Top Quark Physics

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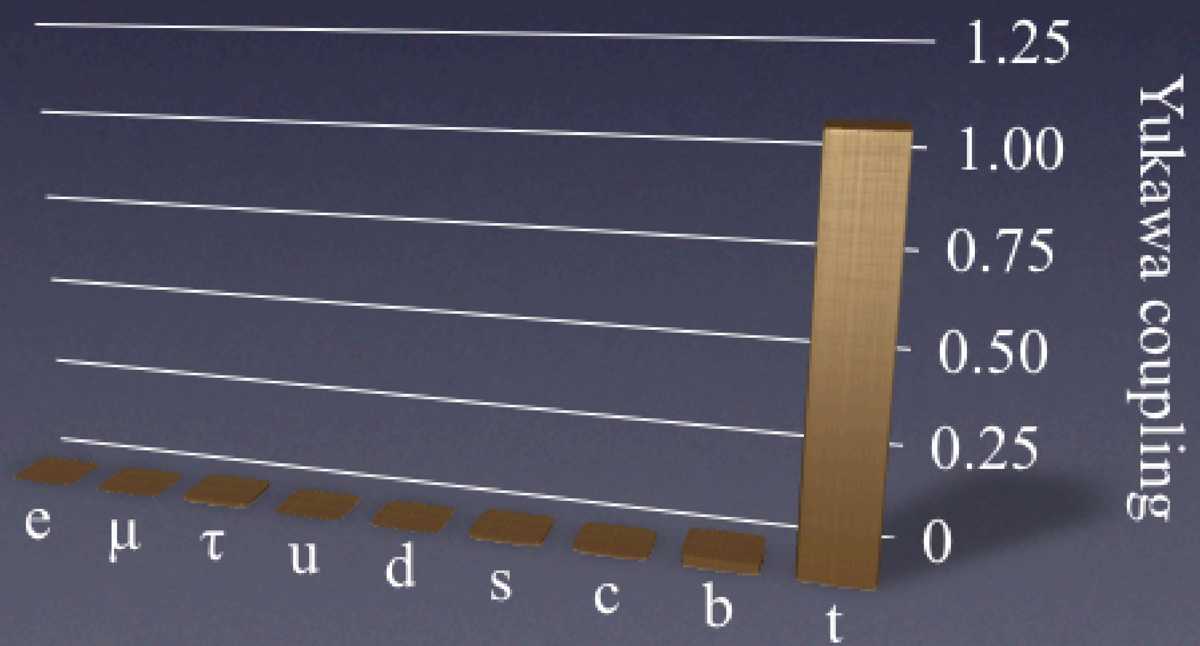
The Top Quark in the SM and Beyond

- 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?

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- Measurements in this talk

Single top cross section

Constraints on *Wtb* couplings

Searches for $H^+ \to tb$, $t \to H^+b$

Search for FCNC

Top quark pair cross section

Top quark mass

Forward-backward charge asymmetry

M_{tt} distribution

Search for t' quark

W boson helicity

Top quark branching fractions

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  - Are there more than three fermion generations?
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- Measurements in this talk
  - Single top cross section
  - Constraints on *Wtb* couplings
  - Searches for $H^+ \rightarrow tb$, $t \rightarrow H^+ b$
  - Search for FCNC
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  - Top quark mass
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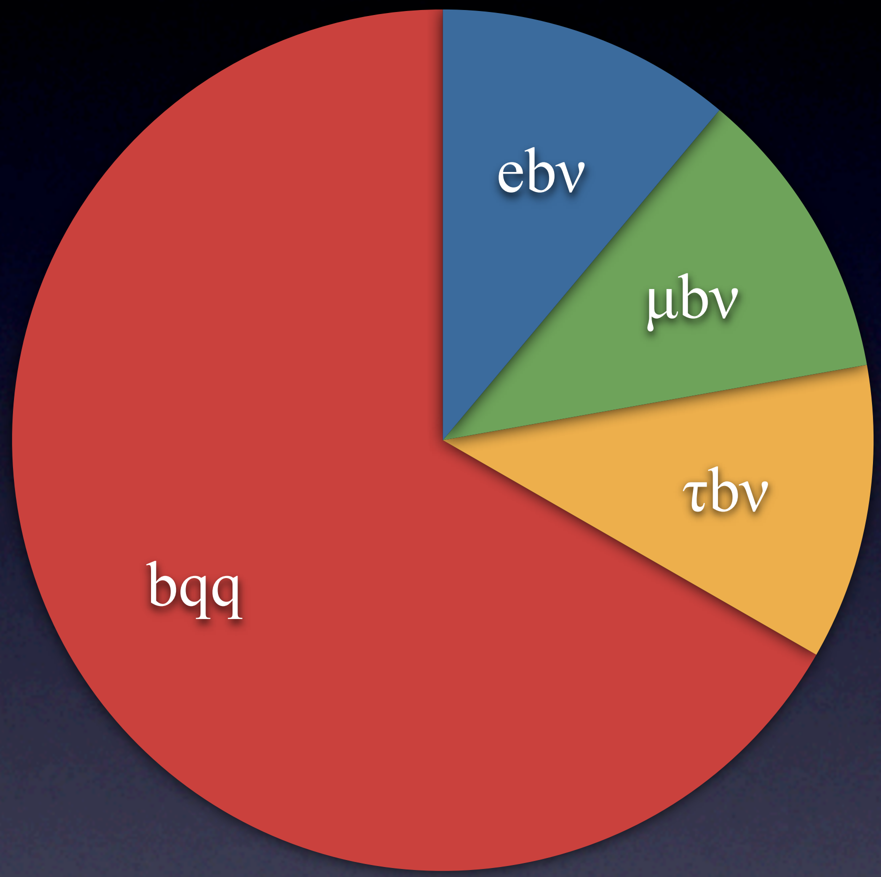
  - M_{tt} distribution
  - Search for t' quark
  - *W* boson helicity
  - Top quark branching fractions

Top Quark Signatures

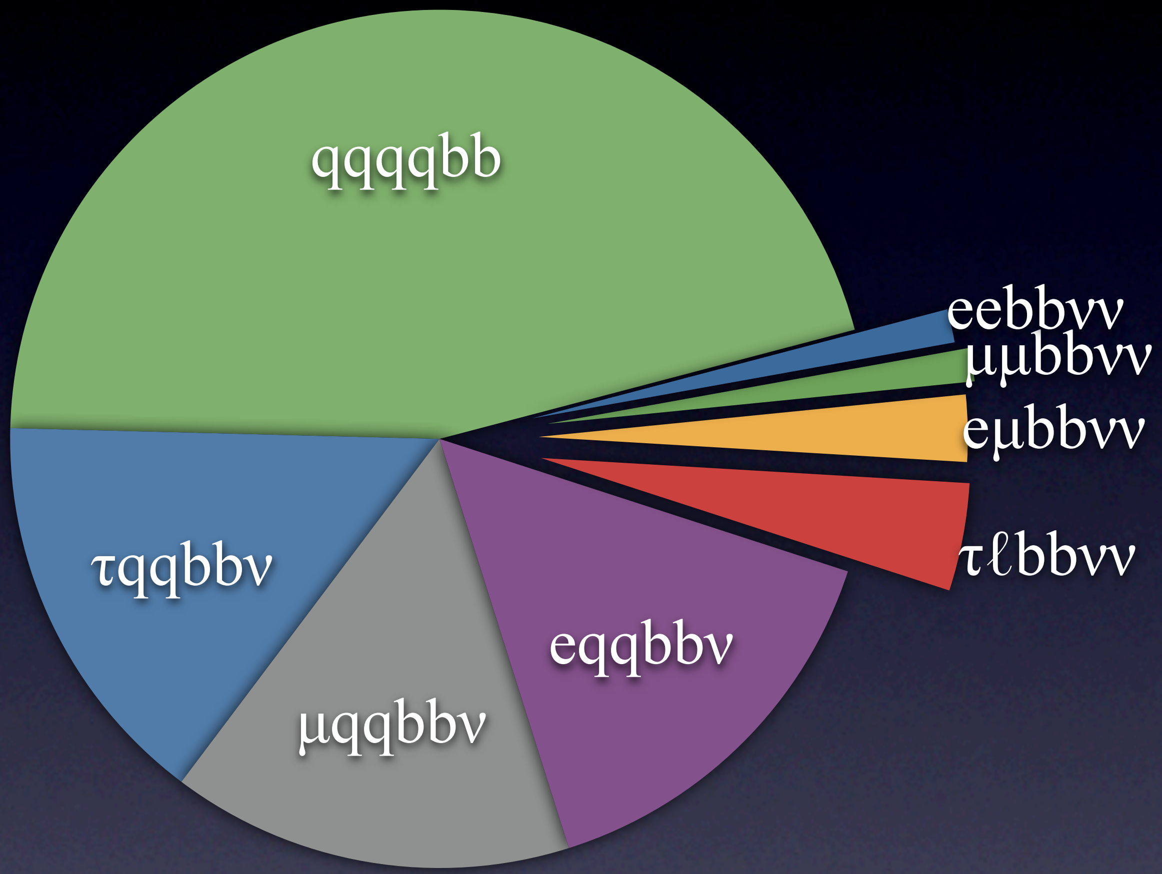
- Single top quark:

Tevatron cross section: ~3 pb



- Top quark pair:

Tevatron cross section: ~7 pb

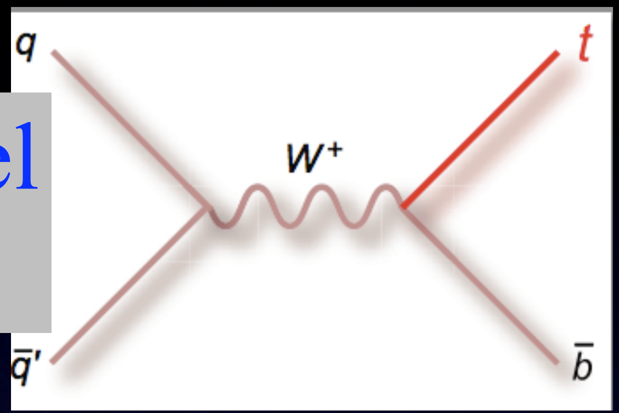


- Dominant backgrounds arise from vector boson + jet production
  - Good *b* jet and lepton ID, missing E_T resolution help in finding top quarks

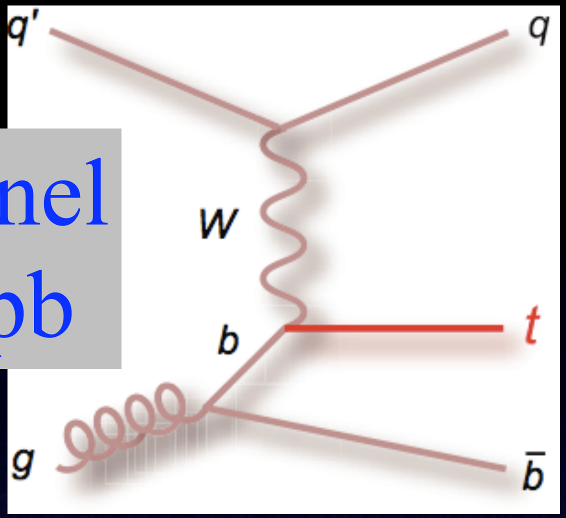
Top Quarks, One at a Time

- 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

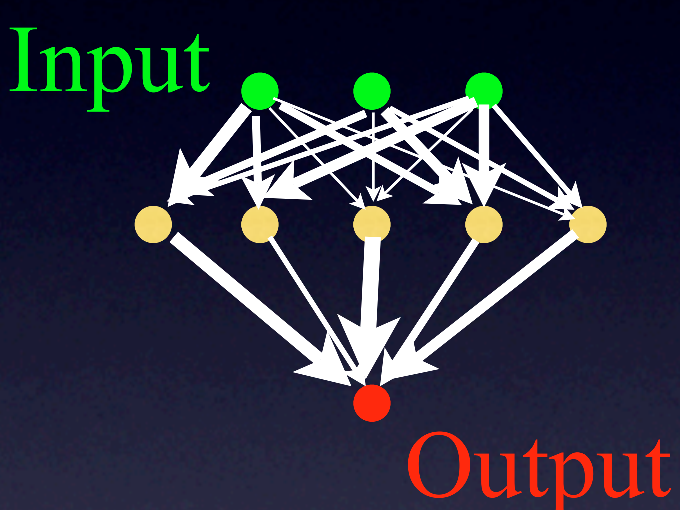
S/B ~1/200 before *b*-tagging

- Need multivariate techniques to extract signal

Multivariate Methods

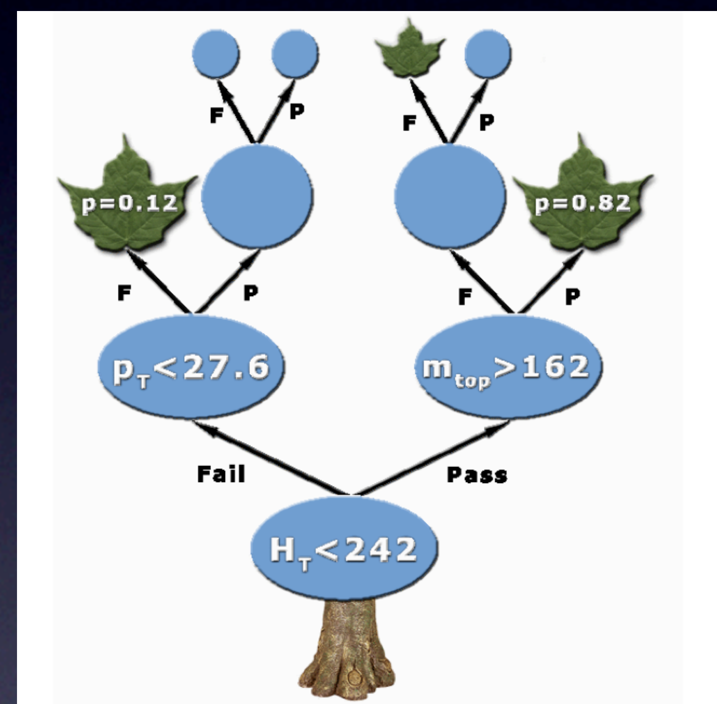
Goal: Given a set of measurements **x**, find $p(S|\mathbf{x}) = \frac{p(S)\,p(\mathbf{x}|S)}{p(S)\,p(\mathbf{x}|S) + p(B)\,p(\mathbf{x}|B)}$

Neural network



Train on MC samples to optimize weights

Decision tree



Training determines "shape" of tree

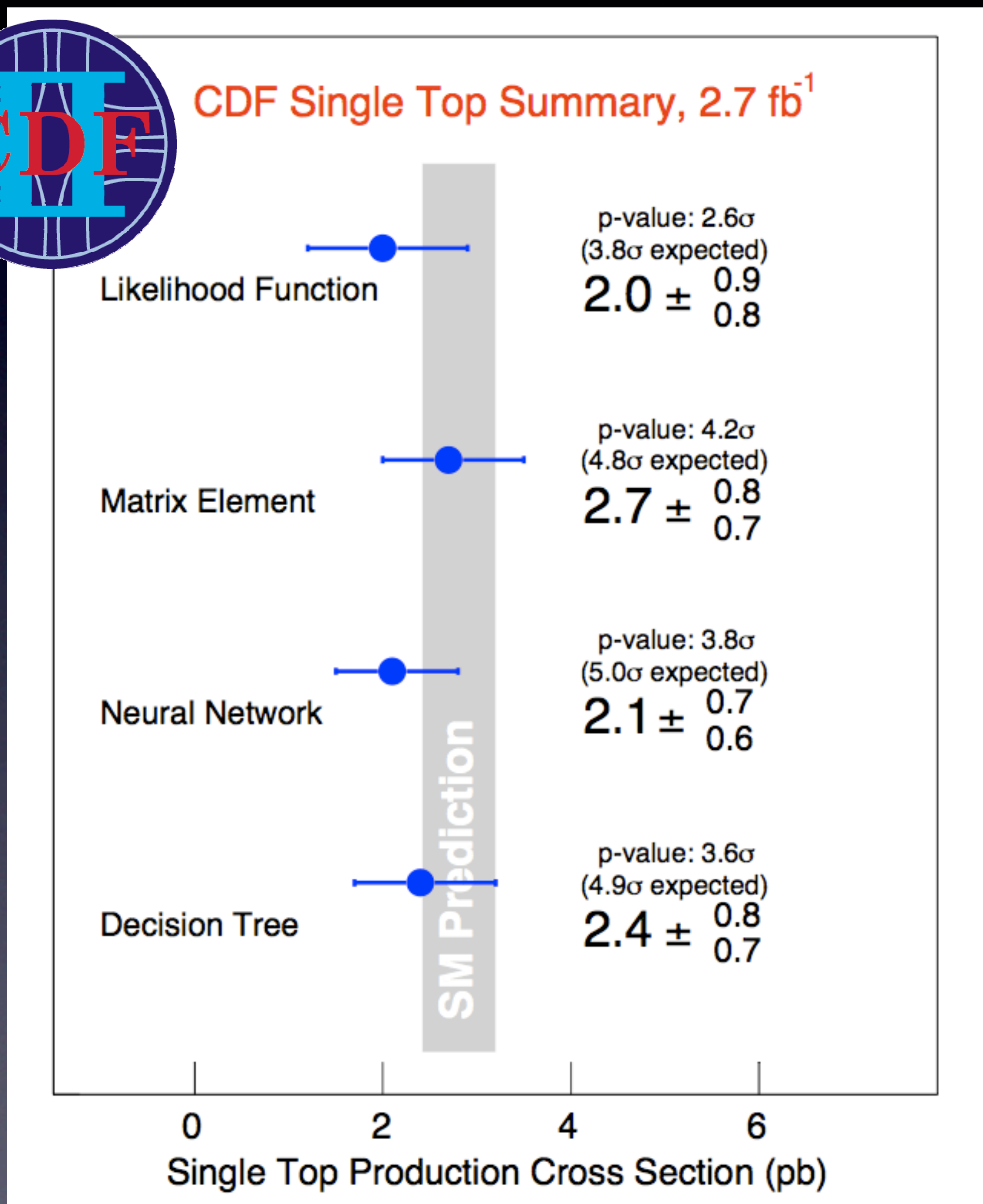
Iterative "boosting" improves performance

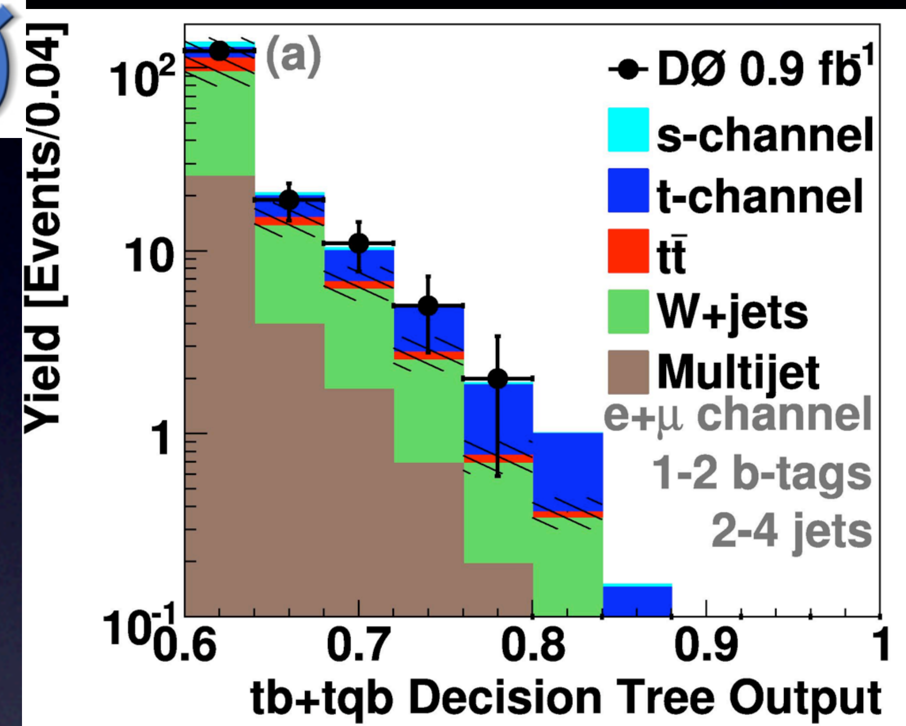
Matrix element

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

Single Top Cross Section

- Both CDF and DØ use several multivariate discriminants to find single top candidates:



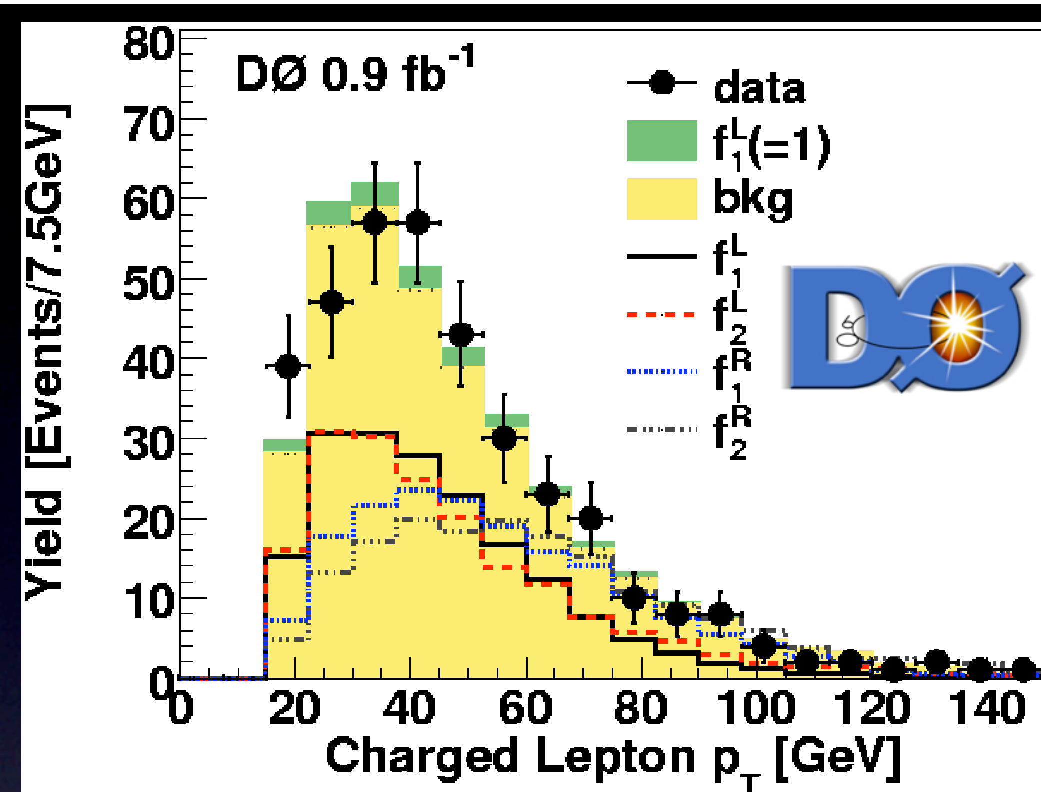


- Combining methods:

DØ: σ = 4.7 ± 1.3 pb
3.6σ significance (obs)
2.3σ significance (exp)
$|V_{tb}| > 0.68$ @ 95% C.L.

Constraints on *Wtb* Couplings

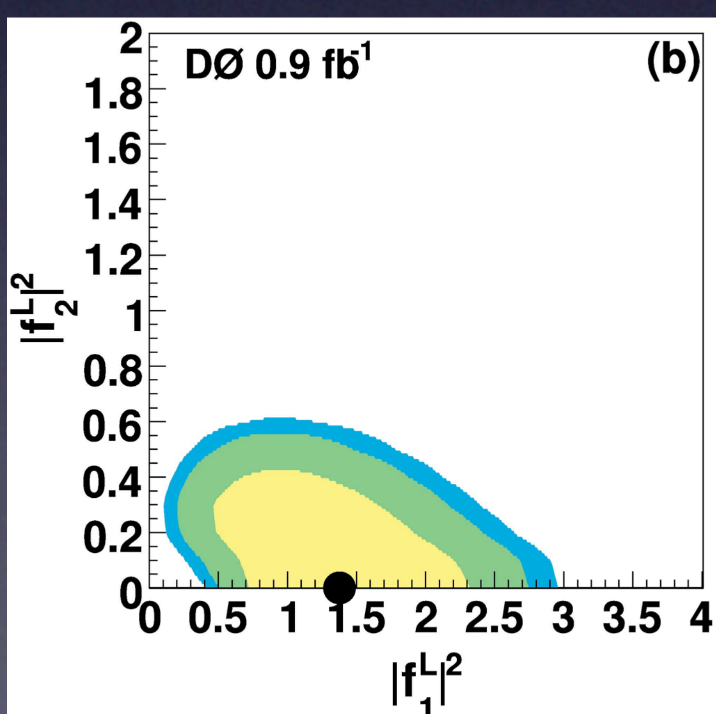
- Rate and kinematic distributions in single top events depend on the *Wtb* coupling structure

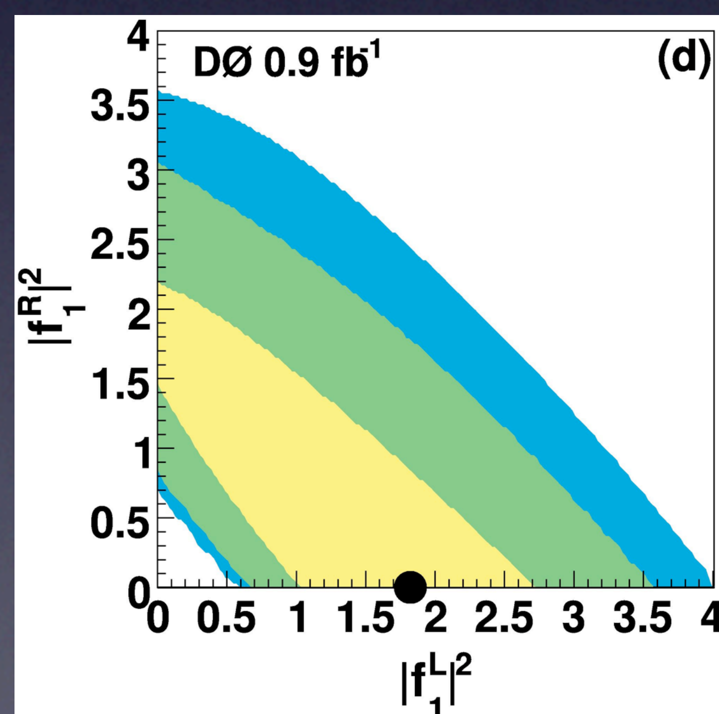


$$\mathcal{L} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t$$

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

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

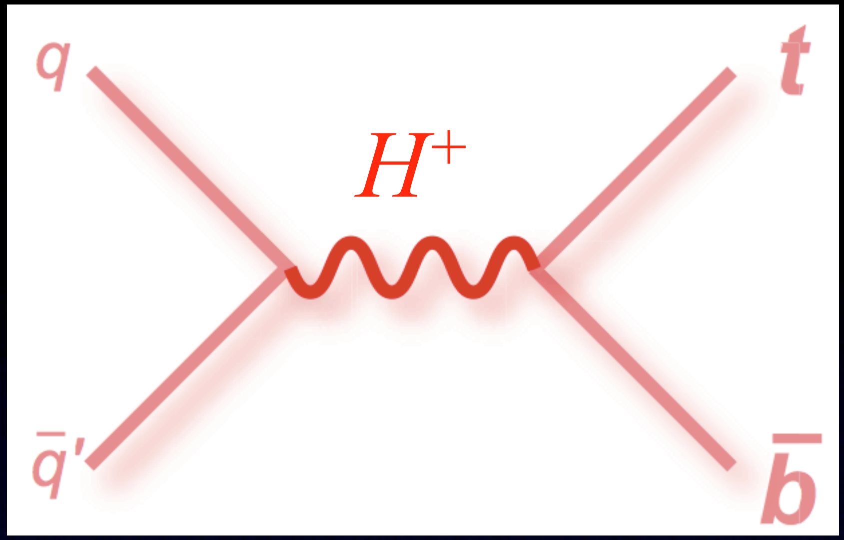


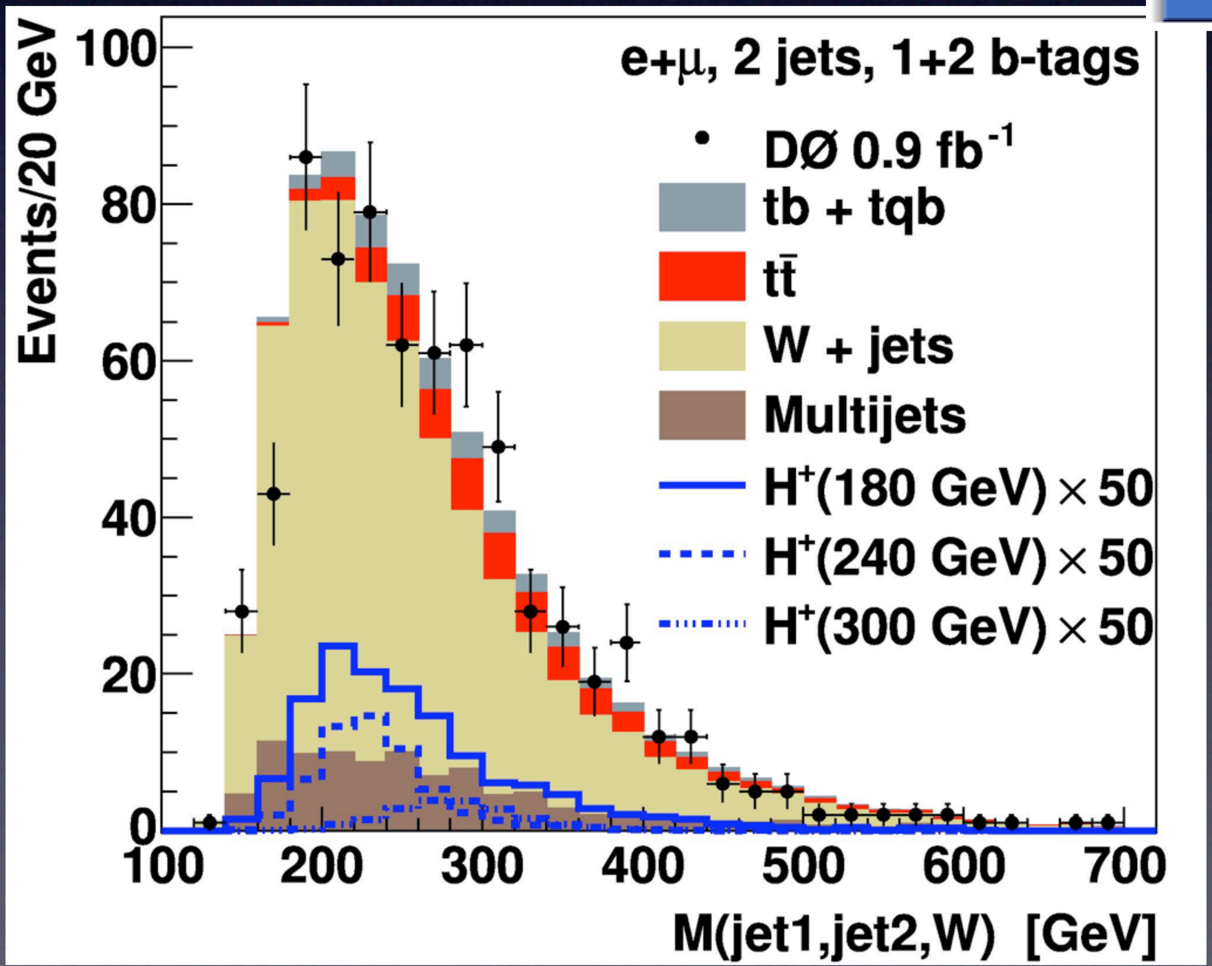


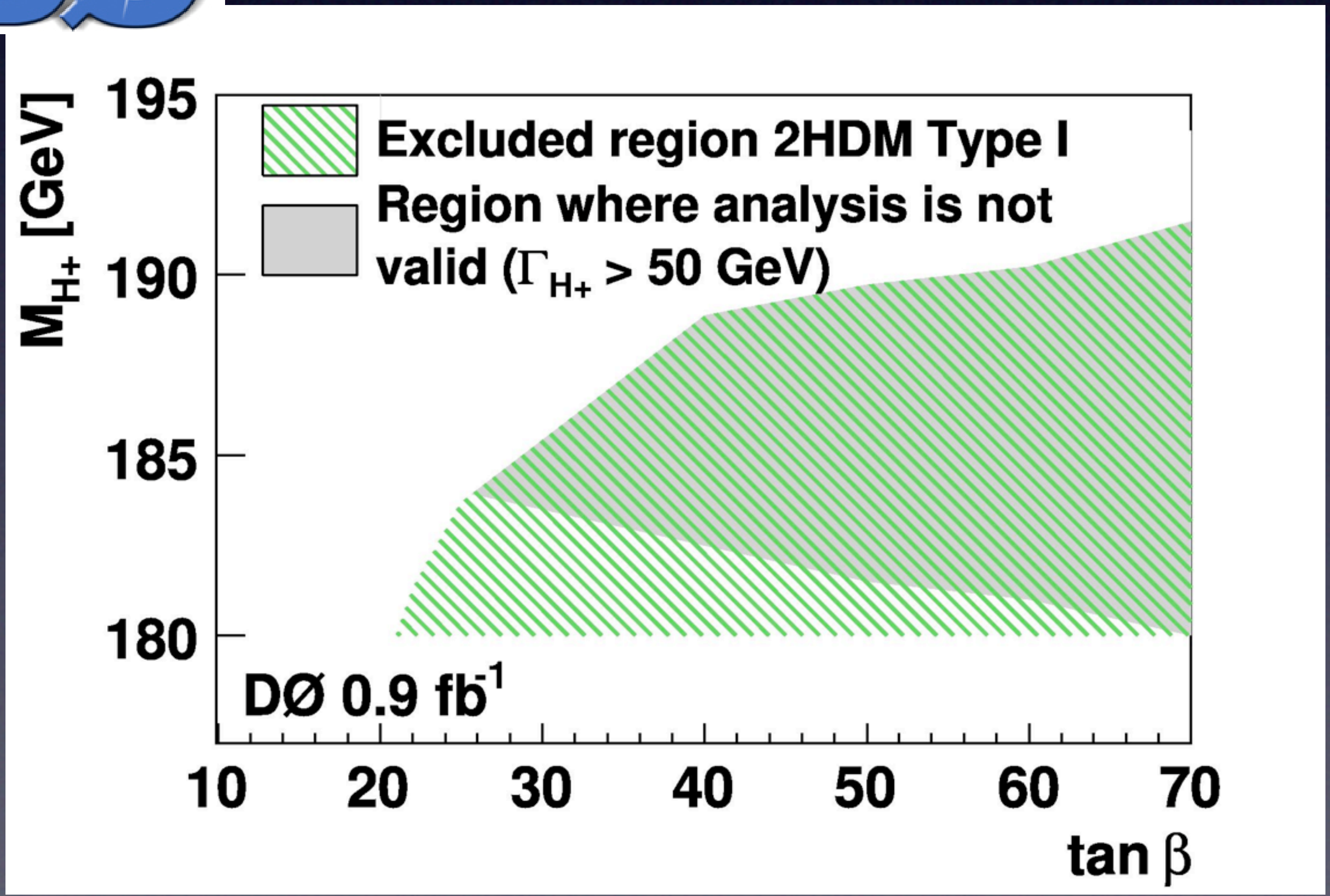
Allowed couplings	Measured values
f_1^L, f_2^L	$\lvert f_1^L \rvert^2 = 1.4^{+0.6}_{-0.5},\ \lvert f_2^L \rvert^2 < 0.5$
f_1^L, f_1^R	$\lvert f_1^L \rvert^2 = 1.8^{+1.0}_{-1.3},\ \lvert f_1^R \rvert^2 < 2.5$
f_1^L, f_2^R	$\lvert f_1^L \rvert^2 = 1.4^{+0.9}_{-0.8},\ \lvert f_2^R \rvert^2 < 0.3$

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}

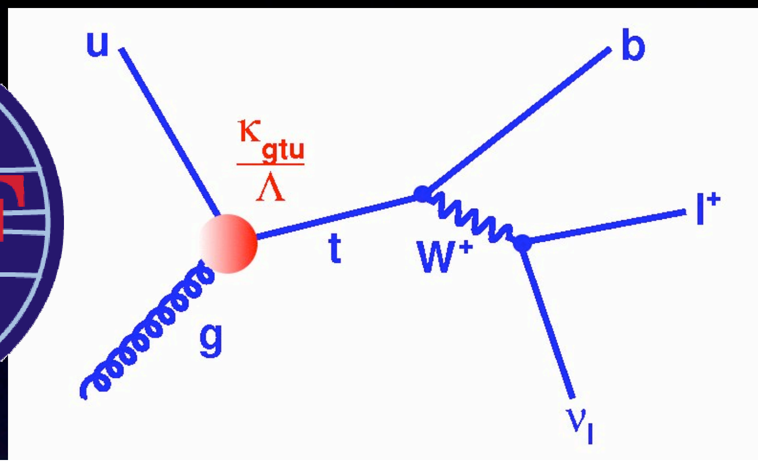


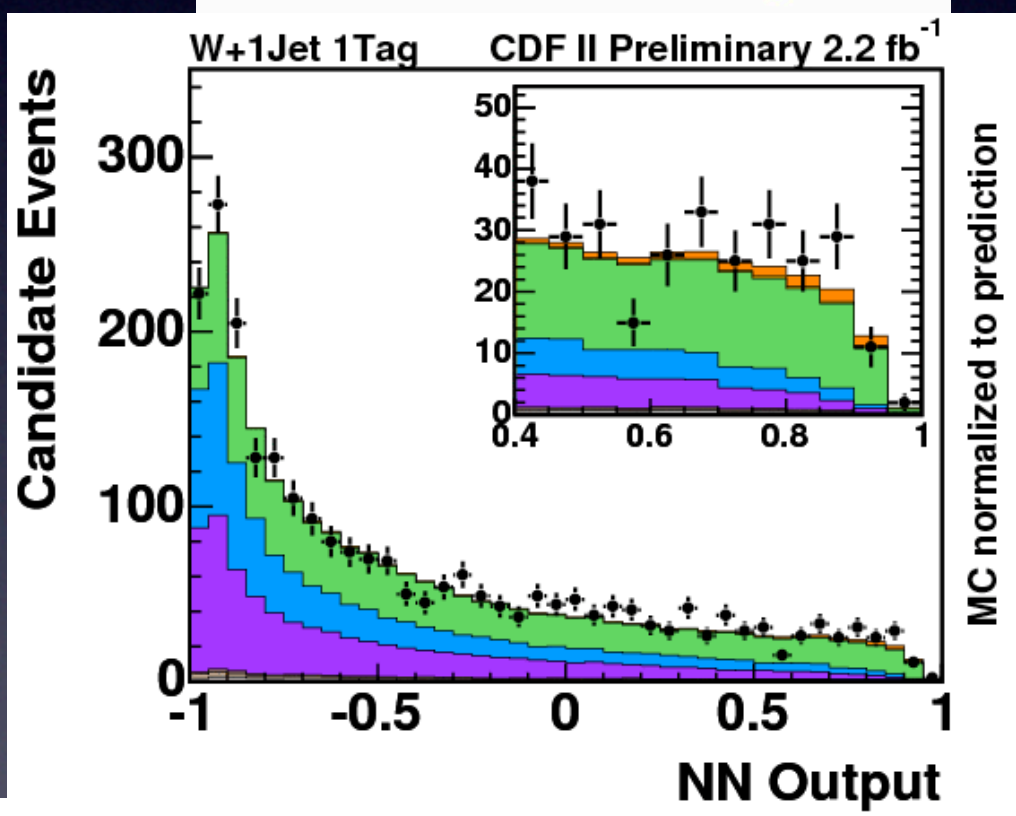




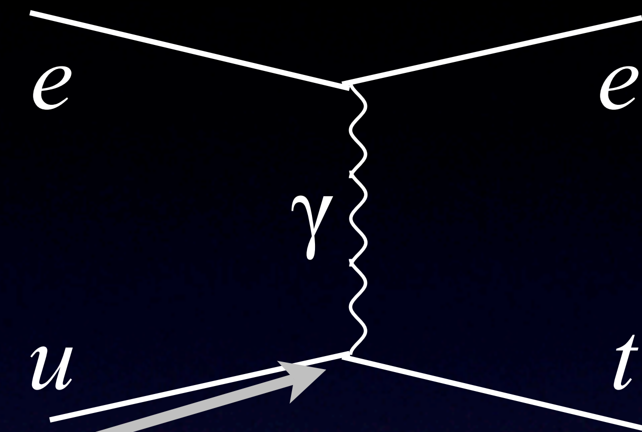
Flavor-Changing Neutral Currents

- FCNC would increase single-top cross section

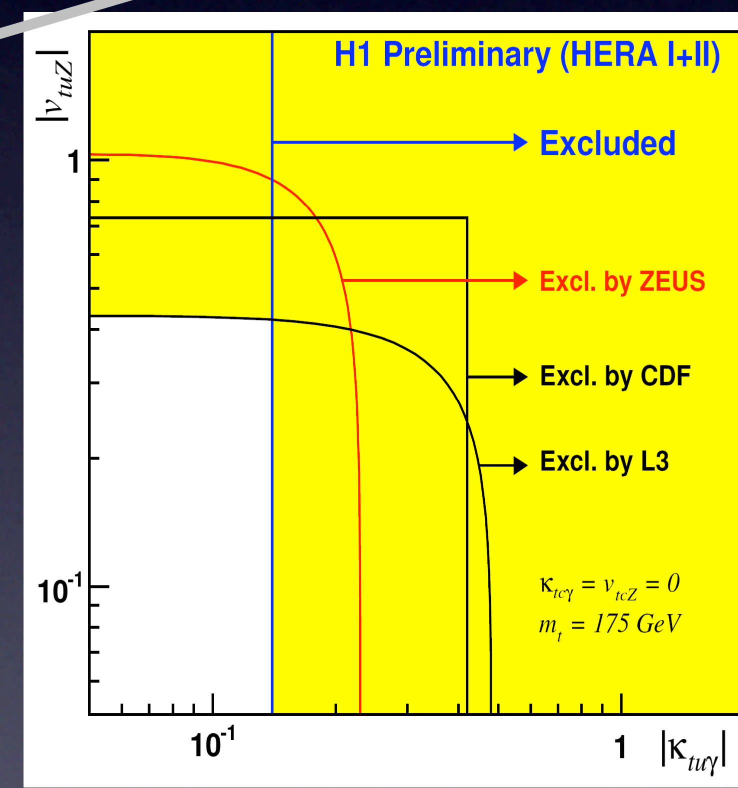




$\kappa_{gtu} / \Lambda < 0.025\ \text{TeV}^{-1}$
$\kappa_{gtc} / \Lambda < 0.105\ \text{TeV}^{-1}$ @ 95% C.L.



Anomalous coupling $\kappa_{tu\gamma}$

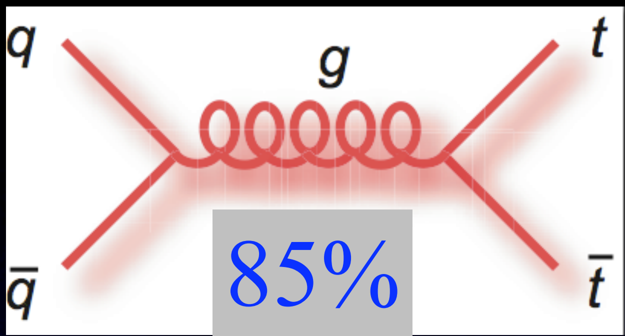


$\sigma(ep \to etX) < 0.16$ pb @ 95% C.L.
$\kappa_{tu\gamma} < 0.14$

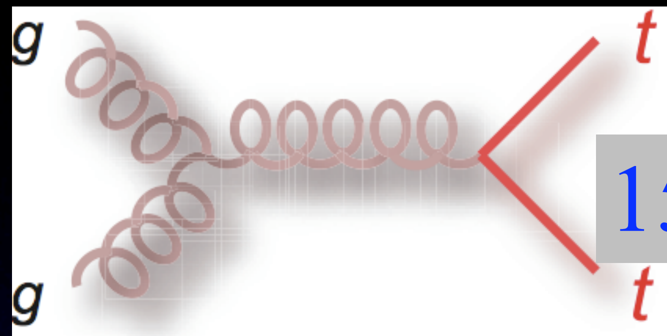
Top Quarks, Two at a Time

- Production at the Tevatron:

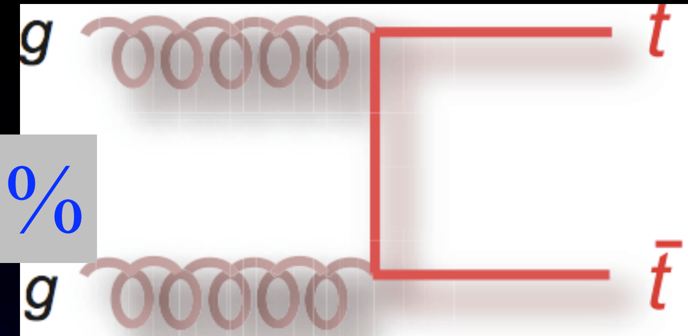
Most top measurements use $t\bar{t}$ events



85%

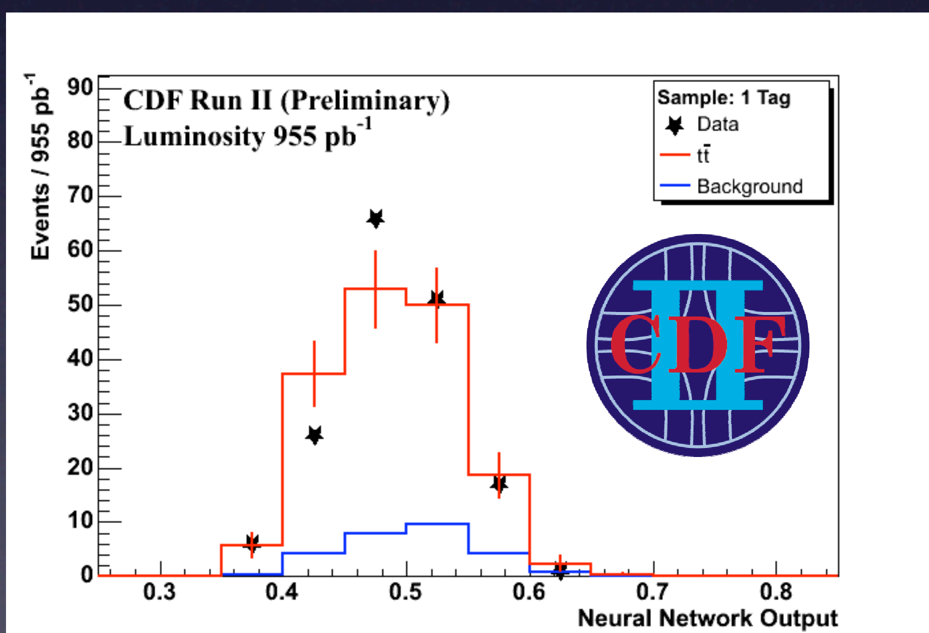


15%

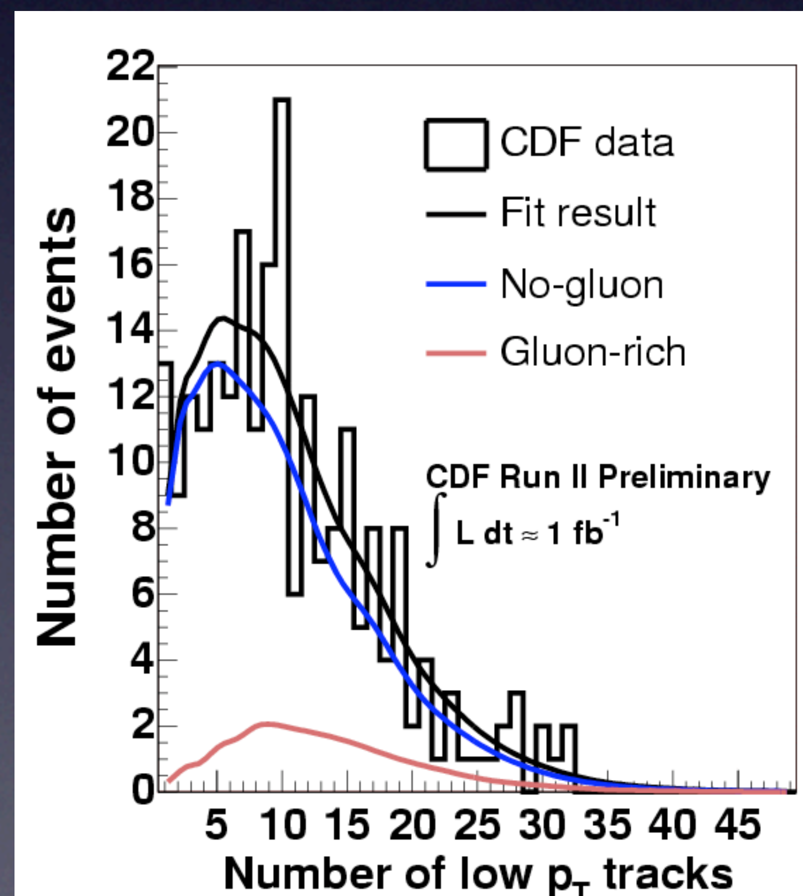


- CDF has measured the $q\bar{q}$ and gg contributions in three ways:

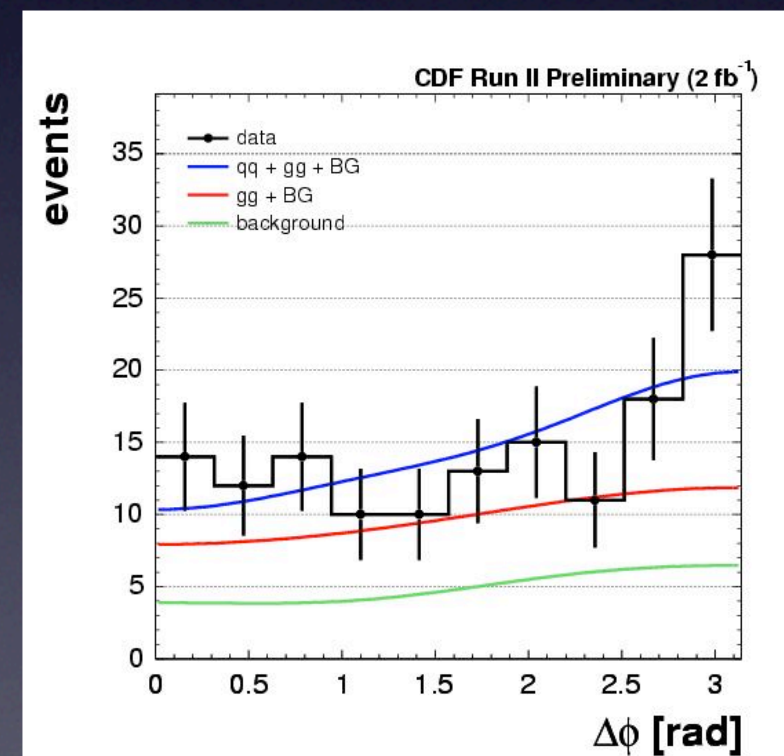
Kinematic neural net, # of low-p_T tracks in ℓ+jets events:



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



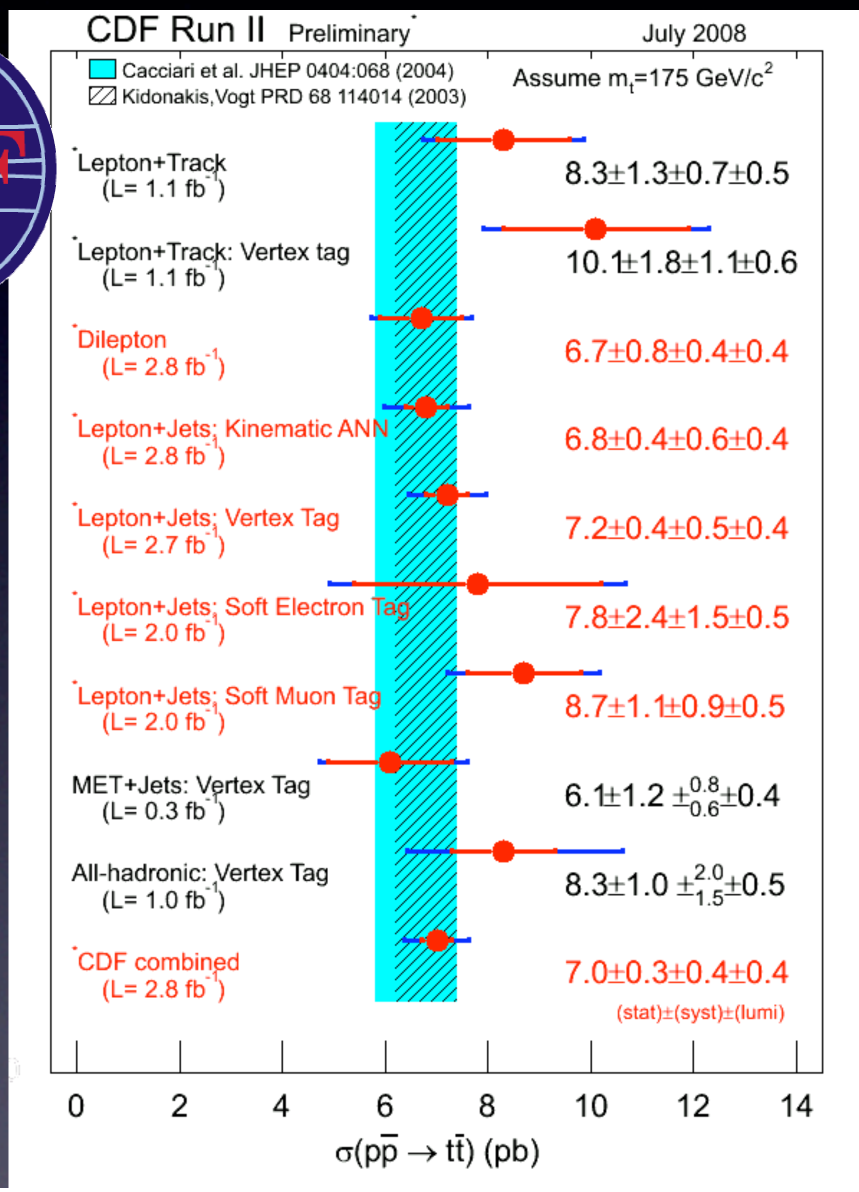
$\Delta\varphi_{\ell\ell}$ in dilepton events:

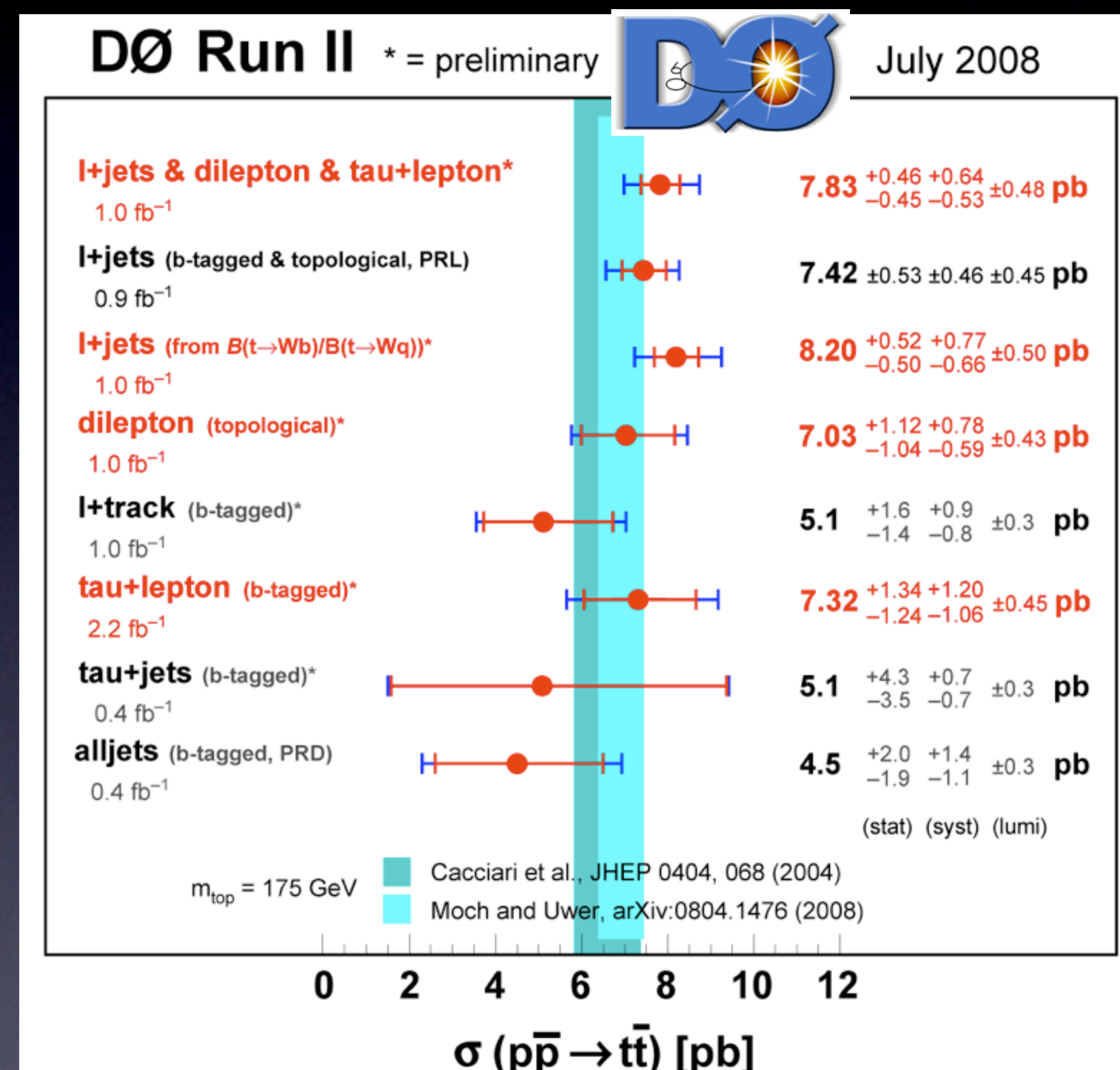


$$F_{gg} = 0.53^{+0.35+0.07}_{-0.37-0.08}$$

Production Cross Section

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





$$\sigma(p\bar{p} \to t\bar{t}) = 7.0 \pm 0.3 \pm 0.4 \pm 0.4 \text{ pb}$$

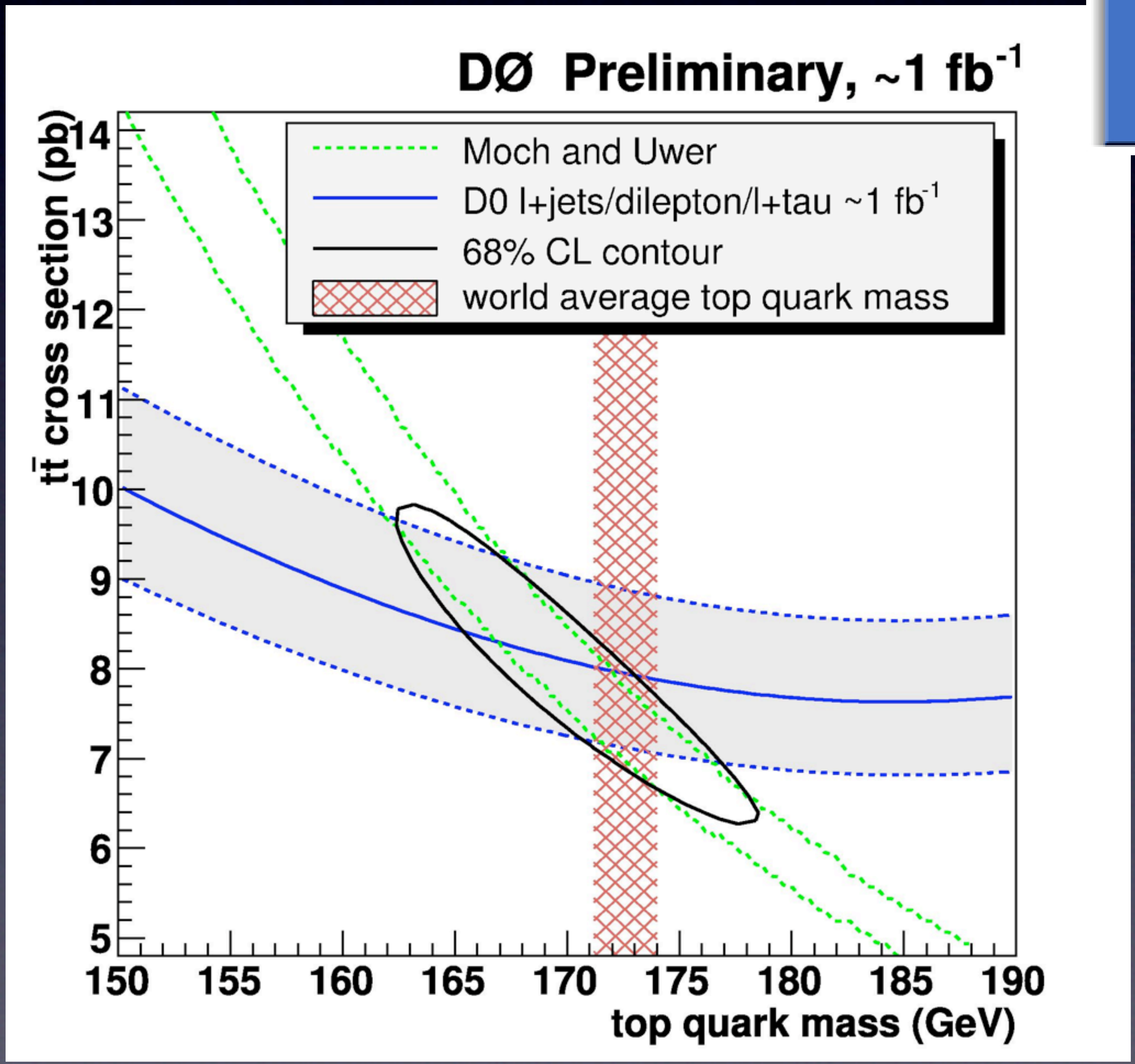
stat. syst. lum.

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

stat. syst. lum.

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



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

Direct Measurement of the Top Quark Mass

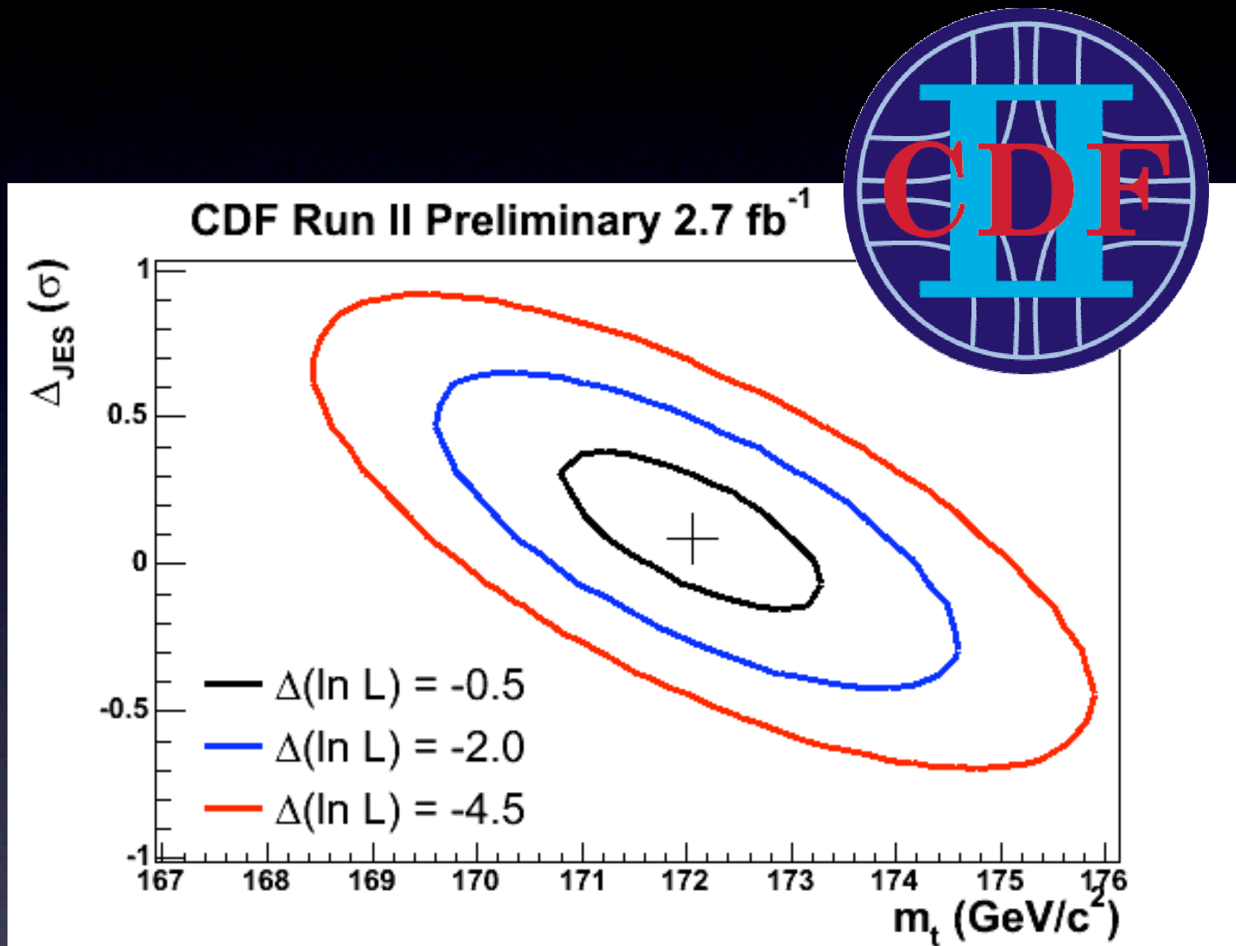
- Goal: measure top mass precisely...
  - to constrain Higgs mass
- ...in as many channels as possible
  - to search for new physics

ℓ+jets modes have optimal combination of rate and background

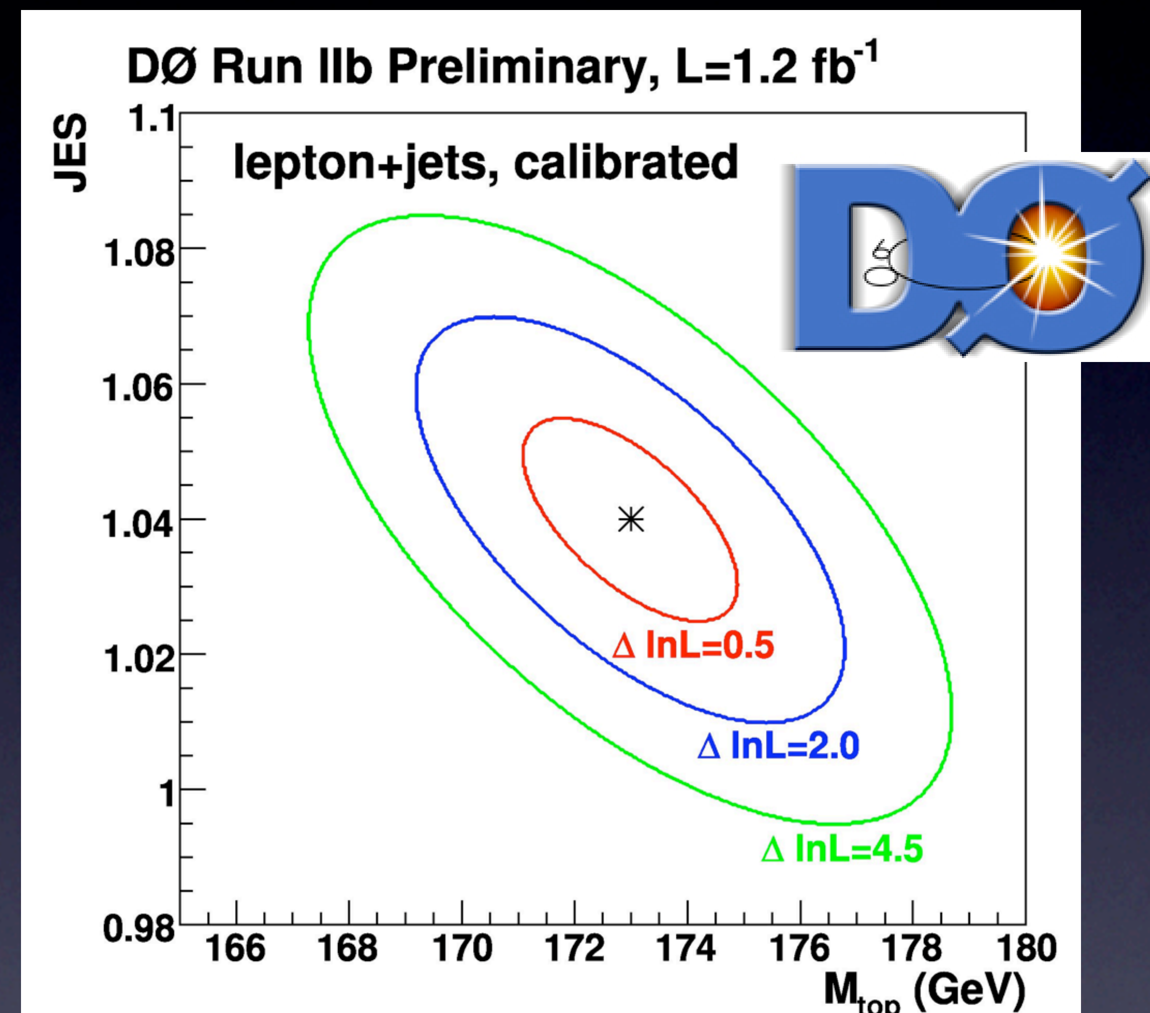
- Matrix element method provides best sensitivity
  - discriminate between top mass hypotheses as well as between signal and background
  - calibrate jet energy measurement from $W \to jj$ in signal events

Top Quark Mass (ℓ +jets)

- Results:



$m_t = 172.2 \pm 1.0 \pm\ 1.3$ GeV

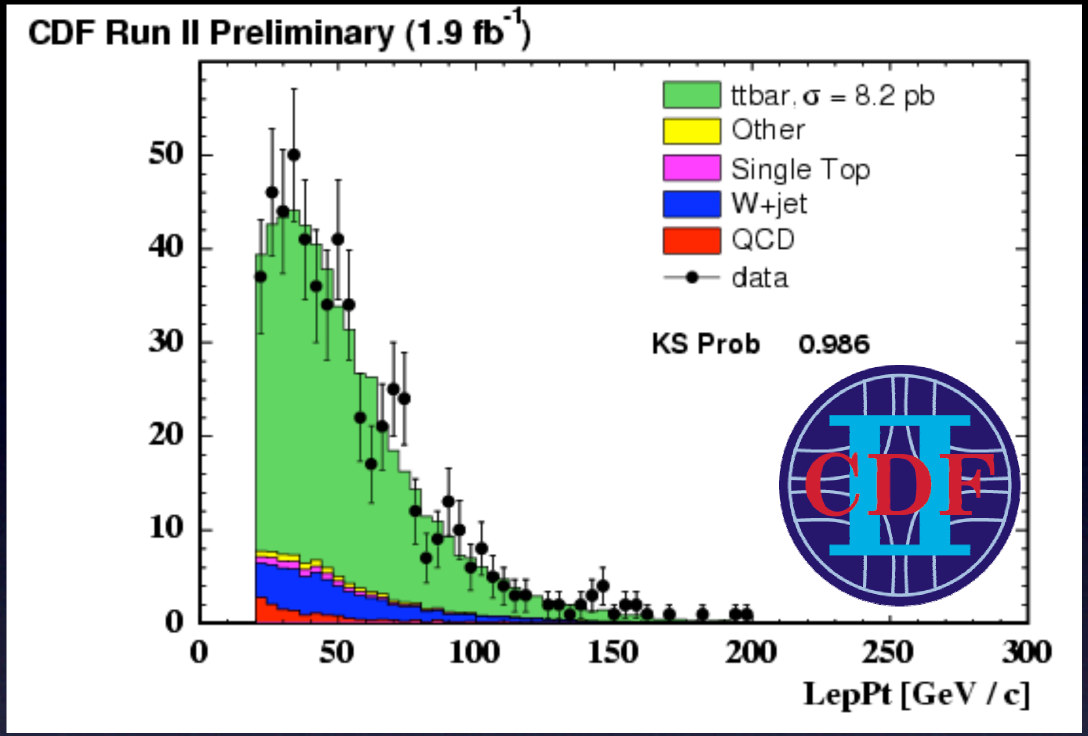


DØ Run II combined (2.2 fb^{-1}):
$m_t = 172.2 \pm 1.0 \pm\ 1.4$ GeV

Top Quark Mass without Jet Energy

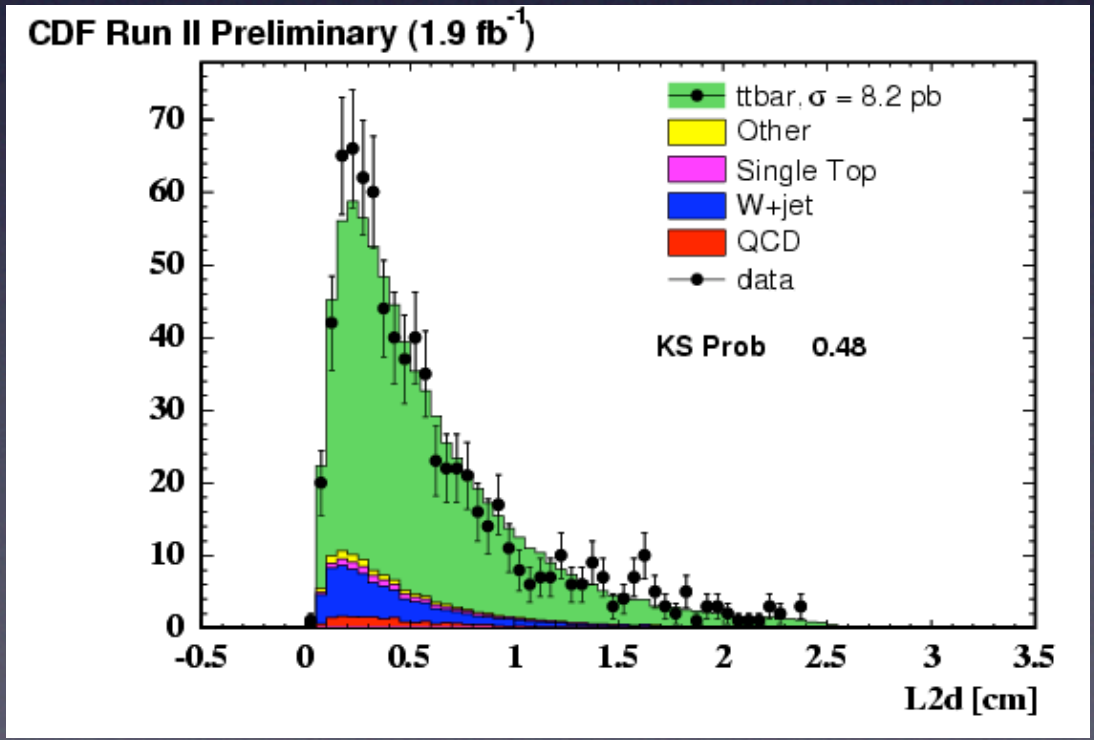
- Use observables that vary with top mass but have no first-order dependence on jet response
  - lepton p_T
  - b decay length in xy plane

$m_t = 175.3 \pm 6.2 \pm 3.0$ GeV



Systematics largely orthogonal to other measurements

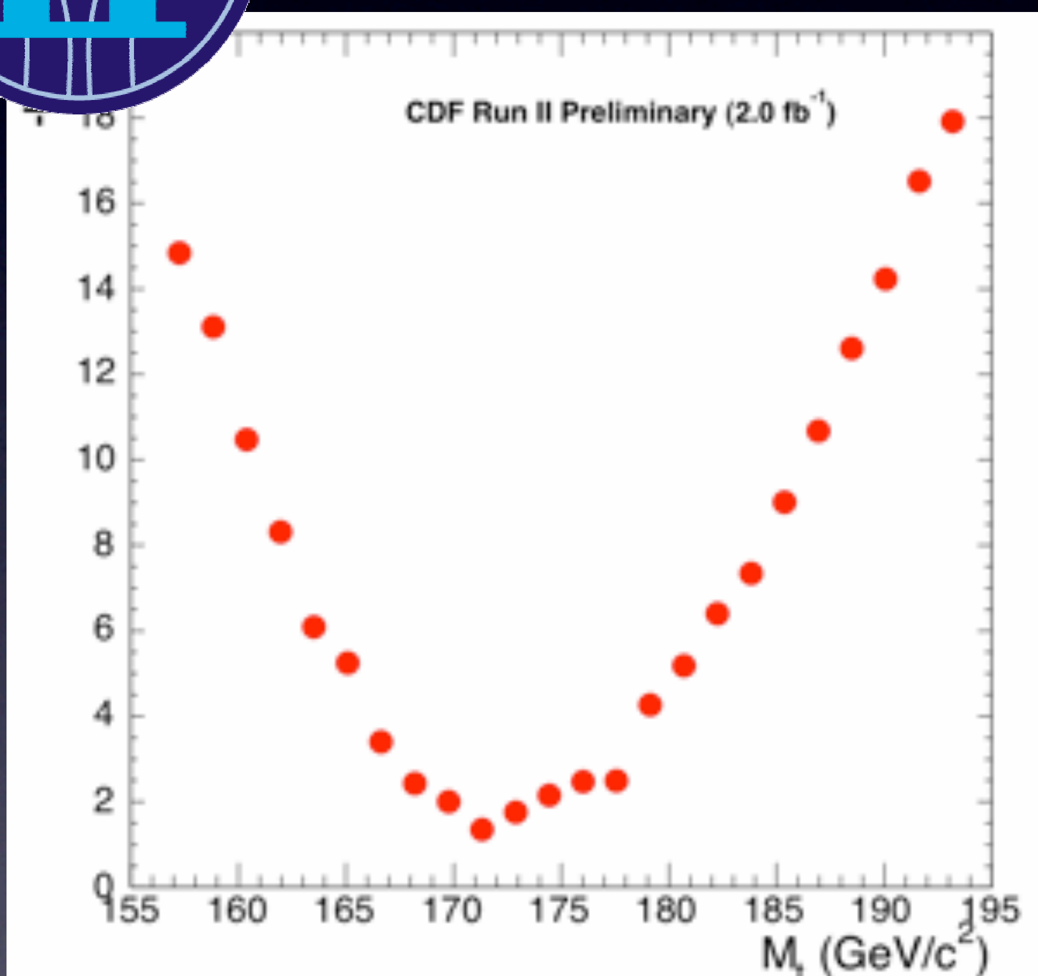
Currently statistics-limited, but will be an important technique at the LHC



Top Quark Mass (Dilepton)

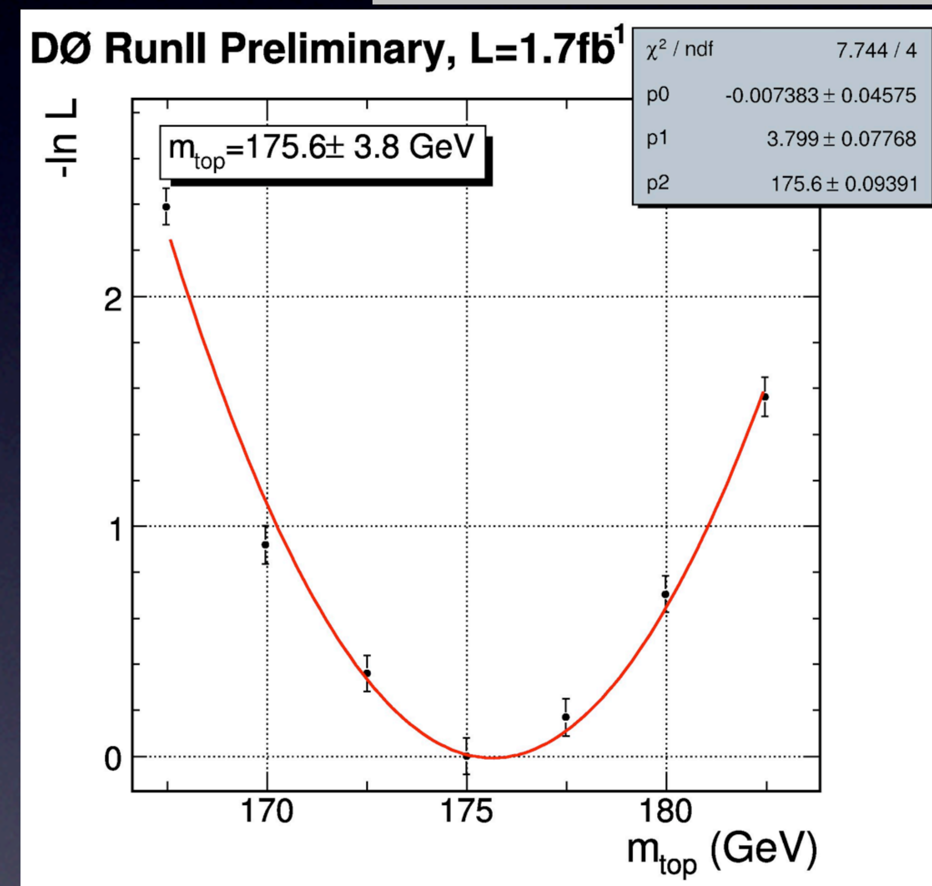
- Matrix element method can also be applied to dilepton events

Matrix Element,
NN event selection



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

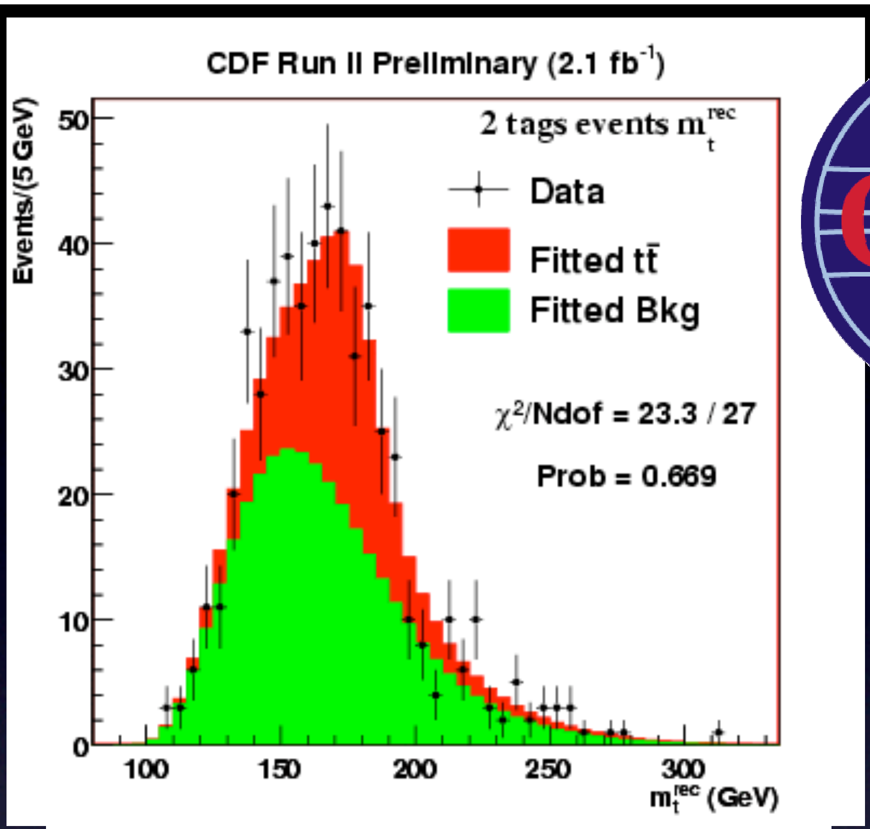
Matrix Element,
$e\mu$ channel

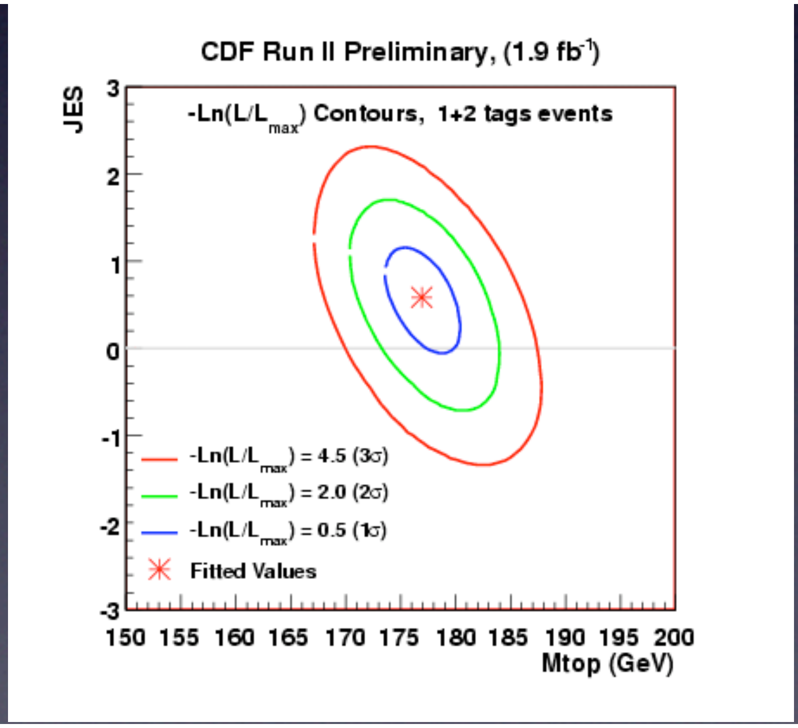


Run II $\ell\ell$ combined (2.8 fb^{-1}):
$m_t = 174.4 \pm 3.2 \pm\ 2.1$ GeV

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

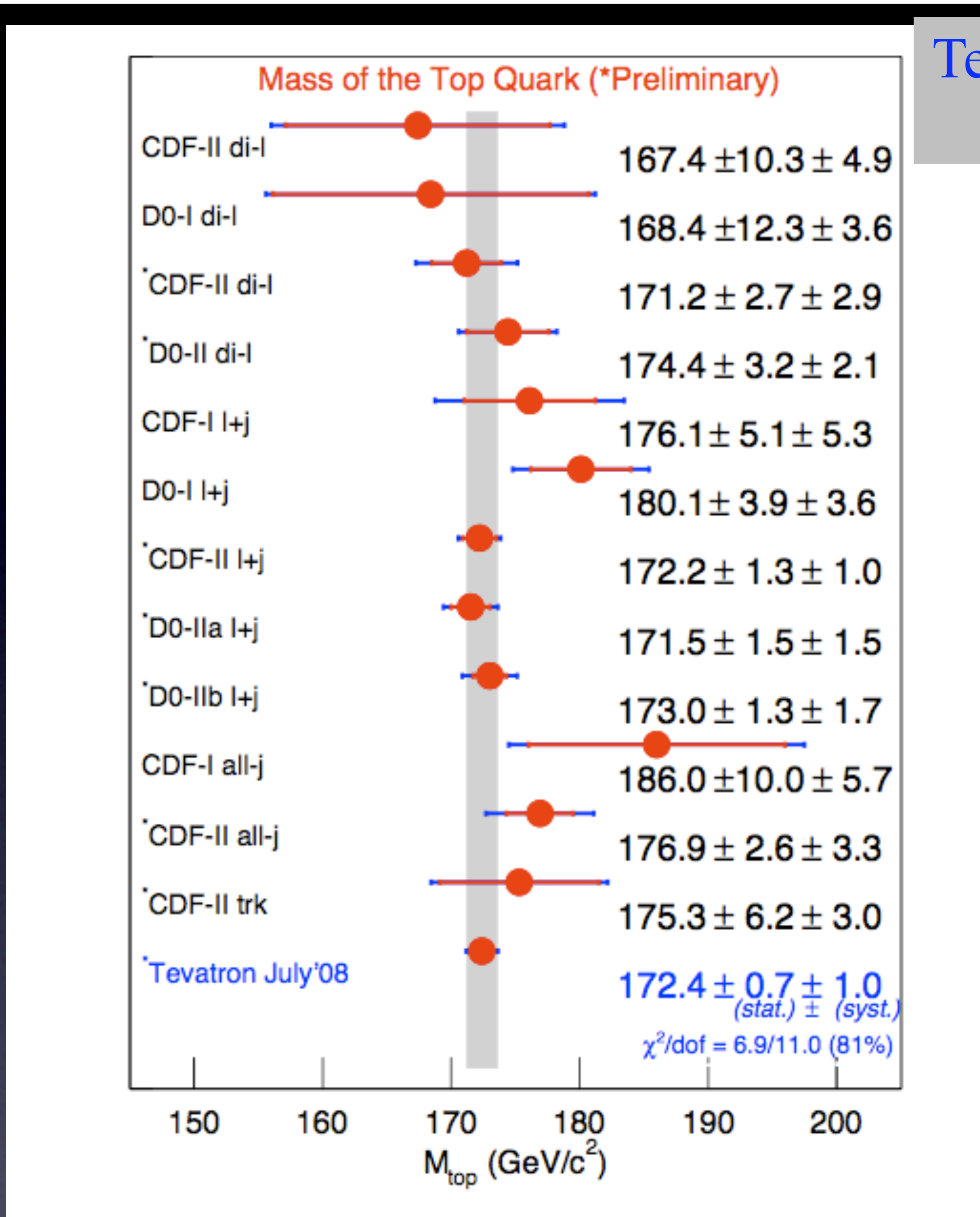




$$m_t = 176.9 \pm 3.8 \pm 1.7 \text{ GeV}$$

World Average Top Quark Mass

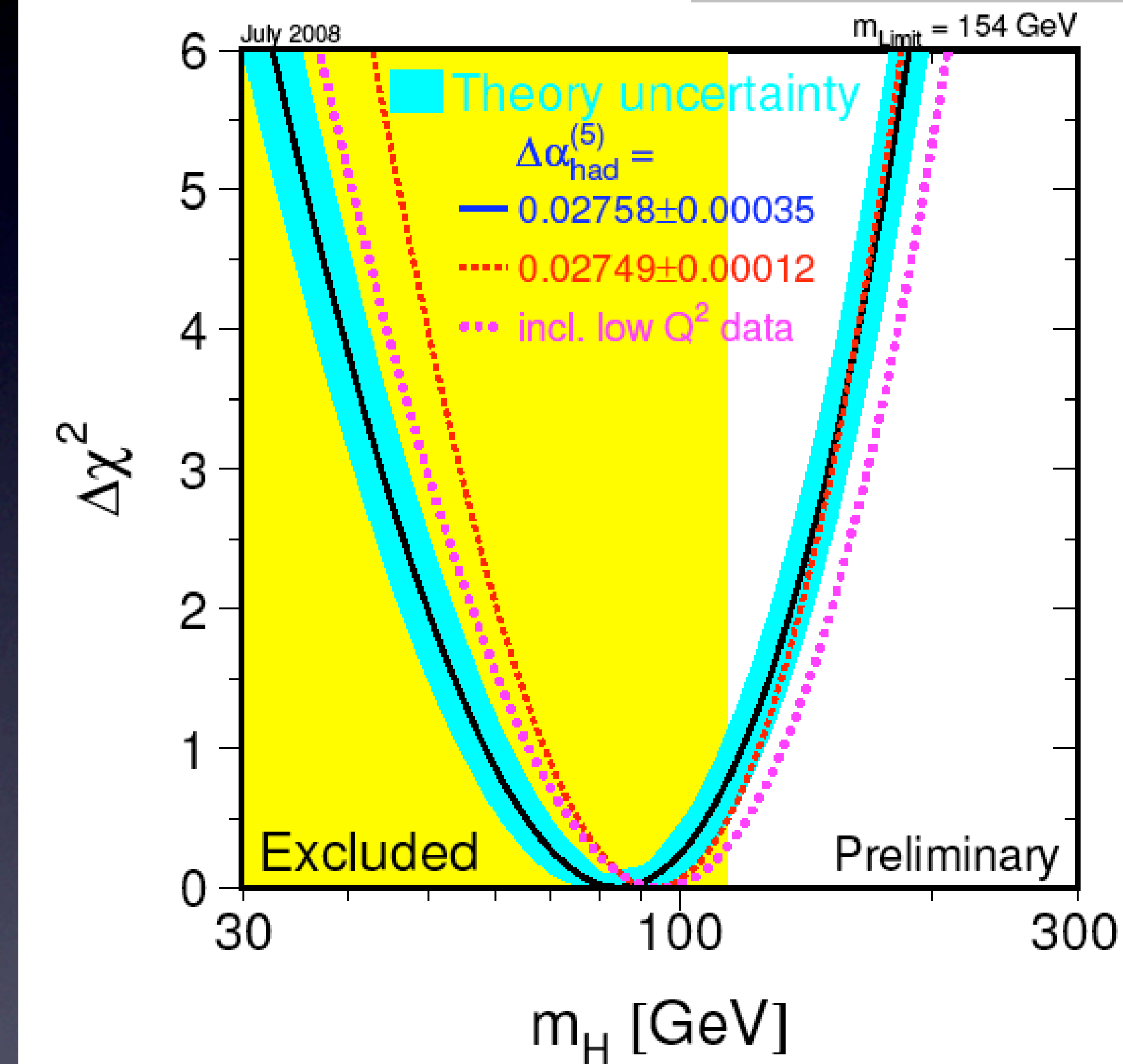
Tevatron Electroweak Working Group



$m_t = 172.4 \pm 0.7 \pm 1.0$ GeV

0.7 % precision

LEP Electroweak Working Group



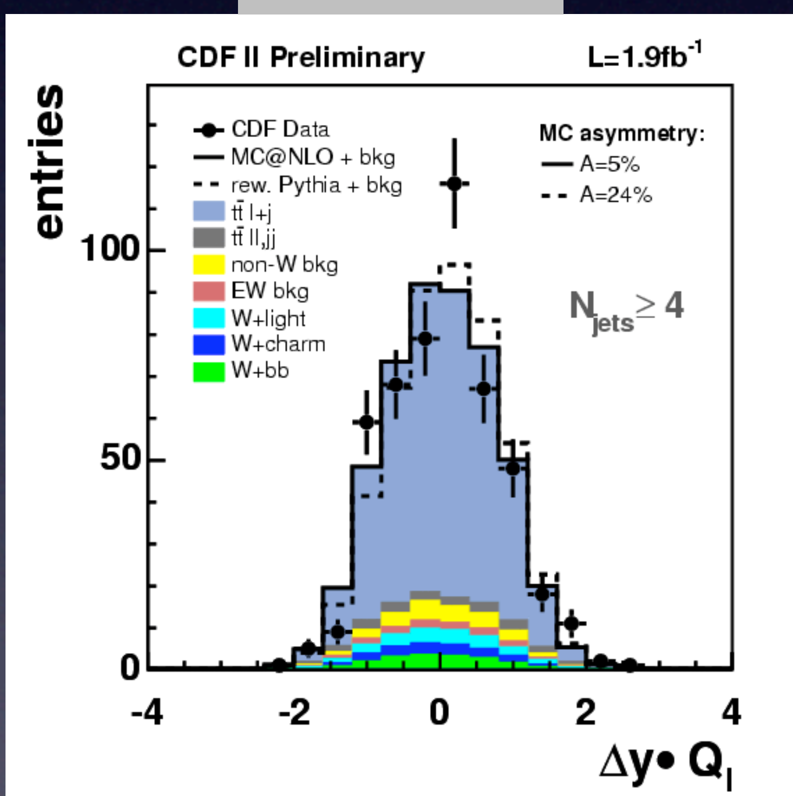
$m_H < 154$ GeV @ 95% C.L.

without direct search limit

Forward-backward Charge Asymmetry

- In SM, small asymmetry in $y_t - y_{\bar{t}}$ (5-10%) arises from NLO effects
  - new physics might enhance the asymmetry

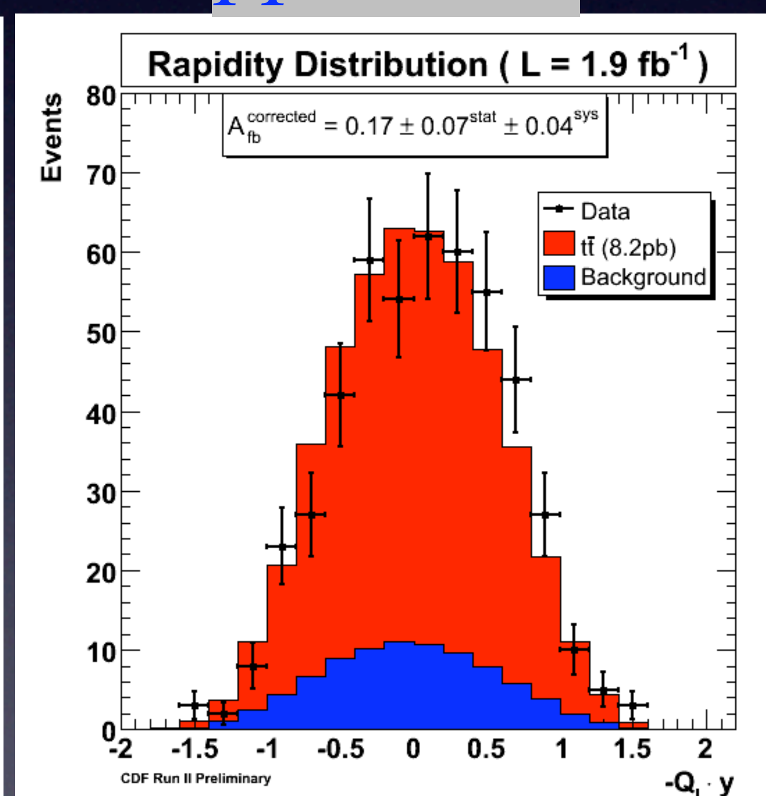
$t\bar{t}$ frame



corrected

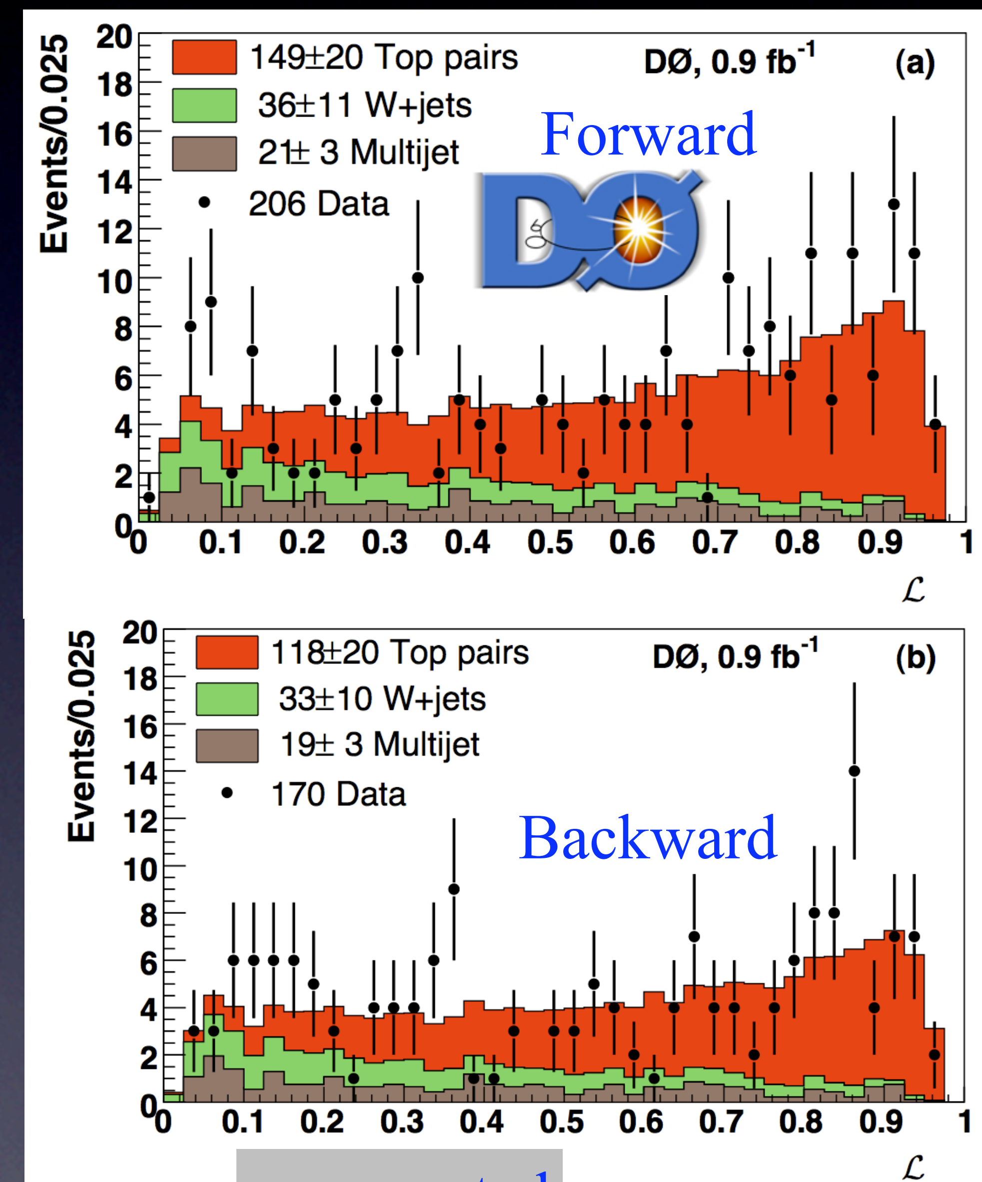
$A_{FB} = 24 \pm 13 \pm 4$ %

$p\bar{p}$ frame



corrected

$A_{FB} = 17 \pm 7 \pm 4$ %

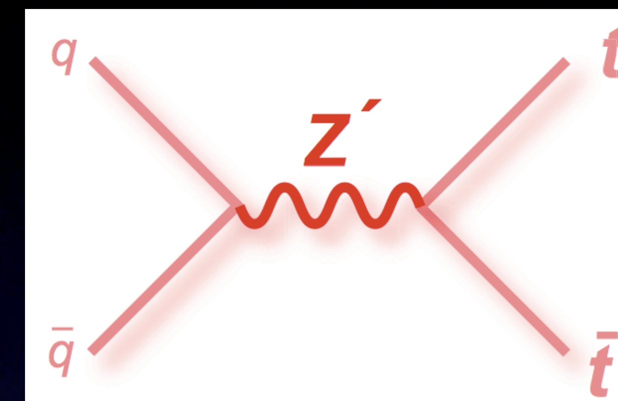


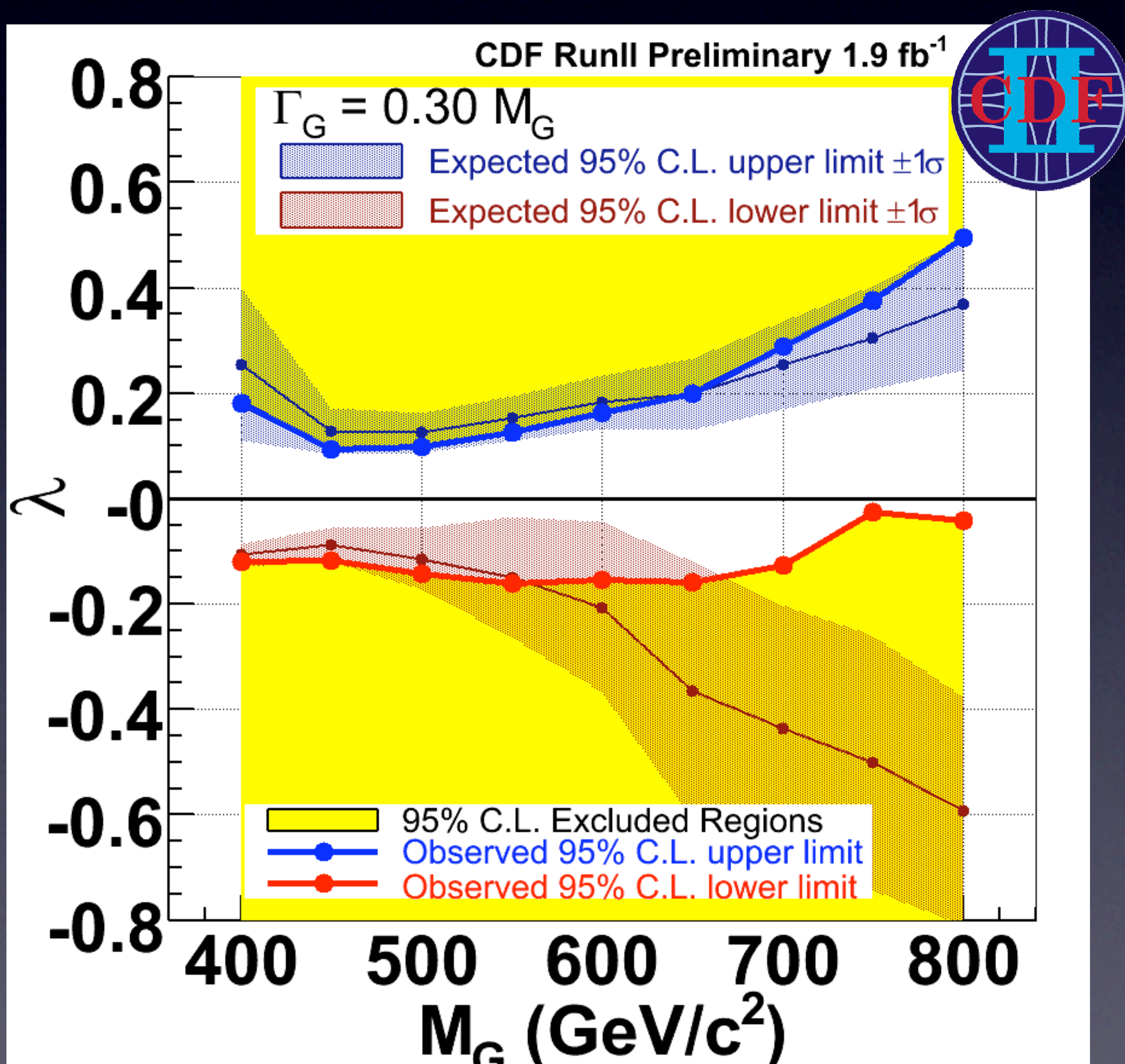
uncorrected

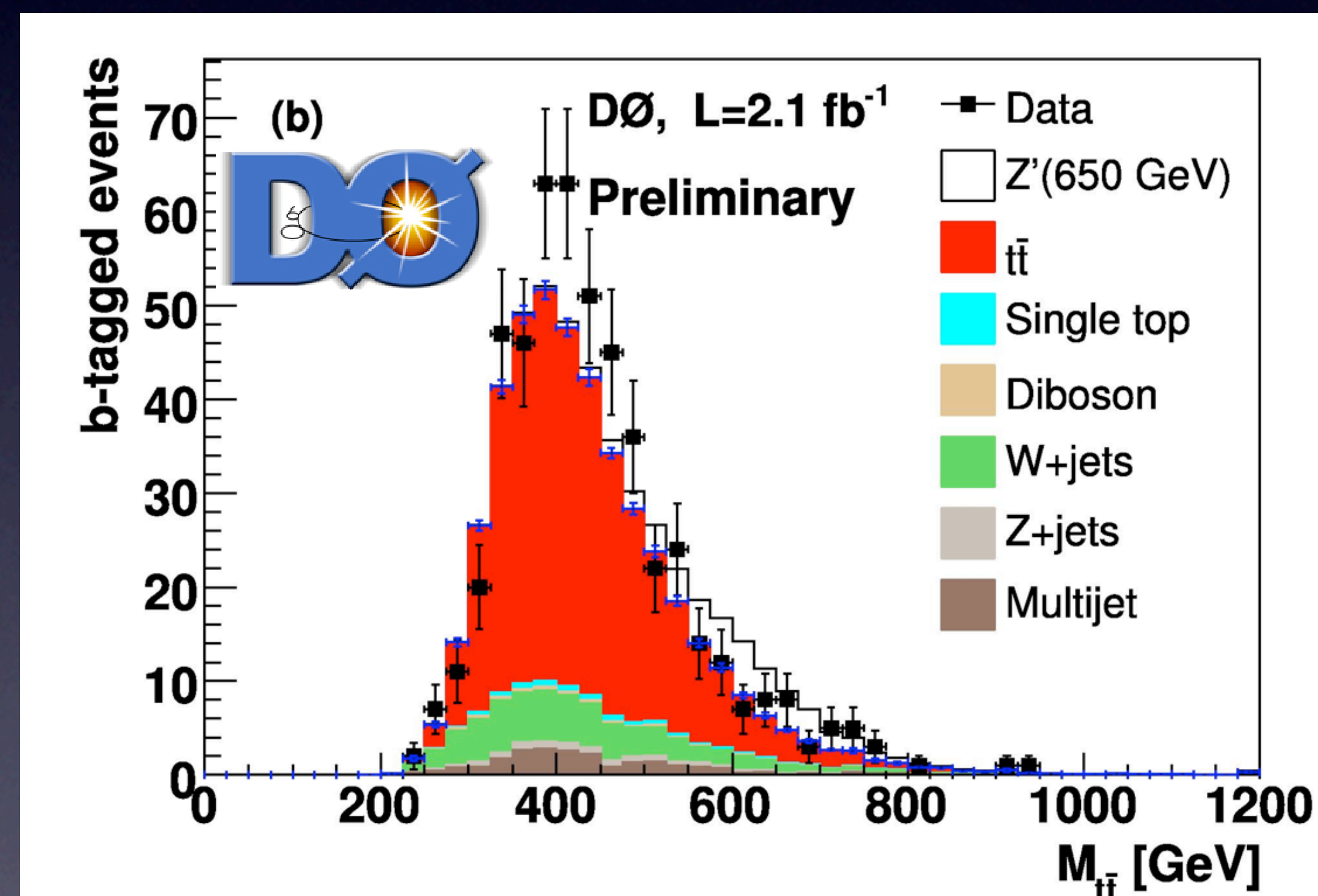
$A_{FB} = 12 \pm 8 \pm 1$ %

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



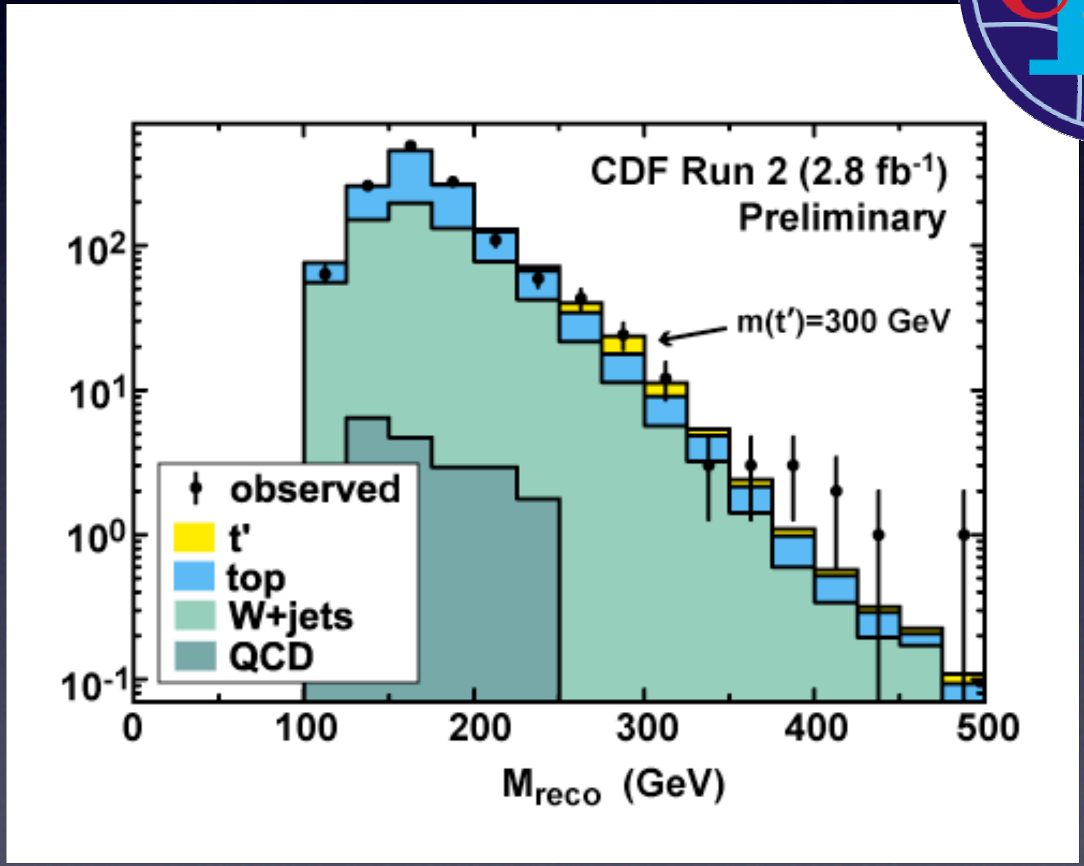


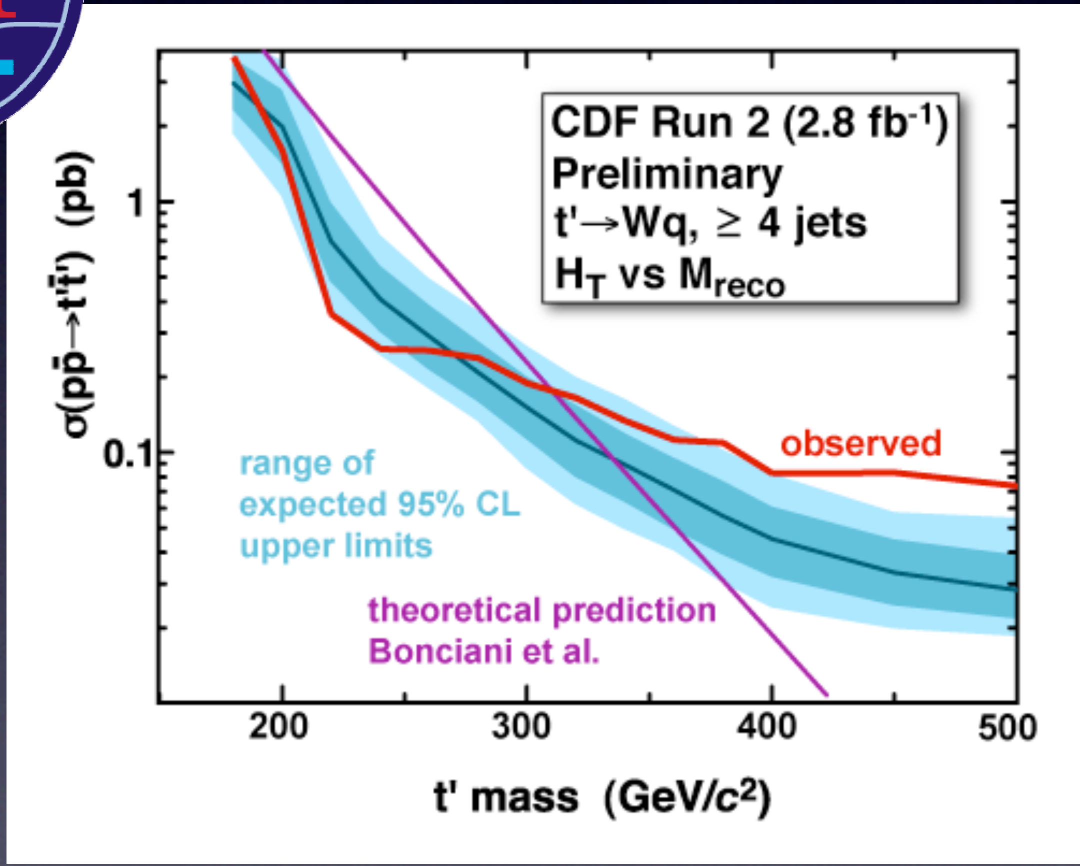


$m_{Z'} > 760$ GeV @ 95% C.L.

Search for t' Quark

- Some SUSY models, and the Little Higgs model, predict the existence of a heavy 4th-generation quark (t')
  - search using distributions of reconstructed top mass and sum of jet p_T

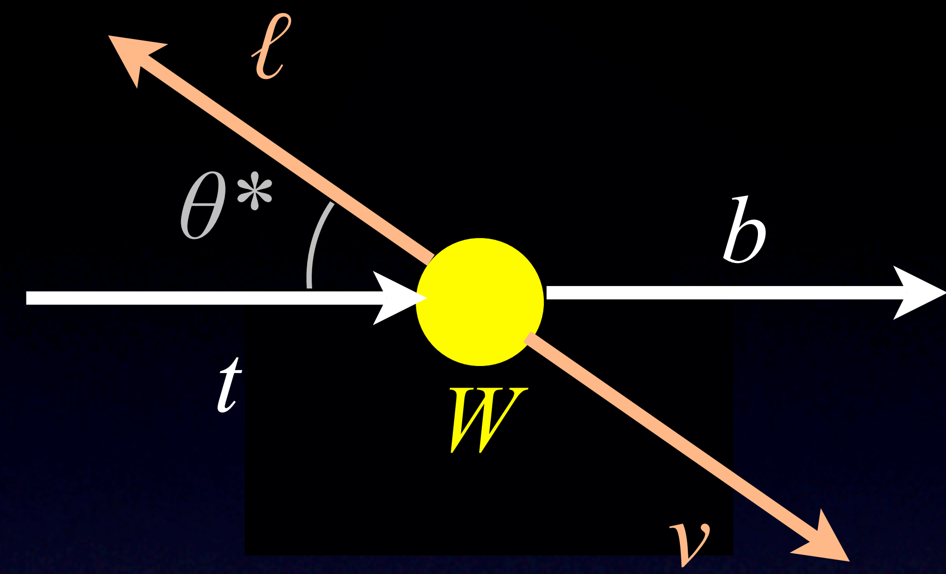


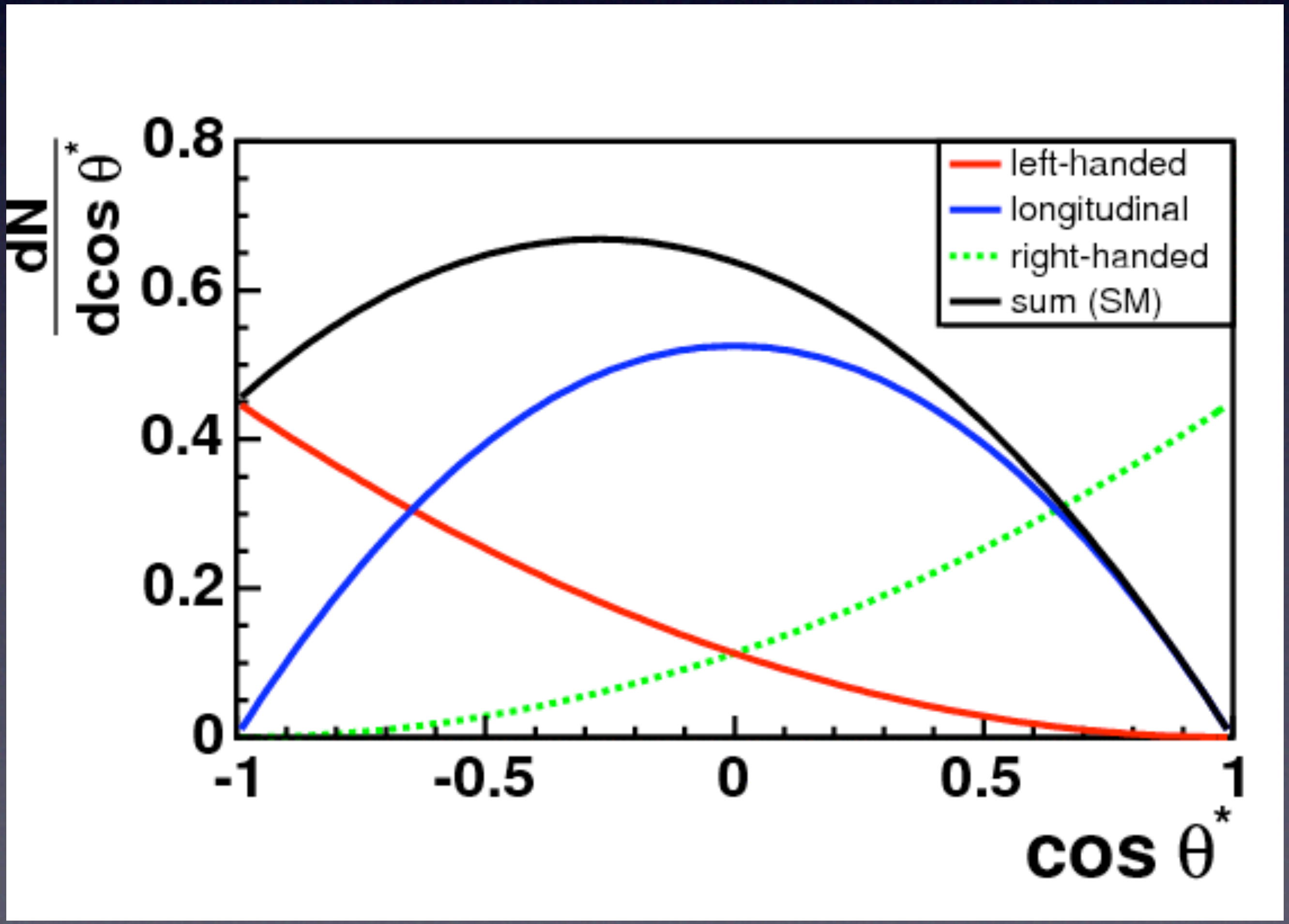


$m_{t'} > 311$ GeV @ 95% C.L.

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





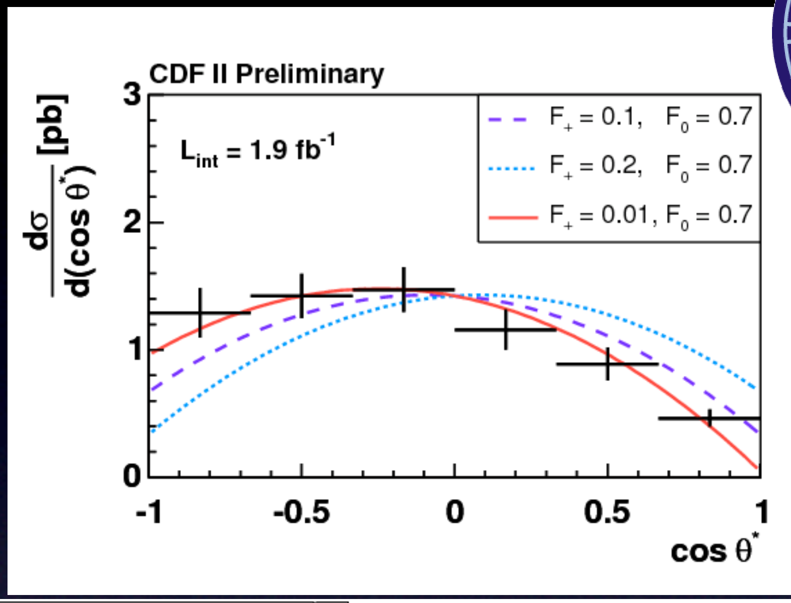
Measurement is based on direct reconstruction of $\cos\theta^*$

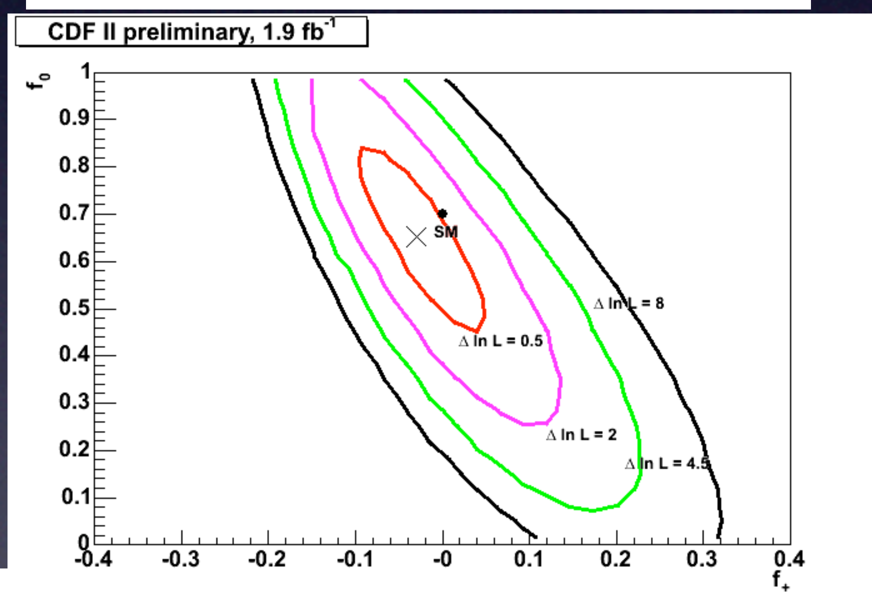
Detector and acceptance effects accounted for by:

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

W Boson Helicity

- ℓ+jets channel

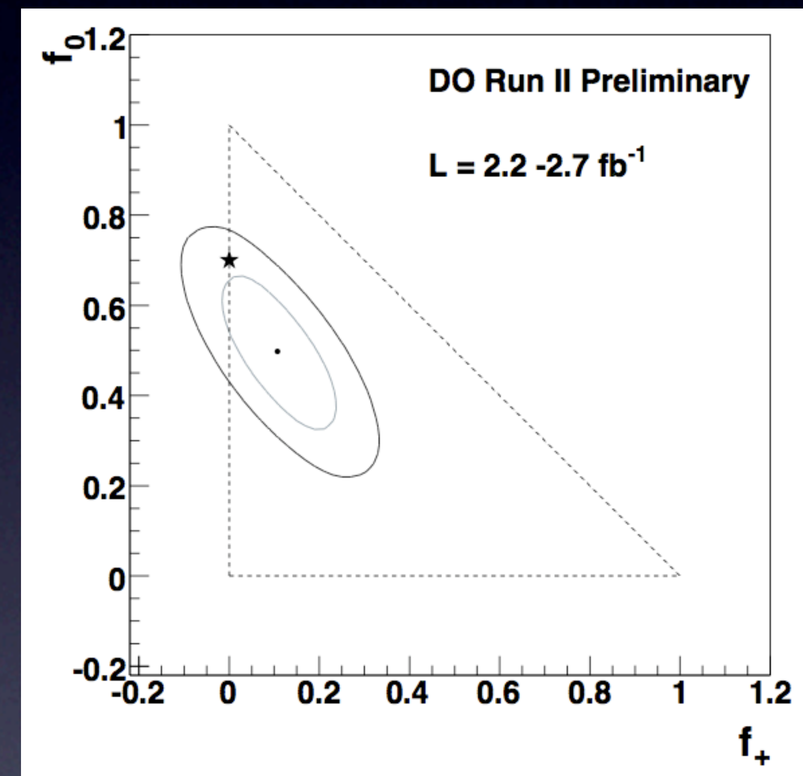




Combination:

$$f_0 = 0.66 \pm 0.16$$
$$f_+ = -0.03 \pm 0.07$$

- Template method
  - ℓ+jets and ℓℓ channels
  - use both *W*'s in each event



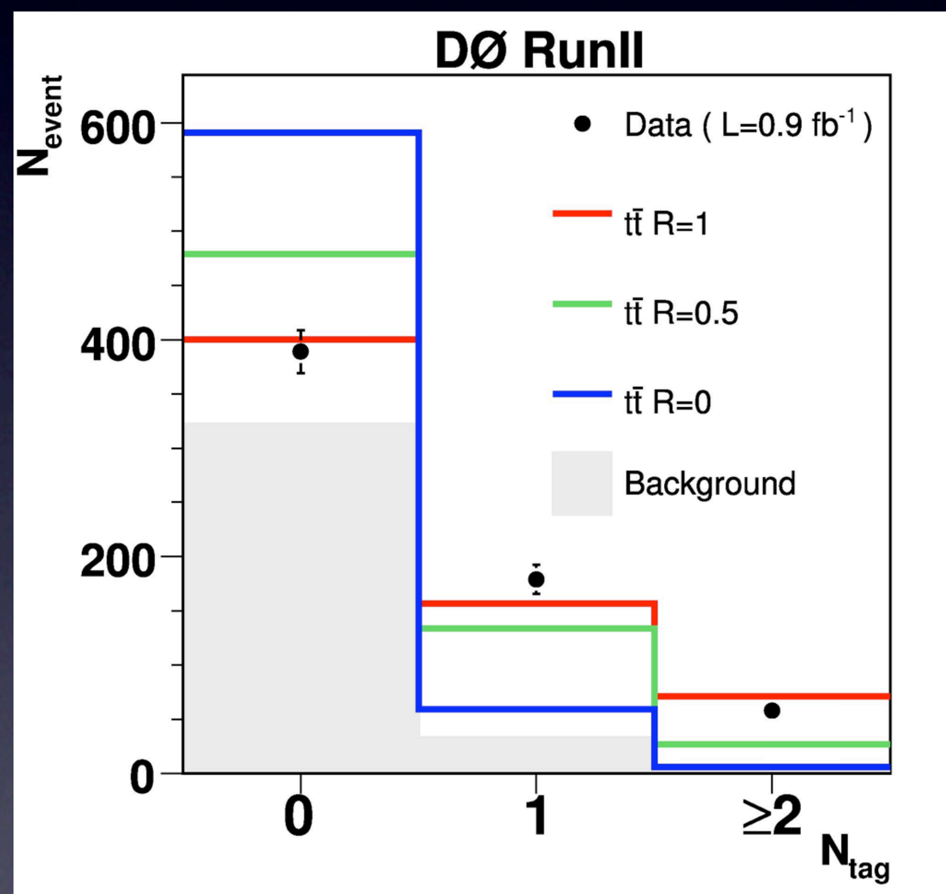
$$f_0 = 0.49 \pm 0.10 \pm 0.08$$
$$f_+ = 0.11 \pm 0.05 \pm 0.05$$

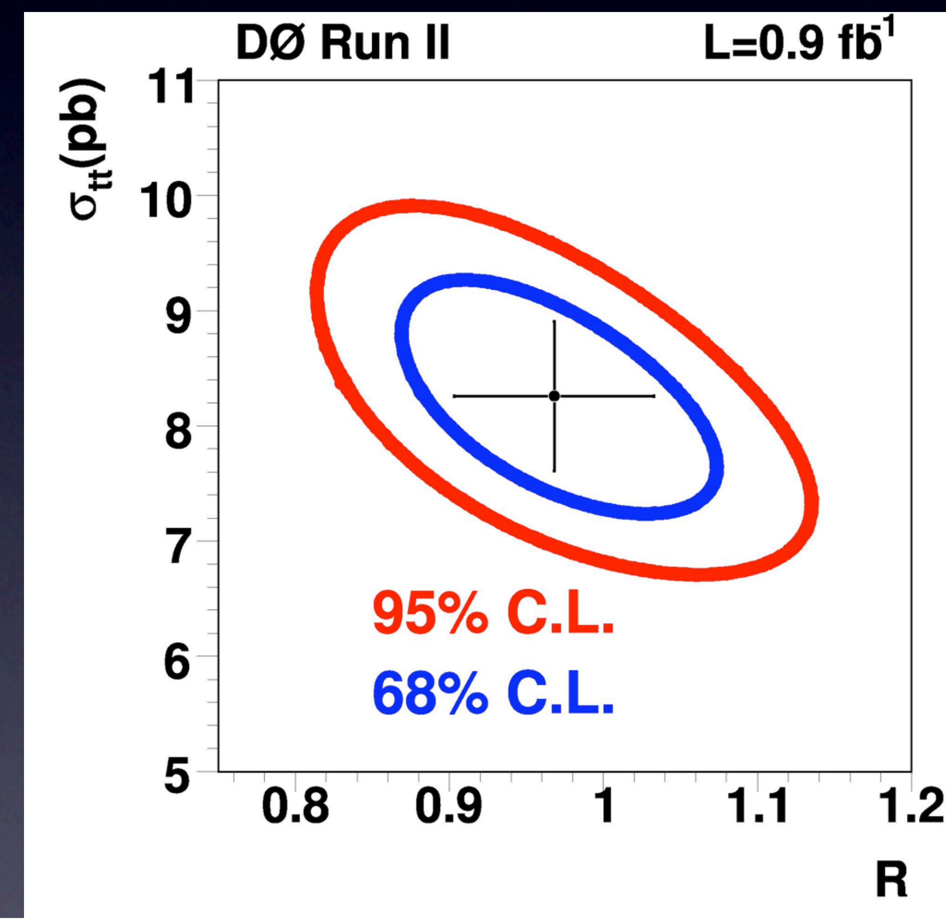
SM *p*-value: 23%

Top Quark Branching Fractions

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

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





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

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

Search for Invisible Decays

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

X is any state with different acceptance than *Wb*

Top Cross Section: Double Loose SECVTX Tag $\left(\int \mathscr{L} dt = 1.9\,\text{fb}^{-1}\right)$

Sample	2 Jets	3 Jets	4 Jets	≥ 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 $t\bar{t}$ (8.8pb)	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

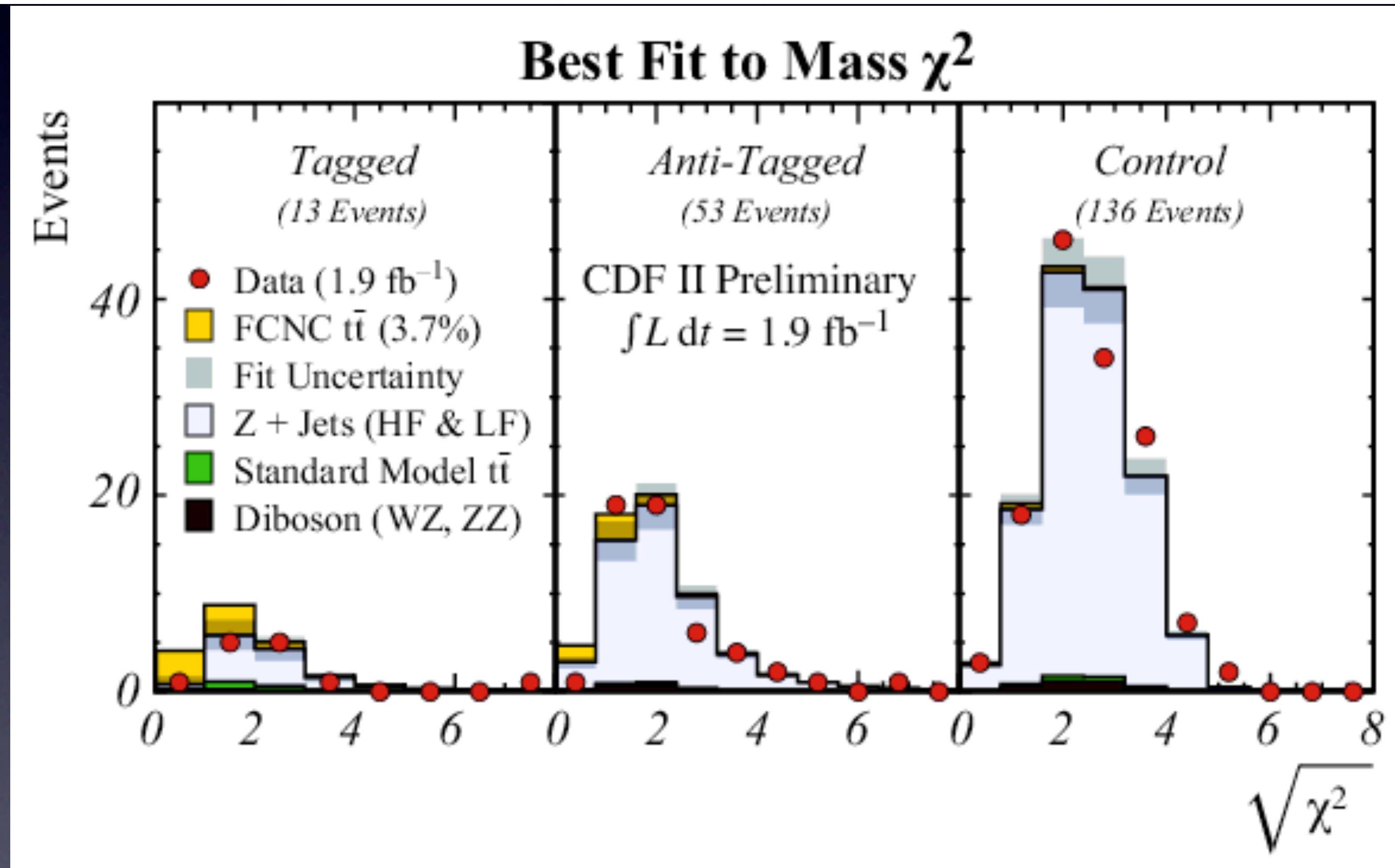
$B(t \rightarrow Zc) < 13\%$

$B(t \rightarrow \text{invisible}) < 9\%$

Flavor-Changing Neutral Currents

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

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

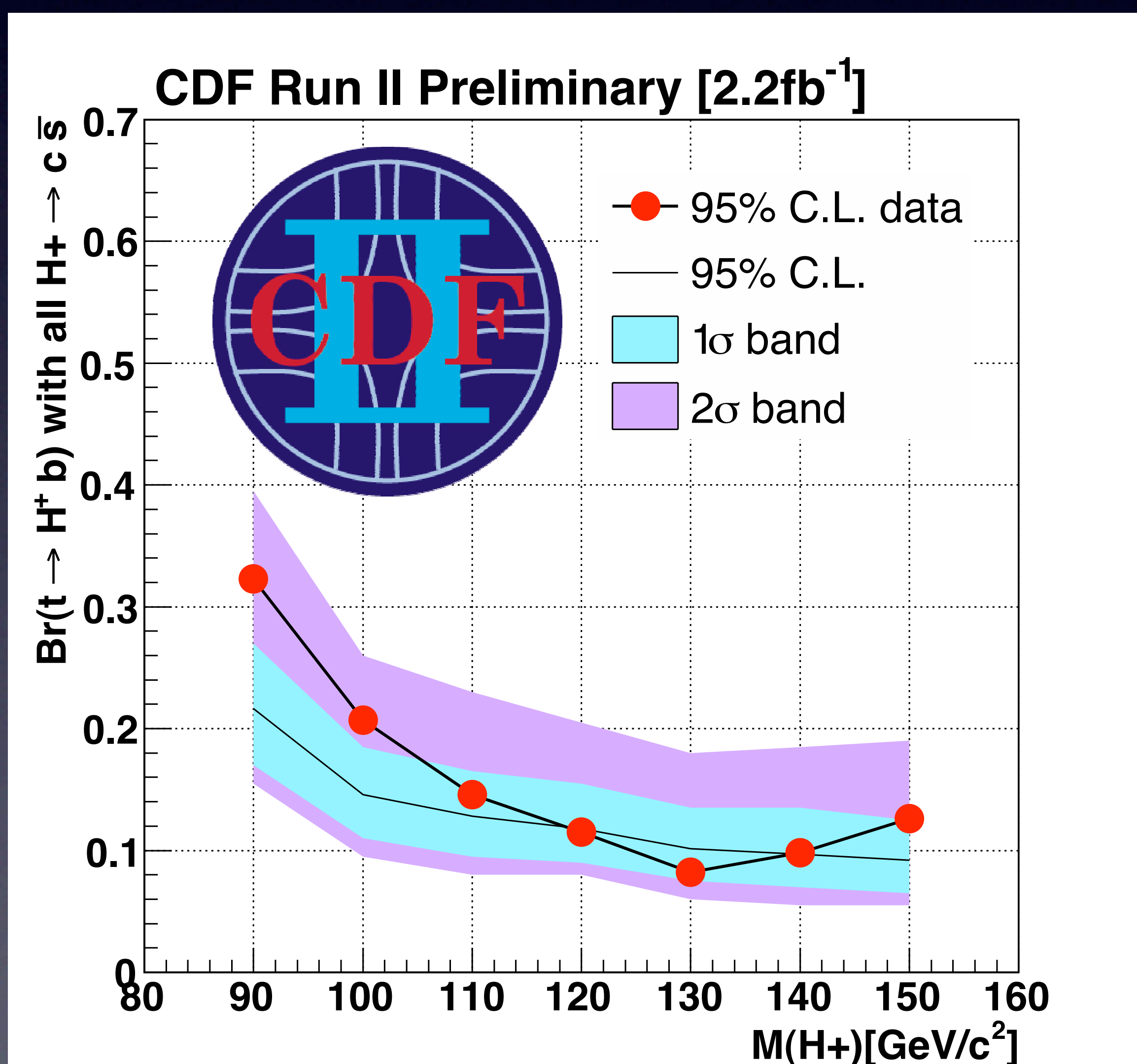


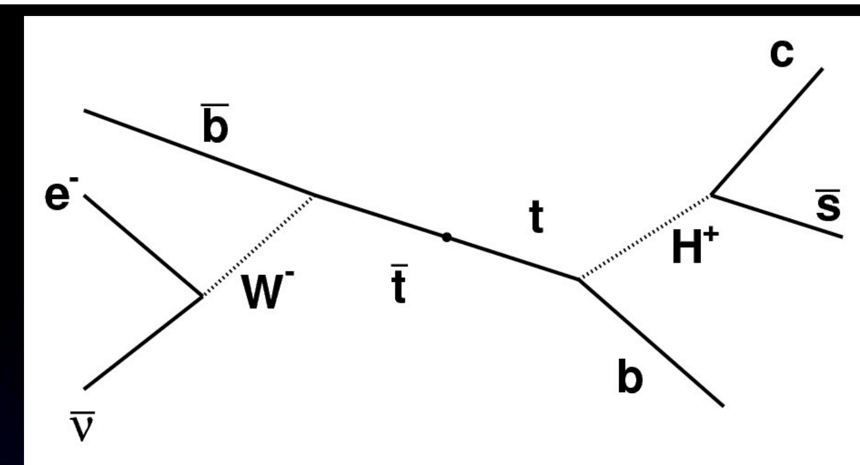
$B(t \to Zq) < 3.7\%$ @ 95% C.L.

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

Use ℓ+jets events with 2 b tags

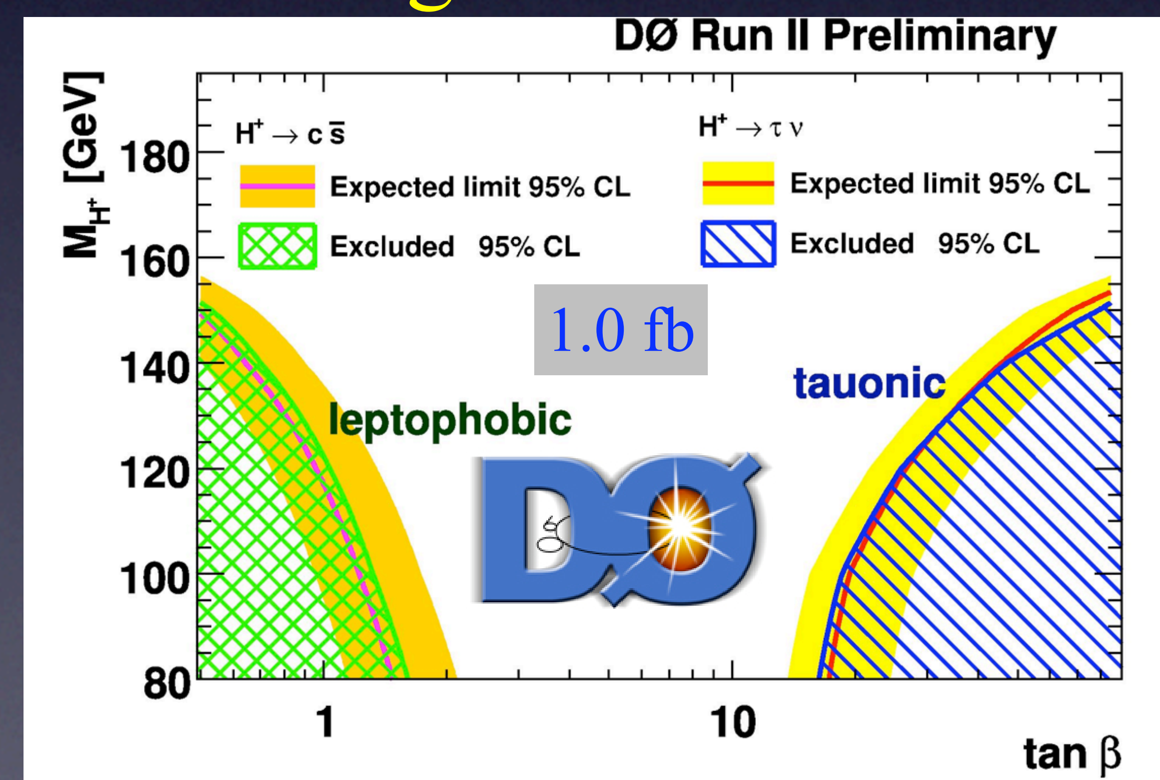
- kinematic fit to select H^+ daughter candidate jets
- plot mass of jet pair





Measure rates across several decay modes

- including τ final states



Top at the LHC

- LHC will be a top factory ($\sigma(p\bar{p} \rightarrow t\bar{t}) \approx 850$ pb) :
  - 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 0.7%
  - several measurement of interaction and decay properties, as well as searches for new particles, have not yet revealed any non-SM effects
- The era of single-top production measurements has begun
- The LHC will provide a major improvement in precision

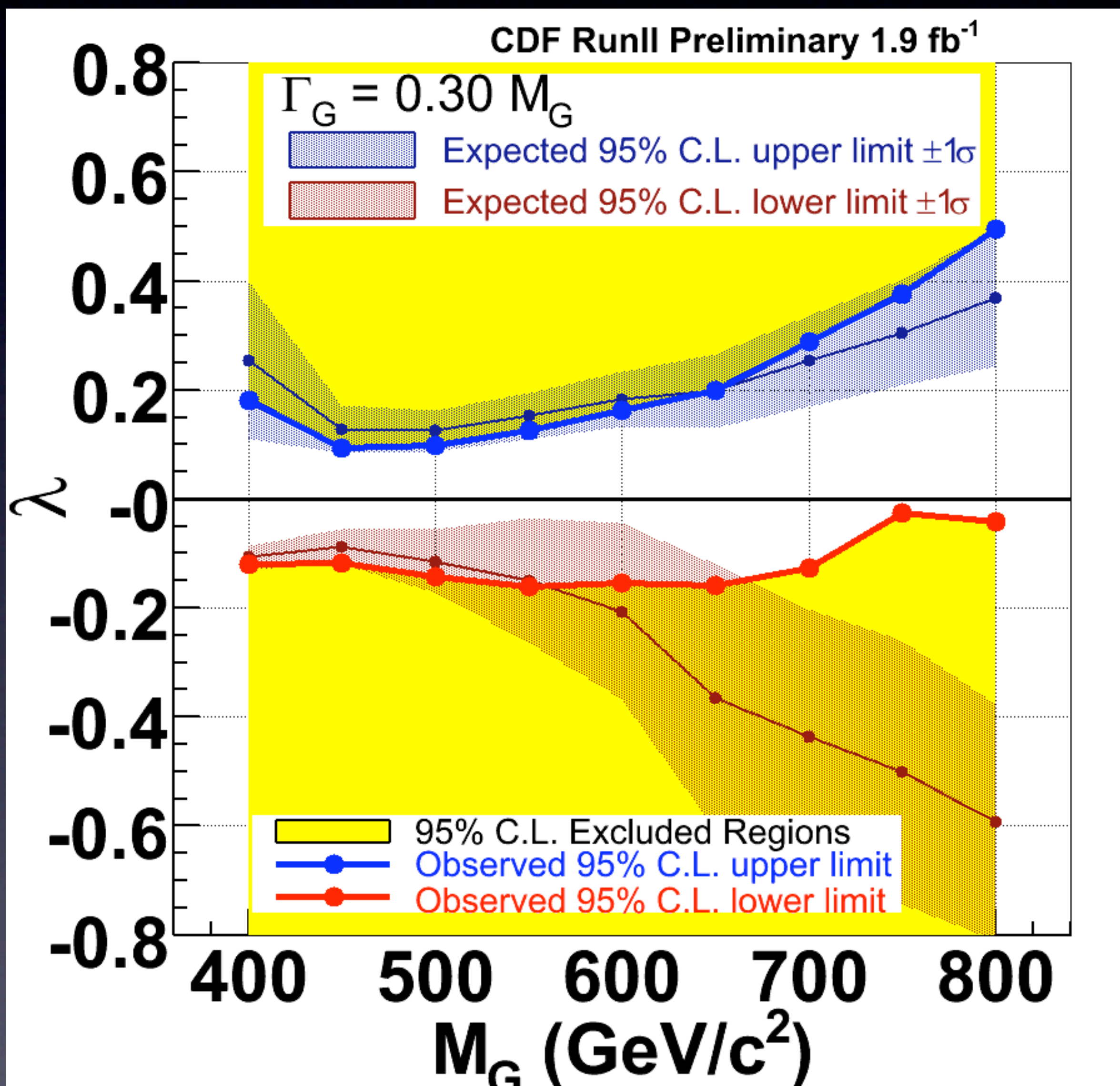
We have learned much about the top quark in the past 13 years
In a few more years it will be as familiar as the *Z* boson and *b* quark

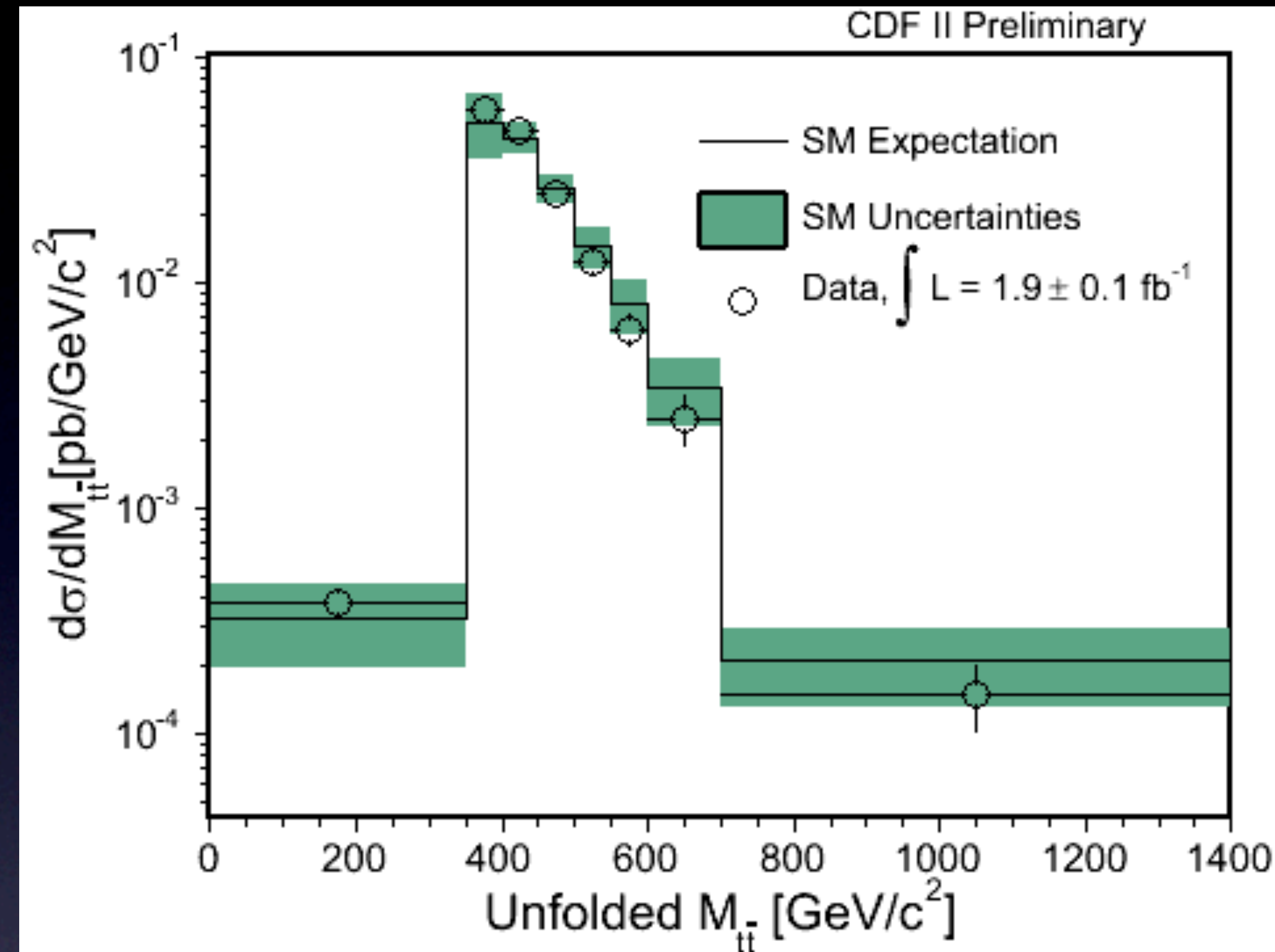
Backup

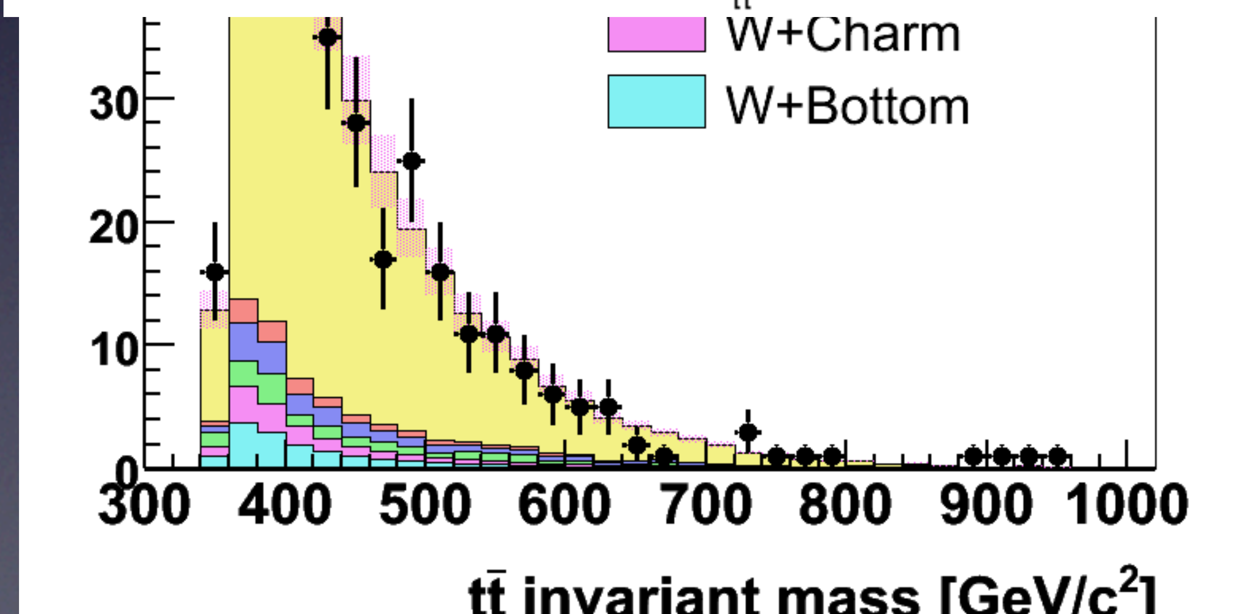
The Top Quark in Experiment

- The world's sample of top quarks comes exclusively from the Tevatron
  - searches for anomalous production also done at HERA
  - "top factory" at LHC is coming soon...
- CDF and DØ detector have similar capabilities for top quark physics
  - data samples are ~3fb^{-1} per experiment → ~20000 $t\bar{t}$ and 7000 single-top events produced
    - ✦ branching ratios and selection efficiencies reduce the sample available for analysis

Search for Resonant ttbar Production

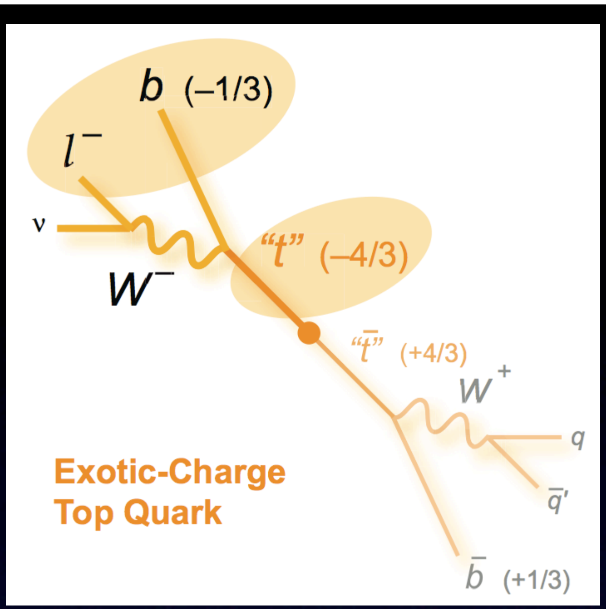


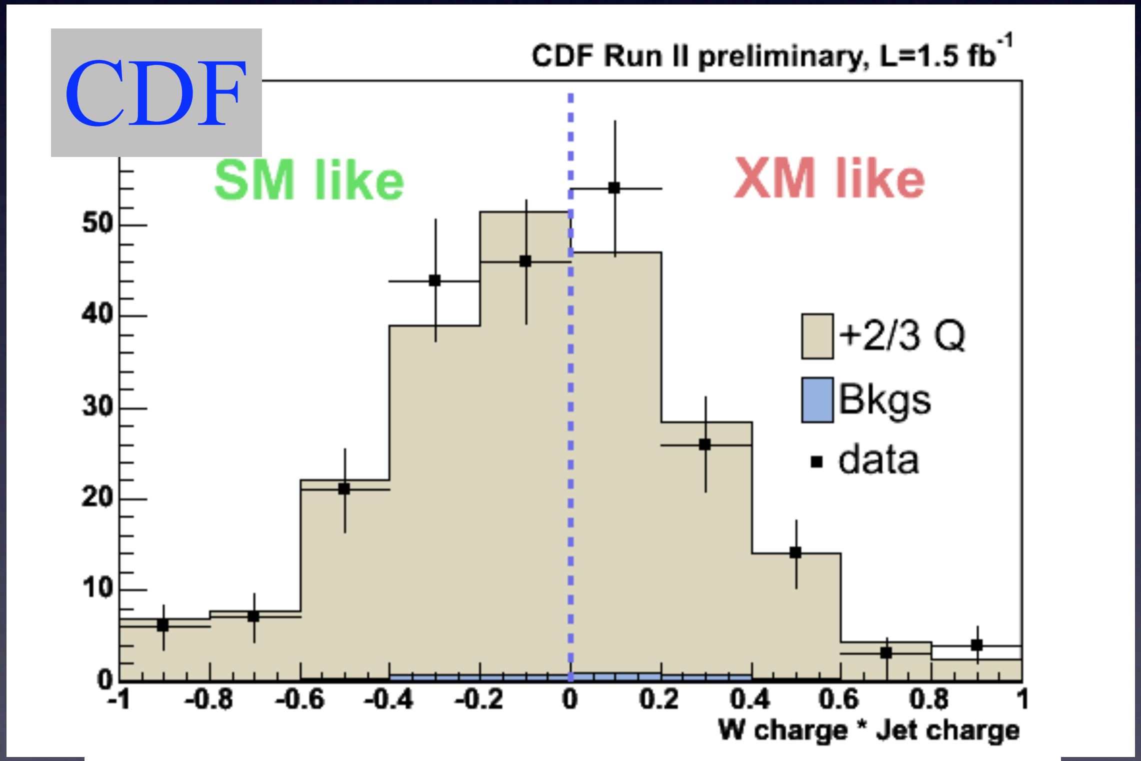




Top Quark Charge

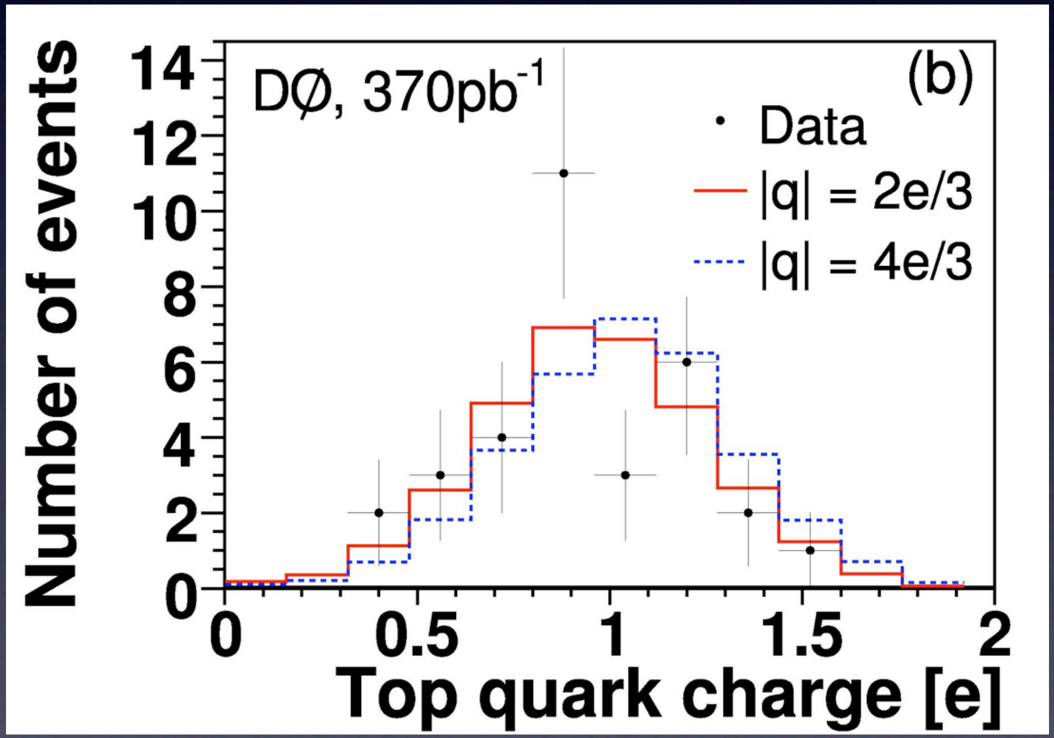
- Have we really observed the top quark, or some new particle with charge 4/3?
- Test by kinematic reconstruction, then measurement of charge of jet paired with the lepton





SM strongly favored

p-value for +4/3: 0.2%



SM favored

p-value for +4/3: 7.8%