Top Quark Properties at the Tevatron

Gabriele Compostella
(INFN-CNAF and University of Padova)
on behalf of the CDF and D0 Collaborations

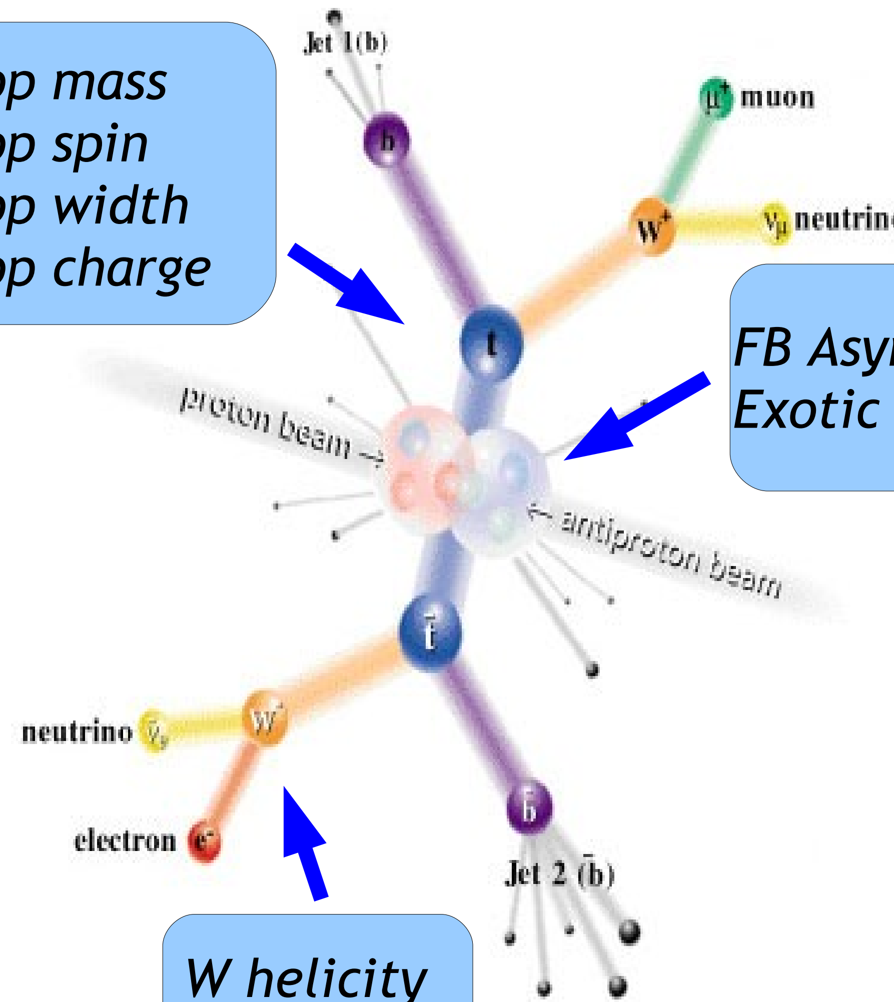
Tevatron program explores all top properties as well as possible sources of new physics:

top quark ***production***
- *top pair production*
- *Single top production*

top quark ***properties***
- *Mass, spin, width, charge*

top quark ***decay***
- *W boson helicity in top decays*
- *Probe the W-t-b vertex*

Exotic sources *of top quarks*
- *Non SM top*
- *Forward-backward asymmetries*

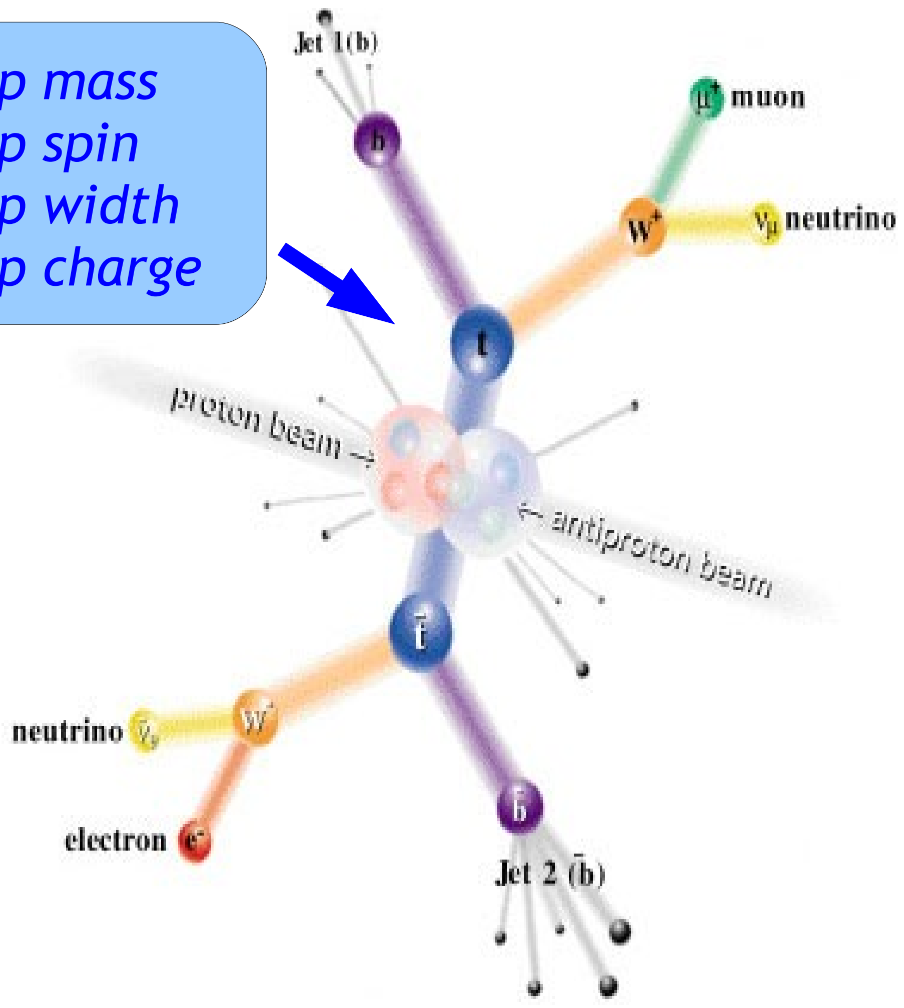


Top mass
Top spin
Top width
Top charge

FB Asymmetry
Exotic production

W helicity
Wtb vertex

Top mass
Top spin
Top width
Top charge

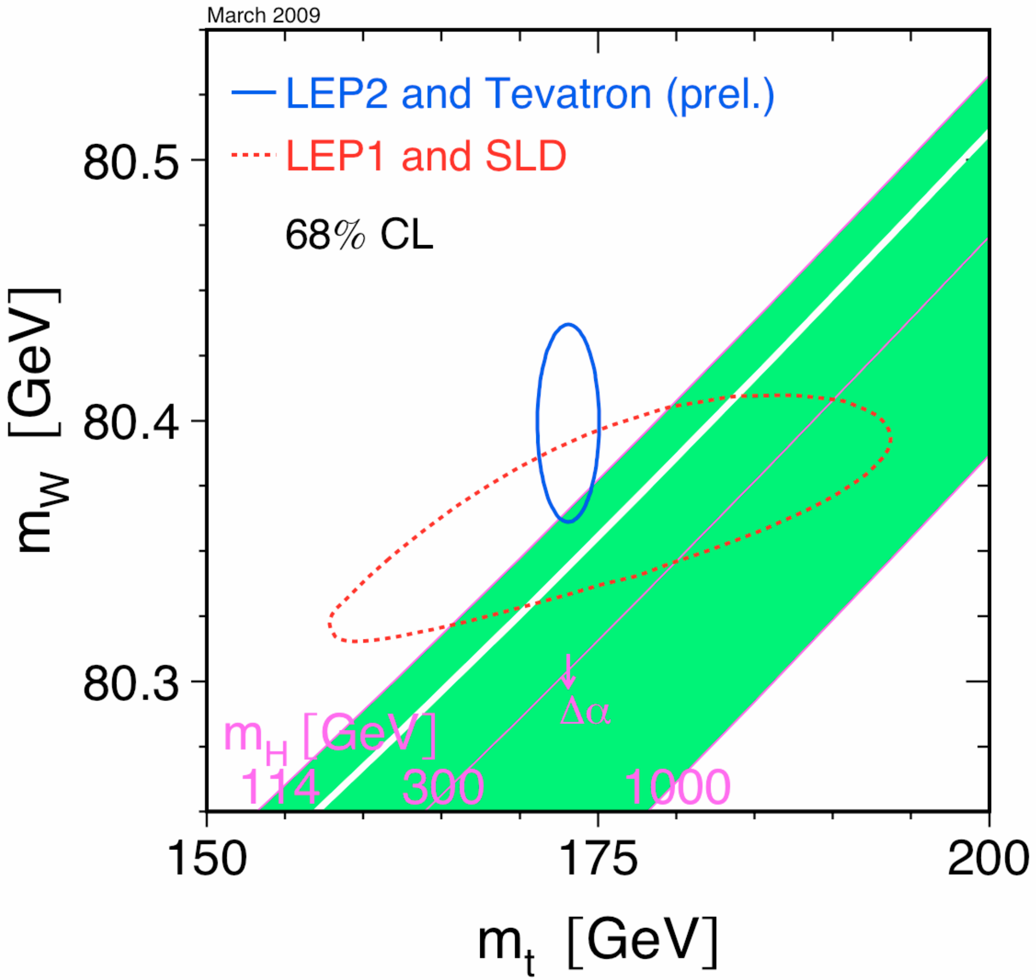


$\Delta M_W \propto \ln M_H$ $\Delta M_W \propto M_{top}^2$

Top quark mass is a fundamental parameter of the Standard Model

Since M_{top} is very large, quantum loops involving top quarks are important when calculating precision observables

Measuring the *W* boson mass and *top* quark mass *precisely* allows for prediction of the mass of the Higgs boson (...if it exists!) and constrain new physics

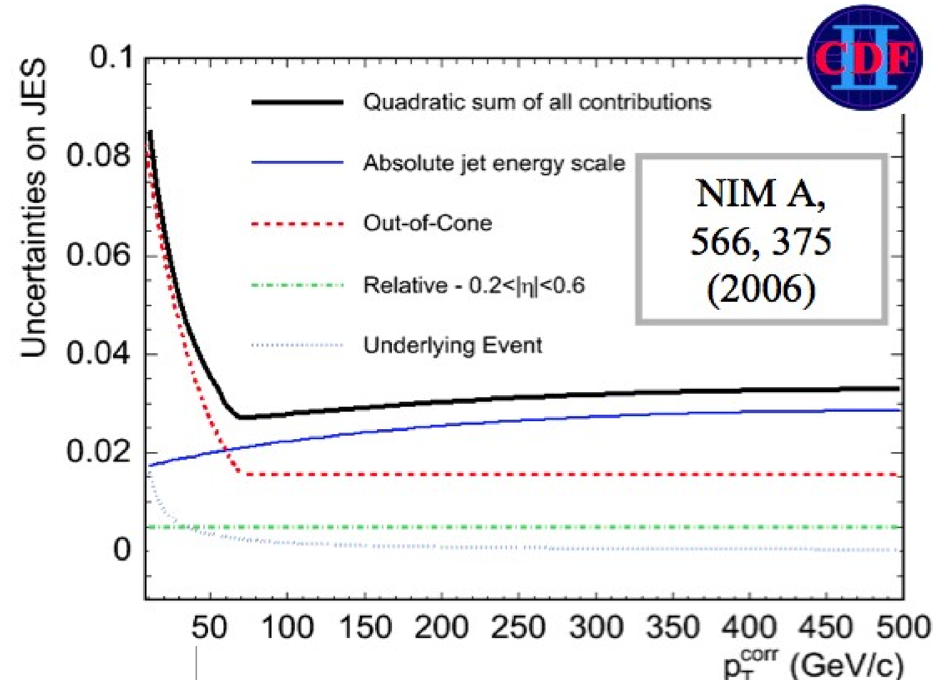


Experimental Challenges

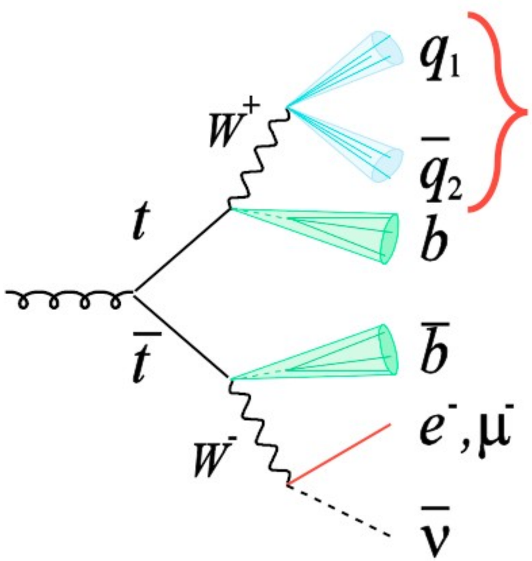
- Measure jets not partons
- Jet-parton assignment
- QCD radiation
- Undetected neutrino energy

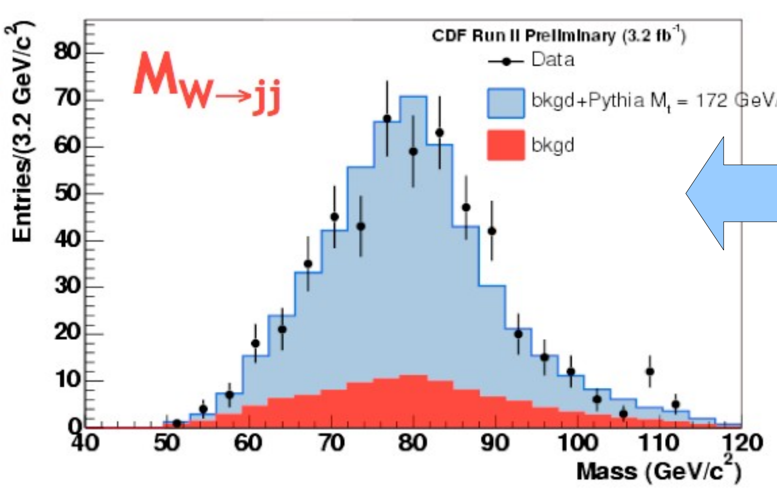
Measure top mass in all channels and with different techniques:
Dilepton
Lepton+jets
All-hadronic

Jet energy scale uncertainty:
Need corrections to obtain parton energy
Jet **E**nergy **S**cale
σJES/JES ≈ 3% to 6%
dominant contribution to δM_{top}(syst)



Can be reduced via
in situ calibration of the JES using the *W mass*





Constrain the invariant mass of the non b-tagged jets to be 80.4 GeV/c^2

Uncertainty on JES scales directly with statistics!

CDF Dilepton and Lepton+Jets combination

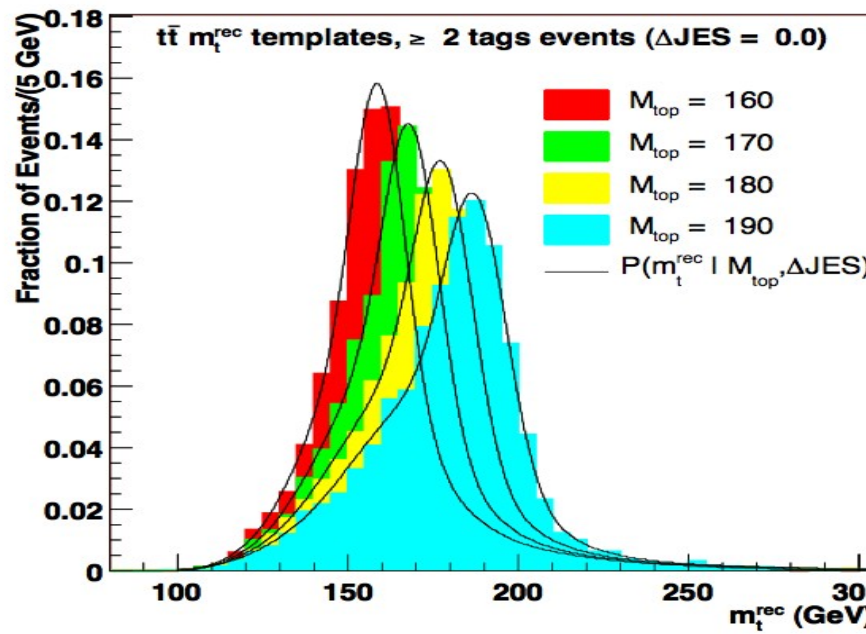
Template Method:

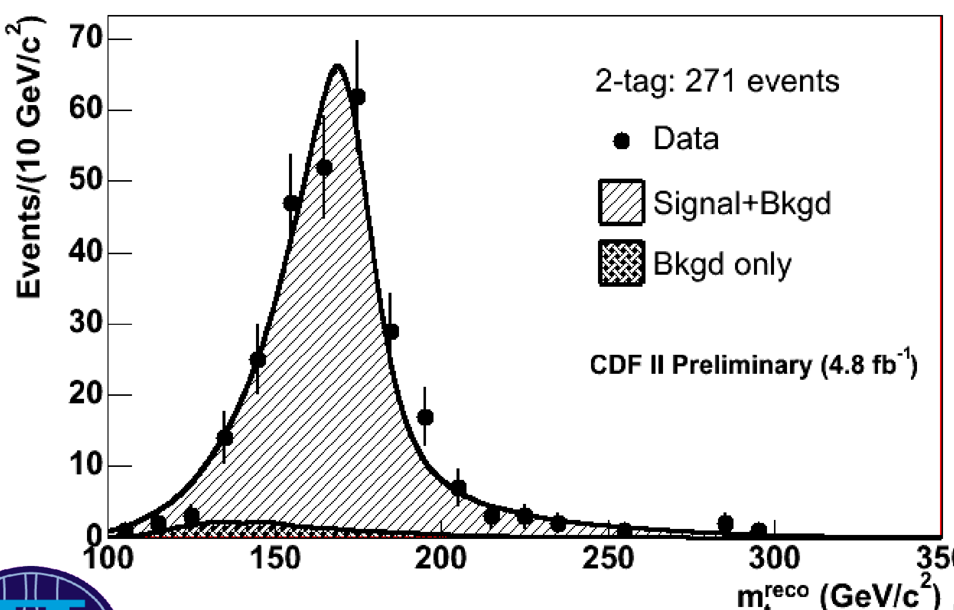
Consider a set of observables *x* sensitive to M_{top}.

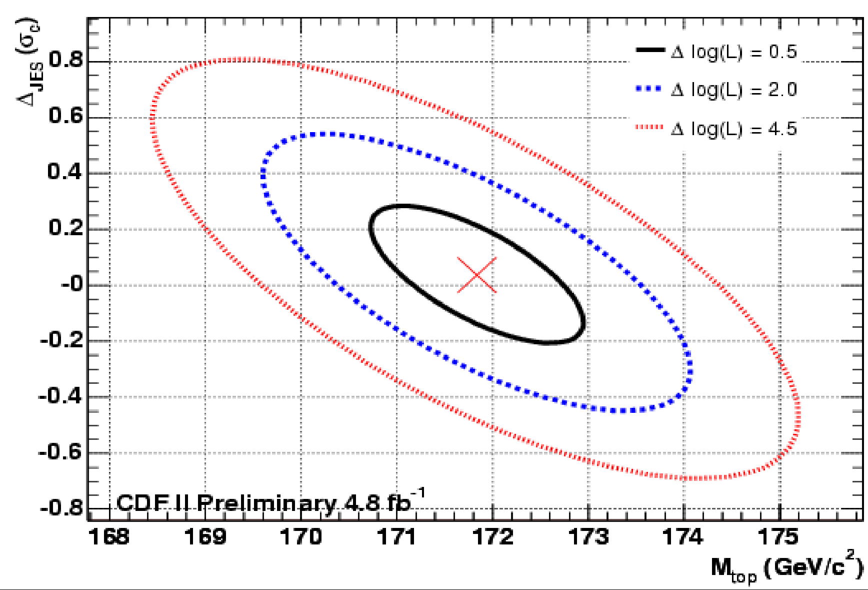
Evaluate and plot the set for each event → "Templates"

Maximize a likelihood where *observed* distributions are compared to expectations for different M_{top} and signal fractions f_{ttbar}

$$\mathcal{L}_{\mathrm{sample}} \propto \prod_{events} \prod_{\vec{x}} \mathcal{L}_{\mathrm{shape}}(x_i | f_{t\bar{t}}, M_{top})$$







Main uncertainties:

Jet-energy-scale, MC modeling

CDF (4.8 fb^{-1}) Joint Template Analysis

M_{top} = 171.9 ± 1.1(stat+JES) ± 0.9(syst) GeV/c^2

High Precision Mass Measurement at D0

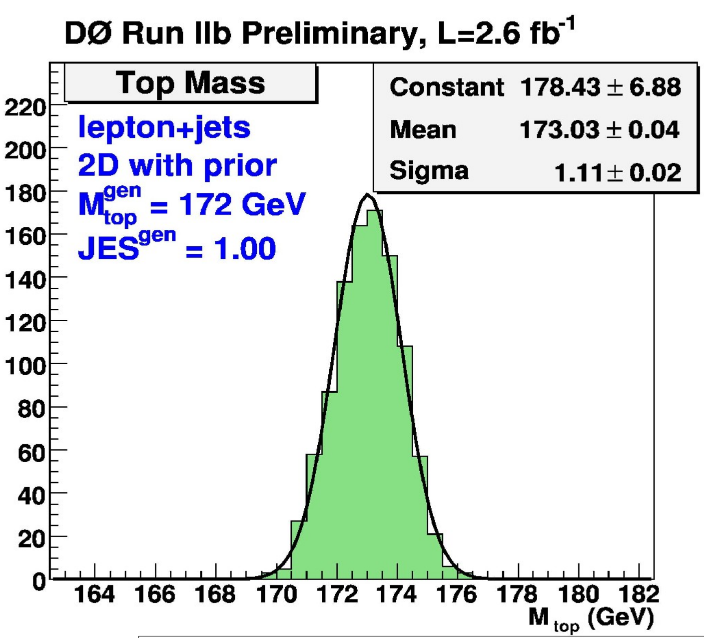
D0 Lepton+Jets with the Matrix Element Method

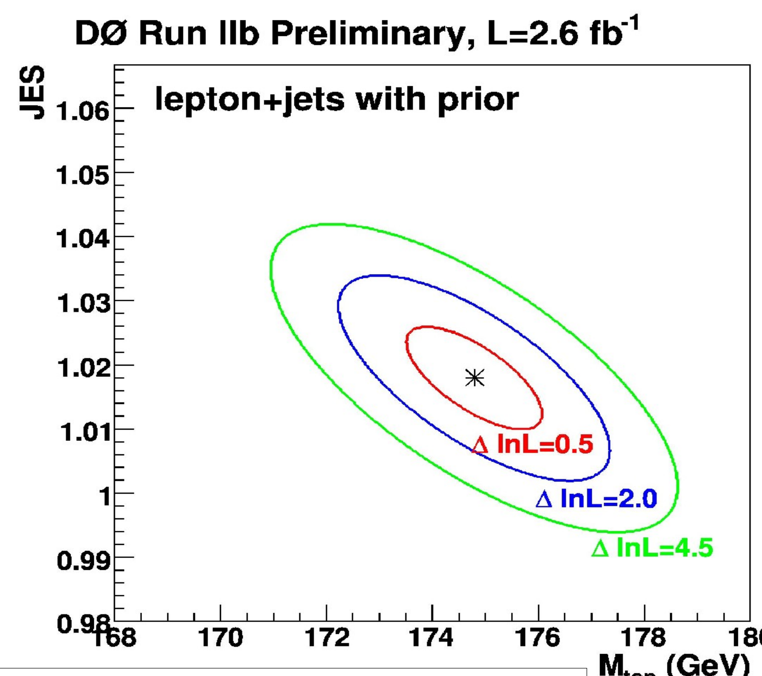
ME Method:
Define the probability P_{evt} that the *observed* kinematics arise from possible signal or bkg kinematics at parton level, then maximize
$L = \prod P_{evt}(M_{top}, JES, f_{top}(M_{top}, JES))$

$$P_{evt}(\vec{x}) = f_{top} \cdot P_{sig}(\vec{x}, m_t, JES) + (1 - f_{top}) P_{bkg}(\vec{x}, JES)$$

$$P_{sig}(\vec{x}) = \frac{1}{\sigma(m_t, JES)} \int f(q_1) dq_1 f(q_2) dq_2 \times |M(\vec{y})|^2 \phi(\vec{y}) dy \times W(\vec{x}, \vec{y}; JES)$$

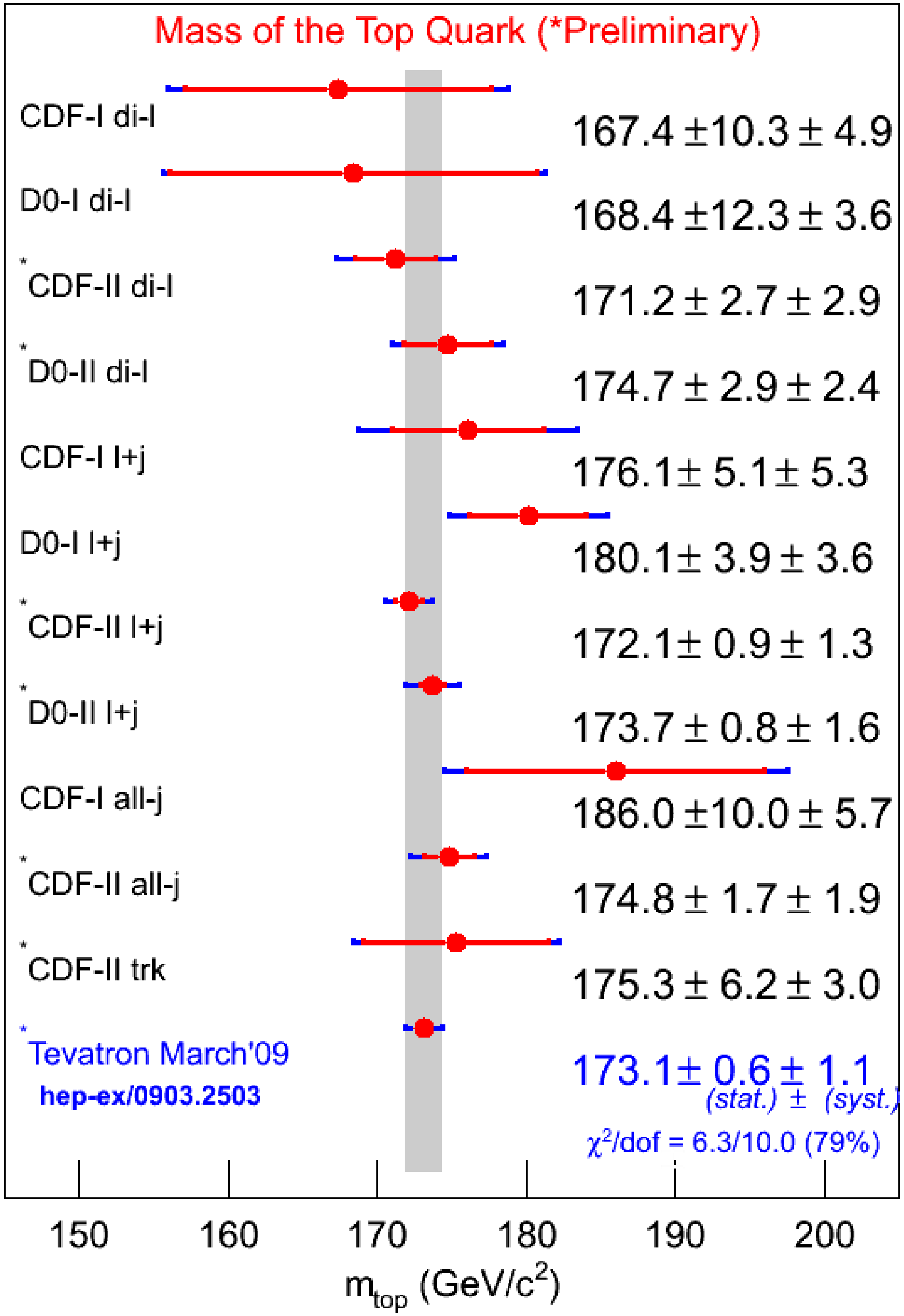
Parton distribution functions | **Differential cross section (LO ME)** | **Transfer Function: maps parton level (y) to reconstructed variables (x)**





D0 (3.6 fb^{-1}) Lepton + Jets Matrix Element Technique
M_{top} = 173.7 ± 0.8(stat) ± 0.8(JES) ± 1.4(syst) GeV/c^2

Tevatron Combination



Tevatron (March 2009):

M_{top} = 173.1 ± 0.6 (stat) ± 1.1 (syst) GeV/c^2

Best results of each experiment in each channel from Run I and Run II combined

Results from different channels and methods are consistent

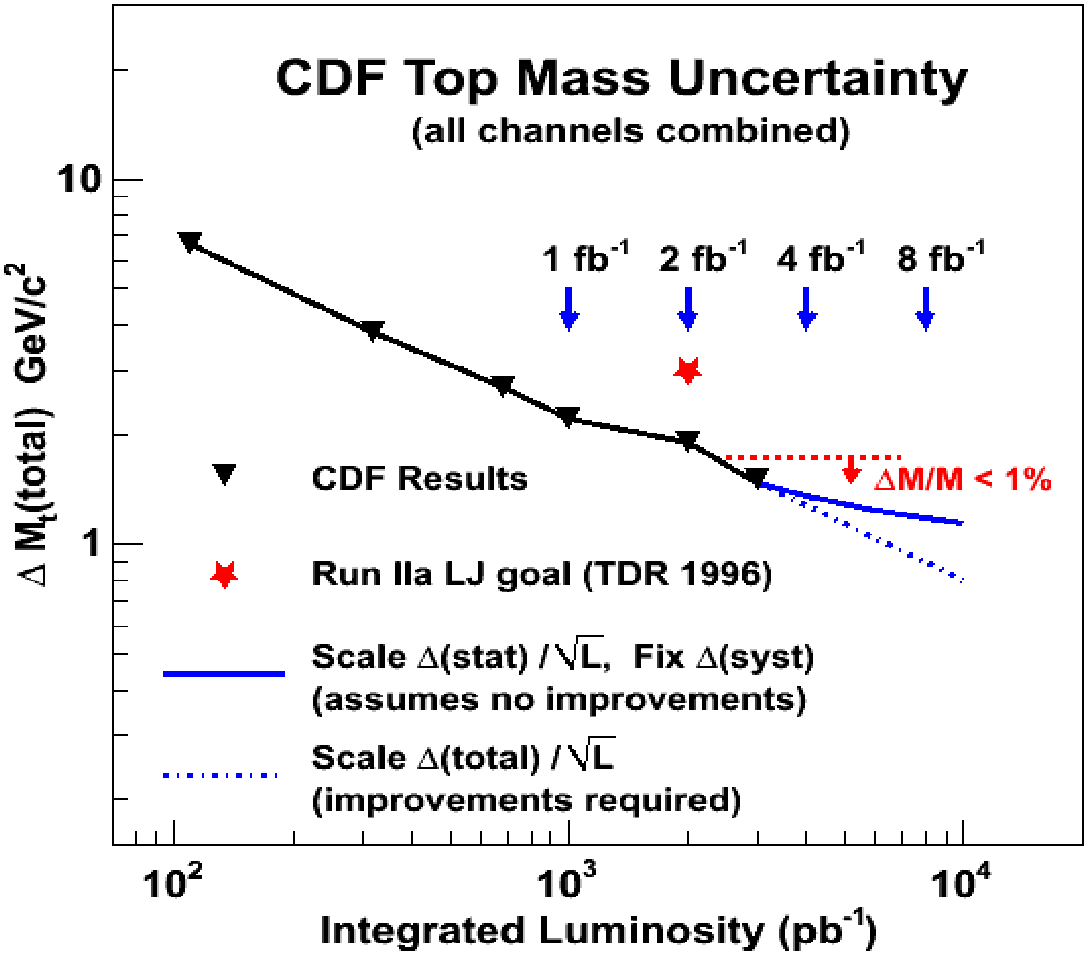
Take into account the statistical and systematic uncertainties and their correlations
(NIM A270 (1988) 110, NIM A500 (2003) 391)

Precision now limited mainly by systematic uncertainties

Joint effort on improving knowledge of systematics

Top Mass projections

CDF example



Magnitude of systematic uncertainties are comparable, dominated by sources which should continue to scale with the statistics of the sample.
Top quark mass precision for single measurement already well beyond RunII goals

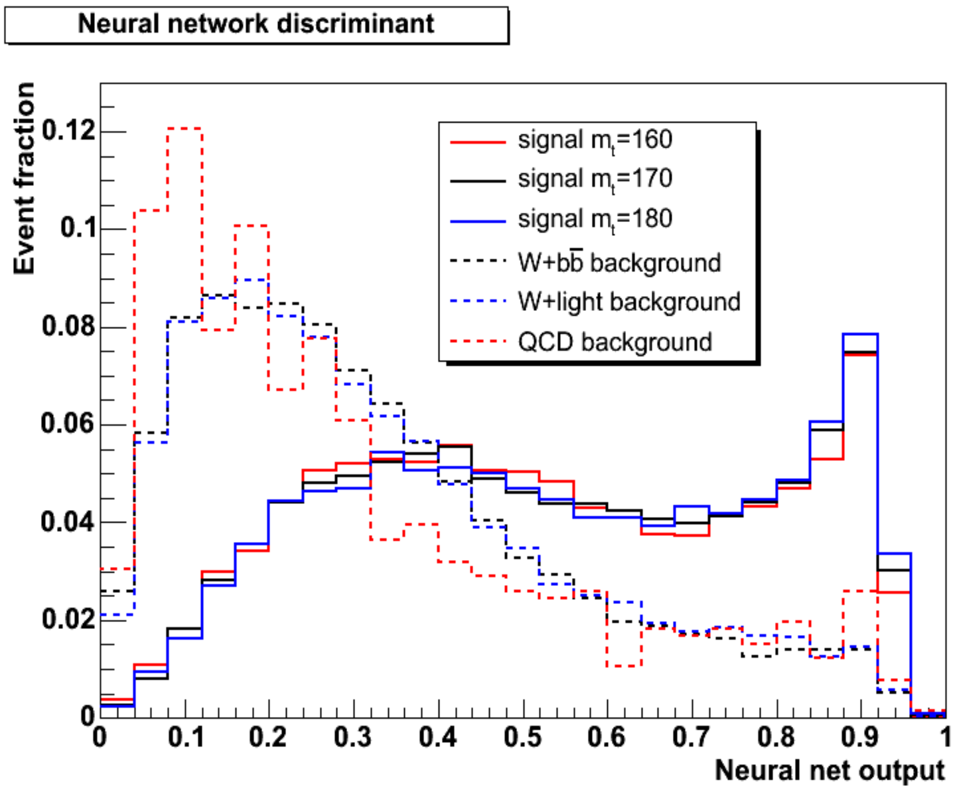
Dilepton and Lepton+Jets

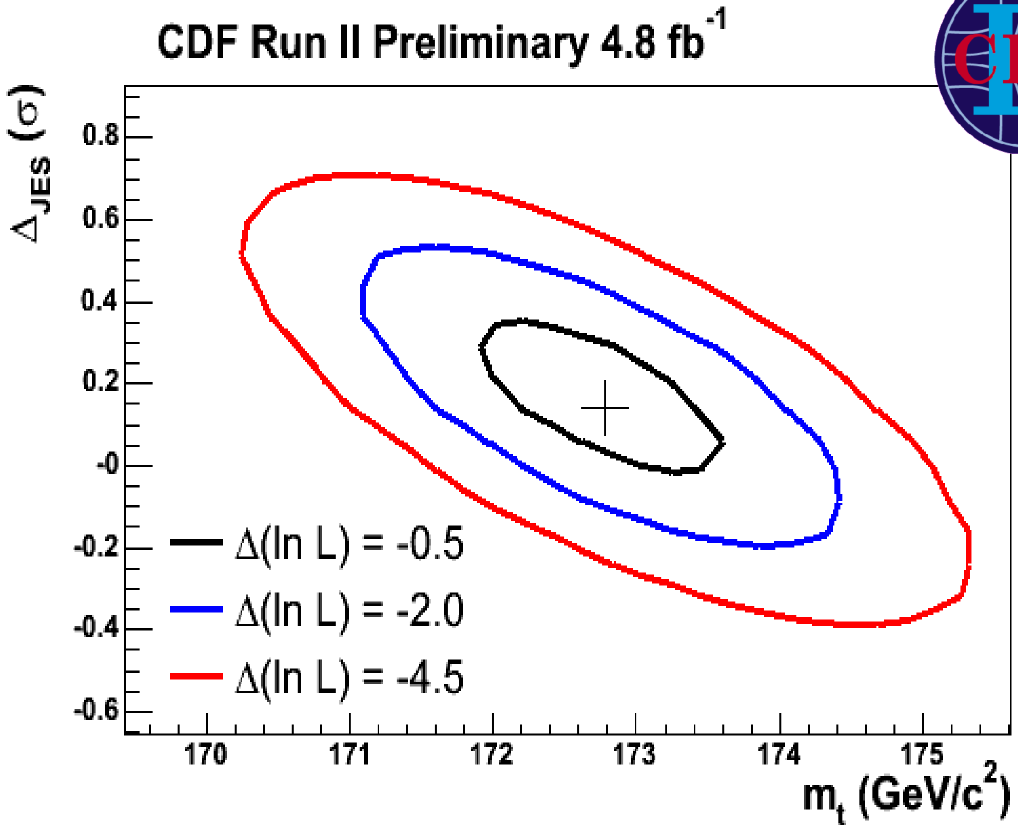
Systematics Source	ΔM_{top} [GeV]
JES	0.6
Generator	0.6
PDFs	0.1
b jet energy	0.3
Bakground shape	0.1
gg fraction	<0.1
Radiation	0.1
MC statistics	0.1
Lepton energy	<0.1
MHI	0.1
Color Reconnection	0.2
Total	0.9

Brand New Top Mass Measurement from CDF

1 week ago, a new CDF measurement of the top quark mass has been approved
This is the most precise measurement ever done, even more precise than the world average

The technique used is similar to the Matrix Element Method
Uses a Neural Network discriminant to distinguish signal and background

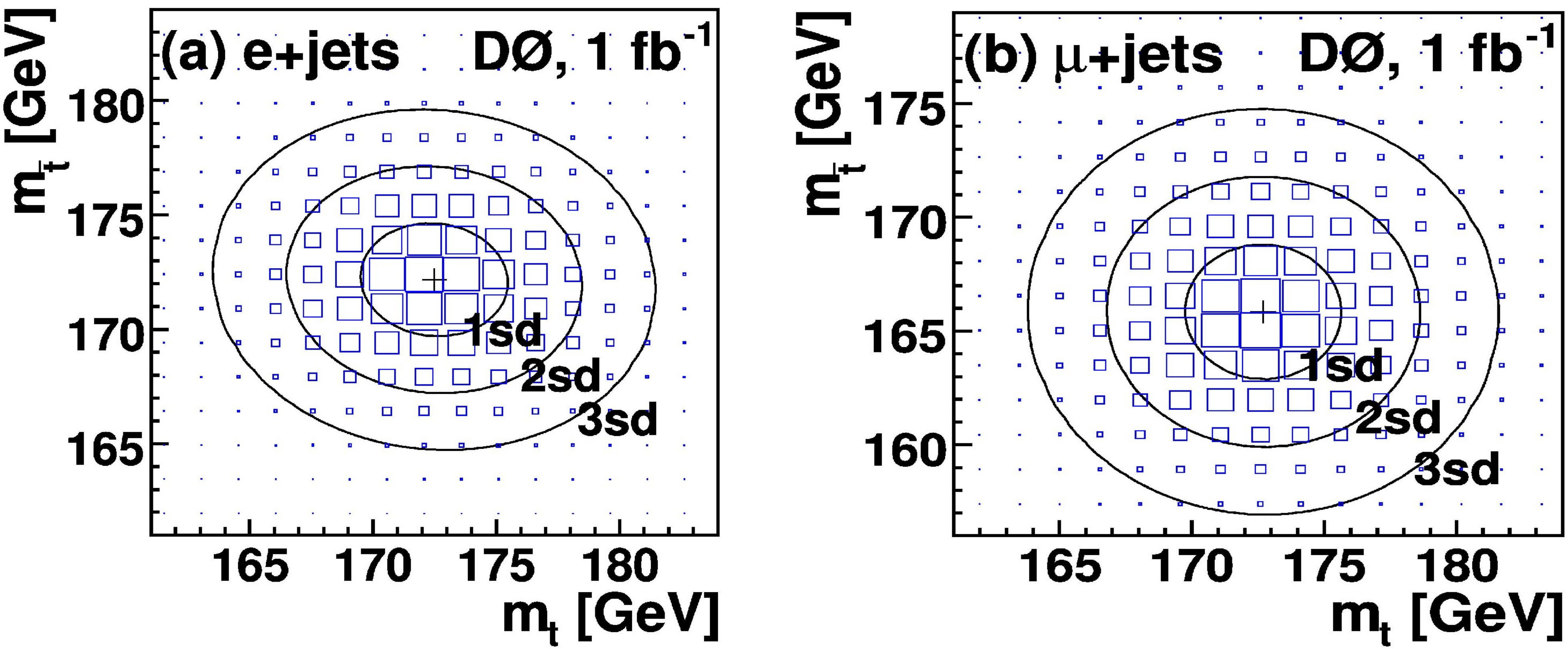




CDF (4.8 fb^{-1}) Lepton+Jets, Multivariate:
M_{top} = 172.8 ± 0.7 (stat) ± 0.6 (JES) ± 0.8 (syst) GeV/c^2 = 172.8 ± 1.3 (total) GeV/c^2

Direct measurement of top antitop mass difference

Mass difference would imply *CPT-violation*
Measured in lepton + jets events (ME technique)



First time measured for a "bare quark"
Consistent with SM expectations

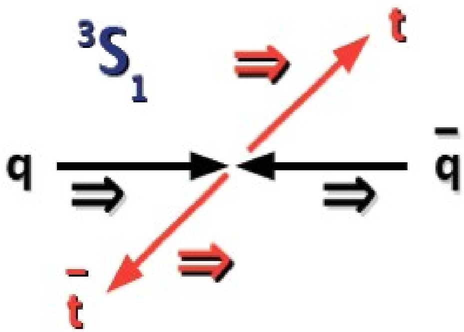
PRL 103, 132001 (2009)

D0 (1 fb^{-1}):
ΔM_{top} = 3.8 ± 3.7 GeV/c^2

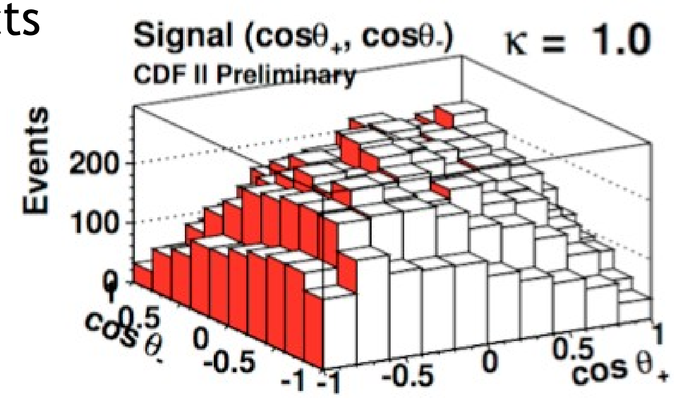
Statistics limited

Top Antitop Spin correlations

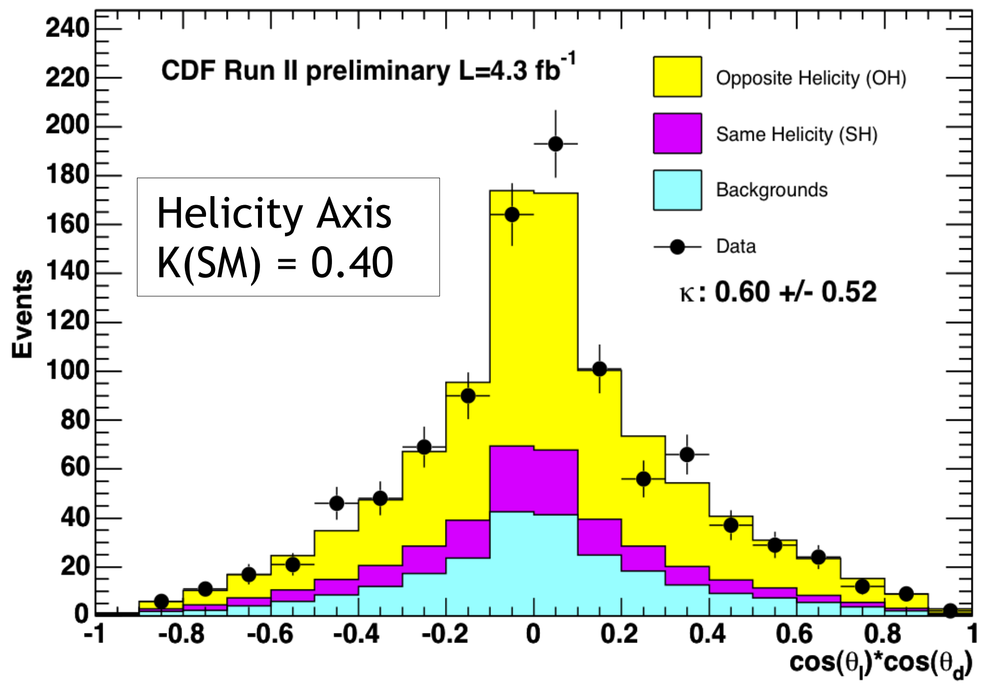
Top spins are correlated only if *top lifetime is short enough*
Spin-spin correlation is observable in the top quark decay products

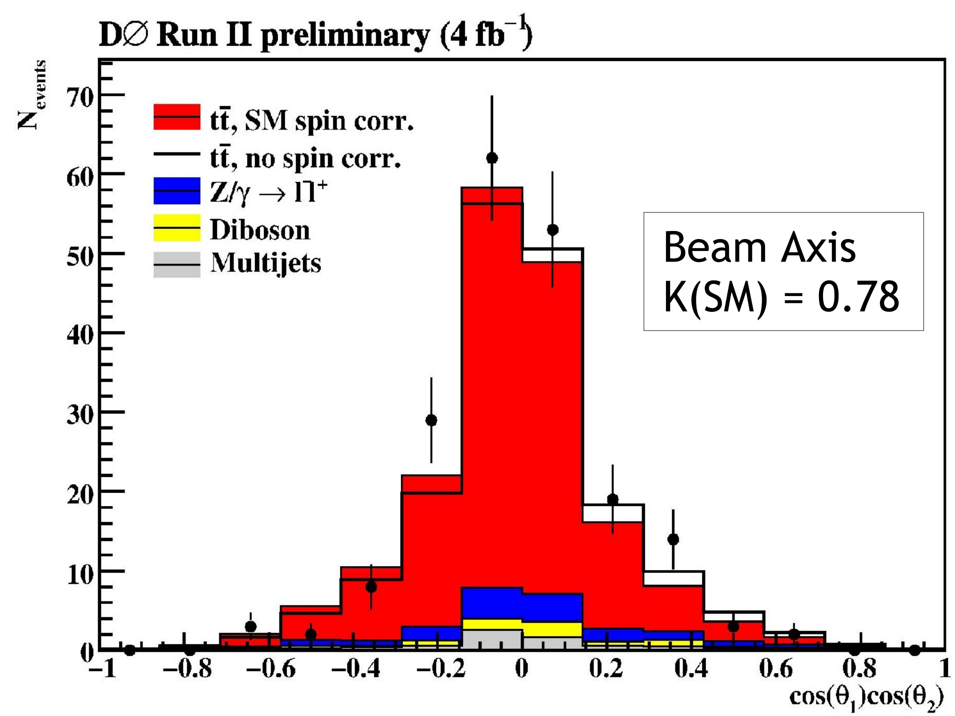


$$\kappa = \frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\uparrow\downarrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\uparrow\downarrow)}$$



Top Pair Spin Correlation





CDF (4.3 fb^{-1}) Lepton+Jets:
K= 0.60 ± 0.50 (stat) ± 0.16 (syst)

D0 (4.2 fb^{-1}) Dilepton:
K= -0.17 + 0.65 - 0.53 (stat + syst)

Short lifetime of top quark decay results in large width Γ_{SM}~1.5 GeV

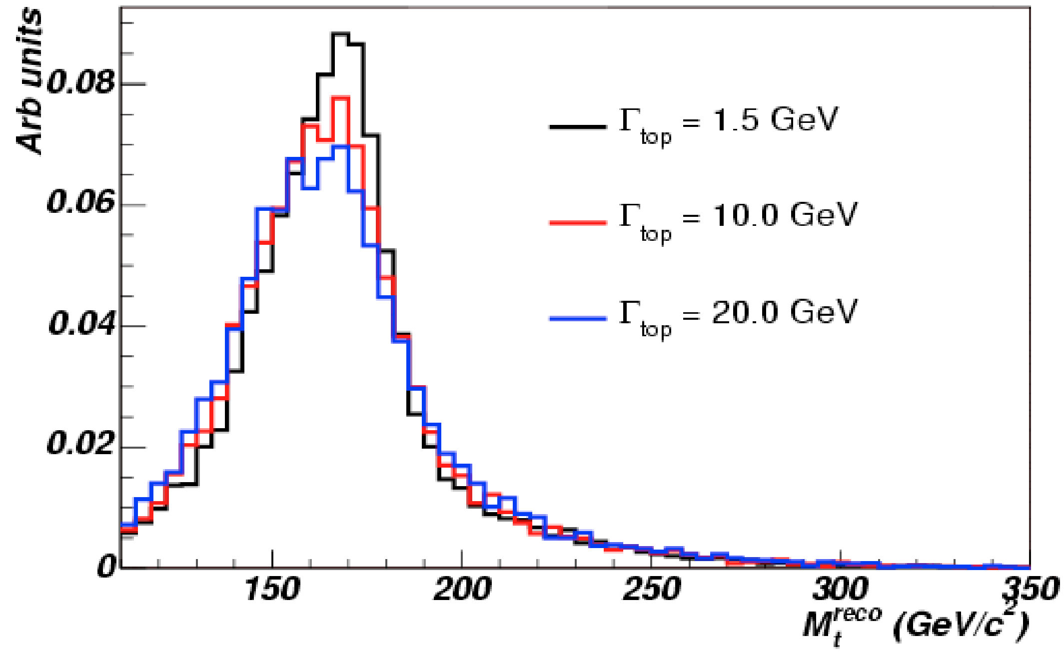
Deviation from SM could indicate presence of *t→bH+ etc*.

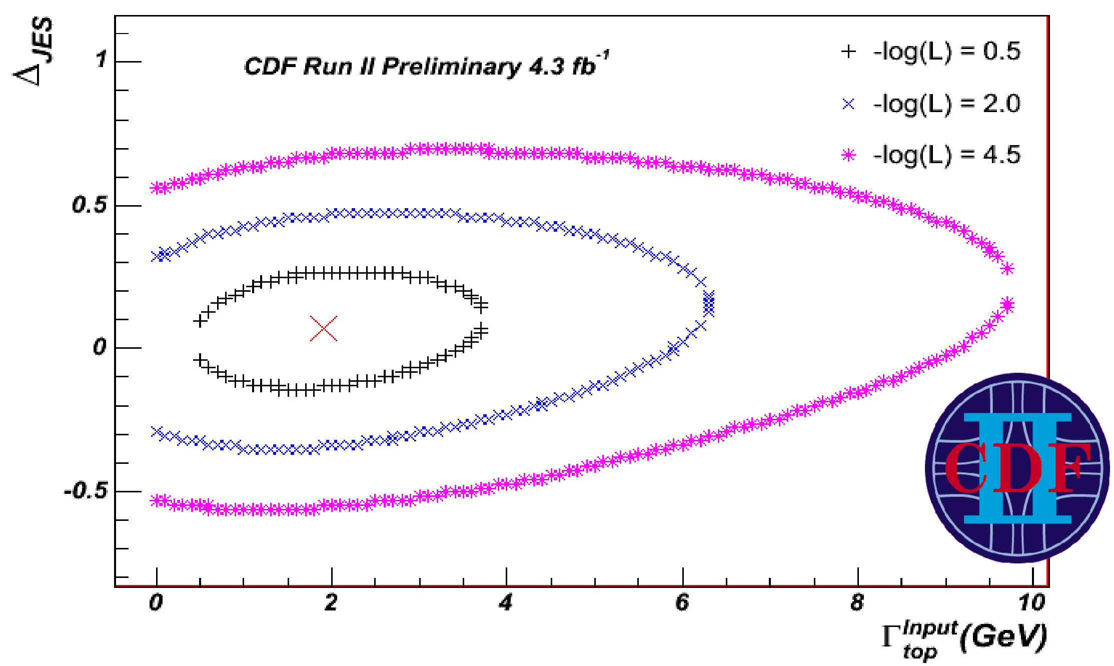
Different width would change top mass line shape → use templates

Method comes from top mass analysis, uses in situ calibration of JES

Dominating source of systematic uncertainty becomes jet resolution

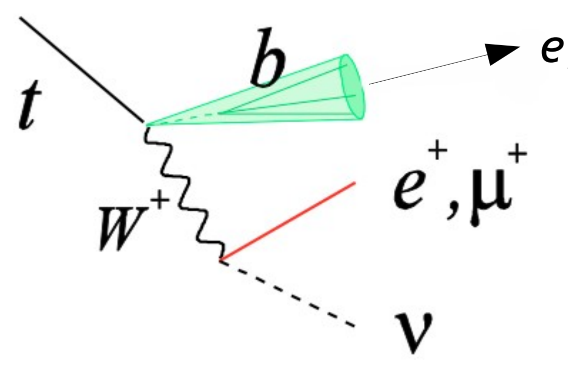
CDF (4.3 fb^{-1}):
Γ_{top} < 7.5 GeV at 95% C.L.

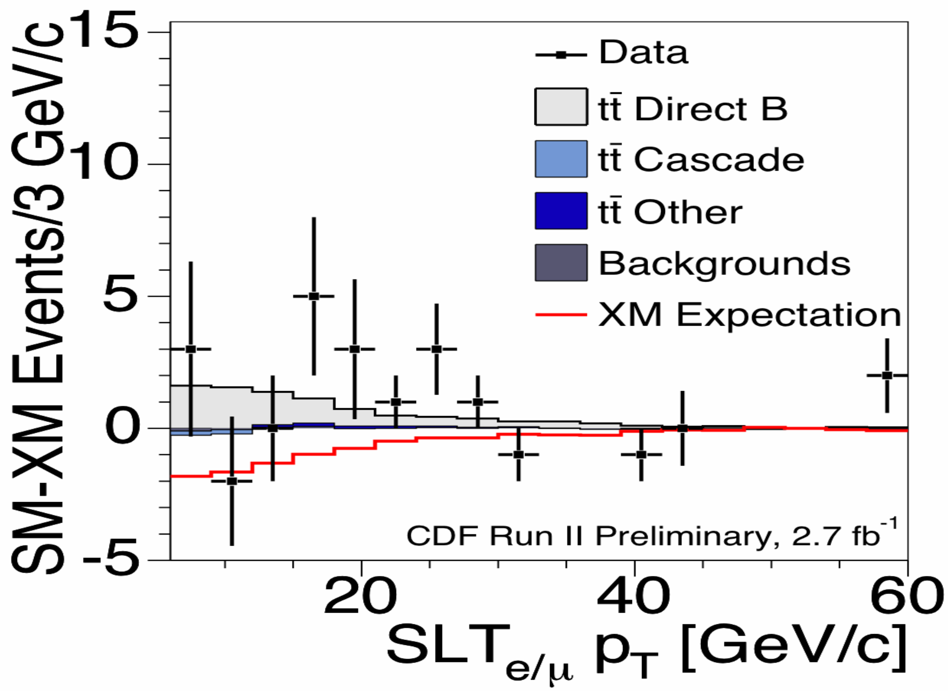




Test hypothesis whether top quark is an exotic particle with Q_{top} = 4/3

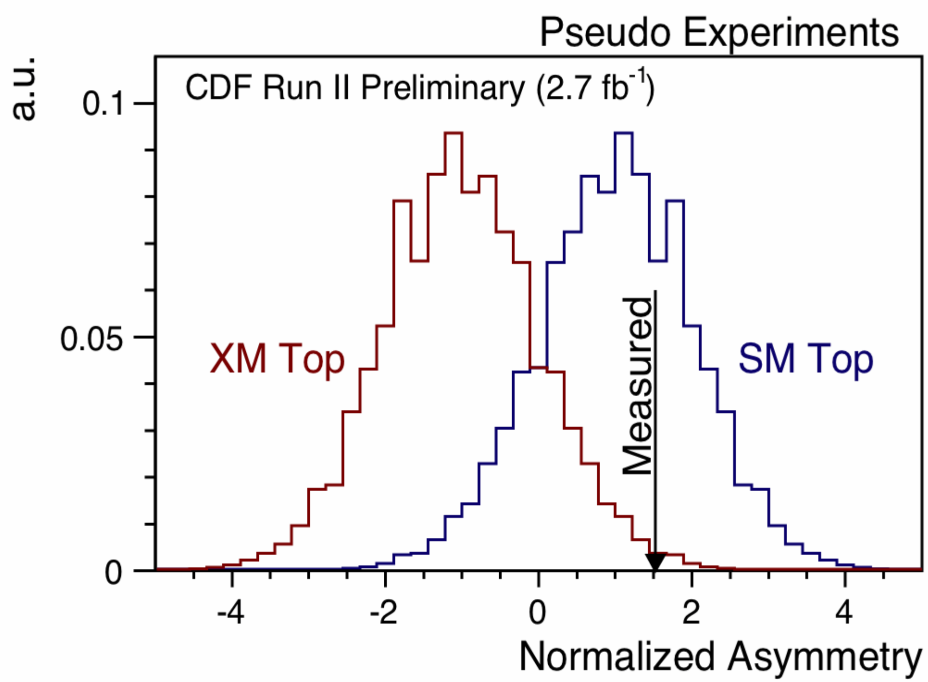
Select Lepton + Jets with *two b*-tags





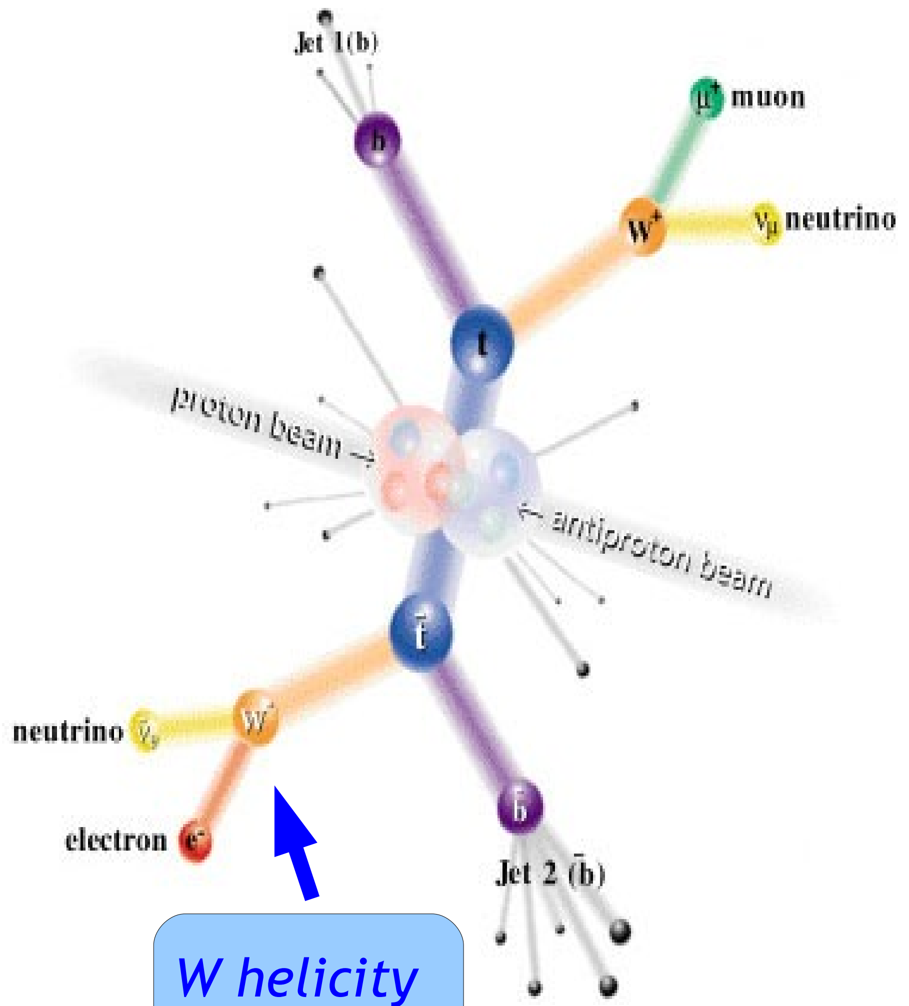
Exotic Model

D.Chang et al., PRD 59 (1999) 091503



CDF (2.7 fb^{-1}):
Excludes Q_{top} = 4/3 at 95% C.L.

D0 (0.37 fb^{-1}):
Excludes Q_{top} = 4/3 at 92% C.L.
PRL 98, 041801 (2007)

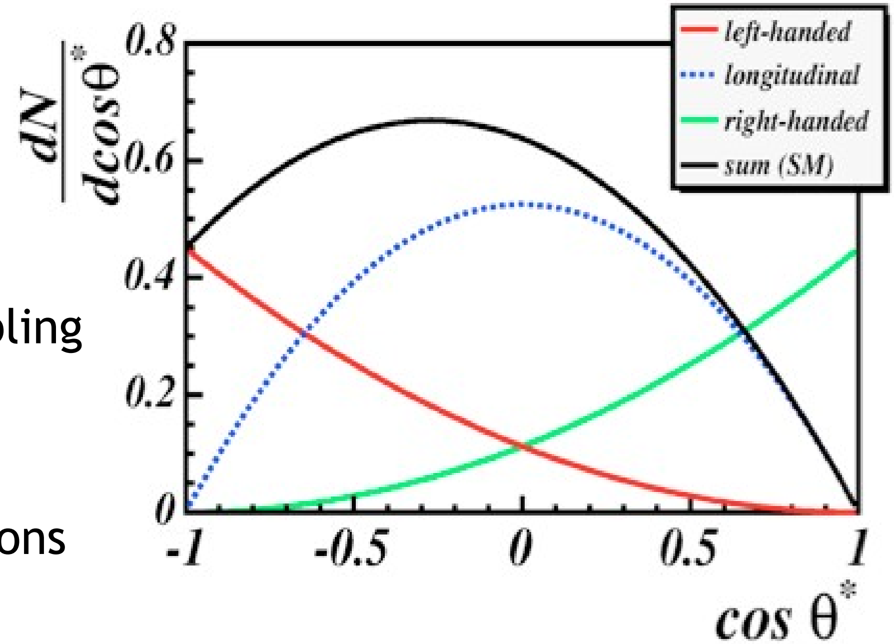


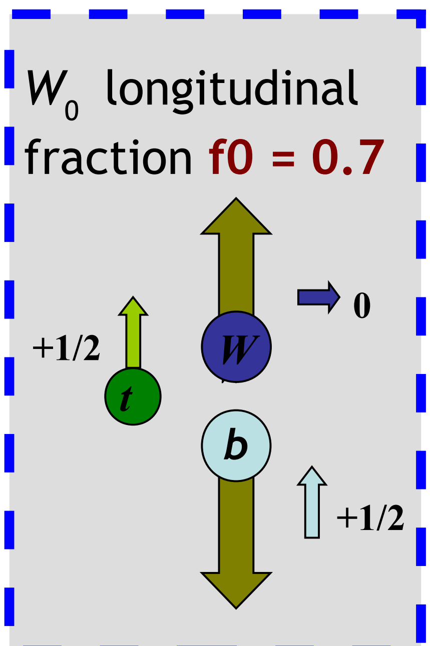
W helicity
Wtb vertex

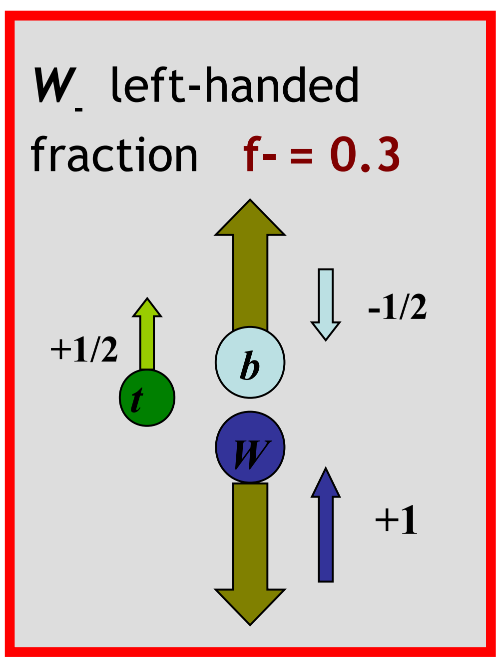
W boson helicity in Top Quark Decay

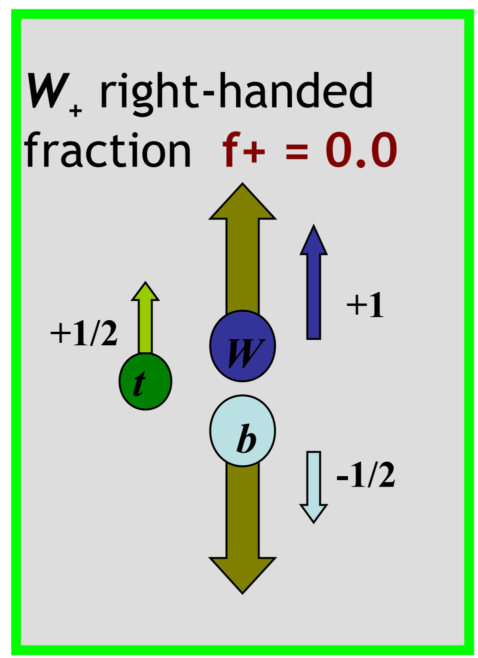
- Examines the nature of the tWb vertex, probing the structure of weak interactions near the Electro-Weak Symmetry Breaking scale
- Stringent test of V-A interaction in SM
- Standard Model predicts purely left handed tWb coupling
- model-independent measurement based on reconstruction of cosθ* distribution

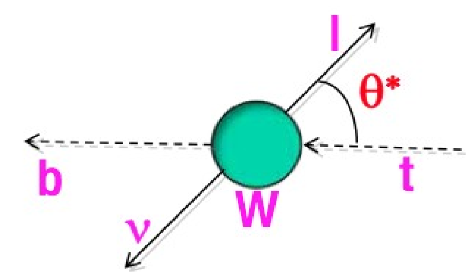
- distribution of cosθ* depends on the W helicity fractions





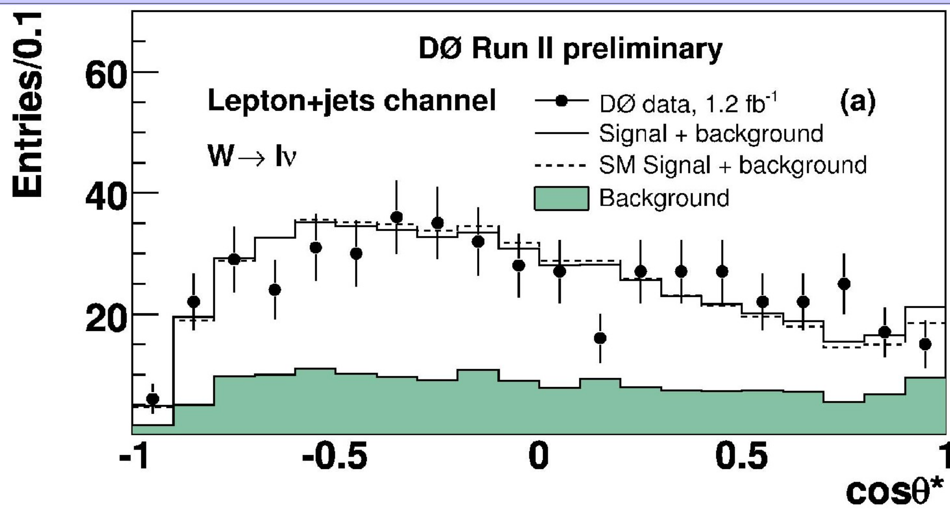


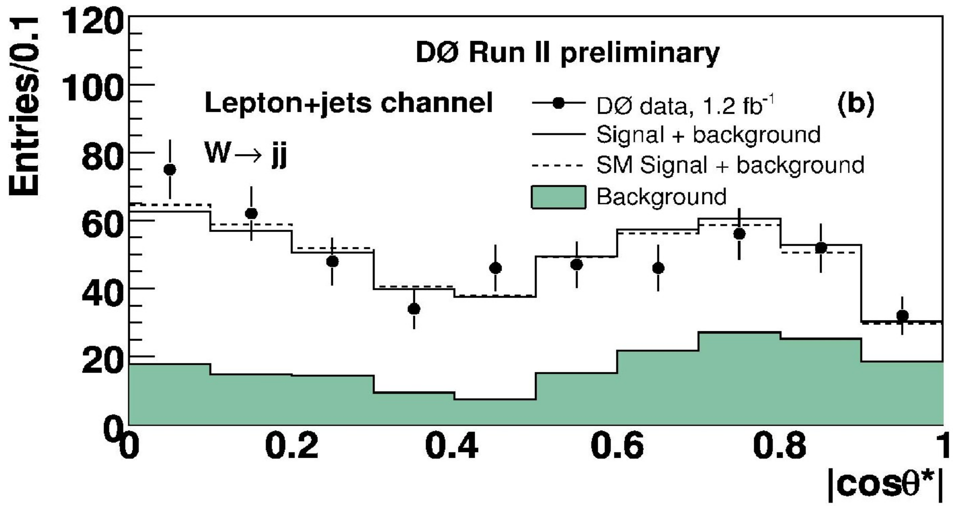




cosθ* angle between the momenta of the down-type fermion and the top quark in the W boson rest frame for each top

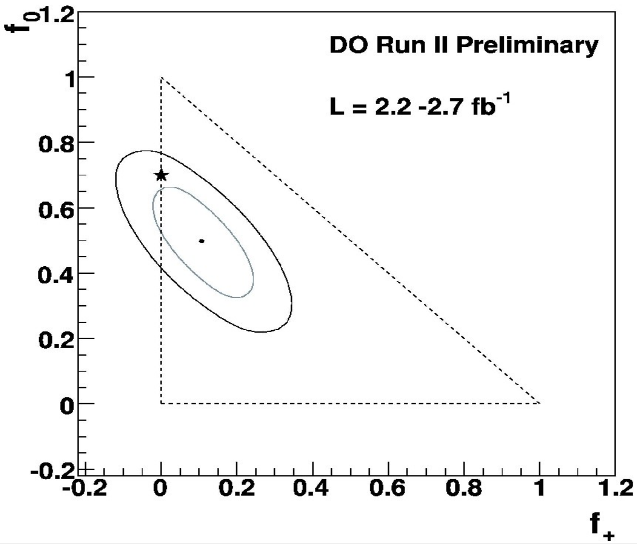
W boson helicity fractions

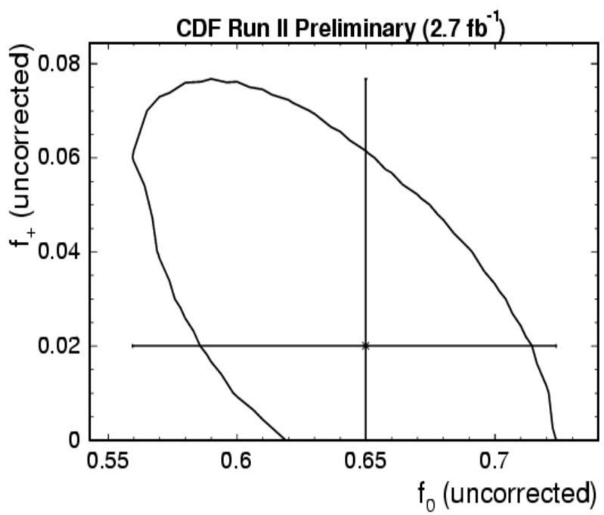




Measure f0 and f+ simultaneously, model independent

D0 LeptonJets + Dilepton (2.7 fb^{-1}):
f0 = 0.49 ± 0.11 (stat) ± 0.09 (syst)
f+ = 0.11 ± 0.06 (stat) ± 0.05 (syst)





CDF LeptonJets (2.7 fb^{-1}), Matrix Element:
f0 = 0.88 ± 0.11 (stat) ± 0.06 (syst)
f+ = -0.15 ± 0.07 (stat) ± 0.06 (syst)

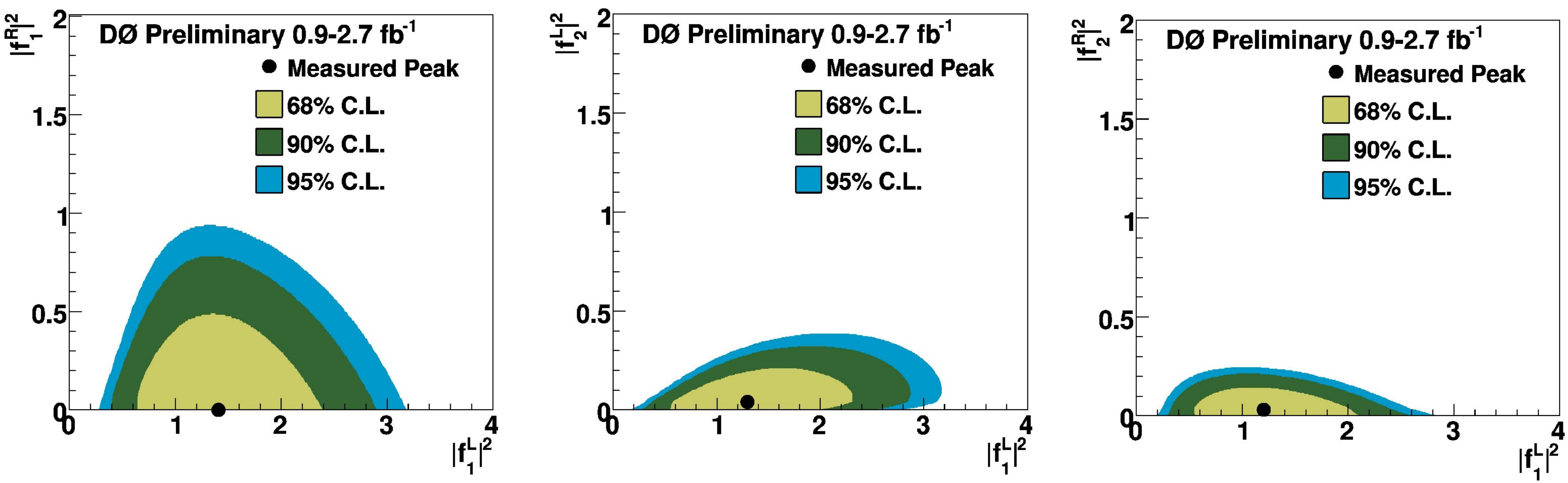
Consistent with the Standard Model

Constrain form factors for anomalous tWb coupling

Combine information from single top production and W helicity measurement from ttbar decay

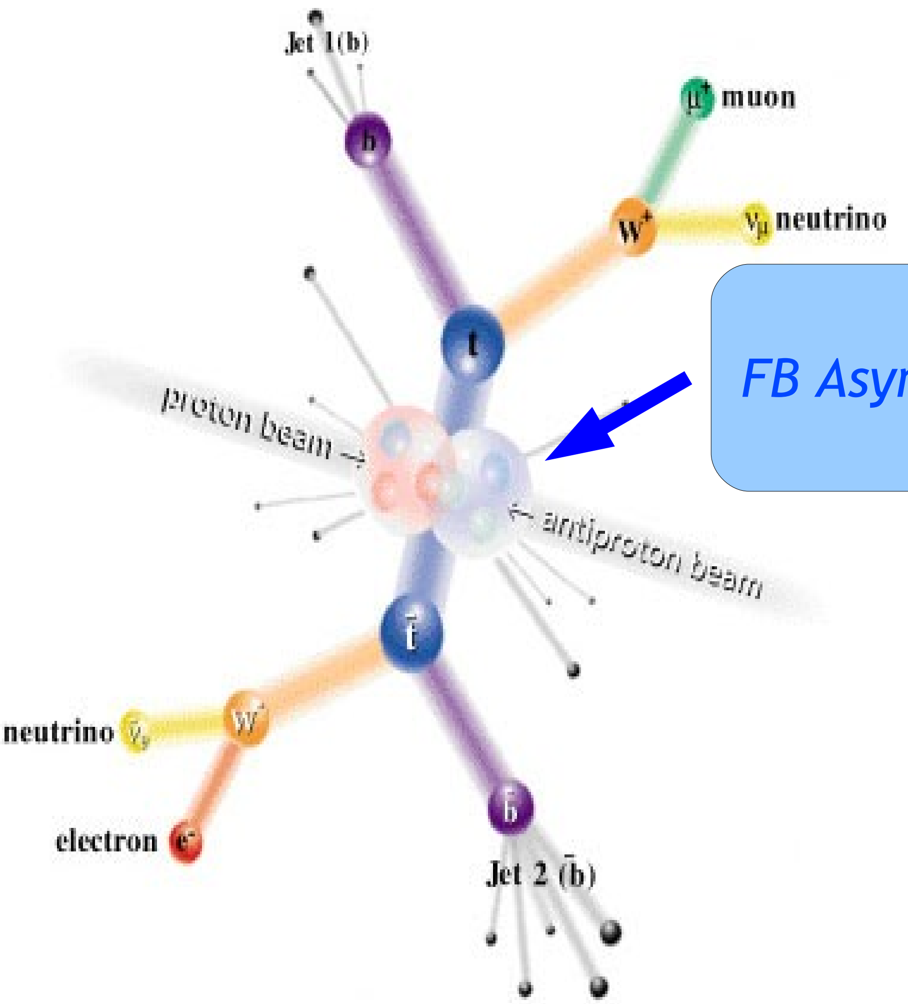
$$L_{tWb} = \frac{g}{\sqrt{2}} W_\mu^- \bar{b} \gamma^\mu \left(f_1^L P_L + f_1^R P_R \right) t - \frac{g}{\sqrt{2} M_W} \partial_\nu W_\mu^- \bar{b} \sigma^{\mu\nu} \left(f_2^L P_L + f_2^R P_R \right) t$$

In Standard Model: $f_1^L = 1, \quad f_2^L = f_1^R = f_2^R = 0$



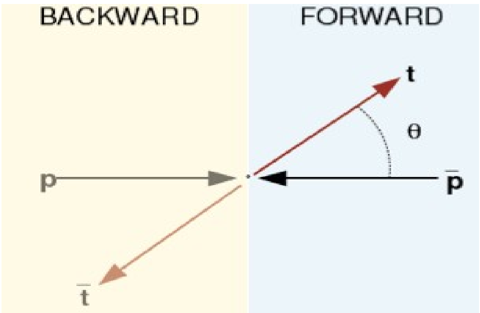
$$\text{for } |f_1^L|^2 = 1 \quad |f_1^R|^2 < 0.72$$
$$|f_2^L|^2 < 0.19 \text{ @ } 95\% \text{ CL}$$
$$|f_2^R|^2 < 0.20$$

Consistent with Standard Model

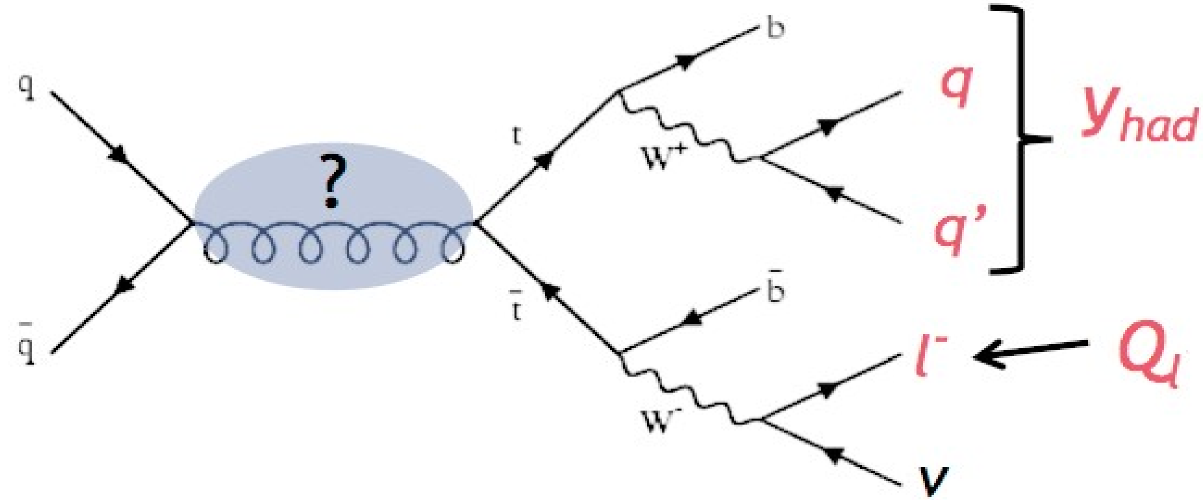


FB Asymmetry

Forward Backward Asymmetry



$$A_{fb} = \frac{F - B}{F + B}$$



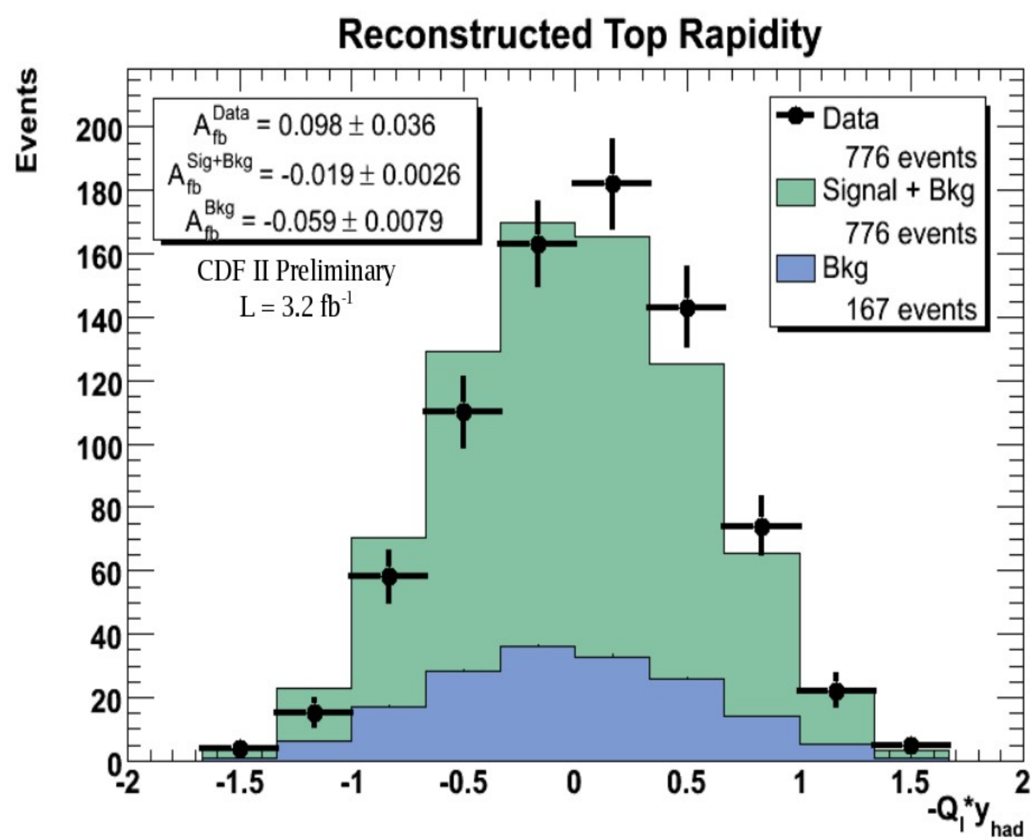
New physics could give rise to *asymmetry* (Z',axigluons,..)

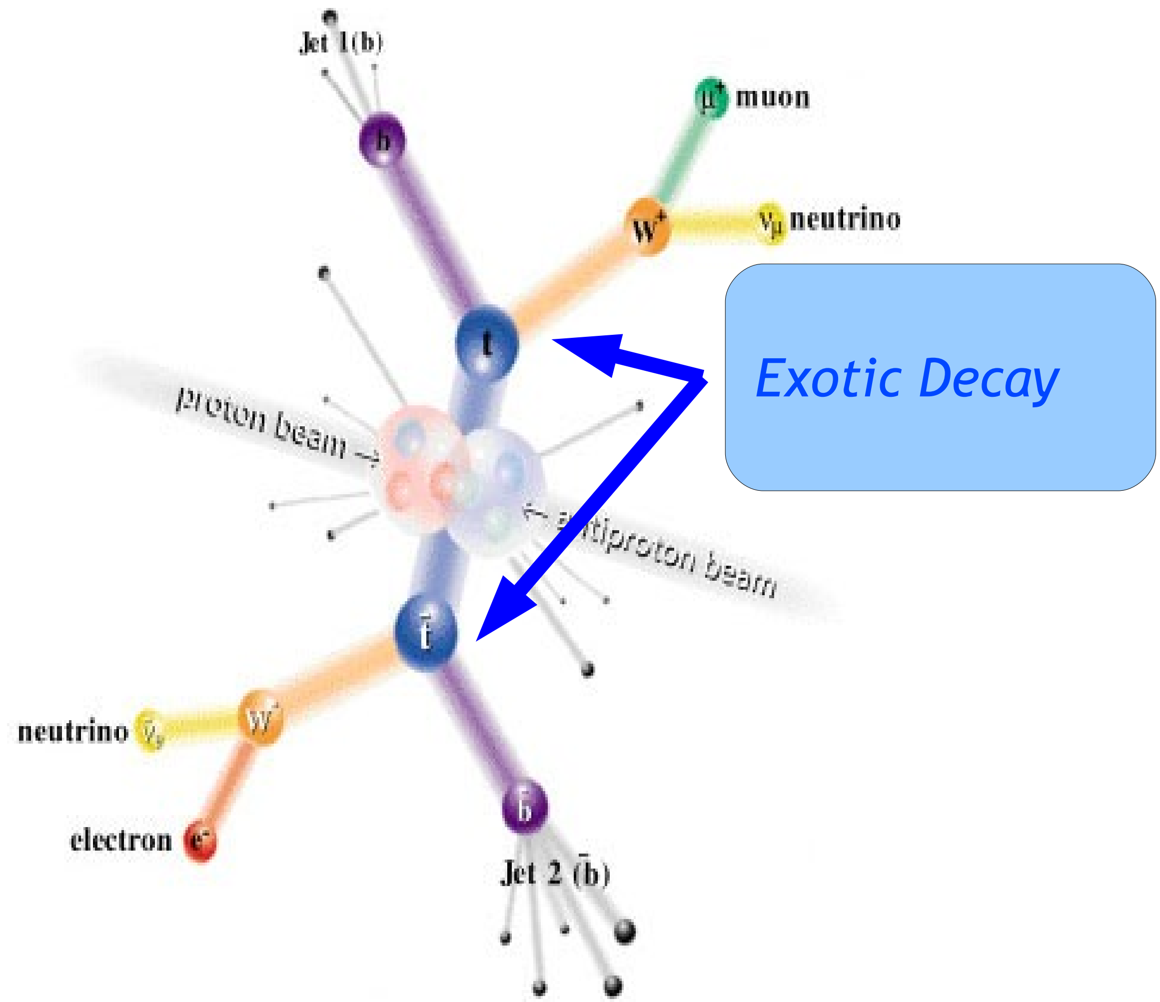
Standard Model predicts
NLO QCD: A_{fb} = 0.05 ± 0.015

CDF (3.2 fb^{-1}):
Afb = 0.19 ± 0.07 (stat) ± 0.02 (syst)

D0 (1.0 fb^{-1}):
Afb det = 0.12 ± 0.08 (stat) ± 0.01 (syst)

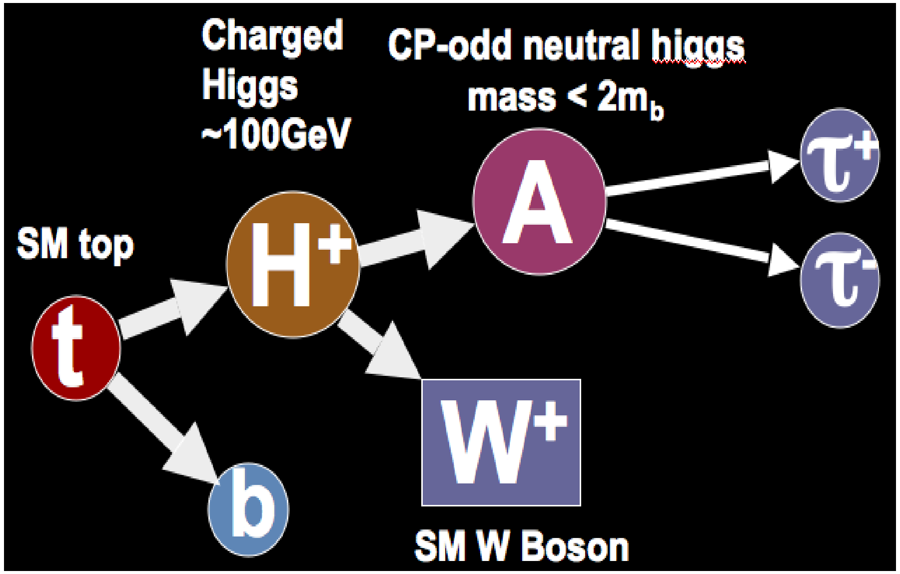
PRL 100, 142002 (2008)

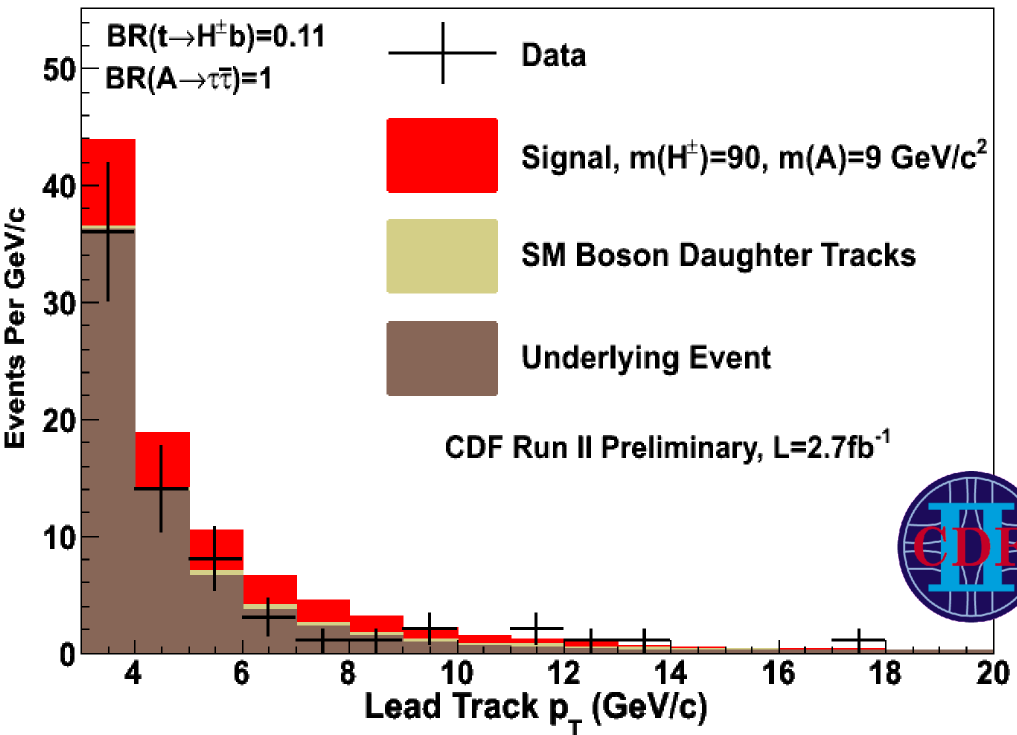


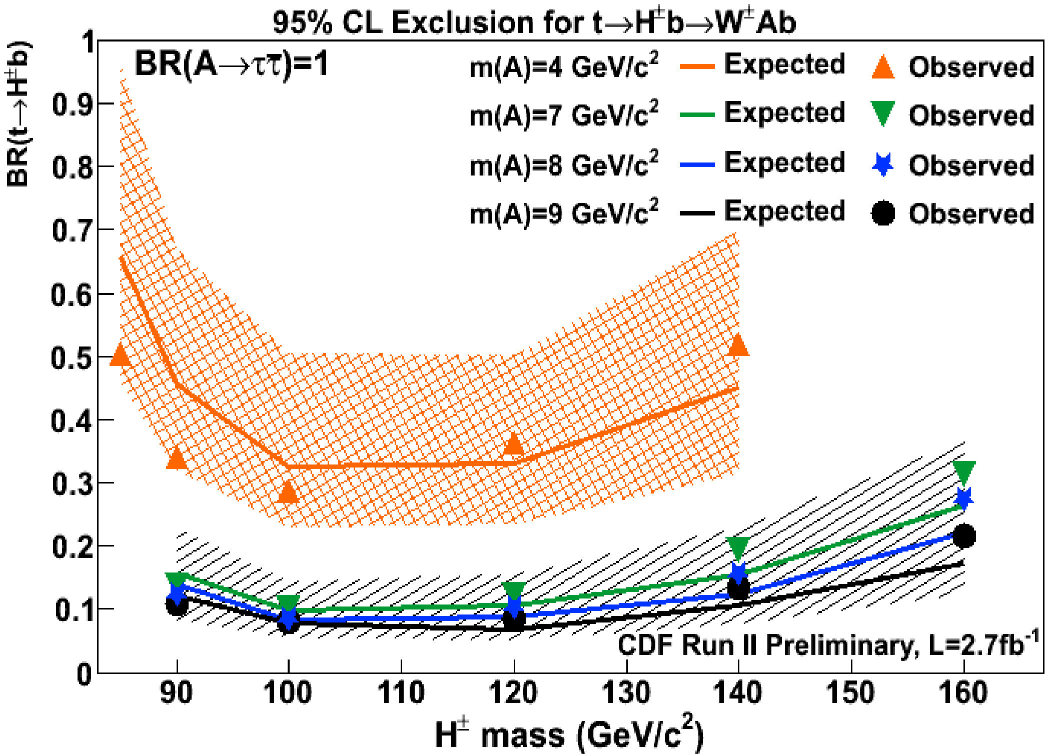

Jet 1(b)
muon
neutrino
Exotic Decay
proton beam →
← antiproton beam
neutrino
electron
Jet 2 (b̄)

Search for NMSSM Higgs in Top Quark Decays

- If a charged higgs of around ~100GeV/c^2 exists, then the branching ratio of top to charged higgs may be LARGE (as high as 10 to 40%)
- This search assumes $m_A < 2m_b$, a region in parameter space not yet experimentally excluded
- Taus should leave low pT isolated tracks in top events



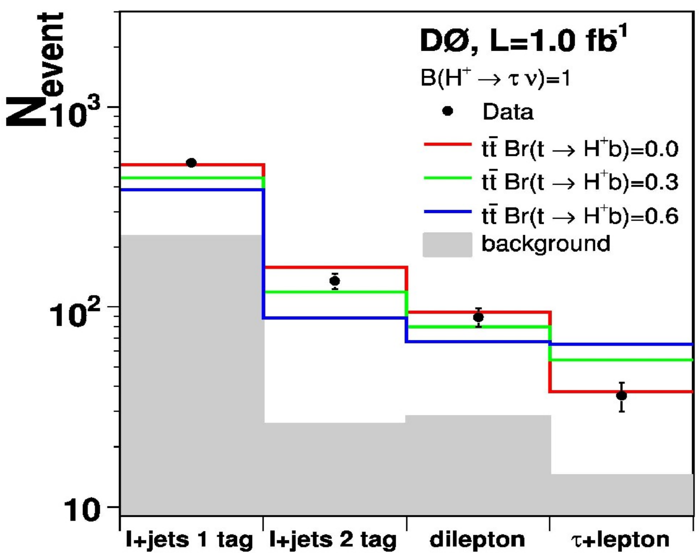


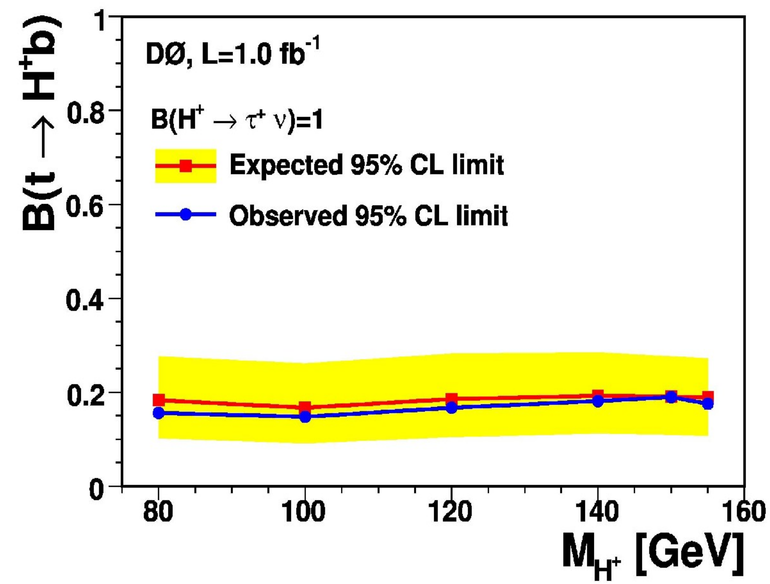


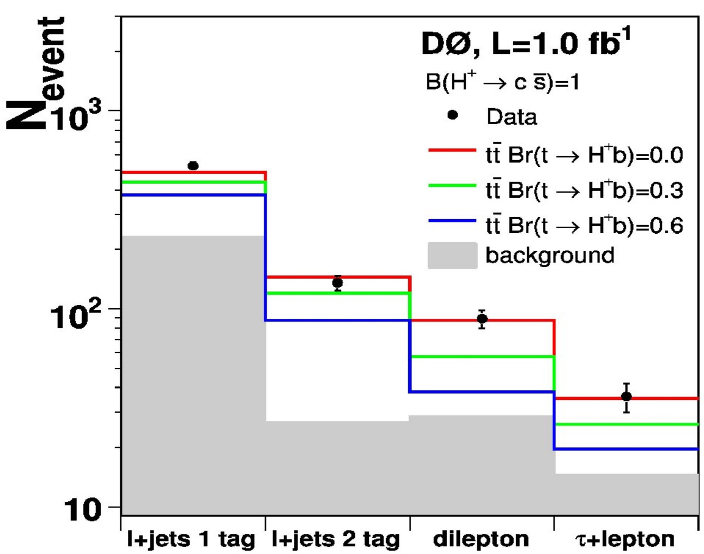
Search for Charged Higgs in Top Decay

If kinematically allowed, t→ H+b happens in SUSY
Charged Higgs decay: H+ → cs or H+ → τν
- Branching ratios depend on *tanβ*

Observable:
Altered rates in final states:
L+jets *to* Dilepton *to* τ + X

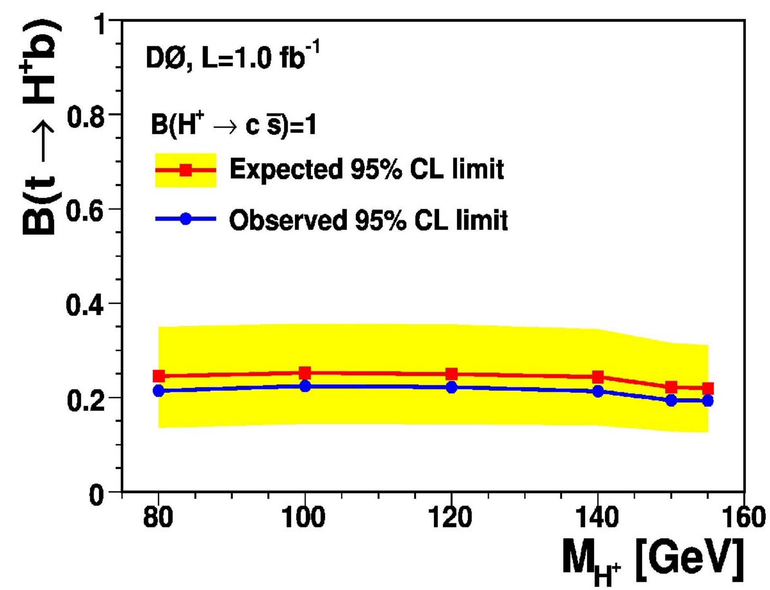






Extract limits

arXiv:0908.1811



Conclusions

- Top quark physics is a rich field in HEP and a broad top physics program is in progress at the Tevatron

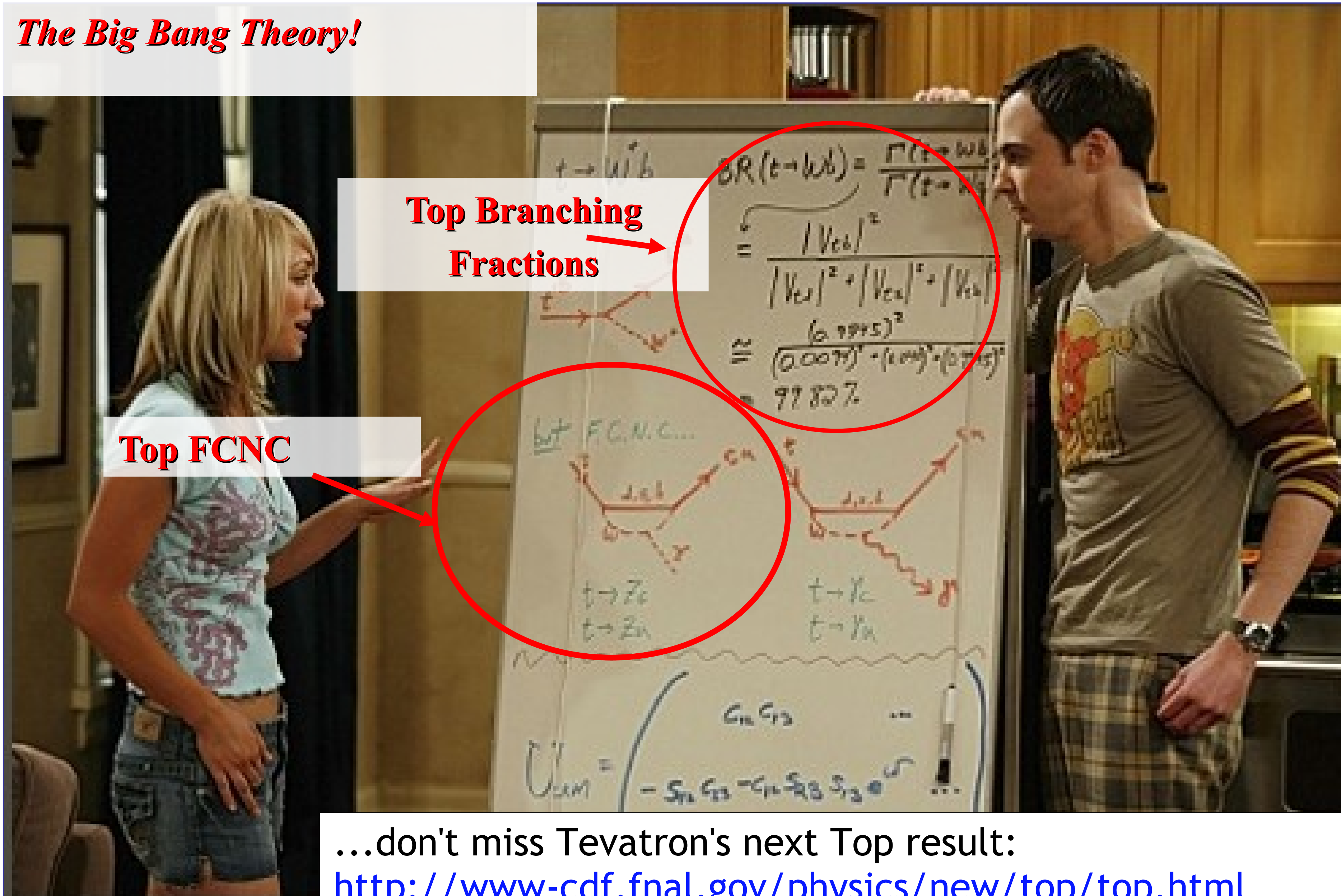
- Top quark mass measurements
  - Most measurements are systematically limited
  - Mass measured to <1% precision for single analysis

- *So far, top quark data is consistent with the SM*

- *Tevatron expects to double data sets if running through 2011*
- *We expect improvements in our understanding of top phyisics!*

- *With the LHC, an huge top quark factory is beginning operations and top physics will continue to play a significant role:*
  - *Understanding of systematic uncertainties would become crucial*
  - *Top is a standard candle, tool for calibrating JES, b-tagging*

Top Quark is on prime time!



...don't miss Tevatron's next Top result:
http://www-cdf.fnal.gov/physics/new/top/top.html
http://www-d0.fnal.gov/Run2Physics/WWW/results/top.htm