Studies of top quark properties at the D0 experiment

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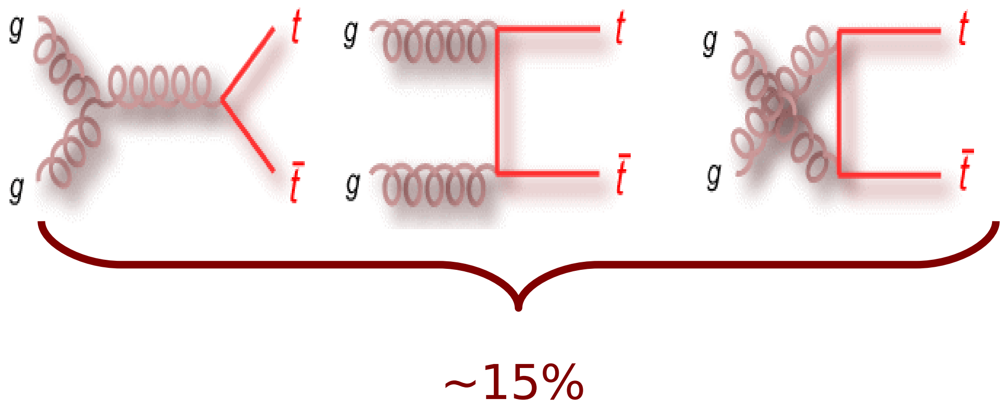
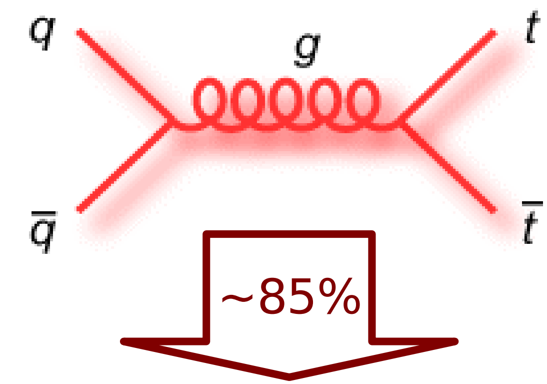
Introduction

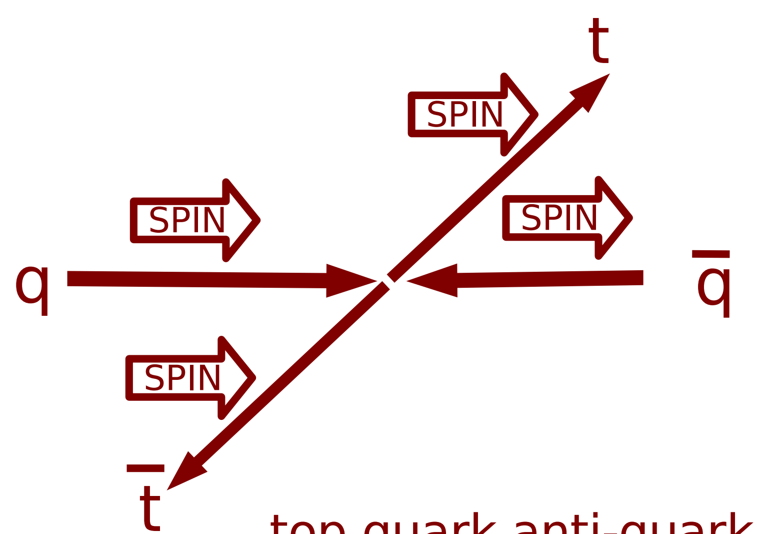
- One of the important question in top physics: is the observed top quark is the Standard Model (SM) top quark?
- We believe that top quark is standard mainly because of
  - top mass is in the good agreement with SM constrains. See update measurement at this conference:
    - today 11:00: mass measurement @ CDF and D0
    - today 16:00: electroweak fit results
  - top pair production cross section is in ~10% agreement with QCD predictions
  - electroweak production of single top quark is in the agreement with SM prediction
  - The top quark is the best place to search for the non SM contributions, because of its high mass
  - Content
    - Spin correlation in top antitop events
    - W helicity and search for the anomalous top quark coupling
    - Forward-backward charge asymmetry in top quark pair production (updated measurement)

Spin Correlation



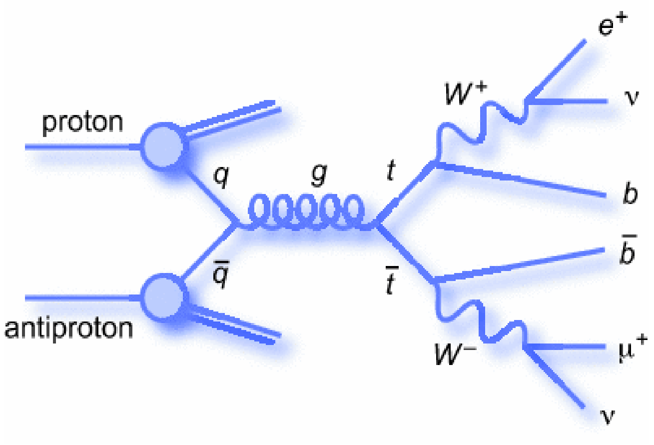


- Top quark has a very short life-time (10^{-25} sec), so it decays before depolarization or hadronization. This mean that spin information transmitted to the decay products (W boson, b quark).
- Top pair production is dominated by the quark anti-quark annihilation at Tevatron.
- The observed spin correlation value may be affected by the non SM scenario.



top quark anti-quark rest frame

- Use dilepton final state for this measurement (ee, $\mu\mu$ or eμ, two high p_T isolated leptons, 2 high p_T jets, topological selection to reduce background contribution)
  - integrated luminosity: 1.1 – 4.2 fb^{-1}



- Use "beam basis" for calculation: angles are measured relative to the beam direction in top (anti)quark rest frame.

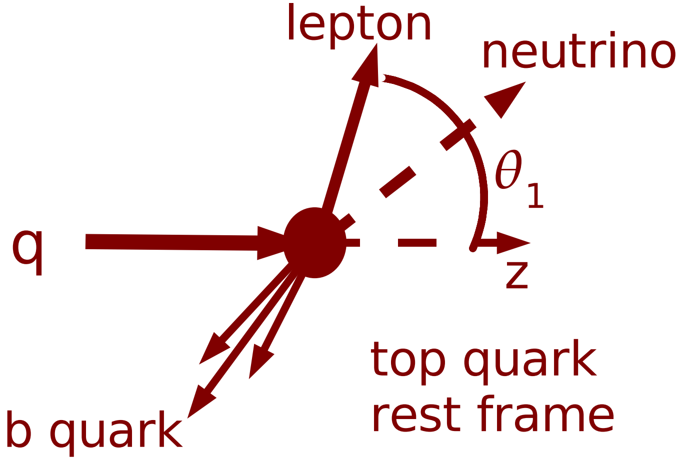
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - C\cos\theta_1\cos\theta_2)$$

coefficient	LO	NLO
C	0.928	0.777

W. Bernreuther, A. Brandenburg, Z. G. Si and P. Uwer, Nucl. Phys. B 690, 81 (2004)

- Make templates for different C values using "reweighting technique"

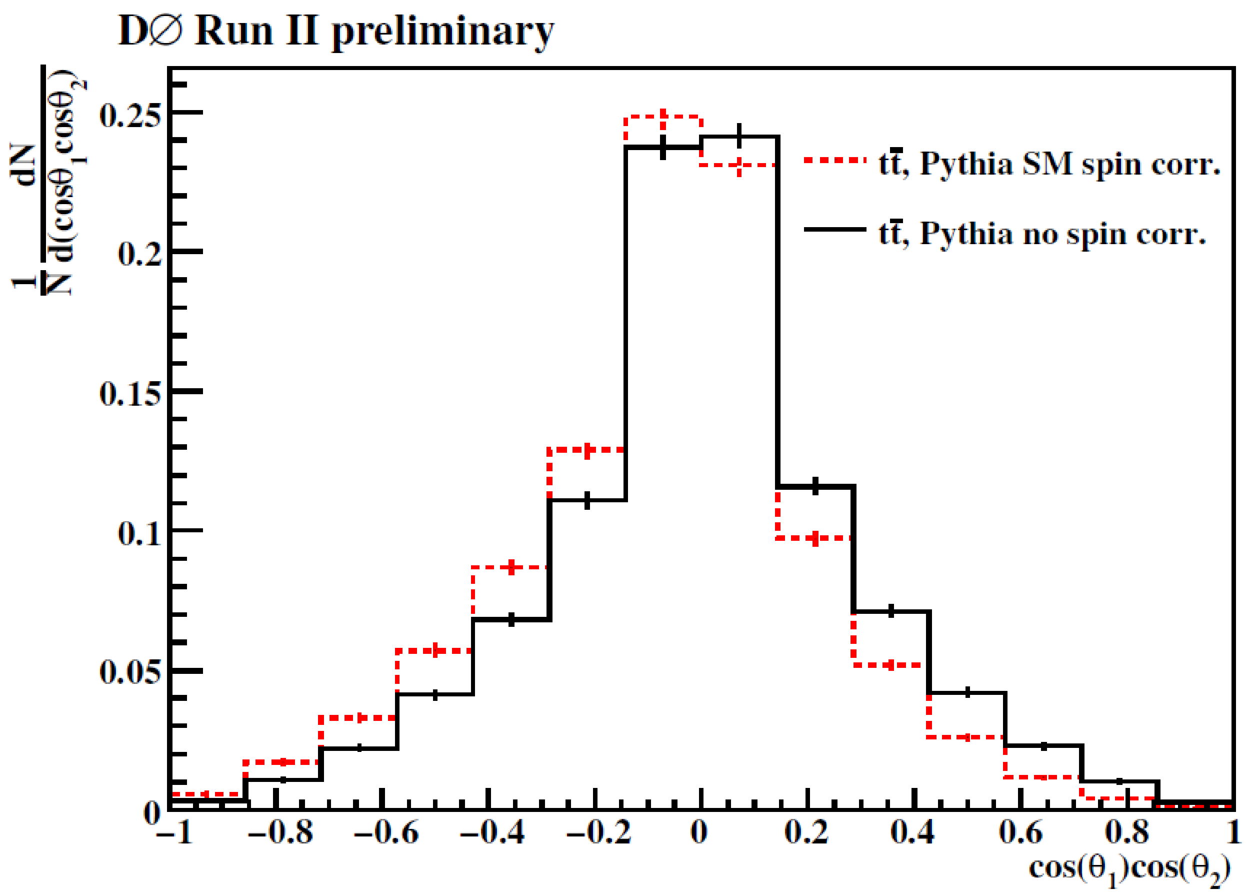
- Compare to data using Maximum Likelihood fit



Spin Correlation: Simulation

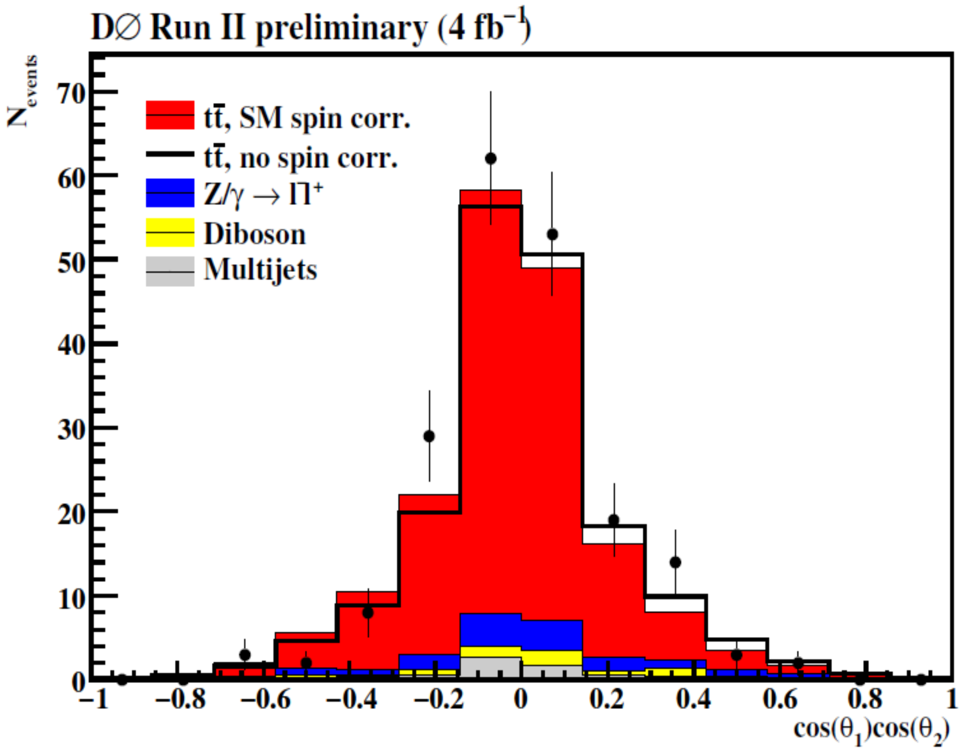
- Using pythia generator (no spin correlation)
- Introduce spin correlation by reweighting each event with

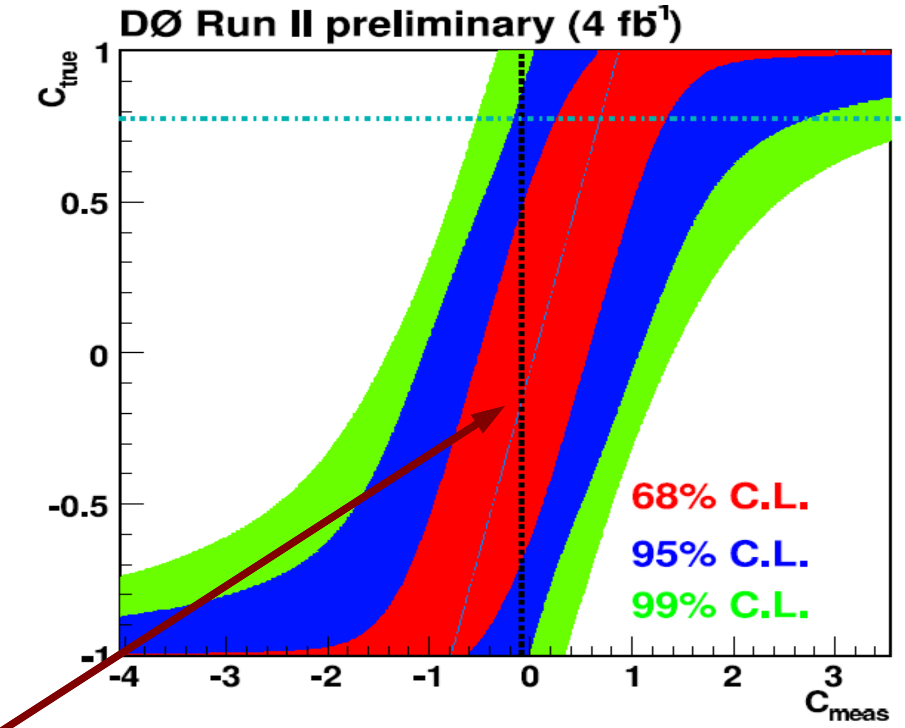
$$w_r(\cos\theta_1 \cos\theta_2) = \frac{1}{4}(1 - C \cdot \cos\theta_1 \cos\theta_2)$$



Spin Correlation: Final State Reconstruction

- Dilepton channel is underconstrained, but we need to know full event kinematics : use constrain from top quark and W boson masses + "neutrino weighting" technique
  - see description of this techniques in a presentation from A. Grohsjean "Precision measurement of the top quark mass and width with the D0 detector" later today
- Build distribution for all possible neutrinos rapidities and use mean value of $\boldsymbol{cos\theta_1 cos\theta_2}$ to produce templates.
- Use maximum likelihood method to fit distribution in data with templates
- Systematic uncertainties are included by varying the template distributions and nuisance parameters incorporated into the maximum likelihood fit





$$C = -0.17^{+0.64}_{-0.53}\,(\text{stat} + \text{syst})$$

SM beam line basis C = 0.777

- Main uncertainties are:
  - statistical ~0.5
  - signal modeling ~0.2
  - top mass dependence ~0.2
- Feldman-Cousins prescription is used for limit setting

More details: D0 note 5950-CONF

W boson Helicity Studies

- V-A structure of t→Wb vertex in SM dictates small right handed polarization of W boson
  - non SM physics will enhance this contribution
- Distinguish between different W helicity state, by reconstructing angle of the W decay products

Longitudinal:

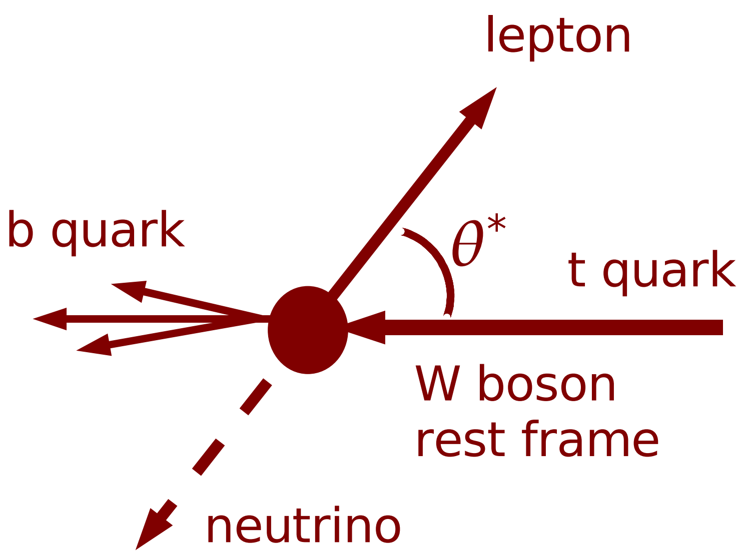
$$f_0 = \frac{\Gamma(t \to W_{\lambda=0} b)}{\Gamma(t \to W b)} \qquad SM : 69.6\%$$

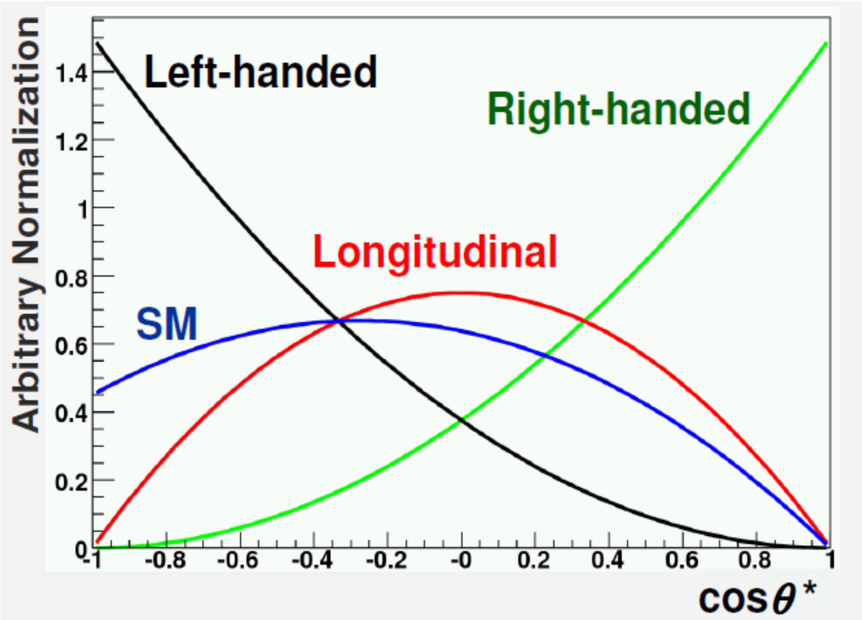
Left-handed:

$$f_- = \frac{\Gamma(t \to W_{\lambda=-1} b)}{\Gamma(t \to W b)} \qquad SM : 30.3\%$$

Right-handed:

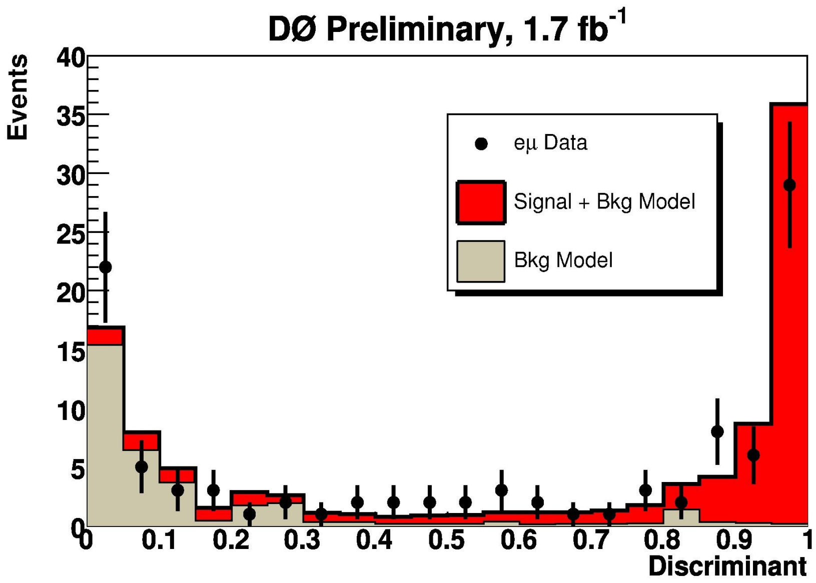
$$f_+ = \frac{\Gamma(t \to W_{\lambda=+1} b)}{\Gamma(t \to W b)} \qquad SM : 0.1\%$$

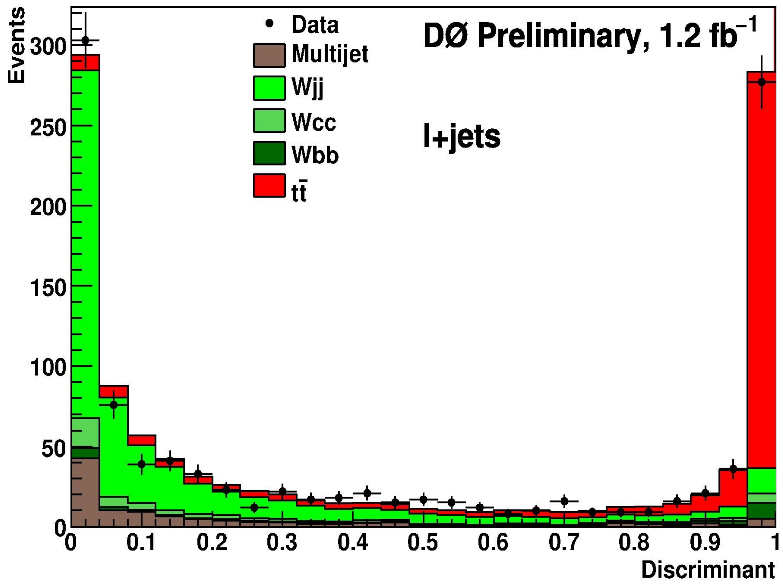




W Helicity: Data Samples

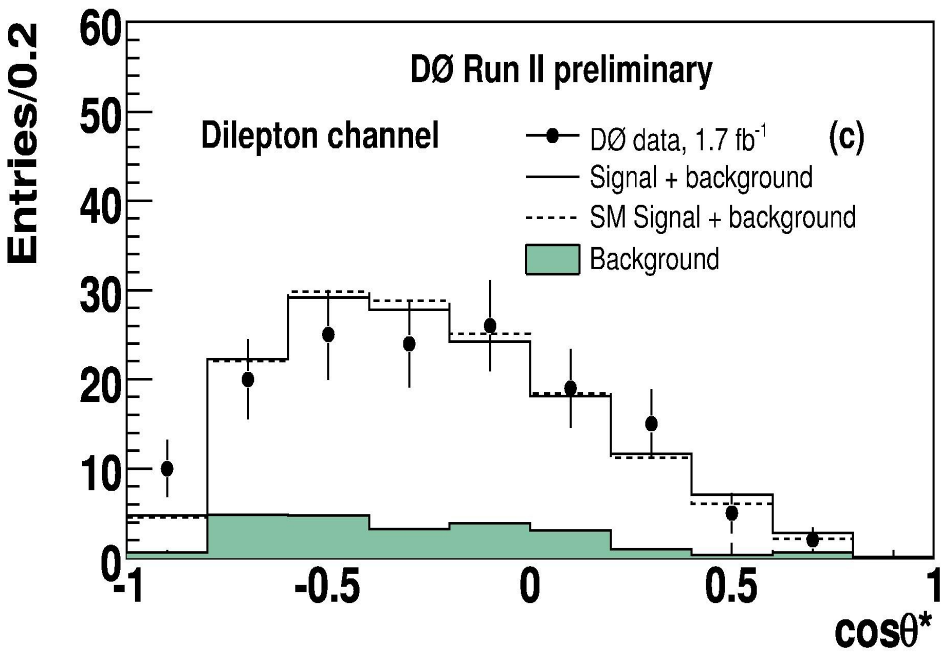
- Dilepton samples
  - ee, $\mu\mu$ or eμ, two high p_T isolated leptons, 2 high p_T jets, multivariate likelihood discriminant to enhance purity of the sample.
  - integrated luminosity: 1.1 – 2.7 fb^{-1}
- Lepton + jets samples
  - e+jets, μ+jets, high p_T isolated lepton, 4 high p_T jets, multivariate likelihood discriminant to reduce background contribution.
  - integrated luminosity: 2.2 fb^{-1}
- MC:
  - Alpgen+Pythia generator
  - generate each of three W boson helicity by reweighting $cos\theta^*$ distribution.



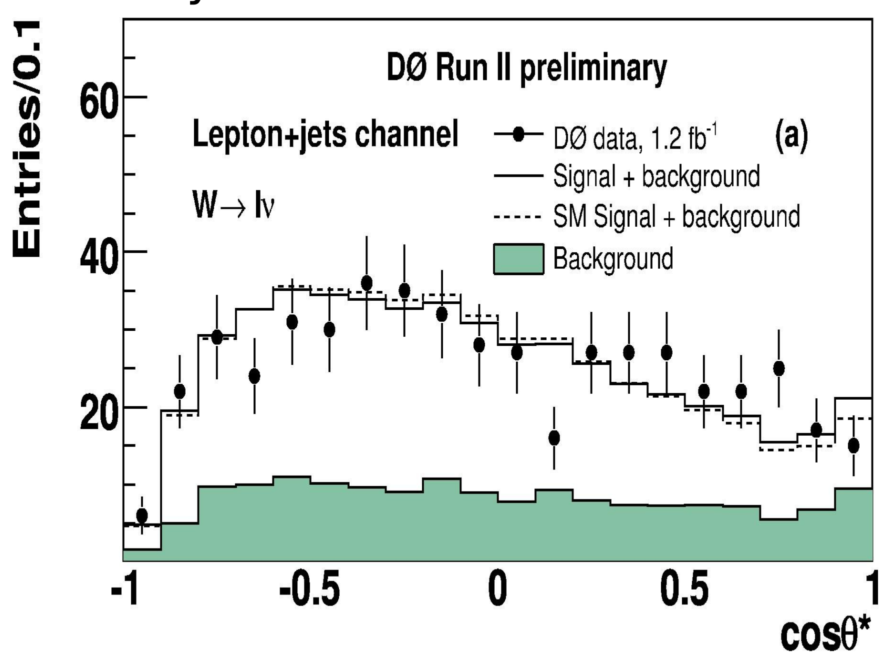


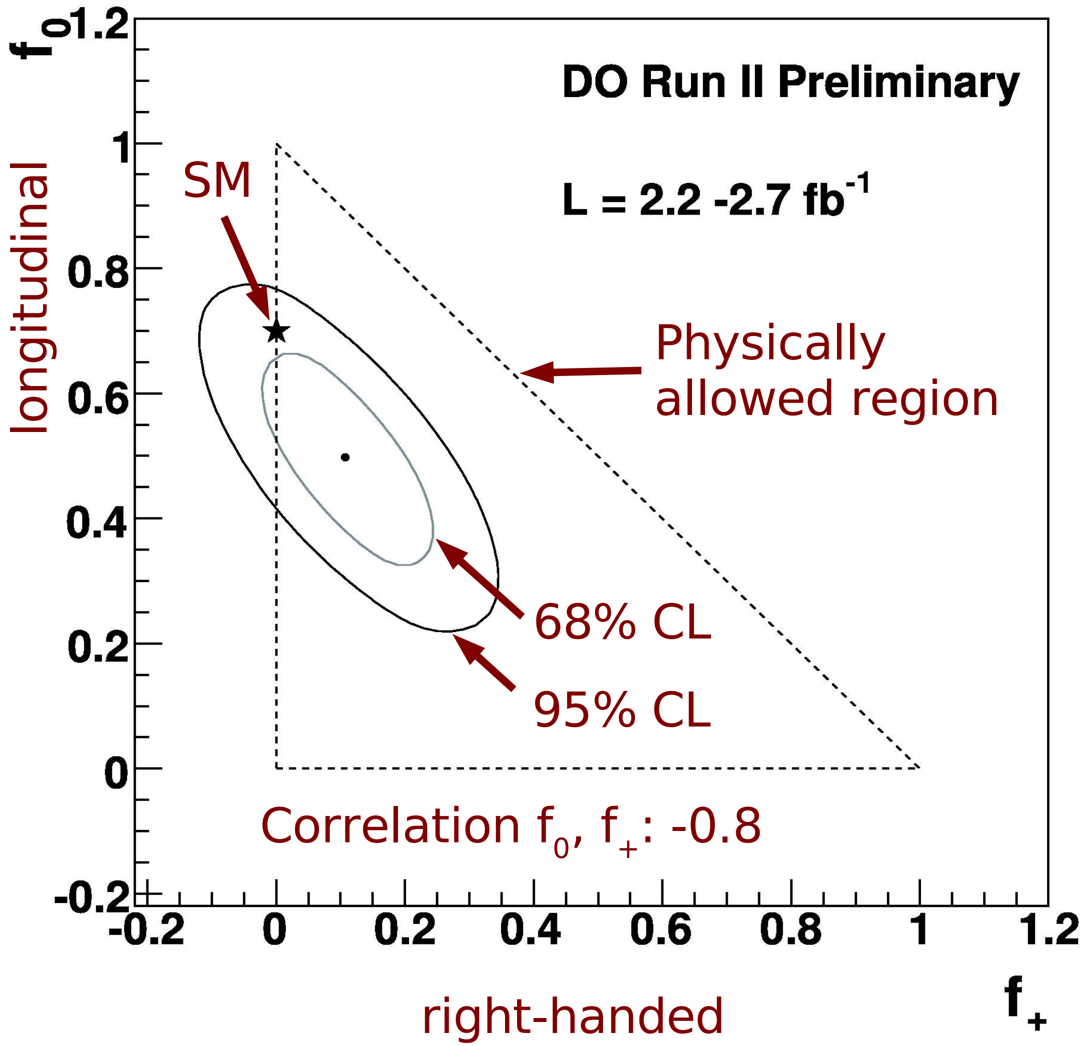
W Helicity: Final State Reconstruction

- Dileptons final state
  - Using top quark mass, W boson mass and two missing E_T projections to constrain final state
  - 8 solutions are possible
  - additionally smear object within their resolution 500 times per event: “resolution sampling”
  - average all solutions



- Lepton+jet final state
  - Use top quark mass and W boson mass constrains to reconstruct full event kinematic
  - Fit partons to the measured objetcs and from 12 available combinations choose one with best fit χ^2 parameter
  - Use both leptonic and hadronic W decays





- Binned Poisson likelihood is constructed $L(f_0, f_+)$ for the data to be consistent with the sum of signal and background templates.
- Main systematics uncertainties are :
  - Signal modeling :underlying event, additional collisions, MC generator
  - Background modeling: shape and yield in low discriminant sample
- *More details: D0 Note 5722-CONF*

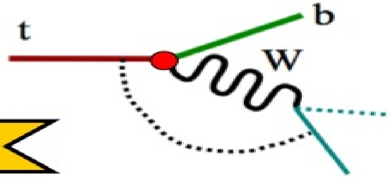
Longitudinal: $f_0 = 0.490 \pm 0.106\ (\text{stat.}) \pm 0.085\ (\text{syst.})$

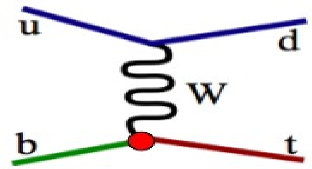
Right-handed: $f_+ = 0.110 \pm 0.059\ (\text{stat.}) \pm 0.052\ (\text{syst.})$

Search For Anomalous Top Quark Couplings

W helicity

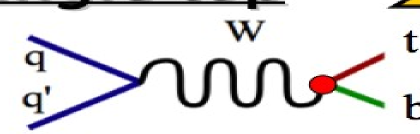
2.7 fb^{-1}





single top

1.0 fb^{-1}



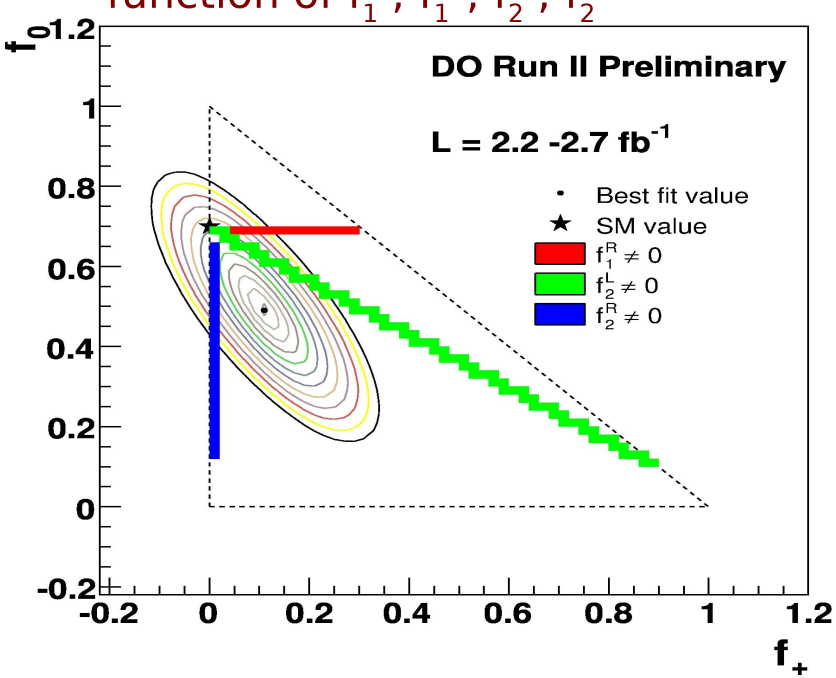
- Using CP-conserving effective Lagrangian for Wtb vertex as

$$\mathcal{L} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}V_{tb}(f_1^L P_L + f_1^R P_R)tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}V_{tb}}{M_W}(f_2^L P_L + f_2^R P_R)tW_{\mu}^{-} + \text{H.c.}$$

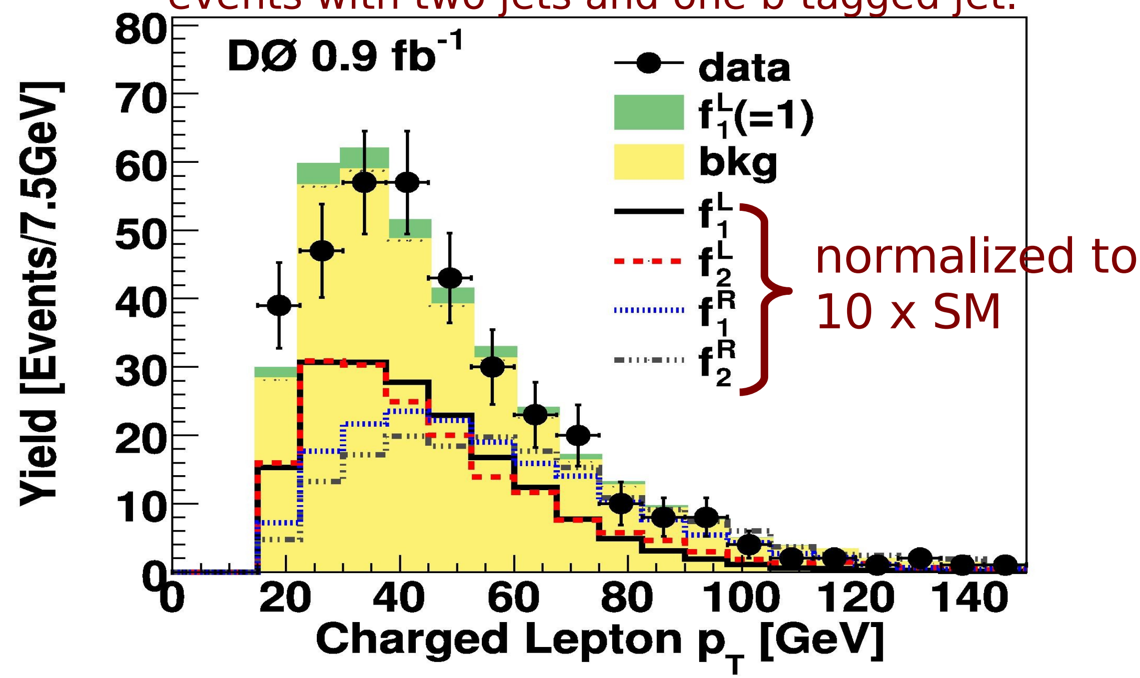
SM — Right-handed vector coupling — tensor couplings

$$P_L = \frac{1}{2}(1-\gamma_5) \qquad P_R = \frac{1}{2}(1+\gamma_5)$$

Reinterpret W helicity fit as a function of f_1^L, f_1^R, f_2^L, f_2^R



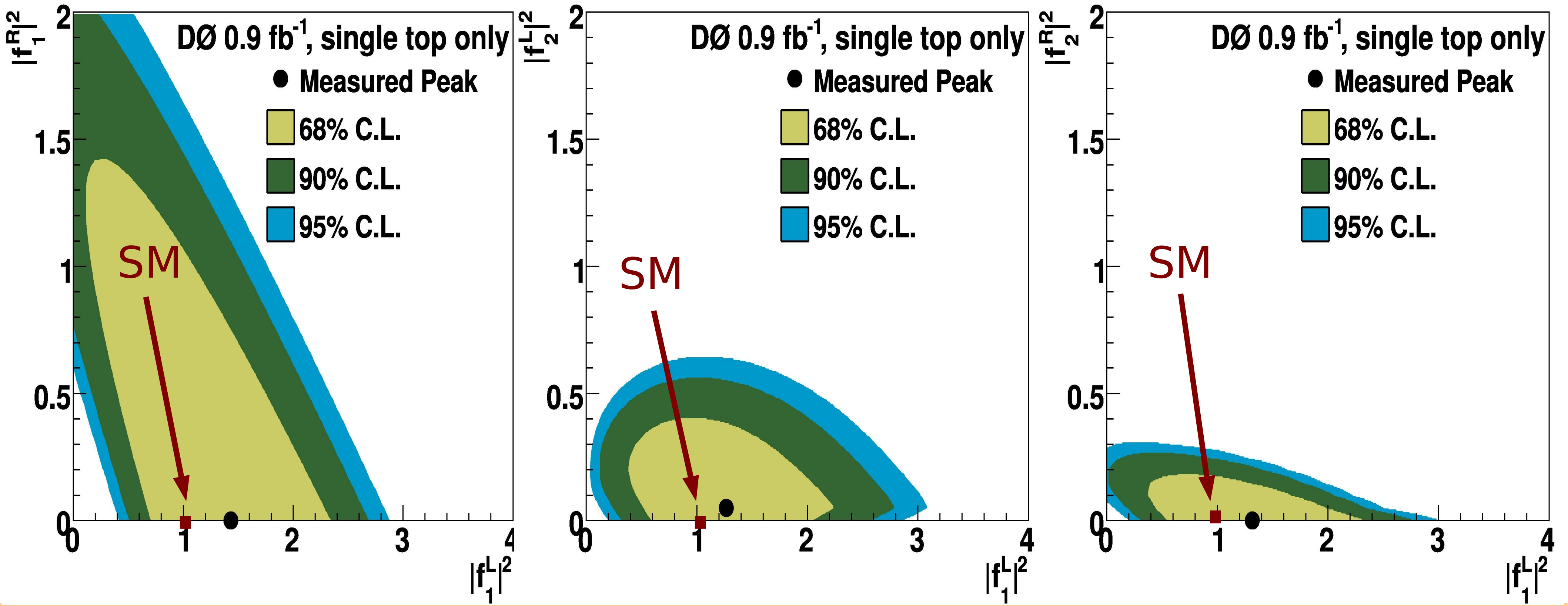
Single top production plus background for events with two jets and one b-tagged jet.



Anomalous Coupling: Combination

- Combine W helicity likelihood with the result of the anomalous couplings search in the single top-quark final state in a Bayesian statistical analysis, yielding a two-dimensional posterior probability density as a function of two form factors.
- Limits on f_1^R, f_2^L and f_2^R are extracted by projecting the two-dimensional posterior on the corresponding form factor axis

Single top only PDFs



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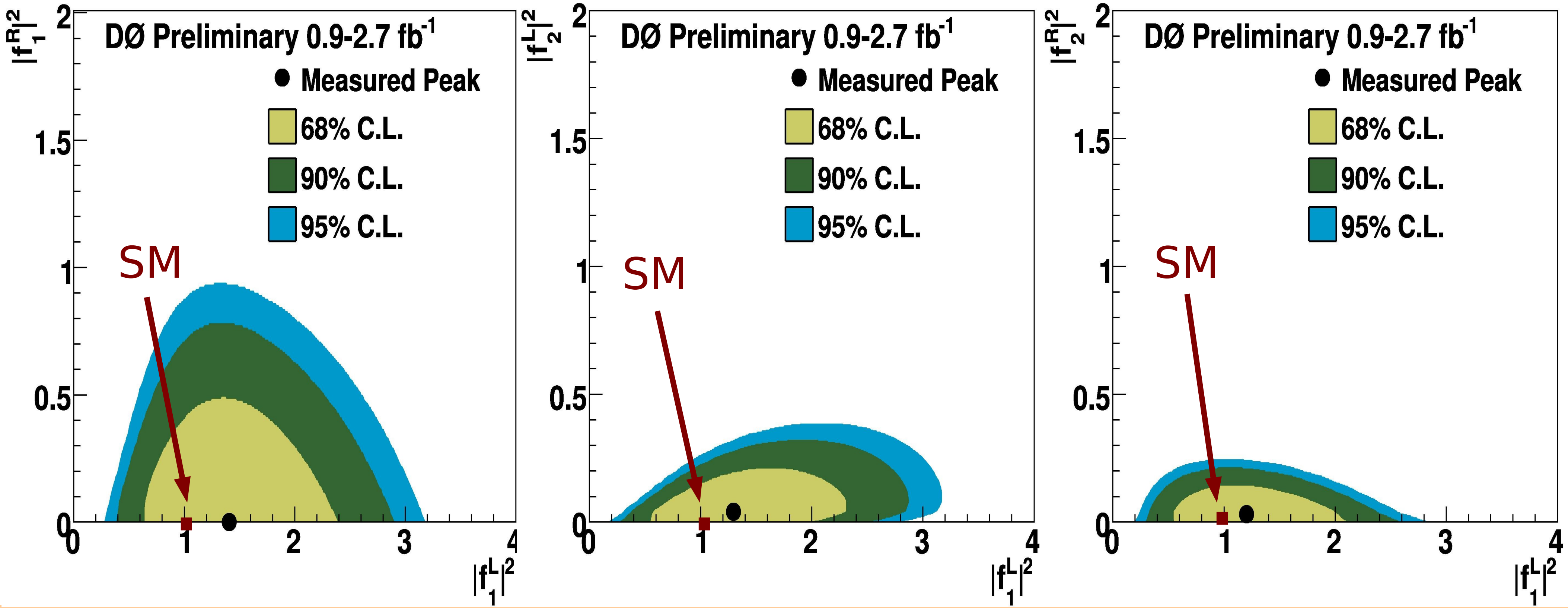
Combined W helicity + single top posterior PDFs



Anomalous Couplings: Results

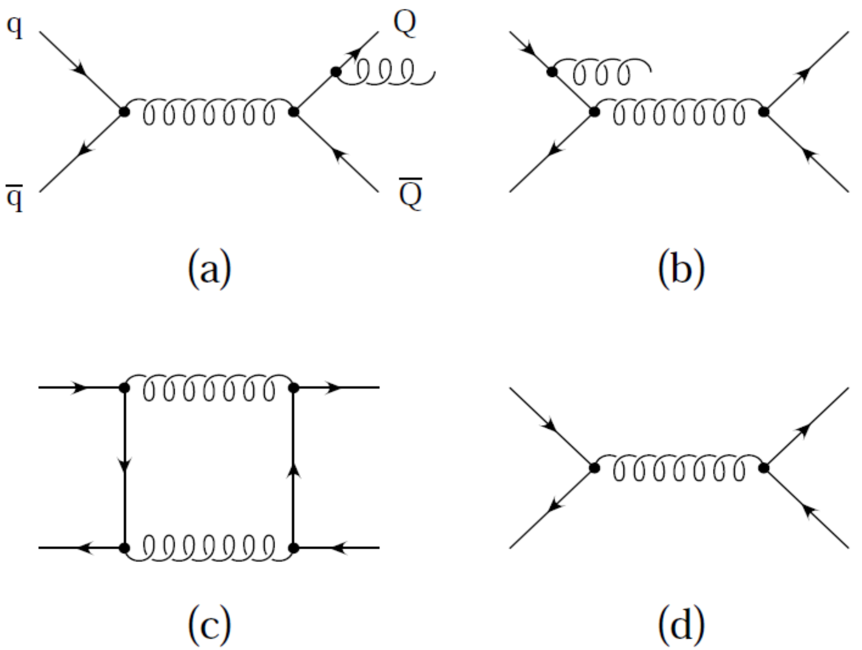
Measured values of the form factors for anomalous Wtb couplings, with uncertainties and upper limits at 95% C.L. for three scenarios.
integrated luminosity
- single top analysis: 0.9 fb^{-1}
- W helicity measurement: 1.1 – 2.7 fb^{-1}

Scenario	Coupling	Coupling limit if $f_1^L = 1$
(f_1^L, f_1^R)	$\|f_1^L\|^2 = 1.36^{+0.56}_{-0.46}$	
	$\|f_1^R\|^2 < 0.72$	$\|f_1^R\|^2 < 0.72$
(f_1^L, f_2^L)	$\|f_1^L\|^2 = 1.44^{+0.65}_{-0.51}$	
	$\|f_2^L\|^2 < 0.30$	$\|f_2^L\|^2 < 0.19$
(f_1^L, f_2^R)	$\|f_1^L\|^2 = 1.16^{+0.51}_{-0.44}$	
	$\|f_2^R\|^2 < 0.19$	$\|f_2^R\|^2 < 0.20$

More details: D0 note 5838-CONF

Forward-Backward Charge Asymmetry

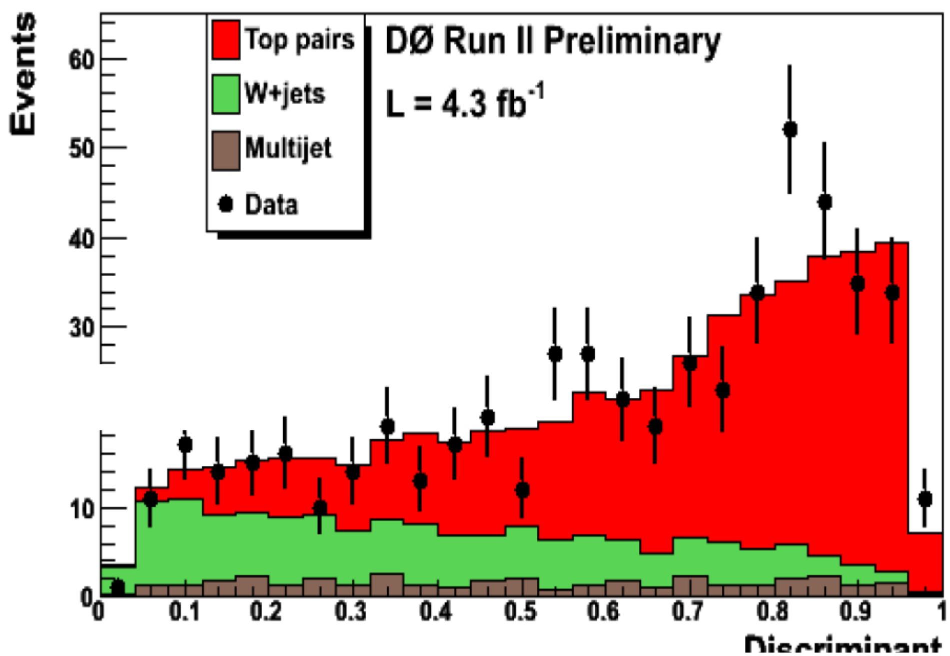
- Proton antiproton initial state is charge asymmetric, but strong interaction is not sensitive to the charge:
  - LO: kinematic distributions in production are charge symmetric
  - NLO 2→2, LO 2→3: expect (5—10)% asymmetry (higher order corrections are small)
  - NLO 2→3: reduce expected asymmetry significantly ⇒ strong dependence from phase space region
- SM asymmetry is small, so asymmetry is a sensitive variable to test the new physics contribution.
- A charge asymmetry can be observed as forward-backward asymmetry defined as



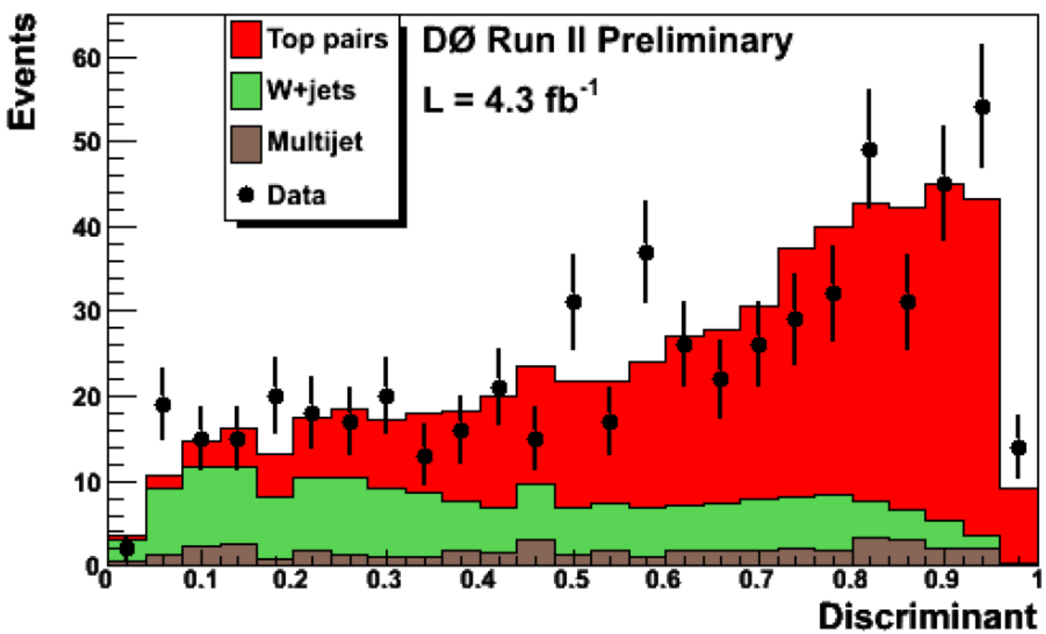
See e.g.:
- J. H. Kuhn and G. Rodrigo, Phys. Rev. D 59, 054017 (1999)
- O. Antunano, J. H. Kuhn and G.Rodrigo, Phys. Rev. D 77, (2008)

$$A_{fb} = \frac{N^{\Delta y>0} - N^{\Delta y<0}}{N^{\Delta y>0} + N^{\Delta y<0}}, \qquad \Delta y = y_t - y_{\bar{t}}$$

- Lepton + jet sample, 4.3 fb^{-1}:
  - one isolated high p_T lepton (electron or muon), at least 4 high p_T jets, at least one jet identified as originating from b quark. Missing E_T selection.
  - To estimate W+jet background, a likelihood discriminant L is defined using variables that do not bias dy for the selected signal.
- Use top and W mass constrains to reconstruct top quark pair. The best χ^2 fit parameter solution is used for each event.
- The measured asymmetry is taken from the relative fraction of events fitted with likelihood fit to the forward and backward signal templates.



discriminant output for events with $\Delta y_{rec}>0$



discriminant output for events with $\Delta y_{rec}<0$

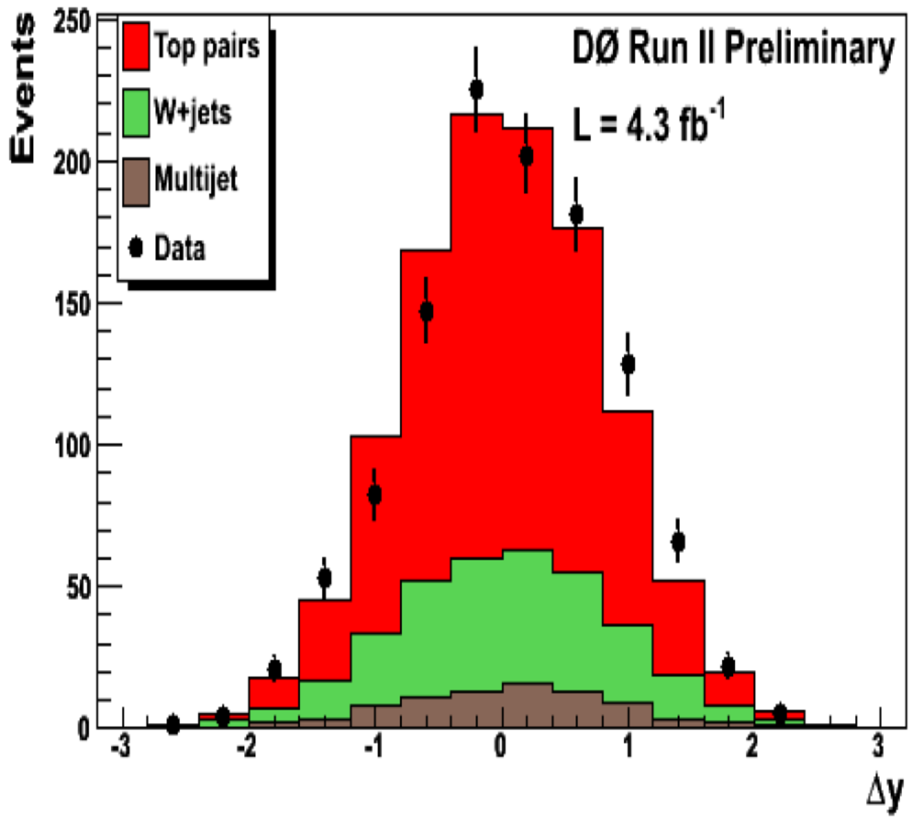
NEW!

MC @ NLO prediction for the observed asymmetry: $1^{+2}_{-1}\%$

Observed asymmetry (uncorrected for effects from reconstruction or selection):

$$A_{fb}^{obs} = 8 \pm 4(stat) \pm 1(syst)\%$$

Further work is needed to evaluate the compatibility of data with the standard model.



More details:D0 note 6062-CONF

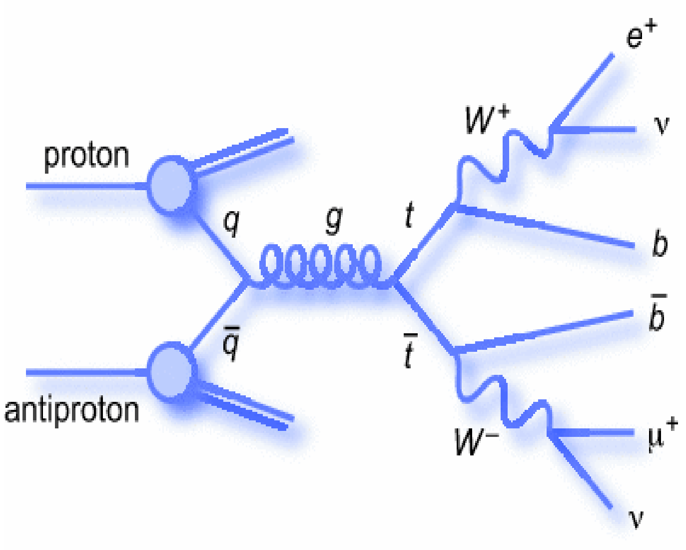
Conclusion

- Many news approaches are under development for the measurements of the top quark properties.
- Current studies of the top properties at D0 show no sign for new physics, but they are statistically limited.
- Analysis with full statistics accumulated at D0 (more than 7 fb^{-1}) are in progress and will tightening the limits on the new physics contribution.

BACK-UP

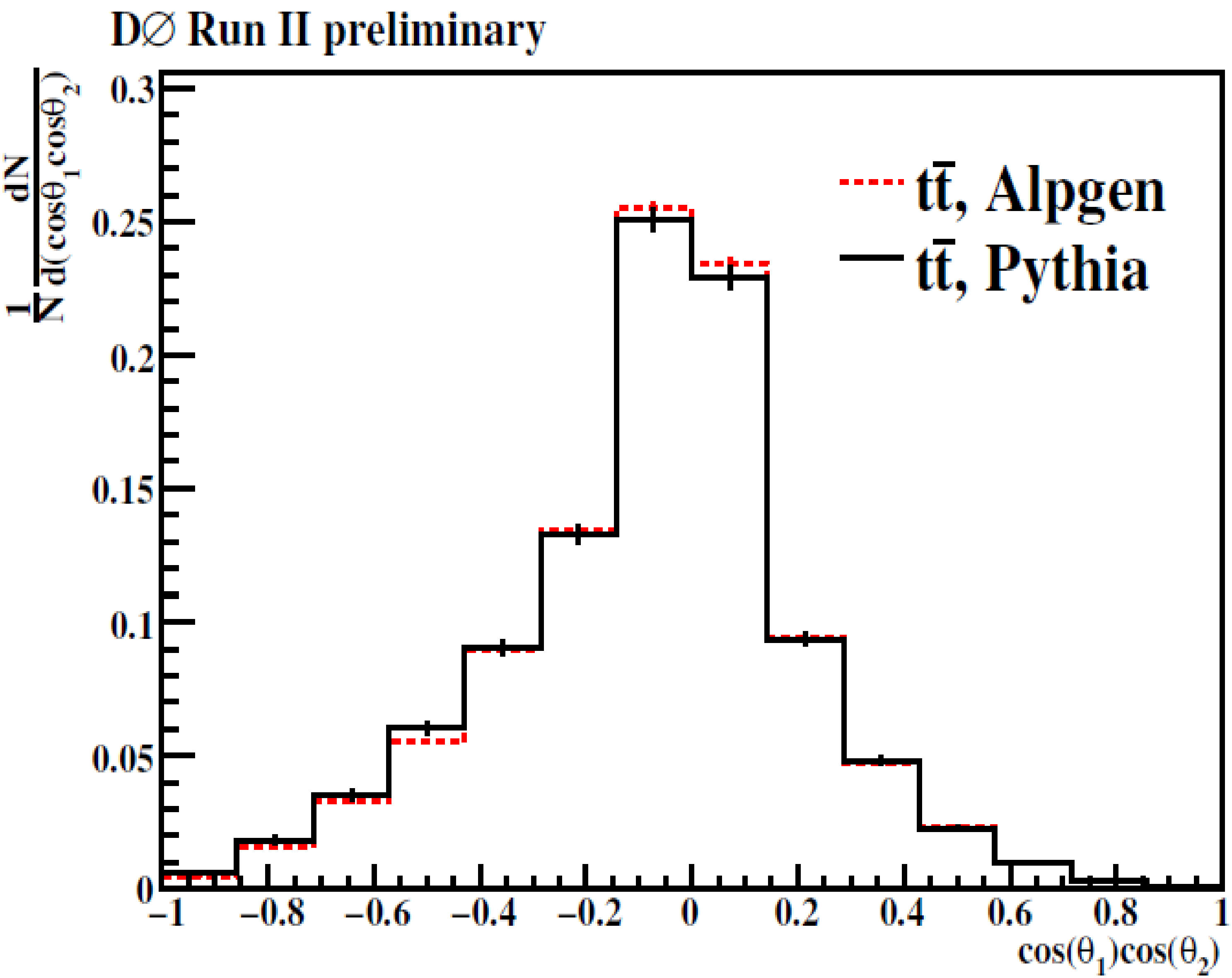
Spin Correlation: Data Samples

- Data samples
  - 2 leptons with p_T>15 GeV (electrons or muons)
  - 2 jets with p_T>20 GeV
  - Additional topological selection to enhance purity of the samples
- Luminosity used in this analysis:
  - ee and $\mu\mu$ 1.1 fb^{-1}
  - eμ 4.2 fb^{-1}



	ee	eμ	μμ
Background	3.4	24.3	5.4
Signal	11.5	140	8.3
Data	17	168	13

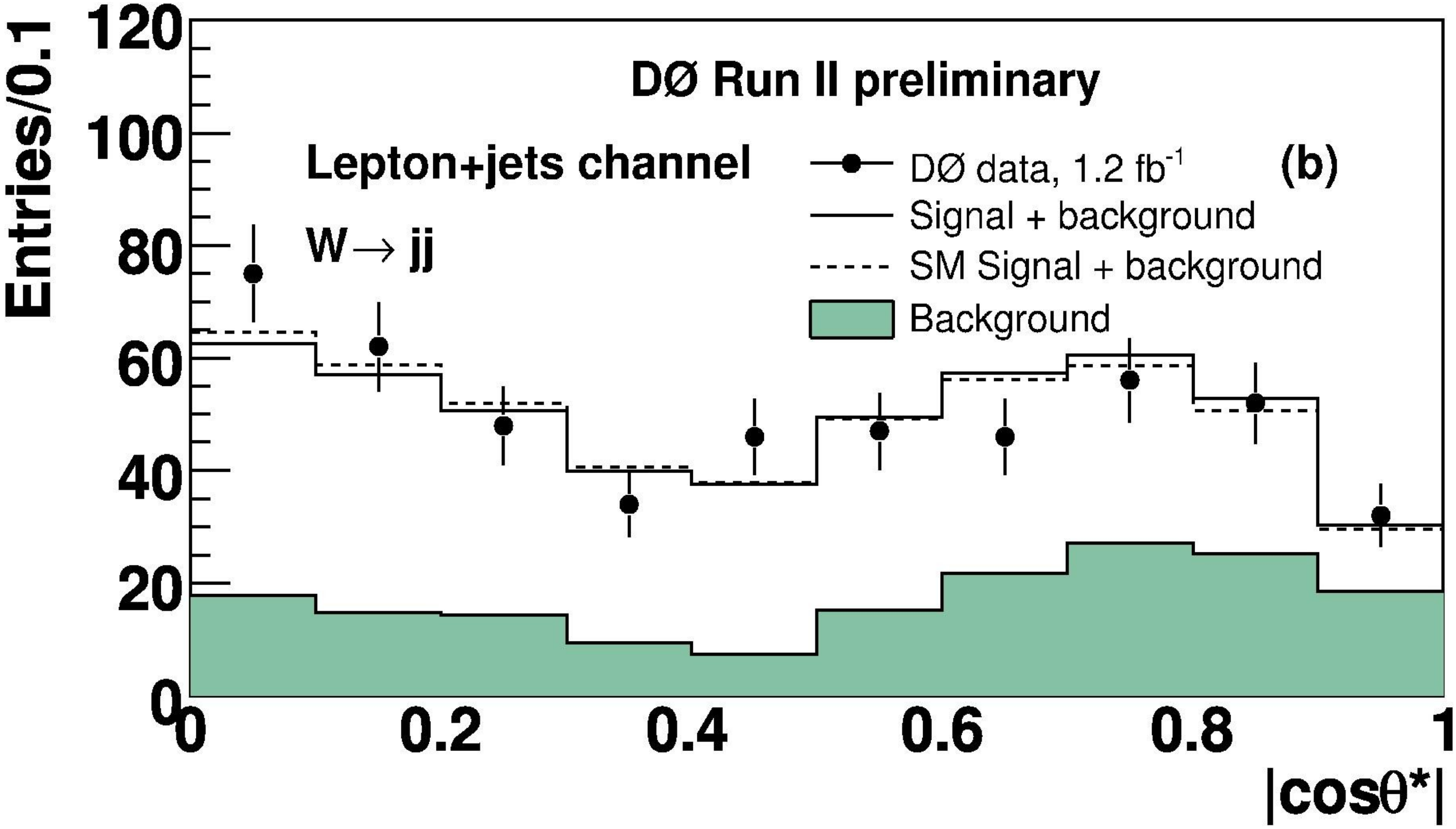
- Main backgrounds:
  - Z+ jets
  - WW, WZ, ZZ
  - instrumental background


DØ Run II preliminary
$\frac{1}{N}\frac{dN}{d(\cos\theta_1\cos\theta_2)}$
0.3
0.25
0.2
0.15
0.1
0.05
0
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
$\cos(\theta_1)\cos(\theta_2)$
$t\bar{t}$, Alpgen
$t\bar{t}$, Pythia

Spin Correlation: Uncertainties

Source	ΔC
Statistical only	+0.503 -0.510
Signal modeling ALPGEN	+0.197 -0.120
Signal modeling MC@NLO	+0.107 -0.085
Top Mass	+0.215 -0.223
Jet energy scale	+0.012 -0.022
Jet energy resolution	+0.000 -0.030
Monte Carlo background x-section	+0.008 -0.008
Monte Carlo signal & bkg branching ratio	+0.002 -0.002
Monte Carlo bkg scale factors	+0.000 -0.000
Monte Carlo statistics	+0.010 -0.010
$t\bar{t}$ cross section error	+0.008 -0.005
Luminosity	+0.002 -0.002
Total systematic	+0.312 -0.270

W Helicity: Hadronic W decays



Charge Asymmetry: Systematics

Source	Effect on Measured A_{fb}	Effect on Predicted A_{fb}
Jet identification efficiency	± 0.1	± 0.3
Jet energy scale	$+0.0/-0.2$	$+0.6/-0.0$
Jet energy resolution	$+0.0/-0.6$	$+0.3/-0.1$
Vertex requirements of jets	± 0.1	± 0.2
Additional collisions	± 0.3	± 0.3
Alternative signal model	± 0.1	not applicable
Top mass uncertainty	± 0.0	not applicable
Top pair p_T model	$+0.1/-0.0$	$+1.0/-0.0$
Monte Carlo statistics of $t\bar{t}$ signal	not applicable	± 0.9
W+jets heavy flavor fraction	± 0.0	not applicable
W+jets asymmetry	± 0.6	not applicable
Fake lepton selection rate	± 0.1	not applicable
True lepton selection rate	± 0.0	not applicable
b-tagging efficiency for heavy flavor	$+0.0/-0.1$	± 0.1
b-tagging efficiency for light flavor	$+0.0/-0.1$	± 0.0
Total	$+0.8/-1.0$	$+1.6/-1.2$