Measurement of the Forward-Backward Asymmetry of $t\bar{t}$ at the Fermilab Tevatron

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FERMI NATIONAL LABORATORY SEMINAR
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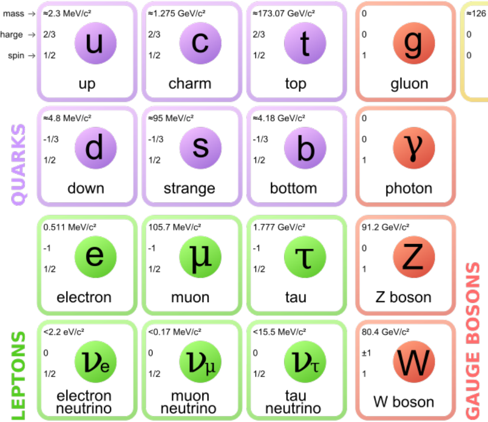
TEXAS A&M UNIVERSITY

The Standard Model - Top Quark



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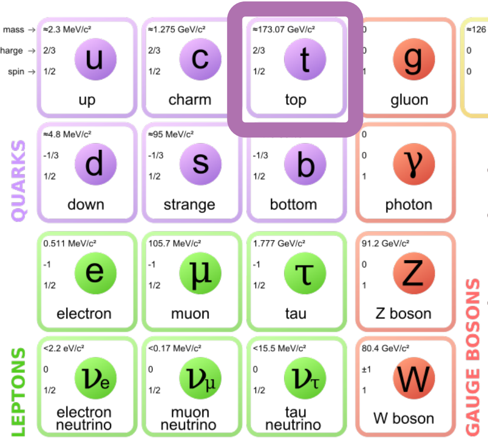


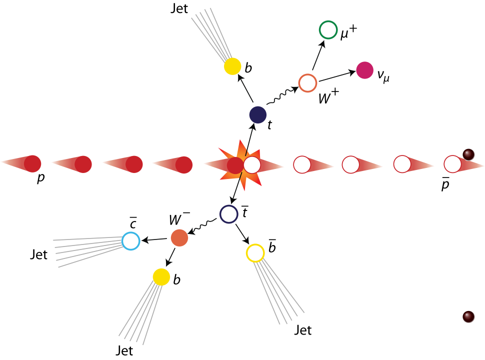
Top Quark

- Observed at Tevatron (1995)
- Very heavy
  - $m_t \simeq 173\ \mathrm{GeV/c^2}$
- Very short lived
  - No time to form hadrons
  - Unique opportunity to study a "bare" quark

Mysterious particle

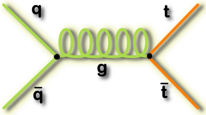
Properties need to be further understood

Top-Quark Pair at Tevatron

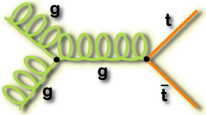


Top-quark pair production at the Fermilab Tevatron

- $p\bar{p}$ collision at Tevatron
  - CP even initial state
  - Different from pp collision and CP odd initial state at LHC
- Unique production mechanism
  - 85% quark annihilation (a) 15% gluon fusion (b)
  - LHC is gluon fusion dominated ($> 90\%$)

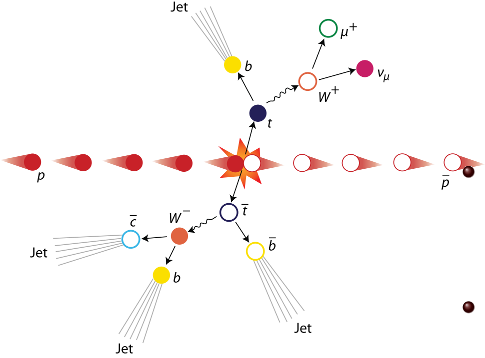


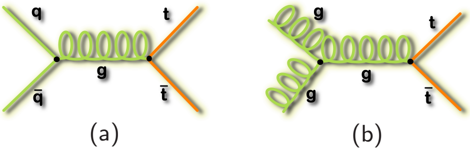
(a)



(b)

Top-Quark Pair at Tevatron



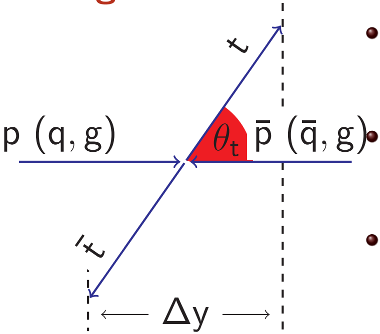


Top-quark pair production at the Fermilab **Tevatron**

- $\sim 70,000\ t\bar{t}$ produced
  - Study events to learn how particles interact
- Tevatron experiment sensitive to certain top-quark production mechanisms and properties

$A_{FB}^{t\bar{t}}$ at Tevatron

- Cross-section, mass and width measured & agree with SM
  What else can we learn about $t\bar{t}$ produced at Tevatron?
- **Angular distribution**



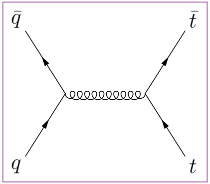
- Simplest observable: forward-backward asymmetry (A_{FB})
- Does top quark prefer proton direction or the opposite?
- Can measure rapidity difference between top and anti-top
- Define A_{FB} of $t\bar{t}$ production:

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z}$$

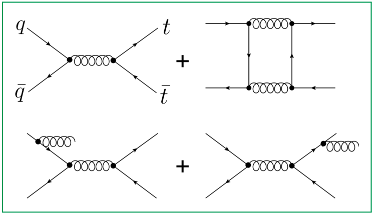
$$A_{FB}^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

$A_{FB}^{t\bar{t}}$ at Tevatron

What does the SM predict?



- No net preference in leading order diagram
- At next-to-leading order (NLO):
  top quark slightly prefers proton direction (forward)
  $\rightarrow$Interference among diagrams
- We compare to $A_{FB}^{t\bar{t}}(\text{NLO}) = 0.088 \pm 0.006$ (PRD **86**,034026 (2012))
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
- However, different SM calculation gives different answers and uncertainties (0.050-0.125)
- **SM calculation still progressing**



$A_{\text{FB}}^{t\bar{t}}$ at Tevatron

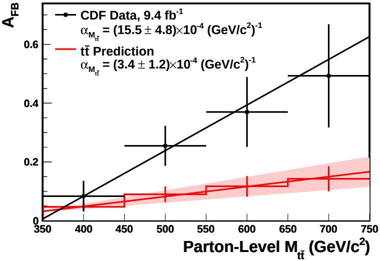
- Previous experimental results?

CDF: $A_{\text{FB}}^{t\bar{t}} = 0.164 \pm 0.047$ (PRD **87**, 092002 (2013))

D0: $A_{\text{FB}}^{t\bar{t}} = 0.106 \pm 0.030$ (arXiv:1405.0421)

- Measured result from CDF in tension with conventional SM calculation, with result from D0 in between

- Perhaps more important: $A_{\text{FB}}^{t\bar{t}}$ vs. $m_{t\bar{t}}$ deviates from SM prediction



$A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron

- Anomalously large $A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron
- Calling for more accurate SM calculation?

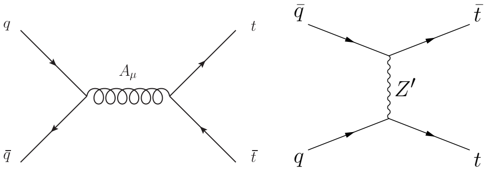
  Or
- Smoking gun for new physics?

$A_{FB}^{t\bar{t}}$ at Tevatron

Possible alternative hypotheses?

Models beyond the SM can predict large $A_{FB}^{t\bar{t}}$

- Axigluons
- Flavor-changing Z' boson
- Beyond-SM W' boson
- Beyond-SM Higgs boson
- Extra dimensions
- ......



$\cdots$

$A_{\mathrm{FB}}^{t\bar{t}}$ at Tevatron

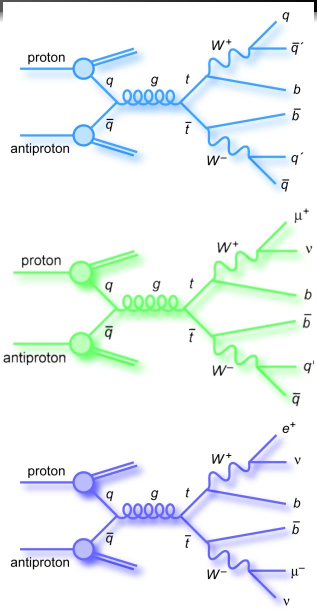
How to look for more evidence for/against new physics?

Pursue in two directions

- Measure $A_{\mathrm{FB}}^{t\bar{t}}$ with more $t\bar{t}$ events in other final states
- Measure other related observables

Top-Quark Pair Decay Modes

- **How does top quark decay?**
- $t \rightarrow Wb$ almost 100% of time
- Three types of final states based on W decay mode:



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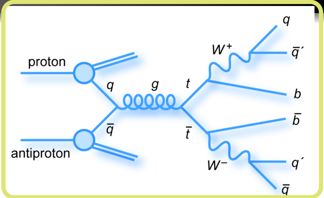
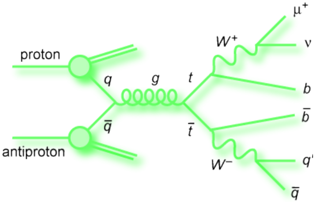
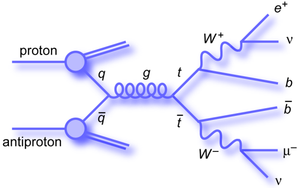
- $t \rightarrow Wb$ almost 100% of time
- Three types of final states based on W decay mode:
  - All hadronic←**Difficult channel**
    - Large branching fraction
    - Hard to determine jet energy/charge
    - Hard to reconstruct $t\bar{t}$







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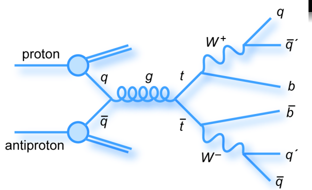
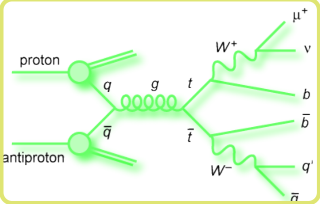
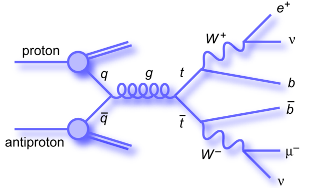
  - Lepton+jets←**Previous result**
    - Decent branching fraction
    - Lepton provides additional handle







Top-Quark Pair Decay Modes

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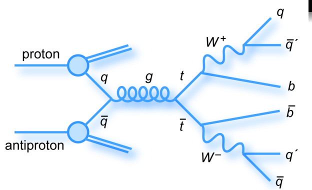
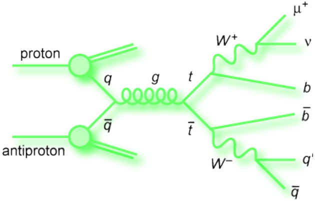
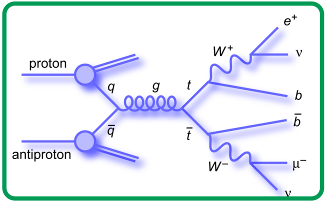
- $t \rightarrow Wb$ almost 100% of time
- Three types of final states based on W decay mode:
  - All hadronic$\leftarrow$**Difficult channel**
    - Large branching fraction
    - Hard to determine jet energy/charge
    - Hard to reconstruct $t\bar{t}$
  - Lepton+jets$\leftarrow$**Previous result**
    - Decent branching fraction
    - Lepton provides additional handle
  - Dilepton $\leftarrow$**Focus of this talk**
    - Small branching fraction
    - Leptons precisely measured
    - Two ν's, hard to reconstruct $t\bar{t}$

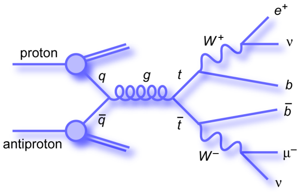






Additional $t\bar{t}$ events in dilepton

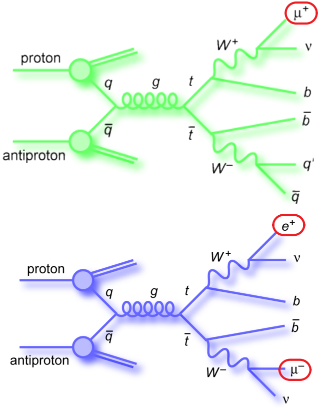
- Previous measurement based on lepton+jets final state
- Can measure $A_{\text{FB}}^{t\bar{t}}$ in dilepton



- Independent dataset with extended detector coverage, different background constitution and estimation methods
- Need to reconstruct 4-momentum of $t\bar{t}$
  $\rightarrow$Tough job in dilepton
- More on this later

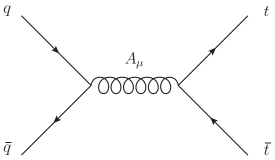
Other observables?

- Two equally important observables with leptons
- Leptonic A_{FB}
  - $$A^{\ell}_{\text{FB}} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$
- Also lepton pair A_{FB} defined with lepton η difference, only in dilepton
- Why consider A^{ℓ}_{FB}?
  - Lepton angles precisely measured
  - Tend to follow direction of parent tops



A_{FB}^{ℓ} at Tevatron

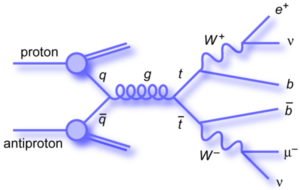
- NLO SM prediction: $A_{FB}^{\ell} = 0.038 \pm 0.003$
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
- Prediction with new physics?
- Based on CDF $A_{FB}^{t\bar{t}}$ result (0.16 ± 0.05), assuming everything else SM-like: $0.070 < A_{FB}^{\ell} < 0.076$
- In new physics models, $A_{FB}^{t\bar{t}}$ and A_{FB}^{ℓ} are **not correlated**.
- **Independent measurements of $A_{FB}^{t\bar{t}}$ and A_{FB}^{ℓ} are crucial**



Example:
Axigluon model
($m = 200$ GeV/c^2, $\Gamma = 50$ GeV)
$\rightarrow A_{FB}^{t\bar{t}} = 0.12$
$-0.06 < A_{FB}^{\ell} < 0.15$
depending on handedness of couplings
(PRD **87**,034039 (2013))

$A_{\mathrm{FB}}^{\ell\ell}$

- Lepton pair A_{FB}
  - $$A_{\mathrm{FB}}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$
- NLO SM prediction: $A_{\mathrm{FB}}^{\ell\ell} = 0.048 \pm 0.004$
- Larger expectations
- Only defined in dilepton, smaller statistics
- Provide extra information to help constraining new physics models



A^{ℓ}_{FB} at Tevatron

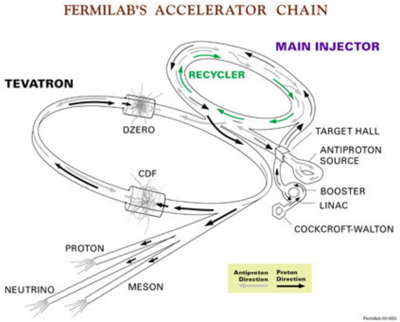
- Measurement of A^{ℓ}_{FB} in lepton+jets at CDF

$$A^{\ell}_{\text{FB}} = 0.094^{+0.028}_{-0.026}, \text{ PRD } \mathbf{88}, \text{ 072003 (2013)}$$

- 1.9σ larger than NLO SM calculation of 0.038 ± 0.003
- Large $A^{t\bar{t}}_{\text{FB}}$ holds in A^{ℓ}_{FB} in the same dataset
- New results presented today:
  1. Confirm or deny this anomaly large asymmetry ($A^{t\bar{t}}_{\text{FB}}$ and A^{ℓ}_{FB}) with the dilepton final state
  2. Measure $A^{\ell\ell}_{\text{FB}}$
  3. What is the best-word-understanding of the A_{FB} results?

Tevatron and CDF

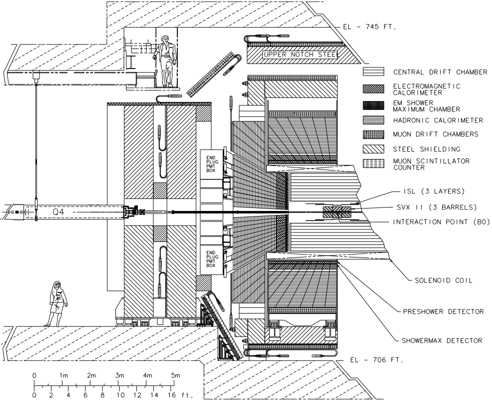
Tevatron



- $p\bar{p}$ collider
- Center-of-mass energy 1.96 TeV
- Run II delivered $12\mathrm{fb}^{-1}$
- Acquired $\sim 10\mathrm{fb}^{-1}$ by CDF

Tevatron and CDF

CDF



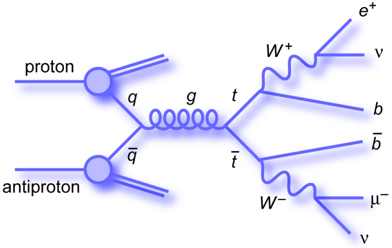
- General purpose detector
  - Solenoid (1.4 T magnetic field)
  - Tracking system
  - Calorimeter system
  - Muon detectors
- Coverage in $t\bar{t}$ dilepton
  - Electron: $|\eta| < 2.0$
  - Muon : $|\eta| < 1.1$
  - Jets : $|\eta| < 2.5$

$t\bar{t} \to$ dilepton

- A_{FB} measurement in lepton+jets: *done*
- Go after the next important final state: $t\bar{t} \to$ dilepton

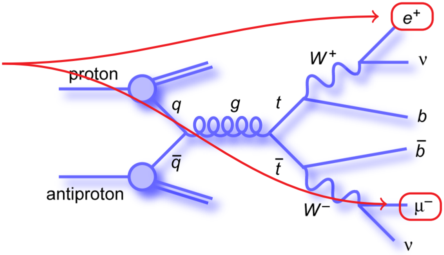
$t\bar{t} \to$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:



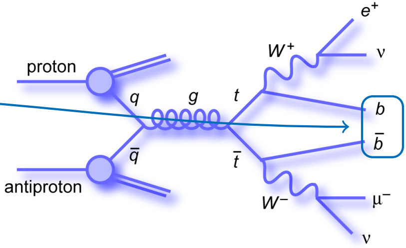
$t\bar{t} \rightarrow$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons



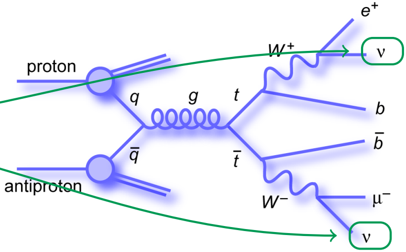
$t\bar{t} \rightarrow$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons
  - At least two jets



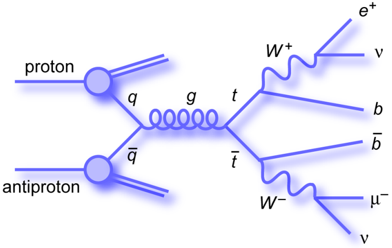
$t\bar{t} \to$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons
  - At least two jets
  - $\not{E}_T > 25$ GeV



$t\bar{t} \to$ dilepton
Event selection

- Need a sample enriched by $t\bar{t}$ events with dilepton signature:
  - Two opposite charged leptons
  - At least two jets
  - $\not{E}_T > 25$ GeV
- Use slightly improved $t\bar{t} \to$dilepton data selection criteria
  (details in the backups)



$t\bar{t} \to$ dilepton
Signal and background modeling

- Signal modeling:
  - Prediction with POWHEG MC (NLO SM w/ only QCD correction)
- Background modeling:
  - Diboson production $(WW, WZ, ZZ, W\gamma)$
    MC prediction
  - Z/γ^*+jets
    MC prediction with correction from data
  - W+jets
    Data-based
  - $t\bar{t}$ non-dilepton
    Prediction with POWHEG MC

Source	Events
Diboson	31.4±5.9
Z/γ^*+jets	50.5±6.2
W+jets fakes	64±17
$t\bar{t}$ non-dilepton	14.6±0.8
Total background	160±21
$t\bar{t}$ ($\sigma = 7.4$ pb)	408±19
Total SM expectation	568±40
Observed	569

- Agreement is excellent (Maybe too good? Probably luck)

$t\bar{t} \rightarrow$ dilepton

- Hard to reconstruct of 4-momentum of $t\bar{t}$ in dilepton
- Measure A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\ell\ell}$ first
- Continue with the full $A_{\mathrm{FB}}^{t\bar{t}}$ afterwards

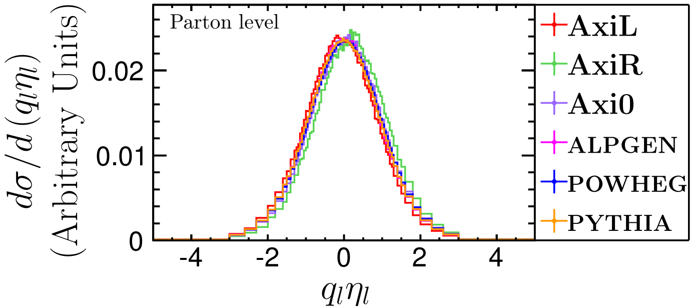
Alternative Signal Modeling

- What does the η_ℓ spectra look like in various scenarios?
  - Test the measurement with both SM and BSM models
- Simulate $t\bar{t}$ in various $t\bar{t}$ production mechanisms
  - SM sample: PYTHIA/ALPGEN (LO) and POWHEG (NLO)
  - Benchmark BSM model w/ axigluon
  - Many more simulated and studied
- Span large range of A_{FB}^{ℓ} and $A_{\text{FB}}^{\ell\ell}$

Model	A_{FB}^{ℓ} (Parton Level)	$A_{\text{FB}}^{\ell\ell}$ (Parton Level)	Description	
AxiL	-0.063(2)	-0.092(3)	Left-handed	Tree-level axigluon m = 200 GeV/c^2 Γ = 50 GeV
AxiR	0.151(2)	0.218(3)	Right-handed	
Axi0	0.050(2)	0.066(3)	Unpolarized	
ALPGEN	0.003(1)	0.003(2)	Tree-level Standard Model	
PYTHIA	0.000(1)	0.001(1)	LO Standard Model	
POWHEG	0.024(1)	0.030(1)	NLO Standard Model	
Calculation	0.038(3)	0.048(4)	NLO SM (PRD **86** 034026 (2012))	

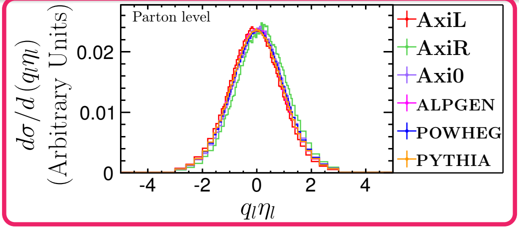
A_{FB}^{ℓ} Methodology - Introduction

$q_\ell \eta_\ell$ spectrum



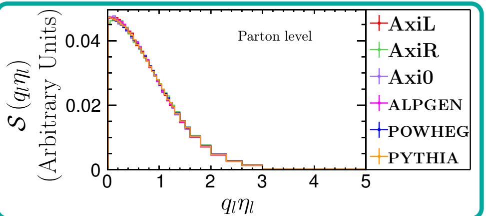
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

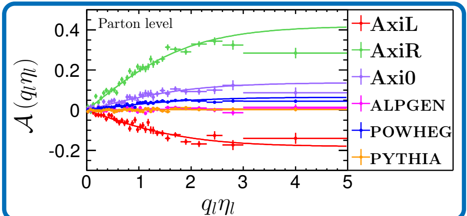
A_{FB}^{ℓ} Methodology - Introduction



- Decomposition of $q_\ell\eta_\ell$ spectrum into symmetric and asymmetric components:

$$\mathcal{S}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}{2}; \mathcal{A}(q_\ell\eta_\ell) = \frac{\mathcal{N}(q_\ell\eta_\ell) - \mathcal{N}(-q_\ell\eta_\ell)}{\mathcal{N}(q_\ell\eta_\ell) + \mathcal{N}(-q_\ell\eta_\ell)}$$





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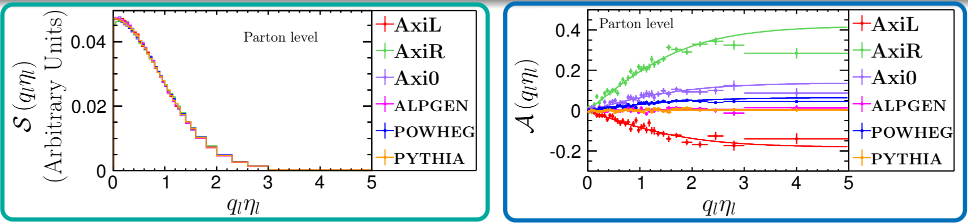

- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models

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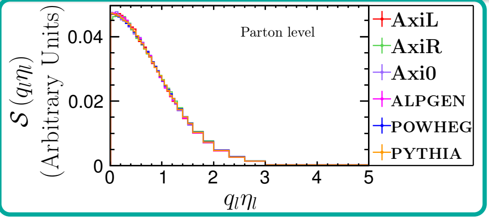
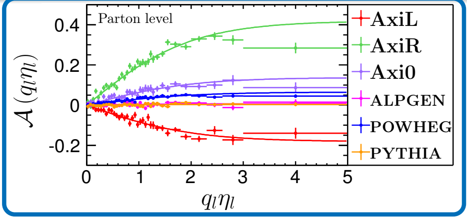
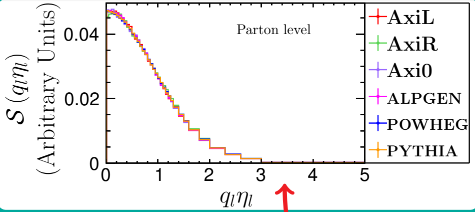
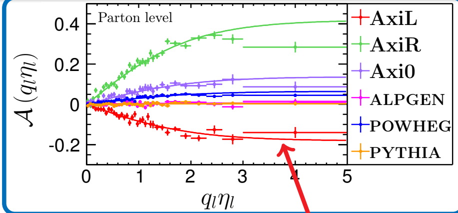




- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell\eta_\ell)$ very different for different models
  - Sensitive to different values of A_{FB}^{ℓ}

A_{FB}^{ℓ} Methodology - Introduction





- $\mathcal{S}(q_\ell\eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell\eta_\ell)$ very different for different models
  - Sensitive to different values of A_{FB}^{ℓ}
- $\mathcal{A}(q_\ell\eta_\ell)$ well modeled with $a \cdot \tanh(\frac{1}{2} q_\ell\eta_\ell)$
  - Function empirically determined

Not well modelled for $q_\ell\eta_\ell > 2.5$

But contribution here is tiny

Detector only goes out to 2.0

A^{ℓ}_{FB} Measurement Methodology

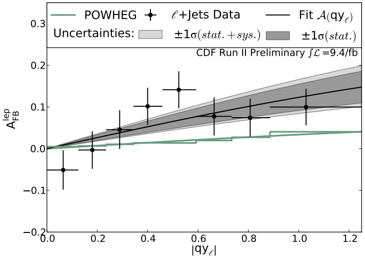
- A^{ℓ}_{FB} rewritten as

$$A^{\ell}_{\mathrm{FB}} = \frac{\int_0^\infty \mathrm{d}q_\ell\eta_\ell \mathcal{A}(q_\ell\eta_\ell)\mathcal{S}(q_\ell\eta_\ell)}{\int_0^\infty \mathrm{d}q'_\ell\eta'_\ell \mathcal{S}(q'_\ell\eta'_\ell)}$$

- A^{ℓ}_{FB} measurement in lepton+jets based on this decomposition and $a \cdot \tanh(\frac{1}{2}q_\ell\eta_\ell)$ modeling

$$A^{\ell}_{\mathrm{FB}} = 0.094^{+0.032}_{-0.029}$$

- 1.9σ larger than SM

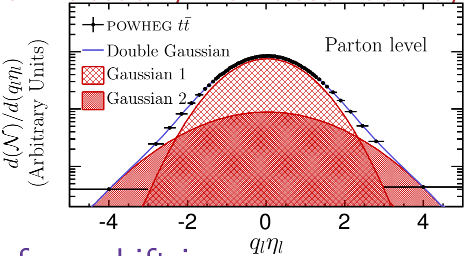


PRD **88** 072003 (2013), CDF

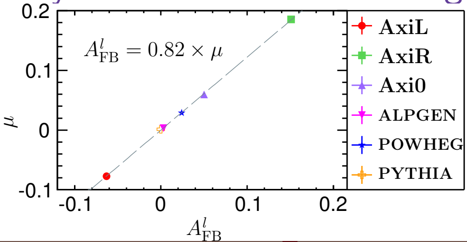
A_{FB}^{ℓ} Methodology Study

Why does the $a \cdot \tanh$ model work so well?

- $q_\ell \eta_\ell$ spectrum actually well described by a double-Gaussian



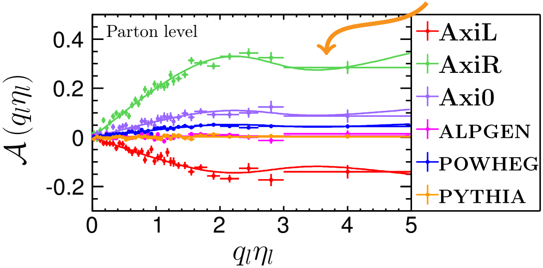
- A_{FB}^{ℓ} comes from shift in mean
  $\rightarrow$ A_{FB}^{ℓ} linearly related with mean in regime of interest



PRD **90**, 014040 (2014)
Z. Hong *et al.*

A_{FB}^{ℓ} Methodology Study

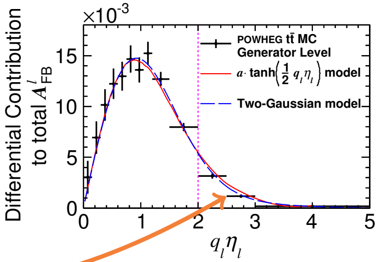
- Double-Gaussian does better job in modeling differential asymmetry in large $q_\ell \eta_\ell$ region



- $\mathcal{A}(q_\ell \eta_\ell)$ still most sensitive way to measure A_{FB}^{ℓ}
  - Provides better effective measure of mean
  - Acceptance of detector mostly cancels out

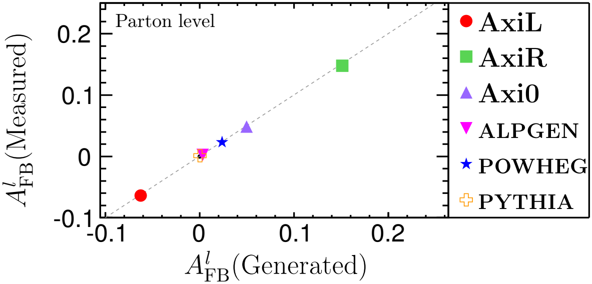
A_{FB}^{ℓ} Methodology Study

- Another way of looking at data: Differential contribution to A_{FB}^{ℓ}
- What do we learn?
  - Asymmetry mostly from $|\eta| < 2.0$
    - Best detector coverages here
  - $a \cdot \tanh\left(\frac{1}{2} q_\ell \eta_\ell\right)$ is excellent for $|q_\ell \eta_\ell| < 2.5$
  - Mismodeling in region with small contribution
  - More than good enough
- Moving forward with $a \cdot \tanh$ model with confidence



A_{FB}^{ℓ} Methodology - Introduction

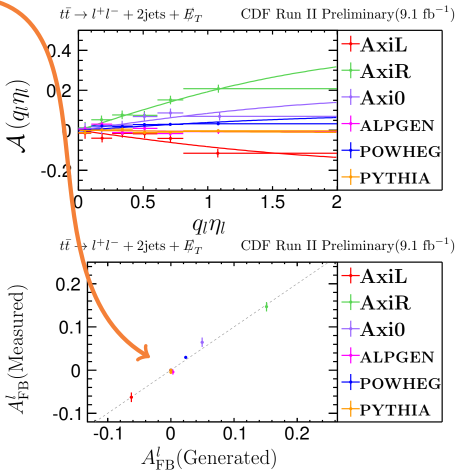
- $a \cdot \tanh$ model works well at parton level



- Does detector response affect the measurement?

A_{FB}^{ℓ} Methodology with Detector Response

- Detector response mostly cancels out in $\mathcal{A}(q_\ell \eta_\ell)$
- No noticeable bias observed
- Measurement strategy:
  - Subtract off backgrounds
  - Fit $\mathcal{A}(q_\ell \eta_\ell)$ with $a \cdot \tanh\left(\frac{1}{2} q_\ell \eta_\ell\right)$
  - Obtain $\mathcal{S}(q_\ell \eta_\ell)$ from POWHEG simulation at parton-level
  - Calculate A_{FB}^{ℓ} with $\mathcal{A}$ & $\mathcal{S}$
- Correct for detector response and extrapolate to inclusive A_{FB}^{ℓ} simultaneously



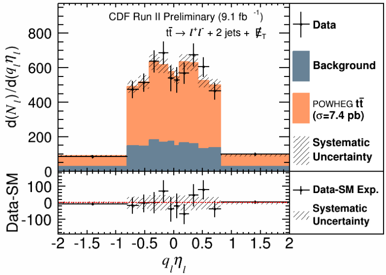
A_{FB}^{ℓ} in dilepton

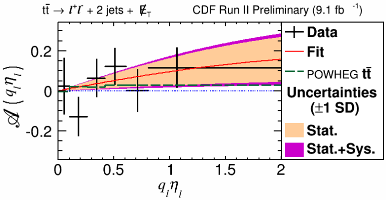
- Measure A_{FB}^{ℓ} with CDF full dataset in dilepton ($9.1\ \mathrm{fb}^{-1}$)

$$A_{FB}^{\ell} = 0.072 \pm 0.052(\text{stat}) \pm 0.030(\text{syst}) = 0.072 \pm 0.060$$

Cf. $A_{FB}^{\ell}(\text{SM,NLO}) = 0.038 \pm 0.003$

- Dominant uncertainty is statistical
- Table of systematic uncertainty in backup
- Result consistent with prediction of new physics from lepton+jets, but also consistent with SM





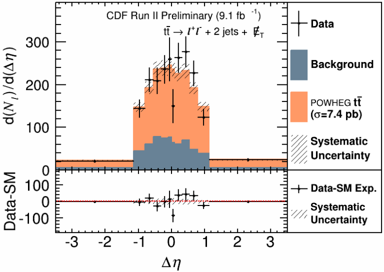
$A_{FB}^{\ell\ell}$ in dilepton

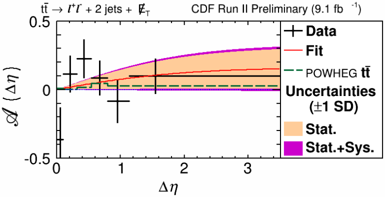
- Measurement techniques validated for $A_{FB}^{\ell\ell}$ as well.
- Measure $A_{FB}^{\ell\ell}$ with the same method

$$A_{FB}^{\ell\ell} = 0.076 \pm 0.072(\text{stat}) \pm 0.039(\text{syst}) = 0.076 \pm 0.081$$

Cf. $A_{FB}^{\ell}(\text{SM,NLO}) = 0.048 \pm 0.004$

- Dominant uncertainty is statistical
- Result consistent with SM



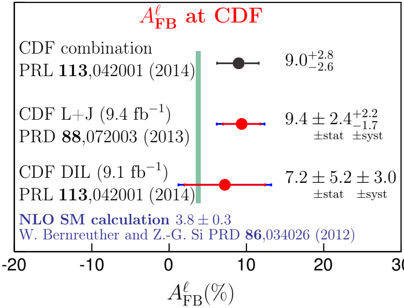


A_{FB}^{ℓ} combination at CDF

- Combined A_{FB}^{ℓ} measurements at CDF
- Based on *best linear unbiased estimator* (BLUE)
- Result is 2σ larger than NLO SM prediction:

$$A_{FB}^{\ell} = 0.090^{+0.028}_{-0.026}$$

- PRL **113**, 042001 (2014) (CDF)



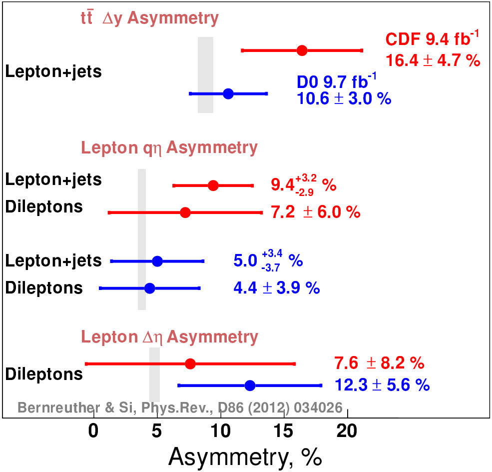
$A_{\rm FB}^{t\bar{t}}$ in dilepton and CDF combination

- Observed large $A_{\rm FB}^{\ell}$ in dilepton as well, continue pursuing $A_{\rm FB}^{t\bar{t}}$ measurement in dilepton
- Then $A_{\rm FB}^{t\bar{t}}$ combination at CDF

Analysis in progress!

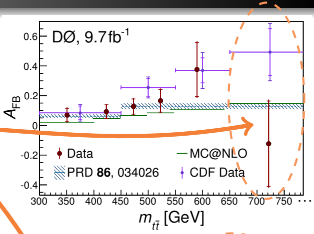
Prospects for a final Tevatron combination

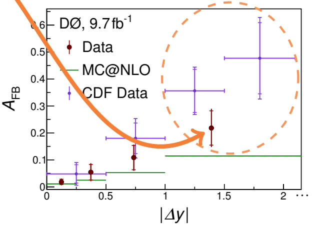
- D0 recently released measurements of A^{ℓ}_{FB}, $A^{\ell\ell}_{FB}$ and $A^{t\bar{t}}_{FB}$
  - Results from D0 smaller, consistent with both CDF and SM

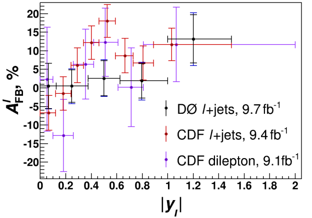


Prospects for a final Tevatron combination

- Total values agree within errors
- Differential distributions have inconsistencies
  - This might account for the differences
- Both experiments working to understand the differences
  - Are the two experiments measuring the same observables?
  - Different techniques causing bias in either/both experiments?
  - Statistical fluctuation?
- Plan: understand the difference and make Tevatron combinations of A^{ℓ}_{FB}, $A^{\ell\ell}_{\mathrm{FB}}$ and $A^{t\bar{t}}_{\mathrm{FB}}$







Conclusions

- The A_{FB} of top-pairs at the Tevatron continue to be tantalizing
- Measurements of $A_{\mathrm{FB}}^{t\bar{t}}$, A_{FB}^{ℓ} and $A_{\mathrm{FB}}^{\ell\ell}$ provide complementary handles to probe the production and decay of $t\bar{t}$
- A_{FB}^{ℓ} at CDF shows 2σ deviation from NLO SM
- Measurement of $A_{\mathrm{FB}}^{t\bar{t}}$ in dilepton in progress
- Understanding the difference between CDF and D0 measurements
  - Looking forward to a final word on this important question from Tevatron as it isn't clear if it can be resolved at the LHC

Backup Slides

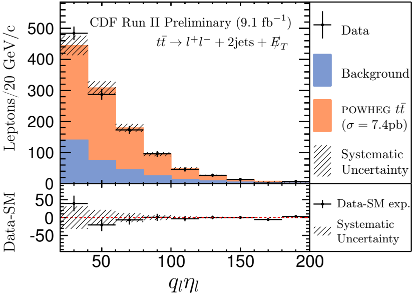
Backup slides

$t\bar{t} \rightarrow$ dilepton event selection criteria

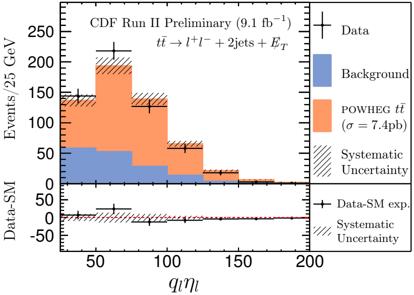
Baseline Cuts	Exactly two leptons with $E_T > 20$ GeV and passing standard identification requirements with following modifications -COT radius exit > 140 cm for CMIO -$\chi^2/ndf < 2.3$ for muon tracks At least one trigger lepton At least one tight and isolated lepton At most one lepton can be loose and/or non-isolated
	$\not{E}_T > 25$ GeV, but $\not{E}_T > 50$ GeV when there is any lepton or jet within 20° of the direction of $\not{E}_T$
	MetSig ($= \frac{\not{E}_T}{\sqrt{E_T^{sum}}}$) $> 4\ \sqrt{\mathrm{GeV}}$ for ee and $\mu\mu$ events where 76 $\mathrm{GeV/c^2} < \mathrm{m_{ll}} < 106\ \mathrm{GeV/c^2}$
	$\mathrm{m_{ll}} > 10\ \mathrm{GeV/c^2}$
Signal Cuts	Two or more jets with $E_T > 15$ GeV within $\lvert\eta\rvert < 2.5$
	$\mathrm{H_T} > 200$ GeV
	Opposite sign of two leptons

Signal and background modeling
Validation

Lepton p_T



$\not{E}_T$



Agreement is excellent

Systematic uncertainty of A^{ℓ}_{FB} measurement

CDF Run II Preliminary (9.1 fb^{-1})

Source of Uncertainty (A^{ℓ}_{FB})	Value
Backgrounds	0.029
Asymmetric Modeling	0.006
Jet Energy Scale	0.004
Symmetric Modeling	0.001
Total Systematic	0.030
Statistical	0.052
Total Uncertainty	0.060

Systematic uncertainty of $A_{\mathsf{FB}}^{\ell\ell}$ measurement

CDF Run II Preliminary (9.1 fb^{-1})	
Source of Uncertainty ($A_{\mathsf{FB}}^{\ell\ell}$)	Value
Backgrounds	0.037
Asymmetric Modeling	0.012
Jet Energy Scale	0.003
Symmetric Modeling	0.004
Total Systematic	0.039
Statistical	0.072
Total Uncertainty	0.082

Comparison of A_{FB}^{ℓ} among SM prediction and measurements at CDF and D0.

Source	A_{FB}^{ℓ}	Description	Reference
Calculation	0.038 ± 0.003	NLO SM	PRD **86**,034026 (2012)
CDF	$0.094^{+0.032}_{-0.029}$	Lepton+jets	PRD **88** 072003 (2013)
	0.072 ± 0.060	Dilepton	Accepted by PRL
	$0.090^{+0.028}_{-0.026}$	Combination	arXiv:1404.3698
D0	$0.042^{+0.029}_{-0.030}$	Lepton+jets, $\lvert q_{\ell}\eta_{\ell}\rvert < 1.5$	arXiv:1403.1294
	0.044 ± 0.039	Dilepton	PRD **88**, 112002 (2013)
	0.047 ± 0.027	Combination	arXiv:1403.1294

A^{ℓ}_{FB} CDF combination

CDF Run II Preliminary

Source of uncertainty	L+J (9.4fb^{-1})	DIL (9.1fb^{-1})	Correlation
Backgrounds	0.015	0.029	0
Recoil modeling (Asymmetric modeling)	$^{+0.013}_{-0.000}$	0.006	1
Symmetric modeling	-	0.001	
Color reconnection	0.0067	-	
Parton showering	0.0027	-	
PDF	0.0025	-	
JES	0.0022	0.004	1
IFSR	0.0018	-	
Total systematic	$^{+0.022}_{-0.017}$	0.030	
Statistics	0.024	0.052	0
Total uncertainty	$^{+0.032}_{-0.029}$	0.060	

$t\bar{t}$ Reconstruction Equations

$$
\begin{aligned}
M^2_{l^+\nu} &= (E_{l^+} + E_\nu)^2 - (\vec{p}_{l^+} + \vec{p}_\nu)^2 = M^2_W \\
M^2_{l^-\bar{\nu}} &= (E_{l^-} + E_{\bar{\nu}})^2 - (\vec{p}_{l^-} + \vec{p}_{\bar{\nu}})^2 = M^2_W \\
M^2_{l^+\nu b} &= (E_{l^+} + E_\nu + E_b)^2 - (\vec{p}_{l^+} + \vec{p}_\nu + \vec{p}_b)^2 = M^2_t \\
M^2_{l^-\bar{\nu}\bar{b}} &= (E_{l^-} + E_{\bar{\nu}} + E_{\bar{b}})^2 - (\vec{p}_{l^-} + \vec{p}_{\bar{\nu}} + \vec{p}_{\bar{b}})^2 = M^2_t \\
(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_x &= (\not{E}_T)_x \\
(\vec{p}_\nu + \vec{p}_{\bar{\nu}})_y &= (\not{E}_T)_y
\end{aligned}
$$

$t\bar{t}$ Likelihood

$$\mathcal{L}(\vec{p}_{\nu}, \vec{p}_{\bar{\nu}}, E_b, E_{\bar{b}}) = P(p_z^{t\bar{t}})P(p_T^{t\bar{t}})P(M^{t\bar{t}})\times$$

$$\frac{1}{\sigma_{\text{jet1}}}\exp\left(-\frac{1}{2}\left(\frac{E_{\text{jet1}}^{\text{measure}} - E_{\text{jet1}}^{\text{fit}}}{\sigma_{\text{jet1}}}\right)\right) \times \frac{1}{\sigma_{\text{jet2}}}\exp\left(-\frac{1}{2}\left(\frac{E_{\text{jet2}}^{\text{measure}} - E_{\text{jet2}}^{\text{fit}}}{\sigma_{\text{jet2}}}\right)\right)$$

$$\frac{1}{\sigma_x^{\not{E}_T}}\exp\left(-\frac{1}{2}\left(\frac{\not{E}_x^{\text{measure}} - \not{E}_x^{\text{fit}}}{\sigma_x^{\not{E}_T}}\right)\right) \times \frac{1}{\sigma_y^{\not{E}_T}}\exp\left(-\frac{1}{2}\left(\frac{\not{E}_y^{\text{measure}} - \not{E}_y^{\text{fit}}}{\sigma_y^{\not{E}_T}}\right)\right)$$

- The ratio of $A^{t\bar{t}}_{\mathrm{FB}}/A^{\ell}_{\mathrm{FB}}$ observed to be consistent when $t\bar{t}$ produced unpolarized and decay like SM
- Based on CDF $A^{t\bar{t}}_{\mathrm{FB}}$ result (0.16 ± 0.05), this yields prediction of $0.070 < A^{\ell}_{\mathrm{FB}} < 0.076$