GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

Observation of the single top production at the Tevatron

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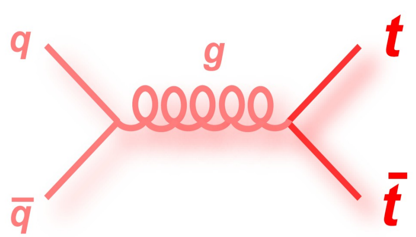
APS April meeting 2009
Denver, May 2 – 5, 2009

Outline

- Motivation
- Signal and background
- Event selection
  - Systematic uncertainties
- Statistical analysis
  - Cross section extraction
  - Significance calculation
- Multivariate Methods
  - Dedicated talks by A.Heinson, C.Gerber, M.Pangilinan (D0) and B.Casal (CDF) in this session
- Combination
- $|V_{tb}|$ measurement
- Summary and outlook

The Top quark

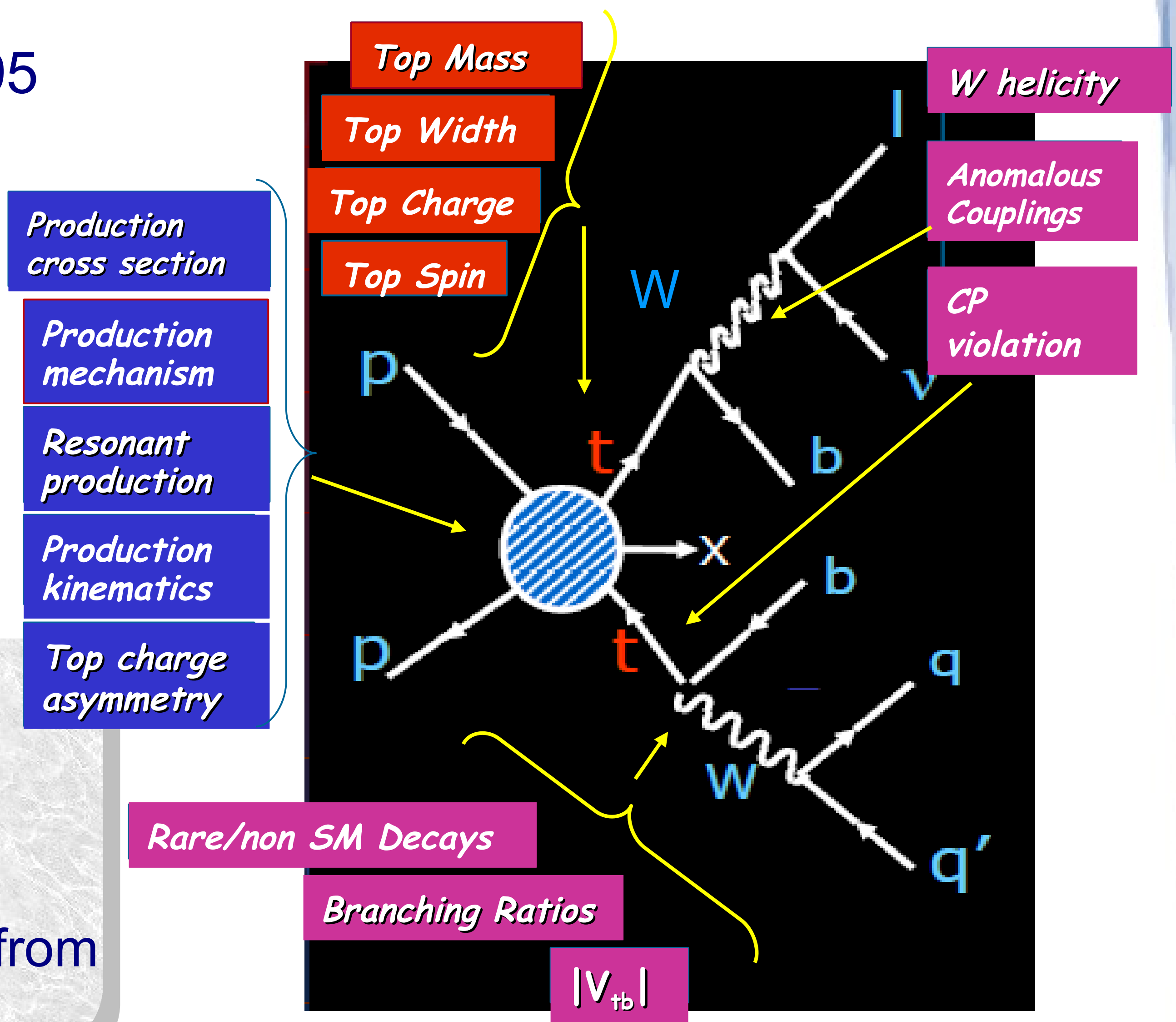
Discovered in March 1995



σ_{NLO}= 6.8±0.6 pb @175 GeV

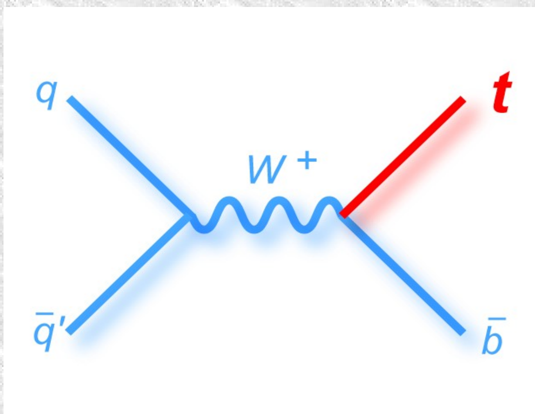
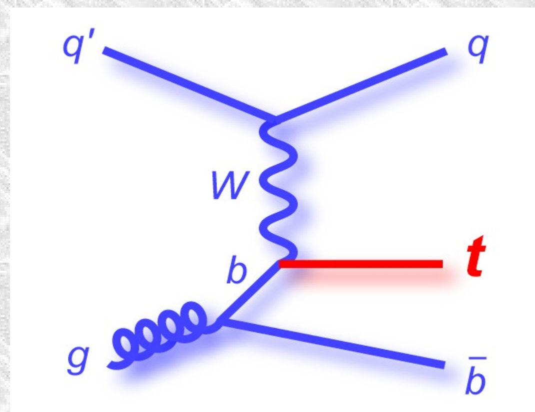
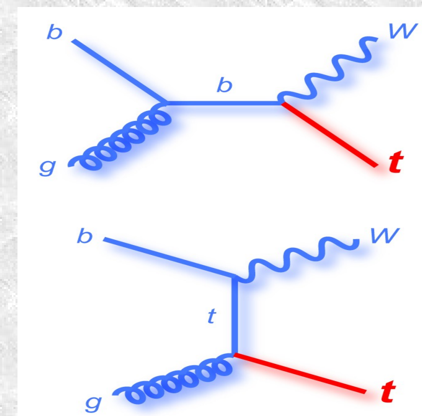
N.Kidonakis et. al., M.Cacciari et. al., S.Moch, P.Uwer et.al.

- Main mechanism
- Distinct signature
- Thoroughly studied
- All knowledge comes from strong production



Electroweak production

- Predicted 10 years before top quark discovery
  S.Willenbrock, D. Dicus, Phys. Rev. D34, 155 (1986); S Cortese and R Petronzio, PLB 253, 494 (1991)
- Observed 14 years after top quark discovery...

s-channel (tb)	t-channel (tqb)	Wt channel
		

m_t (GeV)		s-channel	t-channel	
175	σ_{NLO}	0.88±0.11 pb	1.98±0.25 pb	Z. Sullivan, Phys. Rev. D 70, 114012 (2004)
170	$\sigma_{(N)NLO}$	1.12±0.05 pb	2.34±0.13 pb	N. Kidonakis, Phys. Rev. D 74, 114012 (2006)

Small at Tevatron
Important for LHC

In observation analysis CDF (D0) assumes m_t=175 (170) GeV

Long way to discovery

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**

Run I

Run II

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**

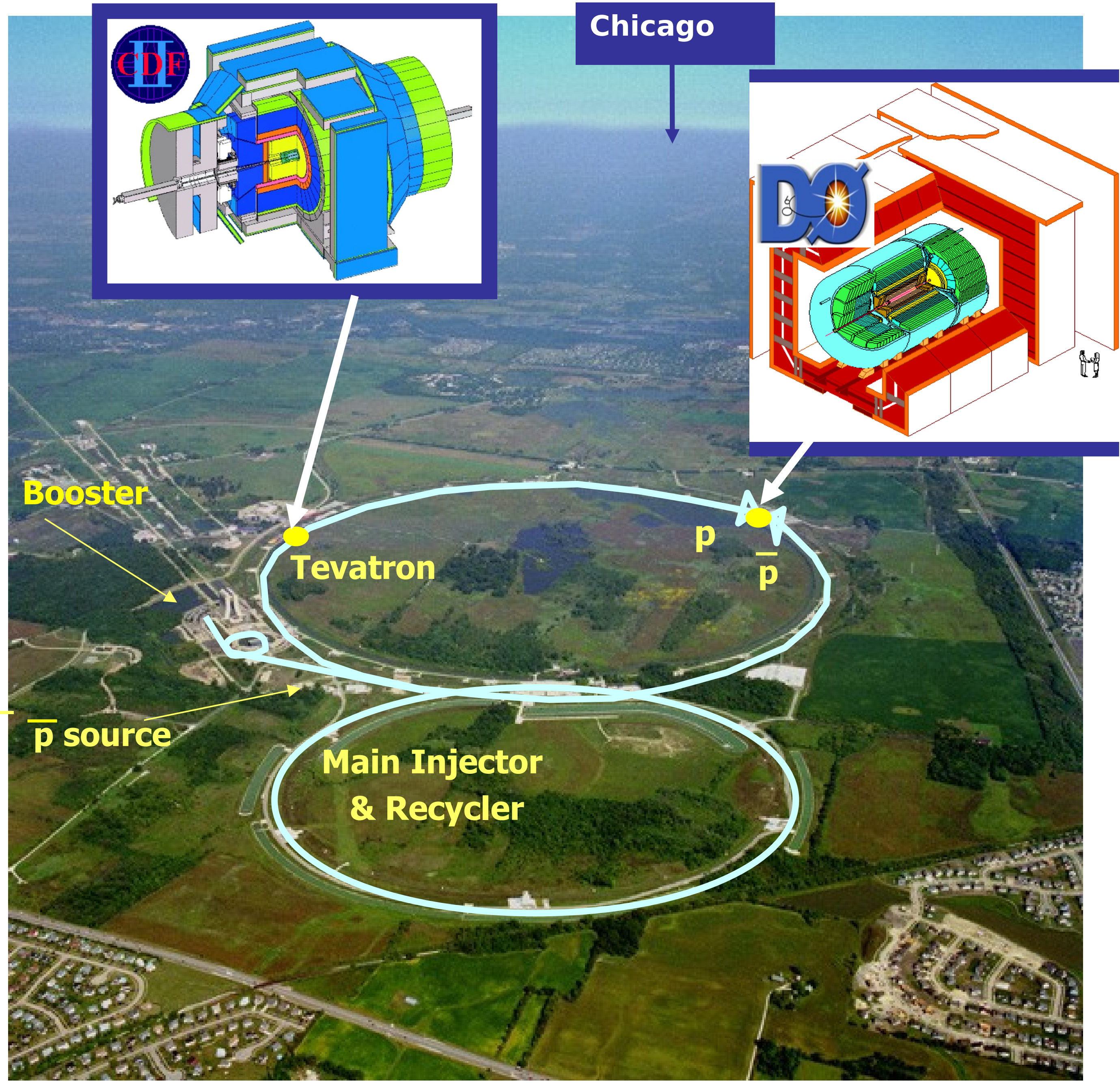
Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
December 2006 DØ (0.9 fb^{-1})			PRL 98, 181802 (2007)
4.7 ± 1.3 pb	2.3 σ	3.6 σ	$\lvert V_{tb} f_1^L \rvert = 1.31^{+0.25}_{-0.21}$ $\lvert V_{tb} \rvert > 0.68$ at 95% CL
September 2008 CDF (2.2 fb^{-1})			PRL 101, 252001 (2008)
2.2 ± 0.7 pb	4.9 σ	3.7 σ	$\lvert V_{tb} f_1^L \rvert = 0.88^{+0.13}_{-0.12}$ $\lvert V_{tb} \rvert > 0.66$ at 95% CL

The Tevatron

- The highest energy particle accelerator in the world
- Proton-antiproton collider with $\sqrt{s}$ = 1.96 TeV

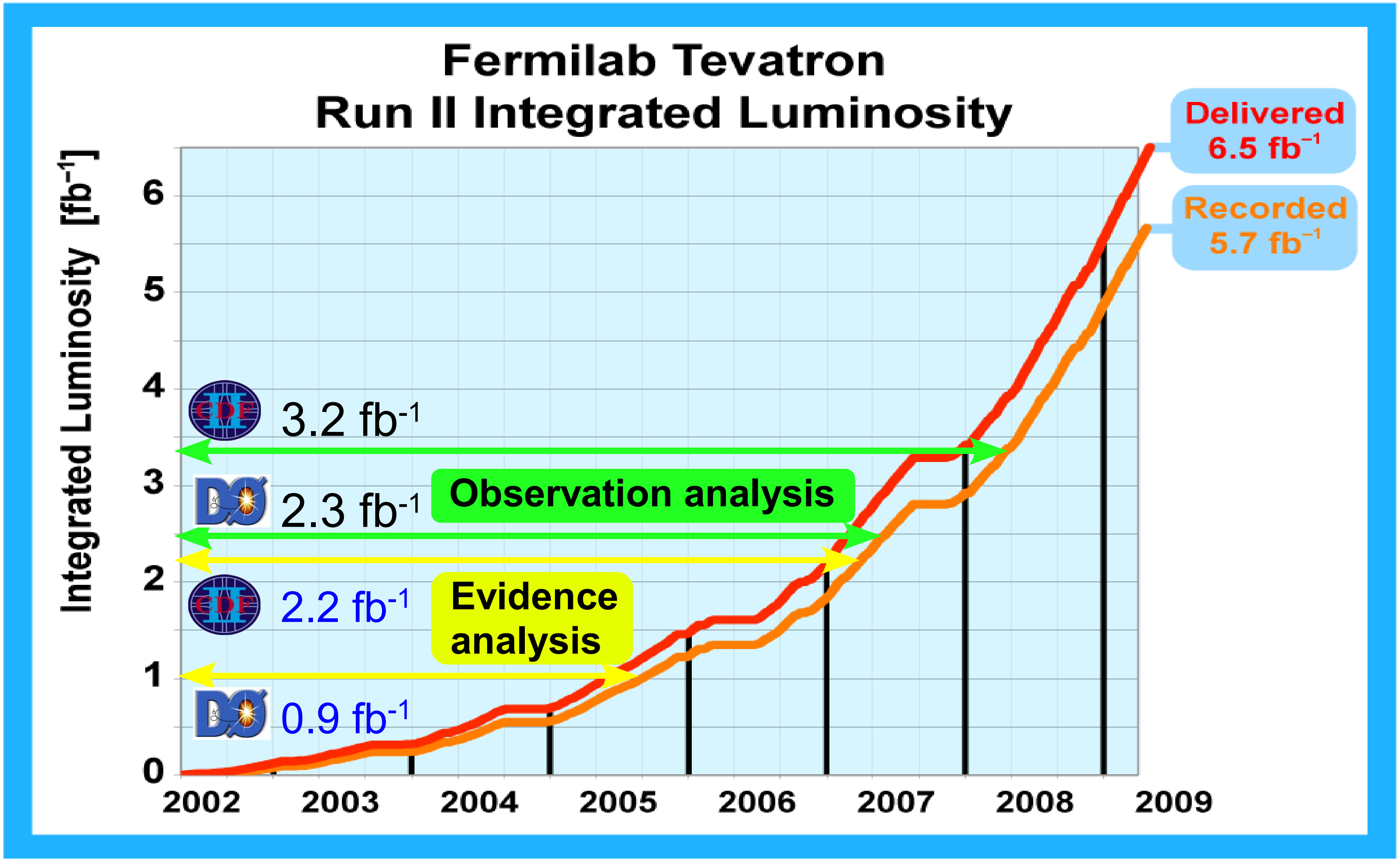
Run I 1992-1995
Top quark discovered!

Run II 2001-11(?)
Single top quark discovered!



Climbing to the top...

Outstanding performance of the Tevatron! THANK YOU!



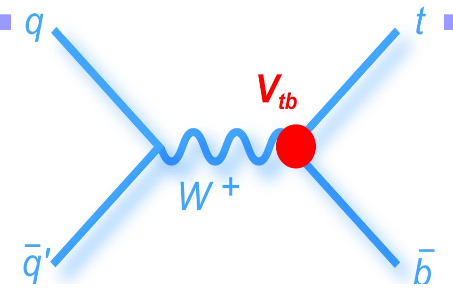
What will we learn?

Access to W-t-b vertex

- Probe V-A structure
- Top quark spin

Direct measurement of $|V_{tb}|^2$

- Test unitarity of CKM matrix
- Is it 3×3 matrix?
- Is 4th generation possible?



$$\sigma \propto |V_{tb}|^2$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yb}? & V_{YX}? \end{pmatrix}$$

Small mixing with 4th family is favored
Quite large mixing is still not excluded

Constraints:

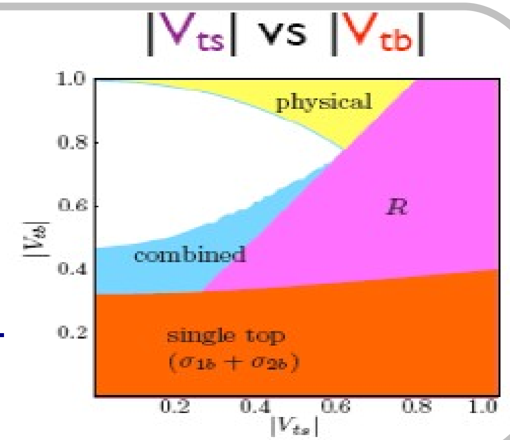
tree-level 3×3 CKM elements
FCNC processes (K-, D-, B_d-, B_s-mixing, b → s)

Assumption: unitary 4×4 CKM matrix

A. Lenz et al. in arXiv 0902.4883 [hep-ph]

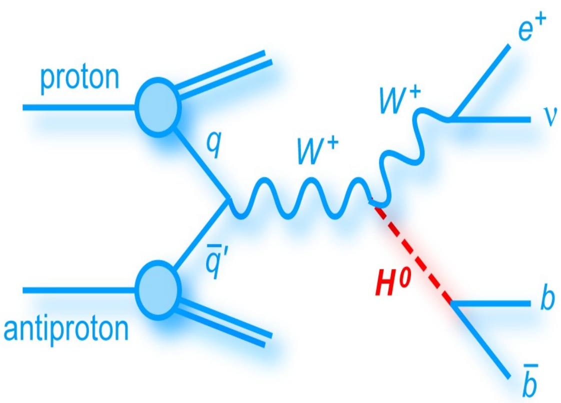
Combination of R_b and s- & t-channel cross sections

J. Alwall et. al., Eur. Phys. J. C49 791 (2007).:



SM and beyond

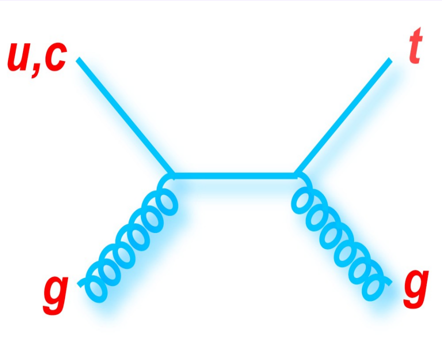
- Milestone for Higgs search in WH channel
  - Same signature, 10 times smaller σ
  - Background to Higgs search

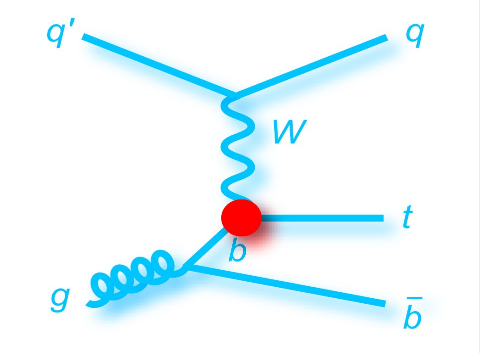


pp→WH

- s- and t-channels are sensitive to different processes beyond the standard model

t-channel

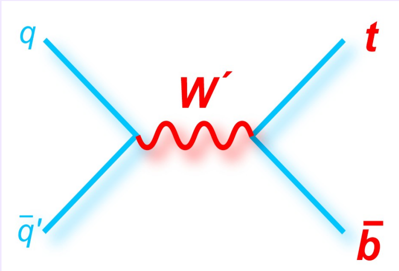


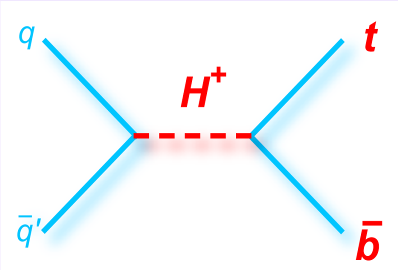


FCNC (ug→t)

Anomalous couplings

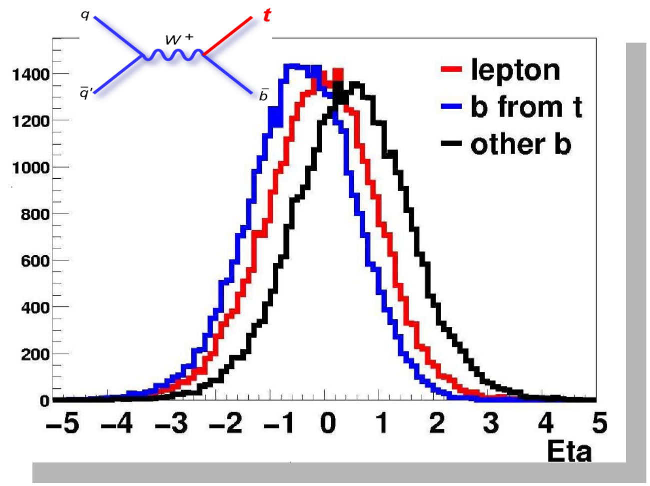
s-channel

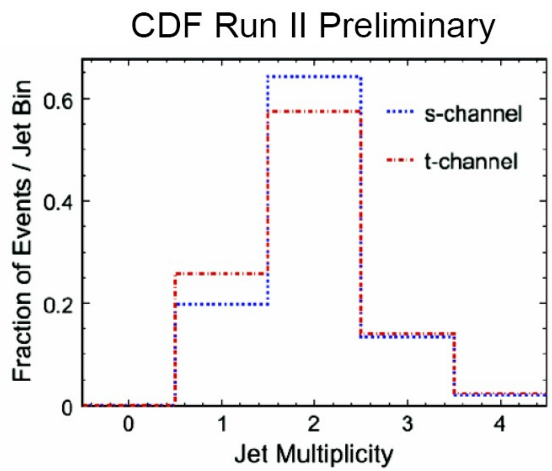




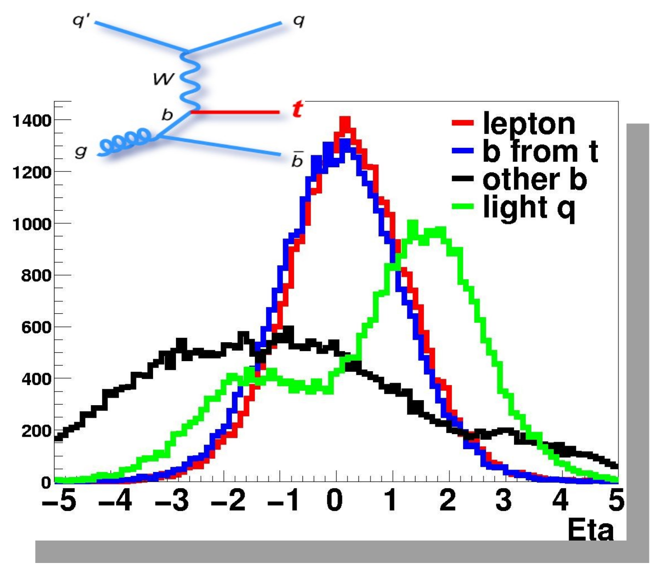
Signal

- s-channel
  2 *b*-jets
  Top quark decay products and the *b* tend to be all central



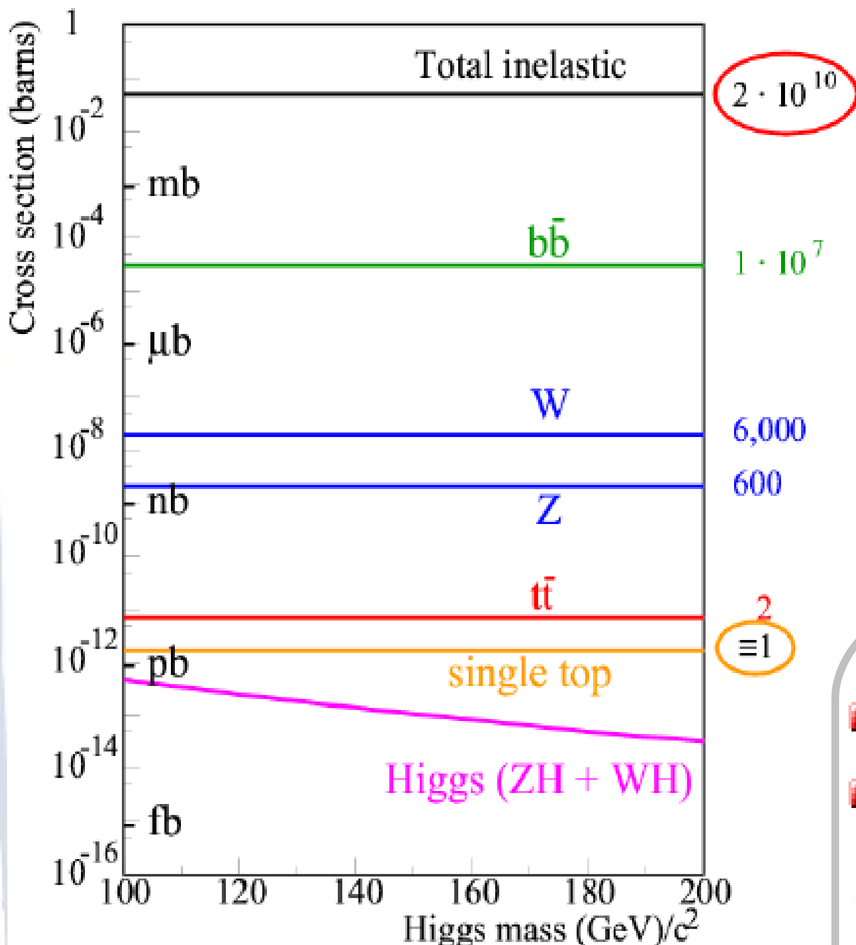


- t-channel
  2 *b*-jets and one light
  One of *b*'s tends to be very close to the beam pipe
- No striking signatures as for $t\bar{t}$
- Signal and background distributions look similar



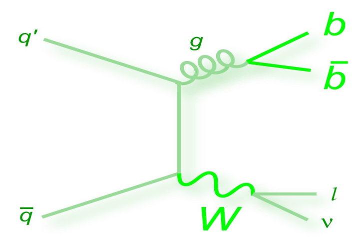
Simulated with
- **CompHEP–SingleTop (D0)**
- **MadEvent (CDF)**
- **Matching of LO and NLO calculations**

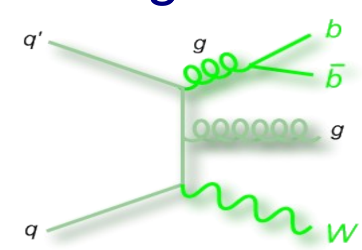
Backgrounds



Other small backgrounds:
Z+ jets, diboson – from MC

W+jets – dominant background

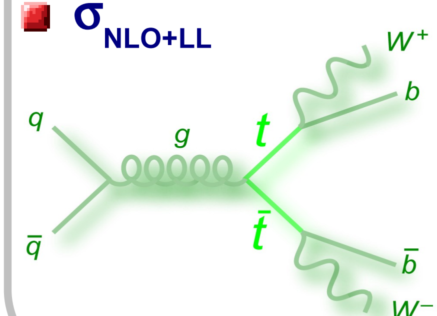




- **Large cross section**
- **Shapes from Alpgen+Pythia MC**
- **Normalization and heavy flavor fractions from data**

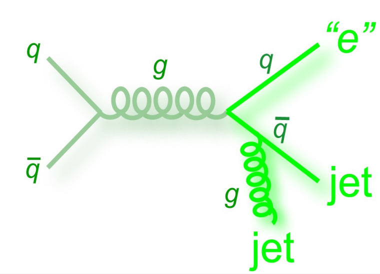
Top pairs

- **Alpgen or Pythia**
- σ_{NLO+LL}



Multijet (instrumental)

- **Jet misidentified as electron**
- **Muon in jet appears isolated**
- **From data**



Building blocks

Data

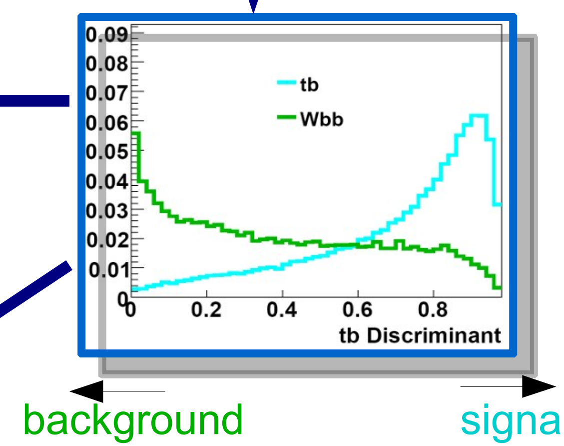
Signal & Background Monte Carlo

Event selection

b-tagging

Background model verification

Signal/Background separation technique



Statistical analysis

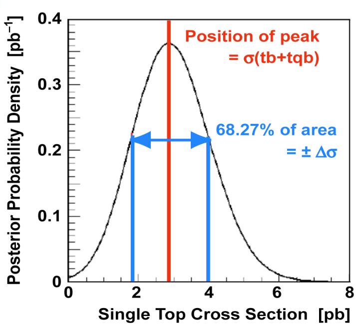
analysis calibration

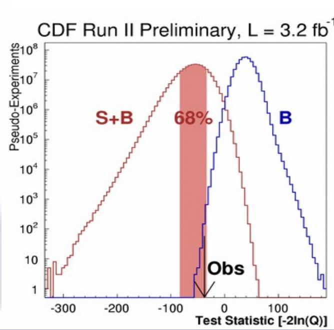
Cross section

pseudo experiments

Significance

Combination

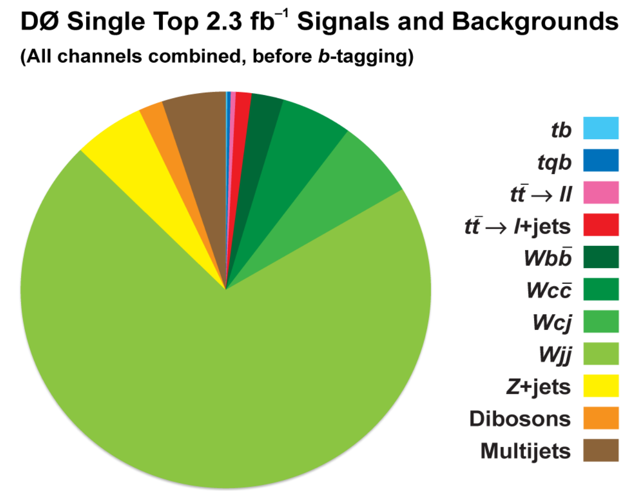


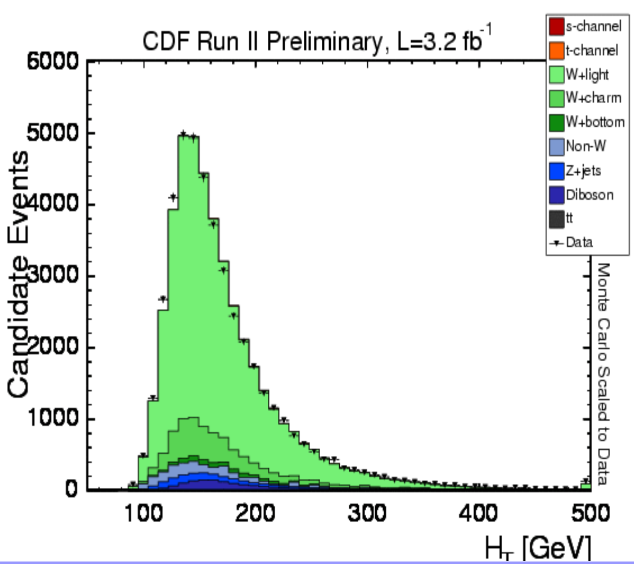


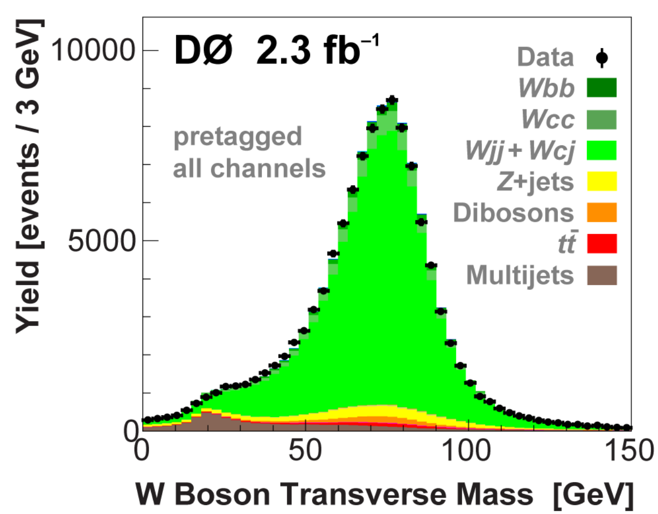
Selection I (l+jets)

Starting S:B = 1:10^9

- Single lepton (e, μ) & MET+ jets triggers
- One high p_T lepton
- MET and 2-4 (D0), 2-3 (CDF) high p_T jets
- Cuts to suppress multijet background
- Veto to suppress Z and $t\bar{t}$







- Verify background model before *b*-jet tagging
- Dominated by W+ light jets

Selection II: *b*-tagging (l+jets)

DØ NN tagger

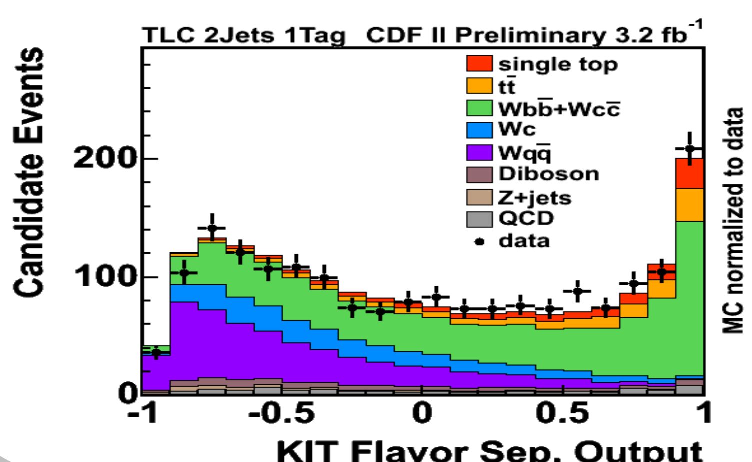
- 1 tight tag (40/9/0.4% *b*/*c*/light) or
- 2 loose (50/14/1.5% *b*/*c*/light)

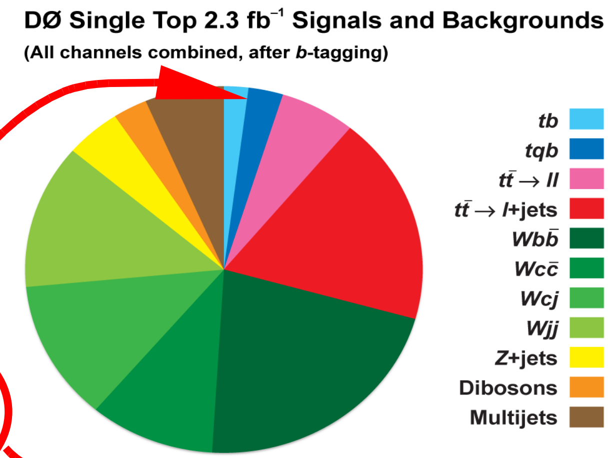
CDF 1 SVX tag

- 50/9/0.5÷1.0% b/c/light

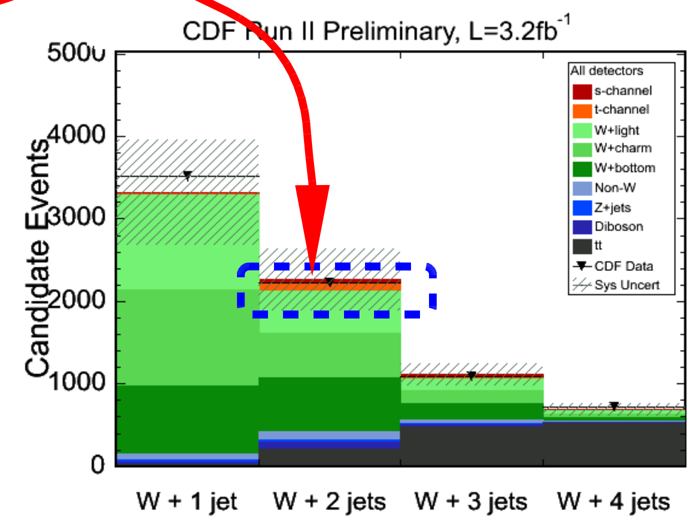
Additional flavor separation

- NN trained with 25 input variables
- Continuous variable
- Improves sensitivity by 10-15%





Single top signal



Signal is smaller than the background uncertainty

Selection II – MET+ jets

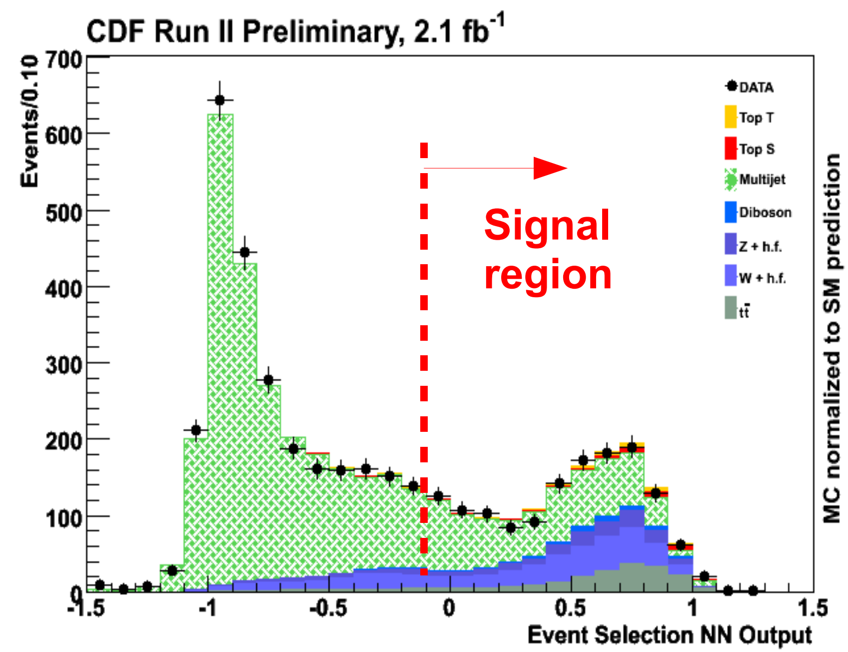
New channel

- Recover non-fiducial leptons and hadronic τ decay
  - Orthogonal to lepton+jets
- MET+ jets trigger

  Huge instrumental background from QCD multijets
- MET>50 GeV and veto leptons
- E_T>35 (25) GeV 1st (2nd) jet
- At least 1 *b*-tag
- NN to suppress multijet bckg

  Signal region: ANN>–0.1

  Control region: ANN<–0.1

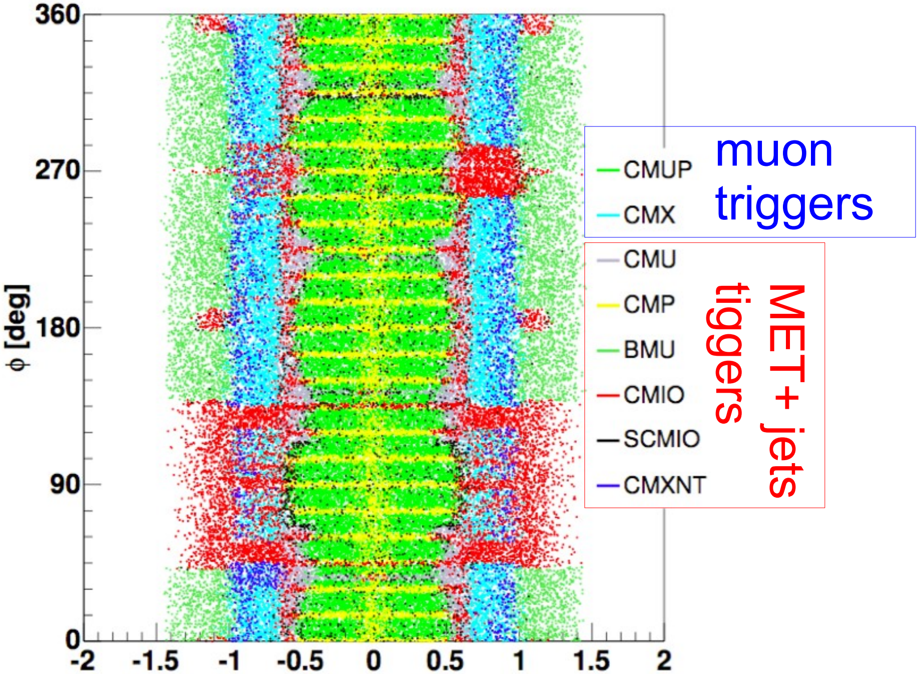


Quantity	Pre-selection	After QCDNN cut	Difference
Signal (S)	75	68	-9%
QCD Background	2960	675	-77%
Total Background (B)	3840	1350	-65%
S/√S+B	1.2	1.8	+50%
S/B	1/50	1/20	+150%

Improvements

- 3.2 fb^{-1} (2.2–2.7 fb^{-1} in summer)
- Extended muon coverage

30% gain in muon acceptance
10-14% gain in sensitivity



- Additional channel MET+ jets

33% increase of acceptance

- Separate s- and t-channel searches

- 2.6 times more data (2.3 fb^{-1})
- 18% larger acceptance
  - **Logical OR of many triggers**
  - **Looser cuts on 2nd jet and muon p_T**
  - **Increased $|\eta|$ for 1st jet (2.5→ 3.4)**
  - **Looser b-tagging requirements for 2 b-tag events**
- Additional cuts to reduce background
- Improved (more detailed) background modeling
  - **Data-based corrections to Alpgen model of W+jets**
- Improved treatment of multijet background

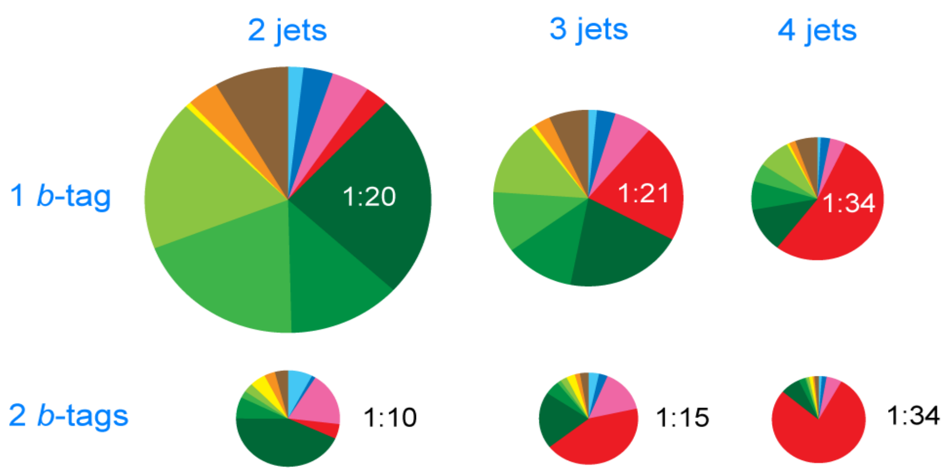
Yields

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

for m_t=170

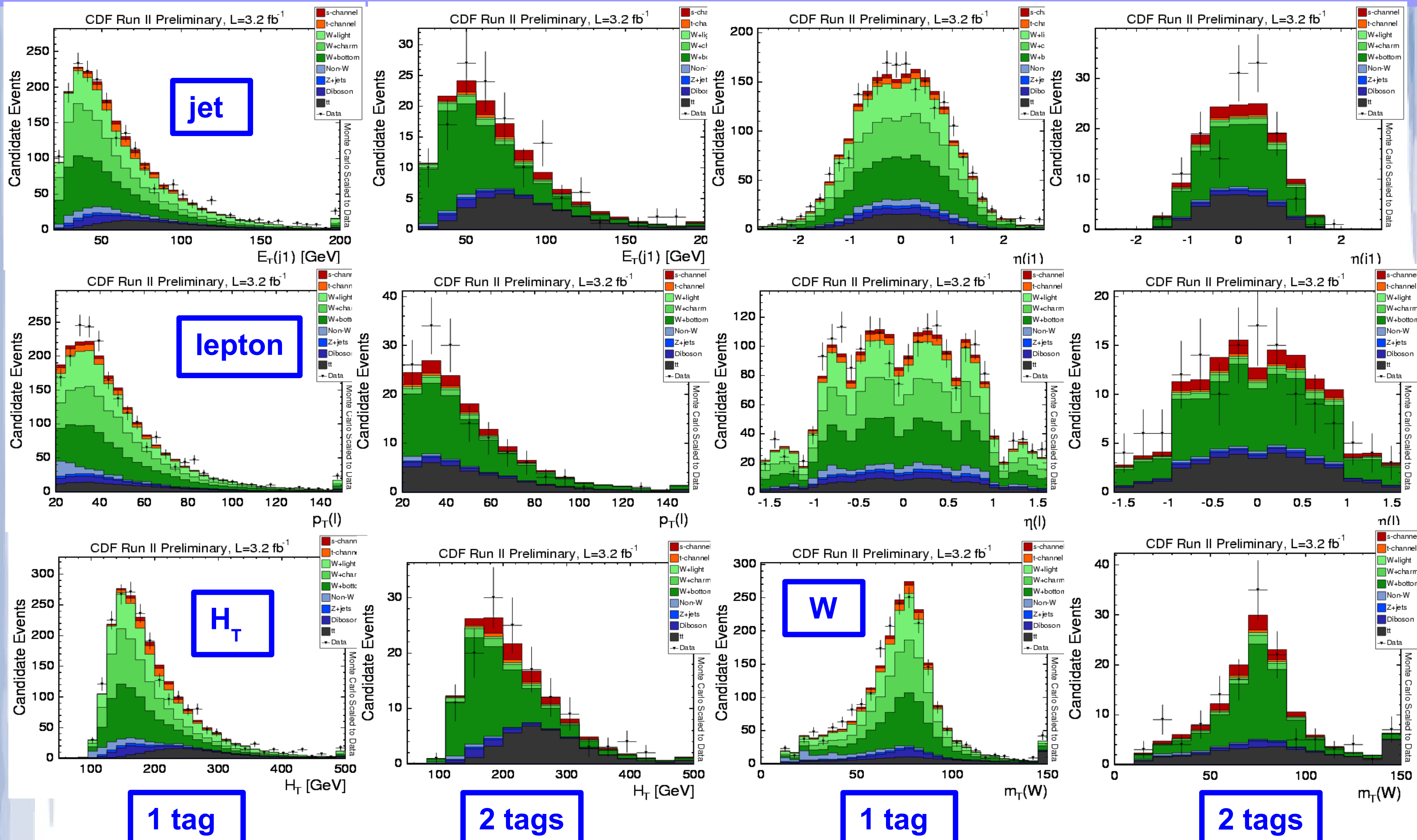
255 events for m_t=175

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



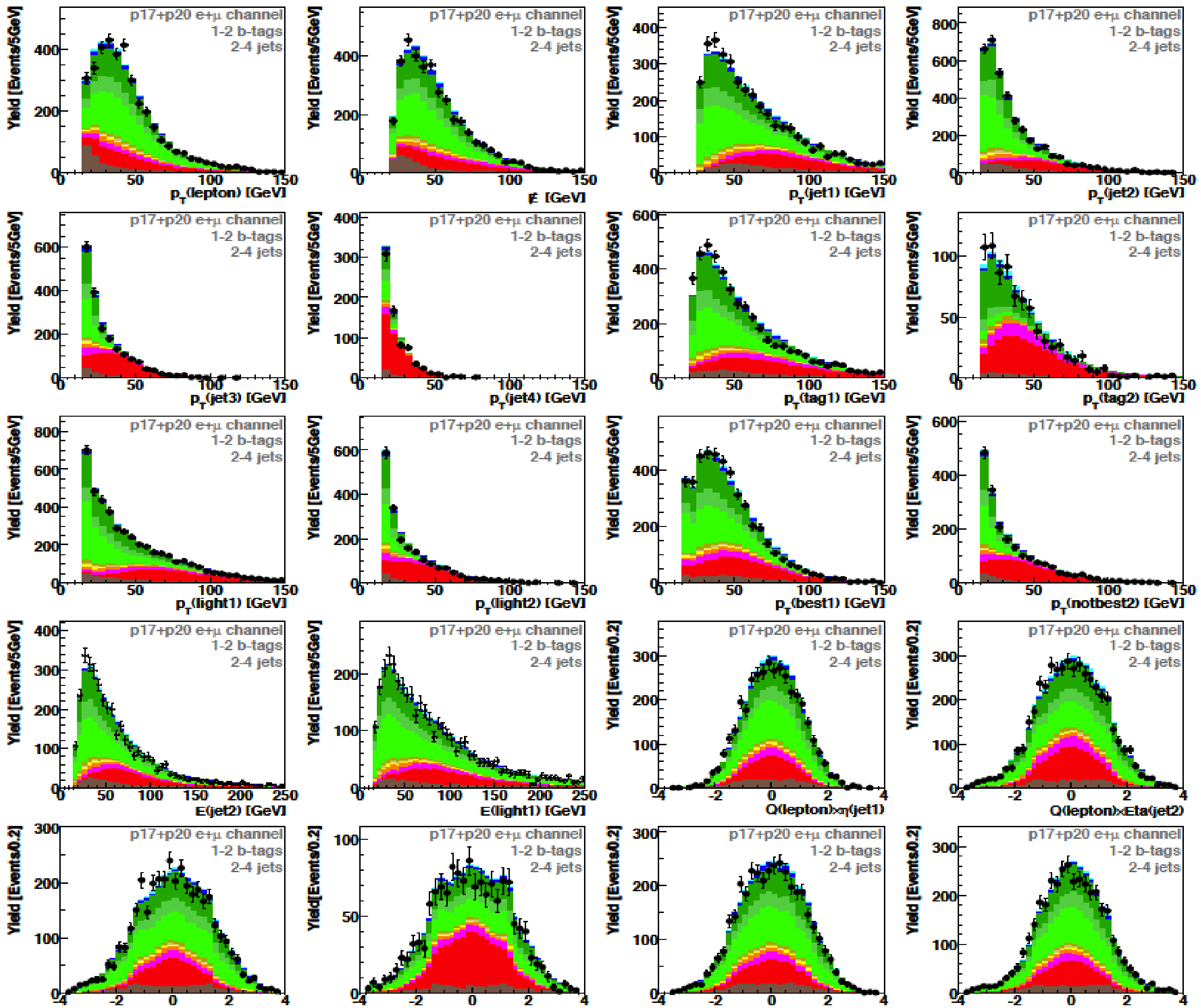
- S:B ratios from 1:10 to 1:34 depending on number of jets and tags
- Most powerful channel - 2 jet, 1 tag – S:B ~ 1:20
- Keep channels separately in the analysis

Background model validation



Background model validation

SINGLE OBJECT KINEMATICS



- Check thousands of distributions to verify background model before and after tagging
- Several classes of variables used in discriminants
  - Single object kinematics
  - Event kinematics
  - Jet reconstruction
  - Top quark reconstruction
  - Angular correlations

Systematics

- Statistically limited measurement
- But systematics is important
- Affects normalization and shapes

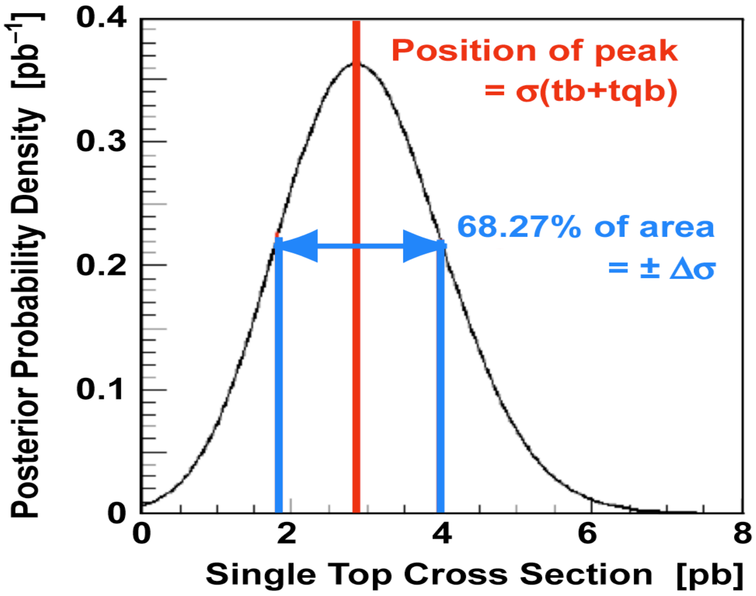
Systematic Uncertainties Ranked from Largest to Smallest Effect on Single Top Cross Section DØ 2.3 fb^{-1}	
Larger terms	
b-ID tag-rate functions (includes shape variations)	(2.1–7.0)% (1-tag) (9.0–11.4)% (2-tags)
Jet energy scale (includes shape variations)	(1.1–13.1)% (signal) (0.1–2.1)% (bkgd)
W+jets heavy-flavor correction	13.7%
Integrated luminosity	6.1%
Jet energy resolution	4.0%
Initial- and final-state radiation	(0.6–12.6)%
b-jet fragmentation	2.0%
$t\bar{t}$ pairs theory cross section	12.7%
Lepton identification	2.5%
Wbb/Wcc correction ratio	5%
Primary vertex selection	1.4%

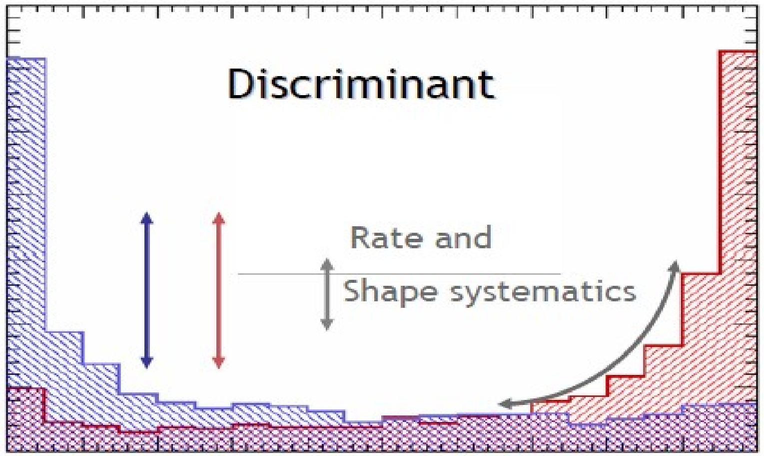
- Estimated for each background and signal source in each analysis channel
- Background uncertainty dominates

Systematic Uncertainty	Rate	Shape
Jet Energy Scale	0...10%	✓
Initial + Final State Radiation	0...15%	✓
Parton Distribution Functions	2...3%	✓
Monte Carlo Generator	1...5%	
Event Detection Efficiency	0...9%	
Luminosity	6%	
Neural Net B-tagger		✓
Mistag Model		✓
Q^2 scale in ALPGEN MC		✓
Input variable mismodeling		✓
Wbb+Wcc normalization	30%	
Wc normalization	30%	
Mistag normalization	17...29%	
ttbar normalization & m_{top}	23%	✓

Cross section

- Discriminant outputs (from each analysis channel separately) are used to measure cross section
- Build Bayesian probability density with flat nonnegative prior for the cross section
- Peak of posterior distribution gives the cross section, 68% interval gives the uncertainty
- Shape and normalization systematic uncertainties are treated through nuisance parameters with Gaussian distribution
  - Correlations are properly taken into account

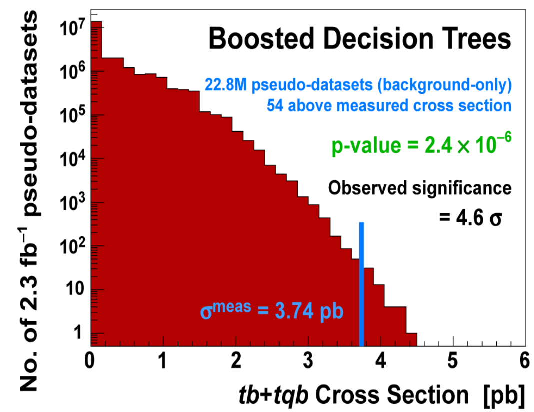




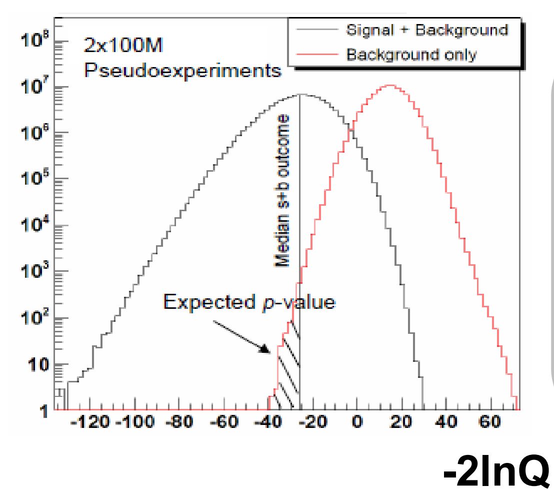
Statistical analysis

- Build ensembles of pseudo-data
  - Includes signal and background events or background only
  - Includes all systematic uncertainties
- Purpose before data
  - Test performance of different methods
  - Measure expected cross section uncertainty
  - Expected significance
- With data
  - Consistency of the measured cross section with the SM
  - Observed significance

Significance – probability of the upward background fluctuation that gives observed result in data



***p*-value:** **Fraction of zero-signal ensemble datasets that give $\sigma \geq \sigma_{meas}$**



Likelihood ratio technique

$$Q = \frac{P(\text{data} \mid s+b, \hat{\theta})}{P(\text{data} \mid b, \hat{\hat{\theta}})}$$

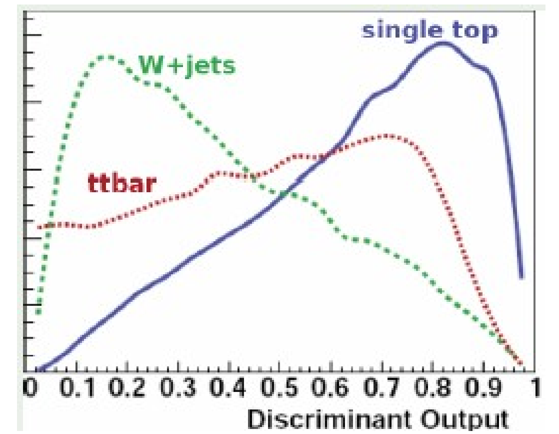
Signal from background separation

Signal model

Background model

Data

Multivariate separation technique

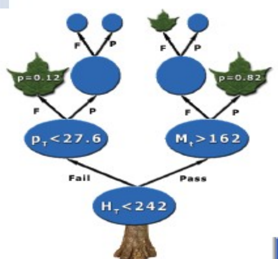


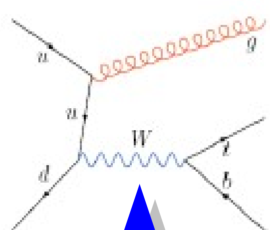
background signal

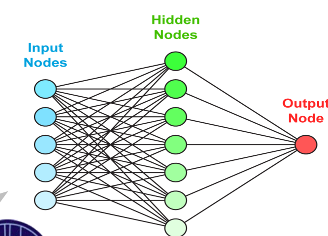
Combine many variables into one discriminant

Test of hypothesis H_0: signal vs hypothesis H_1: background

Boosted decision trees	Matrix elements	Neural Networks	Likelihood function







$$\mathcal{L}^{signal} = \frac{\prod_{i=1}^{n_{var}} P_i^{signal}}{\prod_{i=1}^{n_{var}} P_i^{signal} + \sum_{m=1}^{n_{bkg}} \prod_{i=1}^{n_{var}} P_i^{m} \times a^{m}}$$

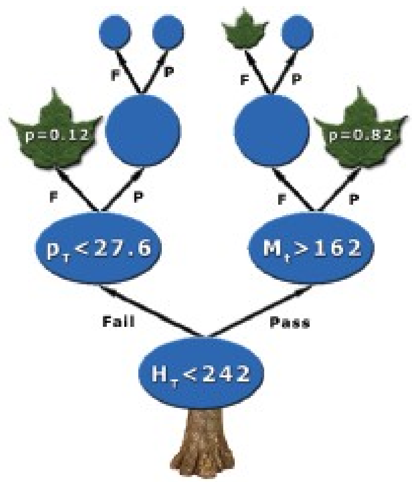
Combined analysis

t-channel + s-channel = one single-top signal
cross section ratio is fixed to SM value.
important for „observation“ and $|V_{tb}|$ test

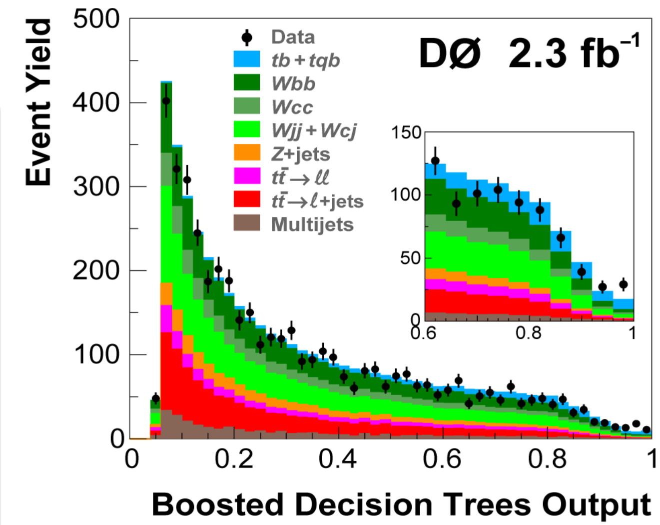
Separate search

consider t-channel and s-channel as separate processes
important for new physics search

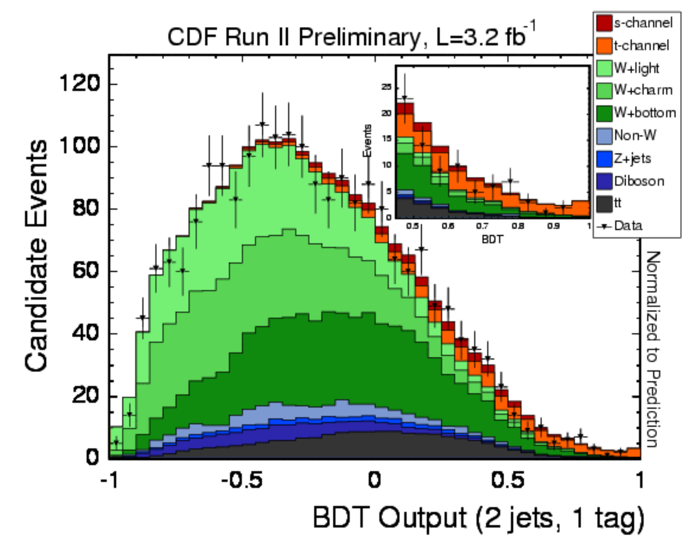
Boosted Decision Trees



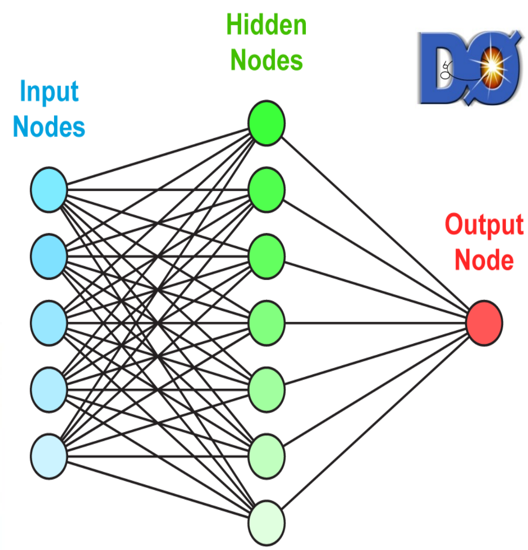
- Cut based technique
- Does not reject events that fail the cuts
- Boosting – averaging over many trees – improves performance and stability
- Adding additional input variables does not degrade performance
- D0: 64, CDF: 20 input variables



	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Obs.	σ_{s+t} [pb]
DØ	2.3	4.3σ	4.6σ	$\mathbf{3.7^{+1.0}_{-0.8}}$
CDF	3.2	5.2σ	3.5σ	$\mathbf{2.1^{+0.7}_{-0.6}}$



Neural Networks



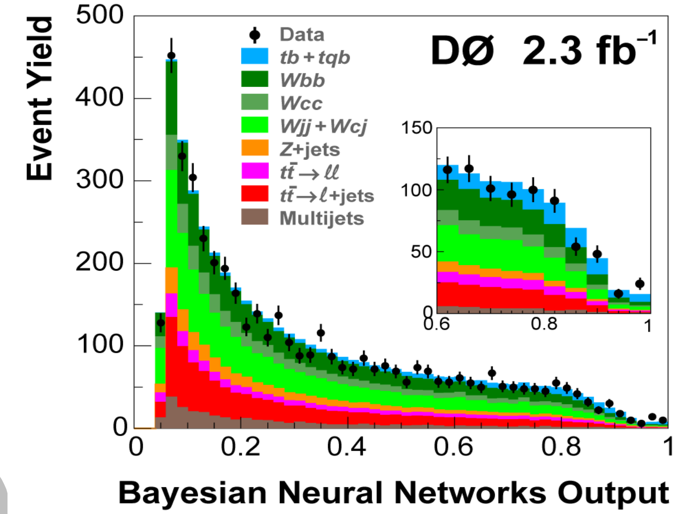
DØ

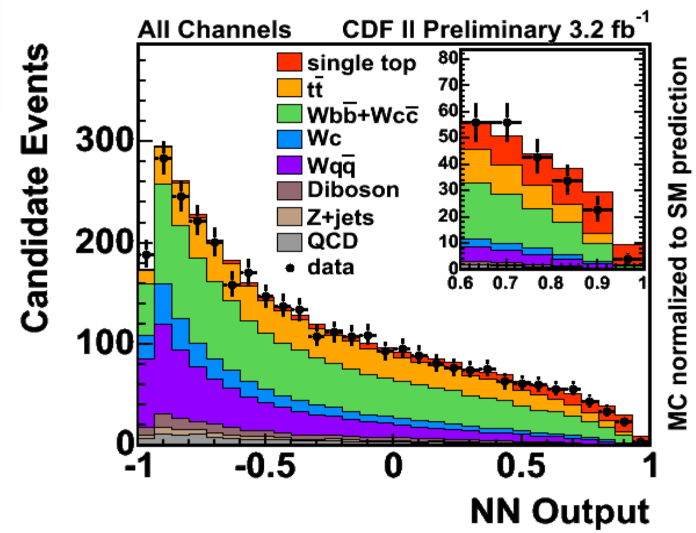
Bayesian NN

- Weighted average over hundreds of networks
- Better stability
- Immune to overtraining
- 18-25 input variables

CDF

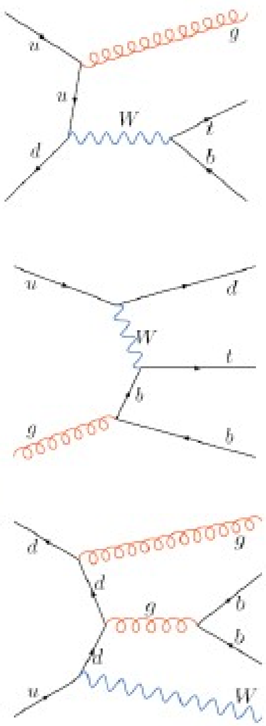
- 4 networks
- Each divided into 2 channels according to the trigger
- 14 variables



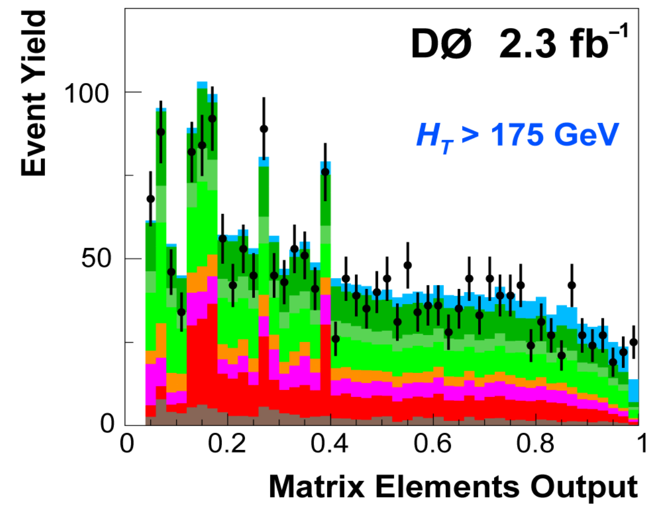


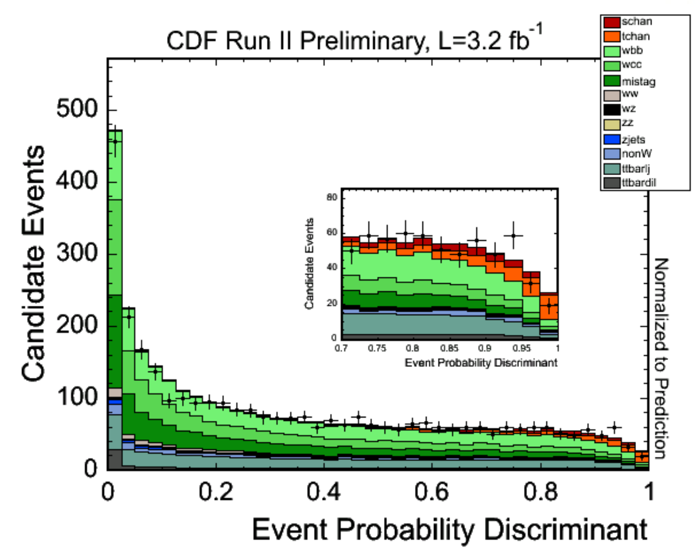
	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
DØ	2.3	4.1σ	5.2σ	$4.7^{+1.2}_{-0.9}$
CDF	3.2	5.2σ	3.5σ	$1.8^{+0.6}_{-0.6}$

Matrix Elements



- Given 4-vectors of reconstructed lepton and jets compute event probability density for signal and background hypothesis
- Probability calculation ingredients:
  - LO matrix elements (s, t, Wbb̄, Wcc̄, Wcj, Wgg, tt̄, ...)
  - Parton Density Functions
  - Detector resolution effects
- Improve performance by
  - D0: splitting samples by H_T into tt̄ and W+jets dominated regions
  - CDF: weighting events by jet flavor probability





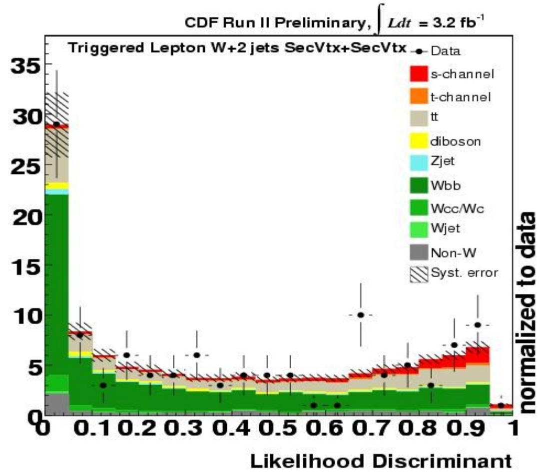
	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
DØ	2.3	4.1σ	5.0σ	$\mathbf{4.3^{+1.0}_{-1.2}}$
CDF	3.2	4.9σ	4.3σ	$\mathbf{2.5^{+0.7}_{-0.6}}$

Multivariate Likelihood Function

$$\mathcal{L}^{signal} = \frac{\prod_{i=1}^{n_{val}} P_i^{\text{signal}}}{\prod_{i=1}^{n_{val}} P_i^{\text{signal}} + \sum_{m=1}^{n_{bkg}} \prod_{i=1}^{n_{val}} P_i^{m} \times a^{m}}$$

Combine many variables into a likelihood function

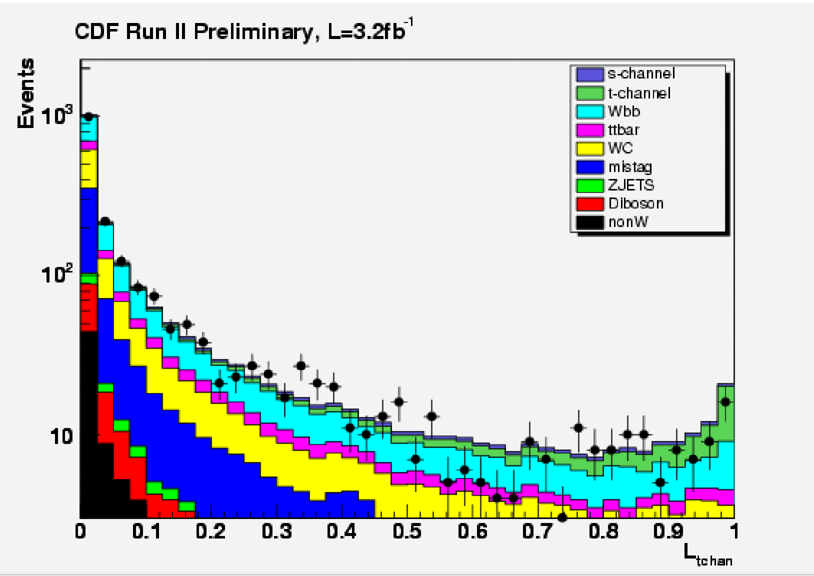
s-channel



- **Events with 2 *b*-tags**
- **2 classes: $\bar{t}t$ and W+HF**
- **9-10 variables**

	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Obs.	σ_{s+t} [pb]
LF	3.2	4.0σ	2.4σ	$\mathbf{1.6}^{+1.0}_{-0.8}$
s-channel	3.2	1.1σ	2.0σ	$\mathbf{1.5}^{+0.9}_{-0.8}$

t-channel likelihood

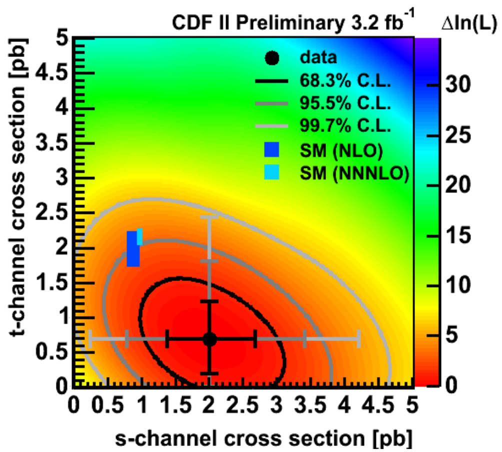


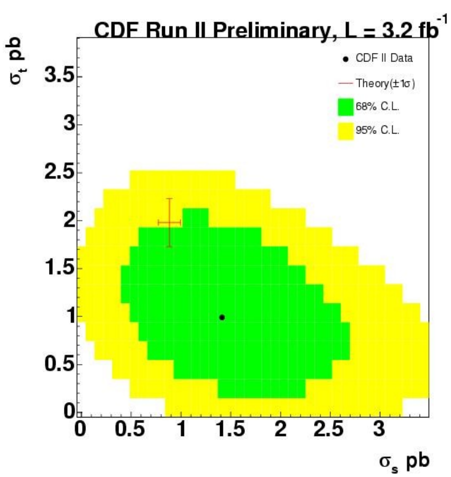
- Signal template built for t-channel
- 4 background classes: W$b\bar{b}$, W$c\bar{c}$/ Wc, $t\bar{t}$, mistags
- 7 (10) variables in 2 (3) jet bin to isolate t-channel contribution

More results...

Separate search using NN

- 5 networks, 2 outputs combined into 2D discriminant in 2j1tag channel

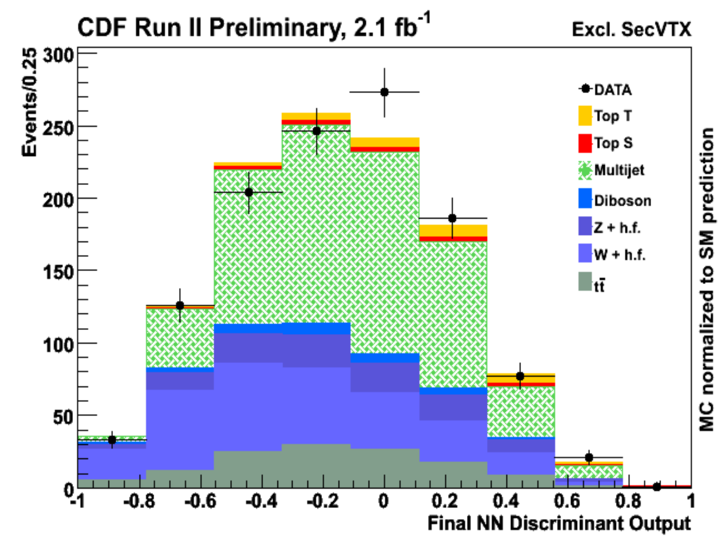




	σ (pb)	
s-ch	$2.0^{+0.7}_{-0.6}$	1.4
t-ch	$0.7^{+0.5}_{-0.5}$	1.0

Simultaneous fit of σ_s and σ_t (LF)

MET+ jets combined search

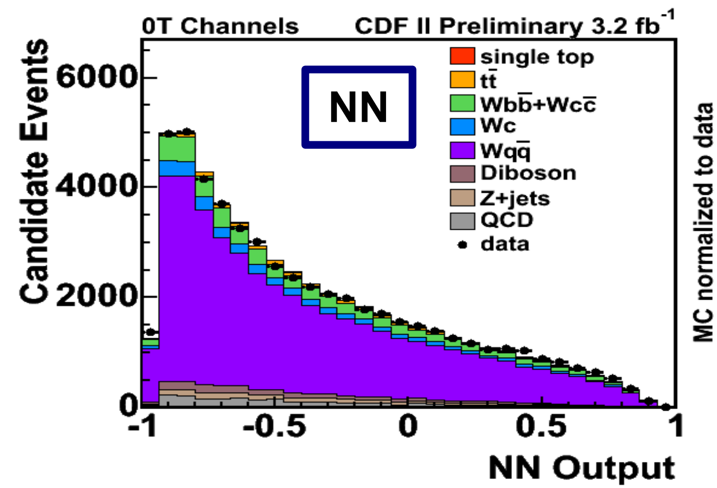


	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Obs.	σ_{s+t} [pb]
$\not{E}_T$+jets	2.1	1.4σ	2.1σ	$4.9^{+2.5}_{-2.2}$

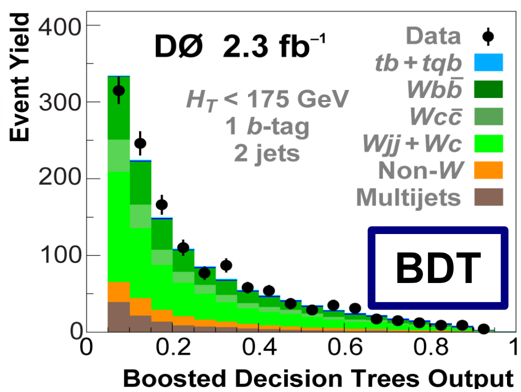
Cross check samples

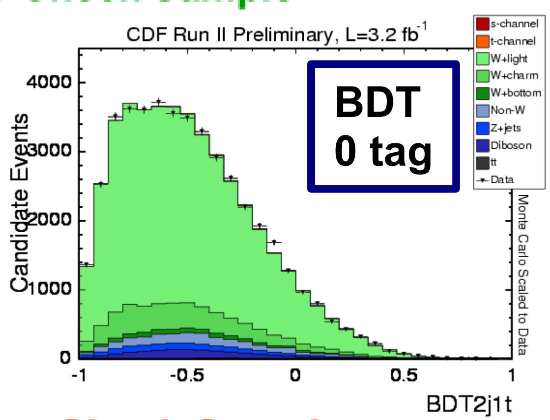
Cross checks of discriminant performance using samples depleted in signal

- Untagged (high statistics)
- W+jets (nj=2, 1 *b*-tag, H_T(l,ν,jets) < 175 GeV)
- $t\bar{t}$ dominated (nj=4, ≥1 *b*-tag, H_T > 300 GeV)

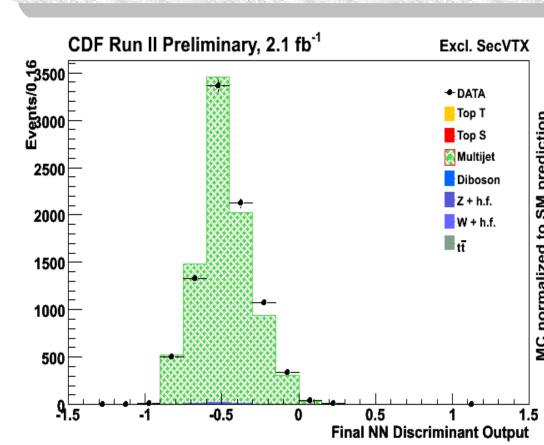


W+Jets Cross-Check Sample

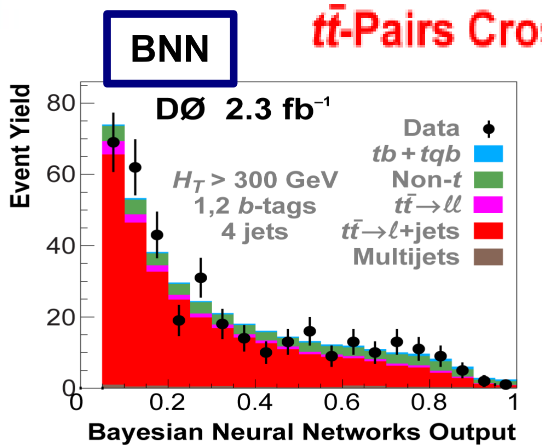


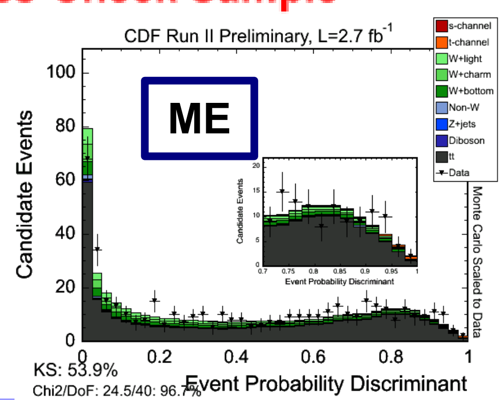


MET + jets
QCD enriched sample



$t\bar{t}$-Pairs Cross-Check Sample





Combinations

Choose a priori to quote combination result as main

CDF

NeuroEvolution of Augmenting Topologies

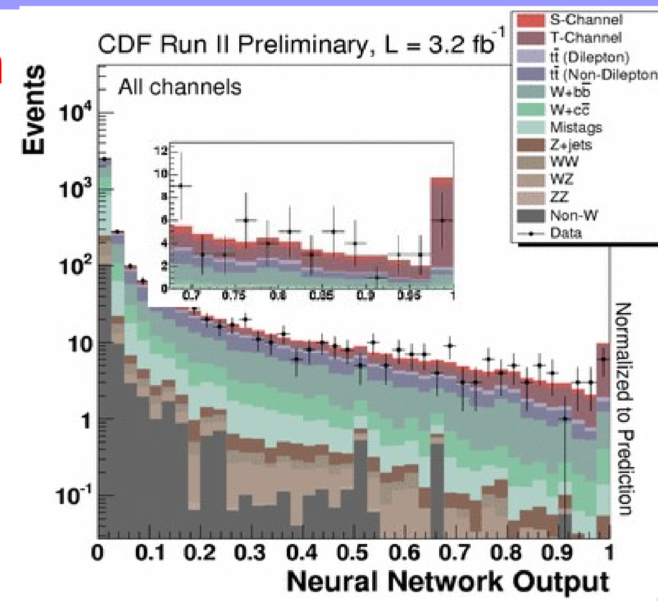
- NN trained to give best expected p-value
- Optimizes network topology, inter-node weights, output binning
- Inputs: **5 l+jets discriminants (BDT, ME, NN, LF, SLF), MET+ jets**
- Sensitivity: 5.2σ→>5.9σ

DØ

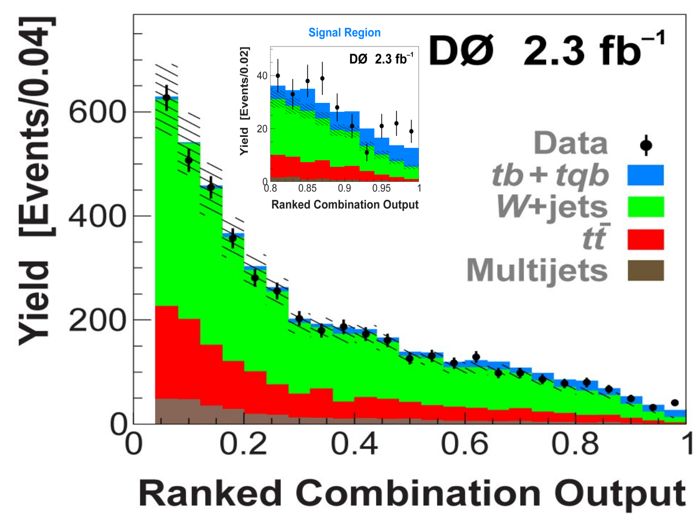
Bayesian Neural Network

- Inputs:

  3 discriminants (BDT, ME, NN)
- 57÷74% correlation
- Sensitivity: 4.3σ → 4.5σ



Final Discriminant



	$\mathcal{L}$ [fb^{-1}]	Significance Exp.	Significance Obs.	σ_{s+t} [pb]
DØ	2.3	4.5σ	5.0σ	$3.9^{+0.9}_{-0.9}$
CDF	3.2	5.9σ	5.0σ	$2.3^{+0.6}_{-0.5}$

Observation !!

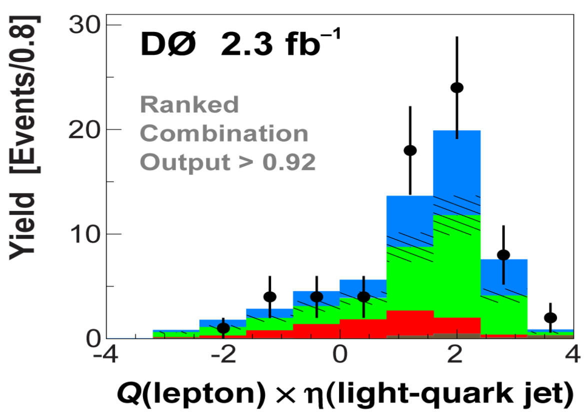
Can we see it?

- Look at high discriminant regions

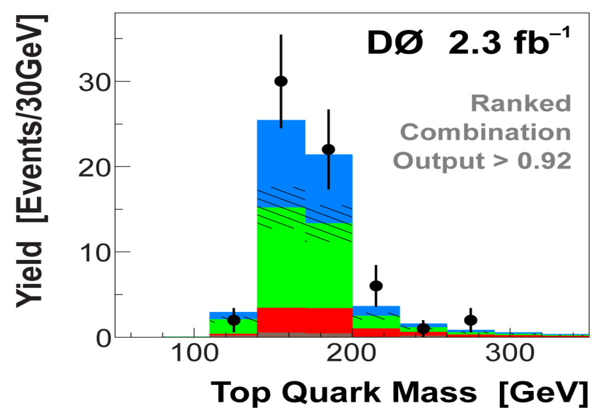
BNN combined D >0.92, all channels

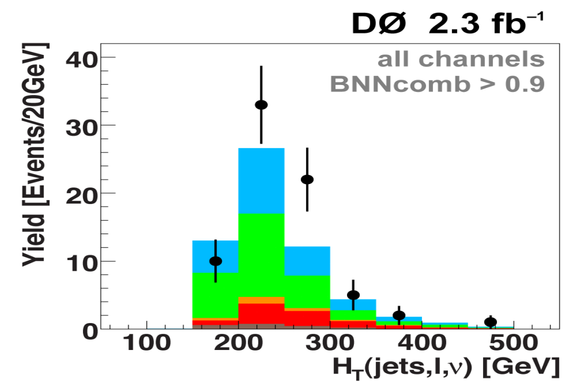
Signal normalized to measured σ

High Signal Region – $Q \times \eta$



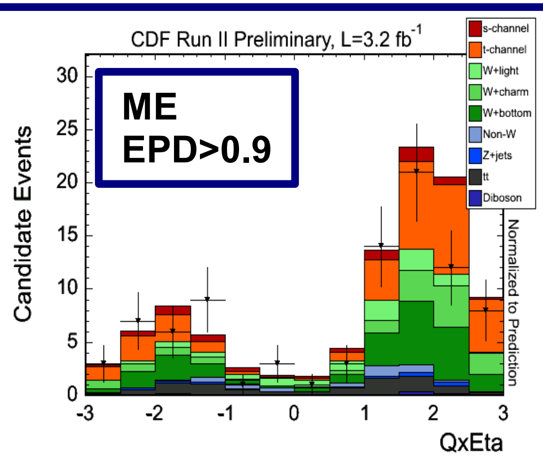
High Signal Region – m_{top}

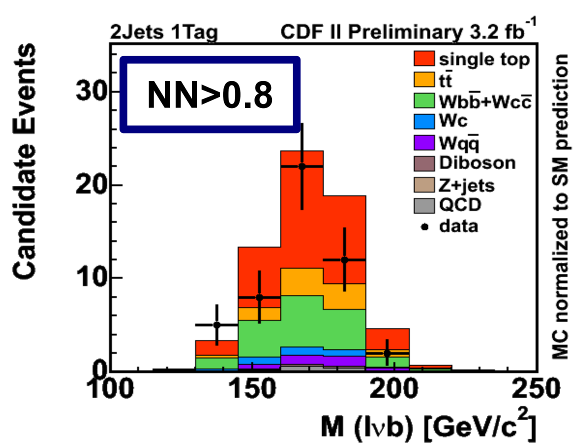


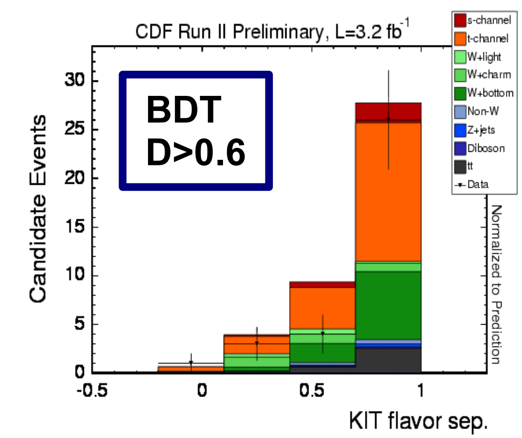


The most sensitive channel: 2 jets, 1 b-tag

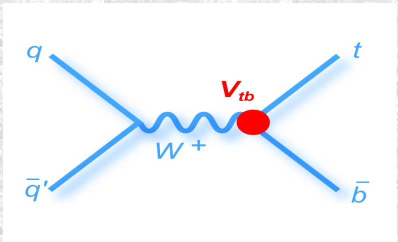
Signal normalized to expected SM σ



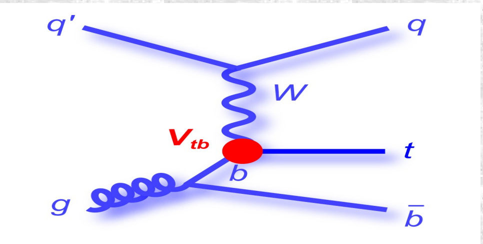




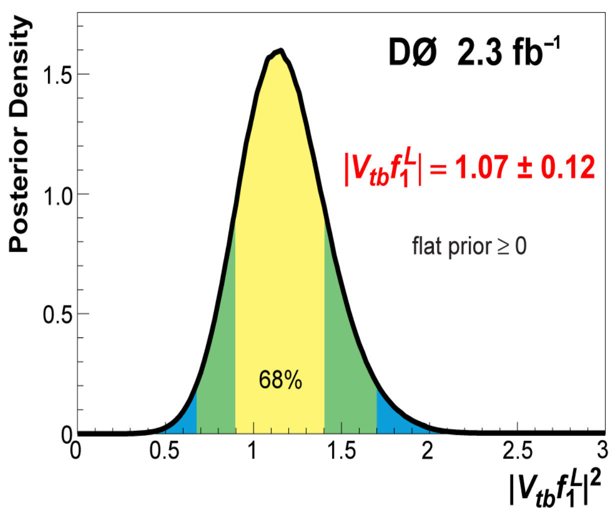
Measurement of $|V_{tb}|$



$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} |V_{tb,SM}|^2$$



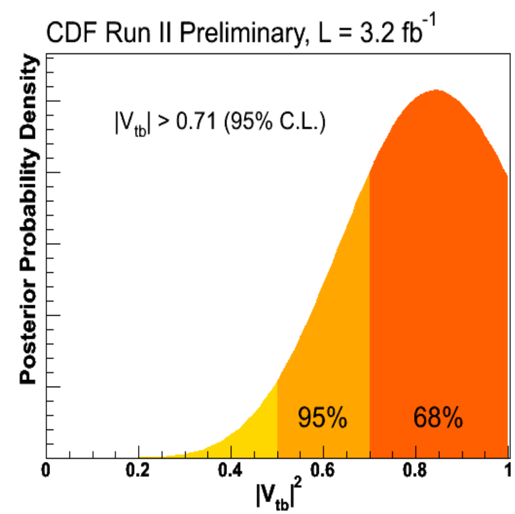
- Assume $|V_{td}|^2+|V_{ts}|^2 << |V_{tb}|^2$, SM (V–A) and CP conserving Wtb vertex
- No assumption on the number of quark families or CKM unitarity



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%



$|V_{tb}f_1^L| = 1.07 \pm 0.11(\text{sys+th})$
$|V_{tb}| > 0.78$ at 95% CL

$|V_{tb}| = 0.91 \pm 0.11(\text{sys}) \pm 0.07(\text{th})$
$|V_{tb}| > 0.71$ at 95% CL

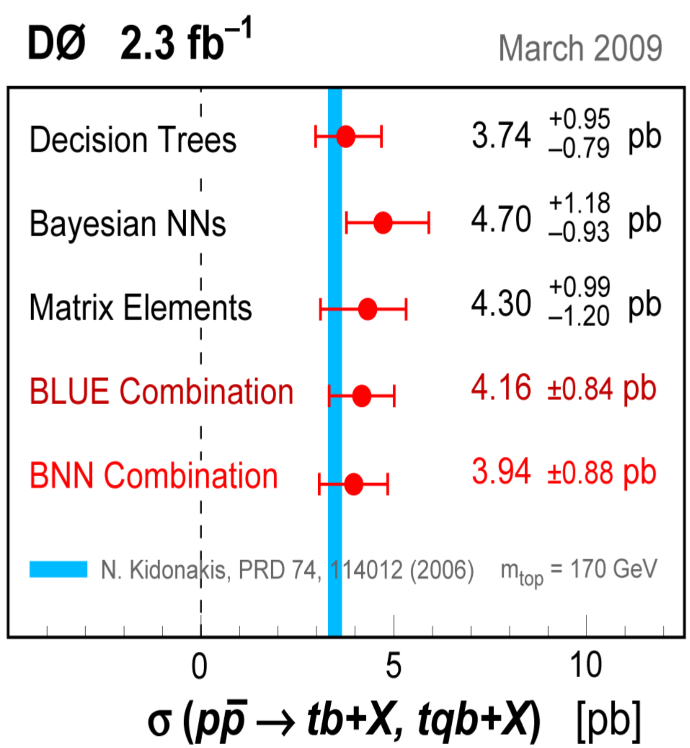
Summary

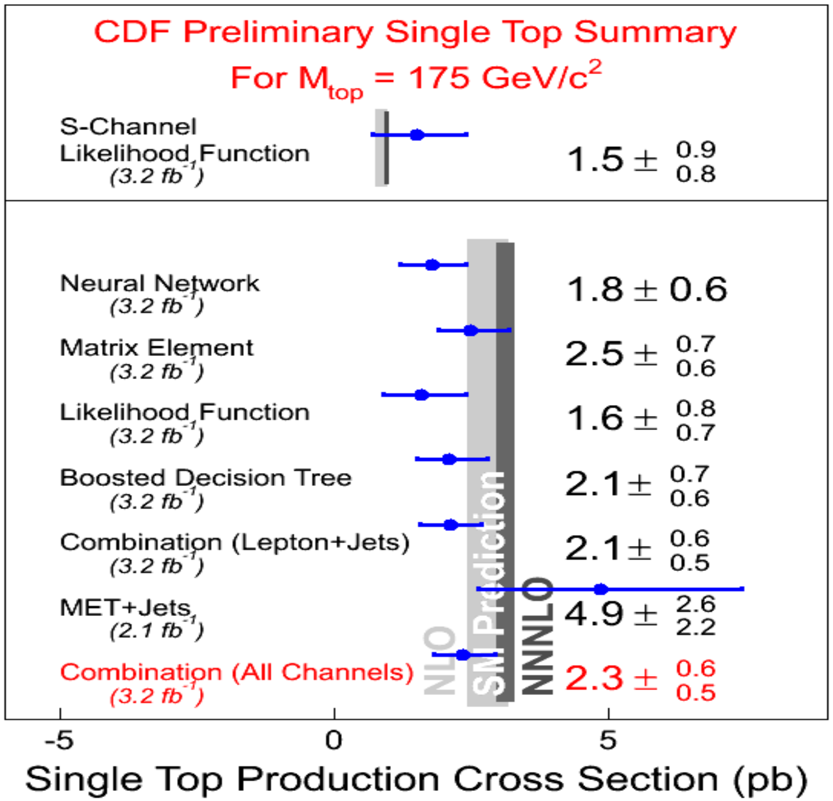
- Single top quark production has been observed at Tevatron by CDF and D0 with signal significance of 5σ
- Both cross section and $|V_{tb}|$ measurements agree with SM

Submitted to PRL

ArXiv:0903.0850

ArXiv:0903.0885



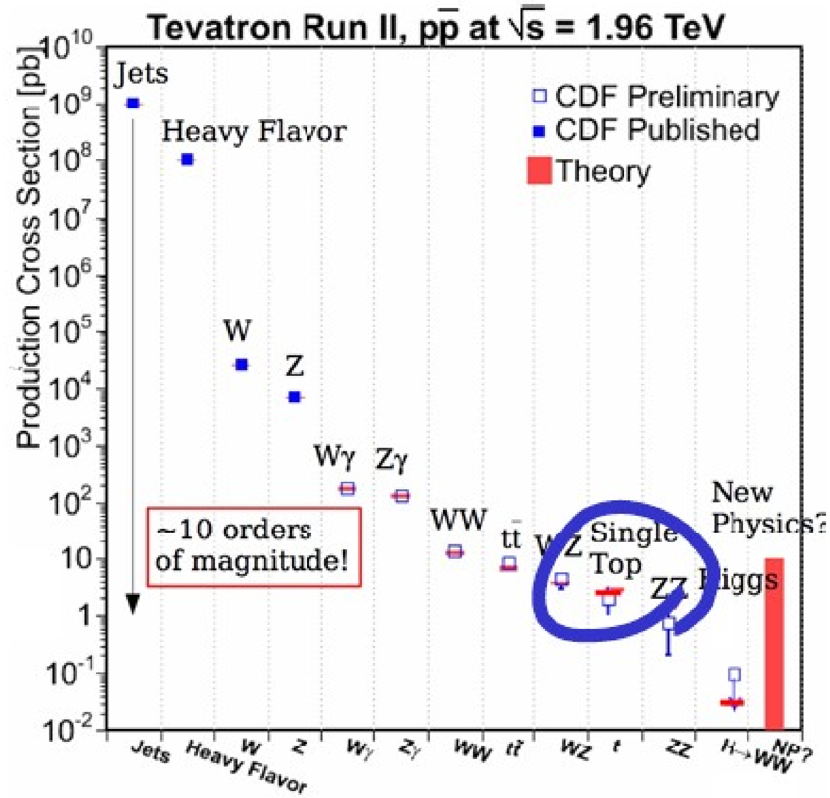


Outlook

This is just the beginning of the single top physics

- Precise measurements of σ_t and σ_s
- Top quark polarization
  - talks by Ji-Eun Jung and B.Casal in this session
- Search for Anomalous Top quark couplings
  - Combination with W helicity from $t\bar{t}$ (in this session talk by R.Schwienhorst)
- W ' and H^+ searches
- Top production through FCNC

From R.Wallny's Wine and Cheese talk, 03/10/2009



Milestone in the race for Higgs Boson !

Public web sites

More details can be found on the public pages of the experiments:

http://www-cdf.fnal.gov/physics/new/top/public_singletop.html

http://www-d0.fnal.gov/Run2Physics/top/singletop_observation

Backup

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