

# Top Quark Measurements at the Tevatron



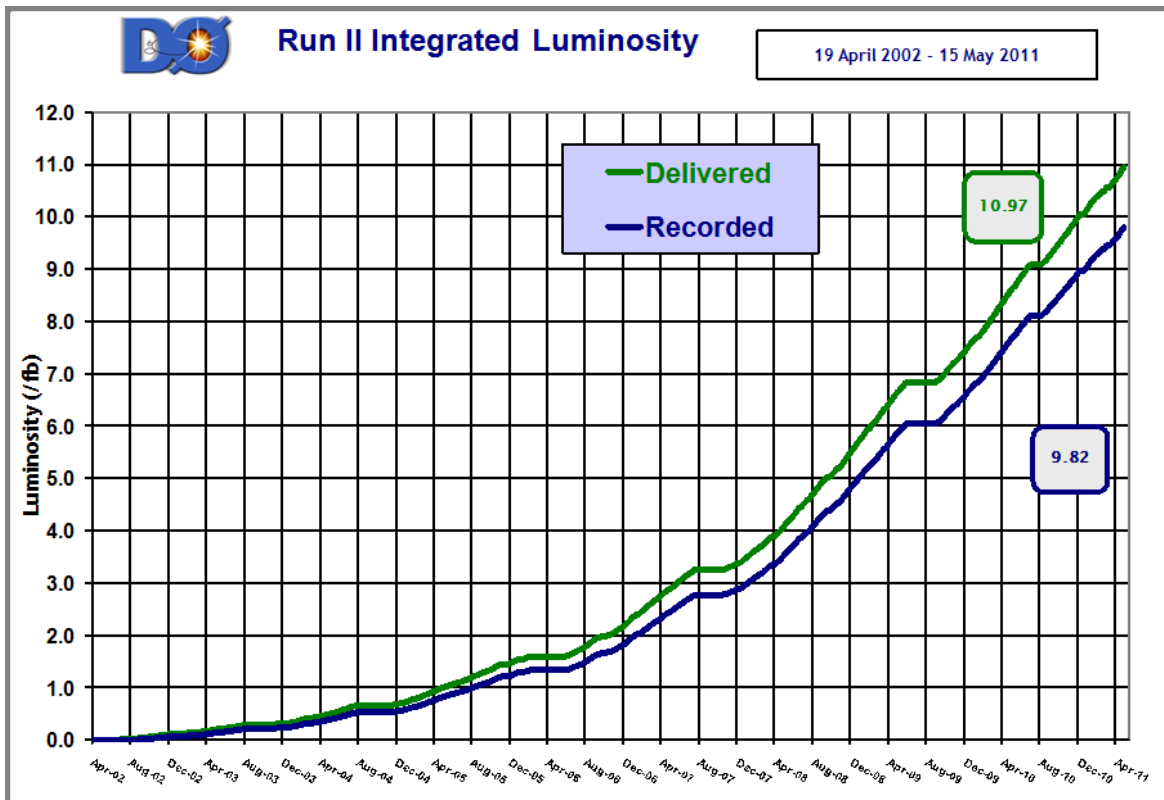
Science & Technology  
Facilities Council

Yvonne Peters

MANCHESTER  
1824

University of Manchester & Fermilab

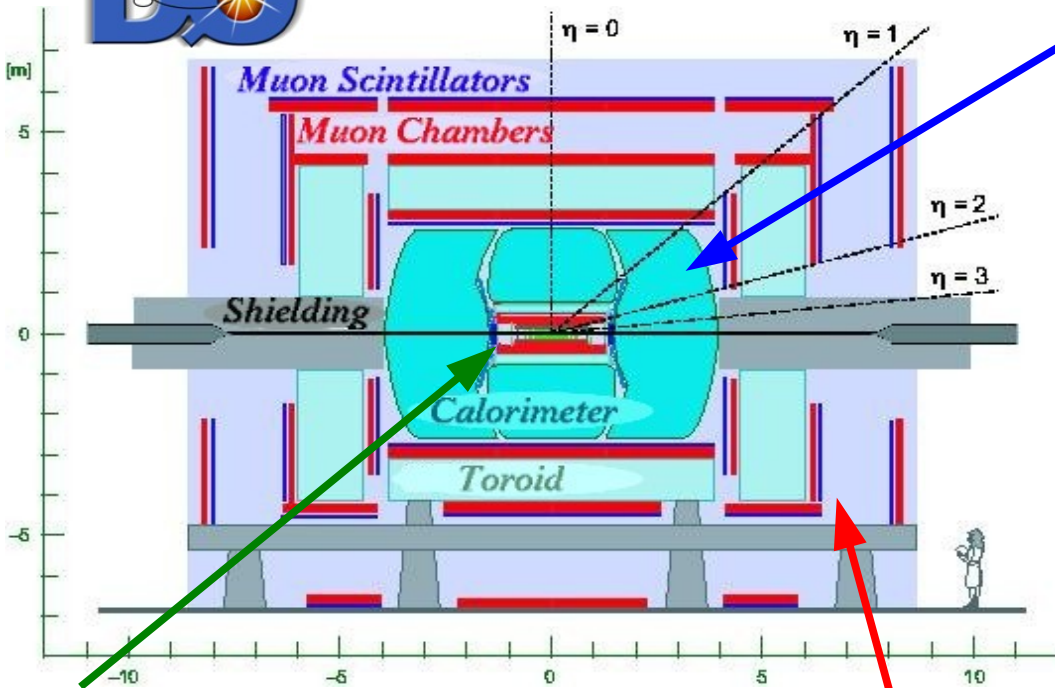
# The Tevatron



$\sim 11\text{fb}^{-1}$  delivered  
 $> 9\text{fb}^{-1}$  on disk per experiment



# The CDF & DØ Detectors



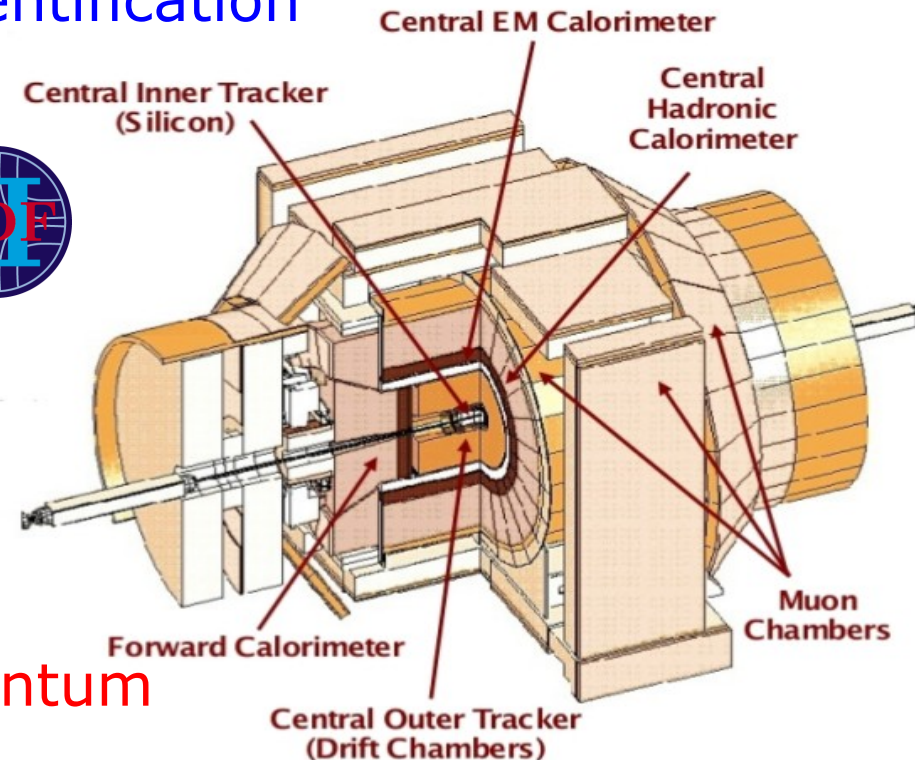
## Calorimeter:

Identification and energy measurement of jets and electrons;  
tau identification

**Tracker:** Detection and momentum measurement for charged particles

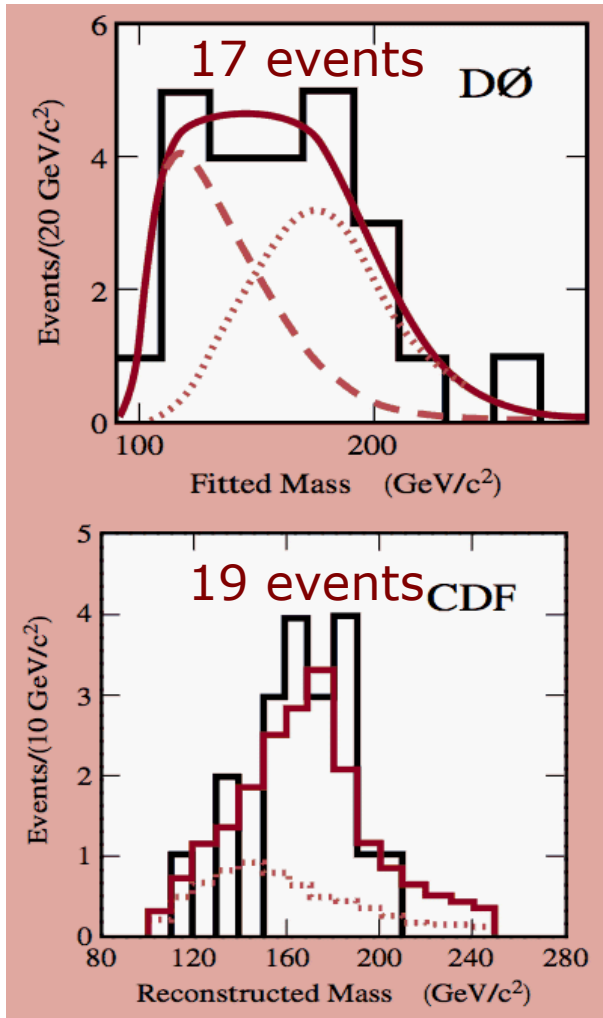
## Muon chamber:

Identification and momentum measurement of muons



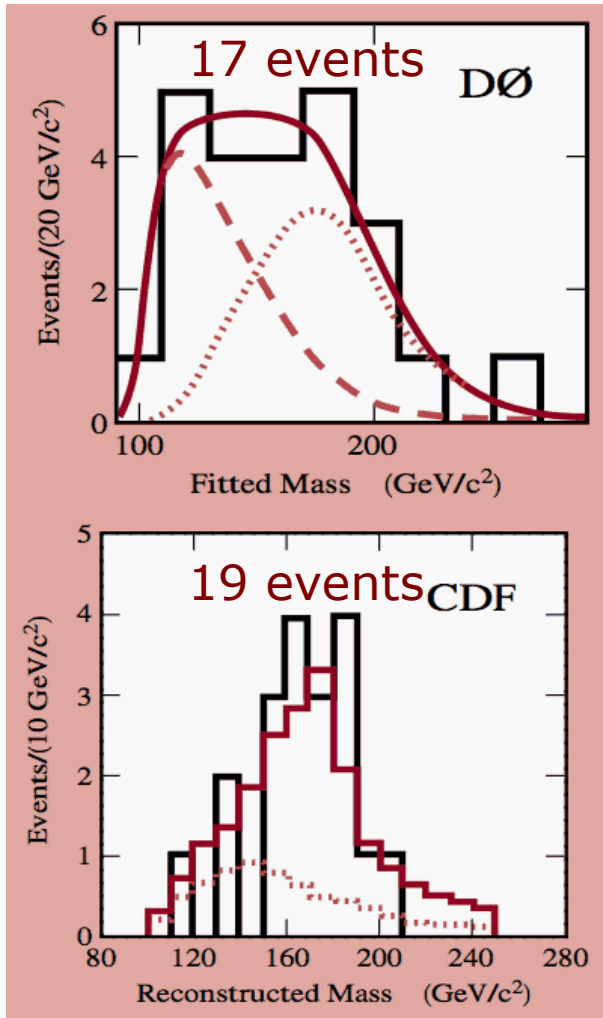
# Top: The Tevatron Particle

Discovered in 1995 by CDF and DØ at Fermilab (with few events)



# Top: The Tevatron Particle

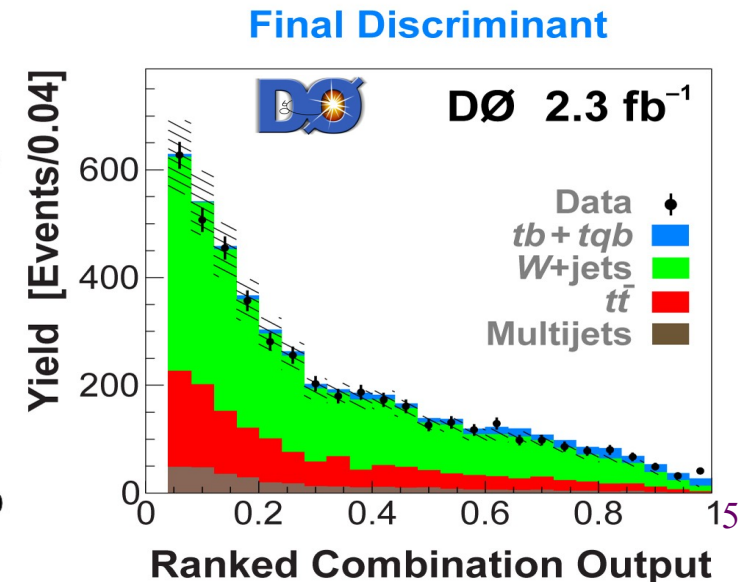
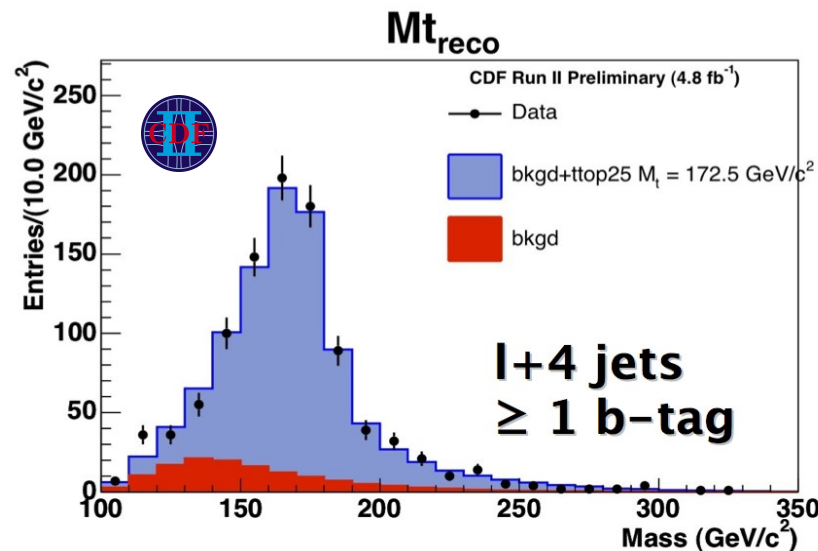
Discovered in 1995 by CDF and DØ at Fermilab (with few events)



Situation today:

1000s of events!

Rediscovered in 2009 in single top production



Since 2010 LHC operating → top quark factory

# All we study about the Top

Top mass  
Top mass difference  
Top charge  
Lifetime  
Top width

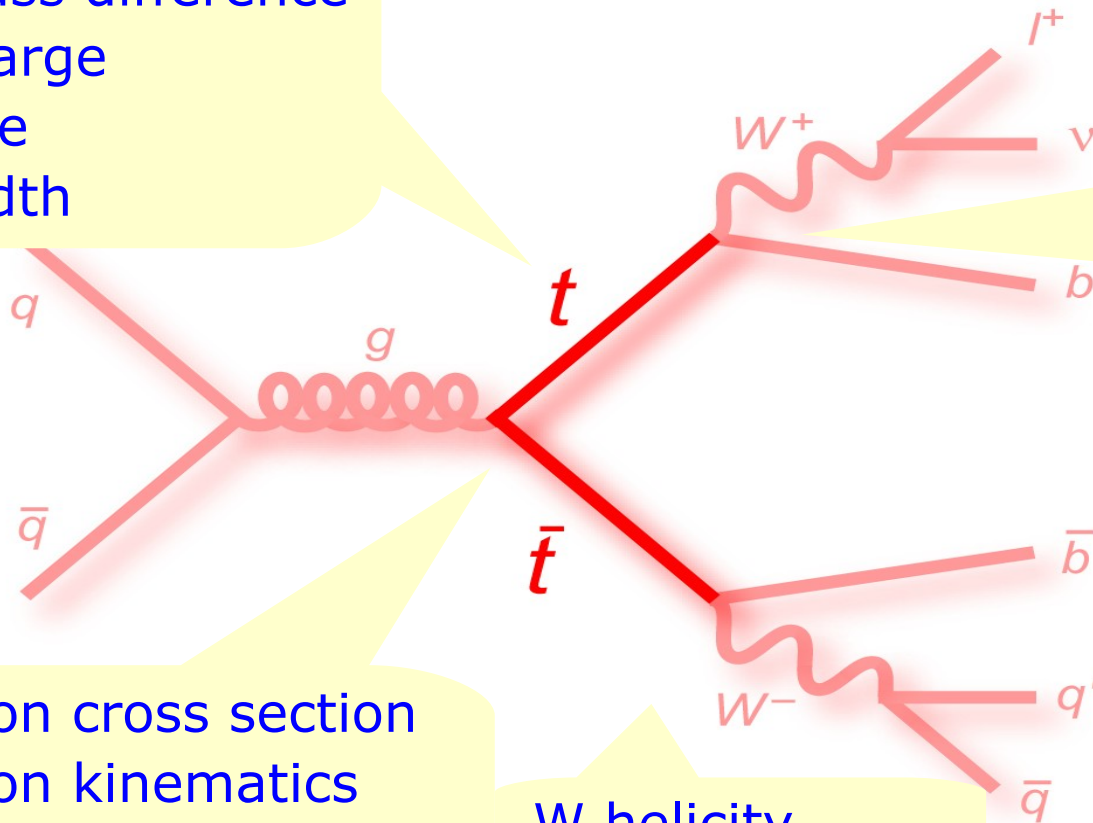
Branching ratios  
 $|V_{tb}|$   
Anomalous coupling  
New/Rare decays

Production cross section  
Production kinematics  
Production via resonance  
New particles

W helicity

Spin correlation  
Charge asymmetry  
Color Flow

s- & t- channel production,  
properties and searches in  
single top events



# What the Tevatron did for us

**Tevatron Legacy!**

Top mass  
Top mass difference  
Top charge  
Lifetime  
Top width

**Tevatron Legacy!**

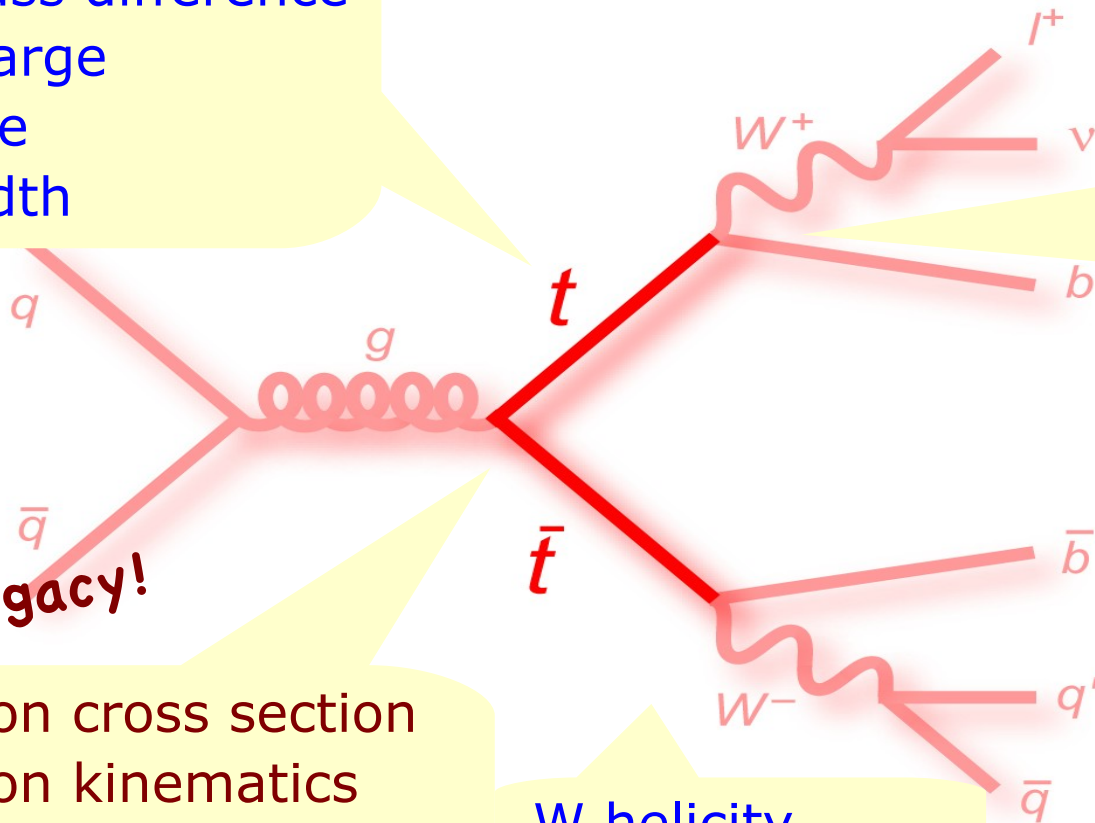
Production cross section  
Production kinematics  
Production via resonance  
New particles

W helicity

Branching ratios  
 $|V_{tb}|$   
Anomalous coupling  
New/Rare decays

Spin correlation  
Charge asymmetry  
Color Flow

s- & t- channel production,  
properties and searches in  
single top events



# What the Tevatron did for us

**Tevatron Legacy!**

Top mass  
Top mass difference  
Top charge  
Lifetime  
Top width

**Tevatron Legacy!**

Production cross section  
Production kinematics  
Production via resonance  
New particles

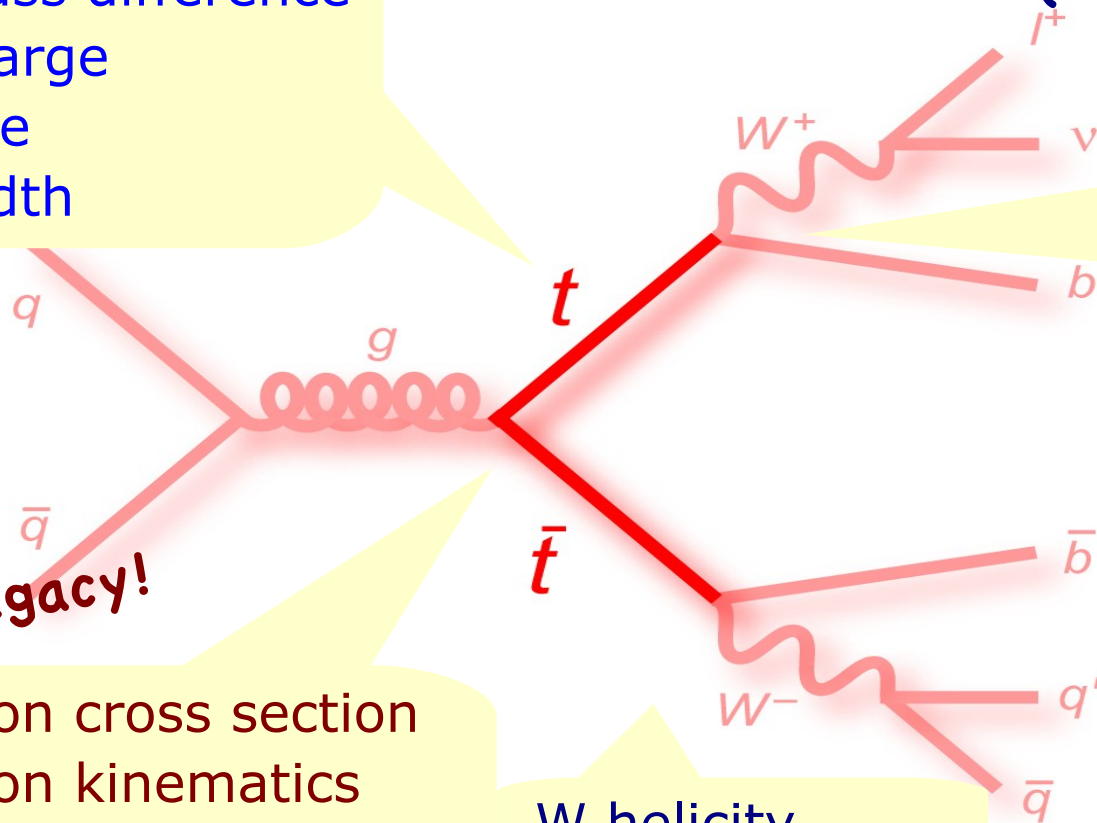
**(Still) competitive to LHC!**

**(Still) competitive to LHC!**

Branching ratios  
 $|V_{tb}|$   
Anomalous coupling  
New/Rare decays

Spin correlation  
Charge asymmetry  
Color Flow

**(Still) competitive to LHC!**  
s- & t- channel production, properties and searches in single top events



# What the Tevatron did for us

**Tevatron Legacy!**

Top mass  
Top mass difference  
Top charge  
Lifetime  
Top width

**Tevatron Legacy!**

Production cross section  
Production kinematics  
Production via resonance  
New particles

**(Still) competitive to LHC!**

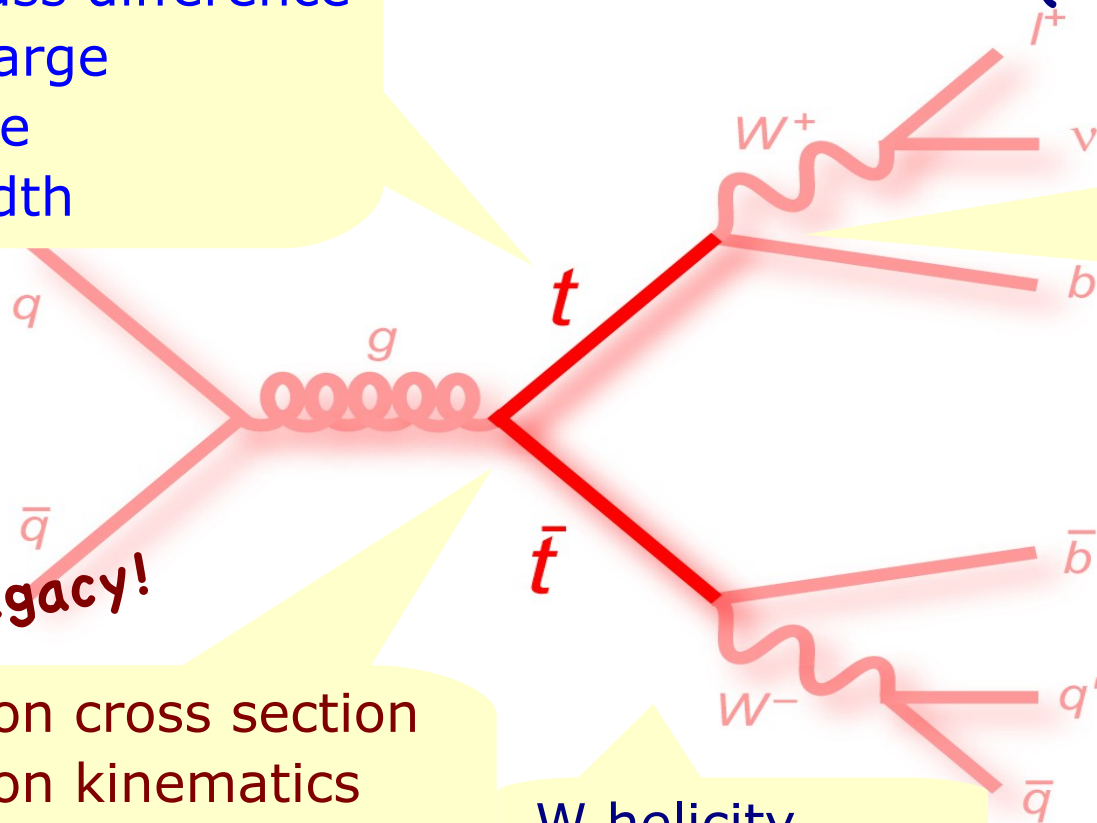
**(Still) competitive to LHC!**

Branching ratios  
 $|V_{tb}|$   
Anomalous coupling  
New/Rare decays

**Complementary to LHC!**

Spin correlation  
Charge asymmetry  
Color Flow

**(Still) competitive to LHC!**  
s- & t- channel production, properties and searches in single top events



# What the Tevatron did for us

**Tevatron Legacy!**

Top mass  
Top mass difference  
Top charge  
Lifetime  
Top width

**(Still) competitive to LHC!**

Branching ratios

$|V_{tb}|$

anomalous coupling

$W$ /Rare decays

**Not to forget:**

**New ideas**

**Sensitive, new methods**

→ All developed during almost  
20 years of top quark physics at the  
Tevatron!

**complementary to LHC!**

spin correlation

charge asymmetry

Color Flow

**Tevatron Legacy**

Production cross section  
Production kinematics  
Production via resonance  
New particles

W helicity

**(Still) competitive to LHC!**

s- & t- channel production,  
properties and searches in  
single top events

# Outline

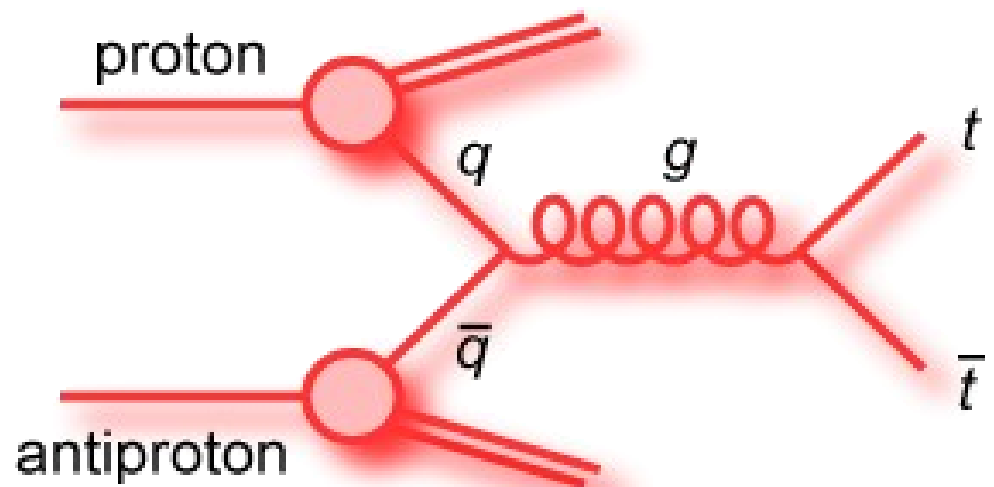
---

Part I: Production

Part II: Properties

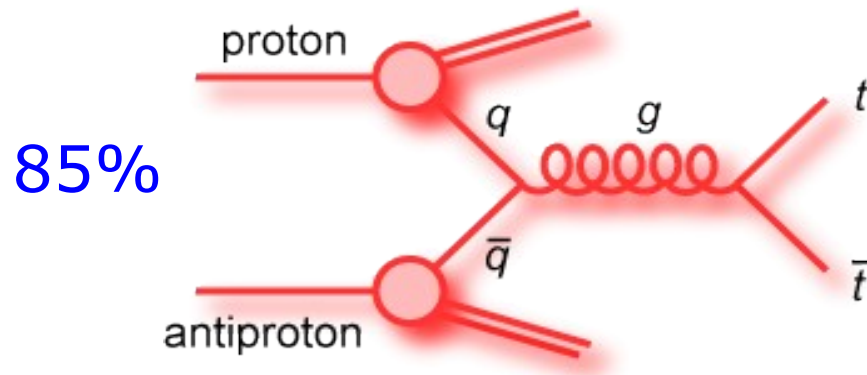
# Part I: Production

- $t\bar{t}$  production
- Differential cross section
- Single top production

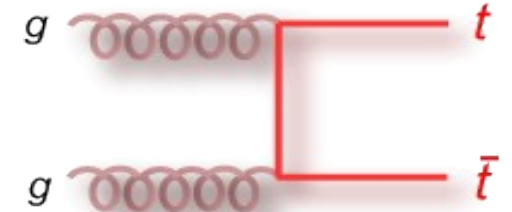


# Top Quark Pair Production

- Via strong interaction
- At the Tevatron:



+ 15%



+ 90%

+ 70%

At LHC:

14 TeV: 10%

7 TeV: 30%

- Production cross section (@Tevatron):

approximate NNLO:  $\sigma = 7.46^{+0.48}_{-0.67} pb$  @  $m_t = 172.5 GeV$

Moch, Uwer, PRD 78, 034003 (2008)

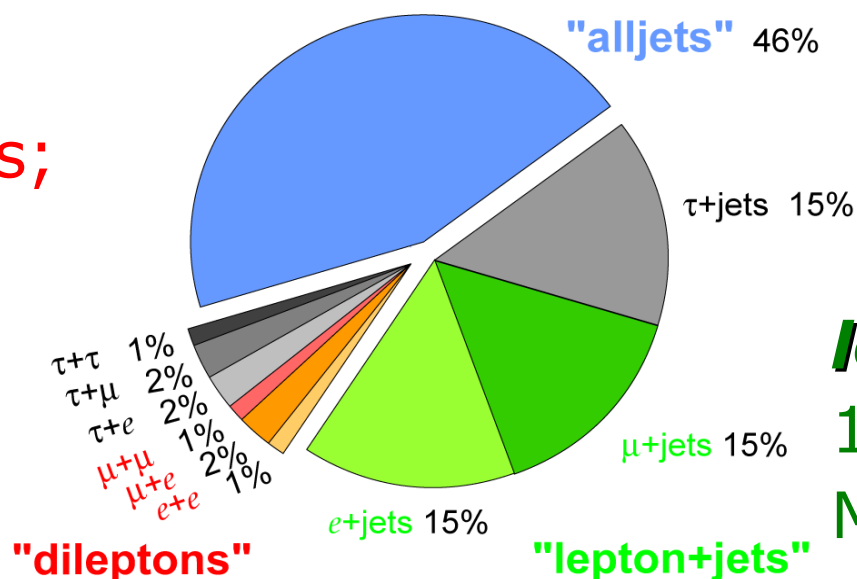
# Final States in $t\bar{t}$

$t\bar{t} \rightarrow W^+ b W^- \bar{b}$  : Final states are classified according to W decay

$$B(t \rightarrow W^+ b) = 100\%$$

pure hadronic:  
 $\geq 6$  jets (2 b-jets)

Top Pair Branching Fractions



**dilepton:**

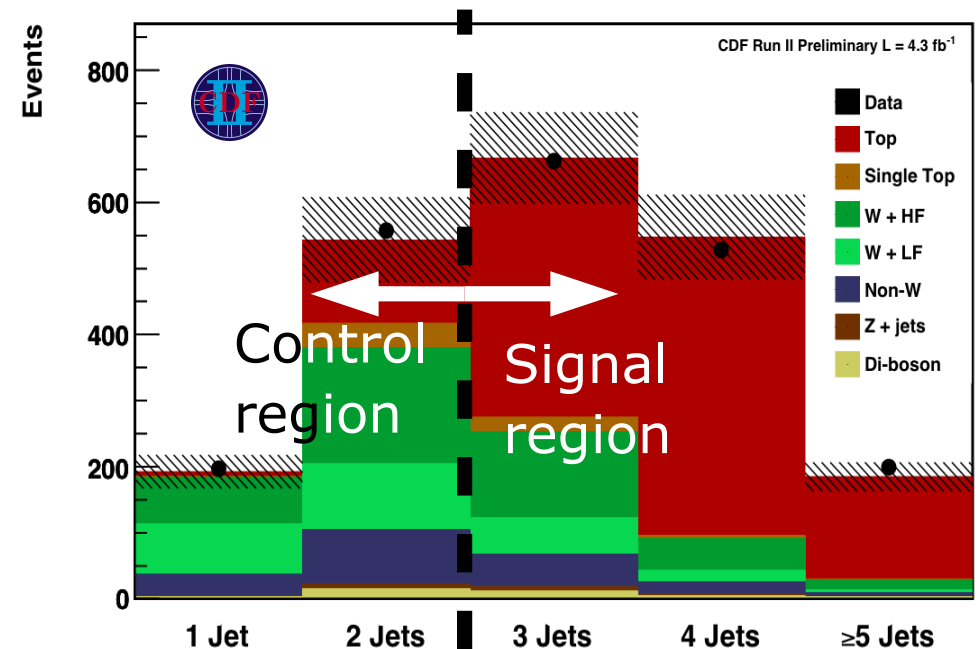
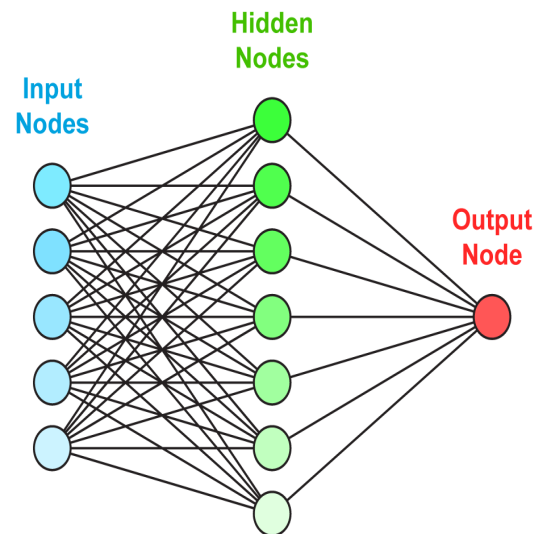
2 isolated leptons;  
High missing  $E_T$   
from neutrinos;  
2 b-jets

**lepton+jets:**

1 isolated lepton;  
Missing  $E_T$  from neutrino;  
 $\geq 4$  jets (2 b-jets)

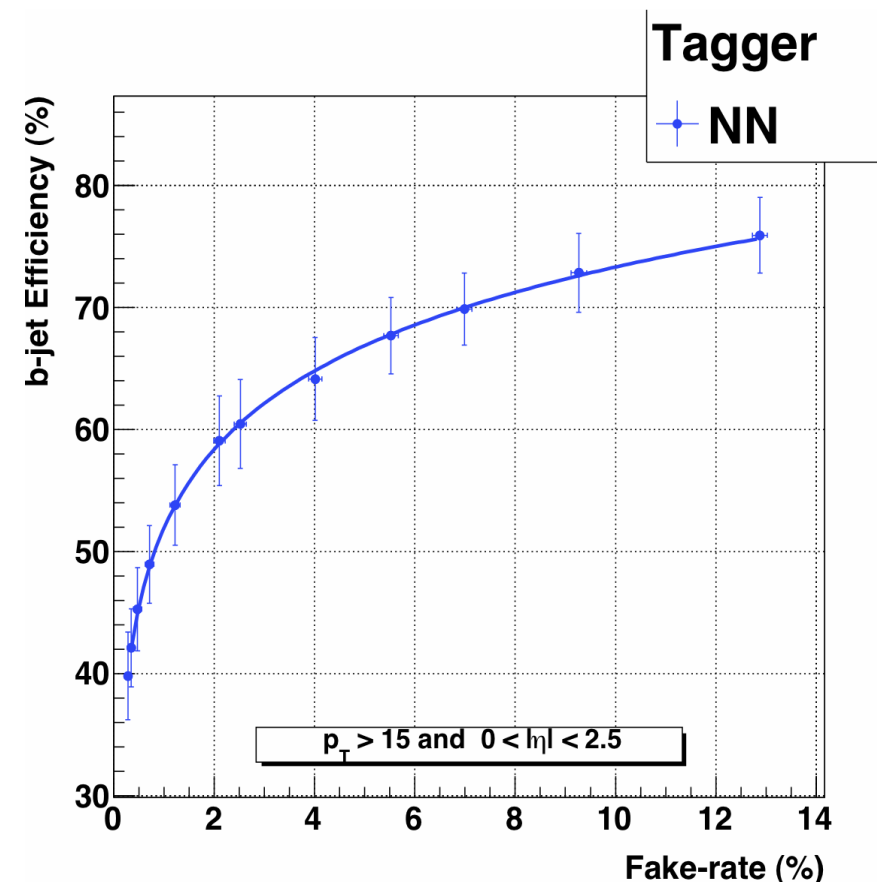
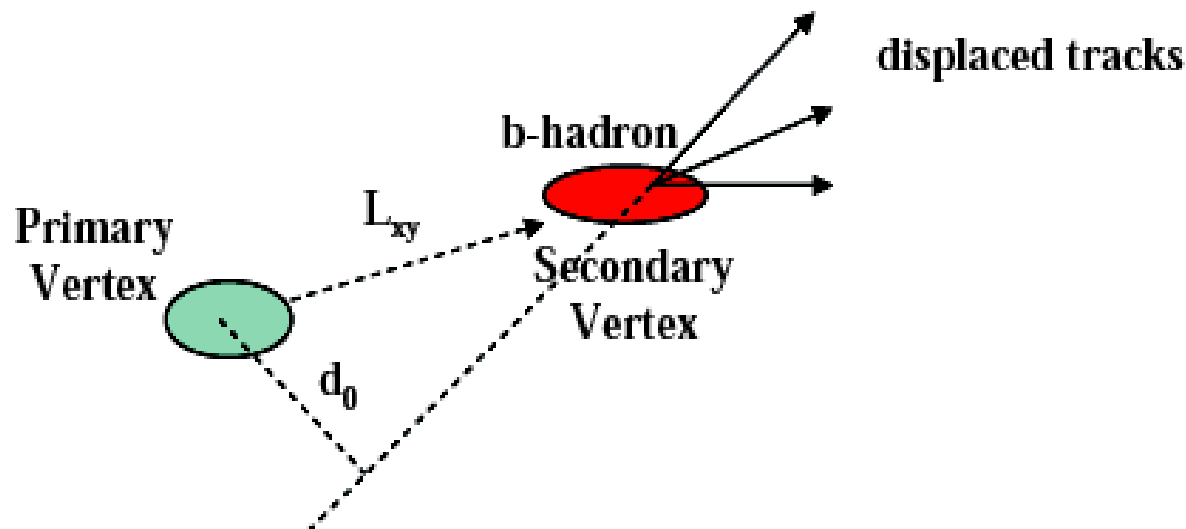
# Cross Section Measurement: Methods

- Use knowledge of signal and background signature to enrich data sample in  $t\bar{t}$  events
- Important tools:
  - B-jet identification
  - Multivariate analysis techniques



# Identification of b-Jets

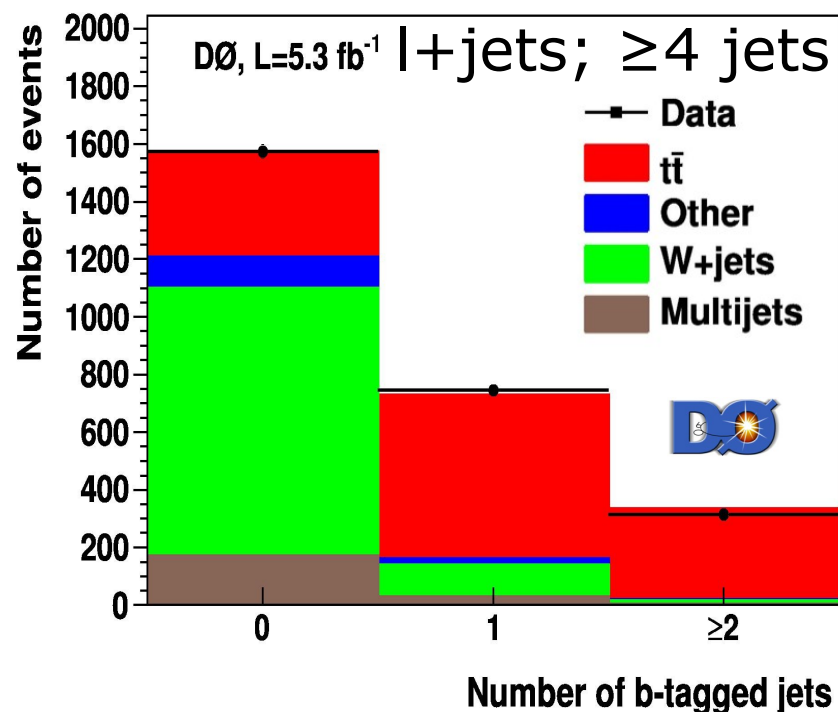
- Important to increase  $t\bar{t}$  purity
- b-hadron: travels some millimeters before it decays
- **Neural Network** (DØ)  
combines properties of displaced tracks and displaced vertices



# $\sigma_{t\bar{t}}$ in $l+jets$

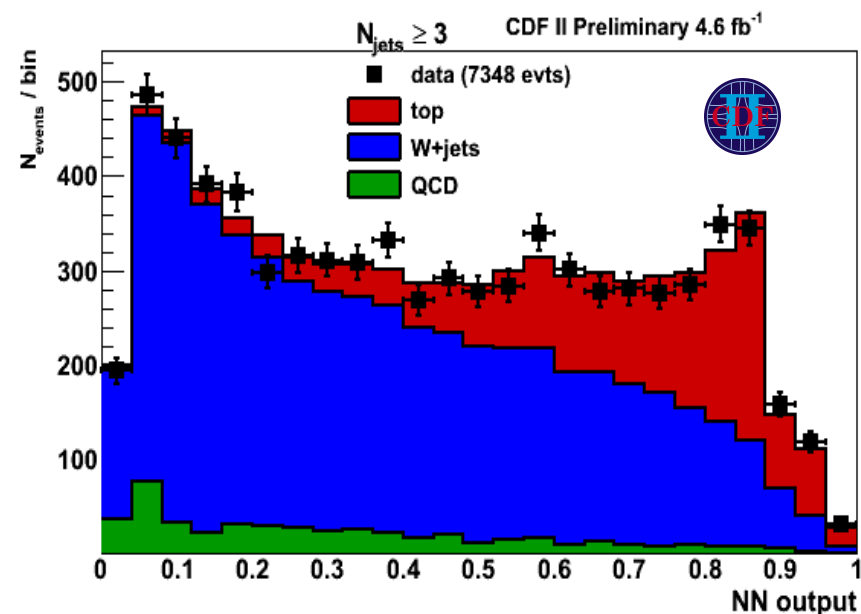
## Split events counting b-jets

- More b-jets  $\rightarrow$  higher purity



## Construct discriminant

- Combine variables discriminating signal and background in NN/BDT



DØ:  $\sigma = 8.13^{+1.02}_{-0.90} (stat + syst) \text{ pb}$

arXiv:1101.0124

$\sigma = 7.68^{+0.71}_{-0.64} (stat + syst) \text{ pb}$

CDF:  $\sigma = 7.22 \pm 0.80 (stat + syst) \text{ pb}$

PRL 105:012001 (2010)

$\sigma = 7.52 \pm 0.66 (stat + syst) \text{ pb}$

# $\sigma_{t\bar{t}}$ in $l+jets$ : Fancy Extensions

■ **Combined method**: combine b-tag and topological information

- Use topological discriminant in low purity channels arXiv:1101.0124

■ **Float systematic** uncertainties

$$D0: \quad \sigma = 7.78^{+0.77}_{-0.64} (stat + syst) pb$$

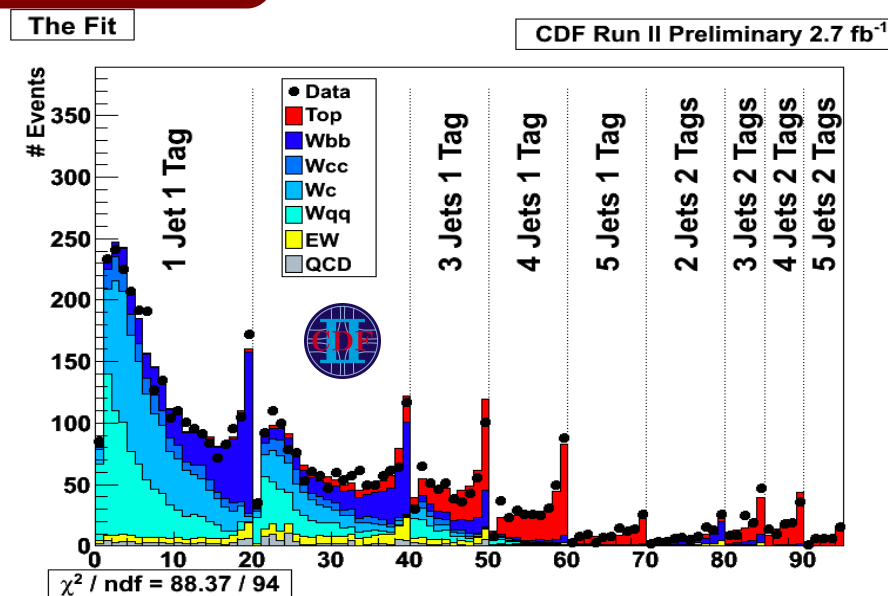
$$CDF: \quad \sigma = 7.64 \pm 0.57 (stat + syst) \pm 0.45 (lumi) pb$$

arXiv:1103.4821

■ Reduce luminosity error by taking **ratio to Z cross section** (for b-tag & topological combined)

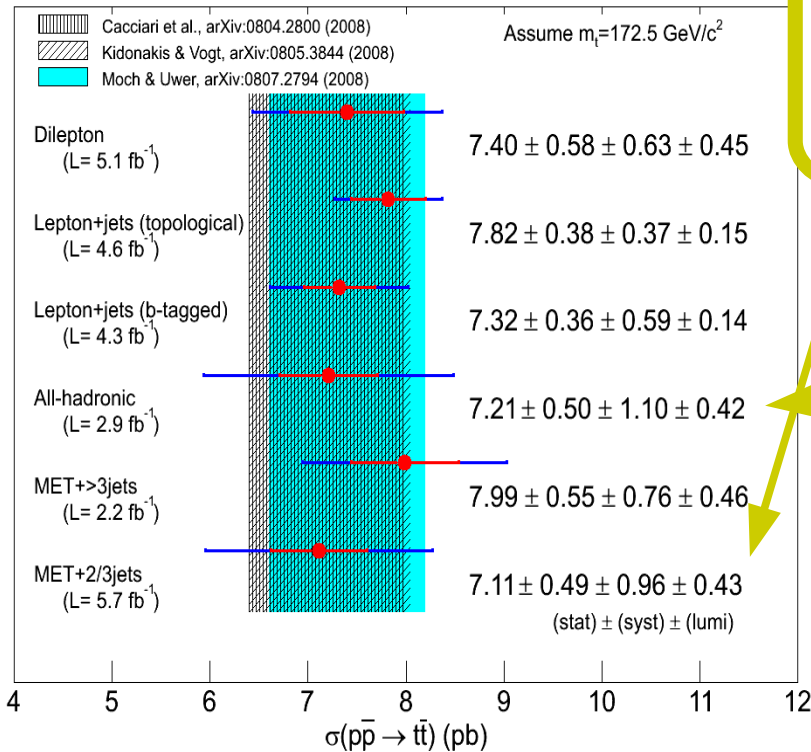
$$CDF: \quad \sigma = 7.70 \pm 0.52 (stat + syst + theory) pb$$

PRL 105:012001,2010



# Other Channels & Combination

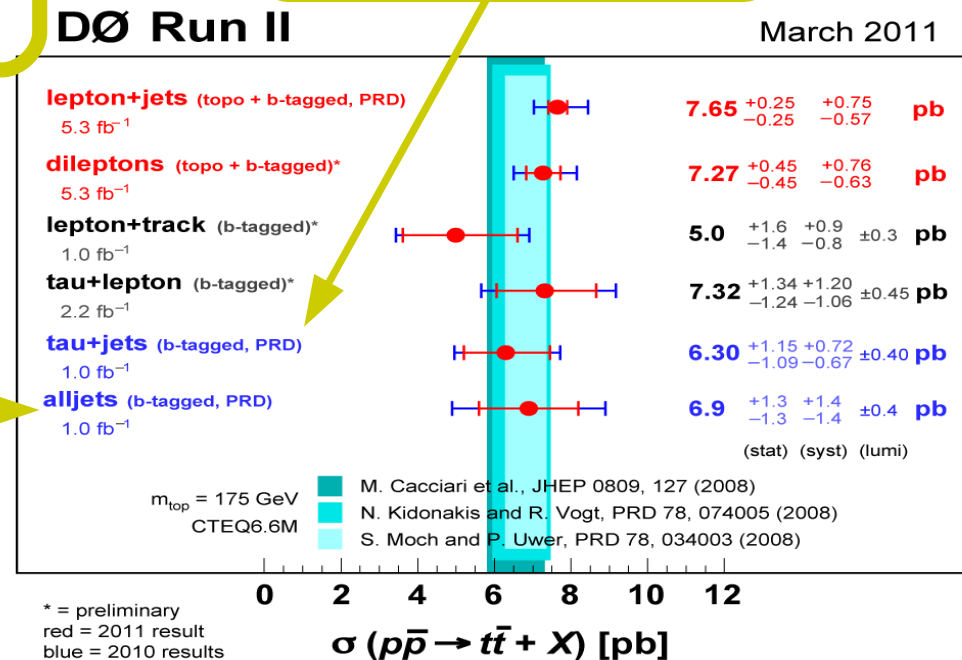
## $\sigma_{t\bar{t}}$ measured in various other channels



$\cancel{E}_T$  + (lepton/jets):  
interesting for  
Higgs search

All hadronic:  
no  $\cancel{E}_T$

$\tau$  + (lepton/jets):  
Interesting for  $H^+$   
search @ high  $\tan\beta$

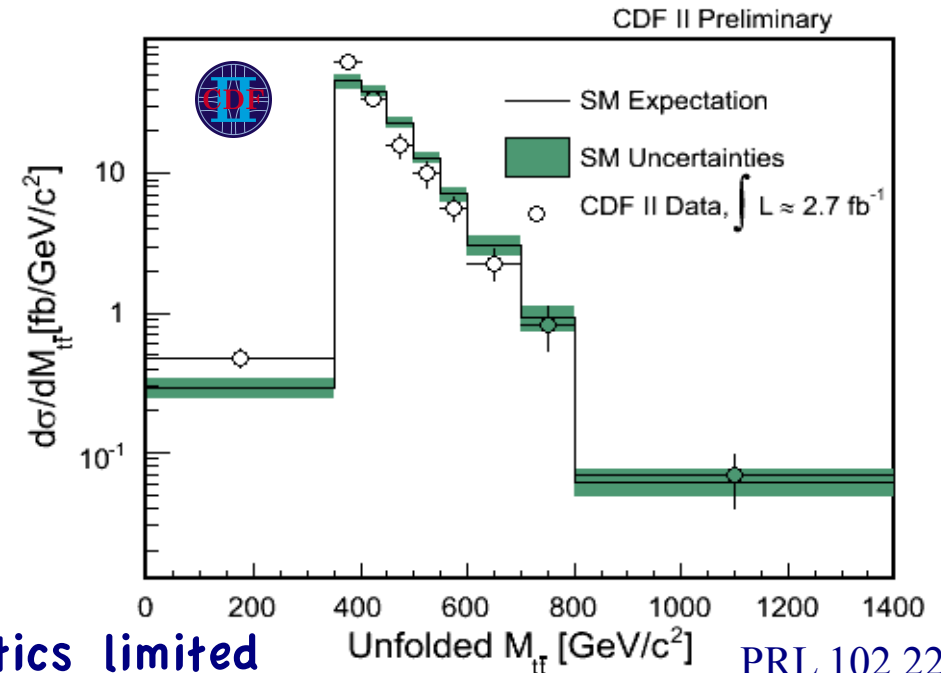
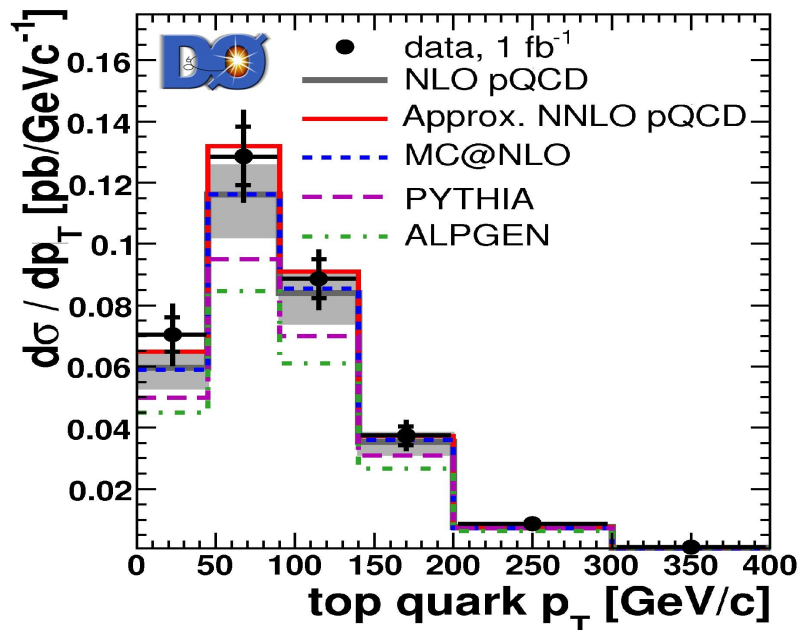


## Deviation of $\sigma_{t\bar{t}}$ from SM or between channel could indicate new physics

- Everything consistent with each other and SM prediction
- Now most measurements systematically limited

# $t\bar{t}$ Differential Cross Section

- Test of perturbative QCD calculations
- Generic probe of non-SM physics
- DØ: top quark  $p_T$ 
  - Window to heavy-quark production
  - Compare to MC generators
- CDF: invariant  $t\bar{t}$  mass
  - Generic test of SM (e. g. resonances)
  - Calculate consistency with SM



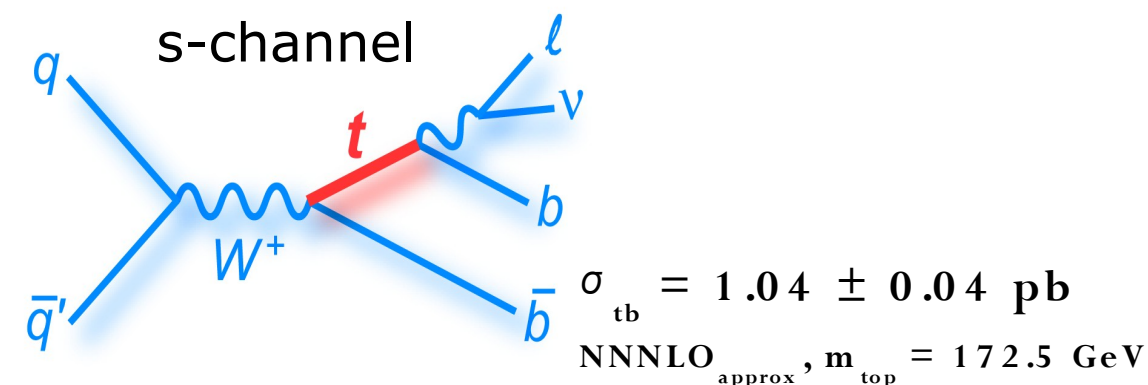
PLB 693, 515 (2010)

Still statistics limited

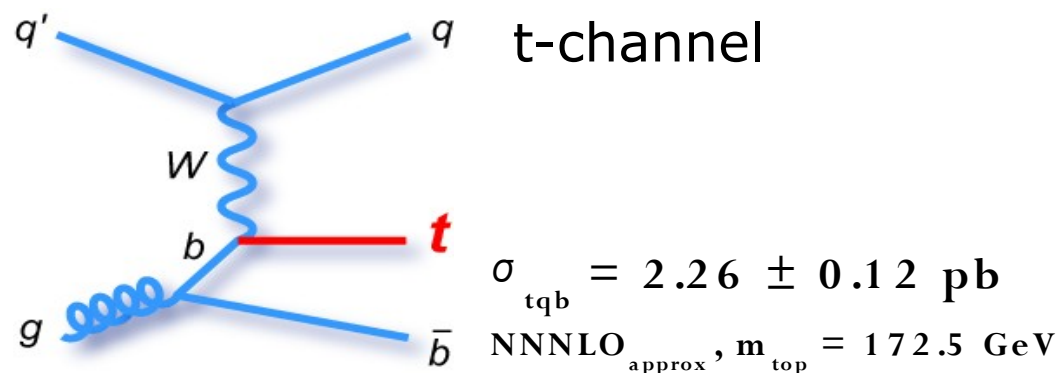
PRL 102 222003

# Single Top: Cross Section Measurement

- Single top quark production via electroweak interaction



Kidonakis, Vogt, PRD 78, 074005 (2008)



- Very challenging:
  - Low signal: similar signature like W+jets!
  - Counting only: Uncertainty on background larger than expected signal

- Use multivariate techniques

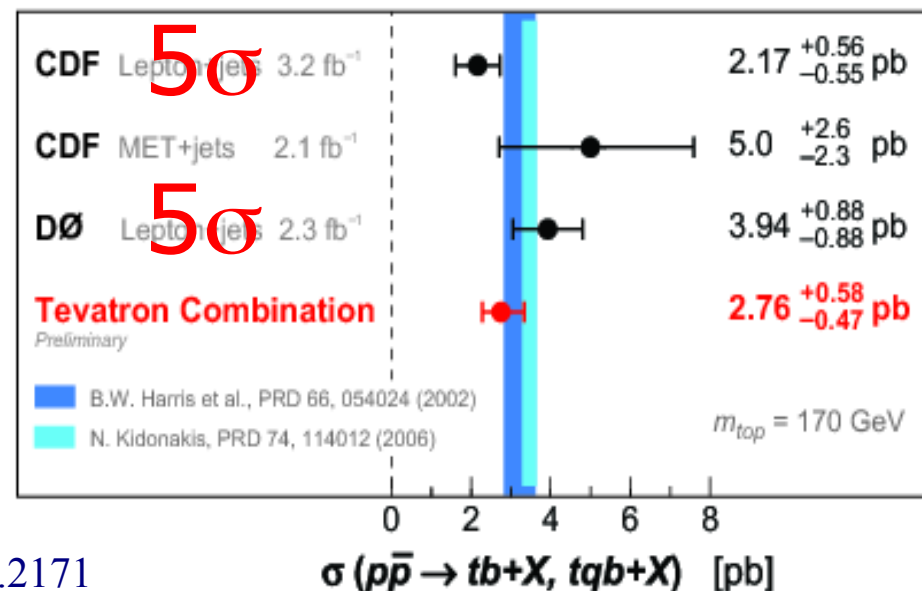
- BDT, Matrix Element, Neural Net, NEAT

- Observation in 2009

arXiv:0908.2171

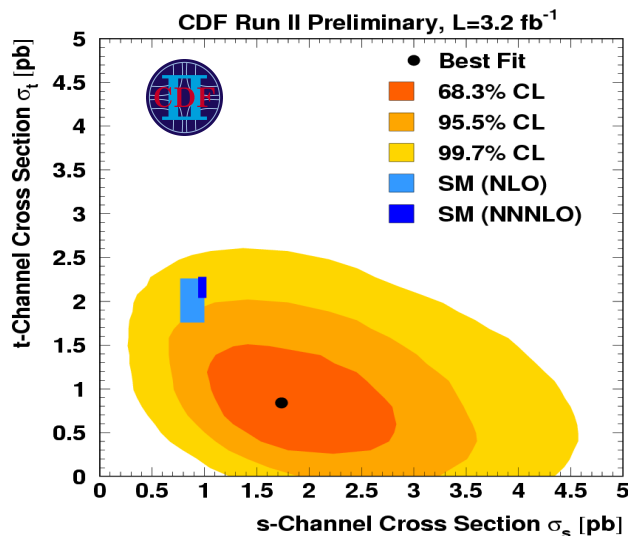
Single Top Quark Cross Section

August 2009

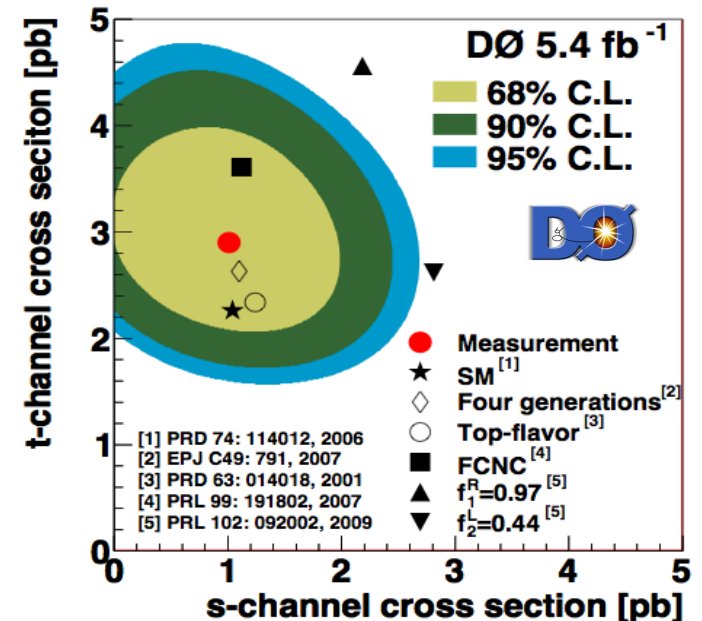


# Single top t-channel

- Measure s- and t-channel simultaneously  
→ no assumption of SM ratio



In agreement  
with SM prediction



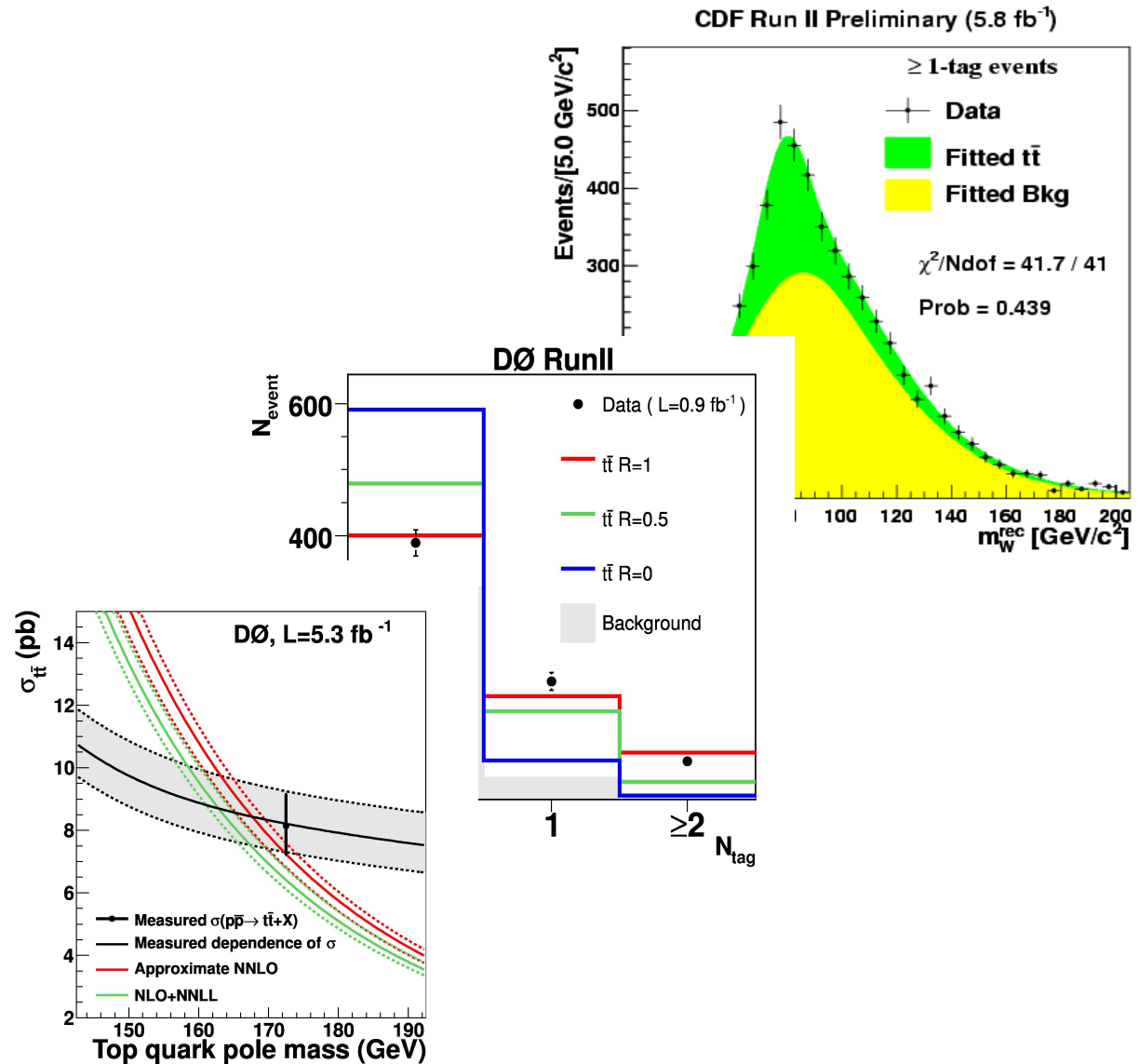
- Train with t-channel as signal and integrate over s-channel:  
t-channel cross section

- DØ: observation of t-channel

$$DØ: \quad \sigma = 2.90 \pm 0.59 (\text{stat} + \text{syst}) \text{ pb}$$

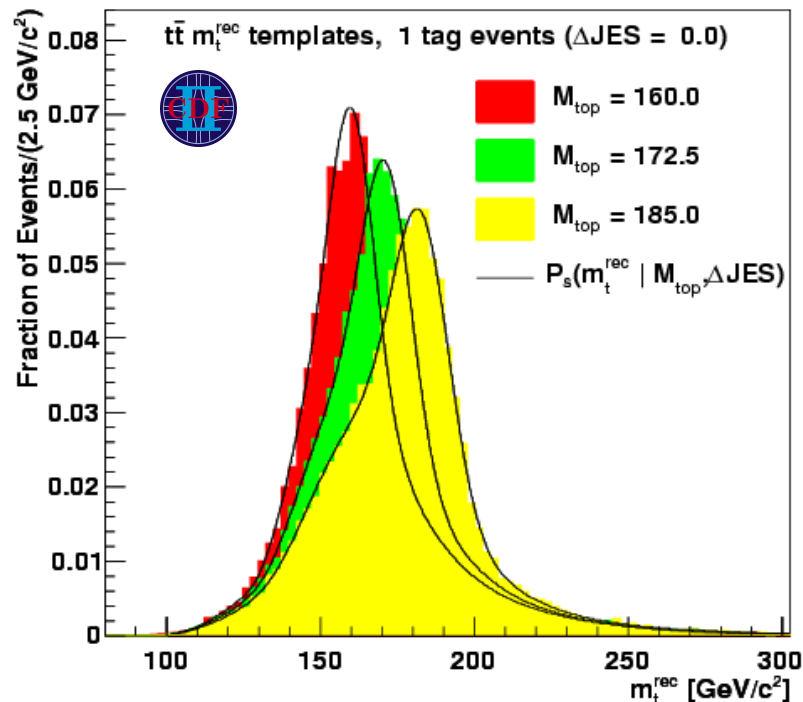
# Part II: Properties

- Mass
- Mass from cross section
- Mass difference
- Width
- W helicity
- Spin correlations
- Color charge asymmetry

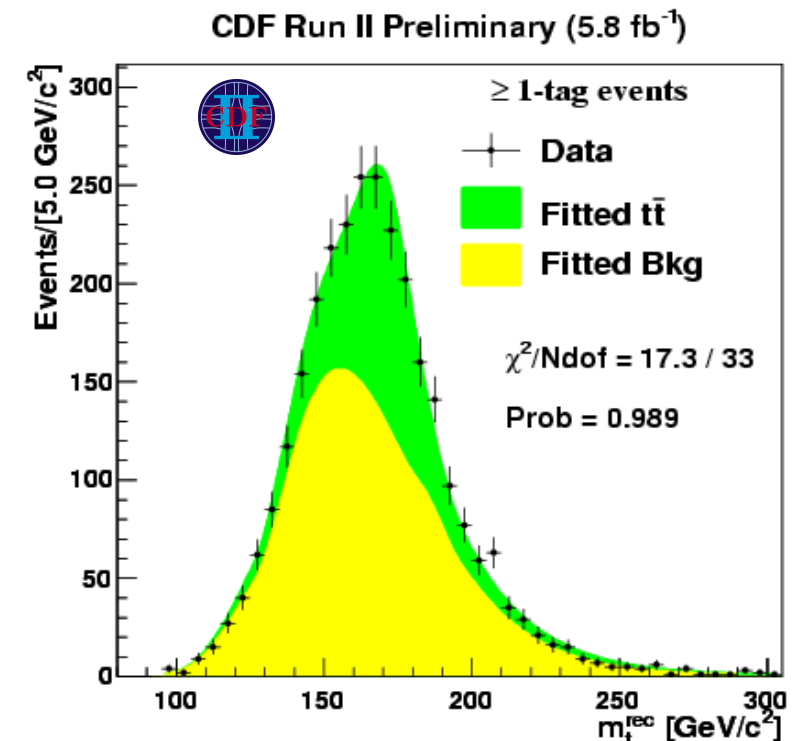


# Top Quark Mass

- Motivation: free parameter of the SM & constraint on Higgs
- Several methods: Template method, matrix element, etc.
  - Methods also used for other analyses, e. g. W helicity & spin correlations
- **Template method**: construct mass dependent template, fit to data



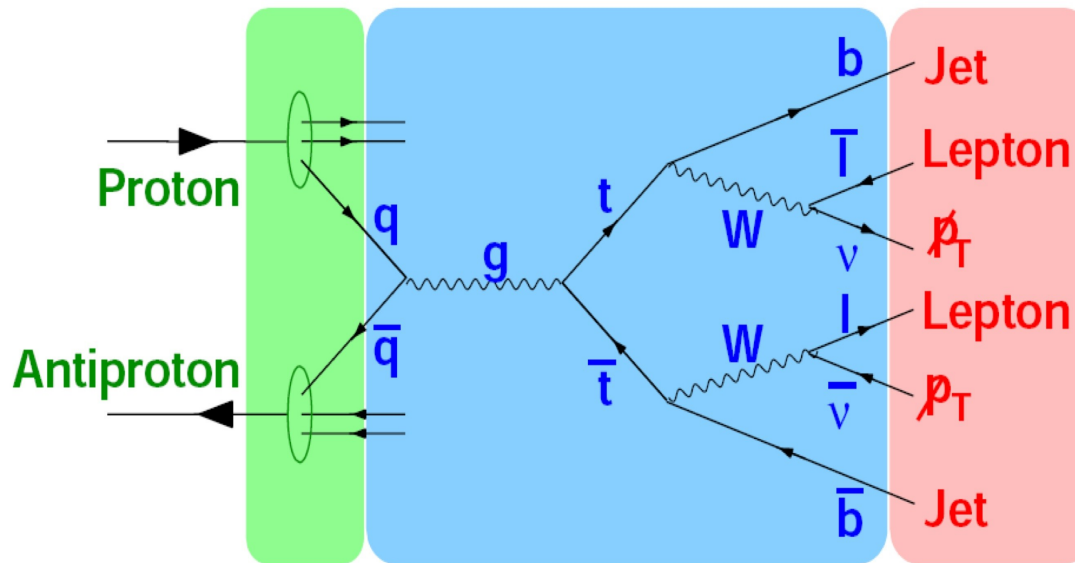
Additionally:  
Take info from  
W mass to  
constrain jet  
energy scale



# Top Quark Mass: Matrix Element Method

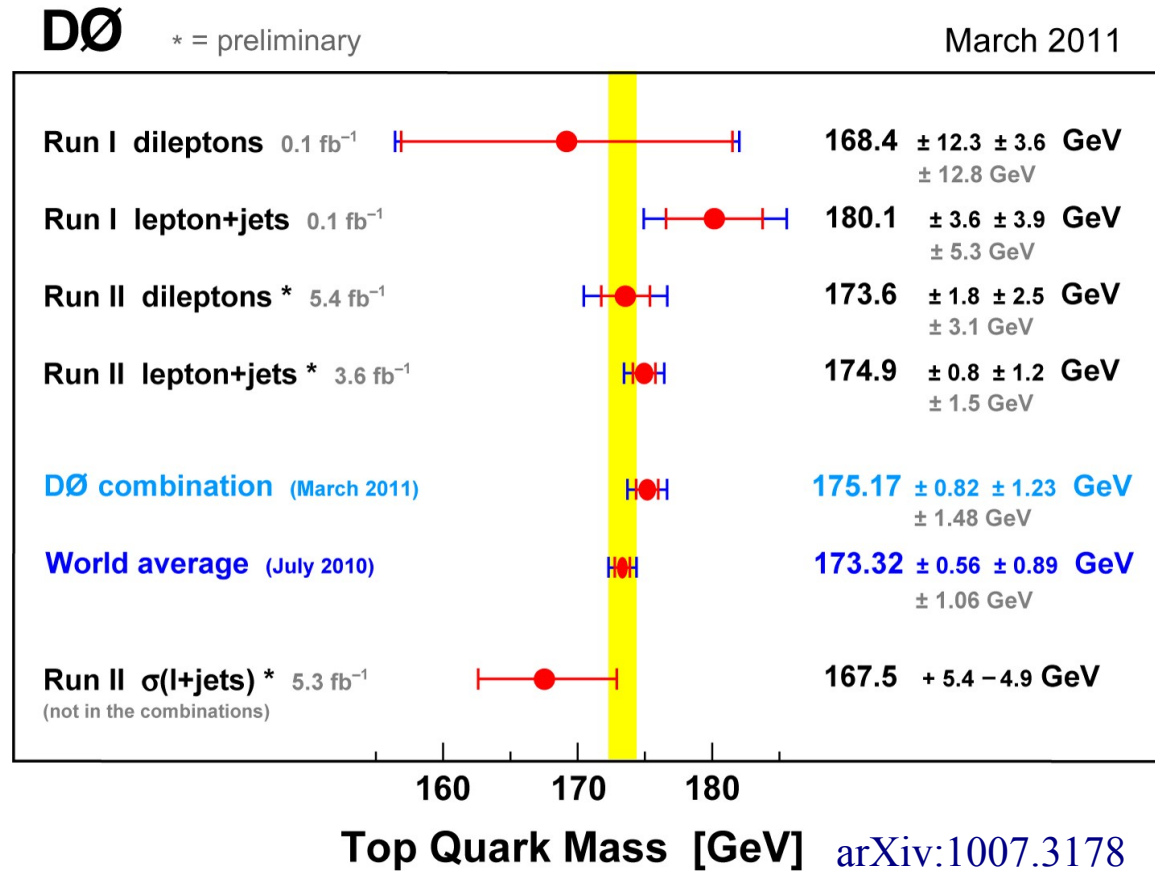
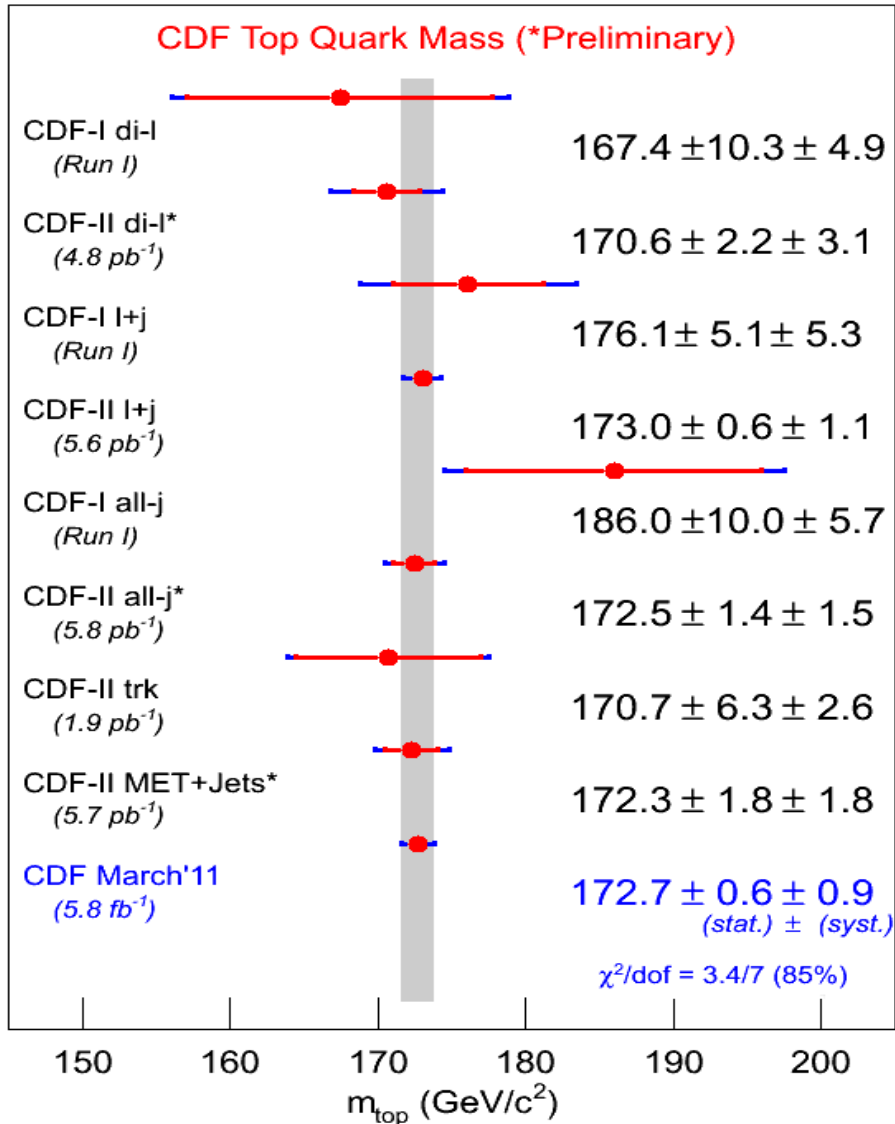
- Use the full event kinematics → most precise method
- For each event calculate probability to belong to certain top mass

$$P_{\text{sig}}(x; m_t) \propto \int \text{PDF} \times \text{Matrix element} \times \text{Transfer function}$$



- Perform likelihood fit of event probabilities
- Probability dependent on top mass (& JES for in-situ fit)

# Top Quark Mass: All Methods & Combinations

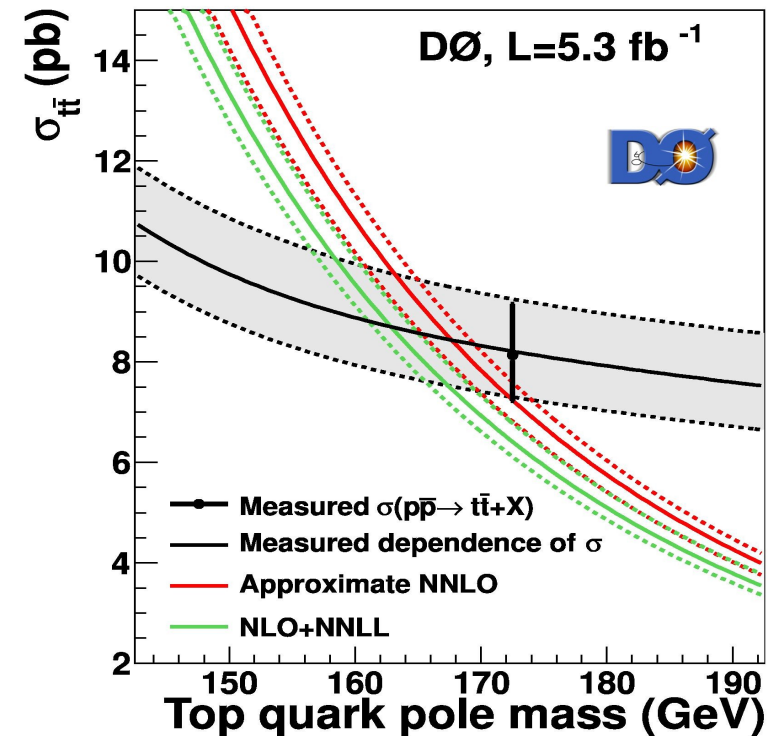


**Systematics limited!**

Main efforts: detailed  
understanding of systematics

# Top Quark Mass: Be aware

- Ongoing discussion: What is theoretical interpretation of the measured parameter?
  - We measure the Monte Carlo top mass parameter
  - Is it the pole mass?
- Alternative method: Extract  $m_t$  from cross section measurement
  - Assuming pole or  $\overline{\text{MS}}$  mass
    - For parameter in MC
    - For theory calculation
- Pole mass:  $m_t = 167.5^{+5.2}_{-4.7} \text{ GeV}$
- Assuming  $\overline{\text{MS}}$  mass leads to  $\sim 7 \text{ GeV}$  smaller value
- World average more compatible with pole mass



arXiv:1104.2887

# Top Quark Mass Difference

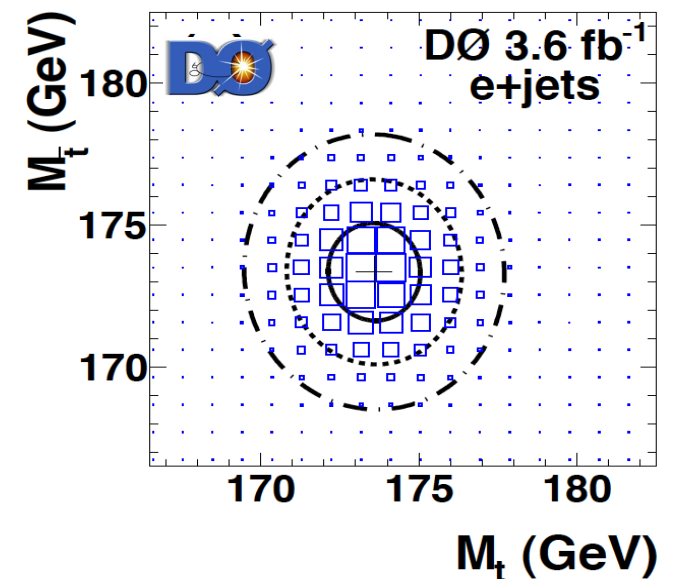
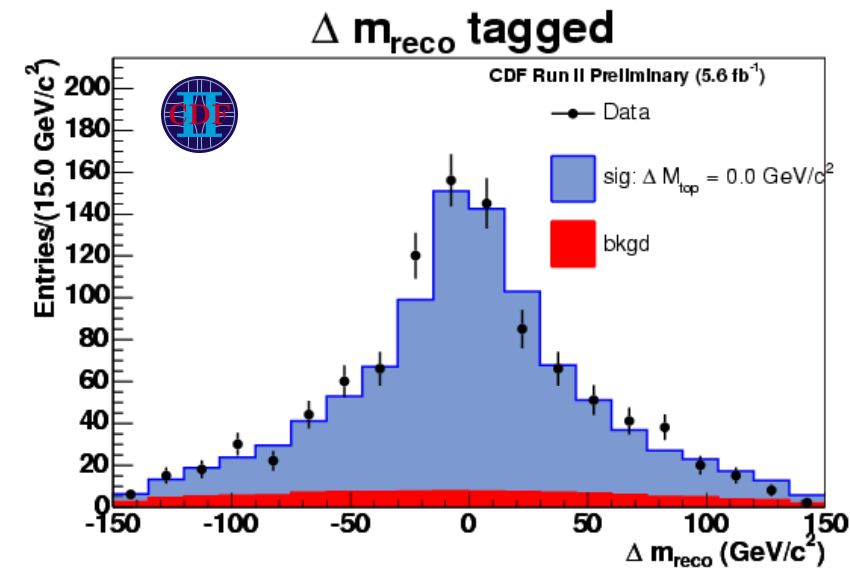
- Are top and anti-top equally heavy?
  - If not: CPT violation!
- CDF: Using template technique
  - Assume average top mass of 172.5 GeV

$$m_t - m_{\bar{t}} = -3.3 \pm 1.7 \text{ GeV} \quad \text{PRL 106, 161801}$$

- DØ: Using Matrix Element technique
  - $P_{\text{sig}}(x; m_t, m_{\bar{t}})$  instead of  $P_{\text{sig}}(x; m_t)$

$$m_t - m_{\bar{t}} = 0.8 \pm 2.0 \text{ GeV}$$

- Statistics limited
- Good agreement with the SM!



# Top Quark Width

- Top lifetime  $\sim 5 \times 10^{-25} \text{ s}$   
=> Top quark decay width is 1.4 GeV
- Top width determination using l+jets events
- Direct: Reconstruct top mass  $\rightarrow$  fit templates

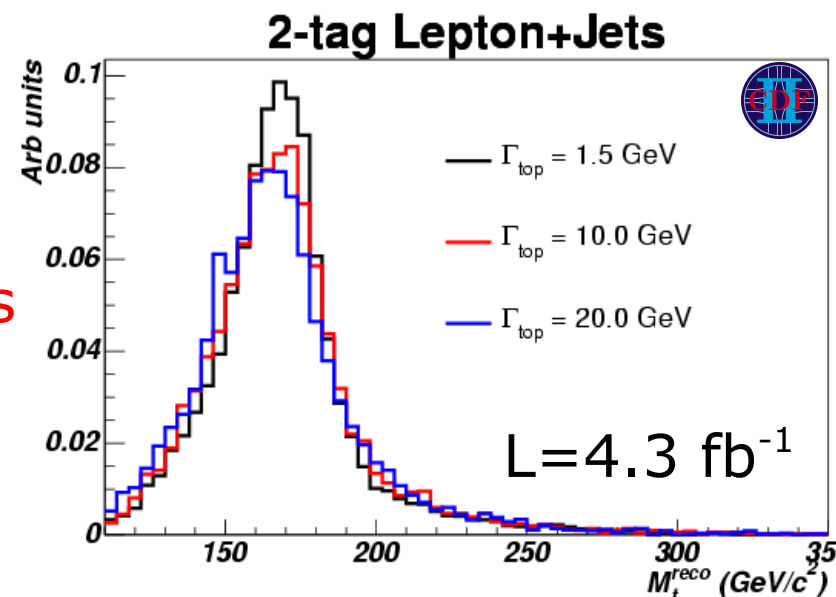
$$0.3 < \Gamma < 4.4 \text{ GeV @68\% CL}$$

$$\Gamma < 7.6 \text{ GeV @95\% CL}$$

- Indirect: Extract partial and total width from combination of R measurement and t-channel cross section
  - Partial width from t-channel cross section

$$\Gamma_t = \frac{\Gamma(t \rightarrow Wb)}{B(t \rightarrow Wb)}$$

Most precise determination of top width!



PRL 105 232003

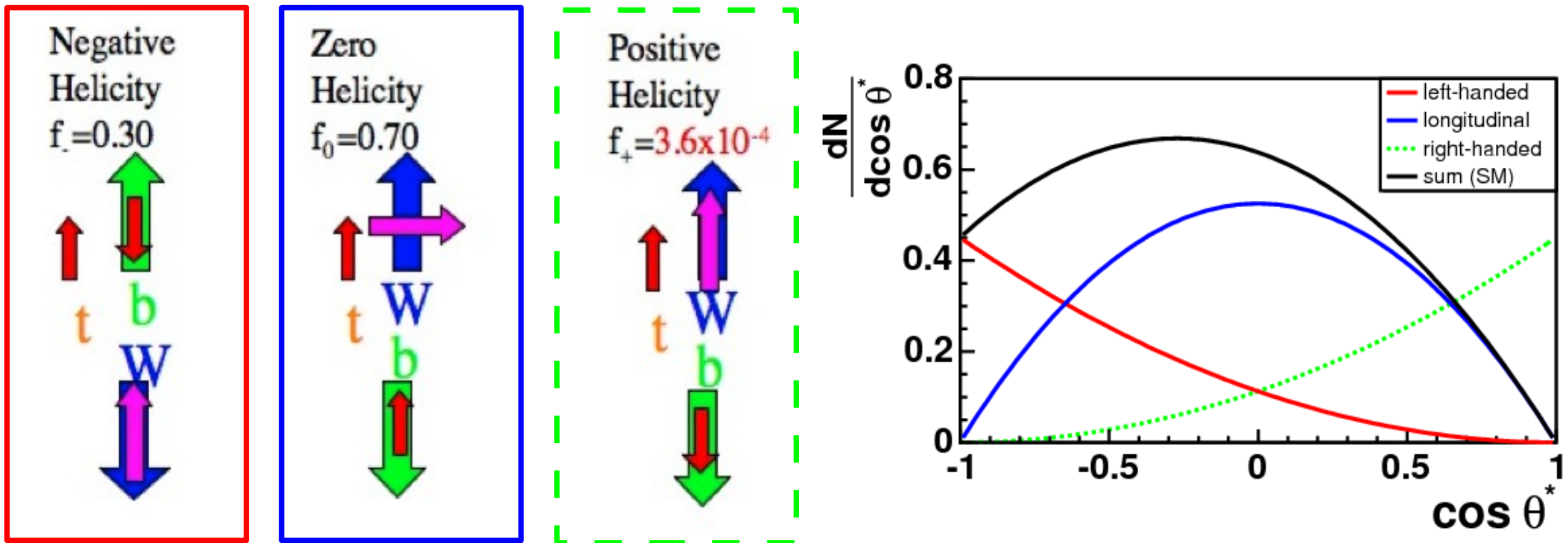
$$\Gamma_t = 1.99_{-0.55}^{+0.69} \text{ GeV}$$

$$\tau_t = \frac{1}{\Gamma_t} = (3.3_{-0.9}^{+1.3}) \times 10^{-25} \text{ s}$$

PRL 106, 022001 (2011)

# W Helicity in Top Quark Decays

- Left handed coupling of W-boson to fermions:  
Not every combination of spin for W and b-quark is allowed

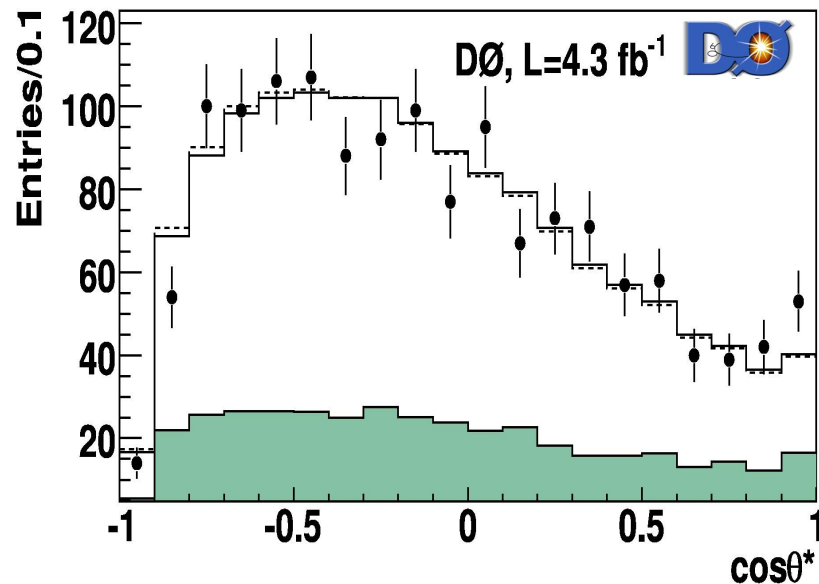


- Measure angle  $\theta^*$  between down-type decay product (lepton, d-, s-quark) of W and top quark in W rest frame

# W Helicity in Top Quark Decays

## Template method

- Fit fraction of  $f_+$ ,  $f_-$ ,  $f_0$  templates to data



l+jets and dilepton

Model independent simultaneous fit:

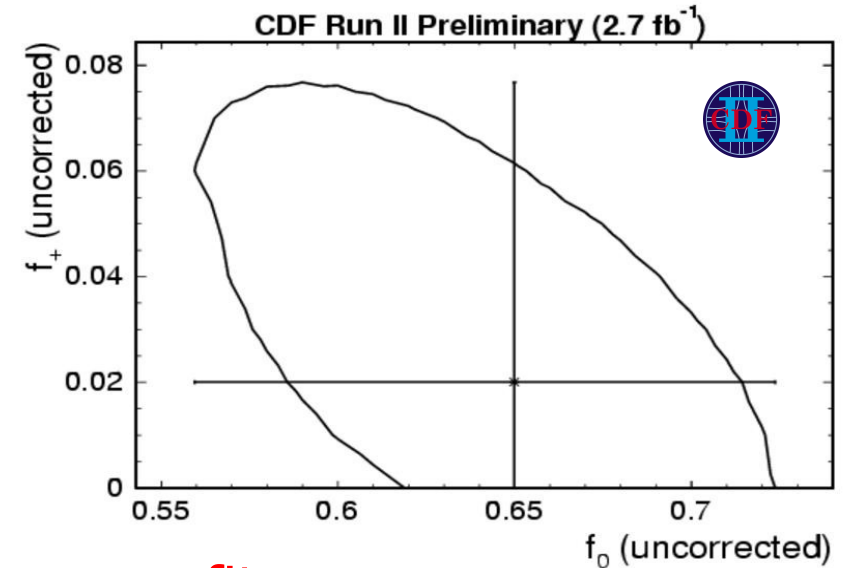
$$f_0 = 0.67 \pm 0.08 \text{ (stat)} \pm 0.07 \text{ (syst)}$$

[arXiv:1011.6549](https://arxiv.org/abs/1011.6549)

$$f_+ = 0.02 \pm 0.04 \text{ (stat)} \pm 0.03 \text{ (syst)}$$

## Matrix element method

- Same method as for mass
- Replace top mass with  $f_0$  &  $f_+$



l+jets

$$f_0 = 0.88 \pm 0.11 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

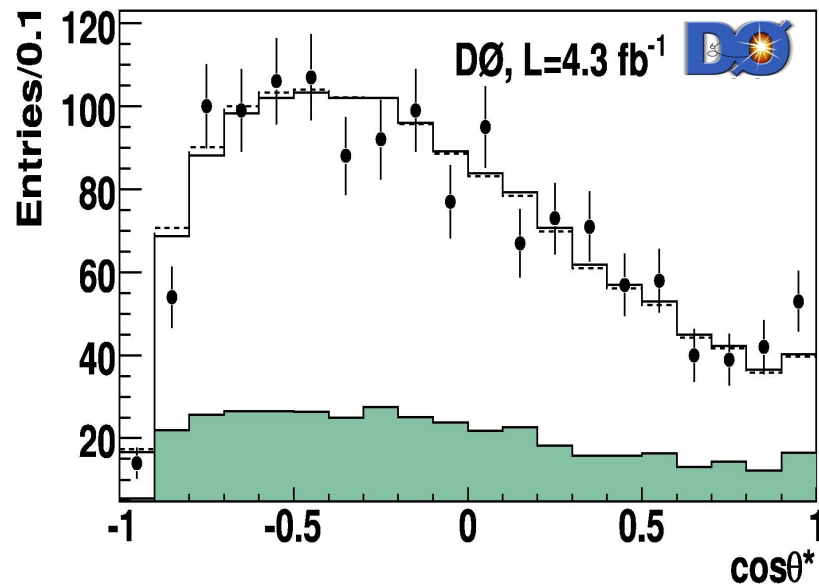
[PRL 105, 042002](https://arxiv.org/abs/1011.6549)

$$f_+ = -0.15 \pm 0.07 \text{ (stat)} \pm 0.06 \text{ (syst)}$$

# W Helicity in Top Quark Decays

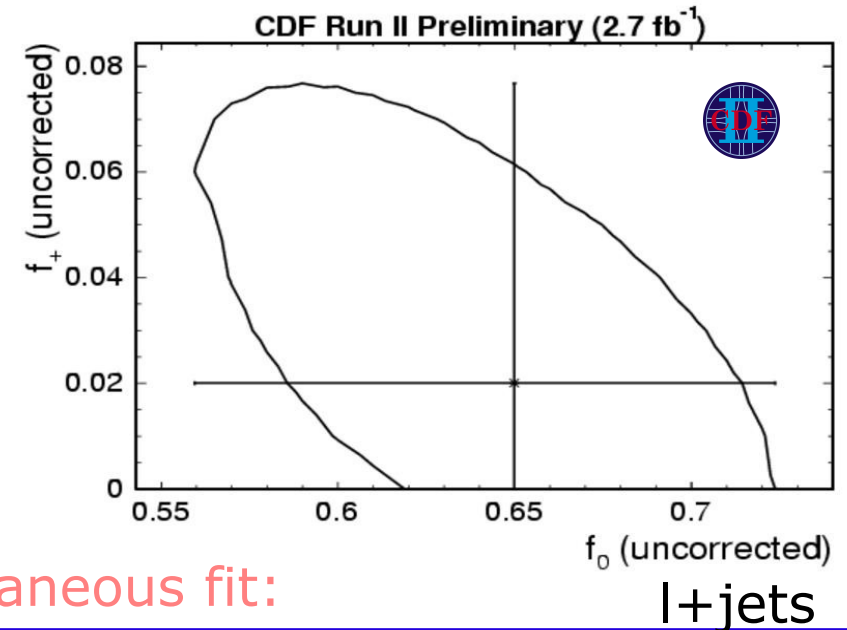
## Template method

- Fit fraction of  $f_+$ ,  $f_-$ ,  $f_0$  templates to data



## Matrix element method

- Same method as for mass
- Replace top mass with  $f_0$  &  $f_+$



l+jets and dilepton

Model independent simultaneous fit:

$$f_0 = 0.67 \pm 0.08 \text{ (stat)}$$

[arXiv:1011.6549](https://arxiv.org/abs/1011.6549)

$$f_+ = 0.02 \pm 0.04 \text{ (stat)}$$

Not shown: new dilepton result from CDF  
Working on W helicity Tevatron combination

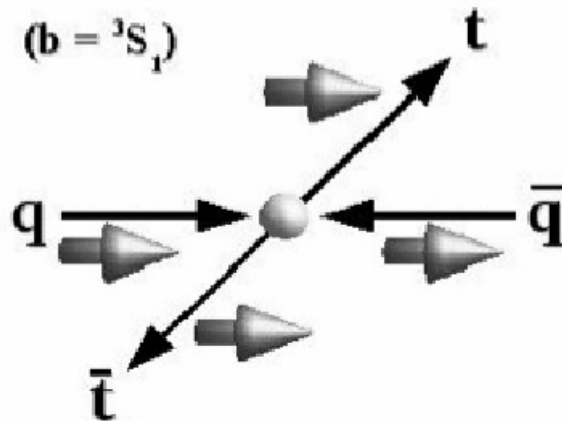
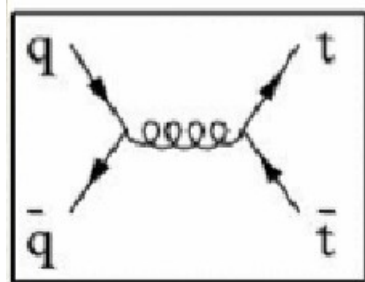
$$f_0 = 0.66 \pm 0.06 \text{ (syst)}$$

PRL 105, 042002

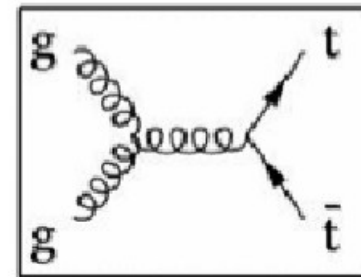
$$f_+ = 0.02 \pm 0.06 \text{ (syst)}$$

# $t\bar{t}$ Spin Correlations

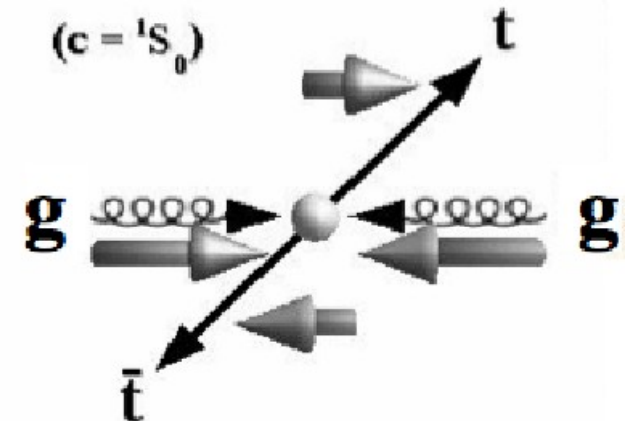
- Top quarks decay before fragmentation
  - Spin information is preserved
- Spin correlation depends on production mode



85%



15%



Complementary to LHC

- We use two methods to explore spin correlations
  - Template based using angular distribution
  - Matrix element based

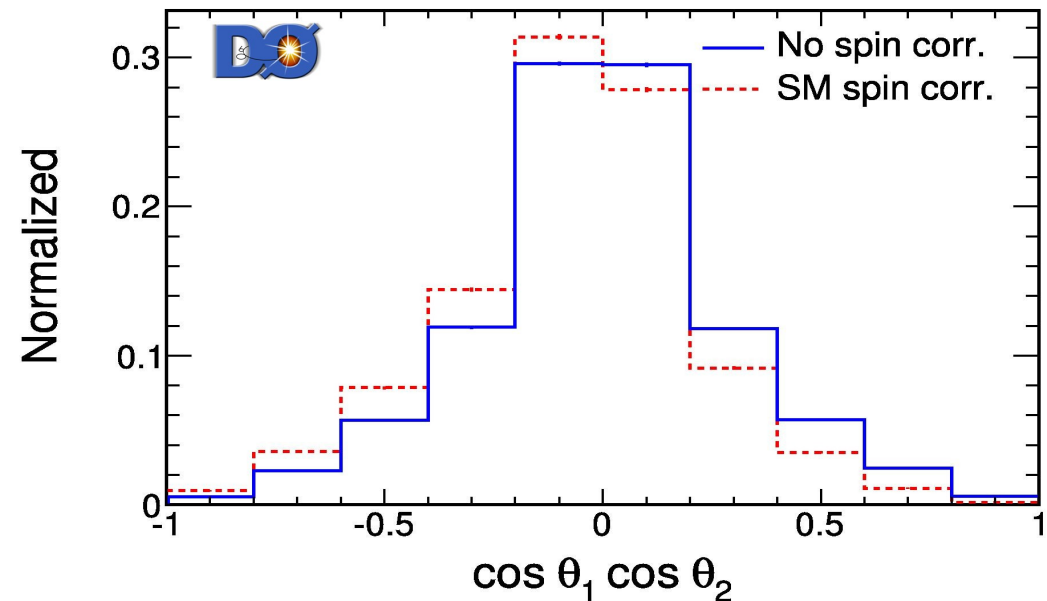
# $t\bar{t}$ Spin Correlation using Angular Distributions

- Use the **angles between decay products and beam axis** to analyse spin
  - Dilepton: Angle of (anti)lepton wrt. beam axis in (anti)top rest-frame
- Differential cross section:

$$\frac{1}{\sigma} \frac{d^2 \sigma}{d \cos \theta_1 d \cos \theta_2} = \frac{1}{4} (1 - C \cos \theta_1 \cos \theta_2)$$

- C**: spin correlation strength
- NLO SM:  $C \approx 0.78$

$$C = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$



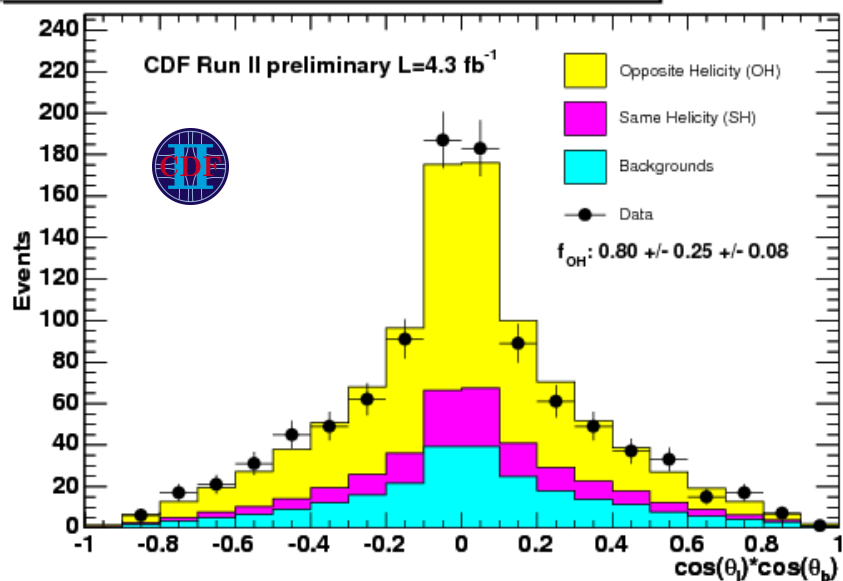
# $t\bar{t}$ Spin Correlations using Angular Distributions

- Three first Run II spin correlation analyses since summer 2009!
- lepton+jets and dilepton results!

*CDF*:  $C = 0.72 \pm 0.64(stat) \pm 0.26(syst)$

Phys.Rev.D83:031104 (2011)

Helicity Angle Bilinear  $\cos(\theta_l)\cos(\theta_b)$ , Fit Result



Beam basis

First extraction of  $t\bar{t}$  spin correlation in l+jets!

$L = 2.8 \text{ fb}^{-1}$

*CDF*:  $C = 0.32_{-0.78}^{+0.55}(stat + syst)$

$L = 5.4 \text{ fb}^{-1}$

*D0*:  $C = 0.10 \pm 0.45(stat + syst)$

arXiv:1103.1871

NLO SM: 0.78

Beam basis

Bernreuther et. al, 04

In agreement with SM

Still statistically dominated

First evidence soon?

STAY TUNED!

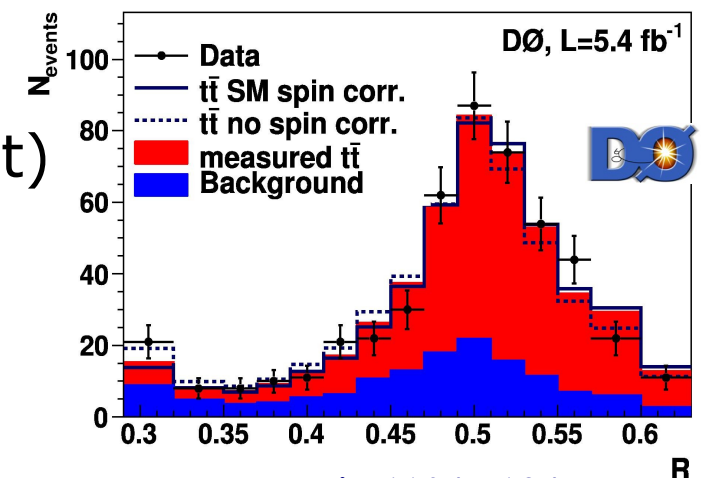
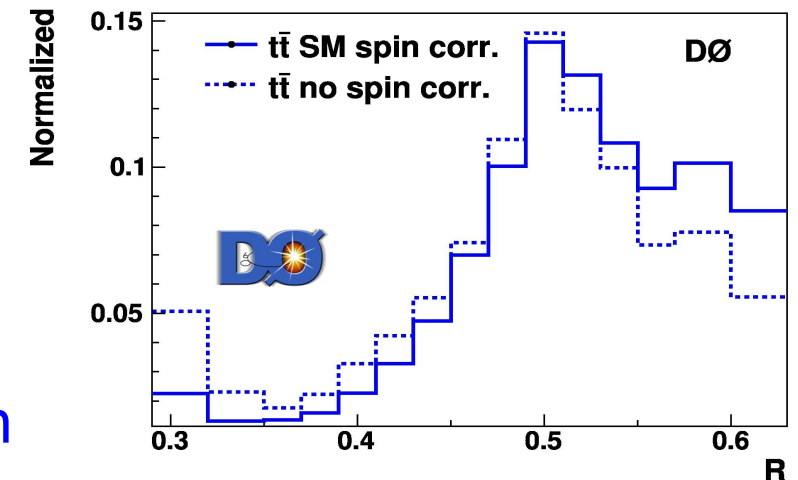
# $t\bar{t}$ Spin Correlations using Matrix Elements

- Test hypothesis of spin correlation ( $H=1$ ) versus no correlation ( $H=0$ )
- Calculate signal probability  $P_{\text{sgn}}$  for  $H=0$  and  $H=1$ , define discriminator:

$$R = \frac{P_{\text{sgn}}(H=1)}{P_{\text{sgn}}(H=0) + P_{\text{sgn}}(H=1)}$$

- Build templates with MC@NLO MC including spin correlation and without spin correlation
- Fit fraction  $f = N_{t\bar{t}}(\text{with spin})/N_{t\bar{t}}(\text{total})$
- Result of template fit:  $f = 0.74^{+0.40}_{-0.41} (\text{stat+syst})$   
→ corresponds to  $C = 0.57 \pm 0.31 (\text{stat+syst})$
- ~30% improved over template method!

**First time sensitive to spin correlations!**



arXiv:1104.5194

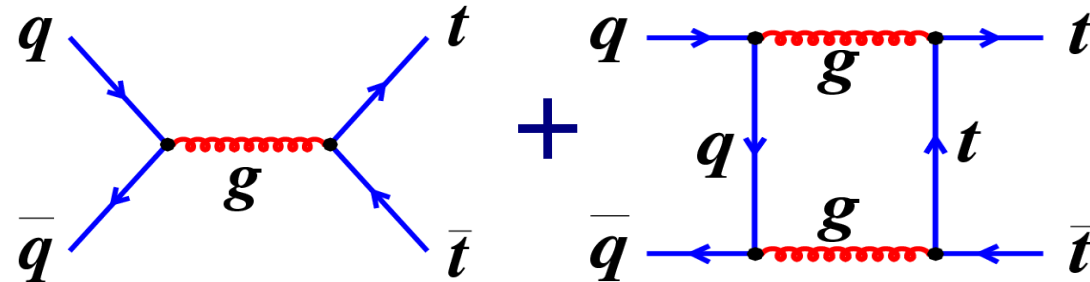
# Color Charge Asymmetry

- LO: No charge asymmetry expected
- NLO QCD: Interference between diagrams

- Tree level and box diagrams:

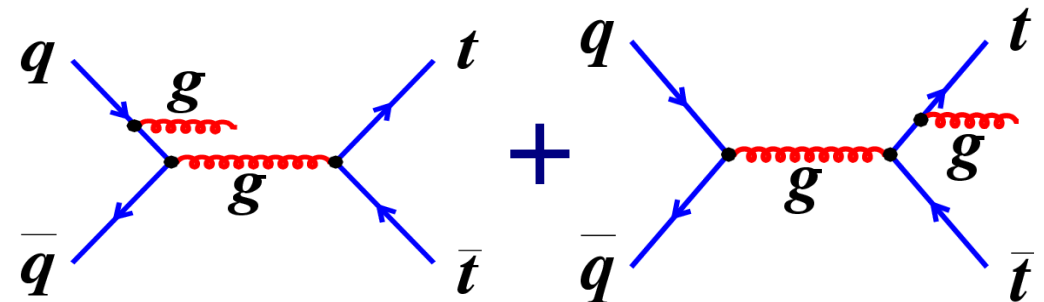
- Positive asymmetry
- Intuitive picture:

QCD coulomb field of incoming quark repels  $t$  to larger, attracting  $\bar{t}$  to smaller rapidity



- Initial and final state radiation:

- Negative asymmetry
- Intuitive picture: acceleration of color charge due to gluon radiated from incoming quark biases top quark to backward direction



- Asymmetry sensitive to new physics, but also phase space

# Color Charge Asymmetry

## Several asymmetry definitions

- In  $t\bar{t}$  rest frame:

$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

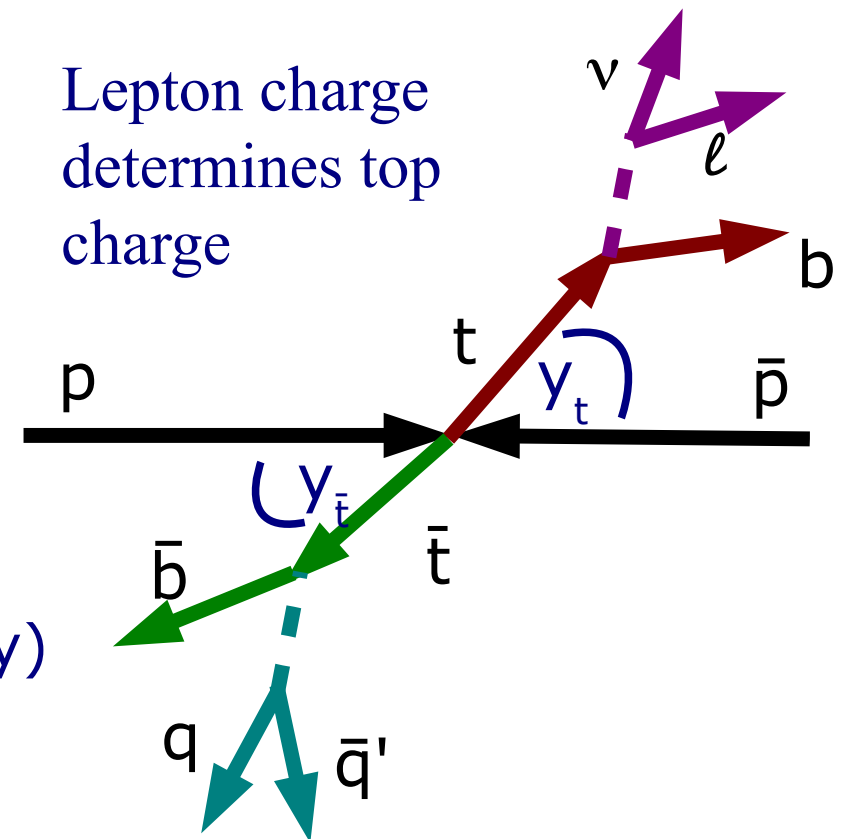
$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right) \quad \Delta y = y_t - y_{\bar{t}}$$

- In lab frame: use rapidity (instead of  $\Delta y$ ) of hadronic (or leptonic) top

## Requires reconstruction of $t\bar{t}$ system

- Kinematic fitter

## We have results in $l$ +jets (CDF & DØ) and dilepton (CDF)



# Color Charge Asymmetry

■ Theory prediction: We use MC@NLO MC  
 $A^{t\bar{t}} = 0.06 \pm 0.01$  at parton level

■ CDF: Unfolding of data with simple matrix inversion (4 bins)

$$A^{t\bar{t}} = 0.158 \pm 0.074$$

arXiv:1101.0034

■ DØ: no unfolding (yet)

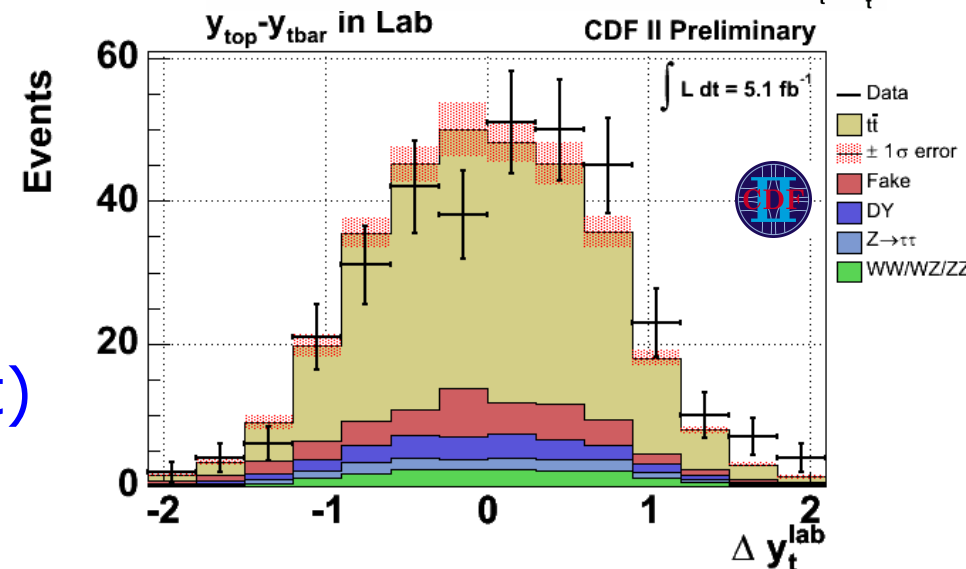
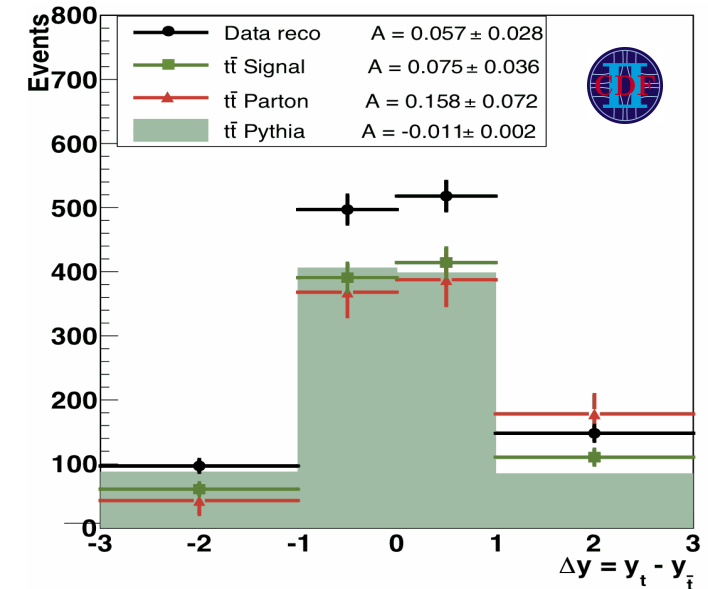
$$A_{\text{obs}}^{t\bar{t}} = 0.08 \pm 0.04$$

■ to be compared to  $A_{\text{pred}}^{t\bar{t}} = 0.01 \pm 0.02$

■ CDF: Dilepton, unfolded:

$$A^{t\bar{t}} = 0.42 \pm 0.15 \text{ (stat)} \pm 0.05 \text{ (syst)}$$

■ to be compared to  $A^{t\bar{t}} = 0.06 \pm 0.01$



# Color Charge Asymmetry

Asymmetry depends on several variables

- Lowest jet momentum,  $t\bar{t}$   $p_T$ ,  
top quark rapidity  $\Delta y$ ,  $m_{t\bar{t}}$

CDF: study  $\Delta y$  and  $m_{t\bar{t}}$  dependence

- Split data  $m_{t\bar{t}} < 450 \text{ GeV}$  &  $m_{t\bar{t}} > 450 \text{ GeV}$

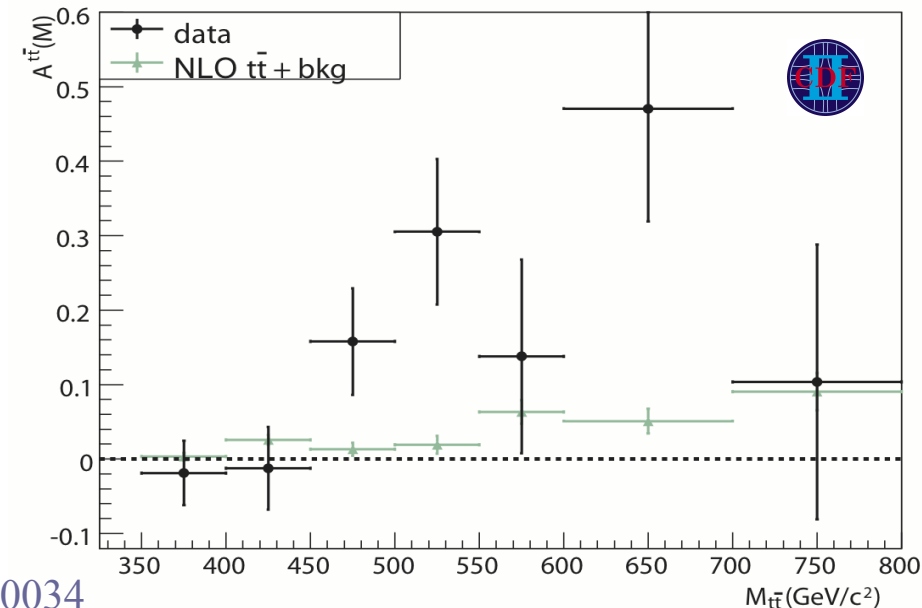
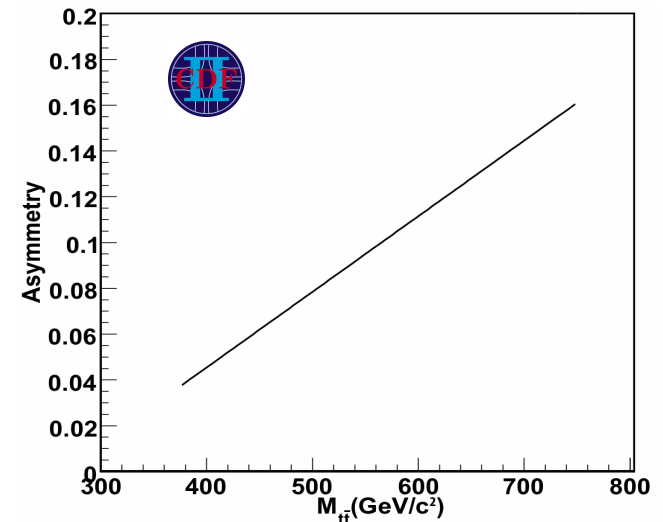
- $m_{t\bar{t}} < 450 \text{ GeV}$

- $A^{t\bar{t}} = -0.166 \pm 0.146 \pm 0.047$
- Prediction:  $A^{t\bar{t}} = 0.040 \pm 0.006$

- $m_{t\bar{t}} > 450 \text{ GeV}$

$\sim 3 \sigma$  off from  
MC@NLO prediction

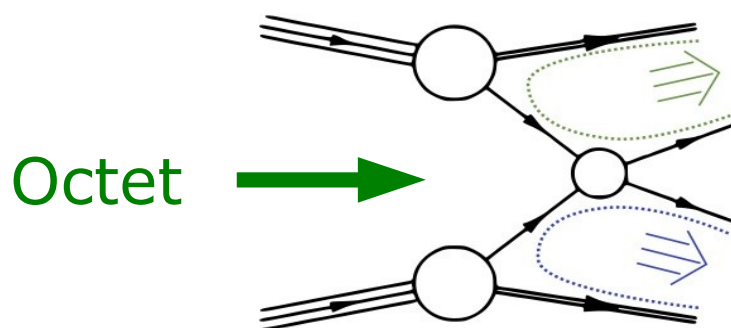
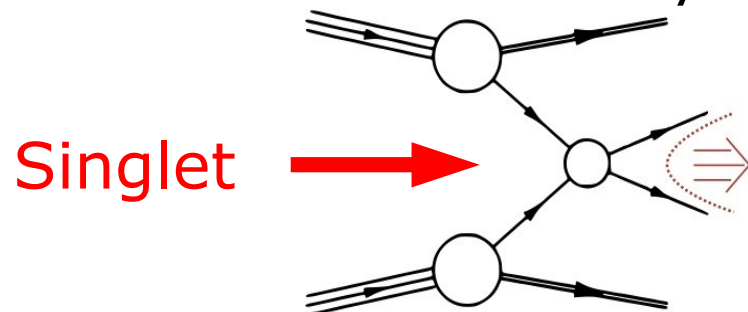
- $A^{t\bar{t}} = 0.475 \pm 0.101 \pm 0.049$
- Prediction:  $A^{t\bar{t}} = 0.088 \pm 0.013$



arXiv:1101.0034

# Other New Results

- **Top charge**: Exotic model with top charge  $-4/3 e$  could be possible
  - Use  $l$ +jets event; extract top charge from lepton charge & jet charge
  - Exclude exotic model at 95% CL
- **Color flow**: Jets carry color, and are thus **color connected** to each other



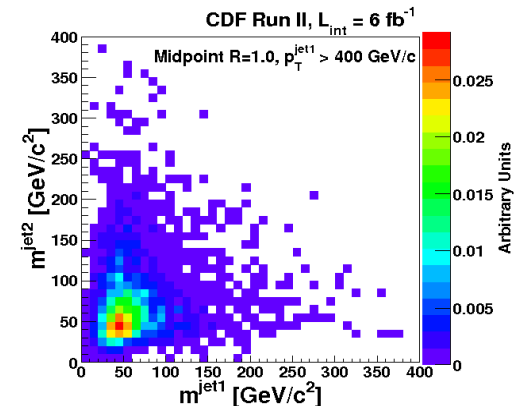
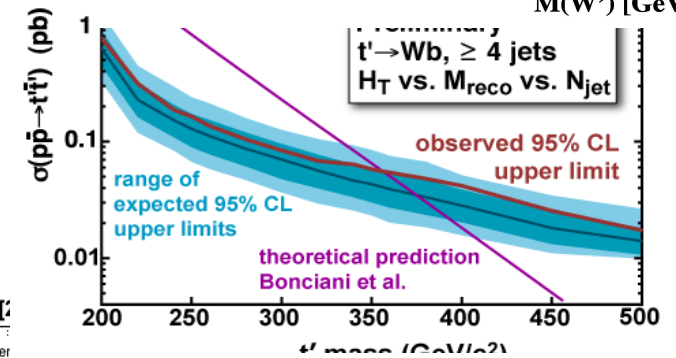
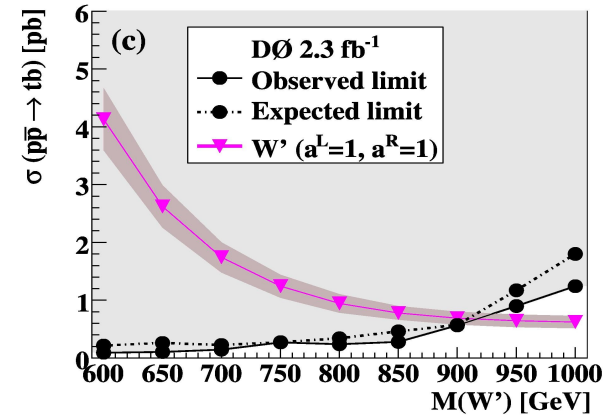
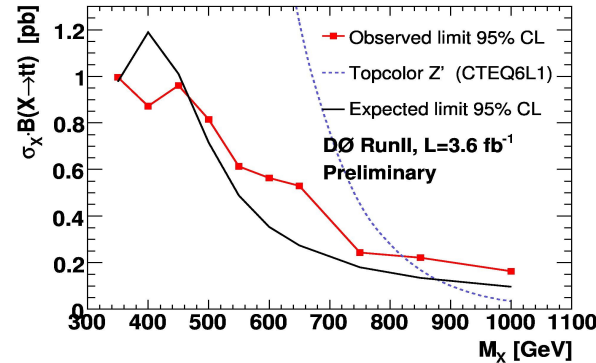
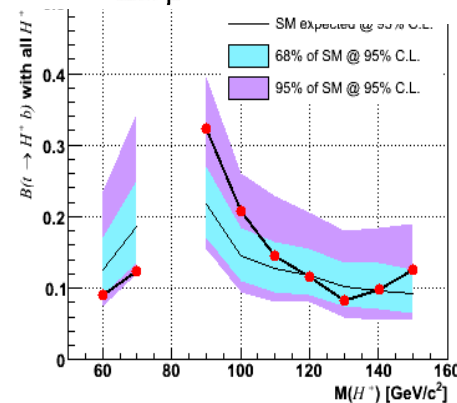
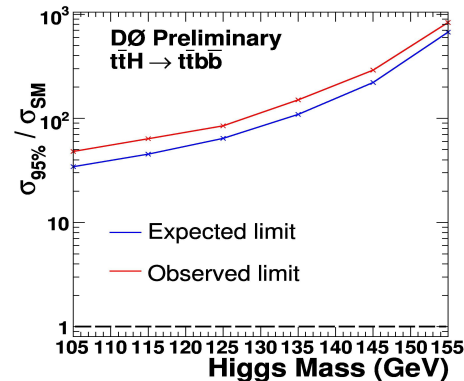
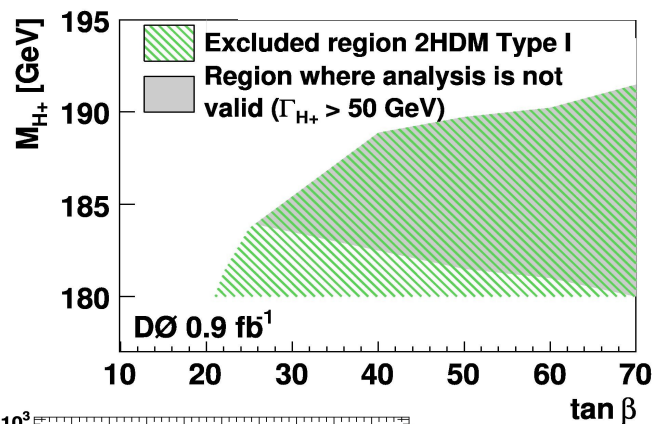
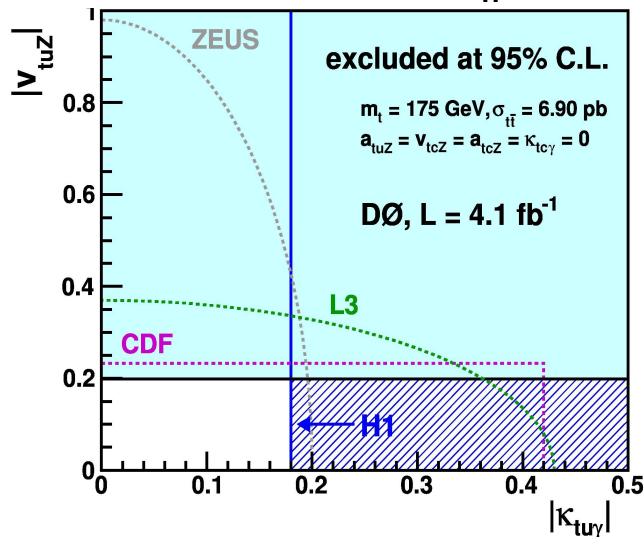
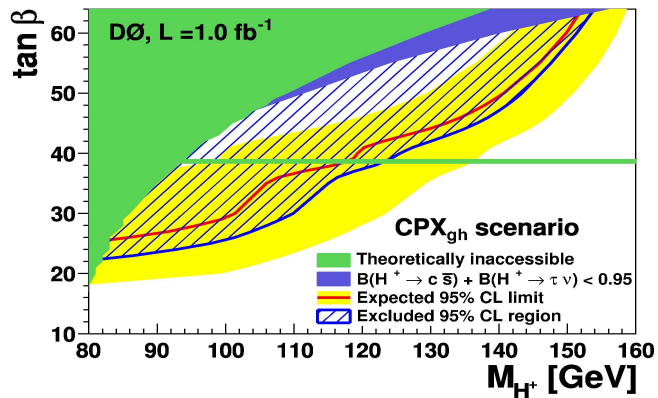
- Pull variable to distinguish singlet from octet
- Use it for **new physics** searches (e. g. ZH)
- Study color flow in  $l$ +jets  $t\bar{t}$  events  $\Rightarrow$  clean  $W \rightarrow jj$  sample
- Result for  $f_{\text{Singlet}} = N_{\text{singlet}} / N_{\text{total}} = 0.56 \pm 0.38(\text{stat+syst}) \pm 0.19(\text{MC stat})$

**First study of color flow in  $t\bar{t}$  events**

Phys. Rev. D 83, 092002 (2011)

# The neglected Part III: Searches in the Top Sector

Many sensitive searches:  
 $t'$ ,  $Z'$ ,  $W'$ ,  $H^+$ , FCNC,  
boosted top,  $t\bar{t}H$ ,...



# Summary and Outlook

- Rich top quark program at DØ
  - Precision **measurements** (cross section, mass)
  - Many new properties analyzed for the first time (e. g. color flow, spin correlation)
  - Sensitive **searches**, e. g. ,  $t'$ , charged Higgs
  - Many analyses complementary to LHC



- Full beauty of top results

DØ: [http://www-d0.fnal.gov/Run2Physics/top/top\\_public\\_web\\_pages/top\\_public.html](http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html)

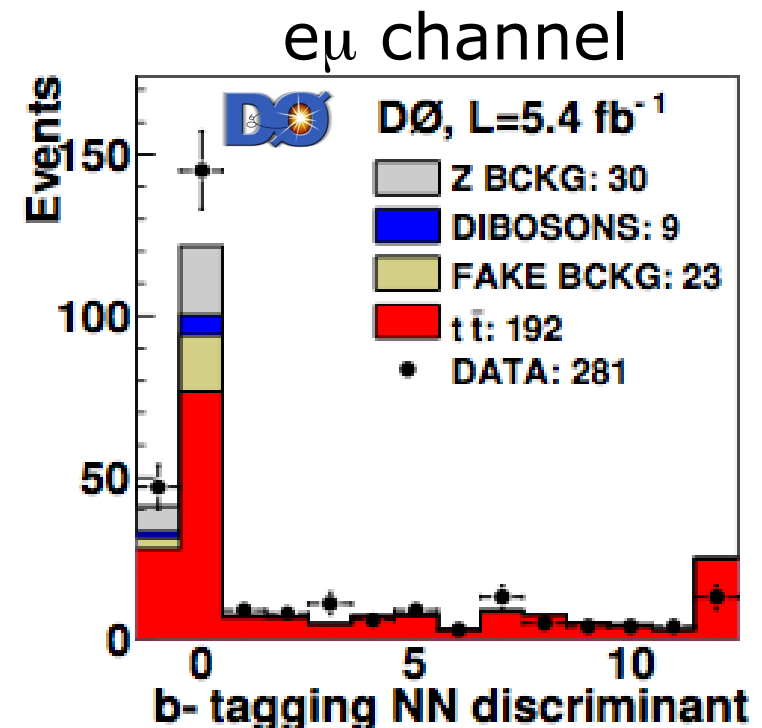
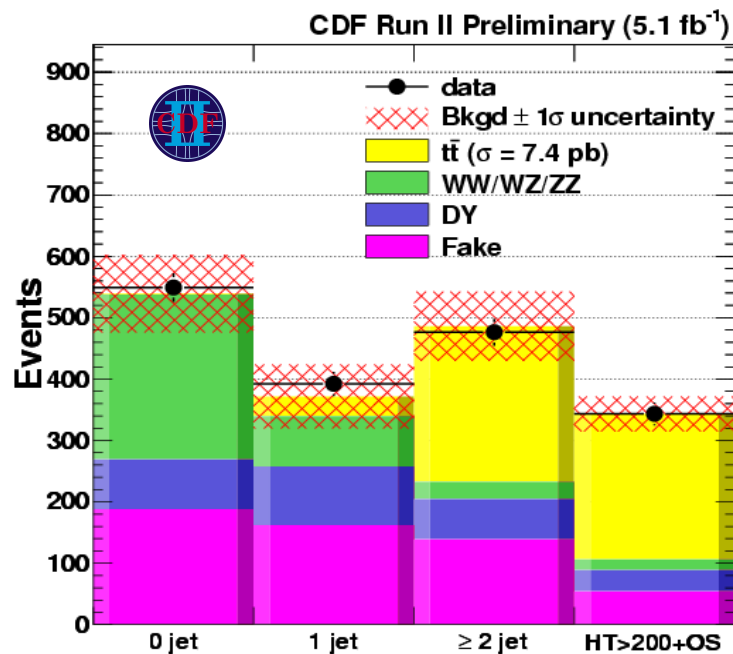
CDF: <http://www-cdf.fnal.gov/physics/new/top/top.html>

- Great performance of the Tevatron
  - More to explore in the top sector
  - Concentrate on legacy & complementary measurements

# Backup

# $\sigma_{t\bar{t}}$ in Dilepton

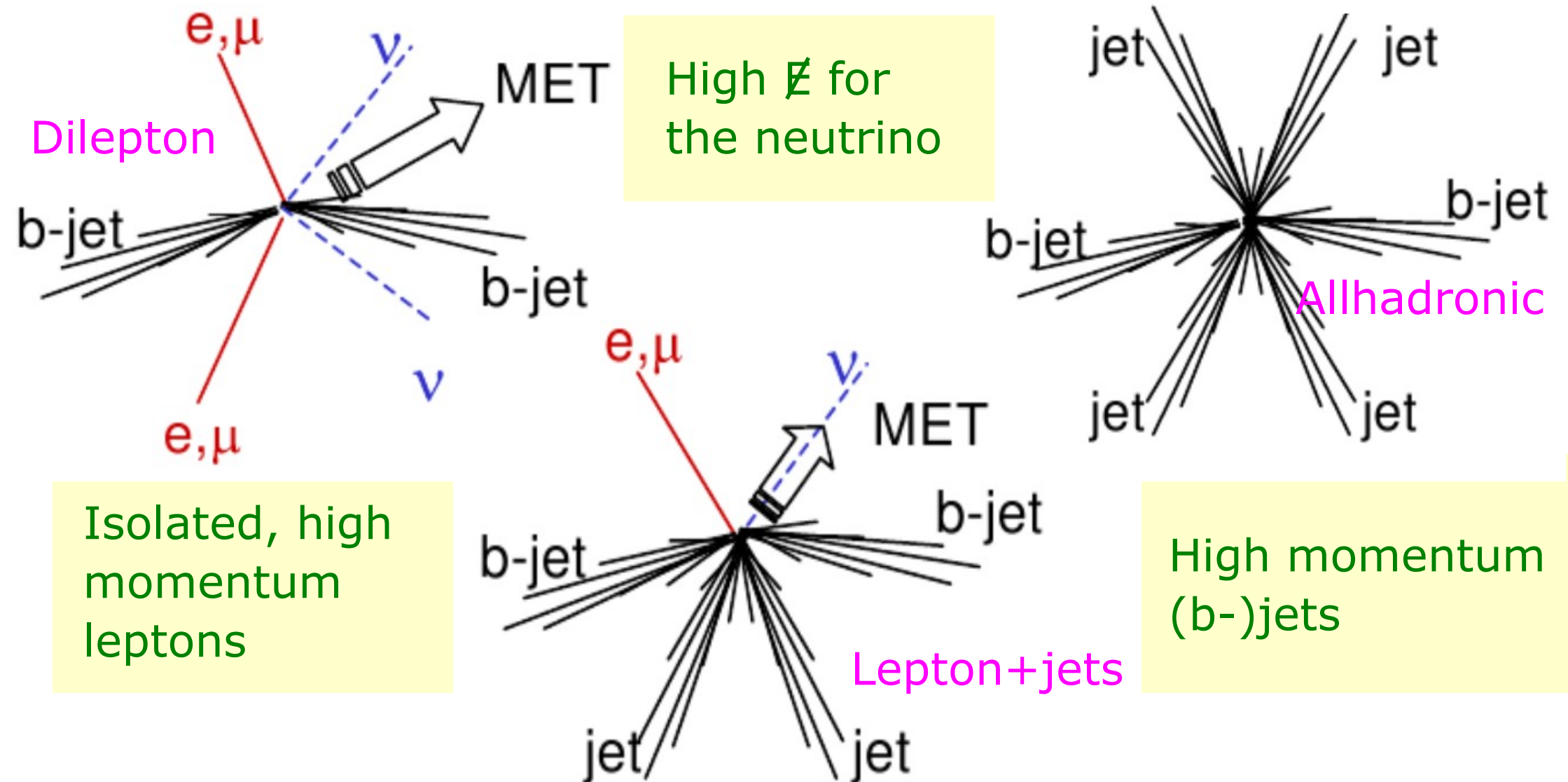
- Very clean channel  $\rightarrow$  use b-jet identification or pure counting
- DØ: Use b-tag NN output as discriminant



$$D0: \quad \sigma = 7.4^{+0.9}_{-0.8} (stat + syst) pb$$

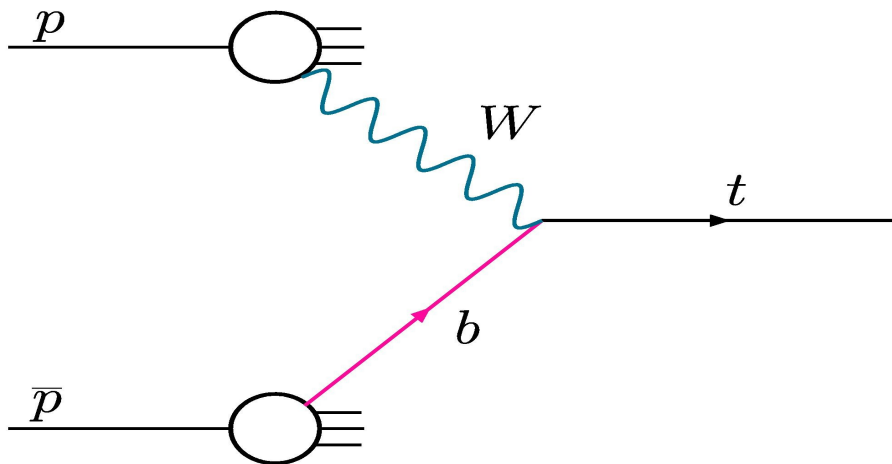
$$CDF: \quad \sigma = 7.25 \pm 0.66 (stat) \pm 0.47 (sys) \pm 0.44 (lumi) pb$$

# Event selection: Use the signature!



# Limit on $|V_{tb'}|$

- Example for new physics affecting the top width
- Use the total width determination to constrain coupling to a fourth generation **b' quark**, with  $m_{b'} > m_t - M_W$ 
  - Will only affect the production
  - Low probability density of b' in proton & antiproton
  - Assume  $|V_{tb}|^2 + |V_{tb'}|^2 = 1$ ,  $|V_{ts}|, |V_{td}| \ll 1$



First limit on W boson coupling to top and b' quark

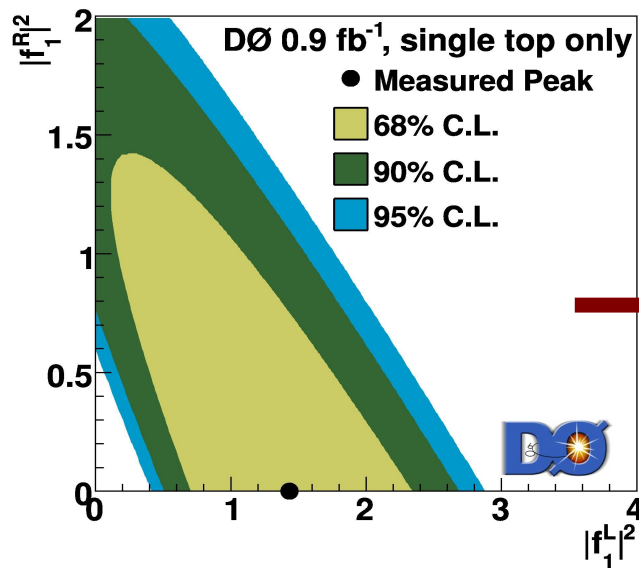
$$|V_{tb'}| < 0.63 \quad @ \ 95\% \text{ C.L.}$$

# W helicity and anomalous couplings

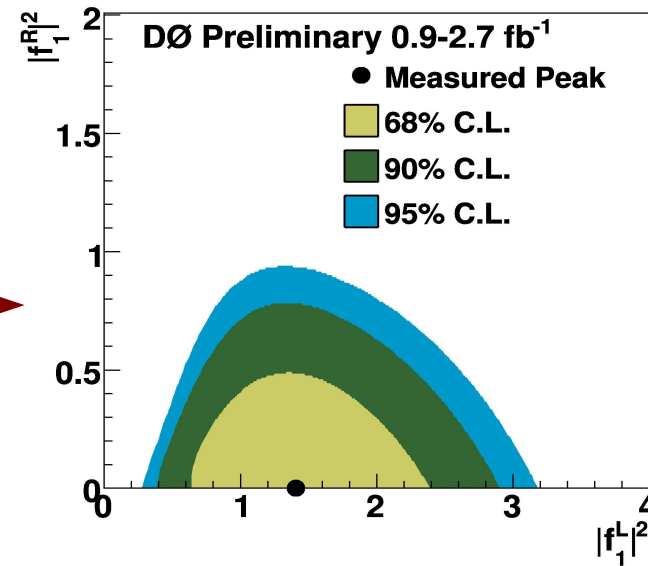
- Form factors  $f_1^L, f_1^R, f_2^L, f_2^R$ : Can be extracted in single top channel

- Single top and W helicity measurement:
  - Usage of all applicable top quark measurements

$$\mathcal{L} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu V_{tb} (f_1^L P_L + f_1^R P_R) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i\sigma^{\mu\nu} q_\nu V_{tb}}{M_W} (f_2^L P_L + f_2^R P_R) t W_\mu^- + h.c.$$



Single top alone



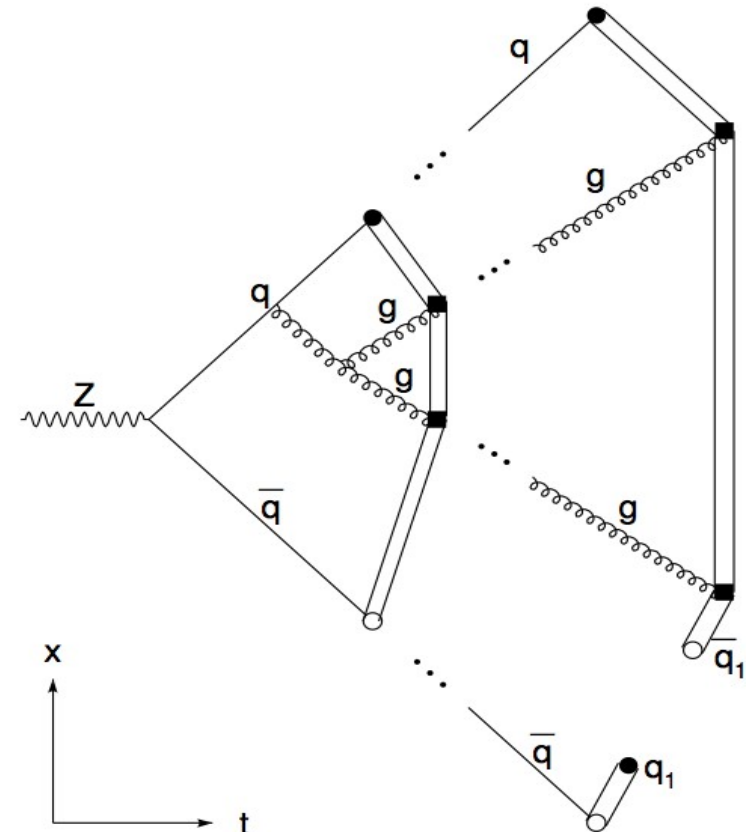
Single top and W helicity

# W helicity: Systematics

Source	Uncertainty ( $f_+$ )	Uncertainty ( $f_0$ )
Jet energy scale	0.007	0.009
Jet energy resolution	0.004	0.009
Jet ID	0.004	0.004
Top quark mass	0.011	0.009
Template statistics	0.012	0.023
$t\bar{t}$ model	0.022	0.033
Background model	0.006	0.017
Heavy flavor fraction	0.011	0.026
$b$ fragmentation	0.000	0.001
PDF	0.000	0.000
Analysis consistency	0.004	0.006
Muon ID	0.003	0.021
Muon trigger	0.004	0.020
Total	0.032	0.060

# String Fragmentation Model

- **Color string** building up between the color connected particles
- Color string has constant energy density (1GeV/fm)
- When quark-antiquark pair separates, potential energy in string increases
  - New  $q\bar{q}$  pair can be built out of the vacuum once energy is large enough
  - **Arise along the lines of color string!**
- Alternative hadronization models exist, all having the idea of **color connection** in common

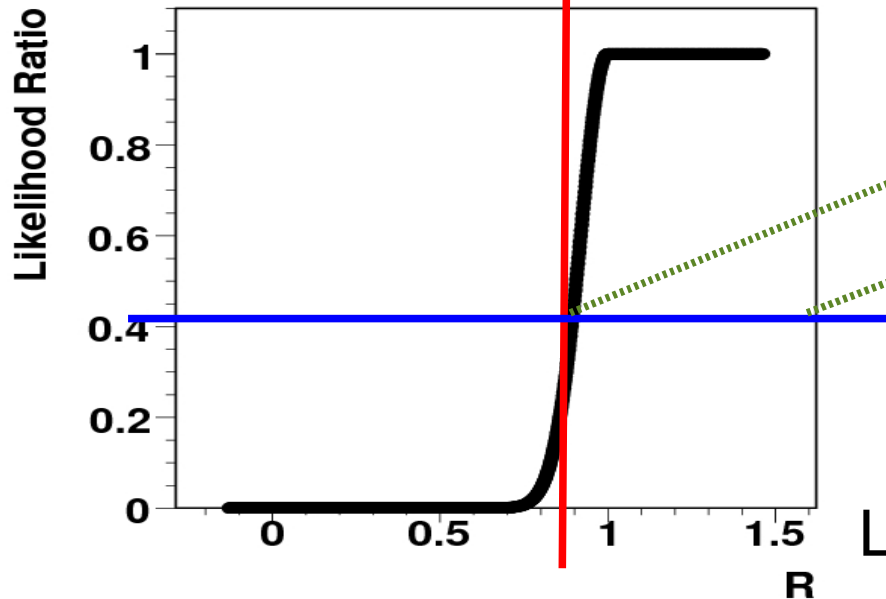
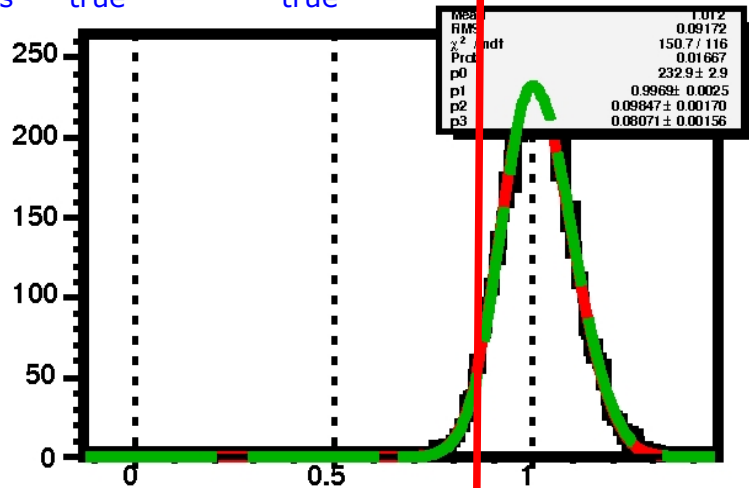


# Feldman & Cousins Limits

- **Feldman & Cousins method for calculation of limits:**
  - **Pseudo-experiments** for various true  $R$  ( $R_{\text{true}}$ )
    - Number of events is chosen randomly within a Poisson distribution
    - All systematic uncertainties are varied randomly within a Gaussian distribution
  - For each true  $R$  one obtains a distribution of measured values  $R_{\text{meas}}$ : normalized distributions are  $P(R_{\text{meas}} | R_{\text{true}})$
  - Application of the “likelihood ratio ordering”:
    - calculation of  $r_{\text{likeli}}(R_{\text{meas}}) = \frac{P(R_{\text{meas}} \setminus R_{\text{true}})}{P(R_{\text{meas}} \setminus R_{\text{best}})}$
    - $R_{\text{best}}$ :  $R_{\text{true}}$  for which  $P(R_{\text{meas}} | R_{\text{true}})$  is maximal
      - has to be within the physically allowed region

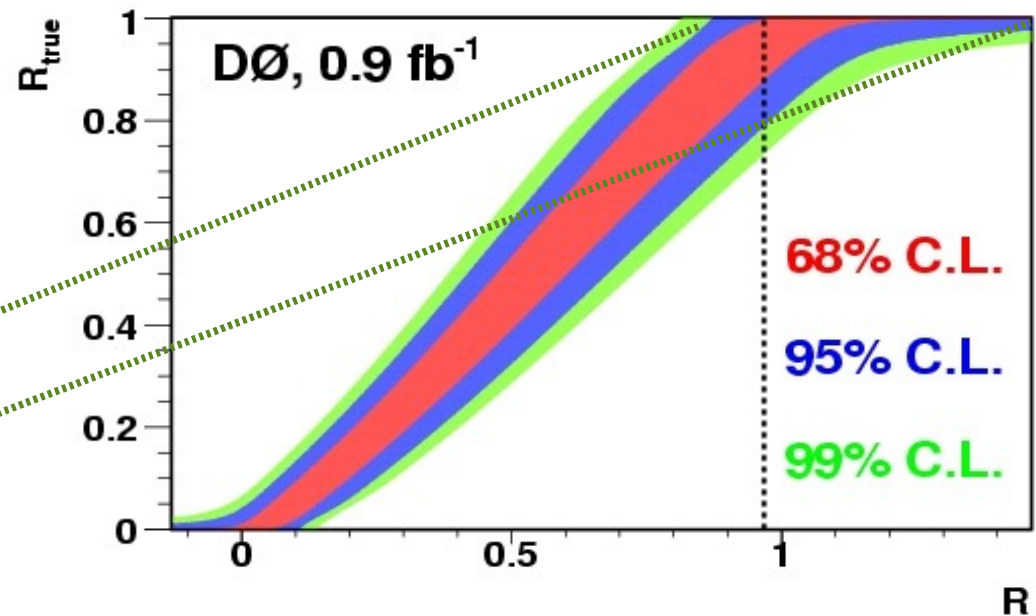
# Feldman & Cousins Limits

$P(R_{\text{meas}} | R_{\text{true}})$  for  $R_{\text{true}} = 1$



Likelihood ratio for  $R_{\text{true}} = 1$

Variation of the blue line until the area of  $P(R_{\text{meas}} | R_{\text{true}})$  is 95% within the interactions points with  $r_{\text{likeli}}$  (red line) is 95%



# Color Flow: Toy MC

- Toy MC study of calorimeter effects:
  - Granularity:  $0.1 \times 0.1$  in  $e \times p$  towers
- Calorimeter noise floor per cell: 150MeV
  - 500MeV threshold for hadron
- Charged particles with  $< 75\text{MeV}$  are ignored due to being bent by magnetic field
- Energy resolution: MC tower is smeared with  $50\%/\sqrt{E[\text{GeV}]}$ 
  - Resolution in hadronic calorimeter
- Noise/pile-up: Each MC tower has a chance of 7% to have added noise to it
  - $p_T$ : Exponential distribution around mean 360MeV

# Some props: Jet Energy Scale

