Measurement of the Forward-Backward Asymmetry in Top Quark Pair Production in $p\bar{p}$ Collisions at 1.96 TeV

Glenn Strycker

University of Michigan

On behalf of the CDF Collaboration

Measurement of the Forward-Backward Asymmetry in Top Quark Pair Production in $p\bar{p}$ Collisions at 1.96 TeV

Glenn Strycker

University of Michigan

On behalf of the CDF Collaboration

1999-2003 2003-2010

Outline

- People Involved
- What is A_{fb} – why study it?
- Theoretical Predictions
- Previous Measurements
- FNAL and CDF Overview
- Measurement Techniques
- Correction Procedure
- Conclusion

People Involved

University of Michigan:

Glenn Strycker

Dan Amidei

Monica Tecchio

University of California, Davis:

Tom Schwarz

Robin Erbacher

Also much work done by the Karlsruhe group:

J. Wagner, T. Chwalek, W. Wagner

Asymmetries in $t\bar{t}$ Production

Constraining heavy colored resonances from top-antitop quark events

Paola Ferrario* and Germán Rodrigo†
Instituto de Física Corpuscular, Consejo Superior de Investigaciones Científicas – UVEG, Apartado de Correos 22085, E-46071 Valencia, Spain.
(Dated: June 30, 2009)

Recent measurements of the top quark charge asymmetry at Tevatron disfavor the existence of flavor universal axigluons and colorons at 2σ. In this letter we explore the possibility of reconciling the data with these models and use the charge asymmetry and the invariant mass distribution of top-antitop quark pair events to constrain the mass and couplings of massive color-octet gauge bosons decaying to top quarks.

PACS numbers: 14.65.Ha, 11.30.Er, 12.10.Dm

The Top Forward-Backward Production Asymmetry has already generated a lot of interest…

Axigluon as Possible Explanation for $p\bar{p} \to t\bar{t}$ Forward-Backward Asymmetry

Paul H. Frampton [a,b,*] Jing Shu [b,†] and Kai Wang [b‡]
[a] *Department of Physics and Astronomy, University of North Carolina, Chapel Hill, NC 27599-3255, USA.*
[b] *Institute for the Physics and Mathematics of the Universe, University of Tokyo, Kashiwa, Chiba 277-8568, JAPAN*

A flavor-nonuniversal chiral color model is introduced. It is used for comparison to the recent data on $\bar{p}p \to \bar{t}t$. We concluded that the data are consistent with interpretation as an axigluon exchange within 1σ and a unique rise and fall behavior is predicated with regard to the asymmetry A^t_{FB} as a function of $t\bar{t}$ invariant mass, which can distinguish our model from others before one discovers the axigluon resonance. Further aspects of the model are discussed.

Asymmetries in $t\bar{t}$ Production

IPMU09-0130
UCI-TR-2009-18

Explorations of the Top Quark Forward-Backward Asymmetry at the Tevatron

Jing Shu [a,*] Tim M.P. Tait [b,†] and Kai Wang [a‡]

[a] *Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Chiba 277 – 8568, Japan*

[b] *Department of Physics and Astronomy, University of California, Irvine, CA 92697*

(Dated: November 17, 2009)

Abstract

We consider the recent measurement of the top quark forward-backward asymmetry at the Fermilab Tevatron, which shows a discrepancy of slightly more than 2σ compared to the SM prediction. We find that t-channel exchange of a color sextet or triplet scalar particle can explain the measurement, while leaving the cross section for $t\bar{t}$ production within measured uncertainties. Such particles have good discovery prospects by study of the kinematic structure of $t\bar{t}$+jets at the LHC.

37v1 [hep-ph] 17 Nov 2009

Asymmetries in $t\bar{t}$ Production

IPMU09-0130
UCI-TR-2009-18

Explorations of the Top Quark Forward-Backward Asymmetry at the Tevatron

Jing Shu [a,*] Tim M.P. Tait [b,†] and Kai Wang [a‡]

[a] *Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Chiba 277 – 8568, Japan*

[b] *Department of Physics and Astronomy,*

37v1 [hep-ph] 17 Nov 2009

I. INTRODUCTION

The huge mass of the top quark, the only Standard Model (SM) fermion whose mass lies at the electroweak scale, may be a clue that the top is special in some way, perhaps serving as a portal to the physics of electroweak symmetry-breaking. Thanks to the wealth of data from the Tevatron, the existence of top is well-established, and fundamental measurements such as its mass have become routine. Interest now turns to more subtle properties, including the characteristics of its production.

LHC.

Asymmetries in $t\bar{t}$ Production

IPMU09-0130
UCI-TR-2009-18

Explorations of the Top Quark Forward-Backward Asymmetry at the Tevatron

Jing Shu [a,*] Tim M.P. Tait [b,†] and Kai Wang [a‡]

[a] *Institute for the Physics and Mathematics of the Universe, The University of Tokyo, Chiba 277 – 8568, Japan*

[b] *Department of Physics and Astronomy,*

37v1 [hep-ph] 17 Nov 2009

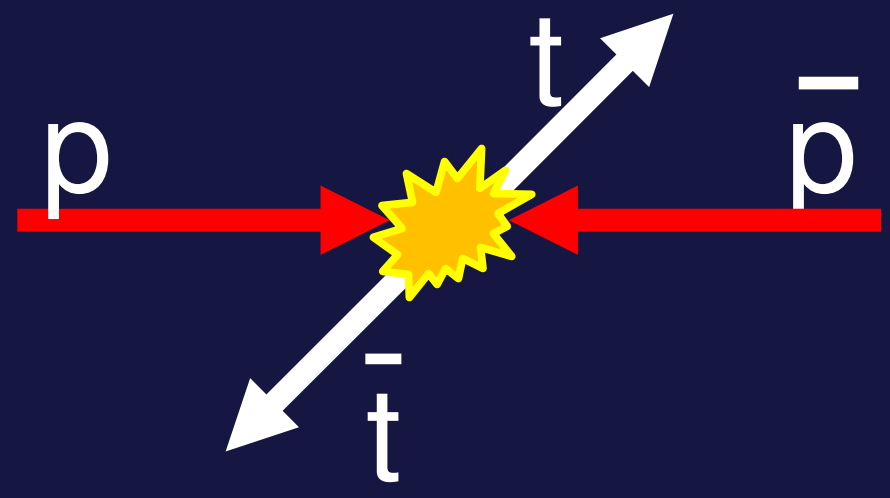
I. INTRODUCTION

The huge mass of the top quark, the only Standard Model (SM) fermion whose mass lies at the electroweak scale, may be a clue that the top is special in some way, perhaps serving as a portal to the physics of electroweak symmetry-breaking. Thanks to the wealth of data from the Tevatron, the existence of top is well-established, and fundamental measurements such as its mass have become routine. Interest now turns to more subtle properties, including the characteristics of its production.

Simple Asymmetries in the $t\bar{t}$ System

Charge Asymmetry:

$$A_C = \frac{N_t(\cos\theta>0) - N_{\bar{t}}(\cos\theta>0)}{N_t(\cos\theta>0) + N_{\bar{t}}(\cos\theta>0)}$$



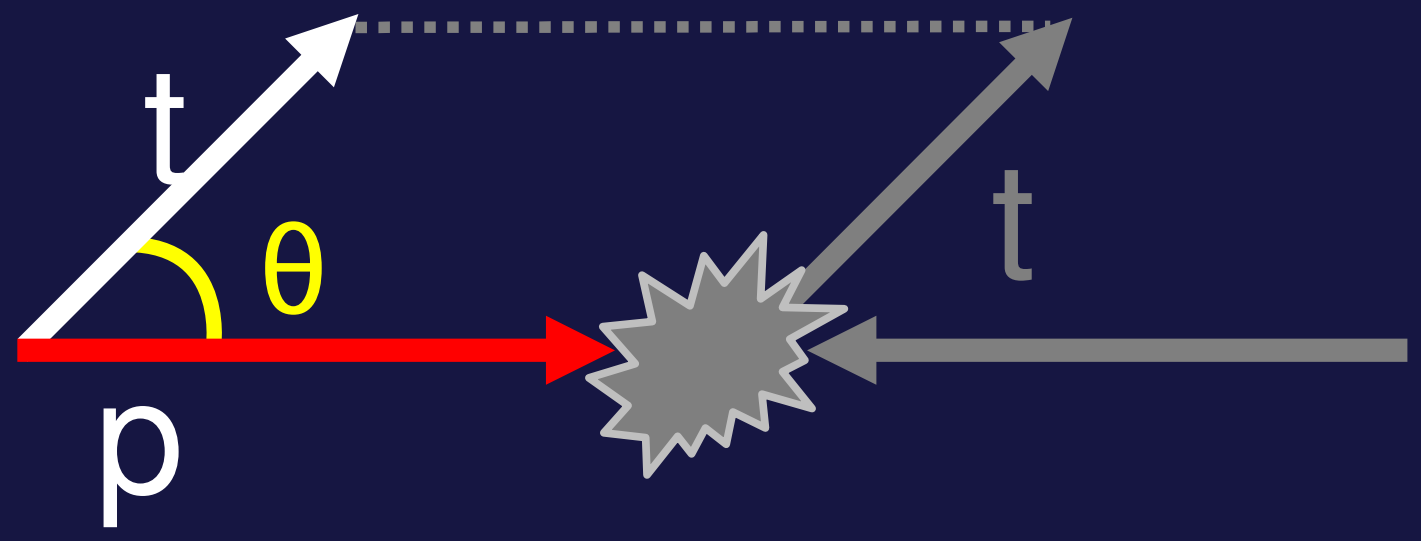
Forward-Backward Asymmetry:

$$A_{fb} = \frac{N_t(\cos\theta>0) - N_t(\cos\theta<0)}{N_t(\cos\theta>0) + N_t(\cos\theta<0)}$$

Assuming CP parity holds,

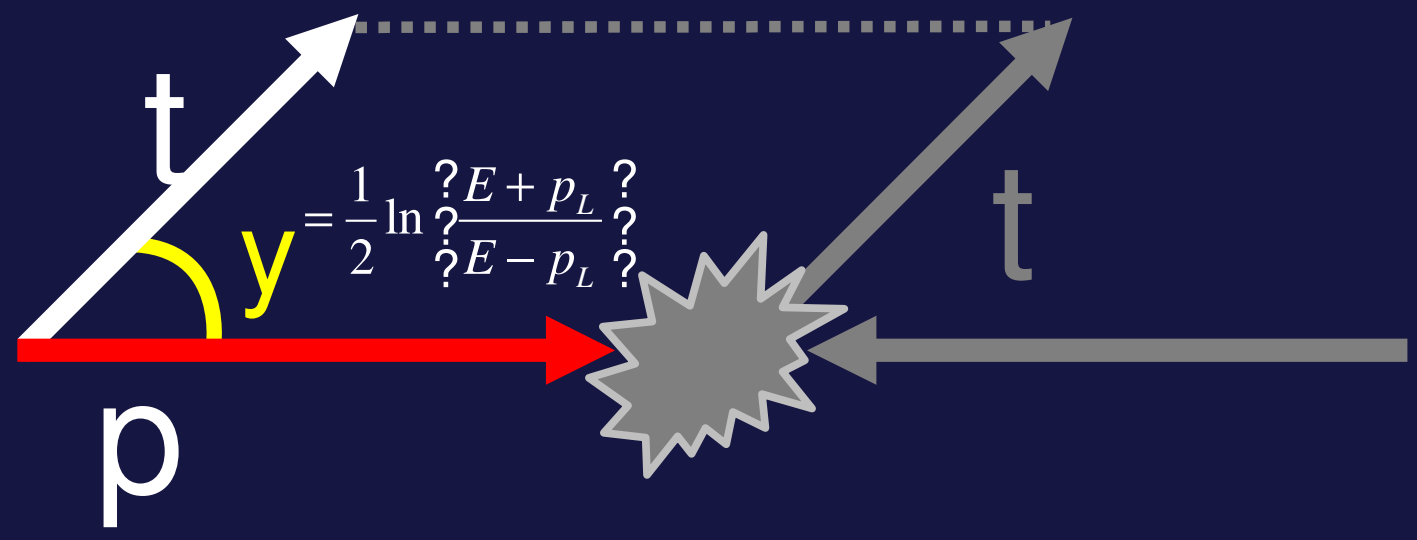
$$N_{\bar{t}}(\cos\theta > 0) = N_t(\cos\theta < 0) \rightarrow A_C = A_{fb} \checkmark$$

Asymmetries in $t\bar{t}$ Production



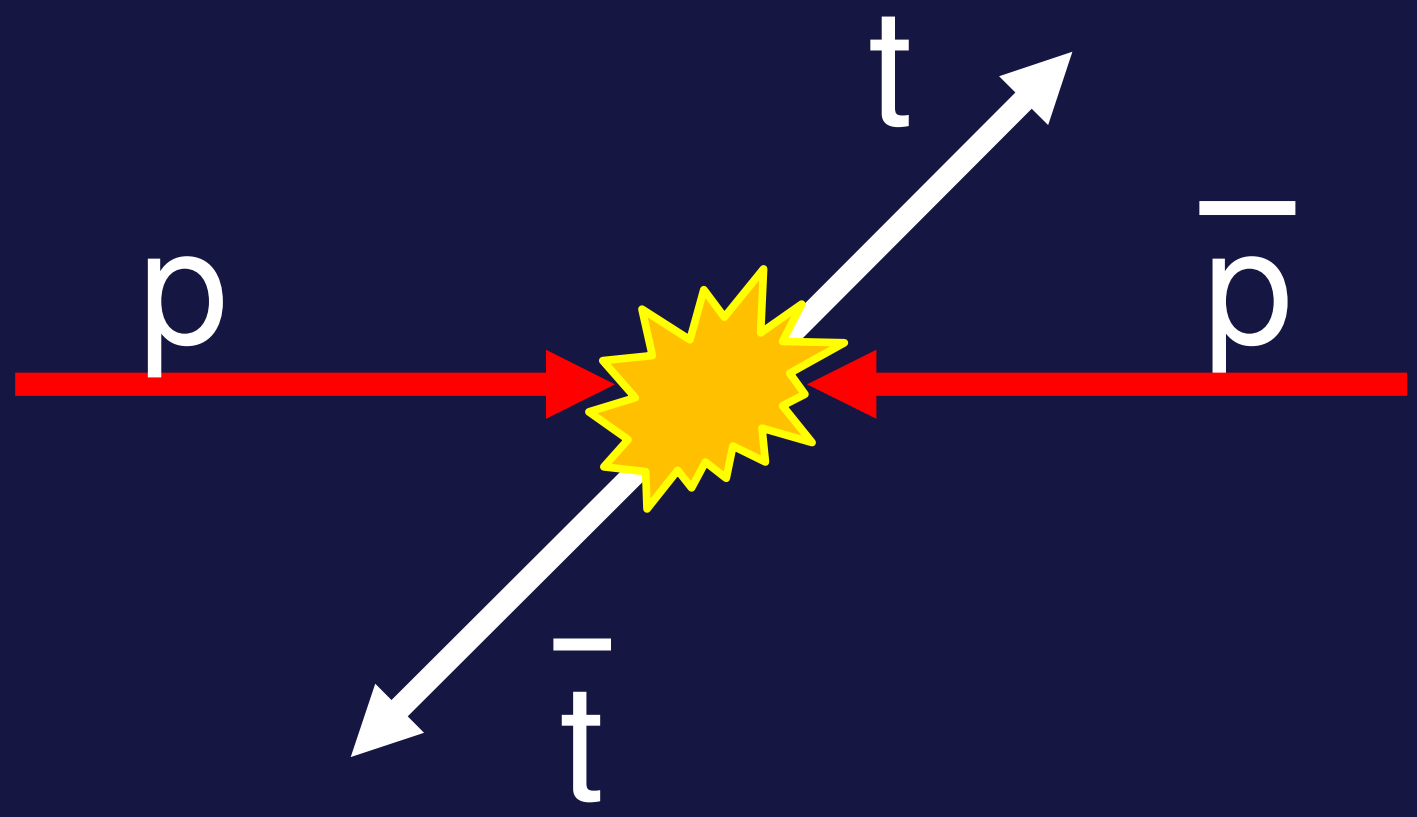
- Use θ, Cos(θ), rapidity (y), Delta y, etc. to measure A_{fb}
- Which variable do we use?
- Which reference frame should we use?
- Possible to do the more complicated measurement $\frac{dA_{fb}}{d\cos}$

Asymmetries in $t\bar{t}$ Production



- Use θ, Cos(θ), rapidity (y), Delta y, etc. to measure A_{fb}
- Which variable do we use?
- Which reference frame should we use?
- Possible to do the more complicated measurement $\frac{dA_{fb}}{d\cos\theta}$

Asymmetries in $t\bar{t}$ Production



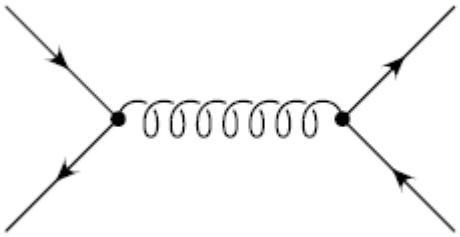
- In lowest order QCD, top quark production is symmetric
- NLO QCD predicts a small asymmetry
- Asymmetries are important tools for understanding weak interactions, as well as for searching for additional (chiral) couplings

Theoretical Predictions

Halzen, Hoyer, Kim; Kuhn, Rodrigo

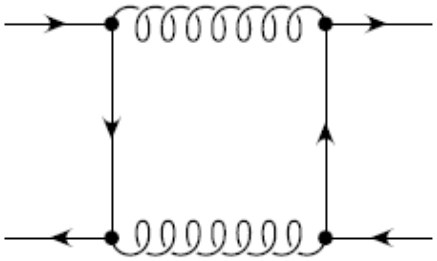
Dittmaier, Uwer, Weinzier; Almeida, Sterman, Vogelsang

$t\bar{t}$



$C_{tt} = -1$

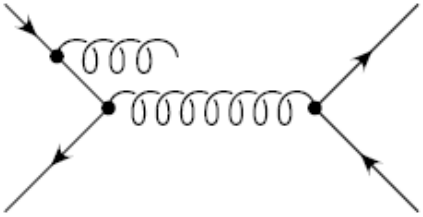
+



$C_{tt} = +1$

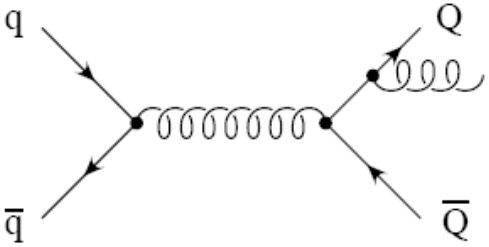
$A_{fb} \sim +10\text{-}12\%$

$t\bar{t}j$



$C_{tt} = -1$

+



$C_{tt} = +1$

A_{fb} (NLO) $\sim -7\%$

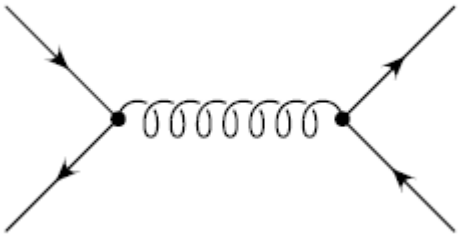
A_{fb} (NNLO) $\sim -1\%$

Consensus working value $A_{fb} \sim 5 \pm 1.5\%$

Theoretical Predictions

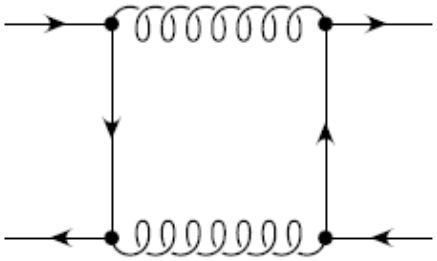
Note that gg→tt results in no asymmetry, so our measurement will be diluted by 15% before any other effects

$t\bar{t}$



$C_{tt} = -1$

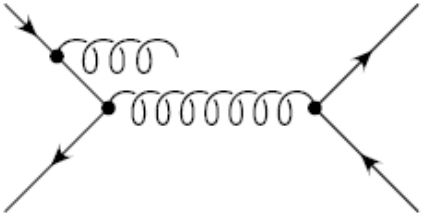
+



$C_{tt} = +1$

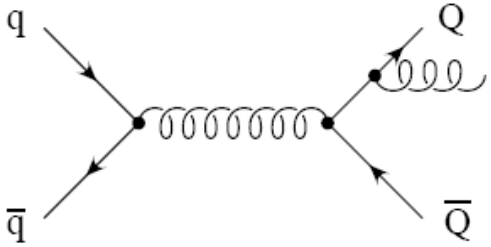
$A_{fb} \sim +10\text{-}12\%$

$t\bar{t}j$



$C_{tt} = -1$

+



$C_{tt} = +1$

A_{fb} (NLO) ~ -7%

A_{fb} (NNLO) ~ -1%

Consensus working value $A_{fb} \sim 5 \pm 1.5\%$

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$
$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$
$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2}$$
$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$
$$+ (g_A^t)^2 (1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

$c = \beta\cos(\theta)$

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c \Big\}$$

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

Vector coupling

Axial coupling

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

m_G = mass of axigluon

Γ_G = width of axigluon

Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

gluon propagator

gluon exchange

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} \boxed{g_V^q g_V^t (1 + c^2 + 4m^2)}$$

$$+ \boxed{2 g_A^q g_A^t c} + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times \big[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c \big] \Big\}$$

Interference Term

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

Note that there is a symmetric part and an asymmetric part

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_s^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

Pole term for axigluon

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big[1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

Again, note that there is a symmetric part and an asymmetric part

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

Since we observe no pole in M_{tt}, this constrains the possible values for g_A and g_V that give a positive asymmetry

$$+ 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2 \Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c]$$

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Lagrangian for Axigluon+Gluon

Allows us to restrict regions for coupling parameters that won't change tt cross section

$$+ 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}[g_V^q g_V^t(1 + c^2 + 4m^2)$$

$$+ 2g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2(1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2(1 + c^2 - 4m^2)) + 8g_V^q g_A^q g_V^t g_A^t c\}$$

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Recent Measurement History

Previously Blessed Results (1.9 fb^{-1}):

A_{fb} cos(θ) method: $A_{fb} = 0.17 \pm 0.08$ (Davis/Michigan)

A_{fb} Δy method: $A_{fb} = 0.24 \pm 0.14$ (Karlsruhe)

Phys. Rev. Lett. 101, 202001 (2008)

D-zero Results (0.9 fb^{-1}):

$A_{fb} = 0.12 \pm 0.08 \pm 0.01$

Fermilab and CDF...

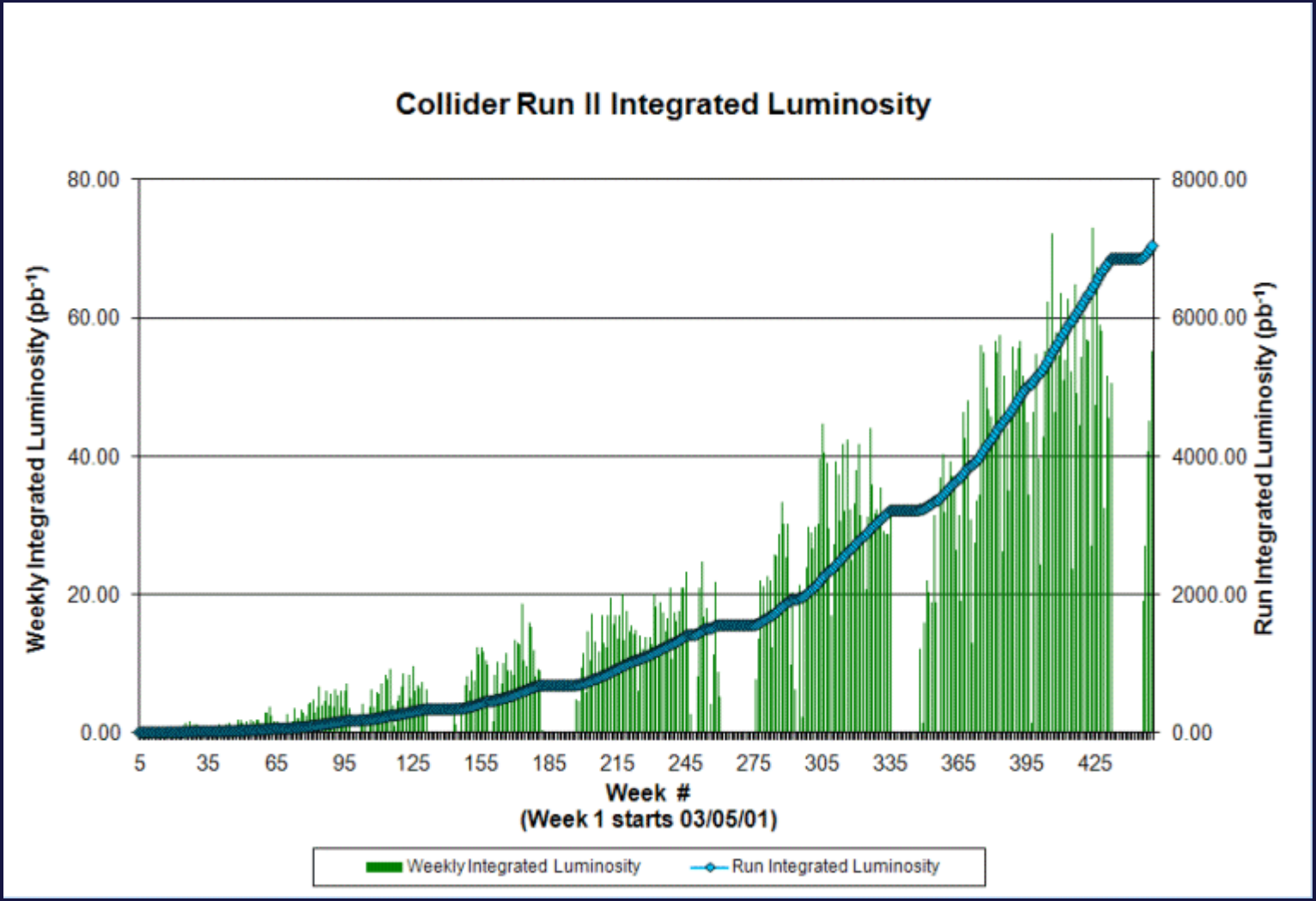
Fermilab

- Tevatron
  ~4 miles around
- 1.96 TeV Collisions
- Over 6 fb^{-1} data integrated luminosity
- We're still the most energetic and highest luminosity hadron collider on Earth!

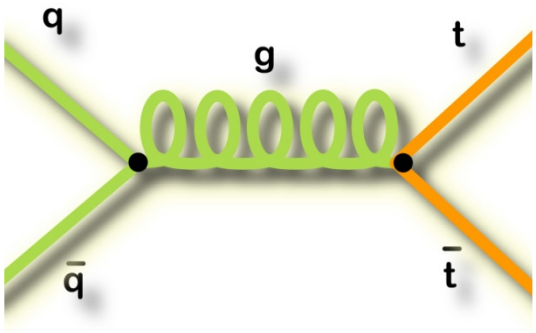
Fermilab

- Tevatron
  ~4 miles around
- 1.96 TeV Collisions
- Over 6 fb^{-1} data integrated luminosity
- We're still the most energetic and highest luminosity hadron collider on Earth!

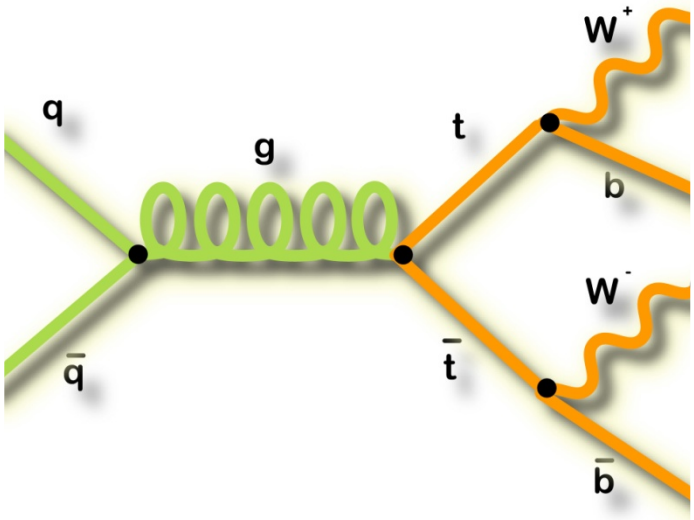
Fermilab


Collider Run II Integrated Luminosity
Weekly Integrated Luminosity (pb-1)
Run Integrated Luminosity (pb-1)
80.00
60.00
40.00
20.00
0.00
8000.00
6000.00
4000.00
2000.00
0.00
5
35
65
95
125
155
185
215
245
275
305
335
365
395
425
Week #
(Week 1 starts 03/05/01)
Weekly Integrated Luminosity
Run Integrated Luminosity

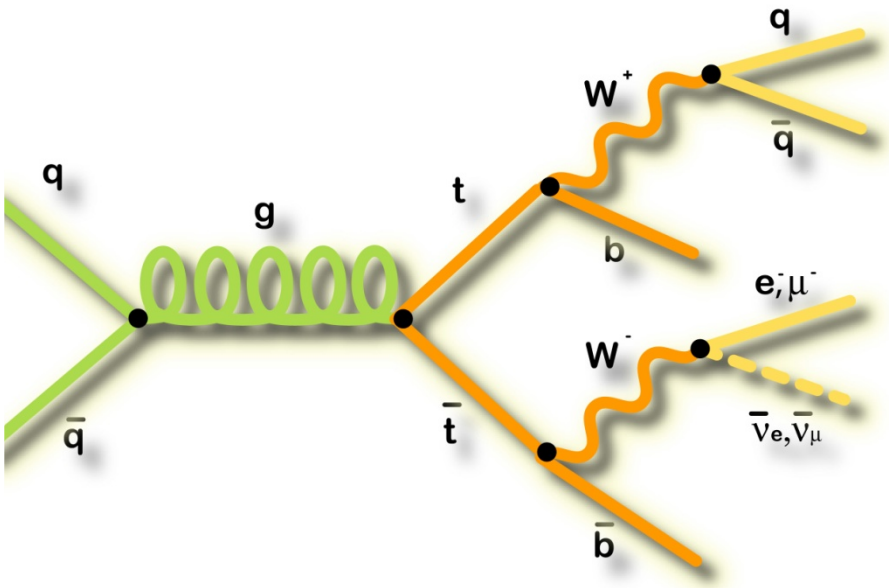
Event Reconstruction



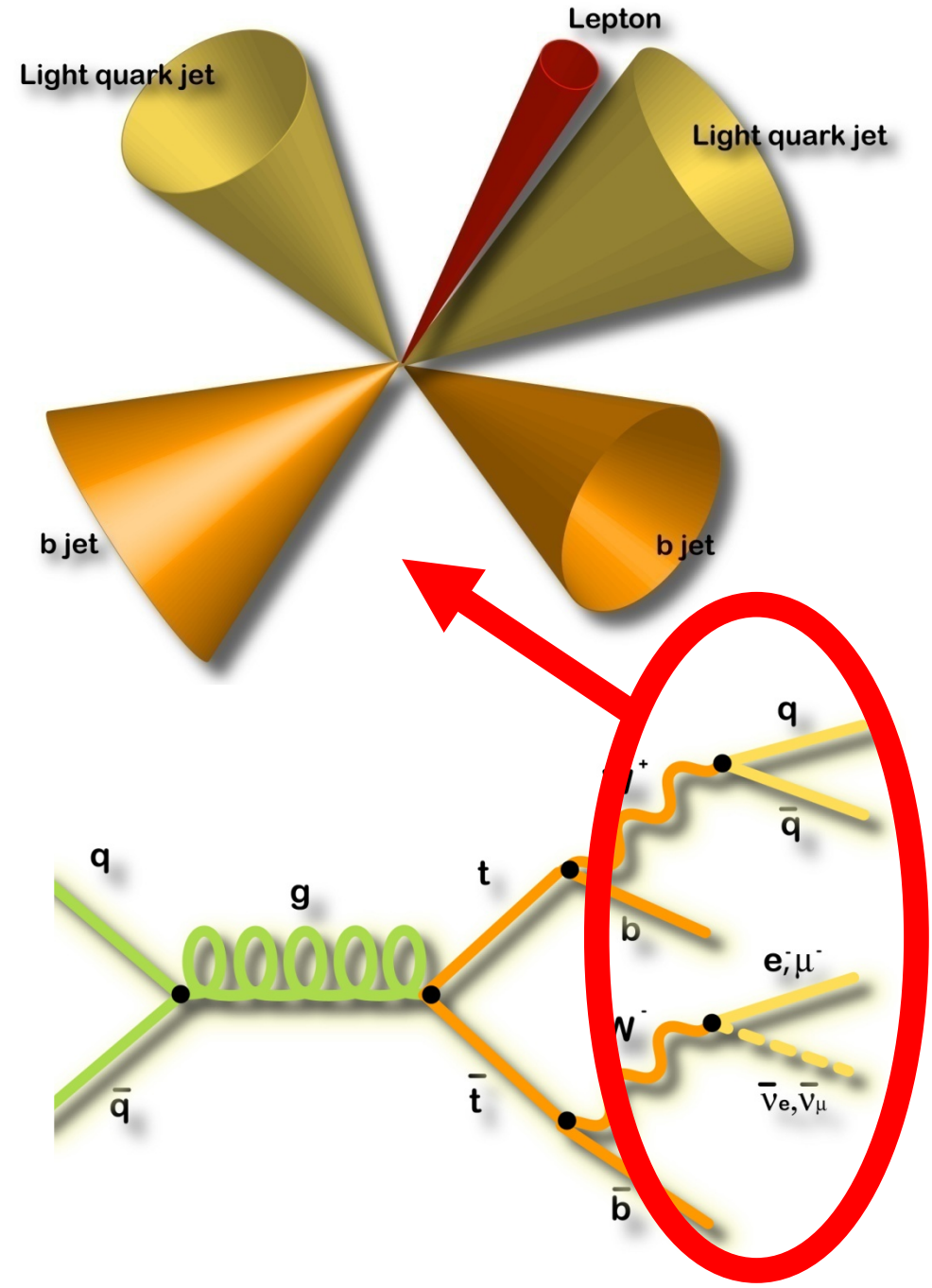
Event Reconstruction



Event Reconstruction



Event Reconstruction



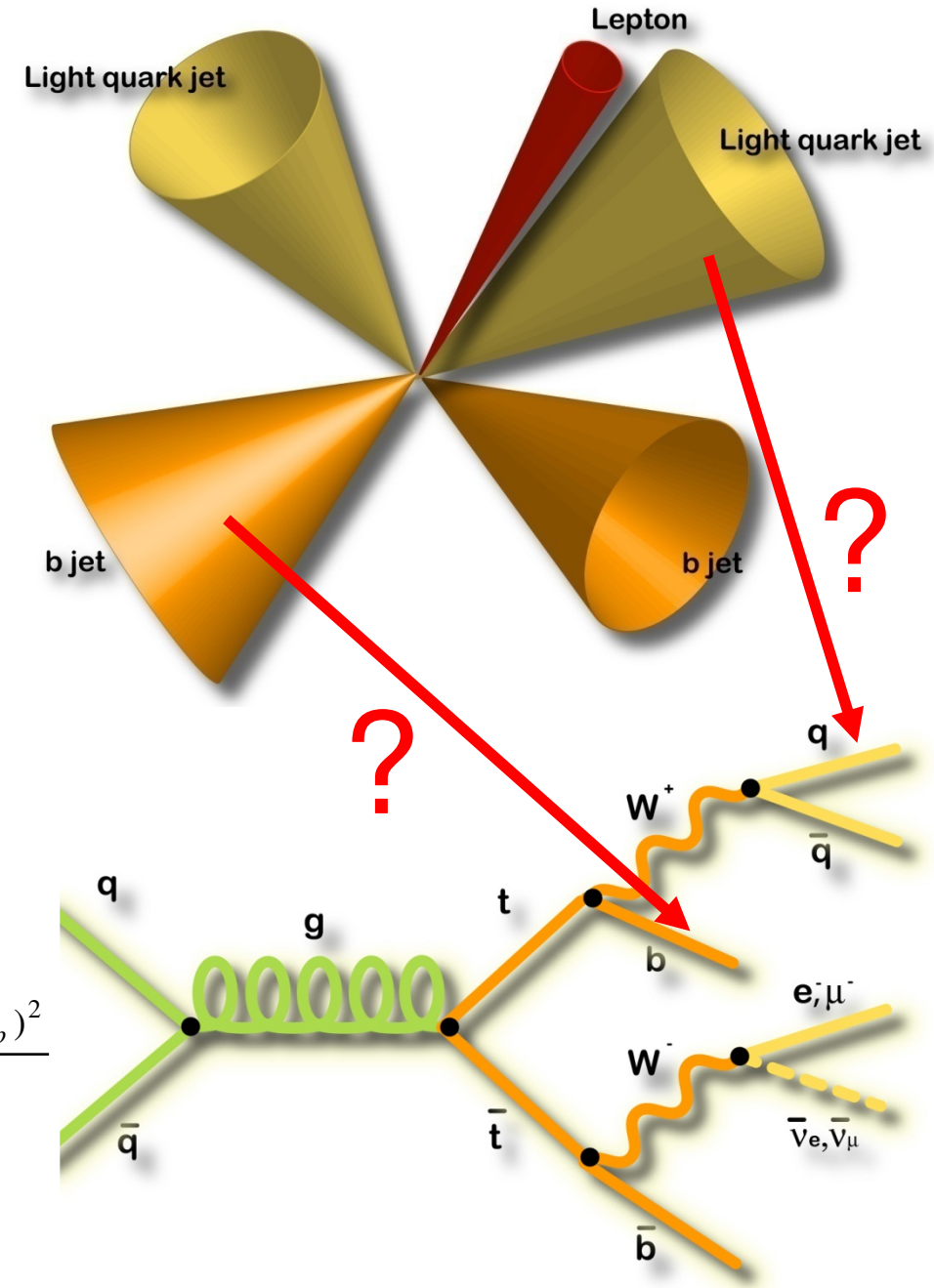
Event Reconstruction

Reconstruction

- Match jets to b, $\bar{b}$, up, down
- Constrain fit W mass to 80.4 GeV/c²
- Constrain fit for a 175.0 GeV/c² Top
- Float momenta of jets within known resolution
- Use combination with lowest χ^2

$$\chi^2 = \sum_{lep,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

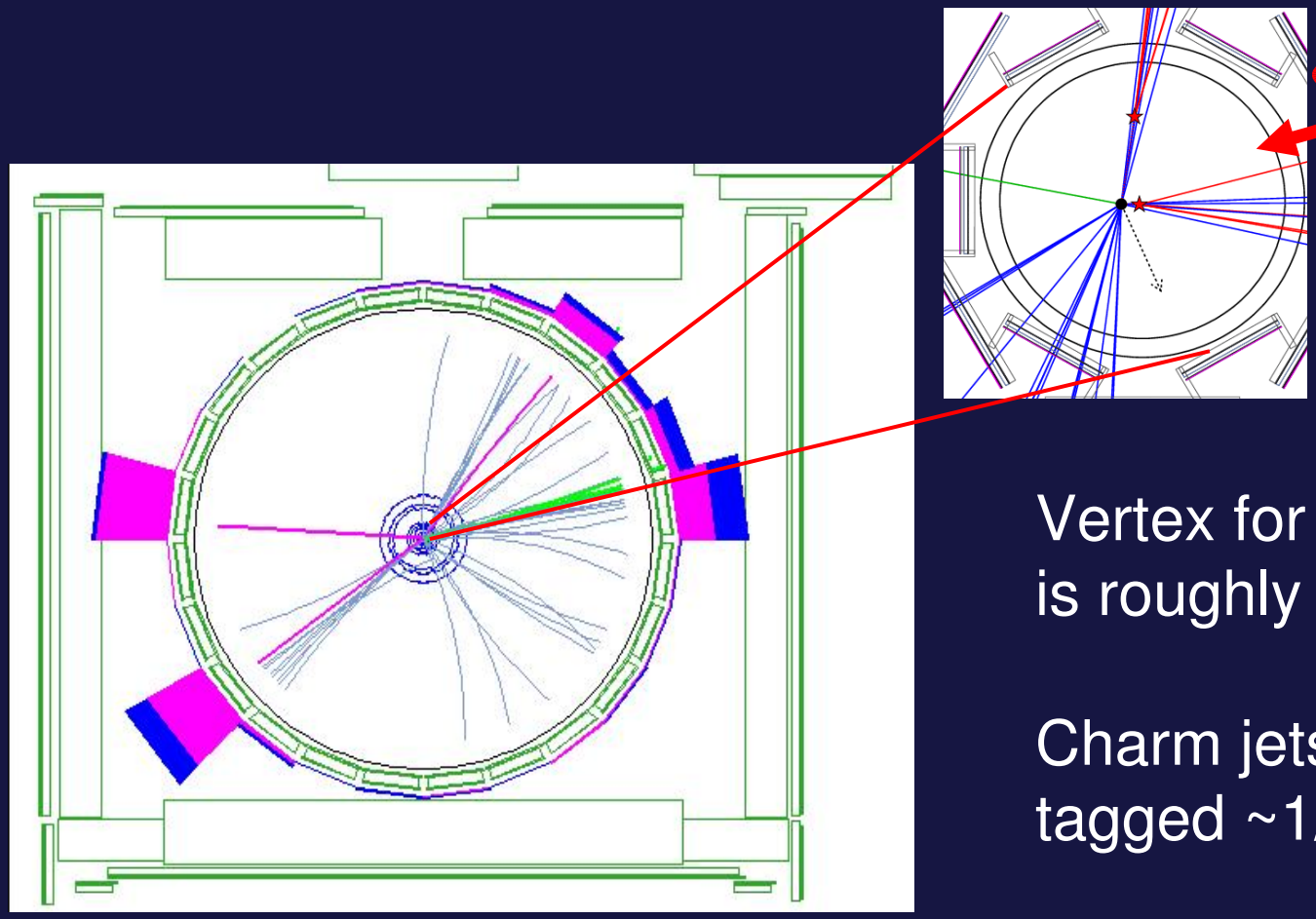
$$+ \frac{(M_{jj} - M_w)^2}{\Gamma_w^2} + \frac{(M_{l\nu} - M_w)^2}{\Gamma_w^2} + \frac{(M_{bjj} - M_{top})^2}{\Gamma_{top}^2} + \frac{(M_{bl\nu} - M_{top})^2}{\Gamma_{top}^2}$$



Top Pair Production and Decay

Lepton + Jets mode:

$$q\bar{q} \rightarrow g \rightarrow t\bar{t} \rightarrow (W^{+}b)(W^{-}\bar{b}) \rightarrow (l^{+}\nu b)(q\bar{q}\bar{b}) \rightarrow l^{+} + \not{E}_{t} + 4j + \geq 1 \text{ “tagged” jet}$$



Top signals isolated using secondary vertex

= “b-tag”

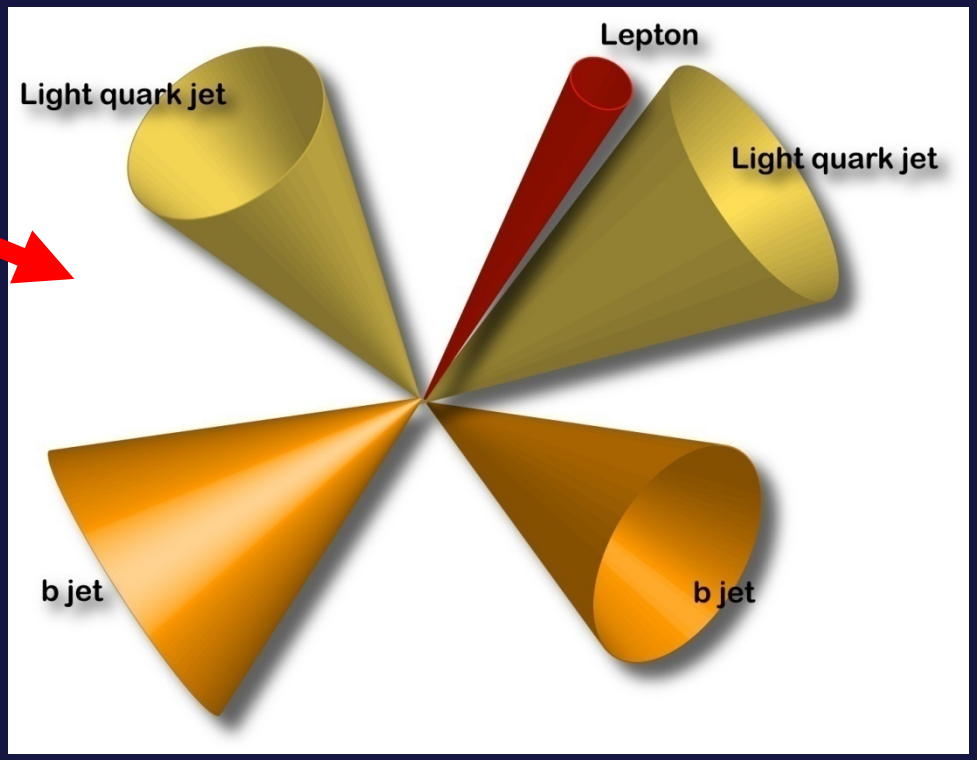
Vertex for b-quarks is roughly ½ mm

Charm jets are only tagged ~1/10 the time

Data Sample

Selection

- Measurement is performed using semi-leptonic top pair decays
- 3.2 fb^{-1} of CDF data
- ≥ 4 jets (Et > 20 GeV and $|\eta| < 2$)
- ≥ 1 b-tagged jet
- 1 electron (Et > 20 GeV and $|\eta| < 1$) –or– 1 muon (Pt > 20 GeV/c and $|\eta| < 1$)
- Missing Transverse Energy > 20 GeV

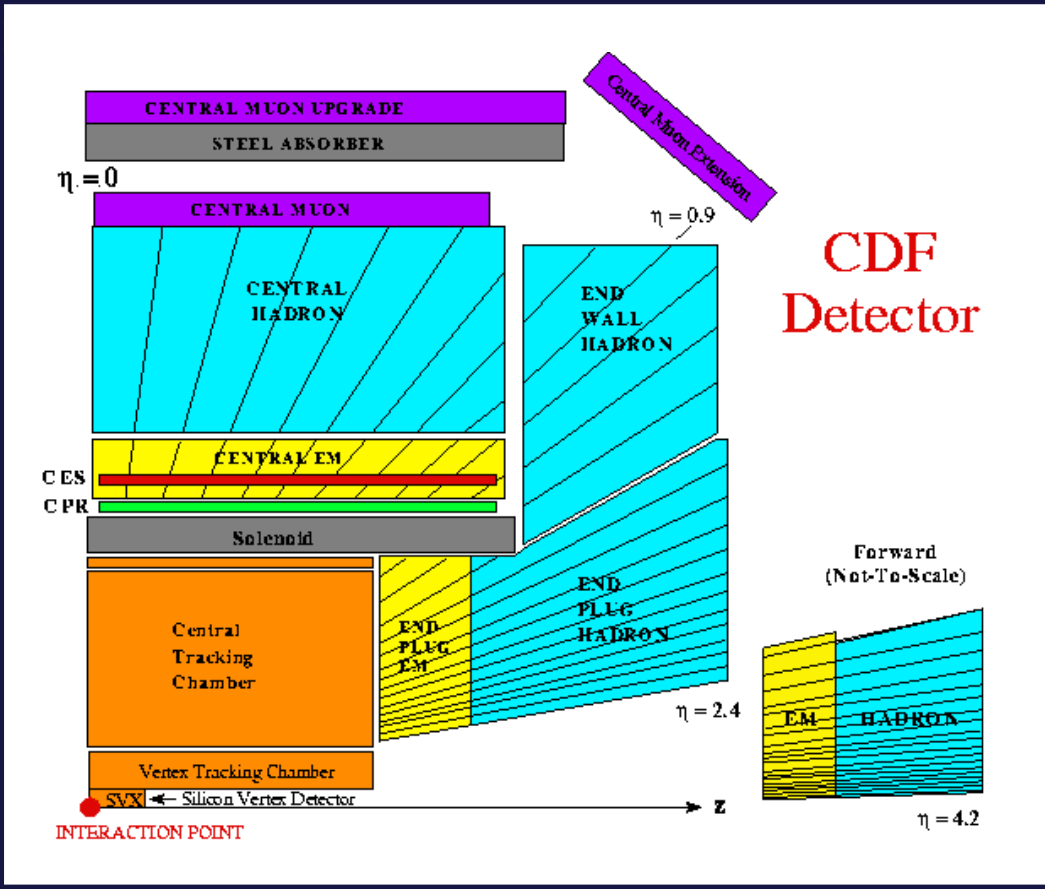


776 Candidate Events

Data Sample

Selection

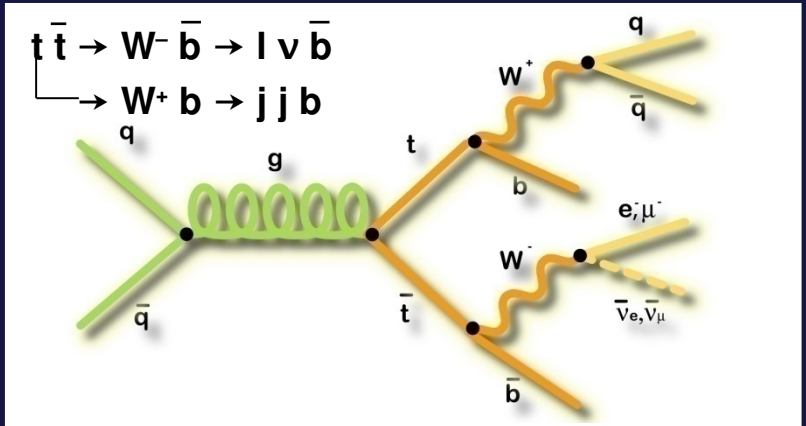
- Measurement is performed using semi-leptonic top pair decays
- 3.2 fb^{-1} of CDF data
- ≥ 4 jets (Et > 20 GeV and |η| < 2)
- ≥ 1 b-tagged jet
- 1 electron (Et > 20 GeV and |η| < 1) –or– 1 muon (Pt > 20 GeV/c and |η| <1)
- Missing Transverse Energy > 20 GeV

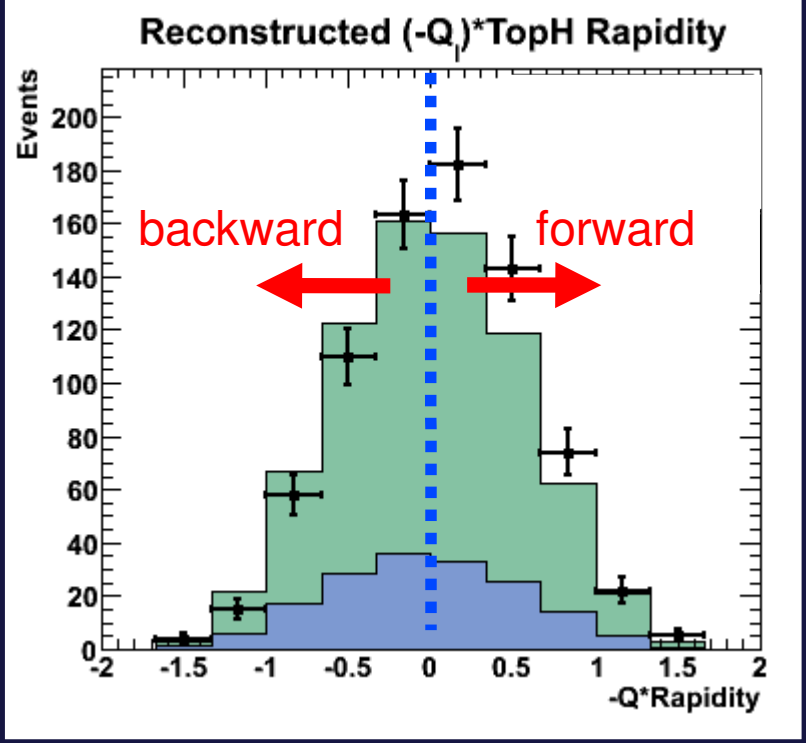


776 Candidate Events

Measurement Techniques

- Hadronic top decay is more accurately reconstructed, so we will measure y_{had}
- Get hadronic top charge from lepton
- Invoke CP invariance and multiply hadronic-only distribution by -1 * lepton charge to find equivalent top rapidity in each event
- Measure A_{fb} using $-Q_{lep} \cdot y_{had}$ in the lab frame, count forward and backward events
- Correct A_{fb} back to parton level





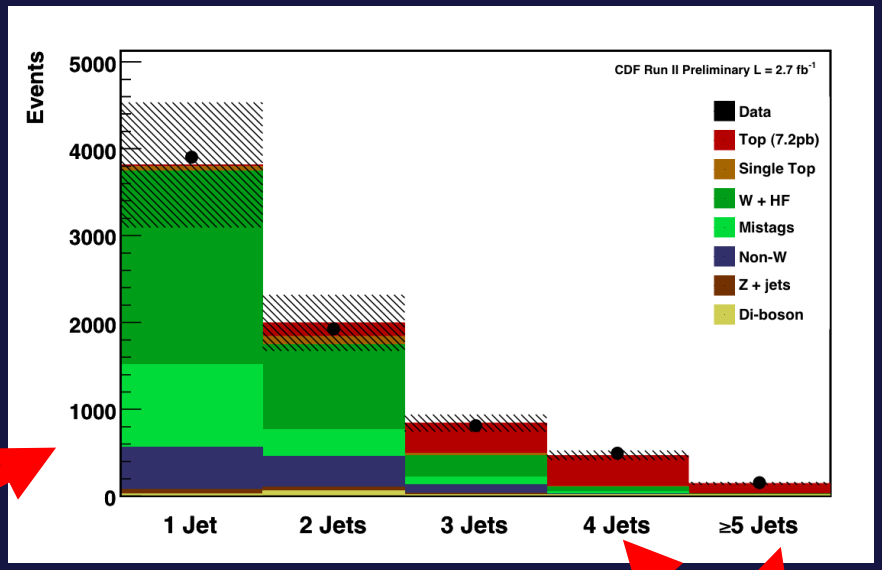
Data Sample

Selection

- Measurement is performed using semi-leptonic top pair decays
- 3.2 fb^{-1} of CDF data
- ≥ 4 jets (Et > 20 GeV and |η| < 2)
- ≥ 1 b-tagged jet
- 1 electron (Et > 20 GeV and |η| < 1) –or– 1 muon (Pt > 20 GeV/c and |η| <1)
- Missing Transverse Energy > 20 GeV

Backgrounds

- Use W+Jets tagged backgrounds to model the ttbar tagged backgrounds present in the semi-leptonic sample



167 ± 34 Background Events

Data Sample

Selection

- Measurement is performed using semi-leptonic top pair decays
- 3.2 fb^{-1} of CDF data
- ≥ 4 jets (Et > 20 GeV and $|\eta| < 2$)
- ≥ 1 b-tagged jet
- 1 electron (Et > 20 GeV and $|\eta| < 1$) –or– 1 muon (Pt > 20 GeV/c and $|\eta| < 1$)
- Missing Transverse Energy > 20 GeV

Backgrounds

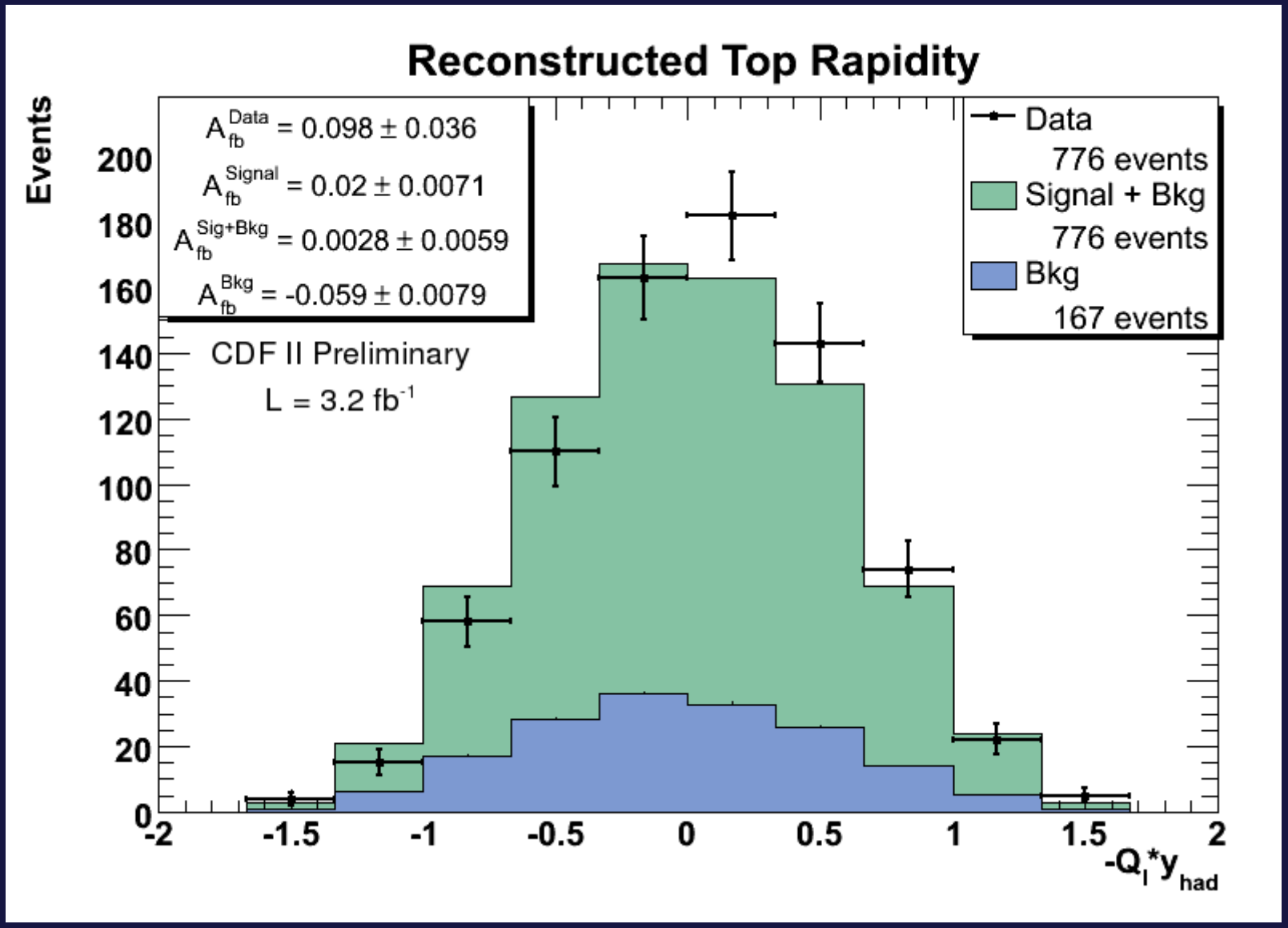
- Use W+Jets tagged backgrounds to model the ttbar tagged backgrounds present in the semi-leptonic sample

Process	
W+HF Jets	86.56 ± 27.40
Mistags (W+LF)	27.43 ± 7.70
Non-W (QCD)	33.44 ± 28.06
Single Top	7.82 ± 0.50
WW/WZ/ZZ	7.57 ± 0.74
Z+Jets	4.78 ± 0.59
Top	569.08 ± 78.81
Total Prediction	736.64 ± 89.22

776 Candidate Events

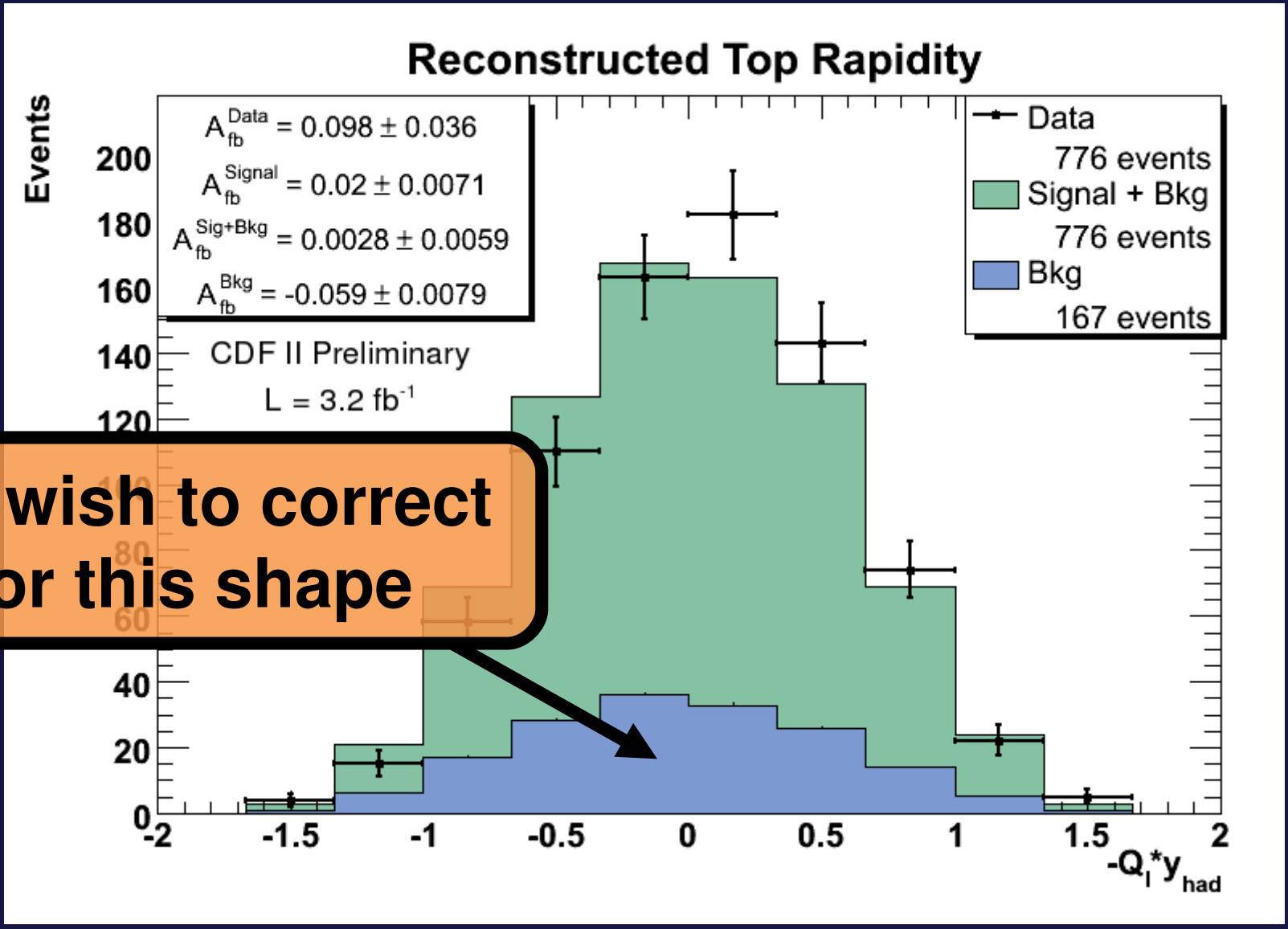
167 ± 34 Predicted Background

Raw Asymmetry



Signal MC is MC@NLO, normalized so signal+background = number of data events

Raw Asymmetry



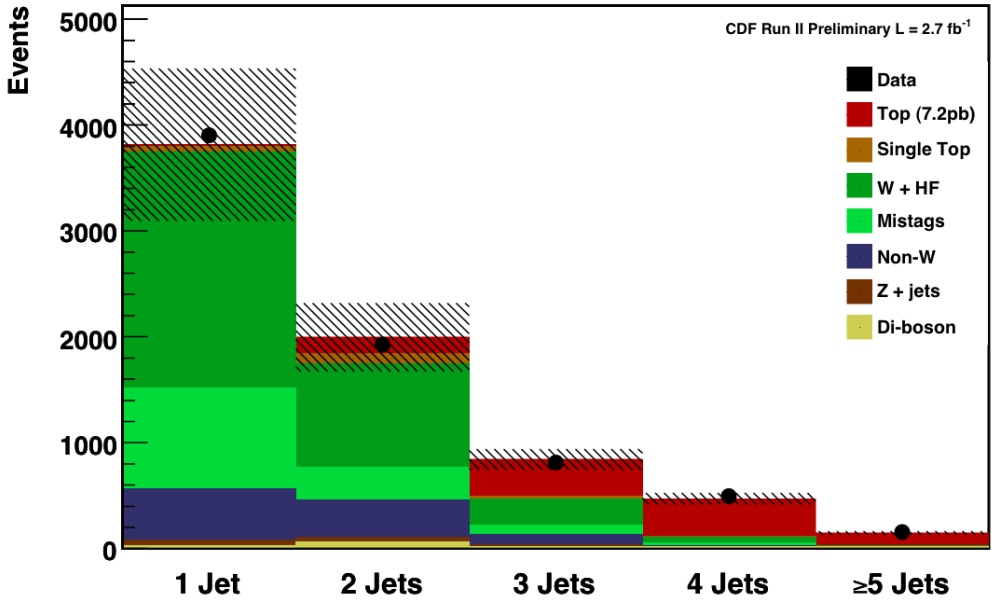
We wish to correct for this shape

Signal MC is MC@NLO, normalized so signal+background = number of data events

Background Subtraction

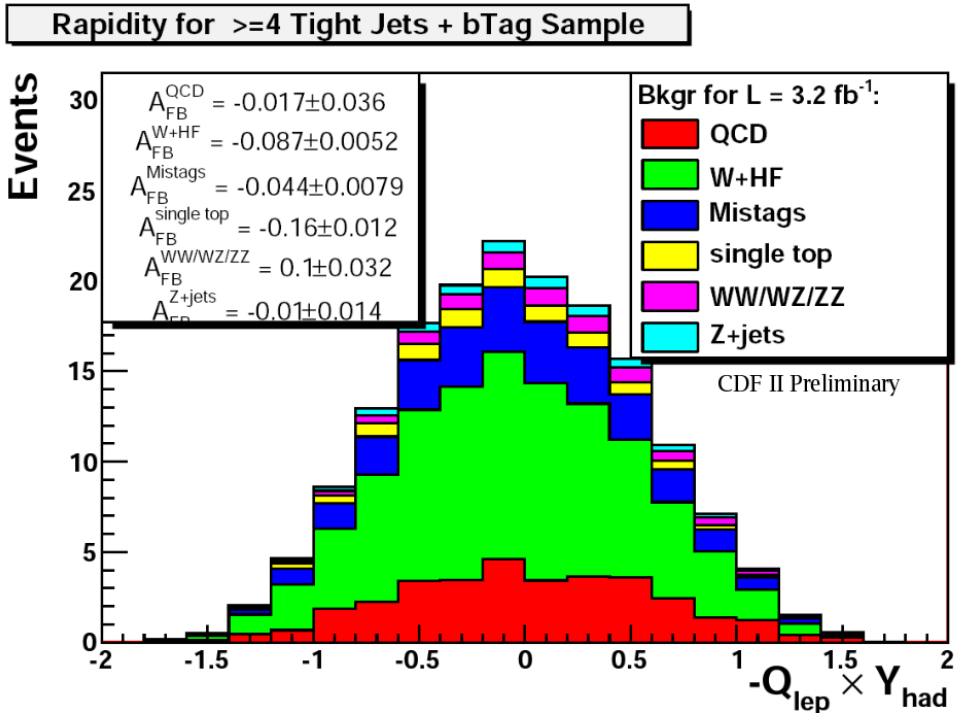
- Background has a known asymmetry that modifies the top A_{fb} measurement
- Check anti-tagged data and MC for consistency and cross-section
- Subtract backgrounds from our data

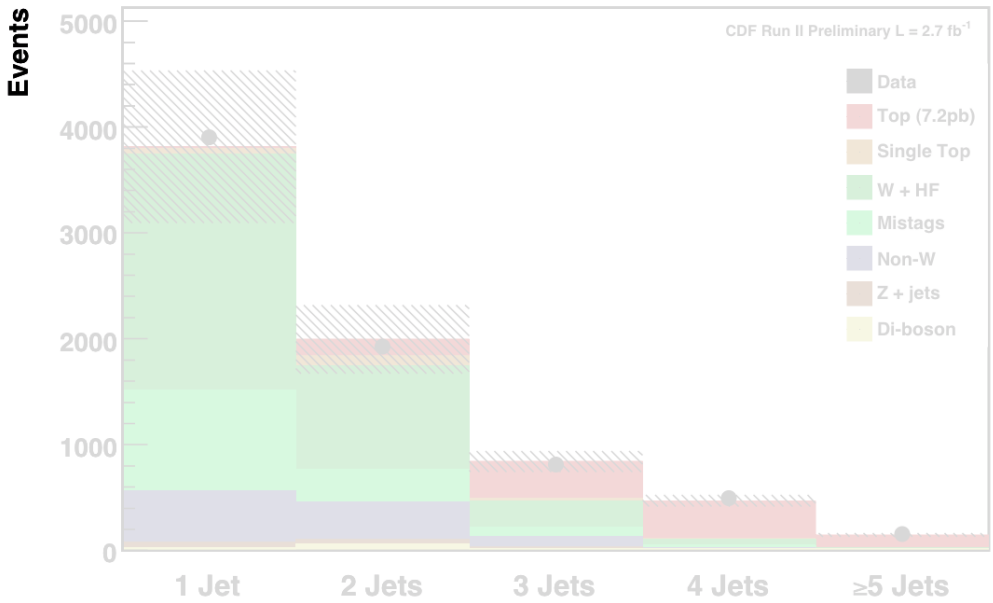
Backgrounds in W+Jets



Background Subtraction

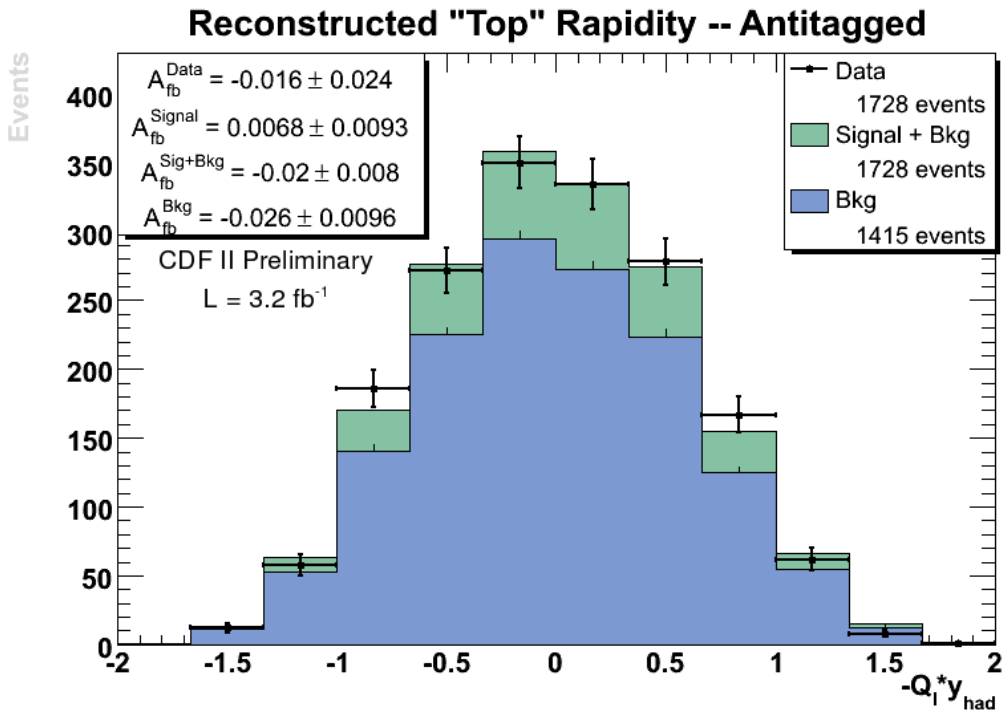
- Background has a known asymmetry that modifies the top A_{fb} measurement
- Check anti-tagged data and MC for consistency and cross-section
- Subtract backgrounds from our data





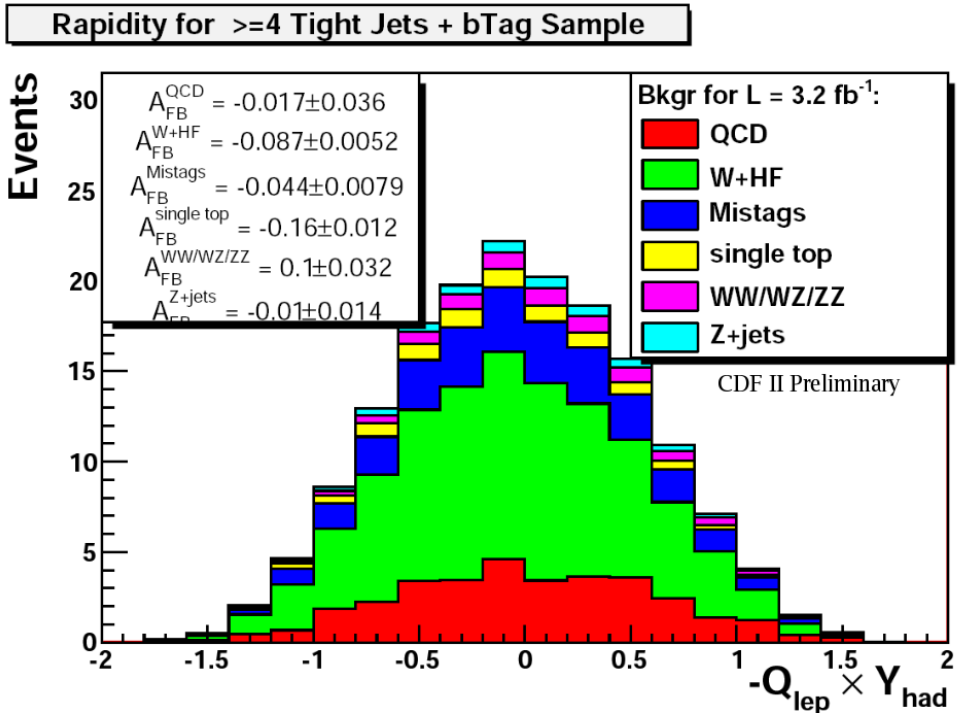
Background Subtraction

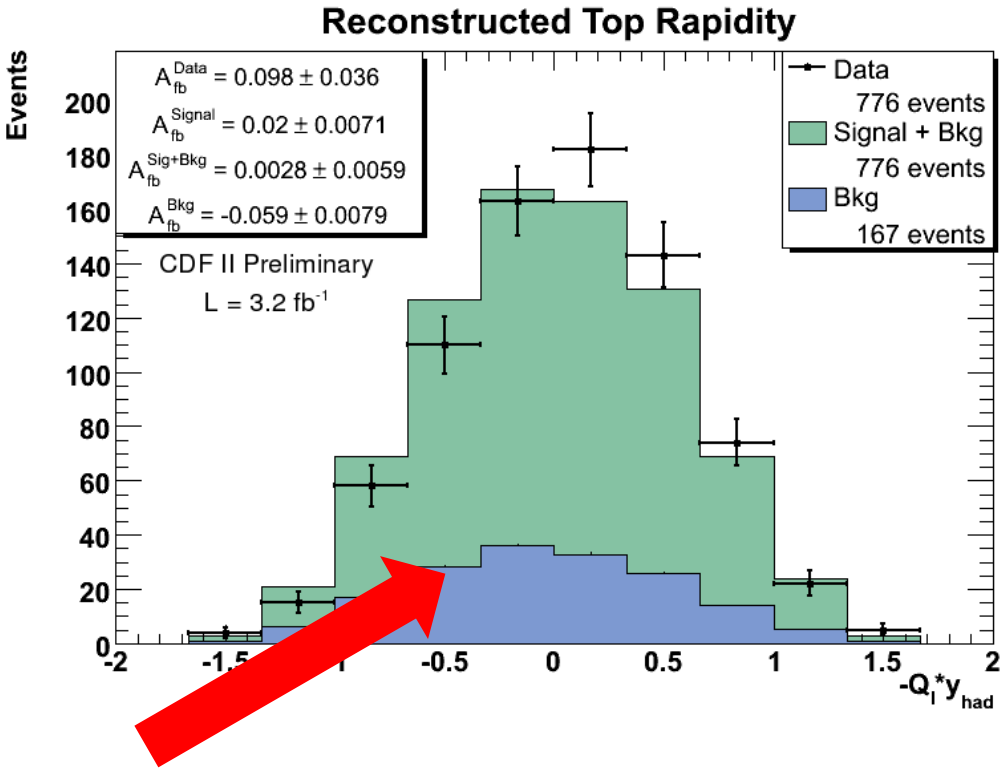
- Background has a known asymmetry that modifies the top A_{fb} measurement
- Check anti-tagged data and MC for consistency and cross-section
- Subtract backgrounds from our data



Background Subtraction

- Background has a known asymmetry that modifies the top A_{fb} measurement
- Check anti-tagged data and MC for consistency and cross-section
- Subtract backgrounds from our data





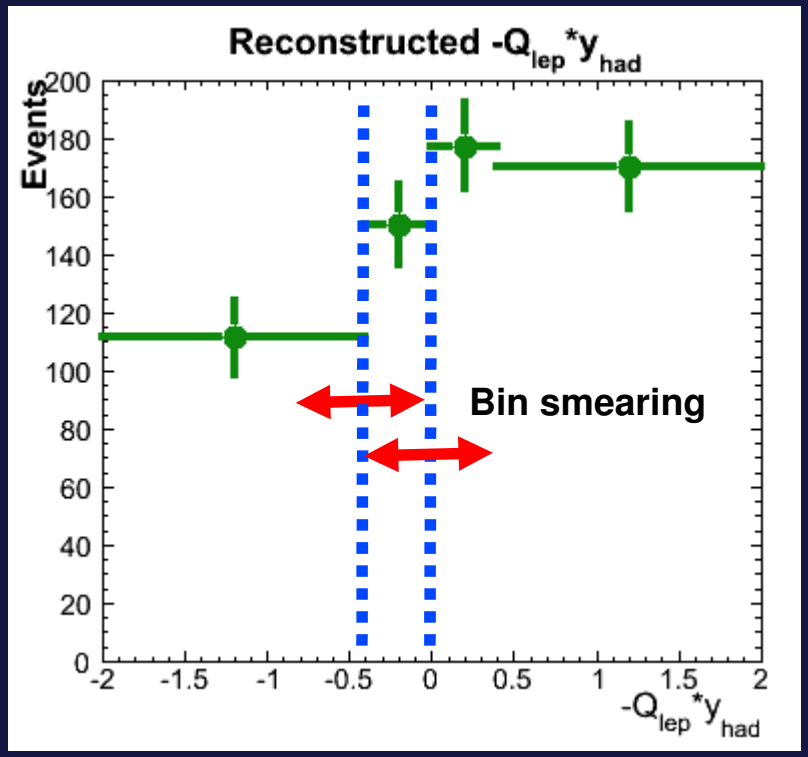
- We subtract off this total background from the data shape, 167 events out of 776 data events, which has A_{fb} = -0.059 ± 0.0079
- Negative values mostly due to electroweak processes (W+HF)

Background A_{fb}s

Process	=4 jets	>=5 Jets	>=4 jets
W+HF Jets	-0.095±0.0078	-0.078±0.007	-0.087±0.0052
Mistags (W+LF)	-0.038±0.012	-0.05±0.01	-0.044±0.0079
Non-W (QCD)	-0.044±0.06	-0.002±0.044	-0.017±0.036
Single Top	-0.18±0.016	-0.12±0.018	-0.16±0.012
WW/WZ/ZZ	0.078±0.046	0.13±0.045	0.1±0.032
Z+Jets	-0.016±0.021	-0.0041±0.018	-0.01±0.014
Total Prediction	-0.07±0.012	-0.045±0.012	-0.059±0.0079

Asymmetry Correction Technique

- We optimize for number of bins and bin spacing
- Reconstruction of the event causes smearing between bins. We use a matrix unfolding technique to correct for this effect.
- Acceptance efficiencies also bias our sample, so an analogous correction is made using an acceptance matrix



$$S_{ij} = N^{ij}_{recon}/N^{i}_{truth}$$

$$A_{ii} = N^{i}_{sel}/N^{i}_{gen}$$

$$N_{corrected} = A^{-1} \bullet S^{-1} \bullet N_{bkg\text{-}sub}$$

Corrected Asymmetry Measurement

$$S = \begin{bmatrix} 0.76\pm0.0096 & 0.13\pm0.0041 & 0.035\pm0.0022 & 0.011\pm0.0012 \\ 0.17\pm0.0046 & 0.66\pm0.0093 & 0.16\pm0.0046 & 0.042\pm0.0023 \\ 0.053\pm0.0025 & 0.17\pm0.0047 & 0.67\pm0.0095 & 0.16\pm0.0045 \\ 0.017\pm0.0014 & 0.042\pm0.0023 & 0.13\pm0.0042 & 0.79\pm0.01 \end{bmatrix}$$

$$A = \begin{bmatrix} 0.981\pm0.00483 & 0 & 0 & 0 \\ 0 & 1.09\pm0.00555 & 0 & 0 \\ 0 & 0 & 1.05\pm0.00547 & 0 \\ 0 & 0 & 0 & 0.901\pm0.00464 \end{bmatrix}$$

$$(A^{-1}\bullet S^{-1}) = \begin{bmatrix} 1.4 & -0.28 & -0.0061 & -0.0043 \\ -0.33 & 1.6 & -0.35 & -0.0084 \\ -0.016 & -0.38 & 1.6 & -0.29 \\ -0.0095 & -0.018 & -0.28 & 1.5 \end{bmatrix}$$

$$S_{ij} = N^{ij}_{recon}/N^{i}_{truth}$$

$$A_{ii} = N^{i}_{sel}/N^{i}_{gen}$$

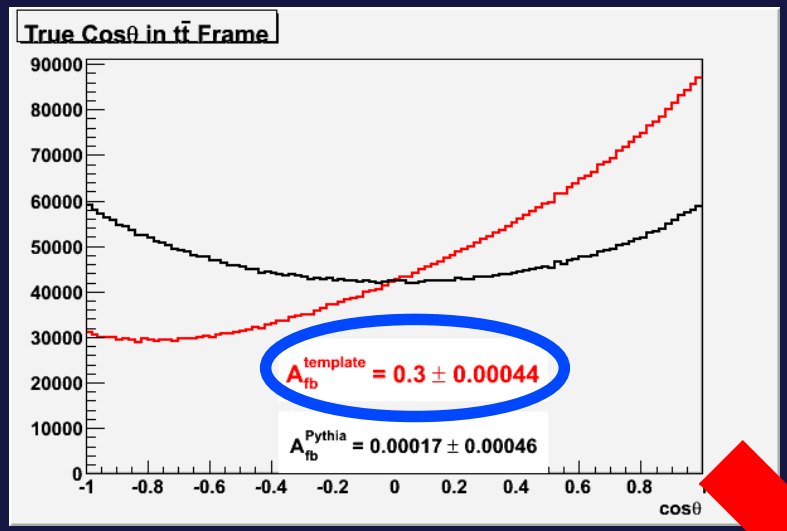
$$N_{corrected} = A^{-1}\bullet S^{-1}\bullet N_{bkg\text{-}sub}$$

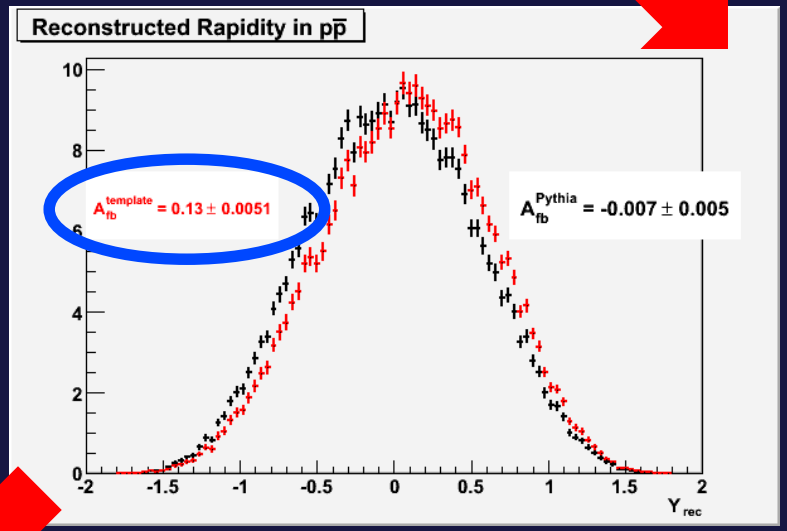
Test of Method

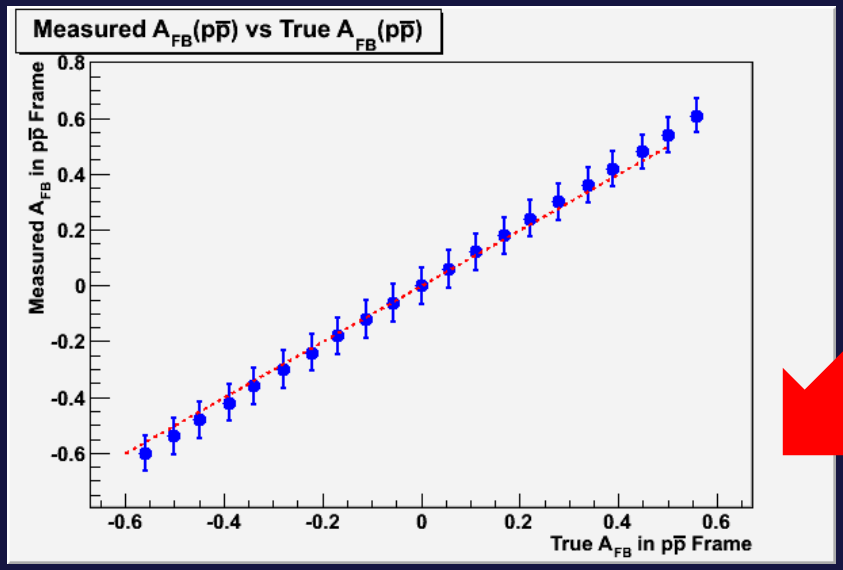
- We make control samples with known asymmetry by reweighting Pythia Cos(θ) signal in the ttbar frame by

$$1+A\cdot\mathrm{Cos}(\theta_{tt})$$

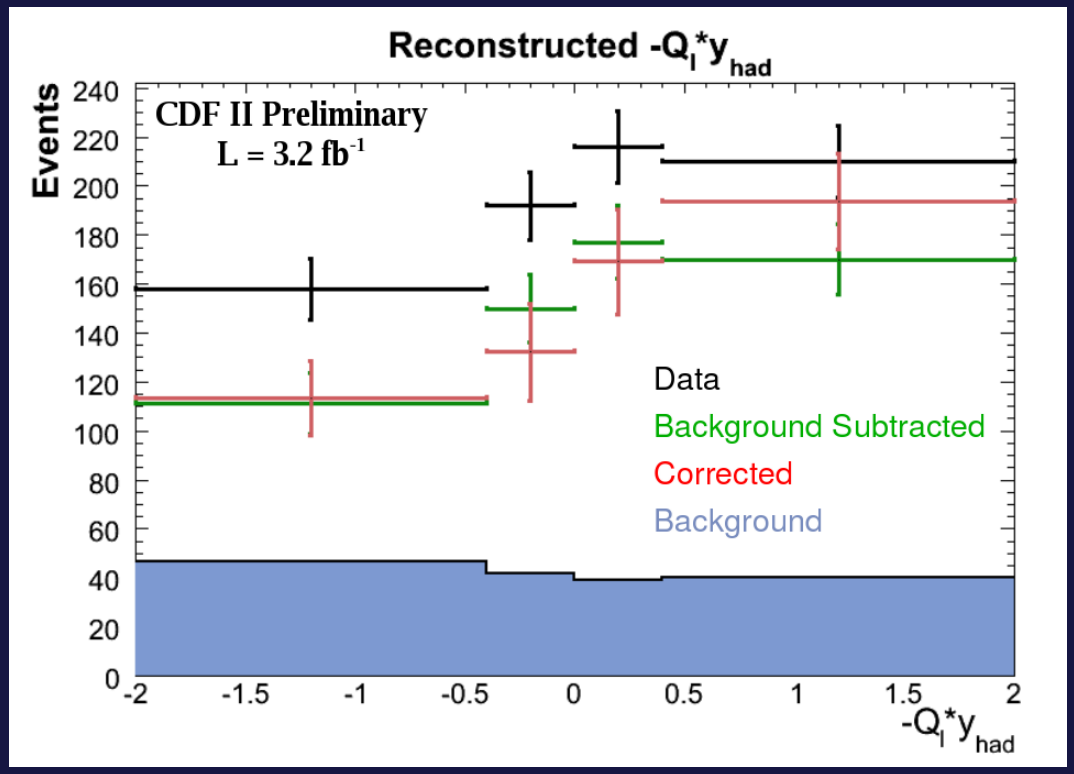
- Propagate these changes to obtain appropriate factors for reweighting Y_{pp}
- Check corrected measurement vs known A_{fb} for $\mathrm{Cos}(\theta_{tt})$ signal





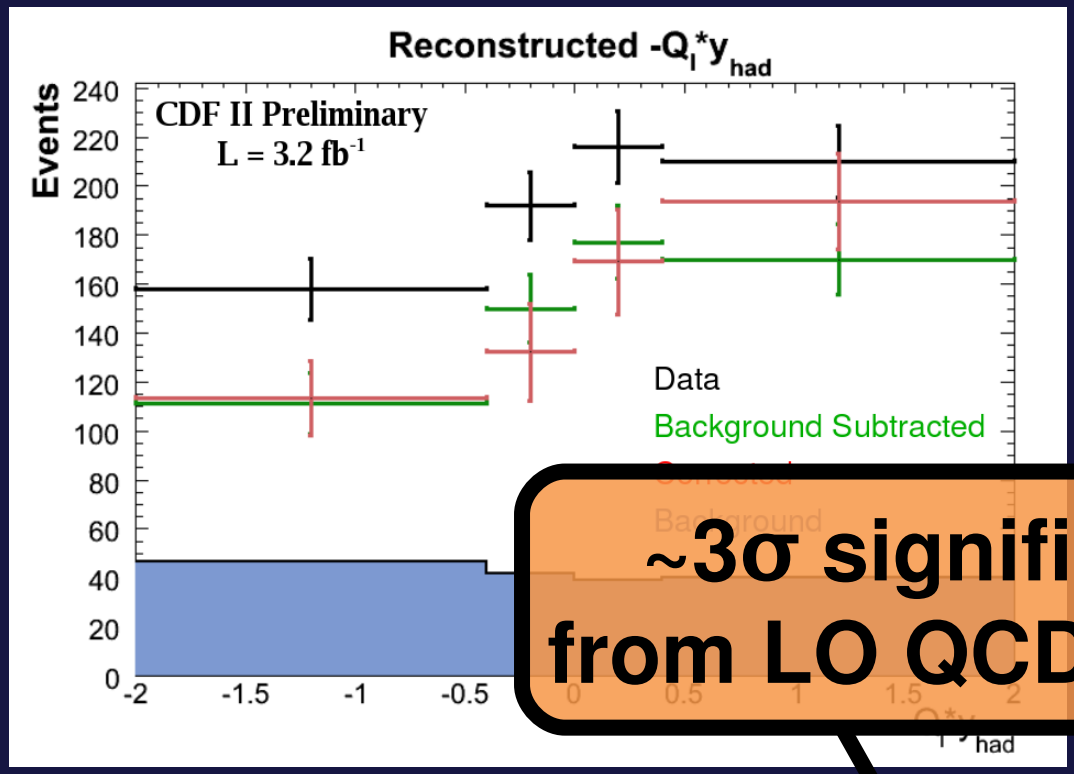


Corrected Asymmetry Measurement



Raw	$A_{fb} = 9.8 \pm 3.6\%$
Bkg-sub	$A_{fb} = 14.1 \pm 4.6\%$
Final Corrected	$A_{fb} = 19.3 \pm 6.5\%$

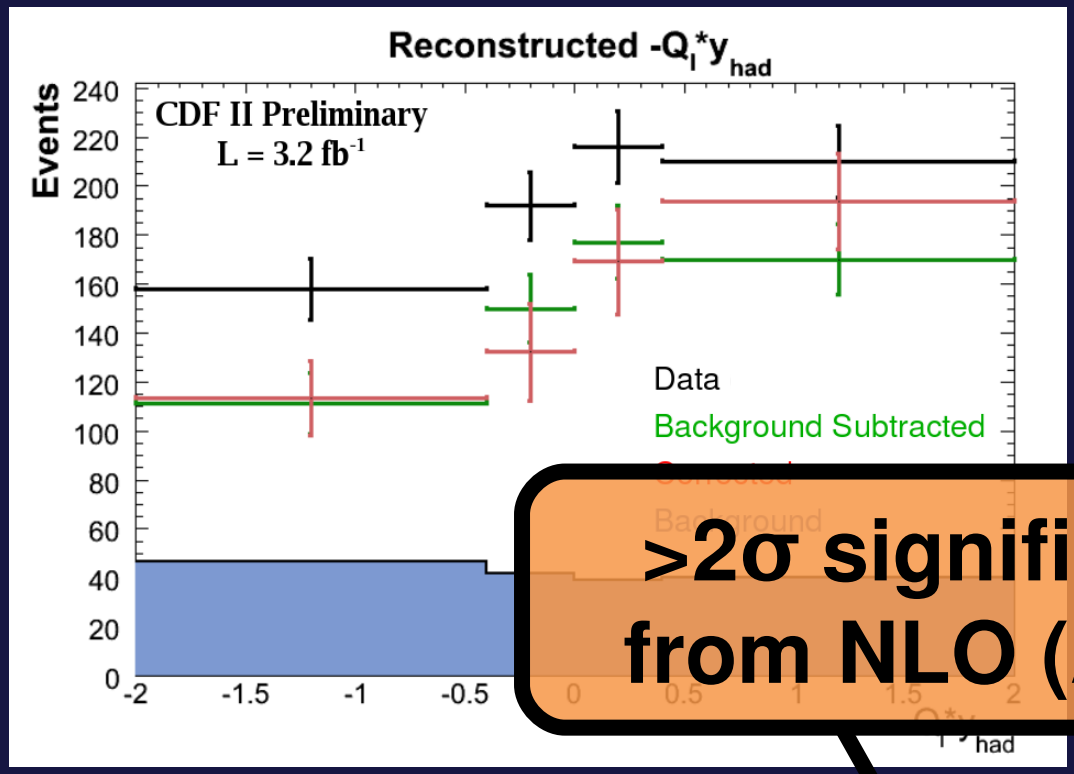
Corrected Asymmetry Measurement



~3σ significance from LO QCD (A=0%)

Raw	$A_{fb} = 9.8 \pm 3.6\%$
Bkg-sub	$A_{fb} = 14.1 \pm 4.6\%$
Final Corrected	$A_{fb} = 19.3 \pm 6.5\%$

Corrected Asymmetry Measurement



>2σ significance from NLO (A~5%)

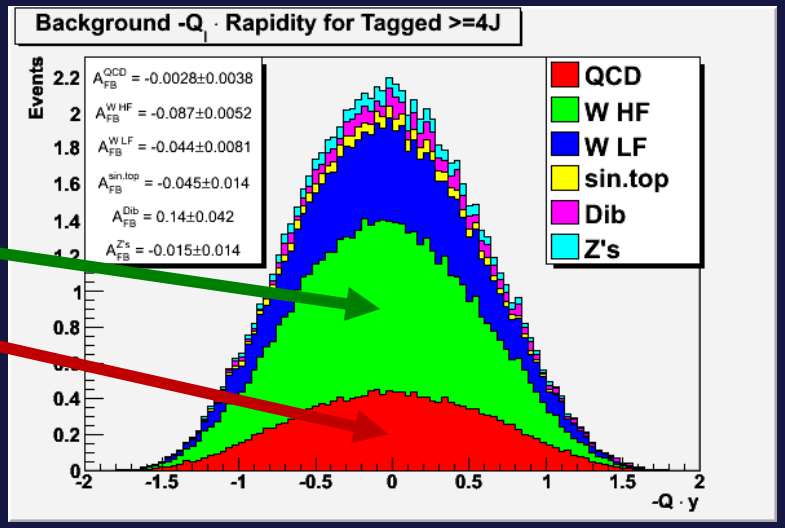
Raw	A_{fb} = 9.8 ± 3.6%
Bkg-sub	A_{fb} = 14.1 ± 4.6%
Final Corrected	A_{fb} = 19.3 ± 6.5%

Background Shape Systematic Uncertainty

Background subtraction is our largest component of the systematic error. We have two main sources: background shape and size.

For the shape uncertainty:

- Take the QCD (or WHF) contribution of the background and rescale it to have the method II number of events.
- Make a distribution using "Reweighted Signal + Modified Bkg"
- Subtract off the original Method II background, unfold, and measure an A_{fb}.
- Compare with nominal value



nominal bkg	QCD	difference	Wbb	difference	new uncertainty
0.187	0.200	0.013	0.178	-0.009	0.013

Sigma is the max abs value of these two differences

Systematic Uncertainties and Final Result

Vary simulated data by ±σ and calculate A_{fb} difference with known sample

	Calc. Uncert.
Background Shape	0.011
Background Size	0.018
ISR/FSR	0.008
JES	0.002
PDF	0.001
MC Generator	0.003
Shape / Unfolding	0.006
Total Uncertainty	0.024

Systematic Errors and Result

Vary simulated data by ±σ and calculate A_{fb} difference with known sample

	Calc. Uncert.
Background Shape	0.011
Background Size	0.018
ISR/FSR	0.008
JES	0.002
PDF	0.001
MC Generator	0.003
Shape / Unfolding	0.006
Total Uncertainty	0.024

Final Corrected A_{fb} = 19.3 ± 6.5 ± 2.4%

Systematic Uncertainties and Final Result

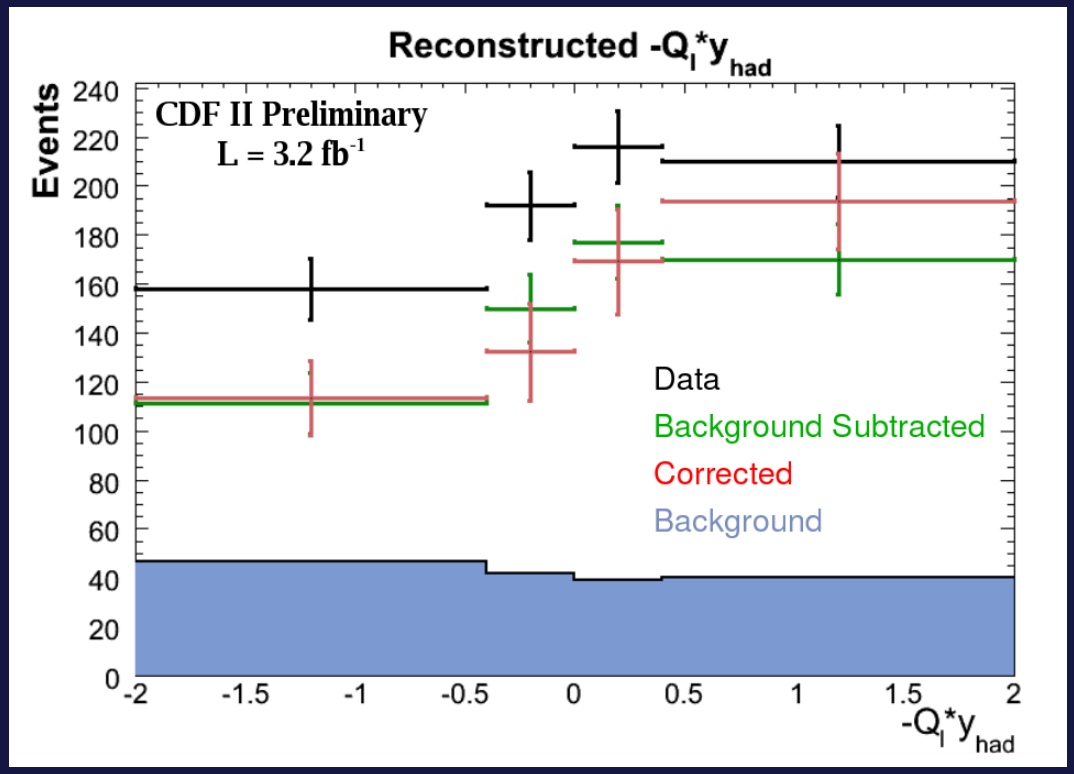
Vary simulated data by ±σ and calculate A_{fb} difference with known sample

	Calc. Uncert.
Background Shape	0.011
Background Size	0.018
ISR/FSR	0.008
JES	0.002
PDF	0.001
MC Generator	0.003
Shape / Unfolding	0.006
Total Uncertainty	0.024

Final Corrected A_{fb} = 19.3 ± 6.5 ± 2.4%

Statistical error dominates total error

Corrected Asymmetry Measurement



Raw	$A_{fb} = 9.8 \pm 3.6\%$
Bkg-sub	$A_{fb} = 14.1 \pm 4.6\%$
Final Corrected	$A_{fb} = 19.3 \pm 6.5\% \pm 2.4\%$

Back to theory…

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta^{\$}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} \Big[g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c \Big] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times \Big[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c \Big] \Big\}$$

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Theoretical Predictions

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

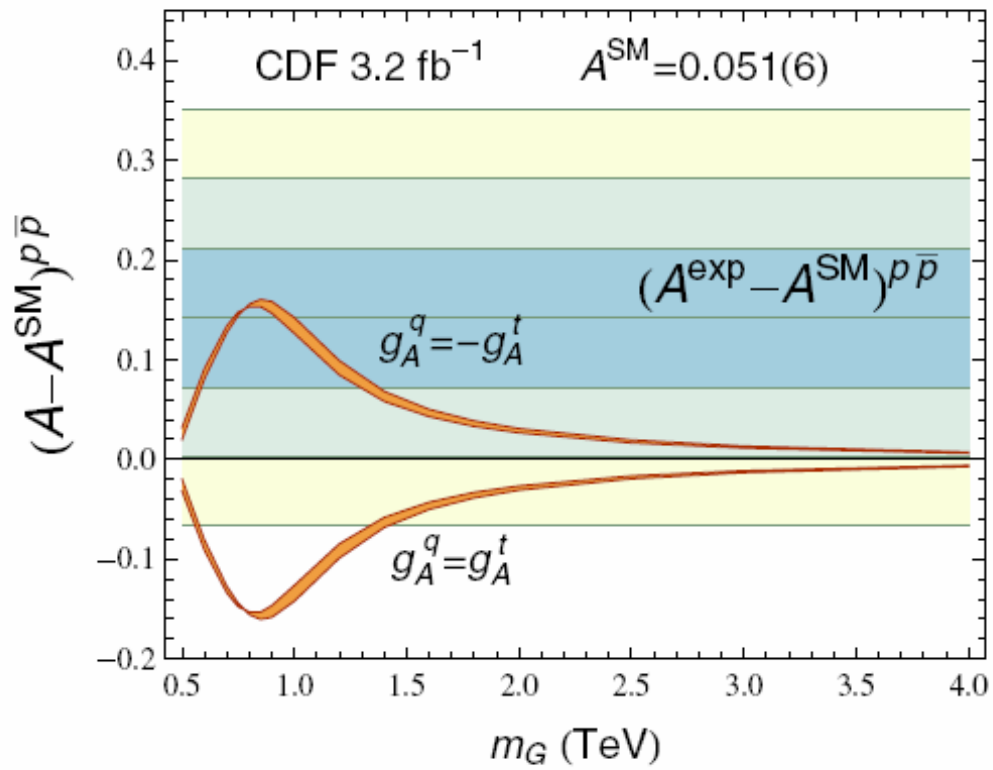


FIG. 1 (color online). Comparison of the axigluon contribution to the top quark charge asymmetry with the 1σ, 2σ, and 3σ contours as a function of the axigluon mass. We also consider the case $g_A^q = -g_A^t = 1$.

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Theoretical Predictions

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$\times [((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

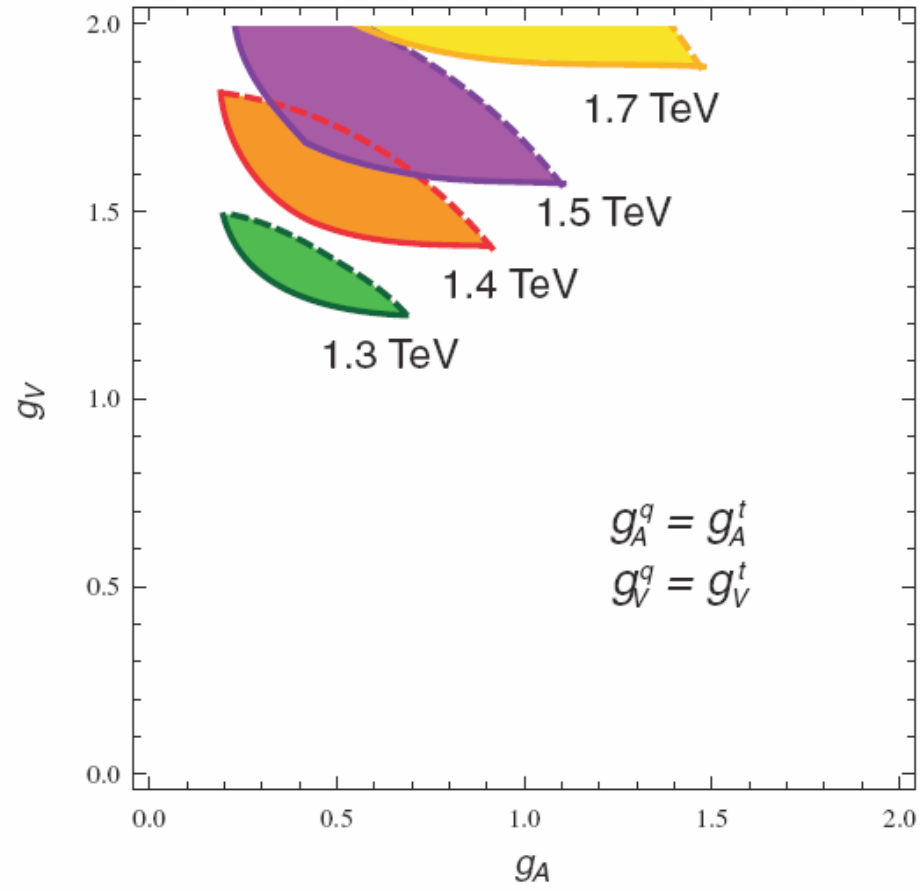


FIG. 2 (color online). Contours at 95% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass for flavor-universal couplings.

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Theoretical Predictions

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2s} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2s(s-m_G^2)}{(s-m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{s^2}{(s-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

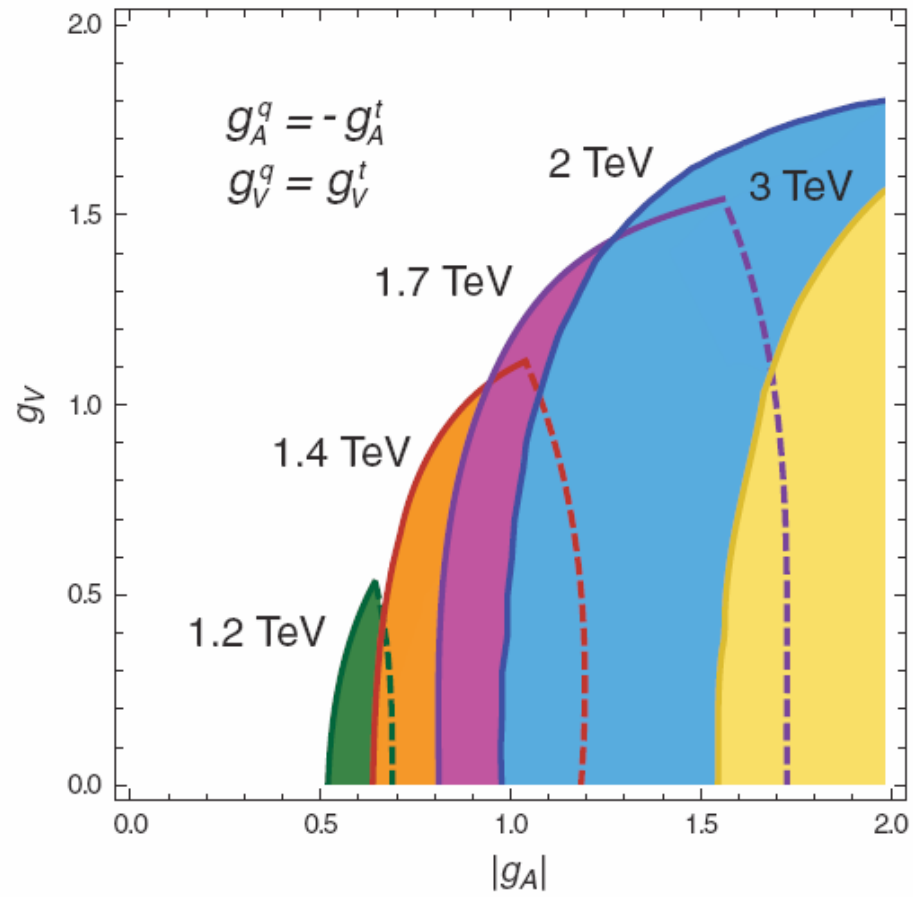


FIG. 3 (color online). Contours at 90% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass and $g_A^q = -g_A^t$.

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Theoretical Predictions

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2s} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2s(s-m_G^2)}{(s-m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{s^2}{(s-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

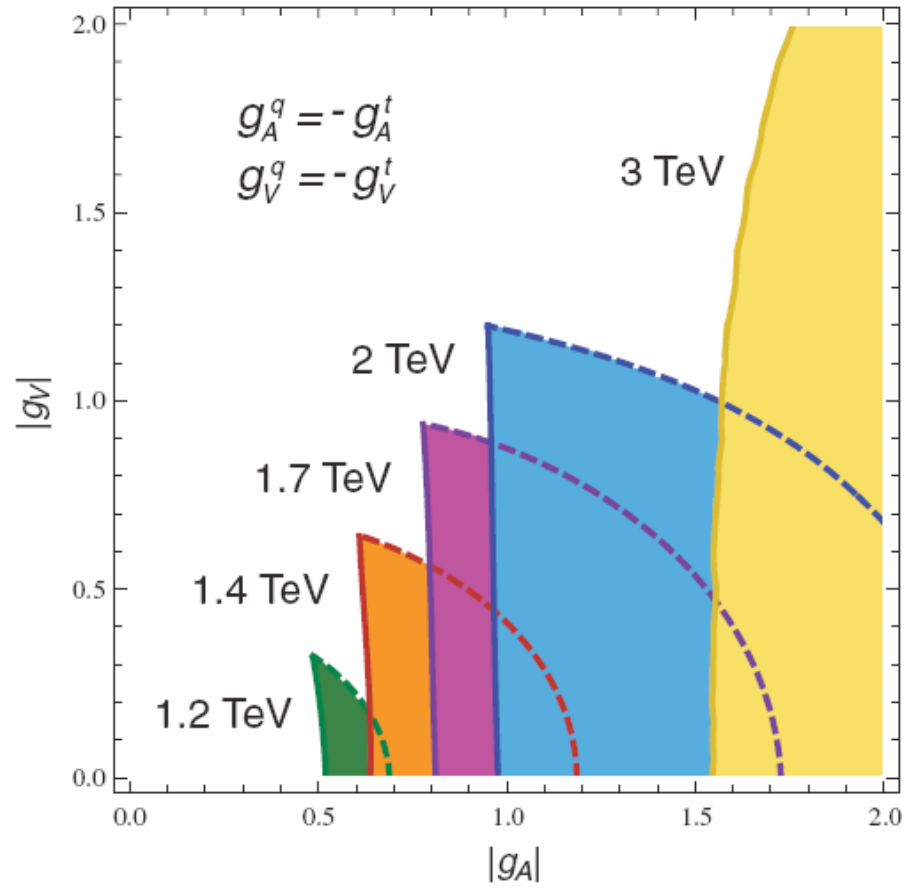


FIG. 4 (color online). Contours at 90% C.L. as a function of the vector and axial-vector couplings for different values of the resonance mass and $g_V^q = -g_V^t$, $g_A^q = -g_A^t$.

*Ferrario and Rodrigo – Physical Review D **80**, 051701(R) (2009)*

Theoretical Predictions

$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\theta} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \Big\{ 1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s}-m_G^2)}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q g_V^t (1 + c^2 + 4m^2)$$

$$+ 2 g_A^q g_A^t c] + \frac{\hat{s}^2}{(\hat{s}-m_G^2)^2 + m_G^2\Gamma_G^2}$$

$$[((g_V^q)^2 + (g_A^q)^2)((g_V^t)^2 (1 + c^2 + 4m^2)$$

$$+ (g_A^t)^2 (1 + c^2 + 4m^2)) + 8 g_V^q g_A^q g_V^t g_A^t c] \Big\}$$

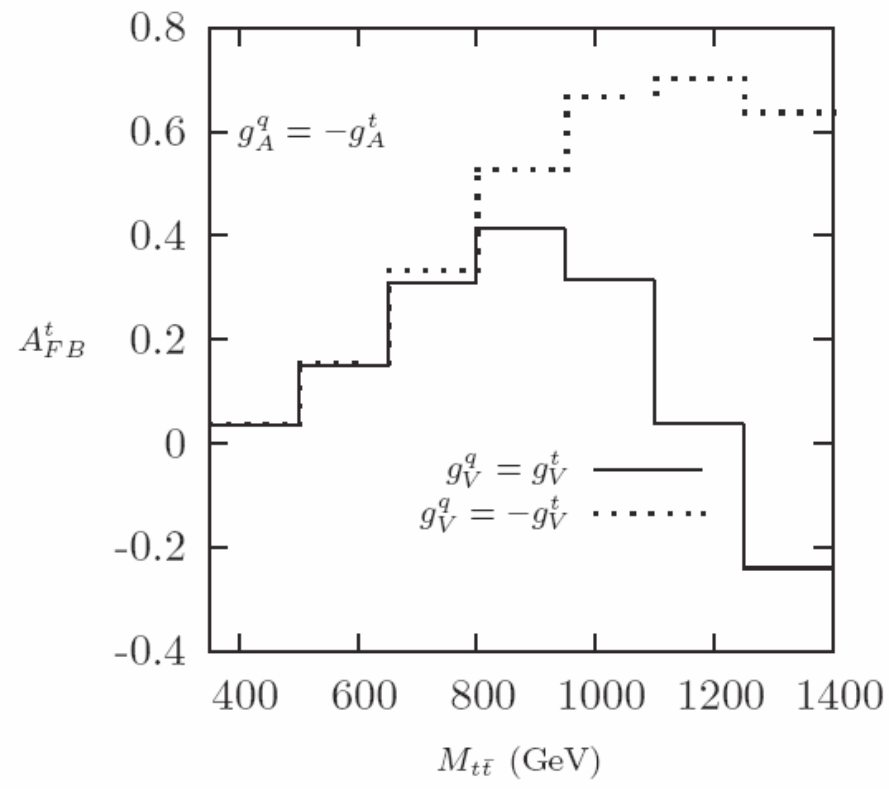


FIG. 2: A^t_{FB} vs. $M_{t\bar{t}}$ with $M_{t\bar{t}}$ integrated over each 150 GeV of $M_{t\bar{t}}$ using the benchmark point, $M_G = 1525$ GeV, $g_V^q = -0.577 g_s$ and $g_A^q = -g_A^t = -1.155 g_s$. The solid line corresponds to our model with $g_V^q = g_V^t$ and dashed line is a comparison plot with $g_V^q = -g_V^t$, as explained in the text.

Frampton, Shu, and Wang – [hep-ph] arxiv:0911.2955 IPMU-09-0135

Future Plans

- dA/dM (A_{fb} vs M_{tt})
- dA/dy (A_{fb} as a function of y)
- increase data set
- understand the systematic uncertainties better
- submit thesis!

Conclusions

- Previous results (1.9 fb^{-1}):

  A_{fb} cos(θ) method: $\mathbf{A_{fb}^{lab} = 17 \pm 8\%}$

- Current results (3.2 fb^{-1}):

  A_{fb} -Q*y_{hadtop} method: $\mathbf{A_{fb}^{lab} = 19.3 + 6.5 + 2.4\%}$

- Are measured values are higher than the 5% SM prediction, but consistent within ~2 sigma

and while our current asymmetry measurement is quite exciting…

Stay tuned for more exciting asymmetries!

The End