Uncovering The Single Top: Observation of the Electroweak Top Quark Production

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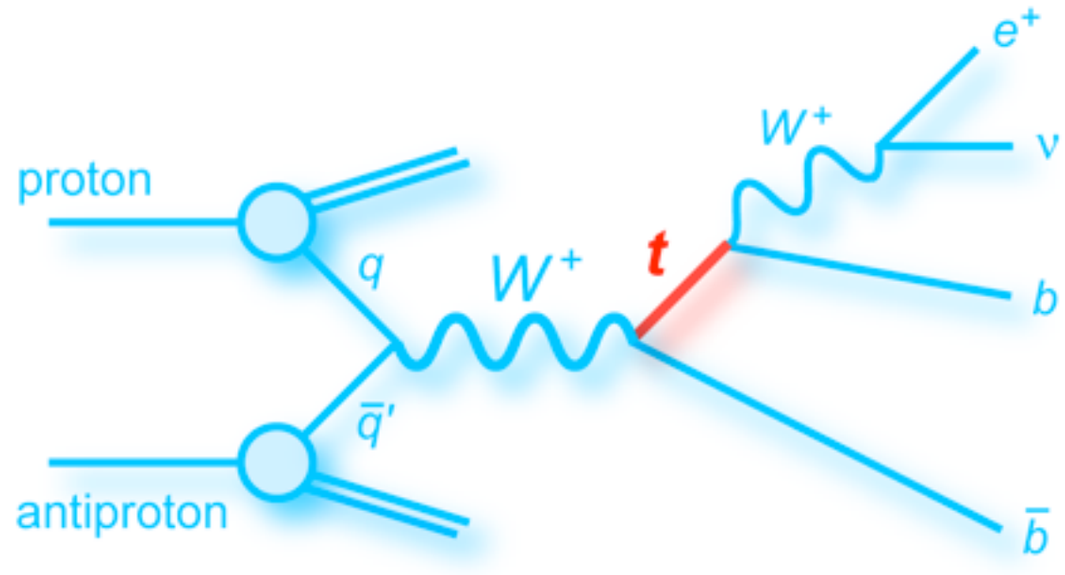
Ph.D. Dissertation Defense

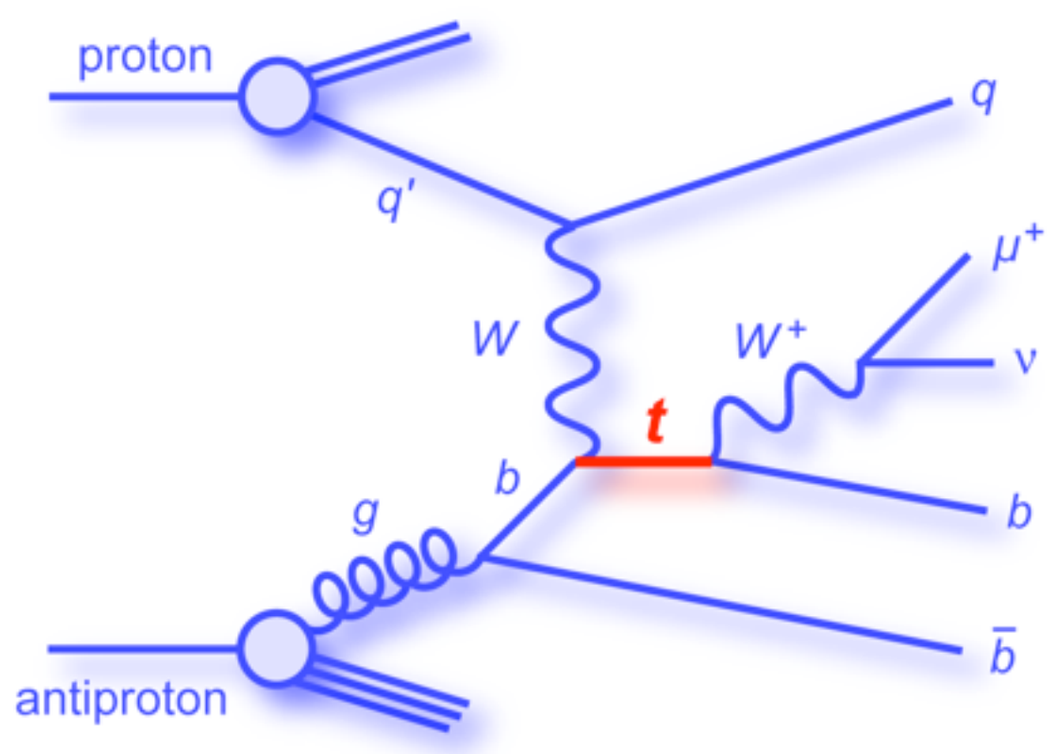
Michigan State University

August 21st, 2009

Outline

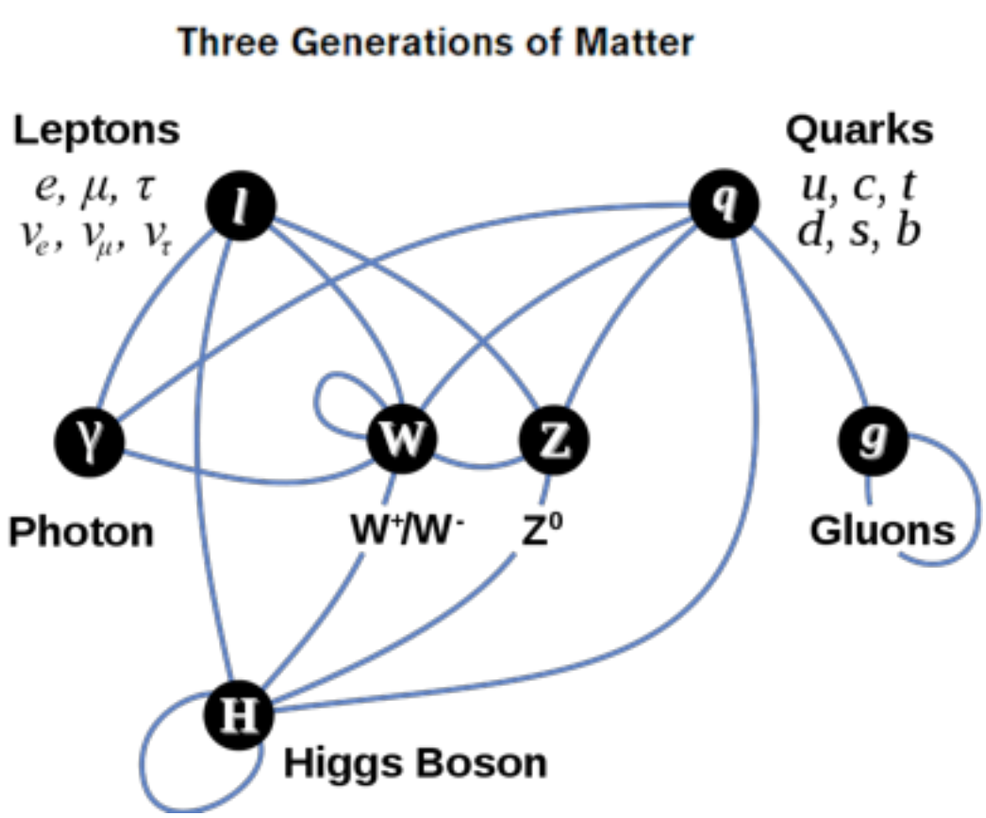
- Theoretical motivation
- Single Top quark production
- Experimental Facilities
- Signal and Background
- Boosted Decision Trees
- Analysis
- Conclusions





Standard Model (SM)

- The SM describes the world around us
- Components:
  - 24 particles of matter
  - 4 mediators
- Interactions of the particles explained by the mediators
- Does not include: gravity, dark matter and dark energy

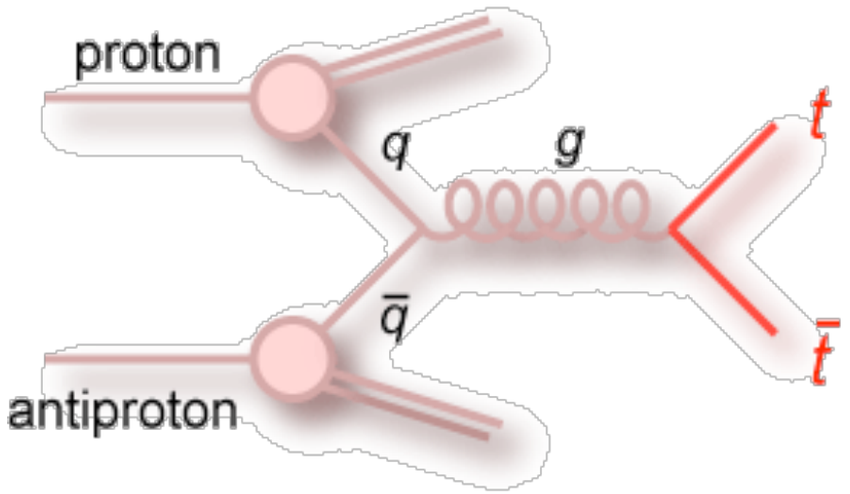


Top Quark

- Heaviest SM particle, mass close a gold's atom

$$m_t = 173.1 \pm 1.3 \text{ GeV}/c^2$$

- Discovered in 1995 at Fermilab
- Spin: 1/2, Charge: + 2/3

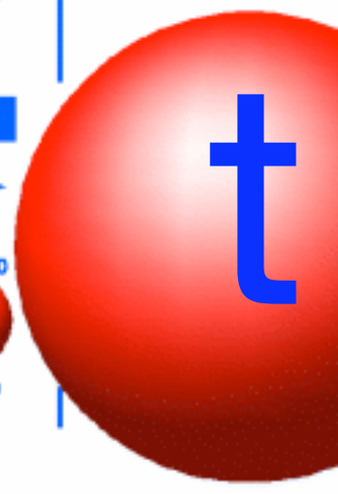


- Mostly produced in quark-antiquark pairs

$$\sigma_{t\bar{t}}(\text{Tevatron}) = 7.62 \pm 0.85 \text{ pb}$$

- Short lifetime ~ 10^{-25} s, it decays before having a chance to hadronize, unique opportunity to study a bare quark

Comparison of the Elementary Particle masses

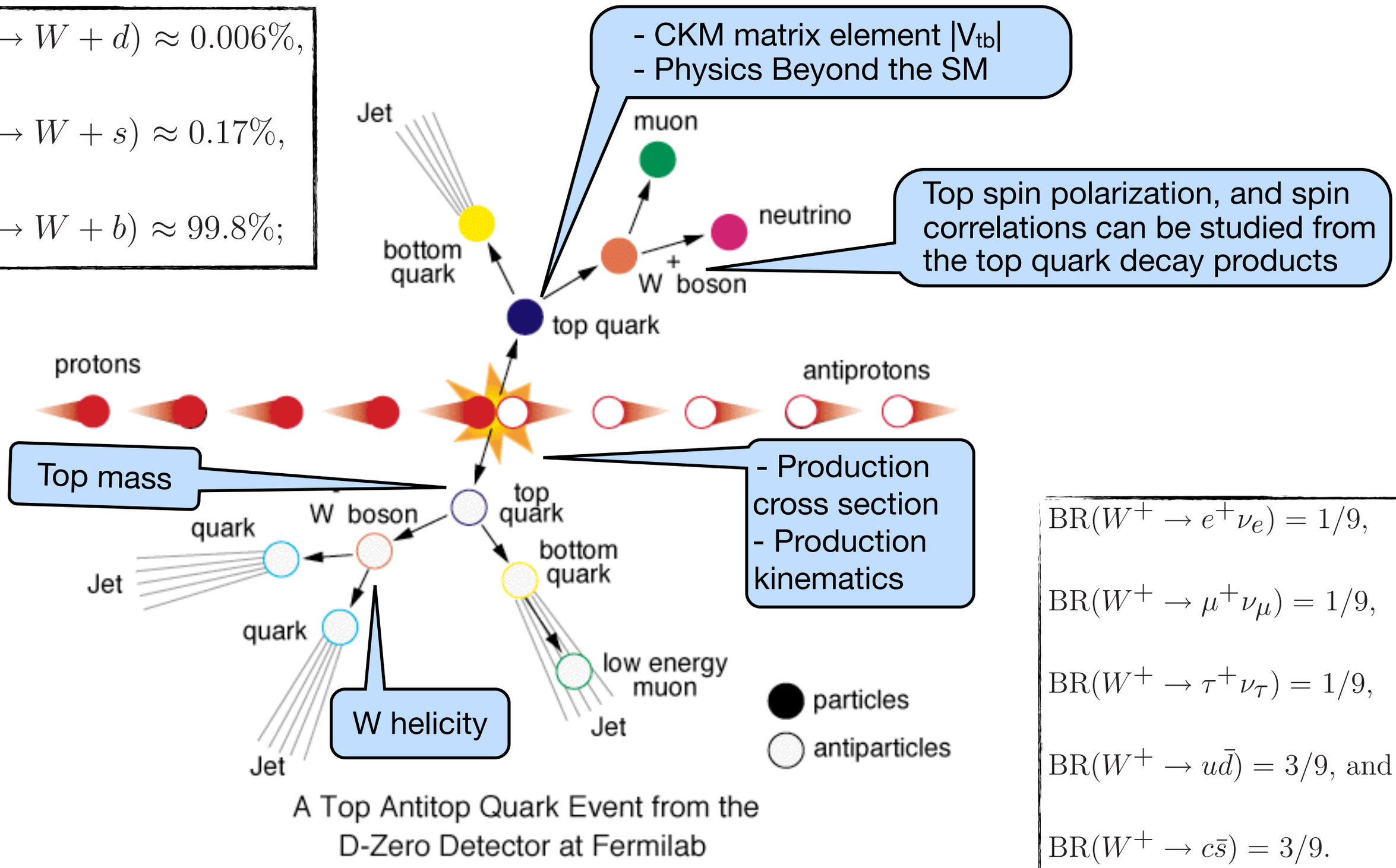


Top Quark Decay

$$\mathrm{B}(t \to W + d) \approx 0.006\%,$$

$$\mathrm{B}(t \to W + s) \approx 0.17\%,$$

$$\mathrm{B}(t \to W + b) \approx 99.8\%;$$



A Top Antitop Quark Event from the D-Zero Detector at Fermilab

$$\mathrm{BR}(W^+ \to e^+\nu_e) = 1/9,$$

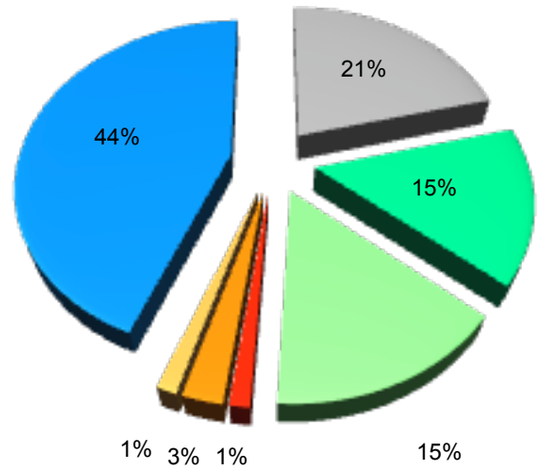
$$\mathrm{BR}(W^+ \to \mu^+\nu_\mu) = 1/9,$$

$$\mathrm{BR}(W^+ \to \tau^+\nu_\tau) = 1/9,$$

$$\mathrm{BR}(W^+ \to u\bar{d}) = 3/9, \text{ and}$$

$$\mathrm{BR}(W^+ \to c\bar{s}) = 3/9.$$

Top Quark Decay

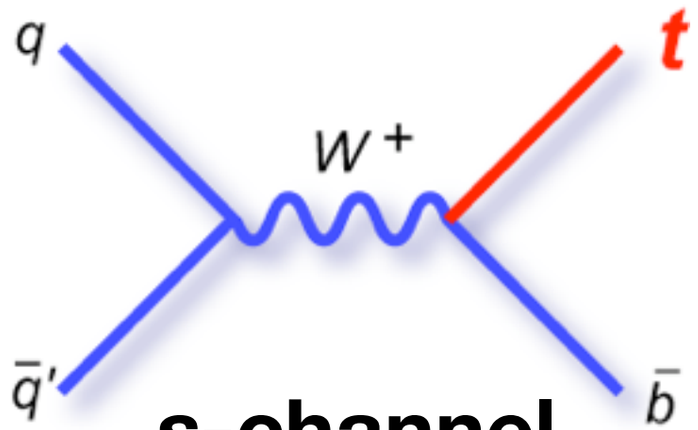


We only see the final states

Particles Seen by the D-Zero Detector at Fermilab in a Top Antitop Quark Event.

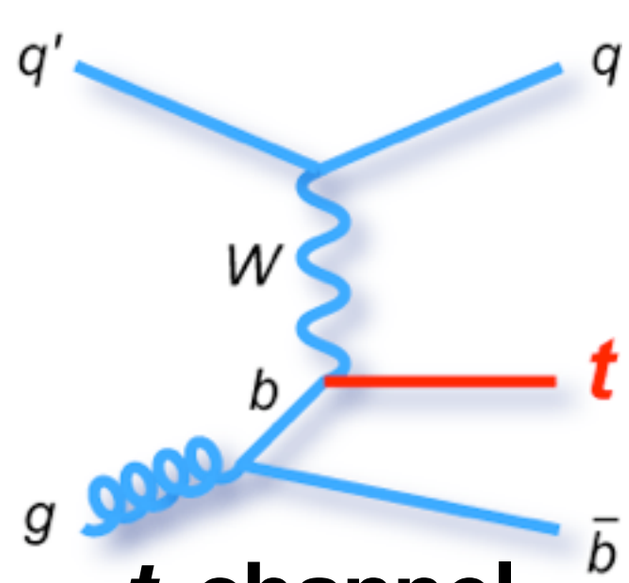
Single Top

- The Standard Model predicts the production of top quark by means of the electroweak interaction
- Only one top quark is produced! hence the name
- Had not been observed until now
- At the Tevatron Collider, there are two dominant Single Top channels:
  - *s*-channel
  - *t*-channel



s-channel

$$\sigma_s = 1.12 \pm 0.05 \text{ pb}$$



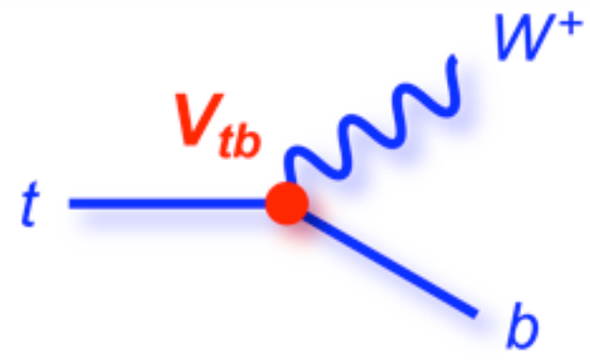
***t*-channel**

$$\sigma_t = 2.34 \pm 0.12 \text{ pb}$$

PRD 74, 114012 (2006), m_t = 170 GeV

Single Top

- Study the *Wtb* vertex:
  - Direct way to measure $|V_{tb}|$ of the *CKM* matrix element
  - Test unitarity of CKM matrix
  - Anomalous *Wtb* couplings



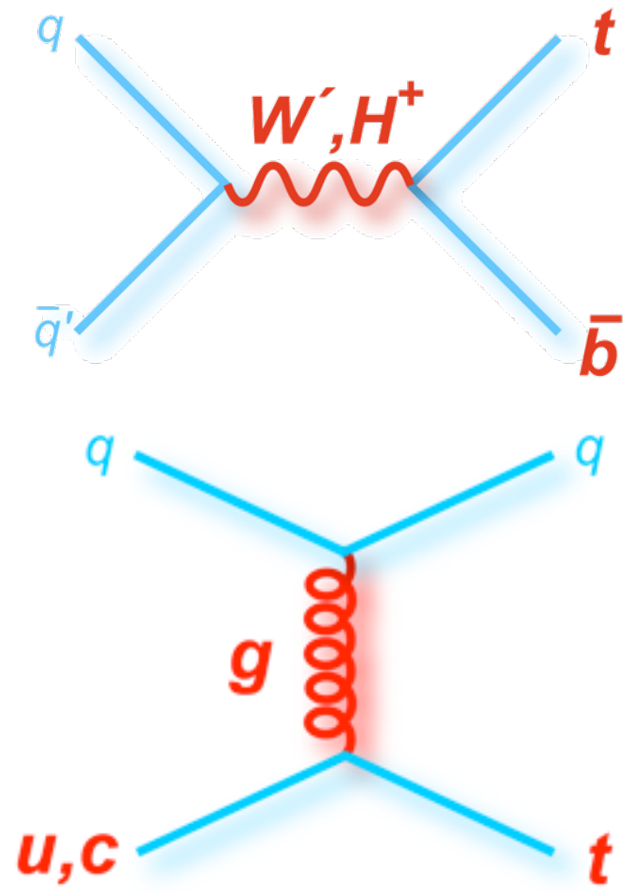
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

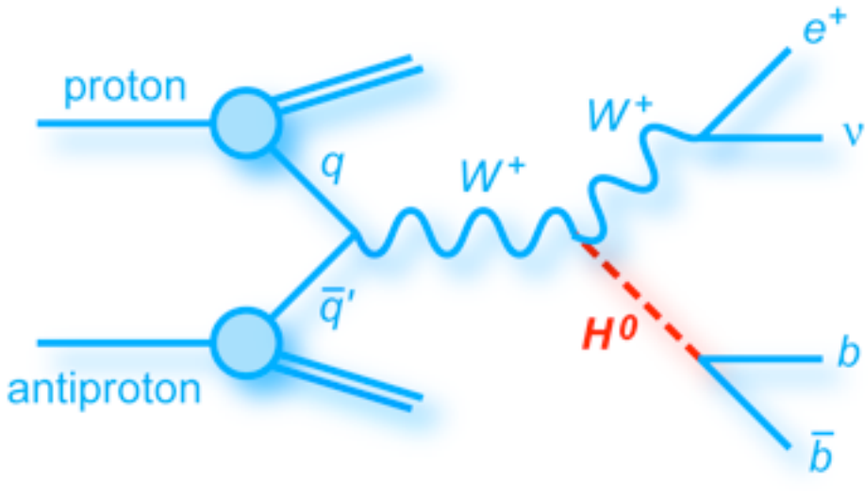
V_{CKM} Relates weak interaction eigenstates to the mass eigenstates

- Study top quark properties:
  - decay width, lifetime, mass
  - polarization: through the top quark decay products
- Use advance analysis techniques
  - Separate small signal from overwhelming background

Single Top

- Sensitive to new physics
  - *W'* boson of topflavor model
  - Charged Higgs boson
  - Charged top pion of technicolor
  - 4^{th} quark generation
  - Flavor changing neutral currents
- Same final state as *WH* associated Higgs production

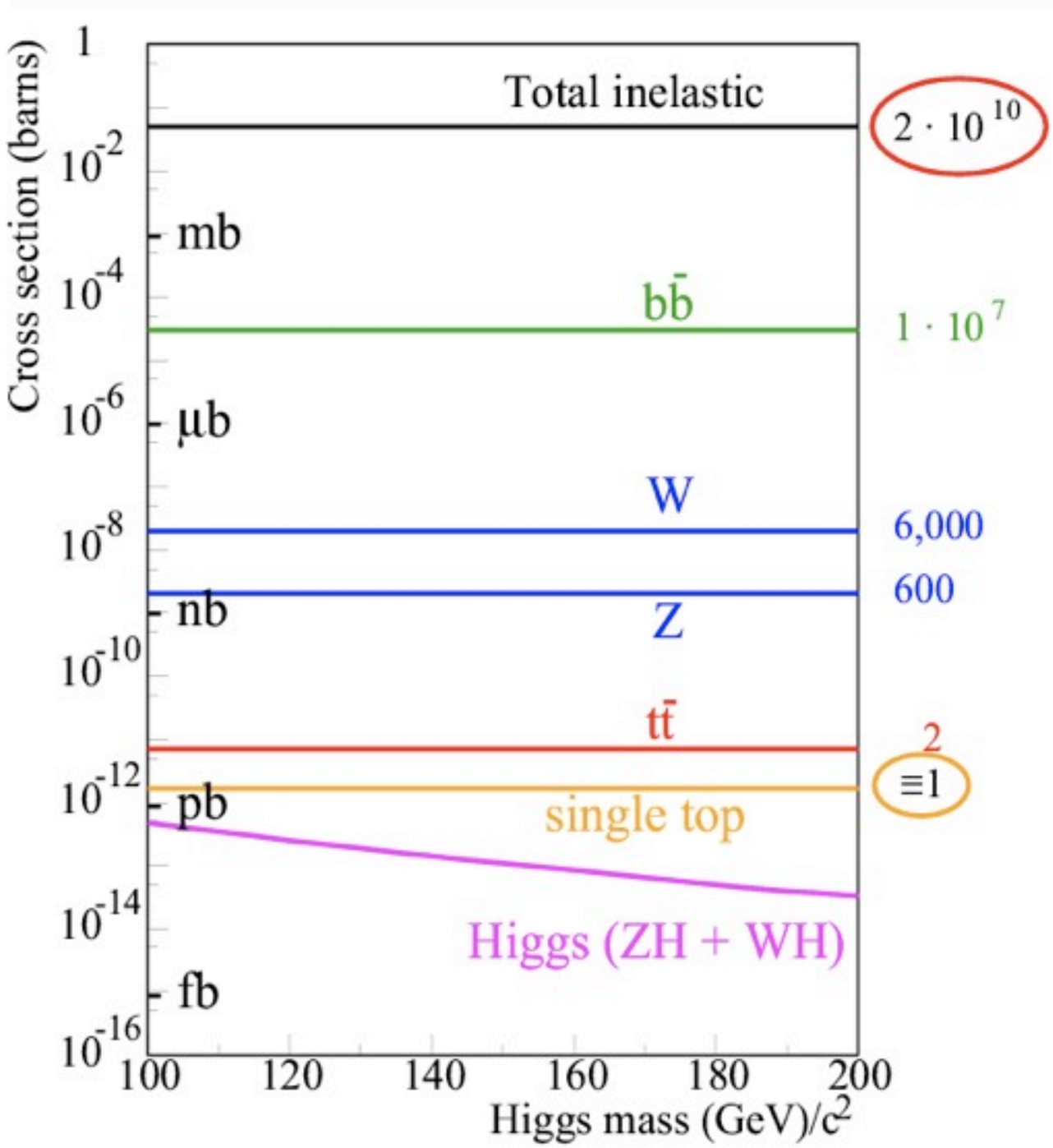




Single Top Challenges

- Very small production rate
  - ~1:20 billion collisions
- Very large backgrounds
  - Processes with the same final state as Single Top, but with a much larger production rate
- Search is like looking for a needle in a haystack
- An exceptional machine and many extraordinary ideas are needed

Cross Sections at √s = 1.96 TeV



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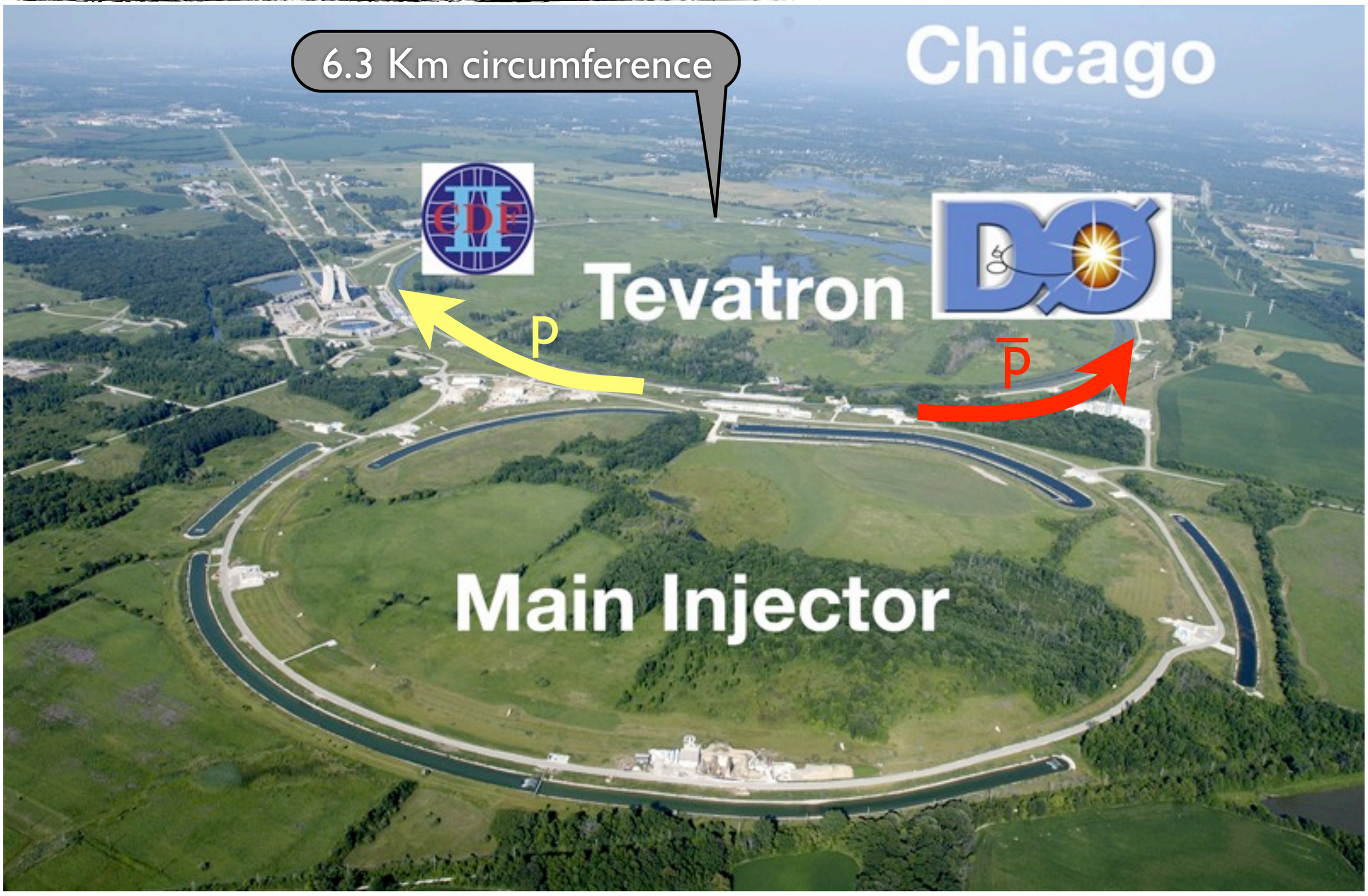
Fermilab


6.3 Km circumference
Chicago
CDF
Tevatron
DØ
p
p̄
Main Injector

Fermilab Tevatron

- Proton-antiproton collider
- Currently highest CM energy

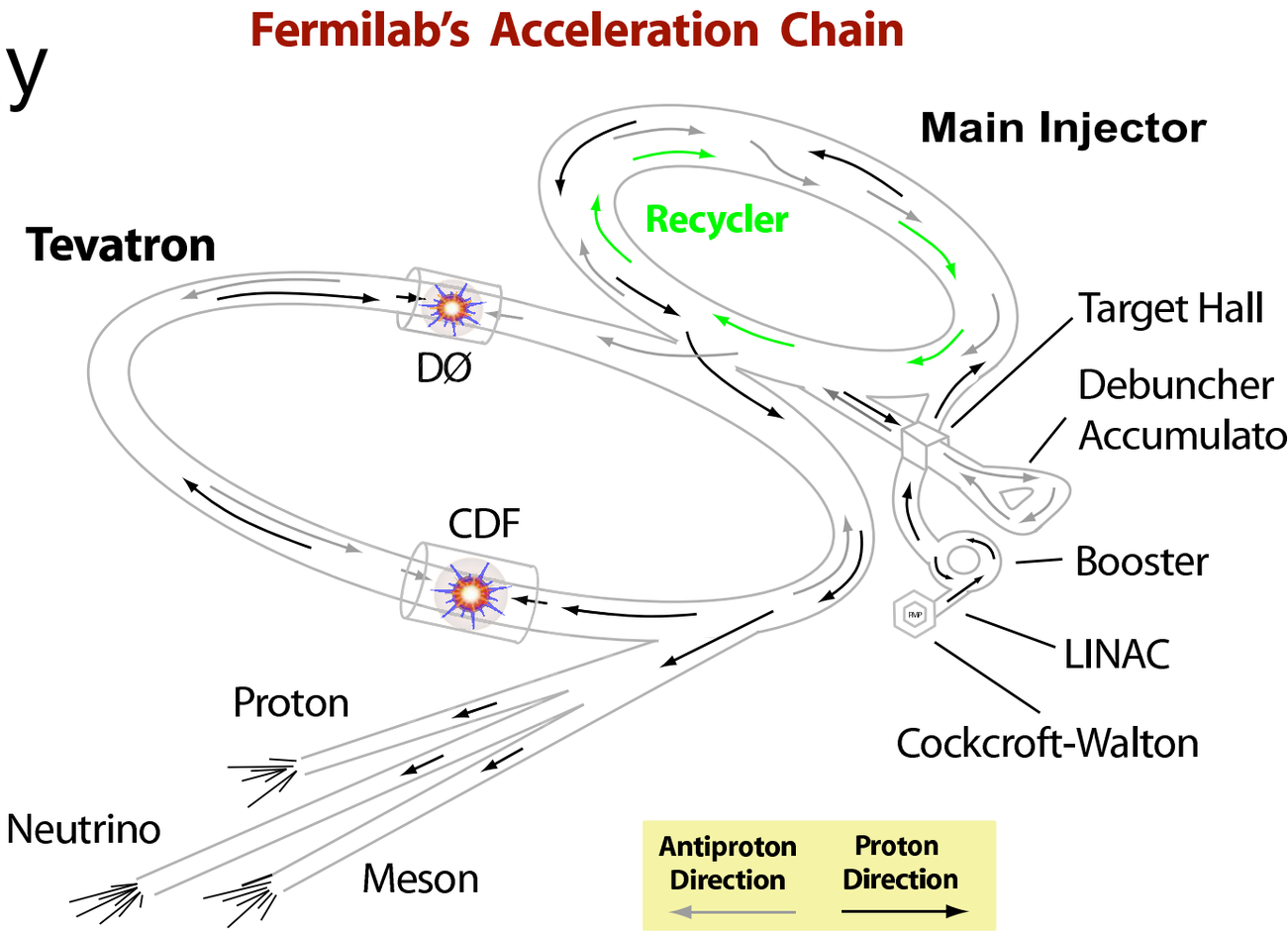
$$\sqrt{s} = 1.96 \text{ TeV}$$

- Instantaneous luminosity:

$$4.0 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$$

- The only top quark factory in the world
- 2 main interaction points:

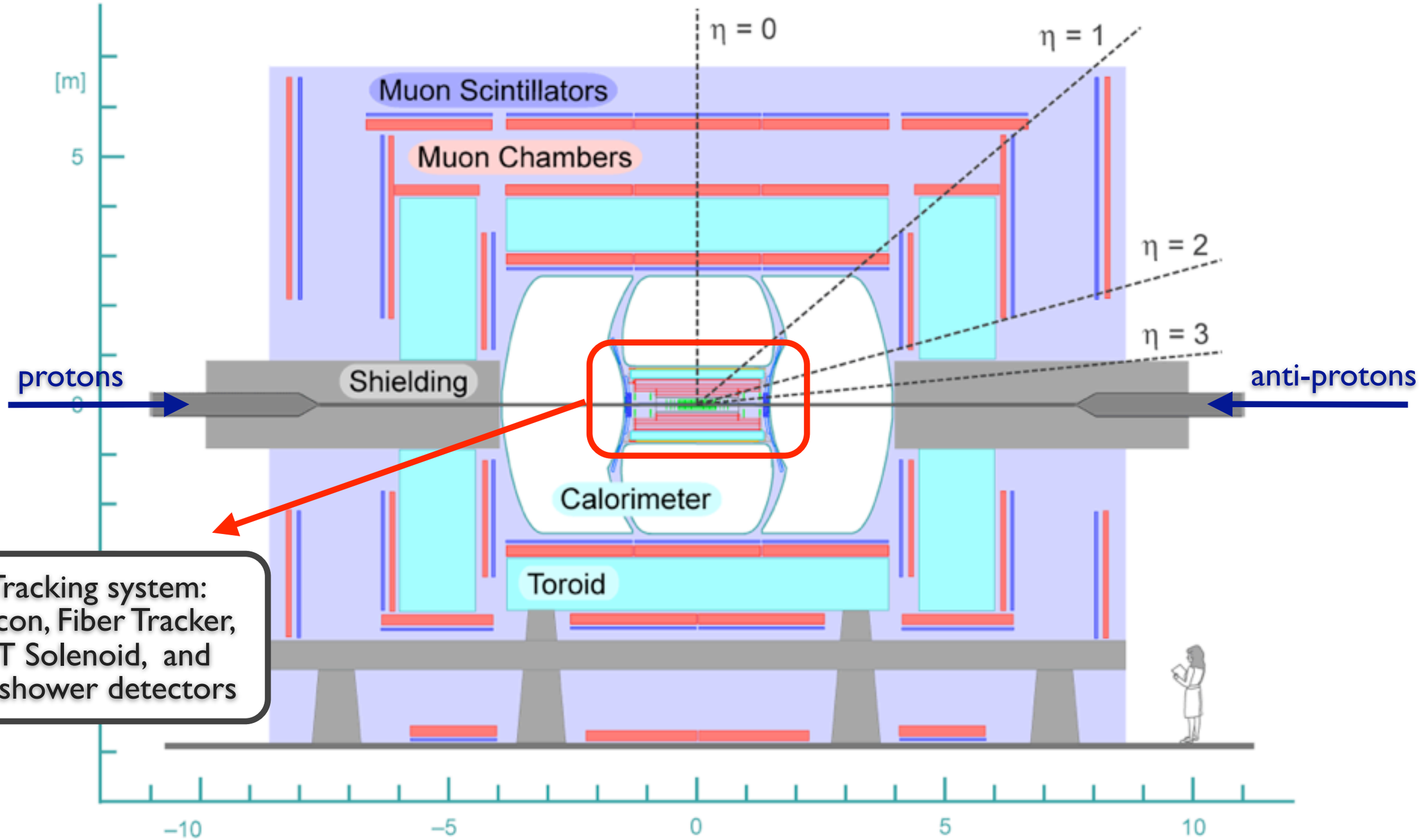
$$\text{CDF and D}\emptyset$$



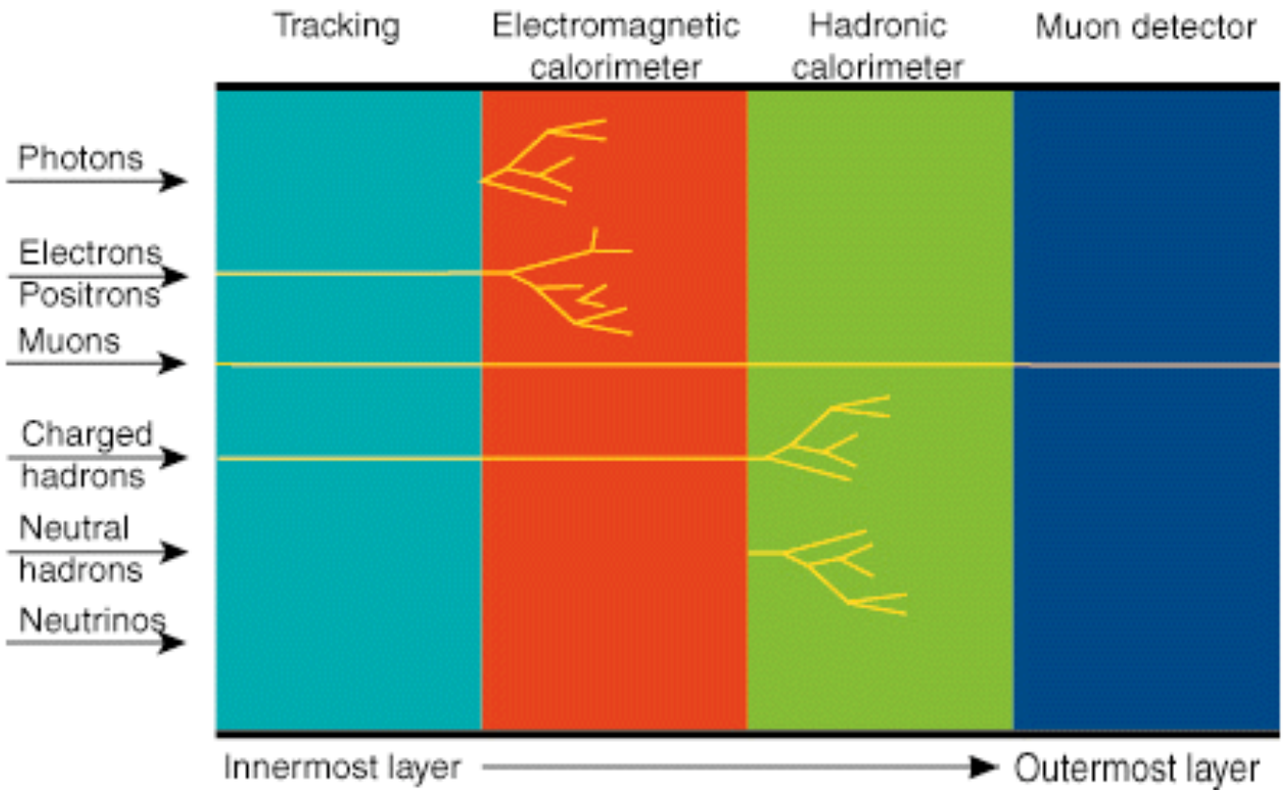
DØ

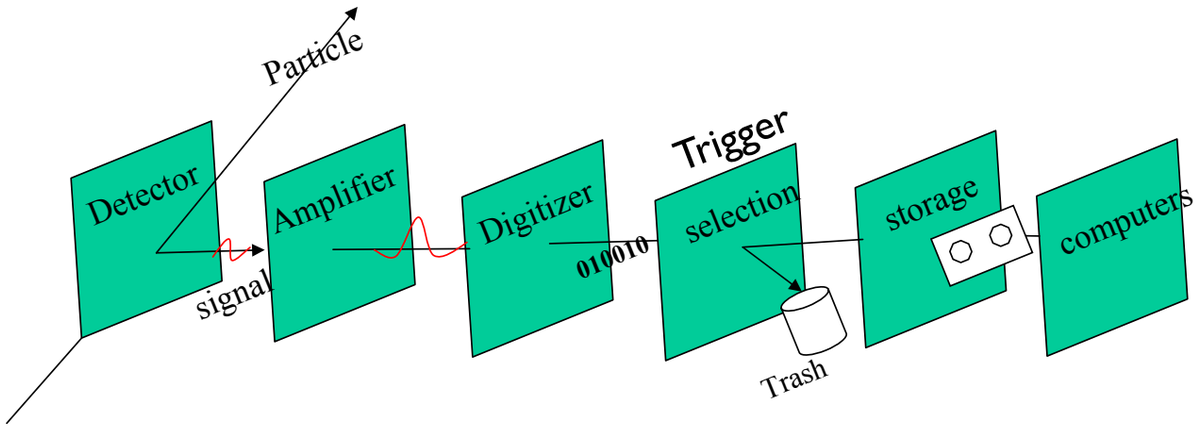
- DØ is a large (5000 tons) experiment on the Tevatron collider at Fermilab
- Run by a collaboration of ~ 500 physicists.

DØ Experiment



DØ Experiment

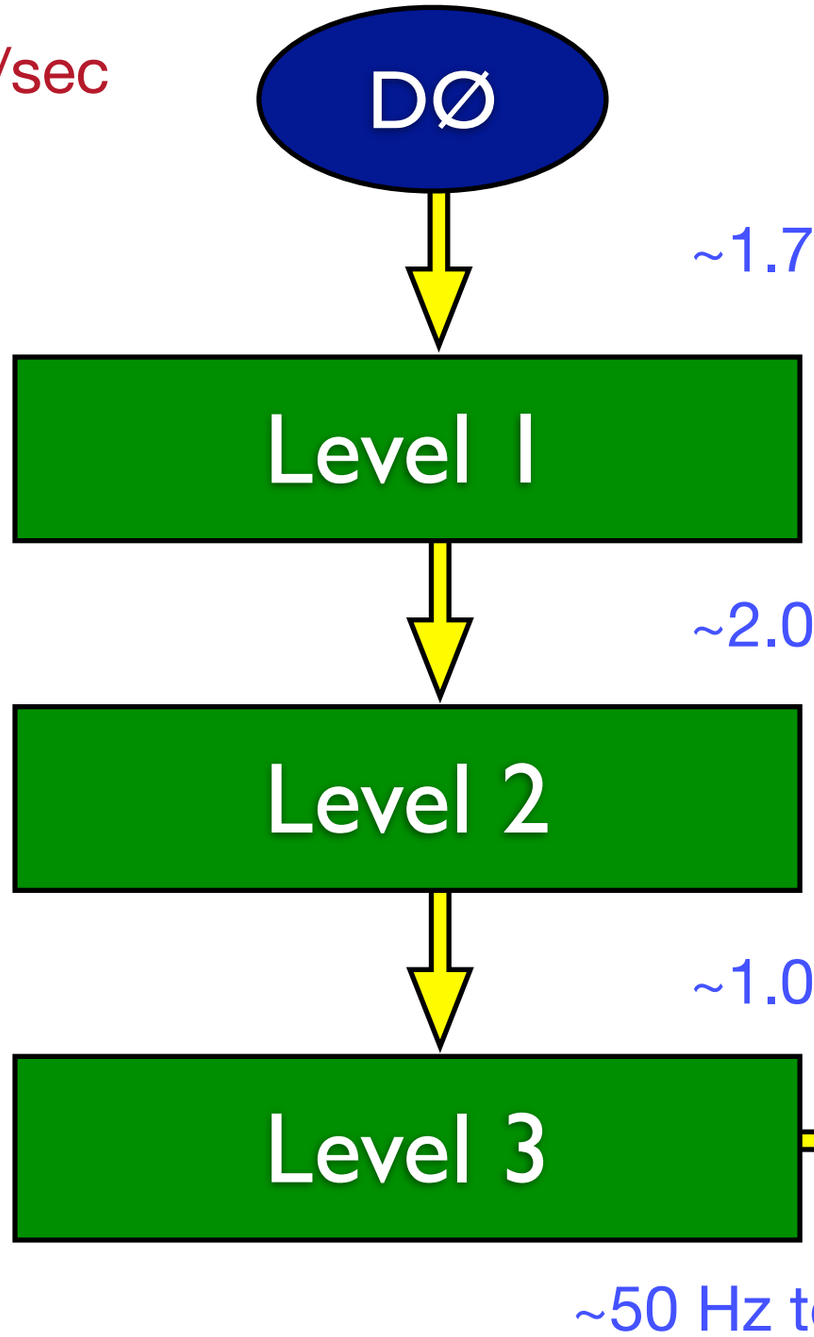




DØ Trigger

- Main Purpose: to remove non-interesting events.

2.5 x 10^6 interactions/sec
396 nsec



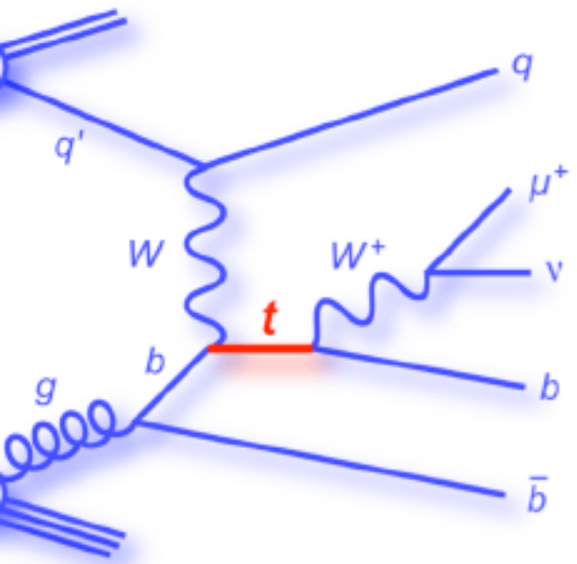
Hardware

Uses correlations
among subdetectors

Microprocessor
processing farm

How does DØ see Single Top?

- Events Signature:



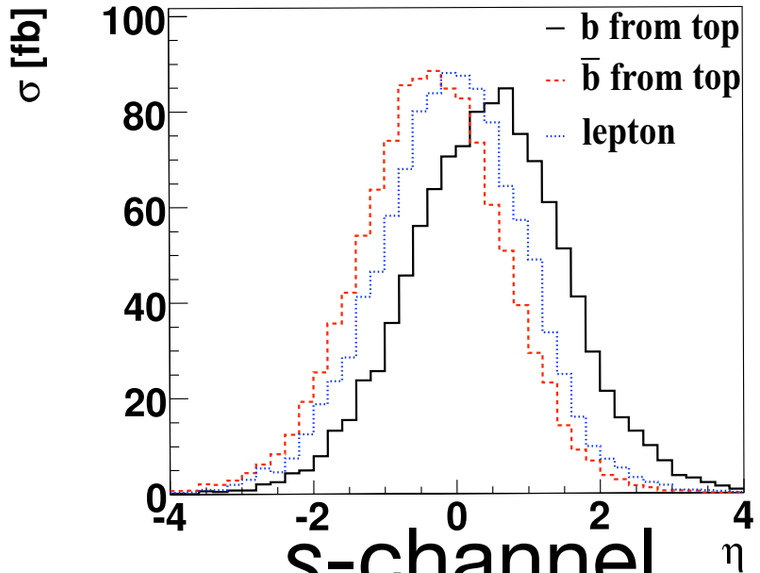
← High p_T jet

← High p_T lepton

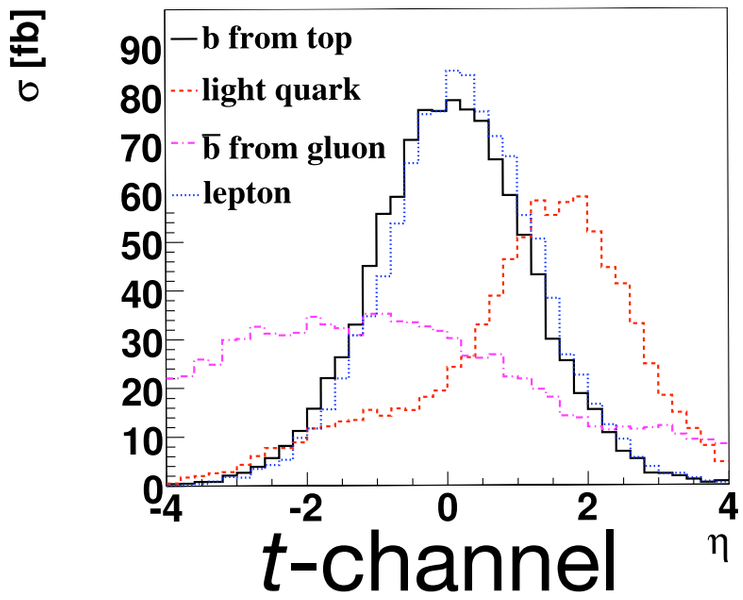
← Missing transverse energy

← High p_T jet ("*b*-tagged")

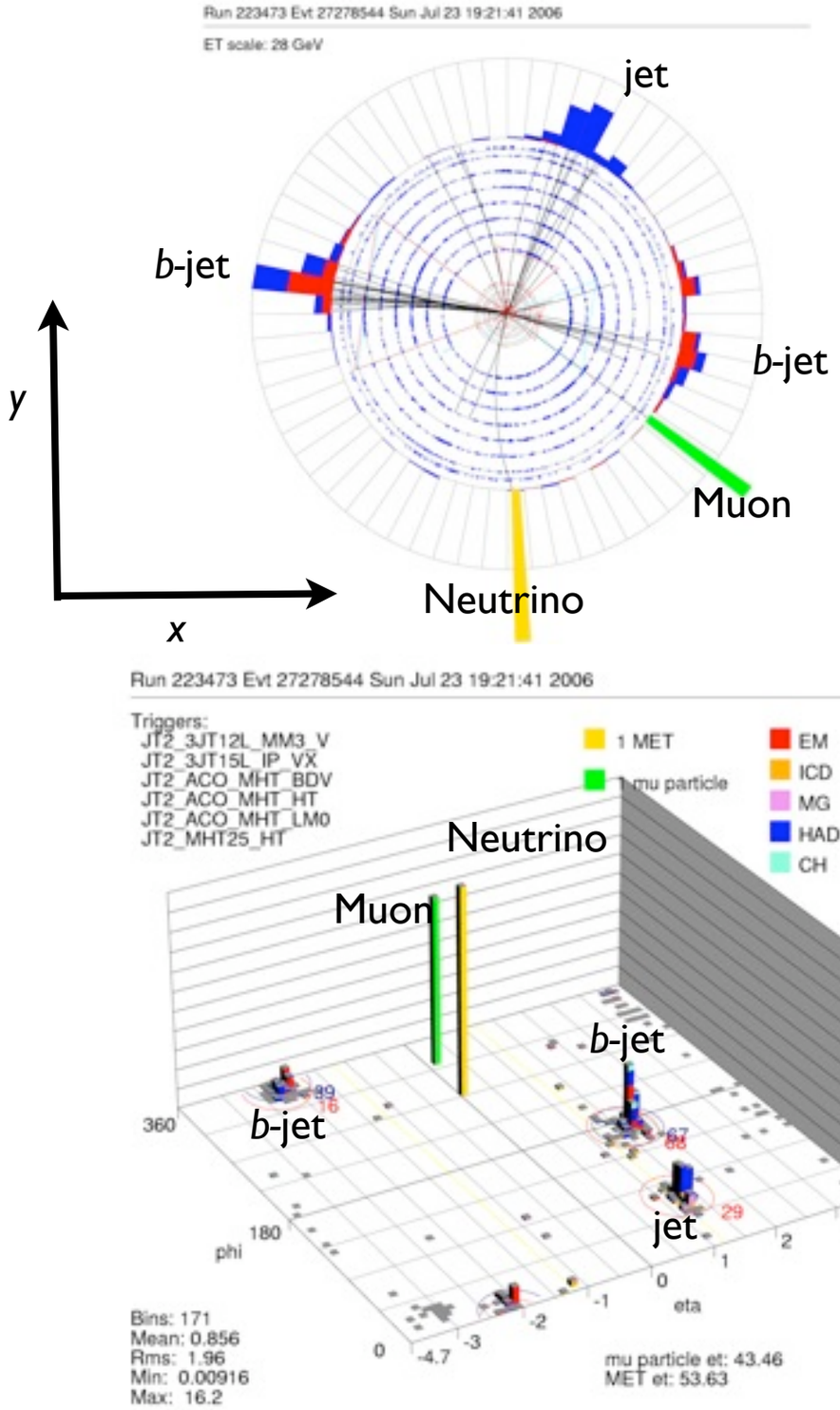
← High p_T jet ("*b*-tagged")

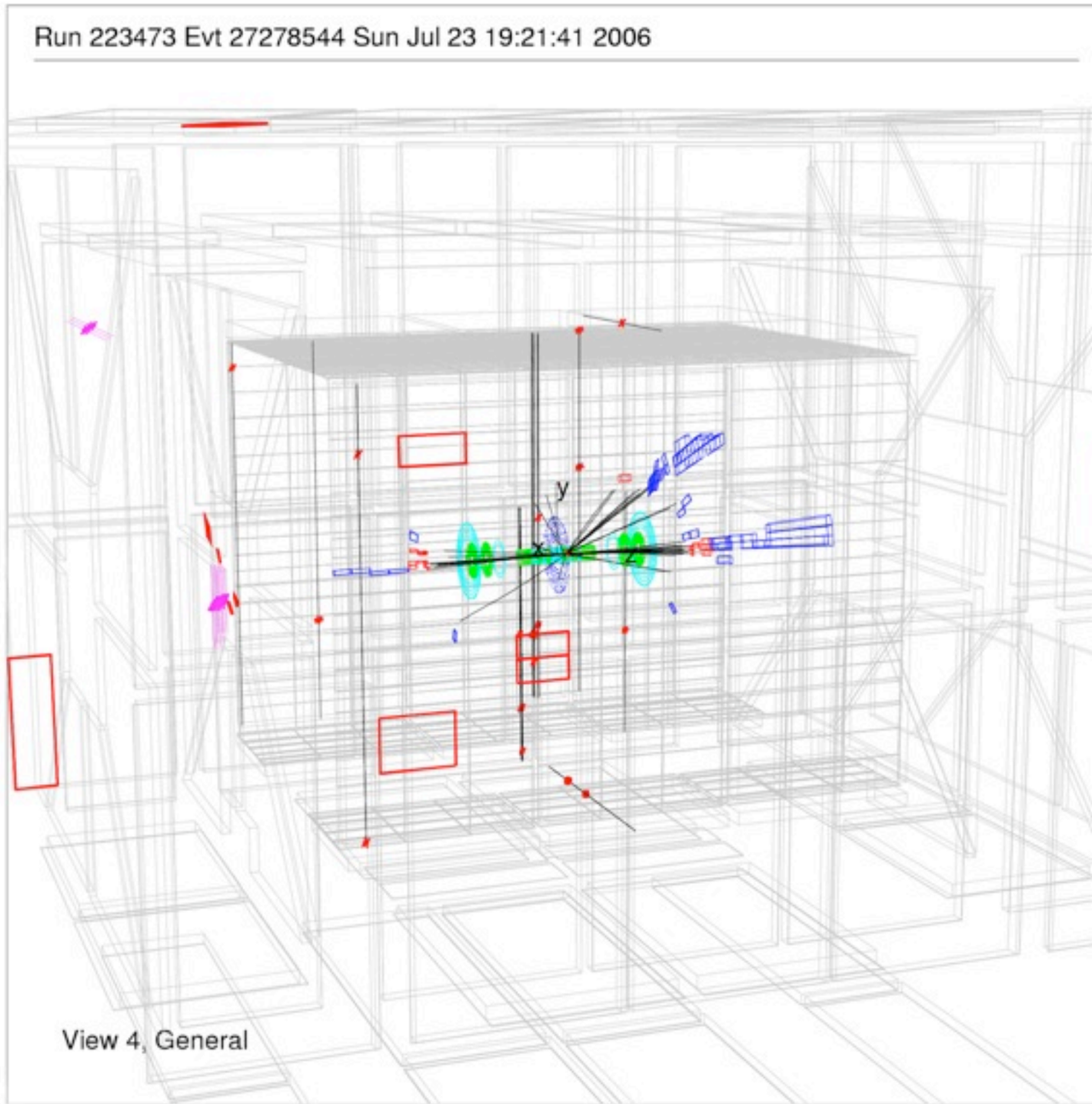


- One high transverse momentum isolated lepton (electron or muon from the *W*)
- Missing Transverse Energy (neutrino from the *W*)
- Two to four high transverse momentum jets:
  - One or two jets associated with a *b*-quark



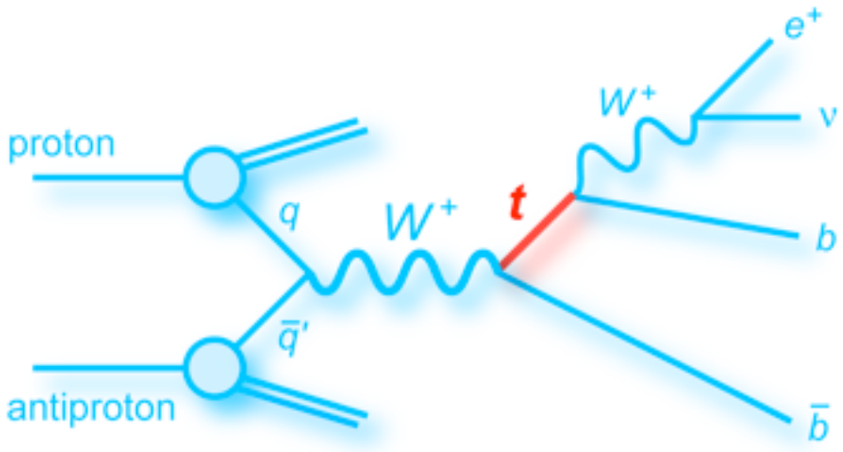
Candidate Event



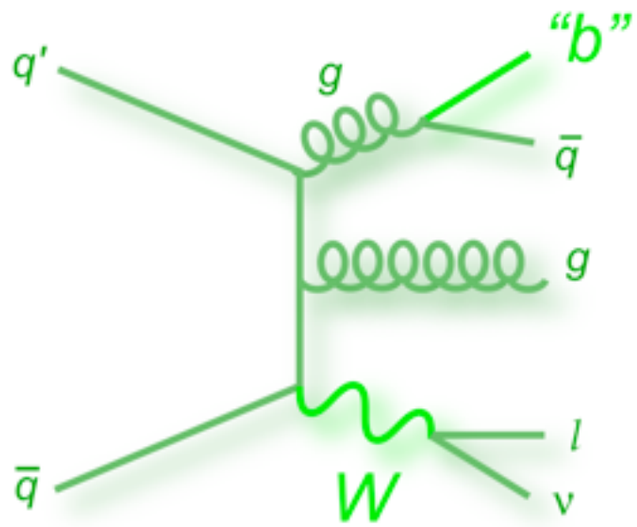


Backgrounds

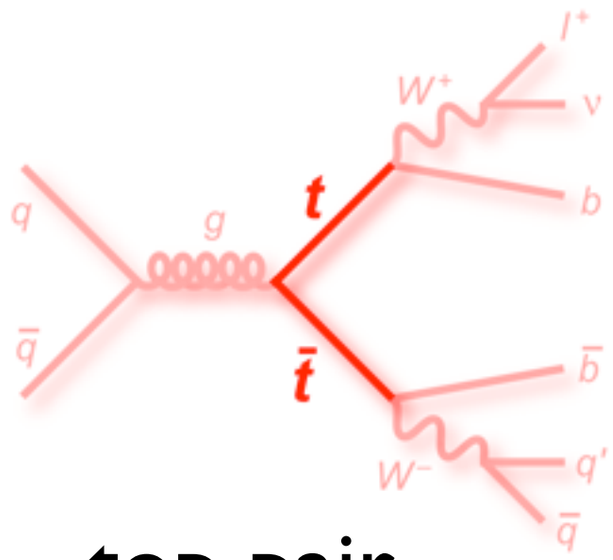
- Same final state as Single Top



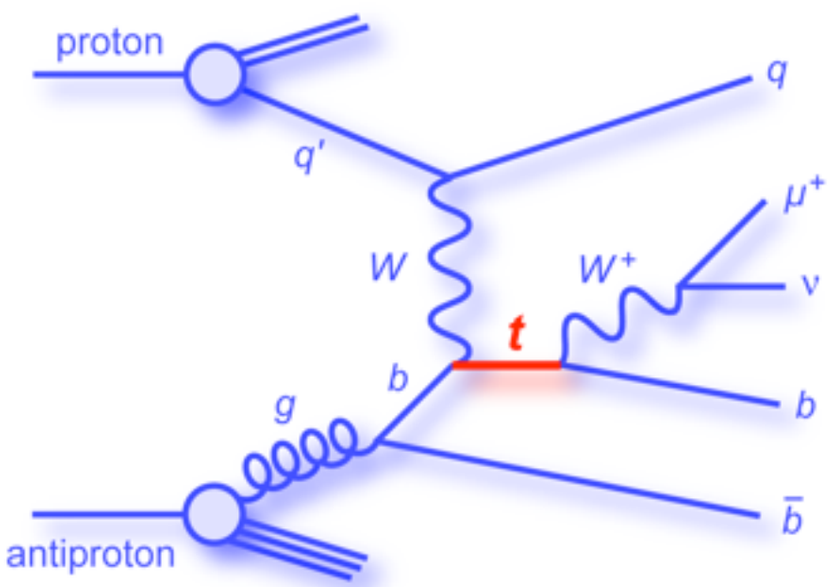
Single Top s-channel



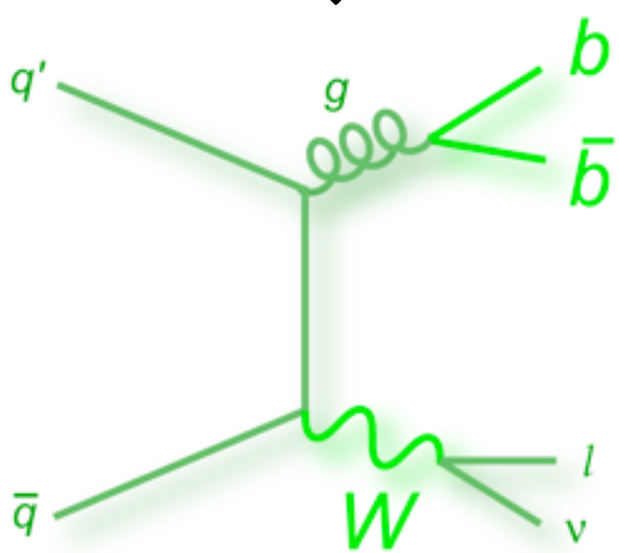
W+jets

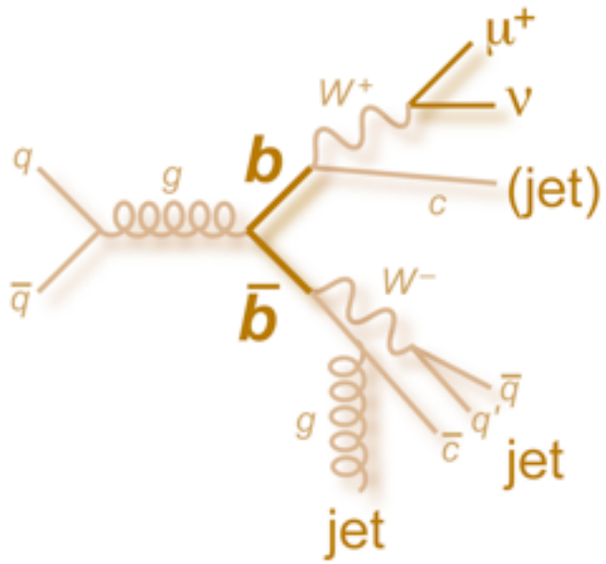


top pair



Single Top t-channel



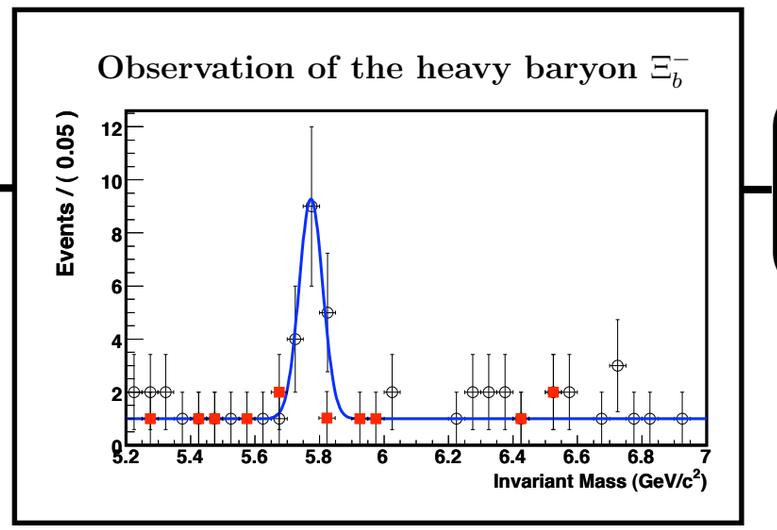


multijets - QCD

Finding The Signal

Traditional cut-based analysis

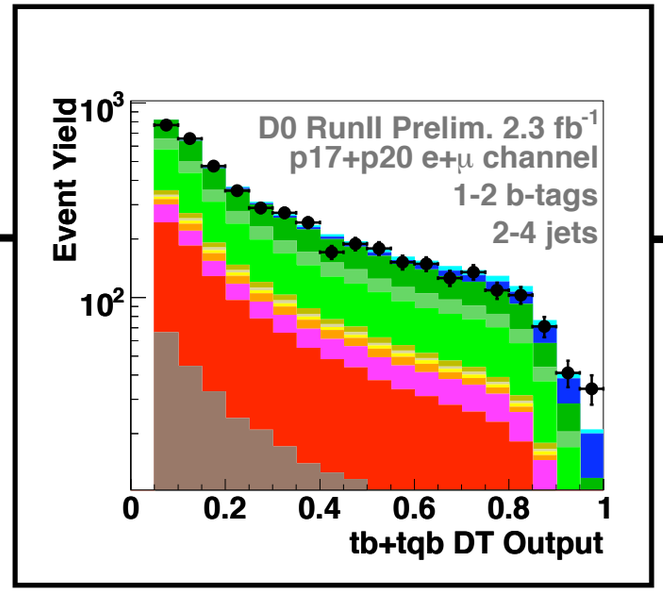
Initial objects → Selection cuts → S:B ratio 20:1



→ Found it!

This analysis

Initial objects → Selection cuts → S:B ratio 1:20 → Multivariate technique



→ Found it!

Single Top Search

Monte Carlo:
Signal and Background Model

~1 year

DØ Data

~6 years

Event selection:
remove background, remove not well-modeled regions

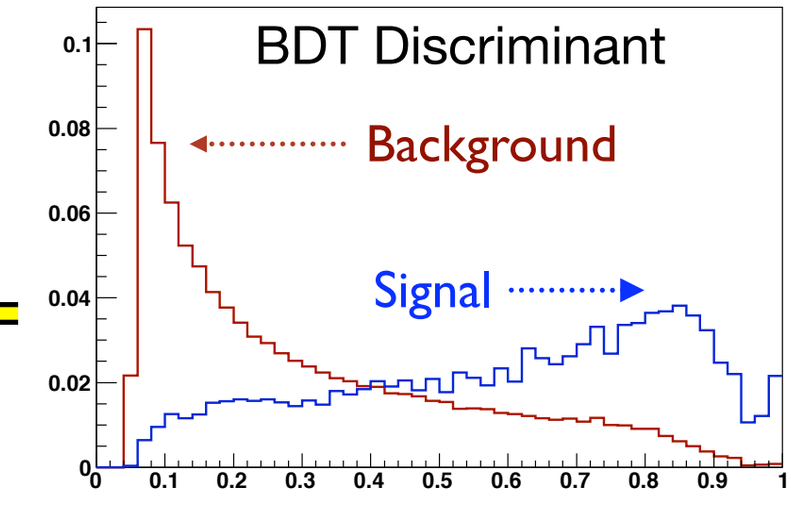
~2 year

MC Corrections:
account for differences in vertex finding, jet reconstruction eff, etc

~1 year

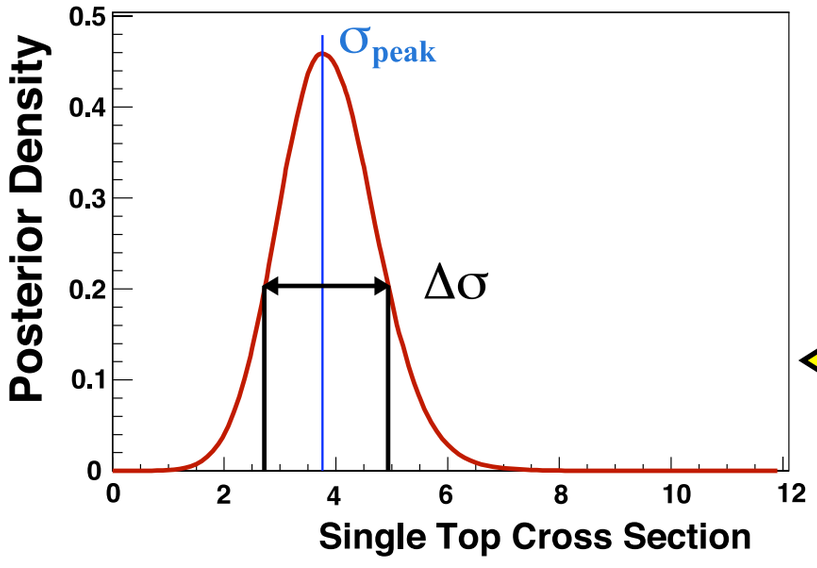
Multivariate Analysis Technique:
Boosted Decision Trees, Separate Signal from Bkg

~1 year



Bayesian Statistical Analysis:
Measure Cross Section

~1 year



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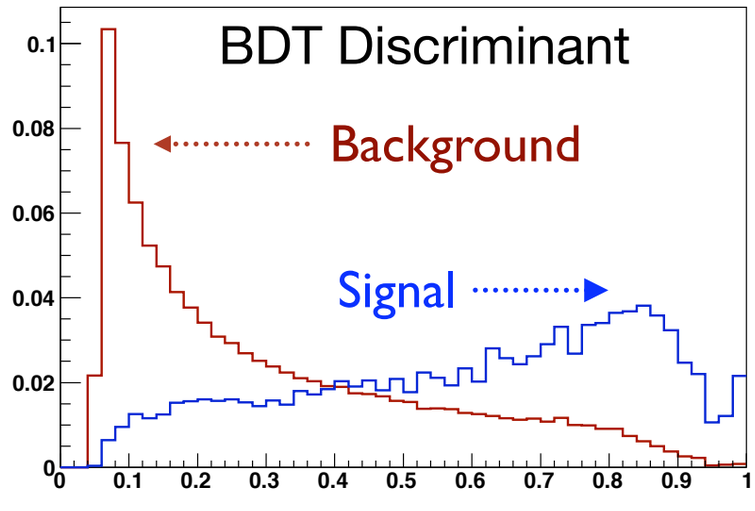

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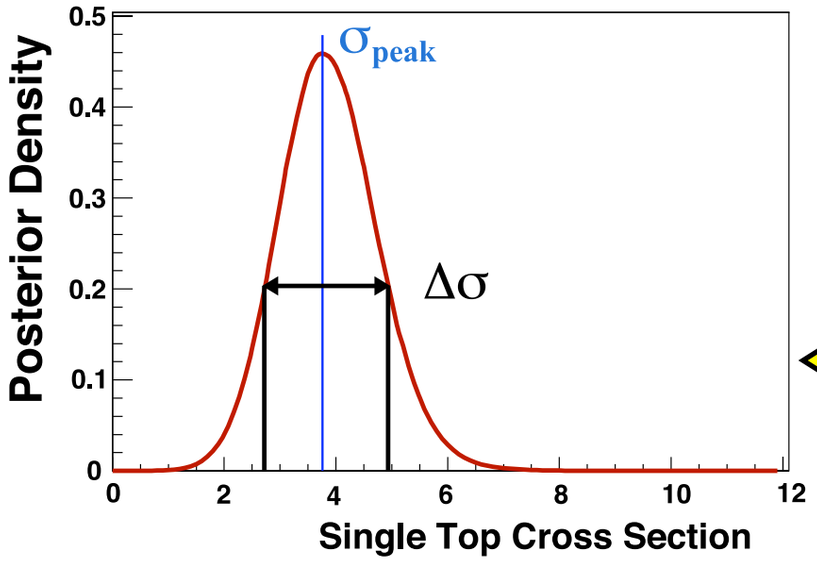
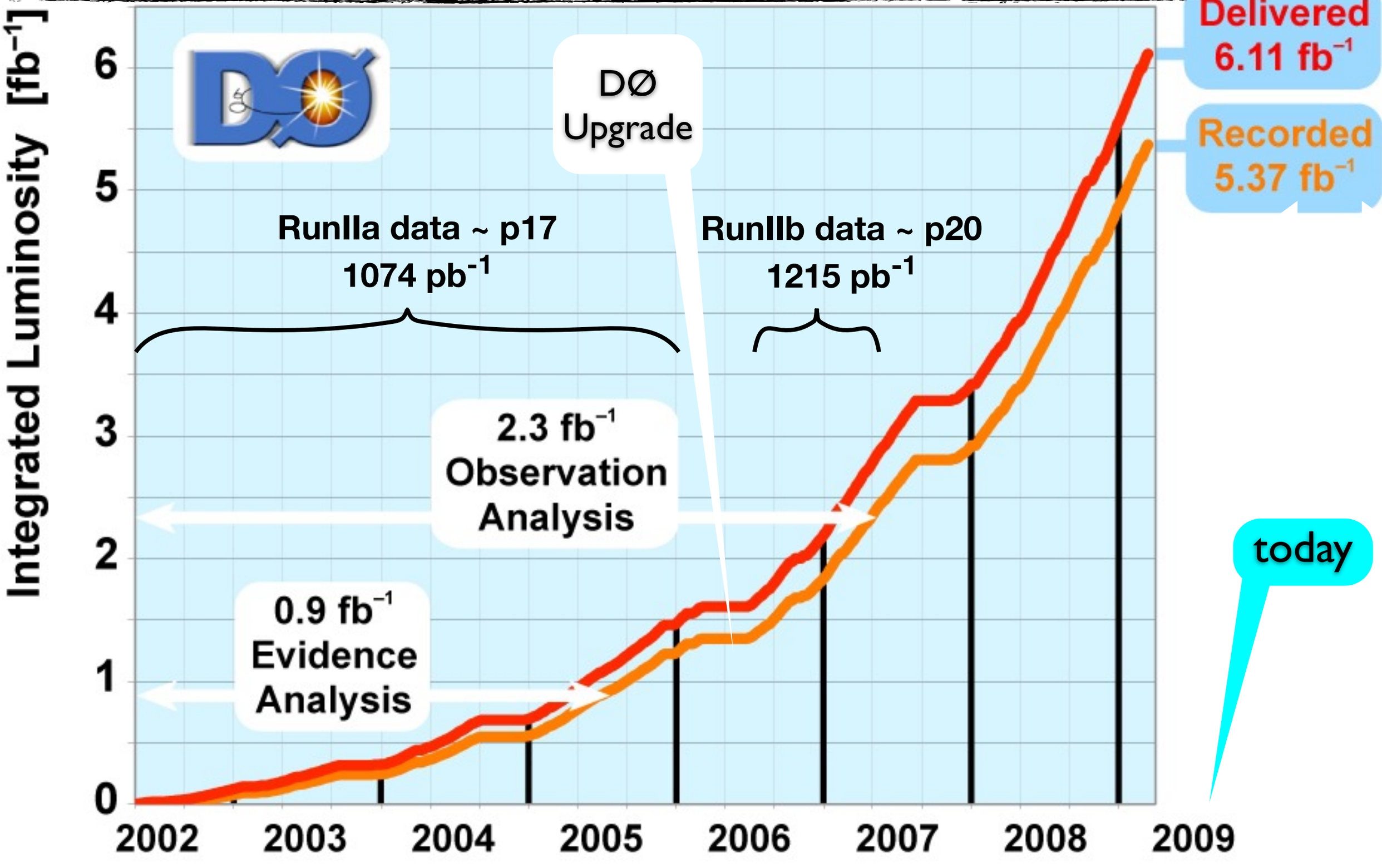
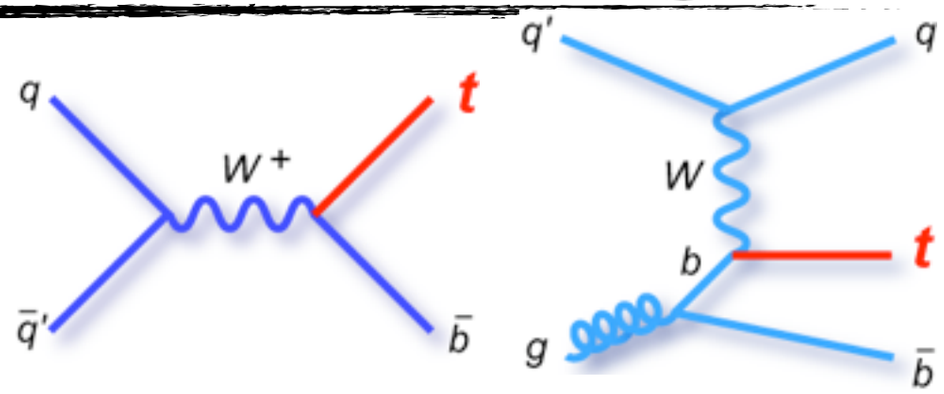


Fermilab Tevatron
Run II Integrated Luminosity

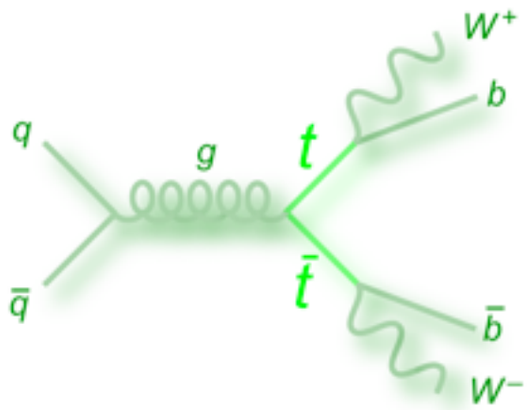


Signal and Bkg. Modeling

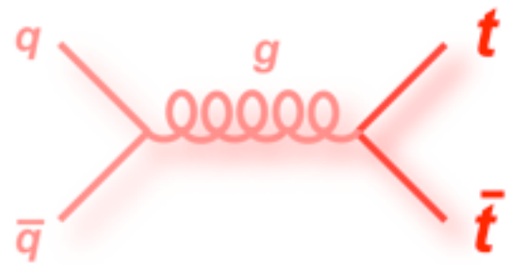
- Single Top ⟶
  - SINGLETOP MC (Based on COMHEP)
  - PYTHIA for parton hadronization



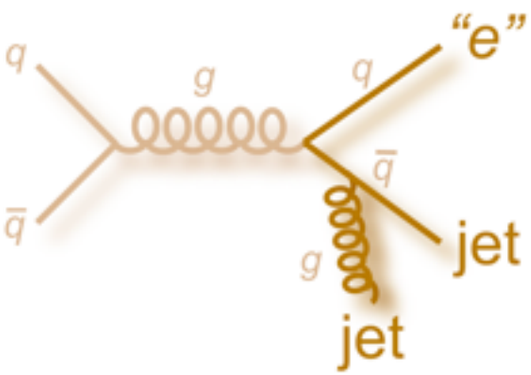
- W+jets ⟶
  - ALPGEN + PYTHIA
  - $\eta(jets),\ \Delta\phi(jet_1, jet_2),\ \Delta\eta(jet_1, jet_2)$ corrected to match data
  - normalized to data
  - W+heavy flavor corrections



- Top Pair ⟶
  - ALPGEN + PYTHIA
  - normalized to theory cross section



- Multijets (QCD) ⟶
  - data with non-isolated leptons



- Additional backgrounds: - Z+jets - Dibosons

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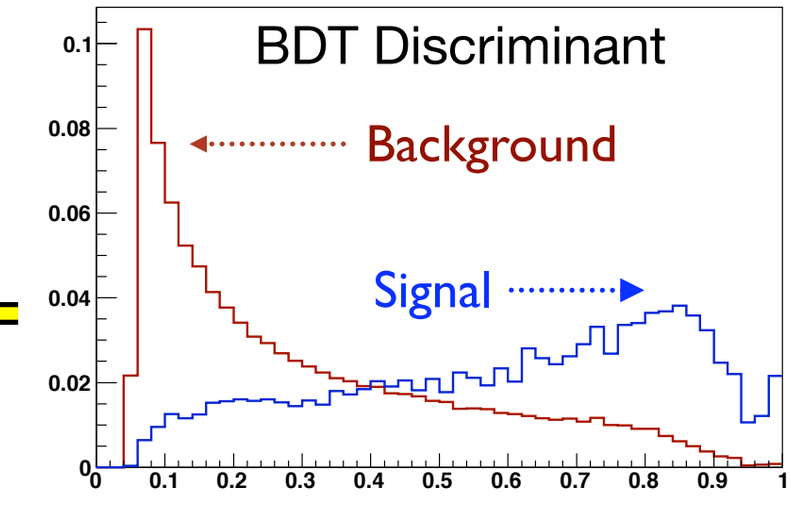

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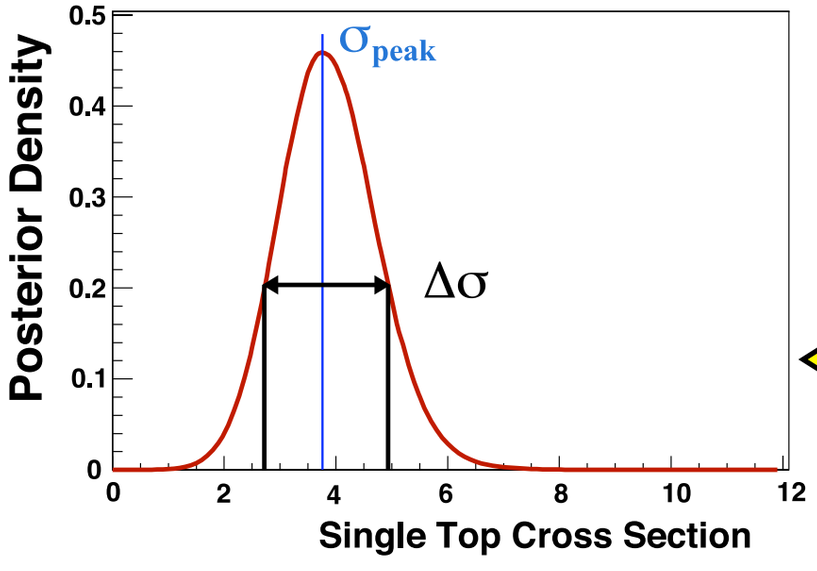
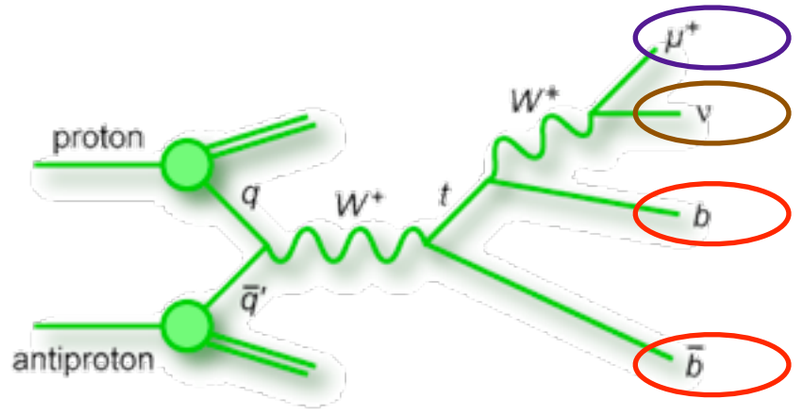
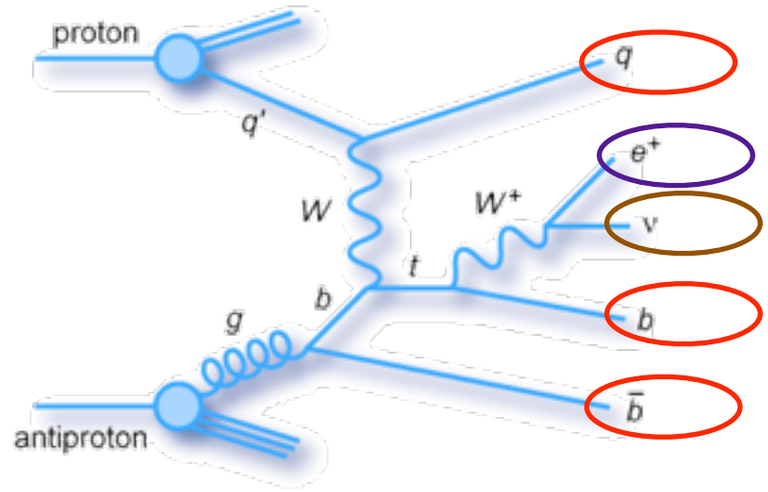


Event Selection

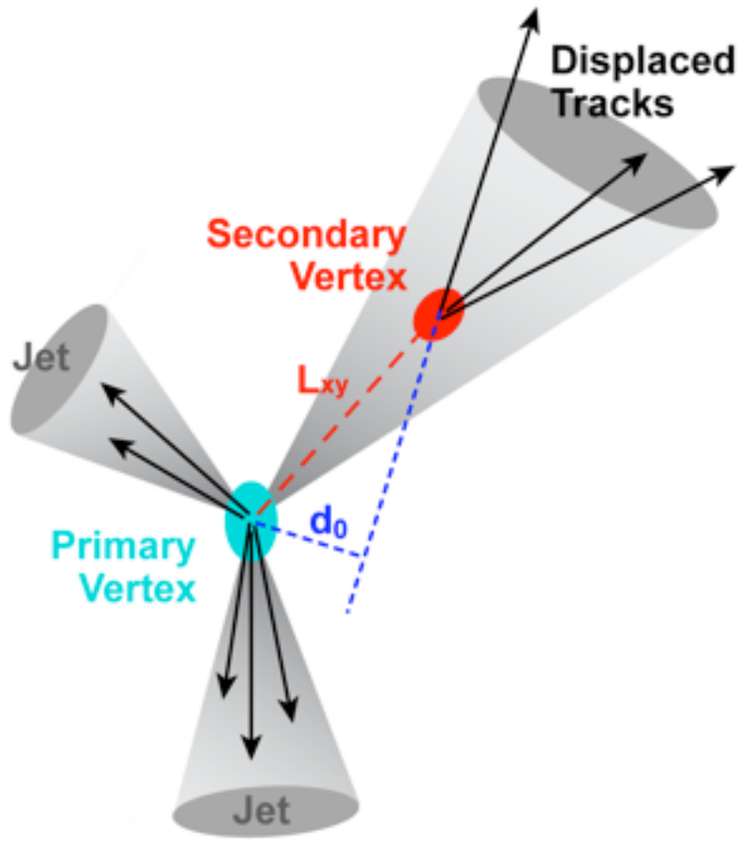
- Many triggers
- One Isolated Lepton:
  - Electron $p_T > 15$ GeV, $|\eta| < 1.1$
  - Muon $p_T > 15$ GeV, $|\eta| < 2.0$
- 20 GeV > MET > 200 GeV
- One *b*-tagged jet and at least one more jet
  - 2-4 jets with $p_T > 15$ GeV, $|\eta| < 3.4$
  - Leading jet $p_T > 25$ GeV
- Cut on scalar sum of transverse energies (alljets, lepton, MET)
- Triangular Cuts:
  $\Delta\phi$(Leading jet, MET) vs MET and $\Delta\phi$(lepton, MET) vs MET





Event Selection (cont.)

- *b*-tagging:
  - Greatly reduces w+jets bkg!
  - Identifies jets coming from a *b*-quark
    - *b*-hadron travel ~ 3 mm before decaying, which creates a secondary vertex
    - The identification uses a neural network algorithm based on the vertex reco variables.



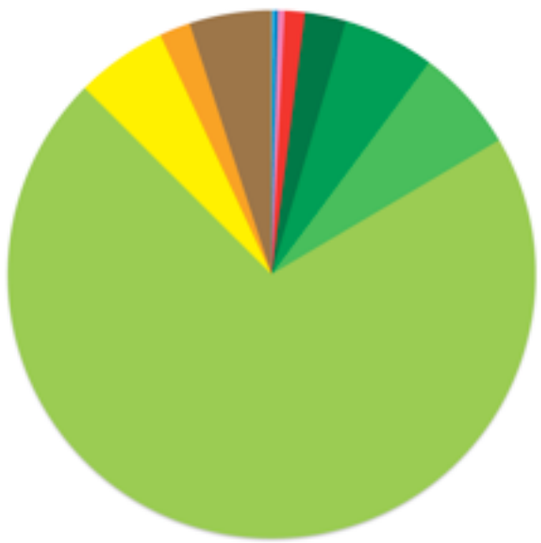
- The selection process results in a total of 24 channels!

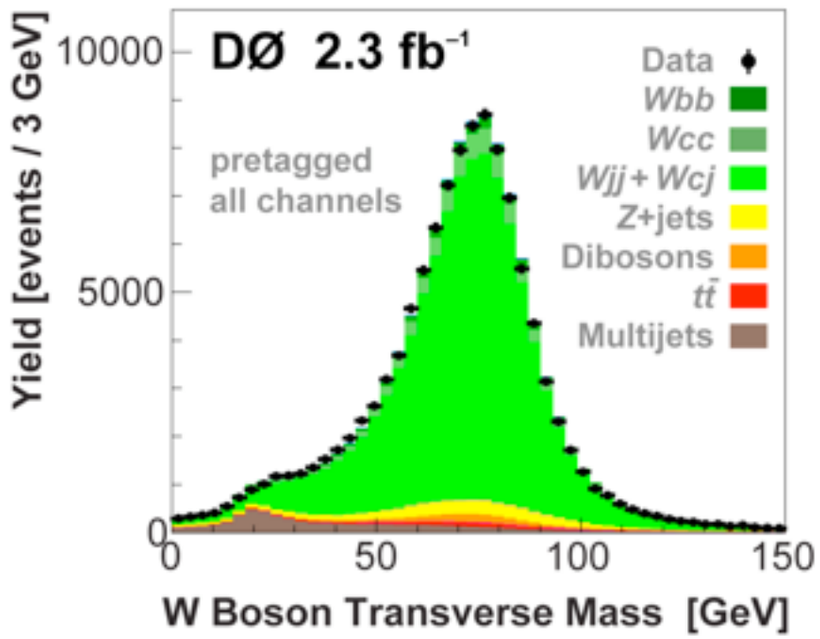
[2 Data Run periods (IIa,IIb)] x [2 lepton types (μ,e^-)] x
[3 jet multiplicities (2,3,4 jets)] x [2 *b*-jet multiplicities (1,2 *b*-jets)]

Good DATA/MC Agreement!

Event Yields in 2.3 fb^{-1} of DØ Data	
e,μ, 2,3,4-jets, pretag	
tb + *tqb*	444
W+jets	98,444
Z+jets, dibosons	8,631
$t\bar{t}$ pairs	1,895
Multijets	5,798
Total background	114,777
Data	114,777

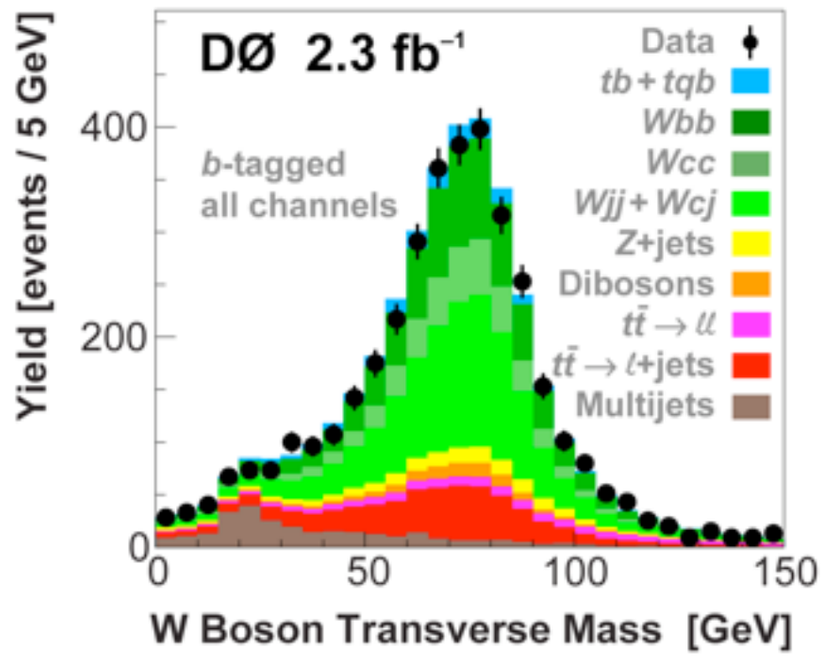
Pre b-tagging





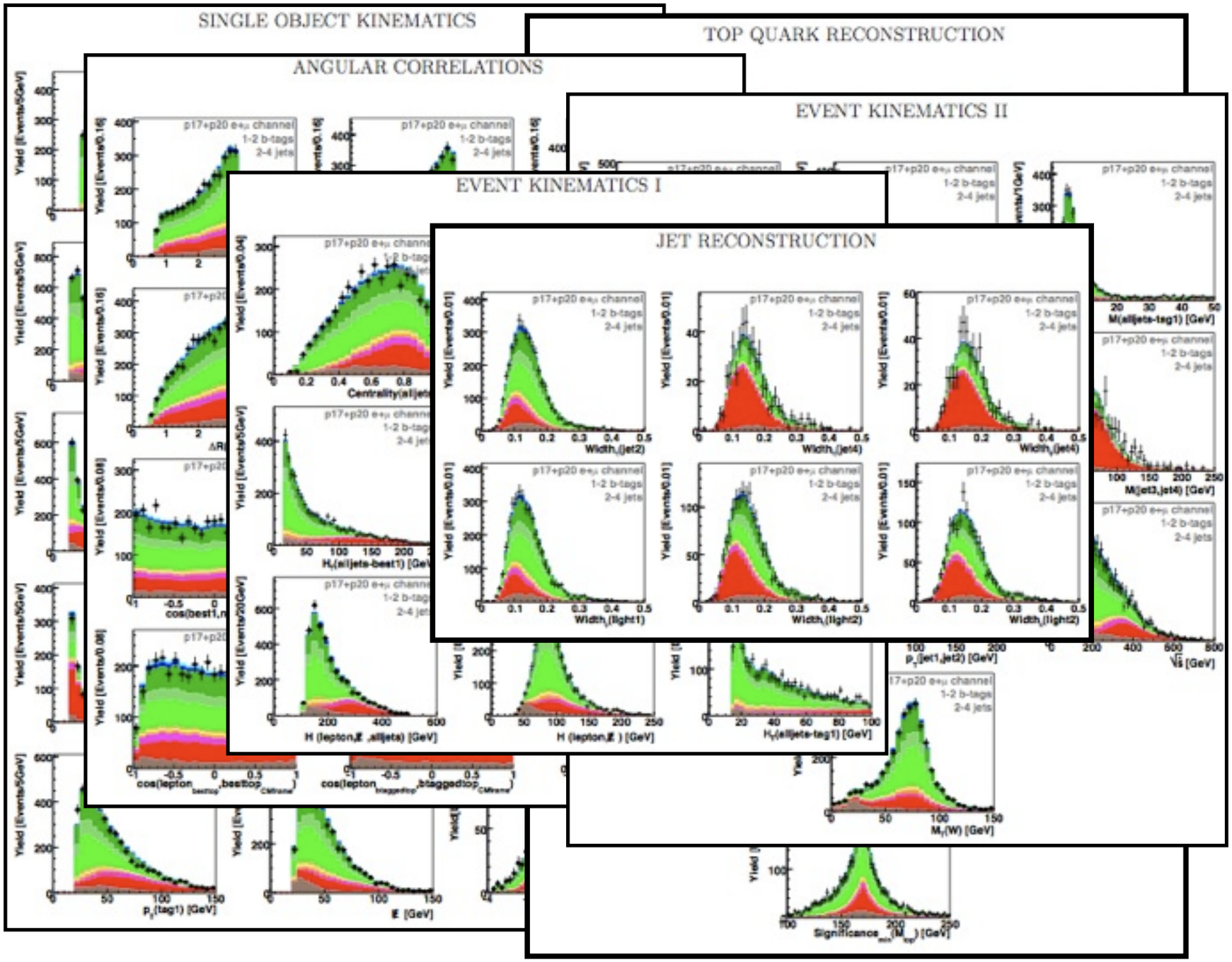
Event Yields in 2.3 fb^{-1} of DØ Data	
e,μ, 2,3,4-jets, 1,2-tags combined	
tb + *tqb*	223 ± 30
W+jets	2,647 ± 241
Z+jets, dibosons	340 ± 61
$t\bar{t}$ pairs	1,142 ± 168
Multijets	300 ± 52
Total prediction	4,652 ± 352
Data	4,519

After b-tagging

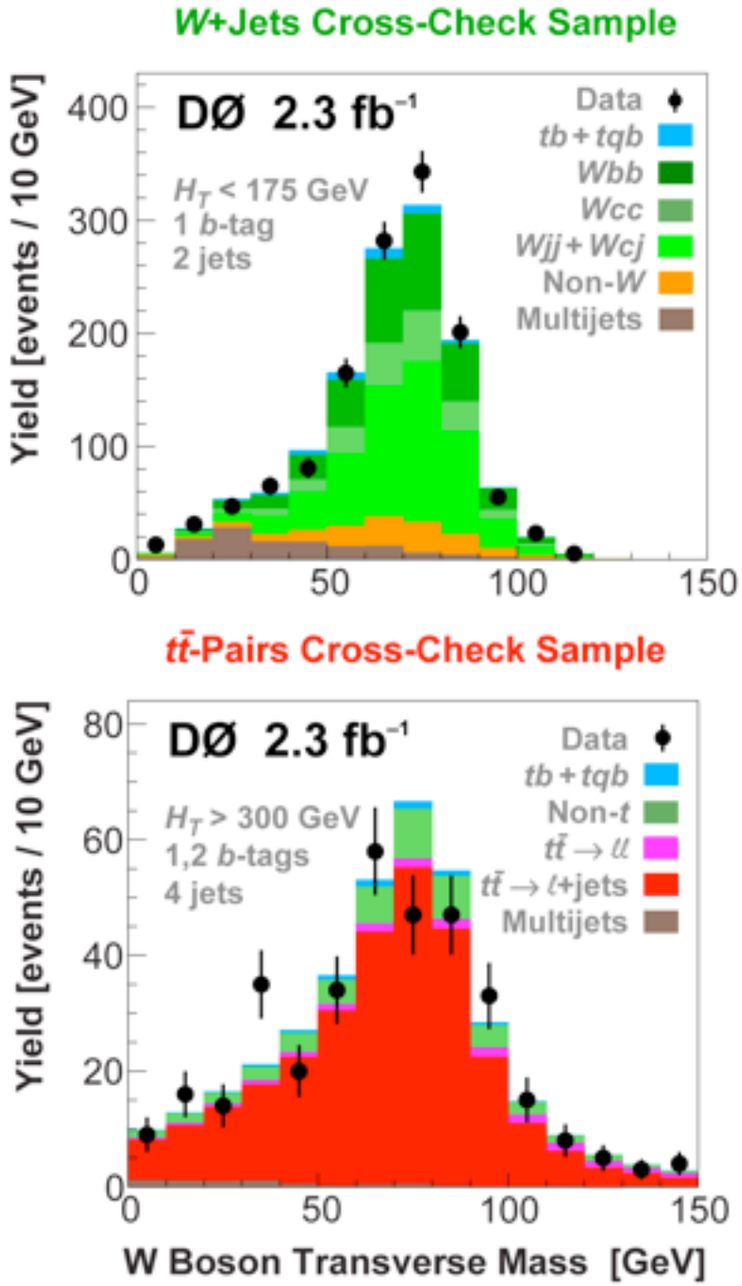


Cross Checks

- Checked good data/mc agreement over 500 distributions on each of the 24 analyses channels!



- data/mc agreement holds on regions dominated by the backgrounds:



Single Top Search

Monte Carlo: Signal and Background Model

~1 year

DØ Data

~6 years

Event selection: remove background, remove not well-modeled regions

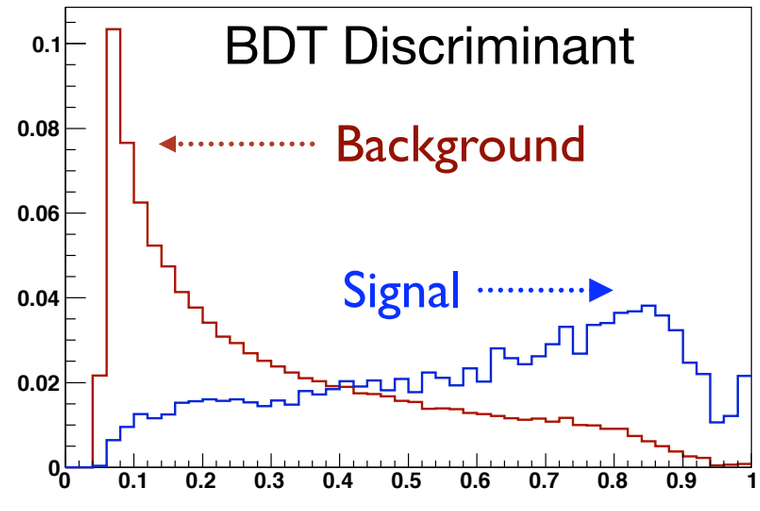
~2 year

MC Corrections: account for differences in vertex finding, jet reconstruction eff, etc

~1 year

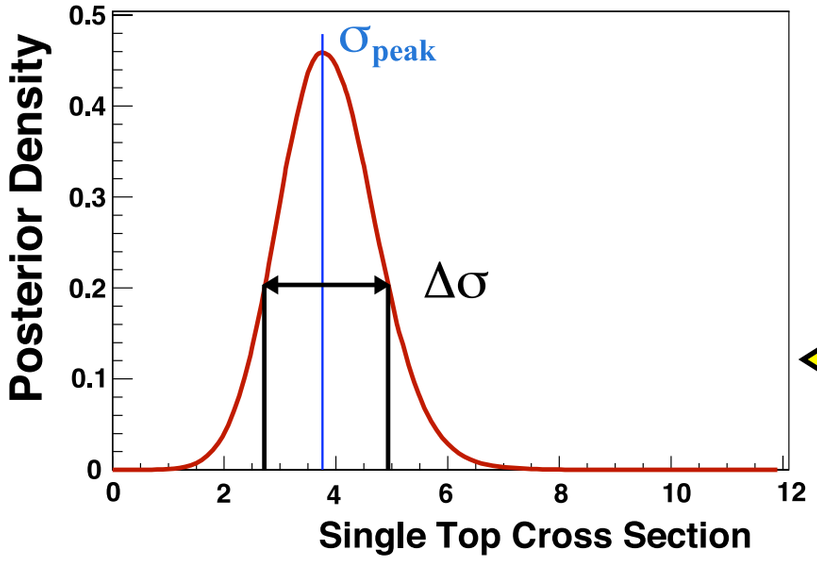
Multivariate Analysis Technique: Boosted Decision Trees, Separate Signal from Bkg

~1 year

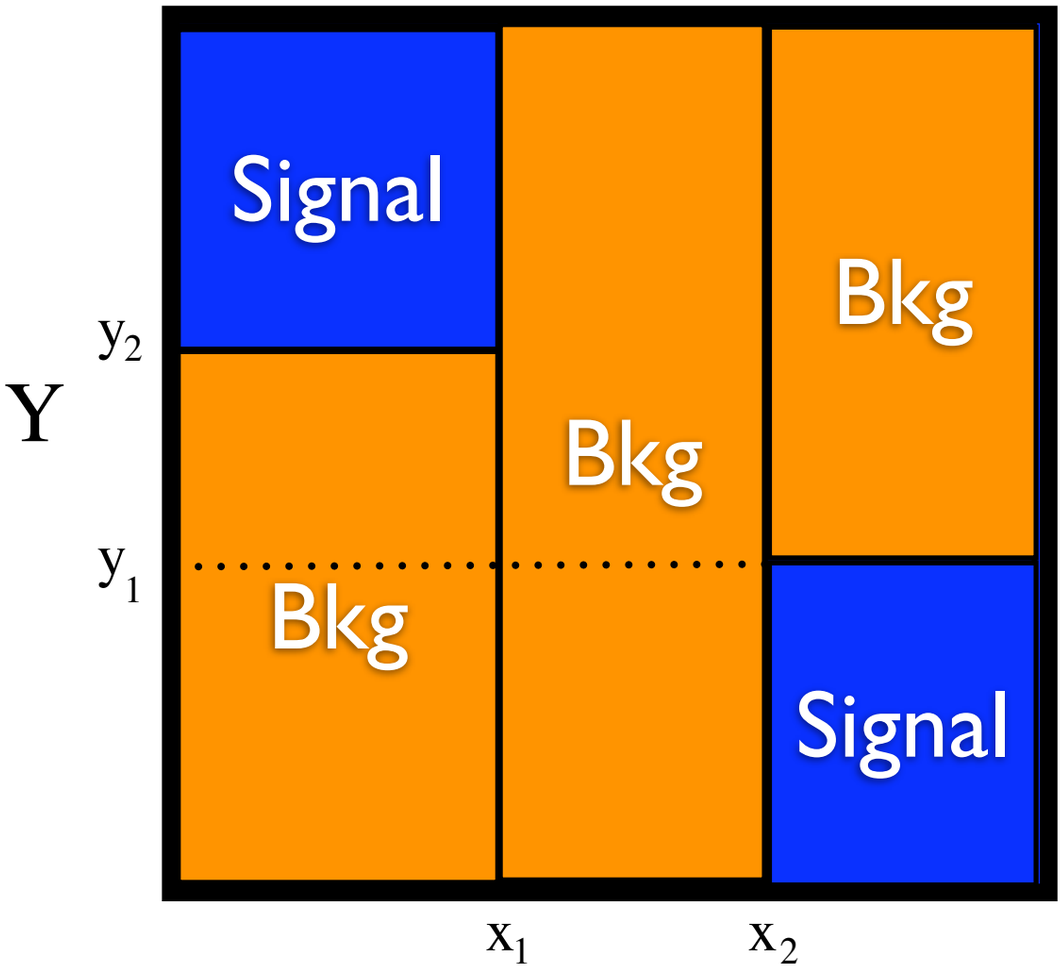


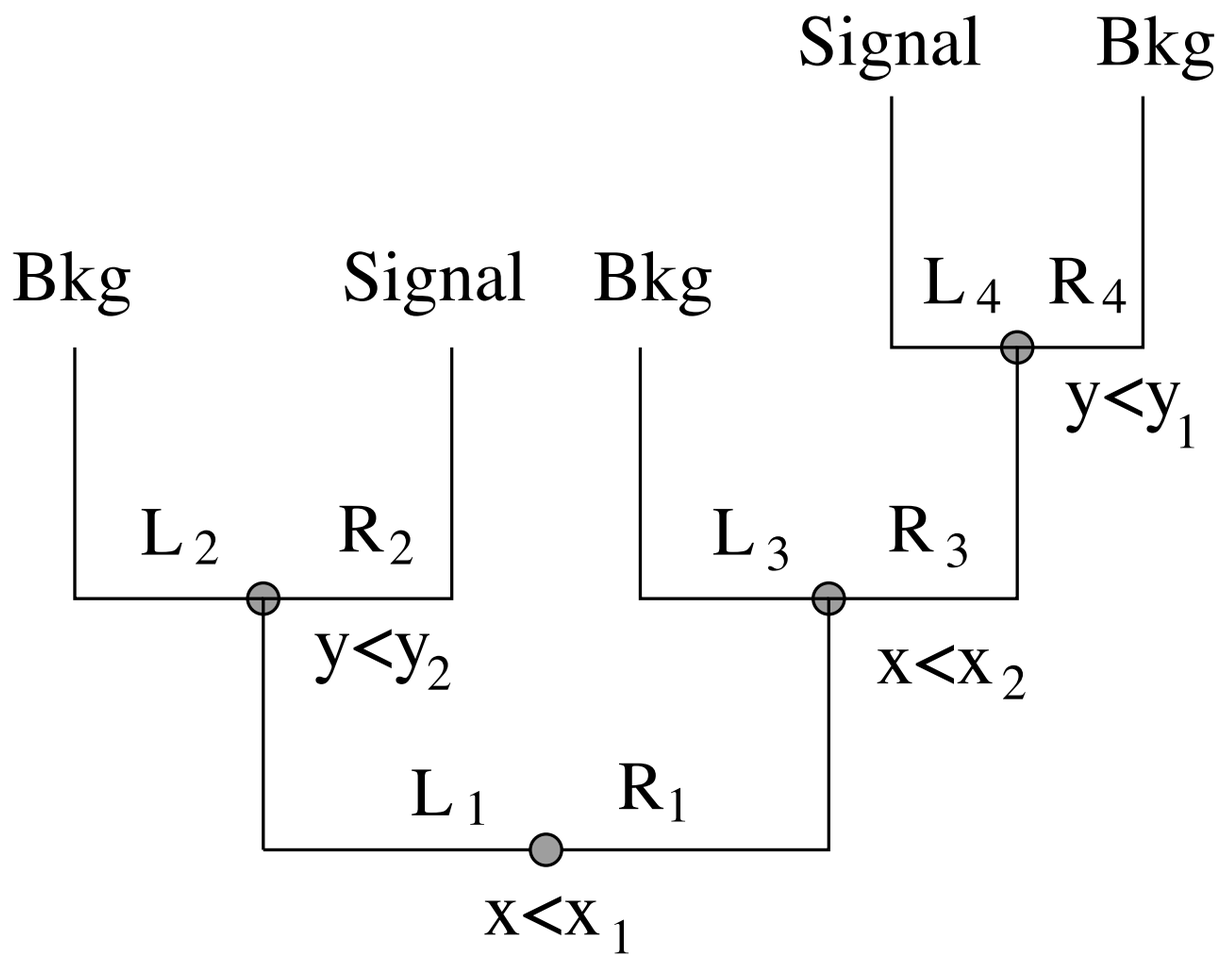
Bayesian Statistical Analysis: Measure Cross Section

~1 year



Toy Decision Tree

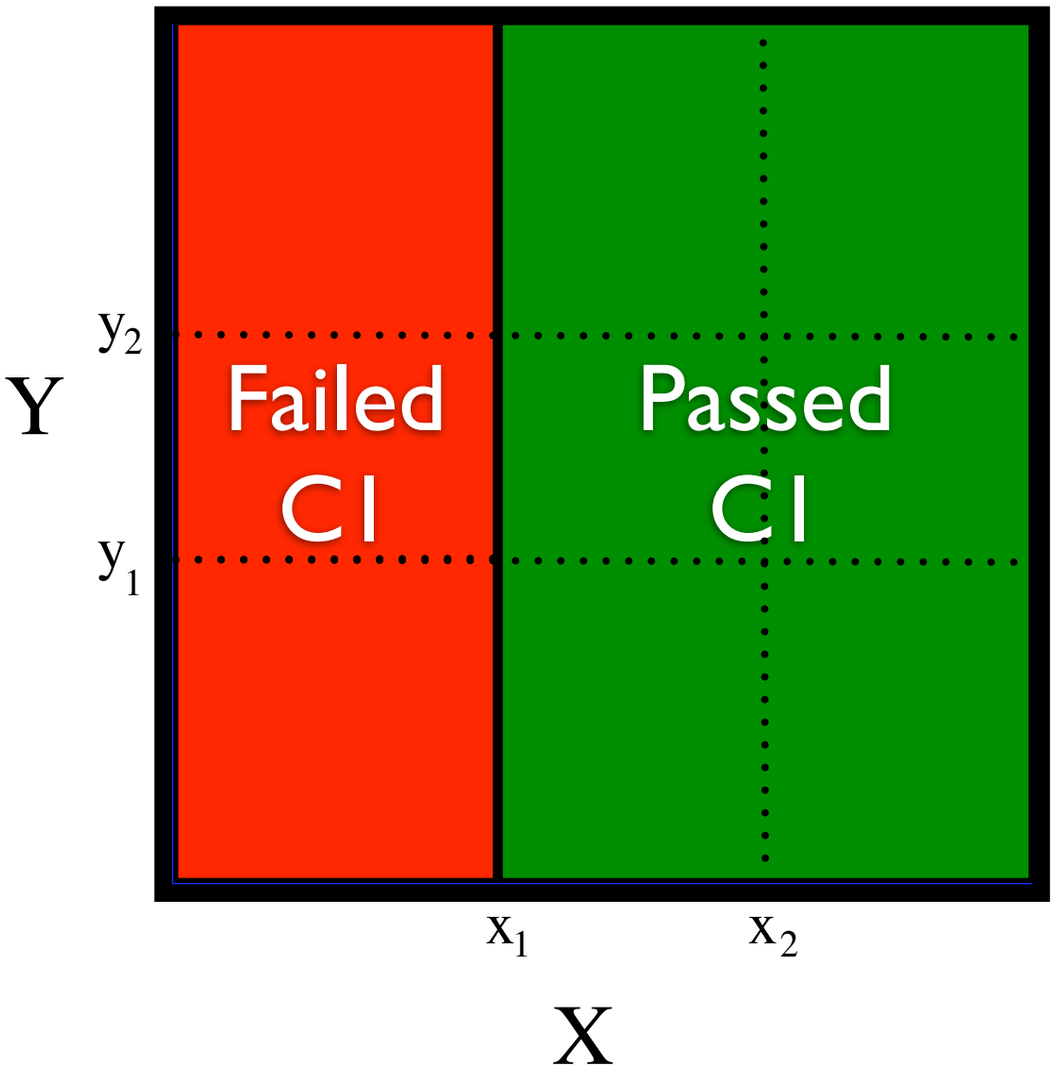


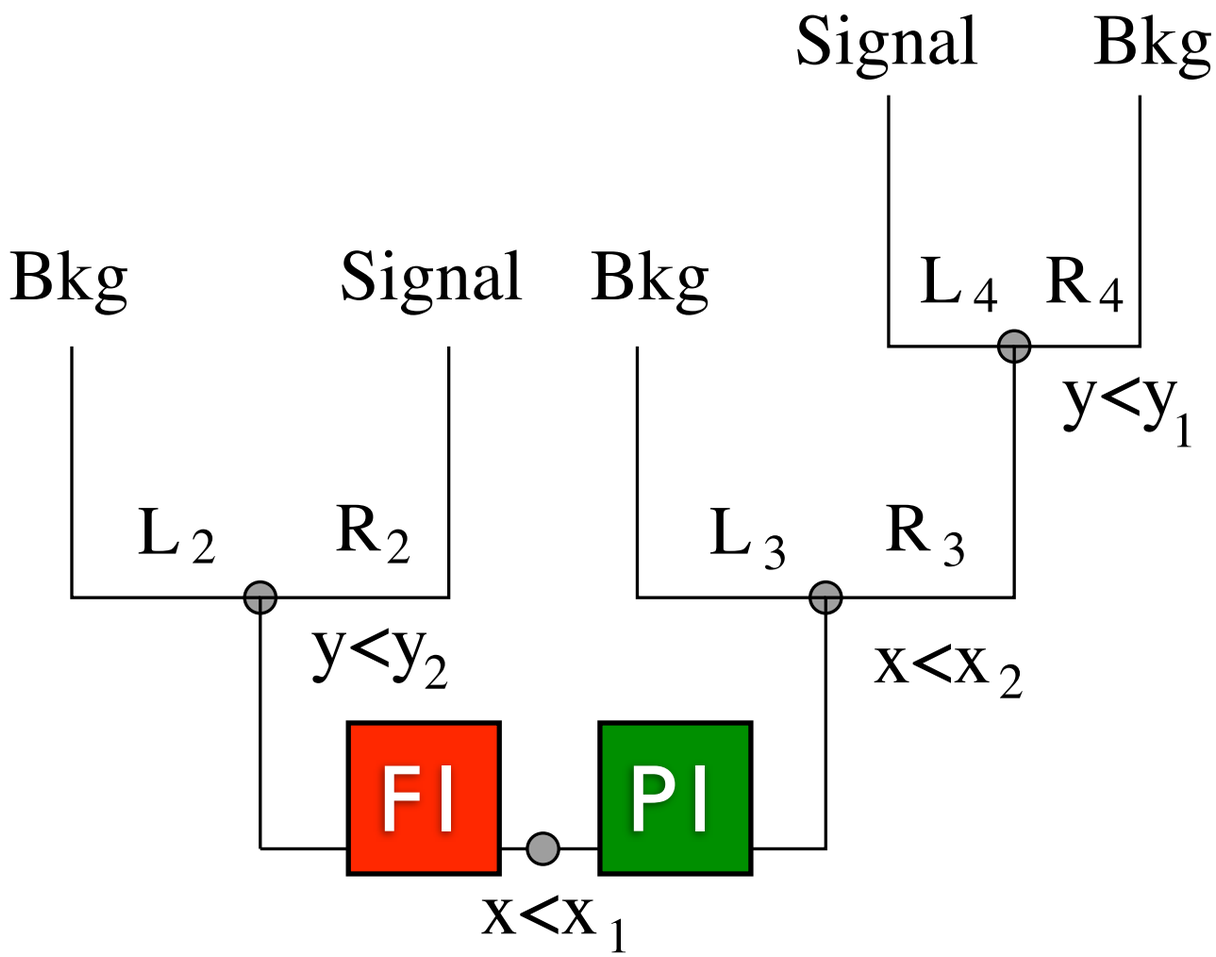


Task: separate signal from background
Issue: A single cut on X or Y does not work!

Solution: Use a series of consecutive cuts, generating a tree structure

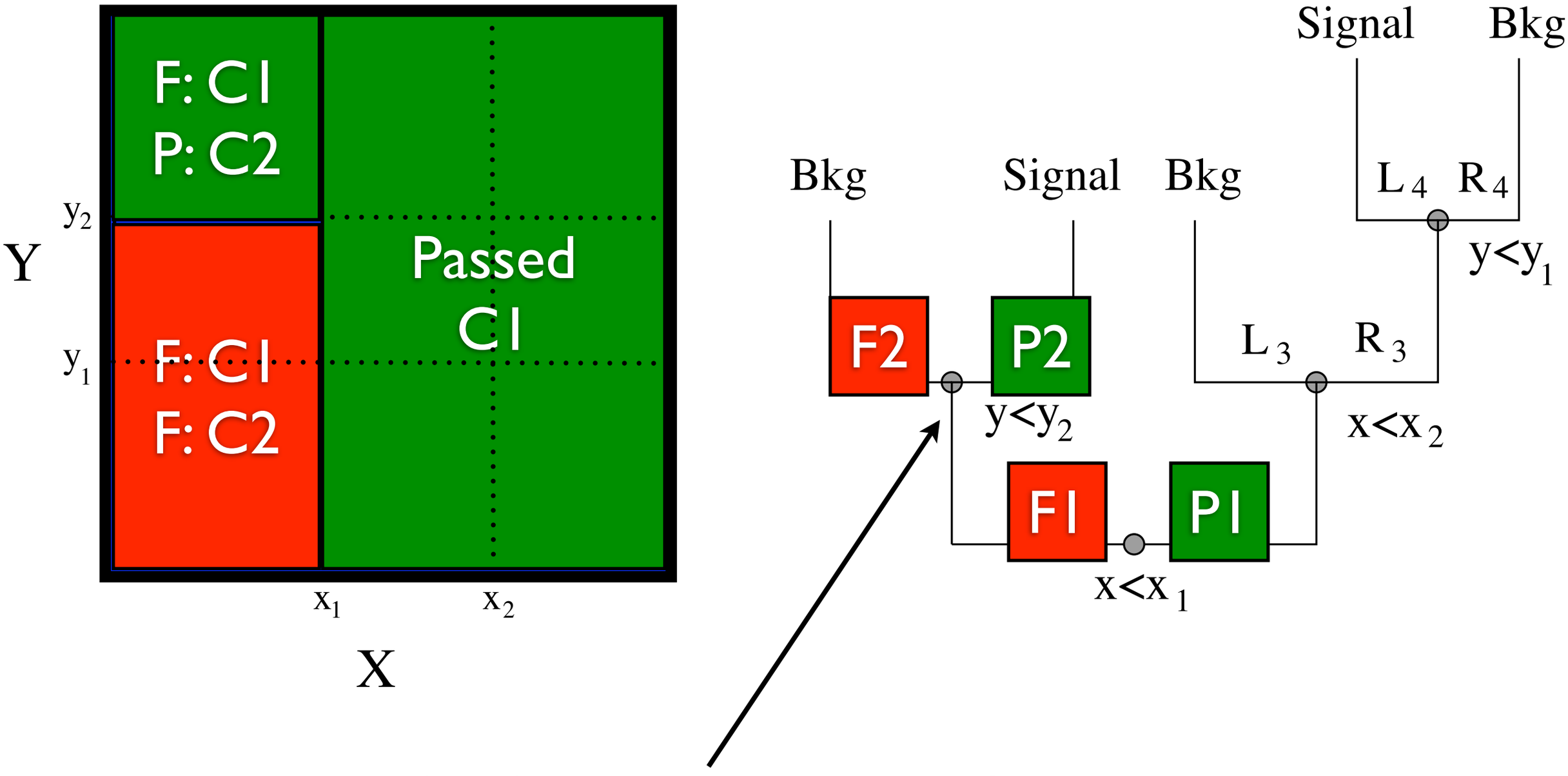
Toy Decision Tree





Cut 1: on the X variable

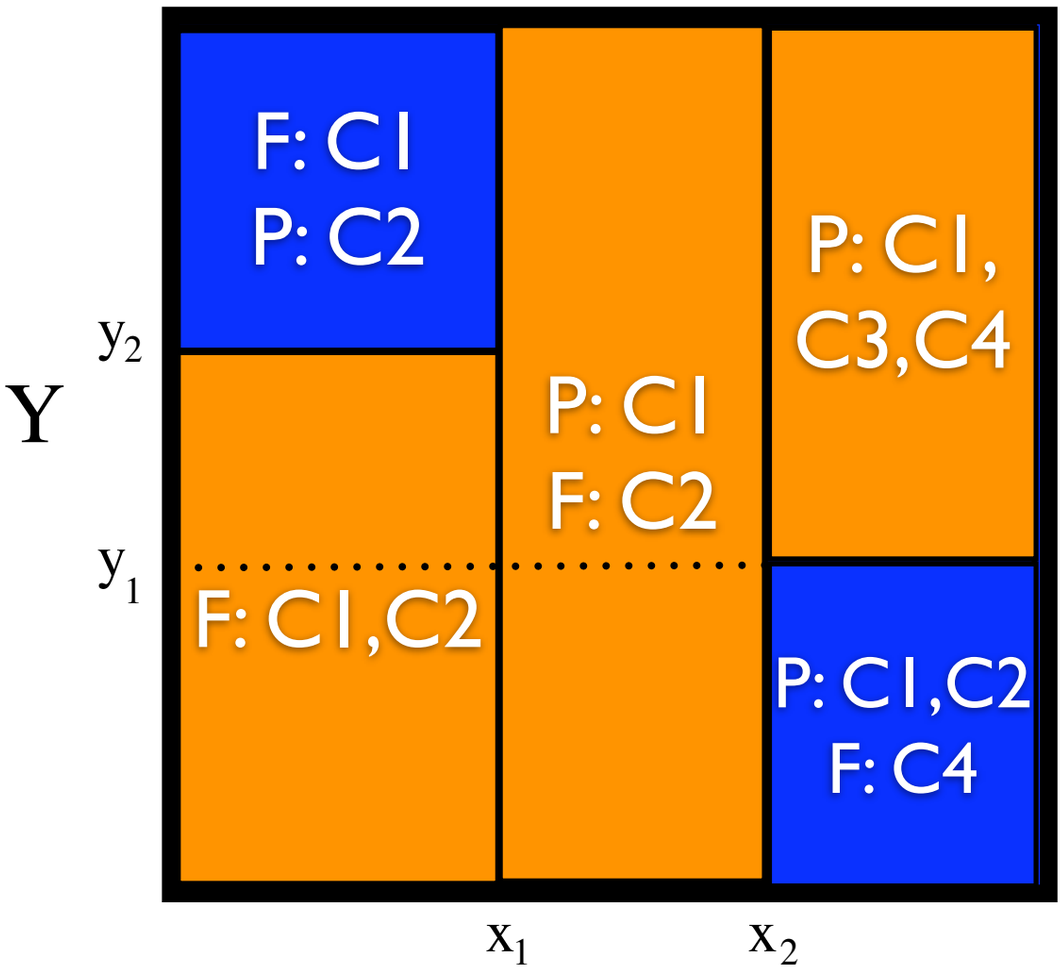
Toy Decision Tree

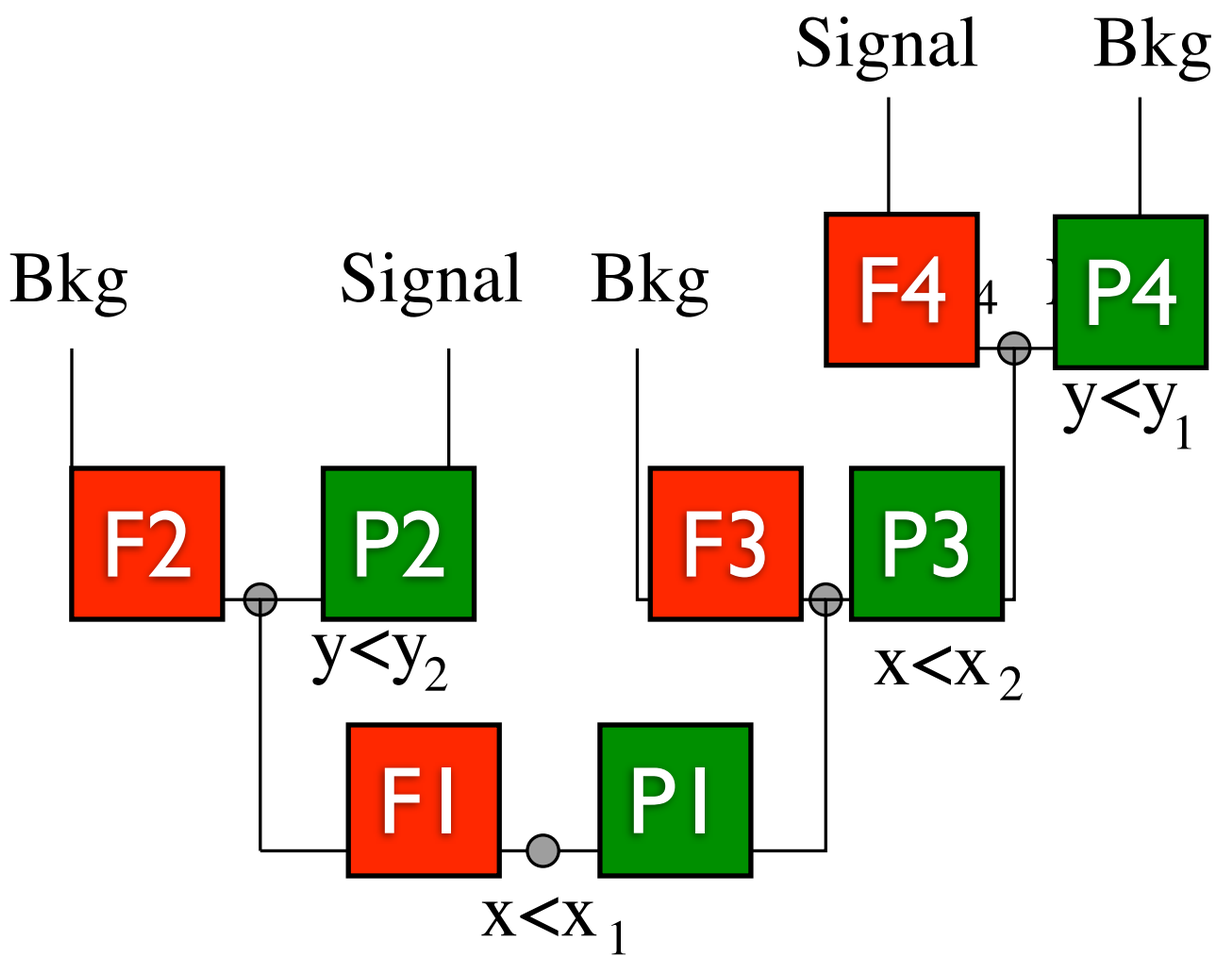


Cut 2: Recovered events that failed the cut 1

Add more cuts...

Toy Decision Tree



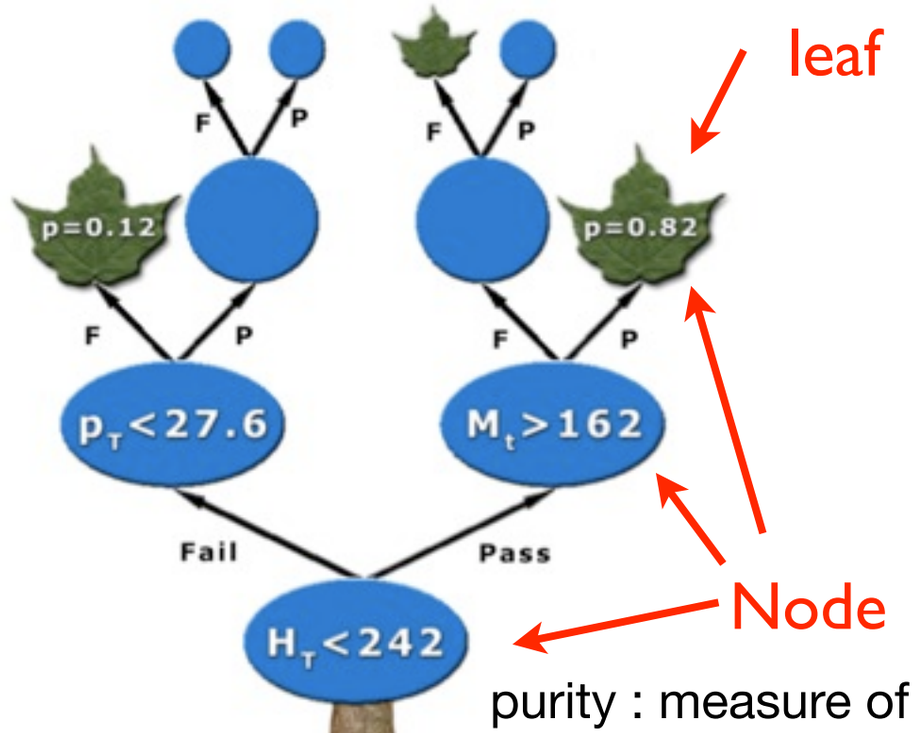


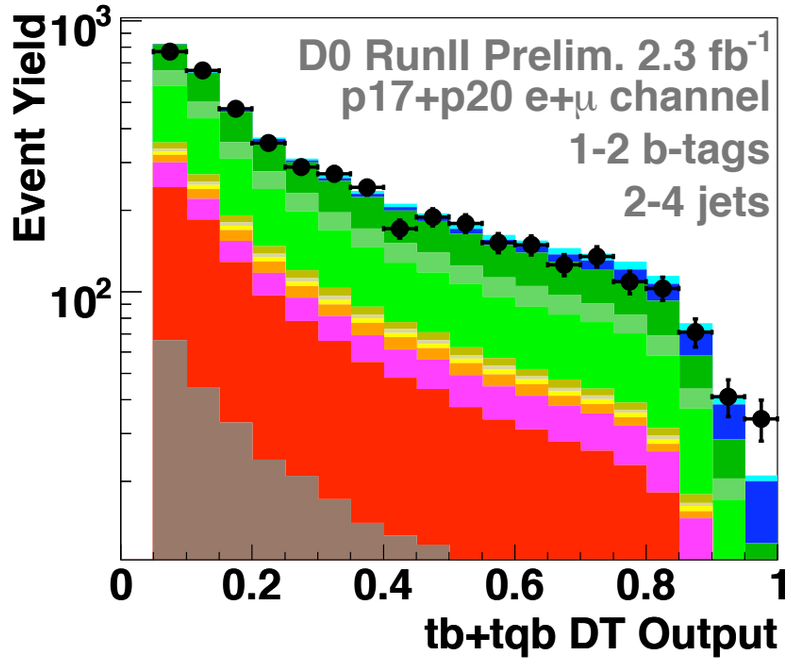
After 4 cuts: Signal and Background regions are separated! Done!

Toy model: only 2 variables, easy to determine cut values

Boosted Decision Trees

- Starting from a list of ~ 500 variables, select only well-modeled variables, and those with the highest discriminating power. This procedure results in a final list of 64 variables
- **Goal:** Recover events that fail a simple cut-based analysis
- Each event will follow a particular path through the DT and will end up in a “leaf”. The associated purity of the “leaf” corresponds to the discriminant output
- **Boosting:** Retrain 50 times to improve separation power, giving increasing importance to hard to classify events





BDTs: Training and Boosting

Training: (MC only!)

1. Signal and Background are normalized to the same value
2. Create the first node
3. Sort all events according to each variable
4. Select the variable and variable value that best split the sample. The splitting results into two child nodes
5. If no split possible, node becomes a leaf
6. Apply steps 3 to 6 recursively

Boosting:

1. Tree T_n is trained
2. Calculate the Tree weight a_n, based on the Tree missclassification rate
3. Events are reweighted according to a_n, such that misidentified events are assigned a higher weight
4. Tree T_{n+1} is built from the reweighted events

Final boosted result is

$$\Sigma(a_n T_n)$$

Single Top Search

Monte Carlo:
Signal and Background Model

~1 year

DØ Data

~6 years

Event selection:
remove background, remove not well-modeled regions

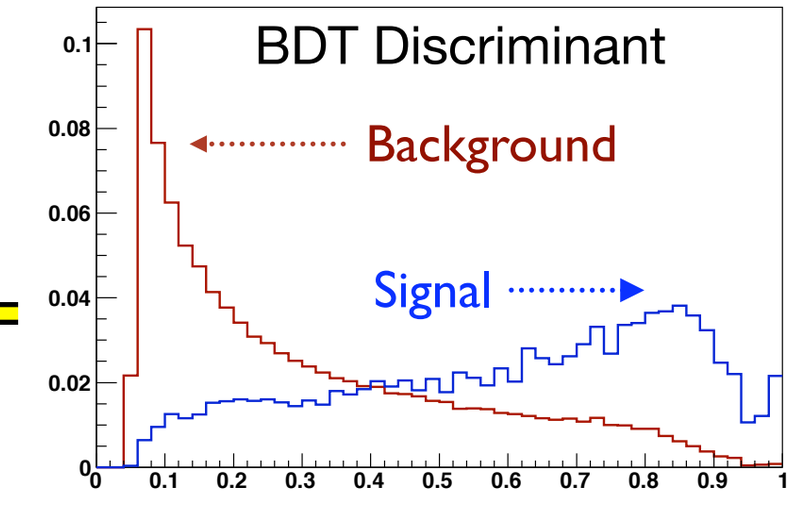
~2 year

MC Corrections:
account for differences in vertex finding, jet reconstruction eff, etc

~1 year

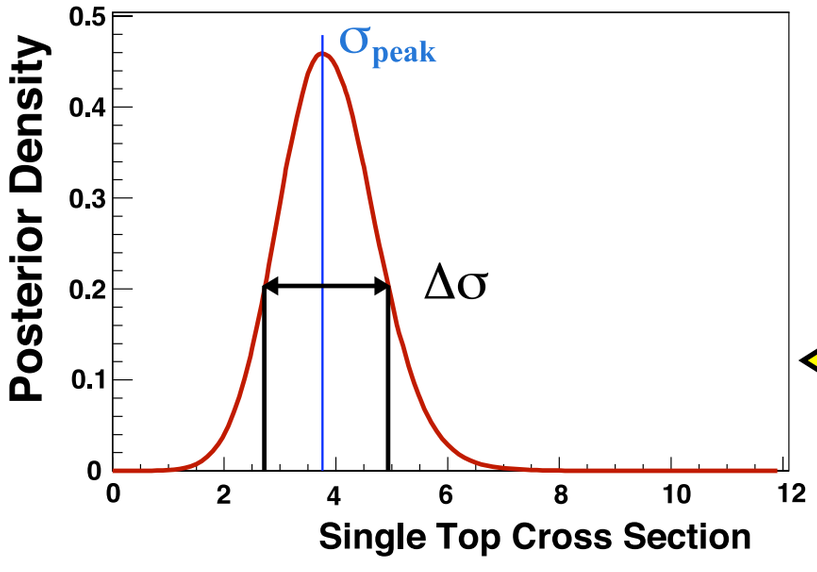
Multivariate Analysis Technique:
Boosted Decision Trees, Separate Signal from Bkg

~1 year



Bayesian Statistical Analysis:
Measure Cross Section

~1 year



Measuring Cross Section

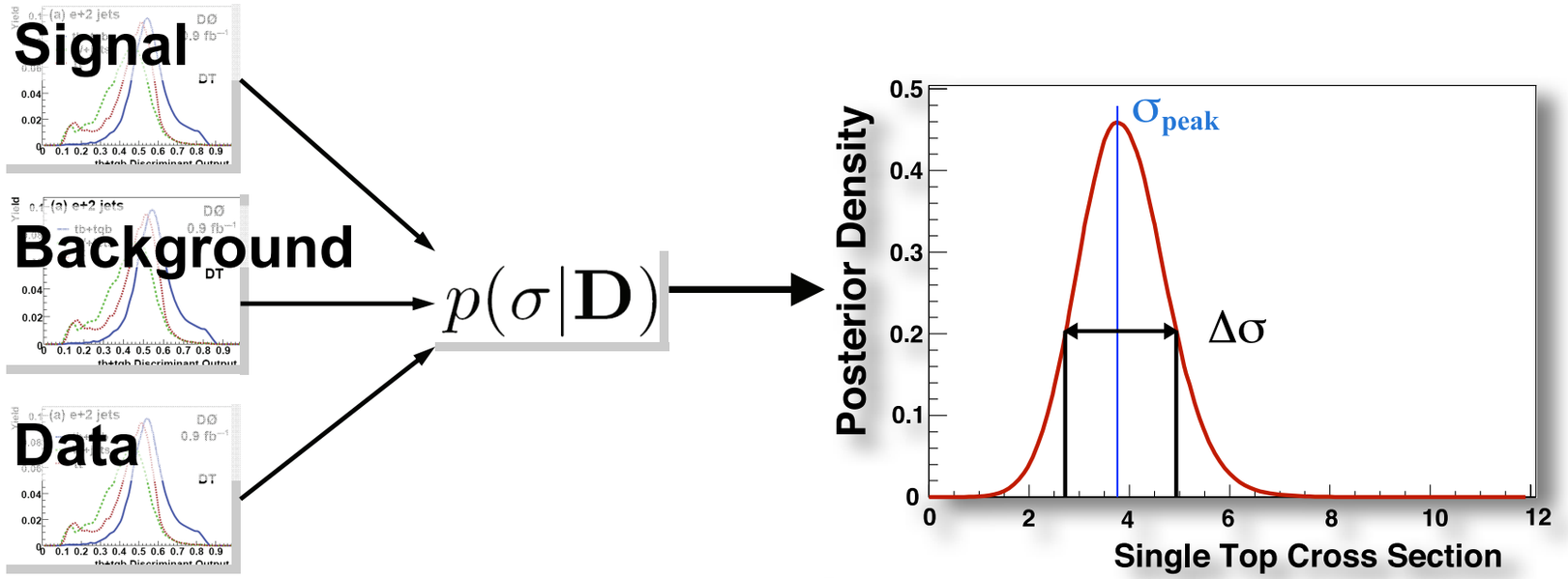
A binned likelihood is used to measure the cross section from the observed binned discriminant distribution.

For a particular bin, the probability to observe *D* events, given *d* expected events is given by the Poisson distribution:

$$p(D|d) = \frac{e^{-d} d^{D}}{\Gamma(D+1)}$$

The likelihood for M bins, corresponds to the product of all bins likelihoods

$$\text{Ł}(\boldsymbol{D}|\boldsymbol{d}) \equiv \text{Ł}(\boldsymbol{D}|\sigma, \boldsymbol{a}, \boldsymbol{b}) = \prod_{j=1}^{M} \text{Ł}(D_j|d_j)$$



From Bayes' Theorem the cross section posterior probability:

$$p(\sigma|\mathbf{D}) = \frac{1}{\mathcal{N}\sigma_{\max}} \int\int L(\mathbf{D}|\sigma, \mathbf{a}, \mathbf{b})\pi(\mathbf{a}, \mathbf{b})\, d\mathbf{a}\, d\mathbf{b}$$

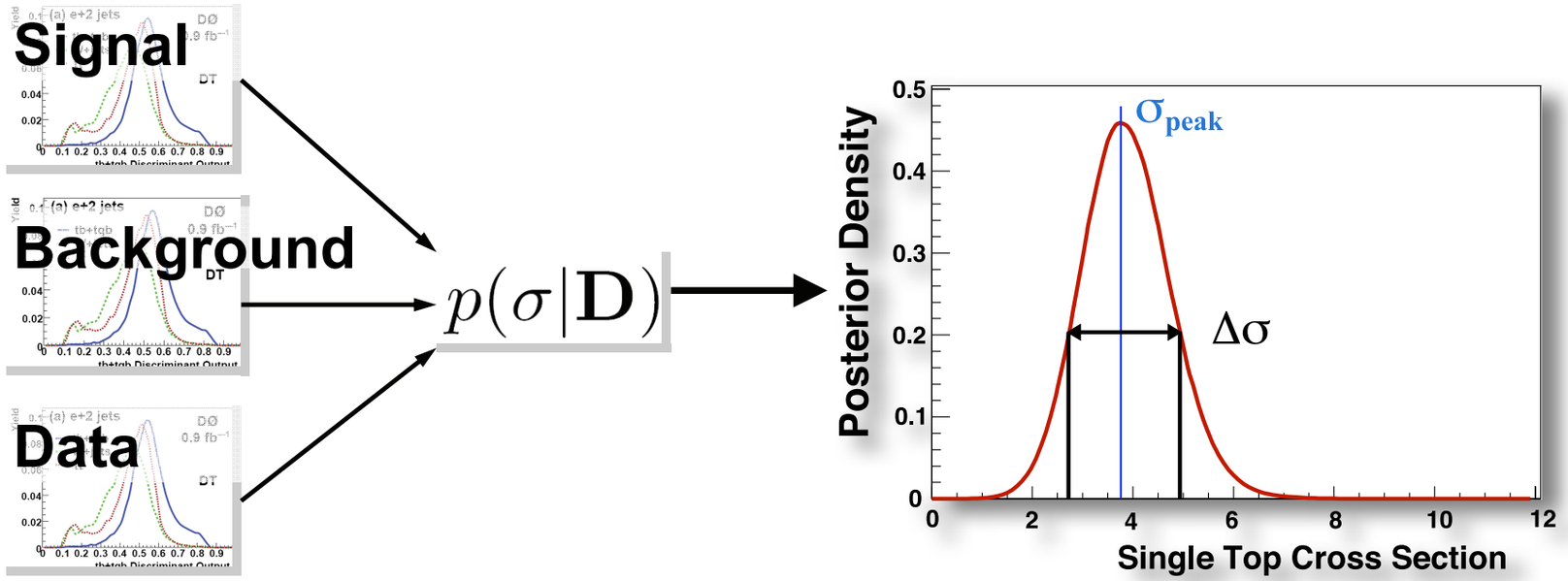
- Cross Section
- Observed Data
- Signal Acceptance
- Back-ground
- Probability of the Signal or Bkg

Measuring Cross Section

A binned likelihood is used to measure the cross section from the observed binned discriminant distribution.

For a particular bin, the probability to observe *D* events, given *d* expected events is given by the Poisson distribution:

$$p(D|d) = \frac{e^{-d} d^{D}}{\Gamma(D+1)}$$



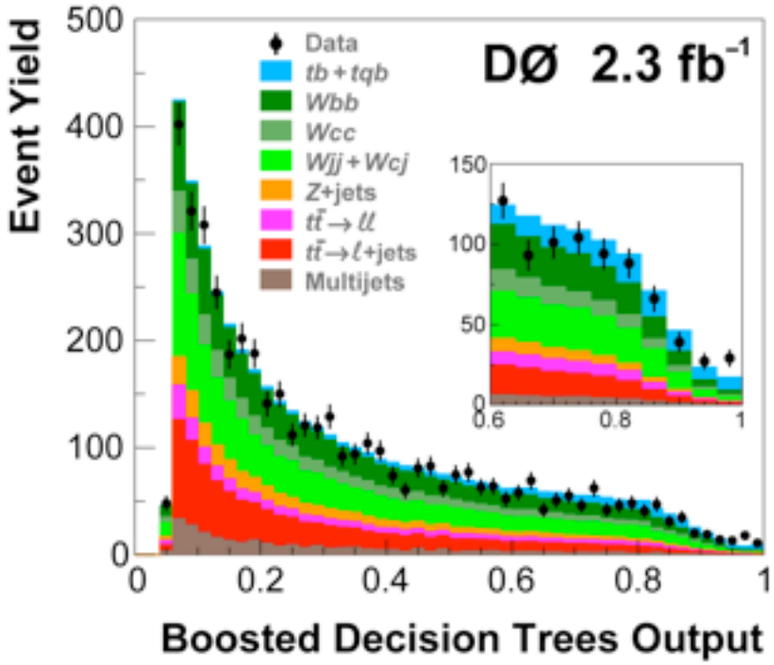
The likelihood for M bins, corresponds to the product of all bins likelihoods

$$\text{Ł}(\boldsymbol{D}|\boldsymbol{d}) \equiv \text{Ł}(\boldsymbol{D}|\sigma, \boldsymbol{a}, \boldsymbol{b}) = \prod_{j=1}^{M} \text{Ł}(D_j|d_j)$$

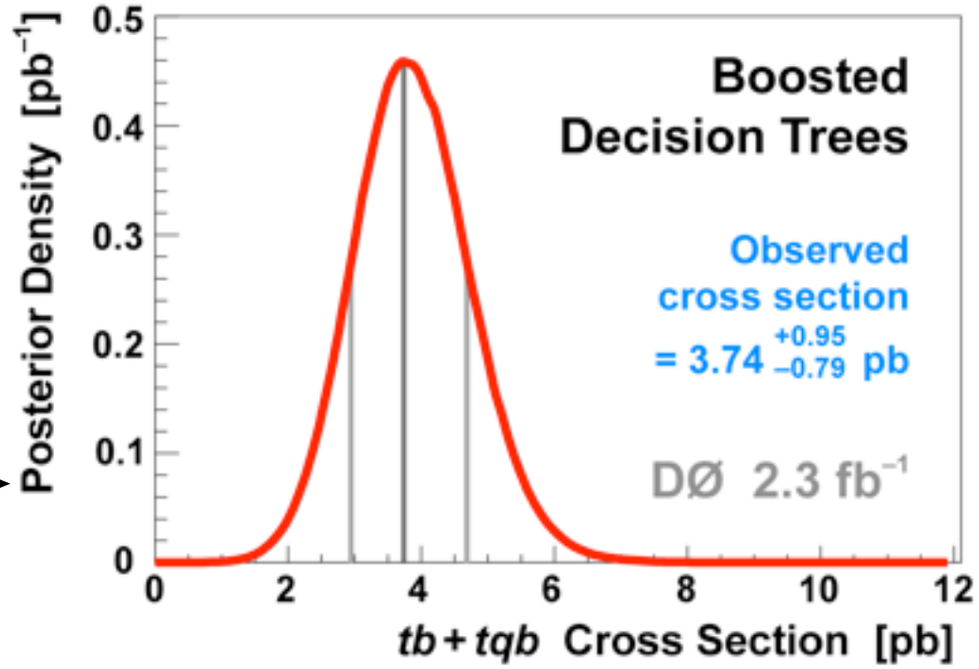
which can be estimated numerically by sampling the prior $\pi(\boldsymbol{a}, \boldsymbol{b})$

$$p(\sigma|\boldsymbol{D}) \sim \frac{1}{\mathcal{N}\sigma_{max}} \frac{1}{K} \sum_{k=1}^{K} L(\boldsymbol{D}|\sigma, \boldsymbol{a}_k, \boldsymbol{b}_k)$$

Cross Section Measurement

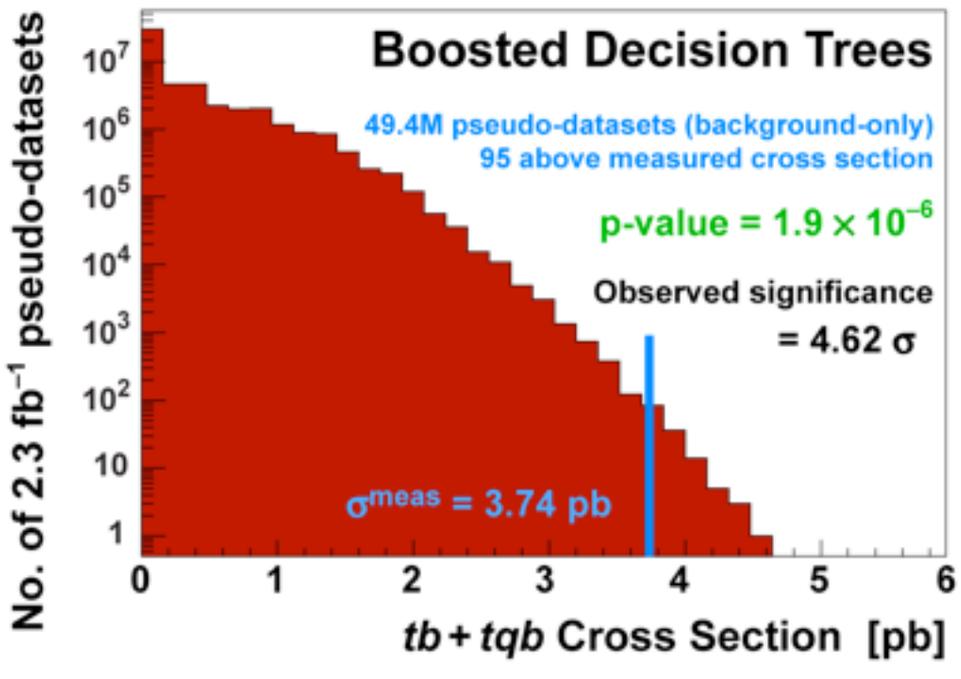


Using Bayesian Statistical analysis, including all systematics and their correlations

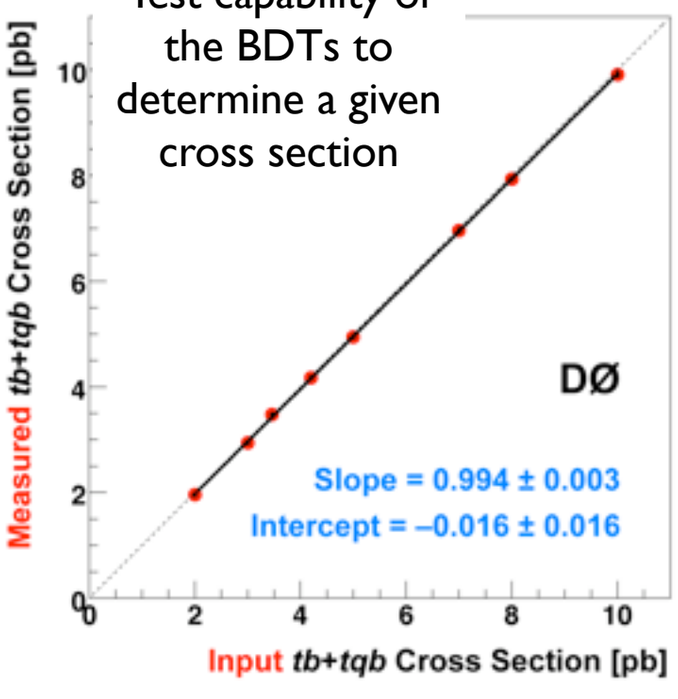


Significance of the measurement is estimated using psuedo-datasets that contain only the background model and all systematic uncertainties.

Count how many pseduo-datasets have a cross section higher than the observed measurement

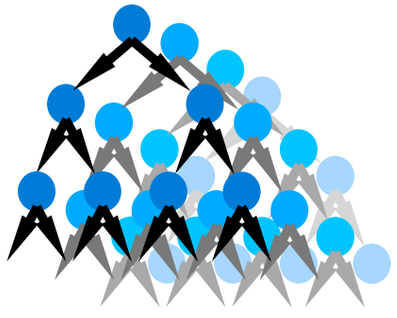


Test capability of the BDTs to determine a given cross section

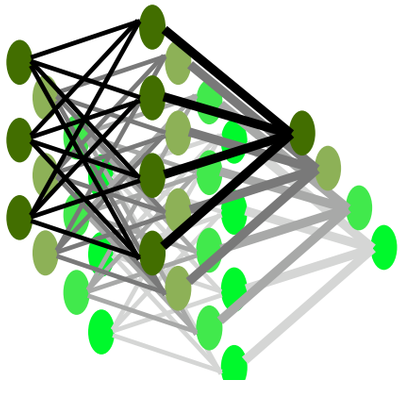


Additional Multivariate Analyses

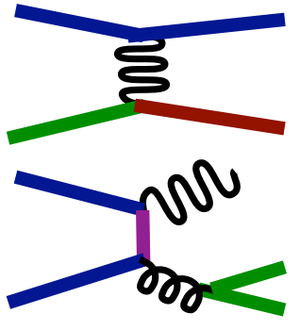
Boosted Decision Trees



Bayesian Neural Networks



Matrix Elements

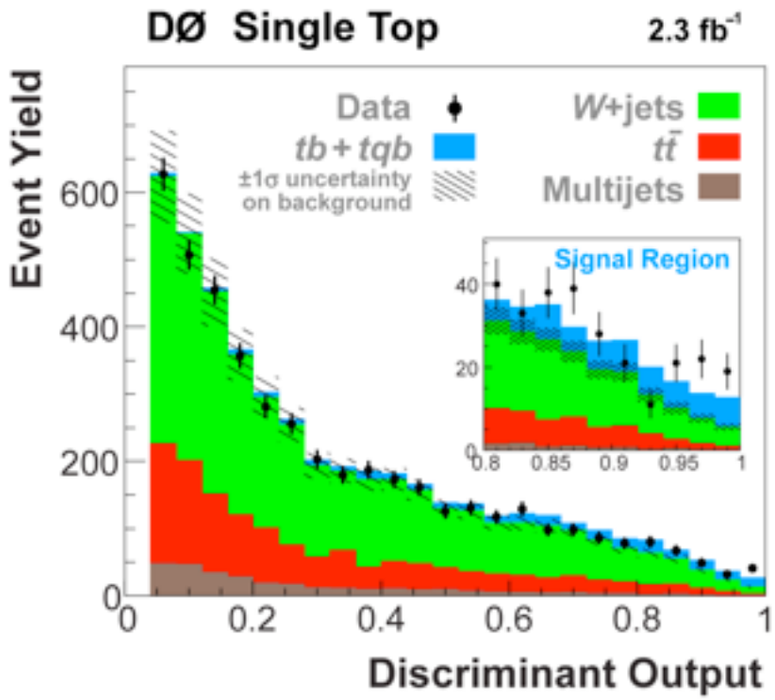


Combined

Using a Bayesian Neural Network that considers the individual analyses discriminant outputs as inputs to the Network.

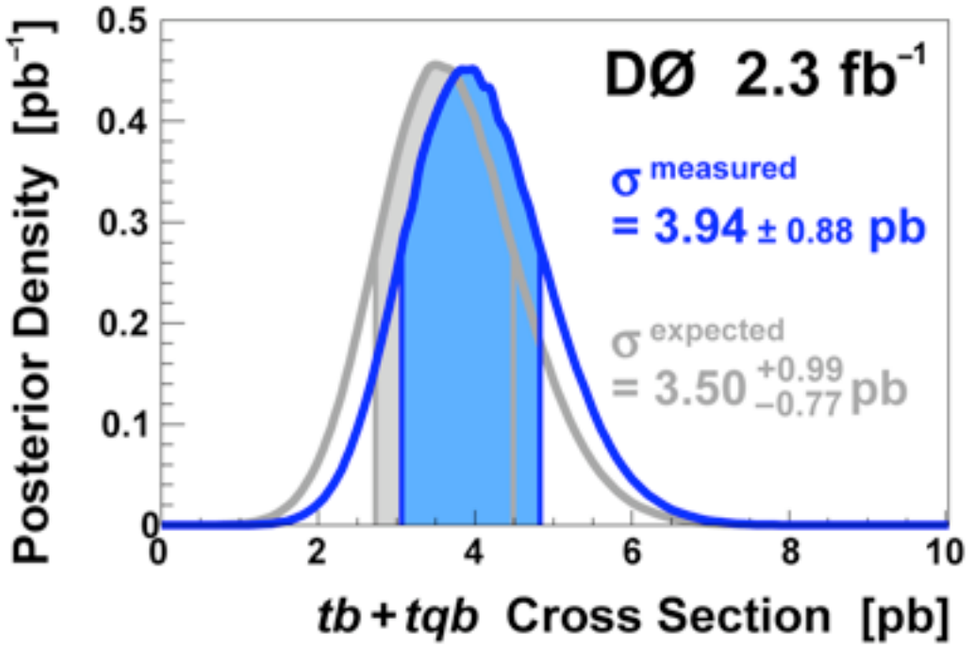
Purpose is to extract all possible information from the DØ data set.

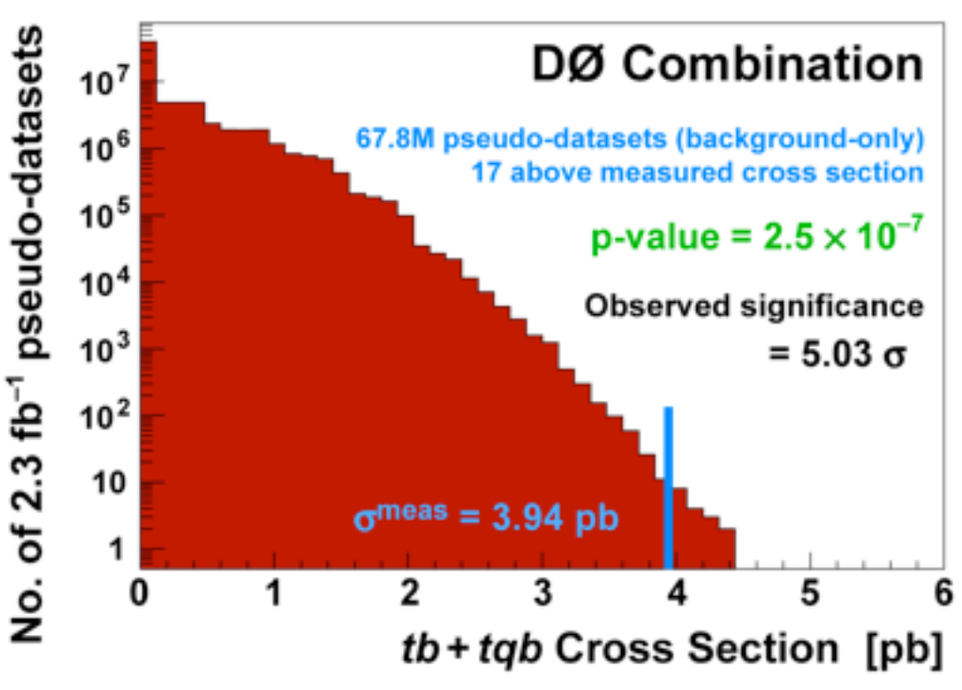
The Combination BNN produces a discriminant output, from where a cross section measurement is obtained



Cross Section Measurements

DØ 2.3 fb^{-1} Single Top Results			
Analysis Method	Single Top Cross Section	Significance	
		Expected	Measured
Boosted Decision Trees	$3.74\ ^{+0.95}_{-0.79}$ pb	4.3 σ	4.6 σ
Bayesian Neural Networks	$4.70\ ^{+1.18}_{-0.93}$ pb	4.1 σ	5.4 σ
Matrix Elements	$4.30\ ^{+0.99}_{-1.20}$ pb	4.1 σ	4.9 σ
Combination	3.94 ± 0.88 pb	4.5 σ	5.0 σ



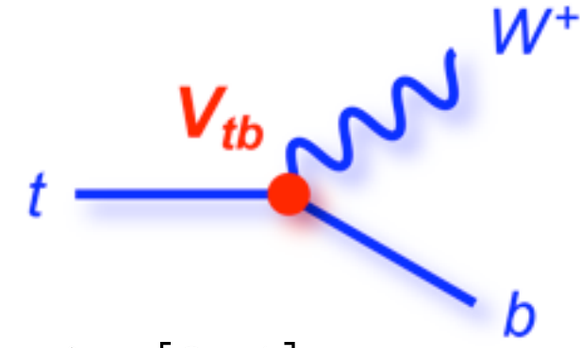


$|V_{tb}|$ measurement

General form of the $|V_{tb}|$ vertex:

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

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

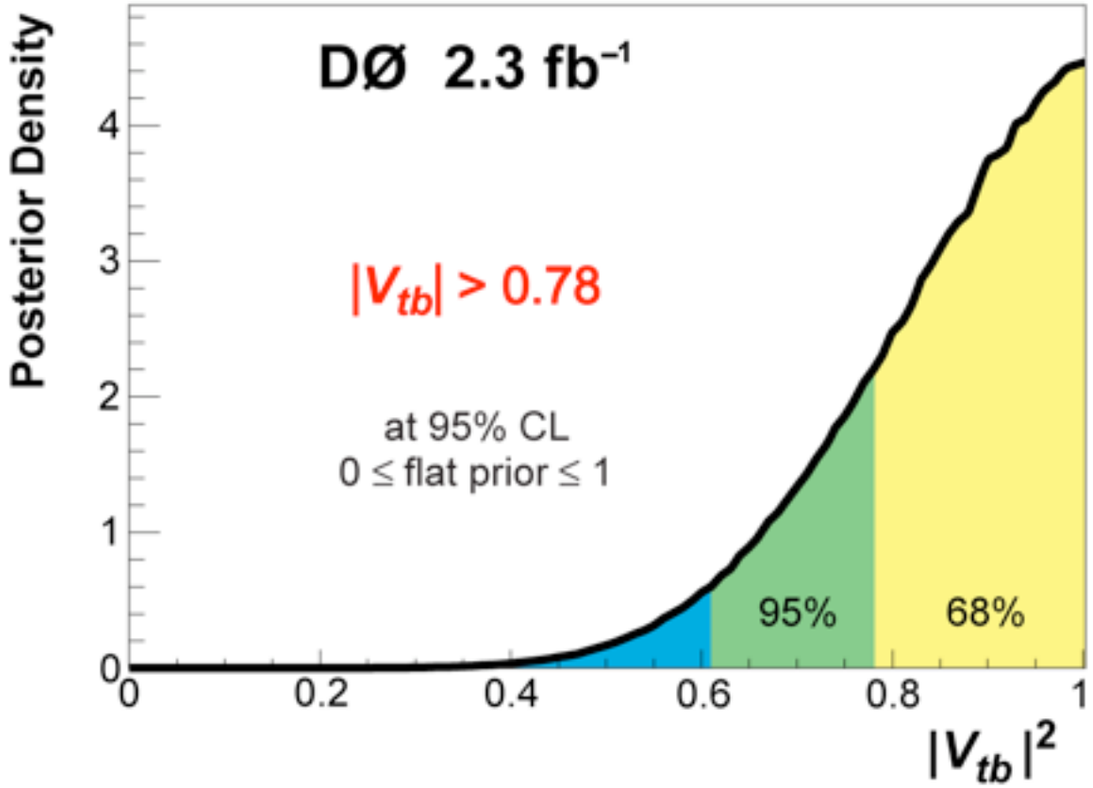


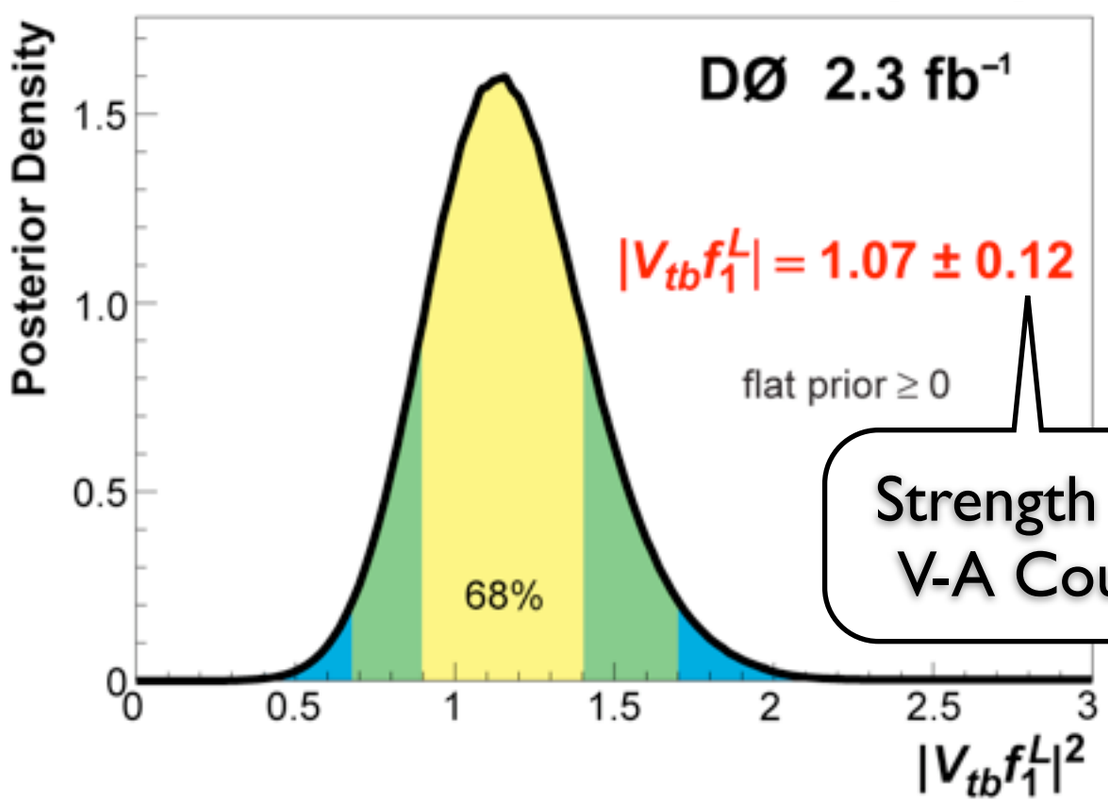
$|f_1^L V_{tb}|$ proportional to the Single Top cross section

within the SM :

$$f_1^L = 1, f_1^R = f_1^L = f_2^L = 0$$

removing the constrain $[0, 1]$:





Strength of the V-A Coupling

Conclusion

- Using 2.3 fb^{-1} of data collected with the DØ detector at the Fermilab Tevatron Collider and Boosted Decision Trees to separate the Single Top signal from the background, the Single Top cross section is measured to be:

$$\sigma(p\bar{p} \rightarrow tb + X, tqb + X) = 3.74\ ^{+0.95}_{-0.74}\ \text{pb},$$

  where the errors include both systematic and statistical uncertainties

- Combining three Single Top analysis the corresponding Single Top cross section is measured to be:

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

- The probability to measure a cross section at this value or higher in the absence of signal is $p = 1.9 \times 10^{-6}$. This corresponds to a significance of 5.03 standard deviations

- A PRL paper containing the result has been accepted for publication. arXiv:0903.0850

- DØ has more that 5 fb^{-1} of data to analyze from where new physics can be studied, and more precise single top measurements can be done

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Calendar

Wednesday, March 11
3:30 p.m.
DIRECTOR'S COFFEE BREAK - 2nd Flr X-Over
4 p.m.
Fermilab Colloquium - One West
Speaker: R. Sekhar Chivukula, Michigan State University

Special Result of the Week

Single and loving it!

Observation of single top-quark production

Accepted to PRL, to be published within a week

J. BackusMayes[81], F. Badaud[13], L. Bagby[49], B. Baldin[49], D.V. Bandurin[58], P. Banerjee[29], S. Banerjee[29], E. Barberis[62], A.-F. Barfuss[15], P. Bargassa[79], P. Baringer[57], J. Barreto[2], J.F. Bartlett[49], U. Bassler[18], D. Bauer[43], S. Beale[6], A. Bean[57], M. Begalli[3], M. Begel[72], C. Belanger-Champagne[41], L. Bellantoni[49], A. Bellavance[49], J.A. Benitez[64], S.B. Beri[27], G. Bernardi[17], R. Bernhard[23], I. Bertram[42], M. Besançon[18], R. Beuselinck[43], ...om[66], A. Boehnlein[49], D. Boline[61], ...[4], G. Brooijmans[69], A. Bross[49], ...er[22], V. Bunichev[38], S. Burdin[42,c], ...min[70], M.A. Carrasco-Lizarraga[33], ...rabarti[71], D. Chakraborty[51], ...L. Christofek[76], T. Christoudias[43], ...[49], M. Corcoran[79], F. Couderc[18], ...A. Das[45], G. Davies[43], K. De[77], ...eau[49], R. Demina[70], D. Denisov[49], ...land[81], A. Dubey[28], L.V. Dudko[38], ...[56], D. Edmunds[64], J. Ellison[47], ... Evdokimov[72], V.N. Evdokimov[39], ... Fisk[49], M. Fortner[51], H. Fox[42], ...rilov[37], P. Gay[13], W. Geist[19], ... B. Gómez[8], A. Goussiou[81], ...es[4], G. Grenier[20], Ph. Gris[13],

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...nd D0 report single top quark events

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Fermilab collider experiments discover rare single top quark

March 9th, 2009

MSU News

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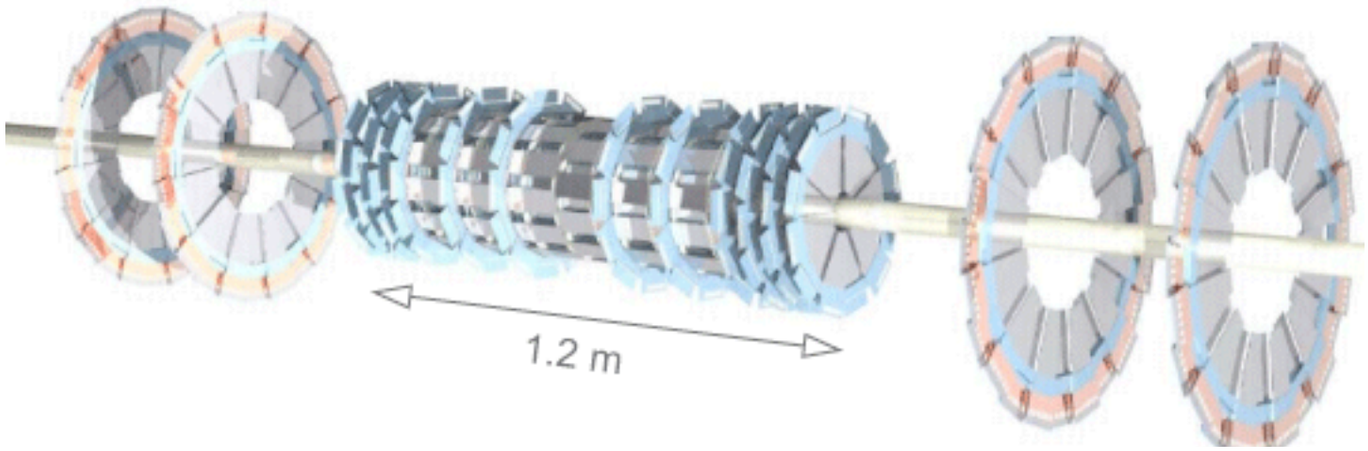
MSU scientists help lead teams in detection of fundamental component of matter

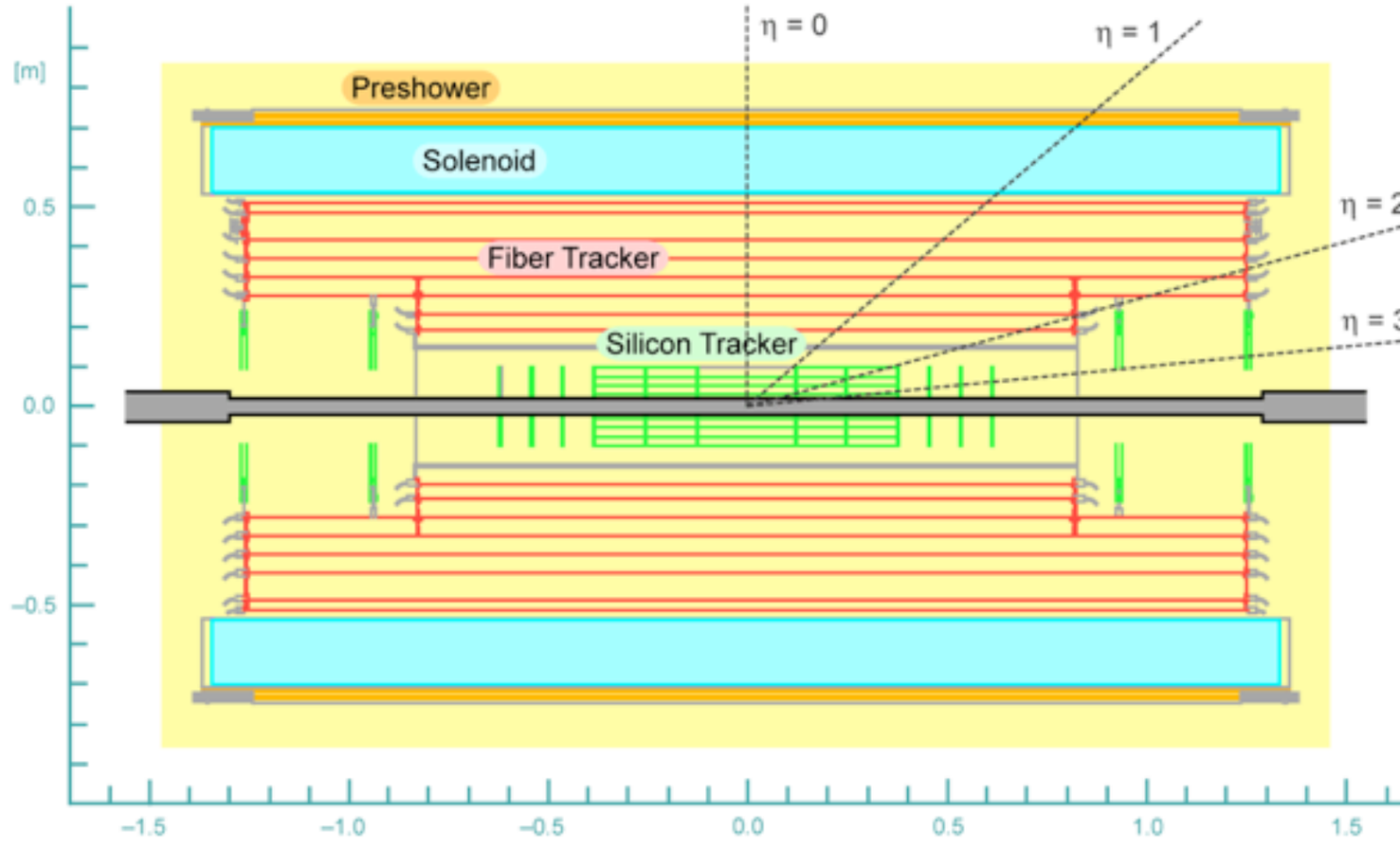
Thank You

- Chip for his support and words of wisdom that guided me through graduate school.
- Reinhard for getting me into Single Top, leading the way to the discovery, and incredible motivational techniques
- Committee members for reviewing my dissertation
- The DØ Single Top group and the BDT team.
  Specially to Dag, Dugan, Monica, Andres, Liang, Ernest, Ann, Cecilia.
- Friends and Family for their support and good company
- Catherine for her patience and for being my tower of strength

Extra Slides

DØ Detector


1.2 m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η = 2
η = 3
[m]
Preshower
Solenoid
Fiber Tracker
Silicon Tracker
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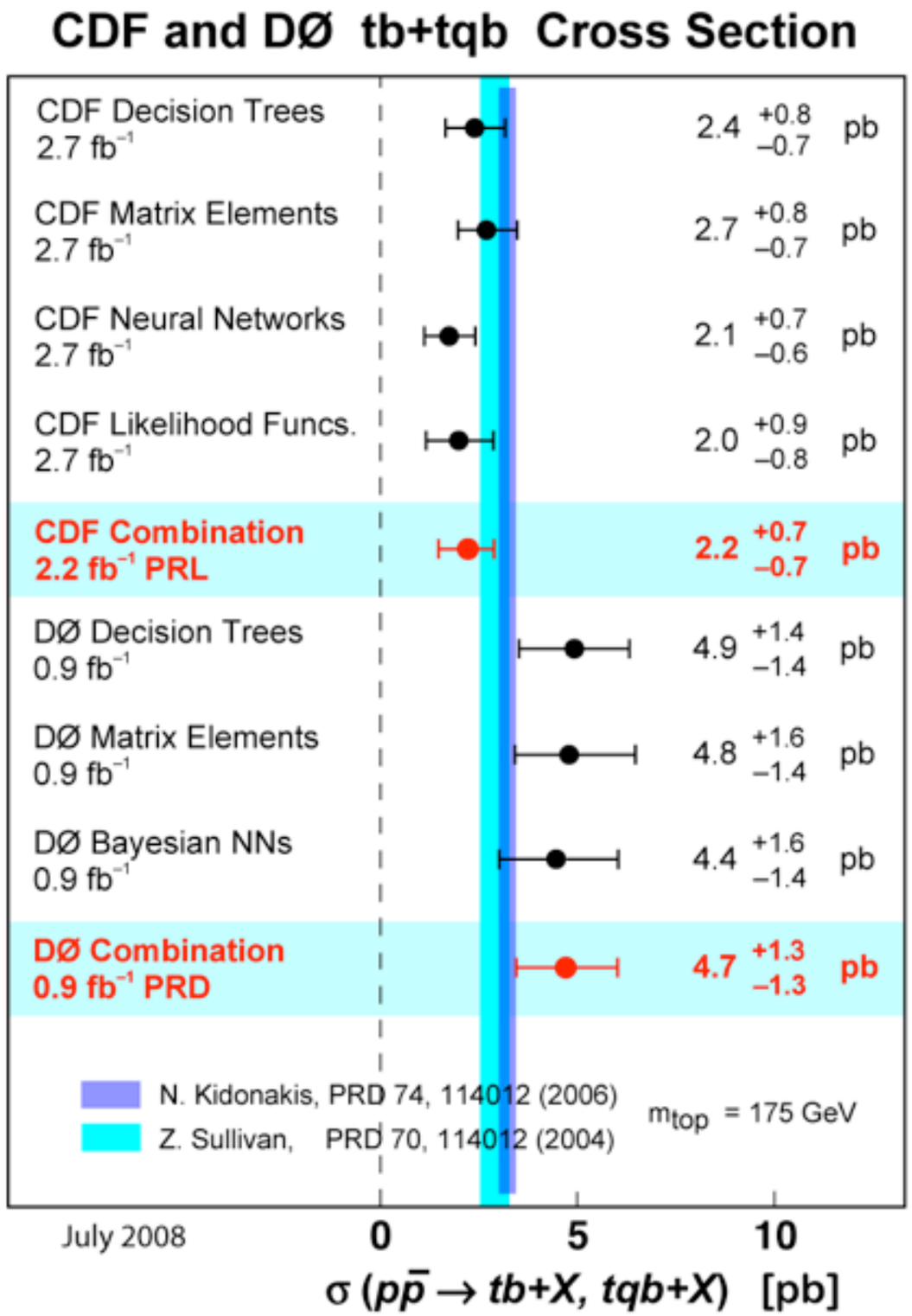
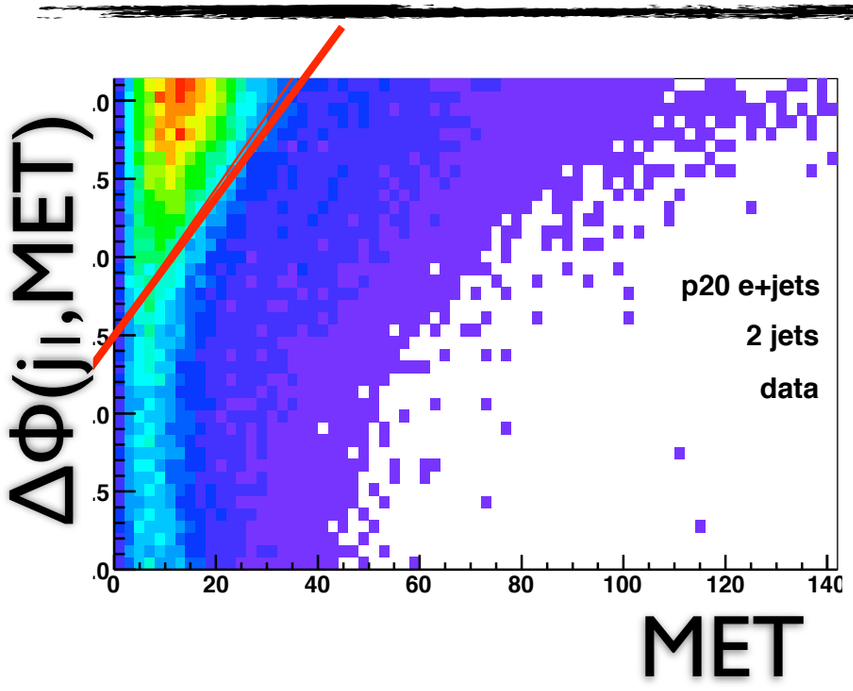
0.0
−0.5
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

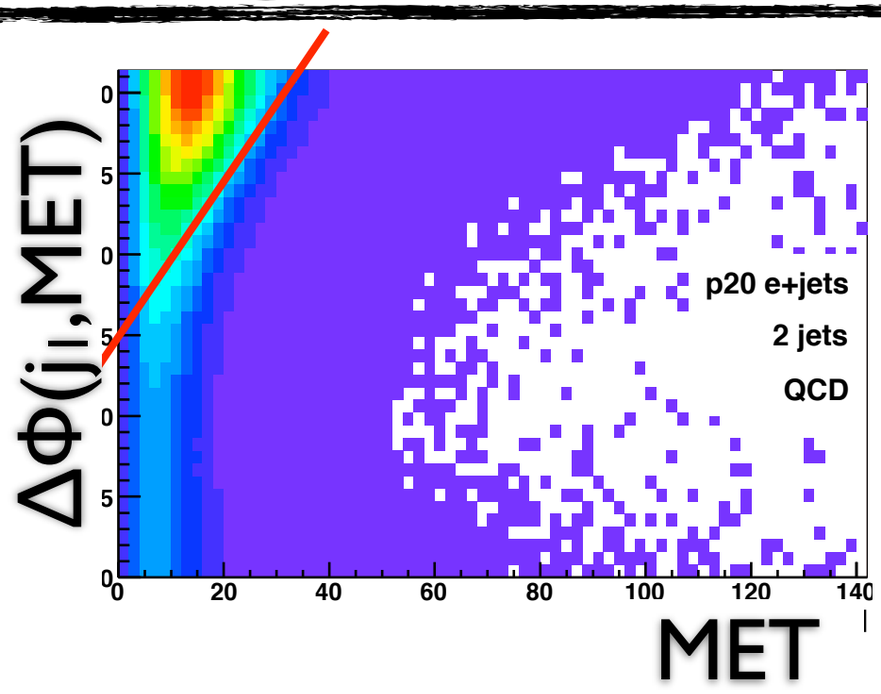
Previous Single Top Results

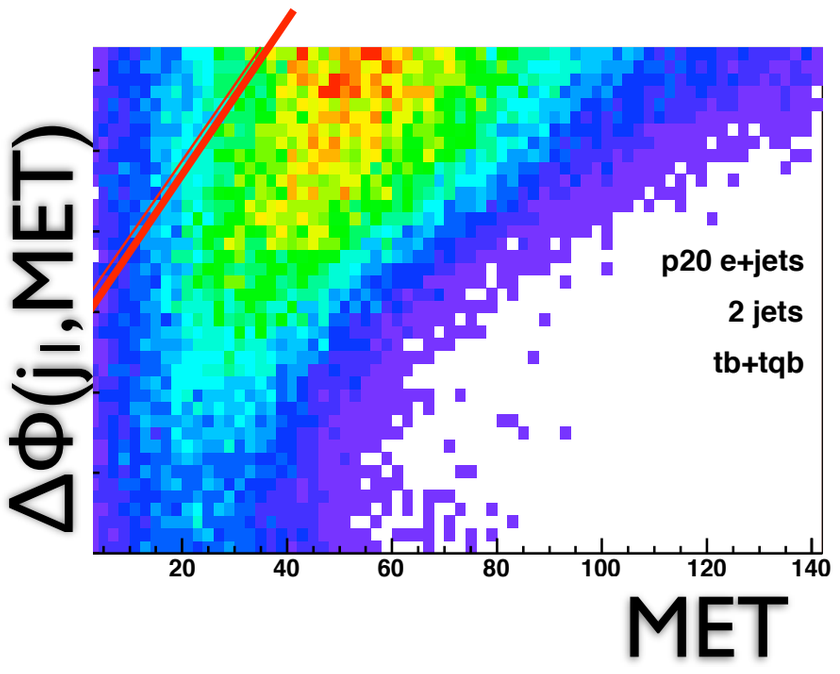
Single Top Cross Section	Signal Significance Expected	Signal Significance Observed	CKM Matrix Element V_{tb}
December 2006 DØ (0.9 fb^{-1})			PRL 98, 181802 (2007)
4.7 ± 1.3 pb	2.3 σ	3.6 σ	$\lvert V_{tb} f_1^L \rvert = 1.31^{+0.25}_{-0.21}$ $\lvert V_{tb} \rvert > 0.68$ at 95% CL
September 2008 CDF (2.2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



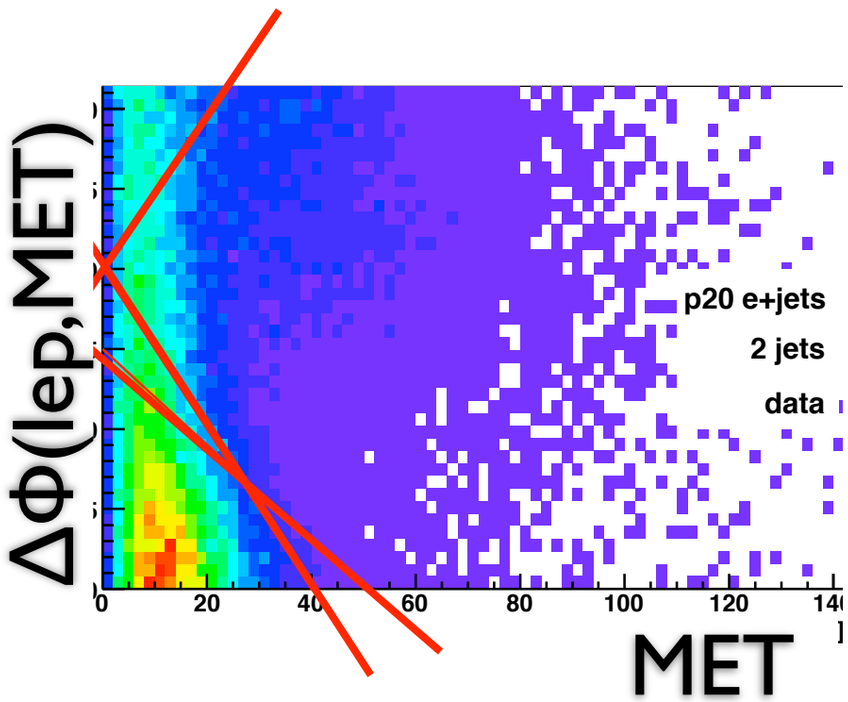
Triangular Cuts



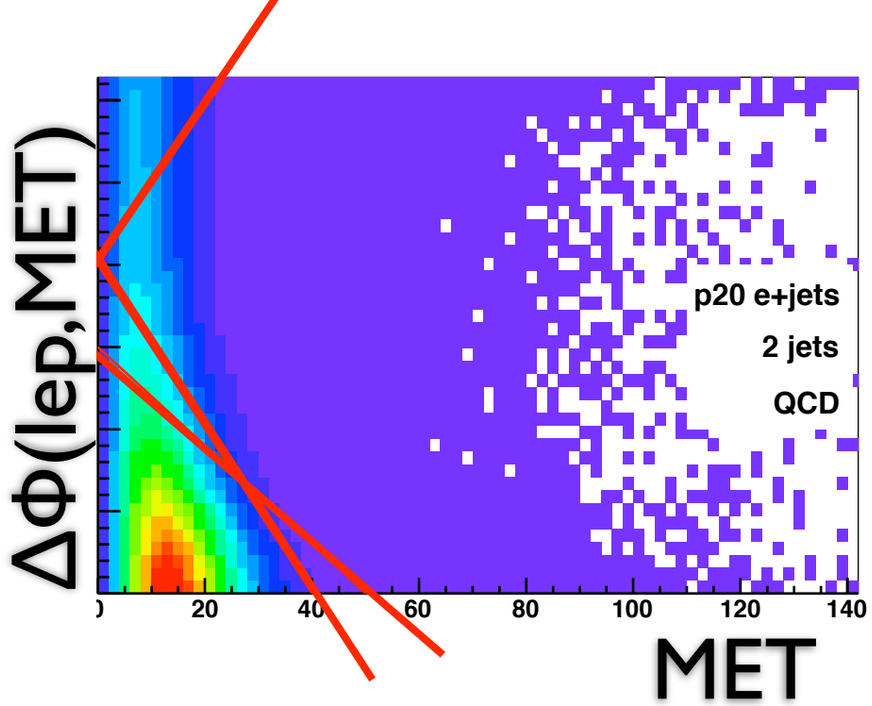




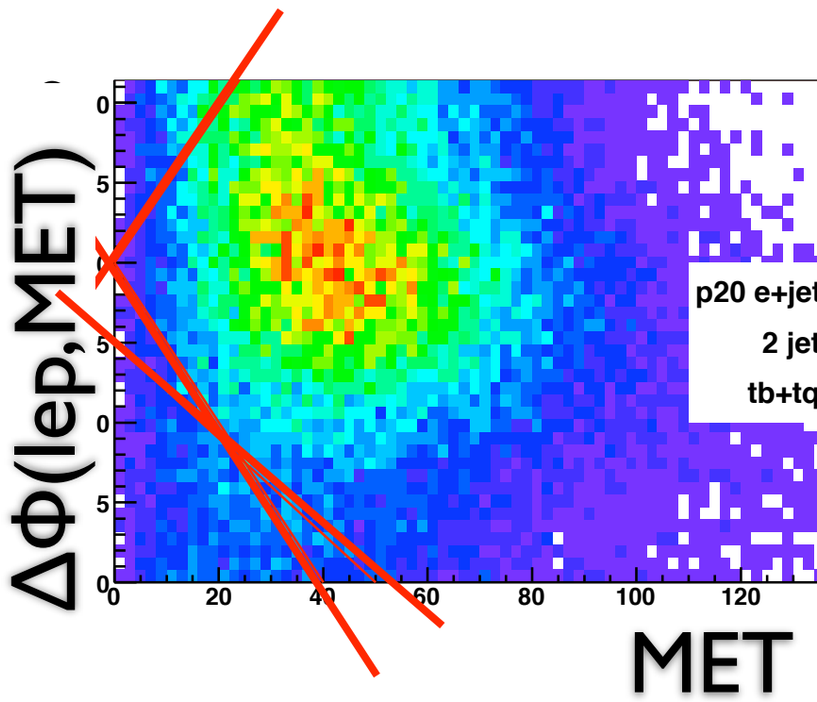
DATA



QCD



SIGNAL



QCD Determination

- Using Reverse Isolation sample: (Traditional)

  QCD = Loose – Tight

- Enlarge sample:
  - Remove the ΔR requirement from the loose sample:

    QCD = SuperLoose (no ΔR) – Tight

- In addition:
  - Correct kinematical distributions by removing jets that are within $\Delta R < 0.5$ of the muon.
  - Properly account for the removed jet MET
- Sample statistics increases by a factor of ~ 10!

W+jet and QCD normalization

- The total number of pre-tagging data events:

$$Y_{\text{pretagged data}} = S_{W+\text{jets}} * Y^{\text{before}-\text{IKS}}_{W+\text{jets}} + Y_{\text{all other MC}} + S_{\text{multijets}} * Y^{\text{before}-\text{IKS}}_{\text{multijets}}$$

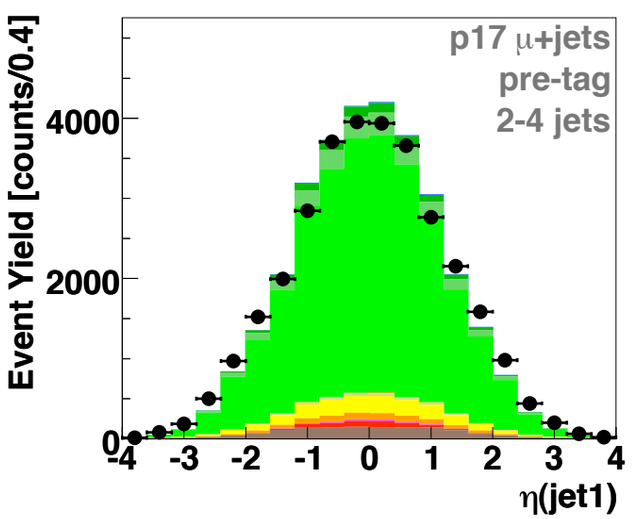
- Using three variable distributions (p_T(lep), MET, M_T(W)):
  - Scan possible values for $S_{W+\text{jets}}$ and $S_{\text{multijets}}$ and select those that give the best KS value
  - Average the constant values and scale samples:

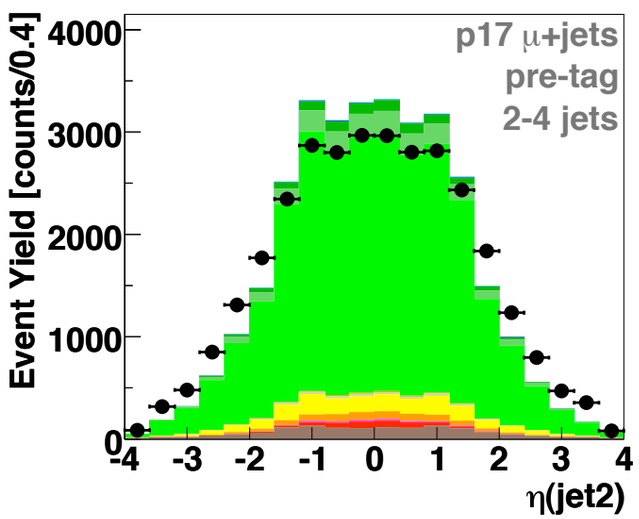
$$S_{\text{multijets}} = \frac{\sum_{i=\text{var1}}^{\text{varN}} S^i_{\text{multijets}} * \text{KS}^i_{\text{max}}}{\sum_{i=\text{var1}}^{\text{varN}} \text{KS}^i_{\text{max}}}$$

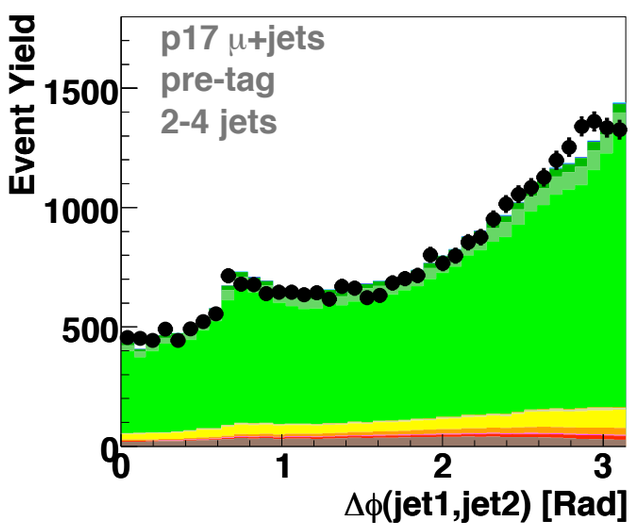
W+jets re-weighting

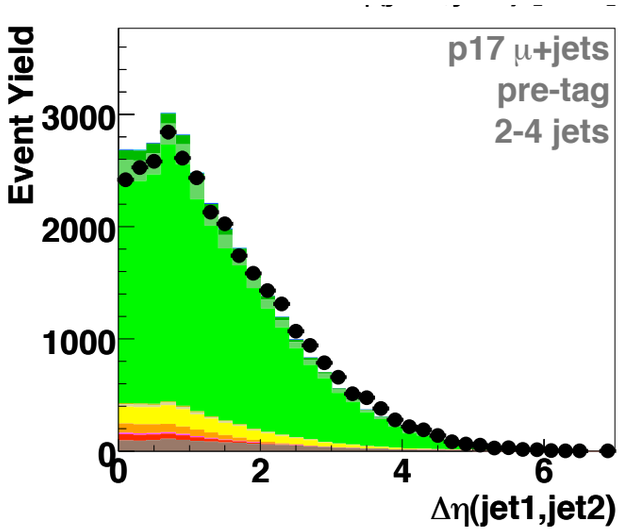
- Purpose: correct ALPGEN modeling discrepancies

BEFORE

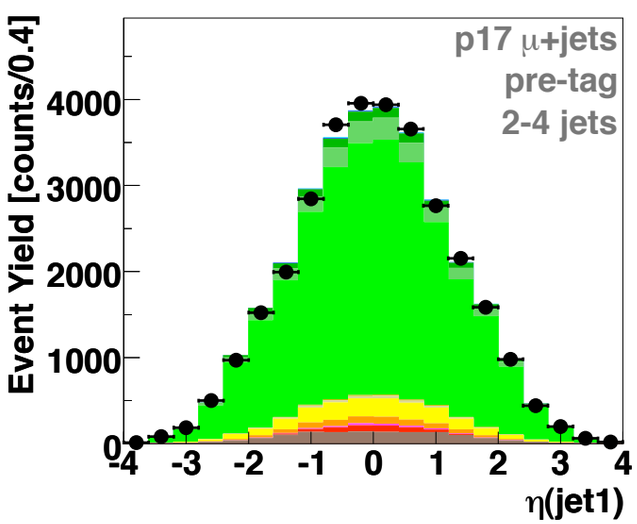


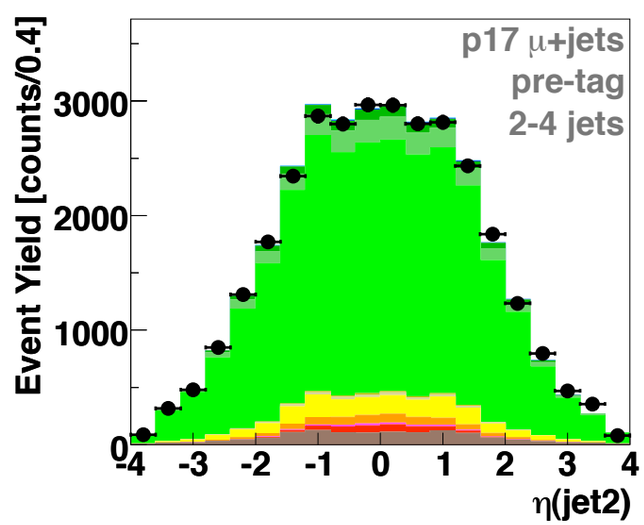


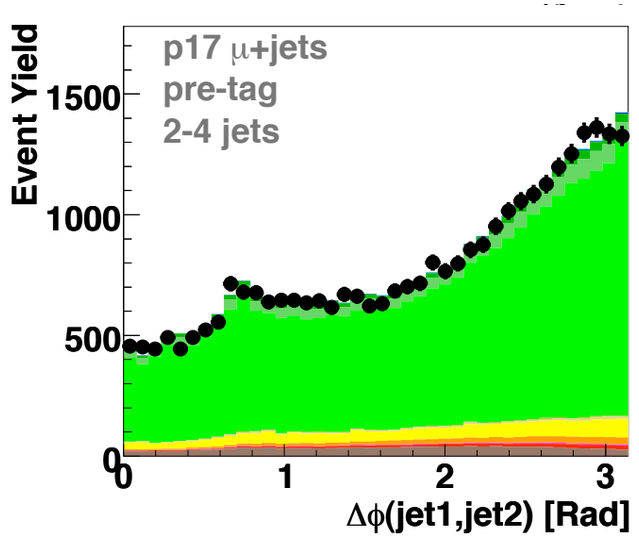


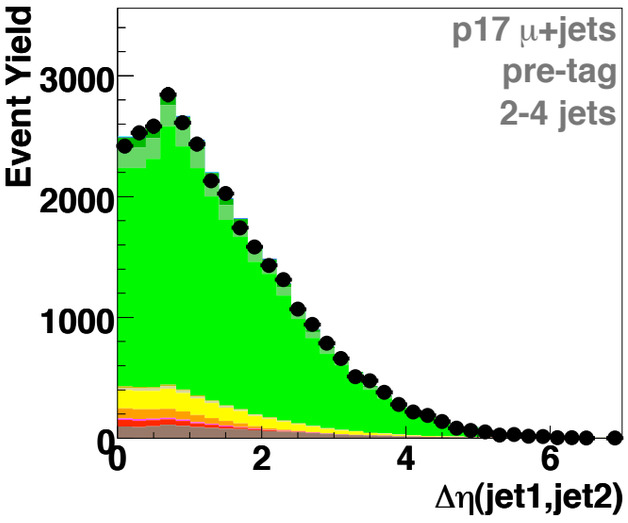


AFTER



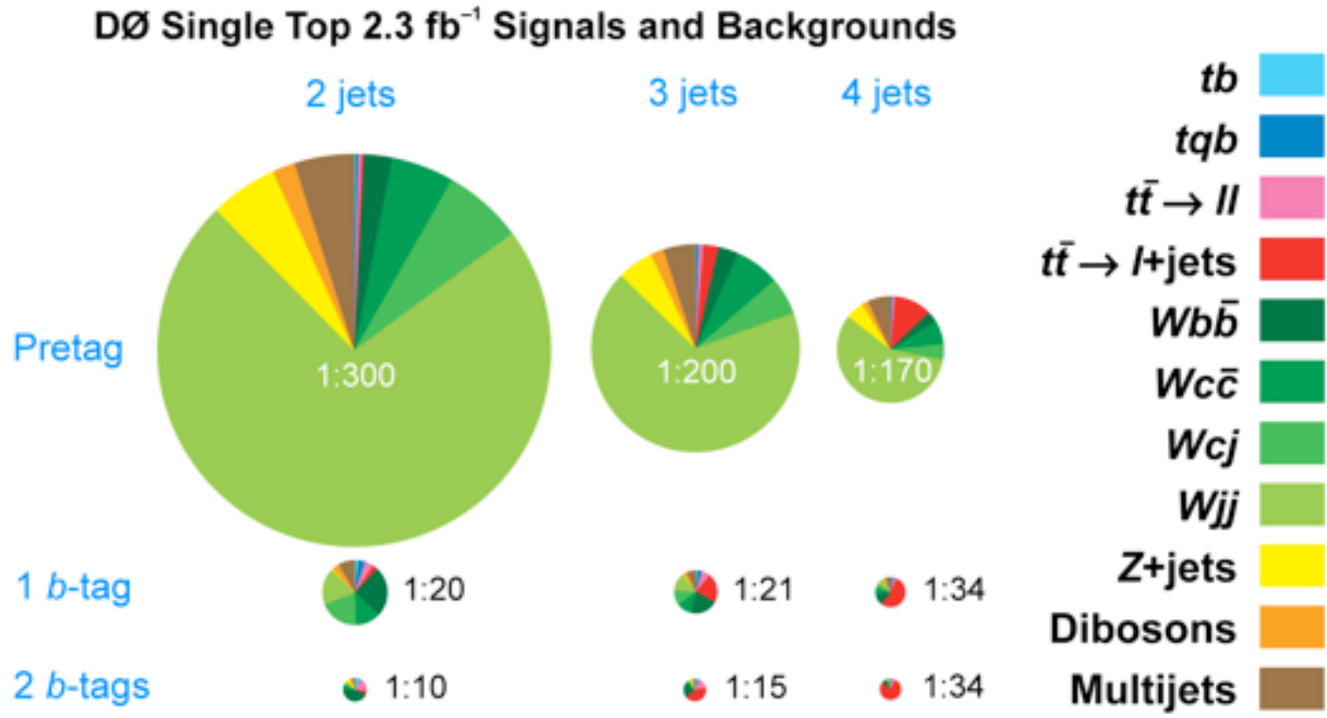






After *b*-tagging Yields

Event Yields in 2.3 fb^{-1} of DØ Data Electron + muon, 1 tag + 2 tags combined			
Source	**2 jets**	**3 jets**	**4 jets**
s-channel *tb*	62 ± 9	24 ± 4	7 ± 2
t-channel *tqb*	77 ± 10	39 ± 6	14 ± 3
$W+b\bar{b}$	678 ± 104	254 ± 39	73 ± 11
$W+c\bar{c}$	303 ± 48	130 ± 21	42 ± 7
$W+cj$	435 ± 27	113 ± 7	24 ± 2
$W+jj$	413 ± 26	140 ± 9	41 ± 3
Z+jets	141 ± 33	54 ± 14	17 ± 5
Dibosons	89 ± 11	32 ± 5	9 ± 2
$t\bar{t} \to \ell\ell$	149 ± 23	105 ± 16	32 ± 6
$t\bar{t} \to \ell$+jets	72 ± 13	331 ± 51	452 ± 66
Multijets	196 ± 50	73 ± 17	30 ± 6
Total prediction	2,615 ± 192	1,294 ± 107	742 ± 80
Data	2,579	1,216	724



Cross Check Samples

- Background dominated regions used to check modeling
- Same selection cuts as the main samples plus:

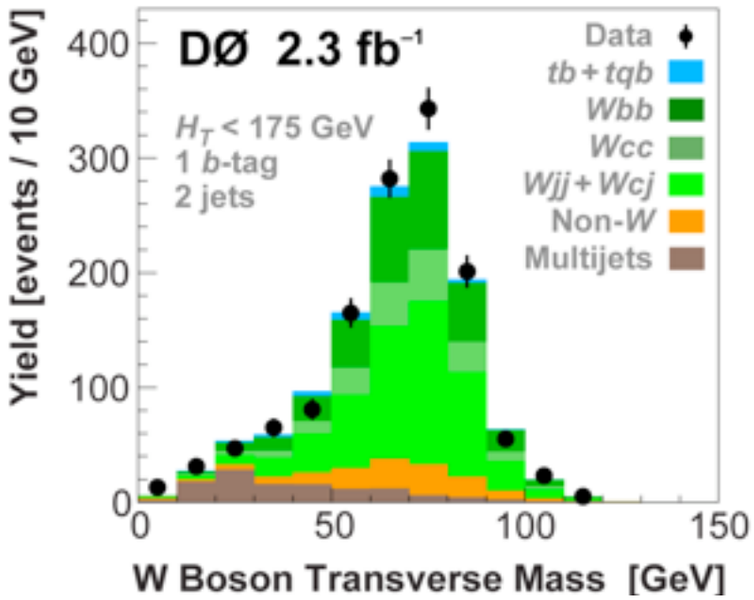
"W+jets" sample

- Exactly two jets
- $H_T(\text{lepton},\not\!\!E_T,\text{alljets}) < 175$ GeV
- One b-tagged jet

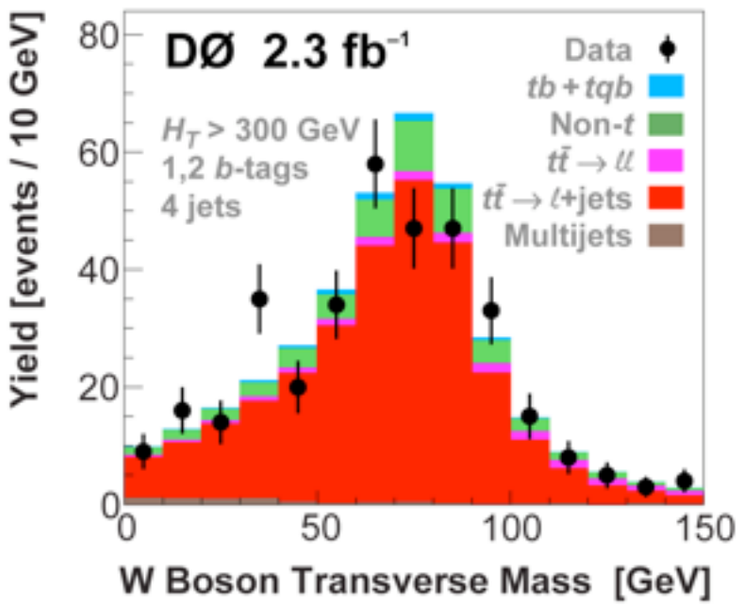
"$t\bar{t}$" sample

- Exactly four jets
- $H_T(\text{lepton},\not\!\!E_T,\text{alljets}) > 300$ GeV
- One or two b-tagged jets

W+Jets Cross-Check Sample



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



Selection of Variables

- Starting from a list of ~ 500 variables, select only well-modeled variables, and those with the highest discriminating power. Resulting in a final list of 64 variables

BDT – Object Kinematics

$p_T(\text{jet2})$
$p_T(\text{jet3})$
$p_T(\text{jet4})$
$p_T(\text{tag1})$
$p_T(\text{light2})$
$p_T(\text{notbest2})$
$p_T(\text{lepton})$
$\not{E}_T$
$Q(\text{lepton})\times\eta(\text{jet1})$
$Q(\text{lepton})\times\eta(\text{jet2})$
$Q(\text{lepton})\times\eta(\text{best})$
$Q(\text{lepton})\times\eta(\text{light1})$
$Q(\text{lepton})\times\eta(\text{light2})$

BDT – Top Quark Reconstruction

$M(W, \text{best1})$ ("best" top mass)
$M(W, \text{tag1})$ ("b-tagged" top mass)
$M(W, \text{tag1}, S2)$ (with 2nd ν solution)
$M(W, \text{jet1})$
$M(W, \text{jet1}, S2)$
$M(W, \text{jet2})$
$M(W, \text{jet2}, S2)$
$M(W, \text{notbest2})$
$M(W, \text{notbest2}, S2)$
$M_{\text{top}}^{\Delta M^{\text{min}}}$
$M_{\text{top}}^{\text{sig}}$
$\Delta M_{\text{top}}^{\text{min}}$
$\text{Significance}_{\text{min}}(M_{\text{top}})$

BDT – Angular Correlations

$\Delta R(\text{jet1,jet2})$
$\Delta R(\text{jet1,lepton})$
$\Delta R(\text{tag1,lepton})$
$\Delta R(\text{light1,lepton})$
$\Delta\phi(\text{lepton},\not{E}_T)$
$\cos(\text{best,lepton})_{\text{besttop}}$
$\cos(\text{best,notbest})_{\text{besttop}}$
$\cos(\text{jet1,lepton})_{\text{btaggedtop}}$
$\cos(\text{tag1,lepton})_{\text{btaggedtop}}$
$\cos(\text{lepton}_{\text{besttop}},\text{besttop}_{\text{CMframe}})$
$\cos(\text{lepton}_{\text{btaggedtop}},\text{btaggedtop}_{\text{CMframe}})$
$\cos(\text{tag1,lepton})_{\text{btaggedtop}}$
$\cos(\text{lepton},Q(\text{lepton})\times z)_{\text{besttop}}$

BDT – Jet Reconstruction

$\text{Width}_\eta(\text{jet2})$
$\text{Width}_\eta(\text{jet4})$
$\text{Width}_\phi(\text{jet4})$
$\text{Width}_\eta(\text{tag1})$
$\text{Width}_\eta(\text{light2})$
$\text{Width}_\phi(\text{light2})$

BDT – Event Kinematics

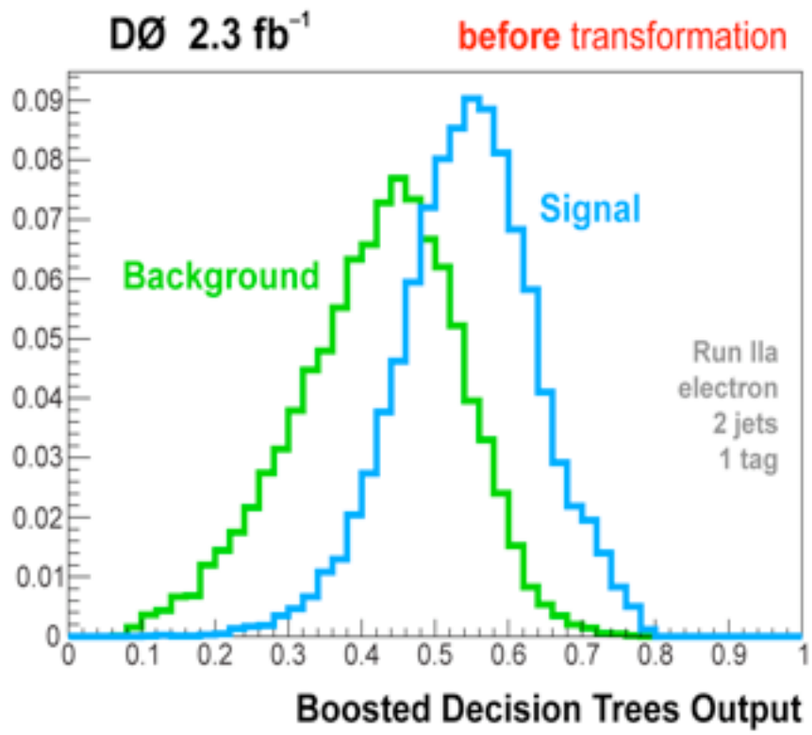
$\text{Centrality}(\text{alljets})$
$H_T(\text{alljets})$
$H_T(\text{alljets}-\text{tag1})$
$H_T(\text{alljets}-\text{best})$
$H_T(\text{jet1,jet2})$
$H_T(\text{jet1,jet2,lepton},\not{E}_T)$
$H_T(\text{alljets,lepton},\not{E}_T)$
$H_T(\not{E}_T,\text{lepton})$
$H(\text{alljets}-\text{tag1})$
$M(\text{alljets})$
$M(\text{alljets}-\text{best})$
$M(\text{alljets}-\text{tag1})$
$M(\text{jet1,jet2})$
$M(\text{jet1,jet2},W)$
$M(\text{jet3,jet4})$
$M_T(\text{jet1,jet2})$
$p_T(\text{jet1,jet2})$
$\sqrt{\hat{s}}$
$M_T(W)$

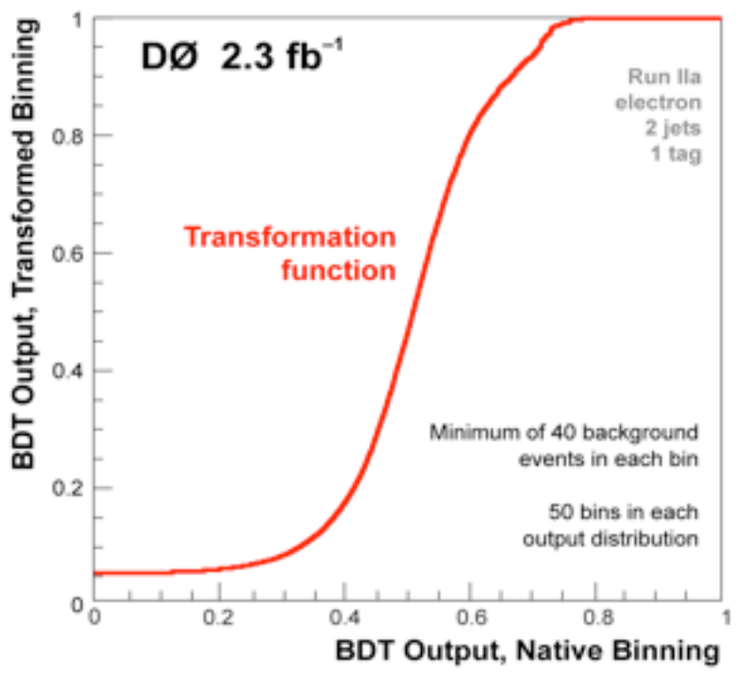
BDT More Powerful Variables

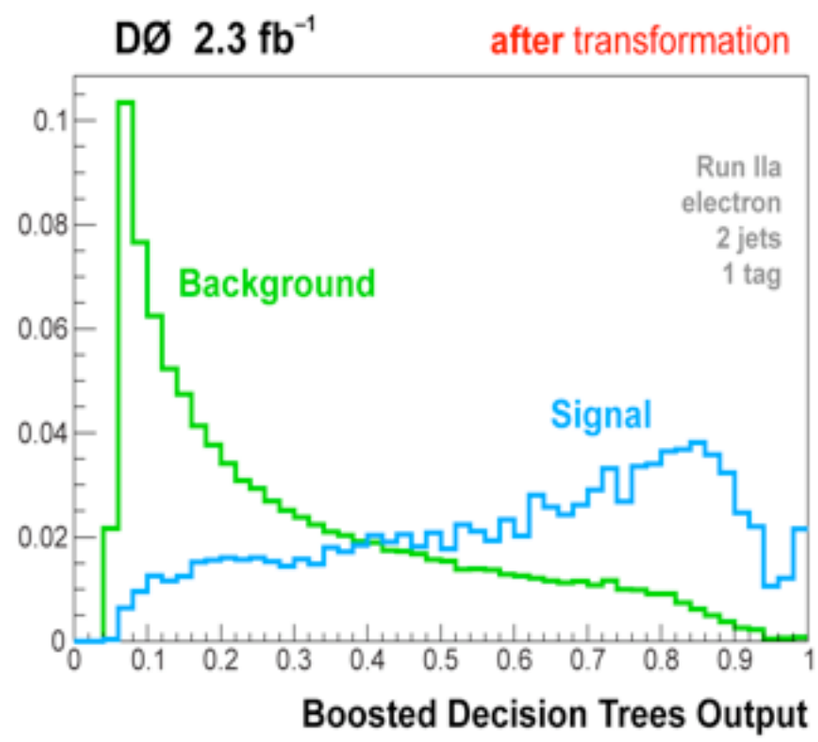
Best Variables to Separate Single Top from W+Jets DØ 2.3 fb^{-1} Analysis	
Object kinematics	$\not\!\!E_T$
	p_T(jet2)
	p_T^{rel}(jet1,tag-μ)
	E(light1)
Event kinematics	M(jet1,jet2)
	M_T(W)
	H_T(lepton,$\not\!\!E_T$,jet1,jet2)
	H_T(jet1,jet2)
	H_T(lepton,$\not\!\!E_T$)
Jet reconstruction	Width$_\phi$(jet2)
	Width$_\eta$(jet2)
Top quark reconstruction	M_{top}(W,tag1)
	ΔM_{top}^{min}
	M_{top}(W,tag1,S2)
Angular correlations	cos(light1,lepton)$_{btaggedtop}$
	$\Delta\phi$(lepton,$\not\!\!E_T$)
	Q(lepton) x η(light1)

Best Variables to Separate Single Top from Top Pairs DØ 2.3 fb^{-1} Analysis	
Object kinematics	pT(notbest2)
	pT(jet4)
	pT(light2)
Event kinematics	M(alljets–tag1)
	Centrality(alljets)
	M(alljets–best1)
	H_T(alljets–tag1)
	H_T(lepton,$\not\!\!E_T$,alljets)
	M(alljets)
Jet reconstruction	Width$_\eta$(jet4)
	Width$_\phi$(jet4)
	Width$_\phi$(jet2)
Angular correlations	cos(lepton$_{btaggedtop}$, btaggedtop$_{CMframe}$)
	Q(lepton) x η(light1)
	ΔR(jet1,jet2)

Discriminant Output Transf

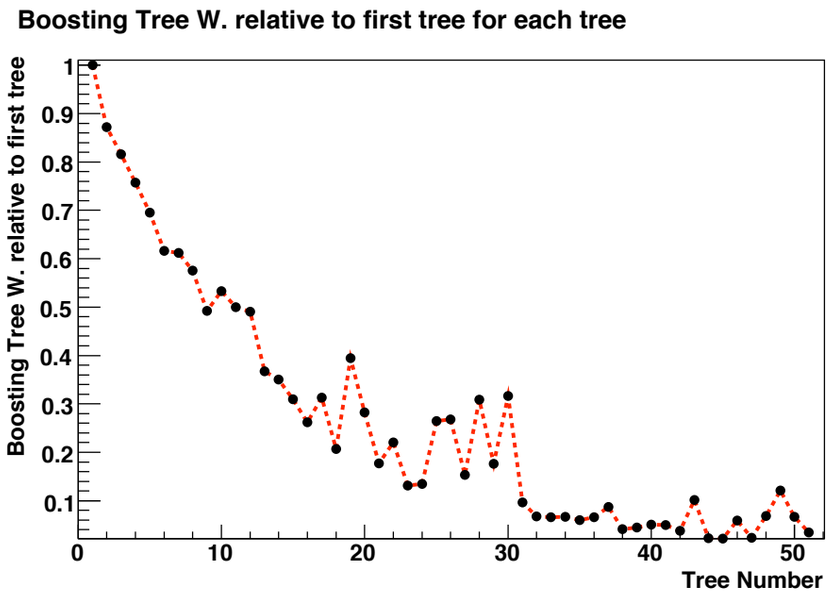


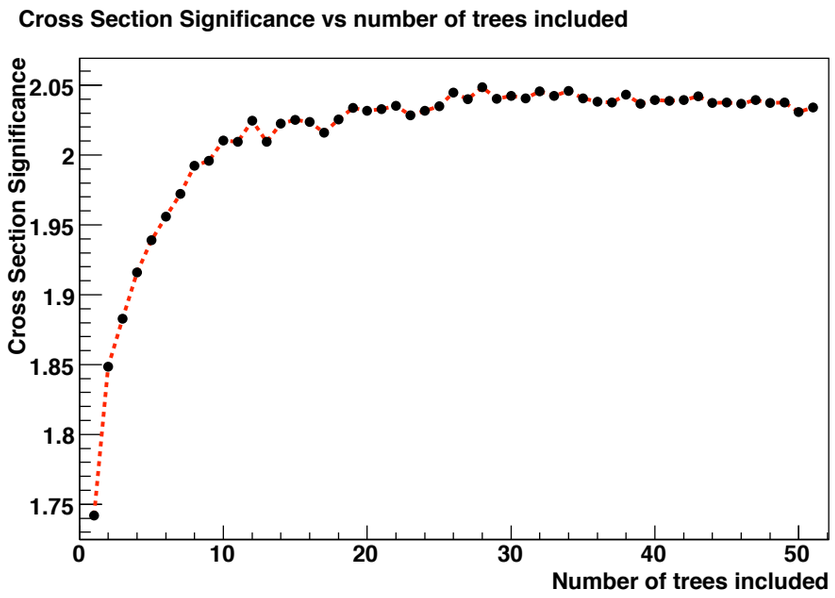


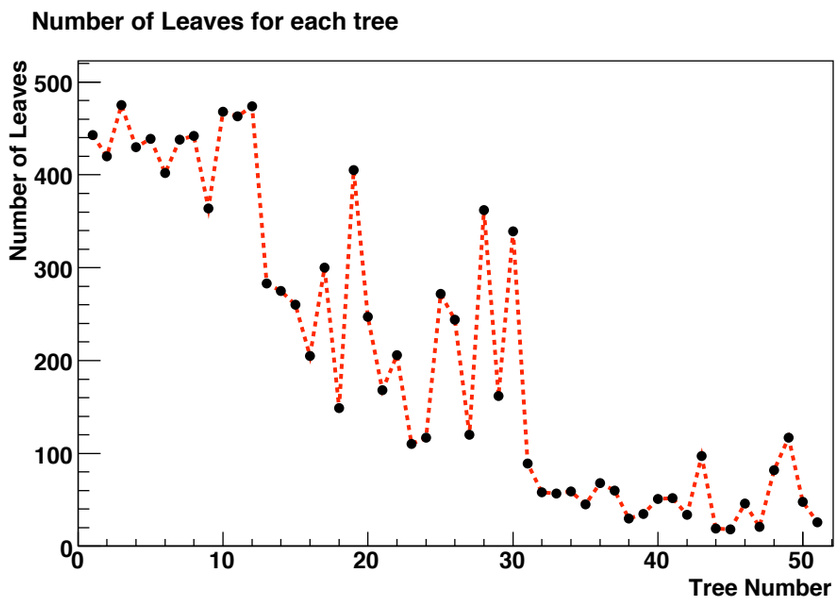


- Purpose: Ensure there are no undefined regions on the output discriminant
- At least, 40 background events are present on each bin

BDT Performance

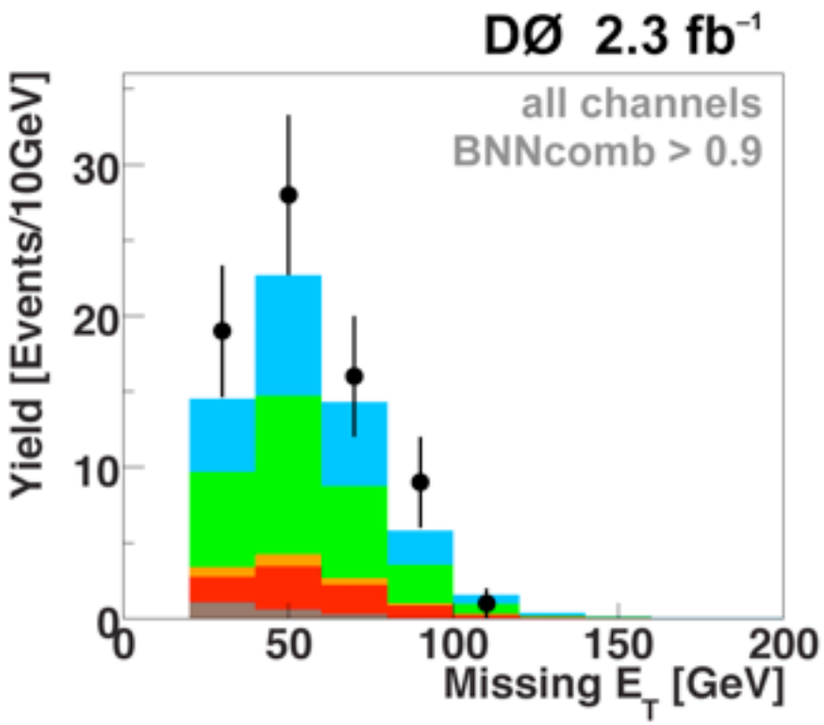


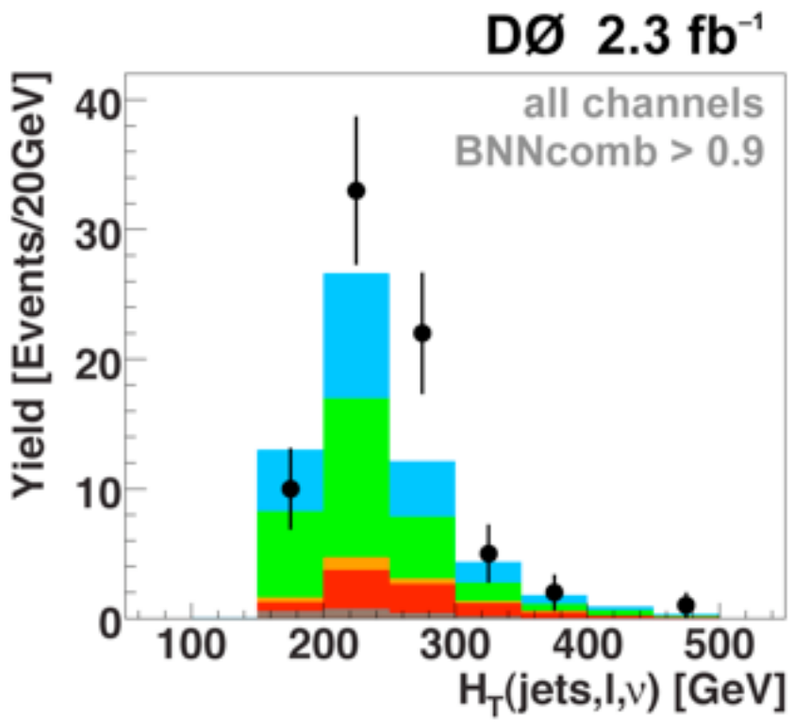


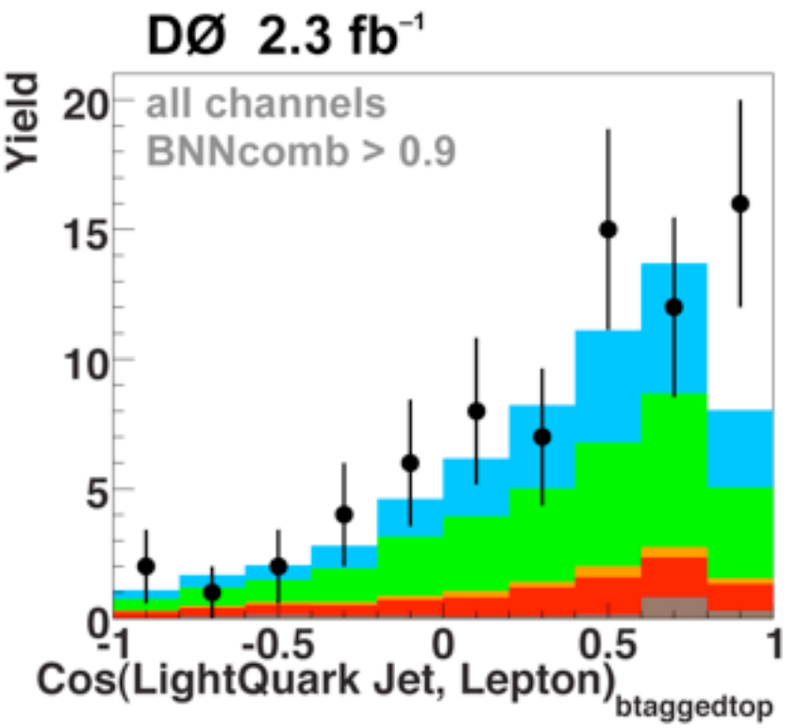


High Discriminant Region

- Data / Monte Carlo agreement holds in the high discriminant region







Systematics

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%

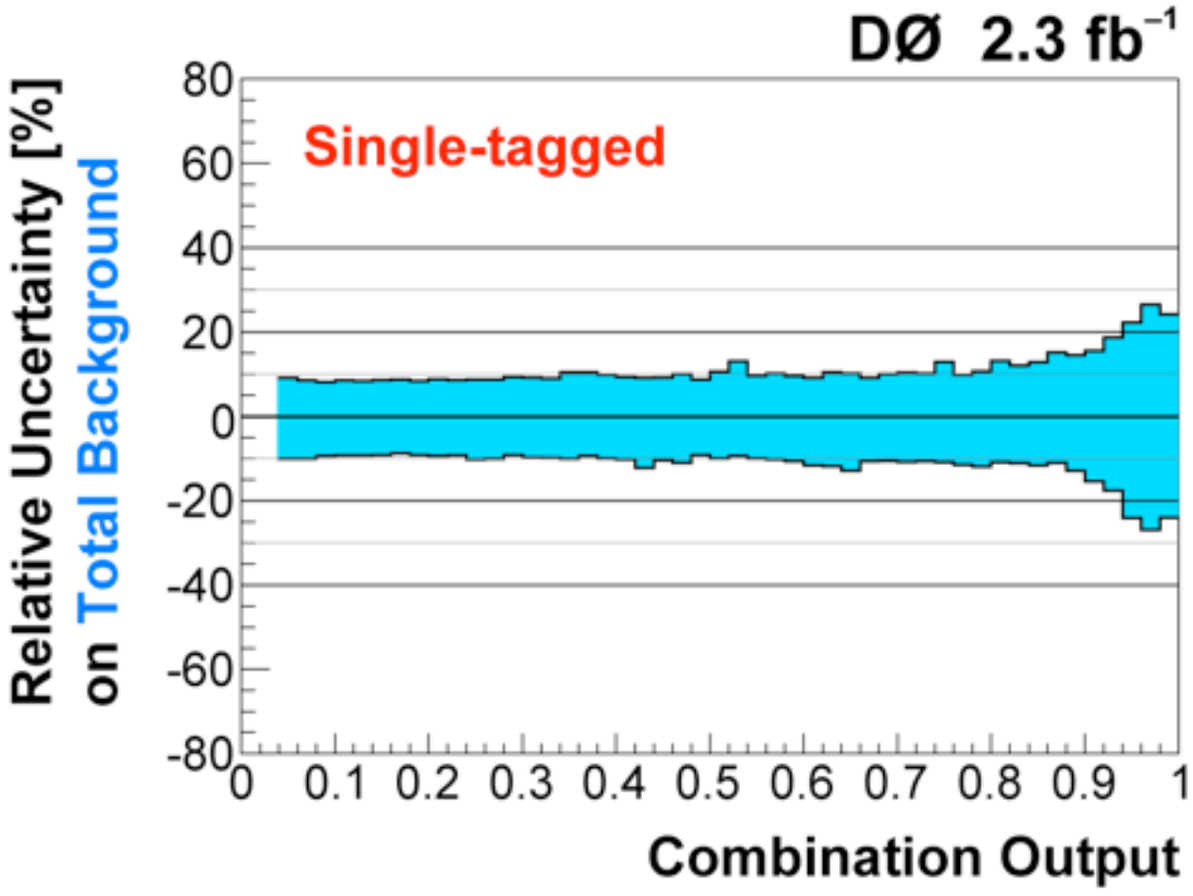
Systematic Uncertainties

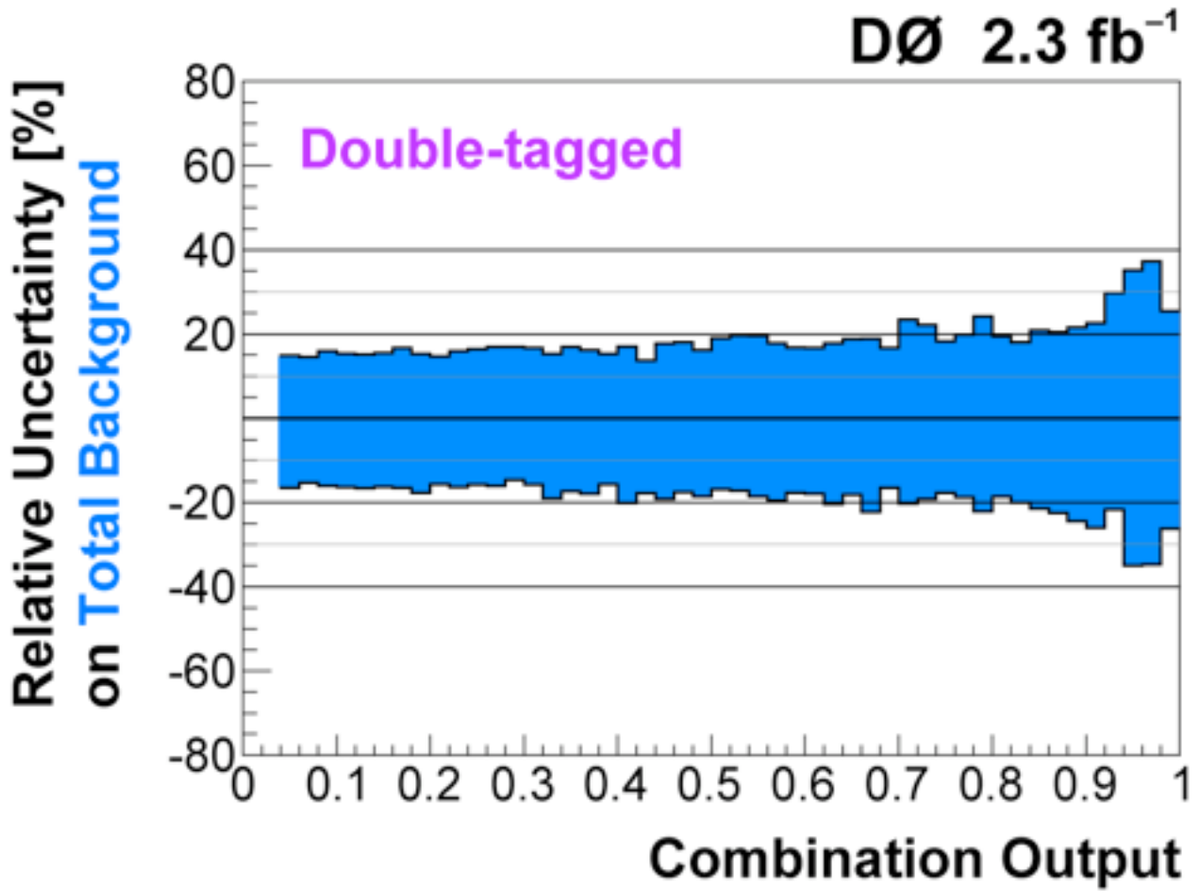
Ranked from Largest to Smallest Effect on Single Top Cross Section

DØ 2.3 fb^{-1}

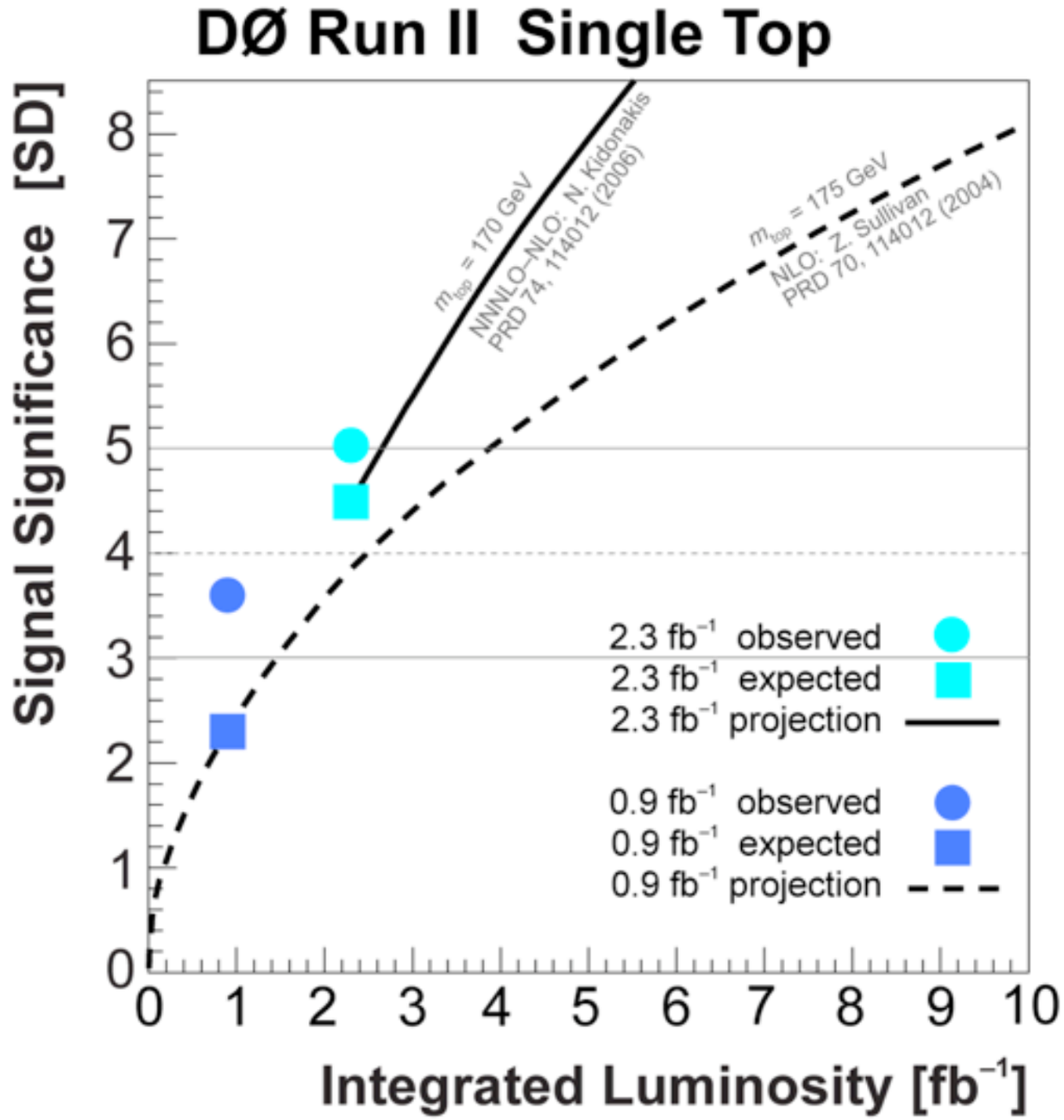
Smaller terms	
Monte Carlo statistics	(0.5–16.0)%
Jet fragmentation	(0.7–4.0)%
Branching fractions	1.5%
Z+jets heavy-flavor correction	13.7%
Jet reconstruction and identification	1.0%
Instantaneous luminosity correction	1.0%
Parton distribution functions (signal)	3.0%
Z+jets theory cross sections	5.8%
W+jets and multijets normalization to data	(1.8–3.9)% (*W*+jets) (30–54)% (multijets)
Diboson theory cross sections	5.8%
Alpgen *W*+jets shape corrections	shape only
Trigger	5%

Relative Uncertainties





Single Top Significance Projection



D0 and CDF Results

Single Top Cross Section	Signal Significance		CKM Matrix Element V_{tb}
	Expected	Observed	
March 2009	**DØ (2.3 fb^{-1})**	arXiv:0903.0850 (m_{top} = 170 GeV)	
3.94 ± 0.88 pb	4.5 σ	5.0 σ	$\left\|V_{tb}f_1^L\right\| = 1.07 \pm 0.12$ $\left\|V_{tb}\right\| > 0.78$ at 95% CL
March 2009	**CDF (3.2 fb^{-1})**	arXiv:0903.0885 (m_{top} = 175 GeV)	
$2.3\ ^{+0.6}_{-0.5}$ pb	>5.9 σ	5.0 σ	$\left\|V_{tb}f_1^L\right\| = 0.91 \pm 0.13$ $\left\|V_{tb}\right\| > 0.71$ at 95% CL

Matrix Element

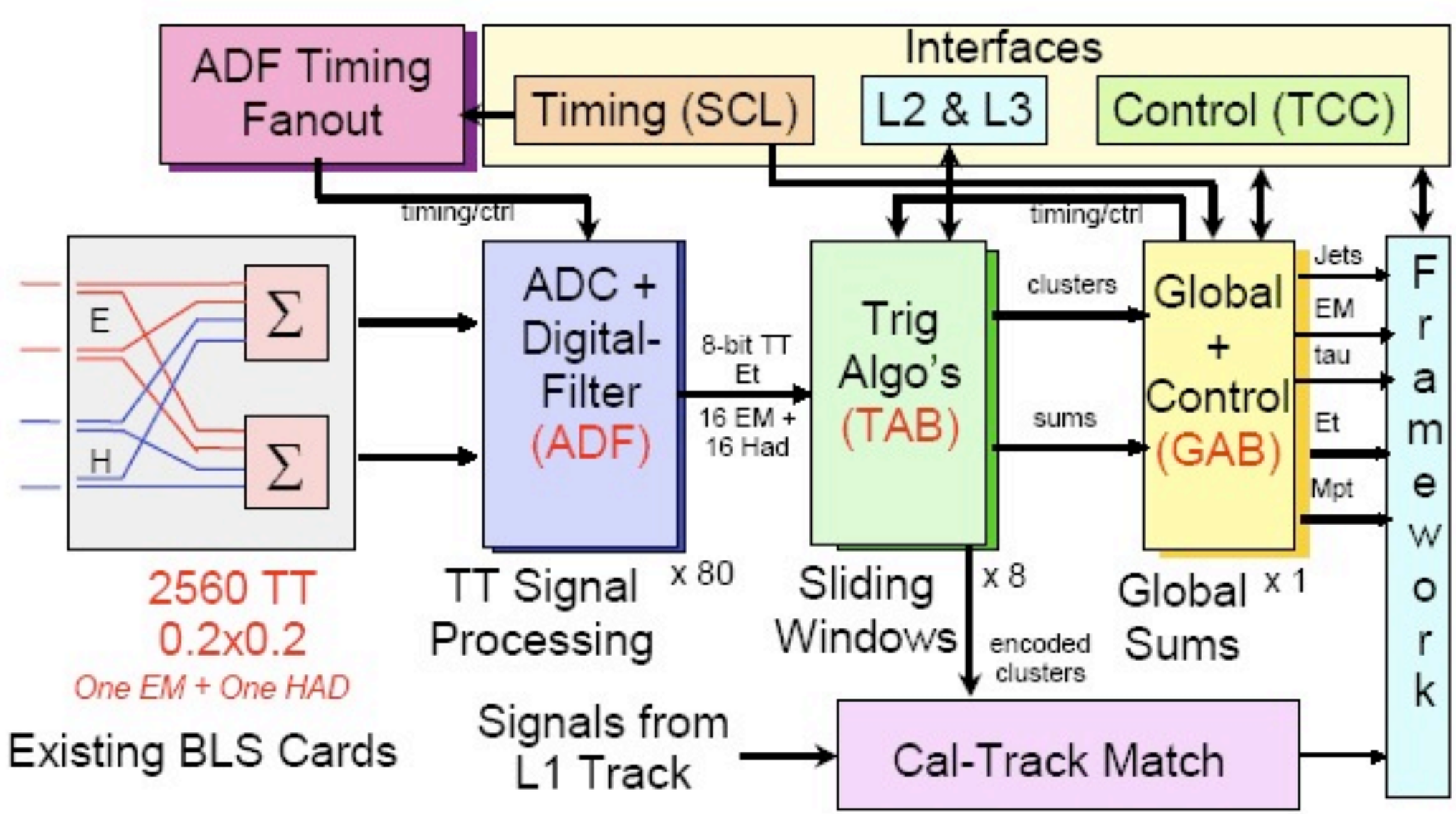
- Pioneered by DØ top mass analysis. Now used in search
- Use the 4-vectors of all reconstructed leptons and jets
- Use matrix elements of main signal and bkgd diagrams to compute event probability density for signal and bkgd hypotheses
- Goal: calculate a discriminant:

$$D_s(\vec{x}) = P(S|\vec{x}) = \frac{P_{signal}(\vec{x})}{P_{signal}(\vec{x}) + P_{bkg}(\vec{x})}$$

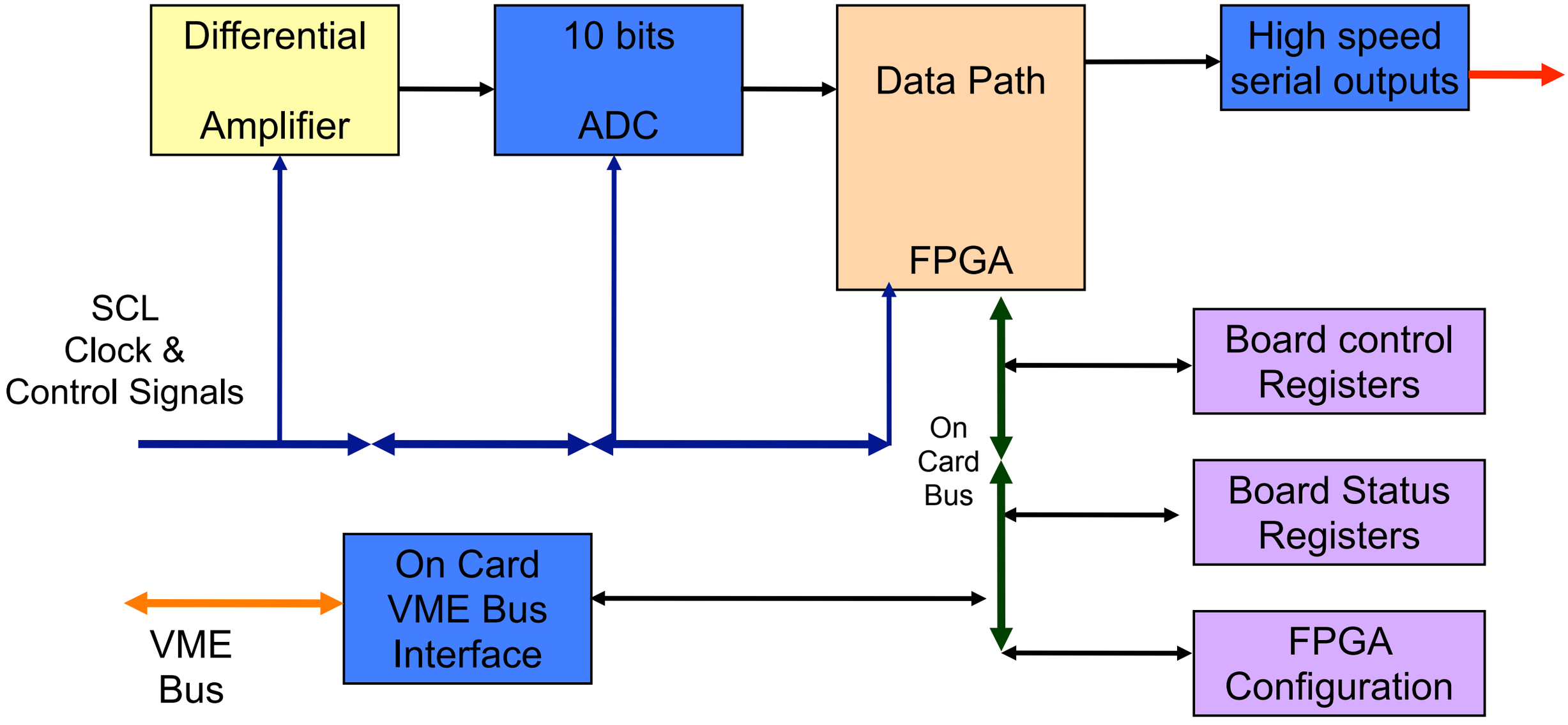
- Encoded in properly normalized differential cross section for process S:

$$P_S(\vec{x}) = \frac{1}{\sigma_S} d\sigma_S(\vec{x}), \quad \sigma_S = \int d\sigma_S(\vec{x})$$

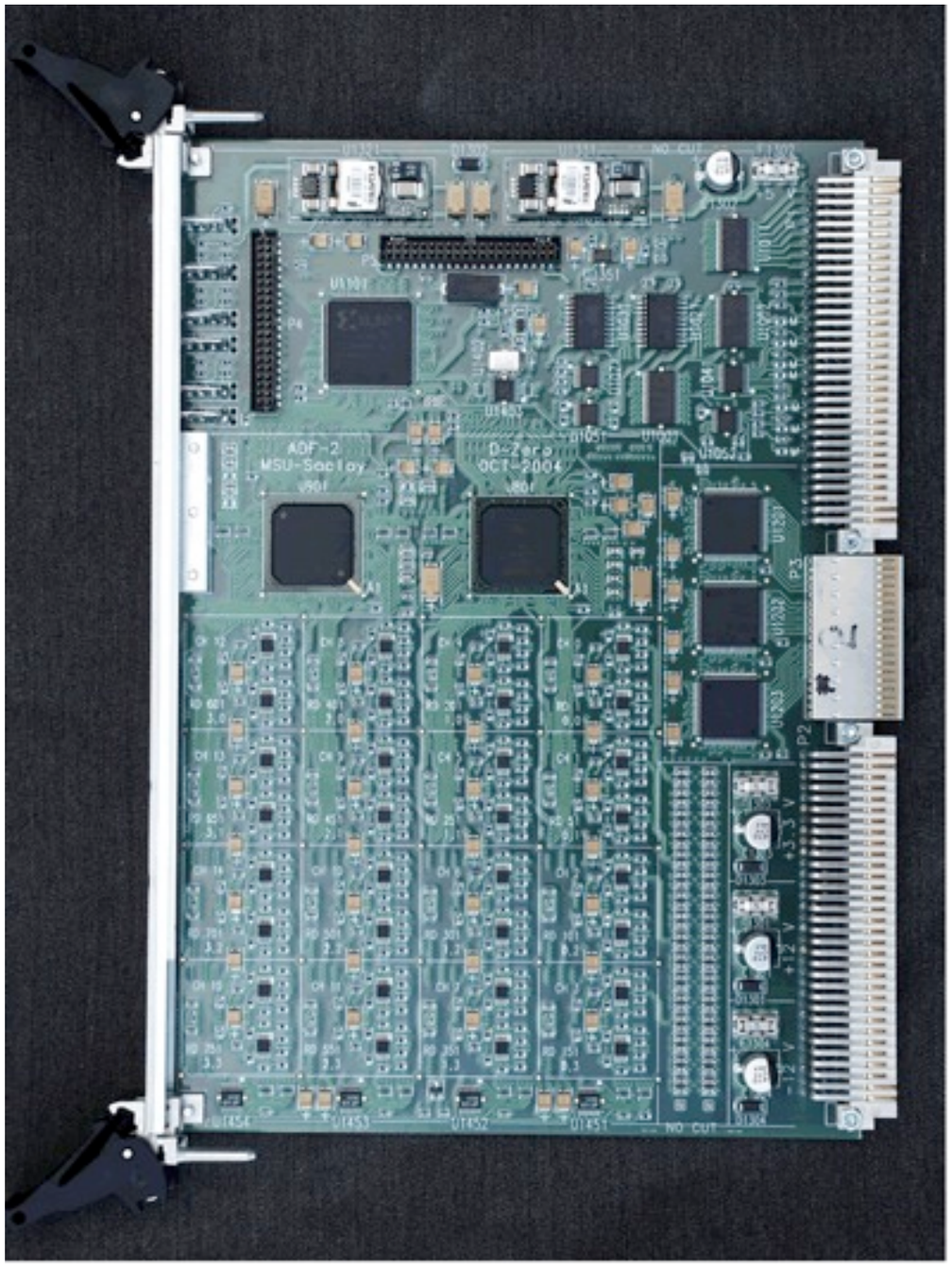
Level 1 Cal Trigger Upgrade

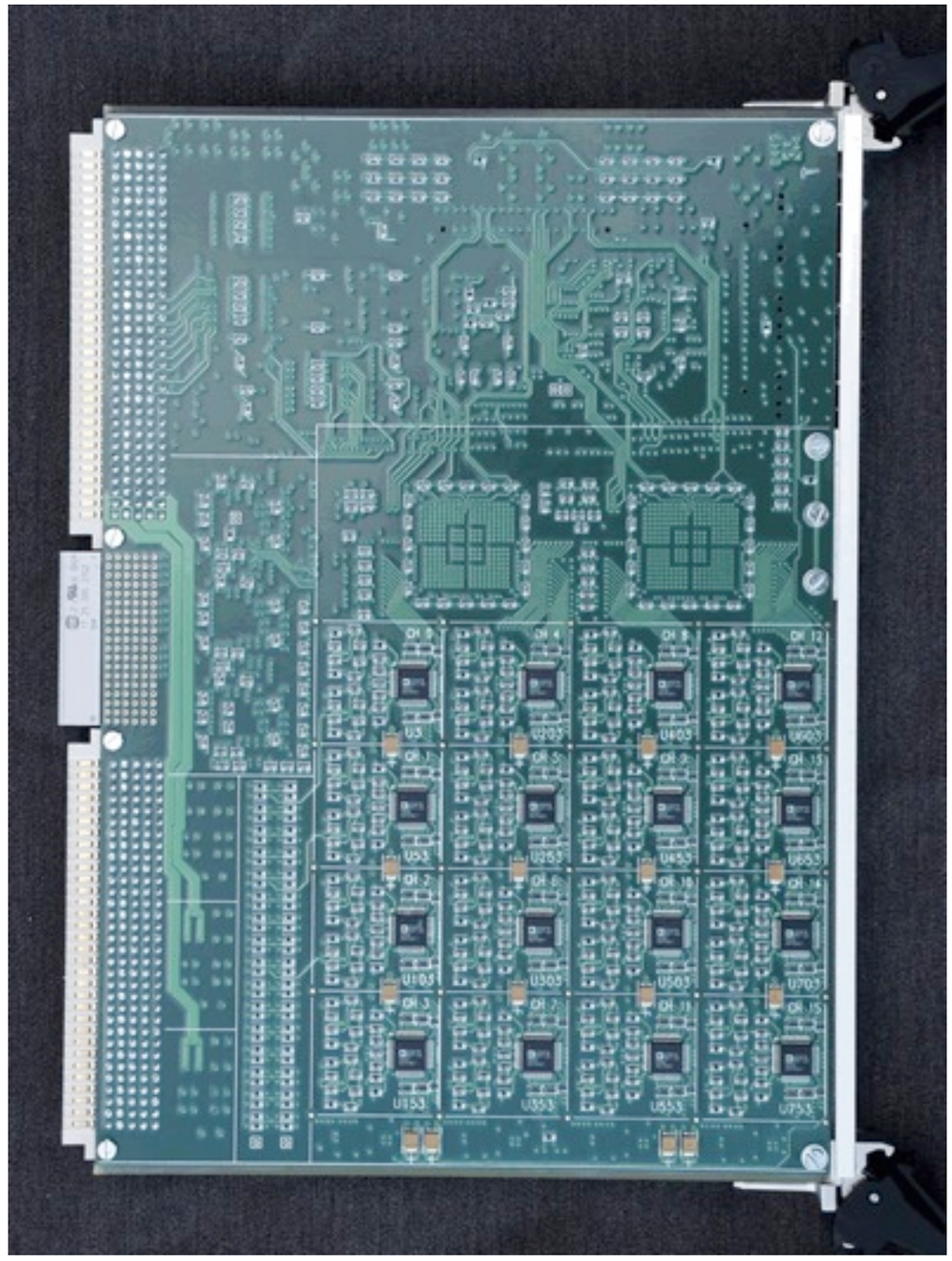


ADF Block Diagram



ADF in Pictures…





Test Waveform Generator System