Measurement of W Boson Helicity Fractions in $t\bar{t}$ Decays at DZero and CDF

Chris Potter (for the CDF and DZero Collaborations)

McGill University, Montreal, Canada

W Boson Helicity: Phenomenology Overview

- See General Analysis of Single Top Production and W Helicity in Top Decay, Chuan-Ren Chen, F. Larios, C.-P. Yuan (hep-ph/0503040v3).

- The generic Lagrangian describing the tbW vertex is:

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

- The W helicity fractions are f_- (left), f_+ (right) and f_0 (longitudinal) are given by

$$\begin{aligned} f_0 &= a_t^2(1+x_0)/[a_t^2(1+x_0)+2(1+x_m+x_p)] \\ f_- &= 2(1+x_m)/[a_t^2(1+x_0)+2(1+x_m+x_p)] \\ f_+ &= 2x_p/[a_t^2(1+x_0)+2(1+x_m+x_p)] \end{aligned}$$

  where $a_t = m_t/m_W$ and x_0, x_p and x_m are simple functions of the $f_i^{L/R}$.

- In $t \rightarrow bW \rightarrow b\ell\nu$ events, if $\cos\theta^\star \equiv c$ is the angle between the charged lepton (or down-type quark) from the W decay and the W in the top rest frame, then the distribution of c is:

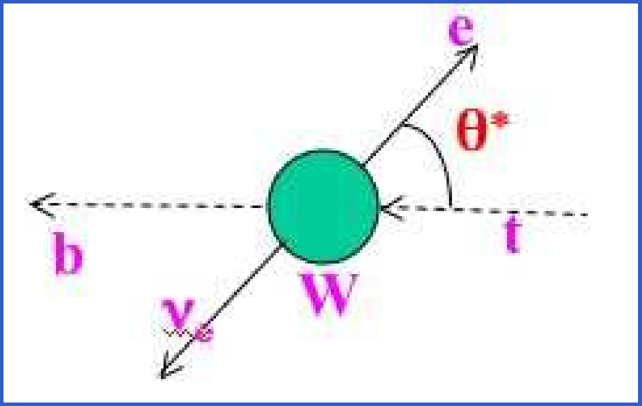
$$\omega(c) \propto f_+(1+c)^2 + 2f_0(1-c^2) + f_-(1-c)^2$$

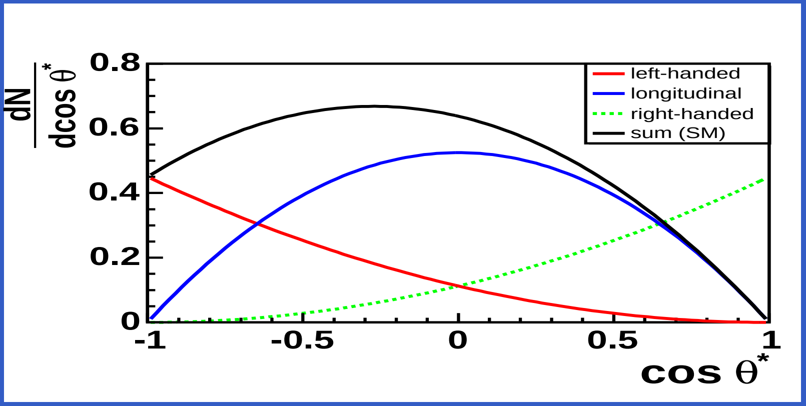
W Boson Helicity: Experimental Overview

- Different models predict different helicity fractions (see hep-ph/0503040v3):

Fraction	SM Prediction	MSSM	Technicolor
f_+	3.4×10^{-4}		
f_0	$\frac{m_t^2}{2m_W^2+m_t^2} \approx 0.703$	0.699	0.707
f_-	$1 - f_0 - f_+ \approx 0.297$	0.301	0.293

- The distributions of $\cos\theta^\star$ for pure left, pure right, pure longitudinal samples, and the SM:





- The DZero and three CDF analyses described here suppress background, impose W and top mass constraints to reconstruct the W and top four-vectors. Then $\cos\theta^\star$ is calculated and a likelihood is constructed.

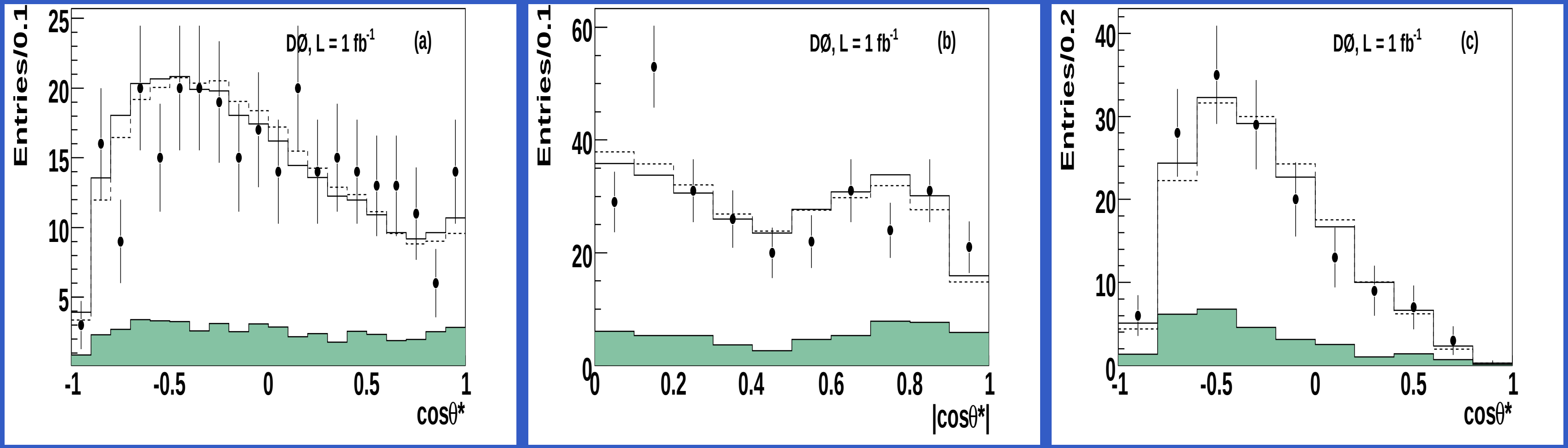
Summary of Recent Tevatron Results

Experiment	Channel	$\mathcal{L}$
DZero	ℓ+jets, dilepton	1fb^{-1}
CDF UM	ℓ+jets	1.9 fb^{-1}
CDF ME	ℓ+jets	1.9 fb^{-1}
CDF TM	ℓ+jets	1.9 fb^{-1}

The results have not yet been combined. All analyses are currently statistics limited, but with more integrated luminosity will soon be systematics limited.

- The DZero analysis employs a two-parameter (f_0, f_+) binned likelihood with $\cos\theta^\star$. It differs from CDF analyses as it reconstructs hadronic W decays and uses the dilepton channel.
- The CDF UM analysis uses the Unfolding Method with a two-parameter (f_0, f_+) binned likelihood with $\cos\theta^\star$.
- The CDF ME analysis uses the Matrix Element technique to construct a two-parameter $(f_0, c_s; f_+ = 0)$ per-event likelihood.
- The CDF TM analysis uses the Template Method to fit $\cos\theta^\star$ and then construct a per-event unbinned extended maximum likelihood.

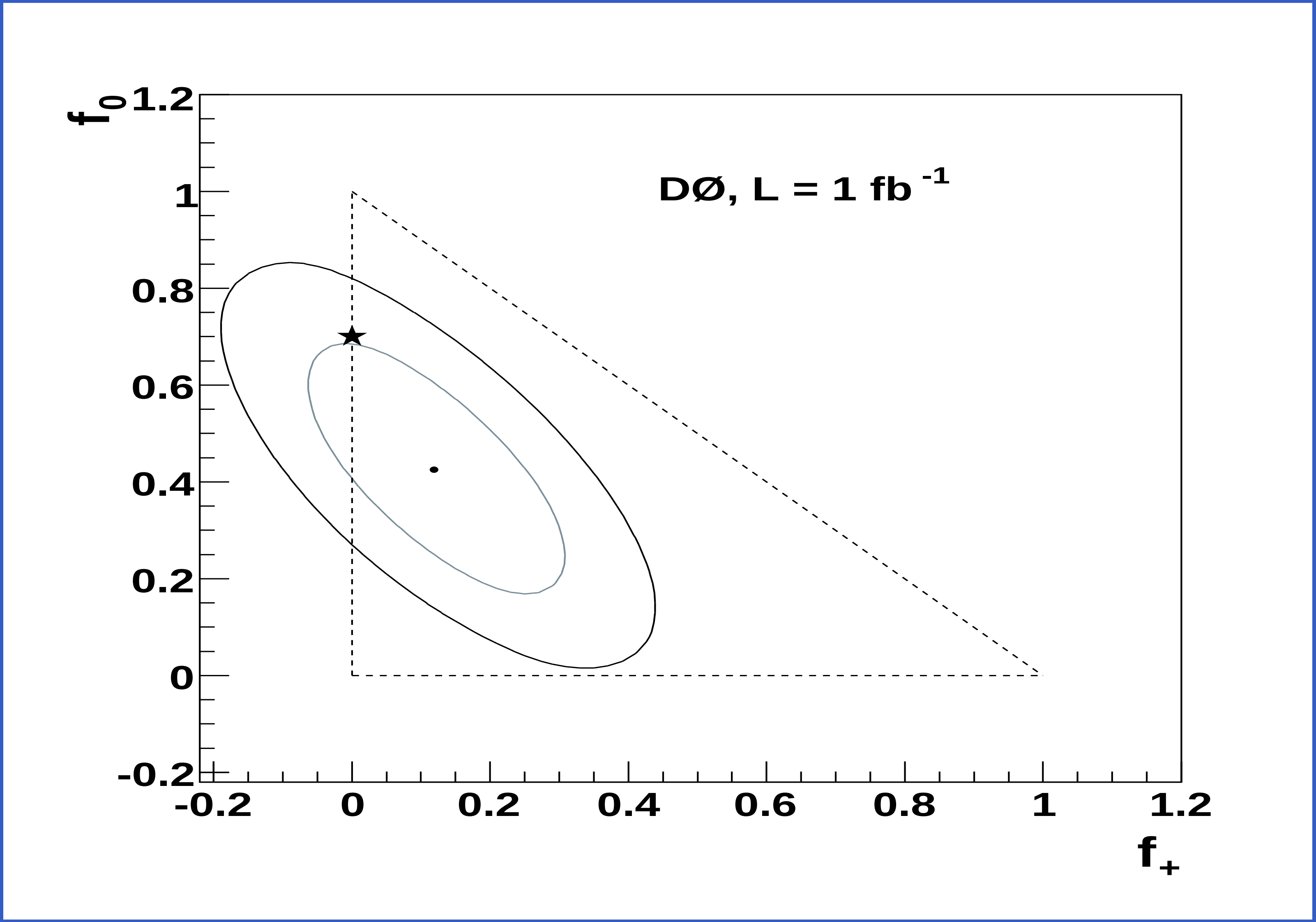
DZero Method



ℓ+jets $\cos\theta^\star$ for leptonic W decay (left), hadronic W decays (middle) and for dilepton events (right).

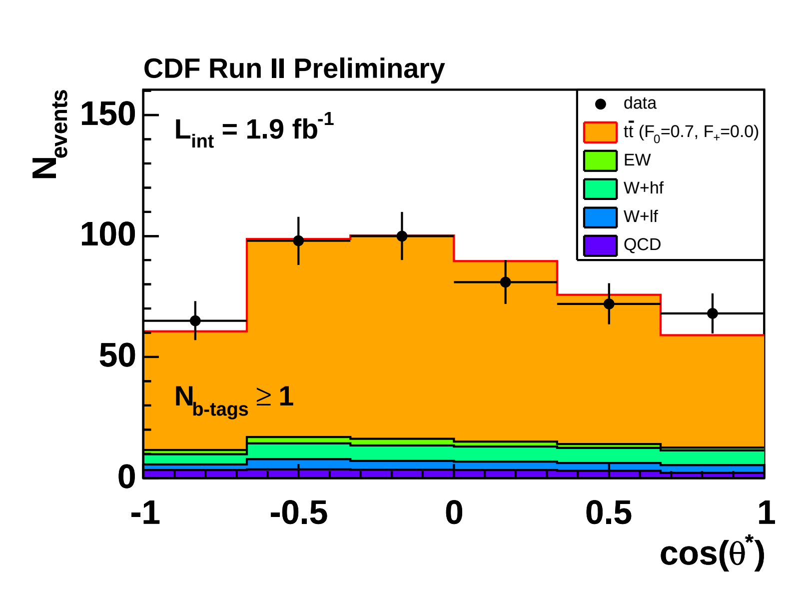
- A discriminant is calculated from kinematics and jet flavor:signal event jets and leptons have higher p_T, are more central, and contain two b-jets.
- The four-vectors of the W bosons and top quarks are reconstructed and $\cos\theta^\star$ is calculated.
- Templates for signal and background with varying helicity states $-, 0, +$ are created. Helicity fractions f_0 and f_+ are extracted from a binned Poisson likelihood $L(f_0, f_+)$.
- The hadronic W decay in the ℓ+jets channel gives an ambiguity in the sign of $\cos\theta^\star$, but $|\cos\theta^\star|$ improves the f_0 statistical error by 20%.

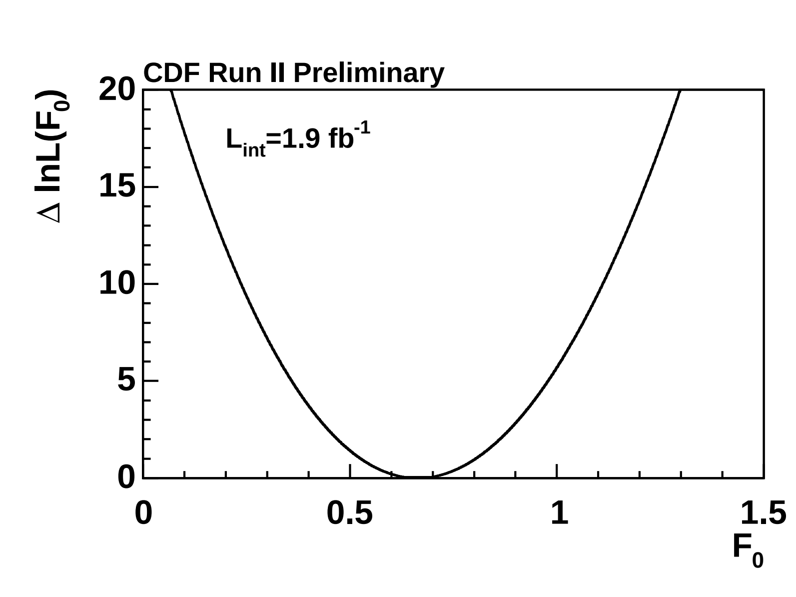
DZero W Helicity Measurement



Result for helicity fractions f_0 (vertical) and f_+ (horizontal) with the 68% and 95% C.L. contours. The triangle decribes the requirement $f_- + f_0 + f_+ = 1$. See PRL 100, 062004, DZero Collaboration, (2008)

CDF Unfolding Method



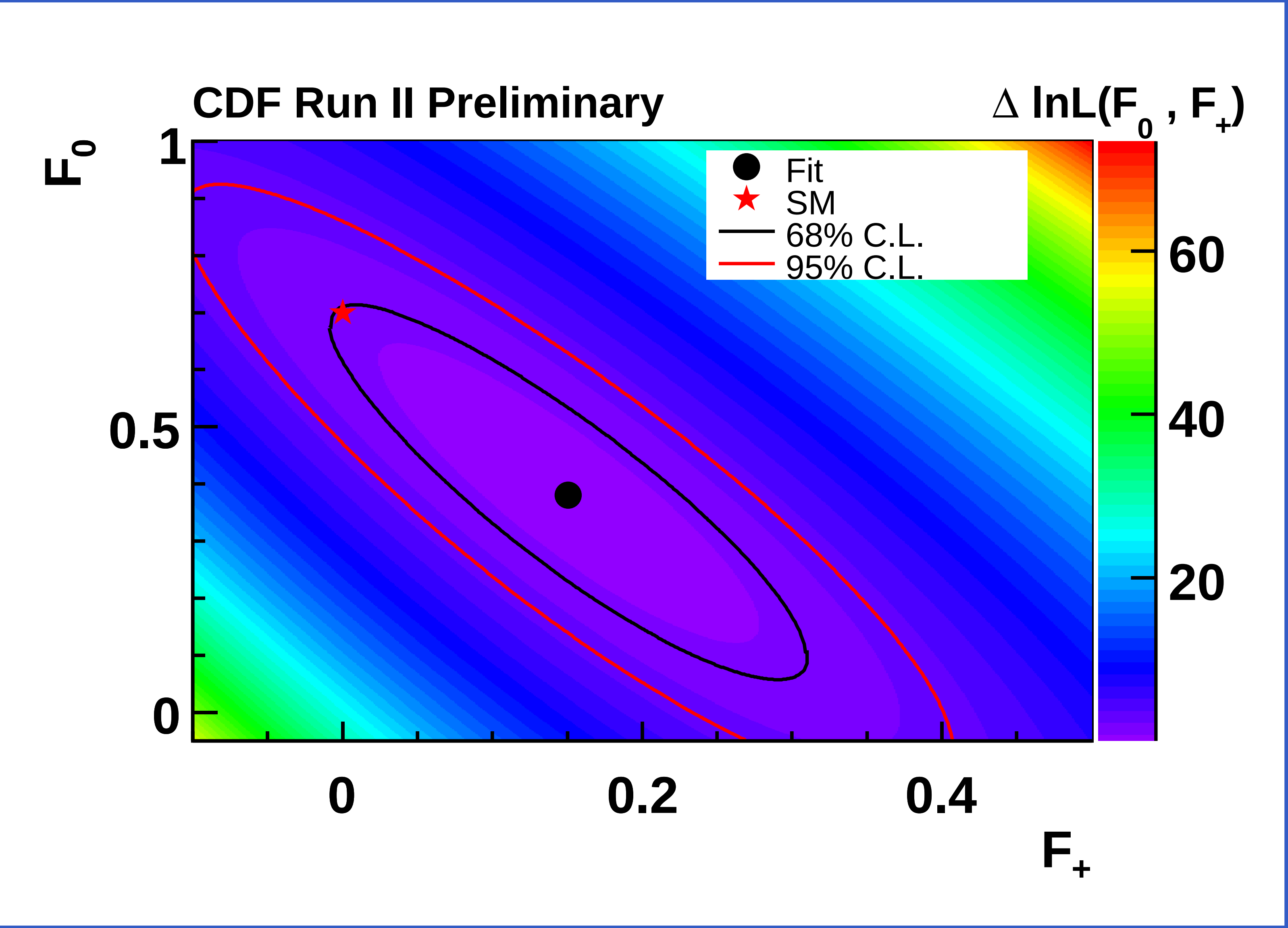


- This measurement is for ℓ+jets channel only, and main backgrounds are W+jets and dijets.
- A quantity $\Psi = P_\nu P_{b-light}\chi^2$ is calculated to suppress background and resolve signal combinatoric ambiguity. P_ν is a weighting factor for p_z^ν, $P_{b-light}$ is a measure of similarity with light jets, and

$$\chi^2 = \frac{(m_{W\to jj} - M_{W\to jj})^2}{\sigma^2_{M_{W\to jj}}} + \frac{(m_{top\to b\ell\nu} - m_{top\to bjj})^2}{\sigma^2_{\Delta M_t}} + \frac{(P_{energy} - \alpha)^2}{\sigma^2_{P_{energy}}}$$

- To extract f_+ and f_0 a binned likelihood $L(f_0, f_+)$is constructed to find the values which maximize the probability for the given data using signal and background templates (-,0,+).

CDF Unfolding Method



$\Delta \ln L(f_0, f_+)$ together with 68% and 95% C.L. contours plotted for f_0 (vertical) and f_+ (horizontal). The red star is the SM value.

CDF Matrix Element Method

- Background is suppressed by requiring isolated high E_T lepton (e or μ), large E_T^{miss}, four or more high E_T jets, tight secondary vertex requirements, and scalar sum of all transverse energy in the event $H_T > 200$ GeV.
- The f_+ parameter is set to zero and matrix elements are employed to generate a likelihood $L(f_0, C_s)$ for N events:

$$L(f_0, C_s) = \prod_{i=1}^{N} C_s P_{t\bar{t}}(\vec{x}_i; f_0) + (1 - C_s) P_{W+jets}(\vec{x}_i)$$

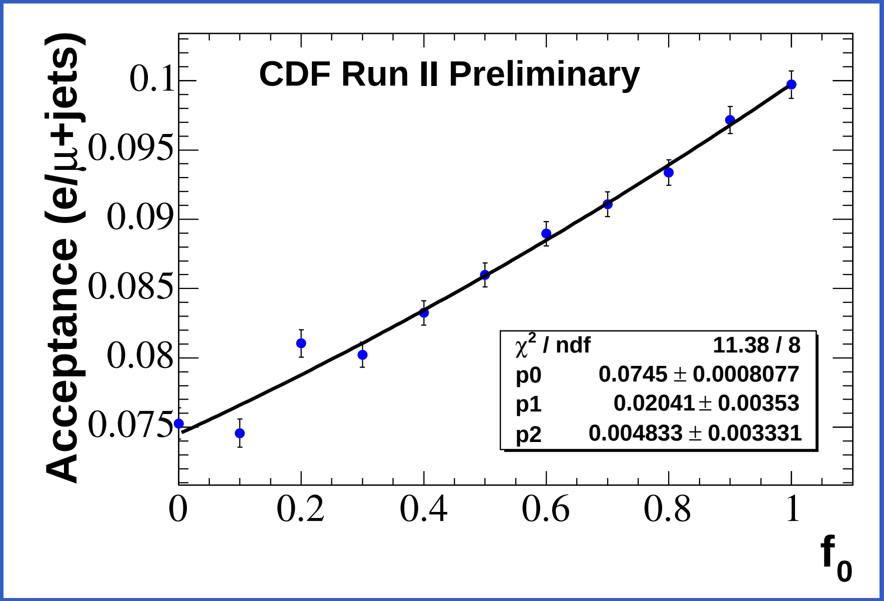
where C_s is the fraction of signal events. Then f_0 is extracted from the liekelihood.

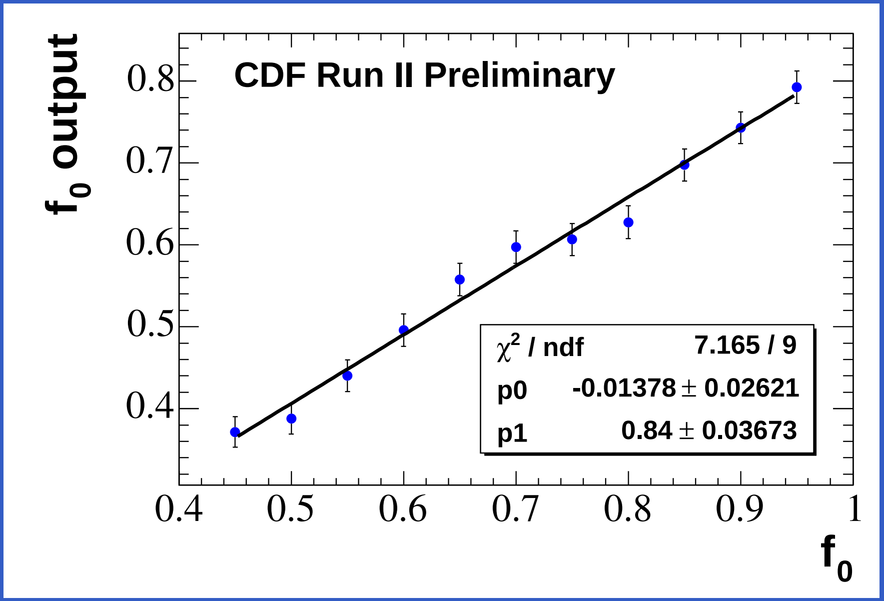
- The probabilities $P(\vec{x})$ are derived for signal $t\bar{t}$ and background (W+jets) by evaluating the leading order matrix elements at the measured vectors $\vec{x}$:

$$P(\vec{x}) = \frac{1}{\sigma_{obs}} \int \frac{d\sigma(\vec{y})}{d\vec{y}} f(\tilde{q}_1) f(\tilde{q}_2) W(\vec{x}, \vec{y}) d\tilde{q}_1 d\tilde{q}_2 d\tilde{p}^x_{t\bar{t}} d\tilde{p}^y_{t\bar{t}} d\vec{y}$$

where f are the parton density functions, $W(\vec{x}, \vec{y})$ is a transfer function describing the probability that parton with $\vec{y}$ will be measured as $\vec{x}$.

CDF Matrix Element Method



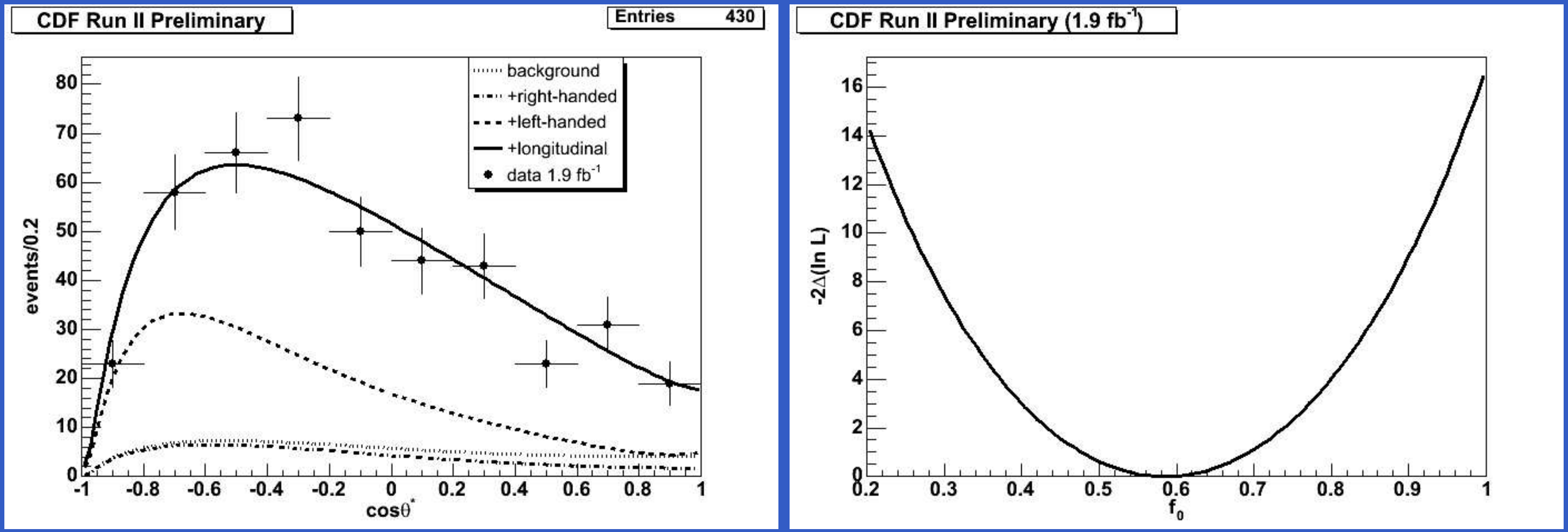


- (Left) Since the signal acceptance depends on the helicity fraction f_0, it is plotted and parametrized for several templates with varying f_0 and fitting the acceptance curve with a straight line.
- (Right) The response (measured f_0 output vs input template f_0) in Monte Carlo simulation is plotted and fitted in order to calibrate the measured f_0 in data.
- As a crosscheck, the separate e and μ channels are evaluated separately:

Electron: $f_0 = 0.660 \pm 0.111(stat)$

Muon: $f_0 = 0.609 \pm 0.128(stat)$

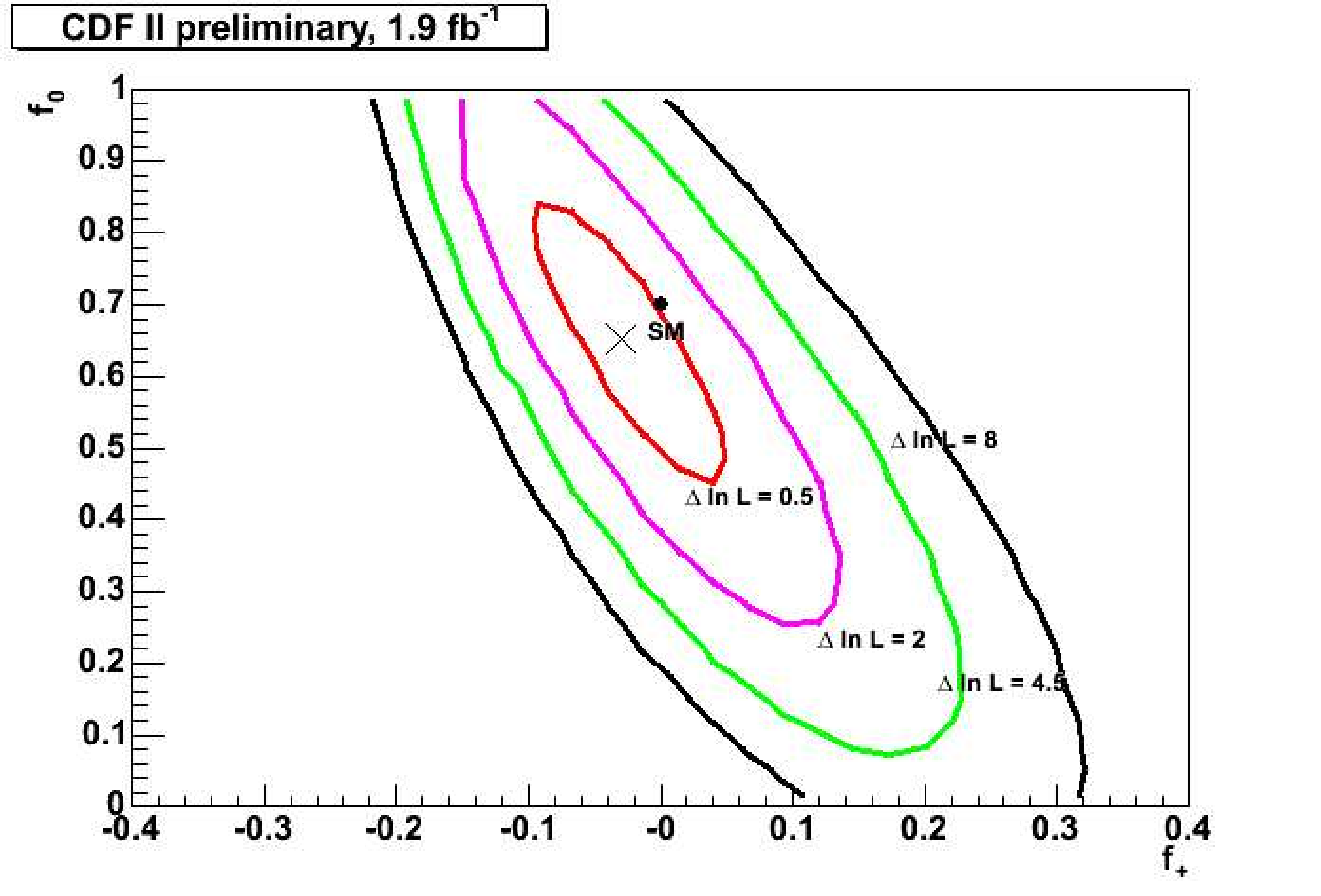
CDF Template Method



- This analysis uses the ℓ+jets channel and suffers background mainly from W+jets.
- Background is suppressed by requiring one e or μ, E_T^{miss}, scalar $H_T > 250$ GeV, four or more jets, one of which is identified as a b-jet by a secondary vertex tagger.
- The $\cos\theta^\star$ distribution is fit with a 3rd degree polynomial times two exponentials.
- An unbinned extended likelihood fitter is used to extract f_+ and f_0 with the likelihood:

$$\mathcal{L} = G(b|\mu_b, \sigma_b) \times P(s + b|\mu_s + \mu_b) \times \prod_{i=1}^{N} [f_b p_b(c) + (1 - f_b) p_s(c)]$$

CDF Template Method



Measured values of (f_+, f_0) and contours of constant $-\Delta \ln \mathcal{L}$ as determined by the 2D fit to data.

Dominant Systematic Uncertainties on f_0

Systematic	DZero	CDF UM	CDF ME	Technique
Generator	11%	2%	8%	Cf PYTHIA to ALPGEN (DZero),HERWIG (ME)
ISR	NA	5%	4%	Turn on/off in PYTHIA (ME and UM)
FSR	NA	7%	3%	Turn on/off in PYTHIA (ME and UM)
PDF	NA	2%	4%	Cf CTEQ to MRST (ME and UM)
Bgd Model	8%	4%	1%	Vary shapes (UM) or control sample (DZero)
Template	8%	NA	NA	Fluctuate template and refit
Total	16%	10%	11%	NB: Not all sources are reported here

- The three dominant reported systematic uncertainty for each analysis are listed (along with the values for the other analyses).
- Uncertainties are evaluated in ensemble tests in which the source of systematic error is sampled repeatedly, the helicity fractions recalculated. The mean difference gives the uncertainty.
- The CDF TM analysis reports that the absolute systematic uncertainty is 5% for f_0, with jet energy scale and signal/background modeling as the dominant uncertainties.

Summary and Conclusions

Experiment	Channel	$\mathcal{L}$	f_+	f_0
DZero	ℓ+jets, dilepton	1fb^{-1}	$0.119 \pm 0.090 \pm 0.053$ $-0.002 \pm 0.047 \pm 0.047$	$0.425 \pm 0.166 \pm 0.102$ $0.619 \pm 0.090 \pm 0.052$
CDF UM	ℓ+jets	1.9 fb^{-1}	$0.15 \pm 0.10 \pm 0.05$ $0.01 \pm 0.05 \pm 0.03$	$0.38 \pm 0.21 \pm 0.07$ $0.66 \pm 0.10 \pm 0.06$
CDF ME	ℓ+jets	1.9 fb^{-1}	-	$0.637 \pm 0.084 \pm 0.069$
CDF TM	ℓ+jets	1.9 fb^{-1}	$-0.03 \pm 0.07 \pm 0.03$ $-0.04 \pm 0.04 \pm 0.03$	$0.65 \pm 0.19 \pm 0.03$ $0.59 \pm 0.11 \pm 0.04$
SM	-	-	3.4×10^{-4}	0.703

- Results in yellow are for simulataneous determination of f_+ and f_0. Results in green are for fixing $f_+ = 0$ for f_0 and $f_0 = 0.7$ for f_+.
- As the Tevatron accumulates luminosity, the statistical errors will go lower than the systematic errors and the analyses will become systematics limited.
- All measurements are consistent with the Standard Model. Systematic errors are at a level such that the measurements are not presently able to discriminate between SM, MSSM and Technicolor predictions, which differ at the percent level.