# Search for Anomalous Wtb Couplings at D0

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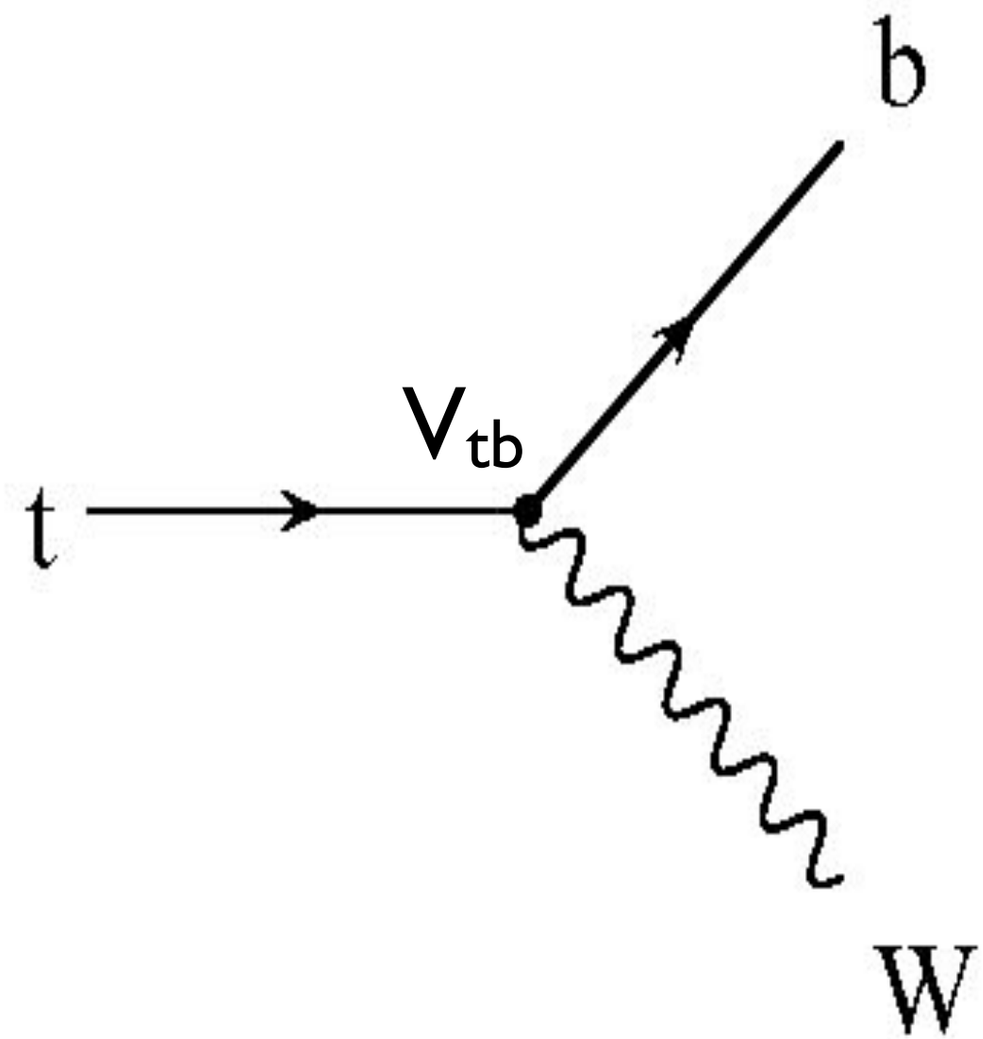
# Top-quark decay

- Top is a standard-model fermion
- It is sufficiently heavy (~173 GeV) to decay to a bottom quark and an on-shell W boson through the weak current
- The SM Lagrangian specifies that the Wtb coupling has a left-handed vector (V-A) structure, with

$$\gamma^\mu(1-\gamma^5)/2 \equiv \gamma^\mu P_L$$

in the Lagrangian



# Unless that isn't true...

- Maybe top has anomalous Wtb couplings, beyond V-A?
- Consider the general Lagrangian for the Wtb interaction:

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

  - Introduces RH vector and LH, RH tensor couplings
  - In the SM, coupling form factors $f_L^V = 1$ and $f_R^V = f_L^T = f_R^T = 0$
- If there were anomalous couplings, we would see deviations from SM predictions in measurements of
  - helicity fractions of W bosons in top decay,
  - rate of electroweak single-top production, and
  - kinematic distributions in single-top events

# Knowledge, assumptions

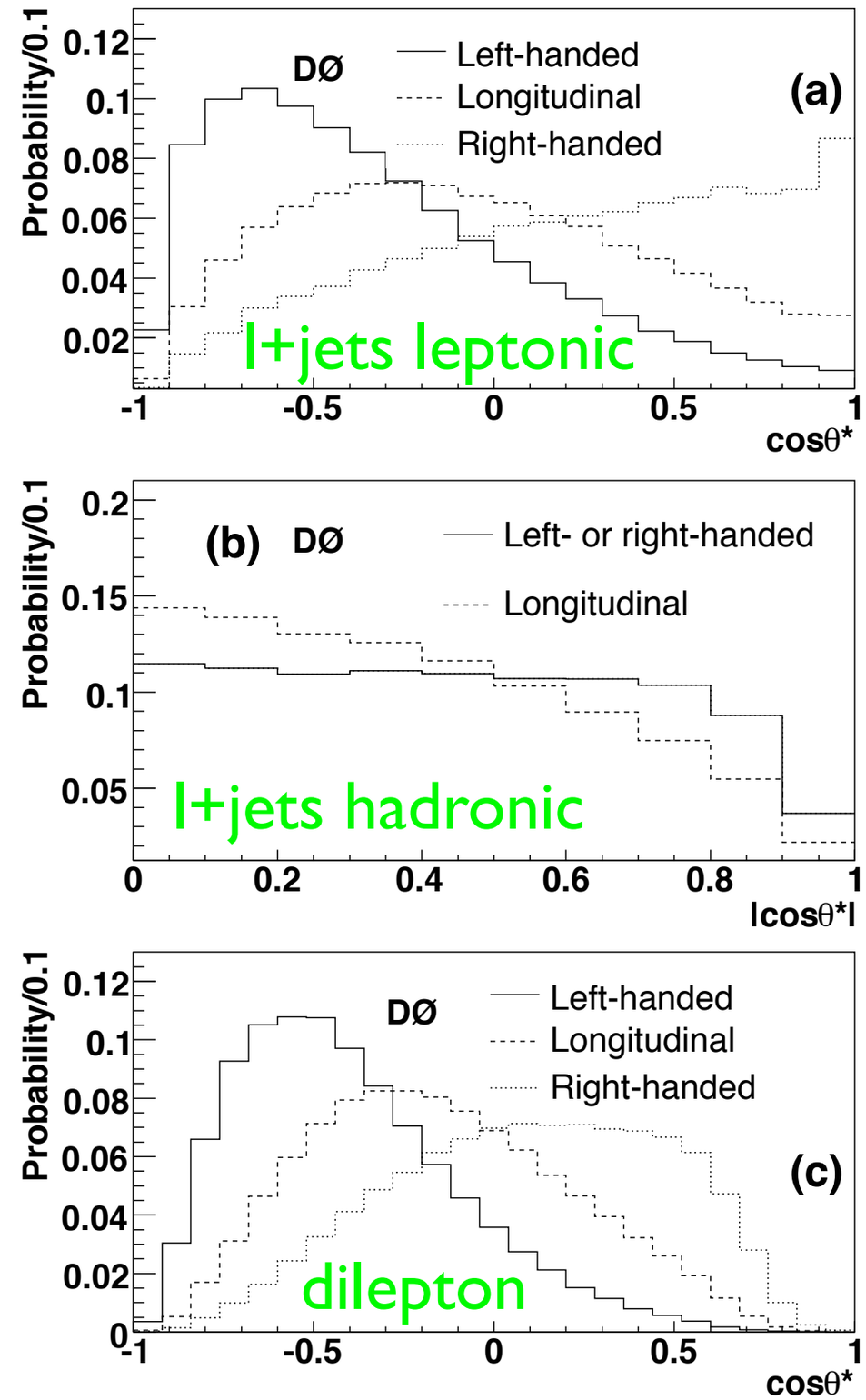
- Not enough data to constrain all four couplings at once:
  - Probe $f_L^V$ and one anomalous coupling simultaneously, while assuming other two couplings are zero
- Existing information:
  - Unitarity constraints require tensor form factors to be less than 0.5
  - $b \rightarrow s\gamma$ measurements give more stringent constraints on the couplings than can be measured directly, but only if one assumes no new physics beyond this in the bottom sector: F. Larios, M. A. Perez, and C.-P. Yuan, Phys. Lett. B **457**, 334 (1999); G. Burdman, M. C. Gonzalez-Garcia, and S. F. Novaes, Phys. Rev. D **61**, 114016 (2000); B. Grzadkowski and M. Misiak, Phys. Rev. D **78**, 077501 (2008); J. P. Lee and K. Y. Lee, Phys. Rev. D **78**, 056004 (2008), and references therein.
- Assumptions in the analysis:
  - Coupling form factors are real, implying CP conservation
  - Top quark is spin-1/2
  - Top decays almost always to Wb
  - Single top production is almost always through W exchange

# Basics

- Tevatron: $\sqrt{s}$ = 1.96 TeV, $p\bar{p}$ collisions, Run II 2001-11; ~12 $fb^{-1}$ delivered, these analyses use 5.4 $fb^{-1}$.
- D0: silicon and fiber trackers inside 2 T solenoid, liquid argon-uranium calorimeter, muon trackers/scintillator with toroid
- W helicity is studied in $t\bar{t}$ events:
  - dilepton: $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow l\nu l'\nu' b\bar{b}$ = two leptons, missing transverse energy, at least two jets
    - 319 events selected, 69 ± 10 background
  - lepton+jets: $t\bar{t} \rightarrow W^+W^-b\bar{b} \rightarrow l\nu qq' b\bar{b}$ = one lepton, missing transverse energy, at least four jets
    - 1431 events selected, 404 ± 32 background
- Single top events are selected with one lepton, missing transverse energy, two or three jets, at least one identified as b
  - Orthogonal to W helicity sample

# W helicity measurement

- Reconstruct helicity angle
  - Angle between direction opposite the top quark and direction of down-type fermion, measured in W rest frame
  - Many tools used in reconstruction: kinematic fits with constraint to top and W masses, b-jet likelihood....
  - Characteristic distributions for left, right, longitudinal W polarization
- Extract helicity fractions with binned maximum likelihood fit to data using templates for signal, background




PRD **83**, 092002 (2011)

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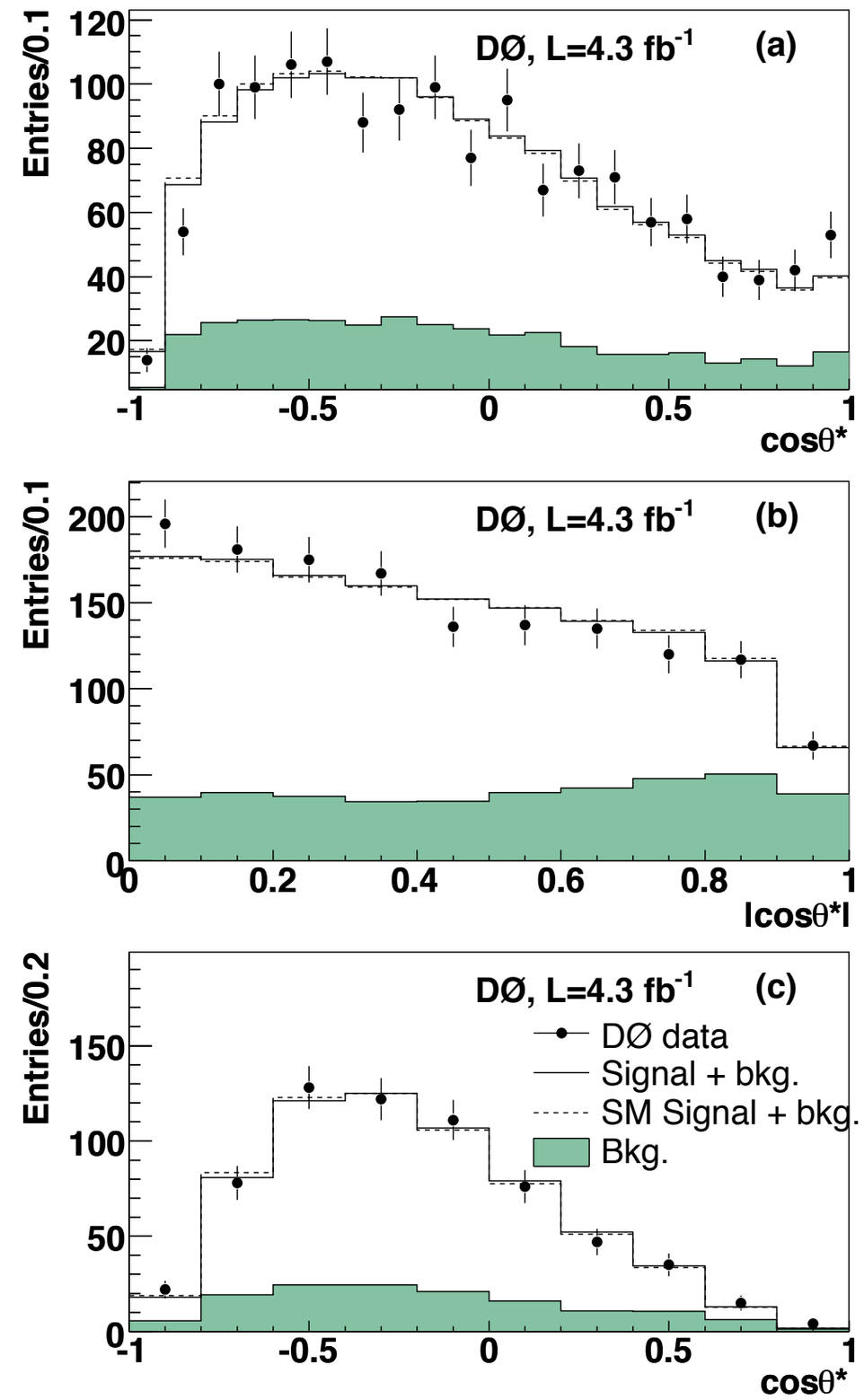
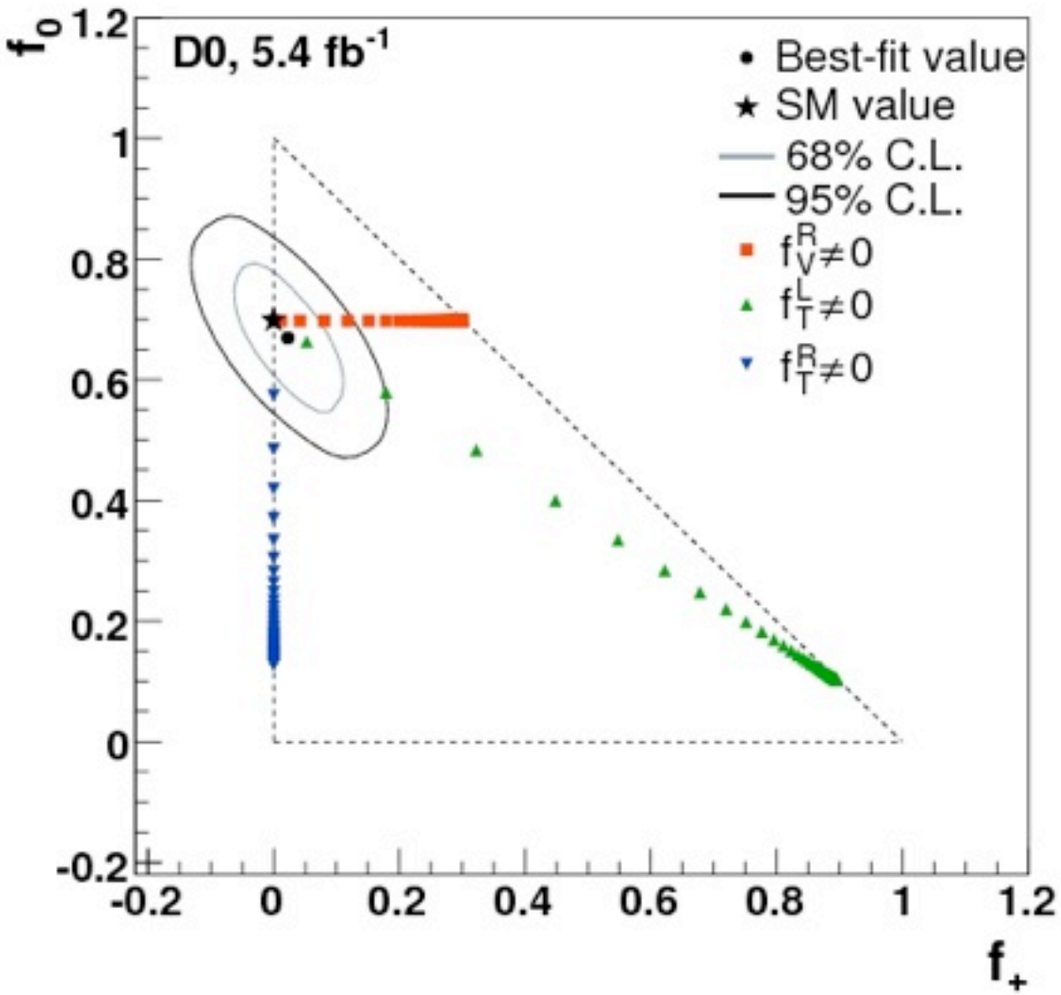
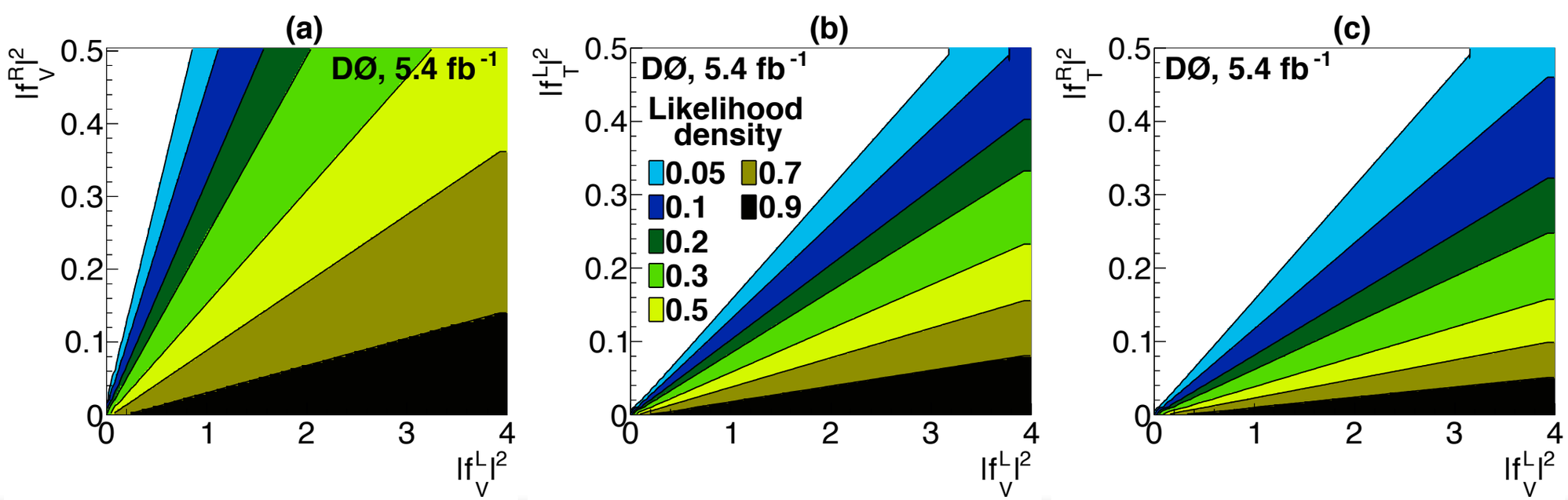



PRD **83**, 092002 (2011)

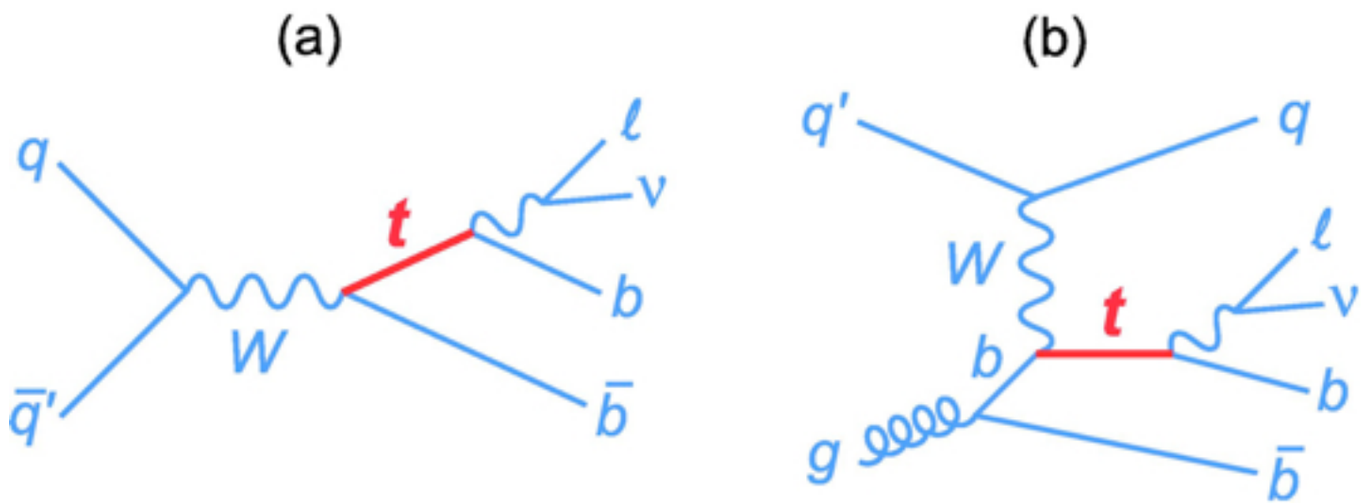
# W helicity results




- SM predicts $f_0$ = 70%, $f_-$ = 30%, $f_+ \simeq 0$
- Result agrees very well with SM
- Non-SM couplings would change the helicity fractions
- This can be used to constrain the ratios of the coupling form factors



# Single-top production rate

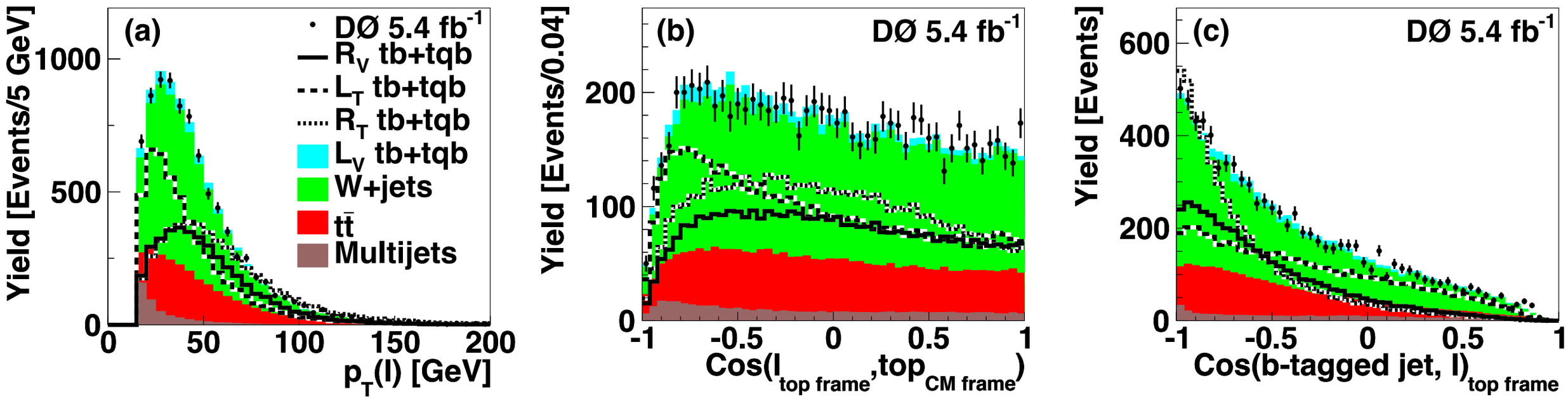



| Source | 2 jets | 3 jets |
|---|---|---|
| $tb$ $(f_{L_T} = 1)$ | 730 ± 38 | 316 ± 25 |
| $tqb$ $(f_{L_T} = 1)$ | 117 ± 6.2 | 86 ± 8.6 |
| $tb$ $(f_{L_V} = f_{L_T} = 1)$ | 607 ± 31 | 284 ± 21 |
| $tqb$ $(f_{L_V} = f_{L_T} = 1)$ | 268 ± 15 | 167 ± 16 |
| $tb$ $(f_{R_V} = 1)$ | 105 ± 6.0 | 43 ± 3.8 |
| $tqb$ $(f_{R_V} = 1)$ | 122 ± 7.2 | 61 ± 5.3 |
| $tb$ $(f_{R_T} = 1)$ | 756 ± 42 | 344 ± 27 |
| $tqb$ $(f_{R_T} = 1)$ | 103 ± 5.8 | 67 ± 6.3 |
| $tb$ (SM, $f_{L_V} = 1$) | 104 ± 16 | 44 ± 7.8 |
| $tqb$ (SM, $f_{L_V} = 1$) | 140 ± 13 | 72 ± 9.4 |
| $t\bar{t}$ | 433 ± 87 | 830 ± 133 |
| $W$+jets | 3,560 ± 354 | 1,099 ± 169 |
| $Z$+jets and dibosons | 400 ± 55 | 142 ± 41 |
| Multijets | 277 ± 34 | 130 ± 17 |
| Total SM prediction | 4,914 ± 558 | 2,317 ± 377 |
| Data | 4,881 | 2,307 |

PLB **708**, 12 (2011)

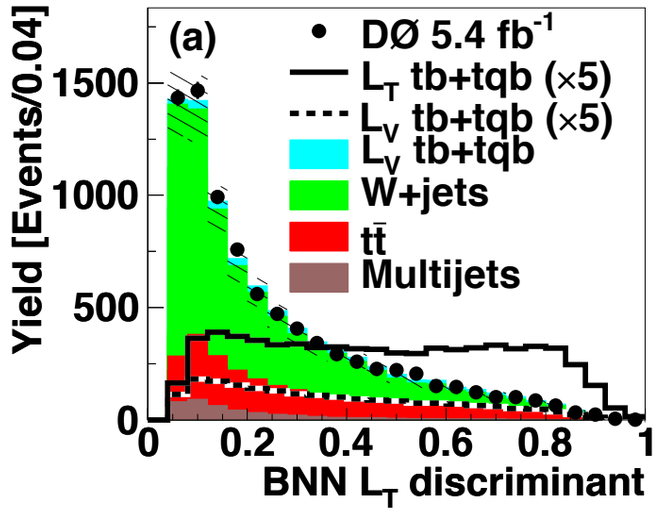
- Single top quarks are produced through Wtb coupling → anomalous couplings affect production rate
- Small signal on big W+jets background, but substantially altered by (some) anomalous couplings

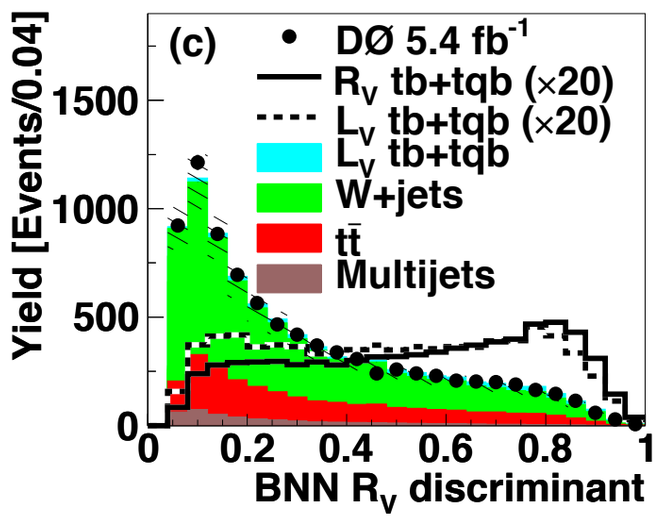
# Single-top kinematics

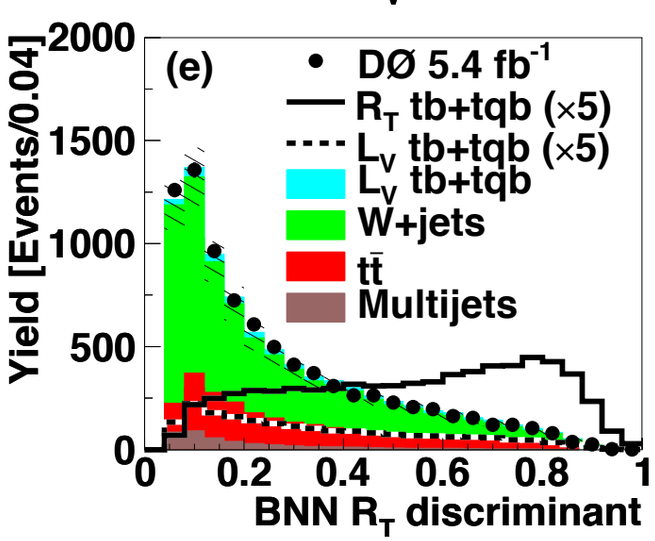



- SM single top can be distinguished from both SM backgrounds and anomalous production/decay by kinematic variables
  - And different anomalous couplings distinct from each other
  - Warning: anomalous signals in plots above are x10 SM single top!
- Use Bayesian neural network to distinguish anomalous, SM signals
  - 18-22 kinematic variables in each BNN
  - Trained with non-SM process as signal, all others as background

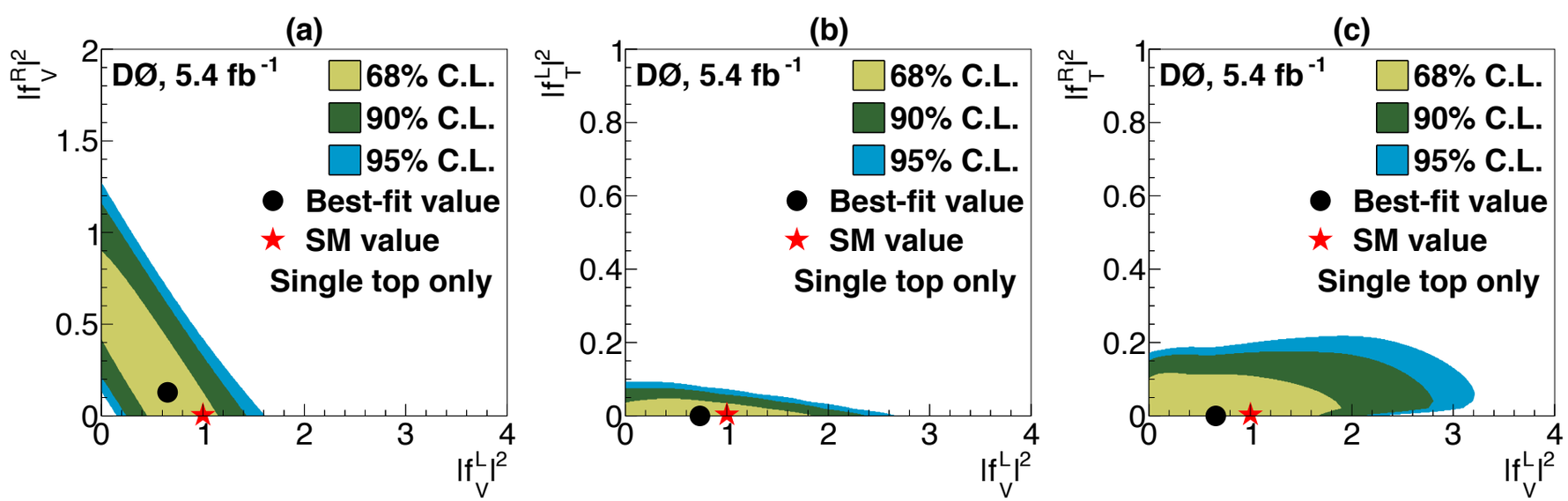
# Single-top results



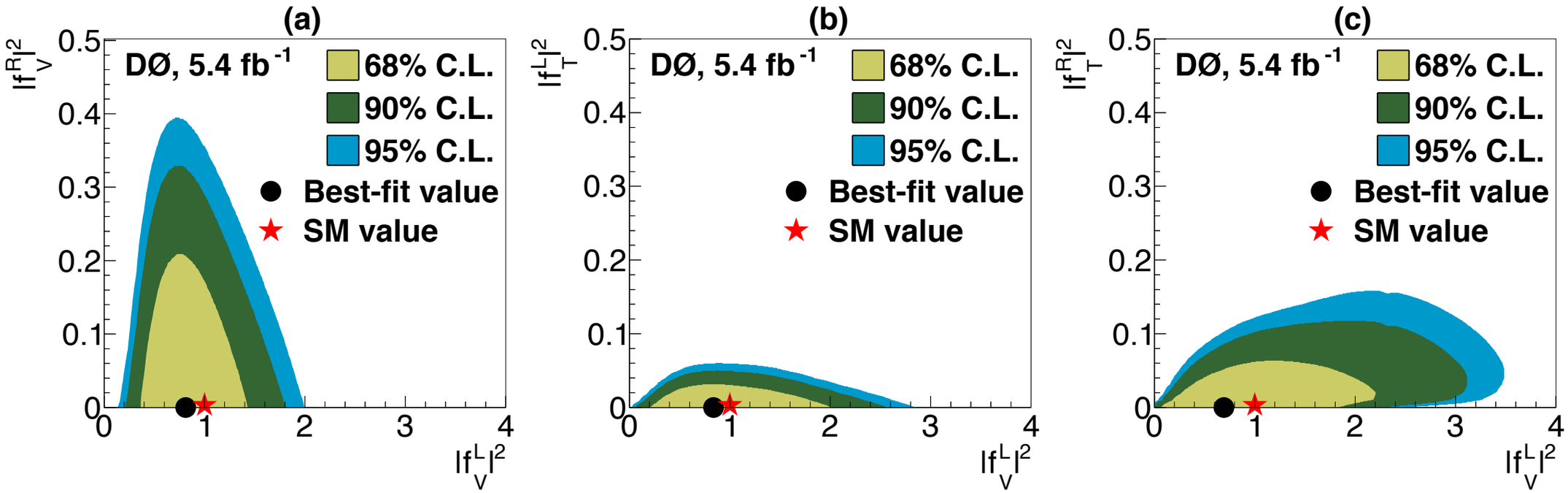




- Use Bayesian statistical approach to compare data to predictions for anomalous couplings
  - Background normalization is absolute, not fit
- Result is 2D probability density distributions for different scenarios
- Data consistent with SM
  - Note shape of probability bands compared to those obtained from W helicity!



# Put it all together




- Use the W helicity likelihood as a prior for the single-top analysis
- Set limits on anomalous couplings by integrating over the left-handed vector contribution to make 1D probability densities

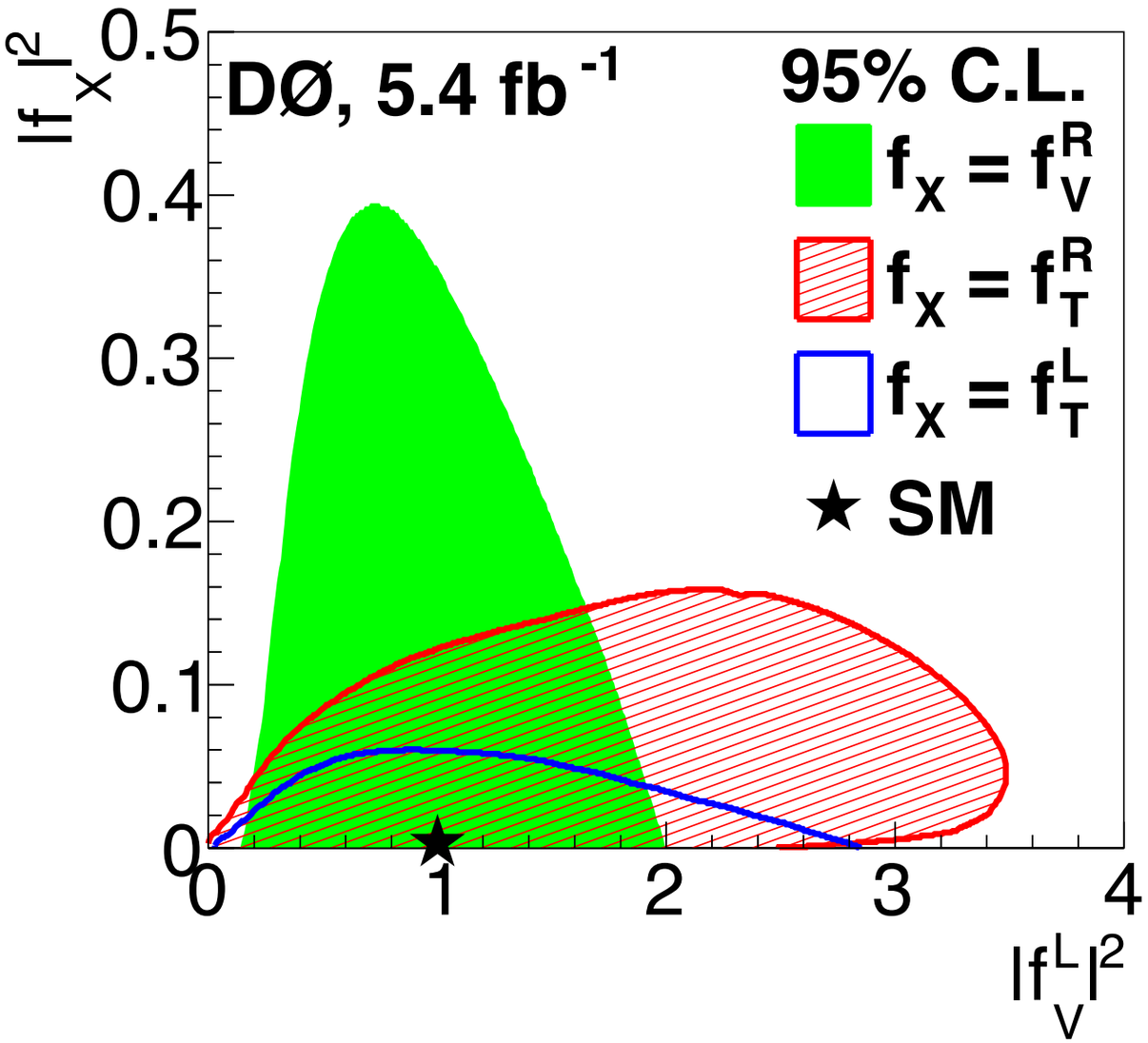
| Scenario | only $W$ helicity | only single top | combination |
|---|---|---|---|
| $\lvert f_V^R\rvert^2$ | 0.62 | 0.89 | 0.30 |
| $\lvert f_T^L\rvert^2$ | 0.14 | 0.07 | 0.05 |
| $\lvert f_T^R\rvert^2$ | 0.18 | 0.18 | 0.12 |

# Systematic uncertainties

- Single-top measurement is statistics limited
  - Largest systematic uncertainties from jet energy scale, b-tagging efficiencies, background normalization
  - Measurement depends on overall signal normalization
- Systematic and statistical uncertainties are about equal for the W helicity measurement
  - Largest systematic uncertainties from $t\bar{t}$ modeling, W+jets heavy flavor content, template statistics
  - Measurement independent of $t\bar{t}$ normalization
- Correlations in systematic uncertainties between the two analyses are handled appropriately

# Summary

- Studies of W helicity in top decays and of single-top production rate and kinematics allow us to probe anomalous Wtb couplings
  - The two analyses are complementary, making the combination powerful
- Best limits on anomalous couplings to date
  - PLB **713**, 165 (2012)
  - This is probably the final D0 result on this topic -- LHC is gaining advantage on statistics




Top quark at age 17: old enough to drive, but only makes left turns!

# Extra Slides

# Alternative parameterization

- Alternative parameterization through effective operators due to Aguilar-Saavedra, NPB 812, 181 (2009), also Zhang, Greiner, Willenbrock, arXiV: 1201.6670 and PRD 83 034006 (2011)
- Λ is scale of new physics, v is EWK symmetry breaking scale, C's are constants for dimension-6 effective operators for 3rd-generation quarks

$$|f_V^L| = 1 + |C_{\phi q}^{(3,3+3)}| \frac{v^2}{V_{tb}\Lambda^2} ,$$

$$|f_V^R| = \frac{1}{2}|C_{\phi\phi}^{33}| \frac{v^2}{V_{tb}\Lambda^2} ,$$

$$|f_T^L| = \sqrt{2}|C_{dW}^{33}| \frac{v^2}{V_{tb}\Lambda^2} ,$$

$$|f_T^R| = \sqrt{2}|C_{uW}^{33}| \frac{v^2}{V_{tb}\Lambda^2} ,$$

- Assuming Λ=1 TeV, find:

$$|C_{\phi q}^{(3,3+3)}| < 14.7, \ |C_{\phi\phi}^{33}| < 18.0, \ |C_{dW}^{33}| < 2.5, \ |C_{uW}^{33}| < 4.1$$

- (ATLAS appears to have stronger limits due different statistical treatment)