# Testing the Standard Model with Top Quarks

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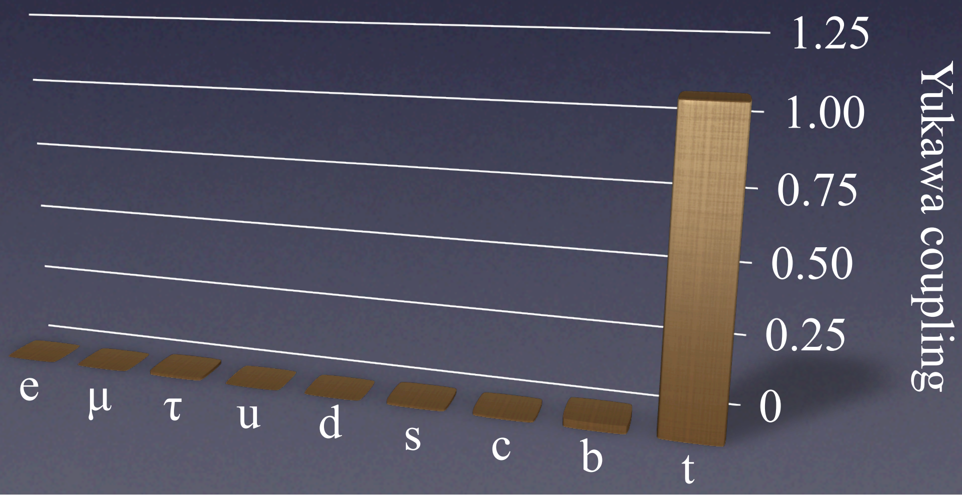
14th Lomonosov Conference
on Elementary Particle Physics
Moscow, Russia
August 25, 2009

# The Top Quark in the SM and Beyond

- All top quark properties (except its mass) are fixed in the SM
  - It's "just" another isospin +½ quark
- In addition, the SM predicts $|V_{tb}| \approx 1$
  - So the top has one dominant decay mode: $t \rightarrow Wb$
- Most of the interest in top quark physics comes from the potential to find non-standard effects
- Is Yukawa coupling a hint?




Top is the only fermion with a "natural" coupling

# What We Can Learn From the Top Quark

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- Questions

What is the Higgs boson mass?

Do we understand heavy flavor production in QCD?

Are there more than three fermion generations?

Are there new massive particles?

Do all quarks have the expected couplings?

Does the CPT Theorem hold for quarks?

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- Measurements in this talk
  - Single top quark production
  - Constraints on *Wtb* couplings
  - Top quark pair cross section
  - Top quark mass
  - Mass difference between top and anti-top
  - Forward-backward charge asymmetry
  - $M_{tt}$ distribution
  - Search for $t'$ quark
  - Spin correlations
  - Searches for $t \to H^+ b$

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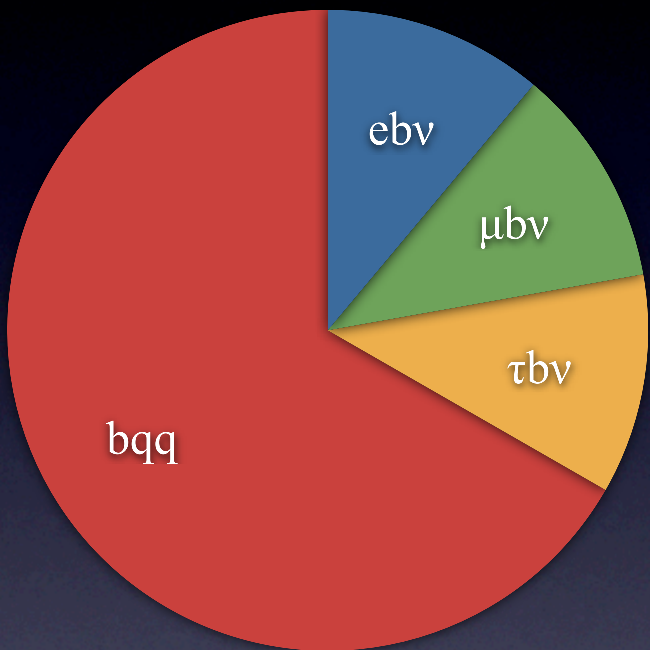
# Top Quark Signatures

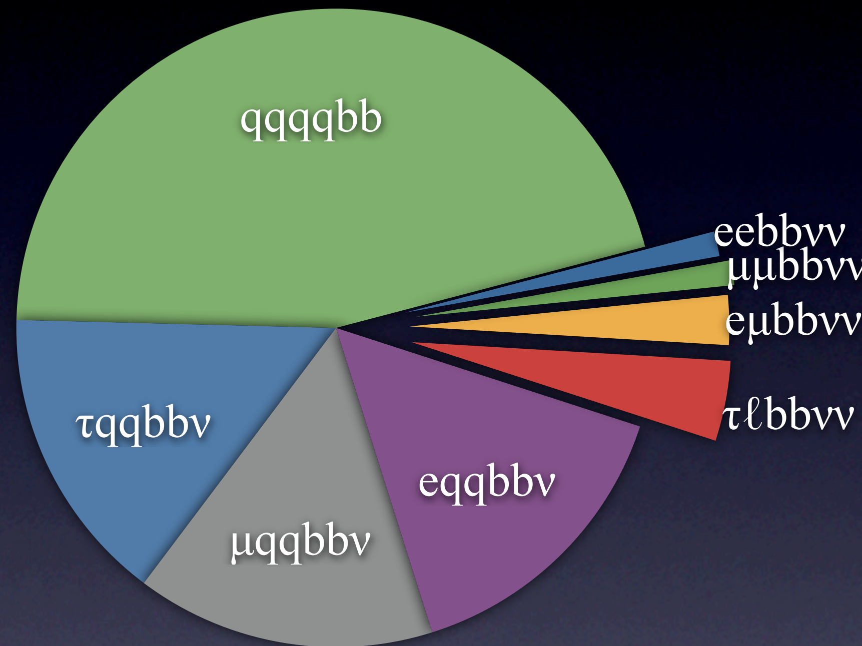
- Single top quark:

Tevatron cross section: ~3 pb




- Top quark pair:

Tevatron cross section: ~7 pb

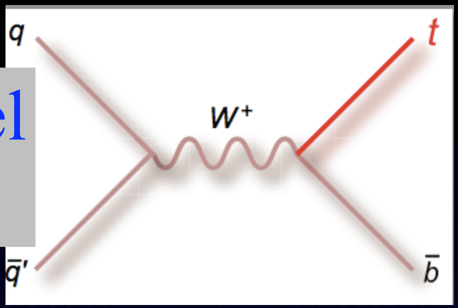



- Dominant backgrounds arise from vector boson + jet production
  - Good *b* jet and lepton ID, missing $E_T$ resolution help in finding top quarks

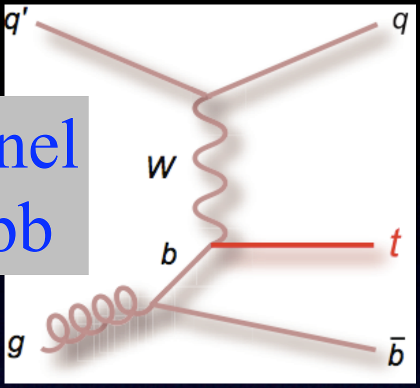
# Top Quarks, One at a Time

- Production at the Tevatron:

s-channel
0.88 pb




t-channel
1.98 pb




- Direct access to the *tWb* coupling
  - overall rate and ratio between s- and t-channels are sensitive to new physics
- Experimental challenge:
  - cross section ~x2 lower than $t\bar{t}$
  - large backgrounds from $W + 2$ jets

S/B ~1/200 before *b*-tagging

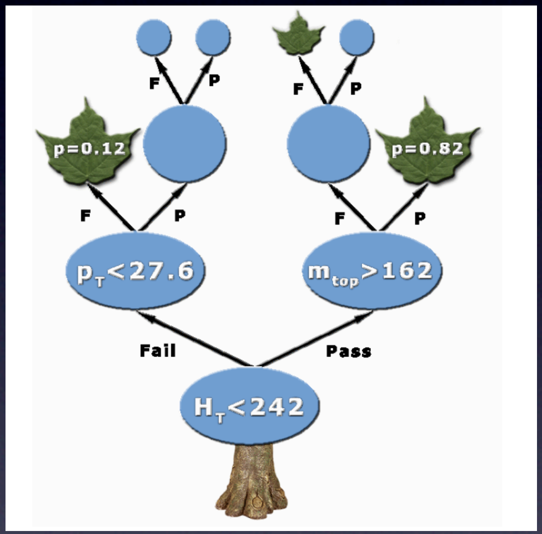
- Need multivariate techniques to extract signal

# Multivariate Methods

Goal: Given a set of measurements **x**, find

$$p(S|\mathbf{x}) = \frac{p(S)\,p(\mathbf{x}|S)}{p(S)\,p(\mathbf{x}|S) + p(B)\,p(\mathbf{x}|B)}$$

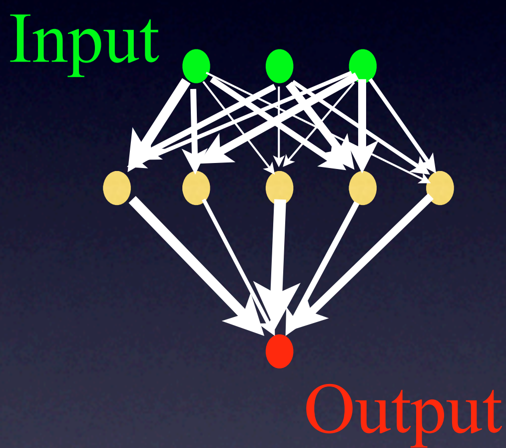
## Boosted decision tree




Training determines shape of tree

Iterative "boosting" improves performance

## Neural network



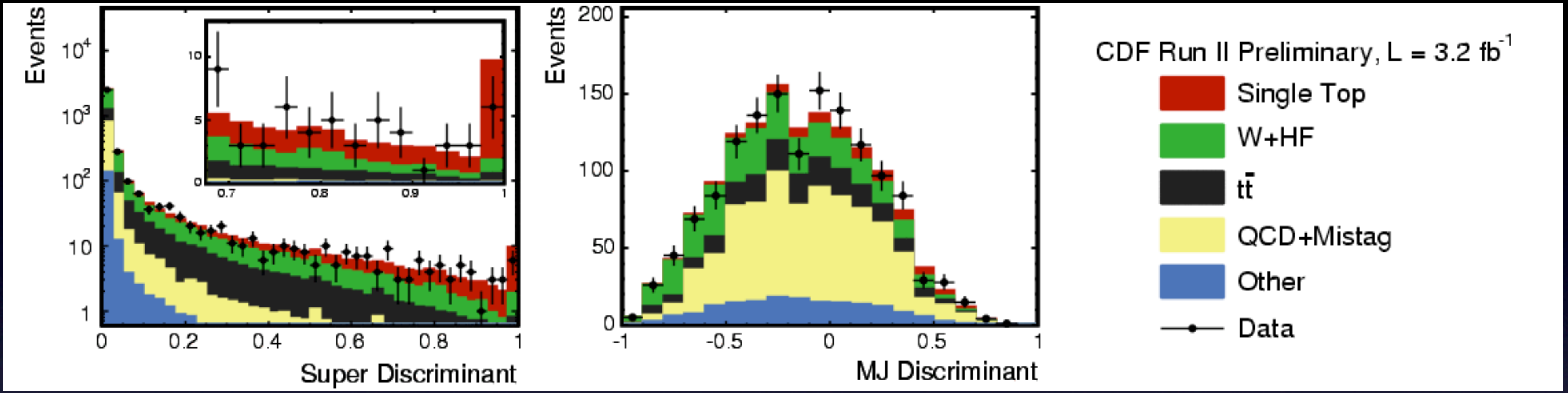

Train on MC samples to optimize weights

## Matrix element

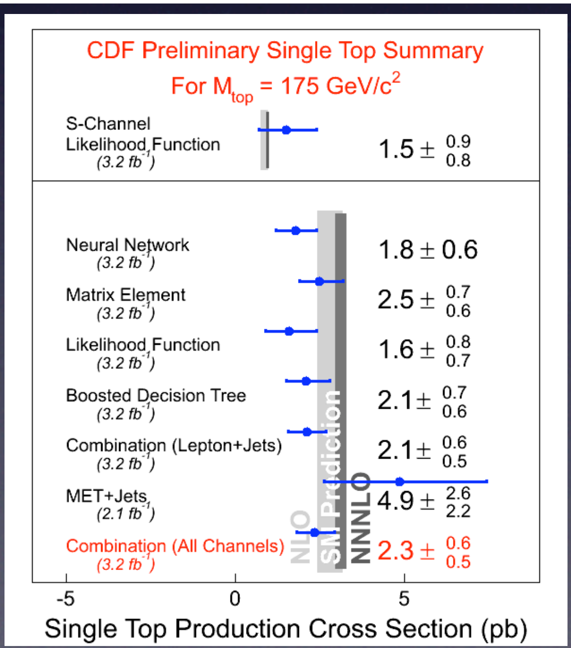
- Calculate $p(S|\mathbf{x})$ from signal and bkg differential cross section matrix elements
- Integrate over detector resolution

# Single Top At CDF

- ℓ+jets: Outputs from BDT, ME, and NN are input to final NN




- Result is combined with missing $E_T$ + jets



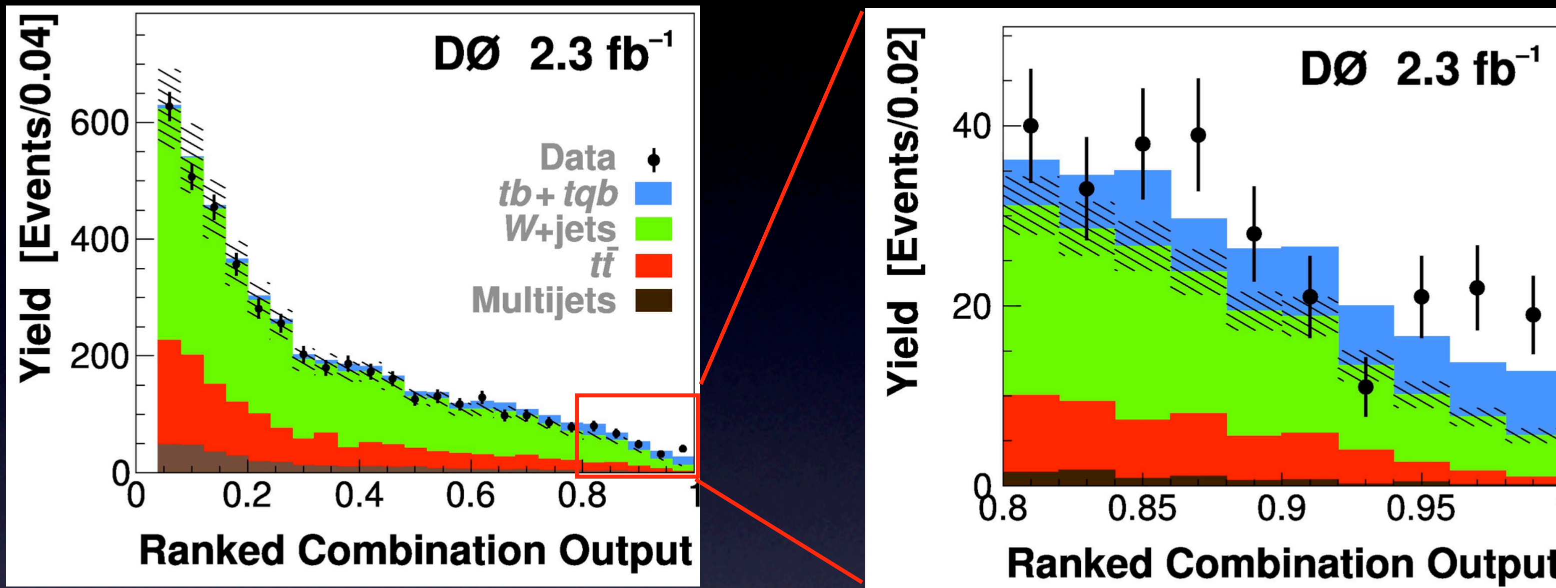

$\sigma = 2.3^{+0.6}_{-0.5}$ pb

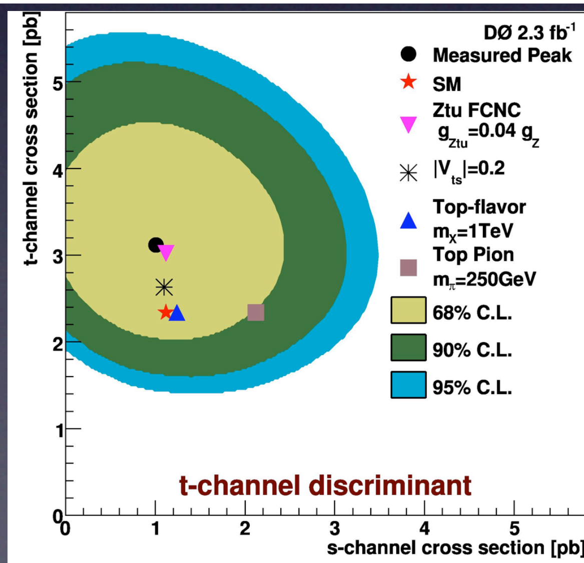
5.0σ significance (obs) [5.9σ exp]

$|V_{tb}| > 0.71$ @ 95% C.L.

# Single Top at DØ

- Outputs from BDT, ME, and NN are input to final NN:




$\sigma_{\text{t-channel}} = 3.14^{+0.94}_{-0.80}$ pb

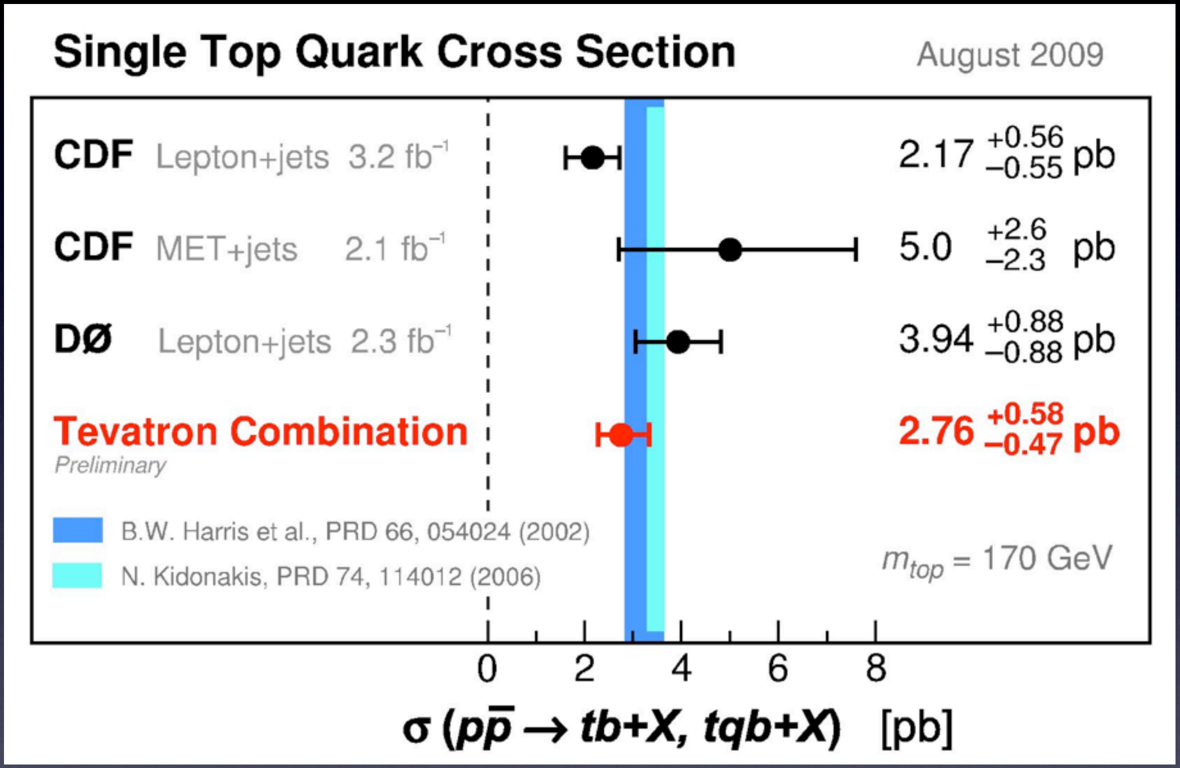
$\sigma_{\text{s-channel}} = 1.05 \pm 0.81$ pb

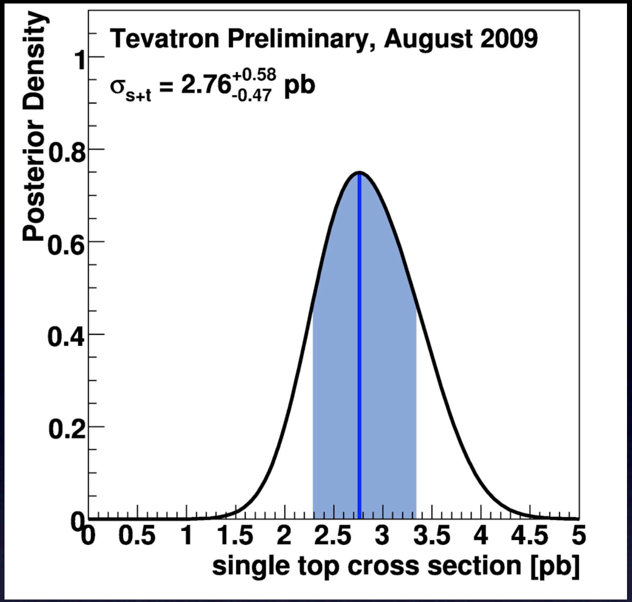
$\sigma_{\text{total}} = 3.94 \pm 0.9$ pb

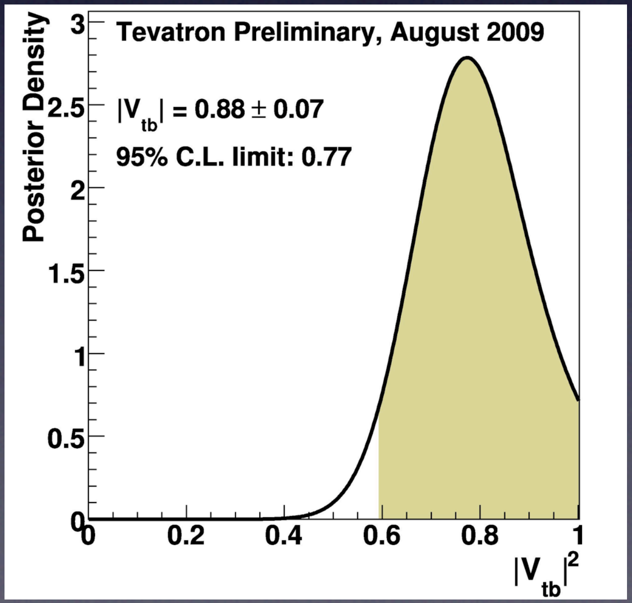
5.0σ significance (obs) [4.5σ exp]

$|V_{tb}| > 0.78$ @ 95% C.L.

# Combined Single Top Cross Section



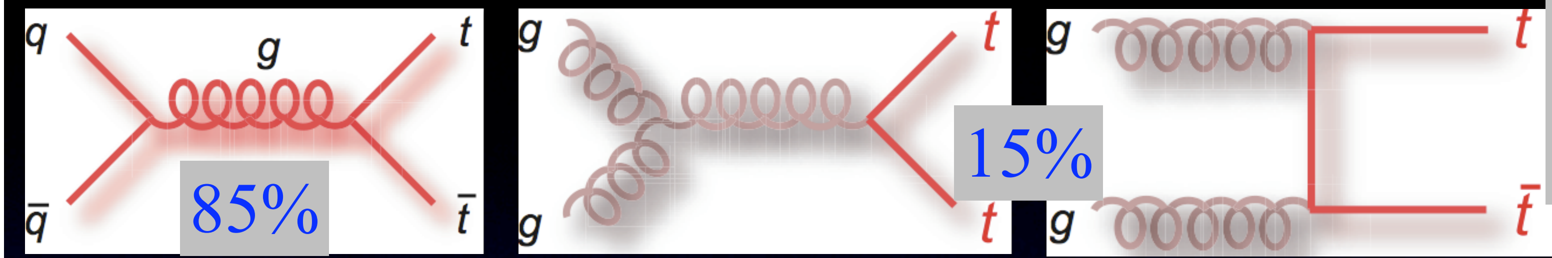




$\sigma = 2.76^{+0.58}{}_{0.47}$ pb

$|V_{tb}| > 0.77$ @ 95% C.L.

# Top Quarks, Two at a Time

- Production at the Tevatron:

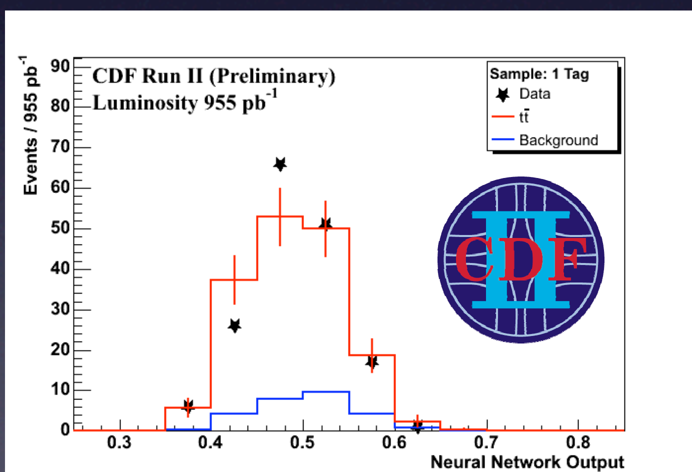



Most top measurements use $t\bar{t}$ events

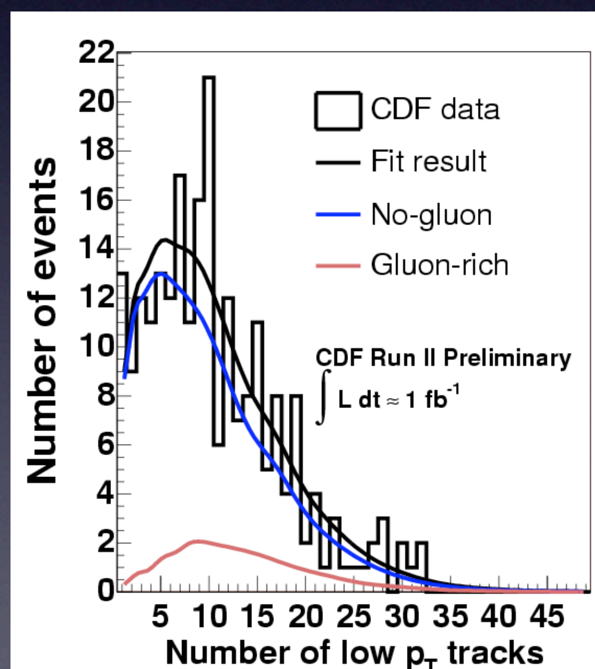
- CDF has measured the $q\bar{q}$ and $gg$ contributions in three ways:

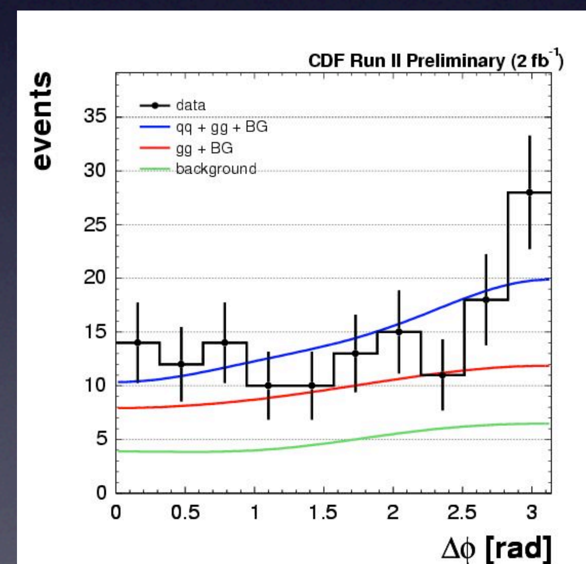
Kinematic neural net, # of low-$p_T$ tracks in $\ell$+jets events:

$\Delta\varphi_{\ell\ell}$ in dilepton events:




$$F_{gg} = 0.07^{+0.15}_{-0.07}$$

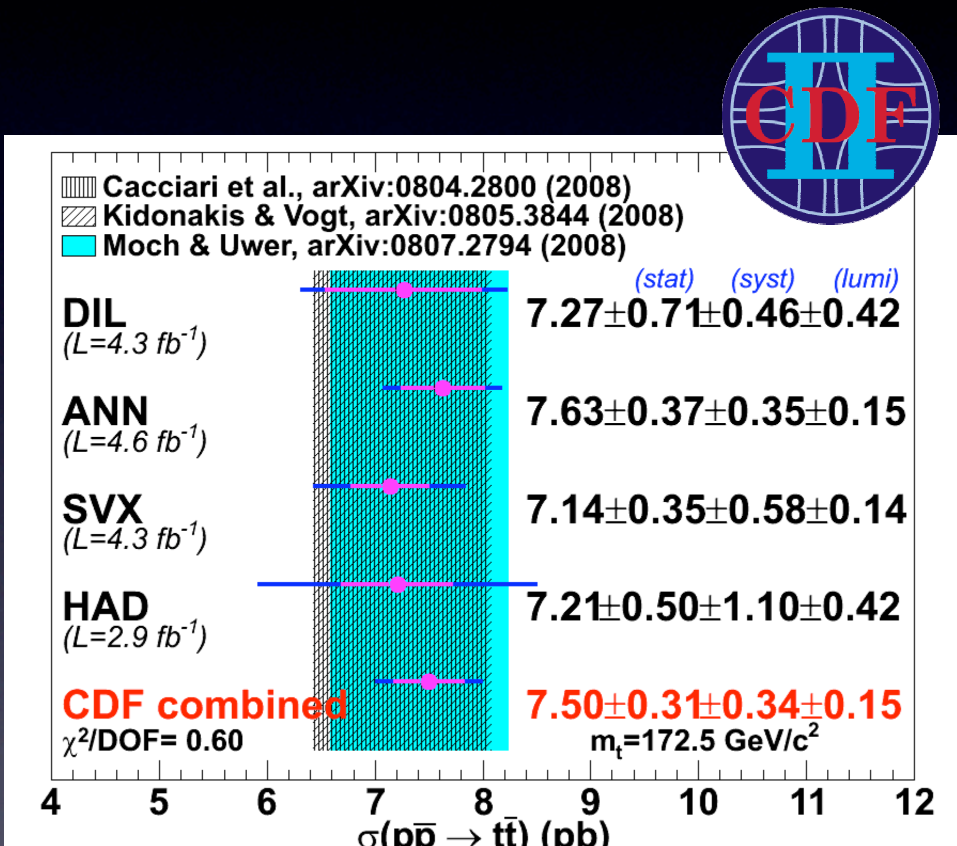



$$F_{gg} = 0.53^{+0.35+0.07}_{-0.37-0.08}$$

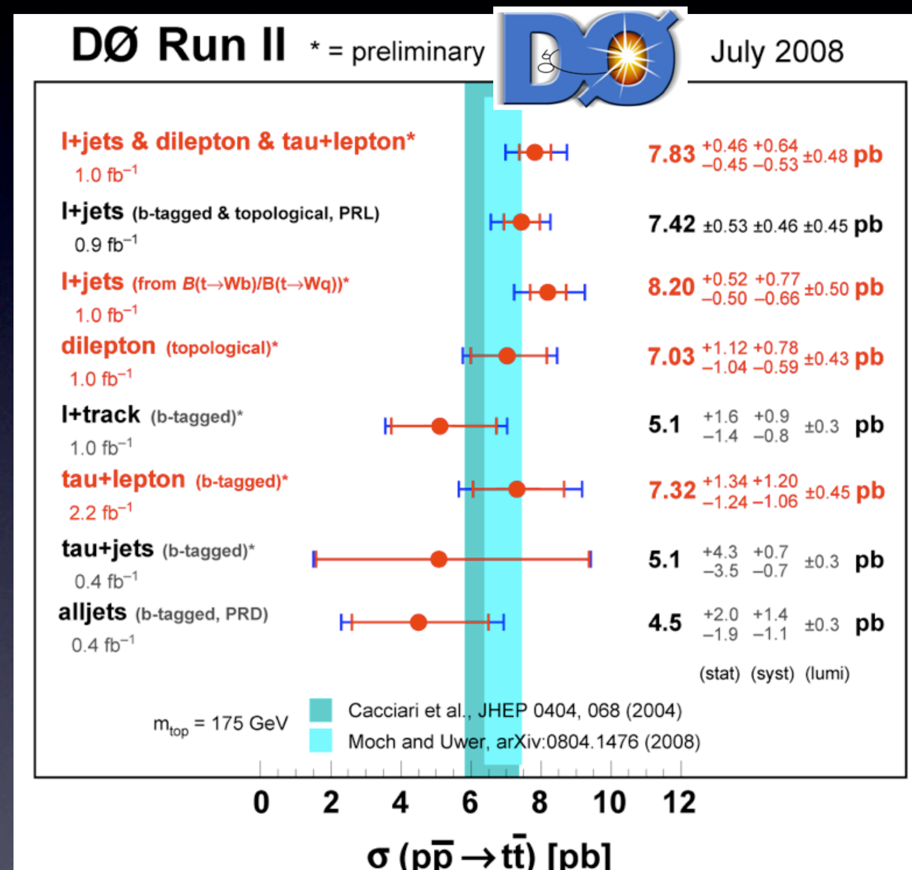
# Production Cross Section

- The $t\bar{t}$ cross section has been measured in many final states
  - new physics may impact final states differently




$\sigma(p\bar{p} \to t\bar{t}) = 7.50 \pm 0.31 \pm 0.34 \pm 0.15$ pb

stat. syst. lum.



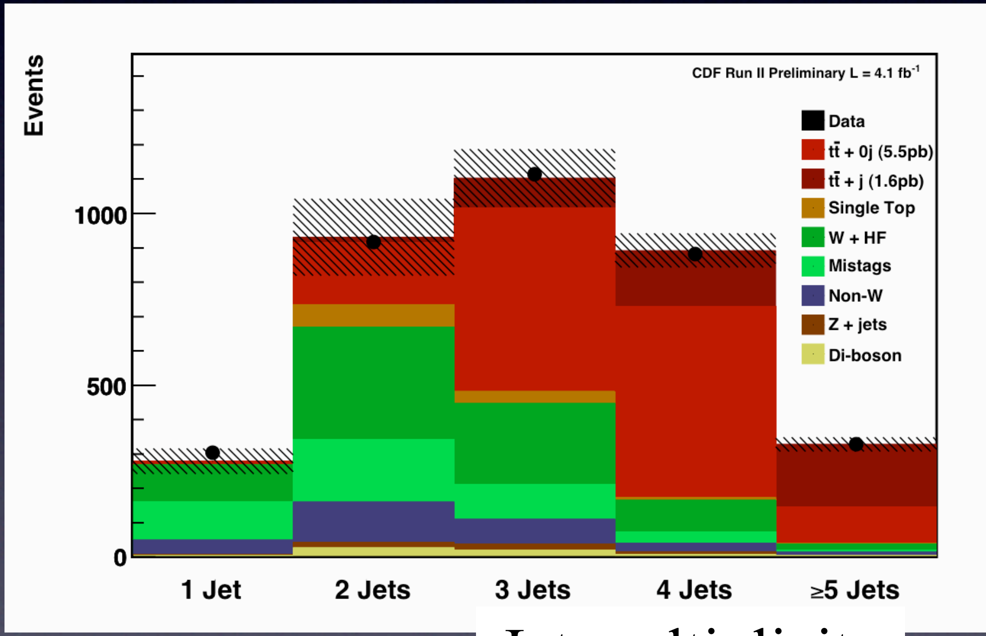

$\sigma(p\bar{p} \to t\bar{t}) = 7.8 \pm 0.5 \pm 0.6 \pm 0.5$ pb

stat. syst. lum.

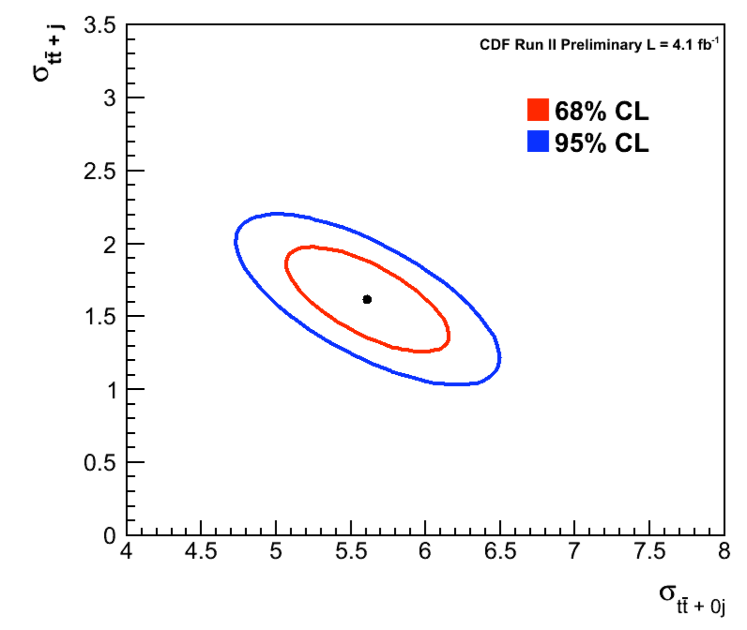
# $t\bar{t}$ + Jet Cross Section

- First measurement of production rate of $tt$ in association with jets
  - Test of perturbative QCD at NLO

QCD NLO prediction: $\sigma\left(p\bar{p} \rightarrow t\bar{t} + j\right) = 1.79^{+0.16}_{-0,31}$ pb




Jet multiplicity




$\sigma(pp \rightarrow tt+j) = 1.6 \pm 0.2$ (stat.) $\pm 0.5$ (syst.) pb

# Direct Measurement of the Top Quark Mass

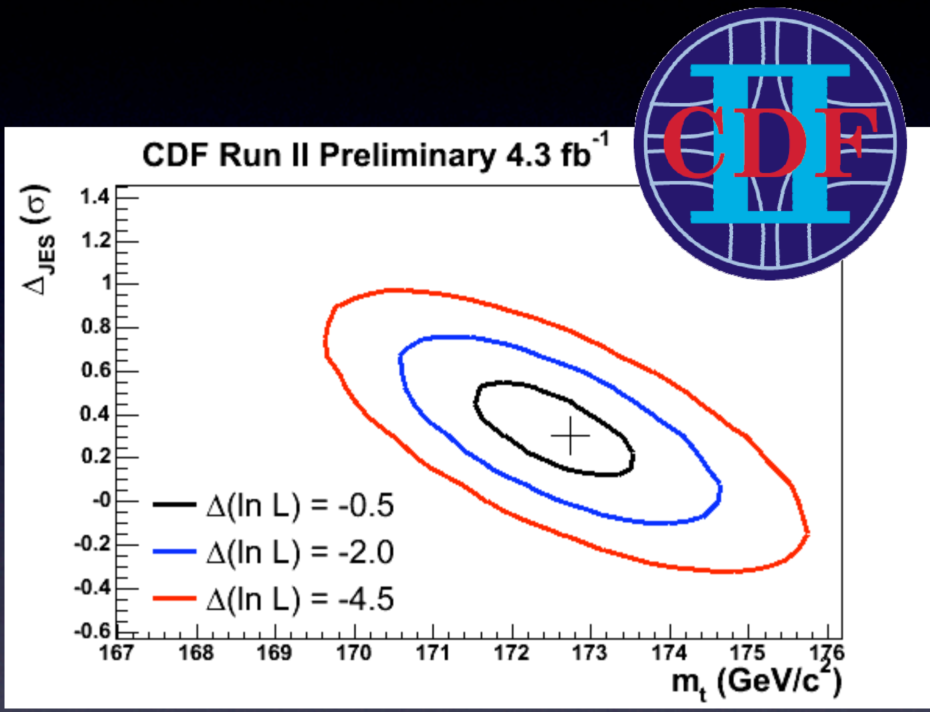
- Goal: measure top mass precisely...
  - to constrain Higgs mass
- ...in as many channels as possible
  - to search for new physics

$\ell$+jets modes have optimal combination of rate and background

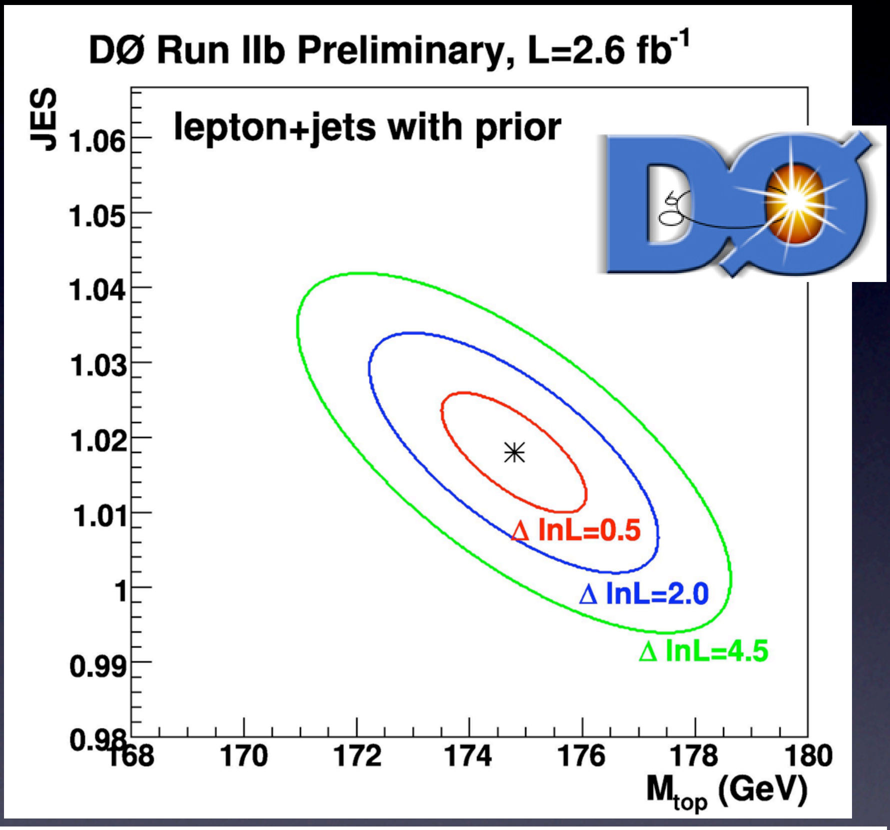
- Matrix element method provides best sensitivity
  - discriminate between top mass hypotheses as well as between signal and background
  - calibrate jet energy measurement from $W \rightarrow jj$ in signal events

# Top Quark Mass ( $\ell$ +jets)

- Results:




$m_t = 172.6 \pm 0.9 \pm 1.3$ GeV

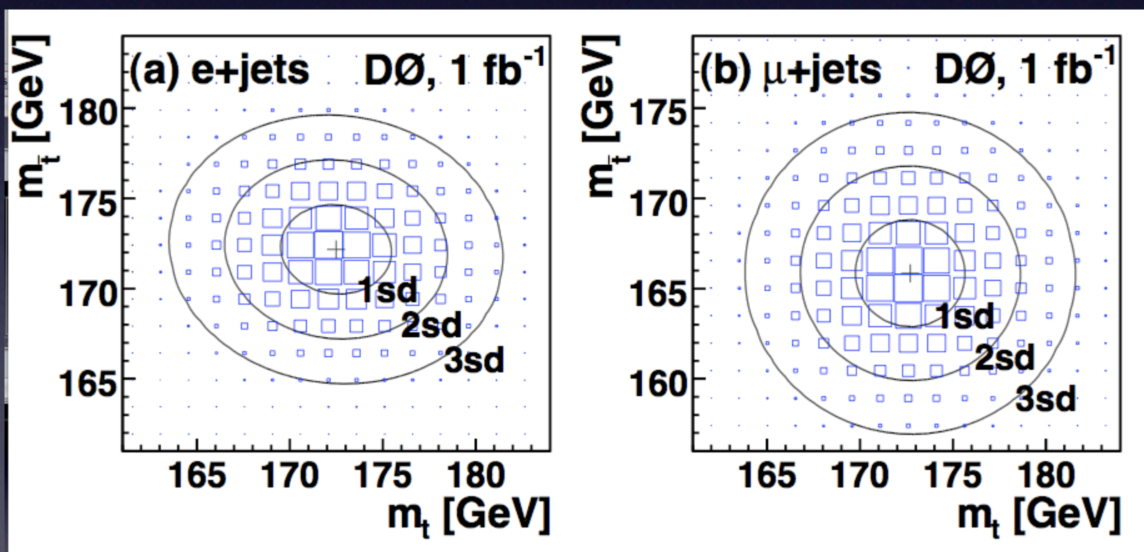


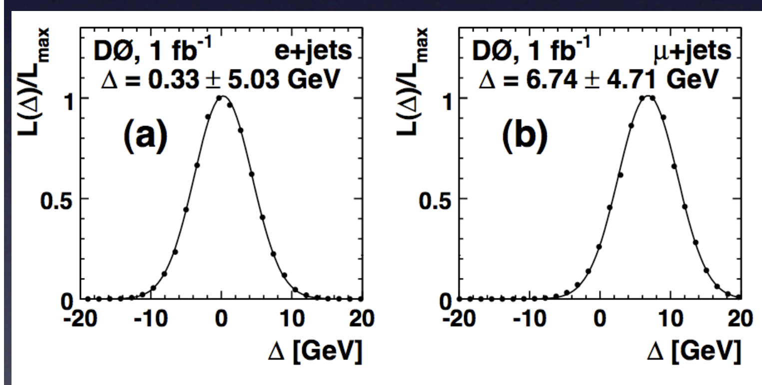

DØ Run II combined (3.6 fb$^{-1}$):
$m_t = 172.2 \pm 1.0 \pm 1.4$ GeV

# Top/anti-top mass difference

- The CPT theorem requires that particles and antiparticles have the same mass
- Extend matrix element method to measure $\Delta = m_t - m_{\bar{t}}$ in $\ell$ + jets events
  - lepton charge tags top flavor

Not directly tested for any quark



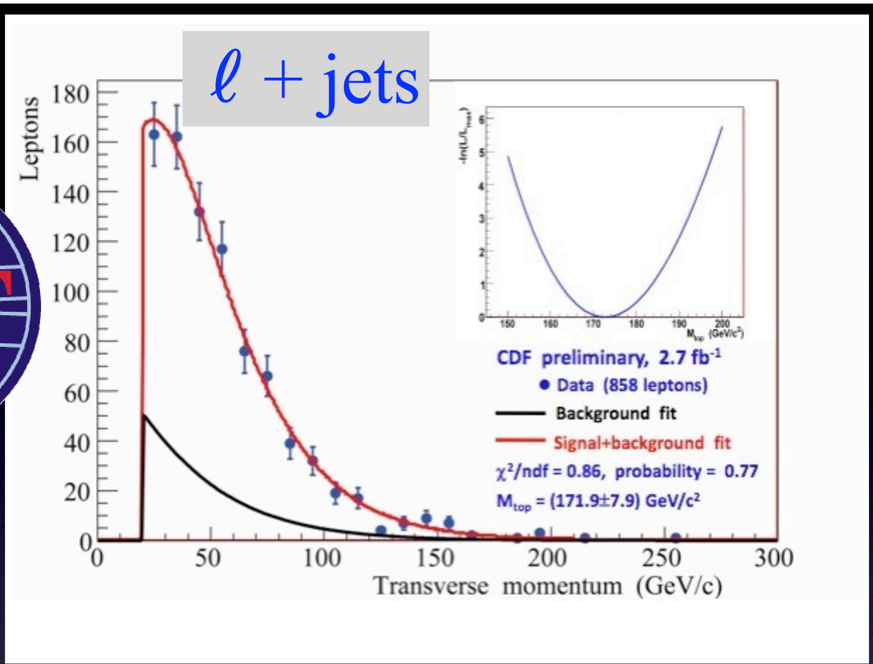




$$\Delta = 3.8 \pm 3.4 \pm 1.2 \text{ GeV}$$

# Top Quark Mass without Jet Energy

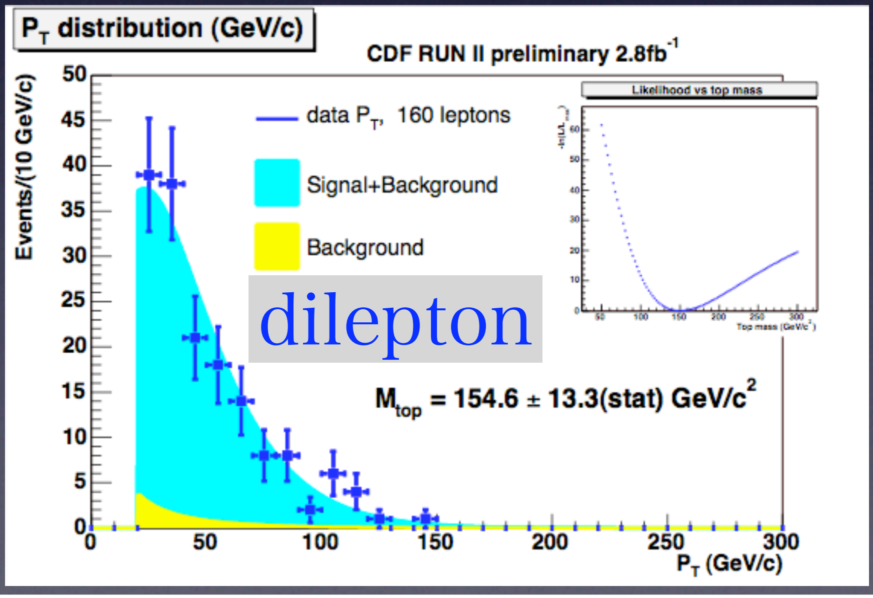
- Use observables that vary with top mass but have no first-order dependence on jet response
  - in this case, lepton $p_T$

$$m_t = 178.2 \pm 7.2 \pm 2.3 \text{ GeV}$$




Systematics largely orthogonal to other measurements

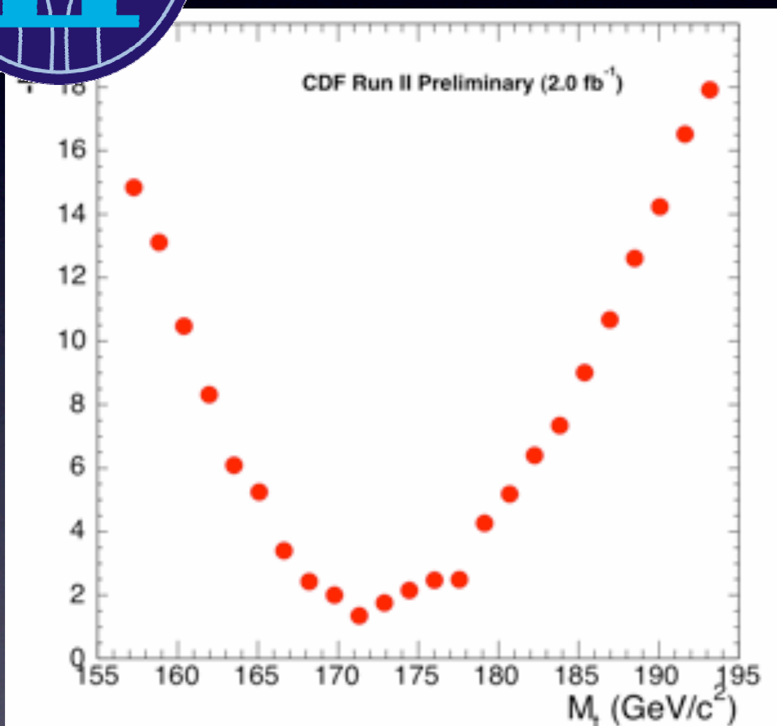
Currently statistics-limited, but will be an important technique at the LHC



# Top Quark Mass (Dilepton)

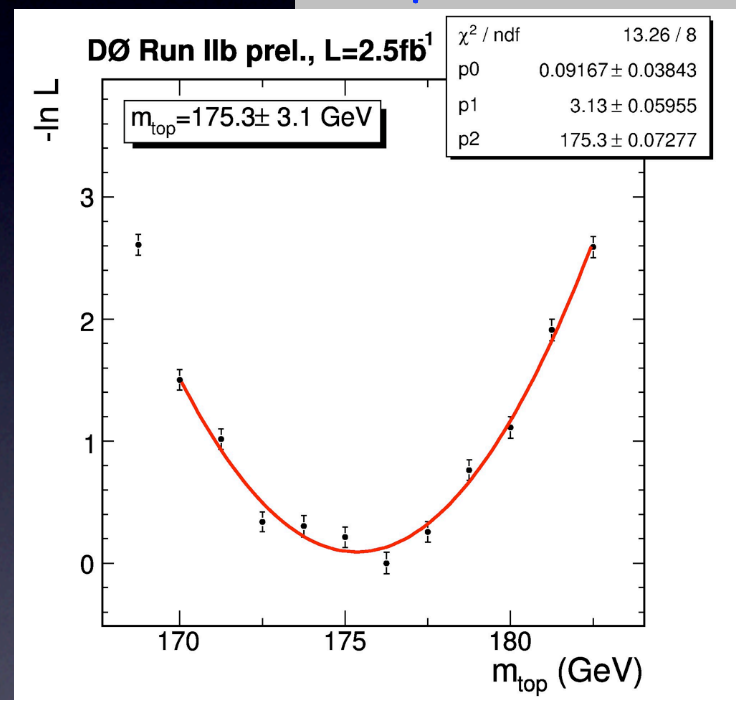
- Matrix element method can also be applied to dilepton events

Matrix Element,
NN event selection




$m_t = 171.2 \pm 2.7 \pm 2.9$ GeV

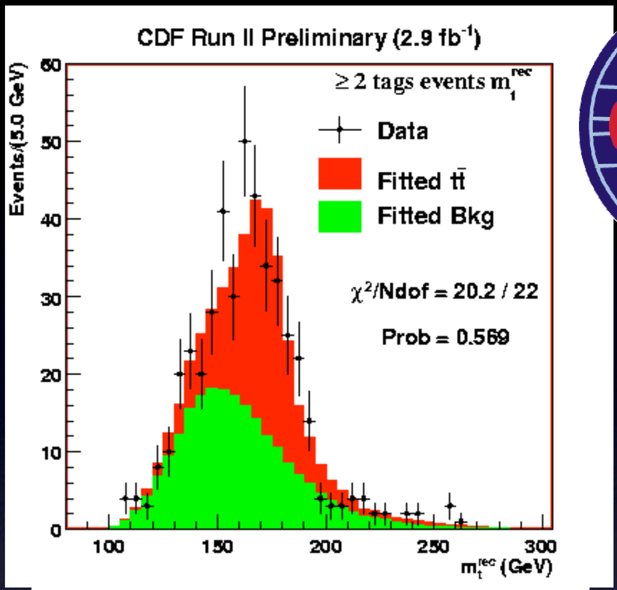
Matrix Element,
$e\mu$ channel

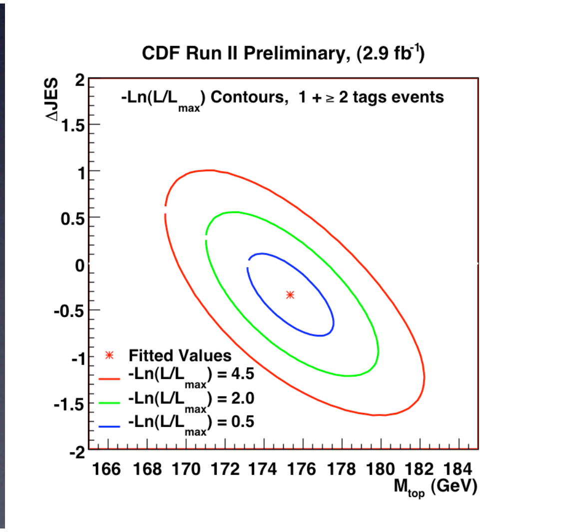



Run II $\ell\ell$ combined (3.6 fb$^{-1}$):
$m_t = 174.7 \pm 2.9 \pm 2.4$ GeV

# Top Quark Mass (all jets)

- Advantages of the all-hadronic channel:
  - largest $t\bar{t}$ branching fraction
  - fully measured final state
- Disadvantage:
  - huge background from multijet production
- *b* identification and neural network trained on kinematic differences are used in event selection

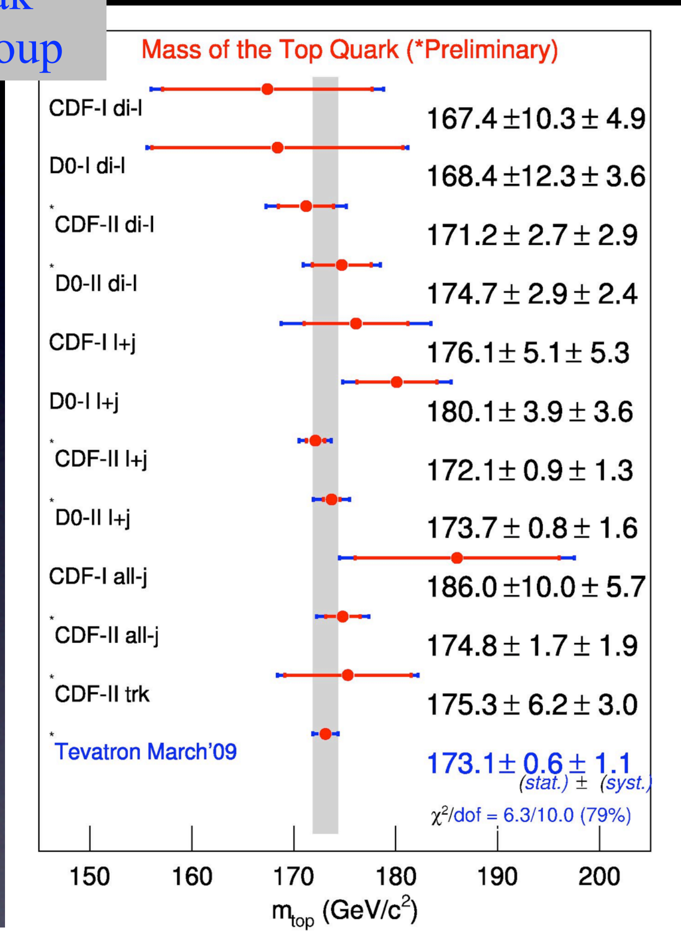


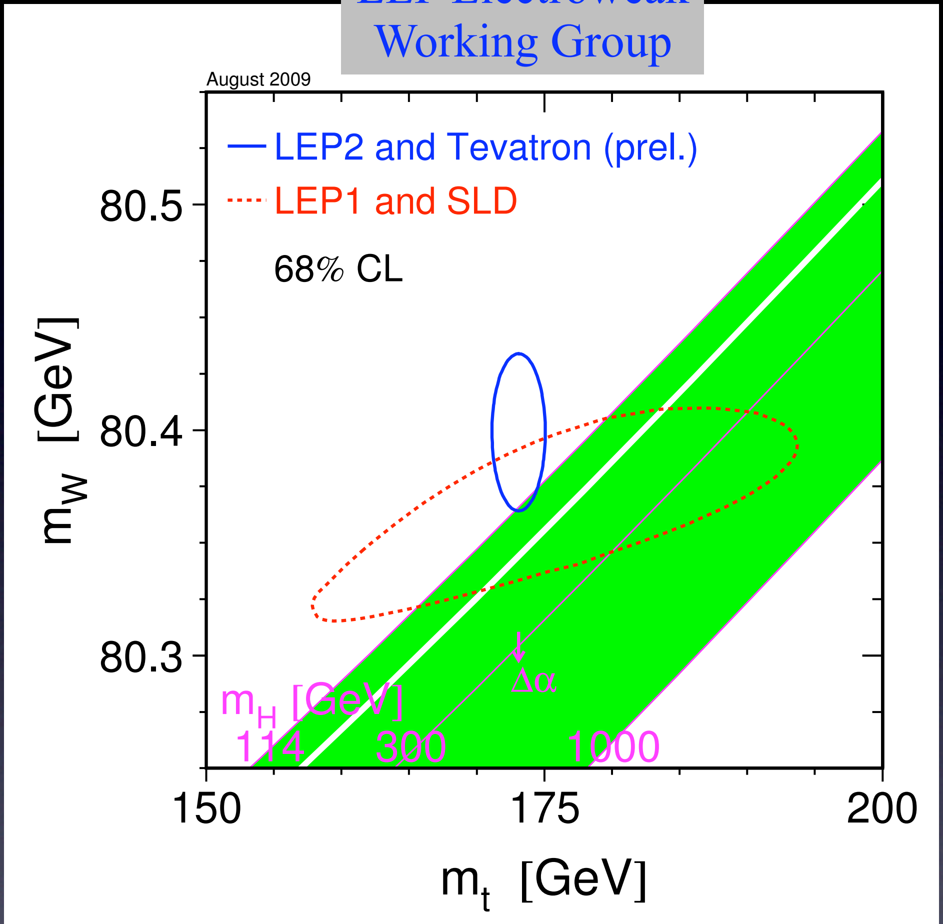

$$m_t = 174.8 \pm 2.4^{+1.2}_{-1.0}\ \text{GeV}$$

# World Average Top Quark Mass

Tevatron Electroweak Working Group




LEP Electroweak Working Group




$m_t = 173.1 \pm 0.6 \pm 1.1$ GeV

0.9 % precision

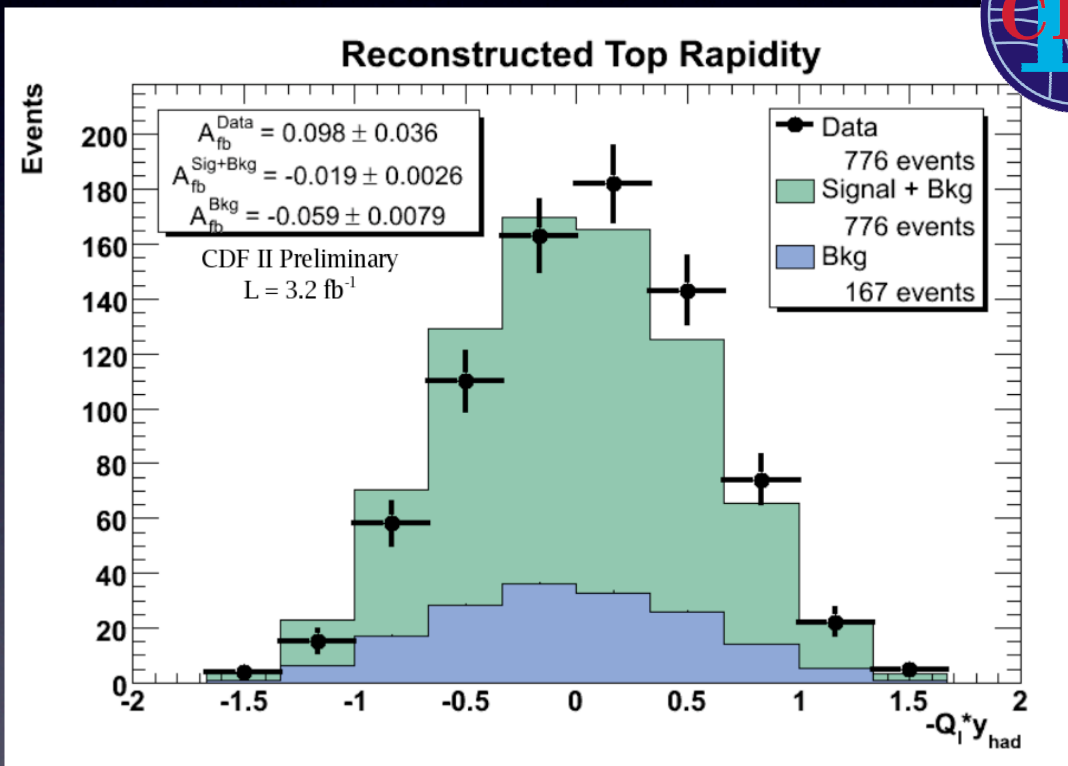
$m_H < 157$ GeV @ 95% C.L.

$< 186$ GeV

with LEP2 limit

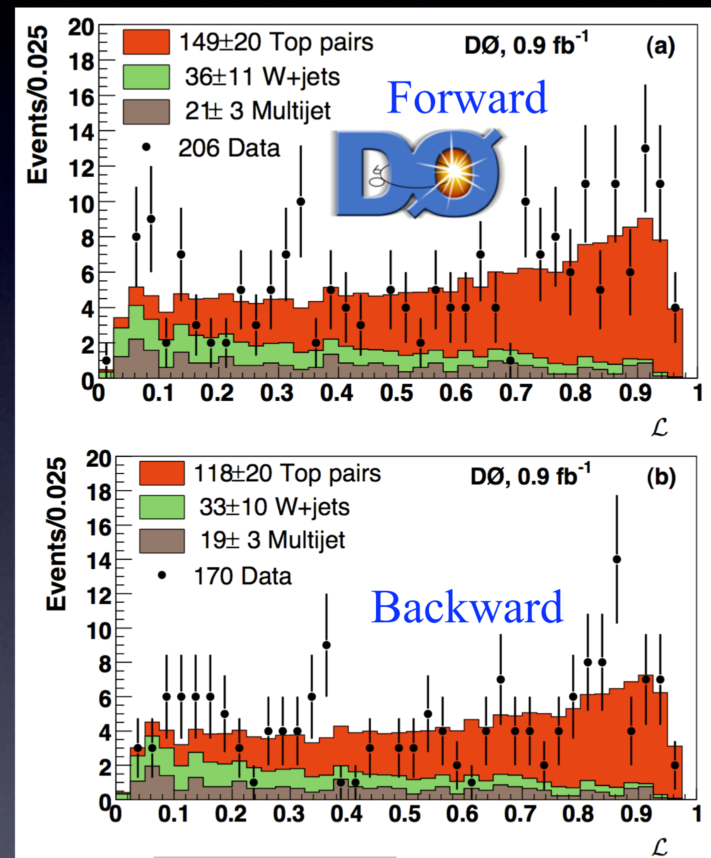
# Forward-backward Charge Asymmetry

- In SM, small asymmetry in $y_t - y_{\bar{t}}$ (~5%) arises from NLO effects
  - new physics might enhance the asymmetry




corrected

$A_{FB} = 19 \pm 7 \pm 2$ %

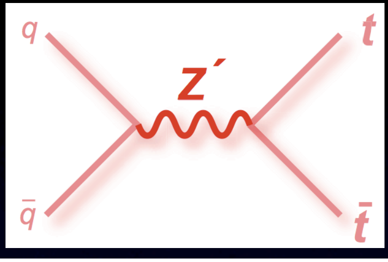



uncorrected

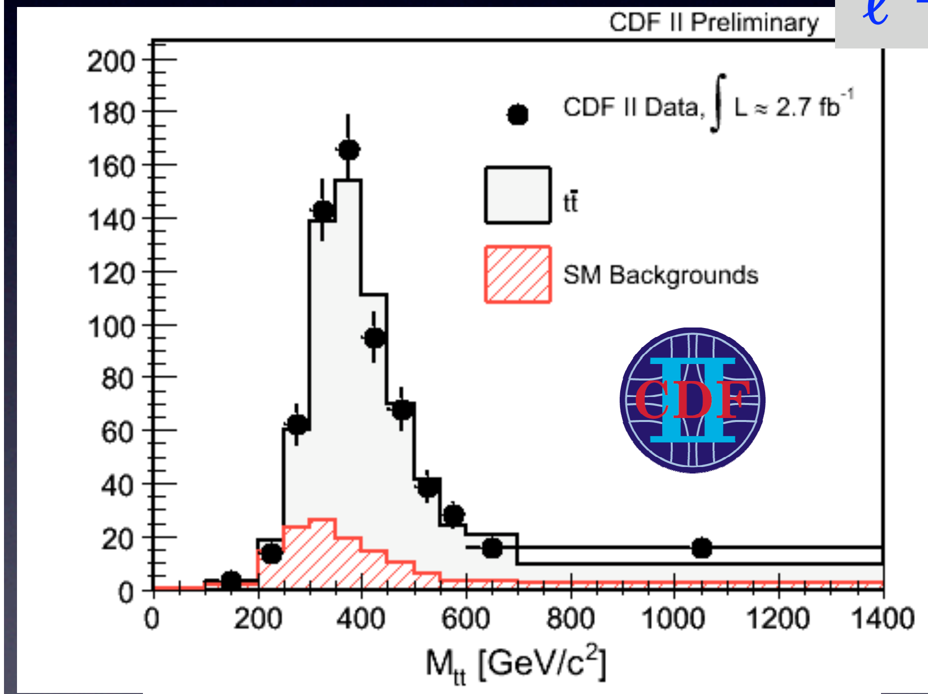
$A_{FB} = 12 \pm 8 \pm 1$ %

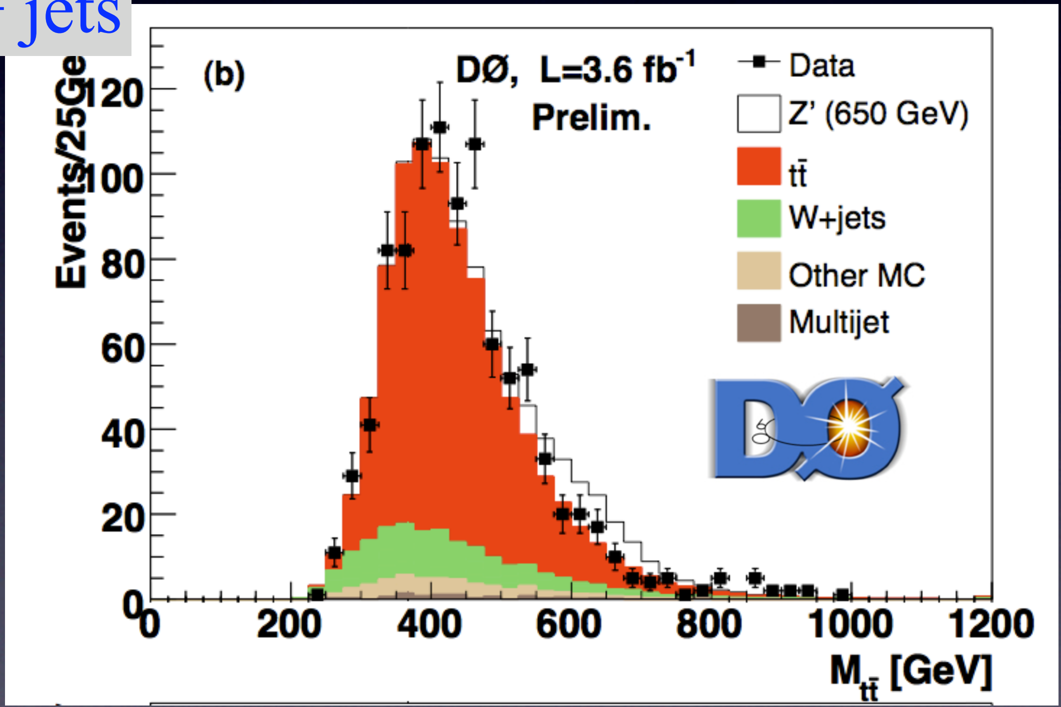
# The $M_{t\bar{t}}$ Distribution

- Non-SM distribution for $t\bar{t}$ invariant mass could indicate
  - presence of an $X \rightarrow t\bar{t}$ resonance
  - interference from non-SM process




$\ell$ + jets



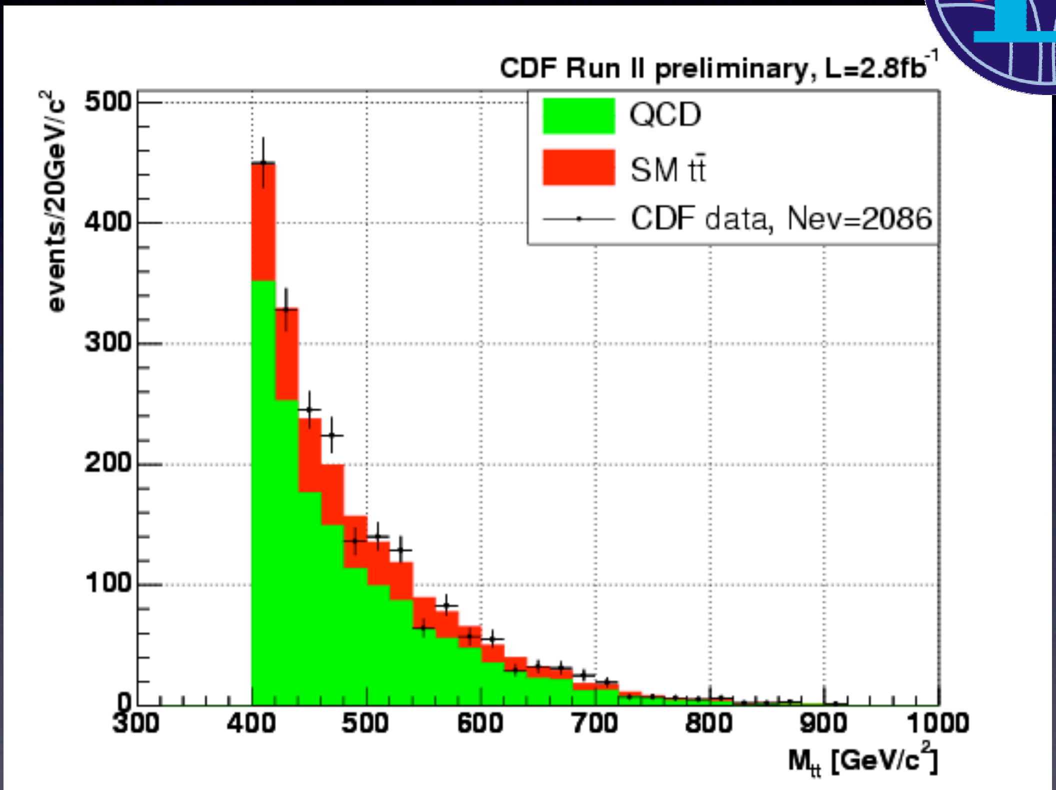



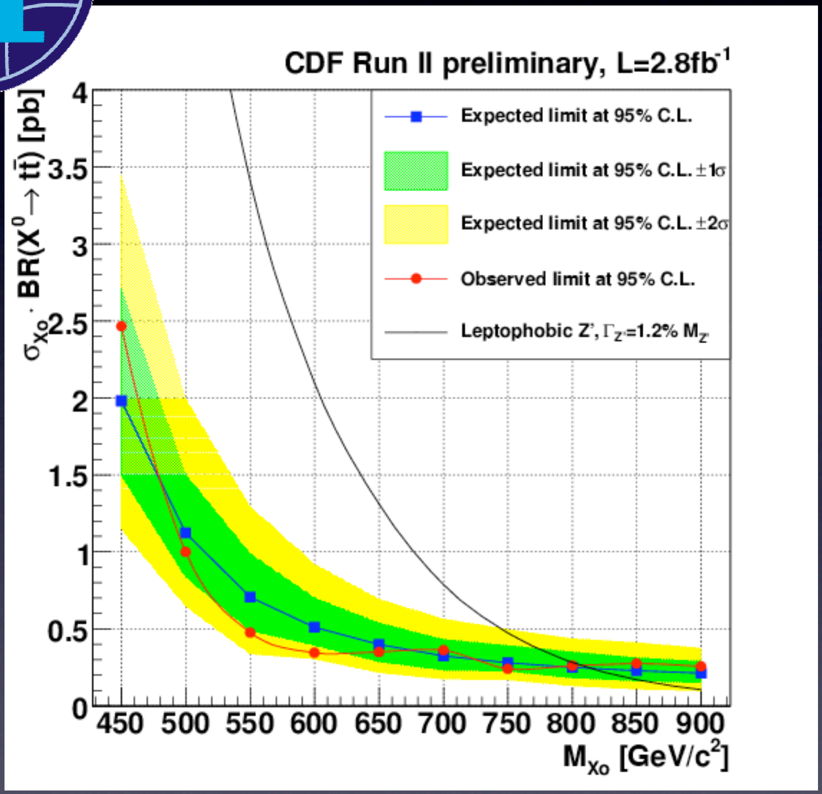

$\chi/M_{\mathrm{pl}} > 0.16$ @ 95% C.L.
for 600 GeV graviton

$m_{Z'} > 820$ GeV @ 95% C.L.

# The $M_{t\bar{t}}$ Distribution

- CDF also measures this distribution in the all-hadronic final state

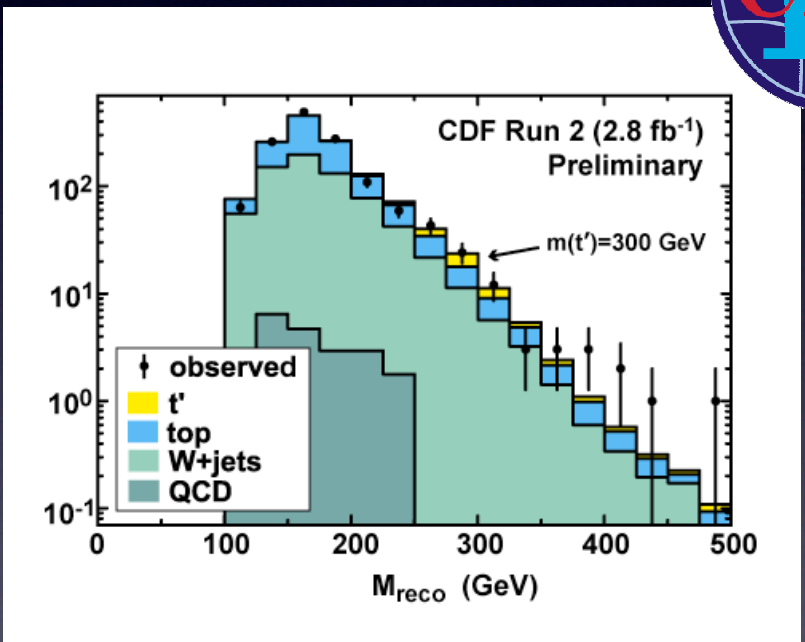


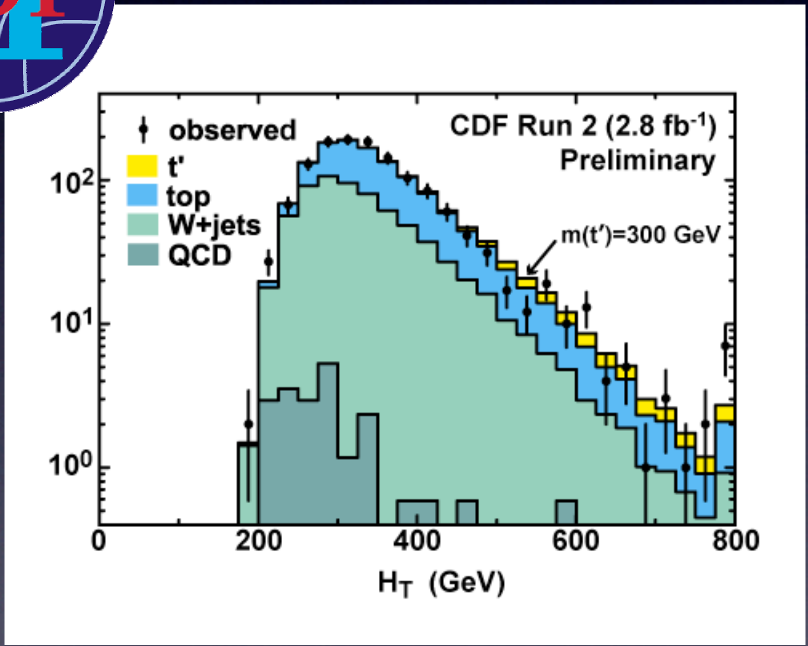




$m_{Z'} > 805$ GeV @ 95% C.L.

# Search for $t'$ Quark

- Some extensions to the SM predict the existence of a heavy 4th-generation quark ($t'$)
  - search using distributions of reconstructed top mass and sum of jet $p_T$

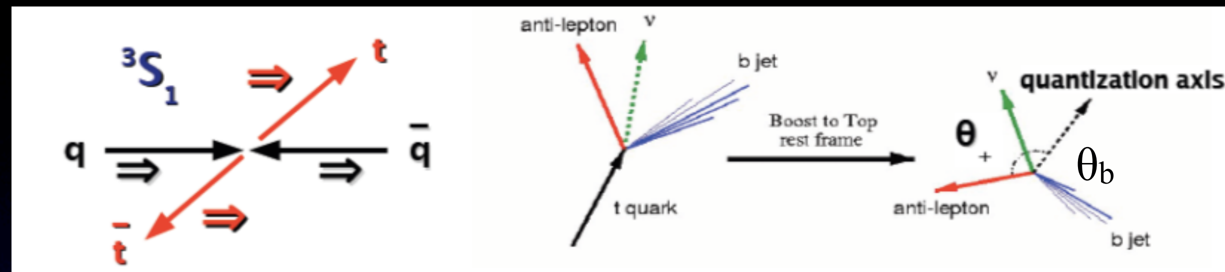



$m_{t'} > 311$ GeV @ 95% C.L.

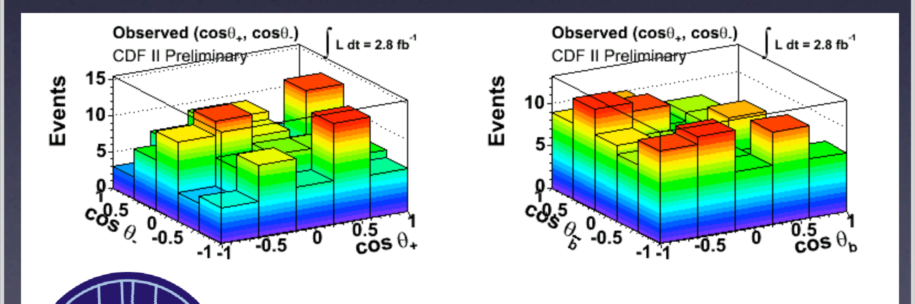
# Spin Correlations

- Spins are expected to be correlated
  - since top decays before spin flips

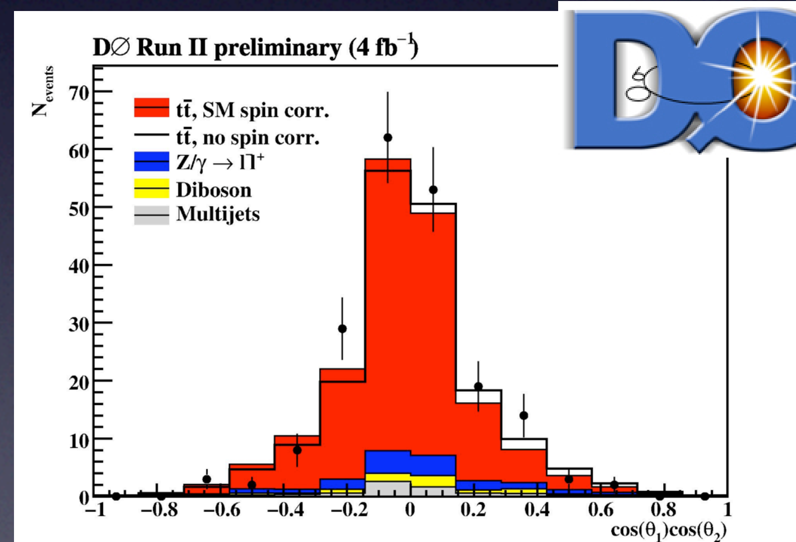



$$C \equiv \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\uparrow\downarrow}}$$

$\approx 0.8$ in SM




$C = 0.320^{+0.545}_{-0.775}$

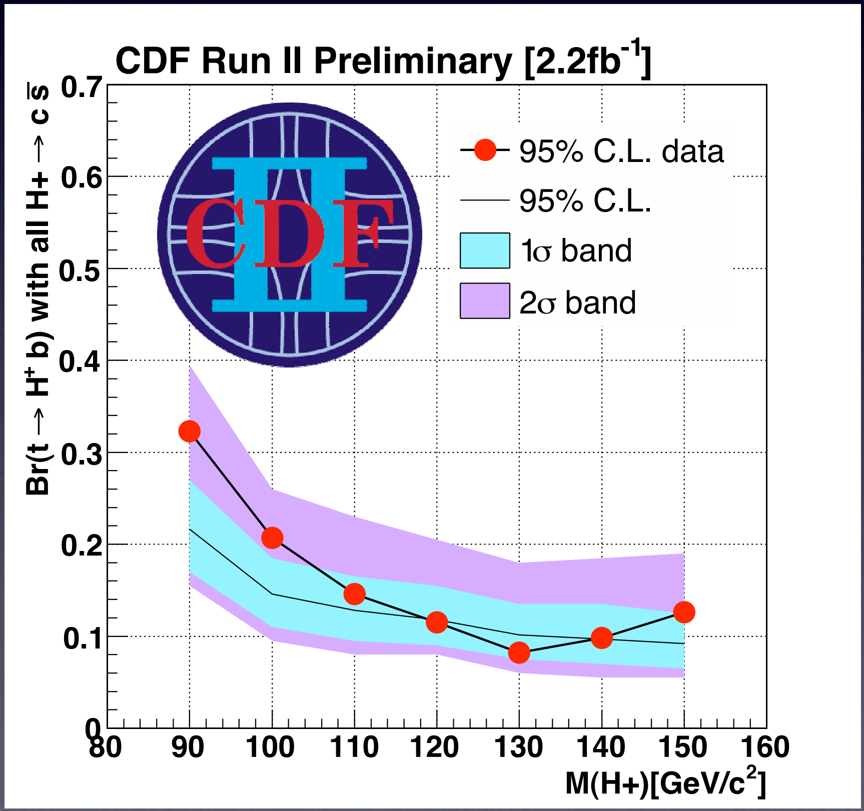


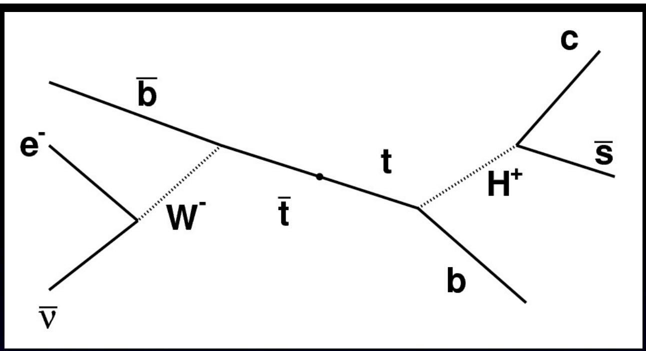

$C = -0.17^{+0.64}_{-0.53}$

# Search for $H^+$ with $M_{H^+} < m_t$

Use $\ell$+jets events with 2 $b$ tags

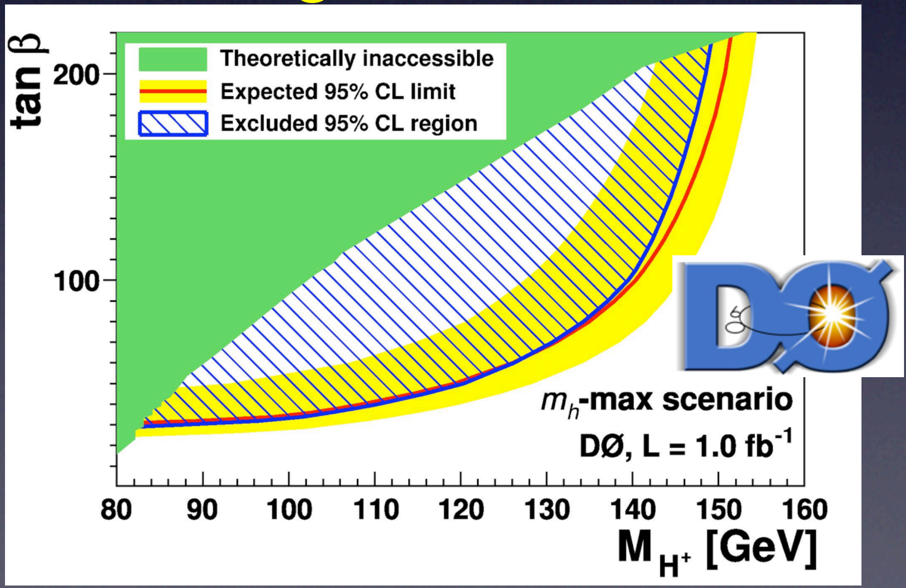
- kinematic fit to select $H^+$ daughter candidate jets
- plot mass of jet pair




Measure rates across several decay modes

- including $\tau$ final states



# Top at the LHC

- LHC will be a top factory ($\sigma(p\bar{p} \to t\bar{t}) \approx 850$ pb at 14 TeV) :
  - one million events per $fb^{-1}$ ➙ can trade statistics for modes with reduced systematics
- Top will be a valuable standard candle for calibrating jet energy scale and *b* identification performance
- Expected precisions with 10 $fb^{-1}$ of low-luminosity data:
  - Top quark mass: total uncertainty of 1 GeV
  - FCNC: sensitivity down to BF's of $10^{-3}$ to $10^{-4}$
  - spin correlations: 4% uncertainty on parameters
  - *W* helicity: measure fractions to 1-2%

# Summary

- The precision and variety of top quark measurements is rapidly improving
  - highlighted by mass measurement with precision of 0.9%
  - several measurement of interaction and decay properties, as well as searches for new particles, have not yet revealed significant non-SM effects
- The era of single-top production measurements has begun
- The LHC will provide a major improvement in precision

We have learned much about the top quark in the past 14 years
In a few more years it will be as familiar as the *Z* boson and *b* quark

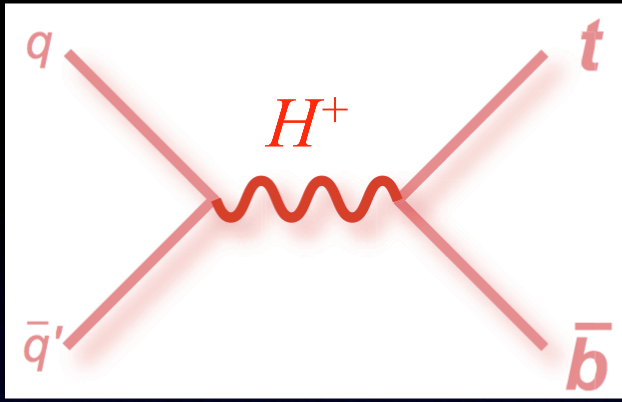
# Backup

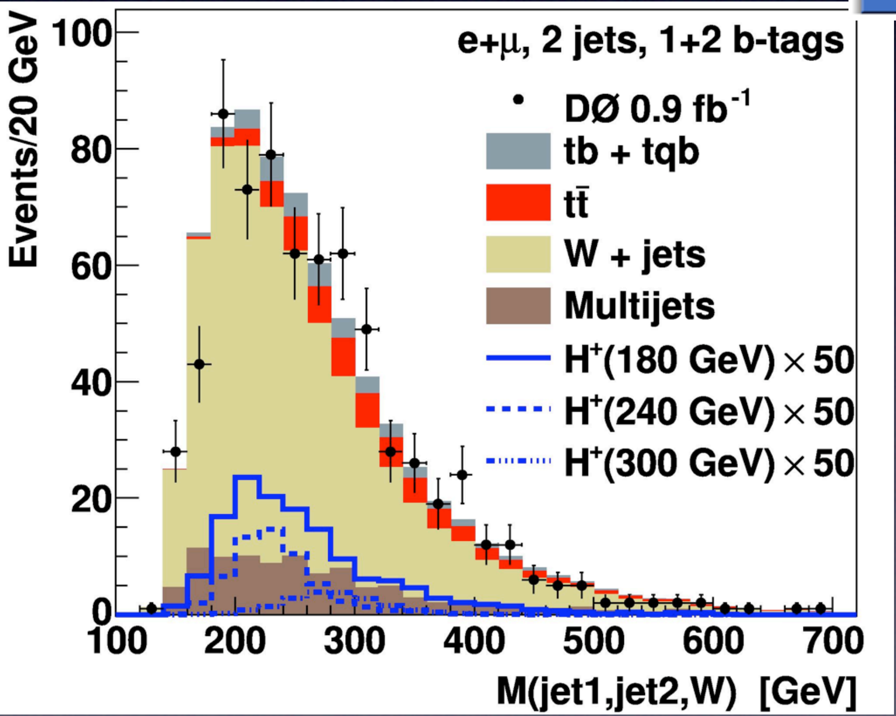
# The Top Quark in Experiment

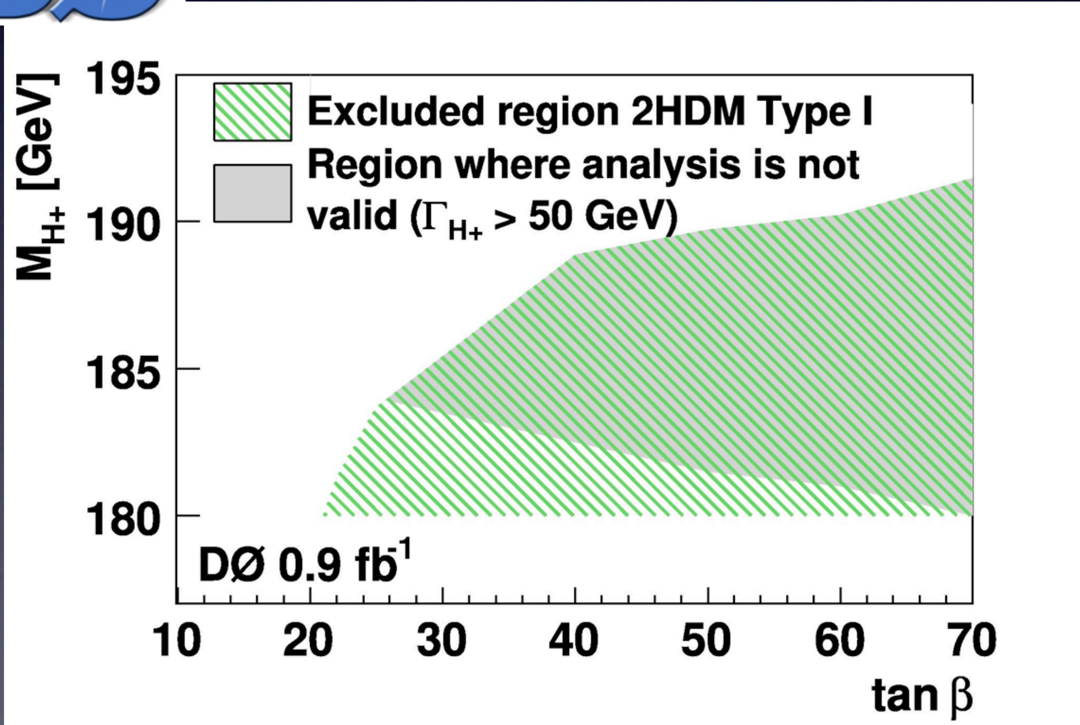
- The world's sample of top quarks comes exclusively from the Tevatron
  - "top factory" at LHC is coming soon...
- CDF and DØ detector have similar capabilities for top quark physics
  - data samples are ~4fb$^{-1}$ per experiment ➙ ~30000 $t\bar{t}$ and 12000 single-top events produced
    - ✦ branching ratios and selection efficiencies reduce the sample available for analysis

# Search for $H^+$ with $M_{H^+} > m_t$

- $H^+ \rightarrow t\bar{b}$ leads to the same final state as s-channel single top production
  - use single top selection to search for $H^+$
  - signals are enhanced rate and resonance in $M_{Wjj}$



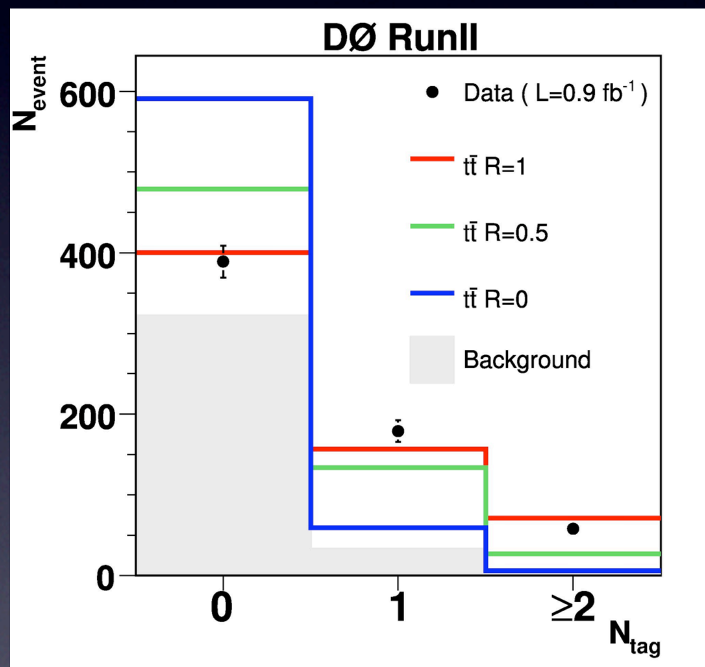



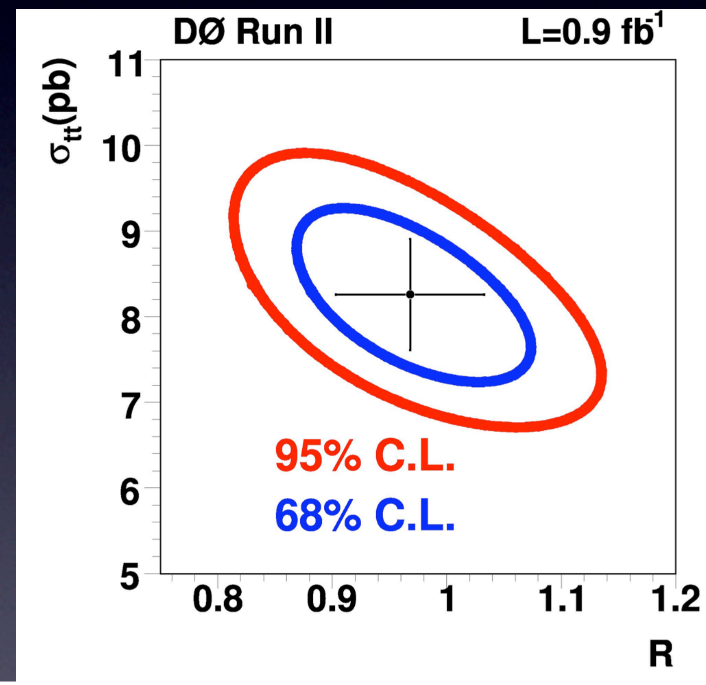



# Top Quark Branching Fractions

- Use top quark event yields with 0, 1, and 2 *b*-tagged jets to measure production cross section and $R \equiv \dfrac{B(t \to Wb)}{B(t \to Wq)}$

$$R = \frac{|V_{tb}^2|}{|V_{td}^2| + |V_{ts}^2| + |V_{tb}^2|}$$




$$R = 0.97^{+0.09}_{-0.08}$$

$$\sigma_{t\bar{t}} = 8.18^{+0.90}_{-0.84} \pm 0.50 \text{ (lumi) pb}$$

# Search for Invisible Decays

- Measure absolute rate (rather than fraction) of events with 2 *b*-tagged jets to determine $B(t \to X)$
  - sensitive to invisible top decays

*X* is any state with different acceptance than *Wb*

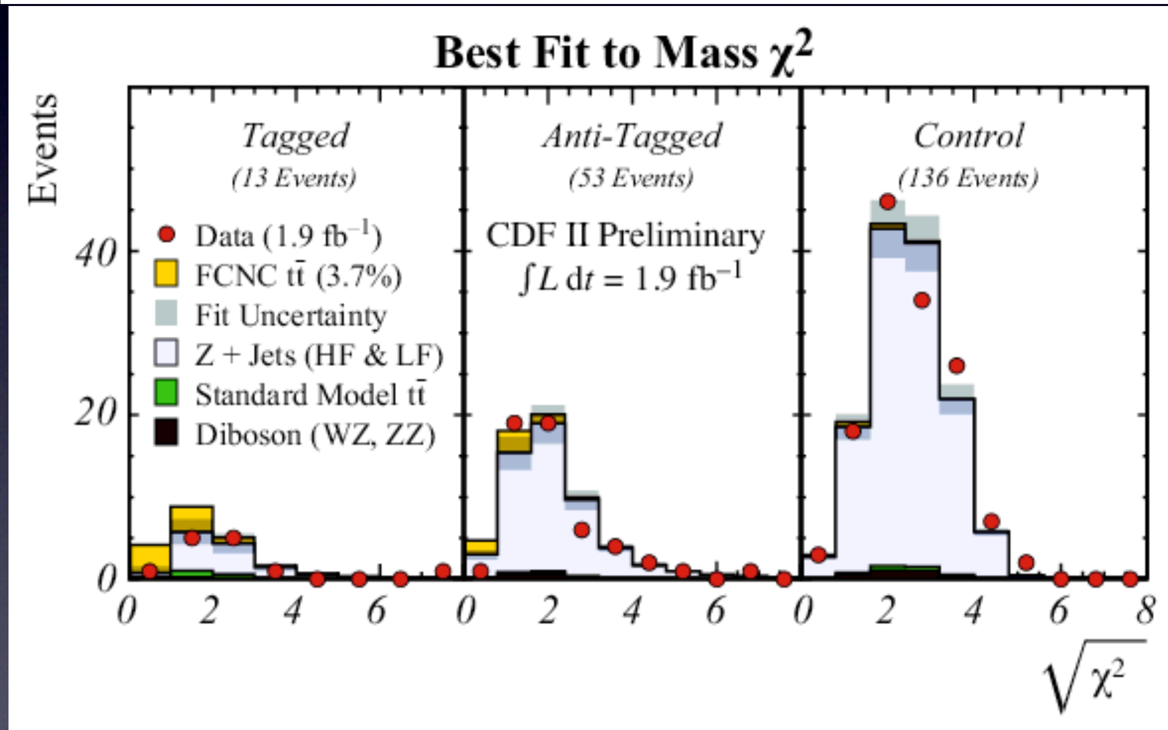
| Top Cross Section: Double Loose SECVTX Tag ($\int \mathscr{L} dt = 1.9\,\text{fb}^{-1}$) | | | | |
|---|---|---|---|---|
| **Sample** | **2 Jets** | **3 Jets** | **4 Jets** | **$\geq$ 5 Jets** |
| $WW$ | 0.5±0.1 | 0.5±0.1 | 0.2±0.0 | 0.1±0.0 |
| $WZ$ | 2.6±0.3 | 0.8±0.1 | 0.2±0.0 | 0.0±0.0 |
| $ZZ$ | 0.1±0.0 | 0.0±0.0 | 0.0±0.0 | 0.0±0.0 |
| Single Top ($s$) | 8.4±1.2 | 2.8±0.4 | 0.7±0.1 | 0.1±0.0 |
| Single Top ($t$) | 2.0±0.3 | 1.8±0.2 | 0.5±0.1 | 0.1±0.0 |
| Z+LF | 1.1±0.2 | 0.7±0.1 | 0.2±0.0 | 0.1±0.0 |
| $Wb\bar{b}$ | 33.9±13.3 | 10.6±4.3 | 2.0±0.9 | 0.5±0.2 |
| $Wc\bar{c}/Wc$ | 6.1±2.5 | 2.7±1.1 | 0.7±0.3 | 0.2±0.1 |
| Mistags | 4.3±1.0 | 2.6±0.7 | 0.7±0.2 | 0.2±0.1 |
| Non-$W$ | 2.7±1.9 | 0.8±1.5 | 0.5±1.5 | 0.2±1.5 |
| Total Background | 61.6±16.6 | 23.4±7.3 | 5.7±3.3 | 1.4±1.7 |
| SM $t\bar{t}$ (8.8 pb) | 32.9±5.2 | 90.2±14.1 | 113.7±17.6 | 41.1±6.3 |
| Total Prediction | 94.5±17.4 | 113.6±15.9 | 119.4±17.9 | 42.5±6.5 |
| Observed | 107.0 | 118.0 | 115.0 | 44.0 |

$$B(t \to Zc) < 13\%$$
$$B(t \to \text{invisible}) < 9\%$$

# Flavor-Changing Neutral Currents

- SM FCNC branching fractions are are ~$10^{-14}$
  - direct searches for $t \rightarrow Zq$ are sensitive to new physics

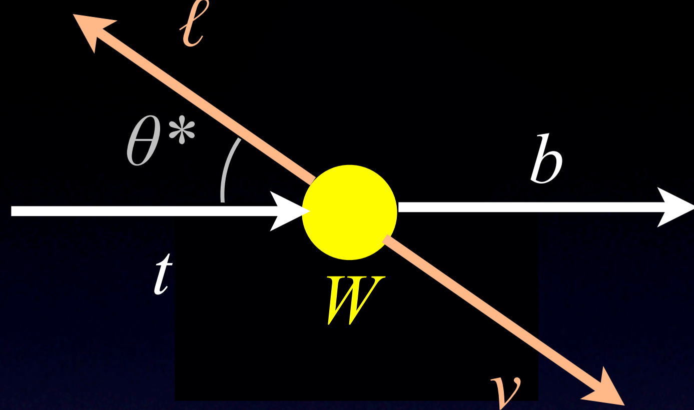
$$\chi^2 = \left(\frac{m_{W,\mathrm{rec}} - m_{W,\mathrm{PDG}}}{\sigma_W}\right)^2 + \left(\frac{m_{t\to Wb,\mathrm{rec}} - m_t}{\sigma_{t\to Wb}}\right)^2 + \left(\frac{m_{t\to Zq,\mathrm{rec}} - m_t}{\sigma_{t\to Zq}}\right)^2$$

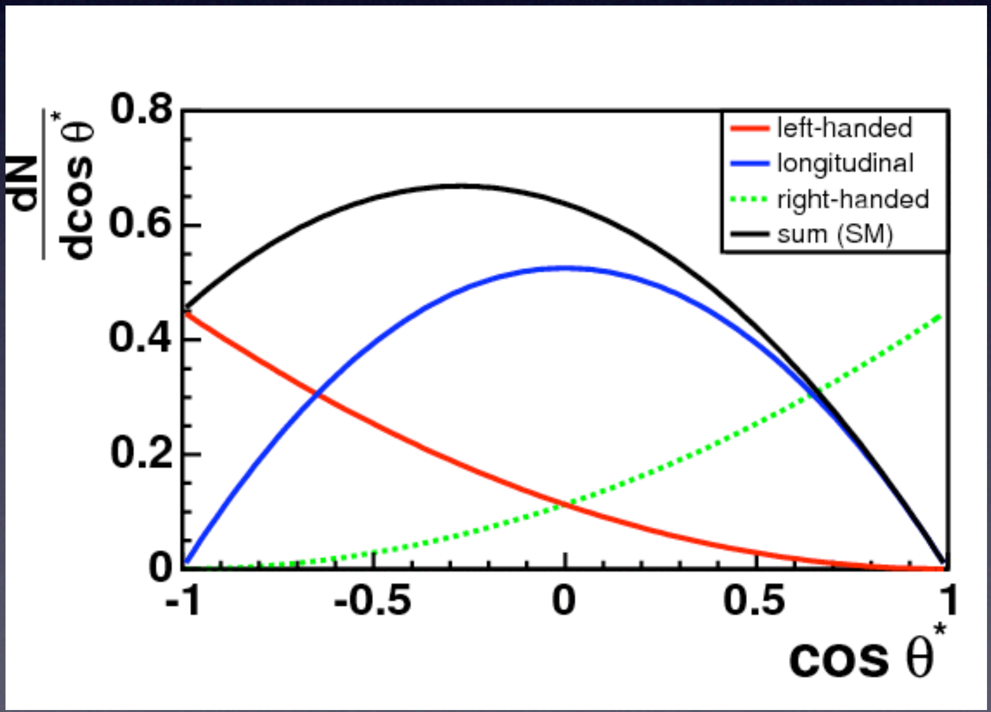



$B(t \rightarrow Zq) < 3.7\%$ @ 95% C.L.

# *W* Boson Helicity

- In the SM, 70% of *W*'s from top decay have helicity 0, 30% have helicity -1
- Direct measurements might reveal non-standard couplings



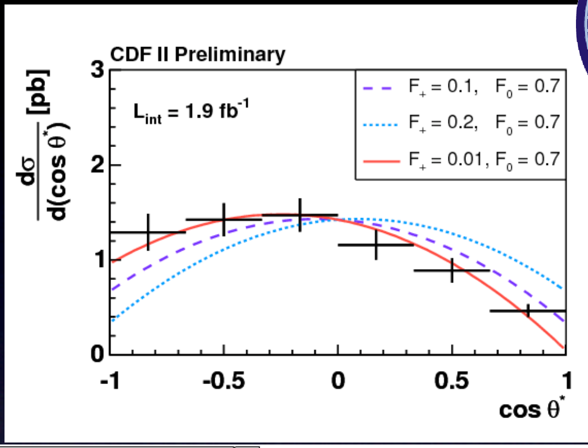

Measurement is based on direct reconstruction of cos$\theta$*

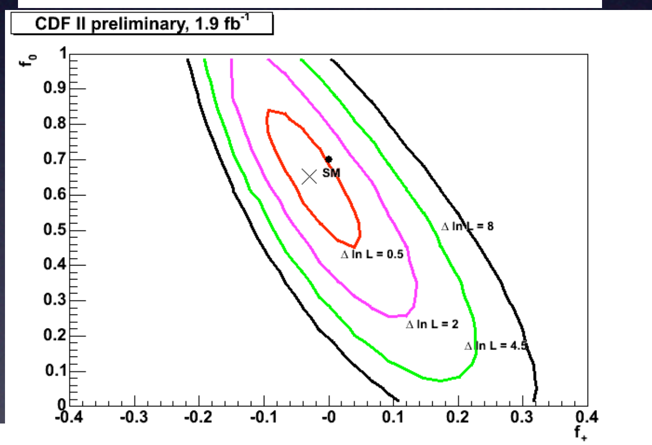
Detector and acceptance effects accounted for by:

- fit to MC templates or
- bin-by-bin unfolding

# $W$ Boson Helicity

- $\ell$+jets channel



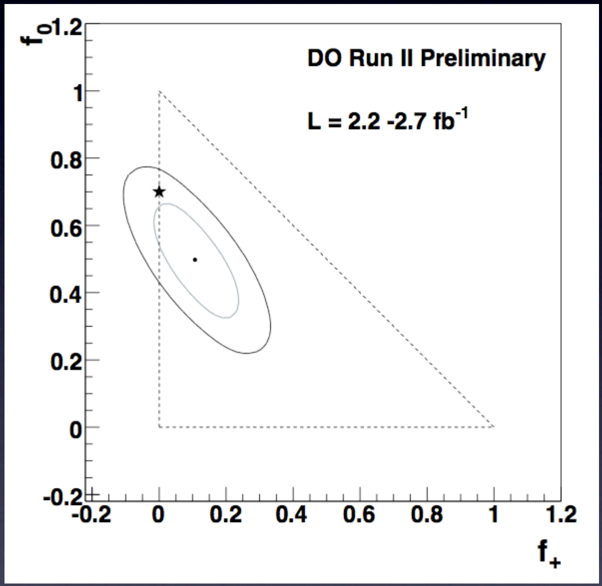




Combination:

$f_0 = 0.66 \pm 0.16$

$f_+ = -0.03 \pm 0.07$

- Template method
  - $\ell$+jets and $\ell\ell$ channels
  - use both $W$'s in each event



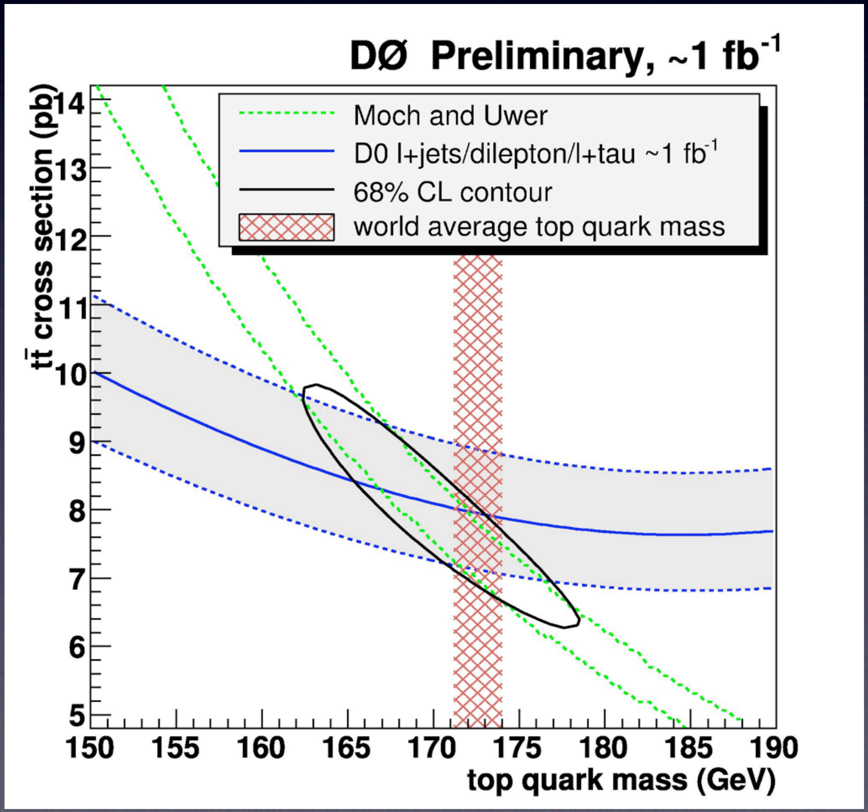

$f_0 = 0.49 \pm 0.10 \pm 0.08$

$f_+ = 0.11 \pm 0.05 \pm 0.05$

SM $p$-value: 23%

# Mass Measurement from Cross Sections

- Assuming that production is governed by SM, can compare measured to calculated cross sections to extract top mass
  - mass is measured in a well-defined renormalization scheme
  - systematics largely uncorrelated with other methods




NLO+NLL cross section:

M. Cacciari *et al.* (2008)

$m_t = 167.8 \pm 5.7$ GeV

Approx NNLO cross section:

S. Moch and P. Uwer (2008)

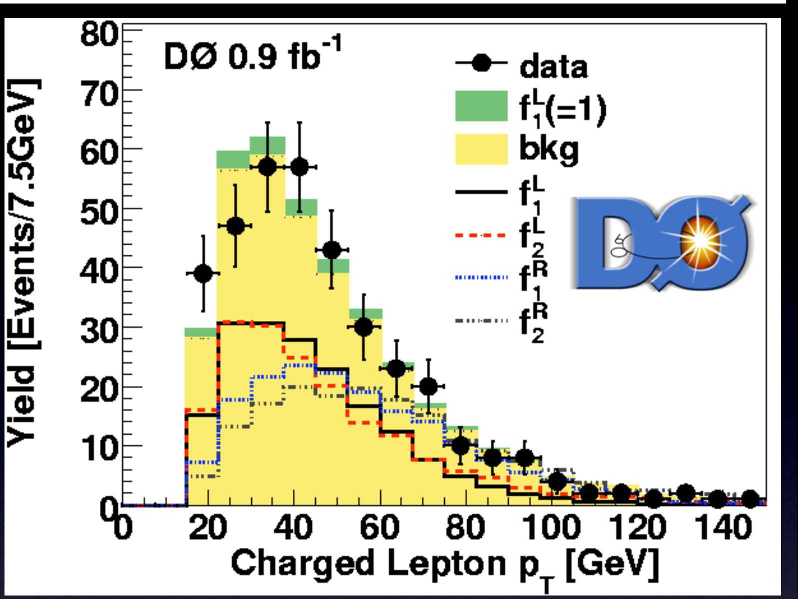
$m_t = 169.6 \pm 5.4$ GeV

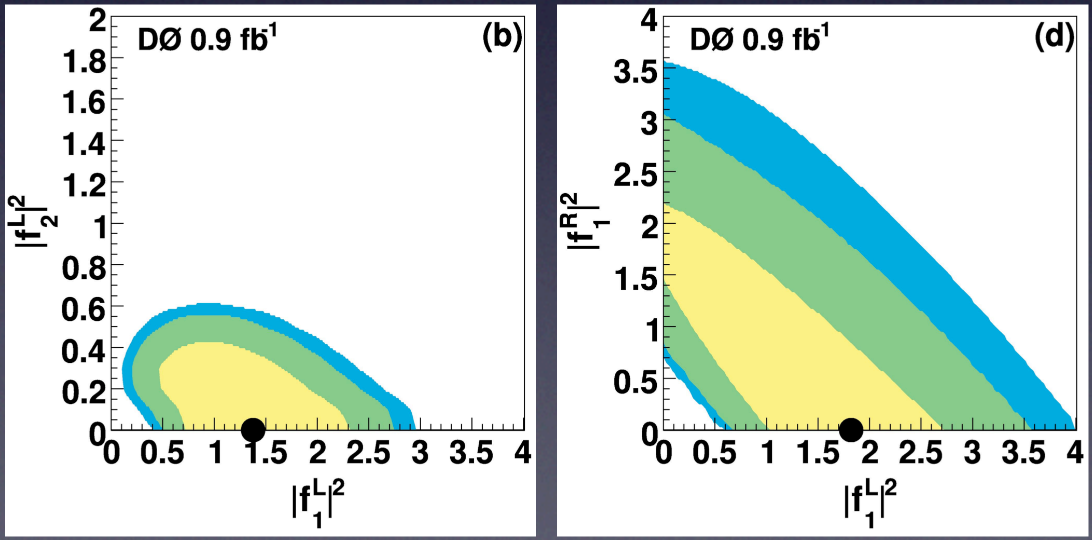
# Constraints on *Wtb* Couplings

- Rate and kinematic distributions in single top events depend on the *Wtb* coupling structure

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

In SM: $f_1^L = |V_{tb}| \approx 1,\ f_1^R = f_2^L = f_2^R = 0$




| Allowed couplings | Measured values |
|---|---|
| $f_1^L, f_2^L$ | $\lvert f_1^L\rvert^2 = 1.4^{+0.6}_{-0.5},\ \lvert f_2^L\rvert^2 < 0.5$ |
| $f_1^L, f_1^R$ | $\lvert f_1^L\rvert^2 = 1.8^{+1.0}_{-1.3},\ \lvert f_1^R\rvert^2 < 2.5$ |
| $f_1^L, f_2^R$ | $\lvert f_1^L\rvert^2 = 1.4^{+0.9}_{-0.8},\ \lvert f_2^R\rvert^2 < 0.3$ |