Combination of W Helicity Fractions in Top Quark Decays at the Tevatron

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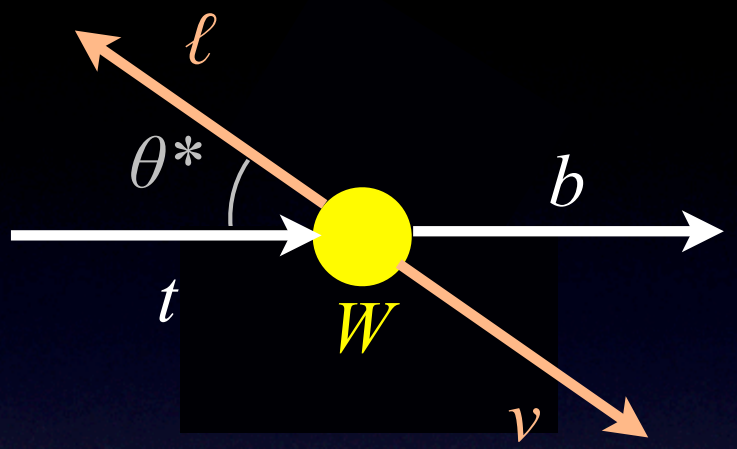
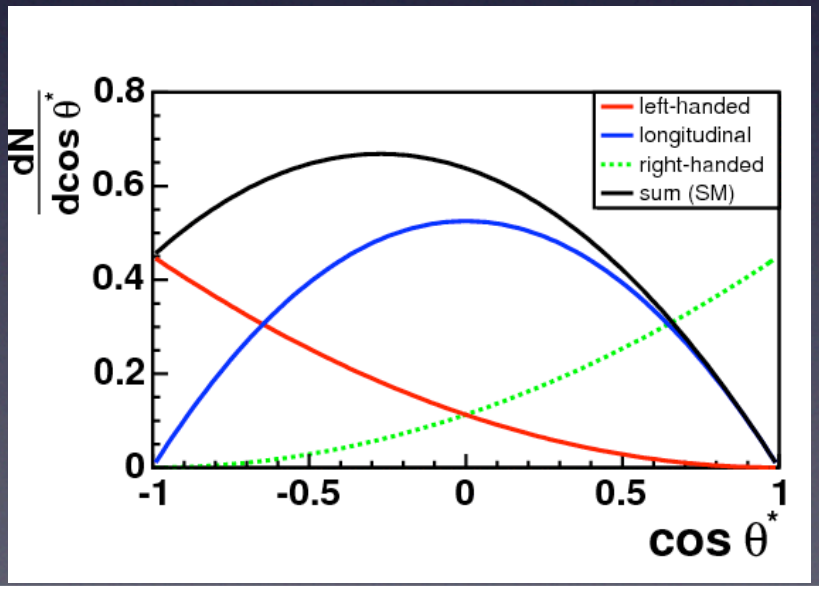
W Boson Helicity

- In the SM, *W*'s from top decay have helicities:
  - -1 (31%)
  - 0 (69%)
  - +1 (~10^{-3})

A. Czarnecki, J. G. Körner, J. H. Piclum, Phys. Rev. D 81, 111503 (2010)



- Direct measurements might reveal non-standard couplings



Measurement methods:

direct reconstruction of cosθ*

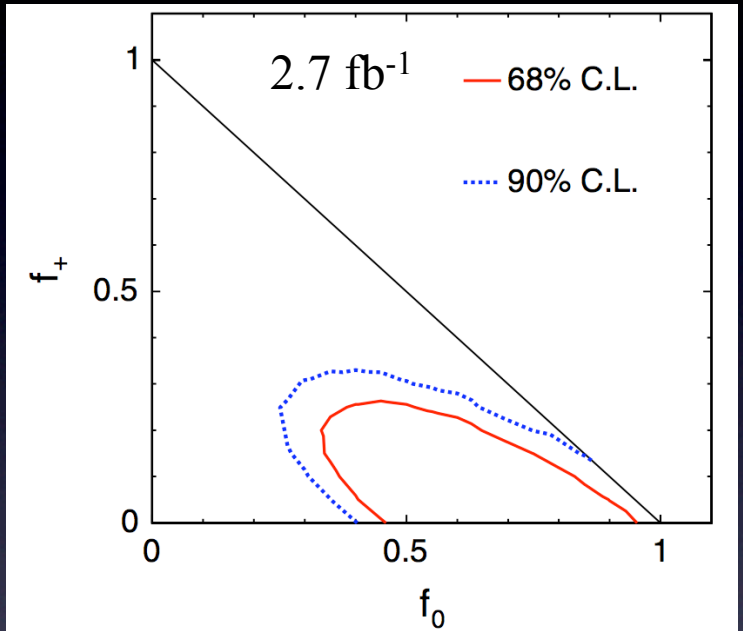
comparison of observed kinematics to matrix element

1D and 2D Measurements

- With three helicity fractions, there are two independent quantities to measure
  - 3rd fraction is fixed since $\Sigma f = 1$
- We choose to measure f_0 and f_+
- Can either measure both fractions simultaneously
  - called a "2D" fit
- or fix one fraction to its SM value and measure the other
  - called a "1D" fit

CDF Measurements

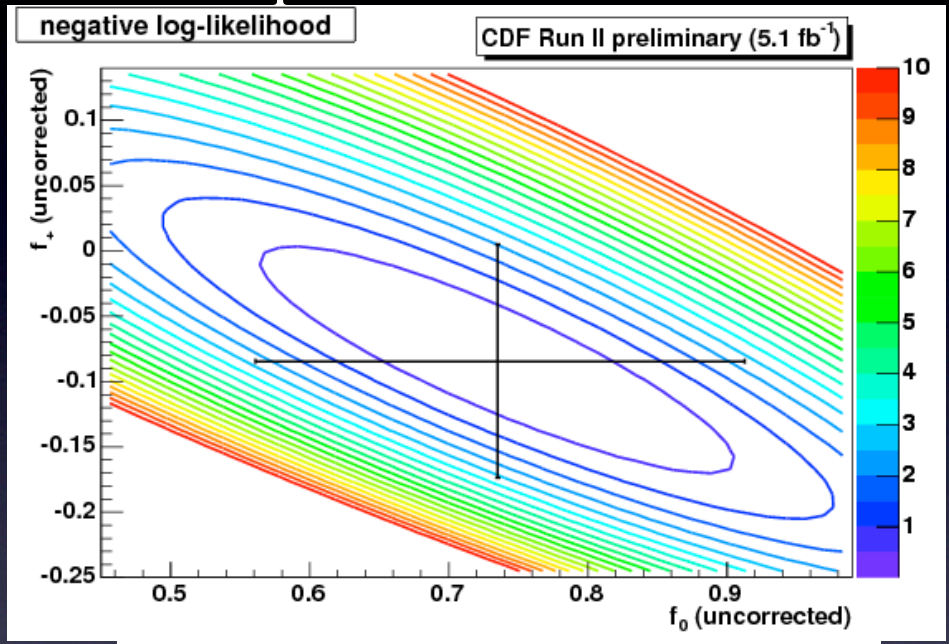
- ℓ+jets channel
  - matrix element method



$$2D: f_0 = 0.88 \pm 0.11 \pm 0.06$$
$$f_+ = -0.15 \pm 0.07 \pm 0.06$$
$$1D: f_0 = 0.70 \pm 0.07 \pm 0.04$$
$$f_+ = -0.01 \pm 0.02 \pm 0.05$$

Phys. Rev. Lett 105, 042002 (2010)

- Dilepton channel
  - template method

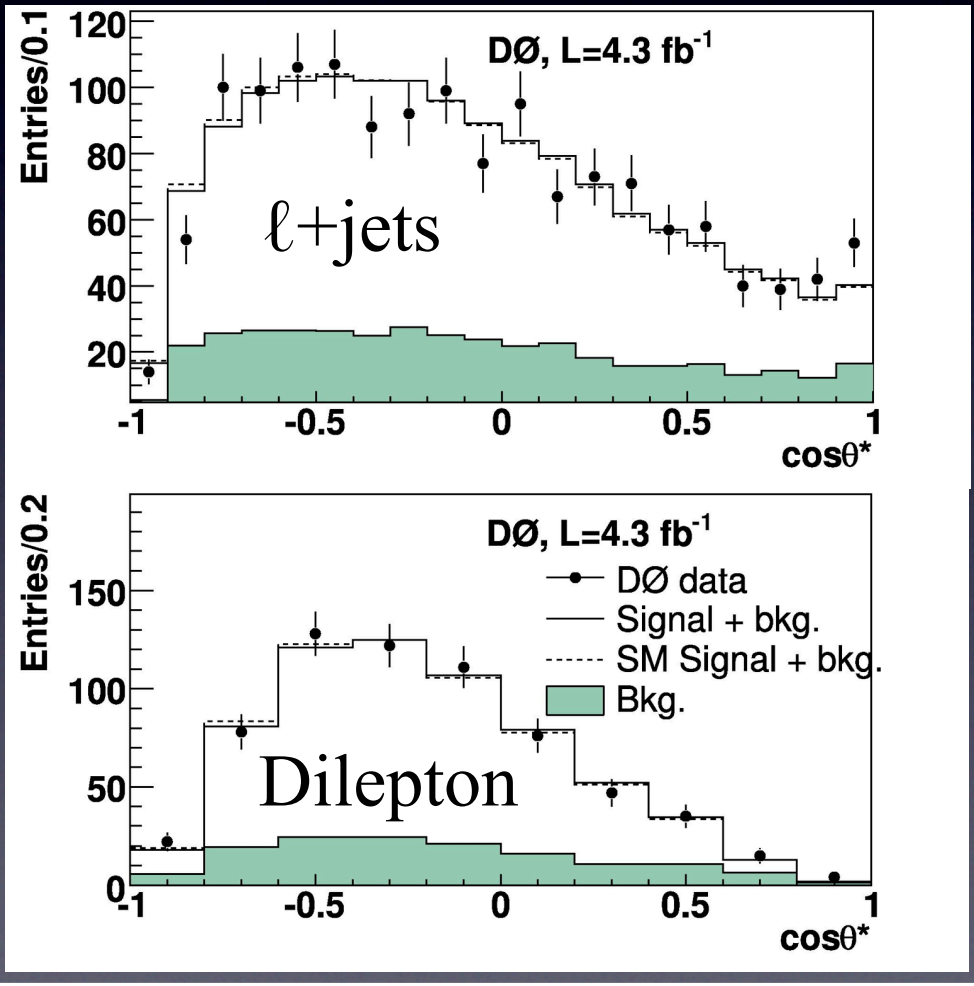


$$2D: f_0 = 0.71^{+0.18}_{-0.17} \pm 0.06$$
$$f_+ = -0.07 \pm 0.09 \pm 0.04$$
$$1D: f_0 = 0.59 \pm 0.09 \pm 0.06$$
$$f_+ = -0.07 \pm 0.09 \pm 0.04$$

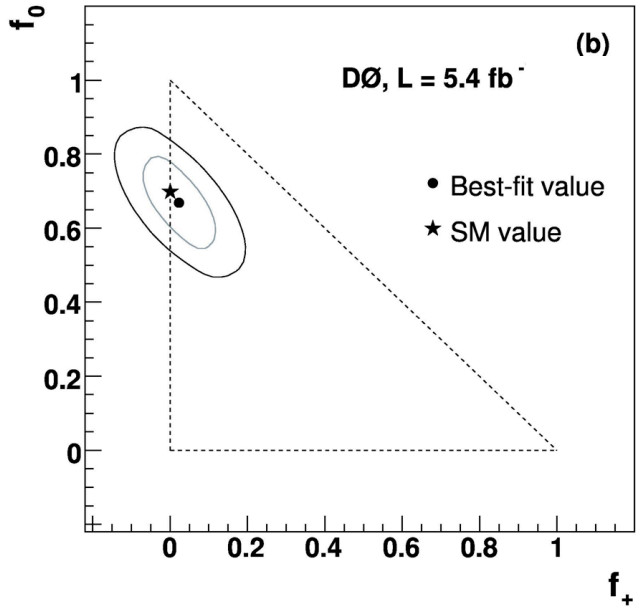
CDF note 10333

DØ Measurement

- ℓ+jets and dilepton channels
- Template fit used to extract fractions



- Results:



2D: $f_0 = 0.74 \pm 0.09 \pm 0.06$
$f_+ = 0.00 \pm 0.05 \pm 0.03$

1D: $f_0 = 0.74 \pm 0.05 \pm 0.05$
$f_+ = 0.01 \pm 0.03 \pm 0.03$

Phys. Rev. D 83, 032009 (2011)

Motivation and Method

- CDF and DØ pursued this combination
  - to obtain best possible precision
  - to ensure that correlated uncertainties were handled properly
  - to have a combination published in a refereed journal
    - ✦ i.e. rather than an arXiv entry from a working group
- The algorithm for the combination is the well-established best linear unbiased estimator approach

A. Valassi, Nucl. Instrum. Methods in Phys. Res. A **500**, 391 (2003)

L. Lyons, D. Gibaut, and P. Clifford, Nucl. Instrum. Methods in Phys. Res. A **270**, 110 (1988).

Top Quark Mass

- The measured helicity fractions depend on the value of the top quark mass
- CDF and DØ treat this dependence differently
  - CDF assumes m_t = 175 GeV, and provides formula for translating results to other top masses
  - DØ assumes m_t = 172.5 GeV, and treats variations as a systematic uncertainty
- For purposes of the combination, CDF revised their results to match DØ's procedure
  - this means the helicity fractions input to the combination differ slightly from the published values

Categories of Uncertainty

- First step is to divide the uncertainties into categories
  - all correlations are *within* a category, not between categories
- Set chosen was:

Statistics

Jet energy scale
including *b* jet scale

Signal modeling
gluon radiation
b fragmentation
PDFs
parton shower model

Top quark mass

Background modeling
including heavy flavor fraction

Analysis-specific
e.g., MC statistics

Detector-specific
Jet ID and energy resolution
Muon ID in DØ

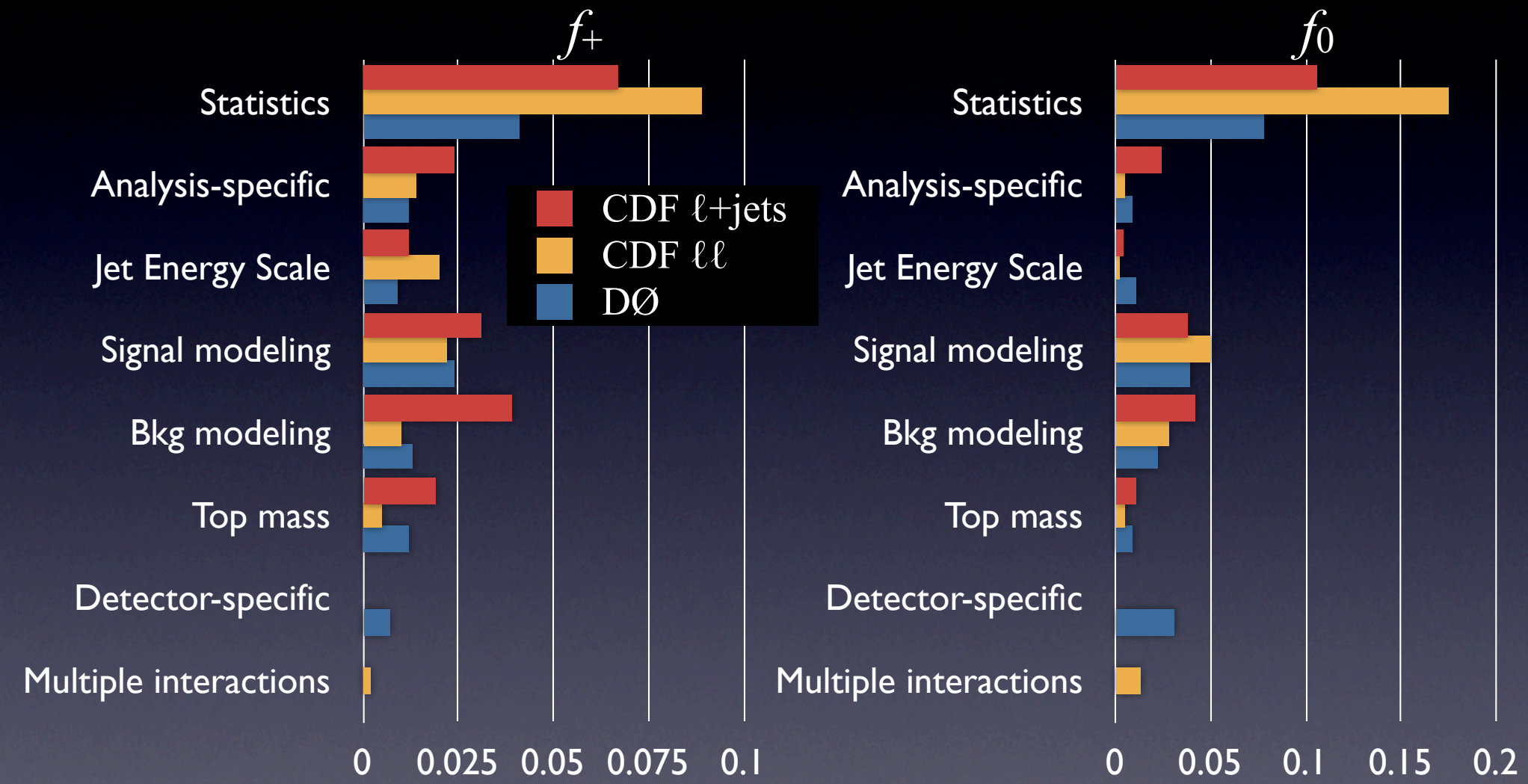
Multiple interactions

Correlations

- Correlations can exist
  - between measurements
    - f_0 and f_+ are strongly anti-correlated in 2D fits
    - statistical correlation coefficients are -0.6 – -0.9
    - approximated as -1 for systematics
  - between analyses (i.e. dilepton and ℓ+jets channels in CDF)
    - detector-specific and multiple interactions
  - between CDF and DØ
    - Jet energy scale, signal and background modeling, top quark mass
- Where correlations exist, 100% correlation is assumed

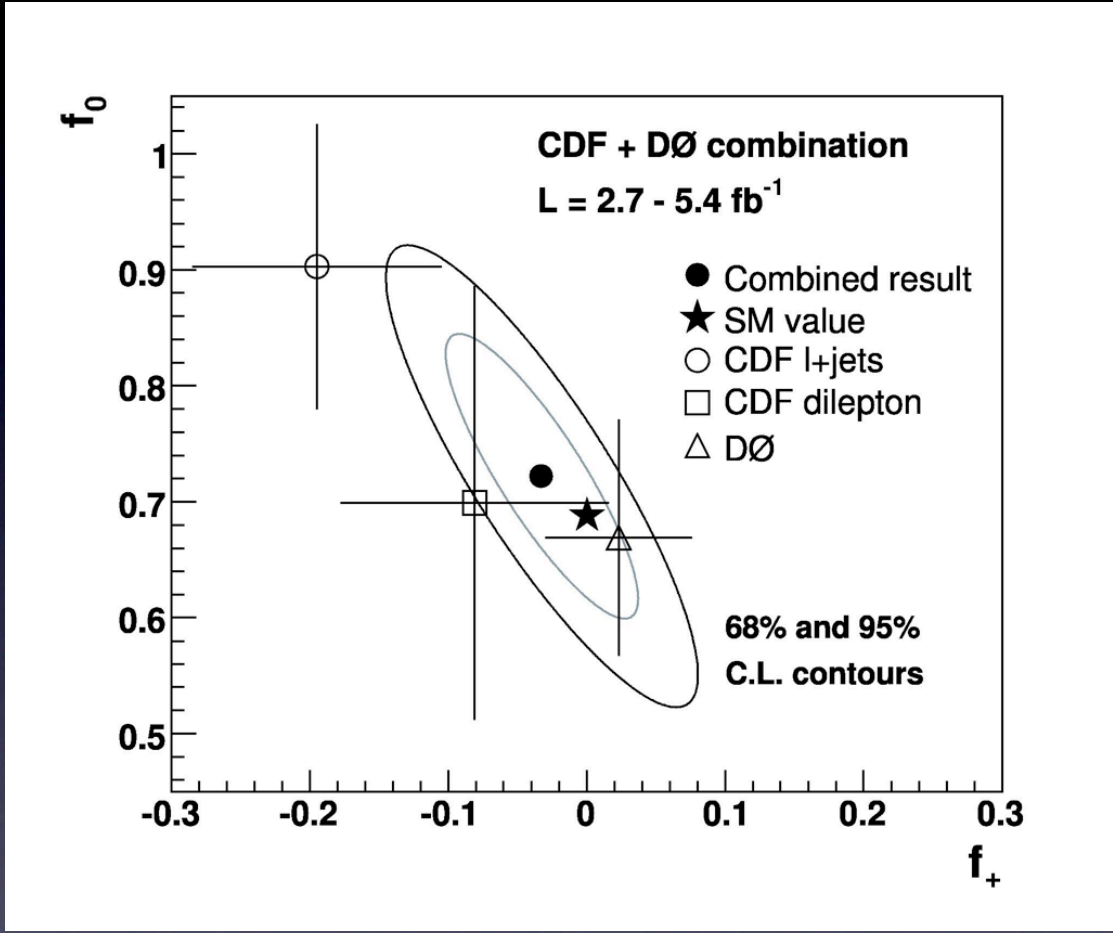
Uncertainties Summarized

- Values shown are from the 2D measurements



Results

- Combination of the 2D measurements gives:



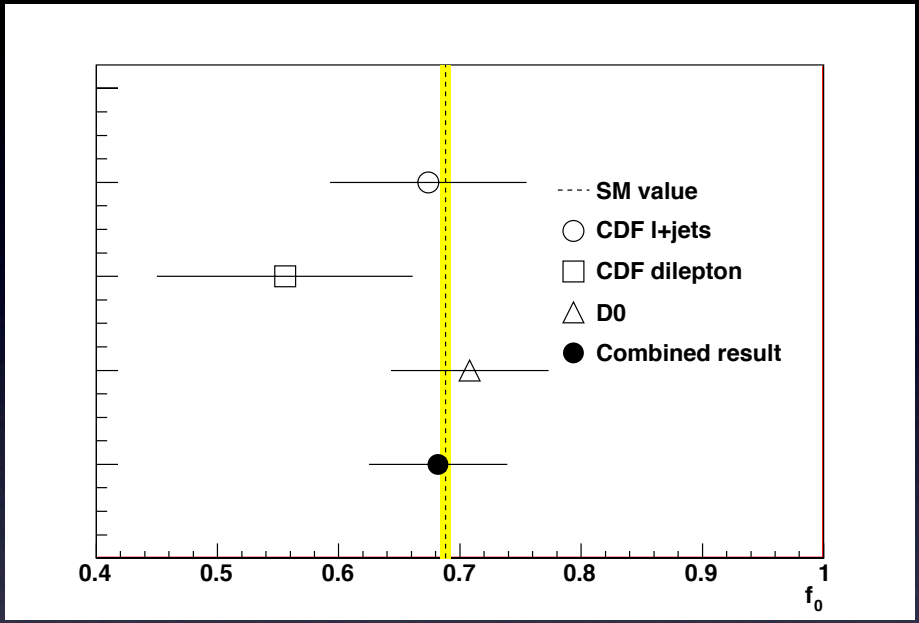
$\chi^2 = 8.86/4$
6% probability

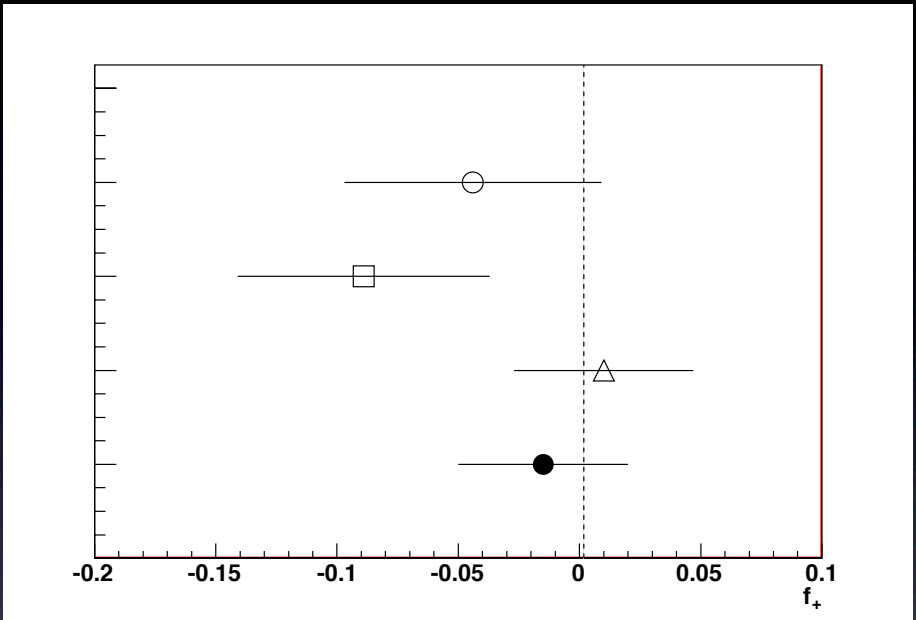
$$f_0 = 0.722 \pm 0.062 \pm 0.052$$
$$f_+ = -0.033 \pm 0.034 \pm 0.031$$

25%
21%
Increase in precision w.r.t. best input measurement

Results

- Combination of the 1D measurements gives:





$$f_0 = 0.682 \pm 0.035 \pm 0.046$$

$$\chi^2 / \text{dof} = 2.12 / 2$$

35% probabilty

19%

$$f_+ = 0.015 \pm 0.018 \pm 0.030$$

$$\chi^2 / \text{dof} = 4.44 / 2$$

11% probabilty

18%

Summary

- Combining CDF and DØ measurements of the *W* helicity fractions in top quark decays yields

$$\text{2D: } f_0 = 0.722 \pm 0.062 \pm 0.052$$
$$f_+ = -0.033 \pm 0.034 \pm 0.031$$
$$\text{1D: } f_0 = 0.682 \pm 0.035 \pm 0.046$$
$$f_+ = -0.015 \pm 0.018 \pm 0.030$$

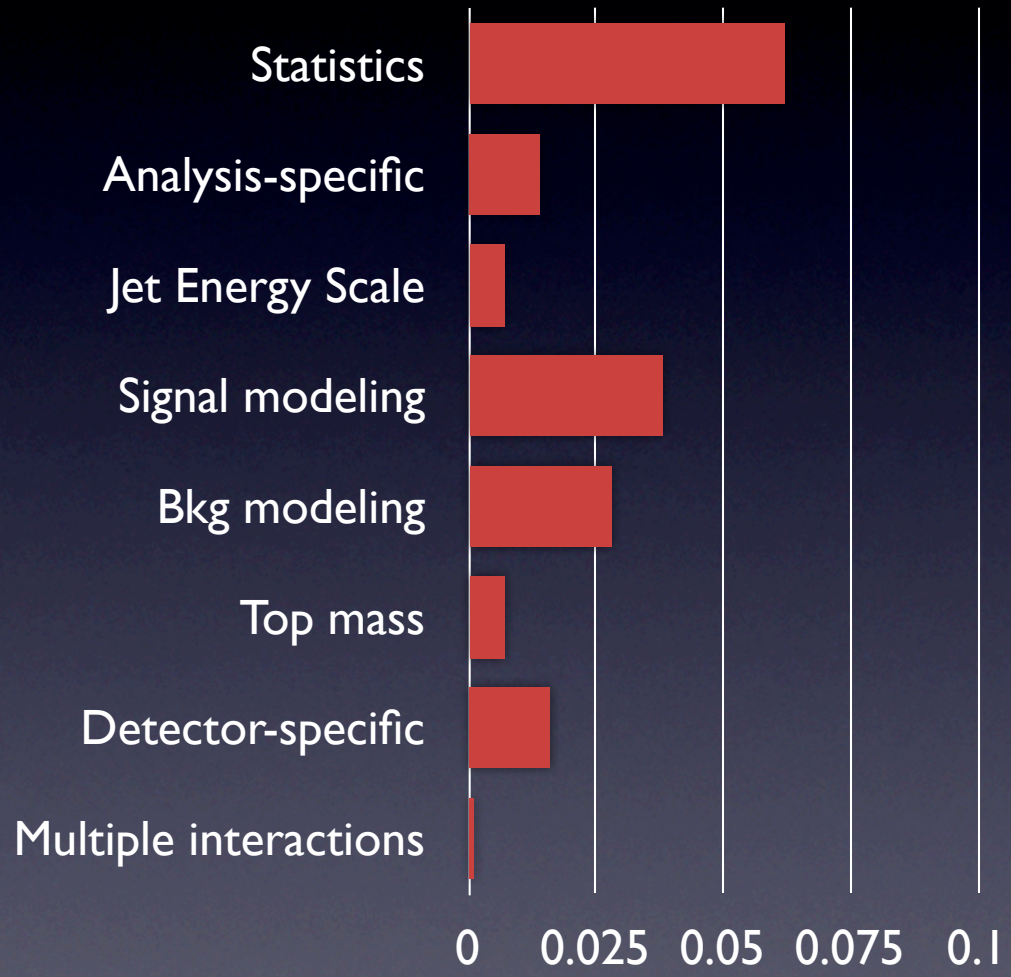
- This is the first Tevatron-wide combination of top quark results done by the experiments themselves
- The result is consistent with the SM expectations
  - full details in

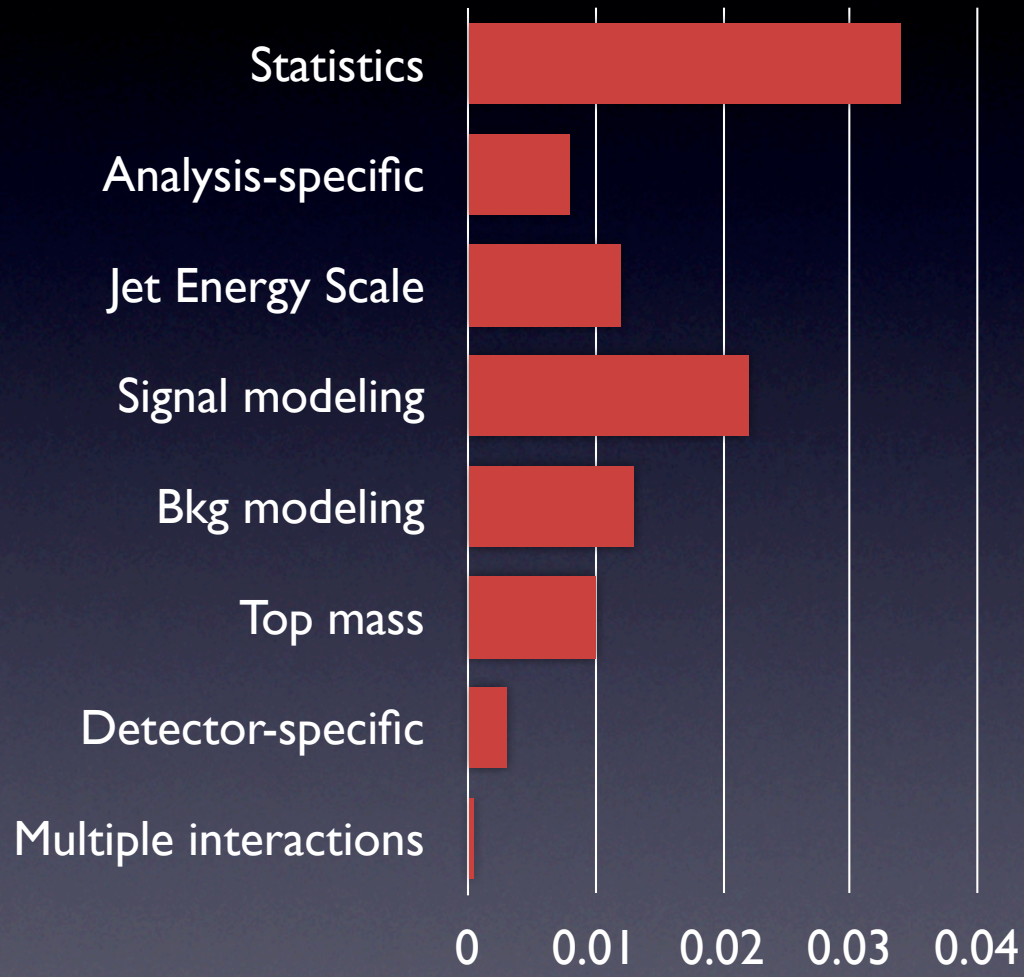
Phys. Rev. D 85, 071106 (2012)

Backup

Uncertainties in Combination

- Values from the combination of 2D measurments





Correlations

- Statistical:

	$f_{0,\mathrm{CDF}}^{\ell+j}$	$f_{0,\mathrm{D0}}$	$f_{0,\mathrm{CDF}}^{\ell\ell}$	$f_{+,\mathrm{CDF}}^{\ell+j}$	$f_{+,\mathrm{D0}}$	$f_{+,\mathrm{CDF}}^{\ell\ell}$
$f_{0,\mathrm{CDF}}^{\ell+j}$	1.0	0.0	0.0	−0.6	0.0	0.0
$f_{0,\mathrm{D0}}$	0.0	1.0	0.0	0.0	−0.8	0.0
$f_{0,\mathrm{CDF}}^{\ell\ell}$	0.0	0.0	1.0	0.0	0.0	−0.9
$f_{+,\mathrm{CDF}}^{\ell+j}$	−0.6	0.0	0.0	1.0	0.0	0.0
$f_{+,\mathrm{D0}}$	0.0	−0.8	0.0	0.0	1.0	0.0
$f_{+,\mathrm{CDF}}^{\ell\ell}$	0.0	0.0	−0.9	0.0	0.0	1.0

Correlations

- Jet energy scale, signal and background modeling, and top quark mass:

	$f_{0,\mathrm{CDF}}^{\ell+j}$	$f_{0,\mathrm{D0}}$	$f_{0,\mathrm{CDF}}^{\ell\ell}$	$f_{+,\mathrm{CDF}}^{\ell+j}$	$f_{+,\mathrm{D0}}$	$f_{+,\mathrm{CDF}}^{\ell\ell}$
$f_{0,\mathrm{CDF}}^{\ell+j}$	1.0	1.0	1.0	−1.0	−1.0	−1.0
$f_{0,\mathrm{D0}}$	1.0	1.0	1.0	−1.0	−1.0	−1.0
$f_{0,\mathrm{CDF}}^{\ell\ell}$	1.0	1.0	1.0	−1.0	−1.0	−1.0
$f_{+,\mathrm{CDF}}^{\ell+j}$	−1.0	−1.0	−1.0	1.0	1.0	1.0
$f_{+,\mathrm{D0}}$	−1.0	−1.0	−1.0	1.0	1.0	1.0
$f_{+,\mathrm{CDF}}^{\ell\ell}$	−1.0	−1.0	−1.0	1.0	1.0	1.0

Correlations

- Analysis-specific:

	$f^{\ell+j}_{0,\mathrm{CDF}}$	$f_{0,\mathrm{D0}}$	$f^{\ell\ell}_{0,\mathrm{CDF}}$	$f^{\ell+j}_{+,\mathrm{CDF}}$	$f_{+,\mathrm{D0}}$	$f^{\ell\ell}_{+,\mathrm{CDF}}$
$f^{\ell+j}_{0,\mathrm{CDF}}$	1.0	0.0	0.0	−1.0	0.0	0.0
$f_{0,\mathrm{D0}}$	0.0	1.0	0.0	0.0	−1.0	0.0
$f^{\ell\ell}_{0,\mathrm{CDF}}$	0.0	0.0	1.0	0.0	0.0	−1.0
$f^{\ell+j}_{+,\mathrm{CDF}}$	−1.0	0.0	0.0	1.0	0.0	0.0
$f_{+,\mathrm{D0}}$	0.0	−1.0	0.0	0.0	1.0	0.0
$f^{\ell\ell}_{+,\mathrm{CDF}}$	0.0	0.0	−1.0	0.0	0.0	1.0

Correlations

- Detector-specific and multiple interactions:

	$f^{\ell+j}_{0,\mathrm{CDF}}$	$f_{0,\mathrm{D0}}$	$f^{\ell\ell}_{0,\mathrm{CDF}}$	$f^{\ell+j}_{+,\mathrm{CDF}}$	$f_{+,\mathrm{D0}}$	$f^{\ell\ell}_{+,\mathrm{CDF}}$
$f^{\ell+j}_{0,\mathrm{CDF}}$	1.0	0.0	1.0	−1.0	0.0	−1.0
$f_{0,\mathrm{D0}}$	0.0	1.0	0.0	0.0	−1.0	0.0
$f^{\ell\ell}_{0,\mathrm{CDF}}$	1.0	0.0	1.0	−1.0	0.0	−1.0
$f^{\ell+j}_{+,\mathrm{CDF}}$	−1.0	0.0	−1.0	1.0	0.0	1.0
$f_{+,\mathrm{D0}}$	0.0	−1.0	0.0	0.0	1.0	0.0
$f^{\ell\ell}_{+,\mathrm{CDF}}$	−1.0	0.0	−1.0	1.0	0.0	1.0

Weight of Each Measurement

- Combination of 2D measurements

Measurement	s.d. from combined values	Weight for f_0 (%)	Weight for f_+ (%)
$f_{0,\mathrm{CDF}}^{2\mathrm{D},\ell+j}$	1.96	44.4	−15.4
$f_{0,\mathrm{D0}}^{2\mathrm{D}}$	−0.87	45.6	8.1
$f_{0,\mathrm{CDF}}^{2\mathrm{D},\ell\ell}$	−0.12	10.1	7.2
$f_{+,\mathrm{CDF}}^{2\mathrm{D},\ell+j}$	−2.10	27.9	−3.6
$f_{+,\mathrm{D0}}^{2\mathrm{D}}$	2.06	−22.0	75.9
$f_{+,\mathrm{CDF}}^{2\mathrm{D},\ell\ell}$	−0.62	−5.9	27.7

Weight of Each Measurement

- Combination of 1D measurements

Measurement	s.d. from combined values	Weight (%)
$f_{0,\mathrm{CDF}}^{1\mathrm{D},\ell+j}$	−0.15	31.3
$f_{0,\mathrm{D0}}^{1\mathrm{D}}$	0.83	58.9
$f_{0,\mathrm{CDF}}^{1\mathrm{D},\ell\ell}$	−1.40	9.9
$f_{+,\mathrm{CDF}}^{1\mathrm{D},\ell+j}$	−0.70	5.2
$f_{+,\mathrm{D0}}^{1\mathrm{D}}$	2.08	72.1
$f_{+,\mathrm{CDF}}^{1\mathrm{D},\ell\ell}$	−1.94	22.7