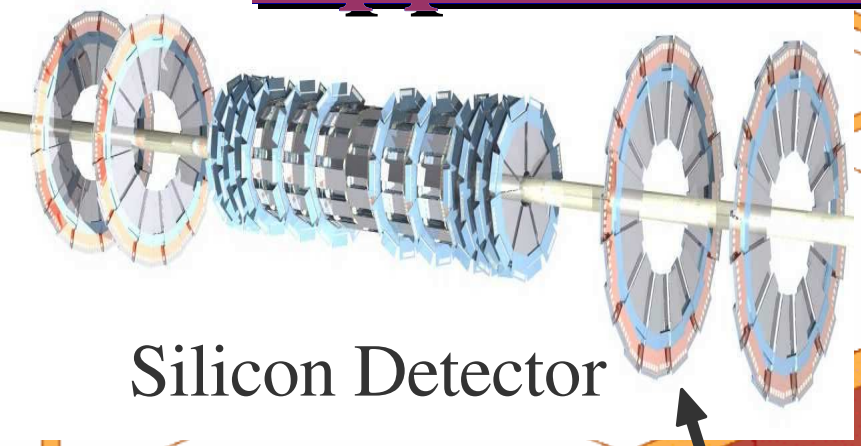
CDF



Experimenters: The DØ Collaboration

- 19 countries
- 80 institutions
- 670 physicists

Apparatus: Run II DØ Detector



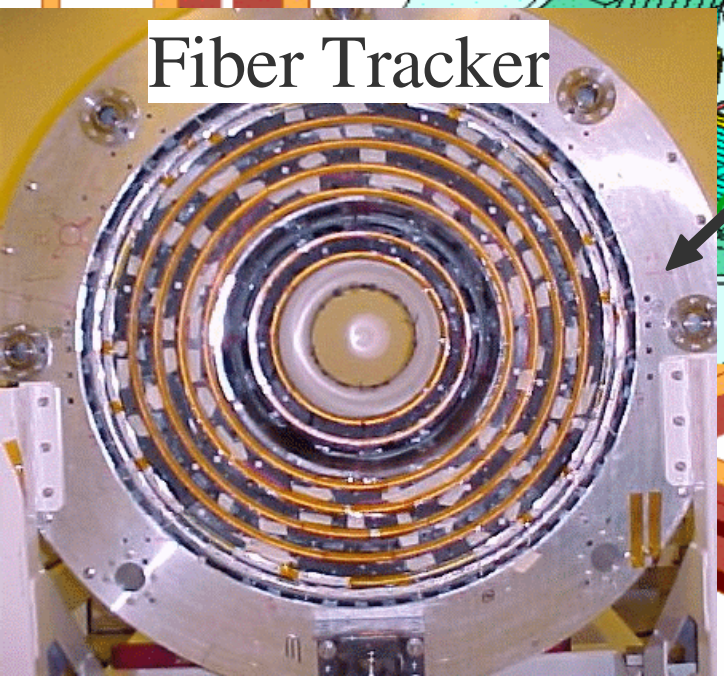
Silicon Detector

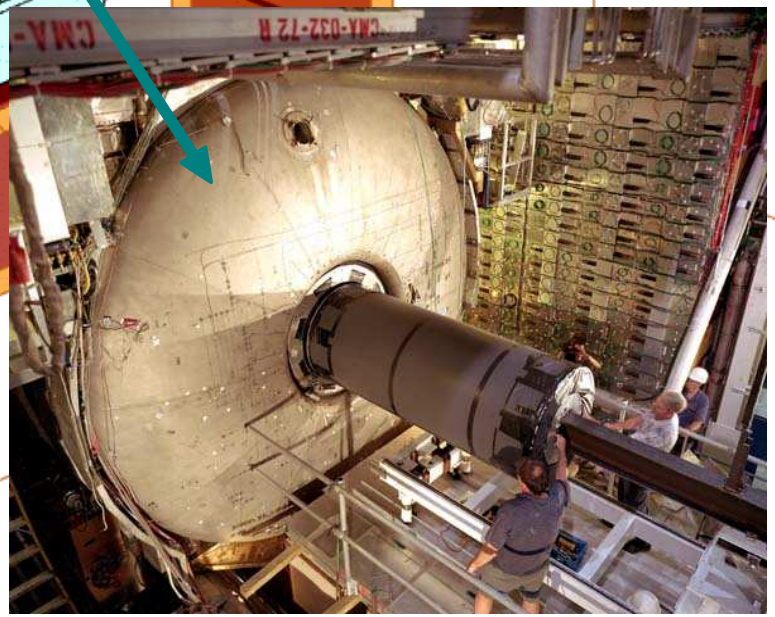
Muon System

Calorimeter

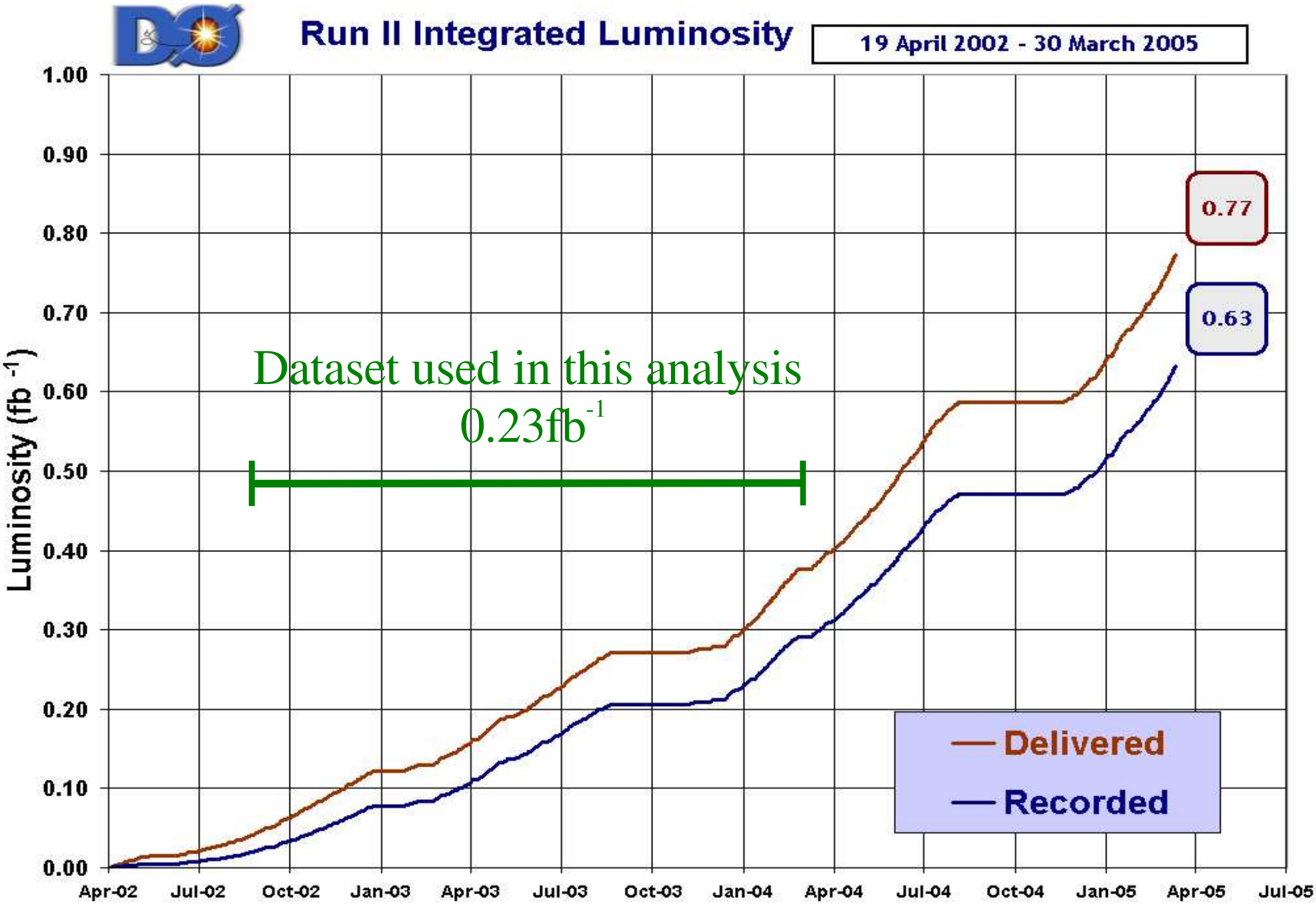
Tracker

Fiber Tracker





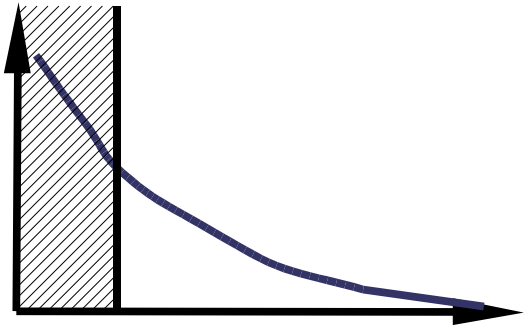
Dataset

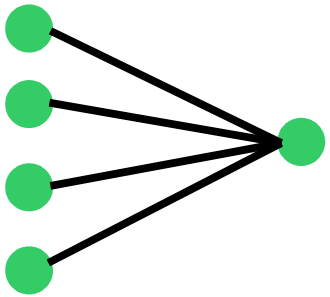

Run II Integrated Luminosity
19 April 2002 - 30 March 2005
Luminosity (fb -1)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
Apr-02
Jul-02
Oct-02
Jan-03
Apr-03
Jul-03
Oct-03
Jan-04
Apr-04
Jul-04
Oct-04
Jan-05
Apr-05
Jul-05
0.77
0.63
Dataset used in this analysis
0.23fb-1
Delivered
Recorded

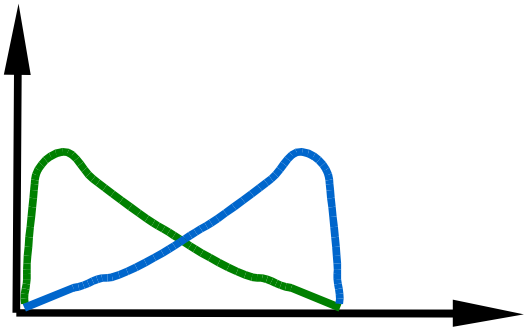
Analysis Outline

Goal:

Maximize Sensitivity



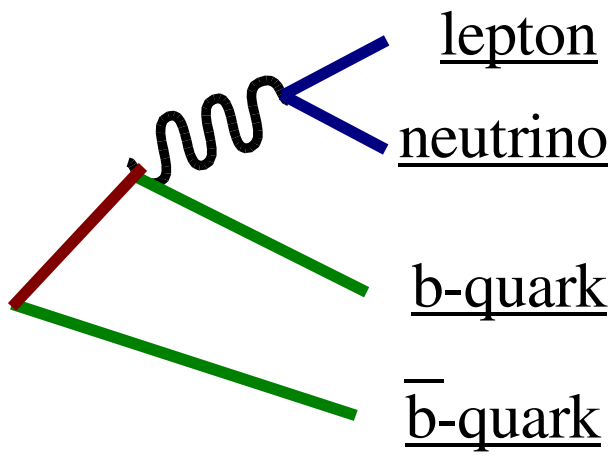




1. Event Selection
   - Select *W*-like events
   - Maximize acceptance
   - Model backgrounds
2. Separate signal from backgrounds
   - Find discriminating variables
   - Cut/combine in multivariate analysis
3. Determine cross section
   - Event counting
   - Likelihood fitting

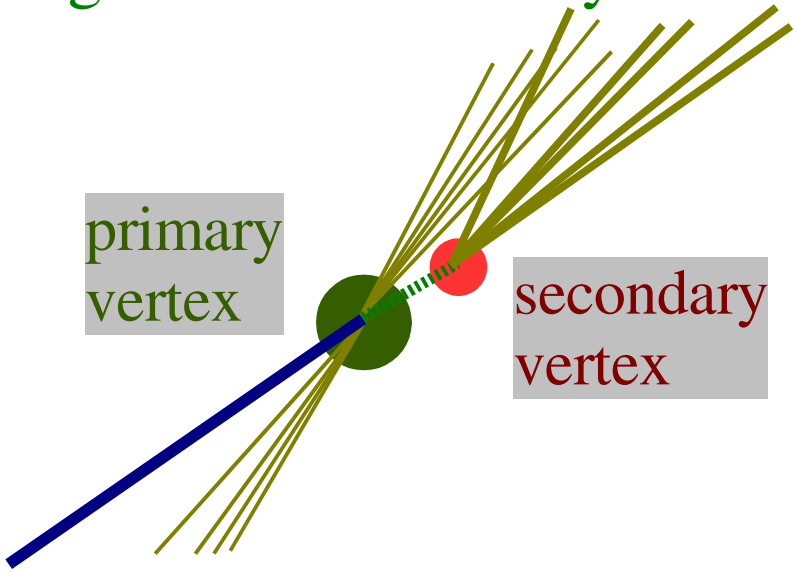
Event Selection

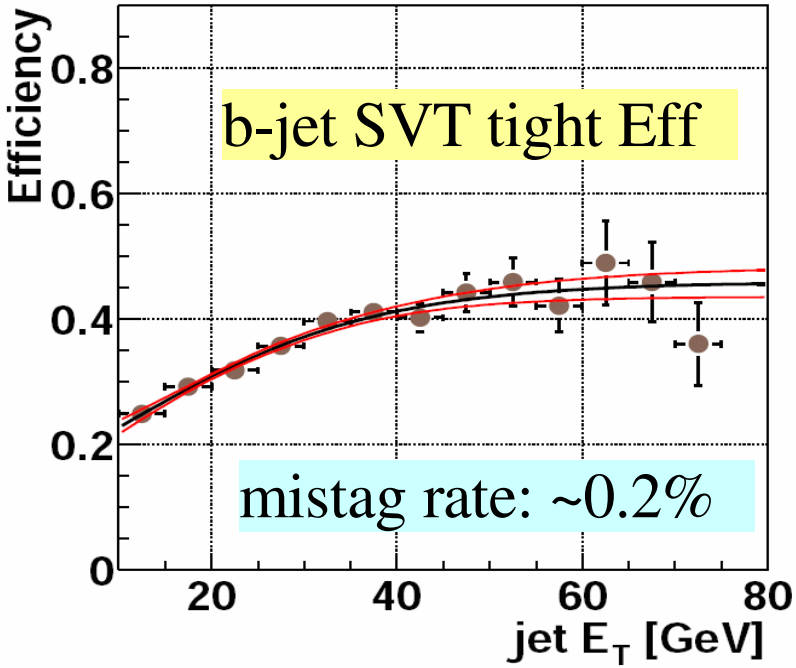
- Trigger:
  - Electron + ≥1 jets muon + ≥1 jets
- Lepton:
  - 1 electron: $p_T > 15$GeV, $|\eta^{det}|<1.1$
  - 1 muon: $p_T > 15$GeV, $|\eta^{det}|<2.0$
- Neutrino: $\not\!\!E_T > 15$GeV
- Jets:
  - $p_T > 15$GeV, $|\eta^{det}|<3.4$, p_T (jet 1)> 25GeV
  - $2 \le n_{jets} \le 4$
- Reject mis-reconstructed events



Event Selection: b-tagging

Algorithm: Secondary Vertex Tag





s-channel

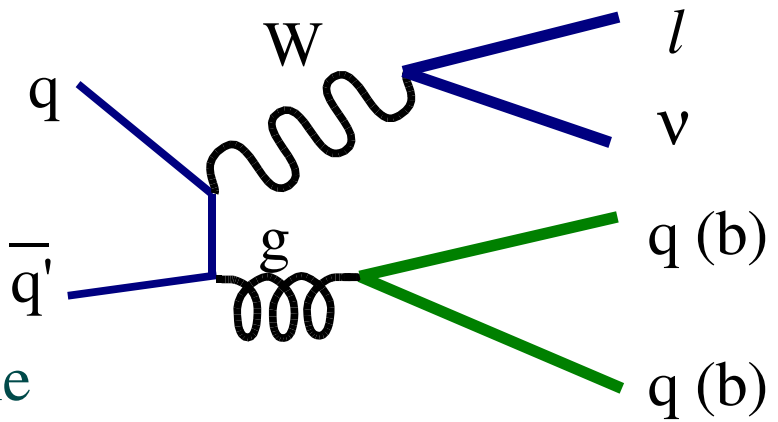
- Final state:
  - 2 high-p_T b-jets
- → Require ≥1 b-tagged jet

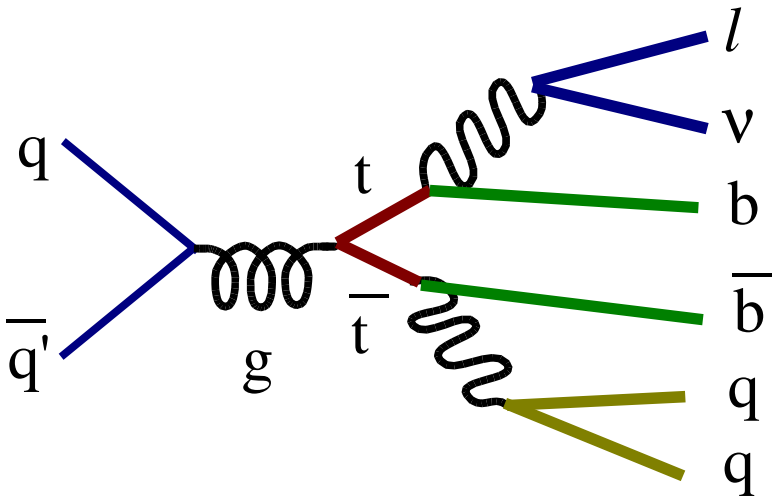
t-channel

- Final state:
  - 1 high-p_T b-jet
  - 1 high-p_T light quark jet
- → Require ≥1 b-tagged jet
- → Require ≥1 untagged jet

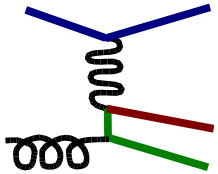
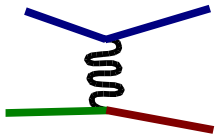
Background Modeling

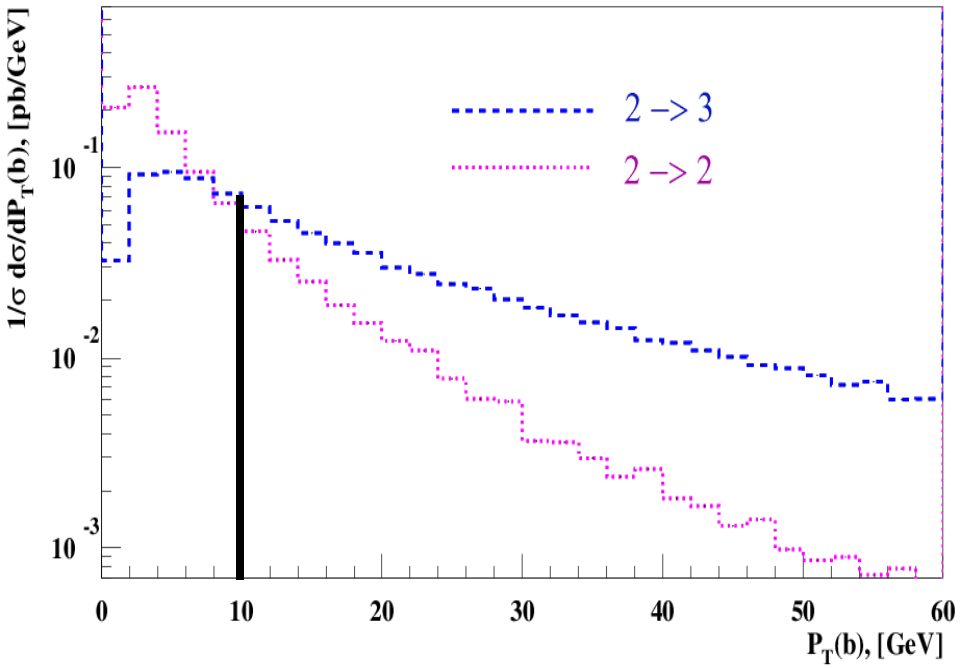
- Based on data as much as possible
- W/Z+jets production
  - Estimated from MC/data
    - Distributions from MC
    - Normalization from pre-tagged sample
    - Flavor fractions from NLO
- Multijet events (misidentified lepton)
  - Estimated from data
- Top pair production
  - Estimated from MC
- Diboson (WZ, WW)
  - Estimated from MC

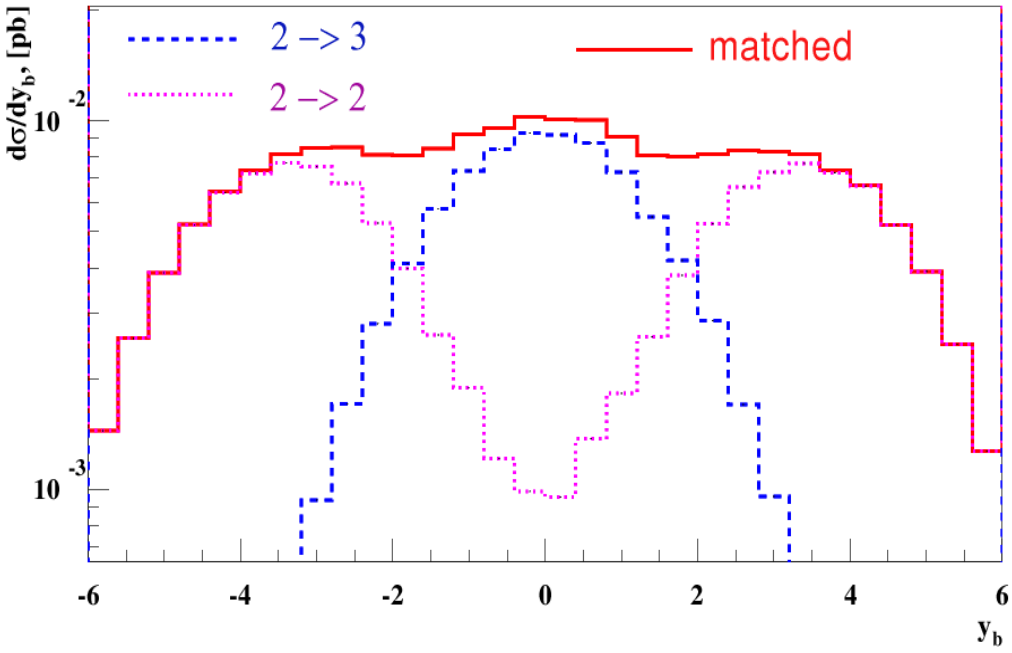




Signal Modeling

- CompHEP-based generator
  - Includes $O(\alpha_s)$ diagrams → reproduces NLO distributions
  - Including top quark spin correlations
- Normalize to NLO cross sections
- t-channel: match 2→3  and 2→2  processes



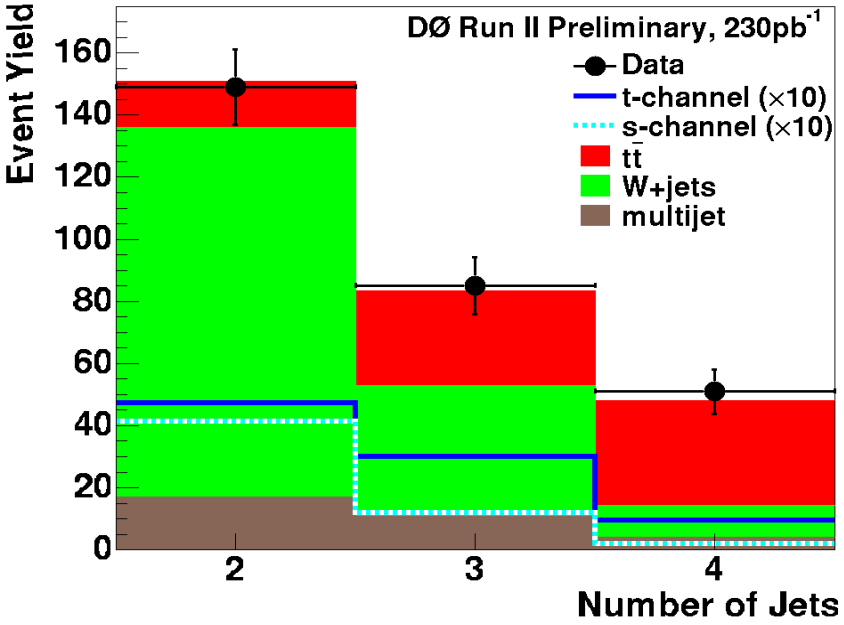


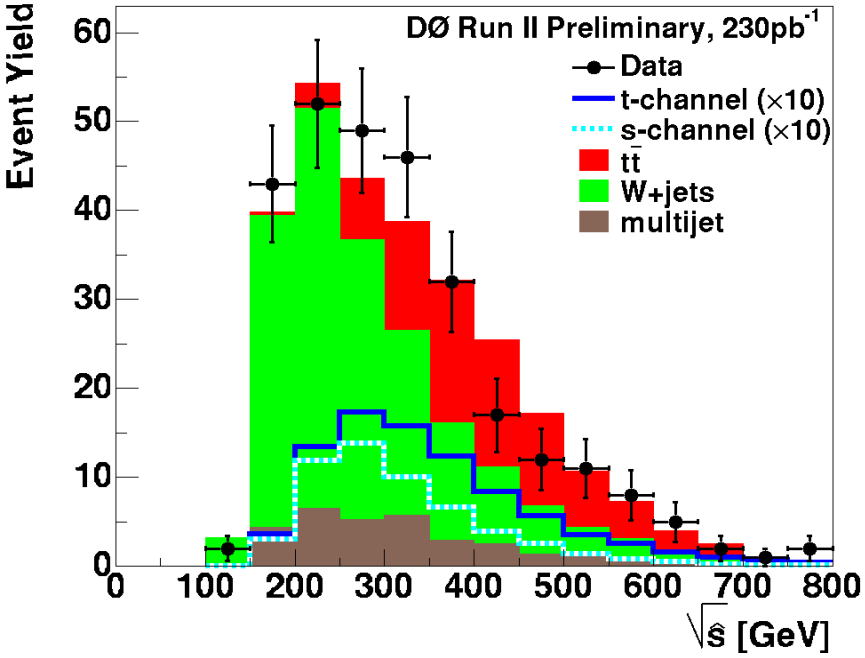
Event Yield

$$Y = L \times \sigma \times Br \times Acc(cuts) \times Eff(b\text{-}tag)$$

	Acc(cuts)	Eff(b-tag)
s-channel:	23%	54%
t-channel:	22%	38%

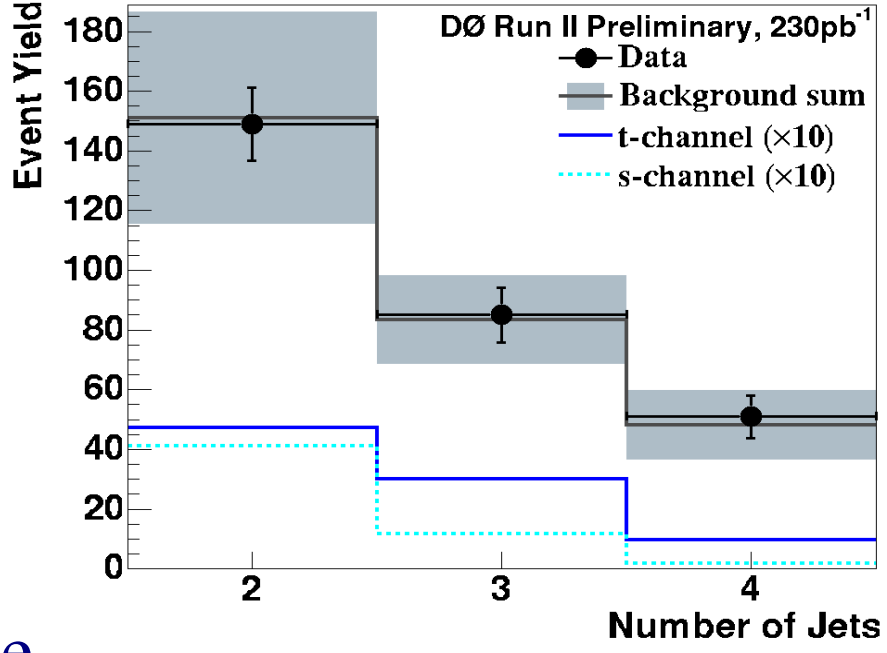
	Event Yields	
	s-channel search	t-channel search
s-channel signal	5.5	4.7
t-channel signal	8.6	8.5
W+jets	169	164
top pairs	78	76
multijet	31	31
Background sum	287±44	276±41
Observed	283	271





Systematic Uncertainties

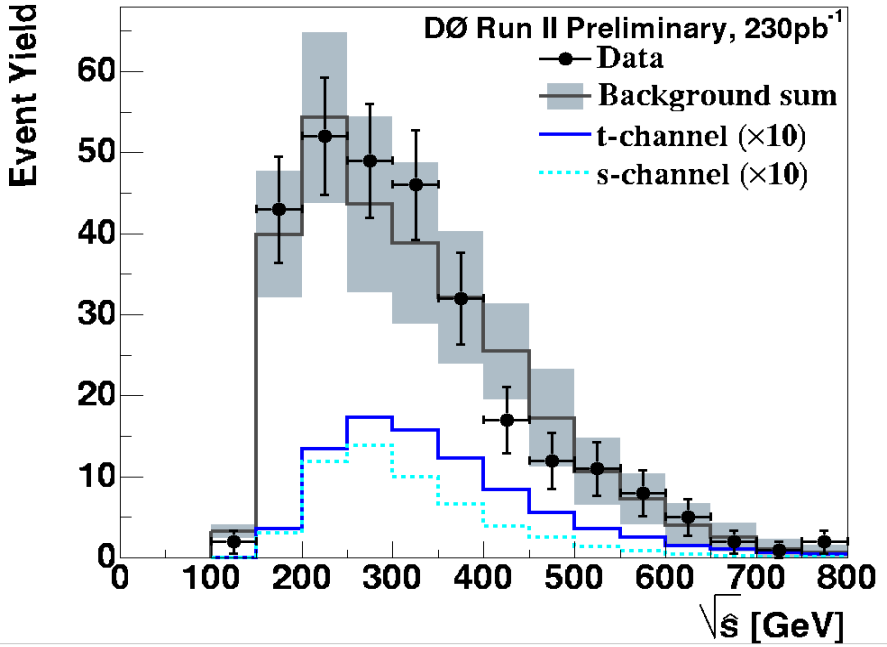
Monte Carlo Systematic Uncertainties	
Theory cross sections	15 %
SVT modeling, single (double) tag	10 %(20 %)
Jet Energy Scale	10 %
Trigger Modeling	6 %
Jet Fragmentation	6 %
Jet ID	5 %
ℓ ID	5 %



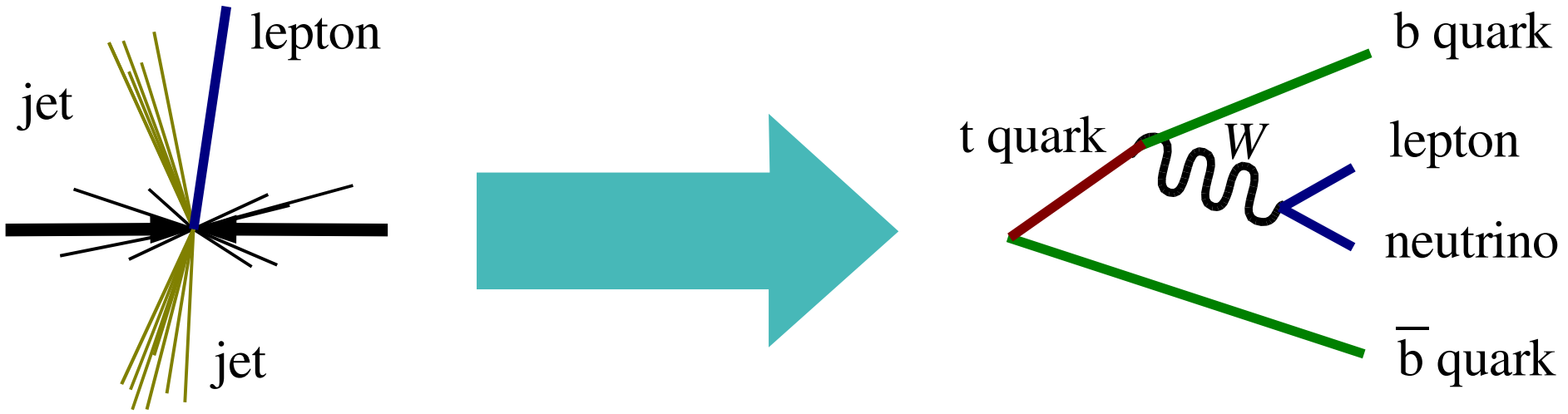
- Some uncertainties also affect shape
  - JES, b-tag and trigger modeling
- Total Uncertainty

	=1 tag	≥2 tags
Signal acceptance	15%	25%
Background sum	10%	26%

Result is statistics limited

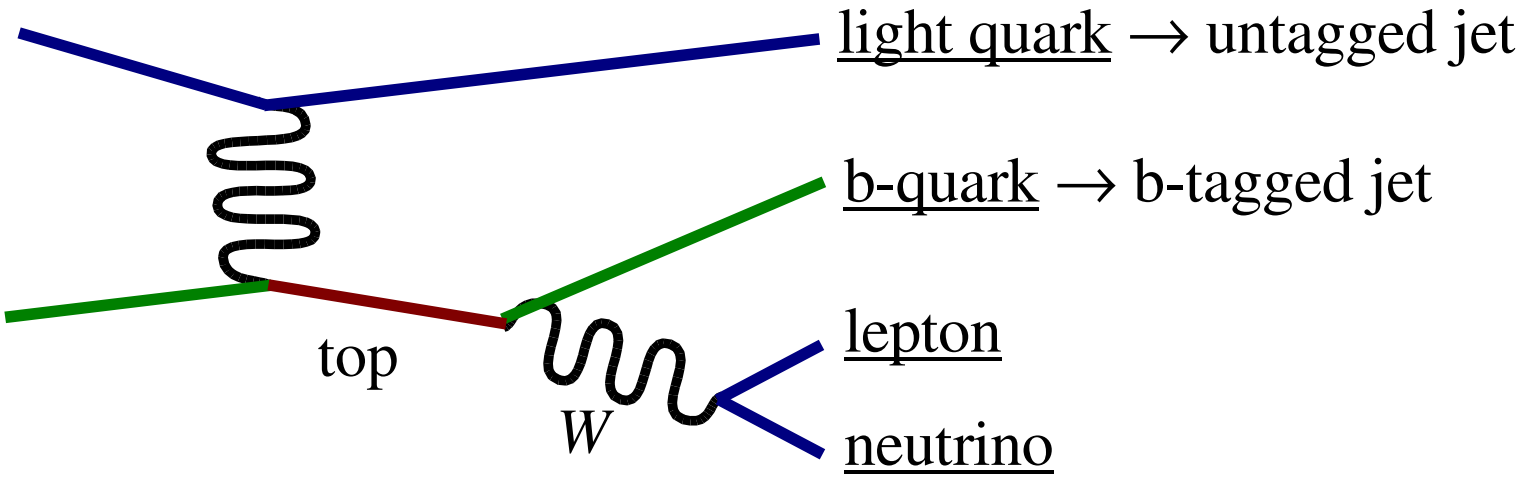


Maximize Sensitivity:
Final State Reconstruction



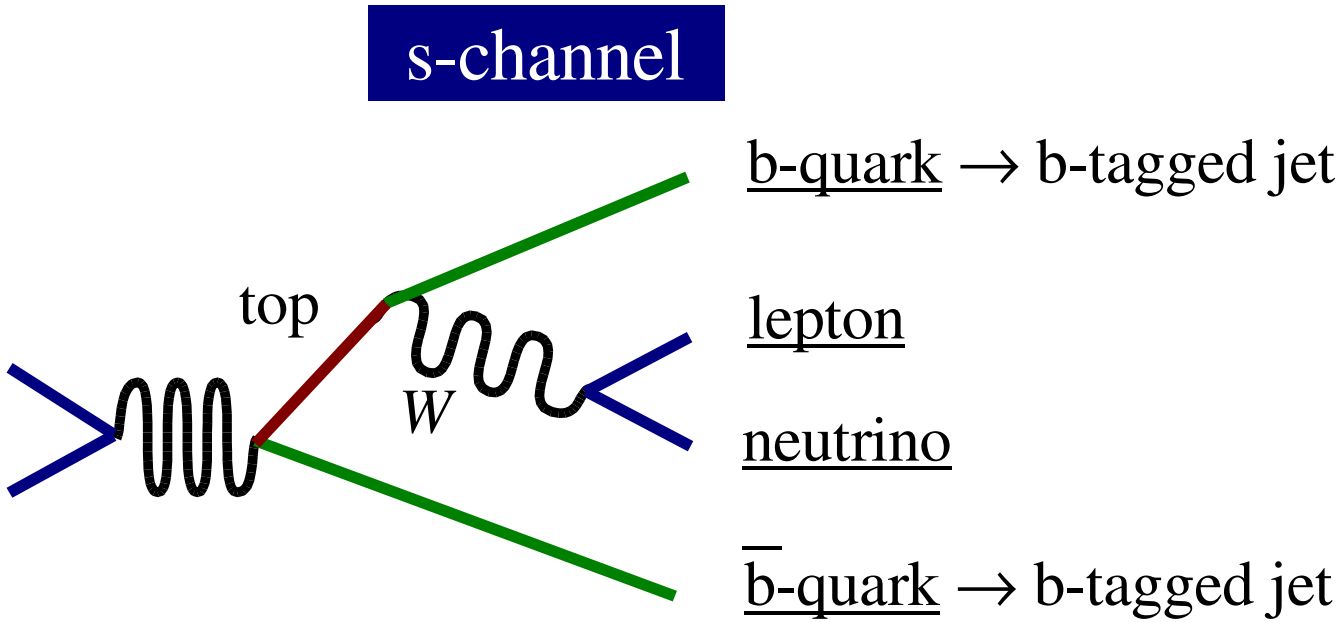
Final State Reconstruction

t-channel



- Reconstruct W from lepton and $\not\!\!E_T$
- Reconstruct top quark from W and leading b-tagged jet
- Reconstruct light quark as leading untagged jet

Final State Reconstruction

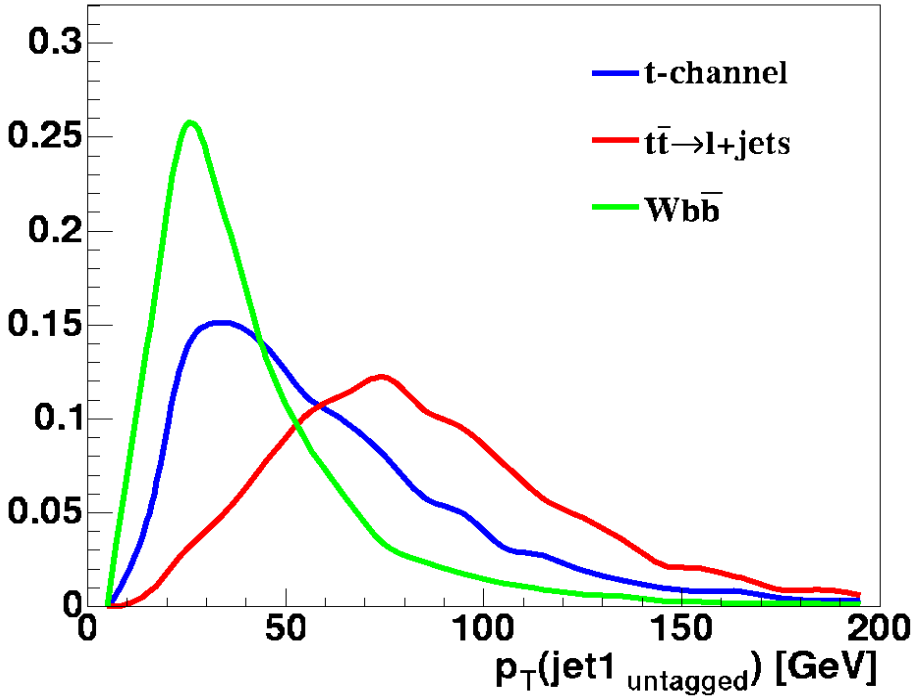


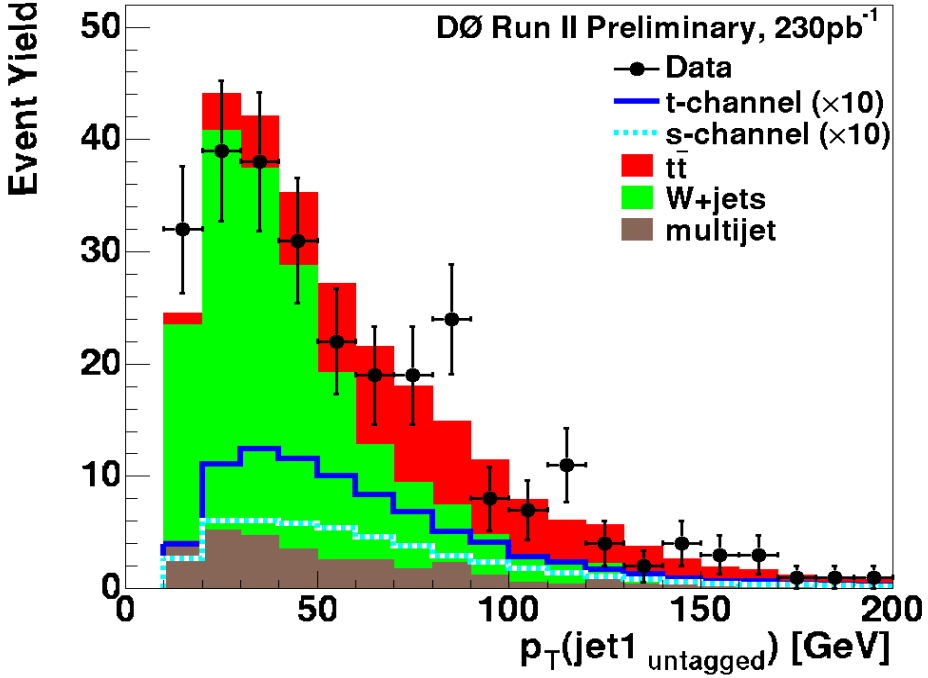
- Reconstruct W from lepton and $\not{E}_T$
- Reconstruct top quark from W and one of the jets using Best Jet Algorithm:
  - Pick jet for which $M(W,\text{jet})$ is closest to true top mass (175GeV)
- Reconstruct $\bar{b}$-quark as leading non-best jet

A Treasure Chest of Discriminating Variables

Object p_T

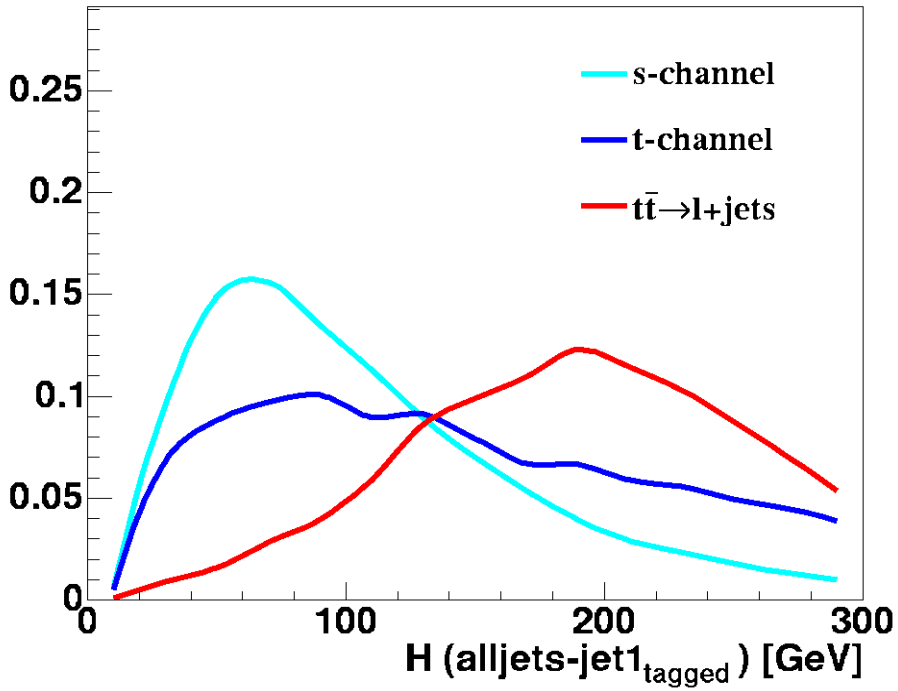
- p_T of jets:
  - Both s-channel and t-channel:
    - $\text{Jet1}_{\text{tagged}}$
  - Only t-channel:
    - $\text{Jet 1}_{\text{untagged}}$
    - $\text{Jet 2}_{\text{untagged}}$
  - Only s-channel:
    - $\text{Jet 1}_{\text{non-best}}$
    - $\text{Jet 2}_{\text{non-best}}$

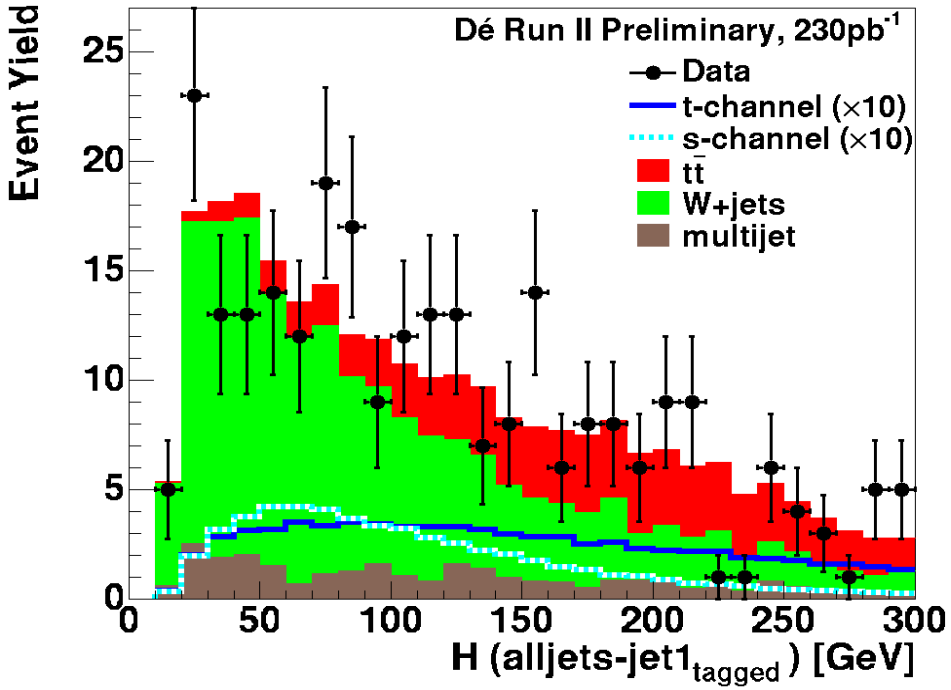




Event Energy

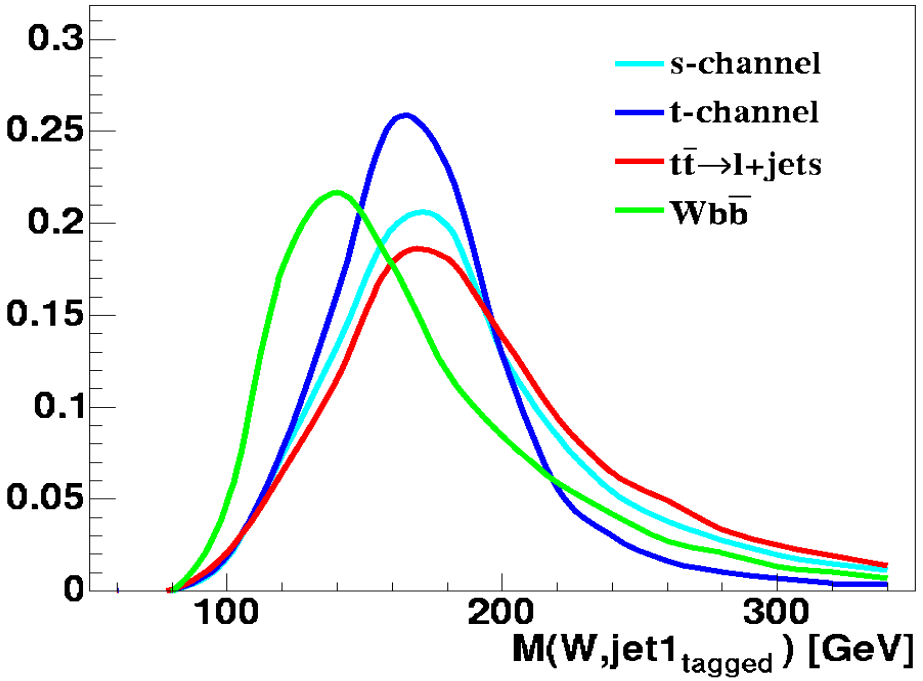
- Total energy $H = \Sigma_i E^i$
  transverse energy $H_T = \Sigma_i E^i{}_T$
  - Both s-channel and t-channel:
    - H(all jets – Jet1$_{\text{tagged}}$)
  - Only t-channel:
    - H_T(all jets)
    - H_T(all jets – Jet1$_{\text{tagged}}$)
  - Only s-channel:
    - H(all jets – Jet$_{\text{best}}$)
    - H_T(all jets – Jet$_{\text{best}}$)

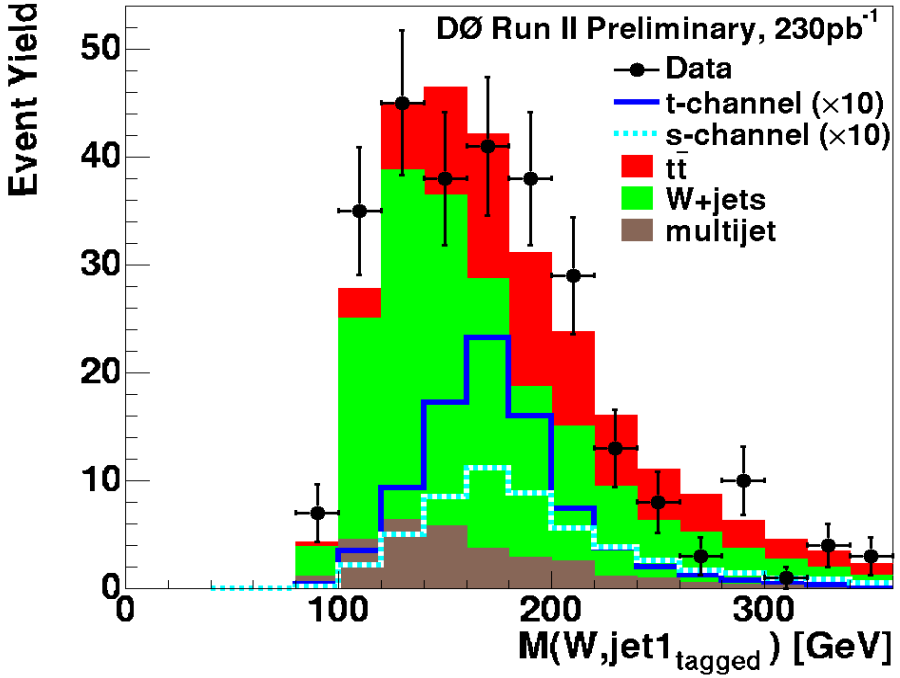




Reconstructed Objects

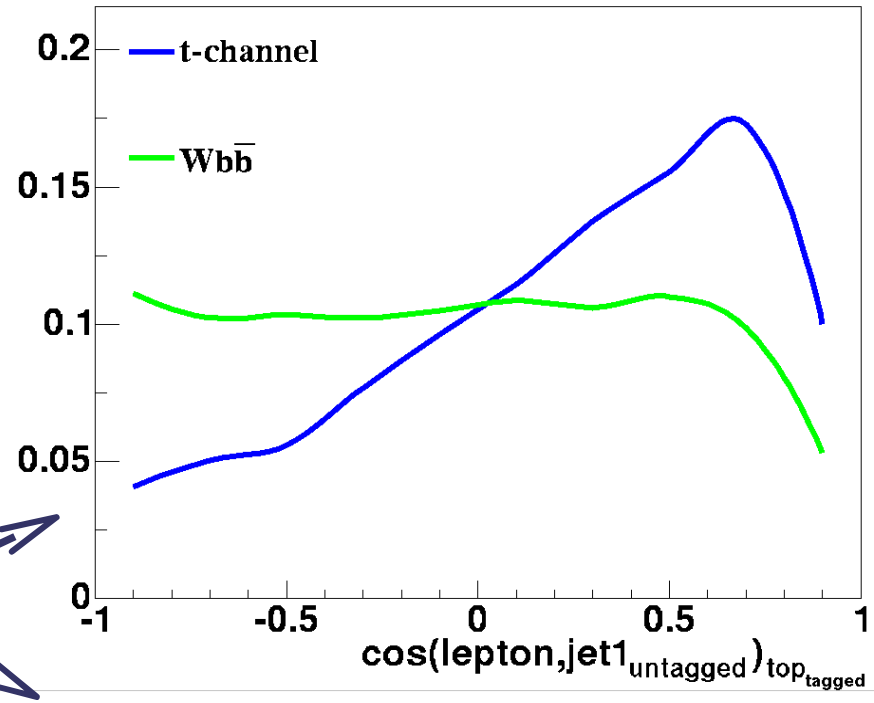
- Both s-channel and t-channel:
  - M(all jets)
  - p_T(all jets – Jet1$_{\text{tagged}}$)
  - M(top$_{\text{tagged}}$)
  - $\sqrt{\hat{s}}$
- Only t-channel:
  - M(all jets – Jet1$_{\text{tagged}}$)
- Only s-channel:
  - M_T(Jet1, Jet2)
  - p_T(Jet1, Jet2)
  - M(all jets – Jet1$_{\text{best}}$)
  - M(top$_{\text{best}}$)

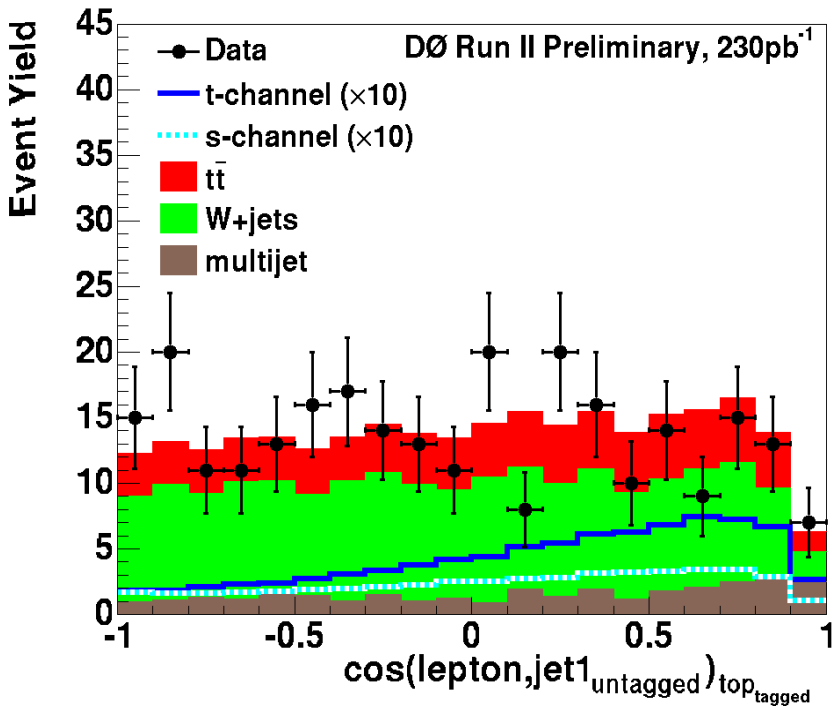




Angular Correlations

- Both s-channel and t-channel:
  - $\Delta R(\text{Jet1, Jet2})$
- Only t-channel:
  - $\eta(\text{Jet1}_{\text{untagged}}) \times Q(\text{lepton})$
  - $\cos(\text{lepton, Jet1}_{\text{untagged}})_{\text{top}_{\text{tagged}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets, Jet1}_{\text{tagged}})_{\text{all jets}}$
- Only s-channel:
  - $\cos(\text{lepton, } Q(\text{lepton}) \times z)_{\text{top}_{\text{best}}}$
    - Spin correlation in optimal basis
  - $\cos(\text{all jets, Jet1}_{\text{non-best}})_{\text{all jets}}$

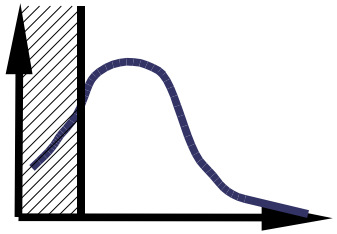




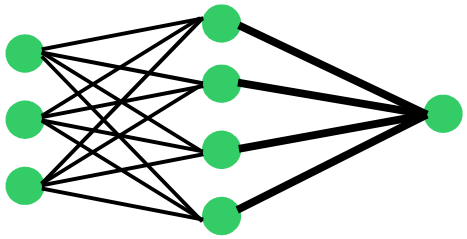
Separating Signal from Backgrounds

- Three analysis methods

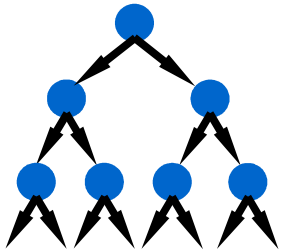
Cut-Based



Neural Networks

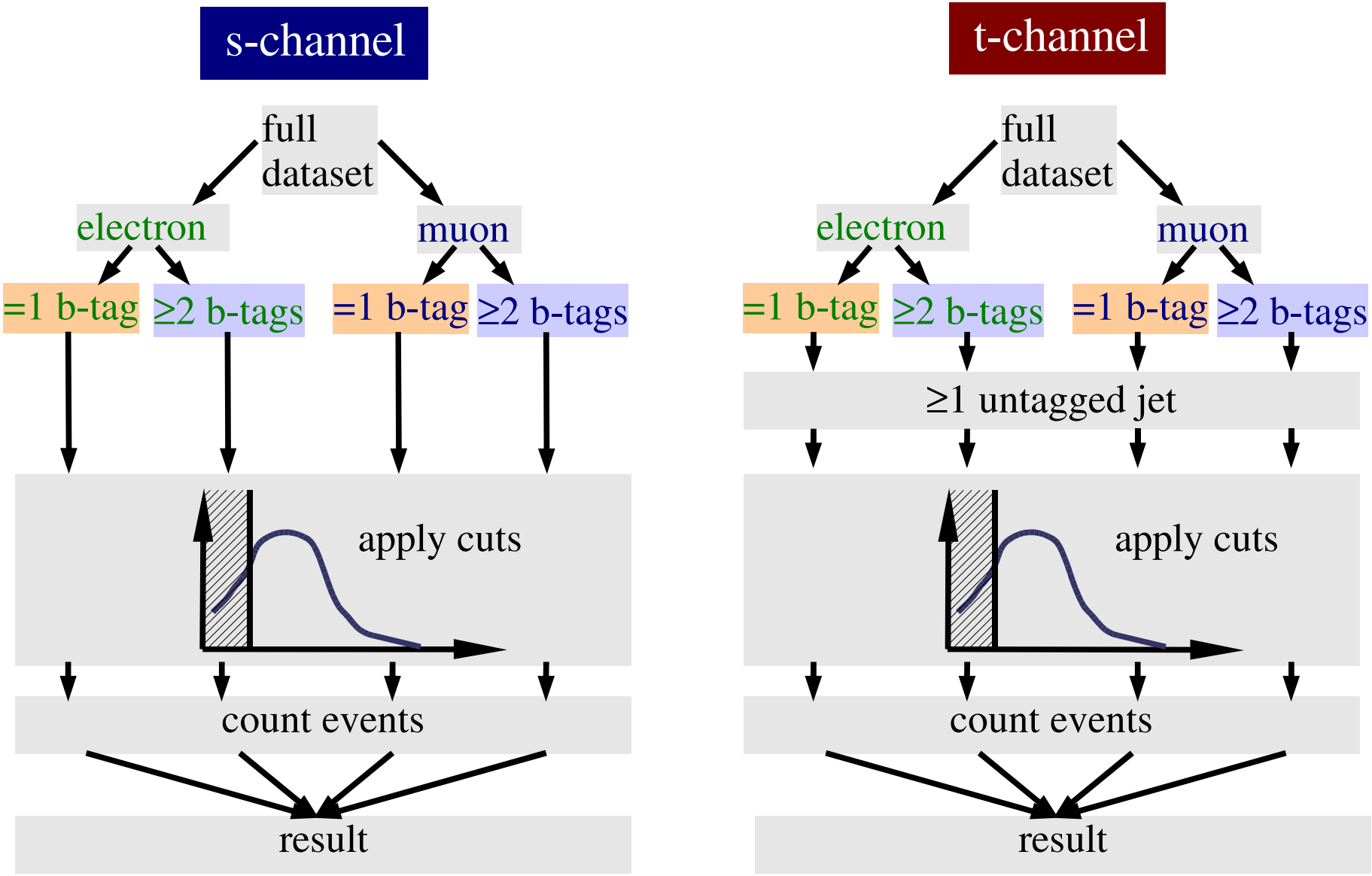


Decision Trees



- Each using the same structure:
  - Optimize separately for s-channel and t-channel
    - Optimize separately for electron and muon channel (same variables)
  - Focus on dominant backgrounds: W+jets, tt
    - W+jets – train on tb-Wbb and tqb-Wbb
    - tt – train on tb – $tt \rightarrow l + \text{jets}$ and tqb – $tt \rightarrow l + \text{jets}$
  - Based on same set of discriminating variables
  - ➔ 8 separate sets of cuts/networks/trees

1. Cut-Based Analysis



1. Cut-Based Analysis

- Cuts on sensitive variables to isolate single top
  - Optimize s-channel and t-channel searches separately
  - Loose cuts on energy-related variables:

$p_T(\text{jet1}_{\text{tagged}})$
$H(\text{alljets} - \text{jet1}_{\text{tagged}})$
$H(\text{alljets} - \text{jet1}_{\text{best}})$
$H_T(\text{alljets})$
$M(\text{top}_{\text{tagged}})$
$M(\text{alljets})$
$M(\text{alljets} - \text{jet1}_{\text{tagged}})$
$\sqrt{\hat{s}}$

	Event Yields	
	s-channel search	t-channel search
s-channel signal	4.5	3.2
t-channel signal	5.5	7
W+jets	103	73
top pairs	28	56
multijet	17	17
Background sum	153±25	149±25
Observed	152	148
Signal/Bkgnd	1:34	1:21

Result

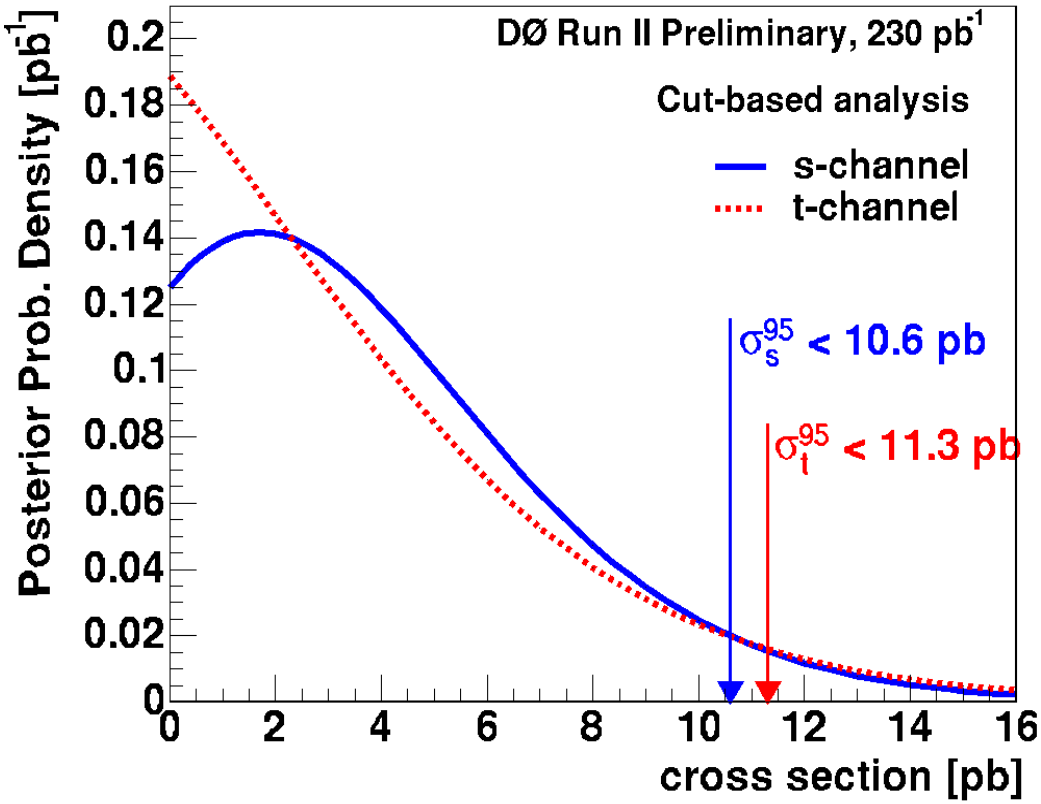
- No evidence for single top signal
  - → Set 95% CL upper cross section limit
  - – Using Bayesian approach
  - – Combine all analysis channels (e, μ, =1 tag, ≥2 tags)
  - – Take systematics and correlations into account

Expected limit: set N_{obs} to background yield

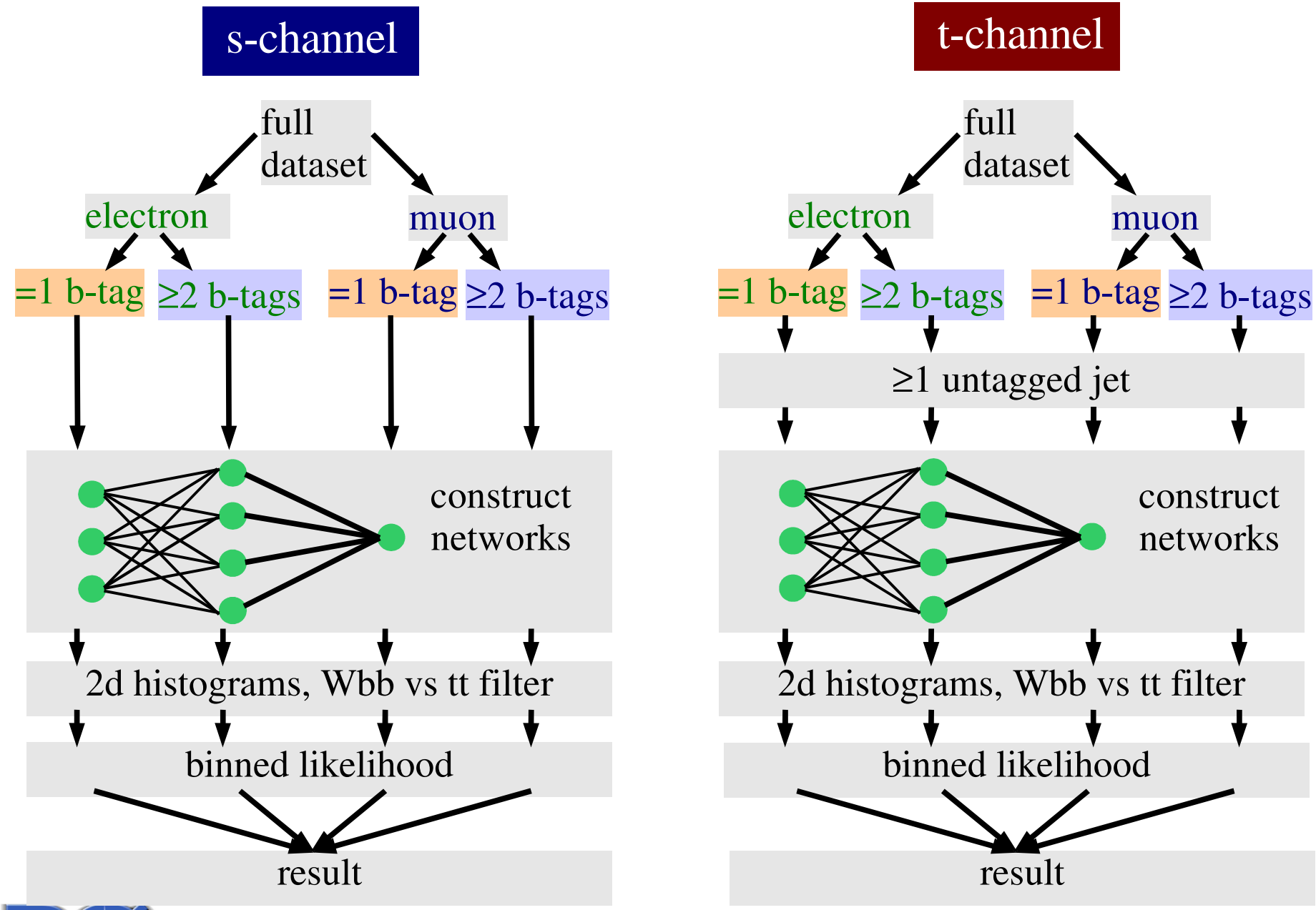
Expected/Observed limit:

σ_s < 9.8 / 10.6 pb

σ_t < 12.4 / 11.3 pb

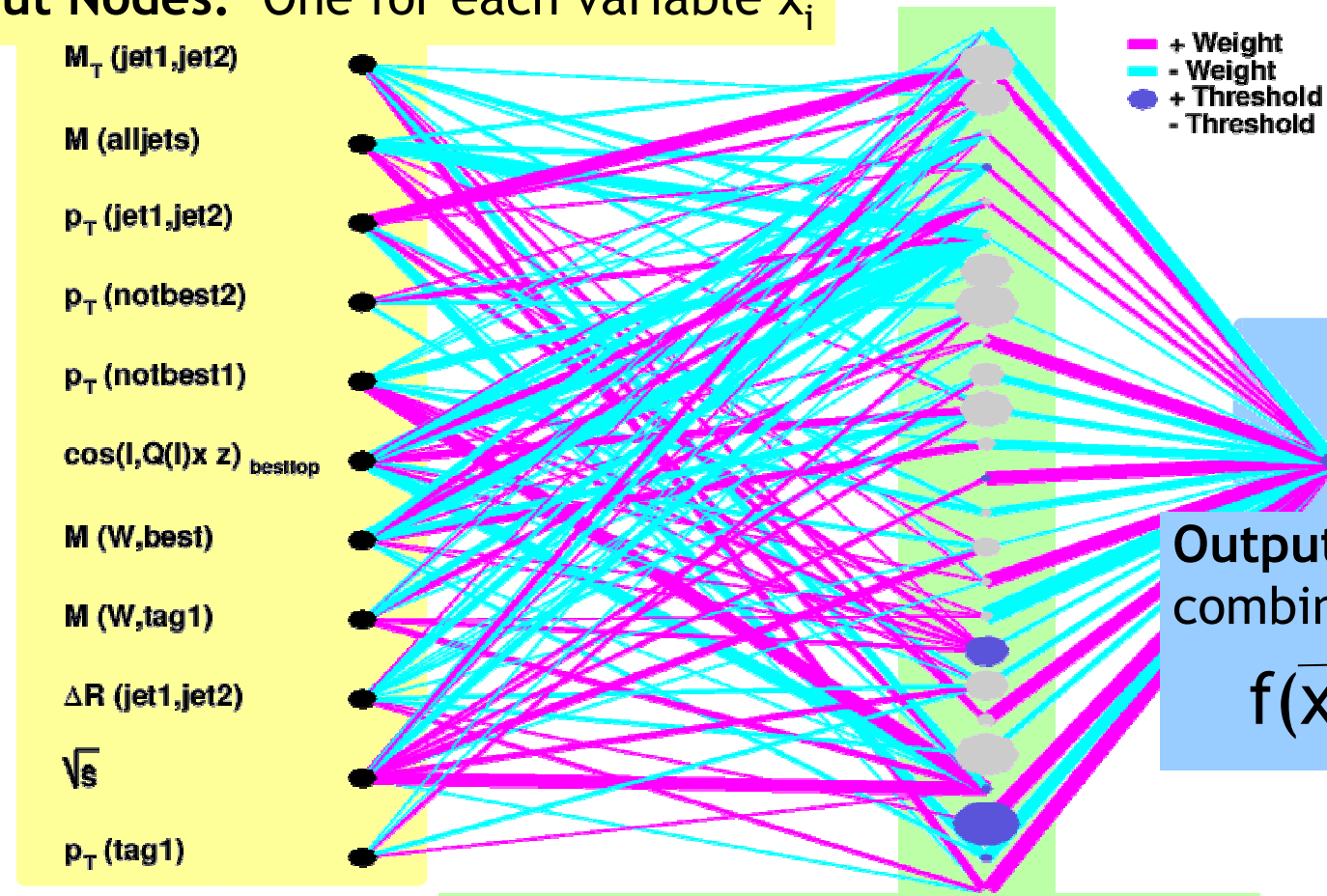


2. Neural Network Analysis



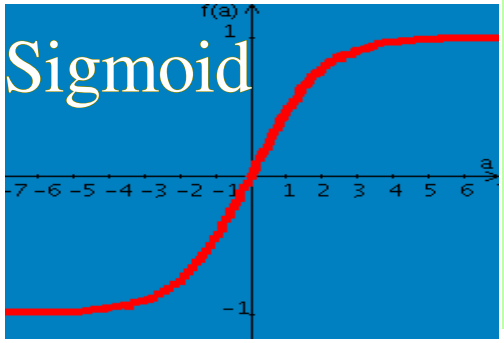
Neural Networks

Input Nodes: One for each variable x_i



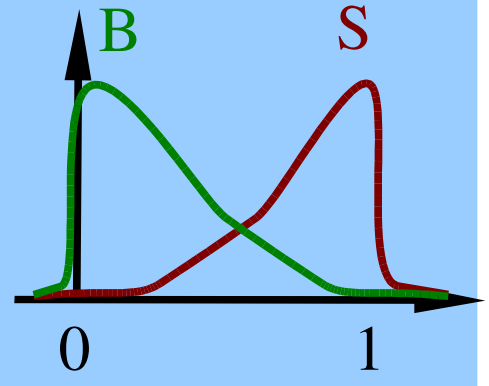
Output Node: linear combination of hidden nodes

$$f(\vec{x}) = \Sigma\, w'_k\, n_k(\vec{x},\vec{w}_k)$$



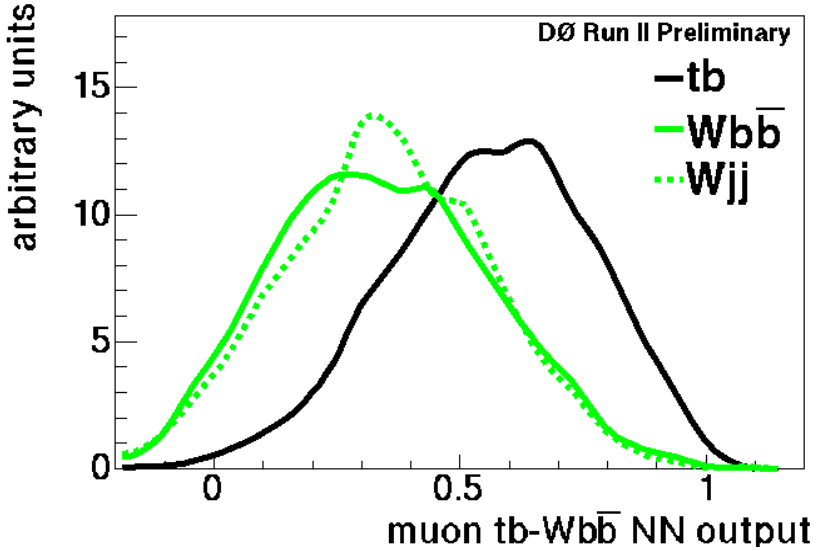
Hidden Nodes: Each is a sigmoid dependent on the input variables

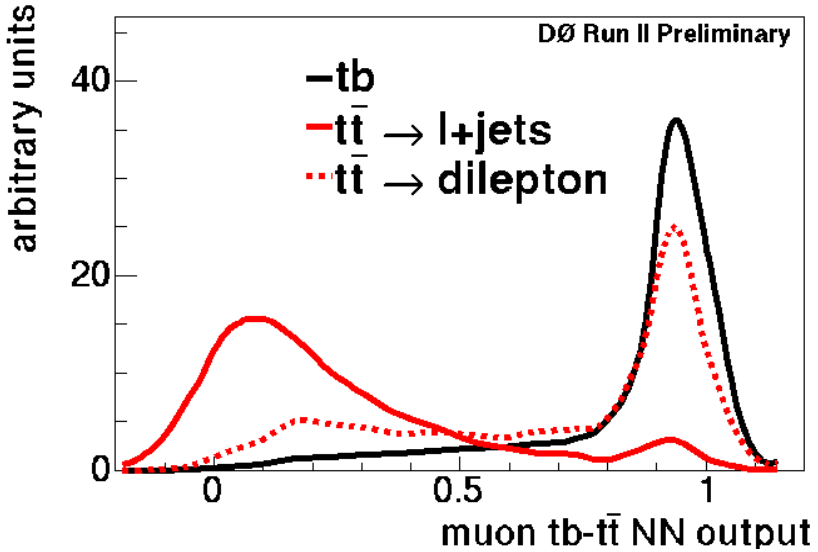
$$n_k(\vec{x},\vec{w}_k) = \frac{1}{1 + e^{-\Sigma\, w_{ik}\, x_i}}$$

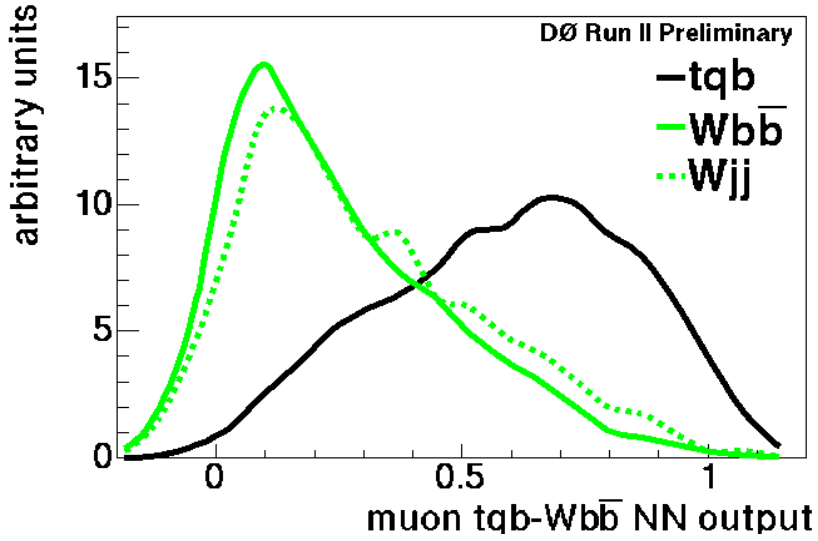


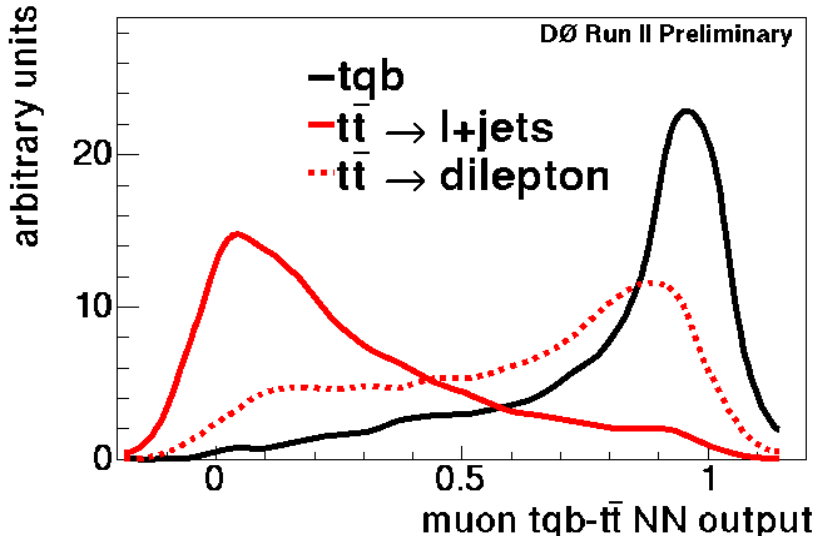
Neural Network Filters

- Focus on the largest backgrounds: Wbb and tt→*l*+jets
- Same variables for electron and muon channel
- Same filter for =1 tag and ≥2 tags

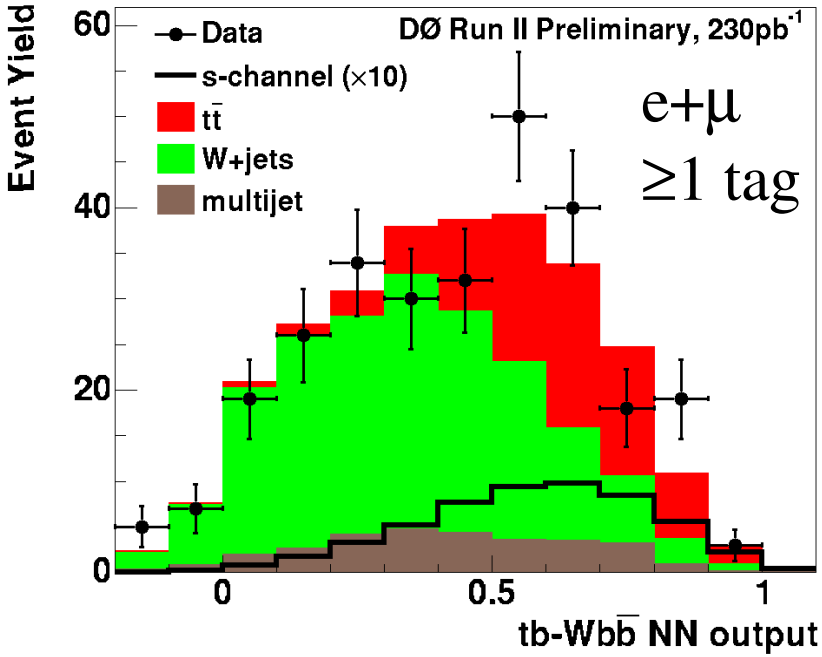


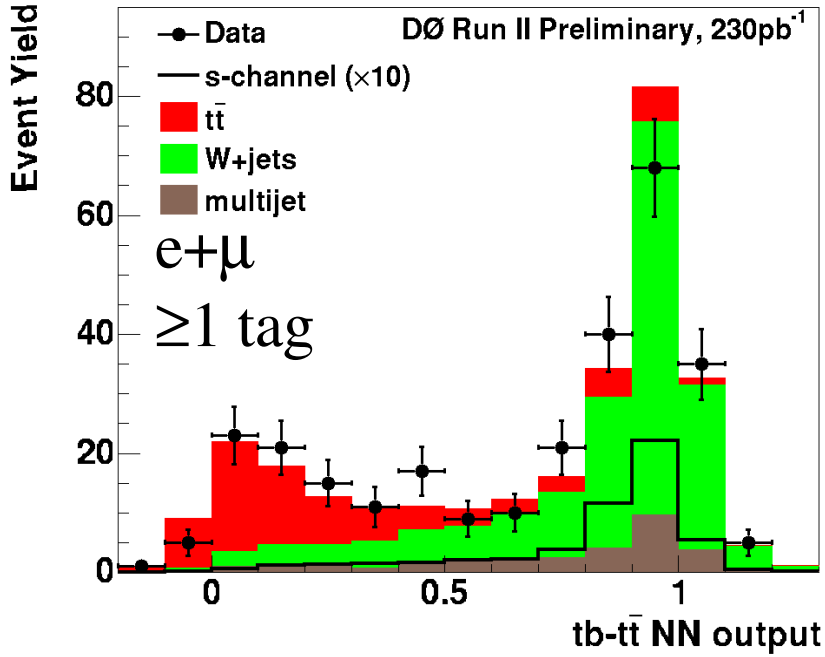


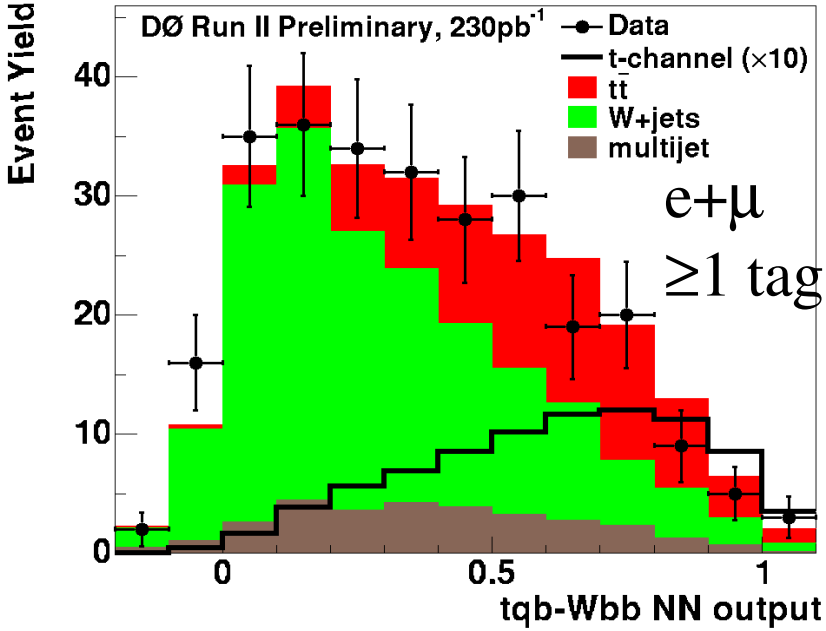


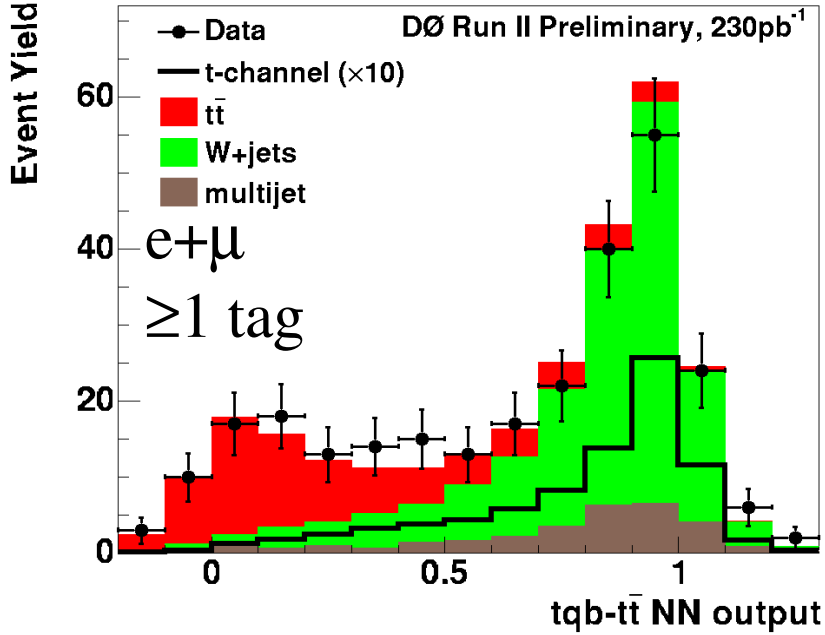


Neural Network Output





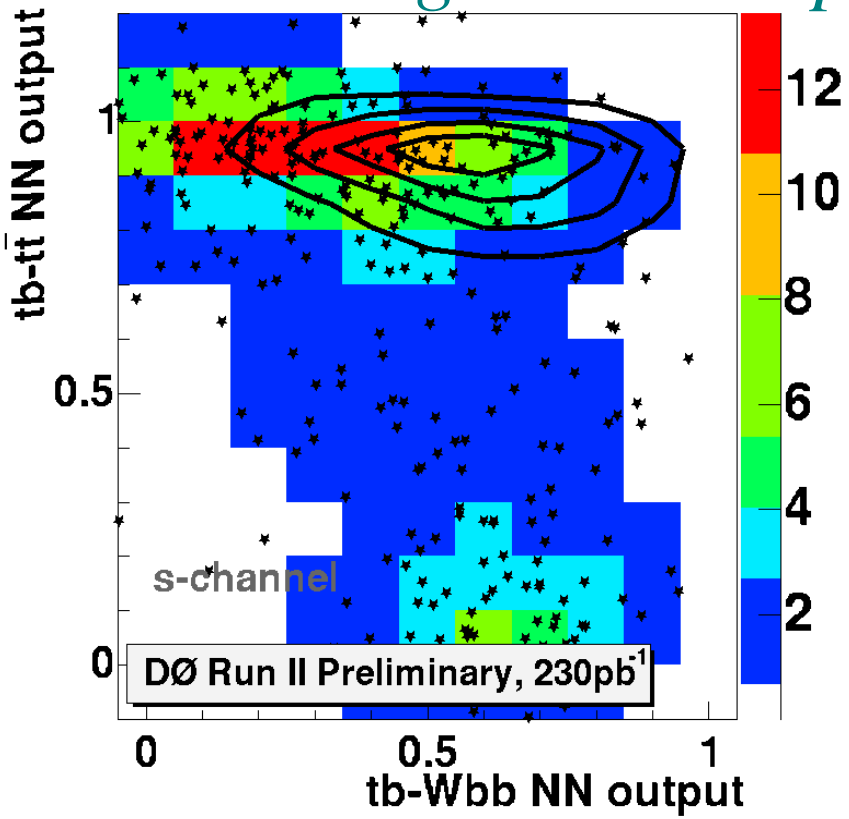


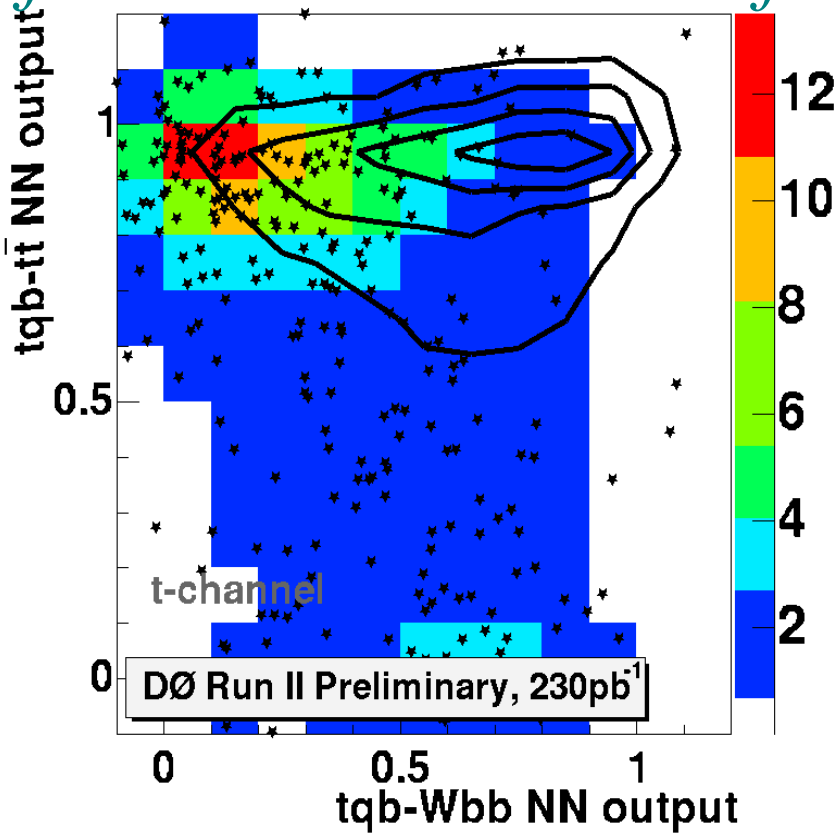


Result

- No evidence for single top signal
  - ➔ Set 95% CL upper cross section limit
  - – Using Bayesian approach in binned likelihood fit
  - – Including bin-by-bin systematics and correlations

2-d histograms as input for binned likelihood fit



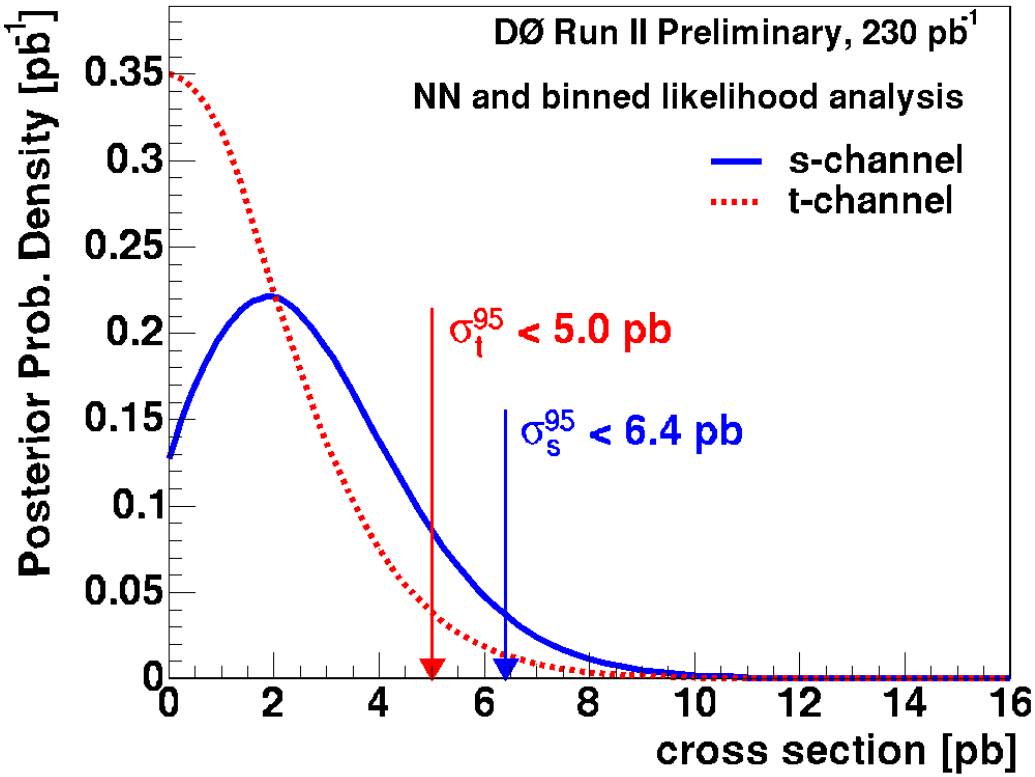


Result

Expected/Observed limit:

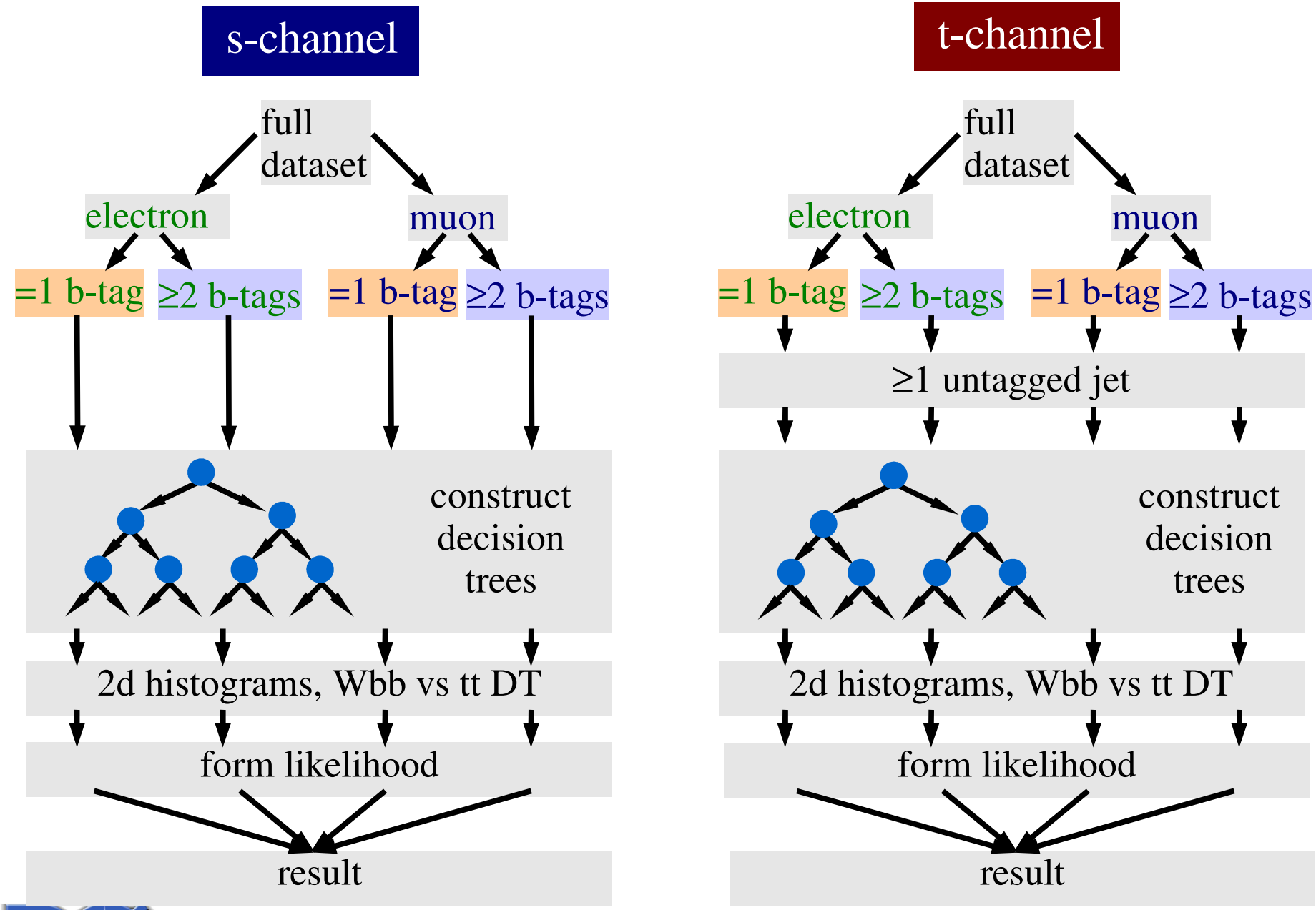
σ_s < 4.5 / 6.4 pb

σ_t < 5.8 / 5.0 pb



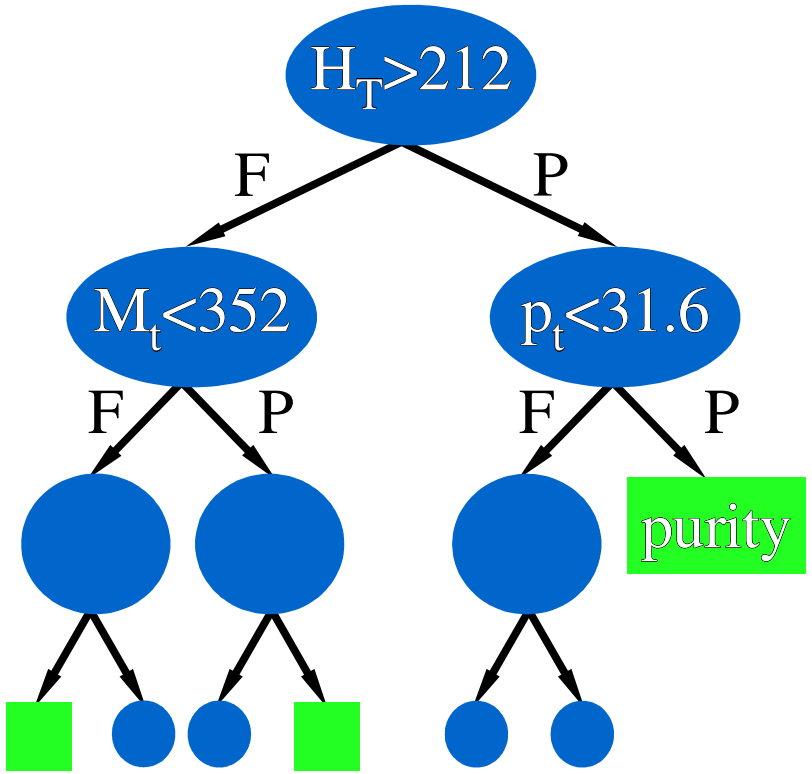
- Most sensitive analysis method
- Improvement compared to cut-based analysis due to:
  - Multivariate analysis
  - Binned likelihood fit

3. Decision Tree Analysis

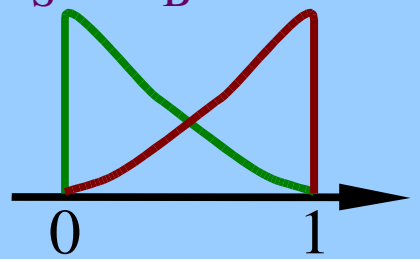


3. Decision Tree Analysis

- For each event, gives probability for an event to be signal
- Widely used in social sciences, recently also in HEP
  - GLAST, Miniboone object ID (see Byron Roe W&C)

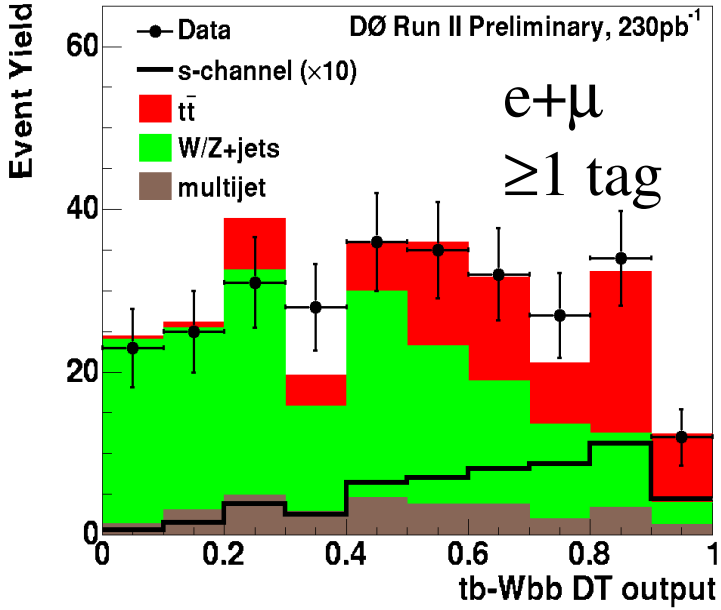


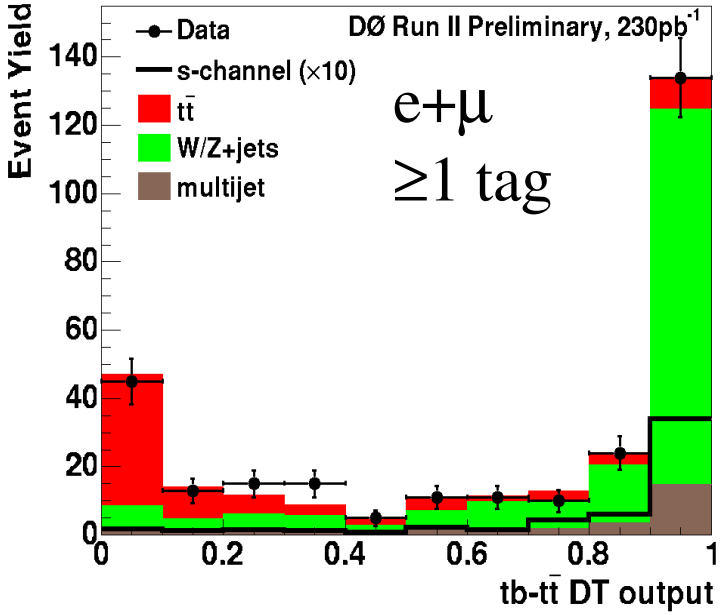
- Send each event down the tree
- Each node corresponds to a cut
  - Pass cut (P): right
  - Fail cut (F): left
- A leaf corresponds to a node without branches
  - Defines purity = $N_S/(N_S+N_B)$
- Training: optimize Gini improvement
  - Gini = $2\, N_S\, N_B\, /(N_S + N_B)$
- Output: purity for each event

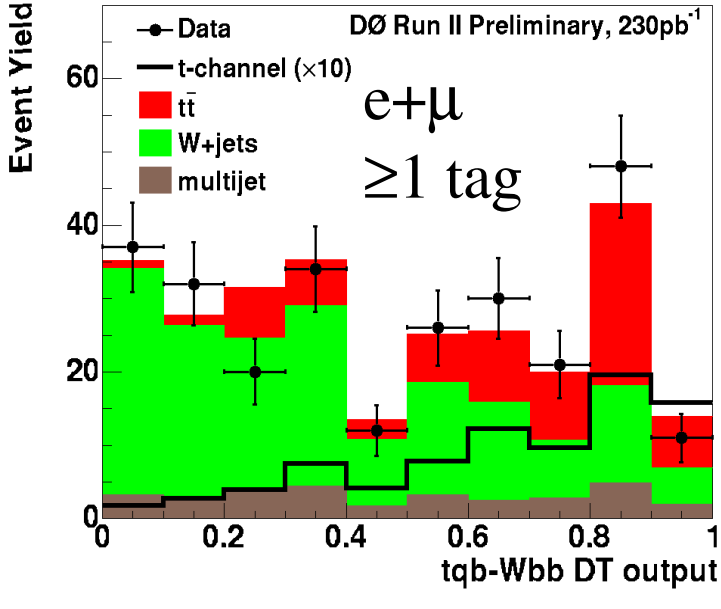


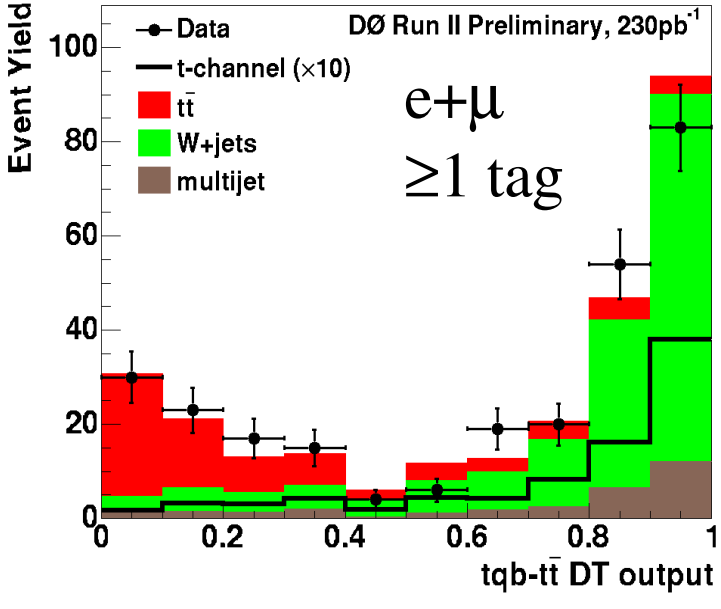
Decision Tree Output

Follow NN approach closely: Same configuration, samples, variables









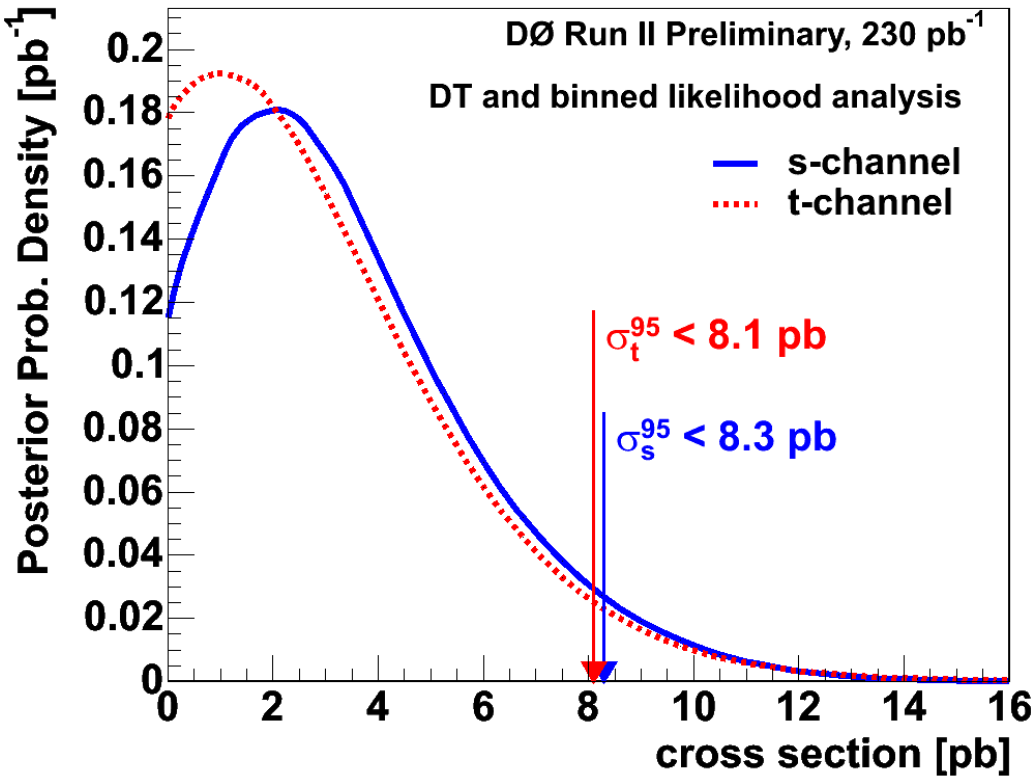
Result

- No evidence for single top signal
  - → Set 95% CL upper cross section limits
  - – Same Bayesian likelihood approach as NN analysis

Expected/Observed limit:

σ_s < 4.5 / 8.3 pb

σ_t < 6.4 / 8.1 pb



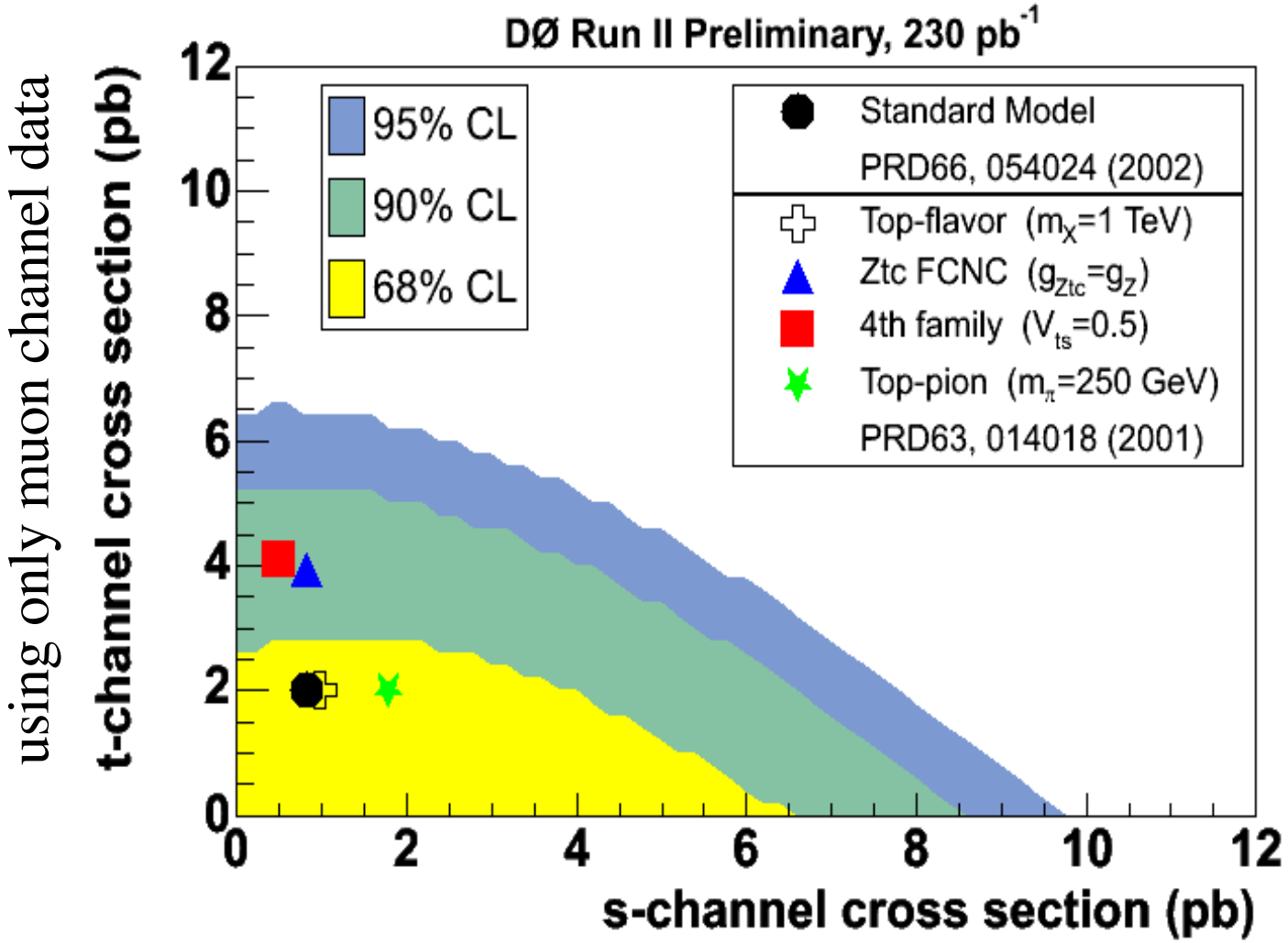
- Sensitivity comparable to Neural Network analysis

Summary

	s-channel	t-channel
NLO cross section	0.88 pb	1.98 pb
95% CL upper cross section limits [pb]		
DØ Run I	17	22
CDF Run II ($160pb^{-1}$)	13.6	10.1
This analysis ($230pb^{-1}$)		
cut-based	10.6	11.3
DTs & binned likelihood	8.3	8.1
NNs & binned likelihood	6.4	5

Sensitivity to non-SM Single Top

using only muon channel data



using only electron channel data

Conclusions/Outlook

- DØ Run II Single Top Analysis with 230pb^{-1} completed
  - Detector, trigger, software etc working and understood
  - 95% CL cross section limits of $\sigma_s < 6.4$ pb, $\sigma_t < 5.0$ pb
  - Factor 2 improvement over previous limits
  - Reaching sensitivity to new Physics
- Single Top is an exciting opportunity for Run II
  - New and old (SM) Physics
- This is just the beginning
  - Expect ×3 dataset by end of year
  - Improve all aspects of the analysis

Dawn of Run II Discoveries