Measurements of Spin Correlation in $t\bar{t}$ Events at D0

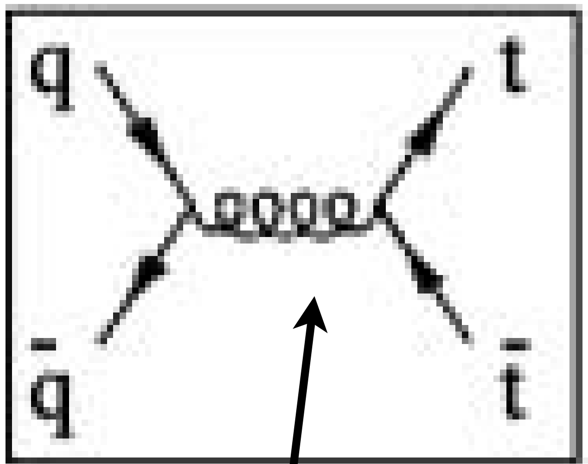
Ken Bloom

DPF 2011
August 10, 2011

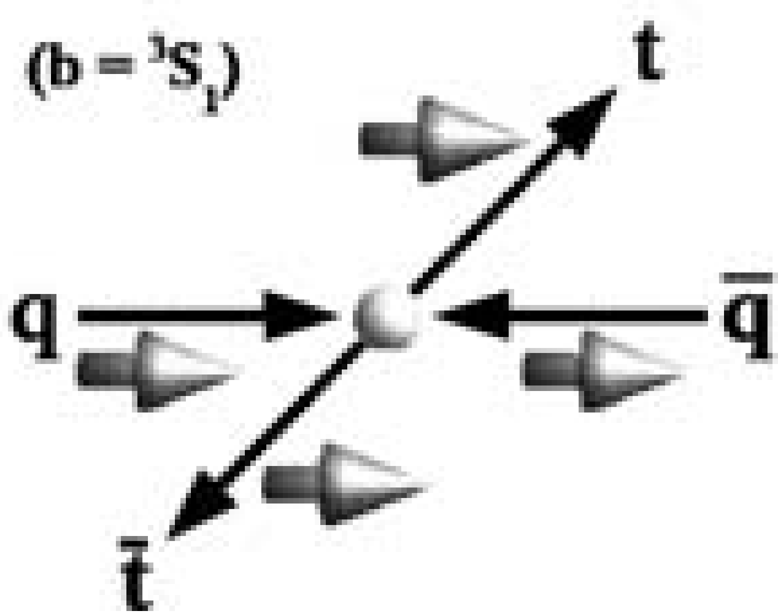
Spin correlations

- In $p\bar{p} \rightarrow q\bar{q}$, the quarks are unpolarized, but spins are correlated
- In general unobservable, as hadronization decorrelates spins
- But the top quark is different
  - Short lifetime (~5 x 10^{-25} s), top decays before fragmentation or spin flip can occur
  - Spin orientation preserved and passed to decay products
- A test of top-quark properties and probe of new physics:
  - Observation of correlation represents upper limit on top lifetime
  - Non-SM decay (e.g. $t \rightarrow H^+ b$) or production (e.g. stop pairs, Z') would have different correlation
- Subtle effect, but now have enough Tevatron data to explore it

Defining correlation



At Tevatron, different at LHC

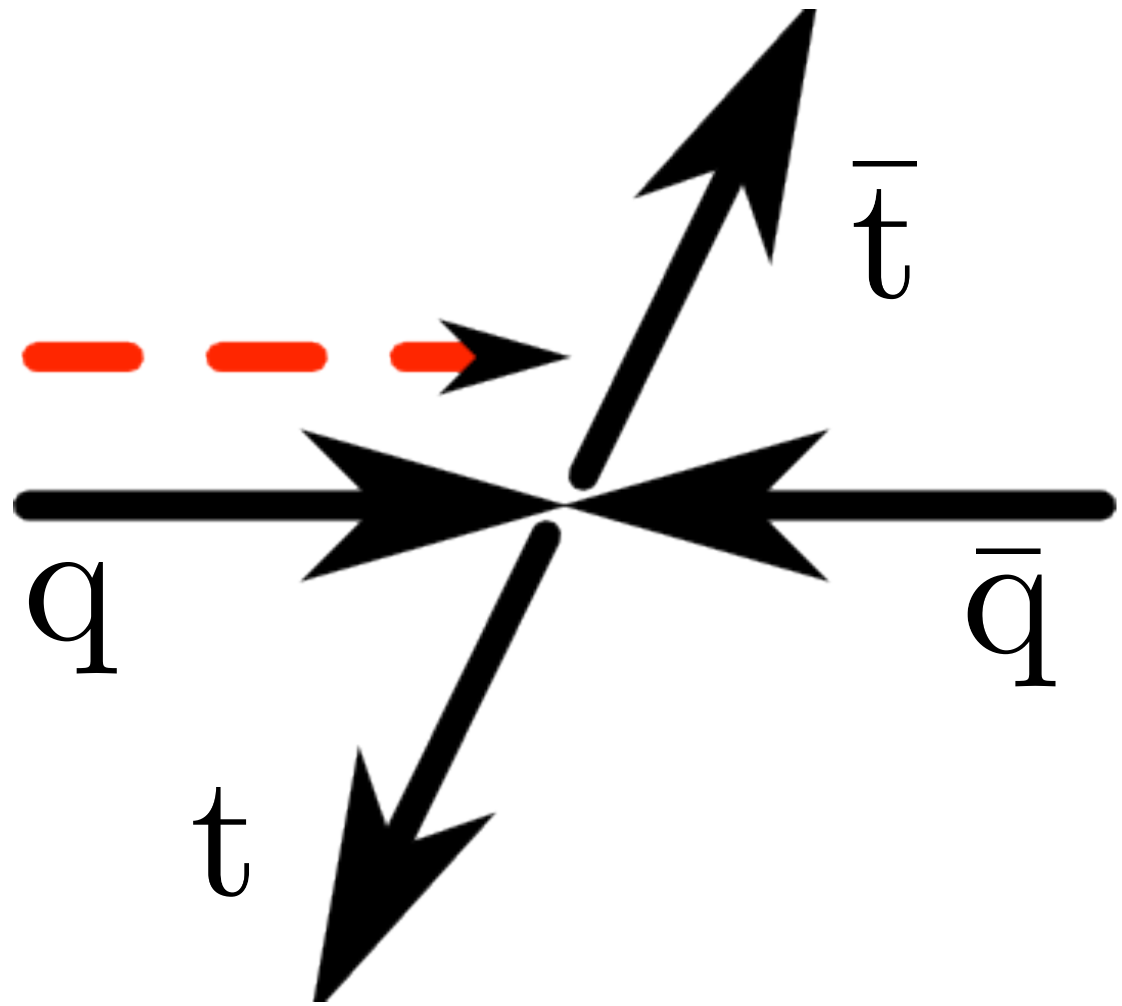


Must have opposite helicity to couple to s-channel gluon

- Define a correlation strength based on the number of top pairs with spins pointing in the same direction

$$A = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

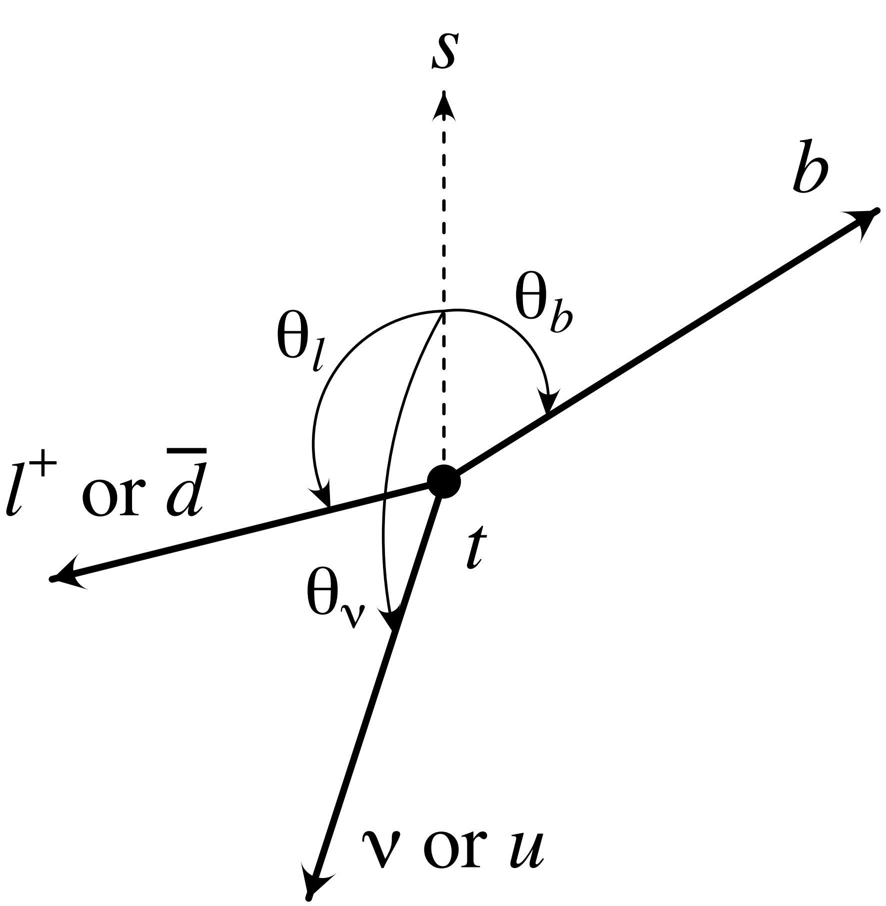
- Spin direction must be defined with respect to a quantization axis
- Choose the beamline axis = direction of colliding hadrons in ZMF
  - Intuitive, easy to construct, optimal for $t\bar{t}$ produced at threshold
- NLO QCD predicts A = 0.777 for this choice
  - (W. Bernreuther et al., 2004)



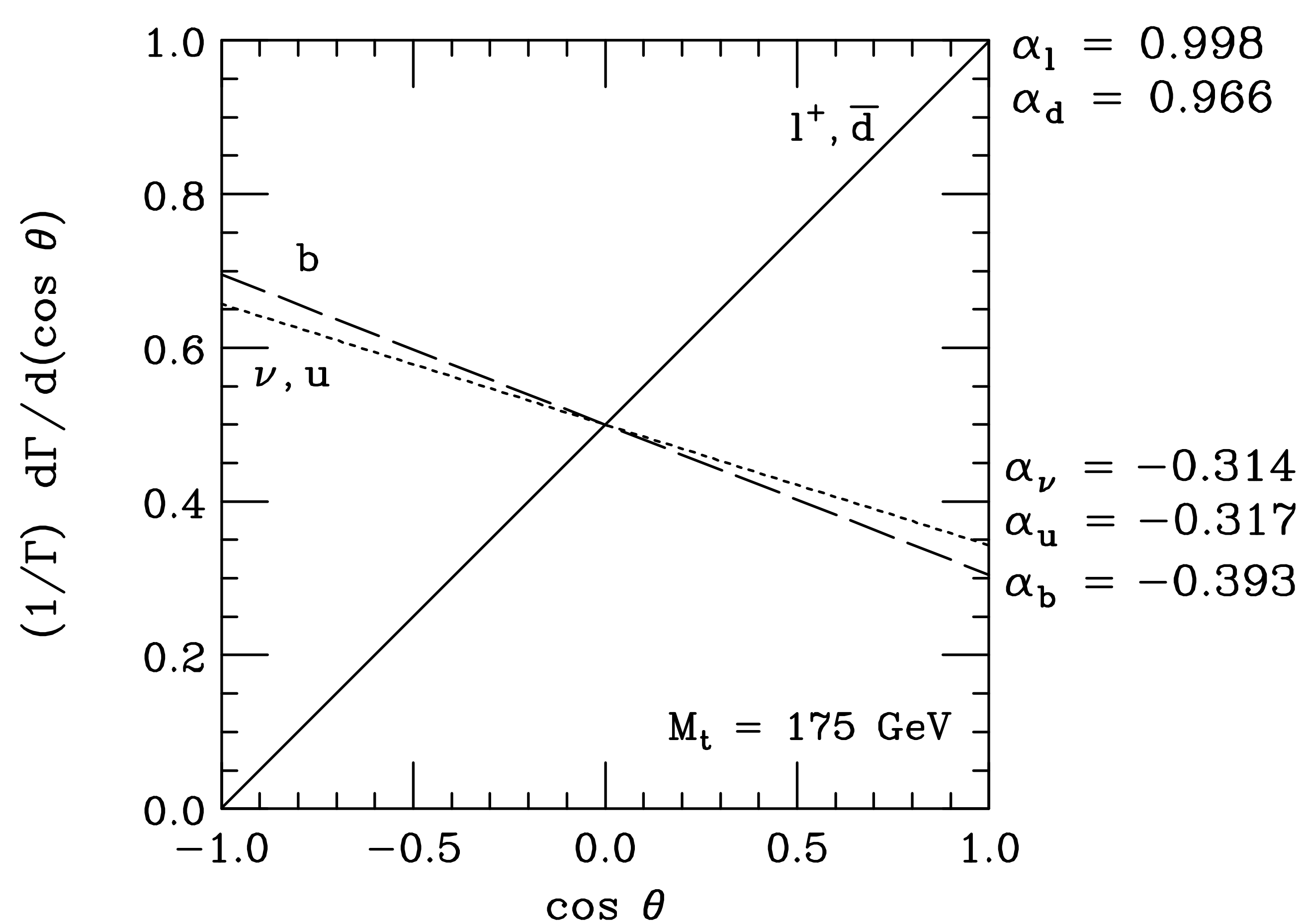
Analyzing top spin

- Top spin is passed to its decay products
  - But different decay products have different analyzing power:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_i} = \frac{1}{2}(1 + \alpha_i \cos\theta_i)$$



Mahlon, TOP 2010 conference



- Leptons from top decay have greatest analyzing power

The measurements

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A\alpha_1\alpha_2\cos\theta_1\cos\theta_2)$$

- Look for correlations between directions of decay products from two different top quarks
  - Write $A\alpha_1\alpha_2$ as C, $\alpha_1\alpha_2 = 1$ for dileptons
- Dilepton mode has best analyzing power, best measurement of decay-product directions, worst statistical power
- Two measurements from D0:
  - Template-based, calculate angles in each event and fit shape for correlated and uncorrelated components (PLB 702, 16 (2011)) -- has been done before with less data
  - Matrix-element-based, use full event kinematics to determine fraction of events that have spin correlation expected in SM (PRL 107, 032001 (2011)) -- new approach!

Not everyone has said it yet

- Tevatron: $\sqrt{s}$ = 1.96 TeV, $p\bar{p}$ collisions, Run II in progress since 2001; almost 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
- $t\bar{t}$ production: ~85% $q\bar{q}$, 15% gg
- $t\bar{t}$ decays: each $t \rightarrow Wb$ ~100%, final states determined by W decay -- all-hadronic, lepton+jets, dilepton (decreasing order of rate, increasing order of number of neutrinos, purity)
- Dilepton final state: two high-p_T leptons, missing momentum due to escaping neutrinos, two jets from b decays (and perhaps additional ISR/FSR)

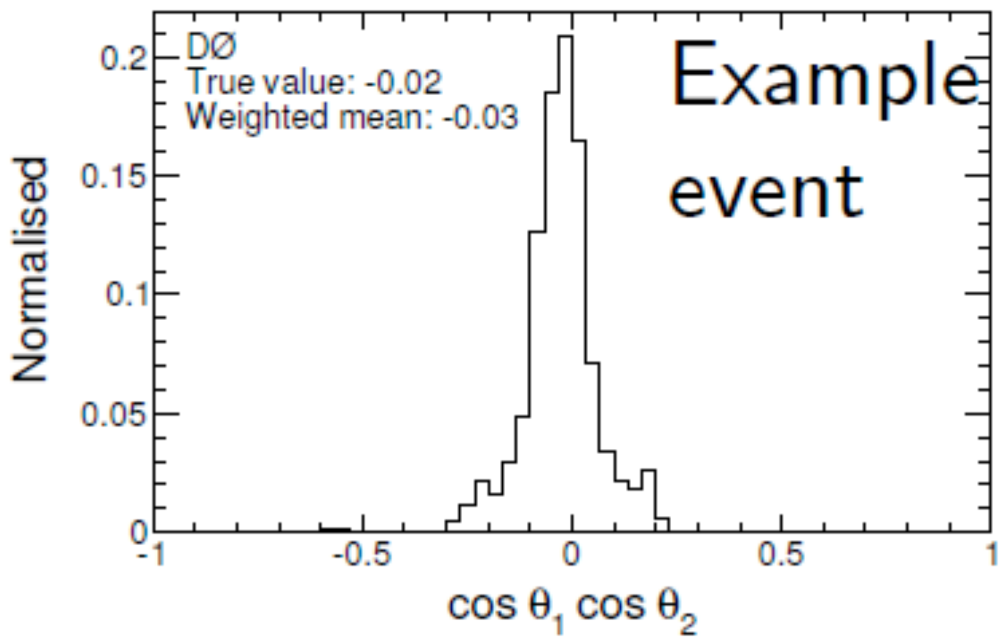
Event selection

- Same event selection for both analyses
- Two high-p_T, isolated, opposite-charge leptons (ee, eμ, μμ)
- At least two high-p_T jets
- Large scalar sum of p_T's of leptons and jets in eμ channel, significant missing energy in ee and μμ channels
- Z/γ* (diboson) modeled by LO MC normalized to NNLO (NLO)
- Instrumental backgrounds arise from π^0 and η misidentified as electrons and real muons in jets that appear to be isolated; both modeled with complementary data samples
- Obtain very pure sample of tt events:

$t\bar{t}$	Z/γ^*	Diboson	Instrumental	Total	Observed
341 ± 30	93 ± 15	19 ± 3	28 ± 5	481 ± 39	485

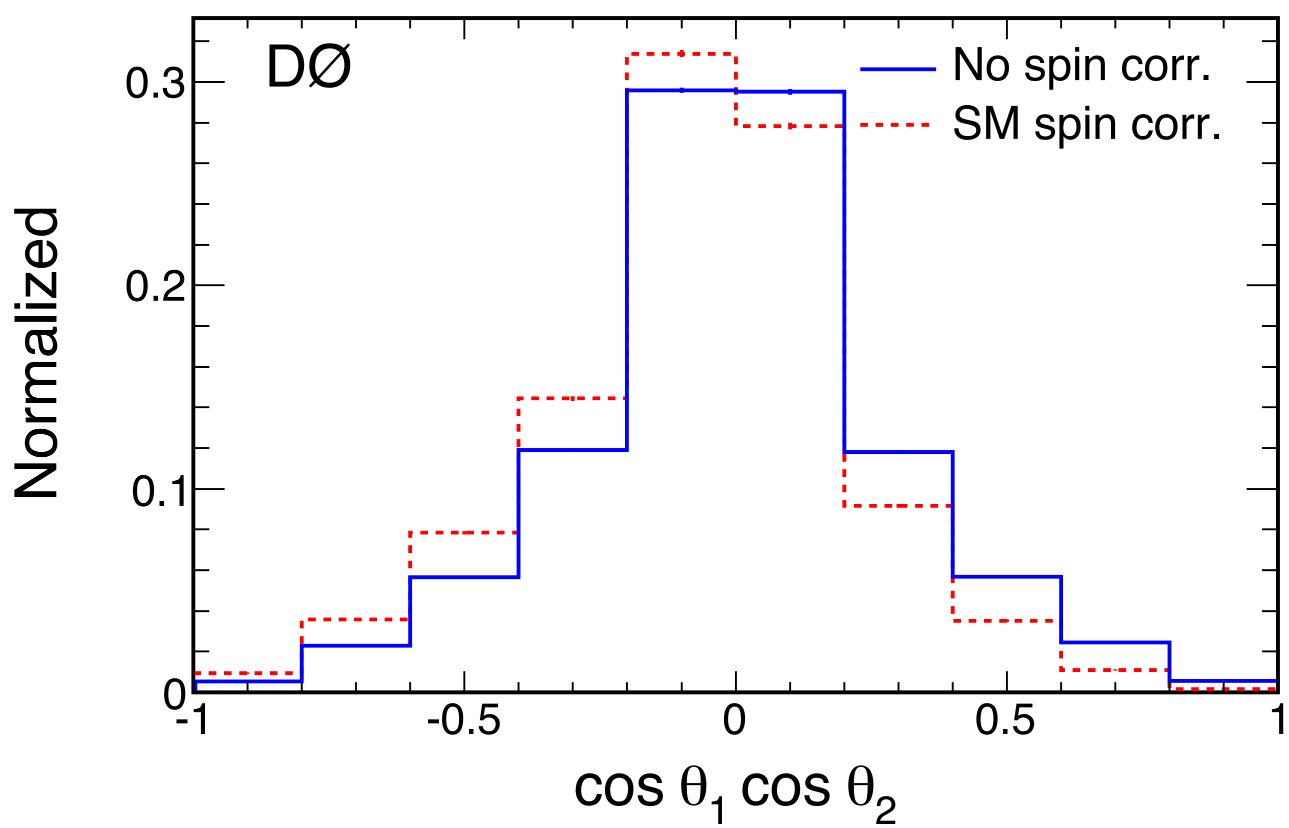
Analysis 1: Event reconstruction

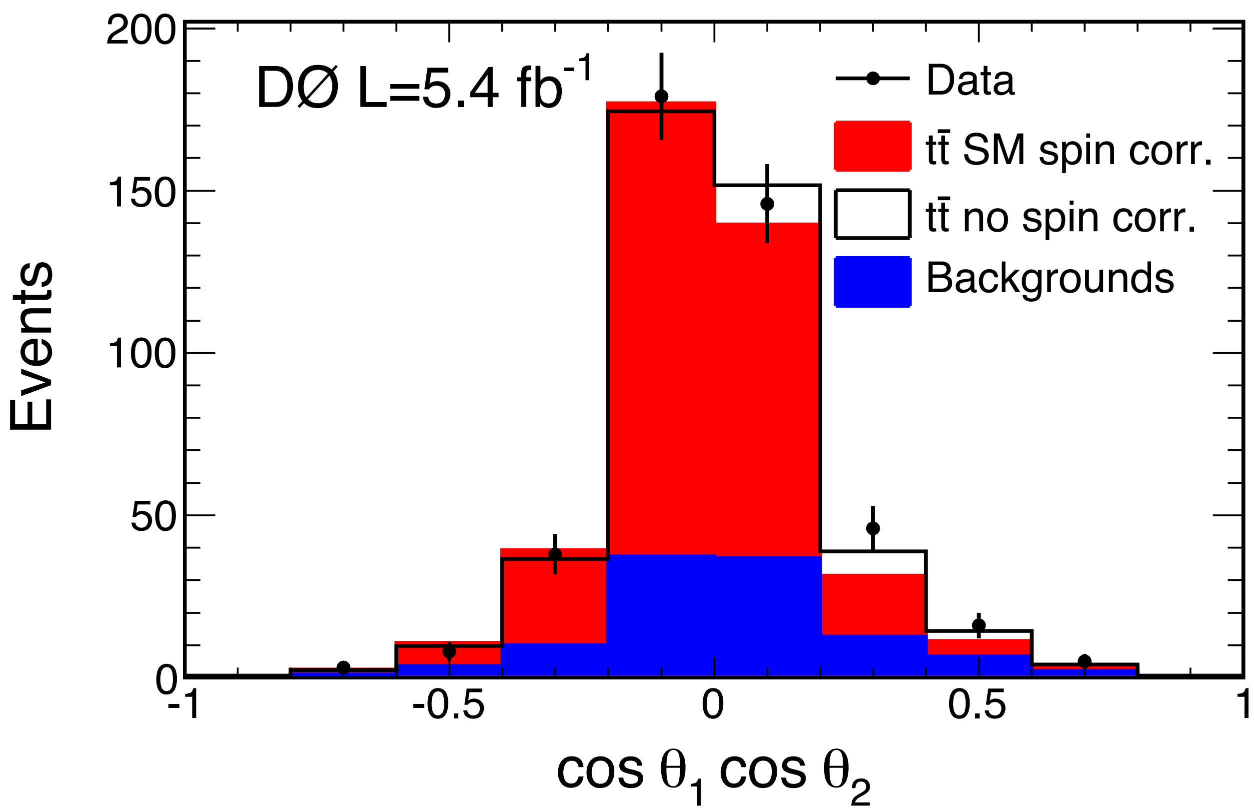
- Need to measure the angle between the lepton and the beamline in the ZMF frame of the $t\bar{t}$ system → full reconstruction of decay
- 18 quantities needed to specify final configuration, but only 12 measured
  - 4 additional constraints from m_t and M_W
- Use "neutrino weighting" technique for remaining kinematics:
  - Sample two values from neutrino η distribution as predicted from $t\bar{t}$ MC, then solve for implied $t\bar{t}$ kinematics to get $\cos\theta_1\cos\theta_2$, neutrino momenta
  - Weight $\cos\theta_1\cos\theta_2$ values by consistency of derived ν's with observed missing E_T
  - Use weighted mean of all solutions as estimator of $\cos\theta_1\cos\theta_2$



Analysis I: Template fit

- $t\bar{t}$ events are simulated with MC@NLO, in which spin correlation can be turned on or off
- With appropriate weighting of simulated samples, $\cos\theta_1\cos\theta_2$ distributions for any value of C can be generated



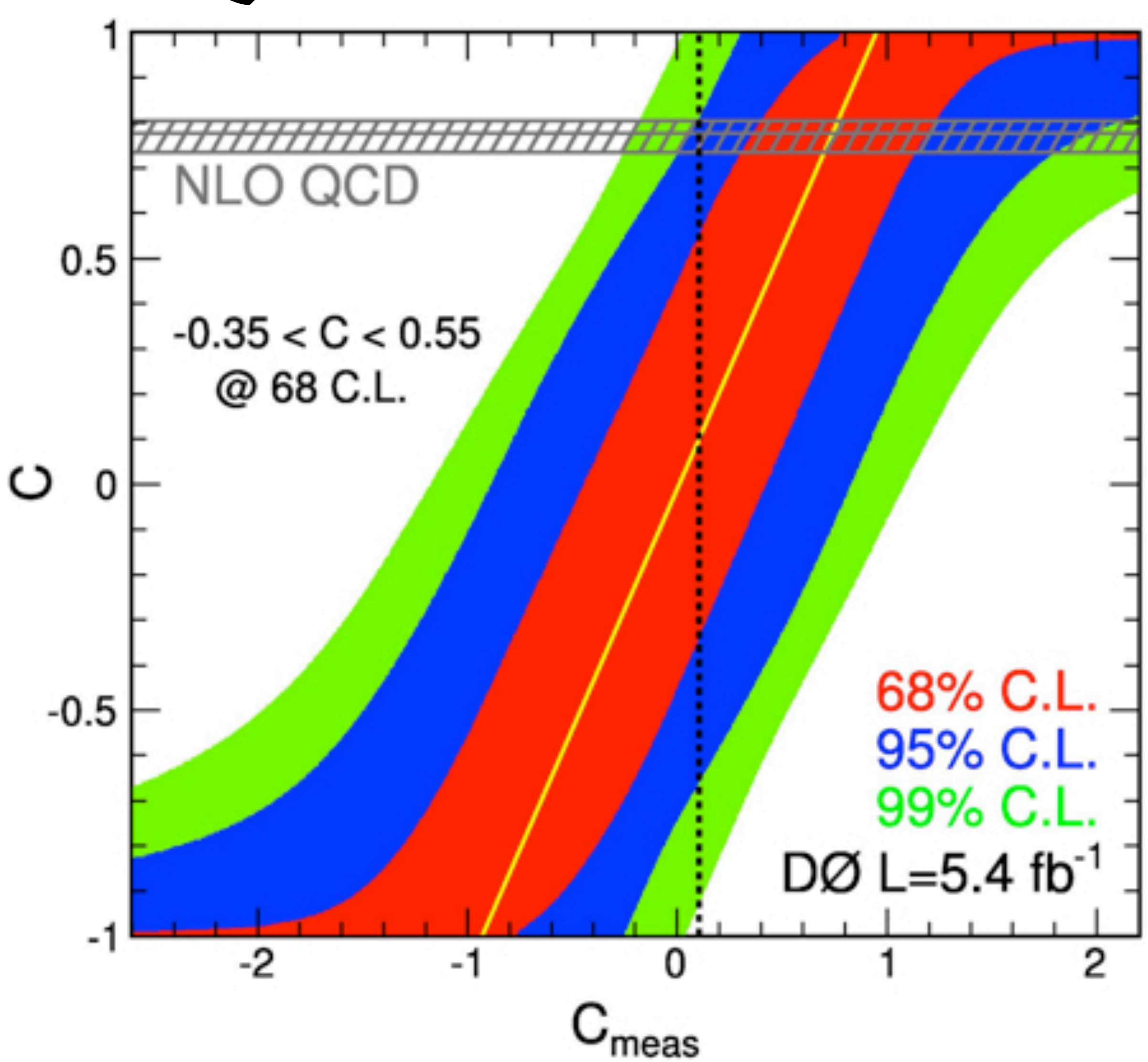


- Find best value of C with binned likelihood fit
  - Systematic uncertainties incorporated as nuisance parameters
  - $t\bar{t}$ cross section allowed to float in fit

Use Feldman-Cousins frequentist approach to find $C = 0.10 \pm 0.45$,

$-0.66 < C < 0.81$ @ 95% CL

NLO QCD: $C = 0.777^{+0.027}_{-0.042}$



Source	+SD	−SD
Muon identification	0.01	−0.01
Electron identification and smearing	0.01	−0.01
PDF	0.02	−0.01
Top Mass	0.01	−0.01
Triggers	0.02	−0.02
Opposite charge requirement	0.00	−0.00
Jet energy scale	0.01	−0.01
Jet reconstruction and identification	0.06	−0.06
Normalization	0.02	−0.02
Monte Carlo statistics	0.02	−0.02
Instrumental background	0.00	−0.00
Background Model for Spin	0.03	−0.04
Luminosity	0.03	−0.03
Other	0.01	−0.01
Template statistics for template fits	0.07	−0.07
Total systematic uncertainty	0.11	−0.11
Statistical uncertainty	0.38	−0.40

Statistical uncertainties dominate by far; limited template statistics (fixable) is leading systematic effect

Analysis 2: Matrix elements

- For each event, can ask: are the kinematics consistent with spin correlations as the SM predicts, or no correlation at all?
- This can be addressed through matrix-element technology:

$$P_{\mathrm{sgn}}(x;H) = \frac{1}{\sigma_{\mathrm{obs}}} \int f_{\mathrm{PDF}}(q_1) f_{\mathrm{PDF}}(q_2) \mathrm{d}q_1 \mathrm{d}q_2 \cdot \frac{(2\pi)^4 \left|\mathcal{M}(y,H)\right|^2}{q_1 q_2 s} W(x,y)\, \mathrm{d}\Phi_6 .$$

Measured event kinematics (x)

Correlation hypothesis, H = c or u (H)

Total cross section (σ_{obs})

Incoming quark PDFs (f_{PDF})

Quark momentum fractions ($q_1 q_2$)

Correlation-dependent matrix element ($\left|\mathcal{M}(y,H)\right|^2$)

Transfer functions ($W(x,y)$)

6-body phase space ($\mathrm{d}\Phi_6$)

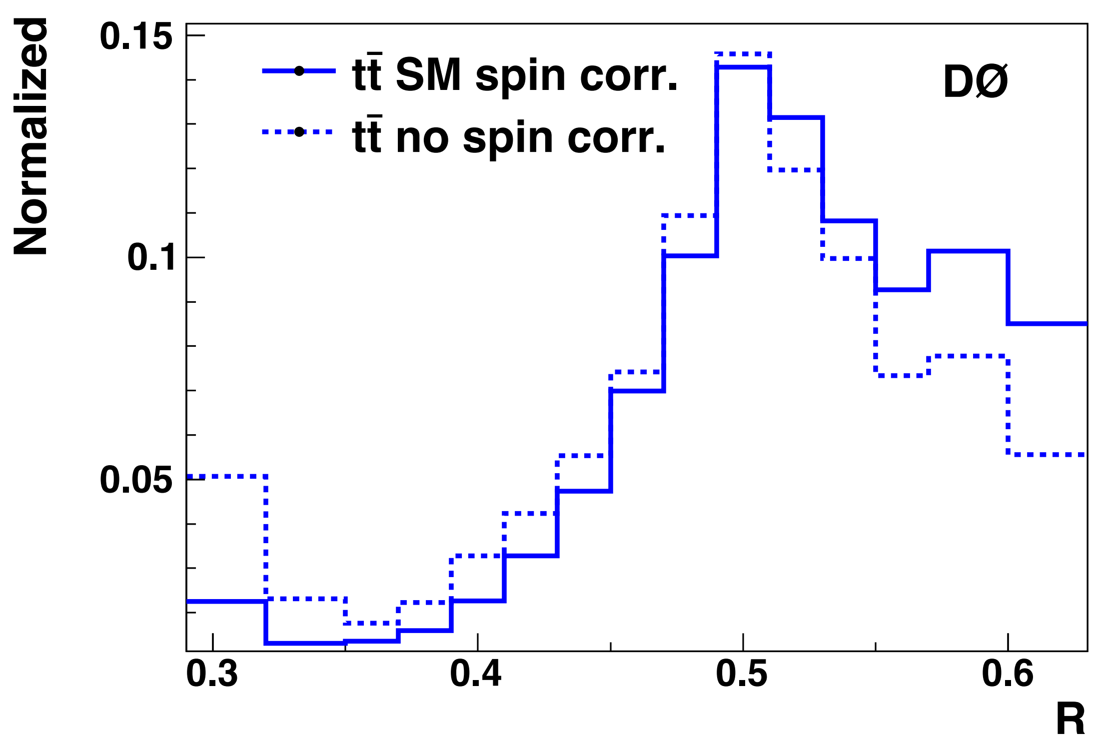
- In contrast to the template measurement, full event kinematics plus theoretical models of production and decay are used, not just lepton angles.

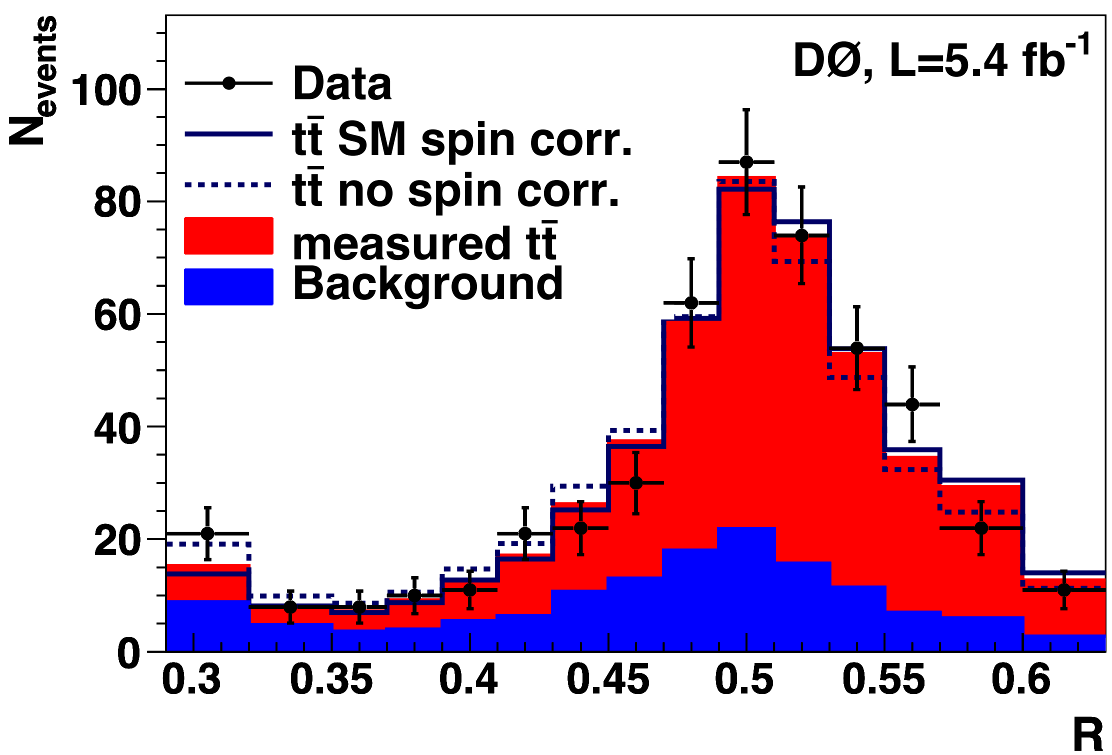
Analysis 2: Hypothesis comparison

- For each event, compute

$$R = \frac{P_{\mathrm{sgn}}(H=c)}{P_{\mathrm{sgn}}(H=u) + P_{\mathrm{sgn}}(H=c)}$$

- Events more consistent with having SM spin correlations will tend to have R closer to 1, those less consistent have R closer to 0.
- But it is still a small effect:

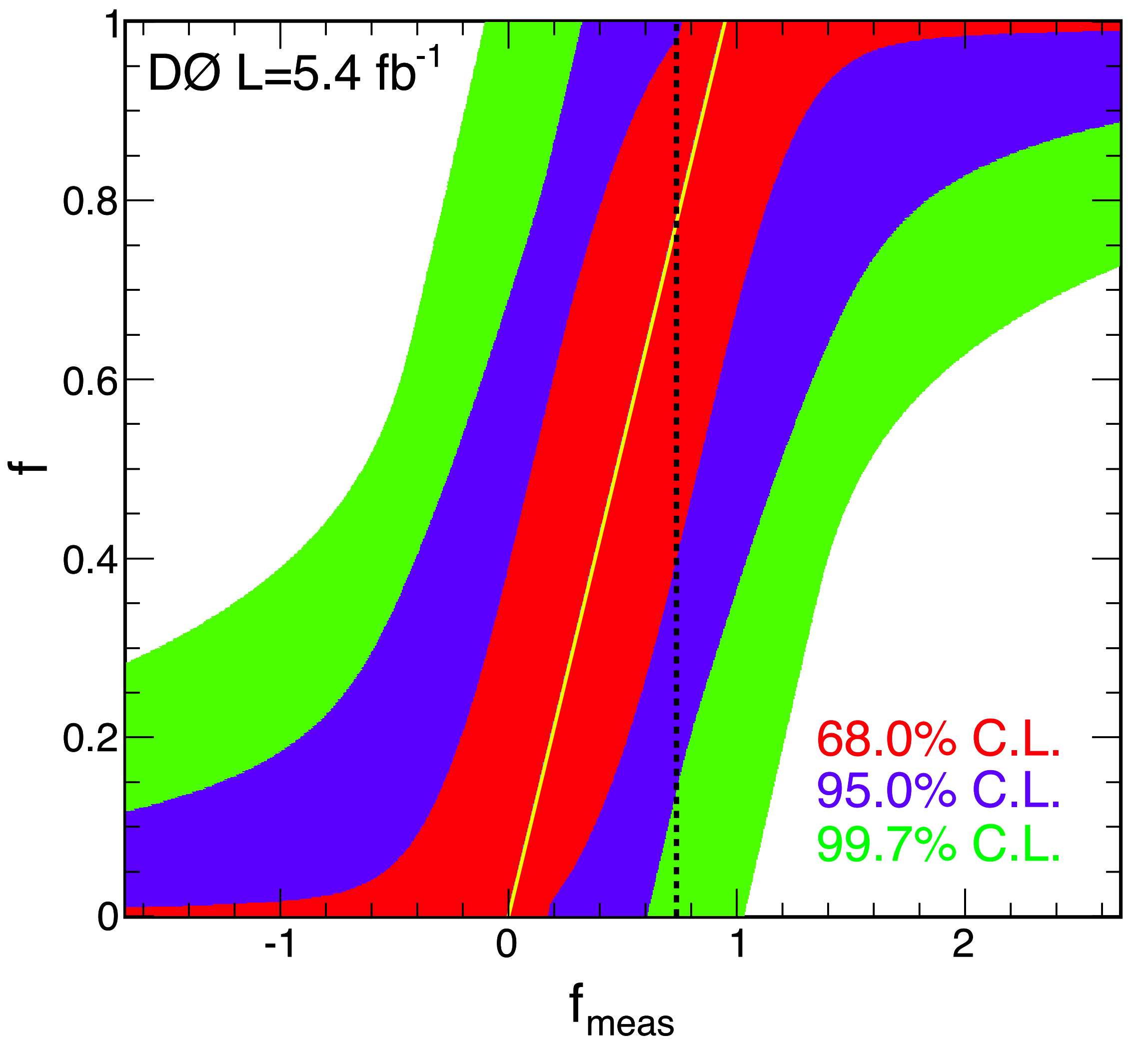




- Fit using binned likelihood as in Analysis 1 to extract fraction of events that show correlation, SM predicts 100%

Analysis 2: Results

Measure $f = 0.74^{+0.40}_{-0.41}$, consistent with SM, exclude f = 0 at 99.6% CL



Source	+1SD	−1SD
Muon identification	0.01	-0.01
Electron identification and smearing	0.02	-0.02
PDF	0.06	-0.05
m_t	0.04	-0.06
Triggers	0.02	-0.02
Opposite charge selection	0.01	-0.01
Jet energy scale	0.01	-0.04
Jet reconstruction and identification	0.02	-0.06
Background normalization	0.07	-0.08
MC statistics	0.03	-0.03
Instrumental background	0.01	-0.01
Integrated luminosity	0.04	-0.04
Other	0.02	-0.02
MC statistics for template fits	0.10	-0.10
Total systematic uncertainty	0.15	-0.18
Statistical uncertainty	0.33	-0.35

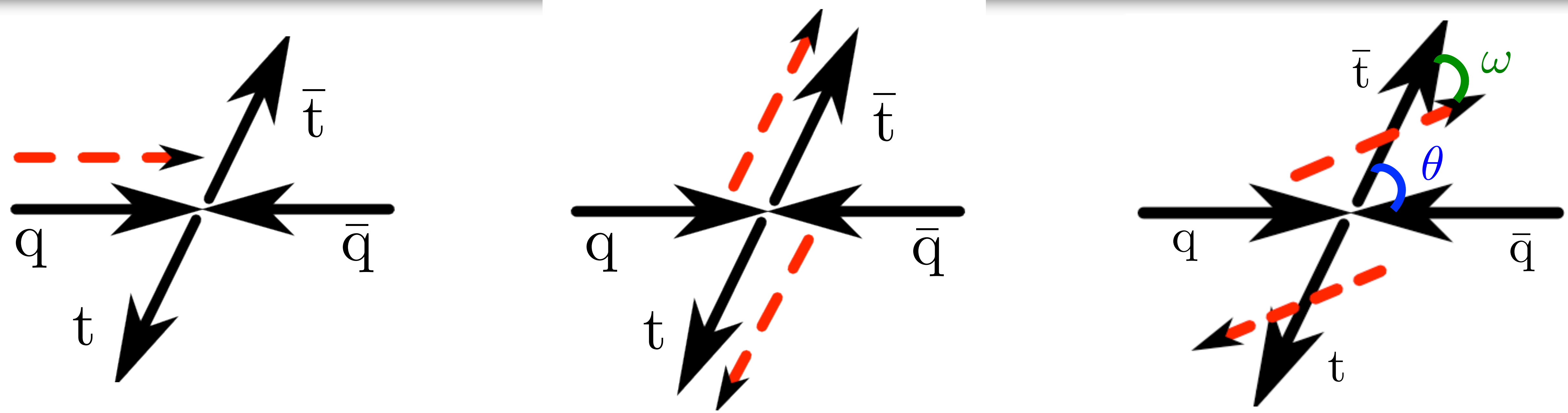
As before, statistical uncertainties dominate; limited template statistics is still leading systematic effect

Summary

- Quark spin correlation is a phenomenon that can only be seen in $t\bar{t}$ production, thanks to the short top lifetime
- But it is a subtle effect that requires large data samples and sophisticated analysis techniques to observe
- Two analyses of dilepton events from D0:
  - Template-based analysis using full reconstruction of top decays gives result within two standard deviations of NLO QCD prediction, but also compatible with no-correlation hypothesis
  - Matrix-element-based analysis gives result consistent with SM hypothesis, and powerful enough to exclude no-correlation hypothesis -- first time ever
- Analyses are both statistics limited, with only ~half the D0 Run II dataset analyzed so far -- more excitement ahead!

Extra Slides

Other quantization axis choices



Beamline | Helicity | Off-Diagonal

- Beamline: Direction of colliding hadrons in ZMF. Easy to construct, optimal for $t\bar{t}$ produced at threshold, A = 0.777
- Helicity: Use direction of (anti)top quark in $t\bar{t}$ ZMF to quantize (anti)top quark spin, A = -0.352
- Off diagonal: Interpolates between the other two, better for production above threshold, A = 0.782
- Measurements described here use beamline axis

Analysis 2: The matrix elements

- The matrix element neglecting spin correlations (H = u) is

Top decay kinematics — Top velocity in ZMF — Sine of angle between incoming parton and outgoing top

$$\sum |\mathscr{M}|^2 = \frac{g_s^4}{9} F\overline{F}\left(2 - \beta^2 s_{qt}^2\right)/2,$$

- And accounting for them (H = c), it's

$$\sum |\mathscr{M}|^2 = \frac{g_s^4}{9} F\overline{F}\left[\left(2 - \beta^2 s_{qt}^2\right) - \Delta\right],$$

Cosines of angles between various initial- and final-state particles

$$\Delta = \frac{(1 - c_{\overline{\ell}q} c_{\ell\overline{q}}) - \beta(c_{\ell\overline{t}} + c_{\overline{\ell}t}) + \beta c_{qt}(c_{\overline{\ell}q} + c_{\ell\overline{q}}) + \frac{1}{2}\beta^2 s_{qt}^2 (1 - c_{\overline{\ell}\ell})}{\gamma^2 (1 - \beta c_{\overline{\ell}t})(1 - \beta c_{\ell\overline{t}})}$$

- Both give the same value of the total tt cross section
- In contrast to the template measurement, full event kinematics plus theoretical models of production and decay are used, not just lepton angles.