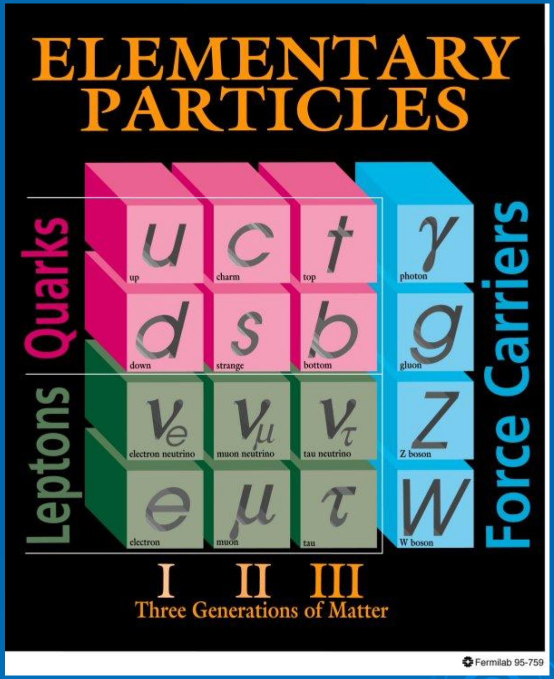
Probing the tWb Vertex: Tevatron Results on Measurement of W-Boson Polarization in Top-quark Decay

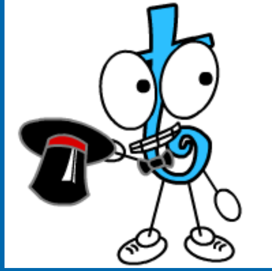
Mousumi Datta
Fermi National Accelerator Laboratory
Hampton University, February 28, 2012

Top Quark Physics

- Existence required by the SM
  - Spin 1/2 fermion, charge +2/3, weak-isospin partner of the bottom quark
- Discovered in 1995 at Tevatron
- Mass surprisingly large ⇒ ~40x heavier than the bottom quark
  - Only SM fermion with mass at the EW scale
- Top decays before hadronization: $\Gamma \sim 1.4$ GeV $\gg \Lambda_{QCD}$
  - Provide an unique opportunity to study a "bare" quark

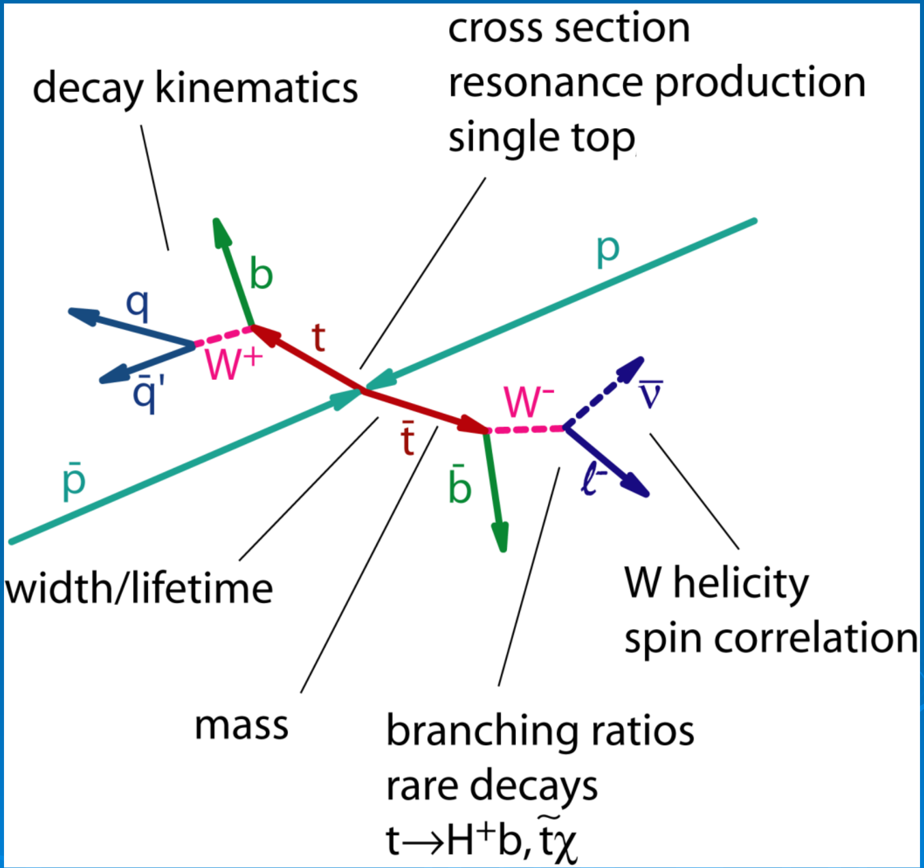


Why Study Top Properties?



Try to address some of the questions:

- Why is top so heavy ?
- Is top related to the EWSB mechanism?
- Is it the SM top?
- Search for beyond SM physics
  - Does top decay into new particles?
  - Couple via new interactions?



Top Quark Pair Production

- At Tevatron top quark predominantly pair produced via strong interaction

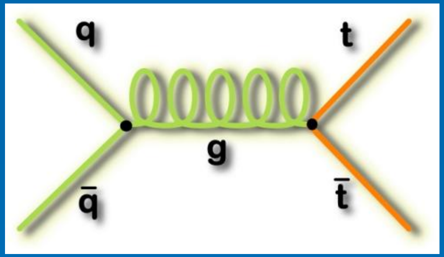
σ_{tt} = 6.8 pb for m_{top}=175 GeV/c^2

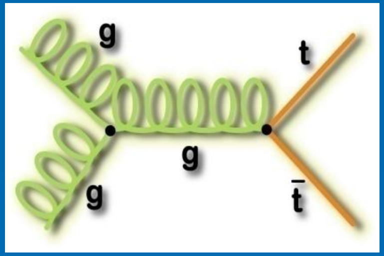
(JHEP 0404:068 (2004), PRD 68, 114014 (2003))

~85% from qq→tt

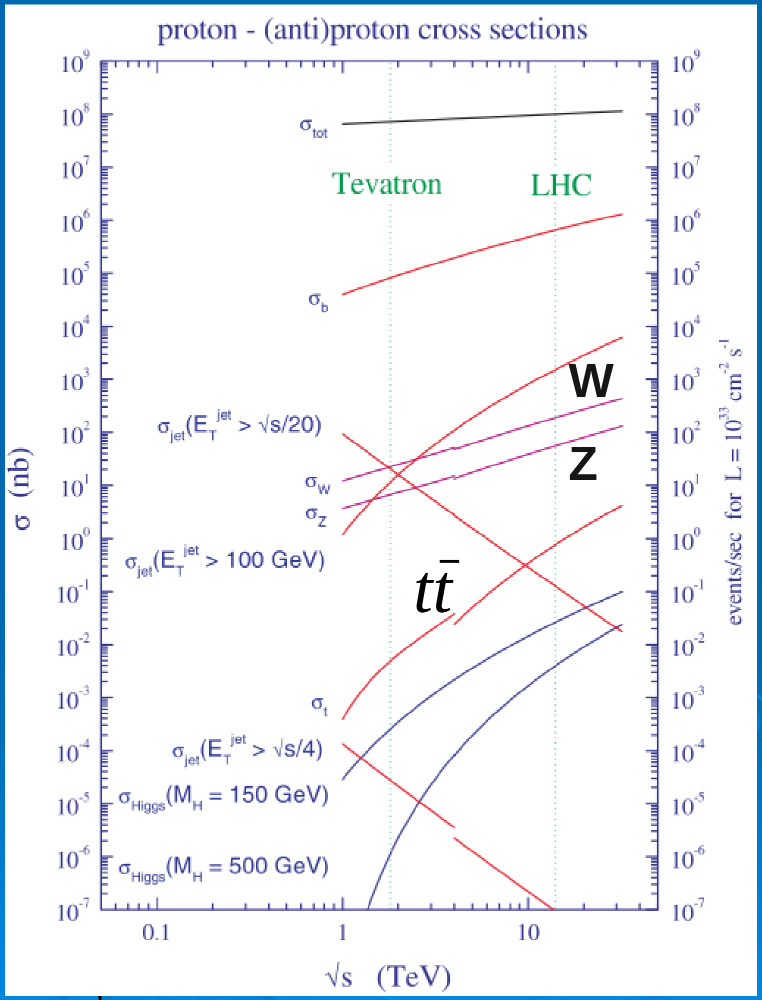
~15% from gg→tt

Pair Production:

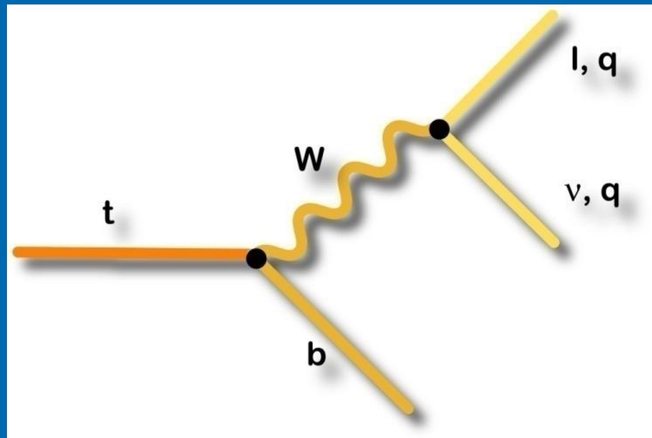




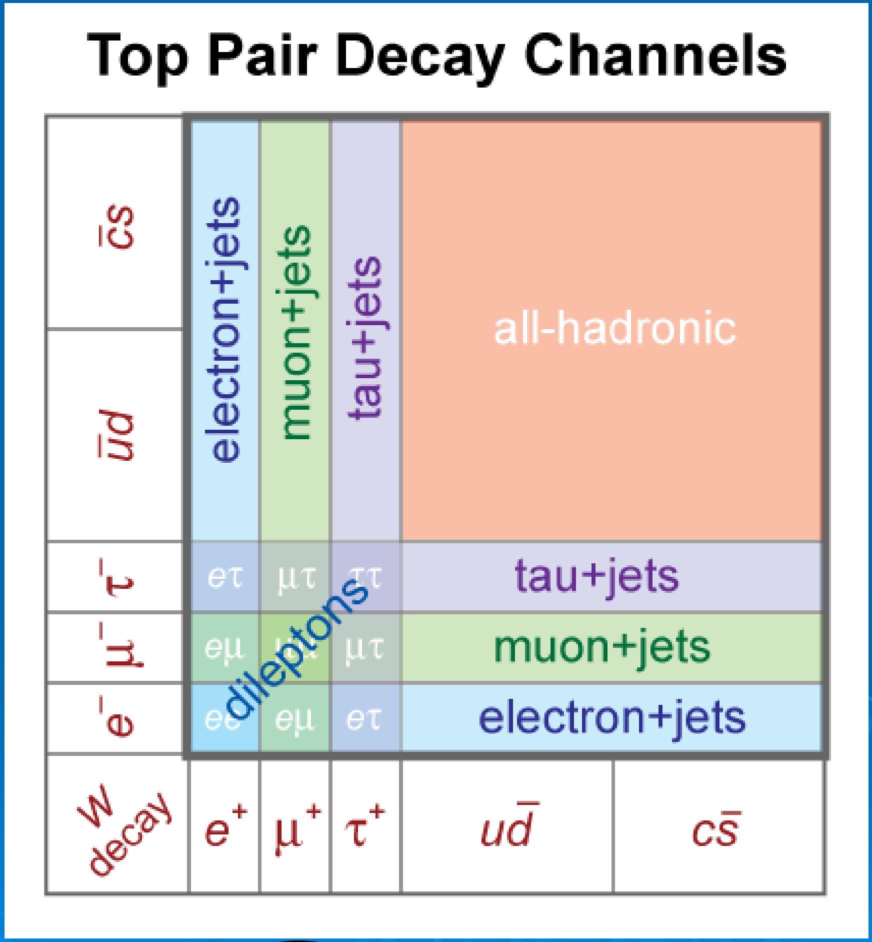
Rare at Tevatron: One top pair (ttbar) per 10 billion inelastic collisions



Top Quark Decay

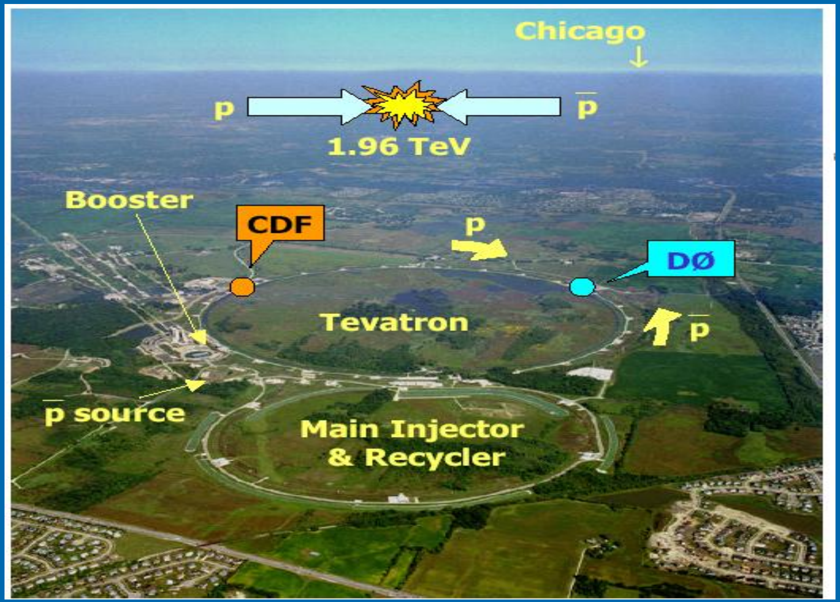


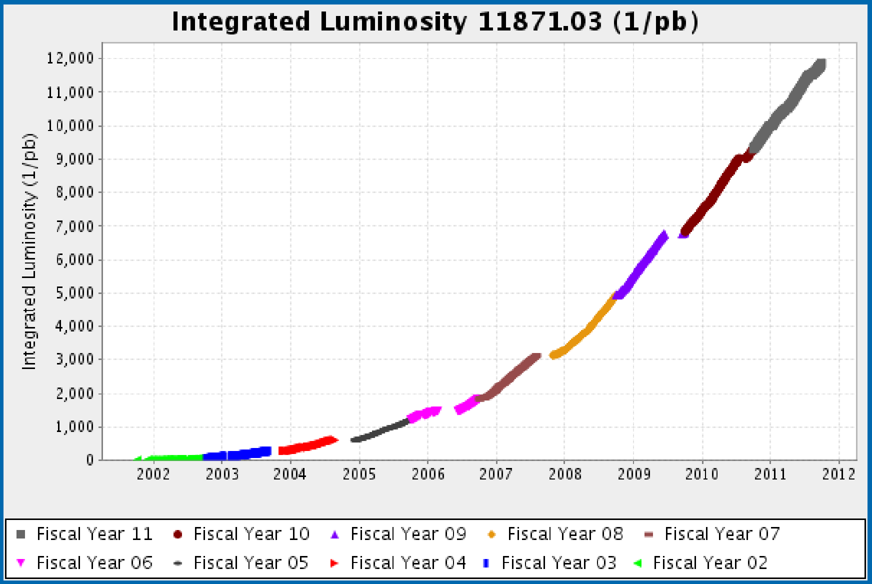
- In the SM: Br($t \rightarrow Wb$) ~ 100%
- Decay channels classified by W decays
- Top pair decay channels ($l=e,\mu$)
  - Dilepton: $l\nu l\nu bb$ *(5%)*
  - Lepton+jets: $l\nu qqbb$ *(30%)*
  - All-hadronic: *qqqqbb (45%)*

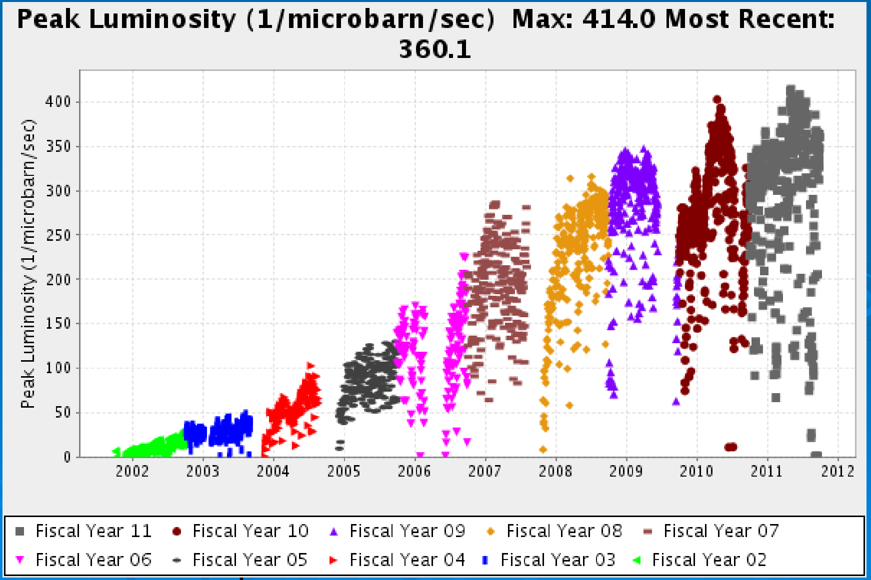


Experiments

Tevatron Run II







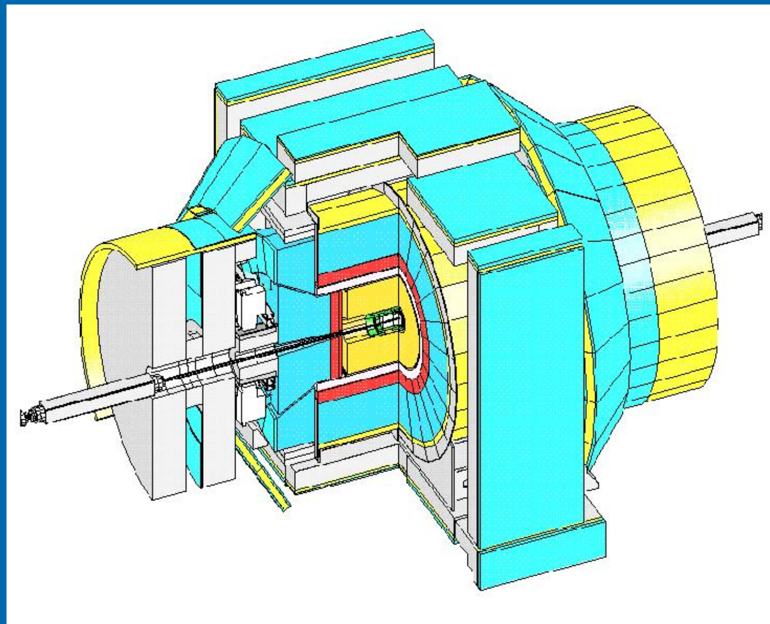
Tevatron Run II

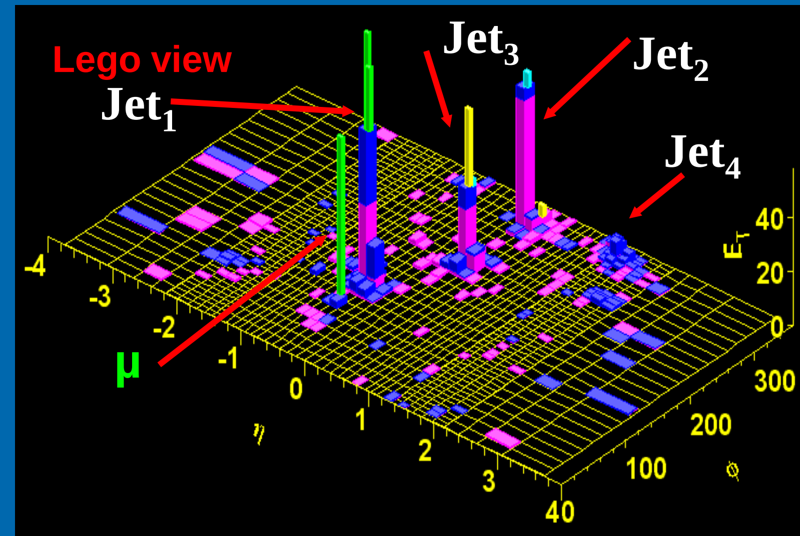
Proton-antiproton collider (2001-2011)

$\sqrt{s}$ = 1.96 TeV

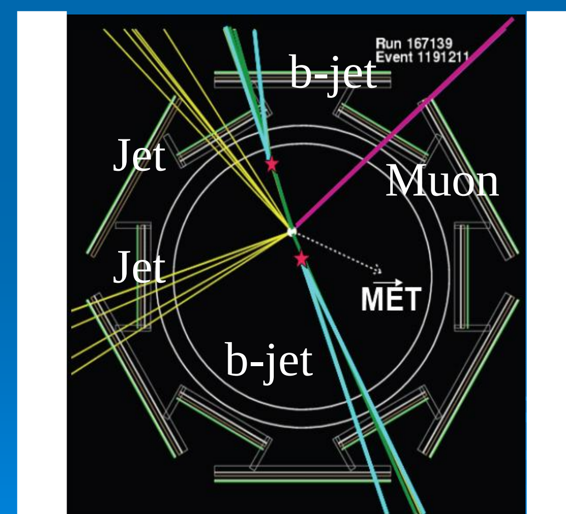
- Peak Luminosity record :
  $4.14 \cdot 10^{32}$ cm^{-2}sec
- Total integrated luminosity delivered :
  ~11 fb^{-1}
  - ~10 fb^{-1} recorded per experiment
  - Doubled data set each year for four years

The CDF Detector





- Silicon tracking
- Large radius drift chamber (r=1.4m)
- 1.4 T solenoid
- Projective calorimetry (|η| < 3.5)
- Muon chambers (|η| < 1.0)
- ***All crucial for top physics!***



Lepton+jets $(l\nu qqbb)$ Candidate

Towards Precision Measurement of Top-quark Properties

- CDF Run I top mass measurement using 67 pb^{-1} (PRL 74, 2626 (1995))

  $M_t = 178 \pm 8$ (stat) ± 10 (syst) GeV/c^2

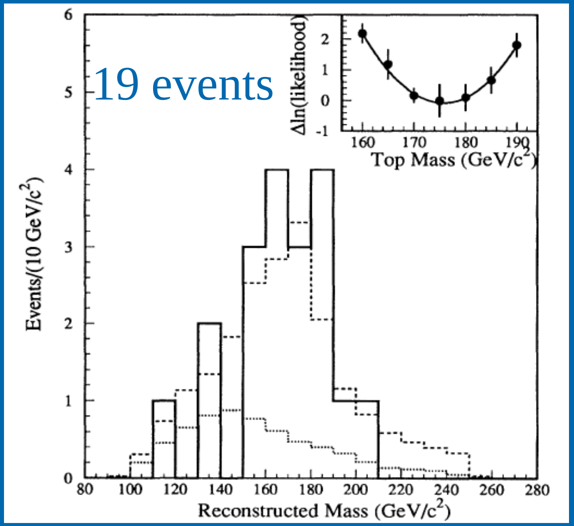
  - Lepton+≥4 jets and ≥1 b-tag

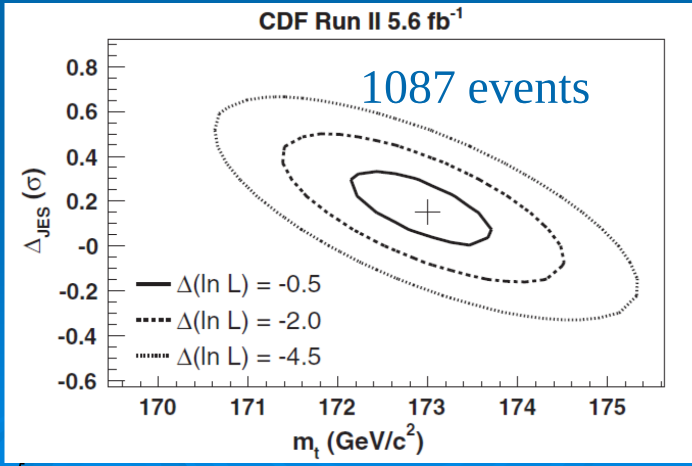
- CDF Run II top mass measurement using 5.6 fb^{-1} (PRL 105, 252001 (2010))

$M_t = 173.0 \pm 0.7$ (stat) ± 0.6 (JES) ± 0.9 (syst) GeV/c^2

  - Lepton+4 jets, ≥1 b-tag and other analysis specific selections

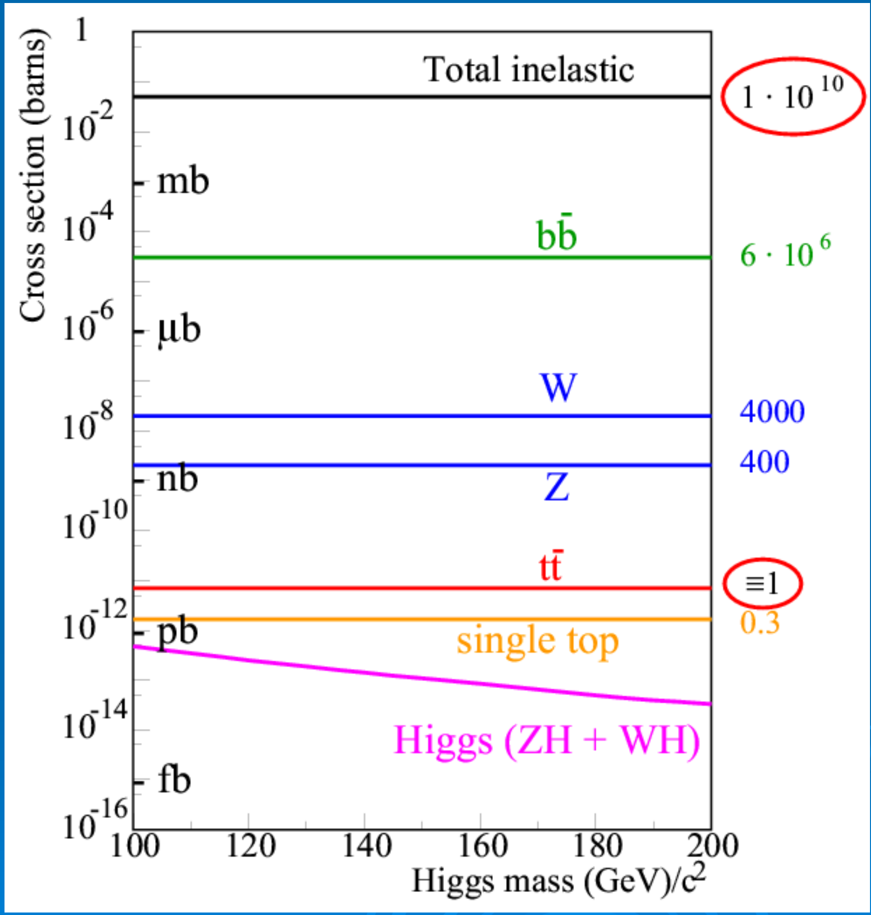
Made possible by lots of efforts in every area: accelerator, detector, trigger, **data acquisition**, offline processing, **calibration and data validation**, **physics analysis**



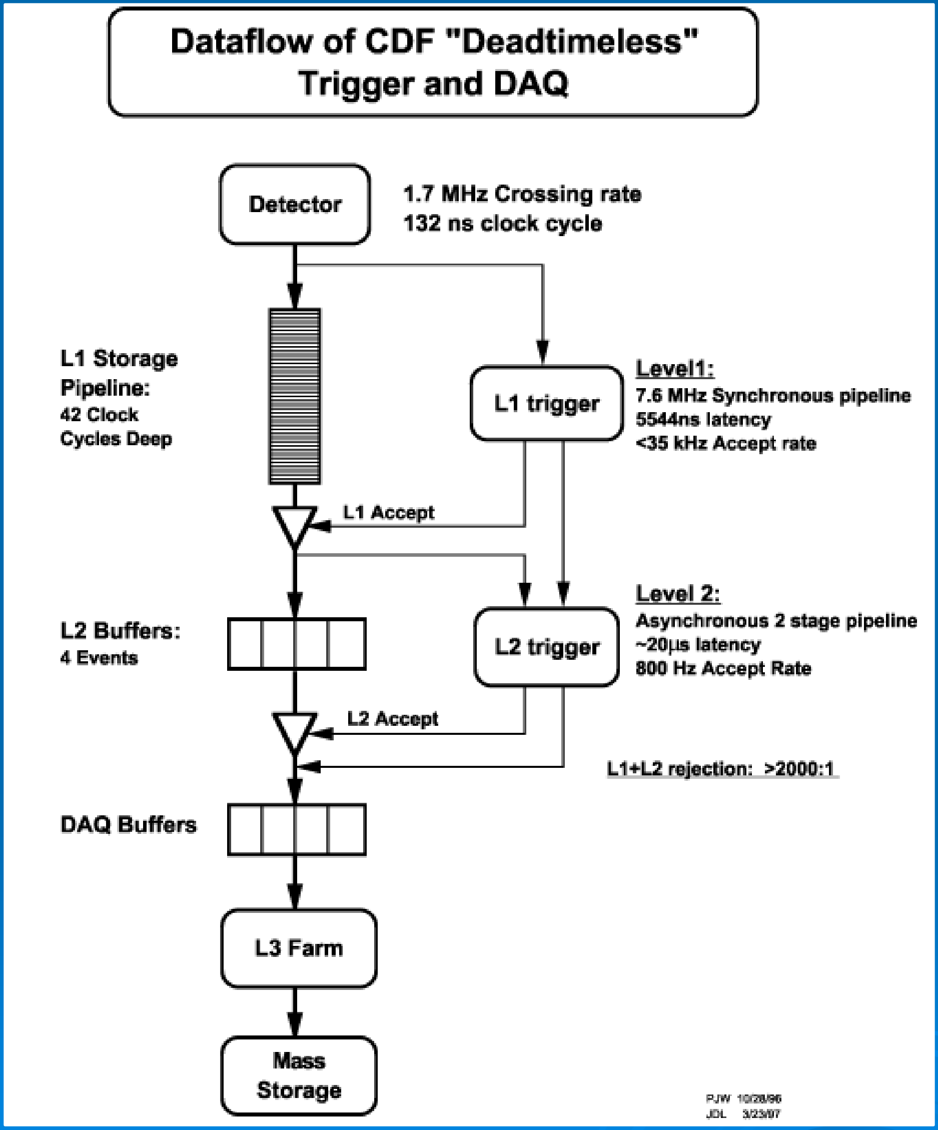


Trigger and DAQ

- The Trigger system is used to filter 100 Hz from 1.7 MHz crossings
- Done in three stages
  - Level 1 trigger (L1) decision made entirely via custom trigger hardware
  - Level 2 trigger (L2) makes fast decision using combination of dedicated hardware and software algorithm
  - Level 3 trigger (L3) performs full event reconstruction using offline style modules
- L1 + L2 rejection > 2000 : 1



CDF DAQ System Overview



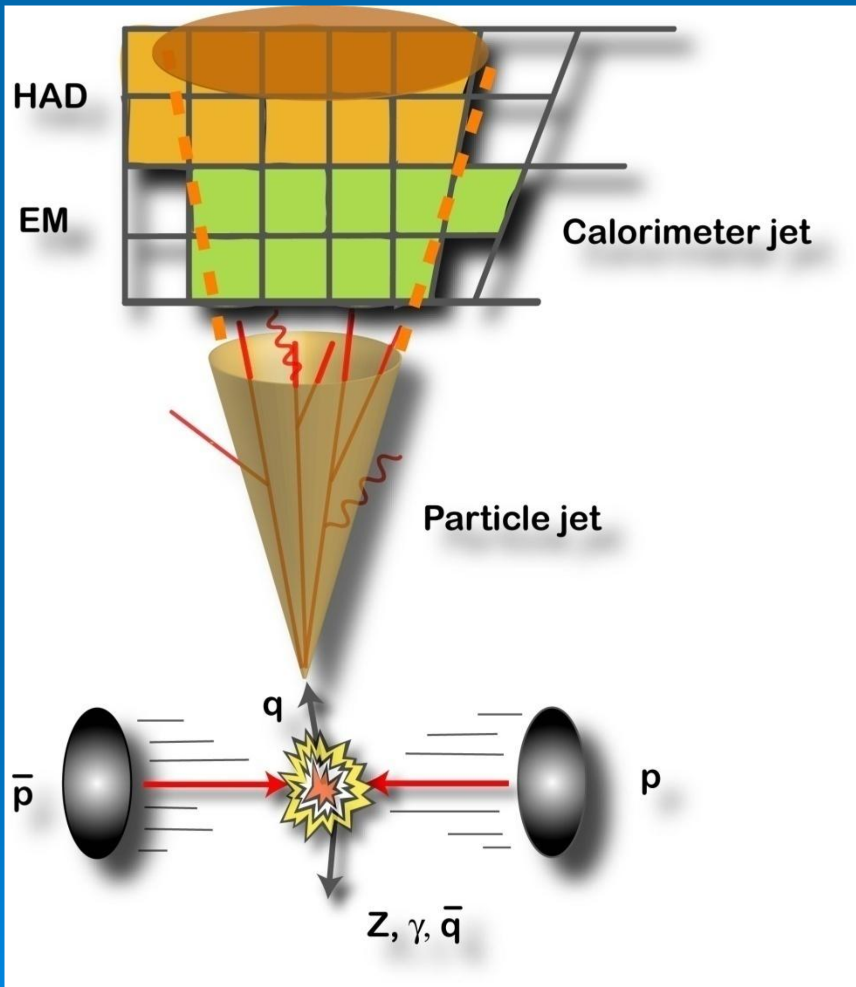
- CDF_CLK: 132 ns
- Frond End of DAQ is a synchronous pipeline holding 42 crossings' worth of data
  - Typical rate out of L1< 30 kHz,
- After L1 accept pipelined data copied into 1 of 4 L2 read out buffers
  - L2 trigger decision takes ~40 µs
  - Typical rate out of L2 <800 Hz
- With L2 accept full event record goes to the L3 farms for offline style reconstruction
  - L3 accepted event data shipped off for permanent storage

Calibration and Validation :
Jet Energy Scale

NIM A, 566, 375 (2006)

Jet Energy Scale (JES)

Jet Energy Scale

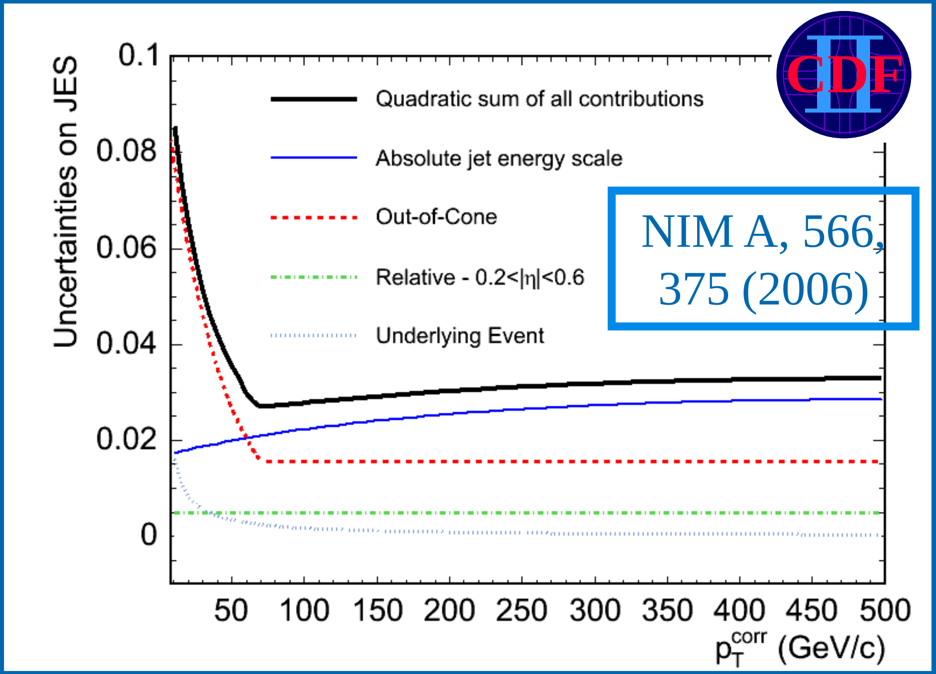


$$P_T^{particle} = \left(P_T^{jet} \times C_\eta - C_{MI}\right) \times C_{Abs}$$

$$P_T^{parton} = P_T^{particle} - C_{UL} + C_{OOC}$$

- **Relative correction (C_η)** : make calorimeter response uniform in η
- **Multiple interaction correction (C_{MI})**
- **Absolute correction (C_{abs})** : corrects calorimeter jet to particle jet
- **Underlying event correction (C_{UL}):** subtract energy from spectator particles (ISR, beam-beam-remnant)
- **Out-of-cone correction (C_{OOC}):** Corrects for particle losses outside the jet cone (FSR, hadronization)

Uncertainty on JES



Systematic uncertainties estimated by comparing data and MC

- Uncertainty on JES ⇒ About 3% systematic uncertainty on Top mass measurement when convoluted with ttbar p_T spectrum

tWb Vertex and W-Boson Polarization from Top-Quark Decay

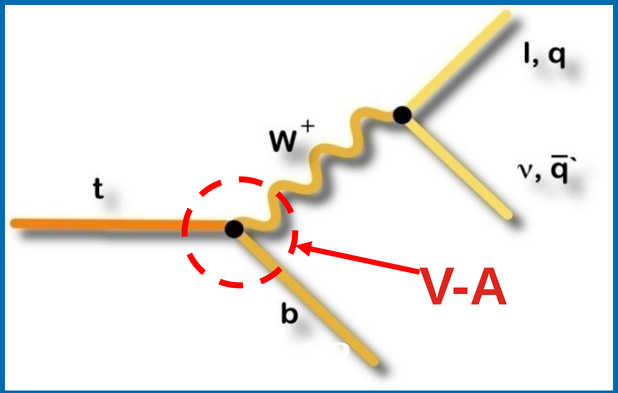
tWb Vertex

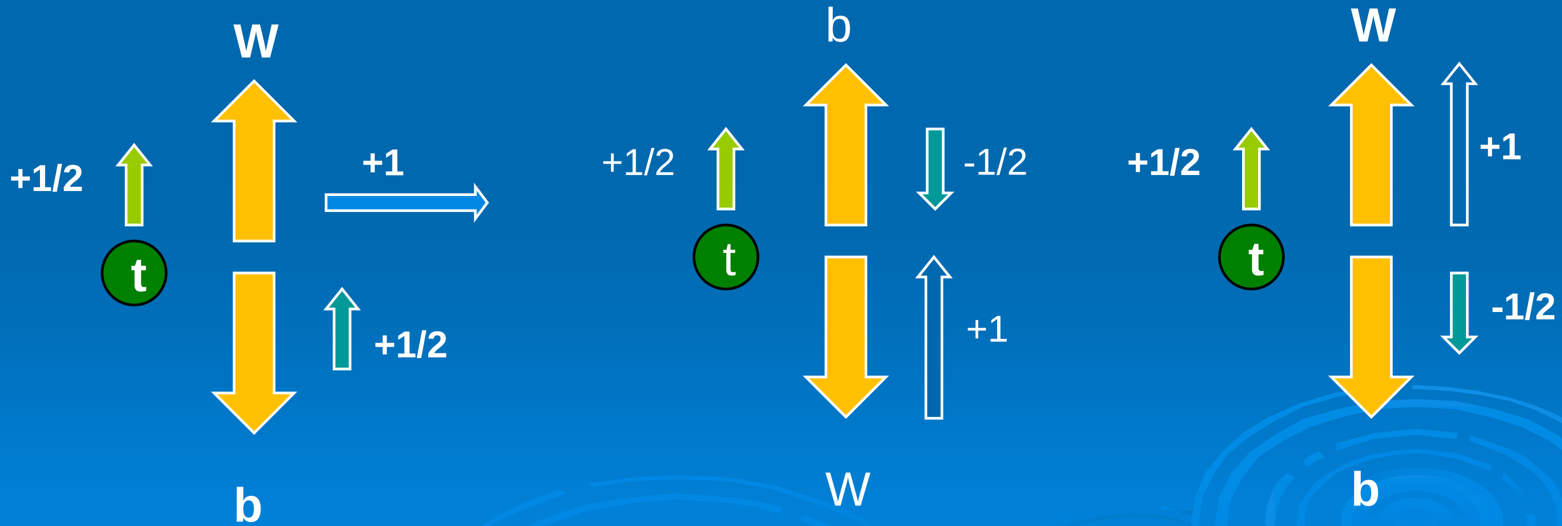
$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t\, W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu} q_{\nu}}{M_W}\left(g_L P_L + g_R P_R\right) t\, W_{\mu}^{-} + \text{h.c.}$$

- Within the SM $V_L = V_{tb} \approx 1$ and anomalous coupling terms $V_R = g_L = g_R = 0$ at the tree level
- The magnitude of V_R constrained by the measured rate of $Br(b \to s\gamma)$: $|V_R| < 0.04$
  - The bound is model dependent
- Contributions from the $\sigma^{\mu\nu}$ terms is suppressed by the q_{ν}/M_W
  - Low energy constraints are not so relevant
- The structure of tWb needs to be probed via angular distributions of top decay products

Polarization of W from Top Decay

- Top decays as a bare quark $\Rightarrow$ spin info transferred to final states
- W-boson polarizations: J.P = 0, 1, -1
- V-A coupling in the SM
- SM expectations
  - longitudinal fraction f_0 ~70%
  - left-handed fraction f_- ~30%
  - right-handed fraction f_+ ~0%

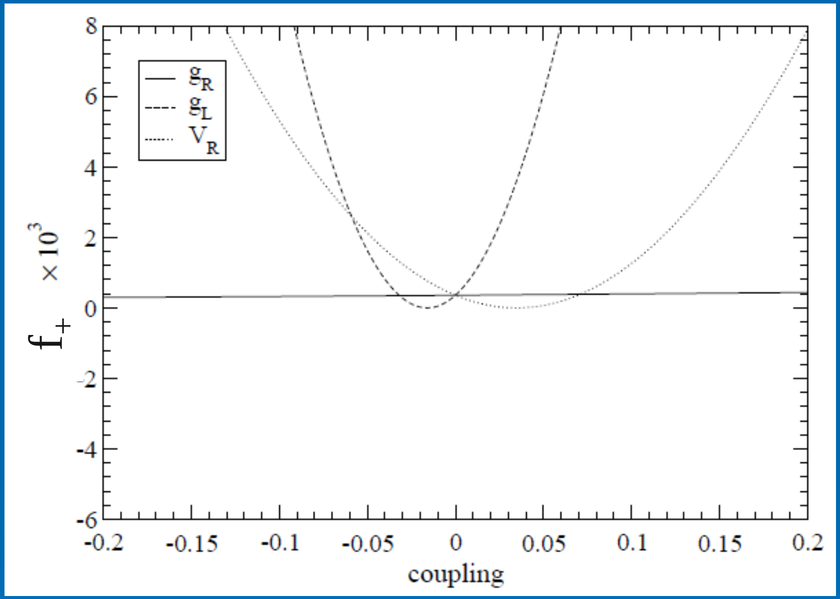


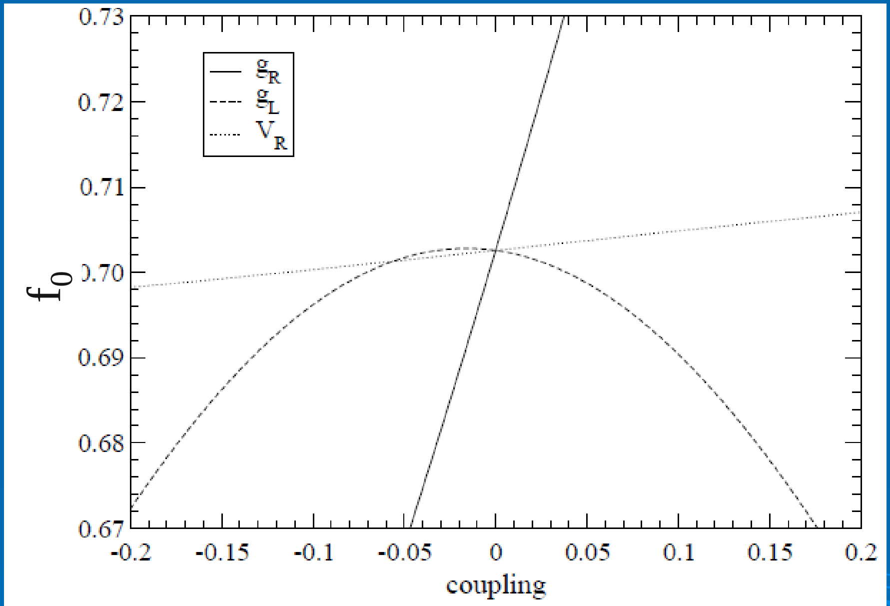


Longitudinal : J.P=0 Left-handed : J.P=-1 Right-handed : J.P=+1

Sensitivity to New Physics

- The SM prediction modified in various new physics models
- W-helicity fractions and ratios are sensitive to non-SM tWb couplings



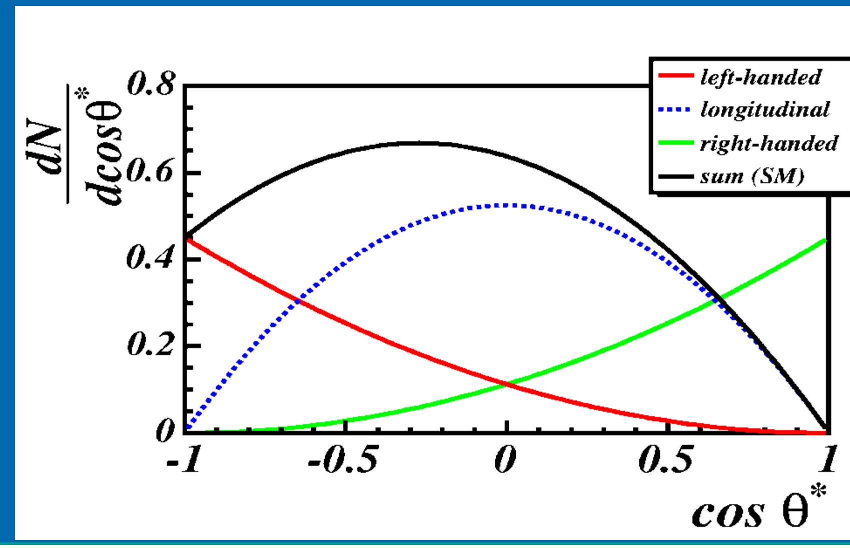


J. A. Aguilar-Saavedra et; al., Eur. Phys. J. C50, 519 (2007)

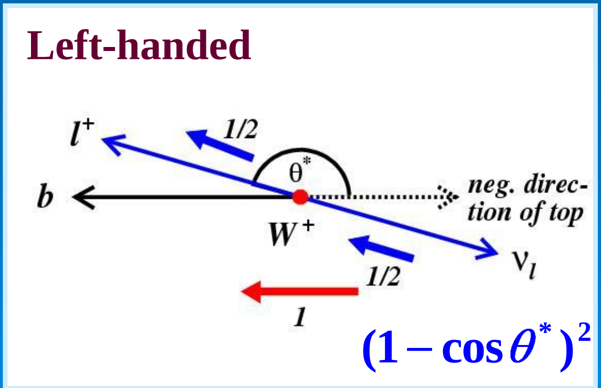
- Measurements of W-polarization fractions and EW single top production together can set constrains on the anomalous coupling form factors.

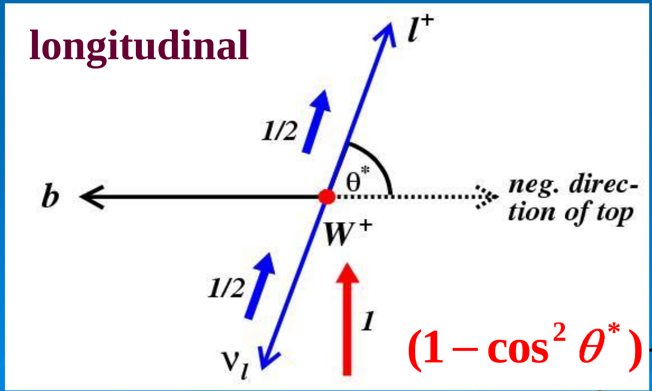
Measuring W Polarization

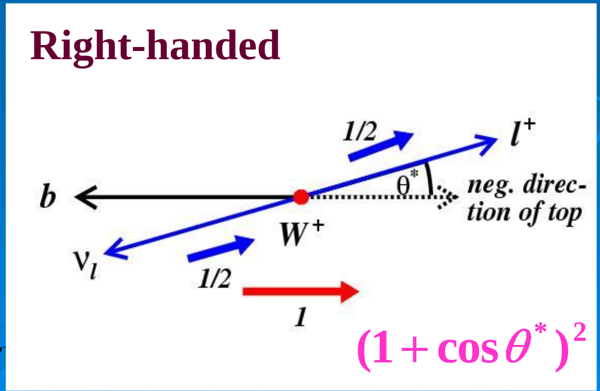
- Polarization states reflected in the angular distribution:
  - θ*: Angle between lepton (down-type quark) in W rest frame and the momentum of the W in the top-quark rest frame



$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = f_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + f_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + f_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$







Measurements

- Measurements performed under three different hypothesis (assuming $f_0+f_++f_- = 1$):
  - Simultaneous measurement of f_0 and f_+
    - Model independent
  - Measurement of f_0 constraining $f_+= 0$
    - Sensitive to anomalous tensor couplings ($\sigma_{\mu\nu}$ terms g_R and g_L)
  - Measurement of f_+ constraining $f_0 = 0.7$
    - Sensitive to anomalous right-handed coupling V_R
- Two different methods are applied
  - Template method
    - Used for most of the measurements
  - Event-by-event likelihood method
    - Applied for D0 Run I measurement of f_0 with fixed $f_+ = 0$ (PLB 617, 1 (2005))
    - The latest CDF analysis

Recent Tevatron Results

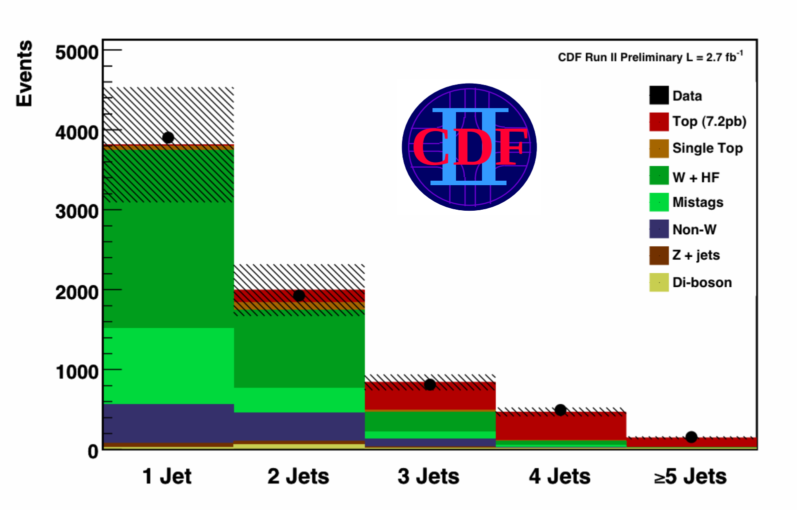
- CDF measurement in lepton+jets (2.7 fb^{-1}):
  - Phys. Rev. Lett. 105, 042002 (2010)
- CDF measurements in dilepton (4.8 - 5.1 fb^{-1}):
  - CDF public notes 10333, 10390
- D0 measurement in lepton+jets and dilepton (5.4 fb^{-1}):
  - Phys. Rev. D **83**, 032009 (2011)

CDF measurement in lepton+jets (2.7 fb^{-1}):

(Phys. Rev. Lett. 105, 042002 (2010))

Event Selection

- Triggers:
  - High P_T leptons triggers
  - Trigger requiring large missing E_T associated with jets
    - Increase acceptance by 30%. Not used in the best previous CDF measurement.
- ≥4 jets with E_T>20 GeV, ≥1 b-tag
- One isolated lepton with E_T>20 GeV
- Missing E_T > 20 GeV



Jet Multiplicity (E_T>20 GeV)

Process	Central e, μ	Forward e	$\not{E}_T$+jets μ
$t\bar{t}$ (σ = 6.7 pb)	478 ± 66	58 ± 8	134 ± 19
W+hf	71 ± 22	13 ± 9	19 ± 6
W+lf	23 ± 6	5 ± 7	6 ± 2
EWK	17 ± 10	3 ± 1	5 ± 3
QCD	28 ± 22	46 ± 37	1 ± 1
Total expected	616 ± 74	125 ± 40	165 ± 20
Observed	650	136	178

Event-by-Event Likelihood

- Use probability densities based on matrix elements of signal (ttbar) and dominant background (W+jets)
- Construct probability density for each event
- Multiply all the event probabilities to obtain likelihood

$$L(C_s, f_0, f_+) = \prod_{i=1}^{N_{evt}} C_s \frac{P_{signal,i}(x; f_0, f_+)}{\langle Acc_{sig}(x; f_0, f_+) \rangle} + (1 - C_s) \frac{P_{bkg,i}}{\langle Acc_{bkg}(x) \rangle}$$

- Matrix element for ttbar is expressed in terms of $\cos\theta^*$ and polarization fractions

$$|M|^2 \propto w_{lep}(\cos\theta^*) \times w_{had}(\cos\theta^*)$$

$$w(\cos\theta^*) = f_+ \frac{3}{8}(1 - \cos\theta^*)^2 + f_0 \frac{3}{4}(1 - \cos^2\theta^*) + (1 - f_0 - f_+) \frac{3}{8}(1 + \cos\theta^*)^2$$

- Likelihood optimized for f_0, f_+ and C_s

Matrix Element Method

$$P_{signal}(x; f_0, f_+) = \sum_{perm.} \int \frac{d\sigma(y; f_0, f_+)}{dy} W(x, y) dq_1 dq_2 f(q_1) f(q_2)$$

- **dσ** is the differential ttbar cross section

$d\sigma = |M|^2 d\Phi$: LO qqbar matrix element from Mahlon & Parke *(PLB 411, 173 (1997); PRD 53, 4886 (1996)).*

- *W(x,y)* models detector resolution effects
  - Relates a set of observable x to corresponding parton level quantities y

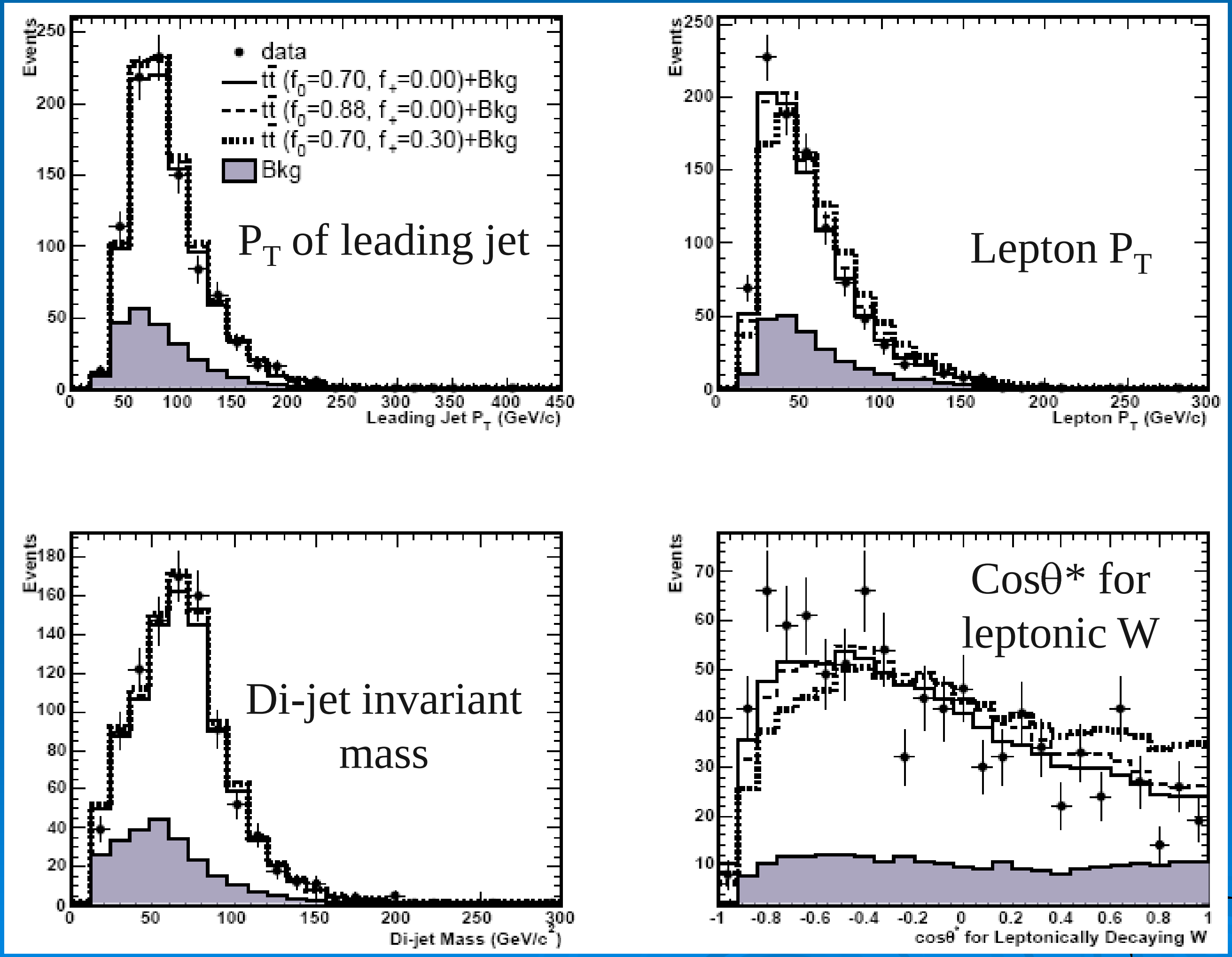
$$W(x, y) = \delta^3(p^y_{lepton} - p^x_{lepton}) \prod_{j=1}^{4} W_{jet}(E^x_j, E^y_j) \prod_{i=1}^{4} \delta^2(\Omega^y_i - \Omega^x_i)$$

- **f(q)** is from the parton distribution function
  - Take into account the flavors of colliding quark and anti-quark
- Partons are identified with the four highest E_T jets and all the corresponding jet-parton permutations are considered

Matrix Element Method (cont')

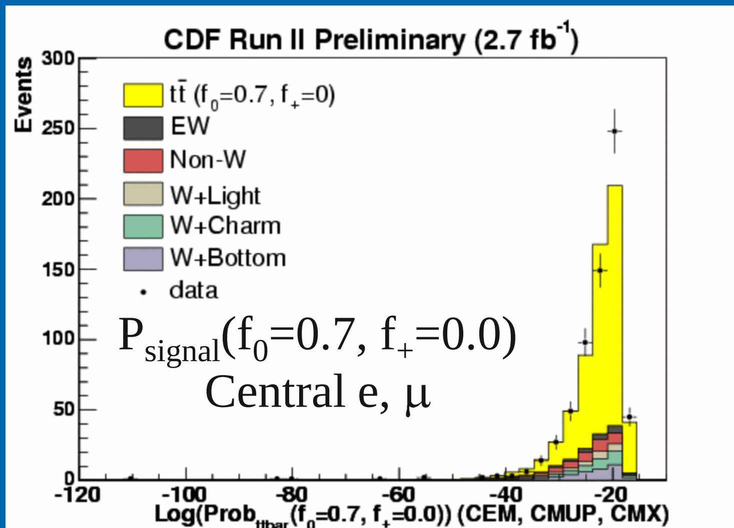
- $P_{bkg\ ,i}$ is similar, no dependence on f_0 and f_+
- Construction of signal and background probabilities are based the techniques used for the top mass measurement (PRL 99, 182002 (2007))

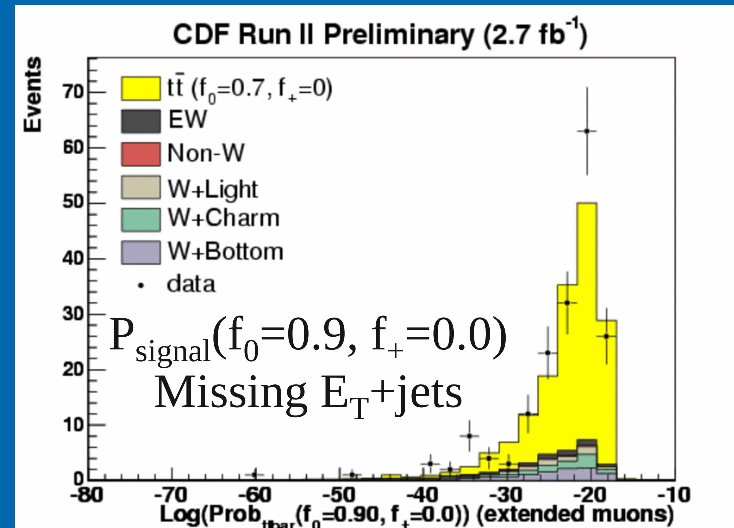
Validation of Signal and Background Modeling

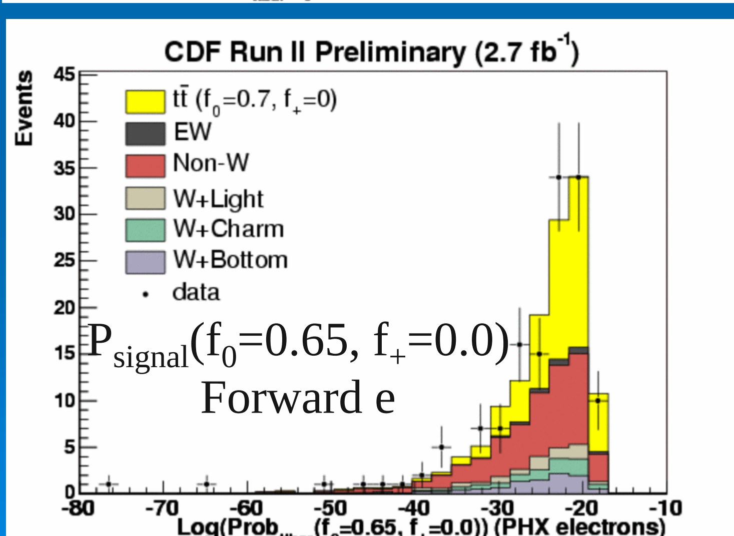


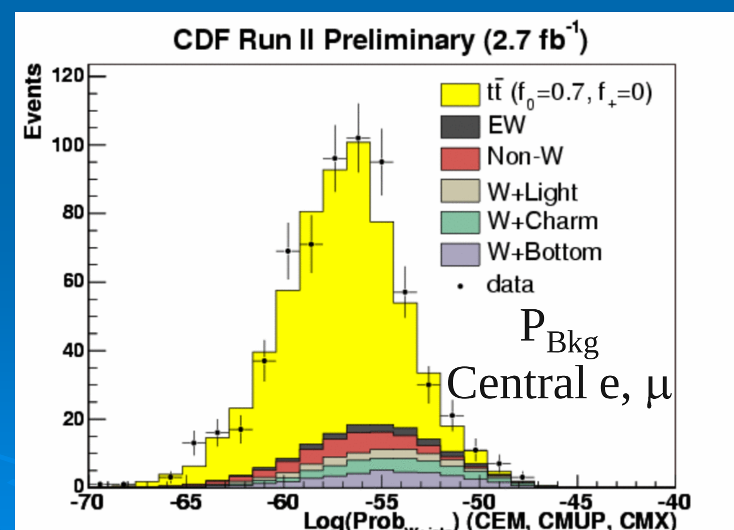
Extensively check signal and background modeling by comparing the data and MC distributions of many different variables in signal sample and high statistics control sample

Signal and Background Probabilities

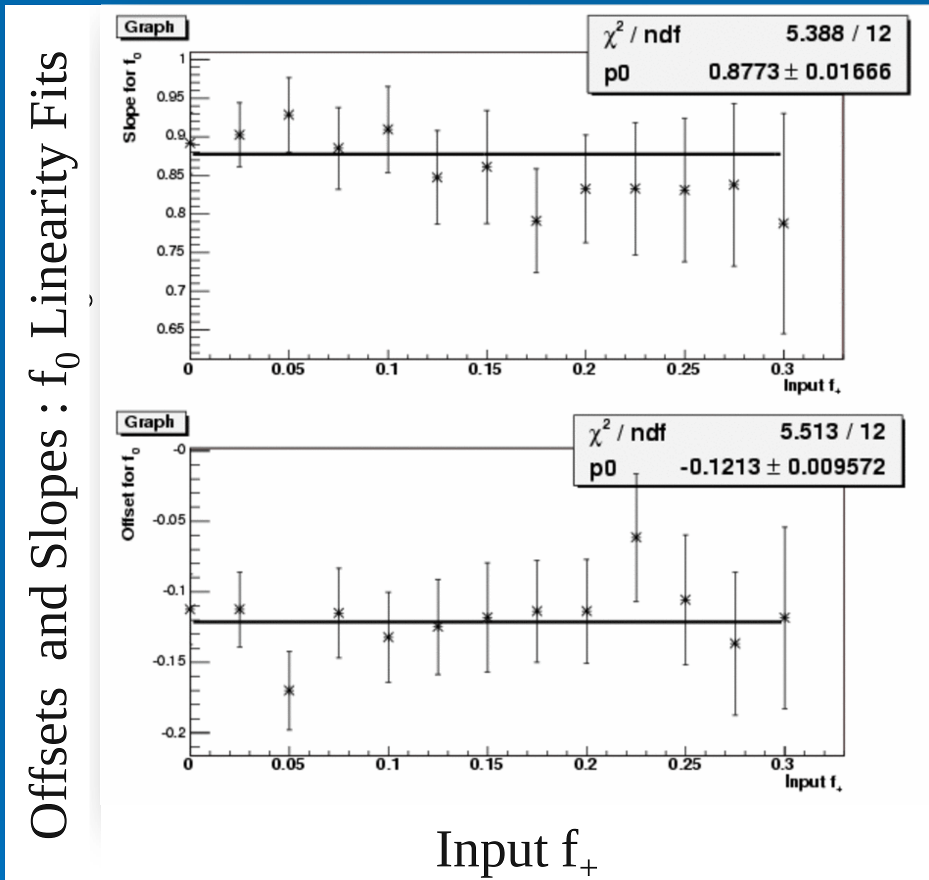


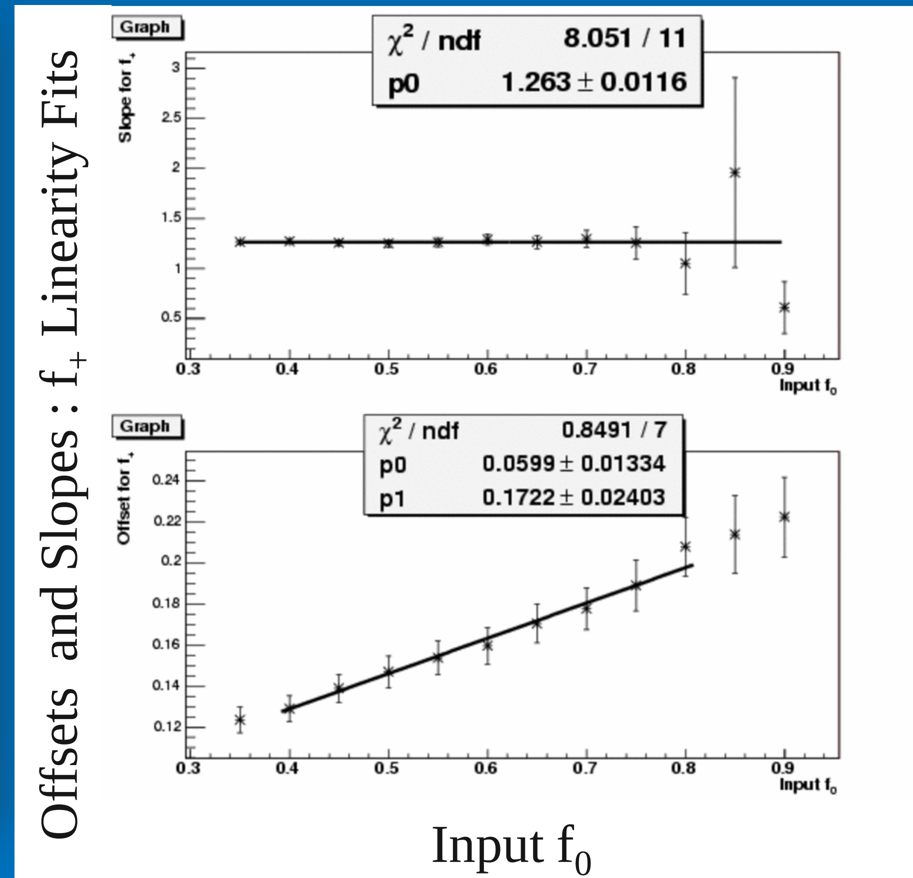






Calibration



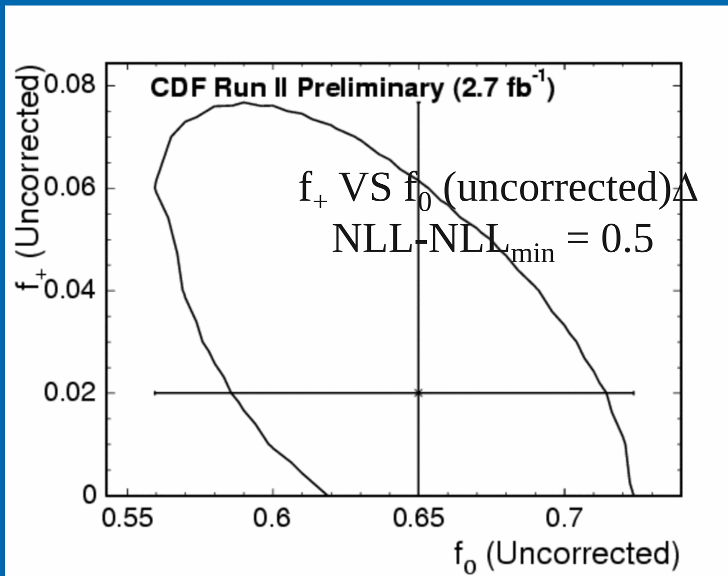


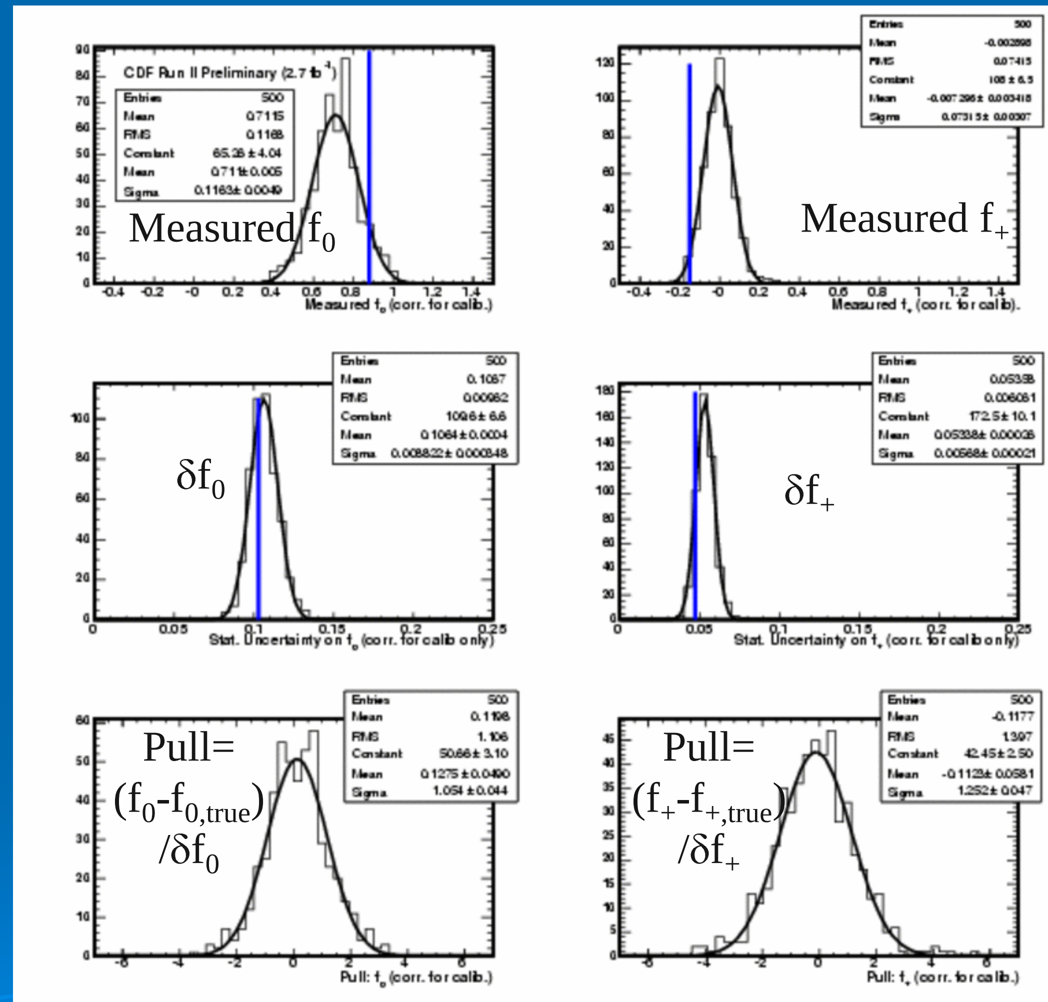
- For the model independent fit we have a family of $f_{0(+)}$ response curves in slices of input $f_{+(0)}$
  - Linear fits to these curves are used to derive calibration functions

Validation and Sensitivity Studies

- Performed data-size pseudo experiments with wide range of (f_0, f_+) input values
  - The fit is unbiased in all cases
  - Find that near physical boundaries the statistical uncertainties are underestimated
    - Apply appropriate corrections to the measured statistical uncertainties
- Assuming SM value of polarization fractions, the expected statistical uncertainties for the simultaneous measurement
  - $\delta f_0 = 0.12$
  - $\delta f_+ = 0.07$

Data Fit: Simultaneous Measurement





- With 828 selected events after all corrections

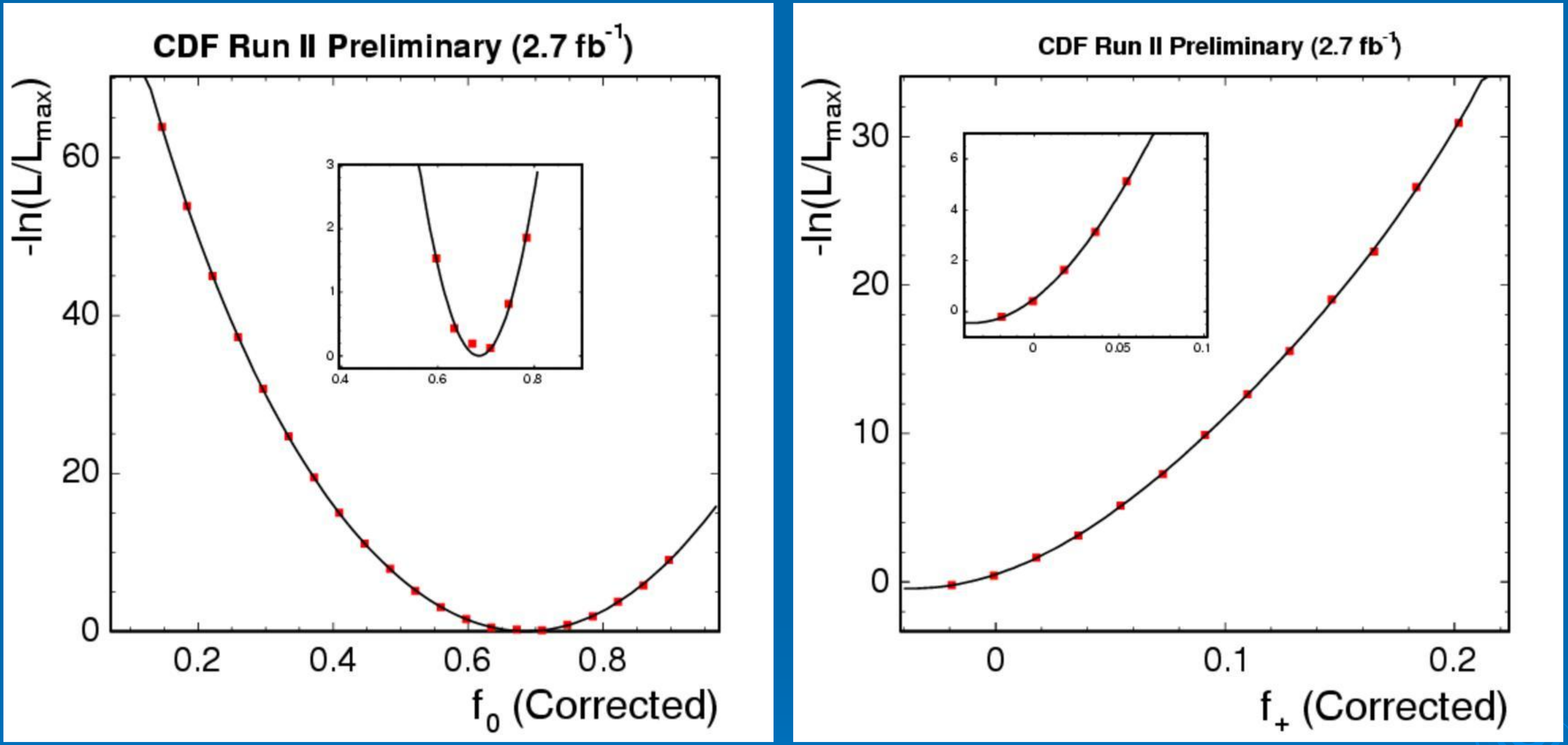
  f_0=0.88 ± 0.11 (stat.)

  f_+= -0.15± 0.07 (stat.)

  Correlation between measured f_0 and f_+ -0.59

Comparing data result with PSEs generated with f_0=0.7, f_+=0.0

Data Fit



- With 964 events after all corrections
  - $f_0 = 0.70 \pm 0.07$ (stat), constraining $f_+=0.0$
  - $f_+ = -0.01 \pm 0.02$ (stat), constraining $f_0=0.7$

Systematic Uncertainty

TABLE II: Summary of systematic uncertainties.

Source	Δf_0	Δf_+	Δf_0 simultaneous	Δf_+ simultaneous
ISR/FSR	0.020	0.018	0.020	0.021
PDF	0.024	0.013	0.009	0.016
JES	0.018	0.017	0.004	0.012
Parton shower	0.012	0.008	0.031	0.017
Background	0.009	0.038	0.042	0.039
Method-related	0.010	0.005	0.024	0.024
b-tag SF	0.004	0.002	0.002	0.002
Total	0.041	0.048	0.062	0.057

Systematic uncertainties are obtained at the SM values of polarization fractions

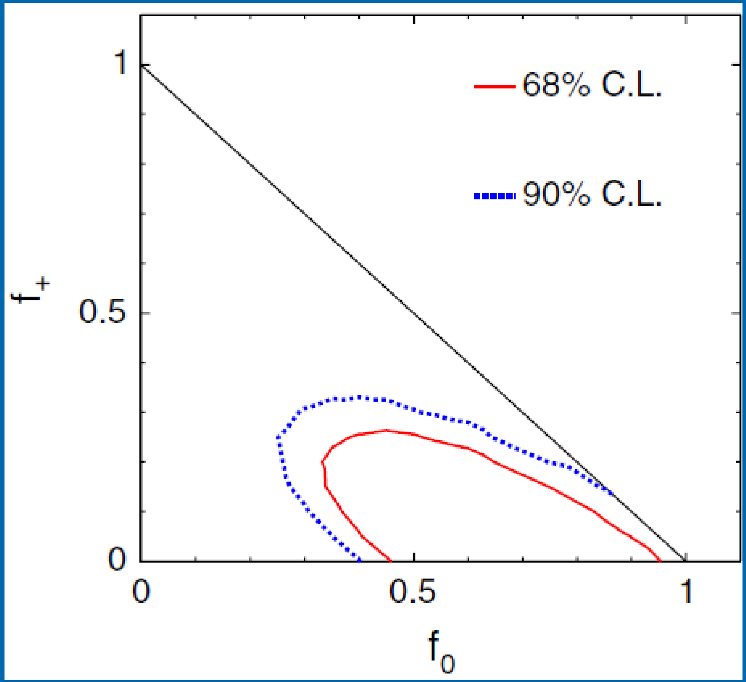
Reduced systematic uncertainty from "parton shower" modeling

- *Existing method uses differences from using two different ttbar MC generators $\Rightarrow$ double counting of systematic uncertainties*
- *Updated method compares between ttbar MC samples where only the parton showering models are changed*

Phys. Rev. Lett. 105, 042002 (2010)

Results

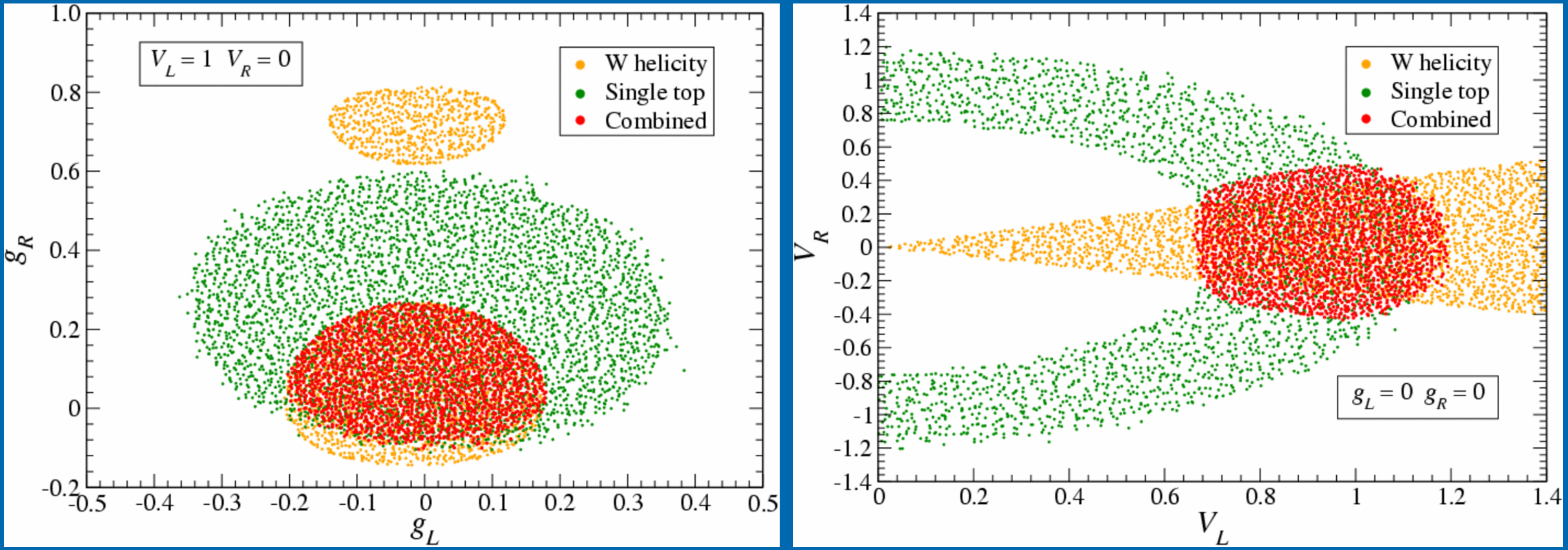
- Simultaneous measurement:
  - $f_0 = 0.88 \pm 0.11$ (stat) ± 0.06 (sys)
  - $f_+ = -0.15 \pm 0.07$ (stat) ± 0.06 (syst)
    - Correlation coefficient of -0.59
    - $\delta f_0=0.13$, $\delta f_+=0.09$
    - Use Feldman Cousins (FC) method to obtain confidence level intervals
- Model dependent measurements:
  - $f_0 = 0.70 \pm 0.07$ (stat) ± 0.04(stat), constraining $f_+=0.0$
  - $f_+ = -0.01 \pm 0.02$ (stat) ± 0.05 (syst), constraining $f_0=0.7$
    - Upper limit at 95% CL : $f_+<0.12$
  - $\delta f_0=0.08$, $\delta f_+= 0.05$



FC Contours include stat+syst uncertainties

A factor of ~1.3 improvement on the precision on f_0 for a 1.4 times increase in luminosity

tWb Coupling with CDF Data

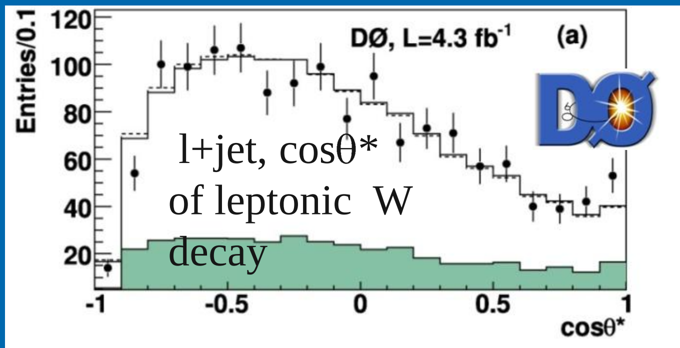


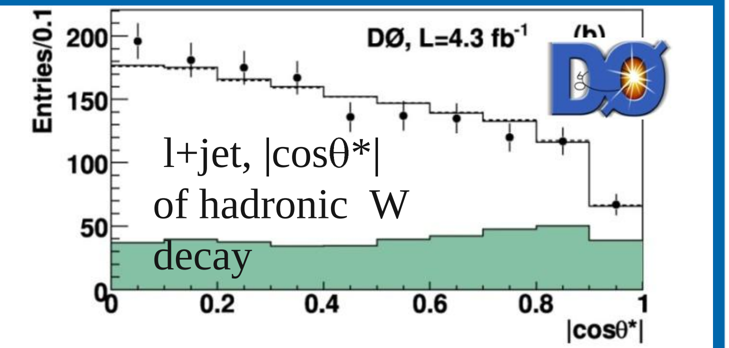
Courtesy of J. A. Aguilar-Saavedra

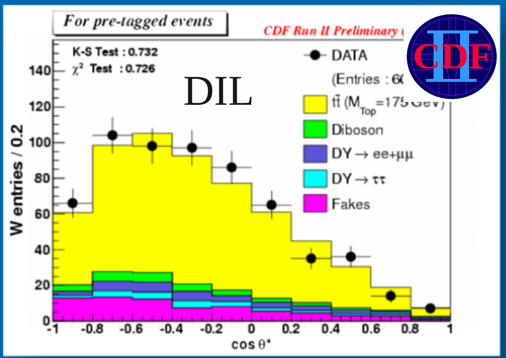
Set Contains on couplings using TopFit : a program to fit the Wtb vertex (http://www-ftae.ugr.es/topfit/)

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\,\gamma^{\mu}\,(V_L P_L + V_R P_R)\,t\,W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\,\frac{i\sigma^{\mu\nu}q_{\nu}}{M_W}\,(g_L P_L + g_R P_R)\,t\,W_{\mu}^{-} + \text{h.c.}$$

Other Recent Tevatron Measurements







	f_0	f_+
D0 (5.4 fb^{-1}, l+jet and DIL)	0.669 ± 0.078 ± 0.065	0.023 ± 0.041 ±0.034
	0.708 ± 0.044 ± 0.048	Fixed f_+ = 0.0
	Fixed f_0=0.7	0.010 ± 0.022 ± 0.032
CDF (5.1 fb^{-1}, DIL)	0.702 ± 0.175 ± 0.062	−0.085 ± 0.089 ± 0.035
	0.556 ± 0.088 ± 0.060	Fixed f_+ = 0.0
	Fixed f_0 = 0.7	−0.089 ± 0.041 ± 0.032

Tevatron Combination

- Combine most recent measurements from CDF and D0
- Take into account the statistical and systematic uncertainties and their correlations (NIM A270 (1988) 110, NIM A500 (2003) 391)
- Combined W-boson polarization fraction:

$$f_0 = 0.722 \pm 0.062 \text{ (stat)} \pm 0.052 \text{ (syst)}$$

$$f_+ = -0.033 \pm 0.034 \text{ (stat)} \pm 0.031 \text{ (syat)}$$

$\chi 2$/ndof 6.67/4 $\Rightarrow$ 7% prob

  - Good agreement among all input measurements
- W-boson polarization fractions are known with precision of δf_0=0.081 and δf_+=0.046

Combination based on 6-9 fb^{-1} data results will be limited by systematic uncertainty. Work in progress.

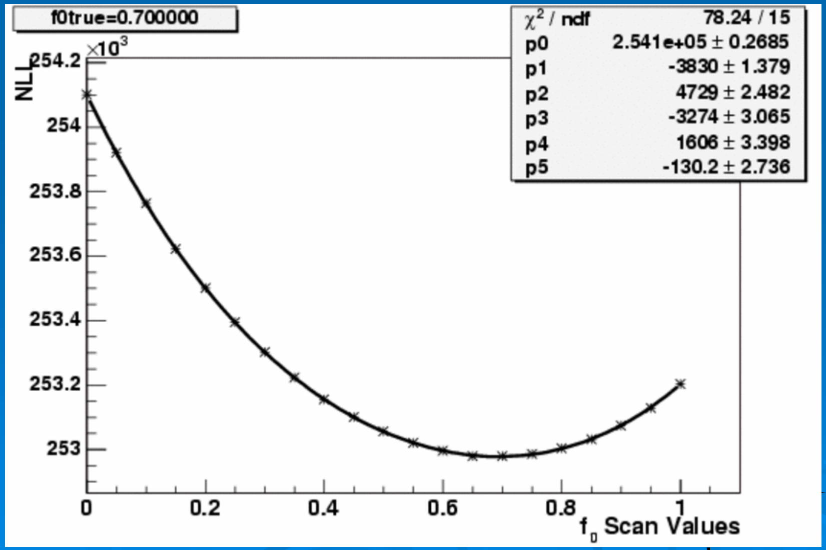
Summary

- Measured W-boson polarization in top decay using a matrix element method in 2.7 fb^{-1} data
  - Increased signal acceptance by 30% compared to the previous published analysis
  - Improves accuracy of f_0 measurement relative to CDF's best by ~20% for same luminosity
- Measurements are consistent with the SM
- Most sensitive measurement of f_0
- Measurements are statistically limited at present
  - Each experiment has ~9 fb^{-1} data
  - Updating CDF lepton+Jets analysis with entire CDF Run II data: $\int L = 8.7\ fb^{-1}$

BACKUP

1D Measurements

- Example: f_0 measurement
  - Same method used in the previous version of the analysis
  - Fix $f_+ = 0$
    - Calculate NLL for f_0=[0-1], 21 points
    - Minimum of NLL is the measured values
    - The contour with ($NLL-NLL_{min}$) = 0.5 is used for obtaining statistical uncertainty



Simultaneous Measurement of f_0 and f_+

- Scan in 2D plane of (f_0,f_+) values
  - Use 208 (f_0,f_+) values satisfying (f_0+f_++f_-)=1
    - Triangular region
- For obtaining stat uncertainty find contour with (NLL-NLL_{min}) = 0.5
  - Use the projection on f_0/f_+ axis