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

Ziqing Hong

University of Florida
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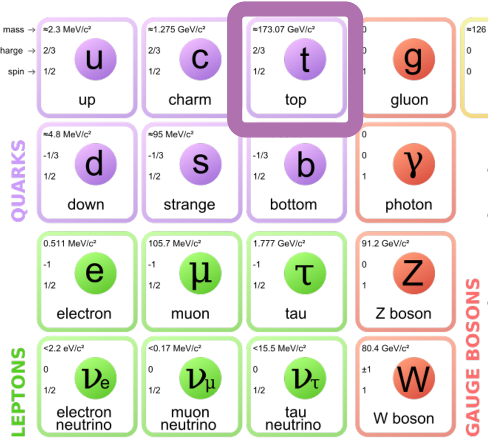
TEXAS A&M UNIVERSITY

The Standard Model - Top Quark



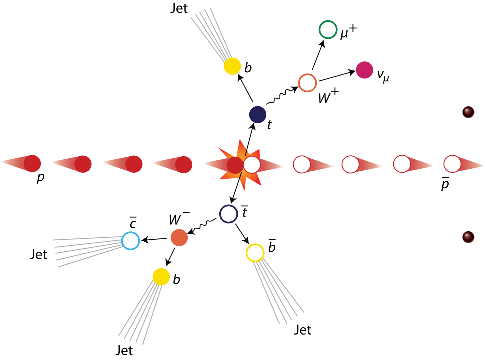
Top Quark

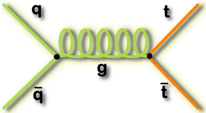
- Observed at Tevatron (1995)
- Very heavy
  - $m_t \simeq 173\ \mathrm{GeV/c^2}$
- Very short lived
  - No time to form hadrons
  - Unique opportunity to study a “bare” quark

Fascinating particle

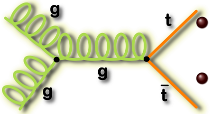
Properties need to be further understood

Top-Quark Pair at Tevatron





(a)



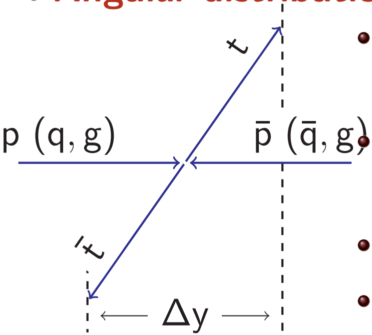
(b)

Top-quark pair production at the Fermilab Tevatron

- $p\bar{p}$ collision at Tevatron
  - CP even initial state
  - **pp collision at LHC**
- Unique production mechanism
  - 85% quark annihilation (a)
    15% gluon fusion (b)
  - LHC is gluon fusion dominated
- $\sim$70,000 $t\bar{t}$ produced
- **Tevatron sensitive to certain top properties**

A_{FB} at Tevatron

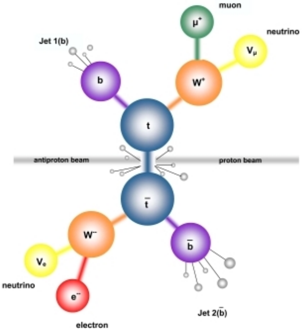
- Cross-section, mass and width measured & agree with SM
  What else can we learn about $t\bar{t}$ produced at Tevatron?
- **Angular distribution**



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

- Simplest observable:
  forward-backward asymmetry (A_{FB})
- Does top quark prefer proton direction or the opposite?
- No asymmetry in leading order SM
- Slight asymmetry starting from next-to-leading order (NLO)
- Data show deviation from prediction
- **Hot topic at Tevatron for years**

A_{FB} observables



Three observables to quantify A_{FB}

1. A_{FB} of rapidity difference (Δy) between top and anti-top

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

   - Need top momenta reconstruction

2. A_{FB} of lepton pseudorapidity (η_ℓ)

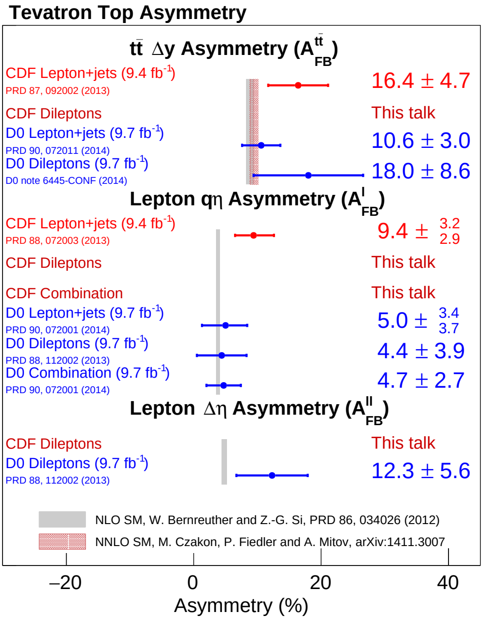
$$A_{FB}^{\ell} = \frac{N(q_\ell \eta_\ell > 0) - N(q_\ell \eta_\ell < 0)}{N(q_\ell \eta_\ell > 0) + N(q_\ell \eta_\ell < 0)}$$

   - Also probing top decay properties

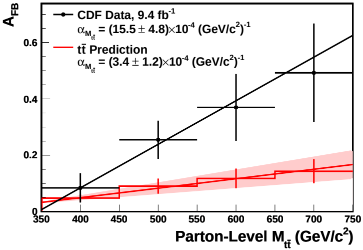
3. A_{FB} of lepton η difference ($\Delta\eta$)

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

   - Only measurable when both W-bosons decay leptonically

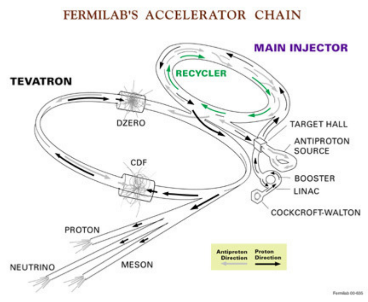


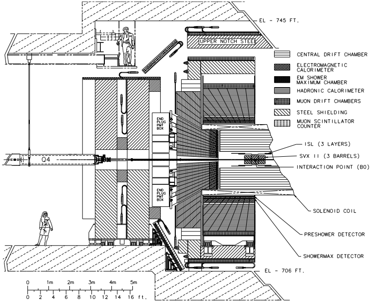
- All higher than prediction
- Perhaps more interesting: $A_{FB}^{t\bar{t}}$ vs. $m_{t\bar{t}}$ deviates from NLO SM prediction



- This talk:
  - Following up in CDF Dilepton channel
  - Best world understanding of top A_{FB}

Tevatron and CDF





Tevatron

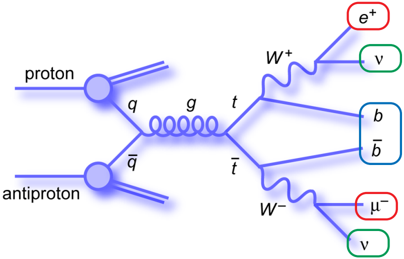
- $p\bar{p}$ collider
- Center-of-mass energy 1.96 TeV
- Run II delivered 12fb^{-1}
- Acquired $\sim 10\text{fb}^{-1}$ by CDF

CDF

- General purpose detector
  - 1.4 T magnetic field
  - Tracking, Calorimeter and Muon systems
- Coverage in $t\bar{t}$ dilepton
  - Electron: $|\eta| < 2.0$
  - Muon : $|\eta| < 1.1$
  - Jets : $|\eta| < 2.5$

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

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



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

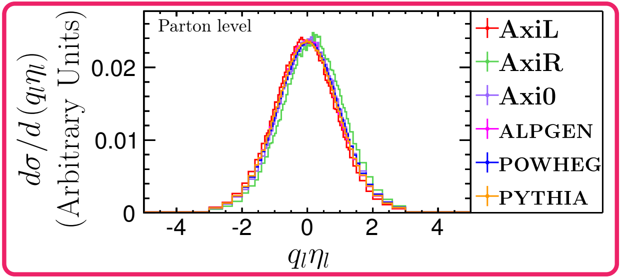
- Signal modeling:
  - Prediction with POWHEG MC (NLO SM w/ only QCD correction)
- Background modeling:
  - Diboson production (WW,WZ,ZZ,$W\gamma$) MC prediction
  - Z/γ^*+jets MC prediction with correction from data
  - W+jets Data-based
  - $t\bar{t}$ non-dilepton Prediction with POWHEG MC

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)

A_{FB}^{ℓ} Methodology

$q_\ell \eta_\ell$ spectrum

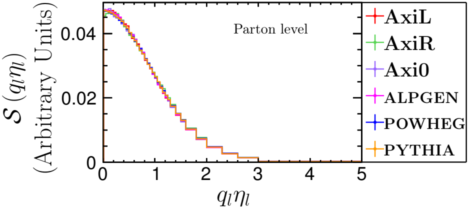


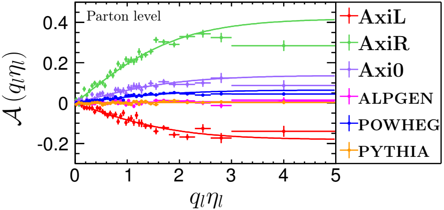
- **Start with A_{FB}^{ℓ} measurement**
- Benchmark models with $-0.06 < A_{FB}^{\ell} < 0.15$
- Difference among models are small
  - Shapes almost identical, tiny shift in the mean
- Acceptance in detector limited
  - No acceptance beyond $|q_\ell \eta_\ell| = 2$
- Need a clever way to measure the subtle difference

A_{FB}^{ℓ} Methodology

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

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





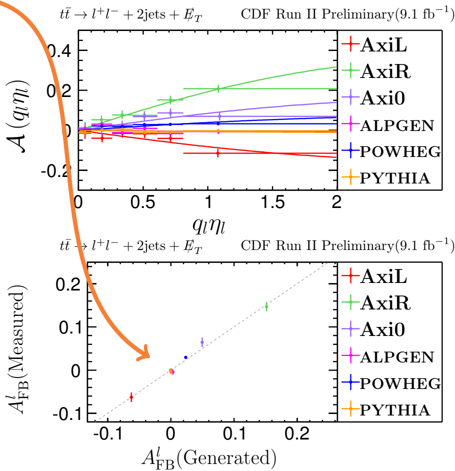
- $\mathcal{S}(q_\ell \eta_\ell)$ consistent among models
- $\mathcal{A}(q_\ell \eta_\ell)$ sensitive to different A_{FB}^{ℓ}
  - Well modeled with $a \cdot \tanh(\frac{1}{2} q_\ell \eta_\ell)$
- A_{FB}^{ℓ} rewritten as

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

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

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



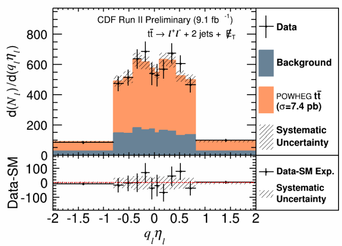
A^{ℓ}_{FB} in dilepton and CDF combination

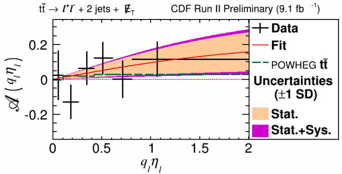
- Measure A^{ℓ}_{FB} with CDF full dataset in dilepton ($9.1\ \mathrm{fb}^{-1}$)

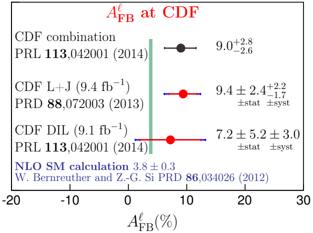
  $A^{\ell}_{\mathrm{FB}} = 0.072 \pm 0.060$

  Cf. $A^{\ell}_{\mathrm{FB}}(\mathrm{SM,NLO}) = 0.038 \pm 0.003$
- Dominant uncertainty is statistical
- Table of systematics in backup
- Combined A^{ℓ}_{FB} measurements at CDF with BLUE
- Result is 2σ larger than NLO SM prediction:

  $$A^{\ell}_{\mathrm{FB}} = 0.090^{+0.028}_{-0.026}$$
- PRL **113**, 042001 (2014) (CDF)



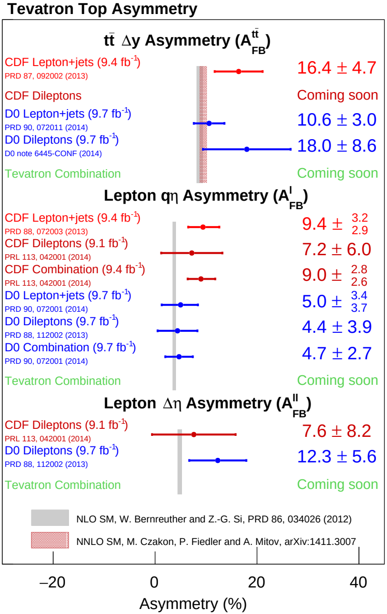




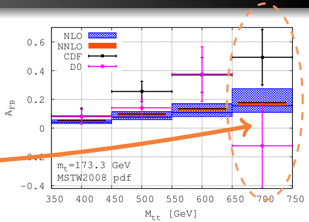
Best-world understanding of top A_{FB}

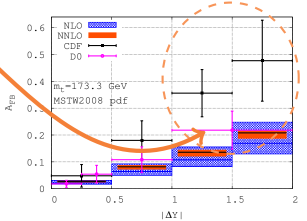
- CDF Dilepton $A_{FB}^{t\bar{t}}$ measurement well underway
- All current results higher than NLO (and NNLO) SM predictions
- Recent preliminary NNLO SM prediction suggests tension reduced

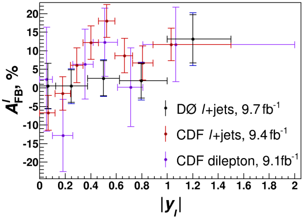
NNLO QCD calculation needed for top kinematics! Especially important for precision measurements at LHC



- Differential A_{FB} show mostly good agreement between CDF and D0
  - Some areas under study
  - 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_{FB}^{ℓ}, $A_{FB}^{\ell\ell}$ and $A_{FB}^{t\bar{t}}$







Conclusions: Top A_{FB}

- The A_{FB} of top-pairs at the Tevatron remains a story does not yet hang together well, but at long last may be resolved
- Measurements of $A_{FB}^{t\bar{t}}$, A_{FB}^{ℓ} and $A_{FB}^{\ell\ell}$ provide complementary handles to probe the production and decay of $t\bar{t}$
- A_{FB}^{ℓ} at CDF shows 2σ deviation from NLO SM, but may be consistent with NNLO. Only time will tell.
- Measurement of $A_{FB}^{t\bar{t}}$ in dilepton in progress
- Working on understanding the difference between CDF and D0 measurements
- Full NNLO SM calculation on the horizon
- Either way it has been an exciting chase for new physics

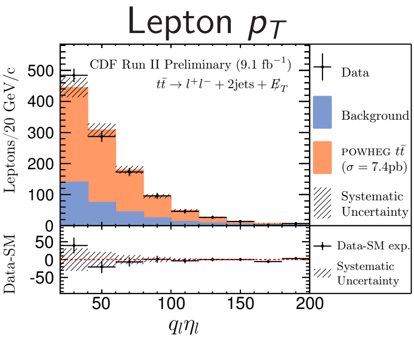
Backup slides

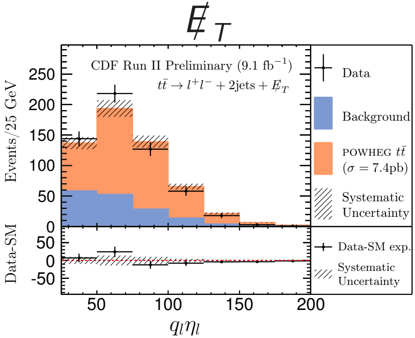
$t\bar{t} \rightarrow$ dilepton event selection criteria

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





Agreement is excellent

Systematic uncertainty of A_{FB}^{ℓ} measurement

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

Source of Uncertainty (A_{FB}^{ℓ})	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 $A_{\mathrm{FB}}^{\ell\ell}$ measurement

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

Source of Uncertainty ($A_{\mathrm{FB}}^{\ell\ell}$)	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	PRL **113**,042001 (2014)
	$0.090^{+0.028}_{-0.026}$	Combination	
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 ($9.4 fb^{-1}$)	DIL ($9.1 fb^{-1}$)	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

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

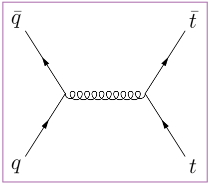
$t\bar{t}$ Likelihood

$$\mathcal{L}(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b, E_{\bar{b}}) = P(p_z^{t\bar{t}})P(p_T^{t\bar{t}})P(M^{t\bar{t}})\times$$
$$\frac{1}{\sigma_{\text{jet1}}}\exp\left(-\frac{1}{2}\left(\frac{E_{\text{jet1}}^{\text{measure}} - E_{\text{jet1}}^{\text{fit}}}{\sigma_{\text{jet1}}}\right)\right) \times \frac{1}{\sigma_{\text{jet2}}}\exp\left(-\frac{1}{2}\left(\frac{E_{\text{jet2}}^{\text{measure}} - E_{\text{jet2}}^{\text{fit}}}{\sigma_{\text{jet2}}}\right)\right)$$
$$\frac{1}{\sigma_x^{\not{E}_T}}\exp\left(-\frac{1}{2}\left(\frac{\not{E}_x^{\text{measure}} - \not{E}_x^{\text{fit}}}{\sigma_x^{\not{E}_T}}\right)\right) \times \frac{1}{\sigma_y^{\not{E}_T}}\exp\left(-\frac{1}{2}\left(\frac{\not{E}_y^{\text{measure}} - \not{E}_y^{\text{fit}}}{\sigma_y^{\not{E}_T}}\right)\right)$$

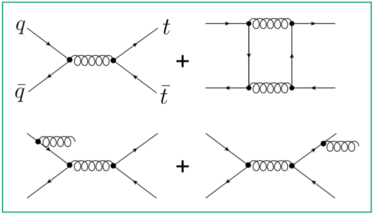
- The ratio of $A_{\text{FB}}^{t\bar{t}}/A_{\text{FB}}^{\ell}$ observed to be consistent when $t\bar{t}$ produced unpolarized and decay like SM
- Based on CDF $A_{\text{FB}}^{t\bar{t}}$ result (0.16 ± 0.05), this yields prediction of $0.070 < A_{\text{FB}}^{\ell} < 0.076$

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



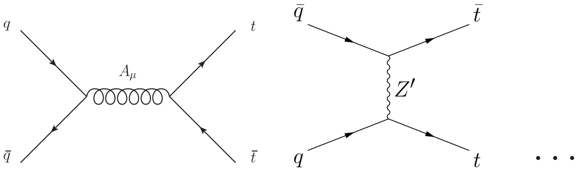
- We compare to $A_{FB}^{t\bar{t}}(\text{NLO}) = 0.088 \pm 0.006$ (PRD **86**,034026 (2012))
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
- However, different SM calculation gives different answers(0.050-0.125)
- **SM calculation still progressing**
  - Preliminary NNLO calculation later



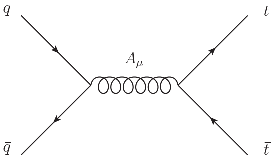
Possible alternative hypotheses?

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
- ......

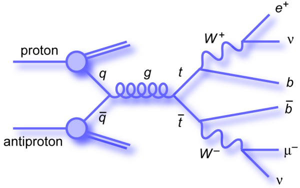


- NLO SM prediction: $A^{\ell}_{\mathrm{FB}} = 0.038 \pm 0.003$
  - Conventional renormalization scale ($\mu_R \sim m_t$) w/ EWK corrections.
- Prediction with new physics?
- Based on CDF $A^{t\bar{t}}_{\mathrm{FB}}$ result (0.16 ± 0.05), assuming everything else SM-like: $0.070 < A^{\ell}_{\mathrm{FB}}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



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

- Lepton pair $A_{\rm FB}$
  - $$A_{\rm FB}^{\ell\ell} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$



- NLO SM prediction: $A_{\rm FB}^{\ell\ell} = 0.048 \pm 0.004$
- Larger expectations
- Only defined in dilepton, smaller statistics
- Provide extra information to help constraining new physics models

Alternative Signal Modeling

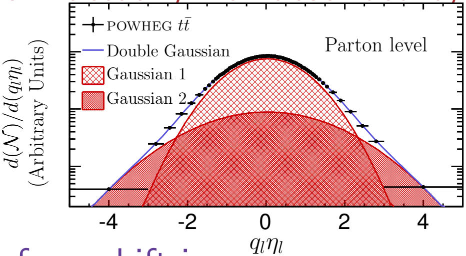
- What does the η_ℓ spectra look like in various scenarios?
  - Test the measurement with both SM and BSM models
- Simulate $t\bar{t}$ in various $t\bar{t}$ production mechanisms
  - SM sample: PYTHIA/ALPGEN (LO) and POWHEG (NLO)
  - Benchmark BSM model w/ axigluon
  - Many more simulated and studied
- 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 $m = 200\ \text{GeV}/c^2$ $\Gamma = 50\ \text{GeV}$
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))	

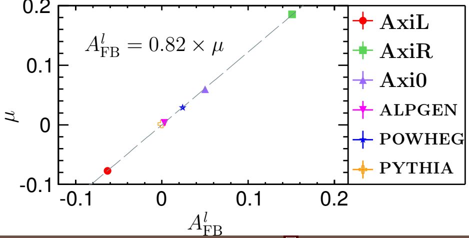
A_{FB}^{ℓ} Methodology Study

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

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

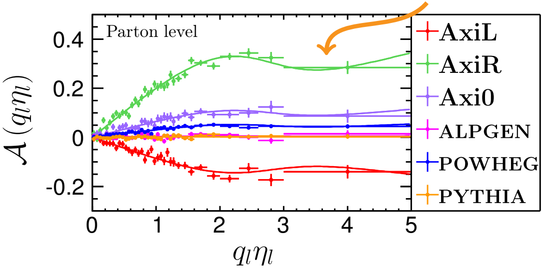


- A_{FB}^{ℓ} comes from shift in mean
  $\rightarrow A_{FB}^{\ell}$ linearly related with mean in regime of interest



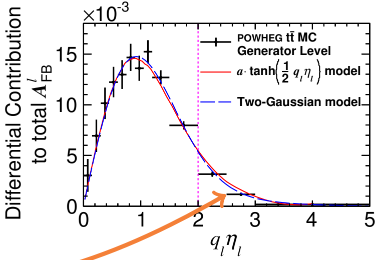
Summarized as PRD **90**, 014040 (2014) Z. Hong *et al.*

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



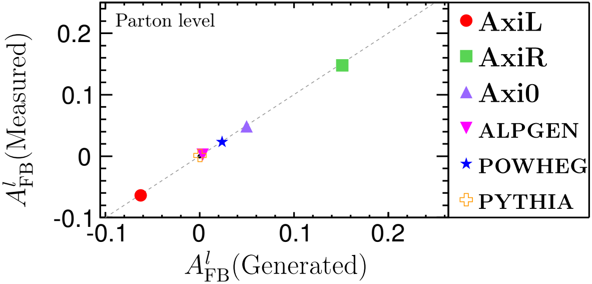
- $\mathcal{A}(q_\ell \eta_\ell)$ still most sensitive way to measure A^{ℓ}_{FB}
  - Provides better effective measure of mean
  - Acceptance of detector mostly cancels out

- Another way of looking at data: Differential contribution to A^{ℓ}_{FB}
- 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

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



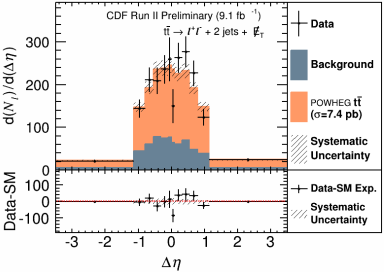
- Does detector response affect the measurement?

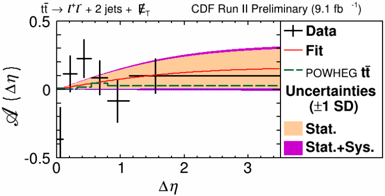
- Measurement techniques validated for $A_{FB}^{\ell\ell}$ as well.
- Measure $A_{FB}^{\ell\ell}$ with the same method

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

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

- Dominant uncertainty is statistical
- Result consistent with SM



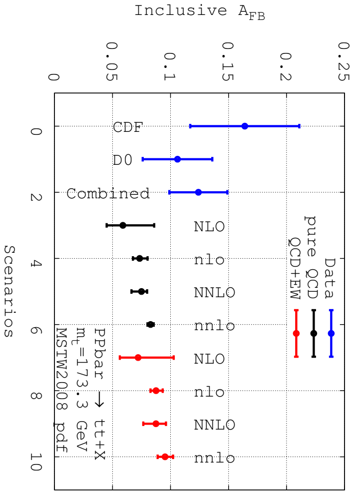


NNLO A_{FB} Prediction

M. Czakon, P. Fiedler and A. Mitov

arXiv:1411.3007

- Very recently, preliminary NNLO prediction suggests tension resolved
- NNLO QCD + LO EW
  $\rightarrow A_{FB}^{t\bar{t}} = 9.5 \pm 0.7\%$
- Deviation between measurements and prediction no longer significant



NNLO QCD calculation needed for top kinematics!
Especially important for precision measurements happening at LHC