Measurement of the W helicity in top quark decays at DØ

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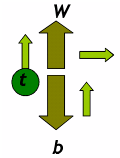
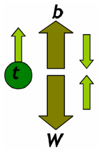
Outline

- Introduction
  - *W* helicity
  - Sensitive variable
- Measurement of the *W* helicity
  - Datasets and event selection
  - Background reduction in the ℓ+jets channel
  - Determination of cos $\theta^\star$
  - Systematic uncertainties
  - Result
- Summary

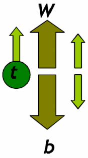
W helicity



Longitudinal fraction f_0



Left handed fraction f_-



Right handed fraction f_+

Test of the SM

Opportunity to look for new physics

- Longitudinal fraction depends only on kinematics:

$$f_0 \approx \frac{m_t^2}{2M_W^2 + m_t^2} = (70.1 \pm 1.6)\%$$

- $V - A$ interaction:
  - f_+ suppressed by factors of order (m_b^2/m_t^2)
  - $f_- \approx 1 - f_0$
- $V + A$ interaction: ▸ model
  - f_- suppressed by factors of order (m_b^2/m_t^2)
  - $f_+ \approx 1 - f_0$

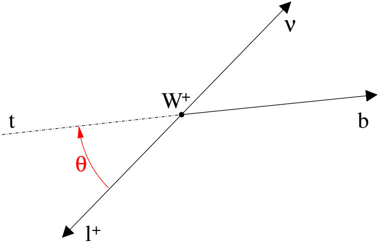
Measurements of the W helicity

- Longitudinal fraction f_0:
  - DØ (Run I): $f_0 = 0.56 \pm 0.31$
  - CDF (Run I): $f_0 = 0.91 \pm 0.39$
  - CDF (Run II, 200 fb^{-1}): $f_0 = 0.74^{+0.22}_{-0.34}$
- Right handed fraction f_+:
  - CDF (Run I): $f_+ = -0.02 \pm 0.11$
  - DØ (Run II, 230 fb^{-1}): $f_+ = 0.00 \pm 0.15$
- Indirect measurements:
  - Measurements of $b \to s\gamma$ have limited a possible $V + A$ contribution in the top sector (assuming that the electroweak penguin contribution is dominant)

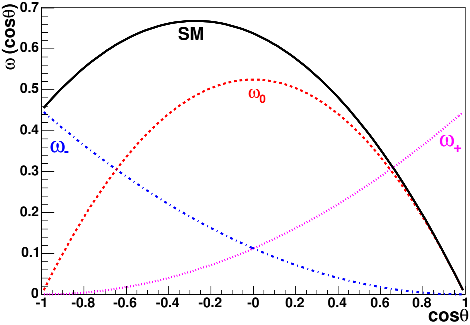
$$f_+ < \mathcal{O}(\%)$$

Sensitive variable: decay angle in W rest frame

W rest frame:



$\theta = 180^\circ -$ angle between lepton and b quark



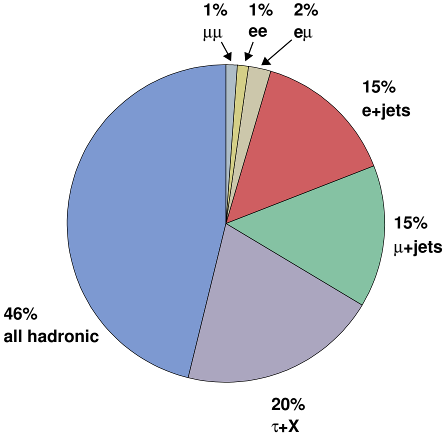
Each helicity state has different dependence on $\cos\theta^\star$:

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

Decay of top quarks

- Top quark decays to W boson and b quark: $\approx$ 100%
- 3 different classes of top pair decays

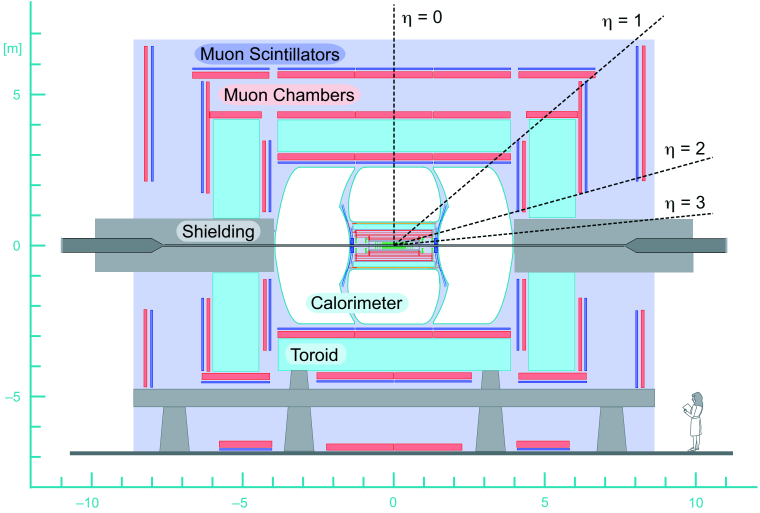
- all hadronic
  - 6 jets ($2b + 2 \times W \rightarrow q\bar{q}$)
- lepton+jets
  - 4 jets ($2b + W \rightarrow q\bar{q}$)
  - 1 charged lepton + 1 neutrino ($W \rightarrow \ell\nu_\ell$)
- dilepton
  - 2 jets ($2b$)
  - 2 charged leptons + 2 neutrinos ($2 \times W \rightarrow \ell\nu_\ell$)



Datasets

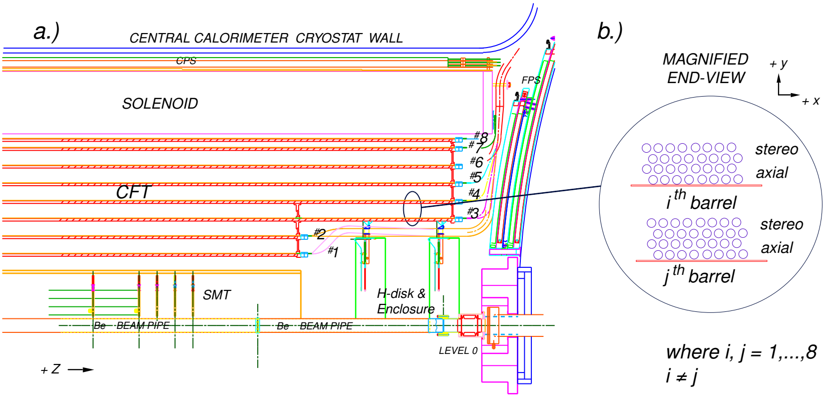
- Data
  - Integrated luminosity: 370 pb^{-1} of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV
  - Two different decay channels: ℓ+jets and dilepton
- Monte Carlo generated with ALPGEN
  - Signal Monte Carlo
    - Top quark mass set to 175 GeV
    - f_0 fixed to 0.7
    - f_+ varied between 0.0 and 0.30 in steps of 0.05
  - Background Monte Carlo
    - W plus 4 jets (light as well as heavy flavor)
    - $Z/\gamma^\star \to \ell\bar{\ell}$ plus 2 jets
    - WW plus 2 jets
- Instrumental background taken from Data

Overview of the DØ detector

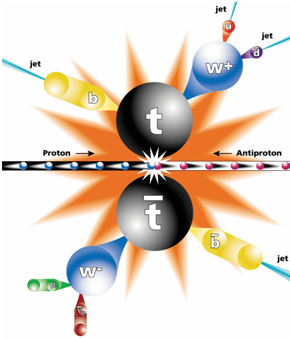


The tracking system

- Silicon vertex detector and fiber tracker inside magnetic field



Event selection



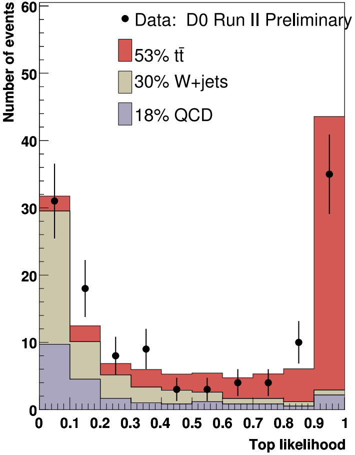
- Lepton+Jets channel
  - Charged lepton (e, μ)
    - $p_T > 15$ GeV, $|\eta| < 1.1$ (2.0)
    - Veto on other lepton with $p_T > 15$ GeV
    - Isolated from jets
  - Missing transverse energy ($\not{E}_T$) > 20 GeV
  - Jets
    - $p_T > 15$ GeV and $|\eta| < 2.5$
    - ≥ 4 jets
- Dilepton channel
  - 2 Charged leptons (ee, $\mu\mu$, $e\mu$)
  - Missing transverse energy ($\not{E}_T$) > 20 GeV
  - ≥ 2 jets
  - Additional cuts:
    - ee, $\mu\mu$: suppress Z background (invariant mass, Z fitter)
    - $e\mu$: $p_T^{\ell} + p_T^{j1} + p_T^{j2} > 140$ GeV

Additional background reduction (lepton+jets)

- Further discrimination between signal and background desired (after preselection: $S/B \approx 0.25 - 1$)
- Use variables which exploit the difference in topology and flavor
  - Aplanarity and Sphericity (4 leading jets plus the lepton)
  - H_T: scalar sum of jet p_T
  - Centrality, defined as $C = \frac{H_T}{H_E}$
  - Minimal dijet mass in the event
  - K'_{Tmin} (scaled minimal distance between two jets)
  - χ^2 from the kinematic fit
  - Average b-tag probability of the two most probable b-jets (based on impact parameter of tracks inside the jet)
- Optimal set of variables and cut on discriminant for e+jets and μ+jets based on maximizing expected $S/\sqrt{S+B}$

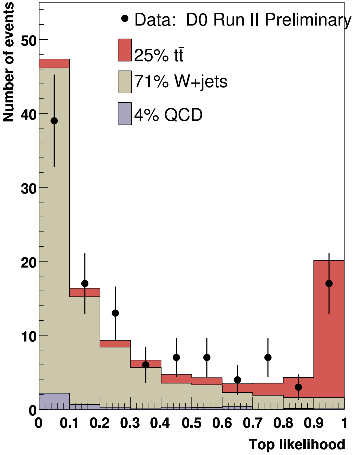
Discriminant $\mathcal{D}$

e+jets



Cut at $\mathcal{D} > 0.35$

μ+jets



Cut at $\mathcal{D} > 0.70$

$t\bar{t}$ reconstruction (lepton+jets channel)

Complete reconstruction of the event:

- Need to assign jets correctly
  - *b*-jets, jets from *W* boson, ISR/FSR
- Neutrino cannot be directly measured
  - Reconstruct p_x, p_y from transverse momentum imbalance
  - Infer p_z from $m_t = m_{\bar{t}}$ (quadratic equation)
- Impose the following constraints
  - Mass of *W* boson is known (80.4 GeV)
  - Both top quarks have equal mass ($m_t \approx 175$ GeV)
- Feed these information into a kinematic fit
  - Obtain 4-vectors of particles for each jet permutation (12)
  - χ^2 from fit as figure of merit for each permutation

Determination of cos $\theta^\star$ in dilepton events

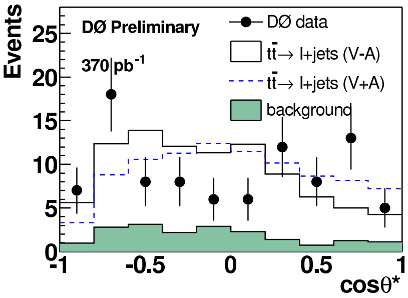
- Dilepton events kinematically underconstrained due to presence of two neutrinos

  $\Longrightarrow$ No kinematic fit possible
- Assume value for top quark mass ($m_t \approx 175$ GeV)

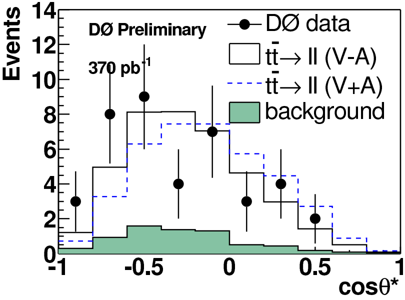
  $\Longrightarrow$ neutrino momenta can be determined (four-fold ambiguity)
- Additional two-fold ambiguity from pairing leptons with jets (only the two highest p_T jets are used)
- Determination of cos $\theta^\star$:
  - Take average of cos $\theta^\star$ values computed by all possible solutions for each lepton
- Advantage: 30% improved sensitivity to f_+ compared to lepton p_T
- Larger dependence on jet energy calibration (still smaller than statistical uncertainty)

cos $\theta^\star$ distribution in data

lepton+jets

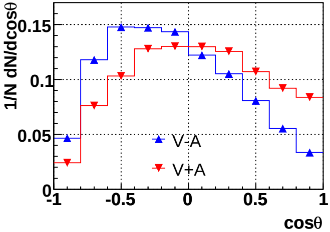


dilepton

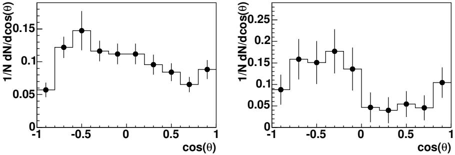


- both channels show good sensitivity
- deficit around cos $\theta^\star \approx 0$ in the lepton+jets channel
  - goodness-of-fit: 2.1% for best-fit and 1.2% for standard model hypothesis (statistical only)
- Analysis on 1 fb^{-1} dataset will provide more insight

Extraction of f_+



- Create templates of $\cos\theta^\star$ for different f_+ values ($t\bar{t}$)



- Create templates for the background (left: W+jets, right: QCD)

Calculate a binwise Poisson likelihood as function of f_+:

$$\mathcal{L}(f_+) = \prod_{i=1}^{N_{bins}} (\mu_i(f_+) + b_i)^{n_i} \cdot \frac{\exp[-(\mu_i(f_+) + b_i)]}{n_i!}$$

Systematic uncertainties

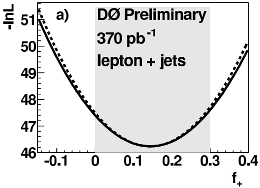
- Systematic uncertainties studied using ensemble tests

Source	lepton+jets	dilepton	combined
Top quark mass	0.033	0.070	0.042
Jet energy scale	0.023	0.039	0.027
Template statistics	0.030	0.024	0.024
$t\bar{t}$ model	0.010	0.018	0.012
Background model	0.014	0.007	0.011
Calibration	0.010	0.010	0.008
Total	0.054	0.087	0.058

- Dominant systematic uncertainties can be reduced further
  - Top quark mass varied by ± 5 GeV, while world average already improved to ± 2.3 GeV
  - Template statistics can be improved with more Data and MC

Combined Result

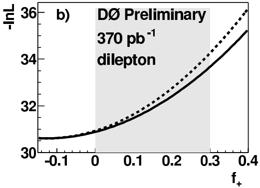
lepton+jets



$0.14 \pm 0.09 \pm 0.05$

+

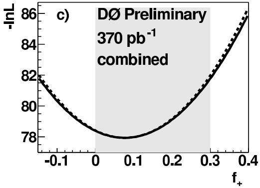
dilepton



$-0.12 \pm 0.16 \pm 0.09$

=

combined



$0.08 \pm 0.08 \pm 0.06$

< 0.24 @ 95% CL

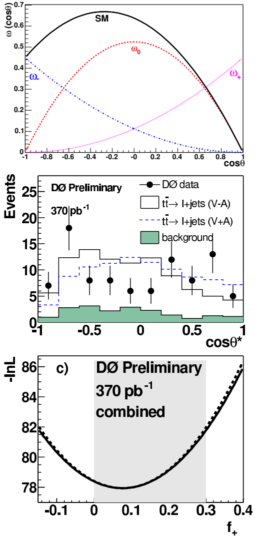
- Independent dataset $\Rightarrow$ statistical combination easy
  - weighted average of individual results
- Combined result excludes pure $V + A$ interaction

Summary and Outlook

- Decay angle in W restframe is sensitive to the fraction of right handed W bosons
- Two different decay channels: ℓ+jets and dilepton
- Reconstruction of $\cos\theta^\star$ in both channels
- Combined result (f_0 fixed to 0.7):

$$f_+ = 0.08 \pm 0.08(stat.) \pm 0.06(syst.)$$

- Outlook:
  - Publication based on this dataset/analysis in preparation
  - Analysis with > 1 fb^{-1}
  - Measure f_0 and f_+ simultaneously



Backup slides

Theoretical models that include a V+A contribution

- Left-right symmetric models:

$$SU(2)_L \times SU(2)_R \times U_Y(1)$$

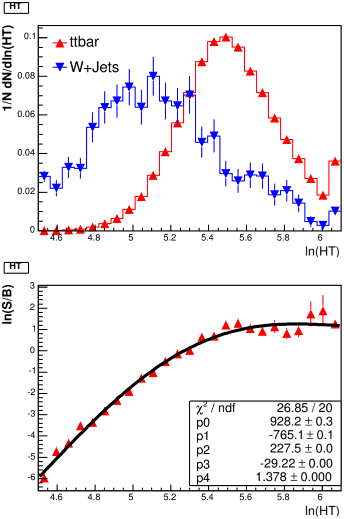
- Minimal SUSY $SO(10)$ model
  - Could explain the mixing angles in the neutrino sector
  - Contains left-right symmetric unification group
- “Mirror fermions”
  - Each fermion in the SM has a mirror fermion ($m \sim 500$ GeV) that has the same quantum number but opposite handedness

Return

Topological discriminant

- Building the discriminant
  - Transformation of the input variables
  - Calculate logarithm of the ratio S/B
  - Fit this ratio with polynomials
- The discriminant is then defined as

$$\mathcal{D} = \frac{\exp\left(\sum_i [\ln(S/B)]^i_{\text{fit}}\right)}{\exp\left(\sum_i [\ln(S/B)]^i_{\text{fit}}\right) + 1}$$



Signal Monte Carlo

- 7 dedicated Monte Carlo Samples (ALPGEN) with different values of f_+: $f_+ = 0.00 \ldots 0.30$ in steps of 0.05
  - f_0 is fixed at the predicted value of 0.70
- Possible interference term between $V - A$ and $V + A$ interaction negligible $\sim (m_b/m_t)^2$
  - All f_+ values can be generated by a linear combination of $V - A$ and $V + A$
  - Interpolate all Monte Carlo samples to create $V - A$ and $V + A$ samples
- Increased precision on $\cos\theta^\star$ distribution