Measurement of the forward-backward asymmetry in $t\bar{t}$ events in the l+jets channel

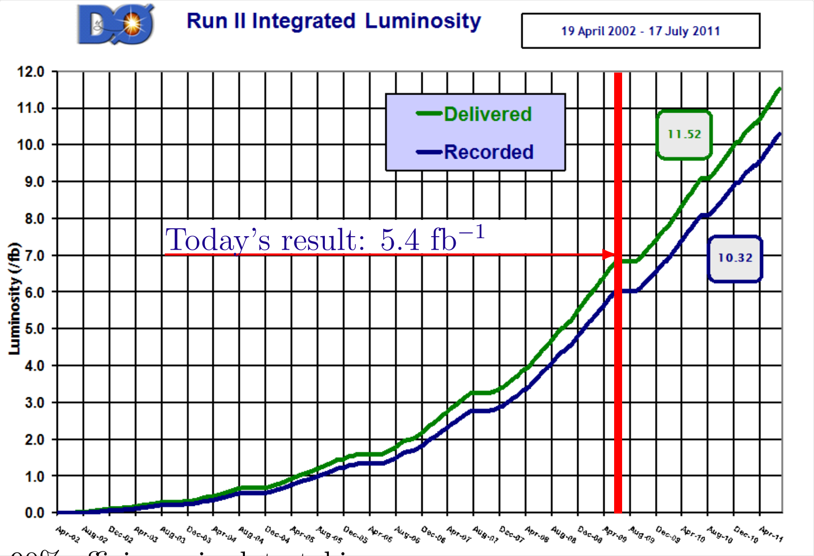
Doug Orbaker
on behalf of the DØ collaboration

July 25, 2011

DØ collaboration

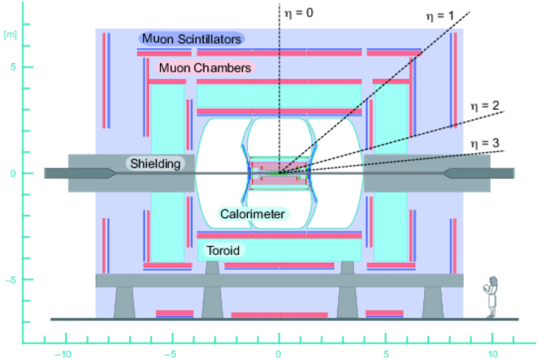
- Made up of about 500 scientists from 20 countries and 86 institutions

DØ luminosity



- 90% efficiency in data taking

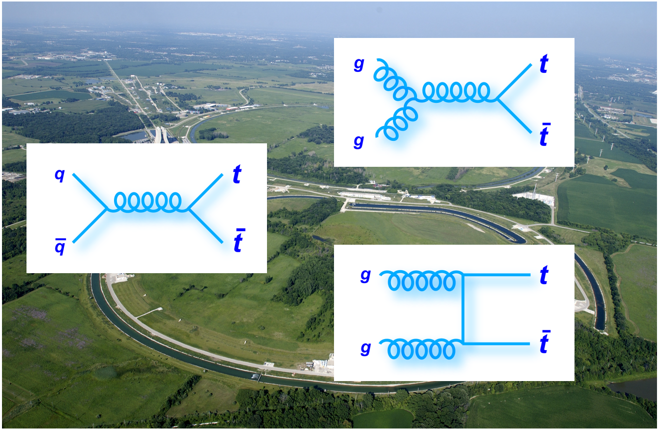
DØ detector



- Designed to detect and identify a broad range of different particles.
- Magnet polarities flipped regularly.

$t\bar{t}$ production at the Tevatron

- Produced via the strong interaction
- 85% $q\bar{q} \to t\bar{t}$ + 15% $gg \to t\bar{t}$



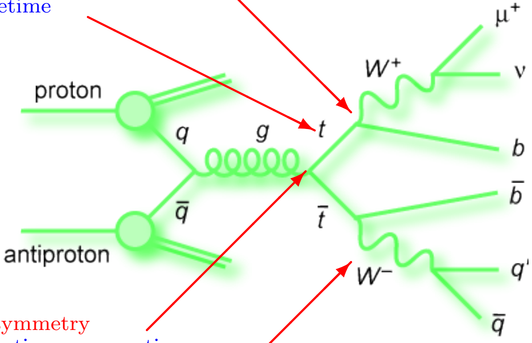
- Asymmetry arises from $q\bar{q} \to t\bar{t}$ initial states
- LHC still not competitive

Lots of properties to study

- Today's topic in red.

Top mass
$t\bar{t}$ mass difference
Top charge
Top width
Lifetime

$|V_{tb}|$
Anomalous couplings
New/rare decays

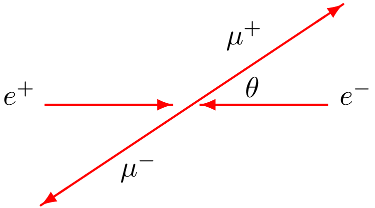


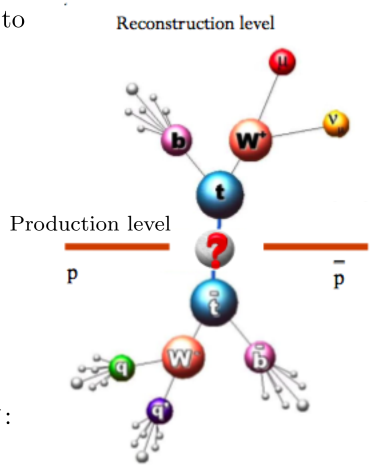
Spin correlation

FB asymmetry
Production cross section
Production kinematics
Resonance production
New particles
Violation of Lorentz invariance/CPT

W helicity

- In early 1980s, an asymmetry observed in $e^+e^- \to \mu^+\mu^-$ at $\sqrt{s} = 35$ GeV $<< M_Z$ used to verify the validity of the EW theory.
  (Phys. Rev. Lett. 48, 1701-1704 (1982))



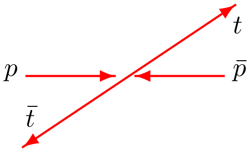


- Similarly, asymmetry in $p\bar{p} \to t\bar{t}$ could give information about new physics.
- $p\bar{p} \to t\bar{t}$ more complicated than $e^+e^- \to \mu^+\mu^-$:
  - Top quark not directly observed, but reconstructed from decay products
  - Lab frame different from collision frame

Definitions

- Does top quark or antitop quark follow direction of proton?
- For $p\bar{p} \to t\bar{t}$, use $y = \frac{1}{2} ln(\frac{E+p_z}{E-p_z})$:
  - Define $\Delta y = y_t - y_{\bar{t}}$
  - Δy invariant to boosts along beamline
  - Reconstructed $\Delta y = q_l \cdot (y_{t,lep} - y_{t,had})$

$$A_{FB} = \frac{N(\Delta y>0) - N(\Delta y<0)}{N(\Delta y>0) + N(\Delta y<0)}$$

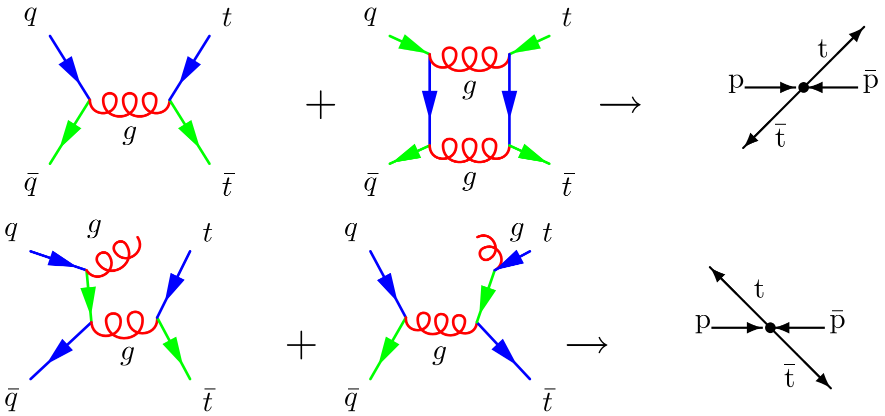


- Also use asymmetry based on lepton from top decay:
  - Very good precision
  - Simple

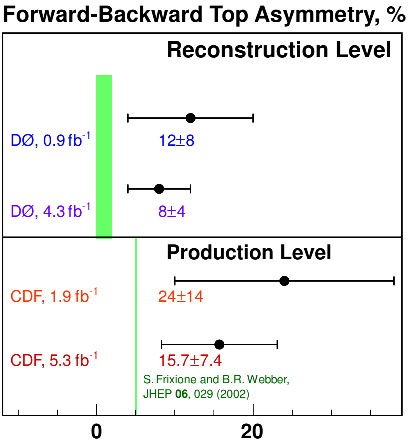
$$A^l_{FB} = \frac{N(q_l y_l>0) - N(q_l y_l<0)}{N(q_l y_l>0) + N(q_l y_l<0)}$$

- Two different types of measurements:
  - Reconstruction level: After selection and reconstruction. Background subtracted data.
  - Production level: Can be directly compared to SM predictions. Unfolding.

- SM predicts no asymmetry at LO in QCD, and a small asymmetry at NLO.



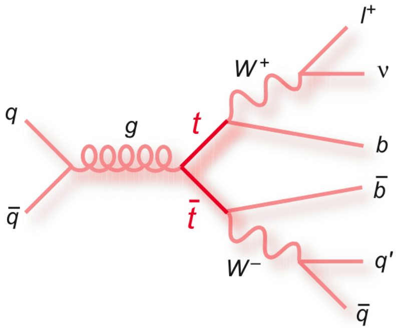
Previous measurements



- DØ results:
  - PRL 100, 142002(2008) for 0.9 fb^{-1}
  - ICHEP 2010 for 4.3 fb^{-1} (preliminary)
- CDF:
  - PRL 101, 202001(2008) for 1.9 fb^{-1}
  - Phys. Rev. D 83,112003 (2011) for 5.3 fb^{-1}

Event Selection and Reconstruction

- Search in the lepton (e/μ) + jets channel



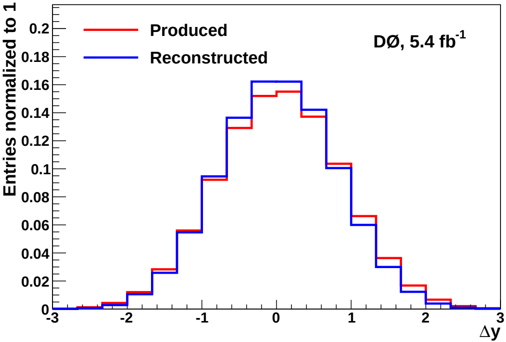
Require:
⇒ 1 lepton with $p_T > 20$ GeV
⇒ $\not{E}_T > 20$ GeV
⇒ ≥ 4 jets with $p_T > 20$ GeV
⇒ At least 1 jet with $p_T > 40$ GeV
⇒ At least 1 jet passing b-tagging requirements; 70% efficient for b jets from top decay and 8% rate of mis-ID.
⇒ Charge of lepton determines which reconstructed quark is the top quark.

- Reconstruct events with a kinematic fitter, requiring $M_W = 80.4$ GeV and $M_t = 172.5$ GeV
- Keep only assignment with lowest χ^2
- 1581 events pass selection

Predictions

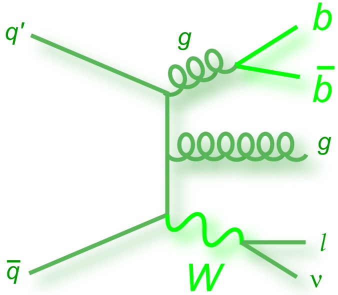
- All predictions made at NLO in QCD via MC@NLO

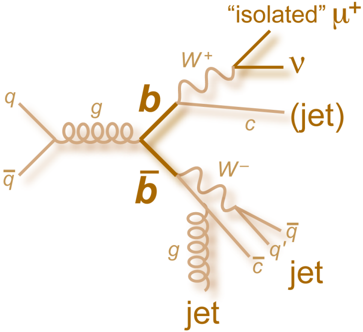
Level	Channel	A_{FB} (%)	A^{l}_{FB} (%)
Production	lepton+jets	5.0 ± 0.1	2.1 ± 0.1
Reconstruction	e+jets	2.4 ± 0.7	0.7 ± 0.6
	μ+jets	2.5 ± 0.9	1.0 ± 0.8
	l+jets	2.4 ± 0.7	0.8 ± 0.6



Backgrounds

- Two main sources of background with similar signature to $t\bar{t}$ events:
  - W+jets - Production of W in association with jets; simulated with ALPGEN+PYTHIA
  - Multijet - Taken from data

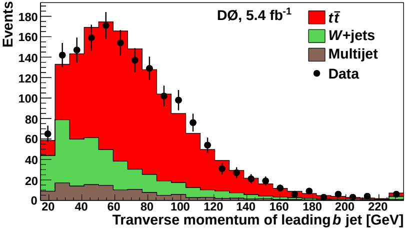


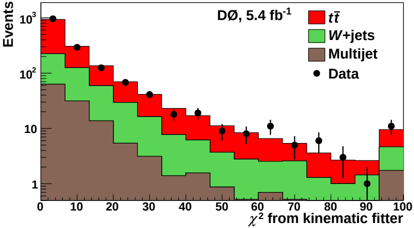


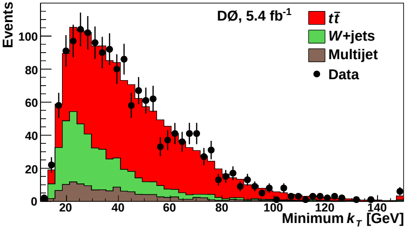
- Other small backgrounds approximated as W+jets: single top, diboson and Z+jets

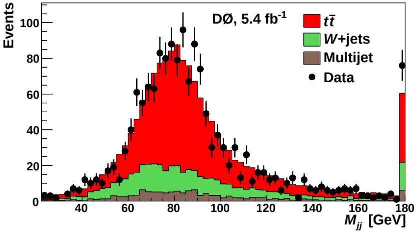
Separating signal from background

- Likelihood discriminant designed to separate $t\bar{t}$ signal events from W+jets background
- Inputs to discriminant have small correlations with $|\Delta y|$



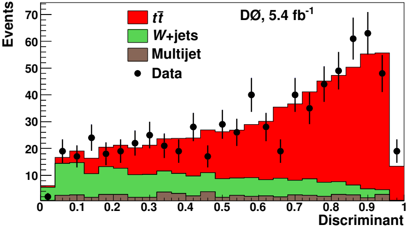




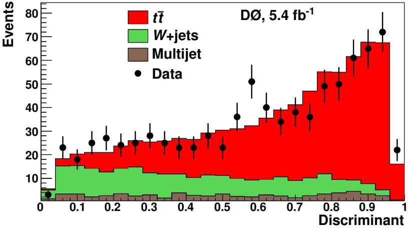


Reconstruction method

- Use maximum likelihood fit to measure reconstructed asymmetry, signal fraction and background fractions
- Templates are:
  - $t\bar{t}$ signal with $\Delta y > 0$
  - $t\bar{t}$ signal with $\Delta y < 0$
  - W+jets background (A_{FB} taken from simulation)
  - Multijet background derived from data (A_{FB} taken from data)

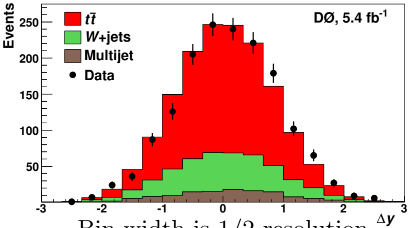


Discriminant with $\Delta y < 0$



Discriminant with $\Delta y > 0$

Results from reconstruction of A_{FB}

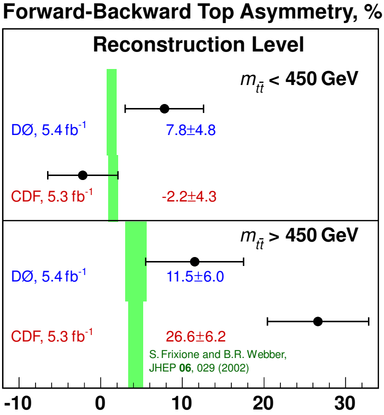


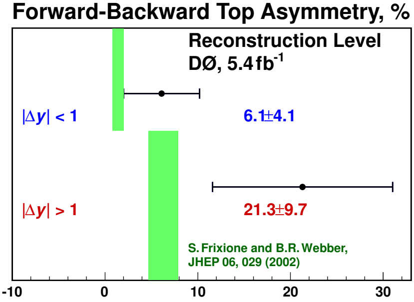
Bin width is 1/2 resolution

	l+≥4 jets	l+4 jets	l+≥5 jets
Raw $N_{\Delta y>0}$	849	717	132
Raw $N_{\Delta y<0}$	732	597	135
A_{FB}(%)	9.2±3.7	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	3.9±0.8	-2.9±1.1

- Measured $A_{\mathrm{FB}} = (9.2 \pm 3.6^{+0.8}_{-0.9})\%$
- Statistical significance from MC@NLO prediction: 1.9 SD

Dependence of A_{FB} on $|\Delta y|$ and $M_{t\bar{t}}$





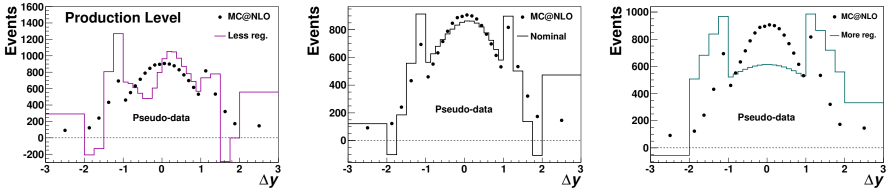
- No significant deviation between A_{FB} at reconstruction level.

What is unfolding?

- Unfolding helps deal with imperfect detector reconstruction.
- Requires knowledge of how detector reconstruction works.
- Example below from Statistical Data Analysis by Glen Cowan.

Unfolding procedures

- Input to unfolding is background subtracted data.
- Use two different unfolding procedures:
  - Maximum Likelihood unfolding with four bins
  - Regularized unfolding with $50 \rightarrow 26 \rightarrow 2$ bins
- Why use regularized unfolding?
  - More accurately describes migrations across the $\Delta y = 0$ boundary between the forward and backward regions
  - Regularization smoothes out noisy components



Unfolding via matrix inversion

- ML unfolding (matrix inversion) with four bins:
  - Binning the same as CDF's measurement.
  - $\vec{n}_{reco} = \mathbf{SA}\vec{n}_{prod} \Longrightarrow \vec{n}_{prod} = \mathbf{A^{-1}S^{-1}}\vec{n}_{reco}$
  - Bin edges at $\Delta y = -3, -1, 0, 1$, and 3
  - Very similar migrations as seen by CDF.
  - Diagonal of $\mathbf{A}$ shows relative acceptance for different Δy ranges and sums to 4.

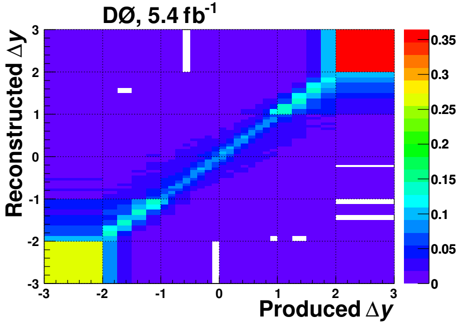
$$\mathbf{S} = \begin{bmatrix} 0.50 & 0.08 & 0.03 & 0.02 \\ 0.35 & 0.65 & 0.24 & 0.11 \\ 0.12 & 0.25 & 0.65 & 0.32 \\ 0.03 & 0.02 & 0.08 & 0.54 \end{bmatrix} \quad \mathbf{A} = \begin{bmatrix} 1.04 & 0 & 0 & 0 \\ 0 & 1.03 & 0 & 0 \\ 0 & 0 & 1.00 & 0 \\ 0 & 0 & 0 & 0.93 \end{bmatrix}$$

$$\vec{n}_{reco} = \begin{bmatrix} 95 \\ 402 \\ 456 \\ 141 \end{bmatrix} \quad \vec{n}_{prod} = \begin{bmatrix} 100 \\ 354 \\ 452 \\ 187 \end{bmatrix}$$

- Statistical uncertainty measured with ensemble testing.
- Unfolded A_{FB} from matrix inversion = 16.9% +/- 8.1%.
- CDF result for same technique: A_{FB} = 15.8% +/- 7.5%.

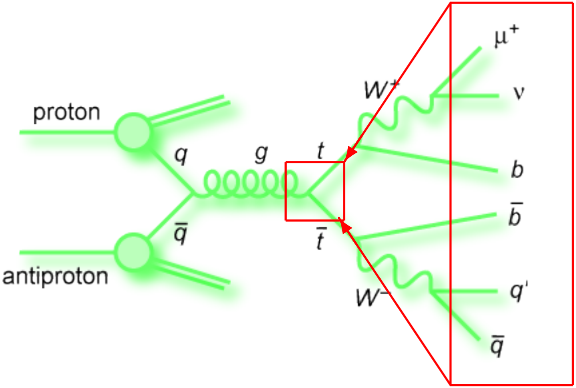
Procedure for regularized unfolding

- Use TUnfold class with 50 $\rightarrow$ 26 bin in Δy and regularization
- Modified TUnfold to use variable binning
- Regularize on curvature, requiring a somewhat continuous derivative of event density



- Ensemble testing used to evaluate:
  - Strength of regularization
  - Statistical fluctuations of backgrounds
  - Model dependence of bias from technique

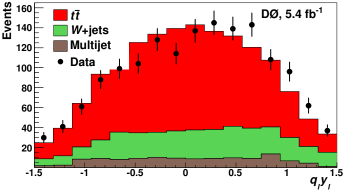
Results with regularized unfolding



- Statistical uncertainty evaluated with ensemble testing.
- Result from regularized unfolding: $A_{\mathrm{FB}} = (19.6 \pm 6.0^{+1.8}_{-2.6})\%$
- Better statistical strength than unfolding by matrix inversion.
- Statistical significance from MC@NLO prediction: 2.4 SD

Lepton-based asymmetry

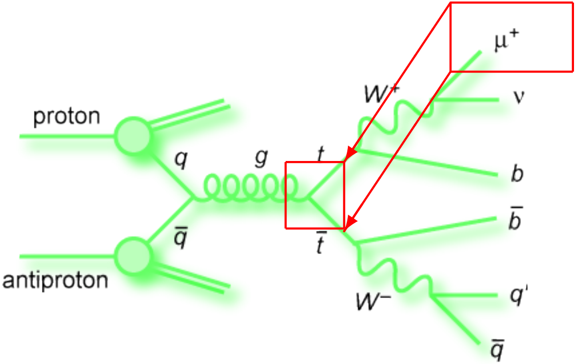
- Simple observable.
- Same technique as measurement of reconstructed A_{FB}.
- Additional selection of $|y_l| < 1.5$ to avoid large acceptance corrections.
- 1532 events.



$$A^l_{\mathrm{FB}} = \frac{N(q_l y_l > 0) - N(q_l y_l < 0)}{N(q_l y_l > 0) + N(q_l y_l < 0)}$$

	$l+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
Raw $N_{q \cdot y_l > 0}$	867	730	137
Raw $N_{q \cdot y_l < 0}$	665	546	119
A^l_{FB} (%)	14.2± 3.8	15.9± 4.3	7.0± 8.0
MC@NLO A^l_{FB} (%)	0.8± 0.6	2.1± 0.6	-3.8± 1.2

Unfolding $A_{\rm FB}^{l}$



- Migrations are very small. Leptons are measured very precisely.
- Correct only for selection: $\vec{n}_{reco} = \mathbf{A}\vec{n}_{prod} \Longrightarrow \vec{n}_{prod} = \mathbf{A}^{-1}\vec{n}_{reco}$
- Statistical uncertainty found with ensemble testing.
- Unfolded $A_{\rm FB}^{l}$, corrected for effects of selection: $\left(15.2\% \pm 3.8^{+1.0}_{-1.3}\right)\%$
- Statistical significance from MC@NLO: 3.4 SD

Systematics

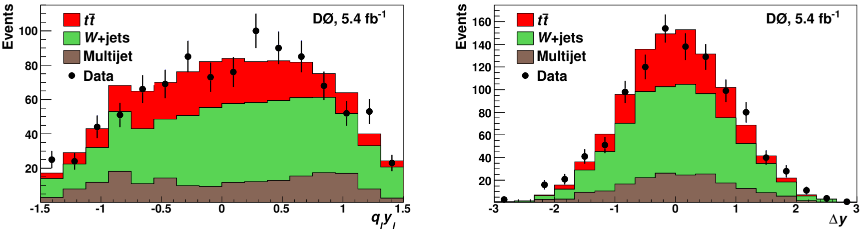
- Systematics uncertainties << statistical uncertainties

Absolute uncertainty on A_{FB} (%)			
	Reco. level		Prod. level
Source	Prediction	Measurement	Measurement
Jet reco	± 0.3	± 0.5	± 1.0
JES/JER	$+0.5$	-0.5	-1.3
Signal modeling	± 0.3	± 0.5	$+0.3/-1.6$
b-tagging	-	± 0.1	± 0.1
Charge ID	-	$+0.1$	$+0.2/-0.1$
Bg subtraction	-	± 0.1	$+0.8/-0.7$
Unfolding Bias	-	-	$+1.1/-1.0$
Total	$+0.7/-0.5$	$+0.8/-0.9$	$+1.8/-2.6$

Absolute uncertainty on A^{l}_{FB} (%)			
	Reco. level		Prod. level
Source	Prediction	Measurement	Measurement
Jet reco	± 0.3	± 0.1	± 0.8
JES/JER	$+0.1$	-0.4	$+0.1/-0.6$
Signal modeling	± 0.3	± 0.5	$+0.2/-0.6$
b-tagging	-	± 0.1	± 0.1
Charge ID	-	$+0.1$	$+0.2/-0.0$
Bg subtraction	-	± 0.3	± 0.6
Total	± 0.5	± 0.7	$+1.0/-1.3$

Cross checks

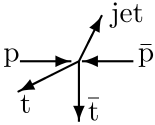
- Simultaneously measured A_{FB} from $t\bar{t}$ and A_{FB} from W+jets
- Measured A_{FB} from W+jets in good agreement with simulation

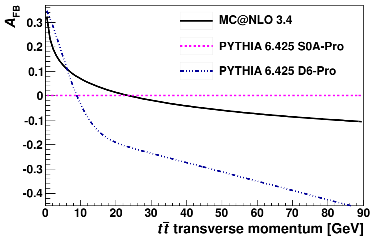


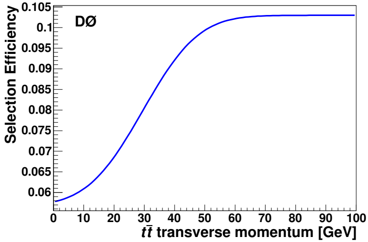
- Checked A_{FB} dependence on solenoid and toroid polarities
  $\Rightarrow$ Found no significant deviations
- Checked A_{FB} by lepton charge
  $\Rightarrow$ Found no significant deviations

$A_{\rm FB}$ and top pair p_T

- Is the amount of gluon radiation the same for forward and backward events?
- In PYTHIA, $p_T^{t\bar{t}}$ is correlated with the asymmetry when angular coherence is turned on
- Coherence at least slightly overstated in simulation



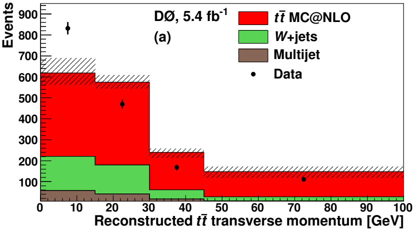


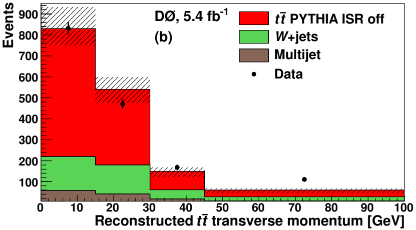


- If correlation exists, backward events selected more often than forward events
- Effect on measurement is included in systematics
- Effect on predictions could be larger

Modeling and top pair p_T

- The correlation between $p_T^{t\bar{t}}$ and A_{FB} may be large
- So we checked the modeling of $p_T^{t\bar{t}}$
- Drastic change needed to get simulation to match data for $p_T^{t\bar{t}}$





Bins of 1/2 resolution. Hash marks = uncertainty from jet reconstruction

- Low $p_T^{t\bar{t}} \rightarrow$ less gluon radiation =? larger predicted A_{FB}

MC@NLO = SM?

- Predicted A_{FB} from $t\bar{t}j$ production changes from $\sim -7\%$ at α_s^3 to -1.5% at α_s^4.

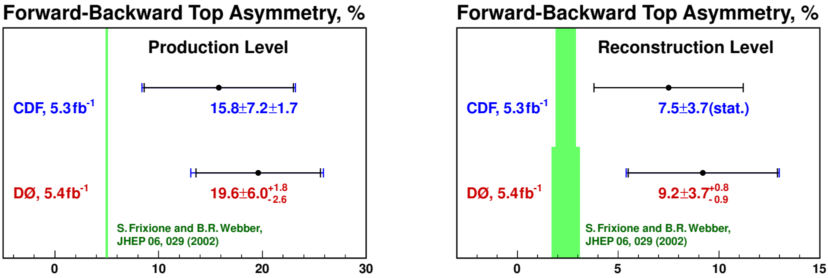
  S. Dittmaier, P. Uwer, and S. Weinzierl, Phys. Rev. Lett. **98**, 262002 (2007).

- Others argue this will not change the inclusive asymmetry.

  K. Melnikov and M. Schulze, Nucl. Phys. B **840**, 129 (2010).

- We choose one particular generator: MC@NLO
- Will future MC generators predict other A_{FB}?

Summary

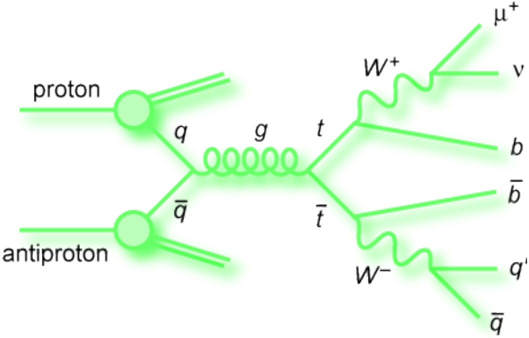


- Inclusive results in agreement between DØ and CDF, and deviate from prediction
- Measure no significant dependencies of A_{fb} on either $m_{t\bar{t}}$ or $|\Delta y|$
- Compare to most useful SM predictions: MC@NLO, but note limitations

Backup Slides

Kinematic fitter

- Answers questions: Which jets came from top quark and which jets came from antitop quark?
- Gets right answer 70% of events where leading four jets are from $t\bar{t}$ decay.
- Constrain m_W to 80.4 GeV and m_t to 172.5 GeV.
- Vary jets within resolution and get χ^2 for each jet permutation.



Reconstructed A_{FB} table

	$l+\geq 4$ jets	$e+\geq 4$ jets	$\mu+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
Raw $N_{\Delta y>0}$	849	455	394	717	132
Raw $N_{\Delta y<0}$	732	397	335	597	135
$N_{t\bar{t}}$	1126±39	622±28	502±28	902±36	218±16
N_W	376±39	173±28	219±27	346±36	35±16
N_{MJ}	79±5	56±3	8±2	66±4	13±2
A_{FB}(%)	9.2±3.7	8.9±5.0	9.1±5.8	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	2.4±0.7	2.5±0.9	3.9±0.8	-2.9±1.1

Reconstructed A^l_{FB} table

	l+≥4 jets	e+≥4 jets	μ+≥4 jets	l+4 jets	l+≥5 jets
Raw $N_{q\cdot y_l>0}$	867	485	382	730	137
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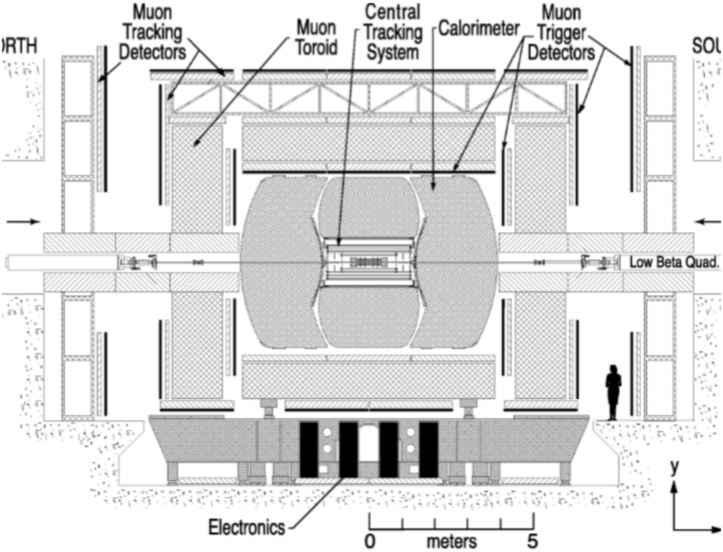
A^l_{FB} (%)	14.2± 3.8	16.5± 4.9	9.8± 5.9	15.9± 4.3	7.0± 8.0
MC@NLO A^l_{FB} (%)	0.8± 0.6	0.7± 0.6	1.0± 0.8	2.1± 0.6	-3.8± 1.2

DØ detector


Muon
Tracking
Detectors
Muon
Toroid
Central
Tracking
System
Calorimeter
Muon
Trigger
Detectors
RTH
SOU
Low Beta Quad.
Electronics
0
meters
5
y