$t\bar{t}$ Spin Correlations at DØ

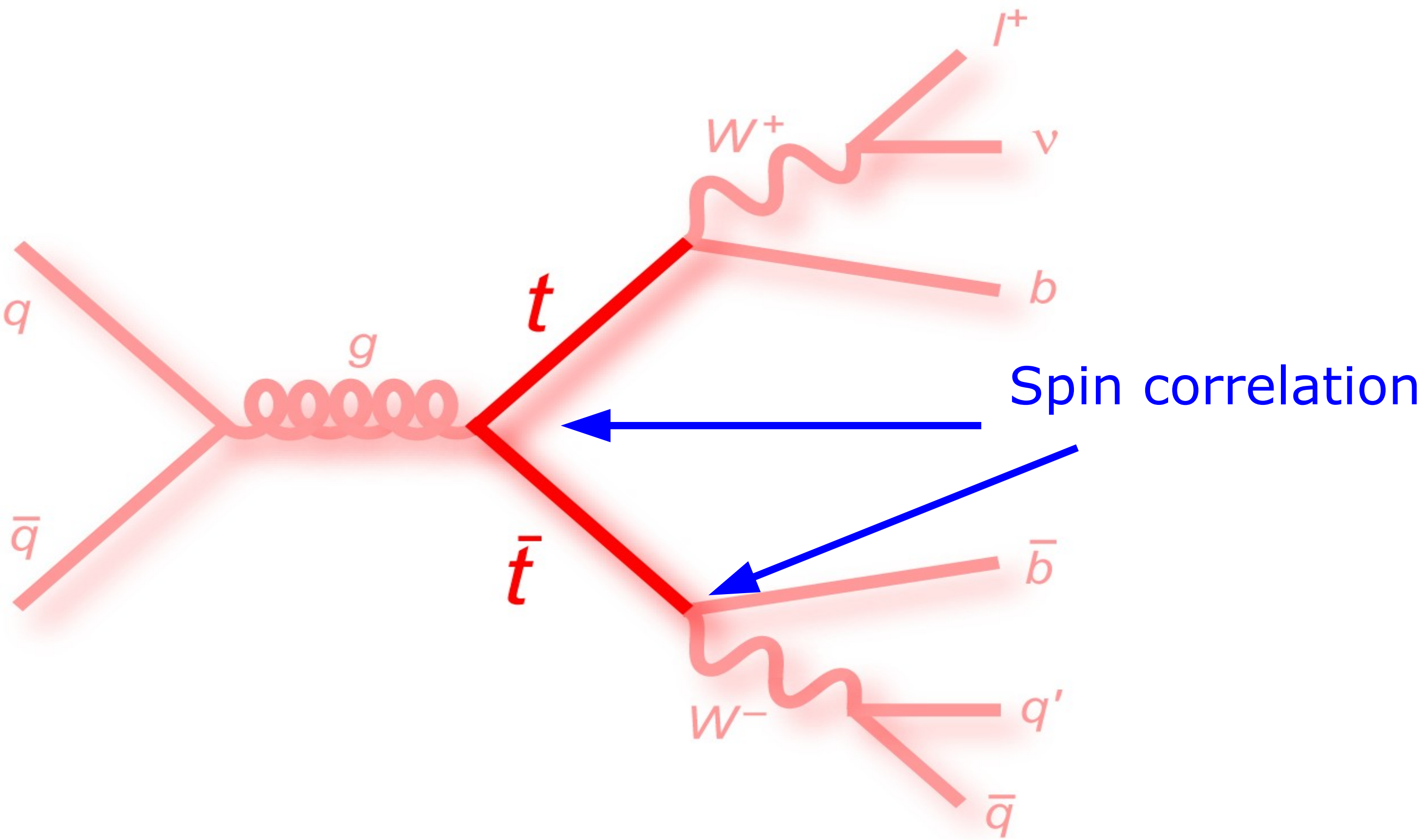
Reinhild Yvonne Peters

Georg-August University Göttingen & DESY

on behalf of the DØ Collaboration

$t\bar{t}$ Spin Correlations

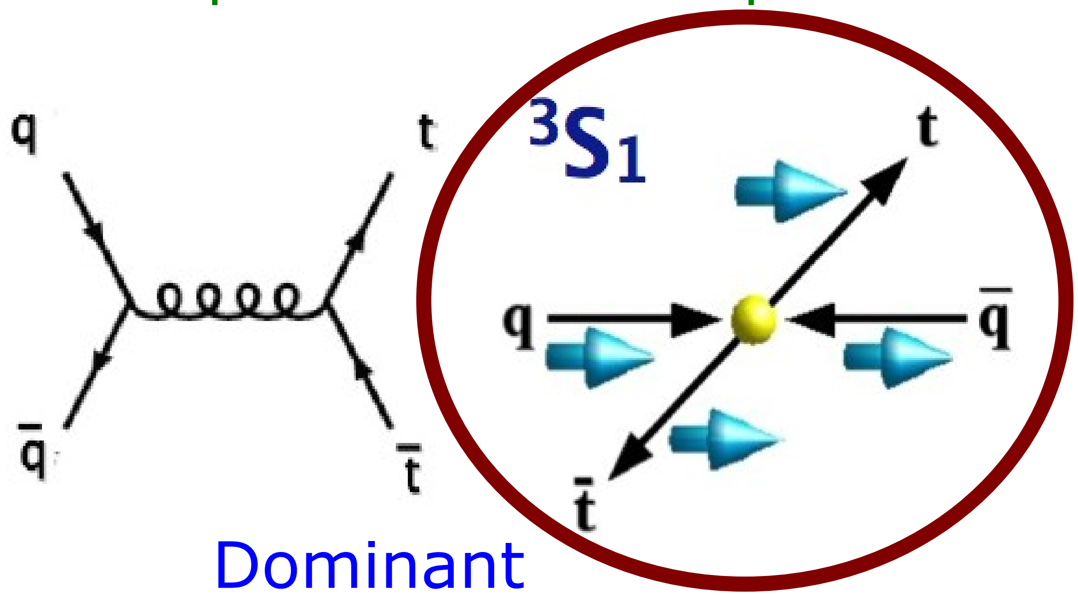
- $t\bar{t}$ spin correlations: test the full chain from production to decay
- test the couplings
  - In $t\bar{t}$ production
  - In top decay



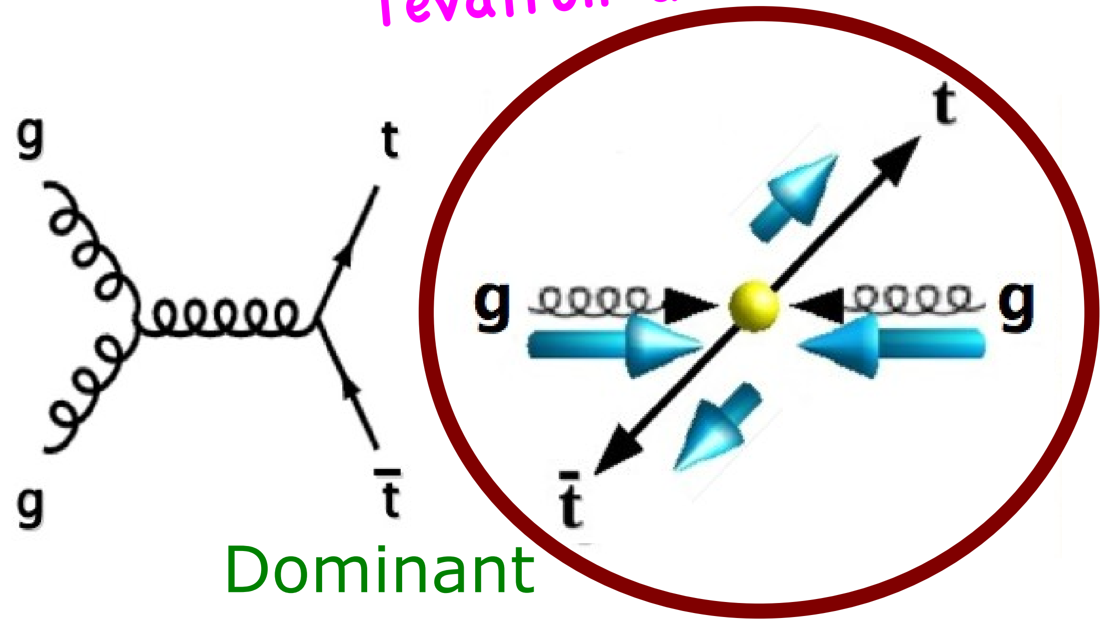
$t\bar{t}$ Spin Correlations

- Top quarks decay before fragmentation
  - Spin information is preserved

Complementary between Tevatron and LHC



Dominant
spin correlation at Tevatron



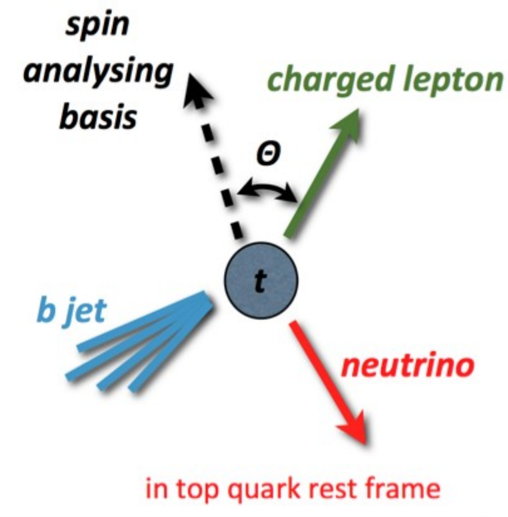
Dominant
spin correlation at LHC

- Different methods:
  - Template based on angular distribution
  - Matrix-Element based

Reminder:
Tevatron $t\bar{t}$ production: 85% $q\bar{q}$ annihilation and 15% gg-fusion
LHC $t\bar{t}$ production: <15% $q\bar{q}$ annihilation and >85% gg-fusion

$t\bar{t}$ Spin Correlation using Angular Distributions

- Use the angles between decay products and beam axis to analyse spin
  - Dilepton: Angle of (anti)lepton wrt. beam axis in (anti)top rest-frame
  - Spin analysing power of charged lepton and down-type quark is 1 (in LO)

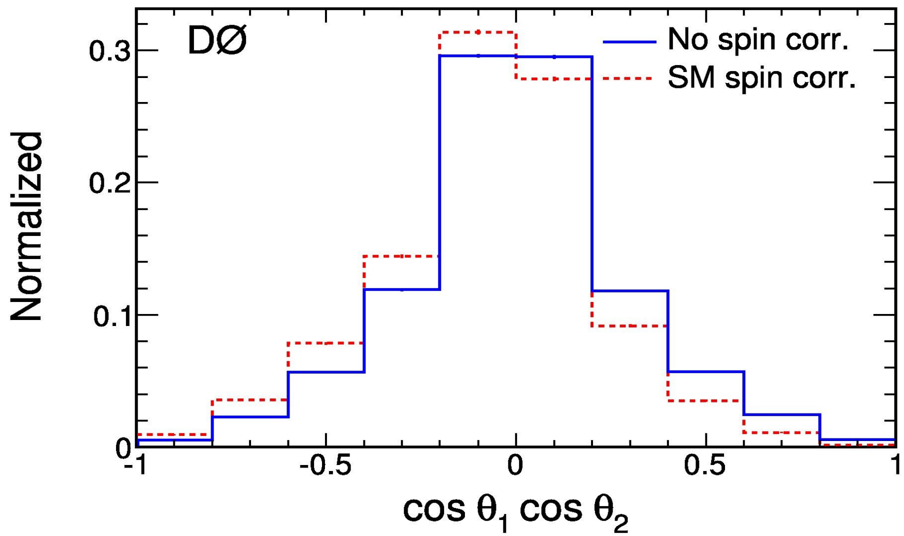


- Differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

  - C: spin correlation strength
  - NLO SM: C≈0.78 (beam axis)

$$\boxed{C=\frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}}$$



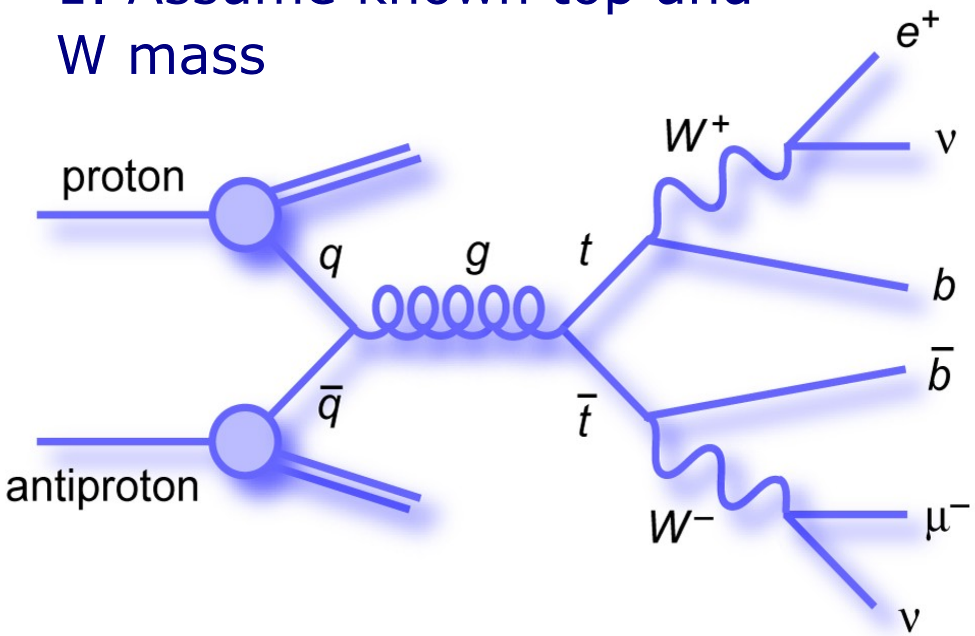
Dilepton Selection and tt Reconstruction

- Measurement based on 5.4fb^{-1} of dilepton Run II data

	$t\bar{t}$	Z	Diboson	Instrumental	Expected	Observed
Number of events	324^{+28}_{-28}	75^{+13}_{-13}	17^{+3}_{-3}	23^{+4}_{-4}	439^{+36}_{-36}	441

- To reconstruct full $t\bar{t}$ system: need to reconstruct neutrino momenta

1. Assume known top and W mass



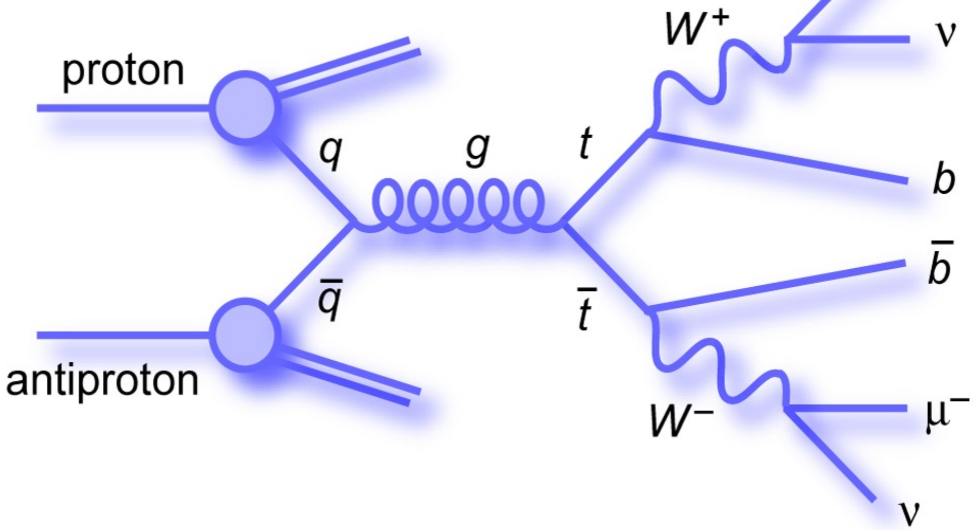
Dilepton Selection and tt Reconstruction

- Measurement based on 5.4fb^{-1} of dilepton Run II data

	$t\bar{t}$	Z	Diboson	Instrumental	Expected	Observed
Number of events	324^{+28}_{-28}	75^{+13}_{-13}	17^{+3}_{-3}	23^{+4}_{-4}	439^{+36}_{-36}	441

- To reconstruct full $t\bar{t}$ system: need to reconstruct neutrino momenta

1. Assume known top and W mass
2. Scan over neutrino pseudo-rapidities



Dilepton Selection and tt Reconstruction

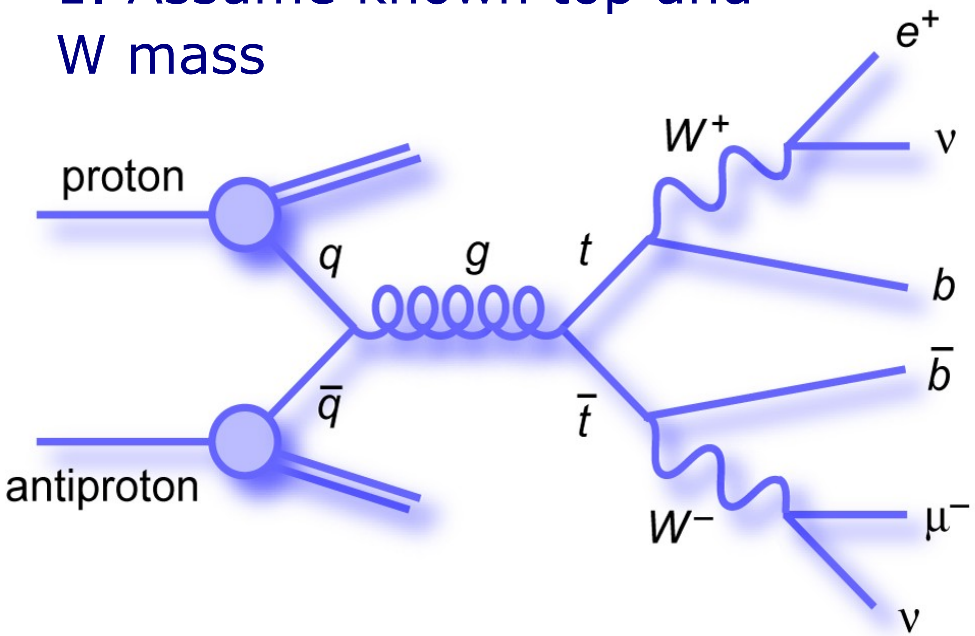
- Measurement based on 5.4fb^{-1} of dilepton Run II data

	$t\bar{t}$	Z	Diboson	Instrumental	Expected	Observed
Number of events	324^{+28}_{-28}	75^{+13}_{-13}	17^{+3}_{-3}	23^{+4}_{-4}	439^{+36}_{-36}	441

- To reconstruct full $t\bar{t}$ system: need to reconstruct neutrino momenta

1. Assume known top and W mass

2. Scan over neutrino pseudo-rapidities



3. Solutions get weighted according to comparison of missing transverse energy and neutrino momenta

Dilepton Selection and tt Reconstruction

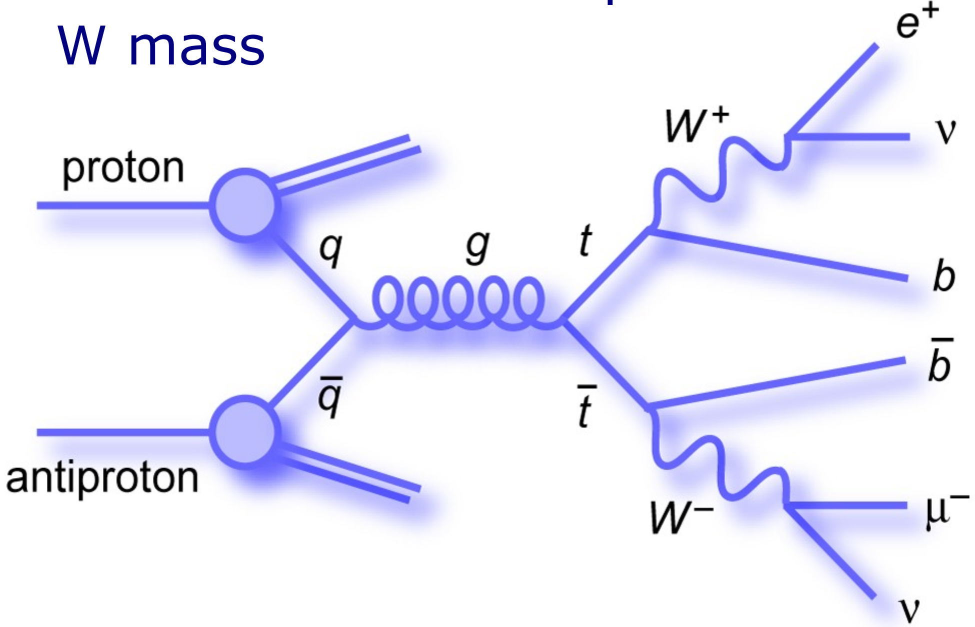
- Measurement based on 5.4fb^{-1} of dilepton Run II data

	$t\bar{t}$	Z	Diboson	Instrumental	Expected	Observed
Number of events	324^{+28}_{-28}	75^{+13}_{-13}	17^{+3}_{-3}	23^{+4}_{-4}	439^{+36}_{-36}	441

- To reconstruct full $t\bar{t}$ system: need to reconstruct neutrino momenta

1. Assume known top and W mass

2. Scan over neutrino pseudo-rapidities

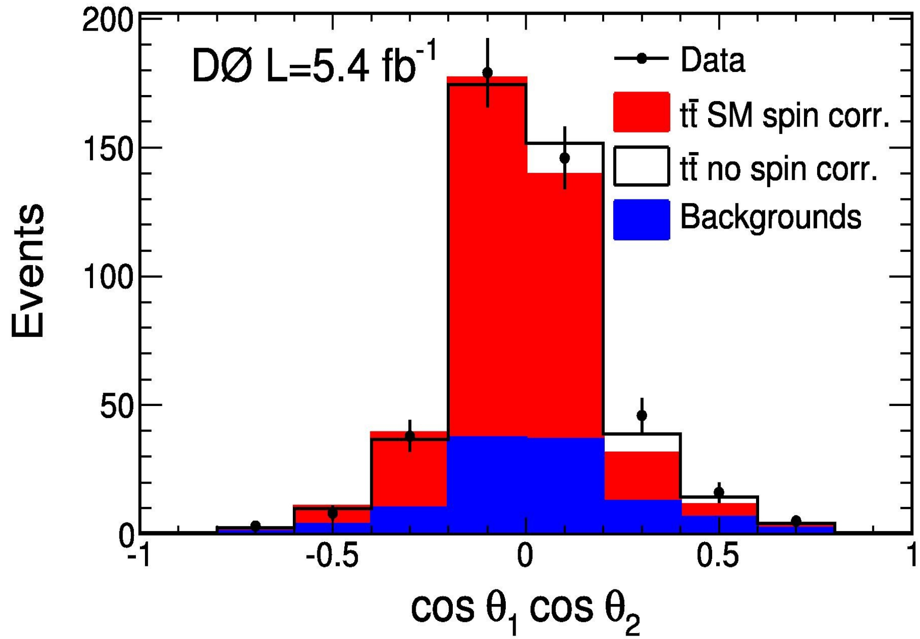


3. Solutions get weighted according to comparison of missing transverse energy and neutrino momenta

4. weighted mean of all solutions → $cos\,\theta_1 cos\,\theta_2$ for considered event

Template-based $t\bar{t}$ Spin Correlations

- Form templates for MC with spin correlation and without spin correlation taken into account (MC@NLO MC)
- Perform maximum likelihood fit
  - Systematics included as nuisance parameters
- Feldman Cousins approach used for limit/value extraction
- Result of template fit of R:
  $C=0.10 \pm 0.45$(stat+syst)
  $\sigma_{t\bar{t}}=7.9^{+1.1}_{-0.9}$ (stat+syst) pb
- Statistics dominated uncertainty

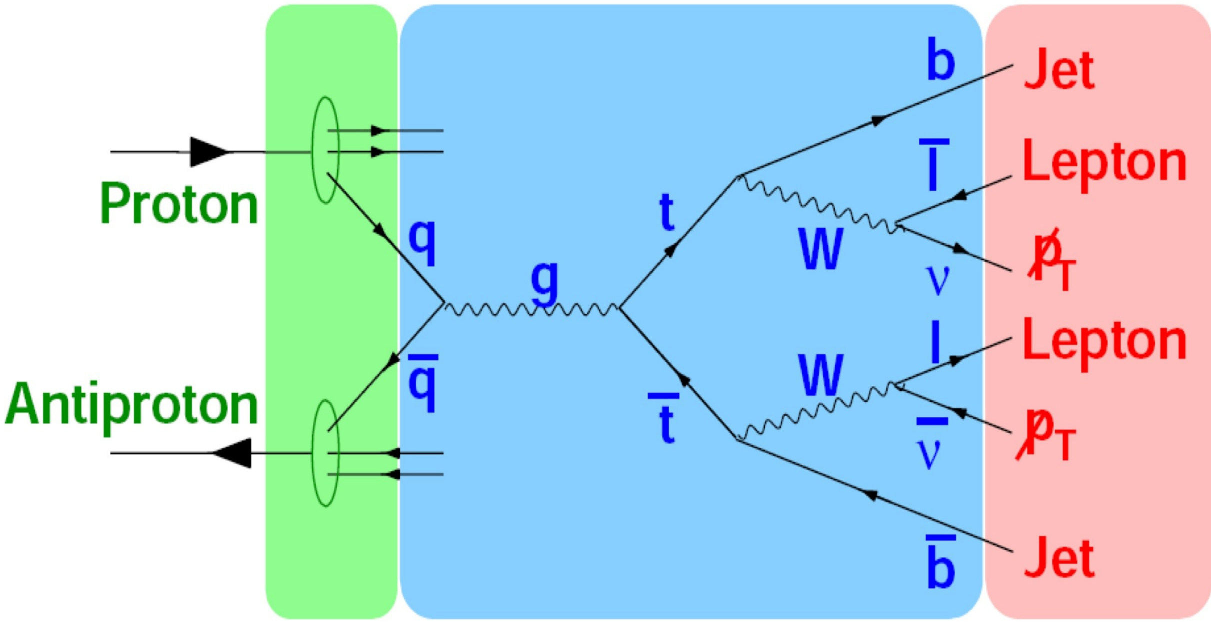


PLB 702, 16 (2011)

$t\bar{t}$ Spin Correlations using Matrix Elements

- Matrix Element Method: most precise method to determine top quark mass → Uses full event information
- Test hypothesis of spin correlation (H=1) versus no correlation (H=0)
- For each event calculate probability to belong to certain hypothesis H

$$P_{sig}(x;H) \propto \int \text{PDF} \times \text{Matrix element} \times \text{Transfer function}$$



$t\bar{t}$ Spin Correlations using Matrix Elements

- Calculate signal probability P_{sgn} for H=0 and H=1

$$\boxed{\sum |\mathscr{M}|^2 = \frac{(1+H)}{2}\frac{g_s^4}{9}F\overline{F}\left(2-\beta^2 s_{qt}^2\right) - H\frac{g_s^4}{9}F\overline{F}\Delta}$$

G. Mahlon and S. J. Parke, Phys. Rev. D 53, 4886 (1995) Phys. Lett. B 411, 173(1997)

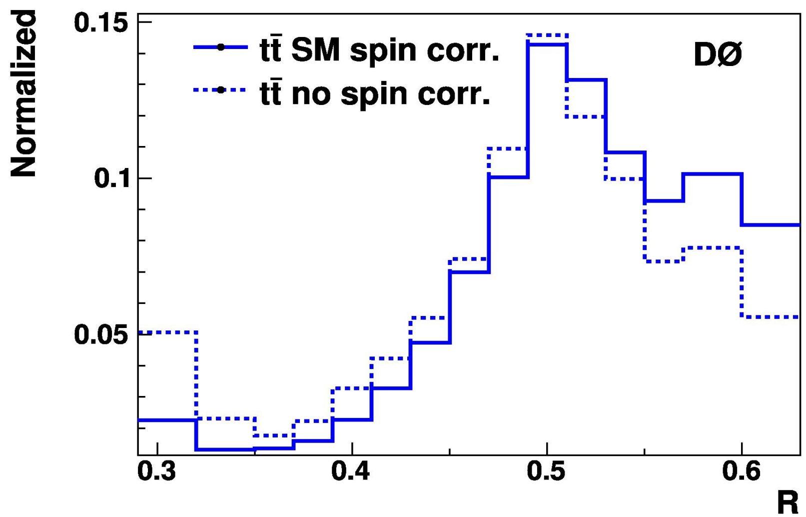
  - H=1: ME calculation takes spin correlation into account
  - H=0: ME calculation averages out spin correlation

- Calculate probability for both matrix elements, define discriminator R:

$$\boxed{R = \frac{P_{\rm sgn}(H=1)}{P_{\rm sgn}(H=0)+P_{\rm sgn}(H=1)}}$$

K. Melnikov and M. Schulze, PLB 700, 17 (2011)

- Build templates for R with MC@NLO MC including spin correlation and without spin correlation



$t\bar{t}$ Spin Correlations using Matrix Elements

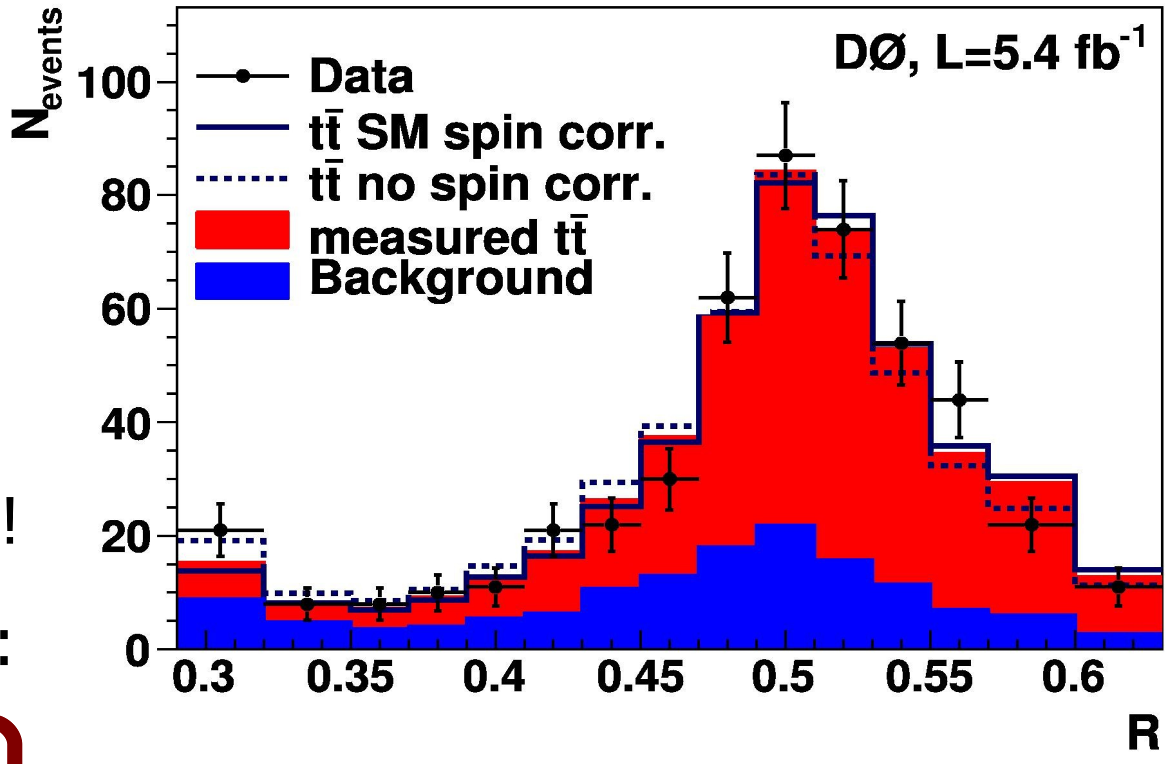
- Fit fraction $f = N_{t\bar{t}}(\text{with spin})/N_{t\bar{t}}(\text{total})$
- Result of template fit of R:

  $f = 0.74^{+0.40}_{-0.41}$ (stat+syst)

  $\sigma_{t\bar{t}} = 8.3^{+1.1}_{-0.9}$ (stat+syst) pb

- Statistics error about 0.35
- About 3σ expected sensitivity!
- Transformation into C ($f{*}C_{SM}$):

$$\boxed{C = 0.57 \pm 0.31 \text{(stat+syst)}}$$



First time sensitive to spin correlations!

New method!

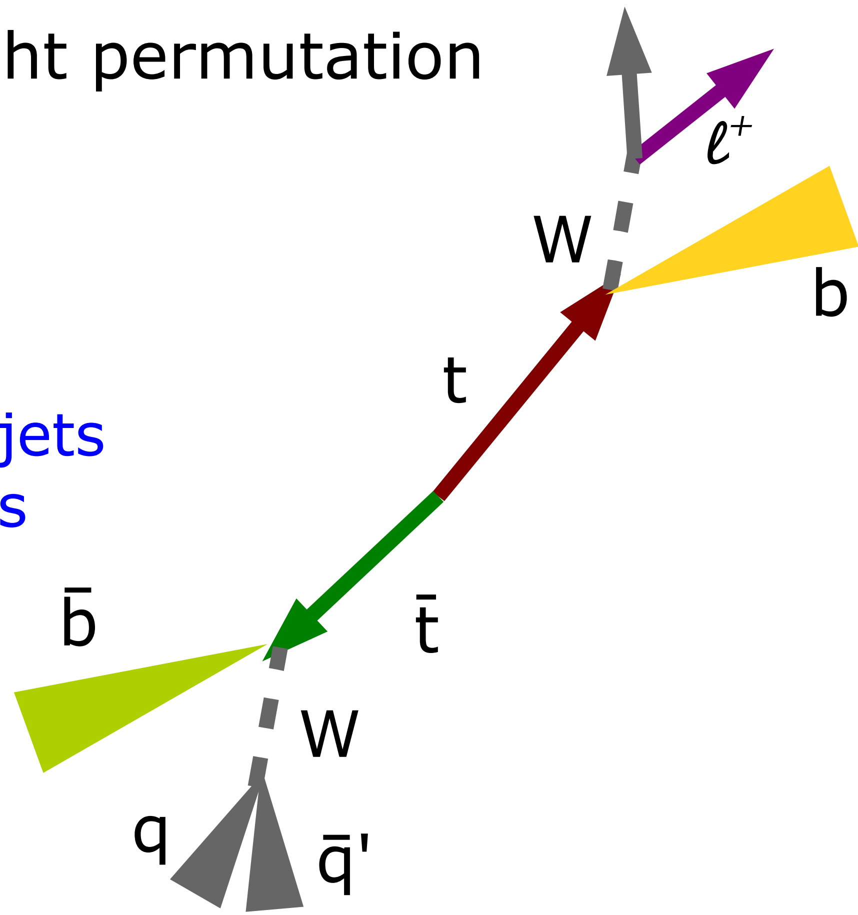
- ~30% improved over template method!

PRL 107, 032001 (2011)

From dilepton to lepton+jets

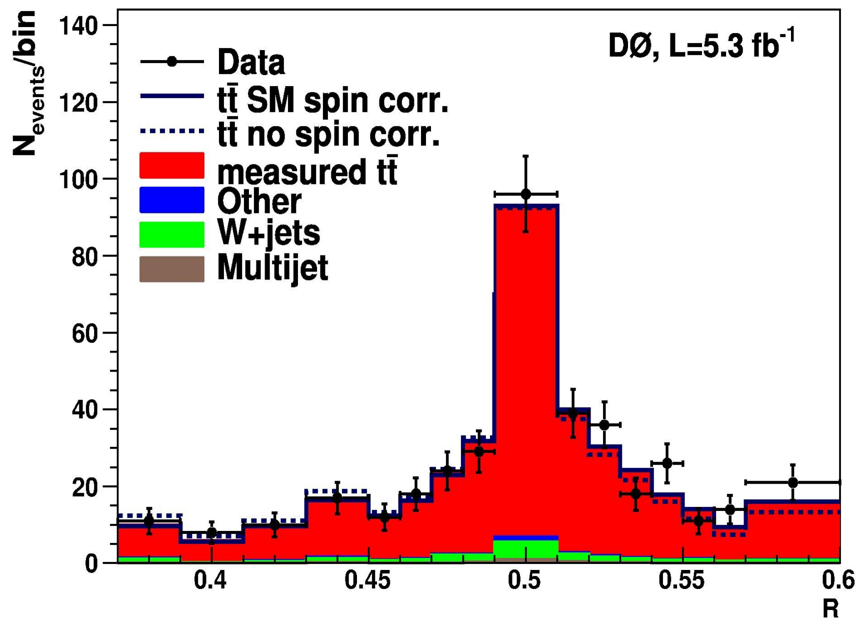
- Use the same method (Matrix Element based) as for dilepton in lepton+jets events
  - Use the same selection as for $t\bar{t}$ cross section (5.4fb^{-1})
- For Matrix Element: need to find right permutation of jets matching to quarks
  - Use events with ≥2 b-tagged jets
    - Use 2 leading b-tagged jets
  - In contrast to mass: assignment of jets from W to down-type quark matters

→ 4 permutations (dilepton: 2)



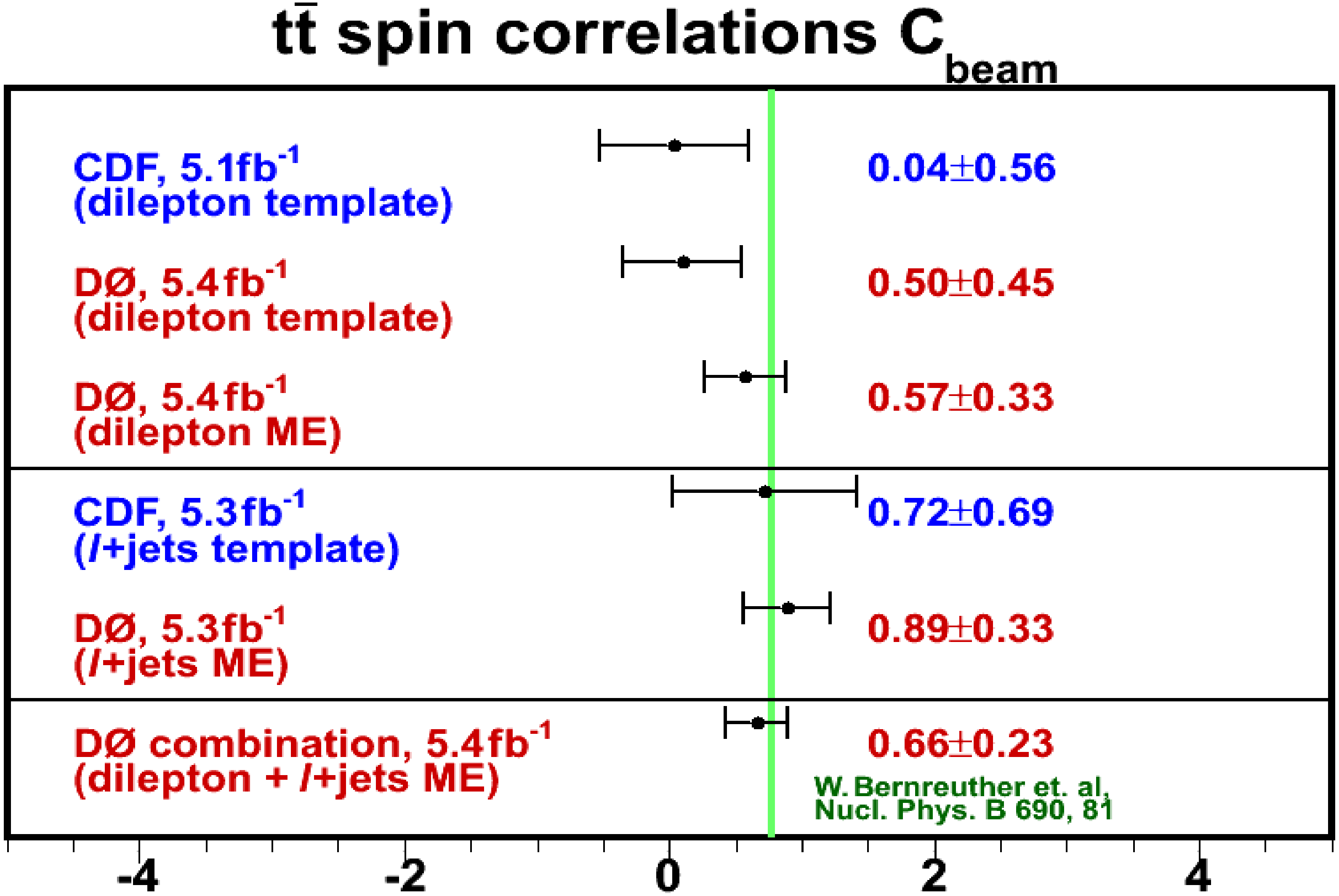
l+jets specific Event Splitting

- Split events according to more or less sensitive regions
  - 4 and >4 events
    - More likely to get wrong jet combination for >4 jets
  - Hadronic mass close (±25GeV) or far from W mass
    - More likely to have jets not from the W for invariant mass too small/large
- Sensitivity in l+jets similar to dilepton
  - ~2x more events
  - ~1/2 correct down-type jets
- Template fit on l+jets and dilepton:
  f=0.85±0.29(stat+syst)



PRL 108, 032004 (2012)

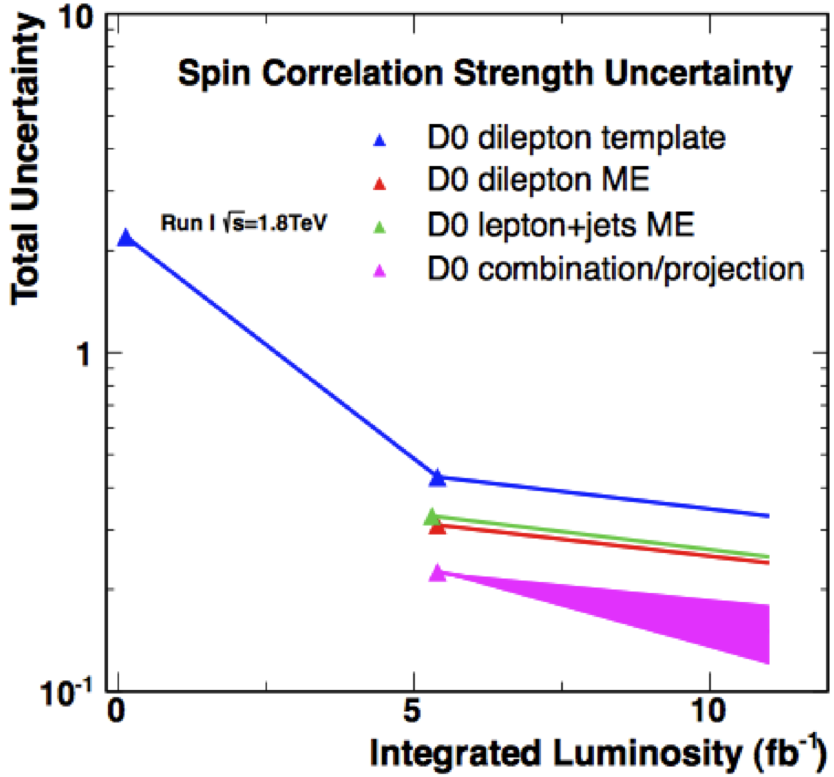
$t\bar{t}$ Spin Correlations: Results



First evidence for non-vanishing $t\bar{t}$ spin correlations!

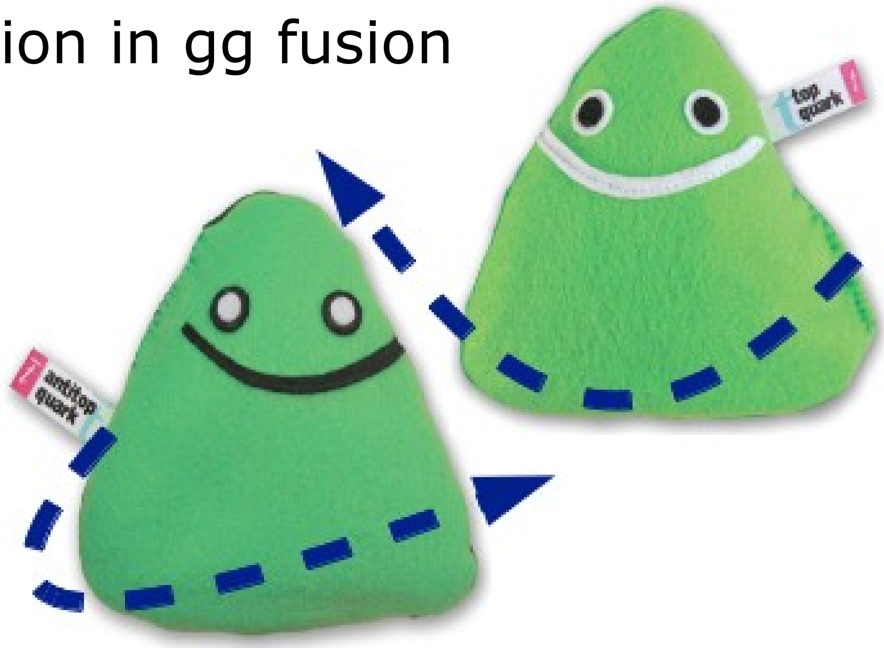
$t\bar{t}$ Spin Correlations

- Run I: spin correlation measurement using 6 events at DØ
- Several spin correlation analyses since summer 2009!
  - Two lepton+jets (DØ, CDF) and three dilepton (CDF, DØ ME & template) results!
    → Sensitive to spin correlations!
- Still statistically limited
  - Should gain at least √2 by using full dataset
  - Additional improvements possible



Summary

- Analyzed $t\bar{t}$ spin correlation using half the Tevatron data set
  - First evidence for non-vanishing $t\bar{t}$ spin correlations!
    $C=0.66 \pm 0.23(\text{stat+syst})$
- $t\bar{t}$ spin correlation complementary between Tevatron and LHC
  - Tevatron: $t\bar{t}$ spin correlation in $q\bar{q}$ annihilation
  - LHC: $t\bar{t}$ spin correlation in gg fusion



BACKUP

The Top Quark

- Heaviest known elementary particle:

$$m_t = 173.3 \pm 1.1\,\text{GeV}$$

arXiv:1007.3178

- Standard Model:
  - Single or pair production
  - Electric charge +2/3 e
  - Short lifetime 0.5×10^{-24}s
    - Bare quark - no hadronization
  - ~100% decay into Wb
  - Large coupling to SM Higgs boson

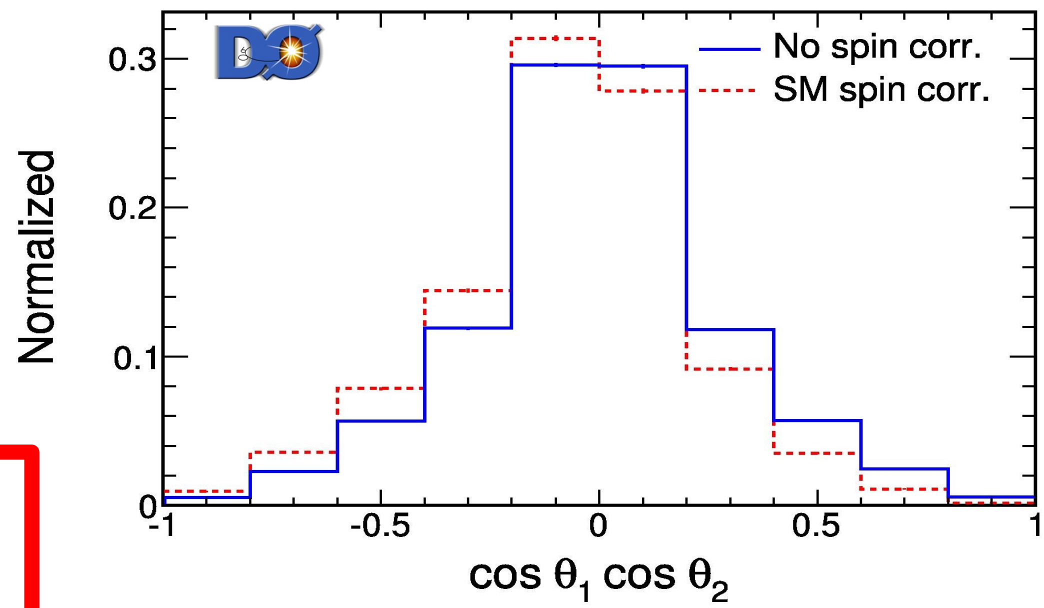
$t\bar{t}$ Spin Correlations using Angular Distributions

- Use the angles between decay products and beam axis to analyse spin
  - Dilepton: Angle of (anti)lepton wrt. beam axis in (anti)top rest-frame
- Differential cross section:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1\, d\cos\theta_2}=\frac{1}{4}(1-C\cos\theta_1\cos\theta_2)$$

  - C: spin correlation strength
  - NLO SM: C≈0.78

$$\boxed{C=\frac{N(\uparrow\uparrow)+N(\downarrow\downarrow)-N(\uparrow\downarrow)-N(\downarrow\uparrow)}{N(\uparrow\uparrow)+N(\downarrow\downarrow)+N(\uparrow\downarrow)+N(\downarrow\uparrow)}}$$

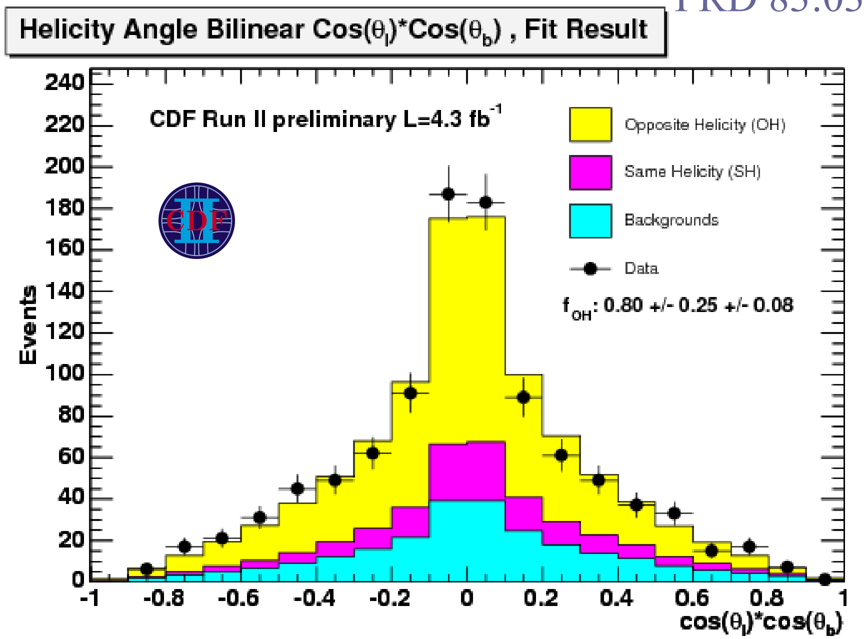


$t\bar{t}$ Spin Correlations using Angular Distributions

- Three spin correlation analyses since summer 2009! + new Atlas result
- One lepton+jets and two dilepton results!

$$CDF: \quad C = 0.72 \pm 0.64(stat) \pm 0.26(syst)$$

PRD 83:031104 (2011)



Beam basis

First extraction of $t\bar{t}$ spin correlation in l+jets!

L=2.8fb^{-1}

$$CDF: \quad C = 0.32^{+0.55}_{-0.78}(stat + syst)$$

L=5.4fb^{-1}

$$D0: \quad C = 0.10 \pm 0.45(stat + syst)$$

PLB 702, 16 (2011)

NLO SM: 0.78

Beam basis

Bernreuther et. al, 04

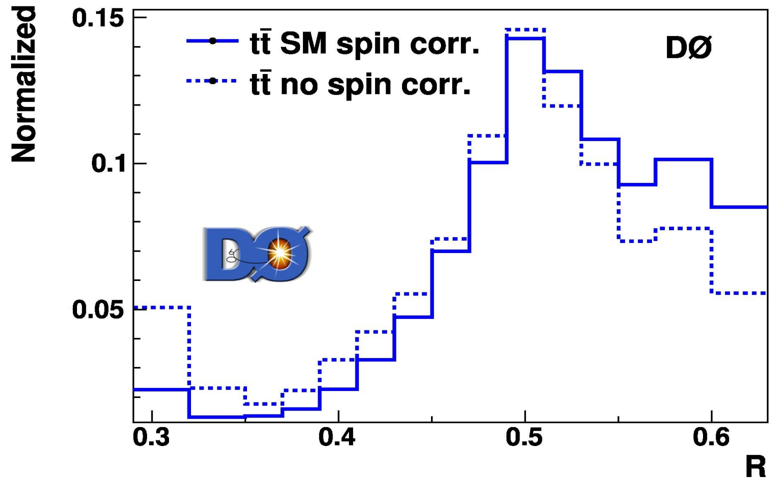
In agreement with SM

Still statistically dominated

$t\bar{t}$ Spin Correlations using Matrix Elements

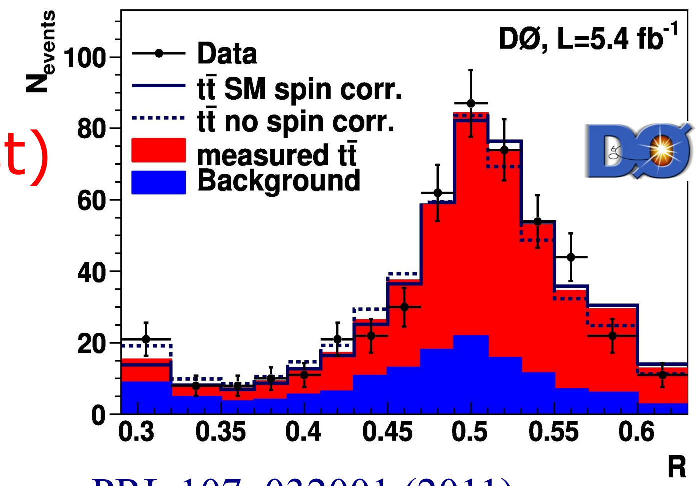
- Test hypothesis of spin correlation (H=1) versus no correlation (H=0)
- Calculate signal probability P_{sgn}, define discriminator:

$$\boxed{R = \frac{P_{\rm sgn}(H=1)}{P_{\rm sgn}(H=0) + P_{\rm sgn}(H=1)}}$$



- Templates based on MC@NLO MC, defining R with and without spin correlation
- Fit fraction $f = N_{t\bar{t}}(\text{with spin})/N_{t\bar{t}}(\text{total})$ to data
- Result of template fit: $f = 0.74^{+0.40}_{-0.41}$ (stat+syst)

  → corresponds to C=0.57 ± 0.31(stat+syst)
- ~30% improvement over template method!



First analysis with expected sensitivity of 3 SD!

PRL 107, 032001 (2011)

ME individual terms

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

$F/\bar{F}$ kinematics of $t/\bar{t}$ decay

β velocity of top quark in $t\bar{t}$ rest frame

s_{xy}(ine) between particles x and y, c_{xy}(osine)

Systematic Tables

- Dilepton:

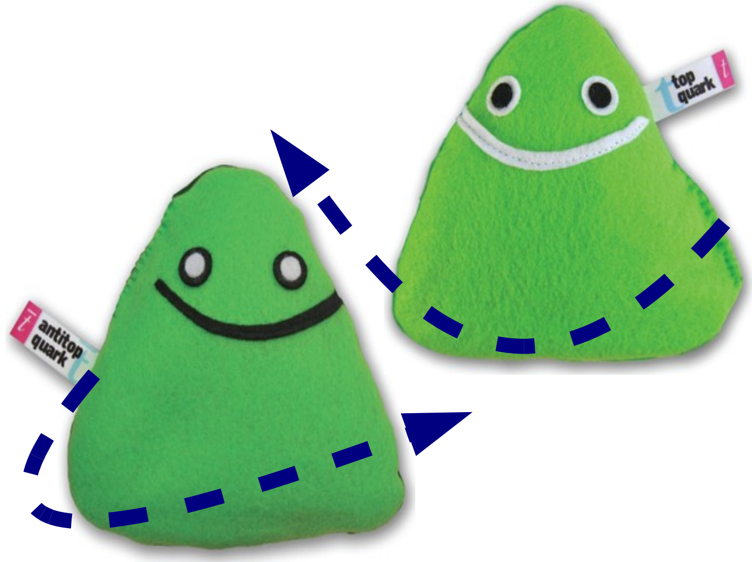
TABLE 2: Summary of uncertainties on f_{meas}.

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

L+jets and dilepton:

TABLE 1: Summary of uncertainties on f_{meas} for the combined fit in dilepton and ℓ+jets channels.

Source	+1SD	−1SD
Muon identification	0.003	−0.003
Electron identification and smearing	0.009	−0.008
PDF	0.058	−0.051
m_t	0.024	−0.040
Triggers	0.007	−0.008
Opposite charge selection	0.002	−0.002
Jet energy scale	0.005	−0.028
Jet reconstruction and identification	0.007	−0.035
b-tagging	0.012	−0.012
Normalization	0.039	−0.043
MC statistics	0.015	−0.015
Instrumental background	0.003	−0.003
Luminosity	0.023	−0.023
Multijet background	0.007	−0.007
Other	0.007	−0.007
MC statistics for template fits	0.156	−0.156
Total systematic uncertainty	0.176	−0.184
Statistical uncertainty	0.251	−0.258


antitop quark
top quark