Measurement of the top quark polarization with the DØ detector

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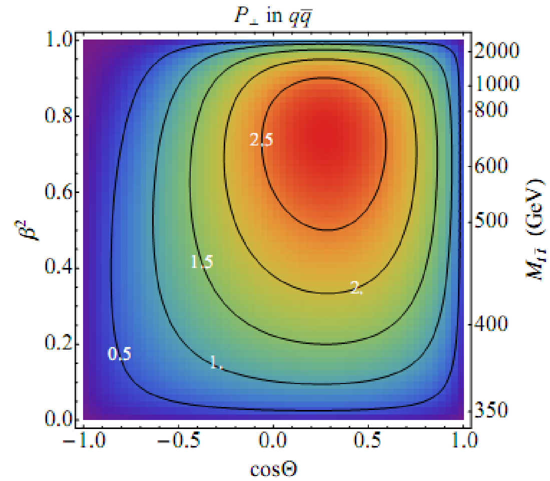
for the DØ collaboration

Motivation

- Top quark is unique, important properties – polarization:
  - in SM top quark pairs produced almost unpolarized in $p\bar{p}$
  - small polarization is generated by SM parity-violating weak interactions (*Bernreuther, Si, Nucl. Phys. B 837 (2010) 90*)
  - various models beyond SM expect non-zero polarization
  - observation of significant non-zero top quark polarization - evidence for BSM physics
- strong motivation to measure top quark polarization at Tevatron
  - **different initial state** to LHC
  - no $p\bar{p}$ results until 07/2015



Baumgart, Tweedie, JHEP 1308 (2013) 072

Introduction

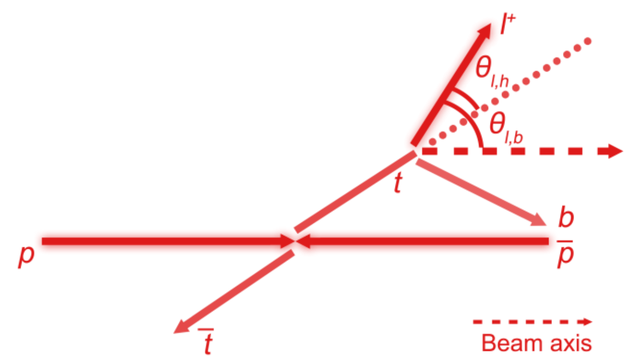
- **Top quark polarization** $P_{\hat{n}}$ can be measured in the top rest frame through the angular distribution of the top quark decay products with respect to a chosen axis $\hat{n}$:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_{i,\hat{n}}} = \frac{1}{2}\left(1 + P_{\hat{n}}\kappa_i \cos\theta_{i,\hat{n}}\right)$$

spin analyzing power: ℓ has ~1, d-type q 0.97, b-quark -0.4, ν has -0.3

decay product : ℓ, q, b, ν

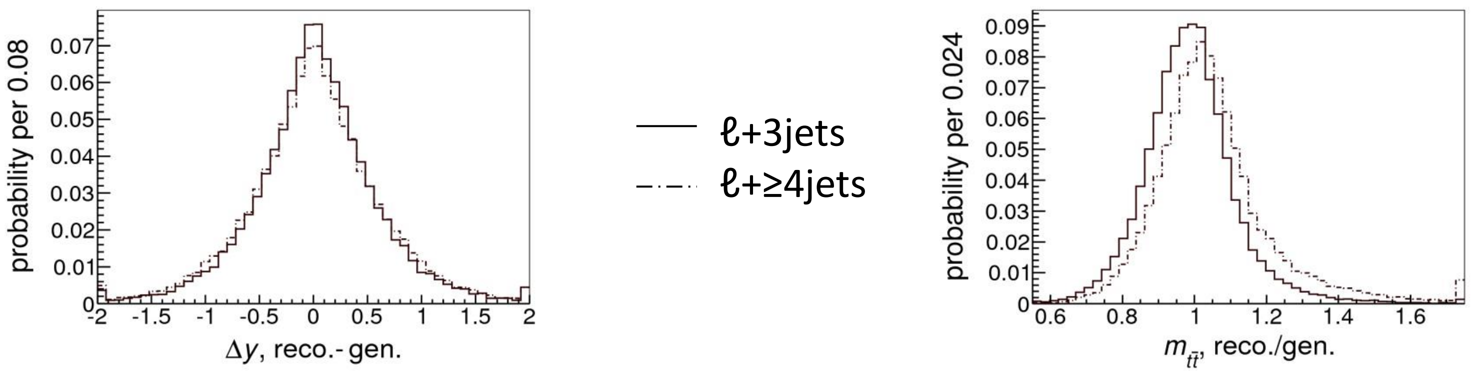
- choice of spin quantization axis:
  - the **beam axis** $\hat{b}$ given by the direction of the proton beam
  - the **helicity axis** $\hat{h}$ given by the direction of the parent top
  - the **transverse axis** $\hat{t}$ given as perpendicular to the production plane (proton × parent top directions)



longitudinal (beam and helicity) angle and axis

Method

- **lepton** is the most sensitive to the top quark polarization and is the most easily identified final state fermion
  - we focus on angular distribution of leptons
- need **full reconstruction** of the $t\bar{t}$ decay - χ^2-based constrained kinematic fit
  - *Demina, Harel, Orbaker, NIM A 788 (2015) 128*
  - allows reconstruction of events with ℓ+3 jets (one jet is lost – jet too soft or due inefficiencies in reconstruction/identification)
  - we use all combinations weighted by χ^2 and *b*-tag probability



Samples/Selection

- full RunII DØ dataset ($p\bar{p}$) of 9.7 fb^{-1}, **ℓ+jets** channel:

  - one isolated lepton ($p_T > 20$ GeV, $|\eta| < 1.1$ for e, $|\eta| < 2.0$ for μ, $y < 2.0$)
  - 3 or more jets ($p_T > 20$ GeV, $|\eta| < 2.5$, leading jet $p_T > 40$ GeV)
  - at least one *b*-tagged jet (MVA alg.)
  - significant missing transverse energy ($E_{T,miss} > 20$ GeV)
  - additional quality cuts

- **sample composition** by maximum-likelihood fit on discriminant of several variables
  $t\bar{t}$ signal (MC@NLO+HERWIG), background ALPGEN+PYTHIA (*W*+jets) or COMPHEP or data-driven (Multijet)

	3 jets		≥ 4 jets	
Source	e+jets	μ+jets	e+jets	μ+jets
W+jets	1741 ± 26	1567 ± 15	339 ± 3	295 ± 3
Multijet	494 ± 7	128 ± 3	147 ± 4	49 ± 2
Other Bg	446 ± 5	378 ± 2	87 ± 1	73 ± 1
$t\bar{t}$ signal	1200 ± 25	817 ± 20	1137 ± 24	904 ± 23
Sum	3881 ± 37	2890 ± 25	1710 ± 25	1321 ± 23
Data	3872	2901	1719	1352

Method

- we **reweight the *W*+jets MC** events so that the $\cos\theta_{\ell,\hat{n}}$ distribution shows good agreement with the data in control region 3 jets, 0 *b*-tag
- our signal $t\bar{t}$ MC sample does have zero polarization, we reweight to **templates $\boldsymbol{P_{\hat{n}} = \pm 1}$** with double distribution $1/\Gamma\, d\Gamma/d\cos\theta_1\cos\theta_2$

$$^{1}/_{4}\left(1 + \kappa_1 P_{\hat{n},1}\cos\theta_1 + \rho\kappa_2 P_{\hat{n},2}\cos\theta_2 - \kappa_1\kappa_2 C\cos\theta_1\cos\theta_2\right)$$

top quark decay product (ℓ or d-type q)

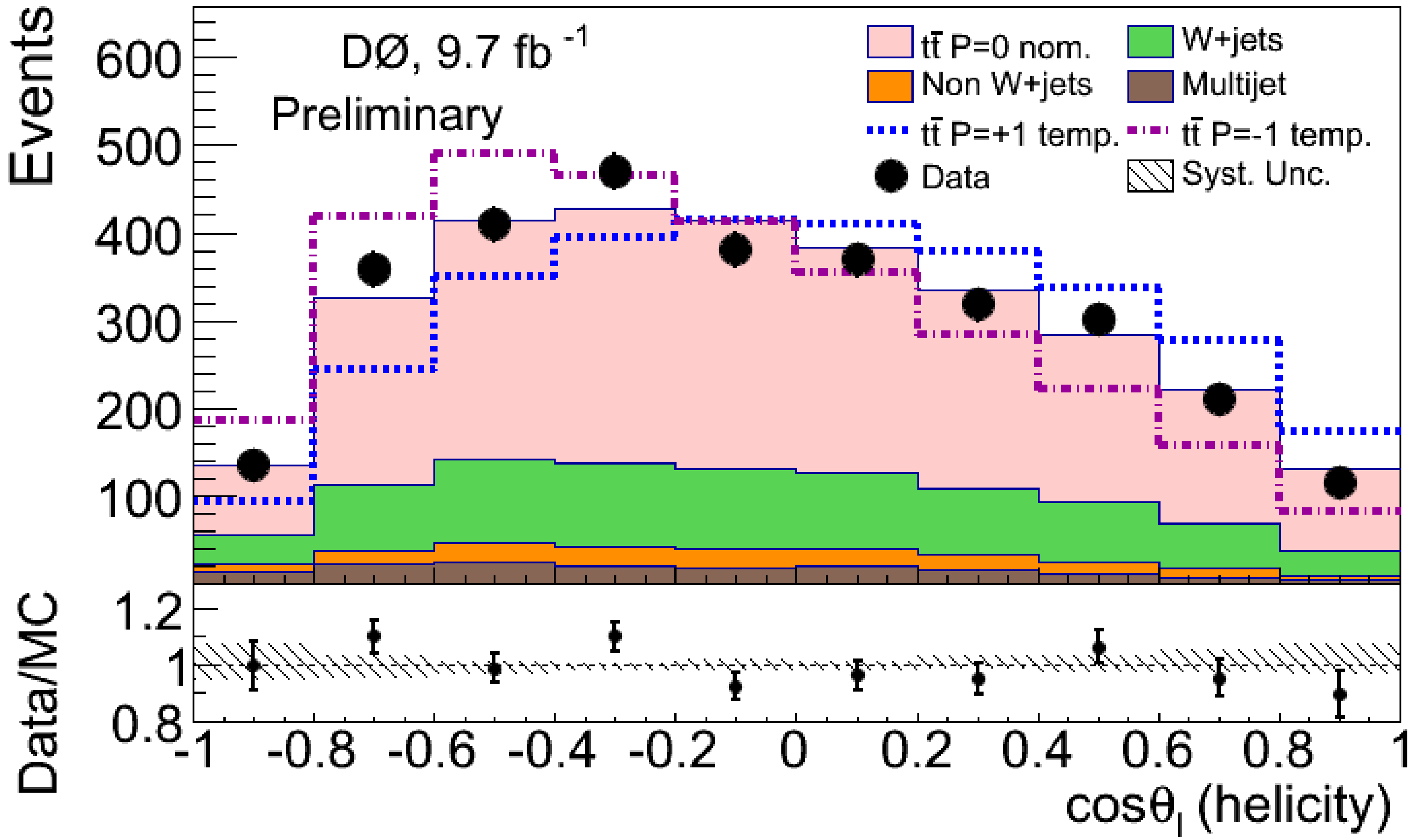
anti-top quark decay product

spin correlation factor -0.368 ($\hat{h}$), 0.791 ($\hat{b}$), 0 ($\hat{t}$)

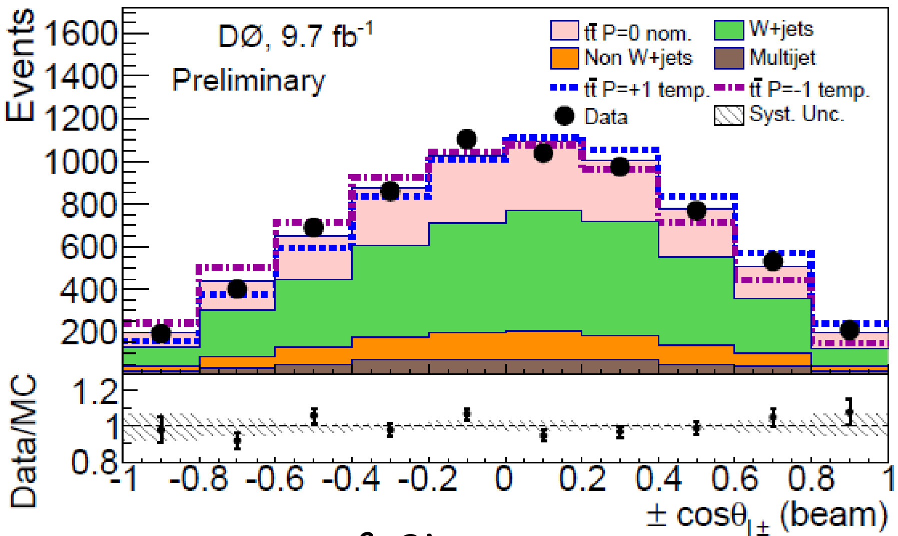
  - in the SM with CP invariance $\rho = 1$ for helicity and $\rho = -1$ for beam and transverse bases (*Bernreuther, J. Phys. G 35 (2008) 083001 (2008)*)
- **simultaneous template fit** is performed to the data using $P = \pm 1$ templates and background expectations
- polarization $P = f_+ - f_-$, where $f_\pm$ are fractions returned in the fit

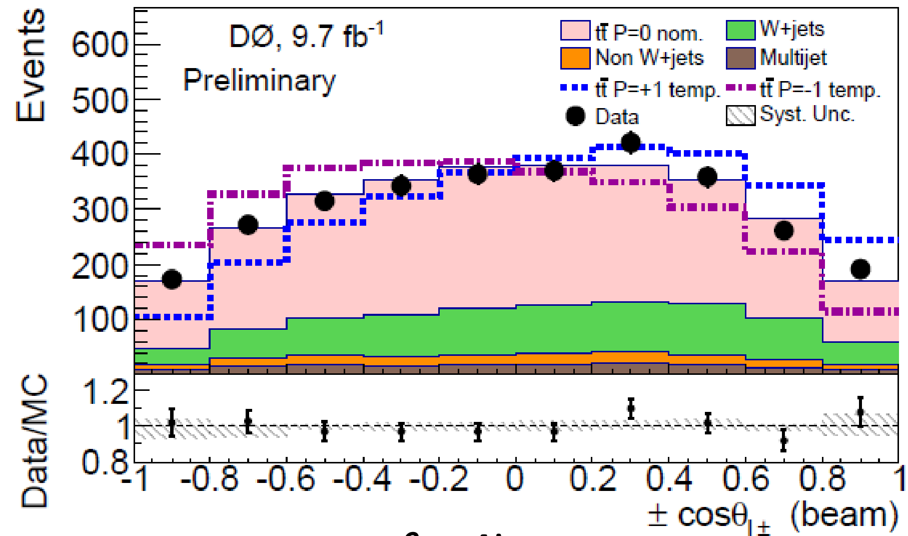
Results

- example of cos θ distribution in data, backgrounds, and signal templates P = +1, 0, -1, selection ℓ+≥4 jets



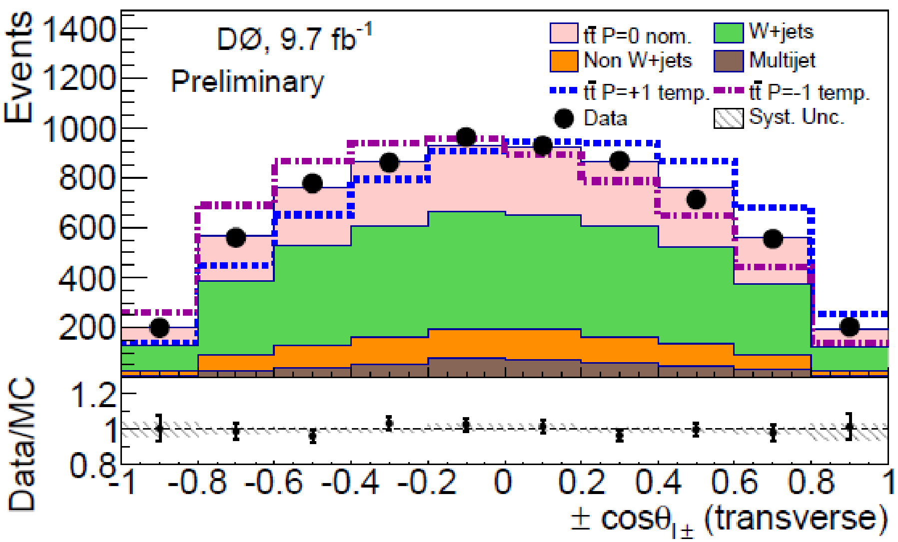
Results

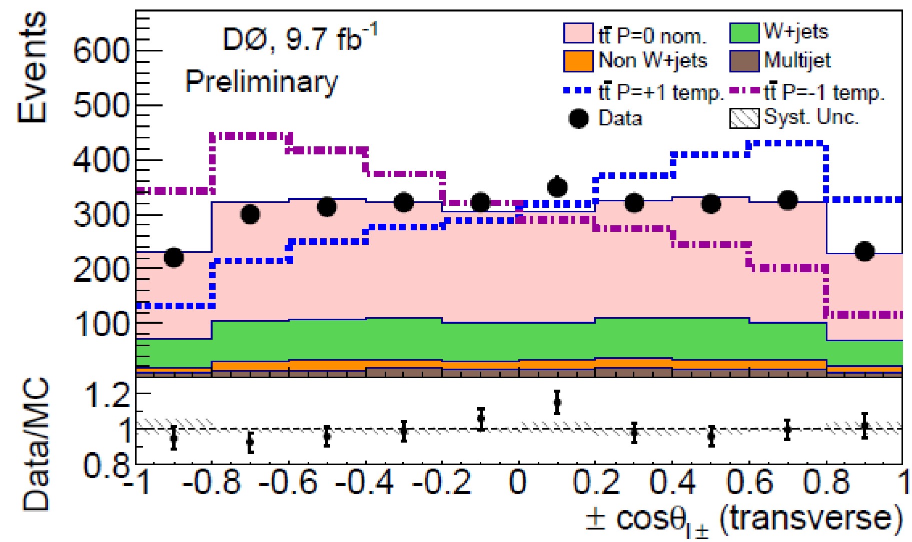




ℓ+3jets

ℓ+≥4jets





Uncertainties

- difference in polarization when using the respective alternative model or uncertainties/assumptions related to method
- three groups of systematic uncertainties:
  - signal and background modeling – dominant contribution from hadronization, higher order correction, PDF
  - detector modeling – dominant JES, *b*-tagging, flavor dependent jets response
  - method – dominant uncertainty on sample composition fit

Source	Beam	Helicity	Transverse
Signal and background modeling	±0.019	±0.022	±0.009
Detector modeling	±0.017	±0.034	±0.011
Method	±0.014	±0.008	±0.005
Total systematic uncertainty	±0.030	±0.041	±0.015
Total statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.060	±0.034

Results/Conclusion

- measured polarizations for the three spin quantization bases

Axis	Measured polarization $P_{\hat{n}}$	SM prediction
Beam	$+0.070 \pm 0.055$	-0.002
Helicity	-0.102 ± 0.060	-0.004
Transverse	$+0.040 \pm 0.034$	$+0.011$

- polarizations are consistent with zero and with the predicted SM values
- **transverse polarization** - measured for the first time at a hadron collider
- recent DØ result along beam axis in dilepton channel
  - $P_{\hat{b}} = 0.113 \pm 0.093$ (*arXiv:1507.05666 [hep-ex] -> PRD*)

The End

- Thank you for your attention

- Back-up slides…

Sample composition

- construct a likelihood discriminant
  - good separation power between signal and W+jets bkg
  - well modeled input variables
  - small or no correlation between input variables and measurement
  - ℓ+3jets

- $k_T^{min} = \min(p_{T,a}, p_{T,b}) \cdot \Delta R_{ab}$, where $\Delta R_{ab} = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}$ is the angular distance between the two closest jets, a and b, and $\min(p_{T,a}, p_{T,b})$ represents the smaller transverse momentum of the two jets;
- aplanarity, $A = 3/2\lambda_3$, where λ_3 is the smallest eigenvalue of the normalized momentum tensor $M_{i,j}$;
- H_T^ℓ, the scalar sum of the jets and lepton transverse momenta;
- $\Delta\mathcal{R}(\text{jet1}, \text{jet2})$, $\Delta\mathcal{R}$ between the leading jet and the second leading jet;
- $\Delta\mathcal{R}(\text{lepton}, \text{jet1})$, $\Delta\mathcal{R}$ between the lepton and the leading jet.

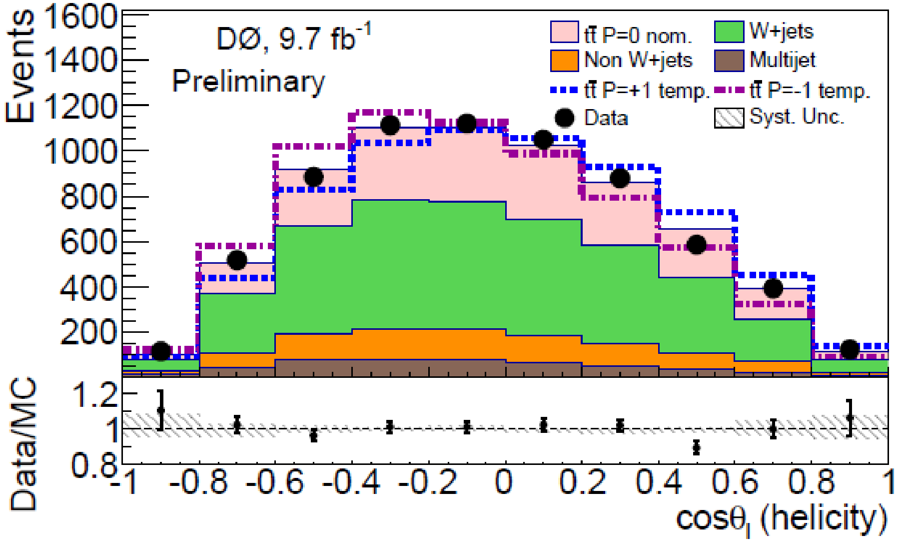
  - ℓ+≥4jets

- k_T^{min};
- aplanarity;
- H_T^l;

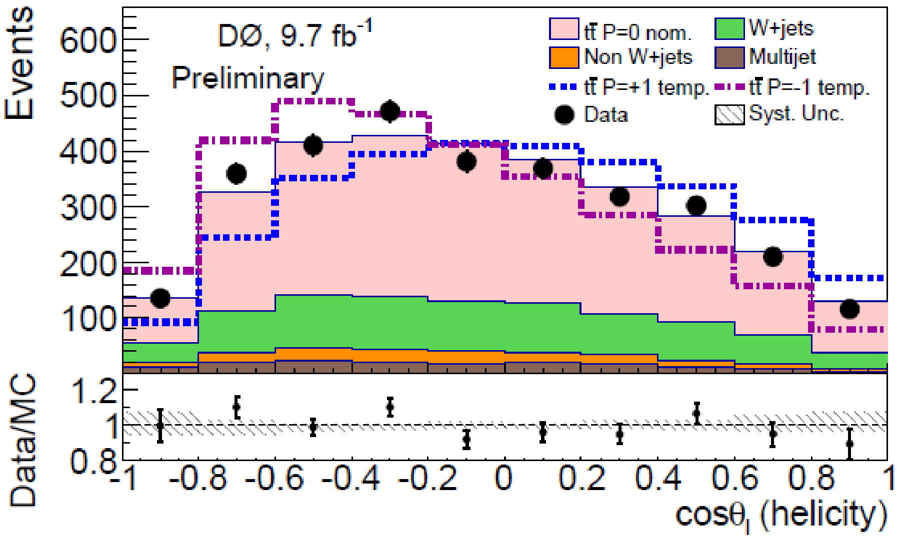
- centrality, $C = H_T/H$, where H_T is the scalar sum of all jet transverse momenta and H is the scalar sum of all jet energies.
- the lowest χ^2 of the different kinematic fit solutions;
- $(p_T^{b_{\text{had}}} - p_T^{b_{\text{lep}}})/(p_T^{b_{\text{had}}} + p_T^{b_{\text{lep}}})$, the relative asymmetry of the transverse momenta of the two b-jet candidates, where b_{lep} is from the top quark that decays to $b\ell\nu$ and b_{had} is from the top quark that decays to $bq\overline{q}'$;
- M_{jj}, the invariant mass of the jets corresponding to the $W \to q\overline{q}'$ decay.

Results

ℓ+3jets



ℓ+4jets



Uncertainties

- complete breakdown of sources:

Source	Beam	Helicity	Transverse
Signal and background modeling:			
Alternate signal	±0.009	±0.014	±0.003
Initial/final state radiation	±0.008	±0.003	±0.003
Color reconnection	±0.003	±0.007	±0.003
Multijet background	±0.001	±0.008	±0.002
Background normalization	±0.004	±0.003	±0.002
b-jet fragmentation	±0.001	±0.001	±0.000
PDF uncertainty	±0.013	±0.011	±0.003
Top quark mass	±0.002	±0.005	±0.003
Instantaneous luminosity	±0.000	±0.002	±0.002
Detector modeling:			
Residual jet energy scale	±0.009	±0.022	±0.003
Flavor-dependent jets response	±0.009	±0.008	±0.007
b-tagging	±0.009	±0.014	±0.005
Trigger efficiency	±0.002	±0.005	±0.001
Lepton momentum scale	±0.002	±0.008	±0.001
$t\bar{t}$ transverse momentum	±0.005	±0.001	±0.002
Jet energy resolution	±0.003	±0.005	±0.005
Jet identification efficiency	±0.001	±0.004	±0.003
Lepton identification	±0.006	±0.016	±0.002
Vertex confirmation	±0.004	±0.002	±0.004
Method:			
W+jets calibration	±0.002	±0.003	±0.001
Sample composition	±0.012	±0.007	±0.004
MC template statistics	±0.001	±0.001	±0.001
A_{FB} uncertainty	±0.005	±0.000	±0.000
Total systematic uncertainty	±0.030	±0.041	±0.015
Total statistical uncertainty	±0.046	±0.044	±0.030
Total uncertainty	±0.055	±0.060	±0.034

Polarization and A_{FB} dependence

- we observe dependence of polarization on forward-backward asymmetry and polarization
  - we correct for difference in A_{FB} as our $t\bar{t}$ signal (MC@NLO) is generated with asymmetry of 5.01 % and recent NNLO calculation (SM) shows asymmetry of 9.5 % (*arXiv:1411.3007 [hep-ph]*)
  - correction 3% in beam axis, 0.2% helicity, negligible transverse
- similarly recent simultaneous measurement of A_{FB} and polarization in dilepton channel obsererved correlation between those 2 measurements
  - due to acceptance and resolution eff. in reconstruction
  - *arXiv:1507.05666 [hep-ex]*