Single Top at the Tevatron

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On behalf of the CDF & DØ collaborations

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Top Quark Production Modes

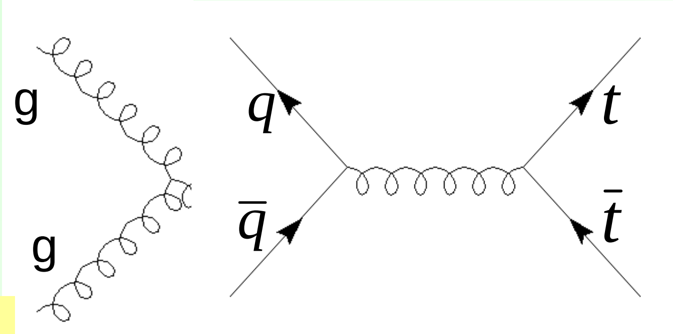
Strong interaction: $t\bar{t}$ **pair**

~85%

Dominant mode $\sigma_{NLO+NLL}$ = 6.7 ± 1.2 pb

Relatively clean signature,

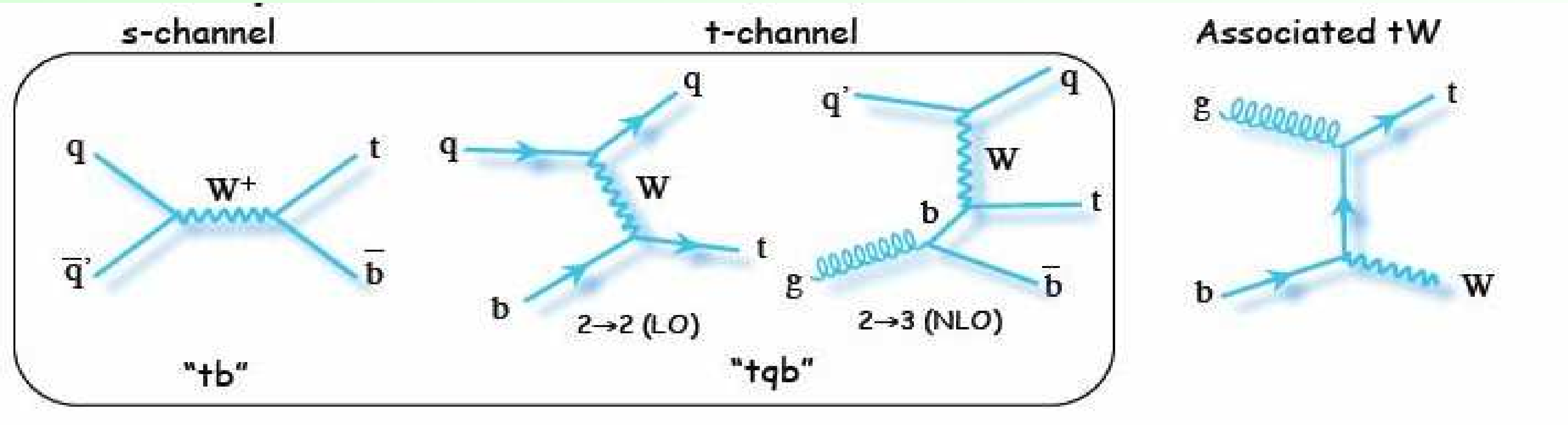
discovery in 1995



~15%

Electroweak interaction: **single top**

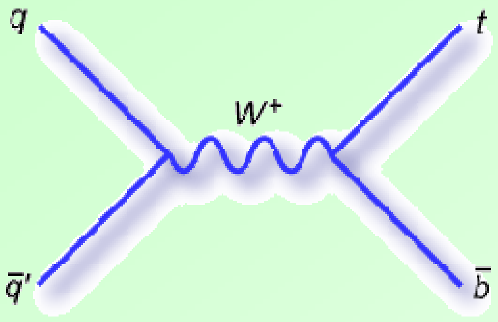
Larger background, smaller cross section → not yet observed !



Top Quark EWK Production

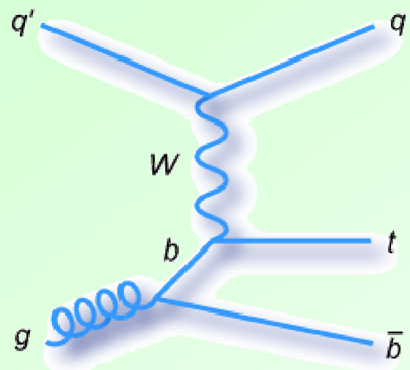
s -channel

$q\bar{q} \rightarrow W^* \rightarrow t\bar{b}$



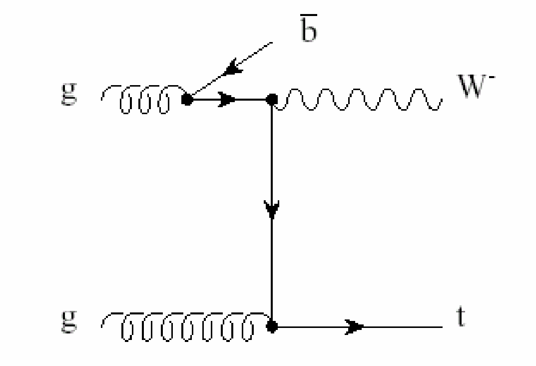
t -channel

$qb \rightarrow q' t$



tW associated production

$bg \rightarrow tW^-$



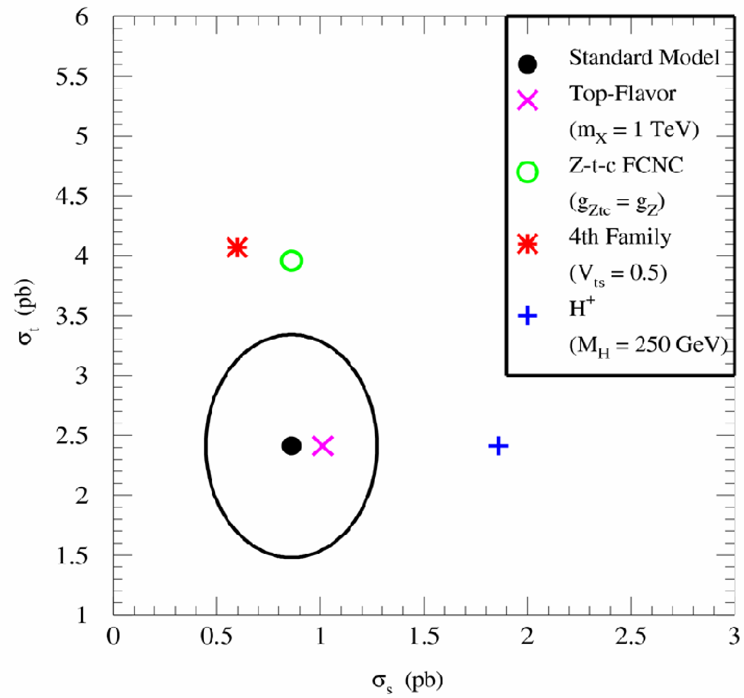
$(m_{top}=175\ GeV/c^2)$		s-channel	t-channel	Associated tW	Combine (s+t)
Tevatron σ_{NLO}		0.88 ± 0.11 pb	1.98 ± 0.25 pb	~ 0.1 pb	
LHC σ_{NLO}		10.6 ± 1.1 pb	247 ± 25 pb	62^{+17}_{-4} pb	
RunI	CDF	< 18 pb	< 13 pb		< 14 pb
95% C.L.	D0	<17 pb	< 22 pb		

B.W. Harris et al.:Phys.Rev.D66,054024 T.Tait: hep-ph/9909352
Z.Sullivan Phys.Rev.D70:114012 Belyaev,Boos: hep-ph/0003260

Why Single Top?

Observation of single top allows direct access to V_{tb} CKM matrix element

- cross section $\propto |V_{tb}|$
- study top-polarization and EWK top interaction



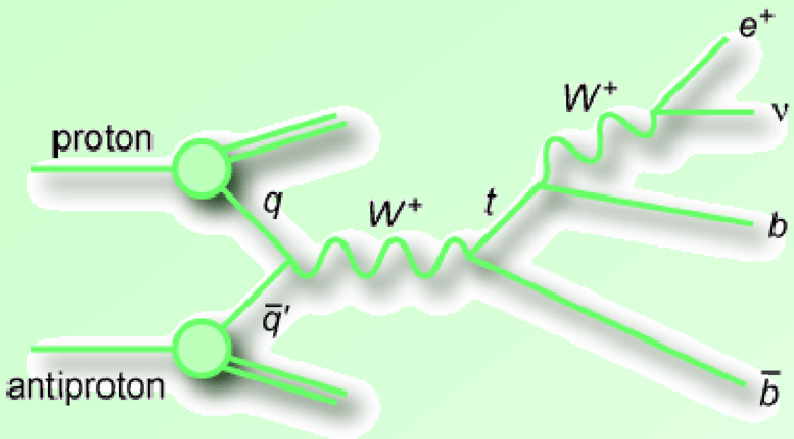
Test non-SM phenomena

- 4th generation
- FCNC couplings like $t \rightarrow Z/\gamma\, c$
- heavy W' boson
- anomalous Wtb couplings

Potentially useful for Higgs searches

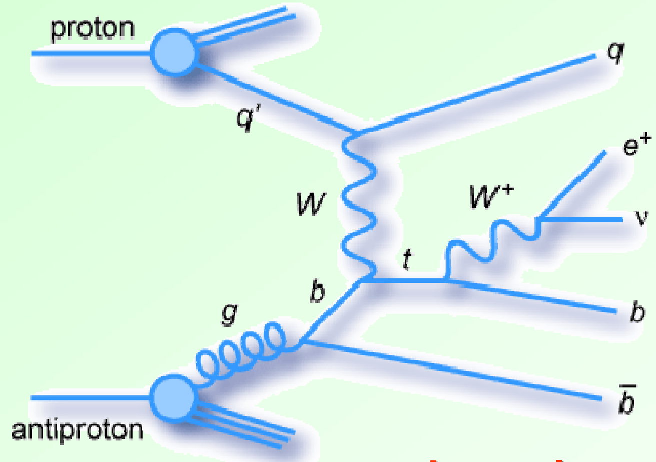
- single top has same final state as Higgs+W (associated) production

Single Top Signature & Background



s-channel

- **$\bar{b}$ quark produced WITH the top**
- **b quark from the top decay**
- **lepton + Missing E_T**



t-channel

- **b quark from the top decay**
- **lepton + Missing E_T**
- **extra light quark**
- **at NLO an additional $\bar{b}$ is radiated**

Backgrounds:

- W/Z + jets production
- Top pair production
- Multijet events

CDF Search Strategy

696 pb^{-1}

- **W selection:**
  - E_T > 20 GeV/c (central and forward electrons)
  - p_T > 20 GeV/c (central muons)
  - Missing E_T > 20 GeV
- **Jets selection:**
  - Exactly 2 jets, at least one is b-tagged
  - Jet E_T > 15 GeV, $|\eta| < 2.8$

Separate Channel Search

2D Neural Network discriminant

+ likelihood fit

Combined Channel Search

1D Neural Network discriminant

+ likelihood fit (Bayesian approach)

Systematics and Event Selection Efficiencies

Source	t-channel	s-channel	$t\bar{t}$
JES	1.8%	1.2%	9.4%
ISR	1%	2%	
FSR	5%	1%	
PDF	2.5%	2.2%	2.4%
MC	2%	1%	
M_{top}	4%	4%	
ϵ_{evt}	10.3%	8%	

Combined (s- and t- channels)

Expected signal	28.2 ± 2.6 events
Expected backg	645.9 ± 96.1 events
Observed	**689 events**

Events detection efficiency(*)

s-channel 1.87 ± 0.15%

t-channel 1.21 ± 0.17%

(∗) Including W→leptons BR

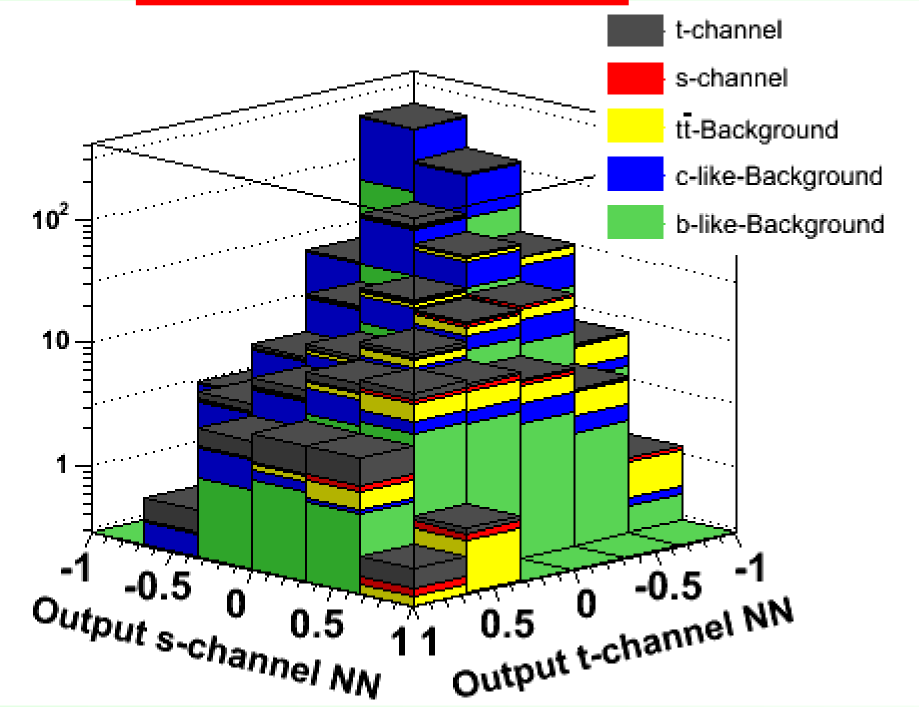
Separate Channel Search with Neural Network

Separation of t-channel and s-channel single-top is important:

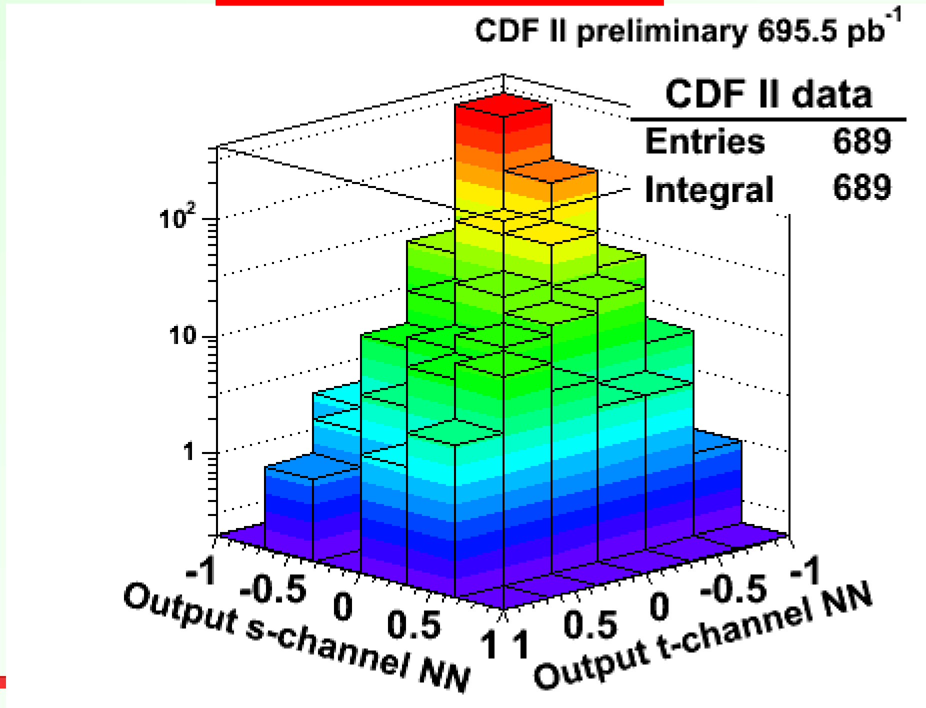
→ **different sensitivity to physics beyond the standard model**

CDF uses *2 networks trained for t- and s-channel ⇒ the creation of the templates for signal and background processes is done in 2dim for both network outputs simultaneously!*

Total expectation



Outputs of data



2dim Likelihood Fit

To the network 2D output,

CDF applies a maximum

likelihood fit

and the best fits for t- / s-channel

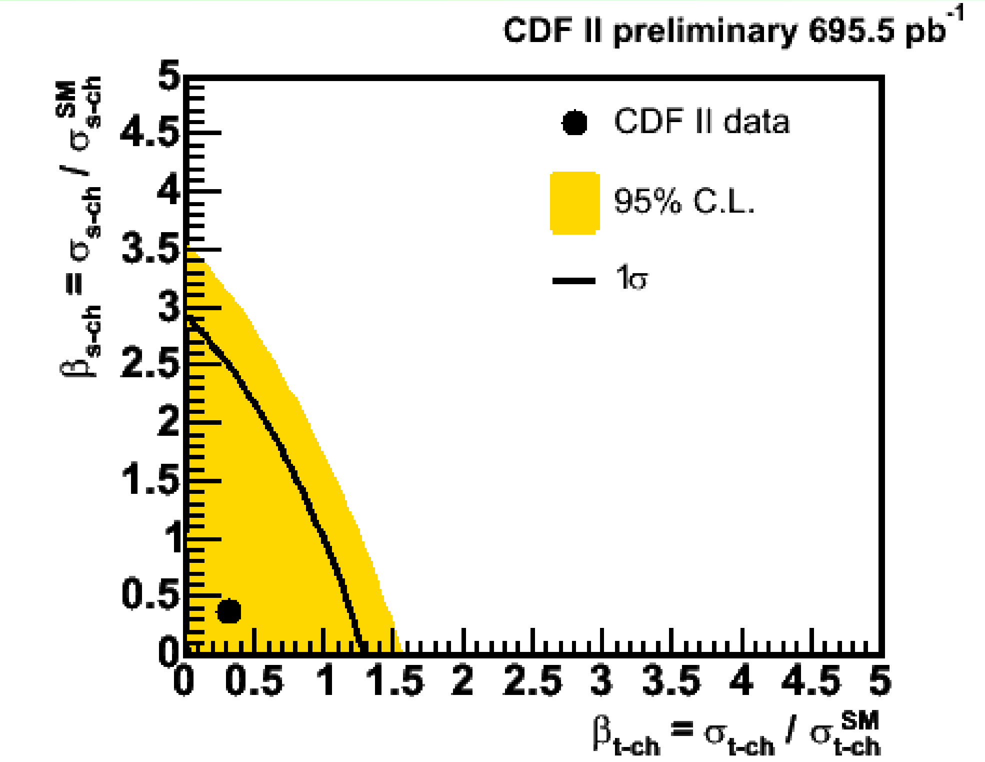
are:

t-channel:

$$\sigma_{t-ch} = 0.6^{+1.9}_{-0.6}(stat)^{+0.1}_{-0.1}(syst)pb$$

s-channel:

$$\sigma_{s-ch} = 0.3^{+2.2}_{-0.3}(stat)^{+0.5}_{-0.3}(syst)\ pb$$



The resulting upper limits are

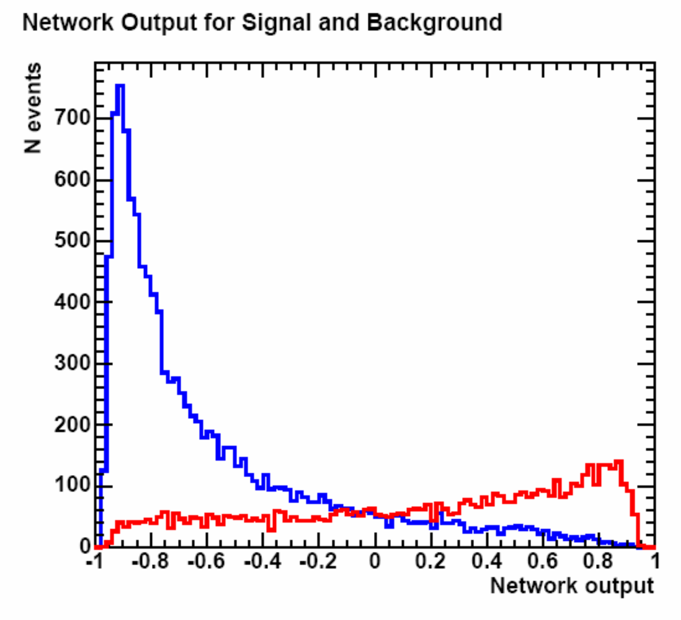
t-channel:

σ < 3.1 pb @ 95% C.L.

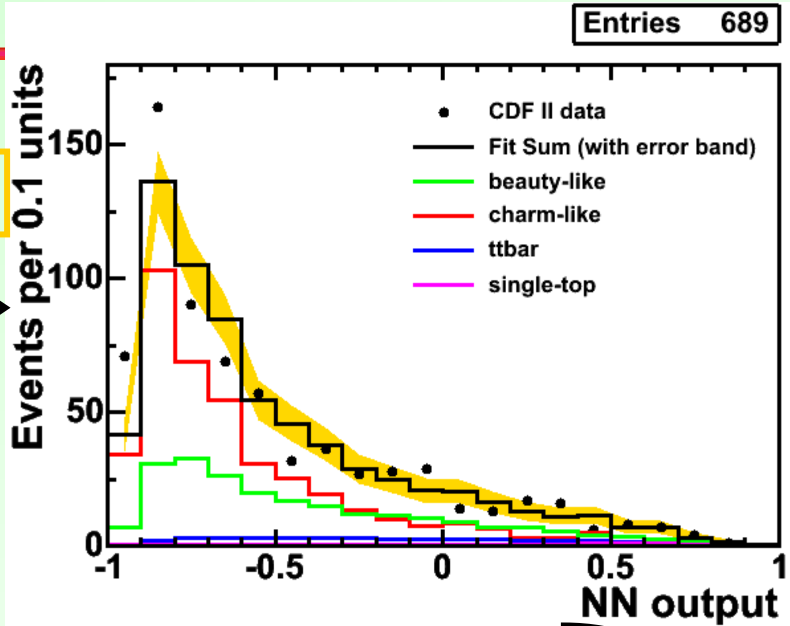
s-channel:

σ < 3.2 pb @ 95% C.L.

Combined Channel Search with Neural Network



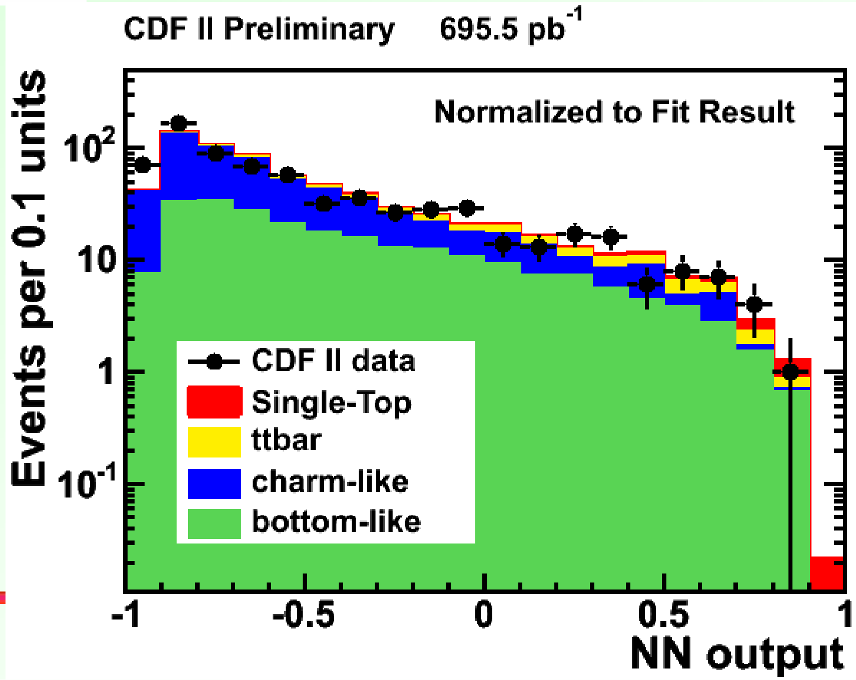
Likelihood fit



For the **combined search**, CDF uses

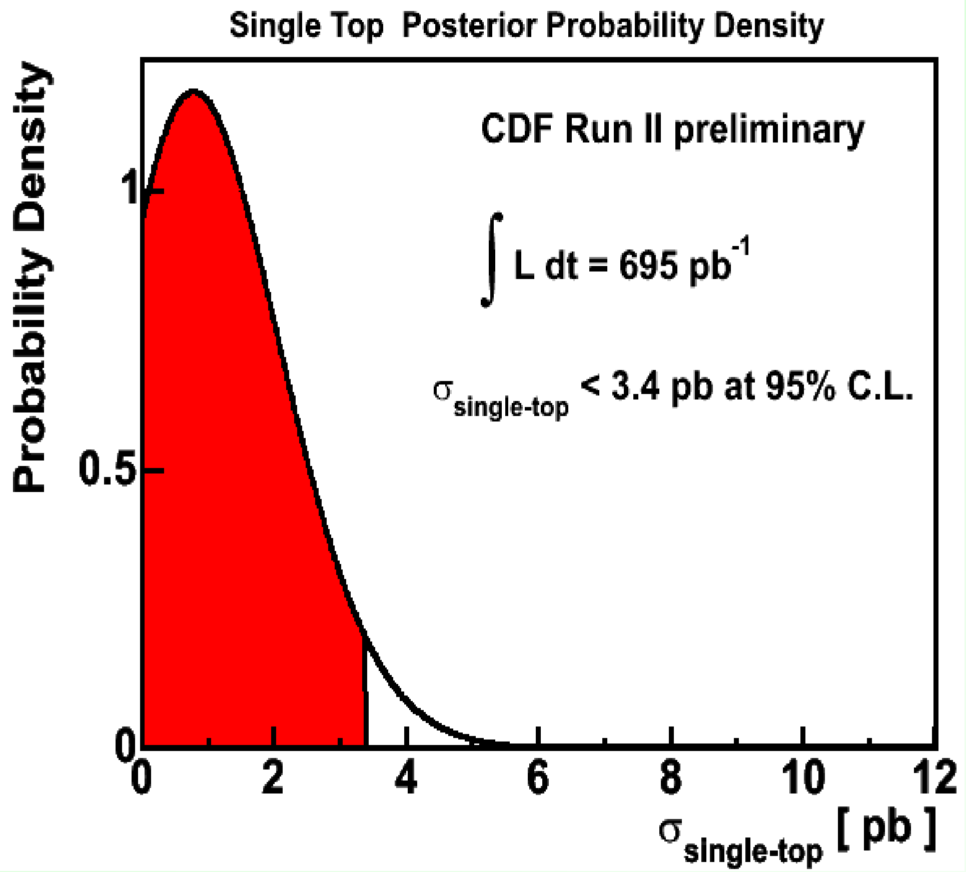
1 network

trained with t-channel



Fit result!

Bayesian interpretation of the NN output histogram



Best fit value:

$$\sigma_{t+s} = 0.8^{+1.3}_{-0.8}(stat)^{+0.2}_{-0.3}(syst)pb$$

The resulting upper limit on the cross section is:

$\sigma_{single\text{-}top}$ < 3.4 pb at 95% C.L.

370 pb^{-1}

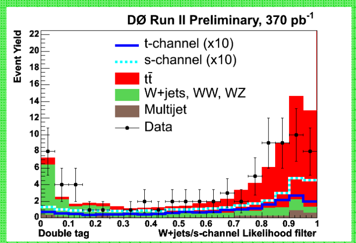
DØ Search Strategy

s/t channel

Full dataset

electron → **slection** → **=1btag** / **≥2btag**

muon → **selection** → **=1btag** / **≥2btag**



Likelihood Discriminant method

2d histograms: W+jet / tt filter

Binned likelihood limit calculation

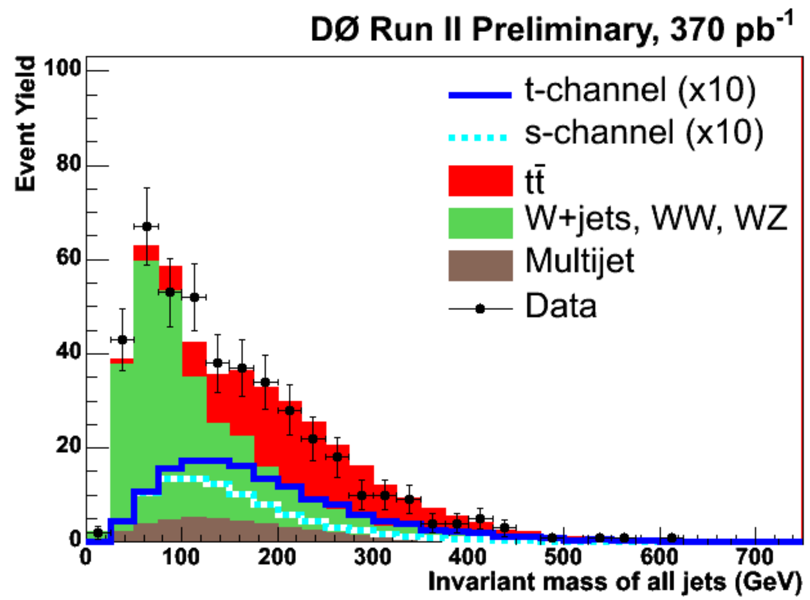
Bayesian limit

Lepton	e p_T > 15 GeV $\lvert\eta\rvert$ < 1.1 μ p_T > 15 GeV $\lvert\eta\rvert$ < 2.0
Neutrino	ME_T > 15 GeV
Jets	2 ≤ Njets ≤ 4 p_T > 15 GeV $\lvert\eta\rvert$ < 3.4 leading jet p_T > 25 GeV and $\lvert\eta\rvert$ < 2.5
Btag	1 or ≥ 2 b-tags

For both s-channel and t-channel:

- **2 sets of data based on final state lepton flavor (electron or muon)**
- **for each set, considered single-tagged (=1tag) events from double-tagged (≥2 tags) events**

In the t-channel, at least one untagged jet



Sample composition

Source	s-channel search	t-channel search
tb	5.5 ± 1.2	4.7 ± 1.0
tqb	8.6 ± 1.9	8.5 ± 1.9
W+jets	169.1 ± 19.2	163.9 ± 17.8
$t\bar{t}$	78.3 ± 17.6	75.9 ± 17.0
Multijet	31.4 ± 3.3	31.3 ± 3.2
Total background	287.4 ± 31.4	275.8 ± 31.5
Observed events	283	271

S/B~2-3%

Bkg domninated by non-top events (~70%)

Monte Carlo Systematic Uncertainties	
Components affecting normalization	
$\sigma_{t\bar{t}}$ theory and mass	18 %
$\sigma_{s(t)}$ theory	15 %(16 %)
Jet Fragmentation	5 %
e (μ) ID	4 %(5 %)
Components affecting shape and normalization	
Single (double) b-tagging modeling	6 %(17 %)
Jet Energy Scale	1-5 %
Trigger Modeling	2-7 %
Jet ID	1-4 %

Event detection efficiency:

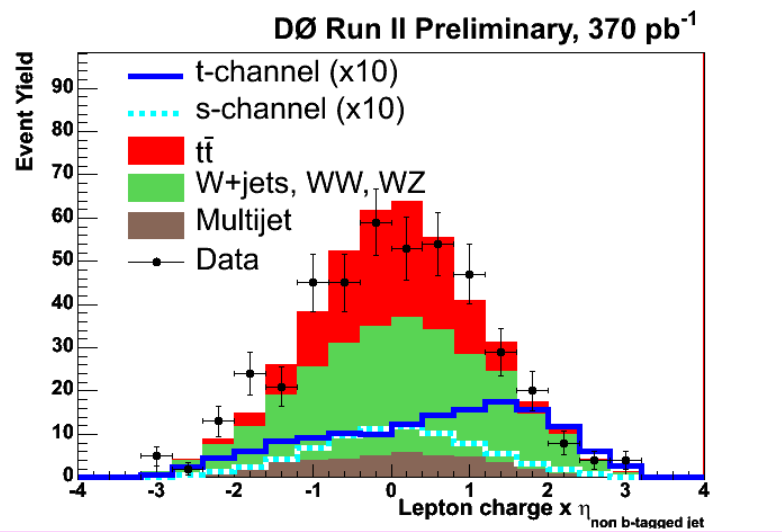
- **s-channel $2.7 \pm 0.2\%$**
- **t-channel 1.9 ± 0.2 %**

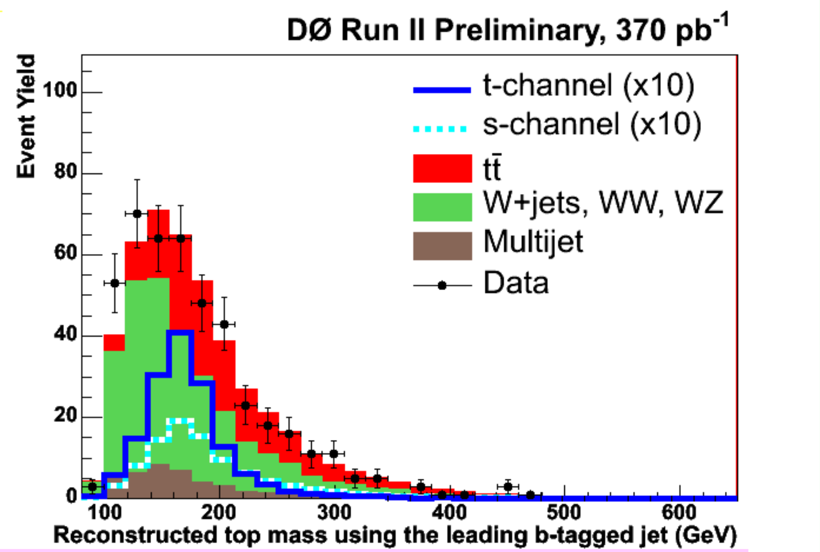
Total syst.	**=1tag**	**$\geq$ 2 tags**
Signal acceptance	**15%**	**25%**
Background sum	**10%**	**26%**

Likelihood Discriminant Method for Separate Channel search

Study various kinematic observables that have a discriminating power against W+jj and tt-bar processes

- Example: (Qℓ·η) and top mass

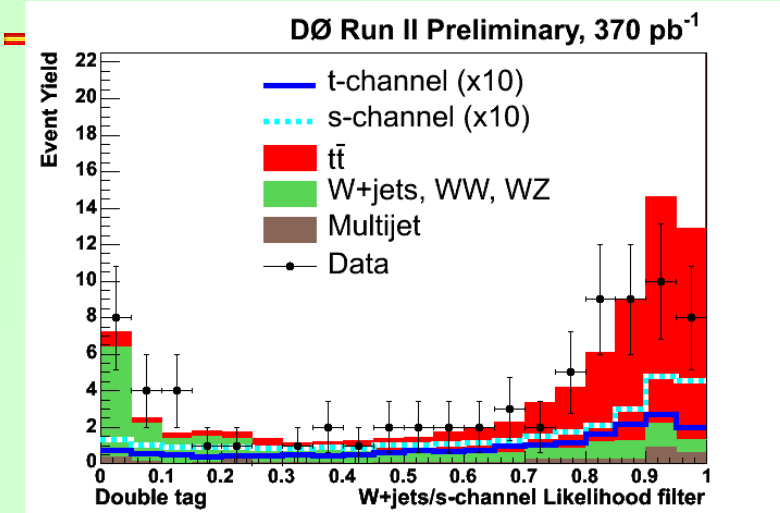


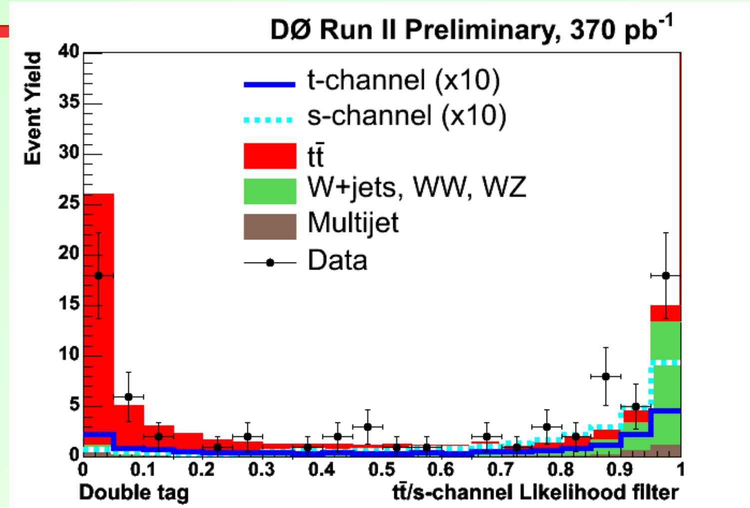


Design 16 likelihood discriminants for S/B separation:

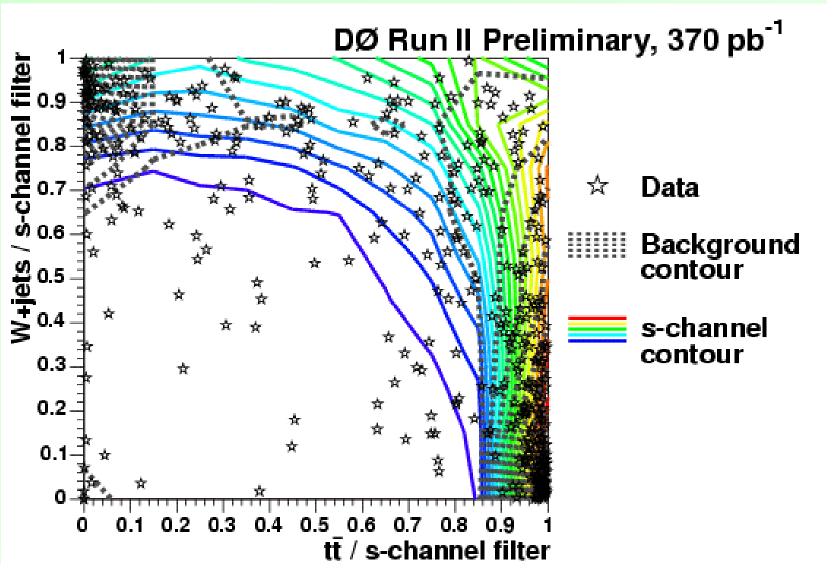
- **4 signal/background pairs: s-channel and t-channel / W+jj and tt-bar**
- **2 b-tagging schemes: 1-tag and 2-tags**
- **2 lepton flavors: electron and muon**

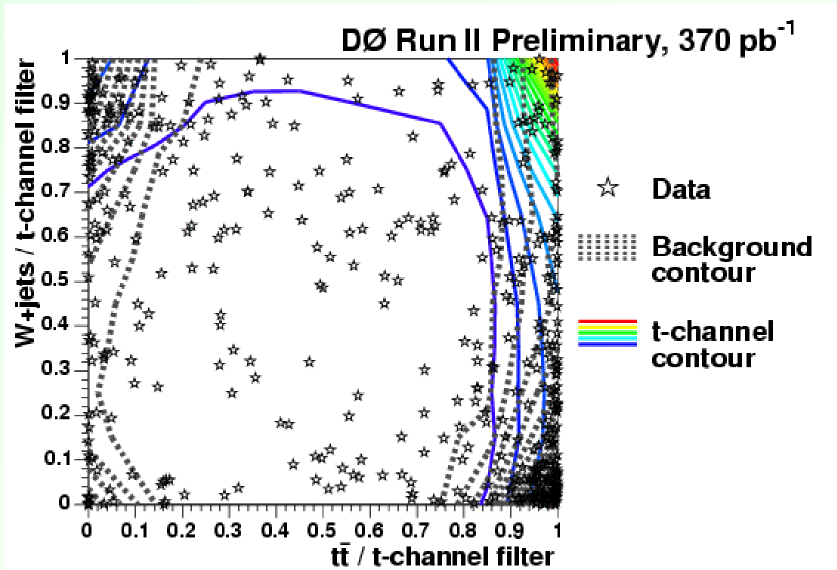
DØ Results



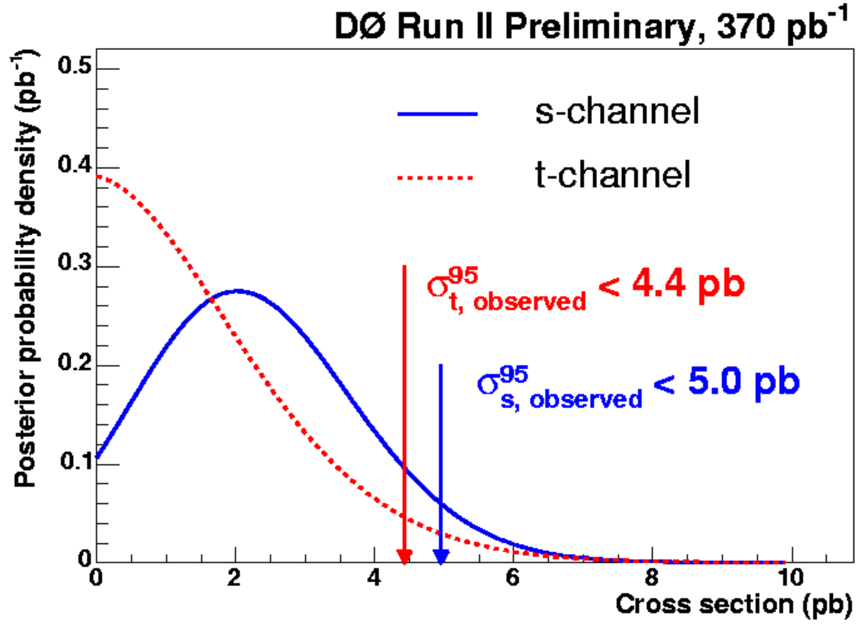


combine results of likelihood discriminants in 2D histograms





NO evidence for a signal, extract limits on cross-section!

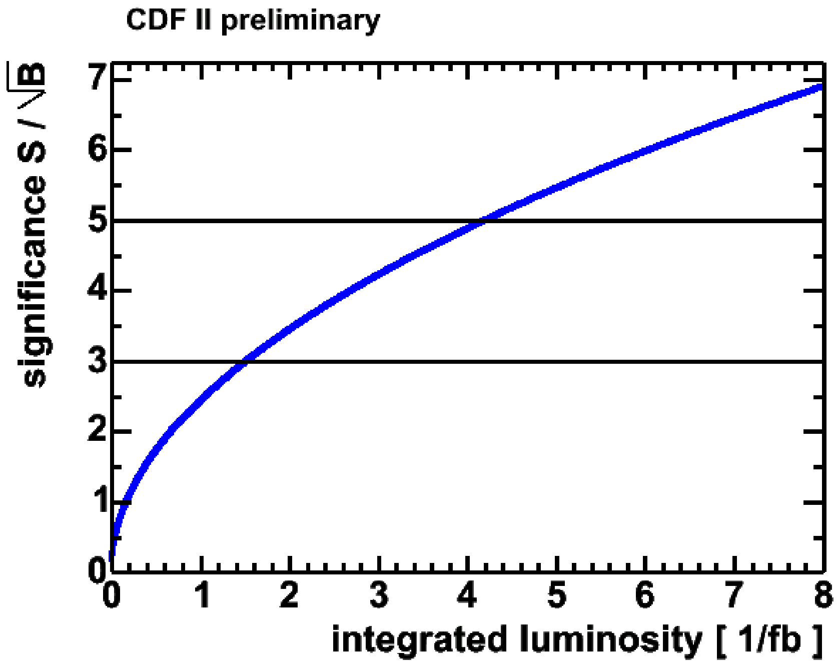


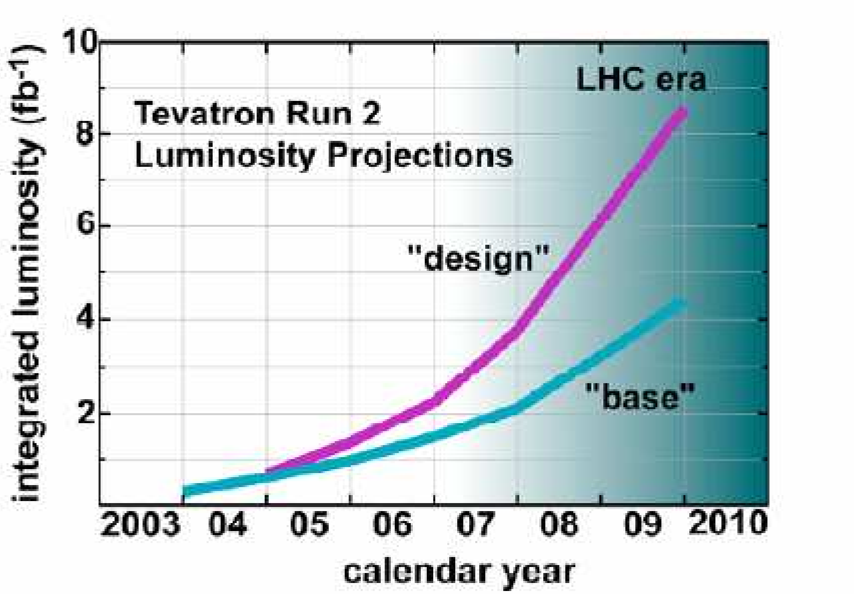
95% CL Bayesian Limits

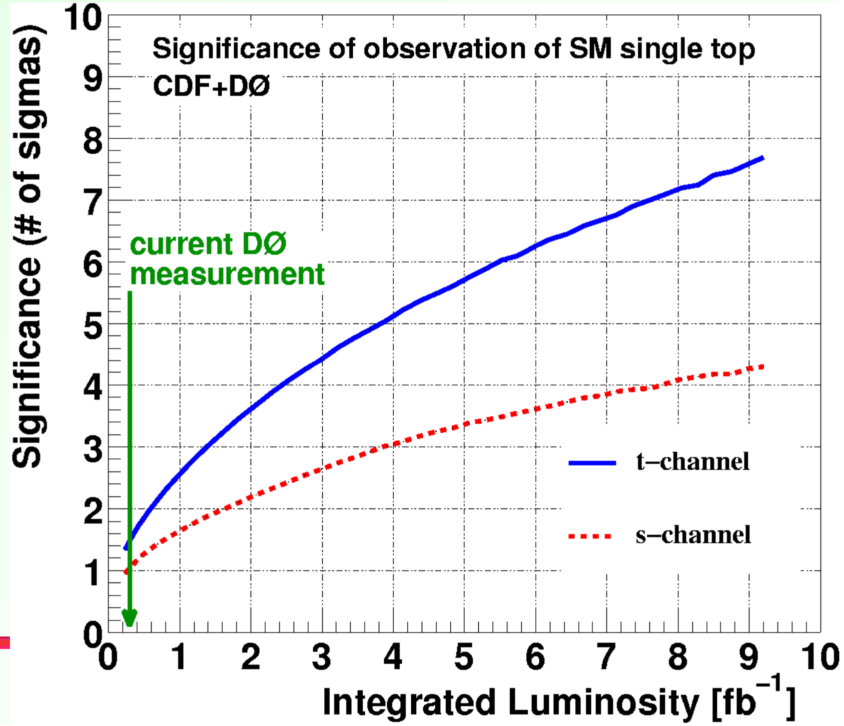
95% Confidence Level Expected/Measured Upper Limits in pb (after final selections, with systematics, using Bayesian statistics)			
		s-channel	**t-channel**
Likelihood Discriminant	Electron	5.8	7.6
	Muon	6.4	5.0
	Combined	**5.0**	**4.4**

Projections

- Assume no improvement in analysis technique, methods, and resolution:
  - It will take 1.5 fb^{-1} of data to have an evidence for a single top production for one experiment!
- Both experiments have more than 1 fb^{-1} on tape!







Summary

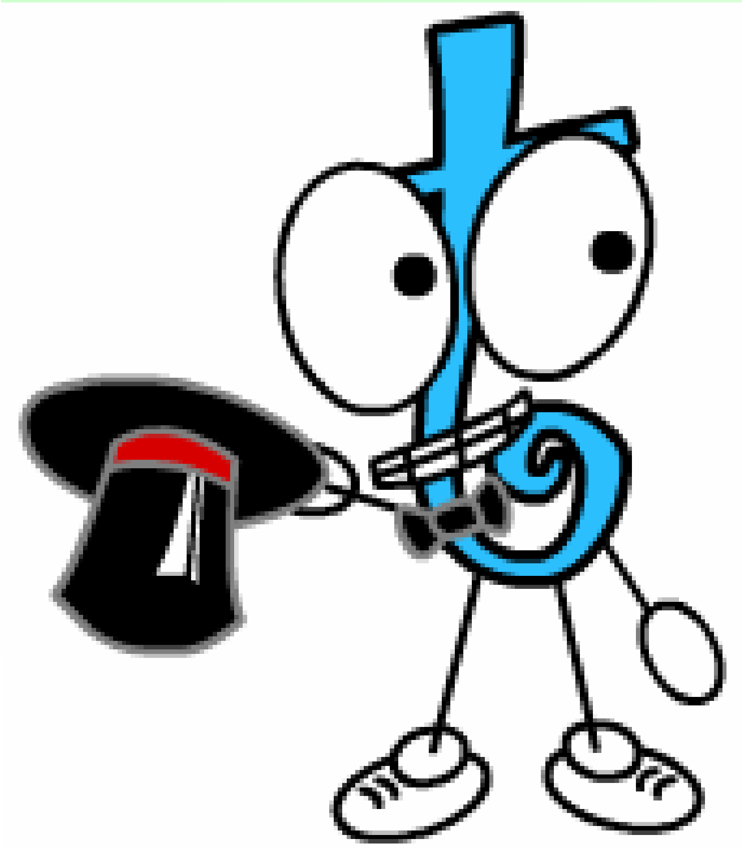
- **Current analyses not only provide drastically improved limits on the single top cross-section, but set all necessary tools and methods toward discovery with larger data sample!**

95% C.L. limits on single top cross-section

Channel	CDF (696 pb^{-1})	DØ (370 pb^{-1})
Combined	3.4 pb	
s-channel	3.2 pb	5.0 pb
t-channel	3.1 pb	4.4 pb

- **Both collaborations aggressively work on improving the results!**

Single Top Discovery is feasible in RunII !!!!

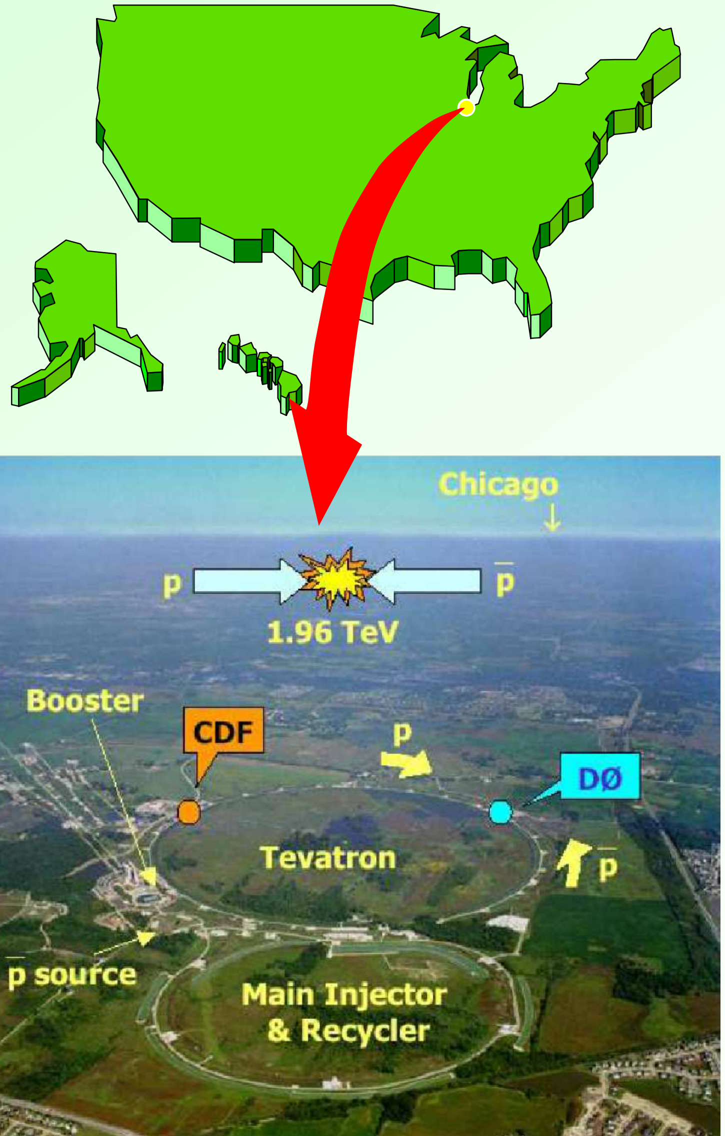


Thanks for your attention!

Backup Slides

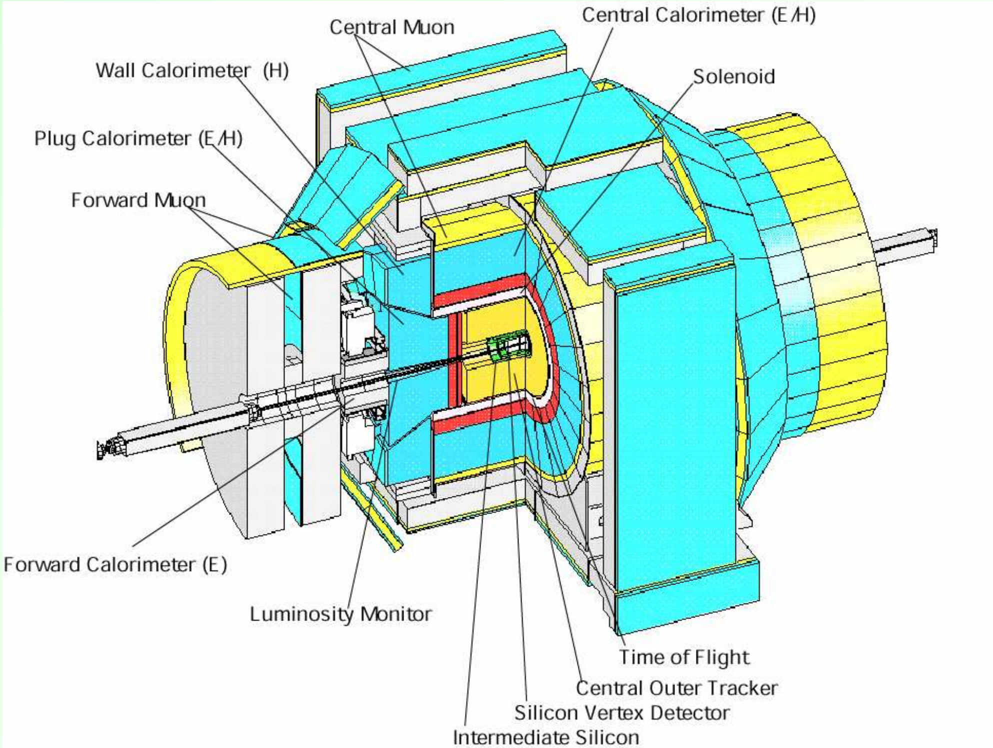
Tevatron $p\bar{p}$ collider

	Run I	Run IIa	Run IIb
Bunches / turn	6×6	36×36	36×36
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Luminosity ($cm^{-2}s^{-1}$)	1.6×10^{30}	1×10^{32}	3×10^{32}
$\int Ldt$ (pb^{-1}/week)	3	17	50
Crossing time (ns)	3500	396	396
Interactions/crossing	2.5	2.3	8
Duration	92/96	01/06	06/09

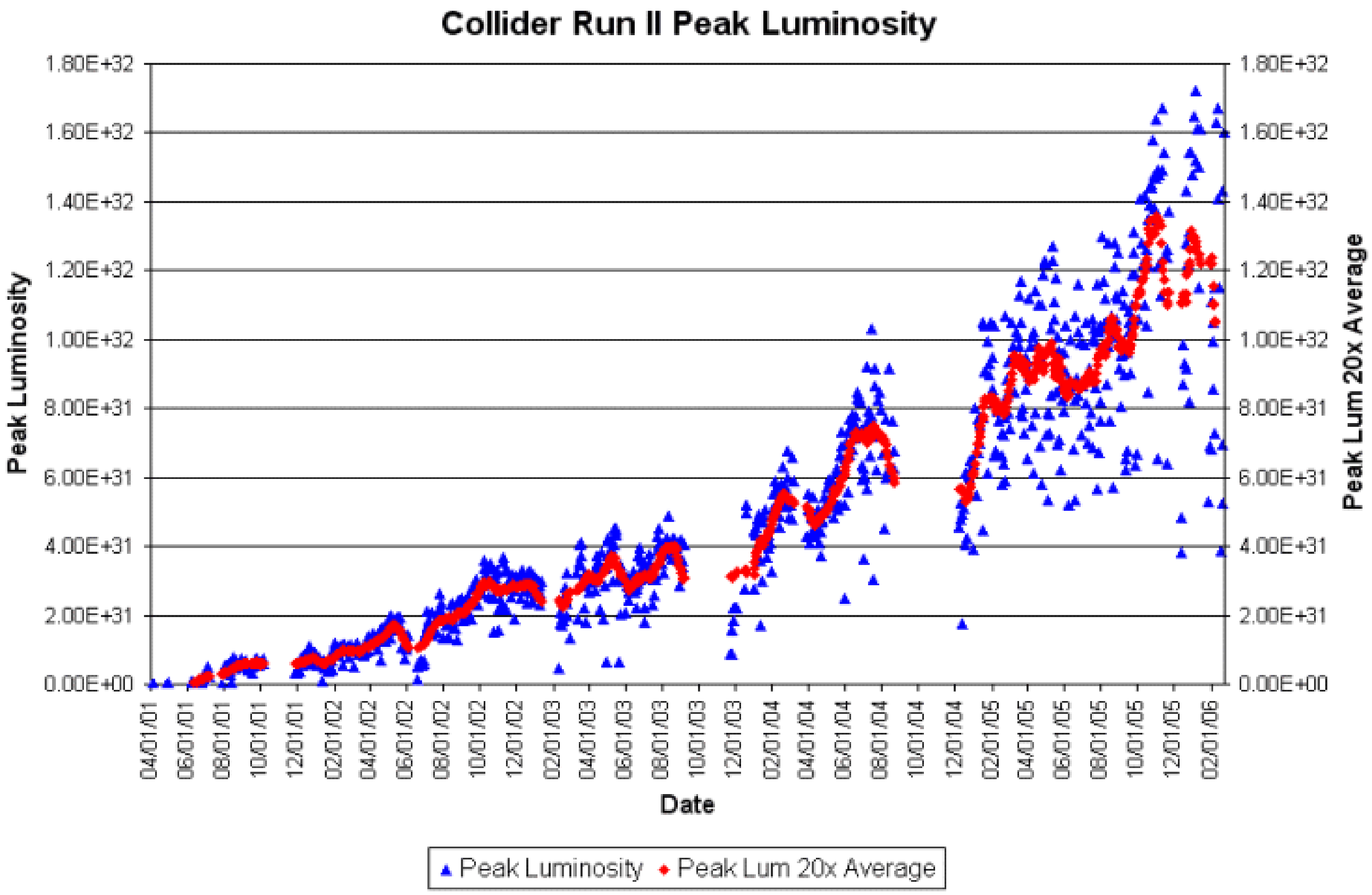


The Run II CDF Detector

- **Similar to most colliding detectors:**
  - **Inner silicon tracking**
  - **Drift Chamber**
  - **Solenoid**
  - **EM and Hadronic Calorimeters**
  - **Muon Detectors**



- **New for Run II:**
  - **Tracking: 8 layer silicon and drift chamber**
  - **Trigger/DAQ**
  - **Better silicon, calorimeter and muon coverage**


Collider Run II Peak Luminosity
Peak Luminosity
Peak Lum 20x Average
1.80E+32
1.60E+32
1.40E+32
1.20E+32
1.00E+32
8.00E+31
6.00E+31
4.00E+31
2.00E+31
0.00E+00
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02/01/06
Date
Peak Luminosity
Peak Lum 20x Average

CDF Collaboration

Canada
McGill Univ.
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USA
Argonne National Laboratory,IL
Brandeis Univ.,MS
Univ. of Chicago,IL
Davis UC,CA
Duke Univ.,NC
FNAL,IL
Univ. of Florida,FL
Harvard Univ.,MA
Univ. of Illinois,IL
The Johns Hopkins Univ.,MD
LBNL,CA
MIT,MA
Michigan State Univ.,MI
Univ. of Michigan,MI
Univ. of New Mexico,NM
The Ohio State Univ.,OH
Univ. of Pennsylvania,PA
Univ. of Pittsburgh,PA
Purdue Univ.,IN
Univ. of Rochester,NY
Rockefeller Univ.,NY
Rutgers Univ.,NJ
Texas A&M Univ.,TX
Texas Tech Univ.,TX
Tufts Univ.,MA
UCLA,CA
Univ. of Wisconsin,WI
Yale Univ.,CT

China
Academia Sinica, Taiwan

Korea
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Univ. di Padova,INFN
Pisa, INFN
Univ. di Roma I,INFN
INFN-Trieste
Univ. di Udine

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Japan
Hiroshima Univ.
KEK
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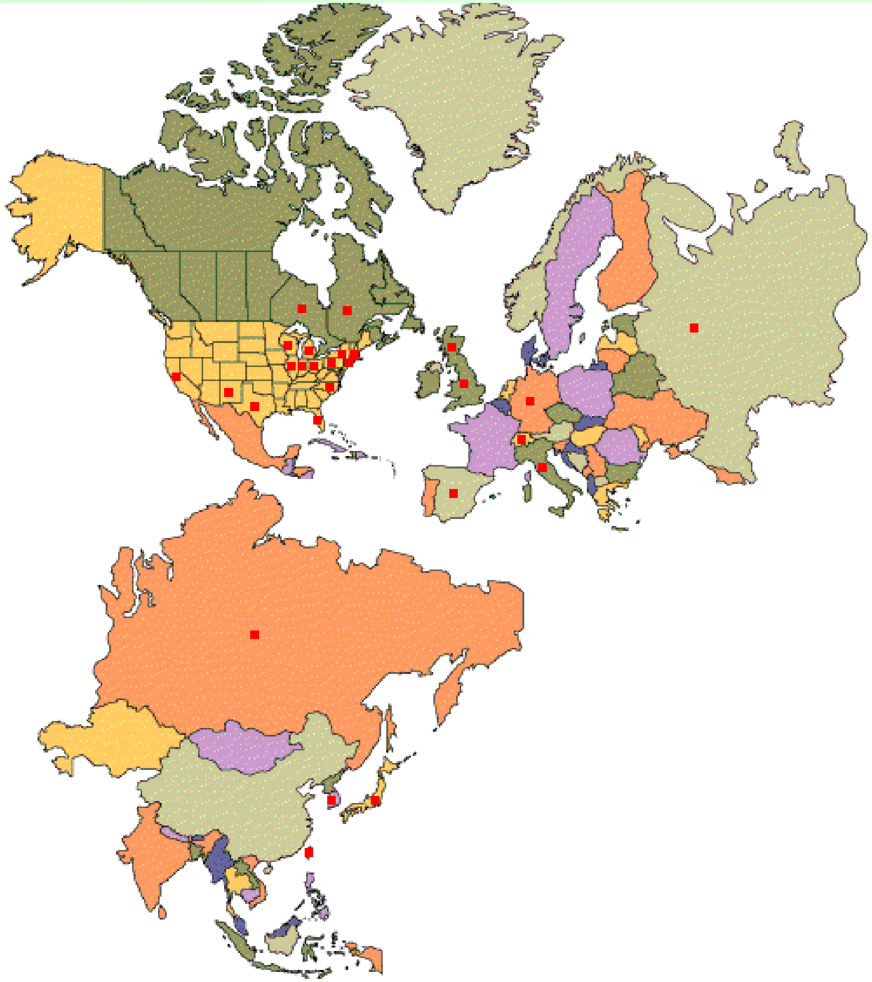
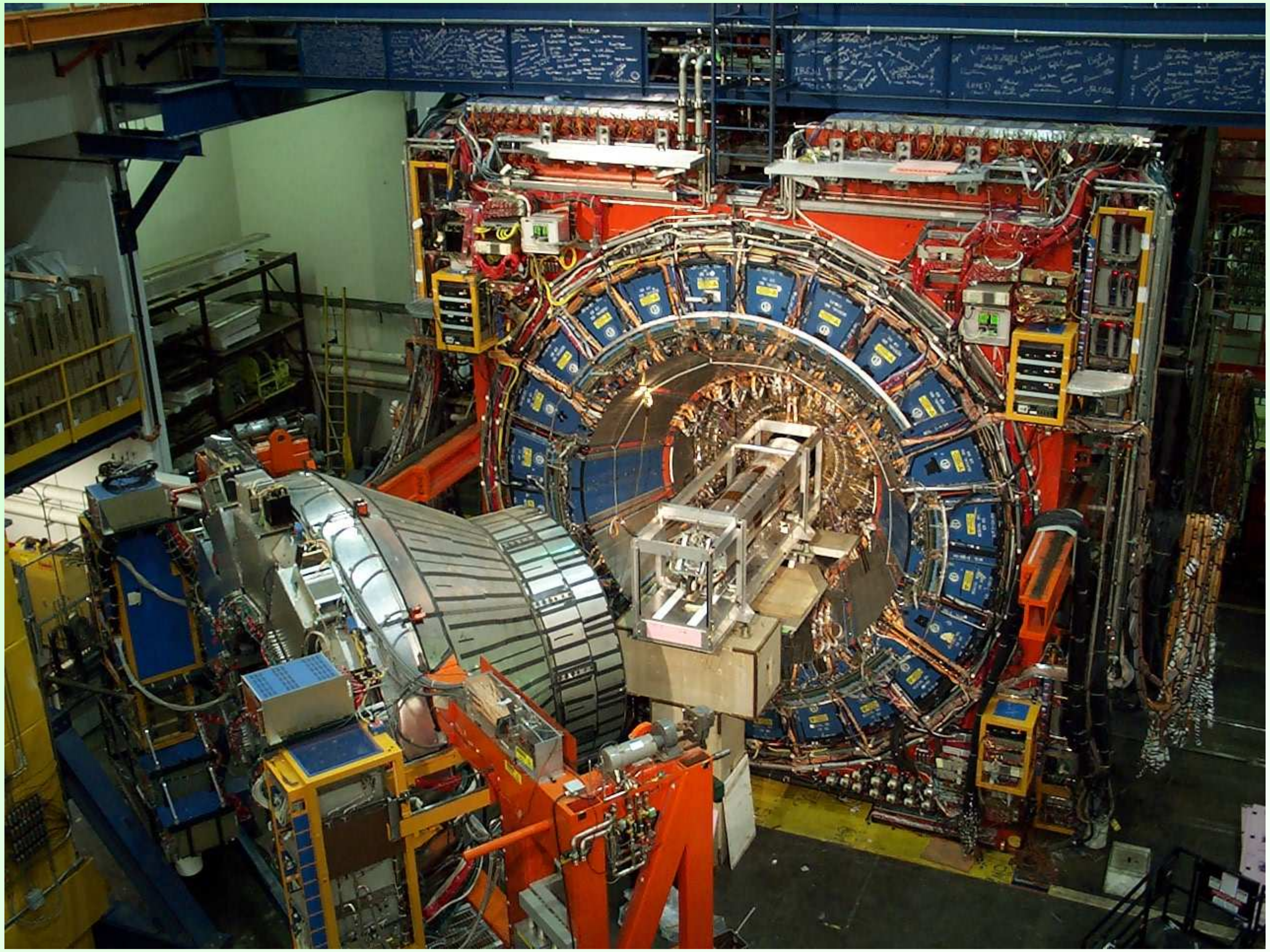
Univ. of Tsukuba
Waseda Univ., Tokyo



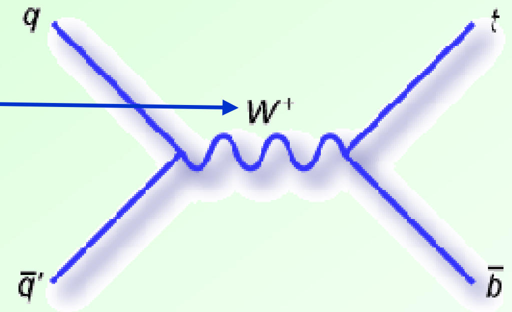


DØ Collaboration

Top Quark EWK Production

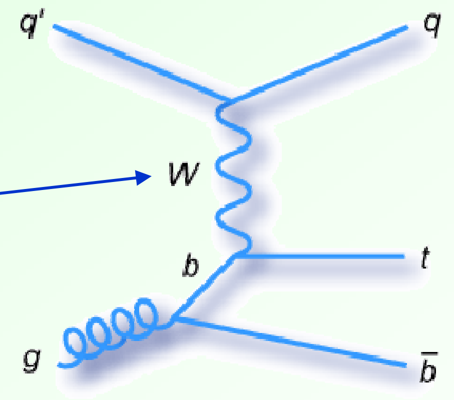
s-channel process $q\bar{q} \to W^* \to t\bar{b}$ involves

a time-like W boson,
$q^2 > (m_t + m_b)^2$



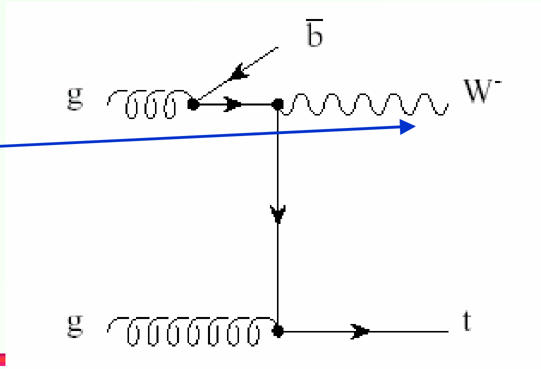
t-channel process $qb \to q't$ involves

a space-like W boson,
$q^2 < 0$

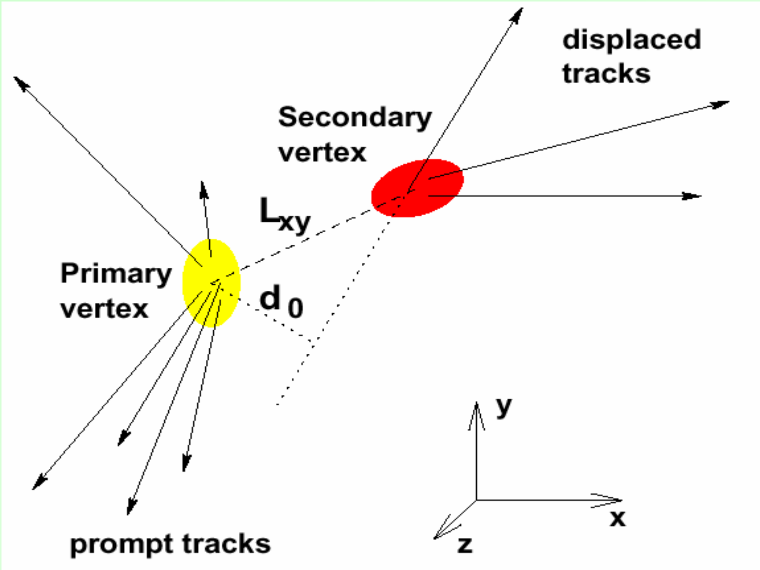


tW associated production process $bg \to tW^-$

an on-shell W boson,
$q^2 = m_W^2$



Lifetime b-tagging methods



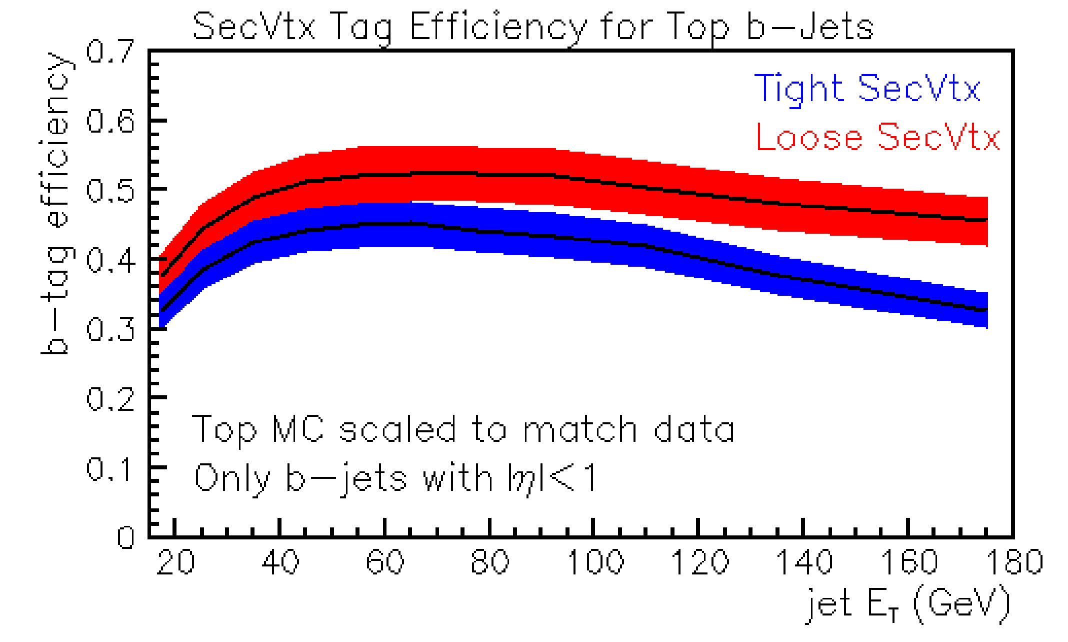
Make use of relatively big Lifetime of B-hadrons

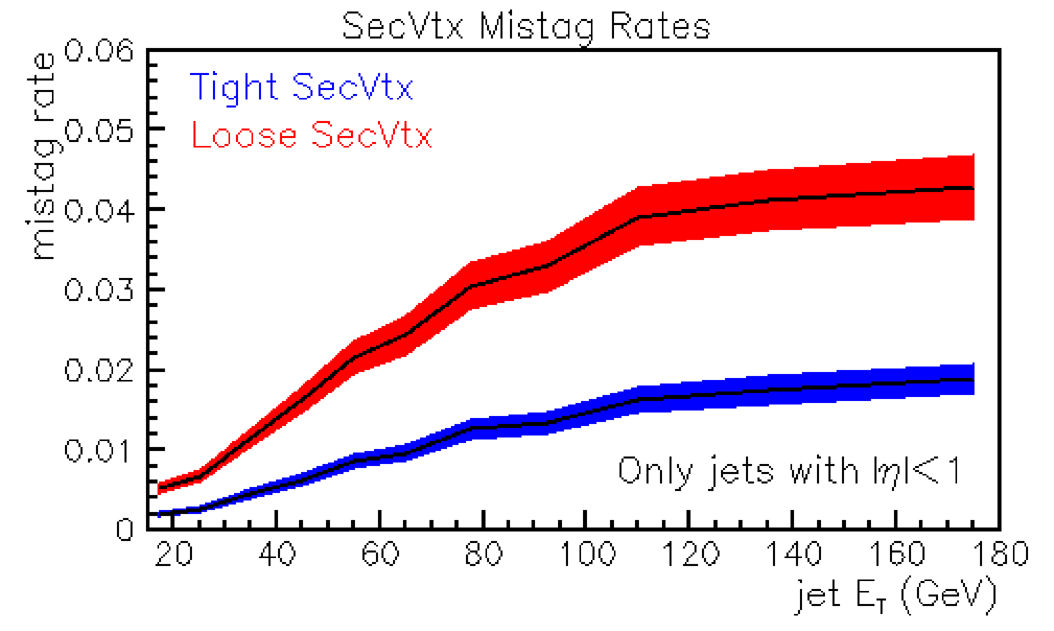
At CDF: Secondary Vertex Tag

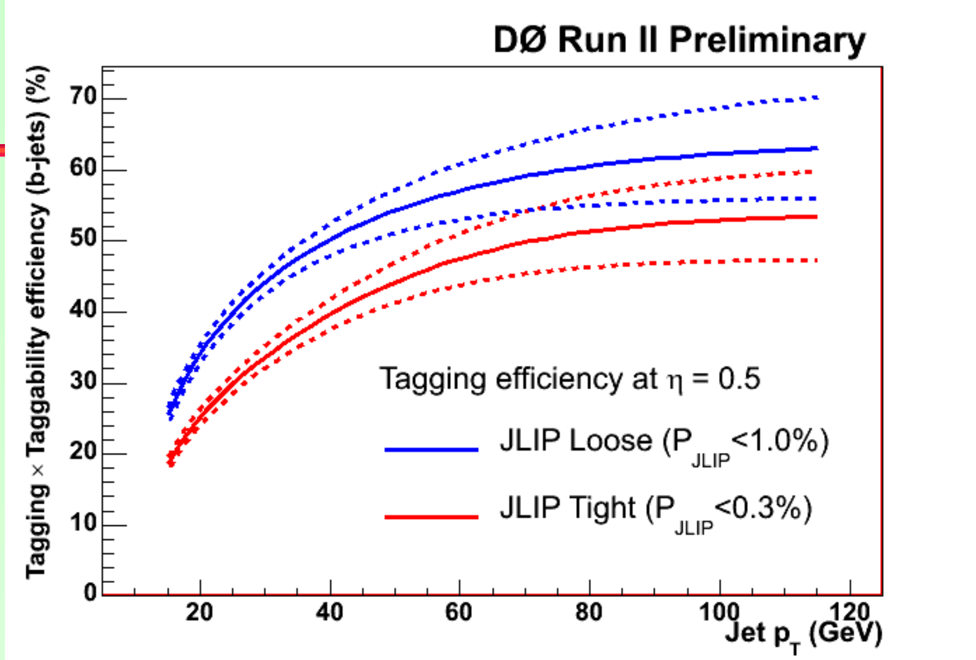
- displaced vertex reconstruction with silicon detector;
- B hadrons travel ~3mm before decay with large track multiplicity

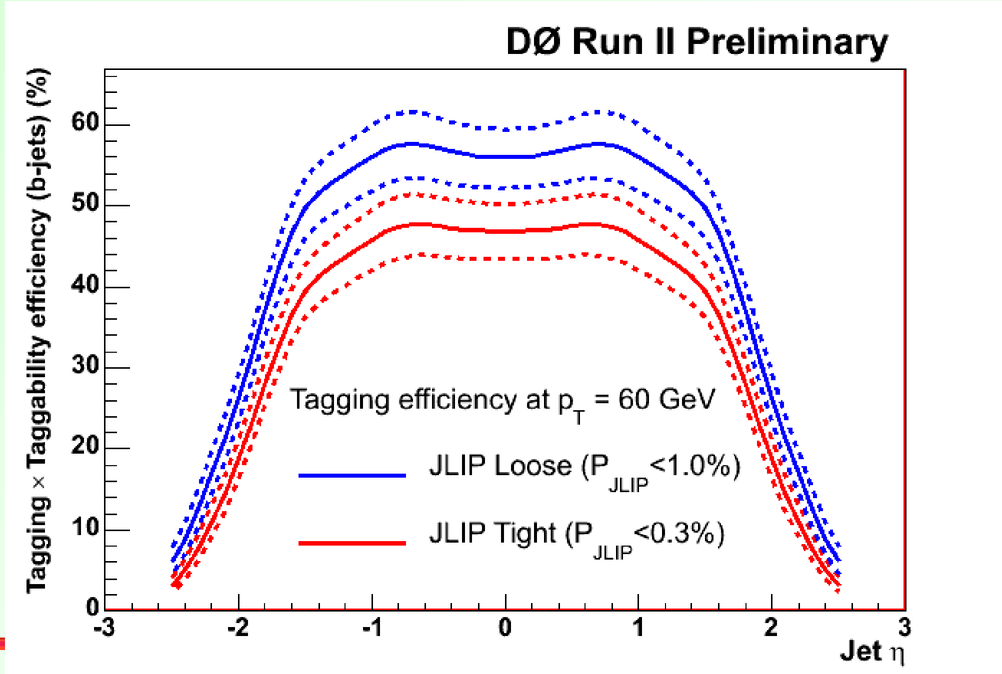
At D0: Jet Lifetime Probability

- for each track in the jet calculate a probability to come from primary vertex based on the IP significance;
- combine probabilities for individual tracks into jet probability;
- jet is tagged if its probability to be a light jet is less than some value (depends on mistag rate)


SecVtx Tag Efficiency for Top b–Jets
b–tag efficiency
Tight SecVtx
Loose SecVtx
Top MC scaled to match data
Only b–jets with |η|<1
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7
20 40 60 80 100 120 140 160 180
jet E_T (GeV)


SecVtx Mistag Rates
mistag rate
Tight SecVtx
Loose SecVtx
Only jets with |η|<1
0 0.01 0.02 0.03 0.04 0.05 0.06
20 40 60 80 100 120 140 160 180
jet E_T (GeV)


DØ Run II Preliminary
Tagging × Taggability efficiency (b-jets) (%)
Jet p_T (GeV)
Tagging efficiency at η = 0.5
JLIP Loose (P_JLIP<1.0%)
JLIP Tight (P_JLIP<0.3%)


DØ Run II Preliminary
Tagging × Taggability efficiency (b-jets) (%)
Jet η
Tagging efficiency at p_T = 60 GeV
JLIP Loose (P_JLIP<1.0%)
JLIP Tight (P_JLIP<0.3%)

Signal and Background Modeling

Understanding the characteristics of **single top signal** crucial for discovery:

- **s-channel MC generators agree well with NLO calculations**
- **t-channel generators are still an issue**

  $\Rightarrow$ Match 2 $\rightarrow$ 3 and 2 $\rightarrow$ 2 processes using the b p_T spectrum

  CDF: MADEVENT D0 : COMPHEP

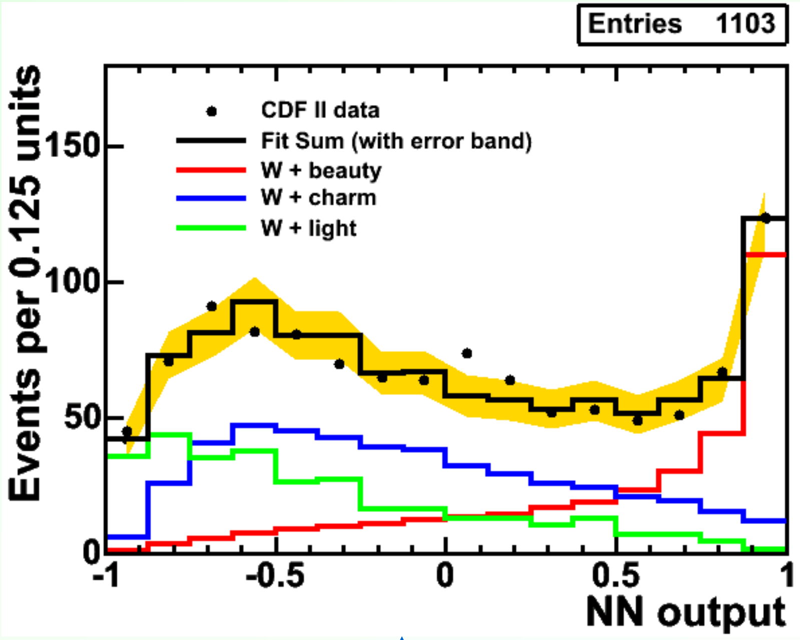
Background based on data as much as possible:

- W/Z + jets production:
  - $\rightarrow$ estimated from data & MC
  - $\rightarrow$ heavy flavor fractions (b,c) from ALPGEN (CDF) and MCFM (D0)
- Top pair production:
  - $\rightarrow$ estimated from PYTHIA (CDF) and ALPGEN (D0)
- Multi-jet events
  - $\rightarrow$ estimated from data
- WW, WZ, $Z\rightarrow\tau\tau$
  - $\rightarrow$ estimated from PYTHIA (CDF) and ALPGEN (D0)

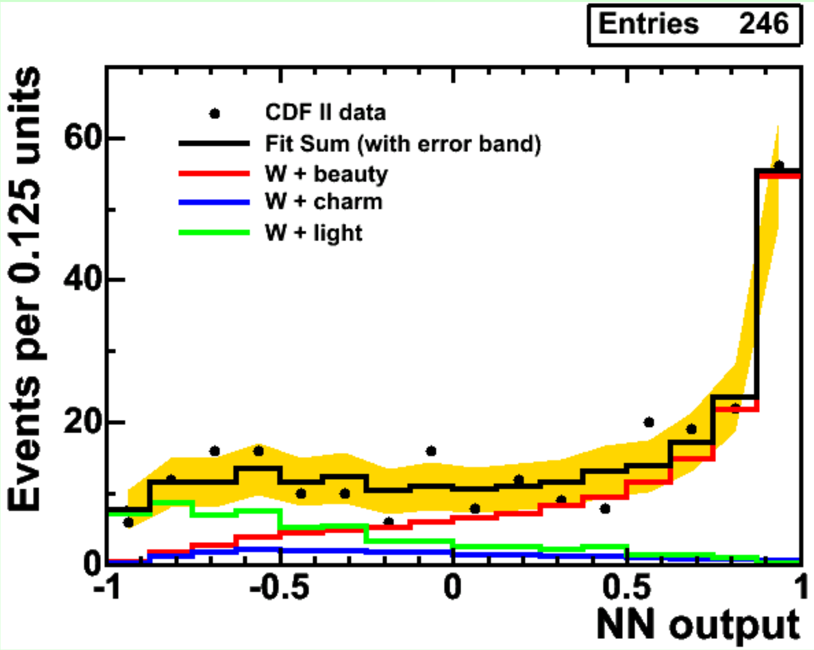
Neural Net b Tagger

- In the W+2 jets bin about 50% of the background does not contain b quarks
- SecVtx gives only digital info (tagged or not tagged) and does not use all information (e.g. vertex mass, track multiplicity, etc.)
- Distinguishing charm and light flavor backgrounds might help to reduce the uncertainties on the background estimate

Using 3 different templates
(beauty, charm and light flavor)
and fitting them to the W+jets data output distributions,
the fitted distributions describe the data well!



Future Plans with the *b* tagger



Expected statistical uncertainty

	1 Jet	2 Jets	3 Jets
beauty	8%	9%	11%
charm	16%	31%	73%
light	15%	22%	35%

- Right now expected statistical uncertainties for charm and light flavor are still bigger than method 2 uncertainties.
- Uncertainties on *b* fraction are small: 8 – 11%
- Apply method 2 results as Gaussian constraints.
- Need to understand non-*W* flavor composition. First studies indicated 80:20 charm:beauty composition.
- $Z \rightarrow \tau\tau$, WW, ZW can be understood from Monte Carlo.

Kinematic Fitter

- We need to reconstruct the top (reco.mass $M_{l\nu b}$, or polarization angle, etc)
- Top is reconstructed poorly; mass resolution:
  - MadEvent: couple of GeV's
  - Reconstructed: 20 GeV (t-channel) 40 GeV (s-channel).
- Why? Because:
  - Jet energies mismeasured (angles OK).
    - This in turn affects Missing Et and Missing Et Phi
  - Neutrino pz : quadratic eqn – W mass constraint.
    Pick the 'correct' solution 70%
  - B-jet from top (s-channel) pick the correct one 53% of the times.
- Kinematic fitter approach allow p_b, and $E_T(\nu)$, $\phi(\nu)$ to vary within uncertainties

$$\chi^2_m = \frac{(p_b^{fit} - p_b^{meas})^2}{\sigma^2_{p_b}} + \frac{(p_{t\nu}^{fit} - E_t^{meas})^2}{\sigma^2_{E_t}} + \frac{(\phi_\nu^{fit} - \phi_\nu^{meas})^2}{\sigma^2_{\phi_\nu}} + \frac{(m_t^{fit} - m_t^{meas})^2}{(0.5GeV)^2}$$

4 fits: 2 b-jet assignments + 2 pz solutions

Multivariate Likelihood

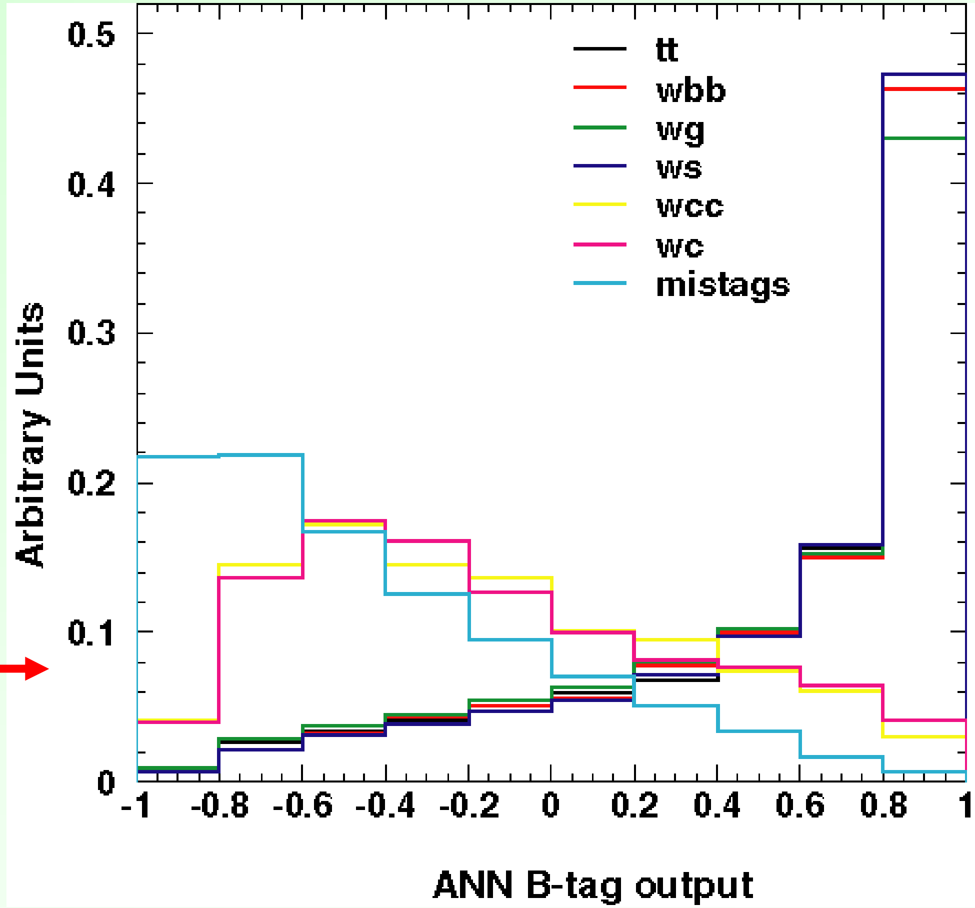
- **Can use this χ^2 for – choosing the b from top (81% correct)**
- **Reconstruct the top rest frame**
- **Calculate matrix element-like quantities**
- **Then, form a combined probability**
  - Different variables for t-channel and s-channel

$$p_i^j(x_i) = \frac{f_i^j(x_i)}{\sum_{k=1}^{5} f_i^k(x_i)} \qquad L^j(\vec{x}) = \frac{\prod_{i=1}^{n_{\mathrm{var}}} p_i^j(x_i)}{\sum_{k=1}^{5} \prod_{i=1}^{n_{\mathrm{var}}} p_i^k(x_i)}$$

k, j is the process index: signal (s- or t- channel), Wbb, Wcc/Wc, mistags, ttbar

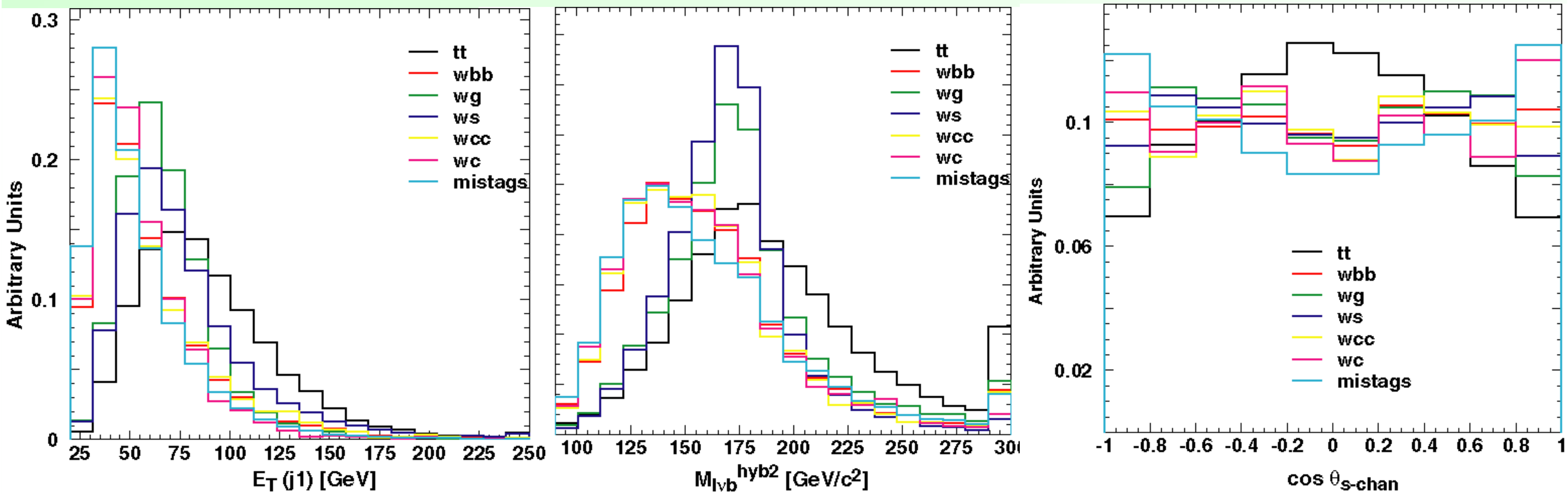
t-channel likelihood function

- **Seven variables:**
  - **H_T, $Q\eta$,, M_{jj}**
  - **$M'_{l\nu b}$ using kinfit to pick pz(ν)**
  - **Polarization angle $\cos\theta_{lj}$,**
  - **MadGraph matrix element (t-ch)**
  - **New: ANN B-tagger**

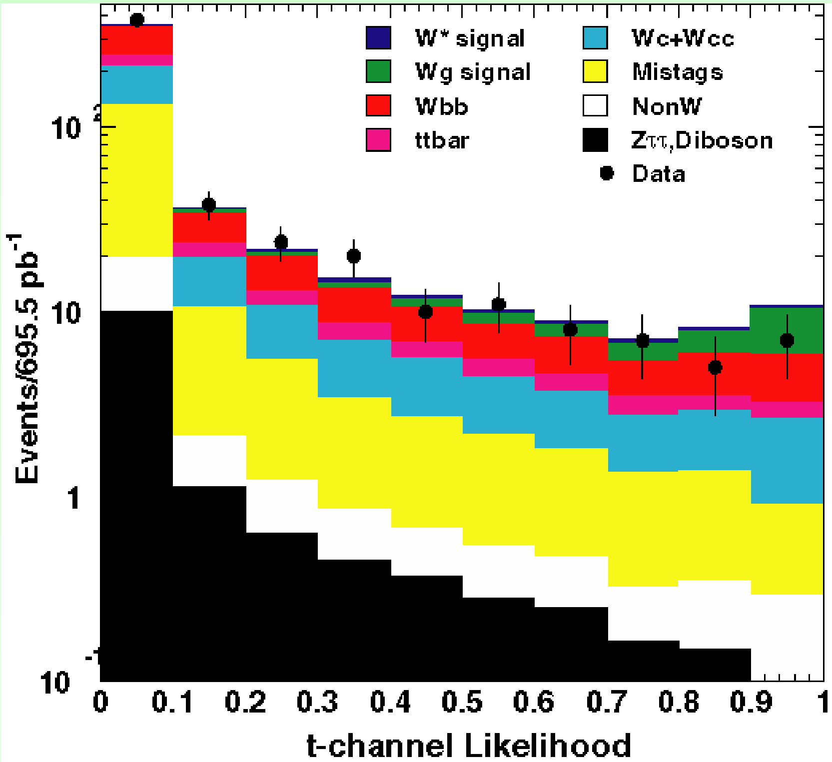


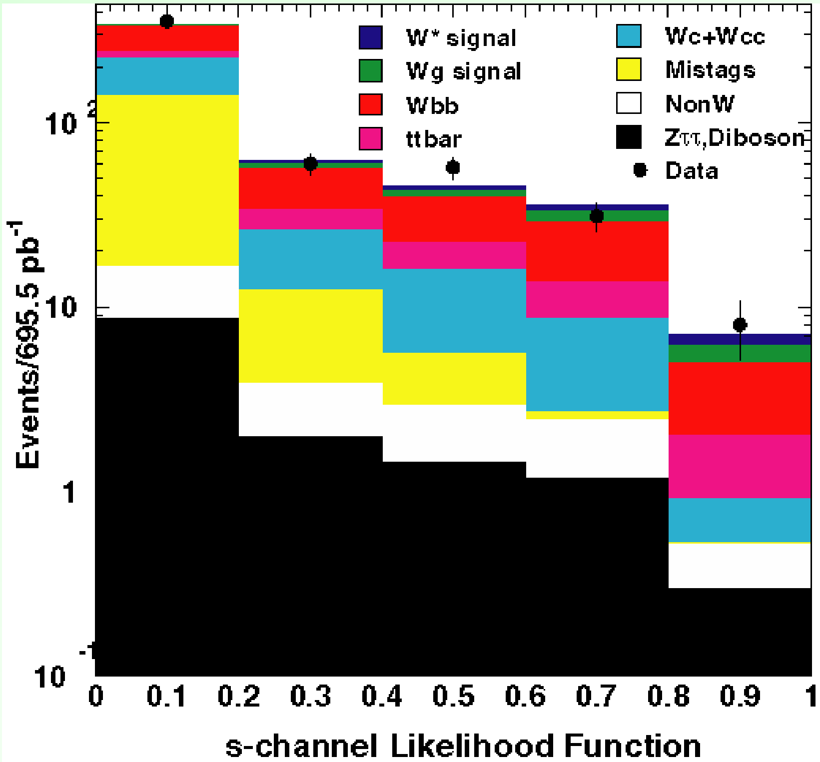
s-channel Likelihood Function

- **Six variables:**
  - **H_T, MadGraph matrix element (t-ch) , ANN *b*-tag**
  - **E_T(j1)**
  - **$M''_{l\nu b}$ with kinfit b-chooser**
  - **Polarization angle $\cos\theta_{\nu\text{-beam}}$ in top rest frame**



t- and s-channel Likelihood Function





Neural Network Discriminants

We use 14 input variables:

1.) $M_{l\nu\beta}$: reconstructed top quark mass for signal events

2.) dijet mass

3.) $\log_{10}(\Delta_{34})$

4.) $Q \cdot \eta$

5.) P_T (lepton)

6.) $\Sigma\,\eta(j)$

7.) η_W

8.) $E_T(j_1)$

9.) $E_T(j_2)$

10.) ANN b-jet

11.) $\Delta(\chi_{12})$ (kinematic fitter)

12.) χ_3^2 (kinematic fitter)

13.) $\cos\theta_{lq}$ (top polarization)

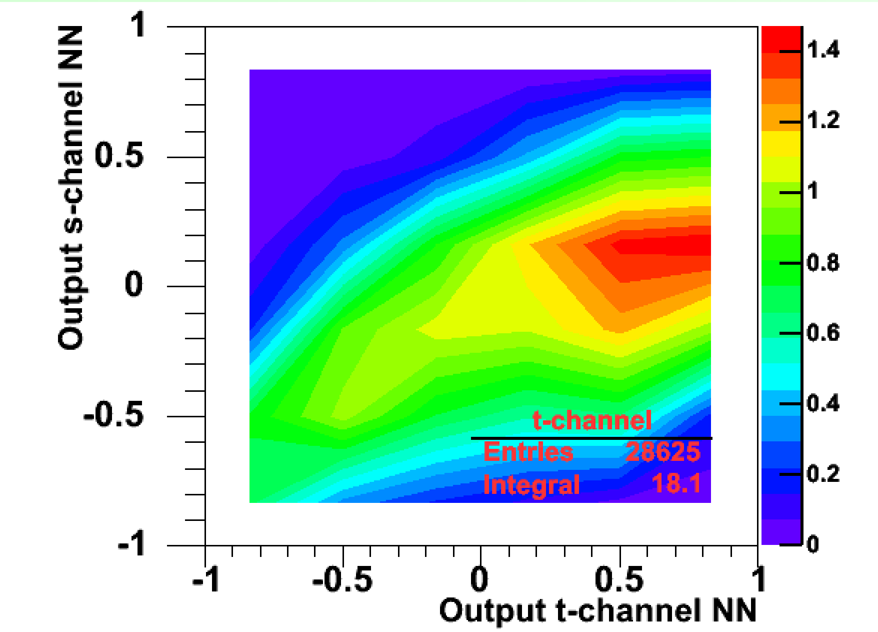
We investigated 42 variables. Add took those with more than 5 sigma significance.

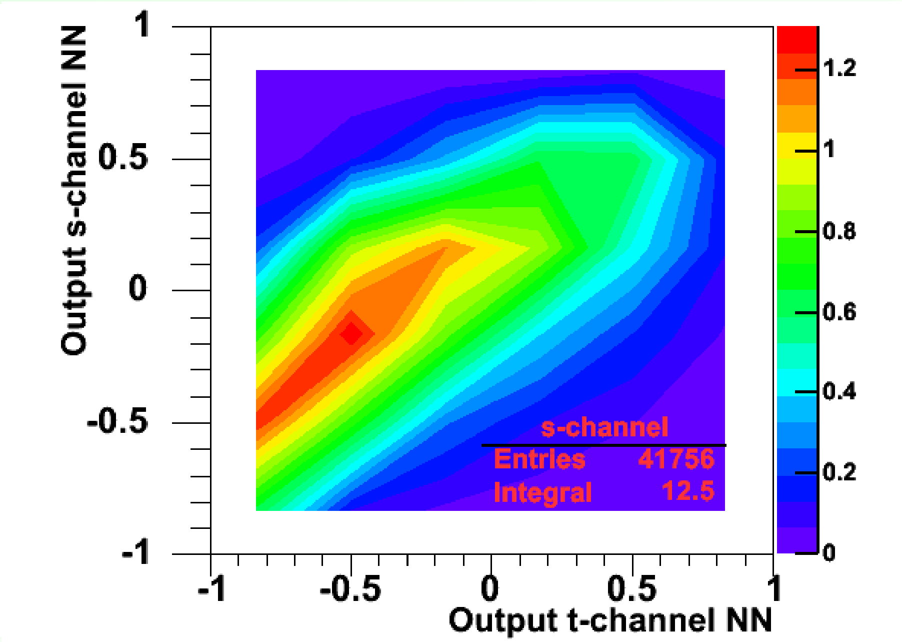
Separate Search with NN

Separation of t-channel and s-channel single-top is important:

→ different sensitivity to physics beyond the standard model

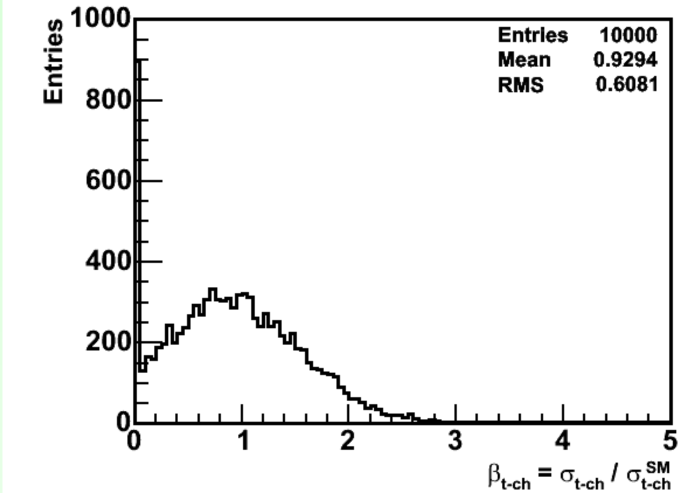
CDF uses *2 networks trained on t- or s-channel*. Also the creation of the templates for signal and background processes is made in the same way even though it is done in 2D for both network outputs simultaneously.

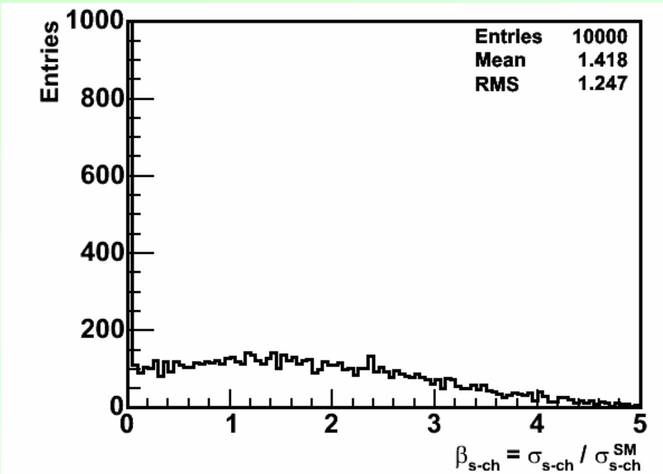


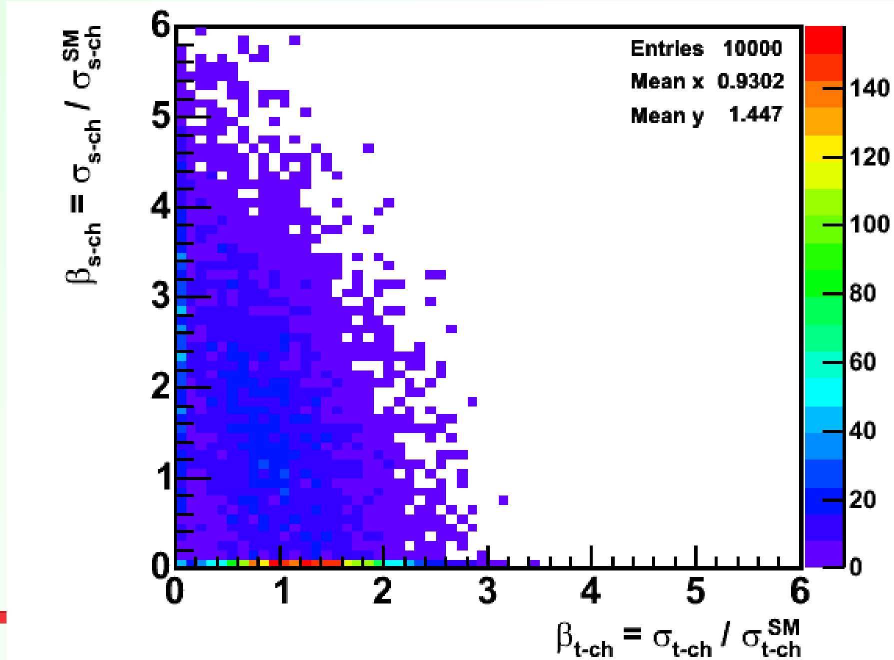


2D NN Analysis Sensitivity

	t-channel	s-channel
RMS	0.61	1.25
95% C.L.	1.99	3.74
# 1st bin	7.9%	21.5%







Combined Channel Search

- **Using one variable: the t-channel likelihood**
- **Searching for s+t combined signal:**
  - **Null hypothesis H0: no SM single-top, just SM backgrounds**
  - **Test hypothesis H1: SM single-top+SM backgrounds**
- **Two types of pseudo-exp – corresponding to H0 and H1. Calculate the distribution of a test statistics Q:**

$$Q = -2 \cdot \ln \frac{P(\mathrm{data}|H1)}{P(\mathrm{data}|H2)}$$

where P is product of Poisson terms

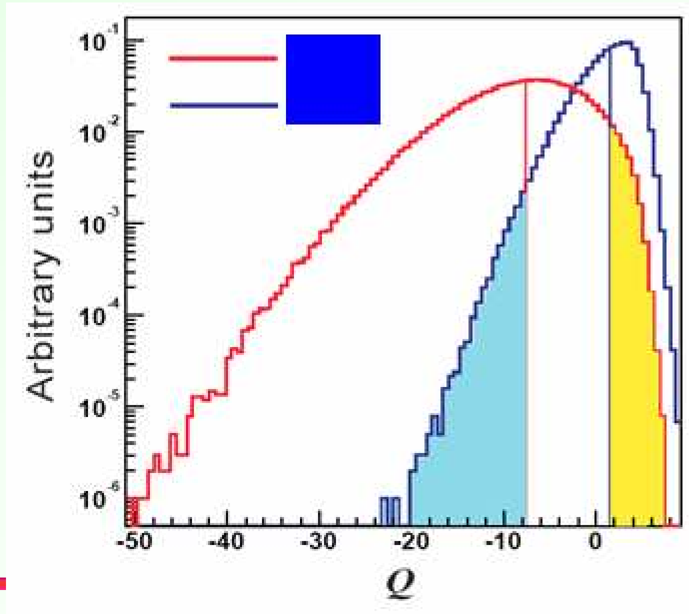
$$P(\mathrm{data}|H1) = \prod_{i=1}^{N_{bins}} P^i = \prod_{i=1}^{N_{bins}} \frac{e^{\mathcal{N}_i^{H1}} \cdot (\mathcal{N}_i^{H1})^{d_i}}{d_i!}$$

Limits

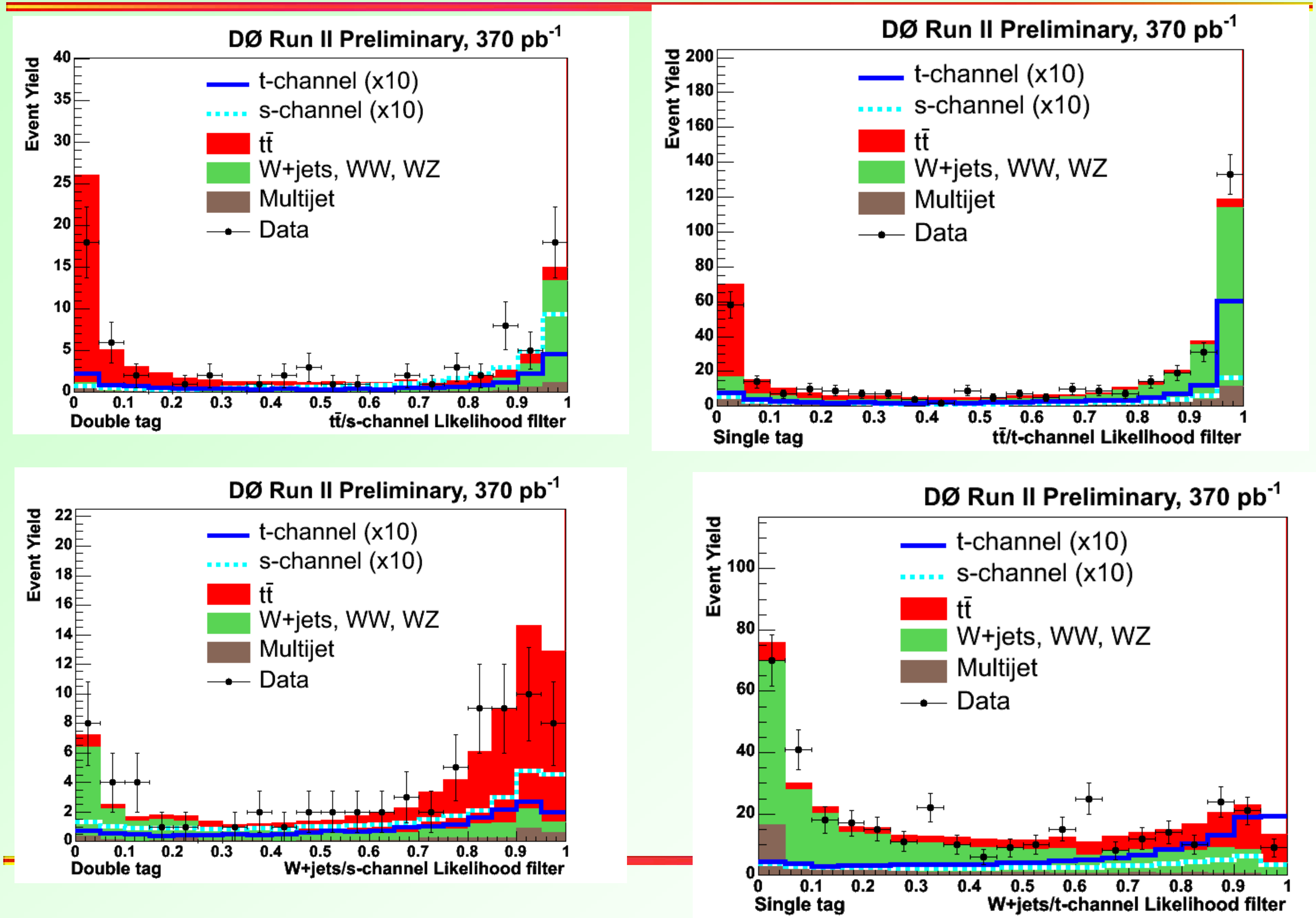
- **We do not expect to rule out SM single-top at 95% C.L.**
- **Result is CL_s=9.4% (don't exclude the SM signal)**
- **Also, 30% of the H1 pseudoexperiments fluctuate to more than the observed data (did not exclude H0 hypothesis= do not discover single top…)**
- **If test hypothesis changes – allowing any rate of single-top like signal (with the same shape as the SM single-top), then:**
  - **Cross section upper limit:**

Expected: 2.92 pb

Observed: 3.40 pb



Likelihood Distributions



DØ Combined Limit