Helicity of W bosons in Top Quark Decays at CDF

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On behalf of the CDF collaboration

DPF 29/10-03/11/2006, Hawaii

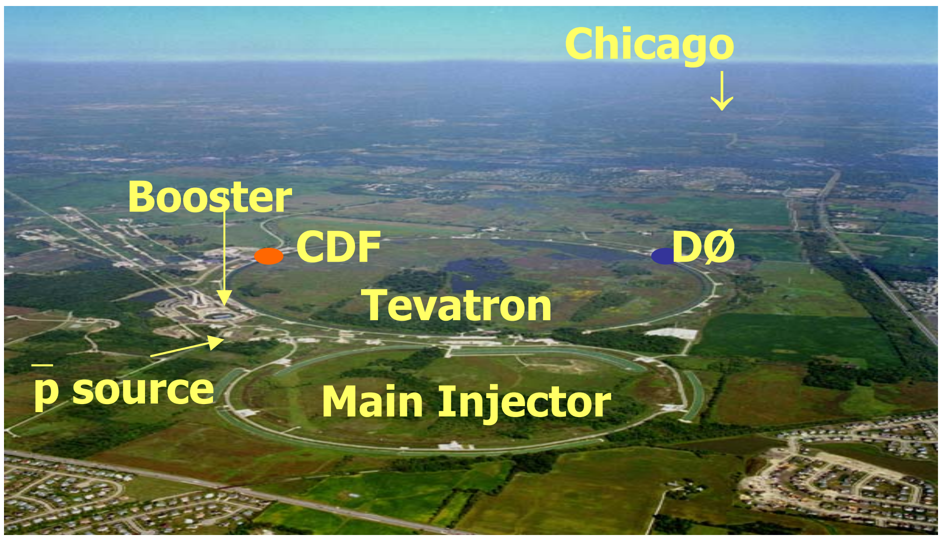
Outline:

- Introduction
- Motivation
- 1D measurement of W helicity fractions with 955pb^{-1} of data
- 2D measurement of W helicity fractions with 955pb-1 of data
- Summary

Top Production at the Tevatron

p-pbar collisions with 1.96TeV center-of-mass energy.

Until LHC turns on - the only place to study top quark



For top mass = 175 GeV

@ √s= 1.96 TeV :

$$\sigma_{t\bar{t}} = 7.3 \pm 0.5(stat.) \pm 0.6(syst.) \pm 0.4(lumi)\, pb$$

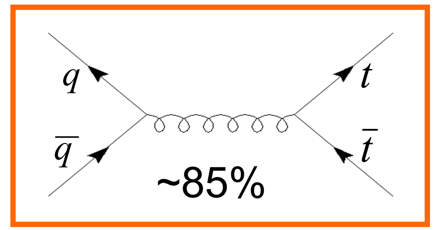
CDF combined

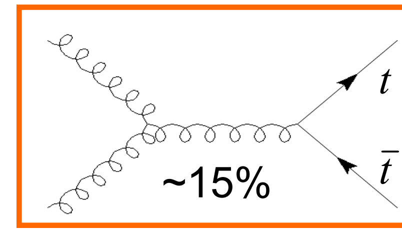
$$\sigma_{t\bar{t}} = 6.7 \pm 0.8\, pb$$

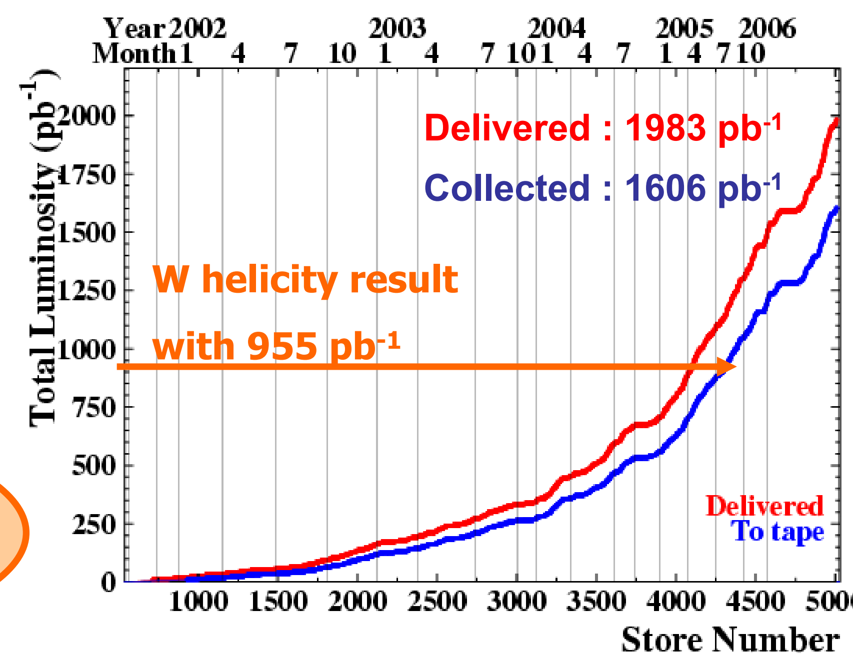
(theory)

Top pair production

Main mechanism for top physics at Tevatron







t-tbar Final States

Top decays before hadronizing

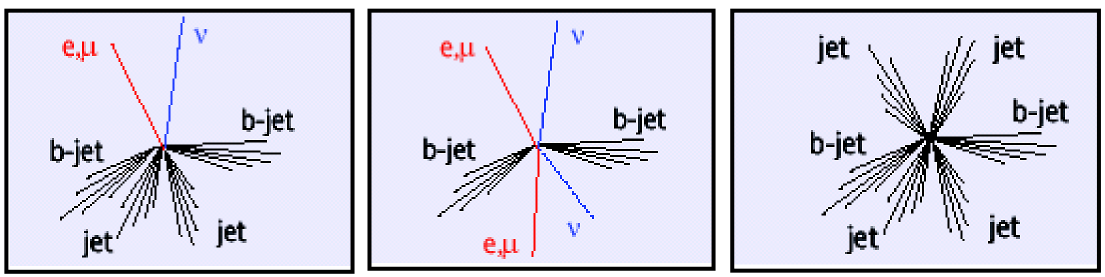
$\tau \sim 10^{-25}$ **s (due to large mass)**

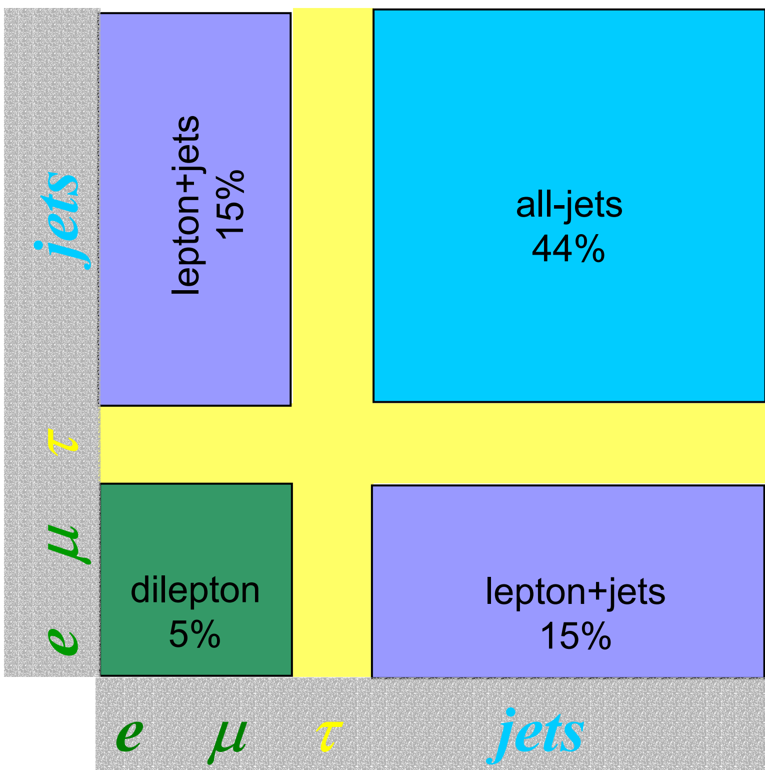
$V_{tb} \sim 1$**;** $M_{top} > M_W + M_b$**:**
Decays to real W

BR(t→Wb) ~ 100%

Final states are classified by the decay of the W's
BR(W→lν) = 1/3
BR(W→qq) = 2/3
In all cases, the final state has 2 b quarks

Lepton+jets Di-lepton All hadronic





Lepton+jets channel:

- **Best compromise → higher statistics than dilepton, less background than all-hadronic**
- **(S:B ~1:3)**
  →Increase S:B by using b-tagging

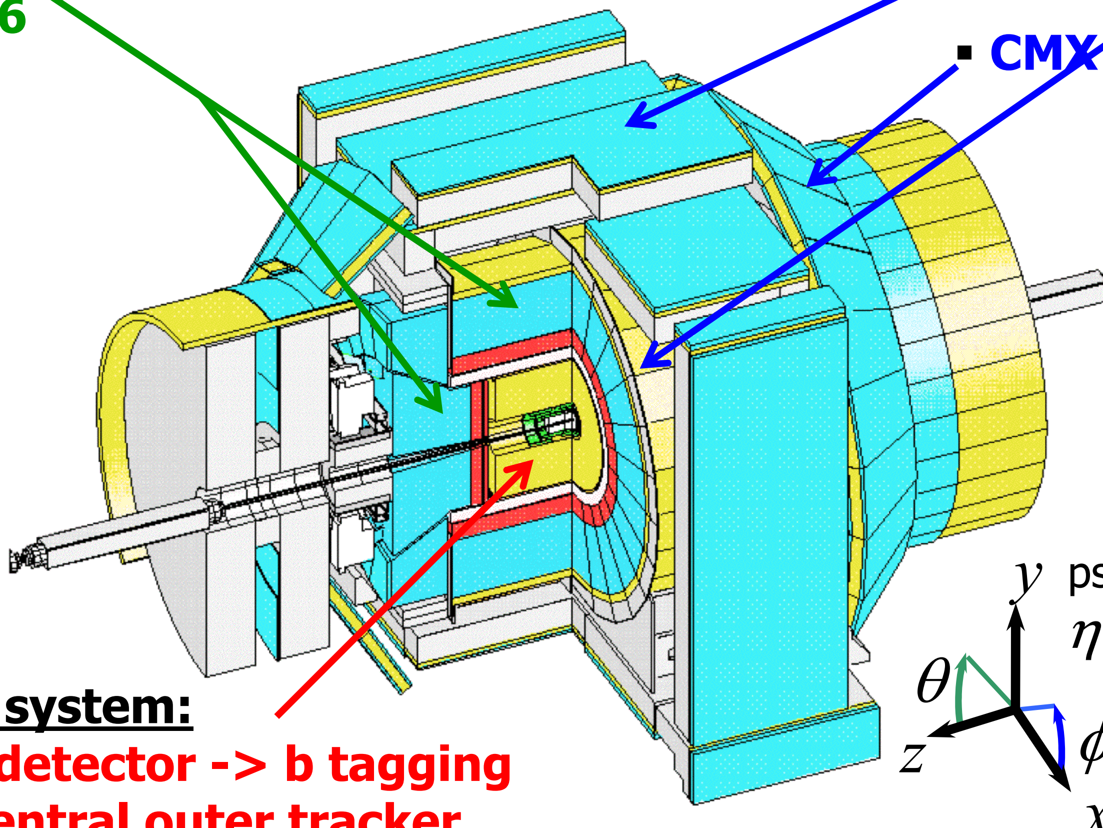
Fully reconstruct the event

The CDF detector

calorimeters
Up to |η|<3.6

Muon system

- CMP ; CMU |η|<0.6
- CMX 0.6<|η|<1.0



pseudorapidity

$$\eta = -\ln\tan(\theta/2)$$

Tracking system:

- Silicon detector -> b tagging
- COT : central outer tracker

Eff. for charged particle tracks:

- ~100% for |η|<1.0
- ~40% for |η|≈ 2.0

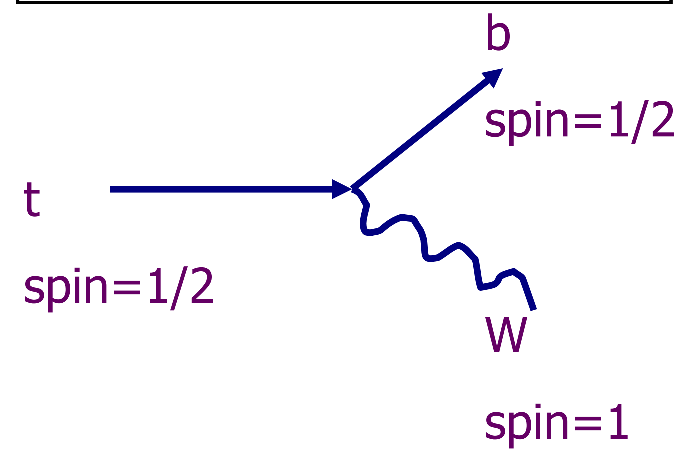
Excellent lepton ID:
~80% eff. for central electrons
~90% eff. for high Pt muons

W helicity in top quark decays

SM top decays via the weak interaction

→ V-A coupling like all other fermions:

$$\frac{ig}{2\sqrt{2}}\bar{t}\gamma^{\mu}\left(1-\gamma^{5}\right)V_{tb}bW_{\mu}$$



Helicity: $H = \vec{J}\cdot\vec{P}$

The longitudinal fraction:

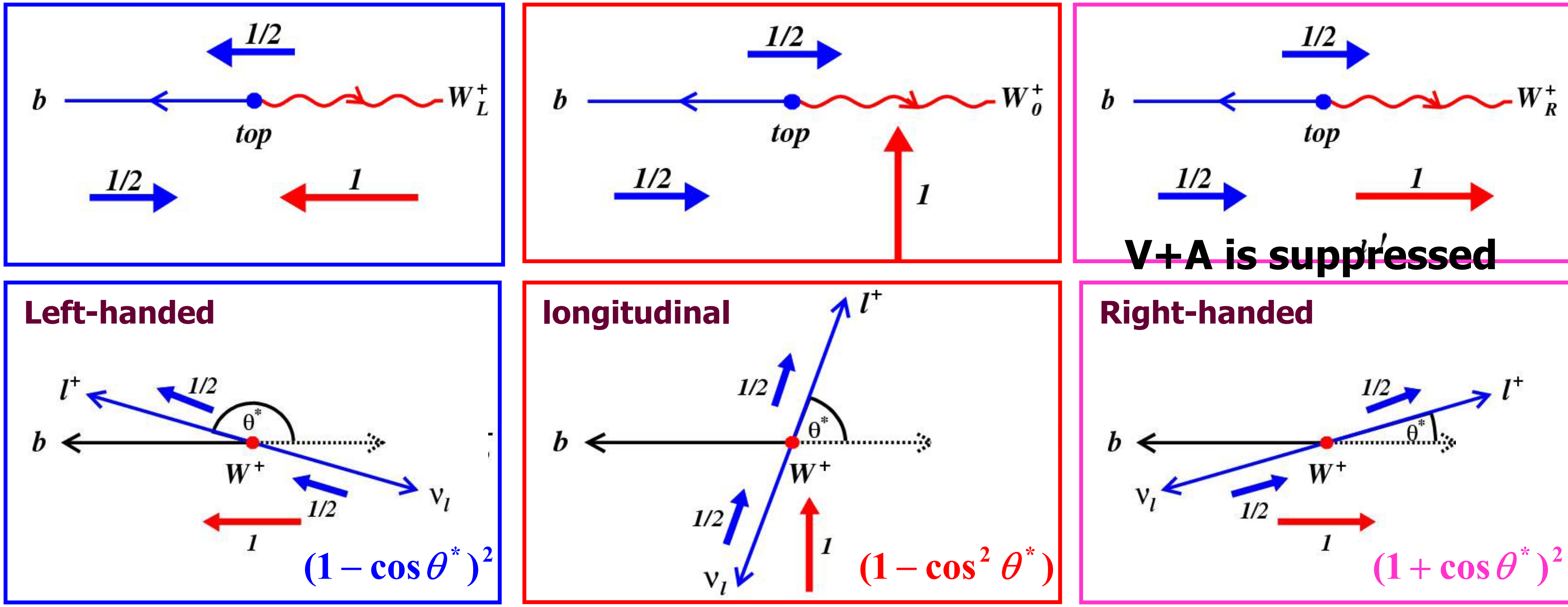
$$f_0 = \frac{\Gamma(W_0)}{\Gamma(W_0)+\Gamma(W_L)+\Gamma(W_R)}$$

$$f_0 \approx \frac{m_t^2}{2m_w^2+m_t^2}$$

This measurement:

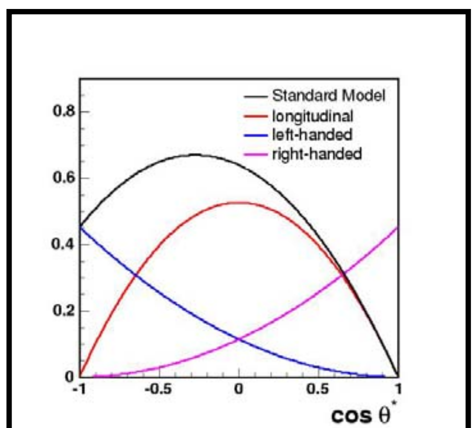
- **Test of the SM, non-zero V+A?**
- **EWSB – prediction of high longitudinal W fraction**

What do we measure ?



SM prediction of helicity fractions (assuming Mt=175GeV):

- **longitudinal f_0 = 0.7**
- **left-handed f_- = 0.3**
- **right-handed f_+ = 0**



We fully reconstruct the event:

$$\cos(\theta^*) = \frac{p_l \cdot p_b - E_l \cdot E_b}{|p_l||p_b|}$$

Analysis Overview

- **lepton+jets selection**
- **fully reconstruct the leptonic top decay using a kinematical fit and boost the charged lepton and the top into the W rest frame.**
- **calculate cos(θ*)**
- **construct templates for left-handed, right handed and longitudinal W's and background**
- **fit helicity fractions using unbinned likelihood fitter.**
- **correct for acceptance effects.**
- **estimate systematic uncertainties.**

Event Reconstruction

Selection main features:

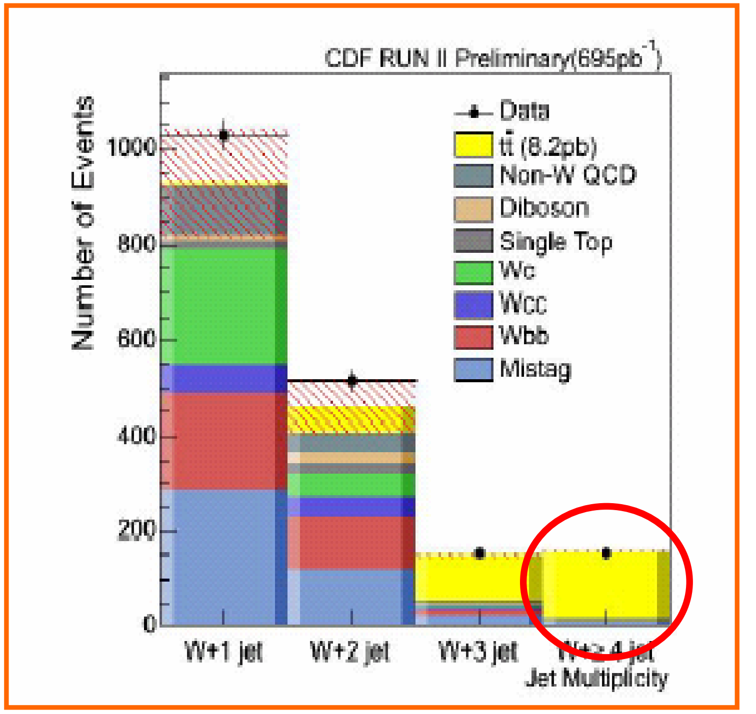
- only one isolated lepton with P_T >20 GeV
- at least 4 jets with E_T > 15 GeV and $|\eta|<2.0$ (JETCLU with $\Delta R=0.4$)
- scale jet energy to correct for both physics and detector effects
- missing E_T > 20 GeV
- at least one jet is tagged with a secondary vertex tagging
- veto on electrons from photon conversion
- veto on events tagged by cosmic ray tagger
- scalar sum of transverse energies of all reconstructed objects (Ht) > 200 GeV
- use kinematic fitter and choose combination with lowest χ^2

Selected Data Sample

Data 220 events (89% signal fraction)

Total background 22.8 events

Scaled to 955pb^{-1}



Background composition

Process		bkg fraction	events fraction
Mistag	9±1.35	39.5%	4.1%
W+h.f.	6.4±1.85	28%	2.9%
Single top	0.54±0.17	2.4%	0.25%
Diboson	1.36±0.07	6%	0.61%
QCD	5.5±1.08	24.1%	2.5%

The Likelihood

Used unbinned likelihood fitter to extract helicity fractions:

$$L = \underbrace{G(b \mid \mu_b, \sigma_b)} \cdot \underbrace{P(s+b \mid \mu_s + \mu_b)} \cdot \prod_{i=1}^{N_s} \underbrace{(f_b p_b(\cos\theta^*) + (1 - f_b) p_s(\cos\theta^*))}$$

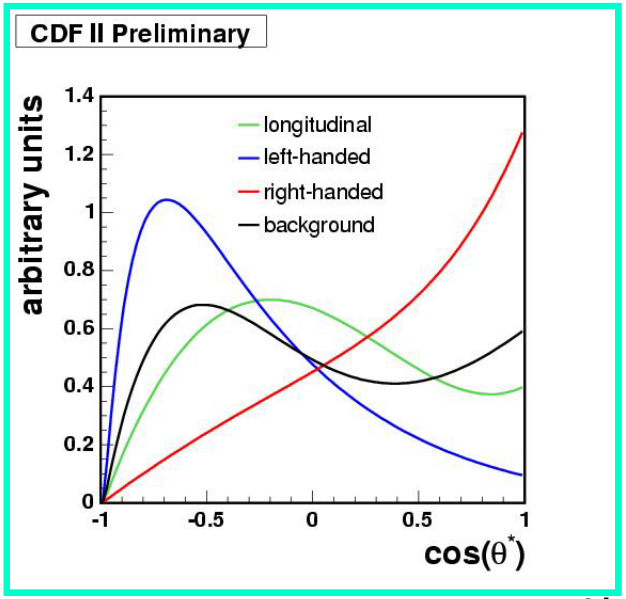
Gaussian bkg constraint

Poisson probability for number of observed events

shape information

$$p_s = F_0 p_0 + F_+ p_+ + (1 - F_0 - F_+) p_-$$

longitudinal (p_0), **right-handed** (p_+), **left-handed** (p_-)



Extract two results by fitting for:

F_0 while F_+=0

F_+ while F_0 is fixed to the SM value @M_t=175GeV

Acceptance Correction

α_i = acceptance for helicity i

F_0=measured fraction ; f_0= true fraction

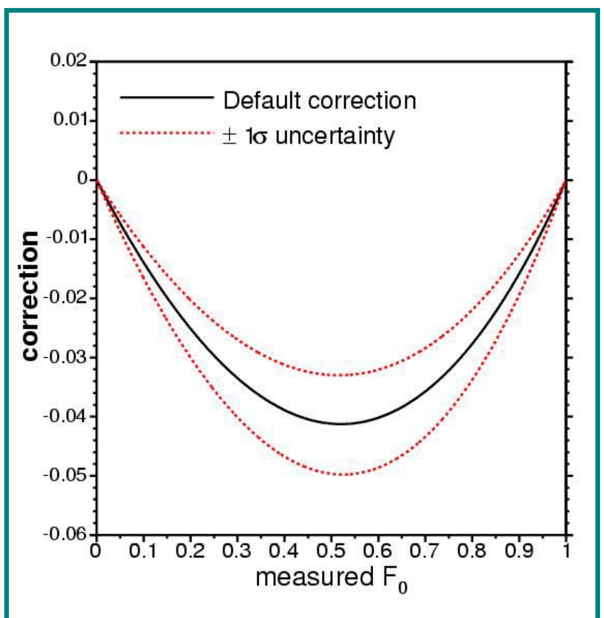
$$R = \frac{Acc.(left-handed)}{Acc.(longitudinal)} = \frac{\alpha_-}{\alpha_0}$$

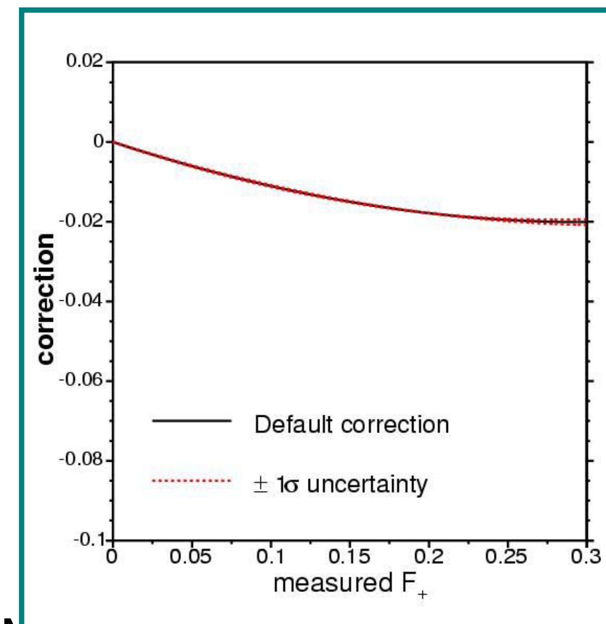
$$correction = \frac{F_0 \cdot (R-1) \cdot (1-F_0)}{1+F_0(R-1)}$$

$$F_0 = \frac{f_0}{R - f_0 \cdot (R-1)}$$

$$F_0 = \frac{\alpha_0 f_0}{\alpha_+ f_+ + \alpha_0 f_0 + \alpha_- f_-}$$

<u>for the right-handed fraction</u>:
Correction for f+ is very small (~0.01) → not applied.
Instead – assign a 1% systematic.





Systematic Uncertainties

We use realistic pseudo experiments to estimate systematic uncertainties while keeping the fit unchanged.

Source	δf_0	δf_+
Bkg model	±0.038	±0.017
JES	±0.013	±0.010
Signal model	±0.020	±0.010
PDF	±0.009	±0.006
ISR/FSR	±0.010	±0.005
MC statistics	±0.020	±0.010
Instantaneous luminosity	±0.007	±0.002
Lepton energy scale	±0.001	±0.002
Acceptance correction	±0.001	±0.001
Total syst.	**±0.053**	**±0.027**
Expected stat. uncertainty	**±0.12**	**±0.06**

Results – Data Fit

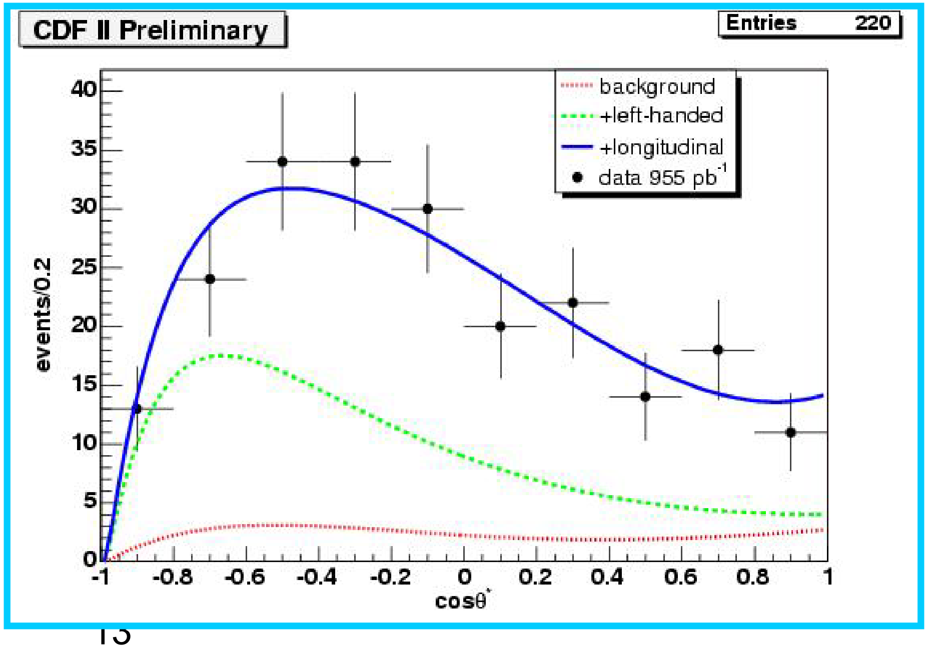
Fitting the data:

$F_0 = 0.65$ (measured)

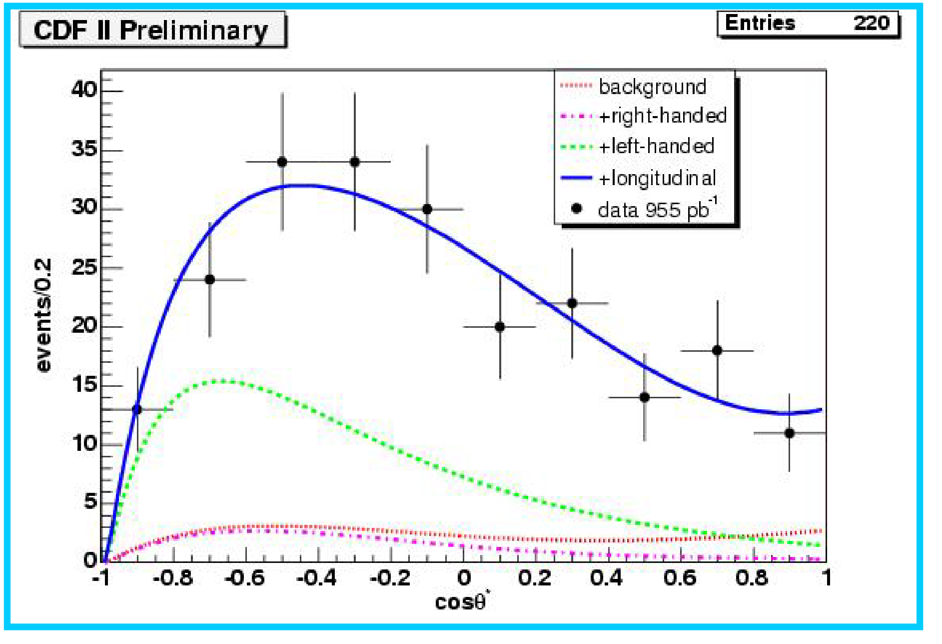
$f_0 = 0.60 \pm 0.12 \pm 0.06$, (corrected) $f_+ = 0$ fixed

$f_+ = -0.06 \pm 0.06 \pm 0.03$, f_0 fixed to SM value @Mt=175 GeV

Fit for longitudinal fraction

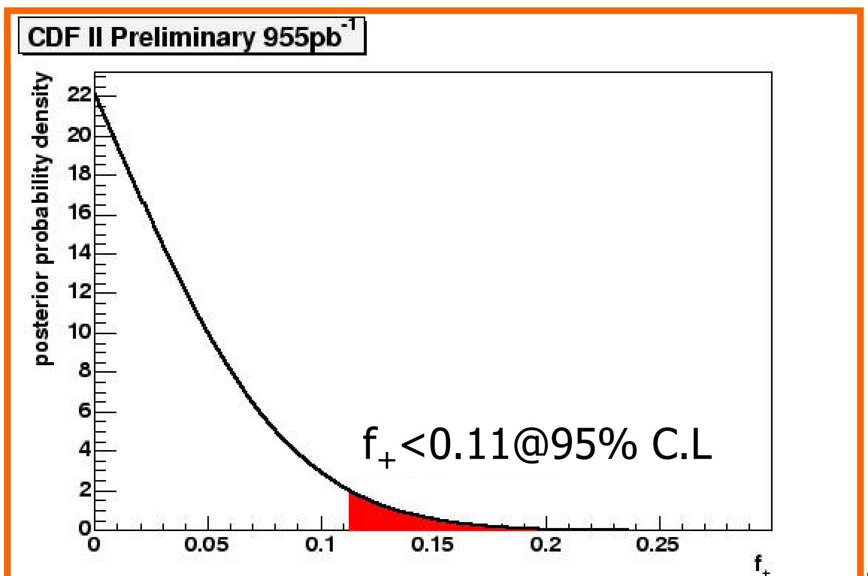


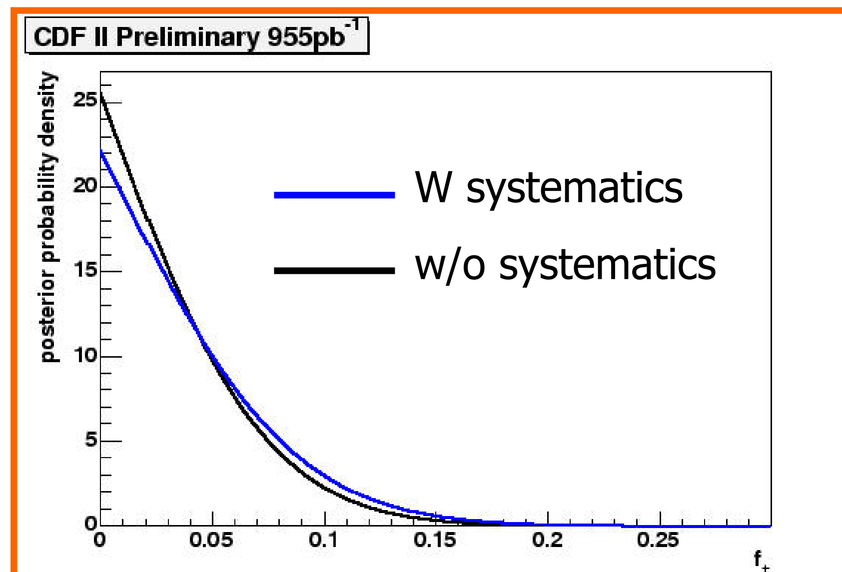
Fit for right-handed fraction



Results – Setting Upper Limit on f_+

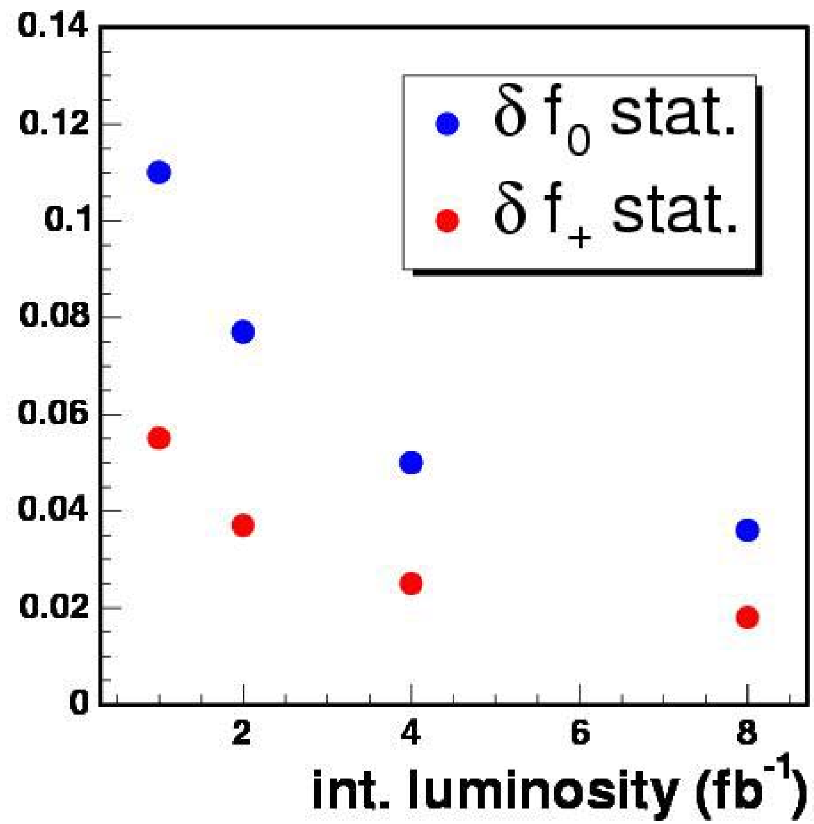
- Bayesian method for setting a limit@95% C.L:
- Model systematic uncertainties as a gaussian with $\mu=0$, $\sigma= 0.027$.
  - Have verified f_+ systematic independent of f_+
- Convolute with likelihood
  - as expected the effect is small, dominated by statistics.





Expected Statistical Uncertainty

- **Assuming no improvements, stat~syst with $4fb^{-1}$.**



2D Fit – First Simultaneous f_0, f_+ measurement !

With the increasing luminosity:

- **Interest in a model independent measurement**
- **V+A coupling bounded by CLEO b→sγ data at a level that cannot be reached even at the LHC.**
- **No assumption on helicity fractions while fitting, probe any deviation from SM (super-symmetry, dynamical electroweak symmetry breaking models, Extra dimensions ….)**

★ **Same data, same reconstruction, same templates etc.** ★

fit for f_0 and f_+ simultaneously, rather than:

- **Fixing f_+ to 0 (=SM) and fitting for f_0**
- **Fixing f_0 to 0.7 (=SM) and fitting for f_+**

---> Less precision, but a more general result

Uncertainties for Simultaneous Fit

source	δf_0	δf_+
Jet Energy Scale	±0.015	±0.008
Background	±0.037	±0.015
ISR/FSR	±0.010	±0.005
Signal Monte Carlo	±0.020	±0.010
MC statistics	±0.020	±0.010
Method	±0.010	±0.010
PDF	±0.009	±0.006
Instantaneous Luminosity	±0.007	±0.002
Total Systematic	±0.053	±0.026
Statistical	±0.246	±0.096
Total Uncertainty	±0.252	±0.099

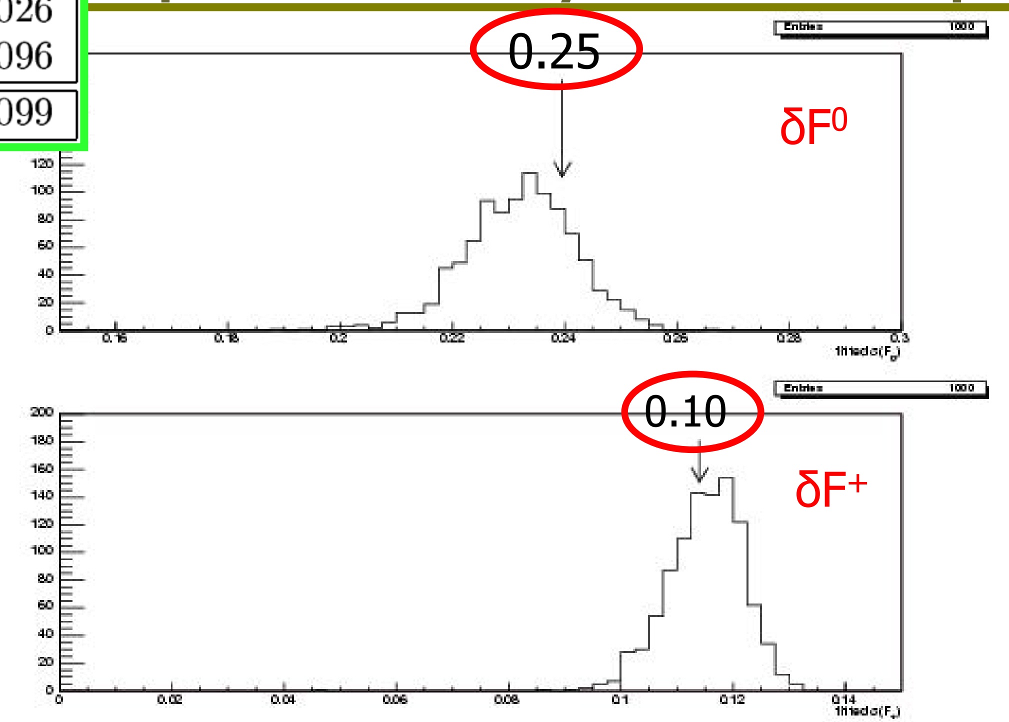
Systematics

Compared with 1D fit –

±0.053 for f_0

±0.027 for f_+

Expected sensitivity from 1000 SM p.e:



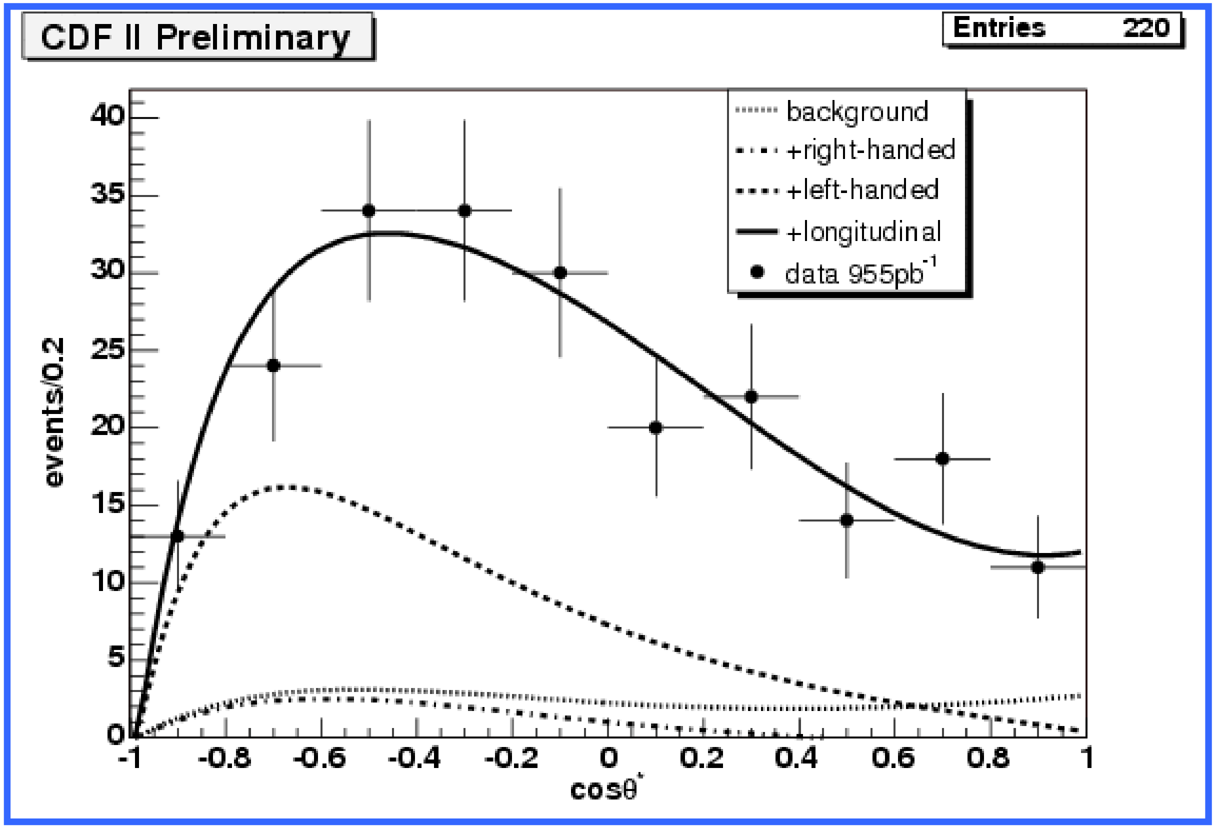
statistical

Compared with 1D fit –

±0.12 for f_0

±0.06 for f_+

2D Fit Results



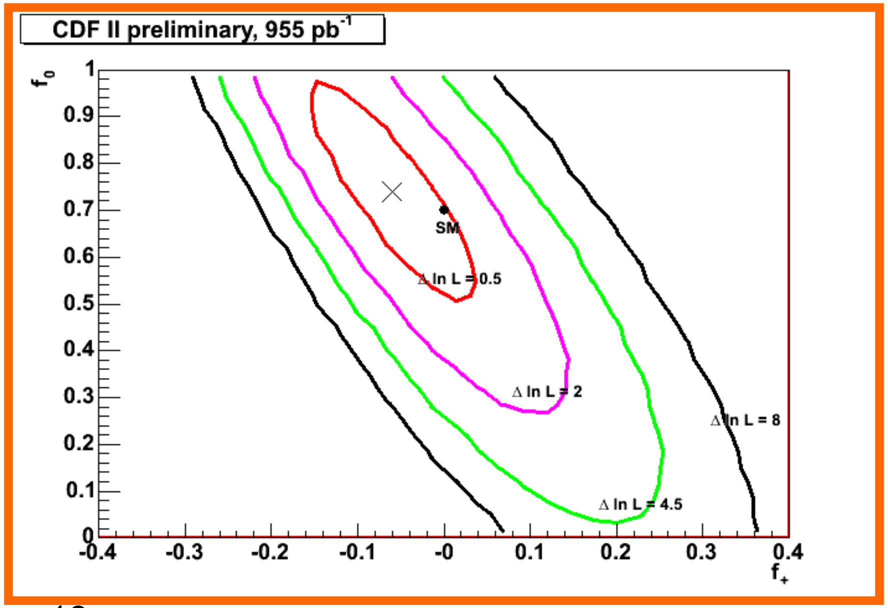
$$f_0 = 0.74 \pm 0.25(stat) \pm 0.06(syst)$$

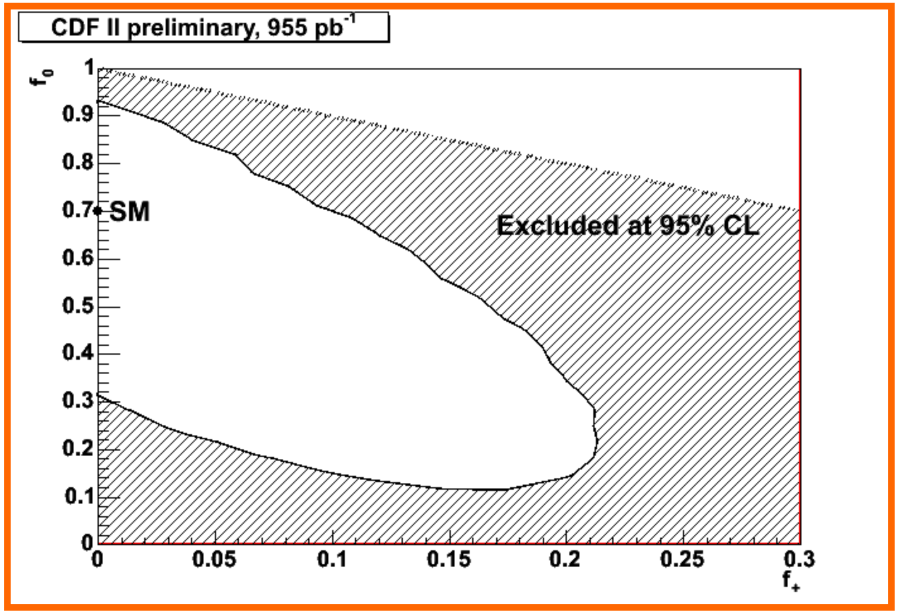
$$f_+ = -0.06 \pm 0.10(stat) \pm 0.03(syst)$$

Limit on f_+?

- **Form probability surface**
- **Find contour of constant probability that captures 95% of the volume under the surface**
- **No systematics in likelihood shape.**

but for 2D fit: stat $\oplus$ syst = stat





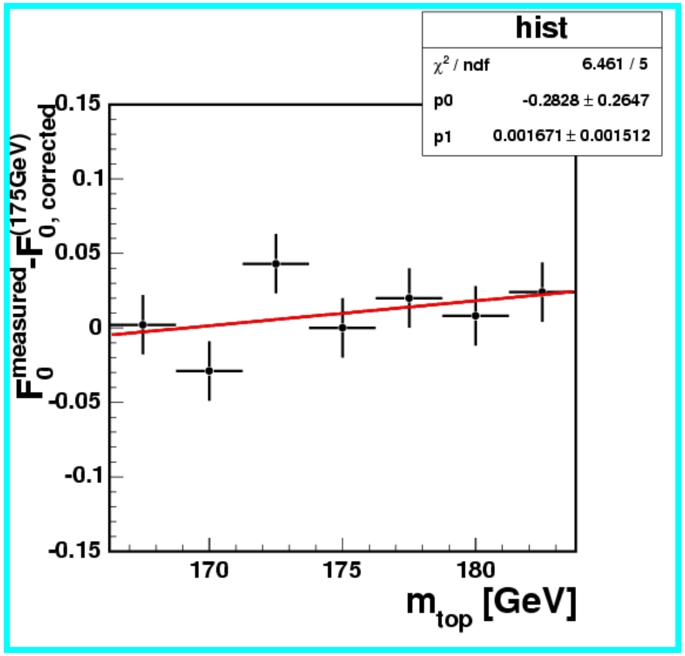
Summary

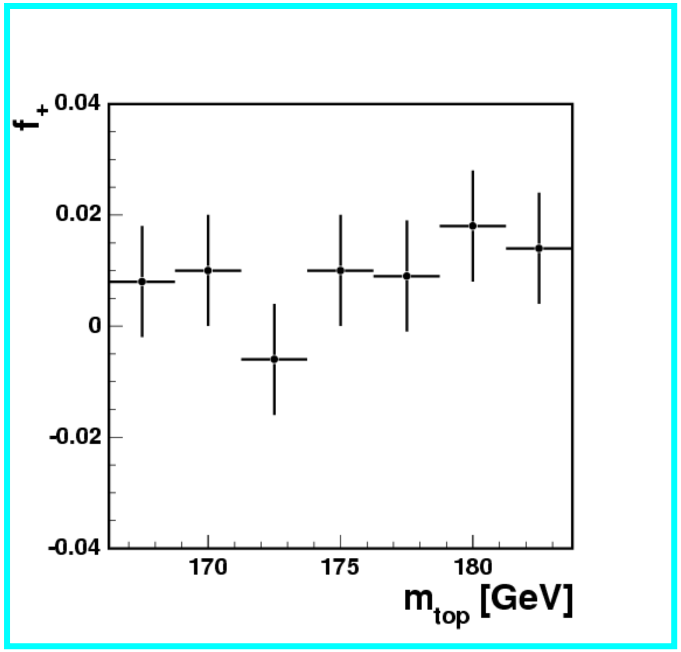
- **Improvement of CDF 1D results of longitudinal and right handed W fractions.**
- **First simultaneous measurement of right-handed and longitudinal W helicity fractions!**
- **Our knowledge of *t-W-b* vertex is still statistically limited.**
- **CDF now factor of 2 better than previous measurements.**
- **However still factor of 2 above current systematics -**
  This is worth doing as a 4 fb-1 analysis on CDF.
  When our errors are dominated by systematics and as long as LHC does not have sys. uncertainties <~10%, the Tevatron results will be hard to beat!
- **Measurement consistent with SM predictions – top decay is of V-A nature.**
- **Other CDF measurements using M_{lb} method and cos(θ*) have been performed and results agree with SM predictions.**
- **winter plans – improve method and use more data, combine measurements and publish results.**

Back up slides

Top Mass Dependence

- Top mass is not constrained in this analysis.
- Fit to a linear function yields a correction of 0.5% for a 1σ variation of the top mass (3 GeV).



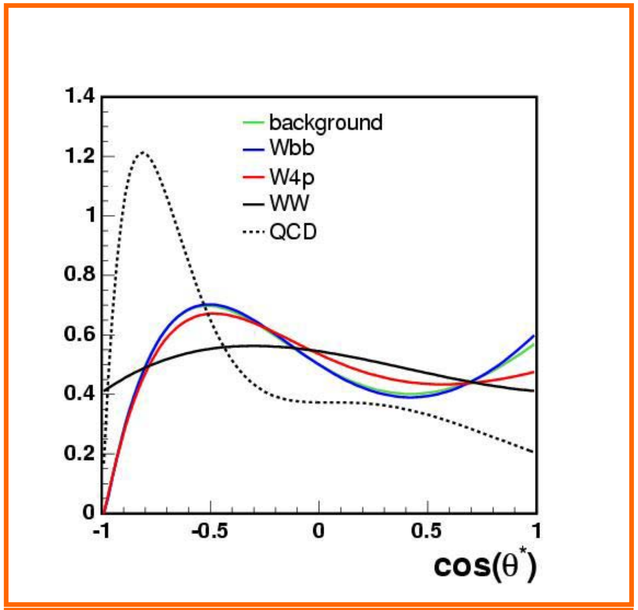


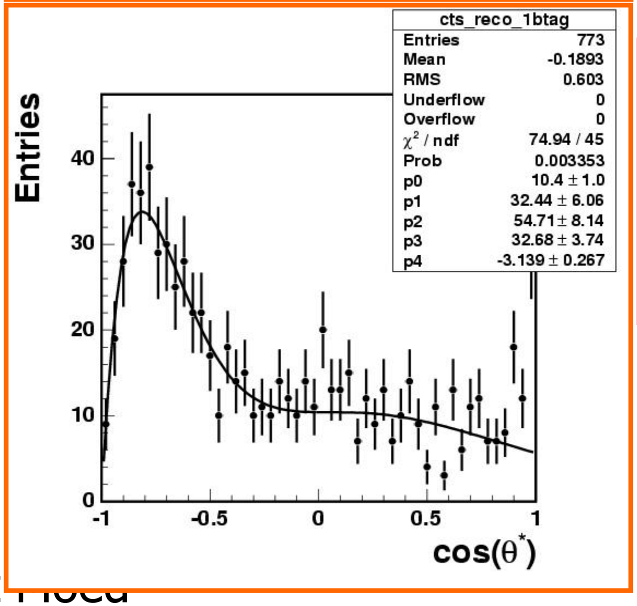
Systematic Uncertainties – Background

Background shape systematic:

- **Assume 100% W4p or 100% Wbb2p**
- **Add 25% special QCD sample**

Vary q2 for W sample





Special QCD sample Multi-jet trigger

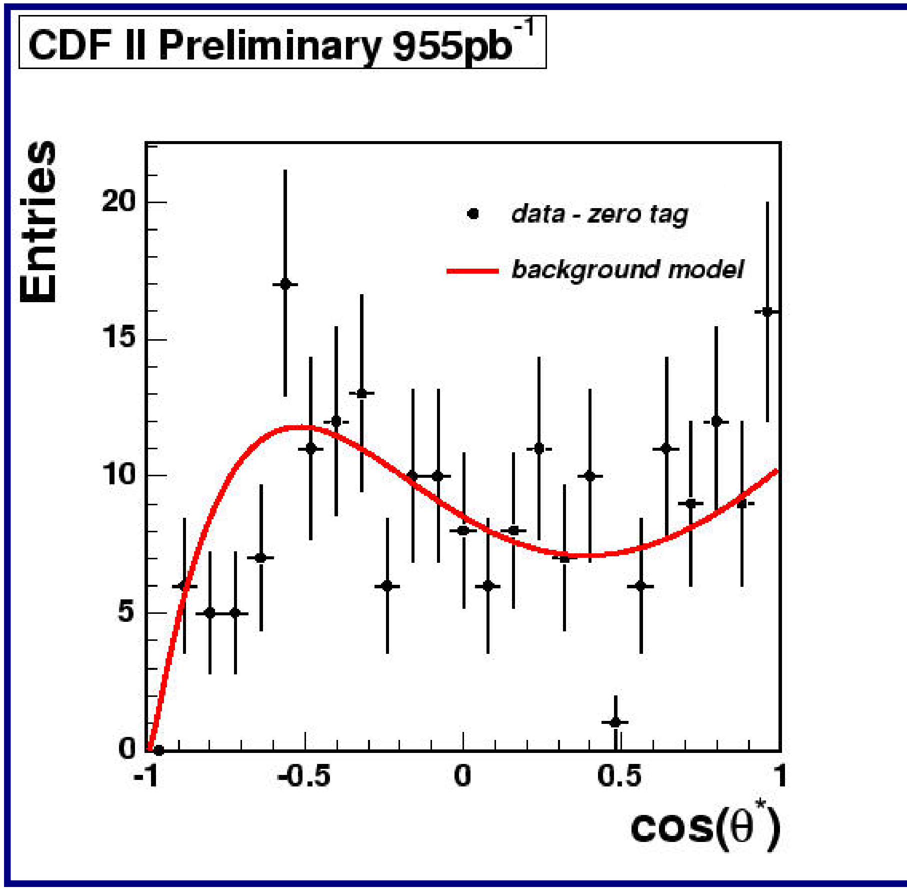
0.8<em<0.95

Ntracks>3

reminder - estimated ~5 QCD events out of 220

Background Dominated Samples

Comparison of 0-tag sample and bkg model

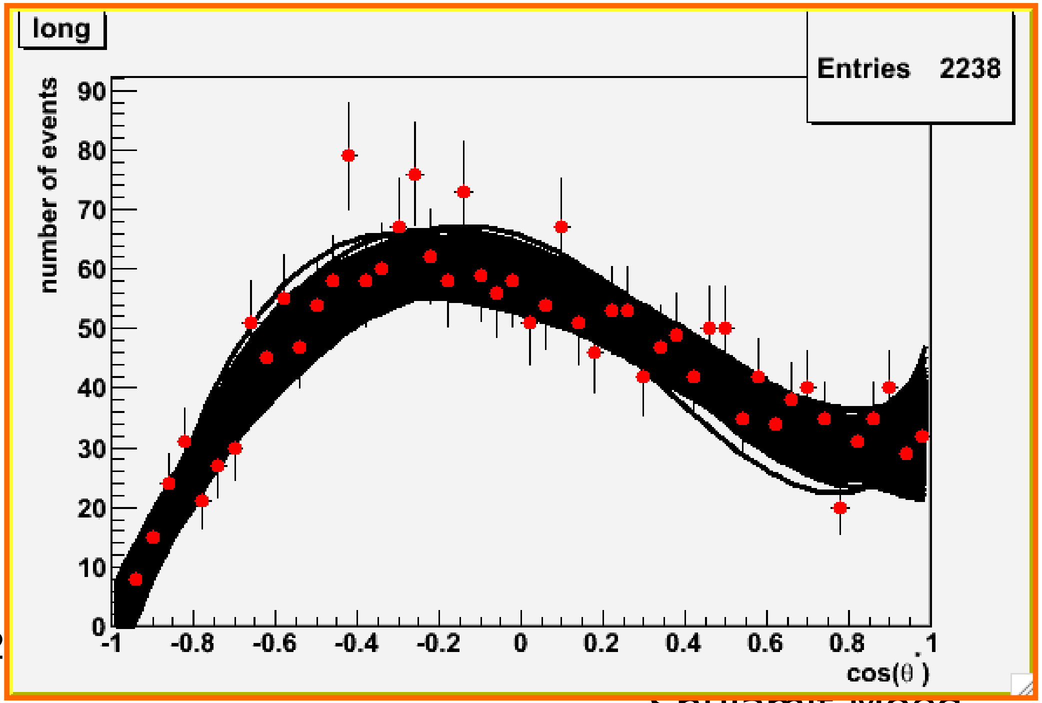


→ We have a reasonable background model

Systematic Uncertainties – MC Statistics

Statistical uncertainty of the parameterizations is not propagated through the analysis → systematic uncertainty:

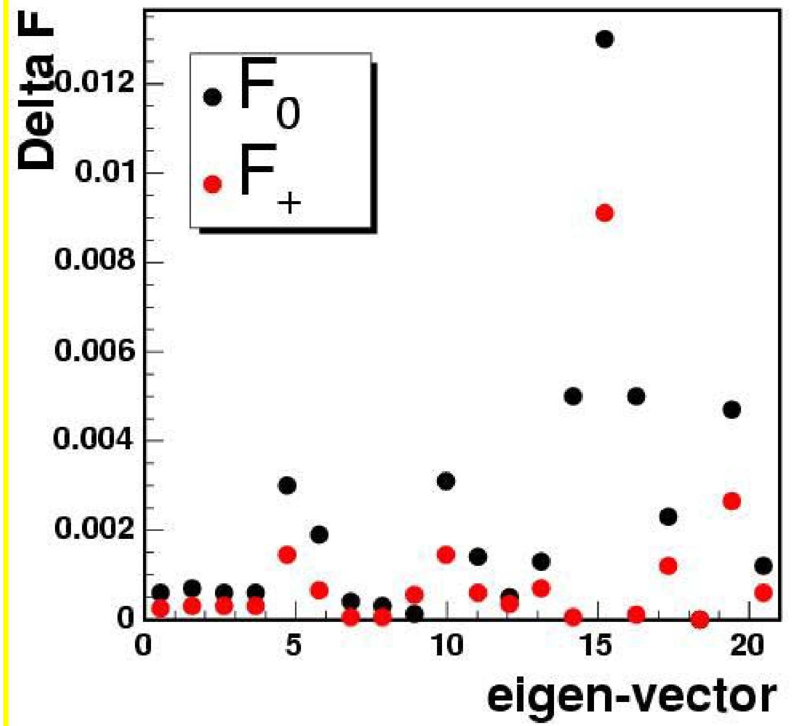
- Re-fitting templates 1000 times, Poisson fluctuate the bins around central value.
- Draw pseudo-experiments from the different fits.
- Take difference in RMS of fitted values as a systematic :



$\delta f_0 = 0.02$ $\delta f_+ = 0.01$

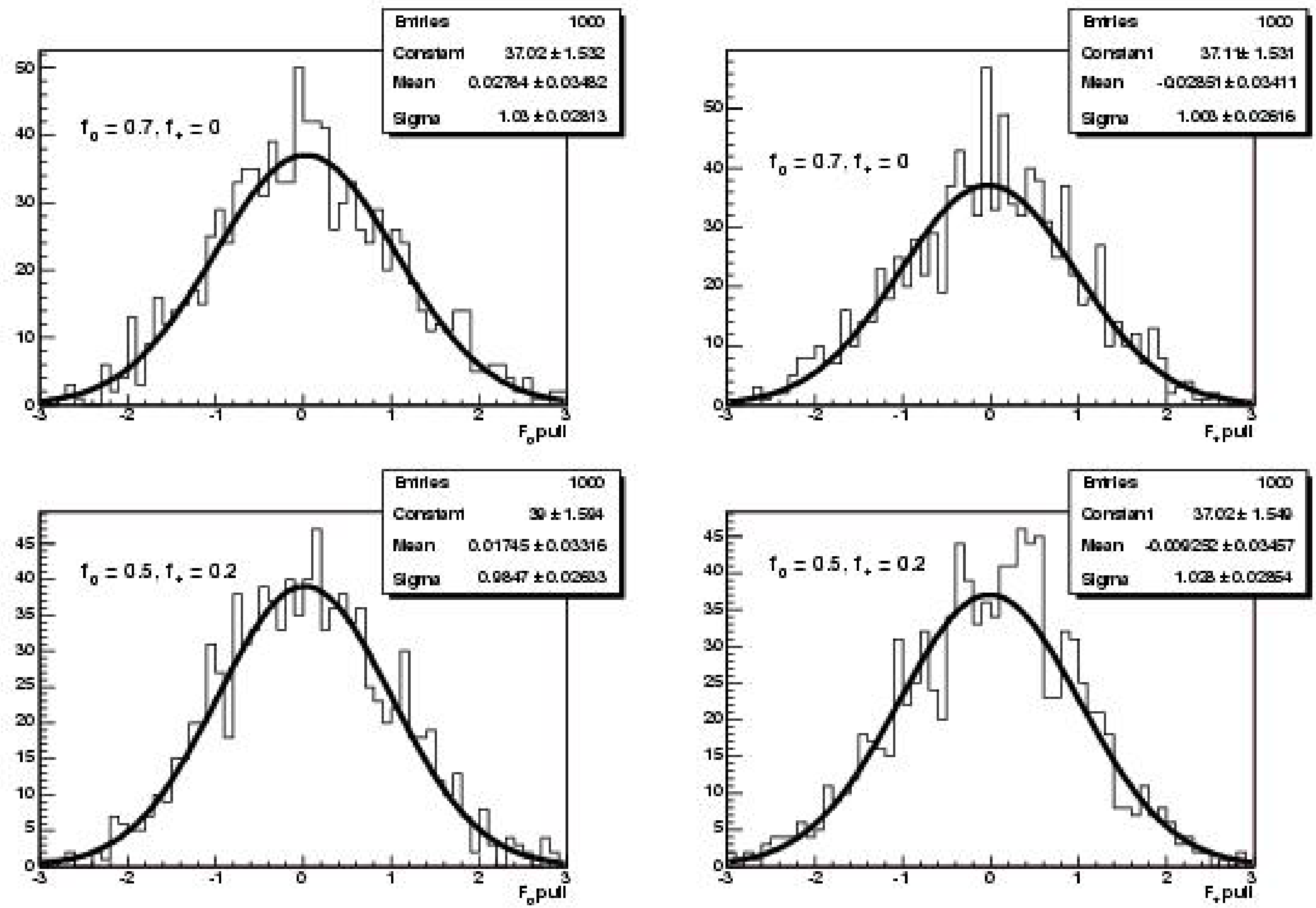
Systematic Uncertainties - PDF

- difference between MRST72 and CTEQ5L.
- difference between MRST75 and MRST72.
- variation of the 20 CTEQ6M eigenvectors.

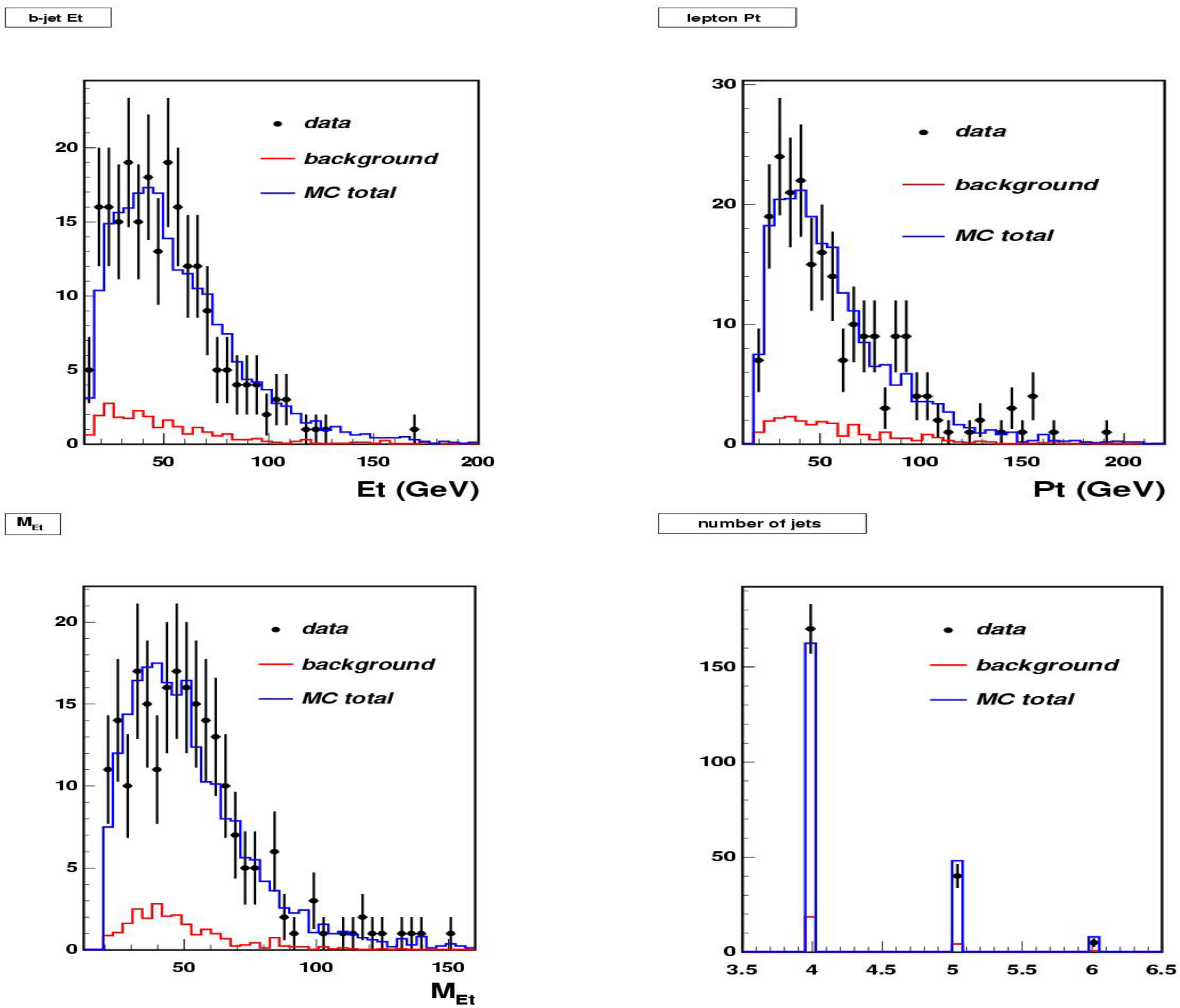


$$\Delta F = \frac{1}{2}\left(\sum_{i=1}^{20}[F(S_i^+) - F(S_i^-)]^2\right)^{1/2}$$

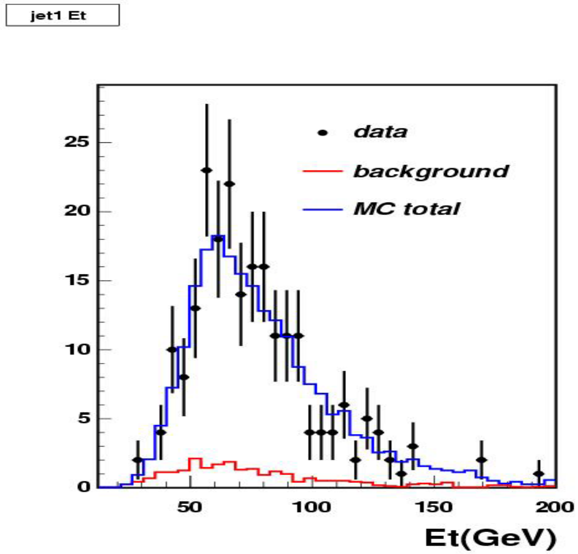
2D Pull Distributions

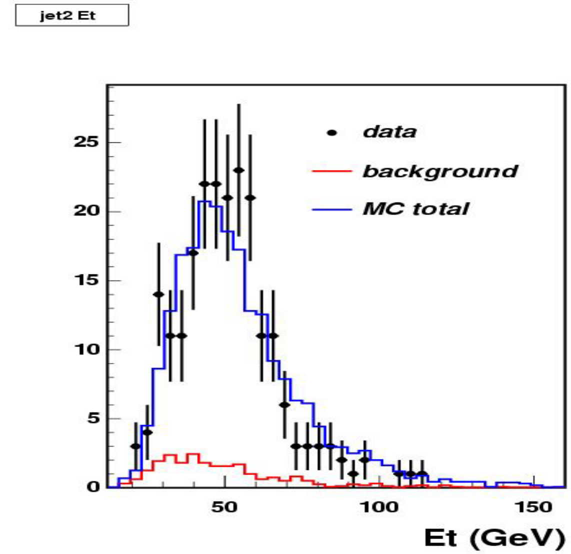


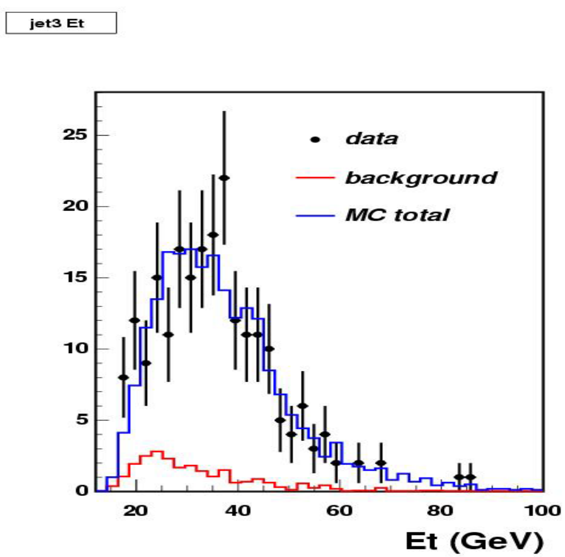
955pb^{-1} – Data/MC Comparison

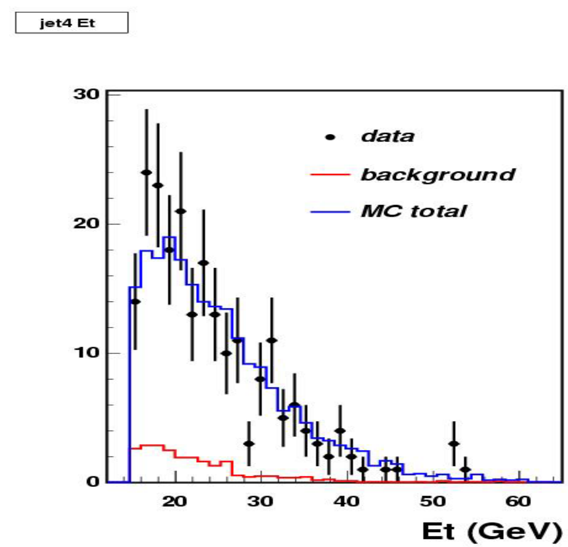


955pb-1 – Data/MC Comparison



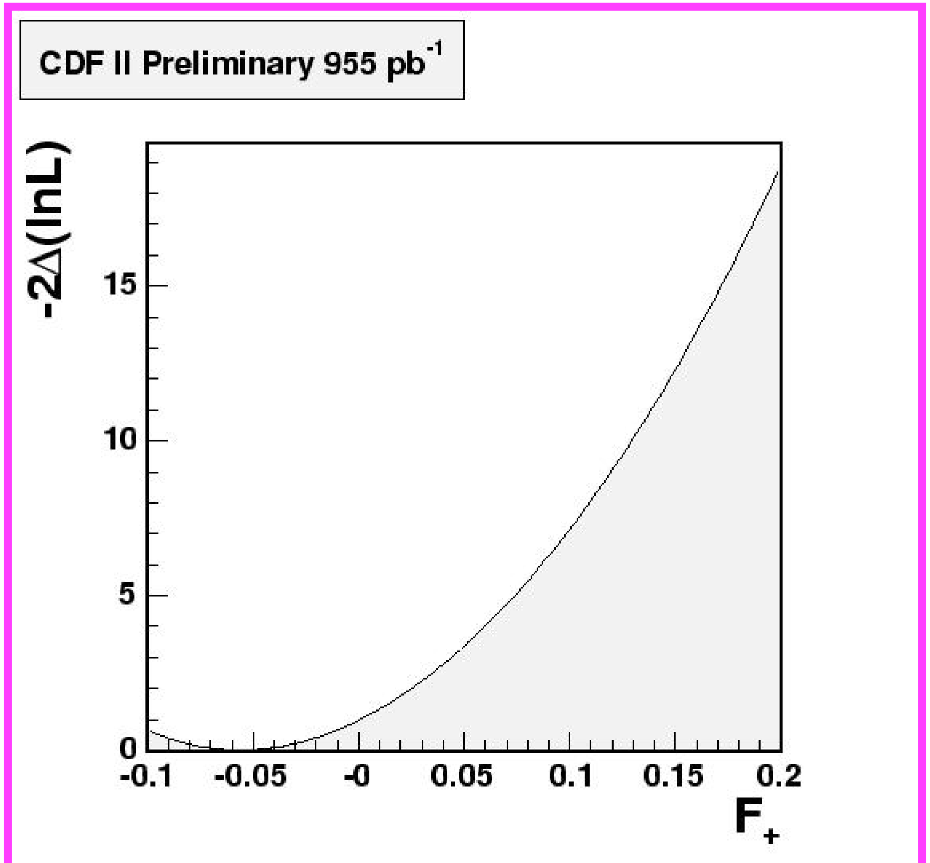




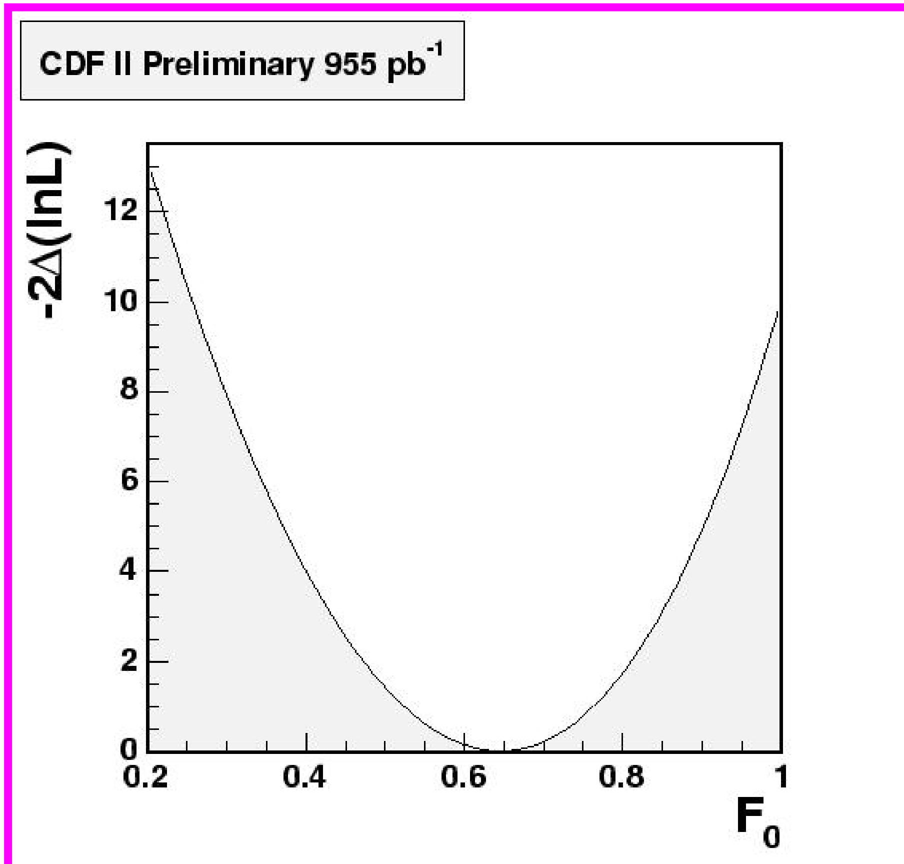


Results - Likelihood Curves

For right-handed fraction

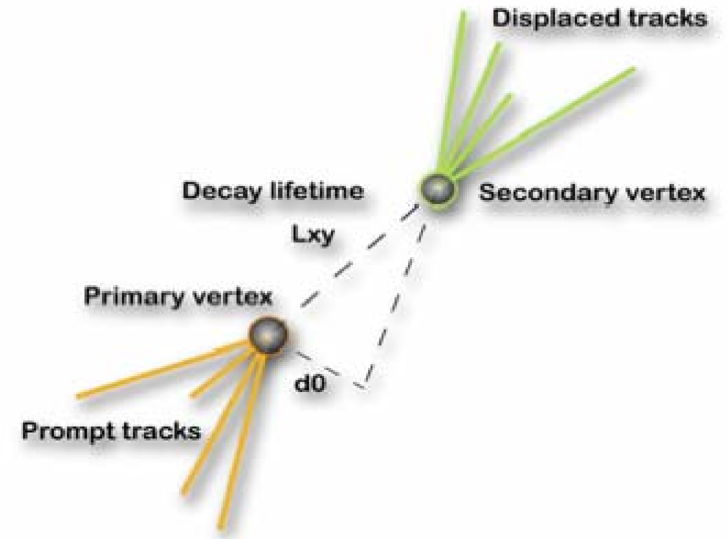


For longitudinal fraction

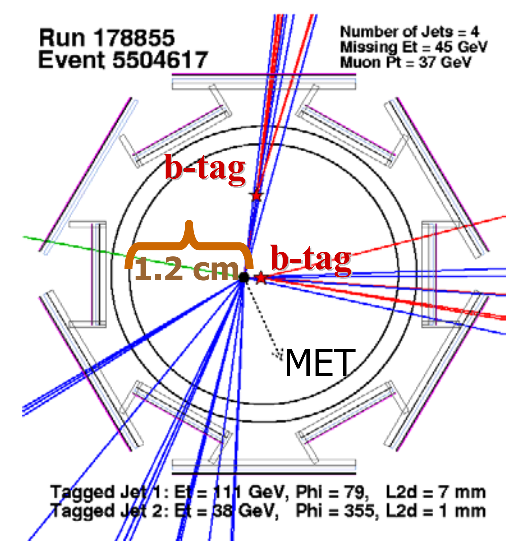


b-jet Tagging

- **Expect t → W b**
  b jet tagging is a very important tool.
  - Every ttbar event contains 2 b-jets
  - Less than 20% of the dominant background (W+jets) contains Heavy Flavor (b/c quarks)
- **B decay signature: displaced vertex**
- **Long life time $c\tau \sim 450\ \mu m$: travels $L_{xy} \sim 3mm$ before decaying**



CDF Event:
Close-up View of Layer 00 Silicon Detector



Require at least 1 jet tagged with the secondary vertex tagging algorithm.

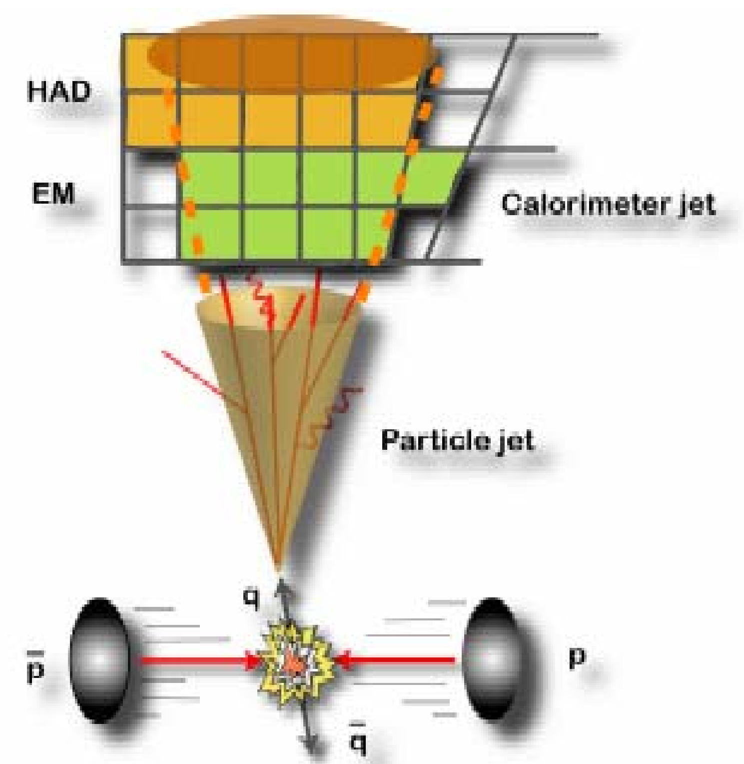
Reduce permutations from 24 to 12!

Jet Energy Scale

Corrections applied to estimate the original parton energies from the observed jet energy in the calorimeter

Jets are corrected for:

- **η dependence correction – homogenous calorimeter response.**
- **subtraction of energy due to pile-up of multiple interactions in the same bunch crossing.**
- **correction for non-linearity and energy loss in the uninstrumented regions of the detectors.**
- **Underlying event energy that falls inside the jet cone.**
- **Jet energy radiating out of the jet cone.**
- **Top specific corrections – flavor and topology of ttbar events.**

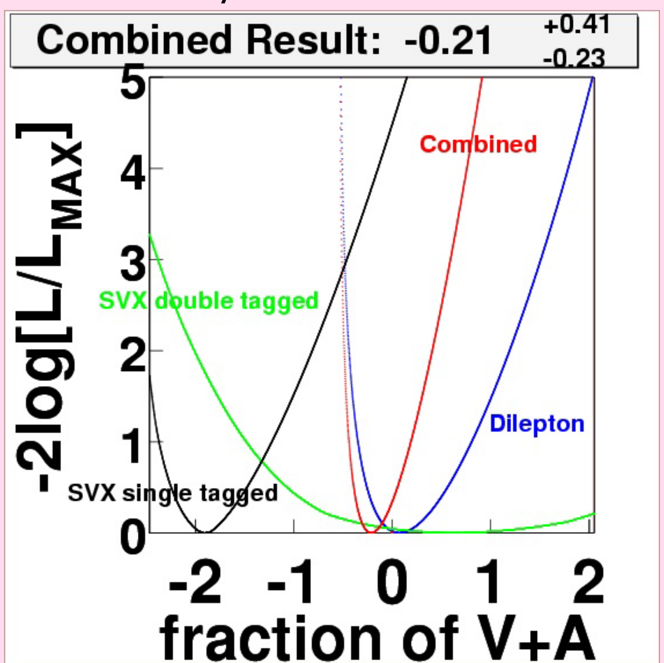


Other W Helicity Measurements

Previously at CDF

RunI $(M_{lb})^2$:

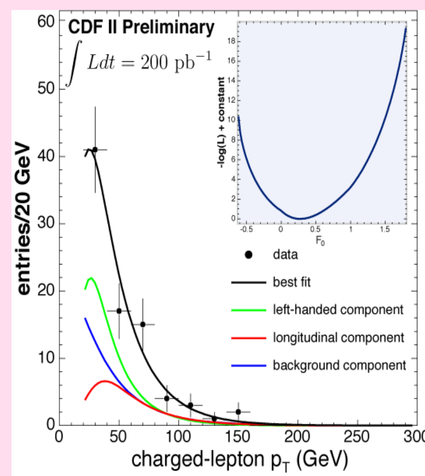
Integrated luminosity= $(109 \pm 7)\, pb^{-1}$

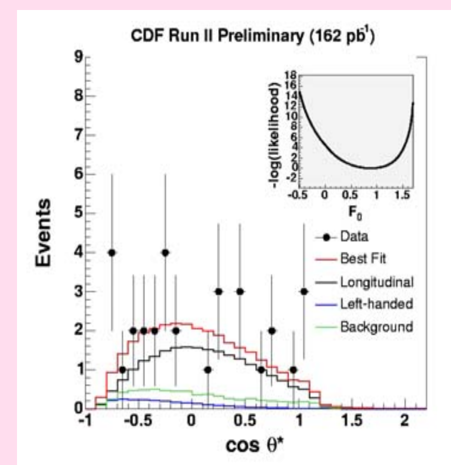


Early RunII:

$$F_0 = 0.74^{+0.22}_{-0.34}$$

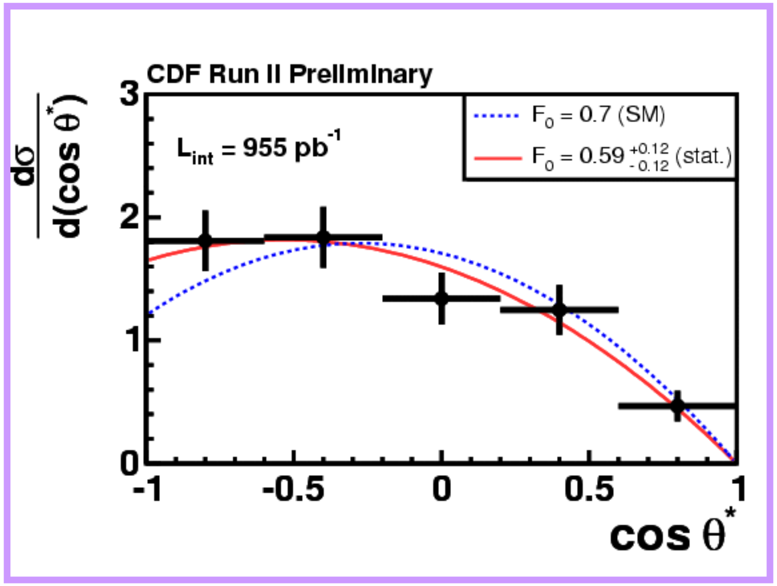
$$F_+ < 0.27 @ 95\% \;\; C.L$$





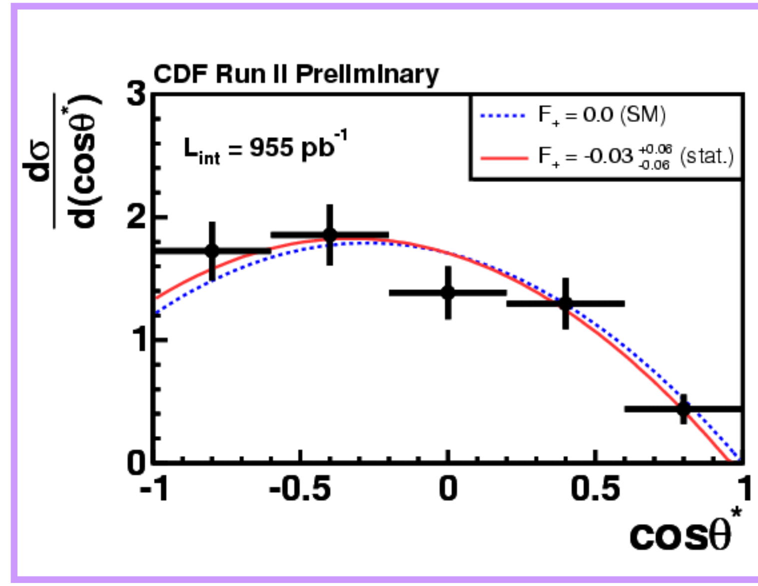
cosθ* (T. Chwalek, D. Hirschbuehl, T. Muller, J. Wagner, W. Wagner) - results

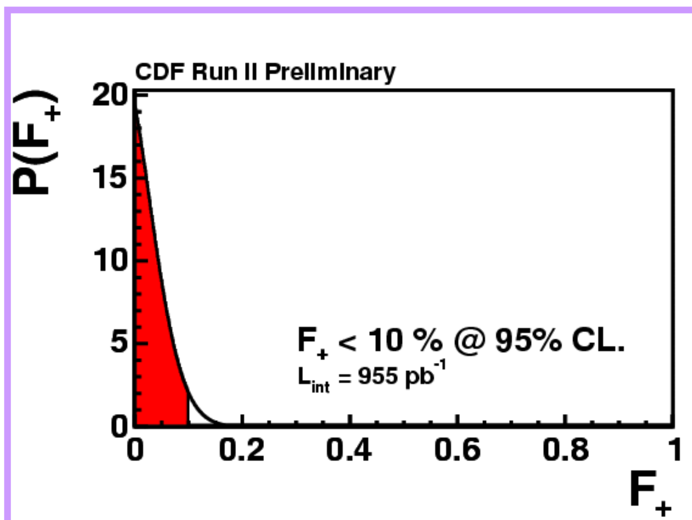
longitudinal fraction



unfolded distributions

right-handed fraction





limit on right-handed fraction