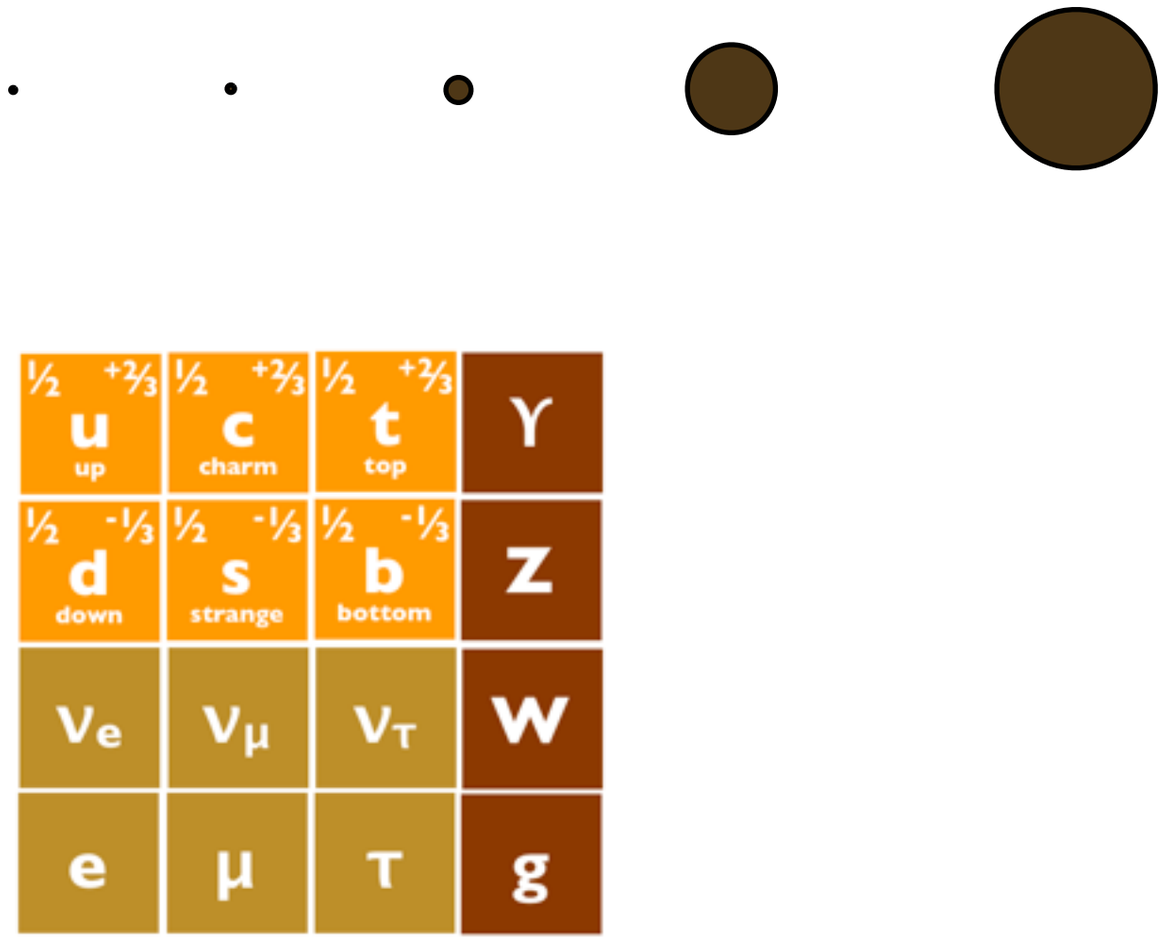
The Forward Backward Asymmetry in Top Production

Tom Schwarz
University of California Davis

On behalf of the CDF and D0 Collaborations at the Tevatron

FPCP 2011
Kibbutz Maale Hachamisha, Israel

up	down	strange	charm	bottom	top
3 MeV	*7 MeV*	*110 MeV*	*1.3 GeV*	*4.3 GeV*	*173 GeV*



Area ∝ Mass

Coupling to Higgs

Top Mass

$$y_t = \sqrt{2} \cdot \frac{m_t}{v}$$

Higgs Vacuum Expectation

Average Energy in the Higgs Field

Coupling to Higgs

173 GeV

$$y_t = \sqrt{2} \cdot \frac{m_t}{v}$$

243 GeV

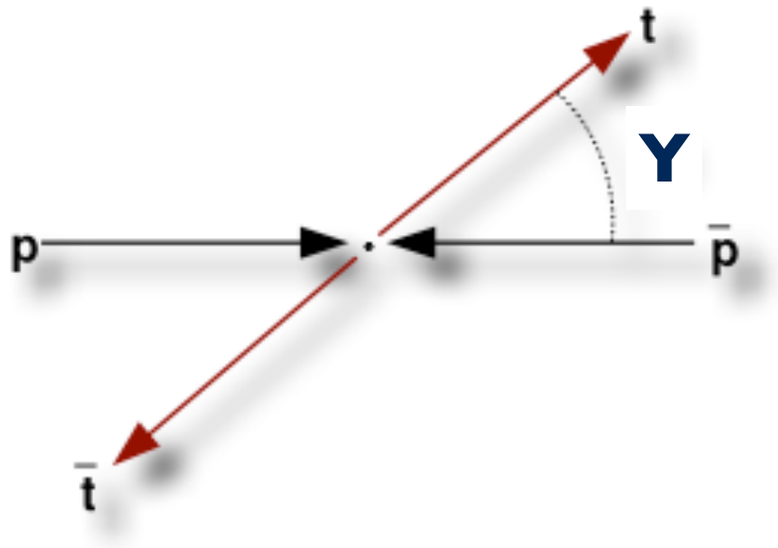
Coupling to Higgs

173 GeV

$$y_t = \sqrt{2} \cdot \frac{m_t}{v} \approx 1.0$$

243 GeV

Top Quark Forward Backward Asymmetry



$$A_{FB} = \frac{F - B}{F + B}$$

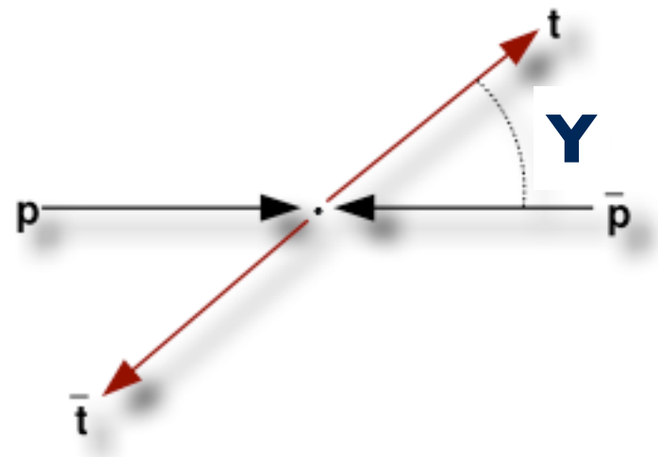
Why Measure It?

- **Test of discrete symmetries of the strong interaction**

$$A_{FB} = \frac{N_{Y>0} - N_{Y<0}}{N_{Y>0} + N_{Y<0}}$$

- **NLO QCD predicts small (~6%) asymmetry from $q\bar{q} \rightarrow t\bar{t}$**

- **New physics can show up: Big Gluons with axial vector coupling**



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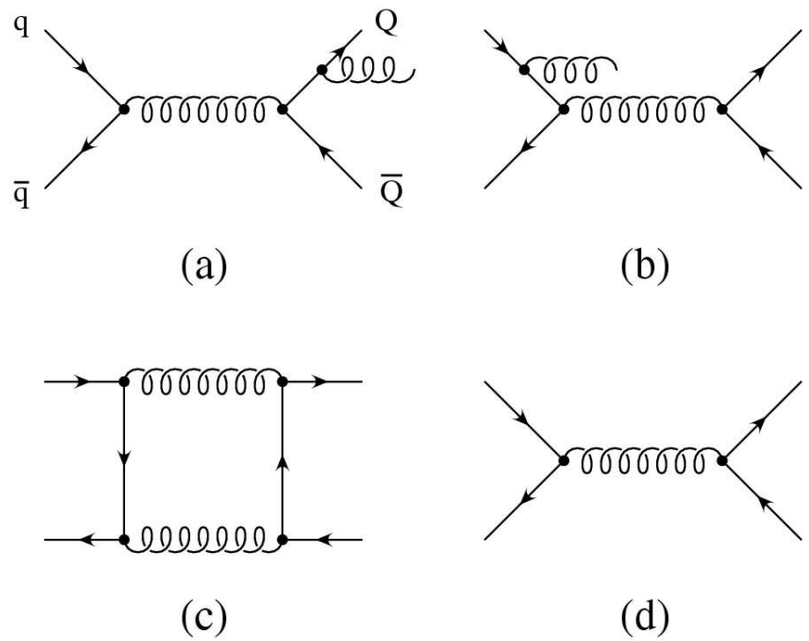

Kuhn, Rodrigo
PRL 81,89 (1998)

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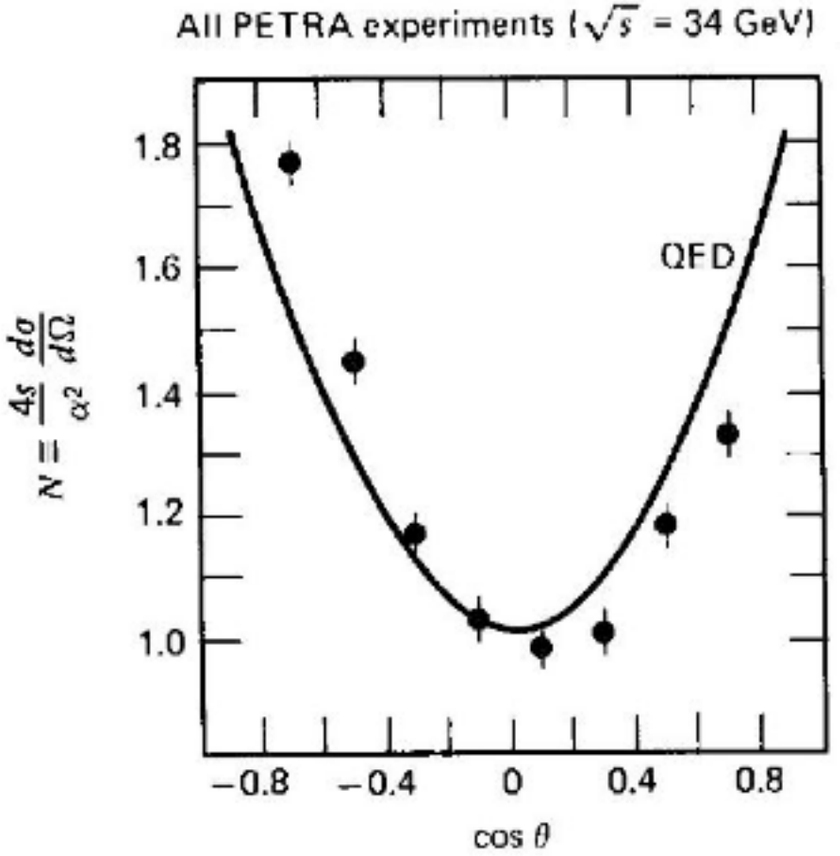


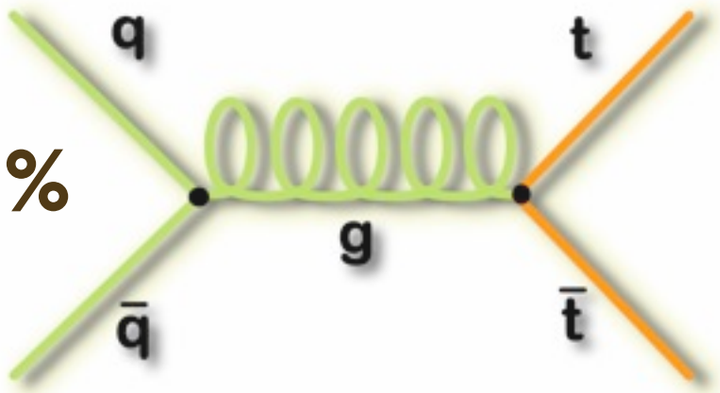
Method

- **Extract $t\bar{t}$ events from data collected at CDF**
- **Reconstruct the production angle of top in these events**
- **Correct for any distortion from the detector, background processes, and the method of reconstructing the angle**
- **Measure A_{FB}**

Production & Decay

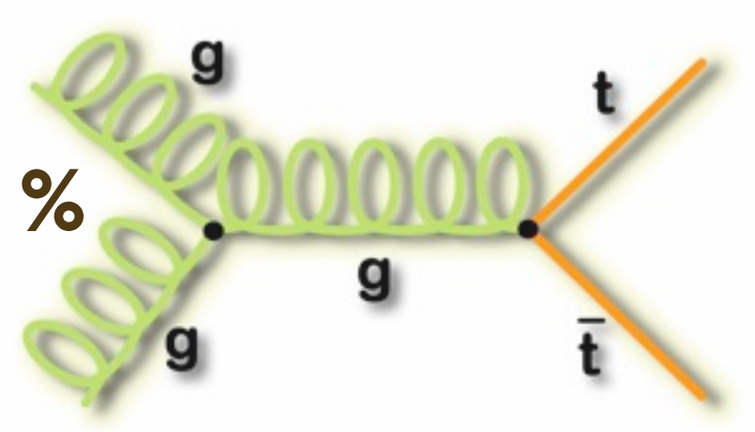
Production

~ 85 %

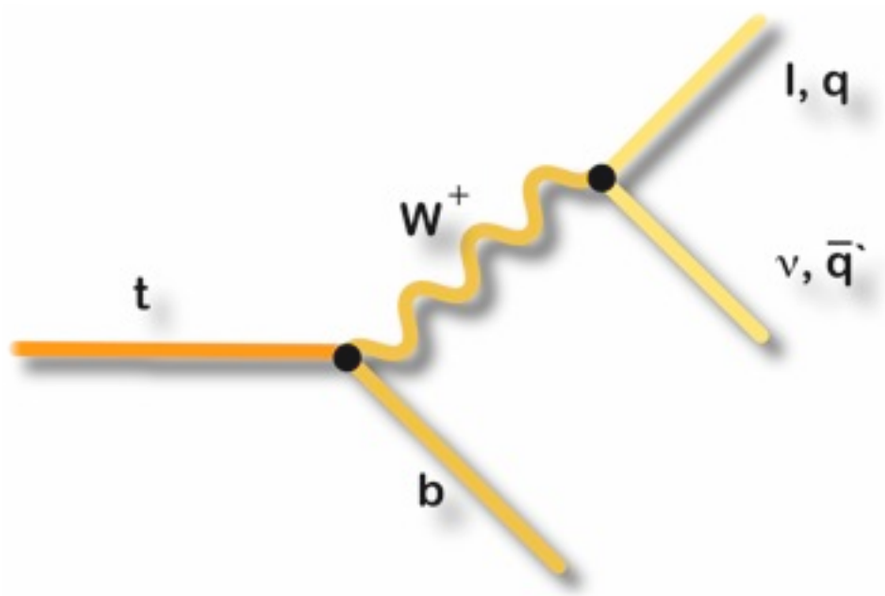


$\sigma_{tt}^{SM} = 7.5$ pb

~ 15 %

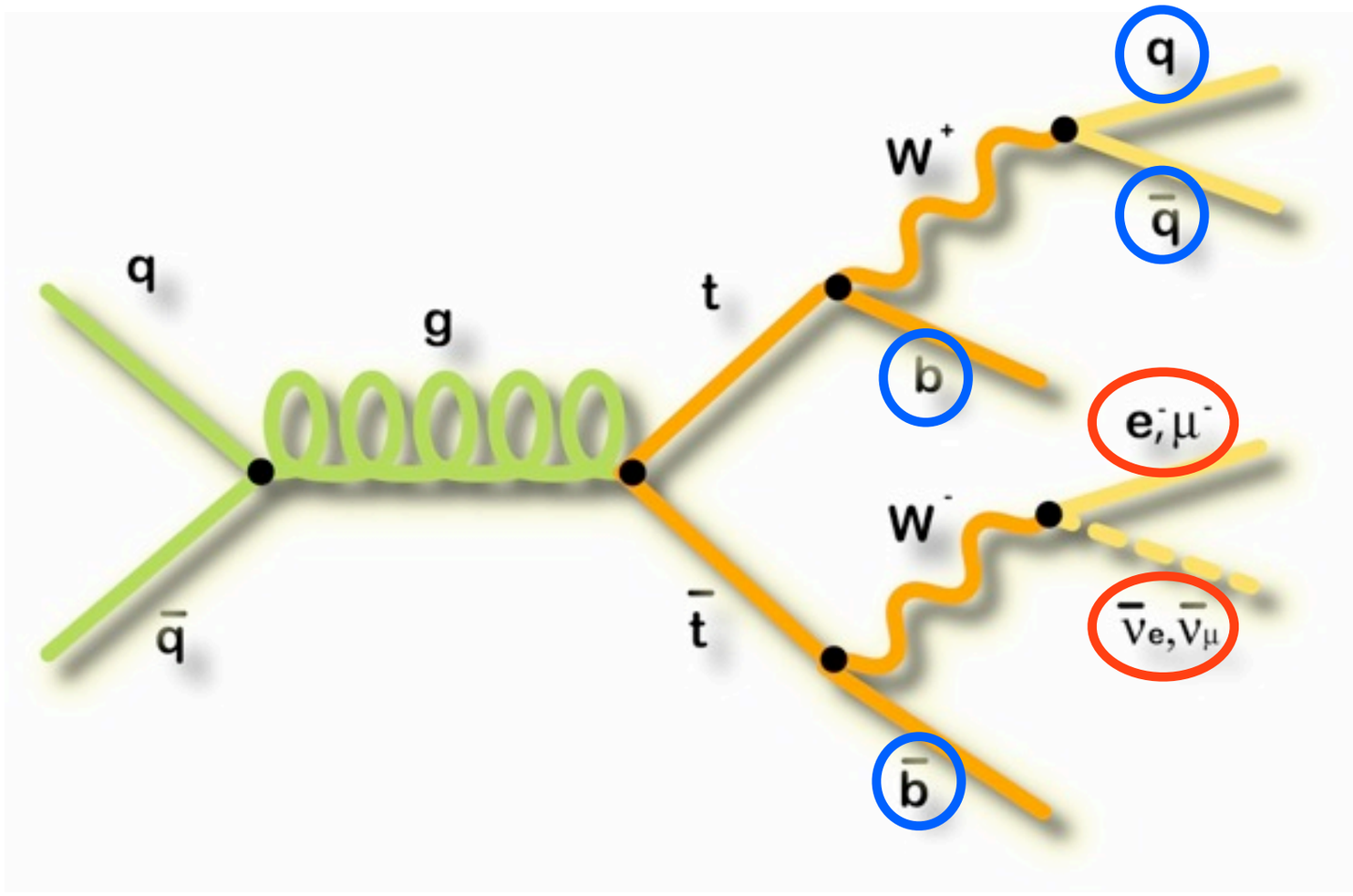


Decay



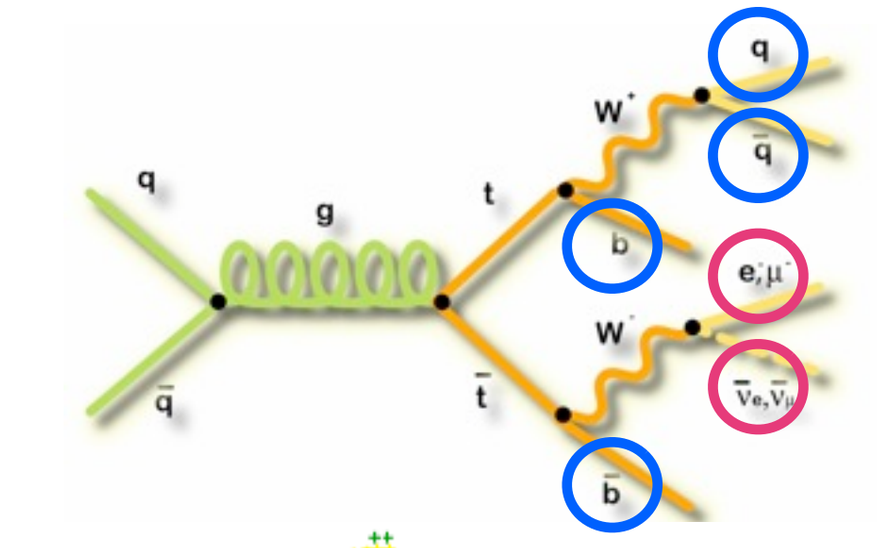
~100 %

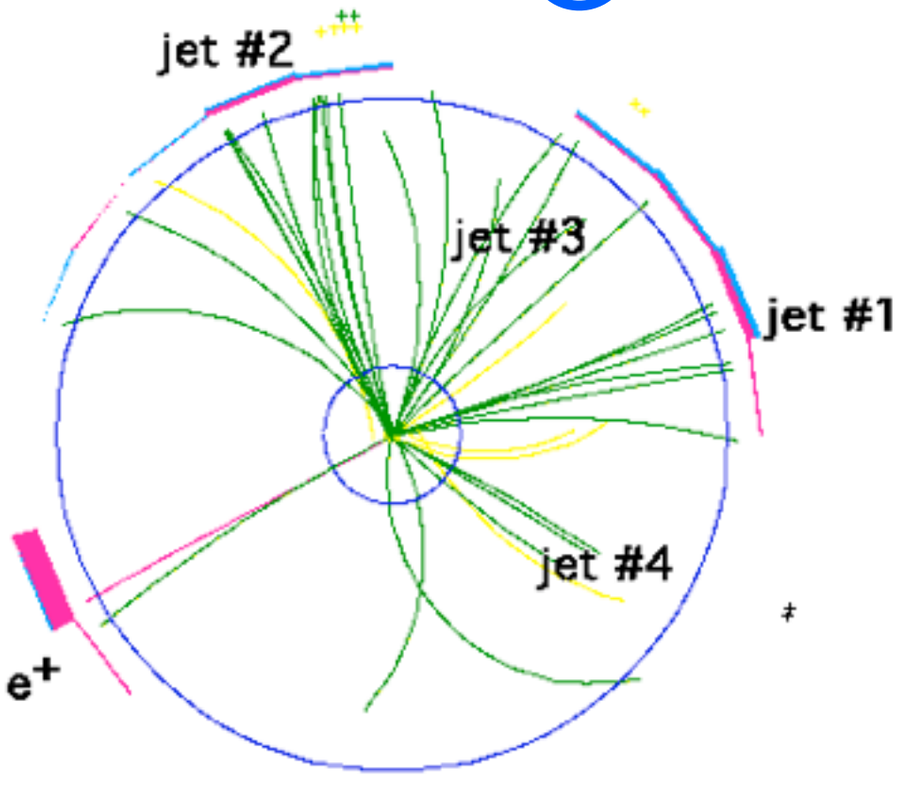
Production & Decay



One Lepton, One Neutrino, and 4 Quarks

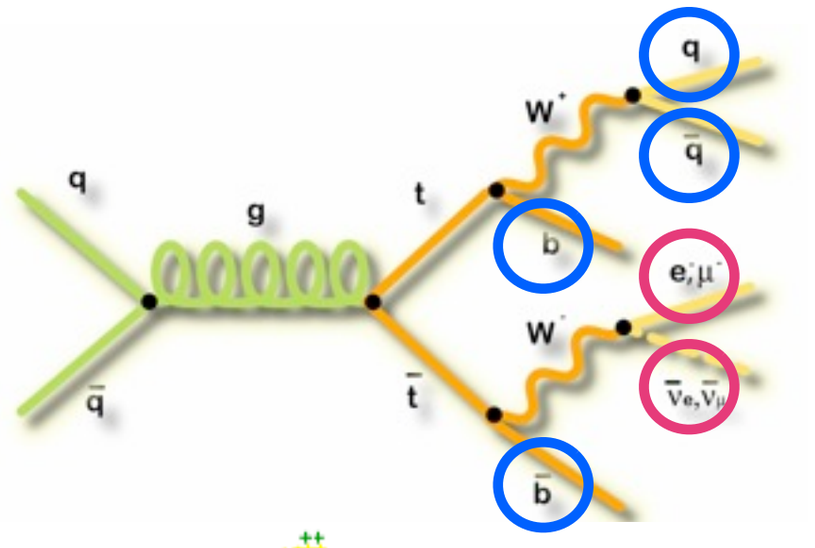
Finding Top



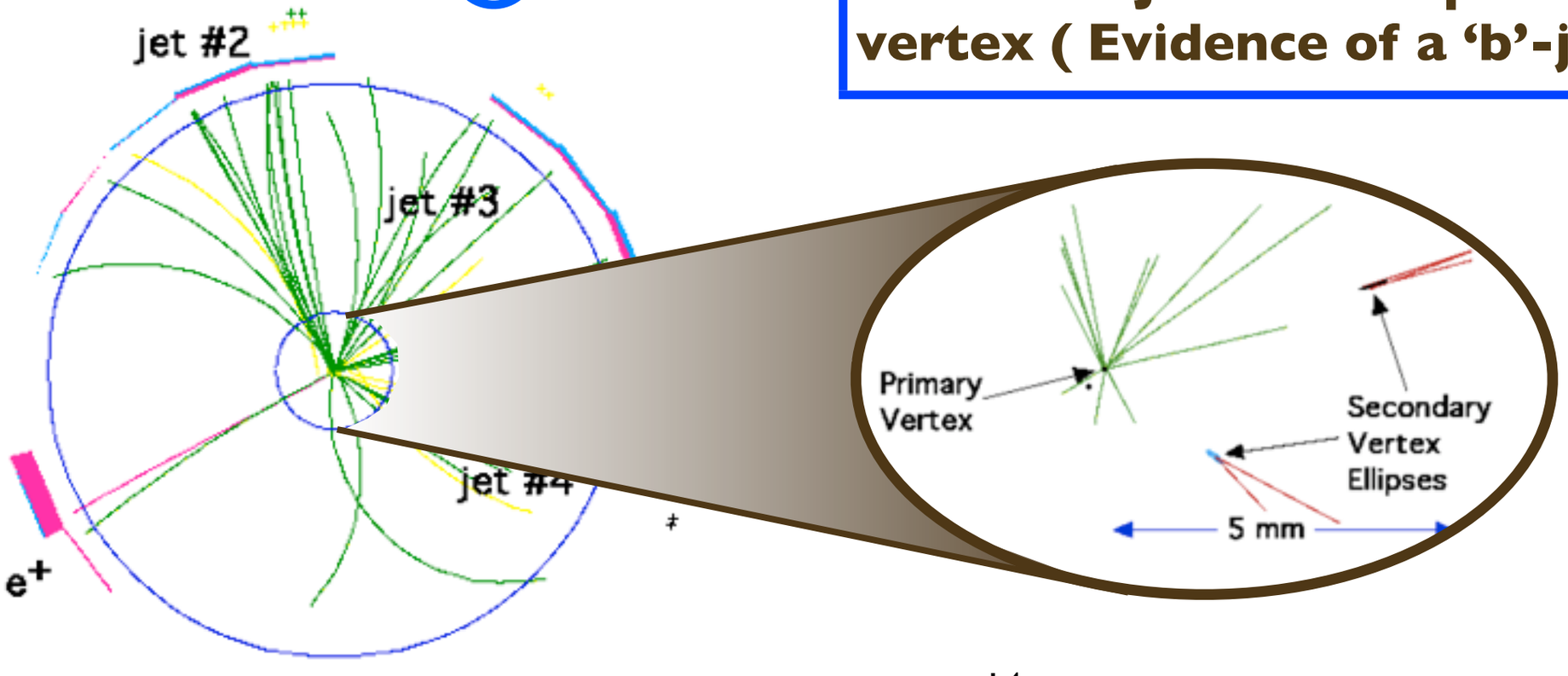


1 Electron or Muon ($E_T \geq 20$ GeV, $\|\eta\| < 1.1$)
Large "Missing" Energy (Et $\geq$ 20 GeV)
$\geq$ 4 Jets (Et $\geq$ 20 GeV, $\|\eta\| < 2.0$)
At least 1 Jet with displaced secondary vertex (Evidence of a 'b'-jet)

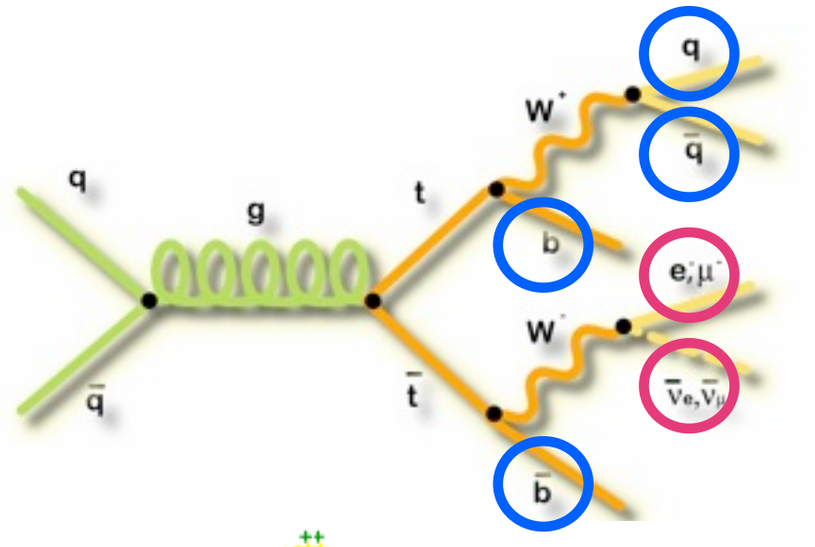
Finding Top

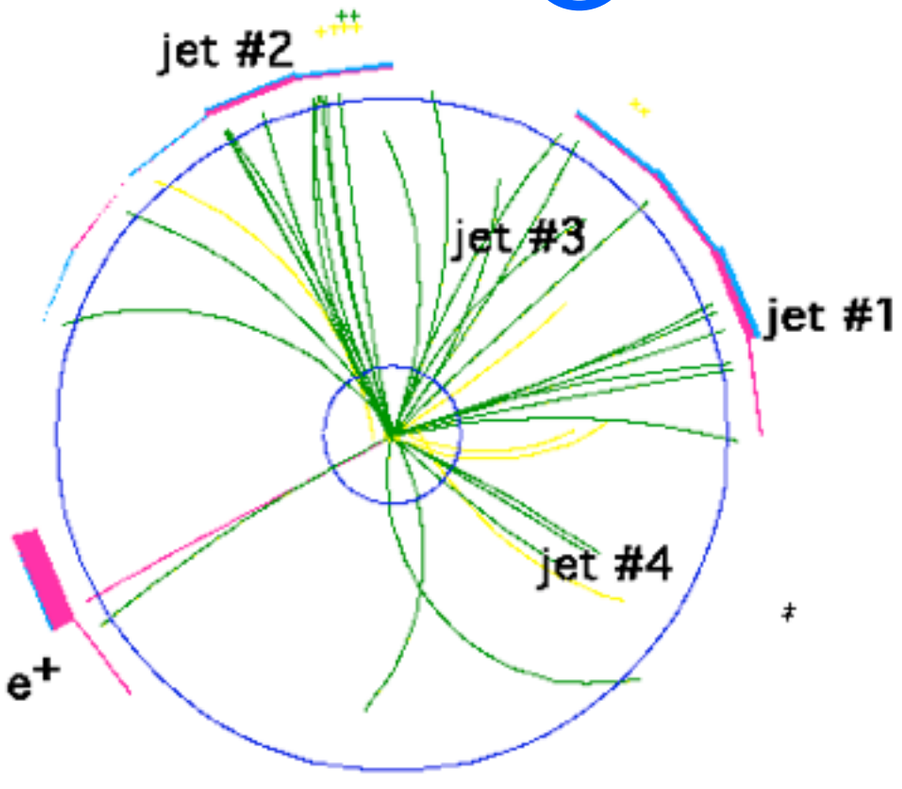


- **1 Electron or Muon ($E_T \geq 20$ GeV, $|\eta| < 1.1$)**
- **Large "Missing" Energy (Et ≥ 20 GeV)**
- **≥ 4 Jets (Et ≥ 20 GeV, $|\eta| < 2.0$)**
- **At least 1 Jet with displaced secondary vertex (Evidence of a 'b'-jet)**



Finding Top





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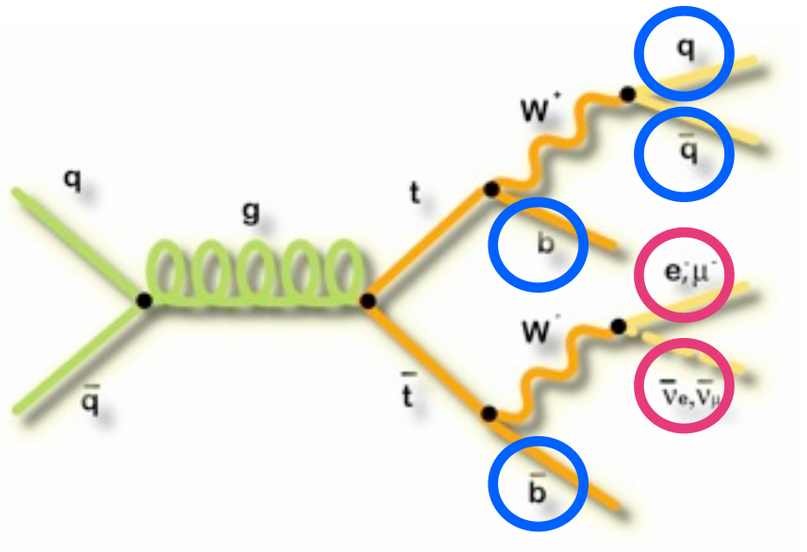
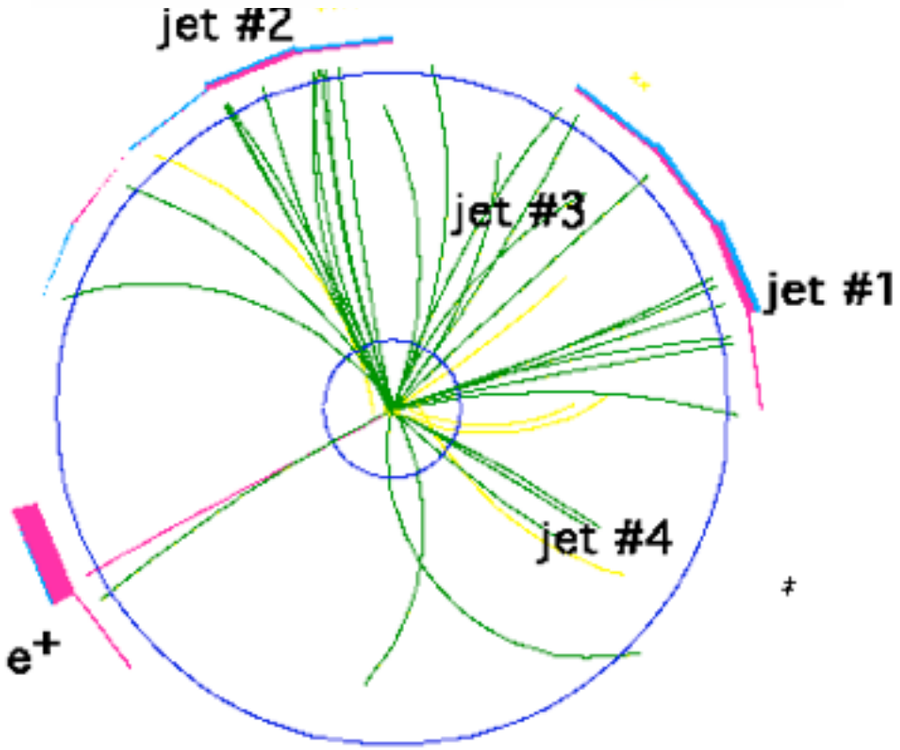
Large "Missing" Energy (Et $\geq$ 20 GeV)
$\geq$ 4 Jets (Et $\geq$ 20 GeV, $\|\eta\| < 2.0$)
At least 1 Jet with displaced secondary vertex (Evidence of a 'b'-jet)

1300 Events (5.3 fb^{-1})
20 % Background

Reconstructing the Top Direction





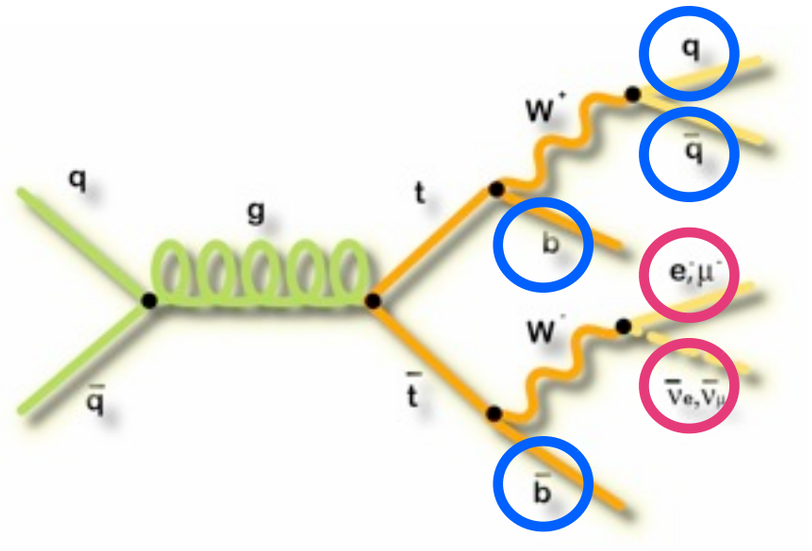
- Reconstruct the top direction from the observables in the detector

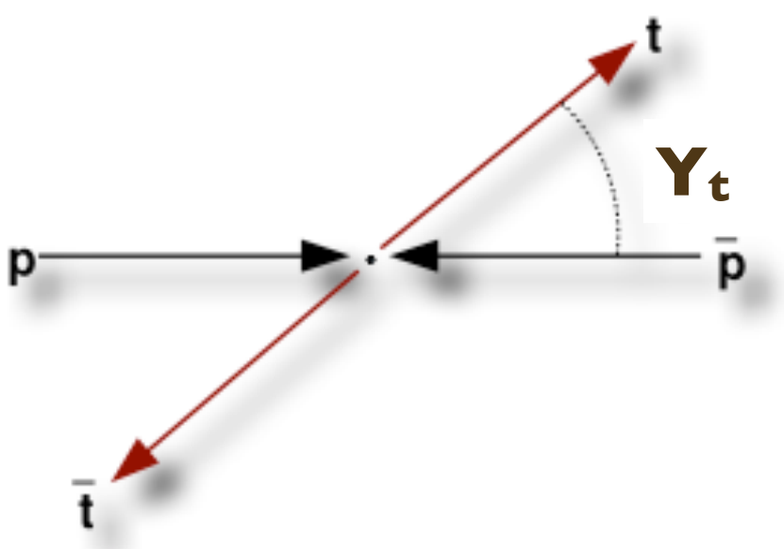
- Algorithm used to match jets to partons → just add 4-vectors to get top direction

- We use the rapidity difference (ΔY) of t→lνb and t→jjb, which is proportional to Y_t in $t\bar{t}$ frame

$$Y_t \propto q_{lepton} \cdot \Delta Y$$

Reconstructing the Top Direction





- Reconstruct the top direction from the observables in the detector
- Algorithm used to match jets to partons → just add 4-vectors to get top direction
- We use the rapidity difference (ΔY) of t→lvb and t→jjb, which is proportional to Y_t in $t\bar{t}$ frame

$$Y_t \propto q_{lepton} \cdot \Delta Y$$

Measurement

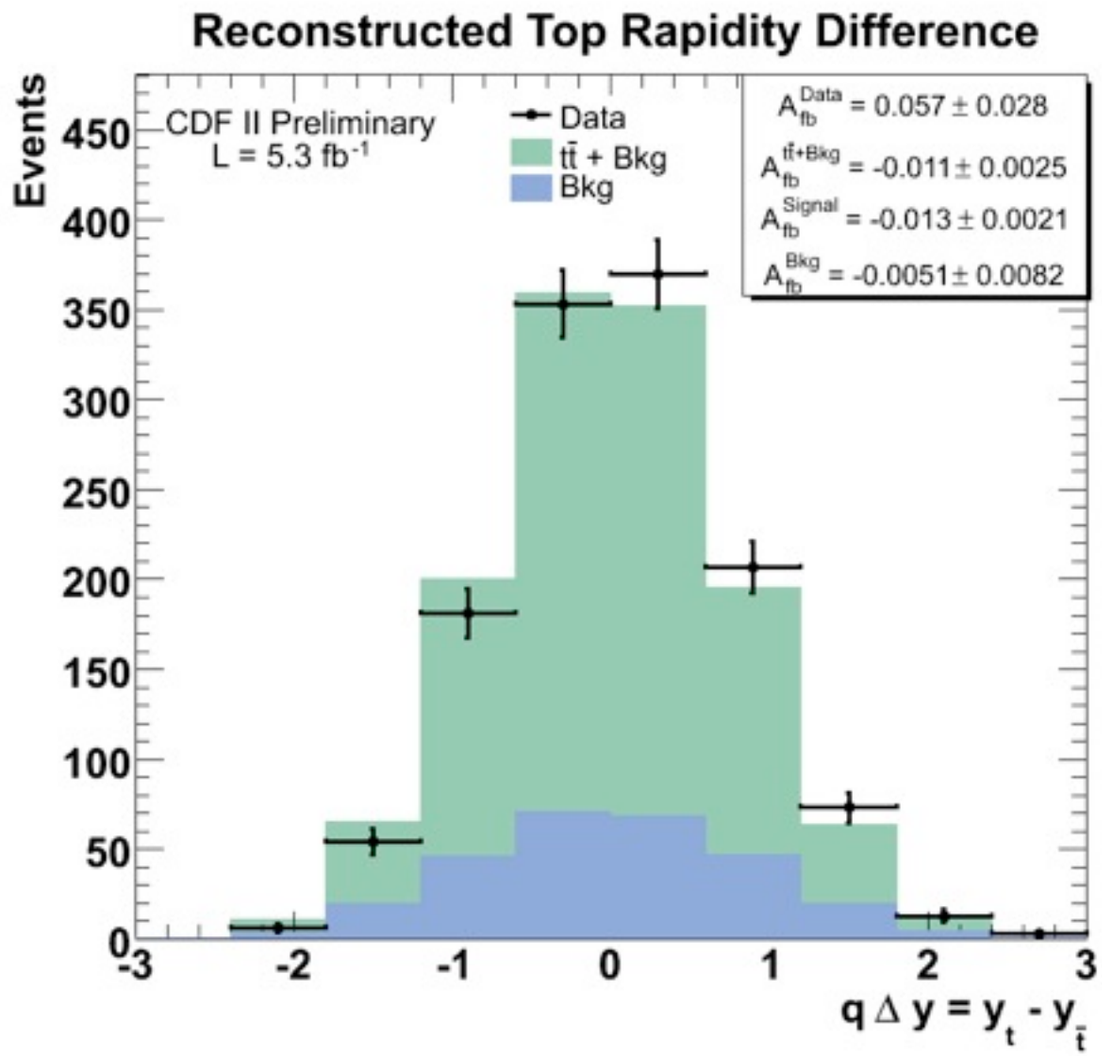
$A_{FB} = 16 \pm 7_{stat} \pm 2_{syst}$ %

5.3 fb^{-1}

Directly comparable to SM

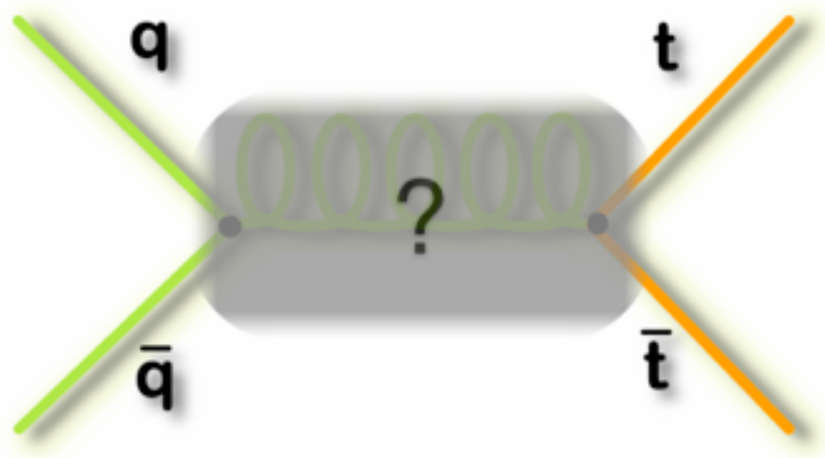
$A_{FB}^{Theory} = 6 \pm 1$ %

Kuhn, Rodrigo PRL 81,89 (1998)

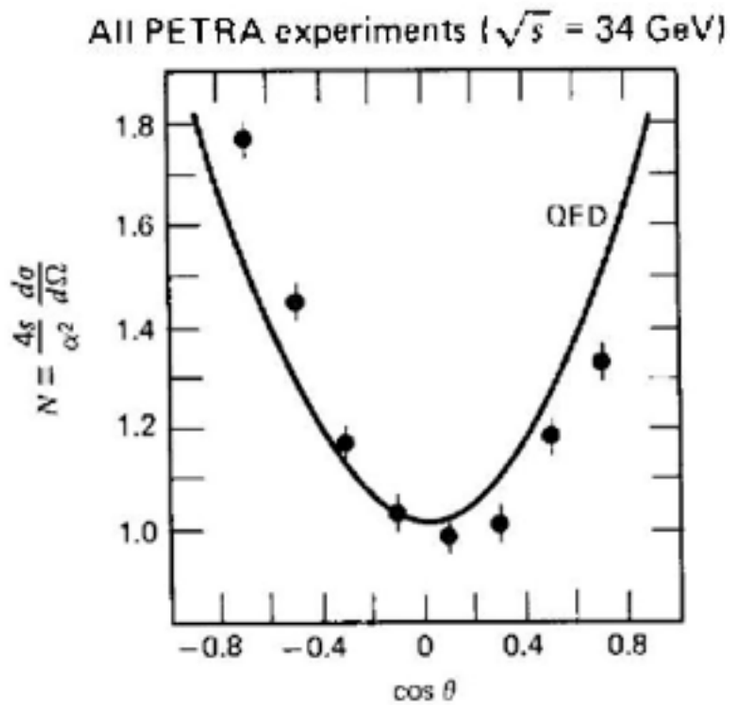


$M_{t\bar{t}}$ Dependence

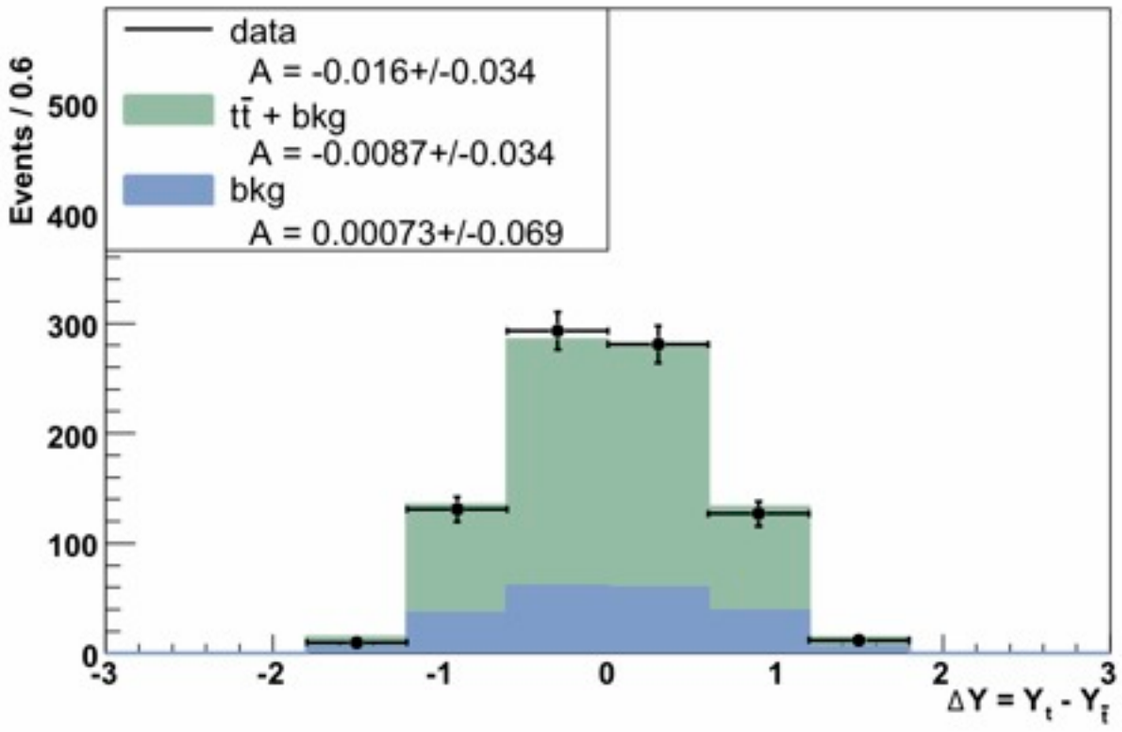
- **A_{FB} could increase at higher energy due to new production mechanisms**

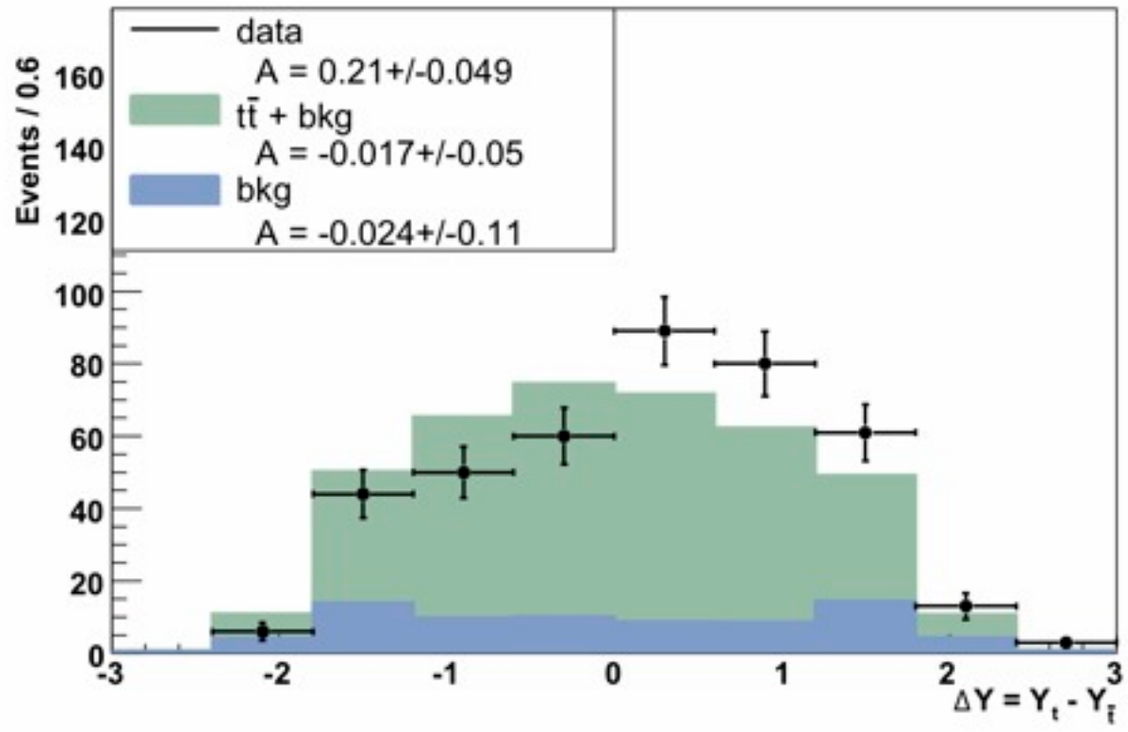


- **Study the asymmetry vs. the mass of the $t\bar{t}$ system ($M_{t\bar{t}}$)**
- **Simply divide sample into high/low $M_{t\bar{t}}$**
- **Use 450 GeV ➜ based on MC studies**



$M_{t\bar{t}}$ Dependence





	Inclusive	M < 450 GeV	M > 450 GeV
Data	5.7 ± 2.8 %	-1 ± 3 %	21 ± 5 %
SM MC	2 ± 0.4 %	1 ± 0.6 %	3 ± 0.7 %

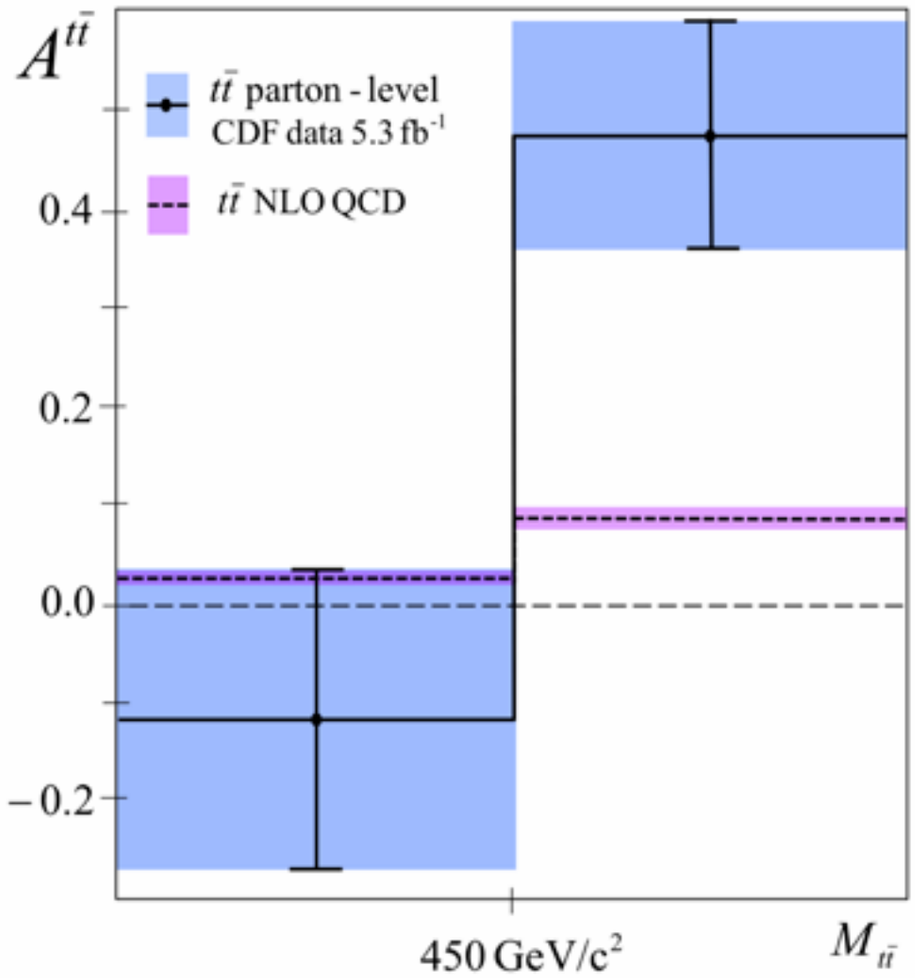
$M_{t\bar{t}}$ Dependence

- **Unfold M_{tt} dependence back to parton level**

A_{FB} = 48 ± 11$_{stat+syst}$ %

5.3 fb^{-1}

A_{FB}^{Theory} = 9 ± 1 %

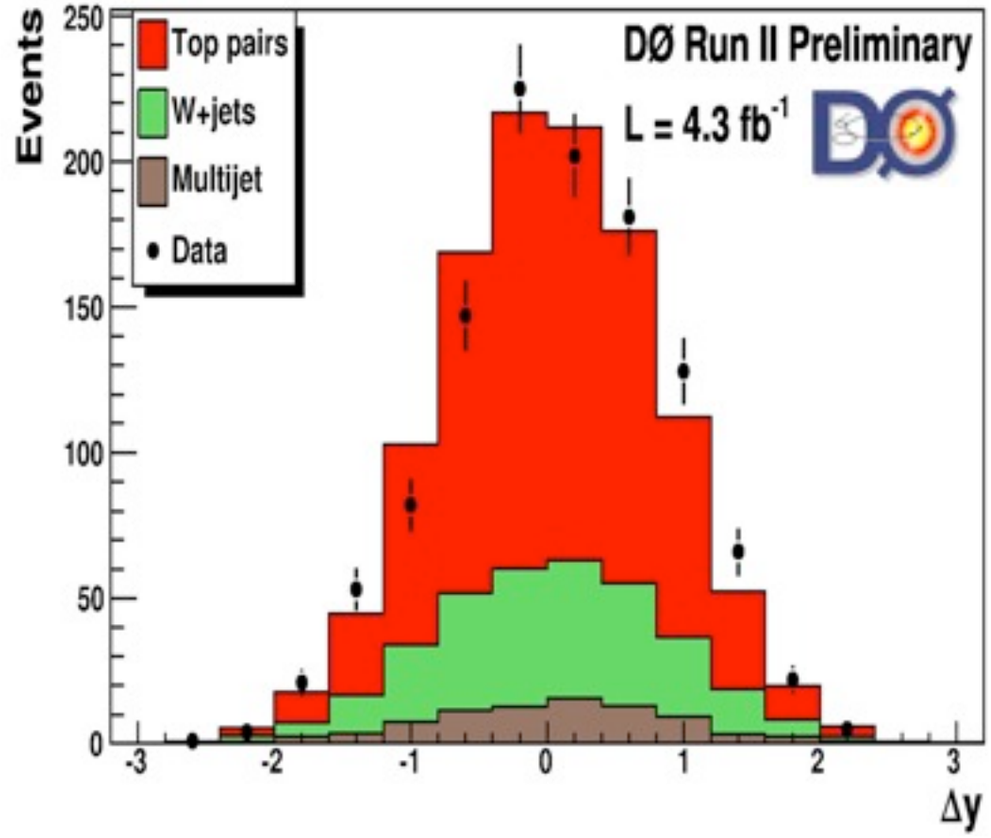


Other Signs?

- DØ collaboration has also performed this measurement

- DØ compares the result to the SM as seen by the detector (only corrects for backgrounds)

$A_{FB}^{data-bkg} = 8 \pm 4_{stat+sys}$ %



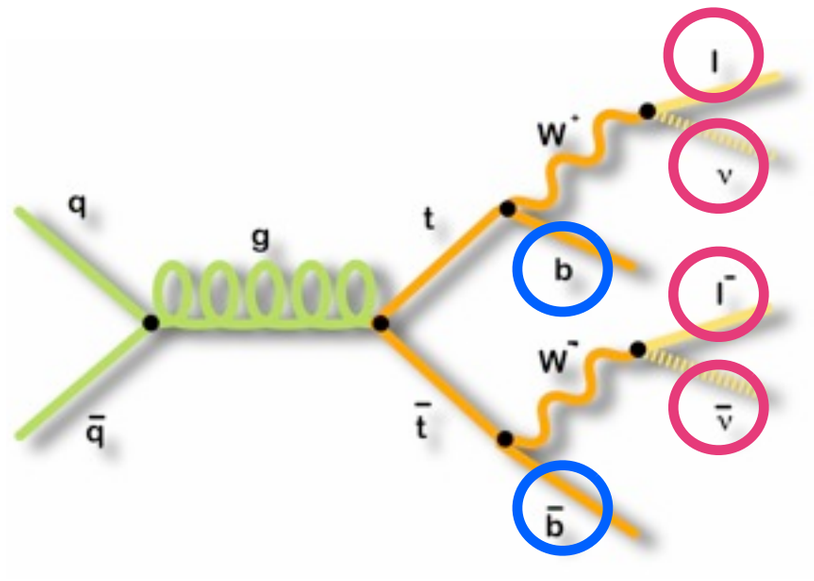
$A_{FB}^{mc@nlo} = 1^{+2.0}_{-1.0}$ %

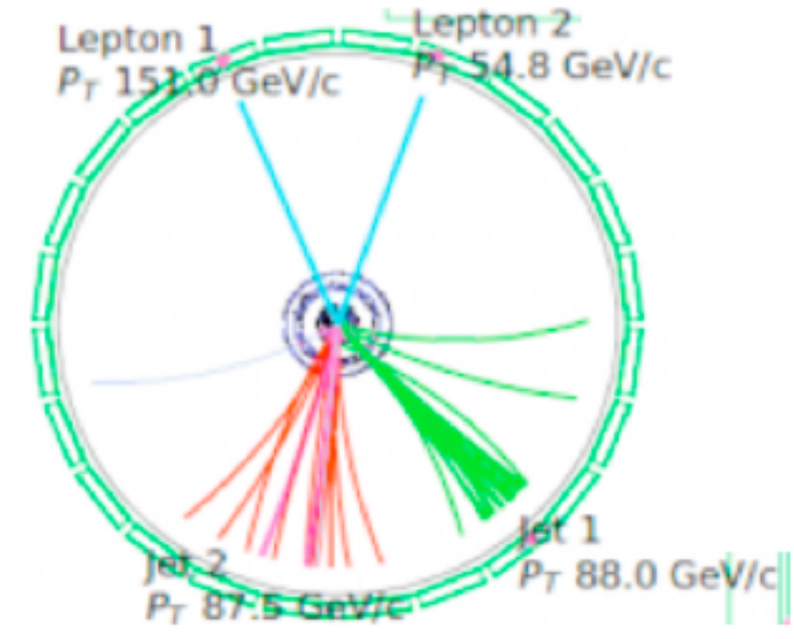
$A_{FB}^{CDF} = 7.5 \pm 3.7$ %

A_{FB} in Dileptons

- **Alternative channel to previous measurement in single lepton+jets events**

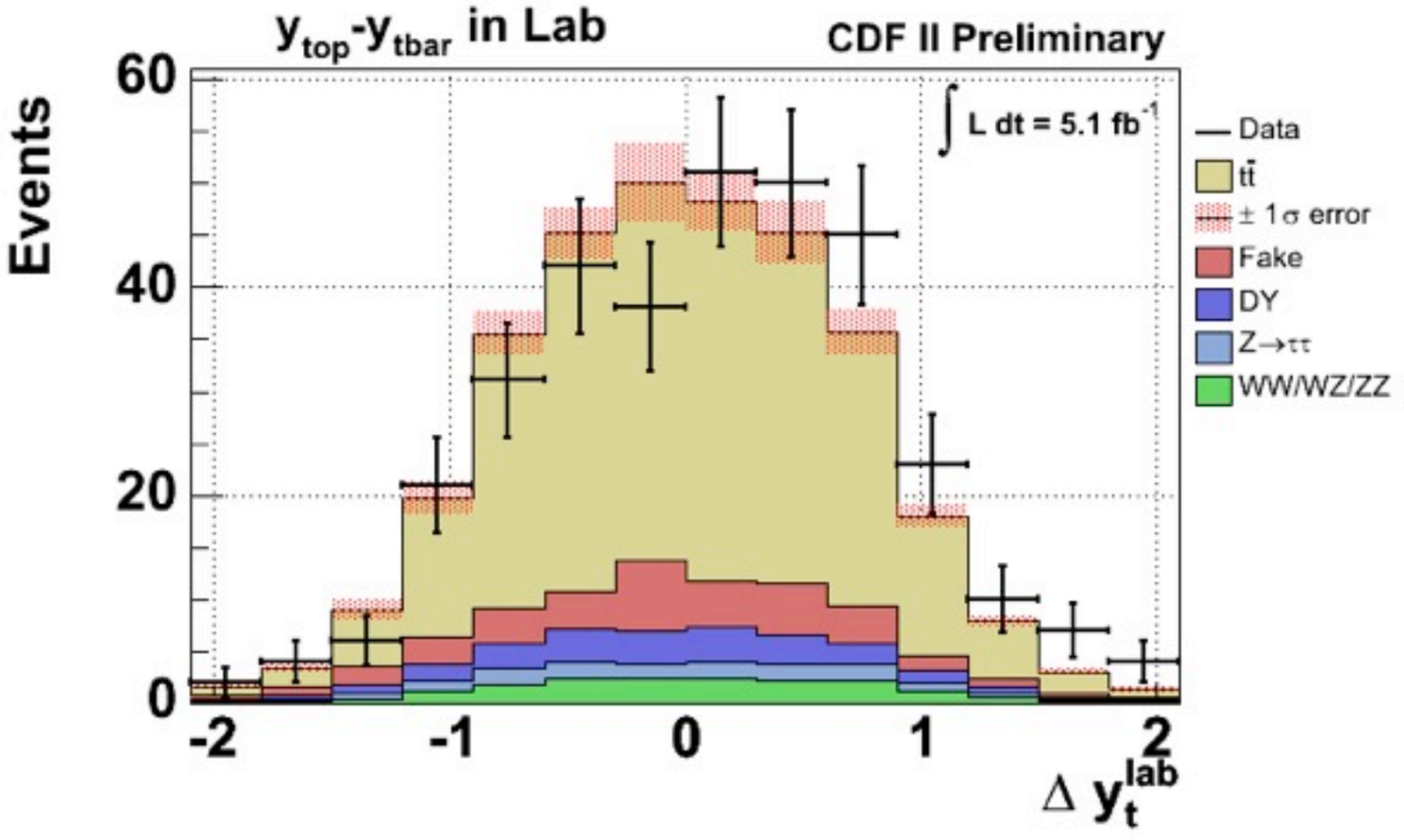
- **Independent events using different reconstruction algorithm**





2 Leptons ($E_T \geq 20$ GeV, $\|\eta\| < 1.1$)
Large "Missing" Energy ($E_T \geq 50$ GeV)
$\geq$ 2 Jets ($E_T \geq 15$ GeV, $\|\eta\| < 2.5$)
$\sum E_T$ (jets, leptons) > 200 GeV

A_{FB} in Dileptons



$A_{FB} = 42 \pm 15_{stat} \pm 5_{syst}$ %

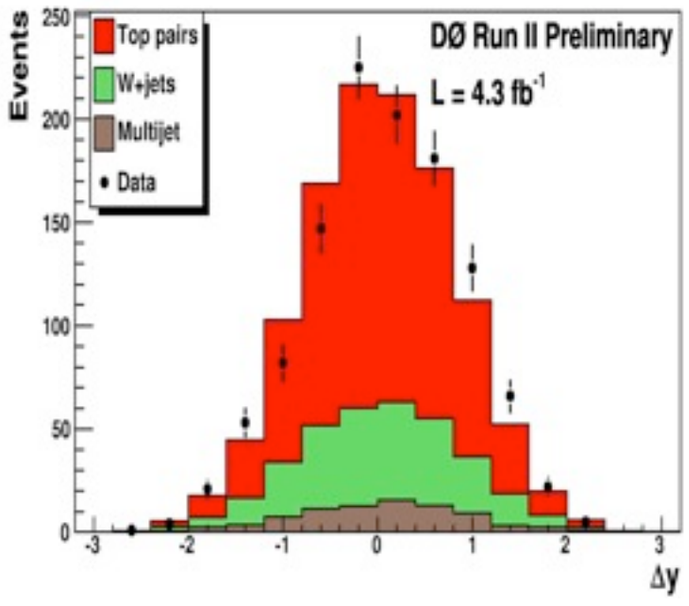
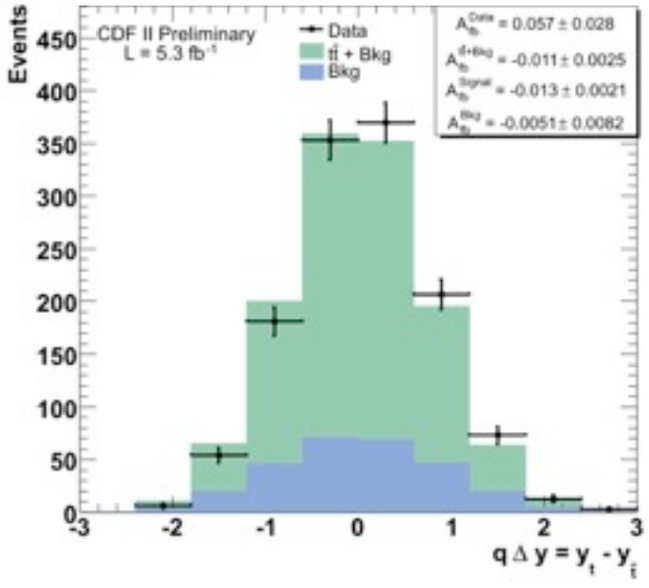
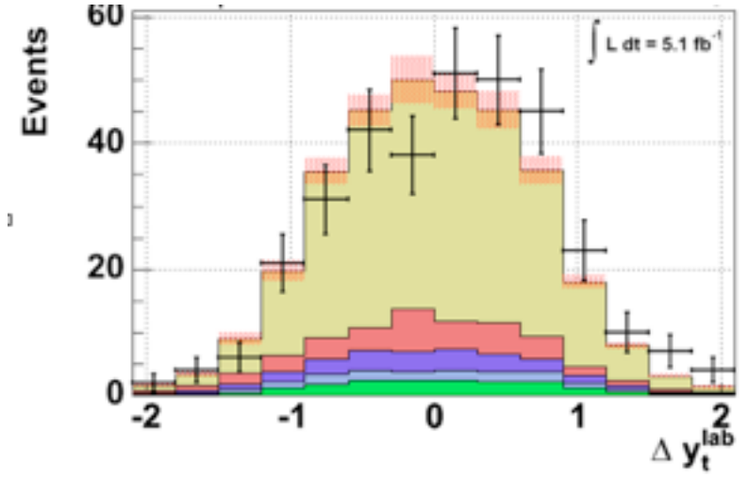
5.1 fb^{-1}

$A_{FB}^{Theory} = 6 \pm 1$ %

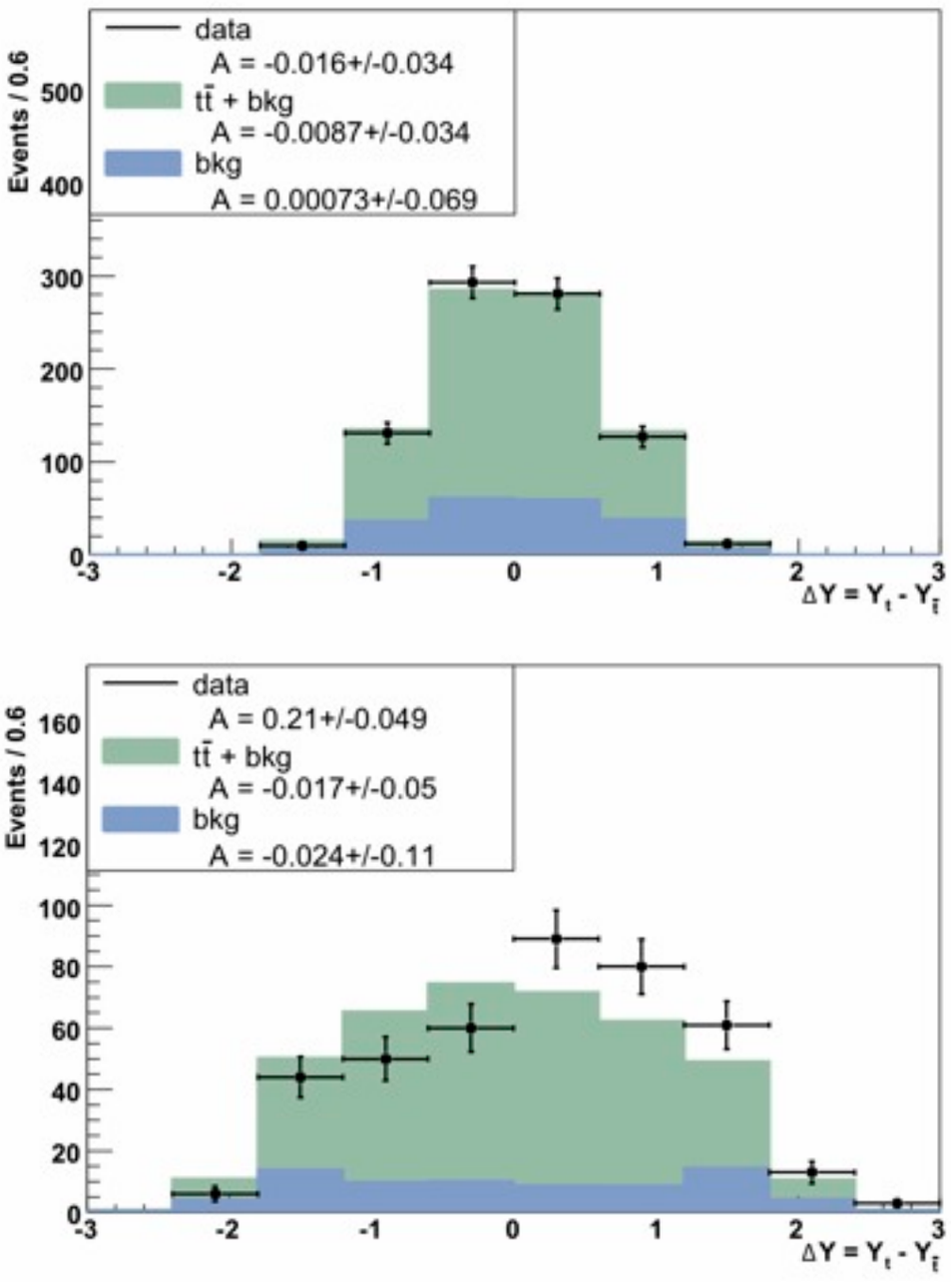
$A_{FB}^{l+Jets} = 16 \pm 7$ %

Summary of Results

Inclusive Asymmetry

A_{FB} = 8 ± 4 %	A_{FB} = 16 ± 7 %	A_{FB} = 42 ± 16 %
~ 2 σ (4 fb^{-1})	~ 2 σ (5 fb^{-1})	~ 2.7 σ (5 fb^{-1})
		
A_{FB}^{sm} ~ 1 %	A_{FB}^{sm} ~ 6 %	A_{FB}^{sm} ~ 6 %

Summary of Results



For M_{tt} > 450 GeV

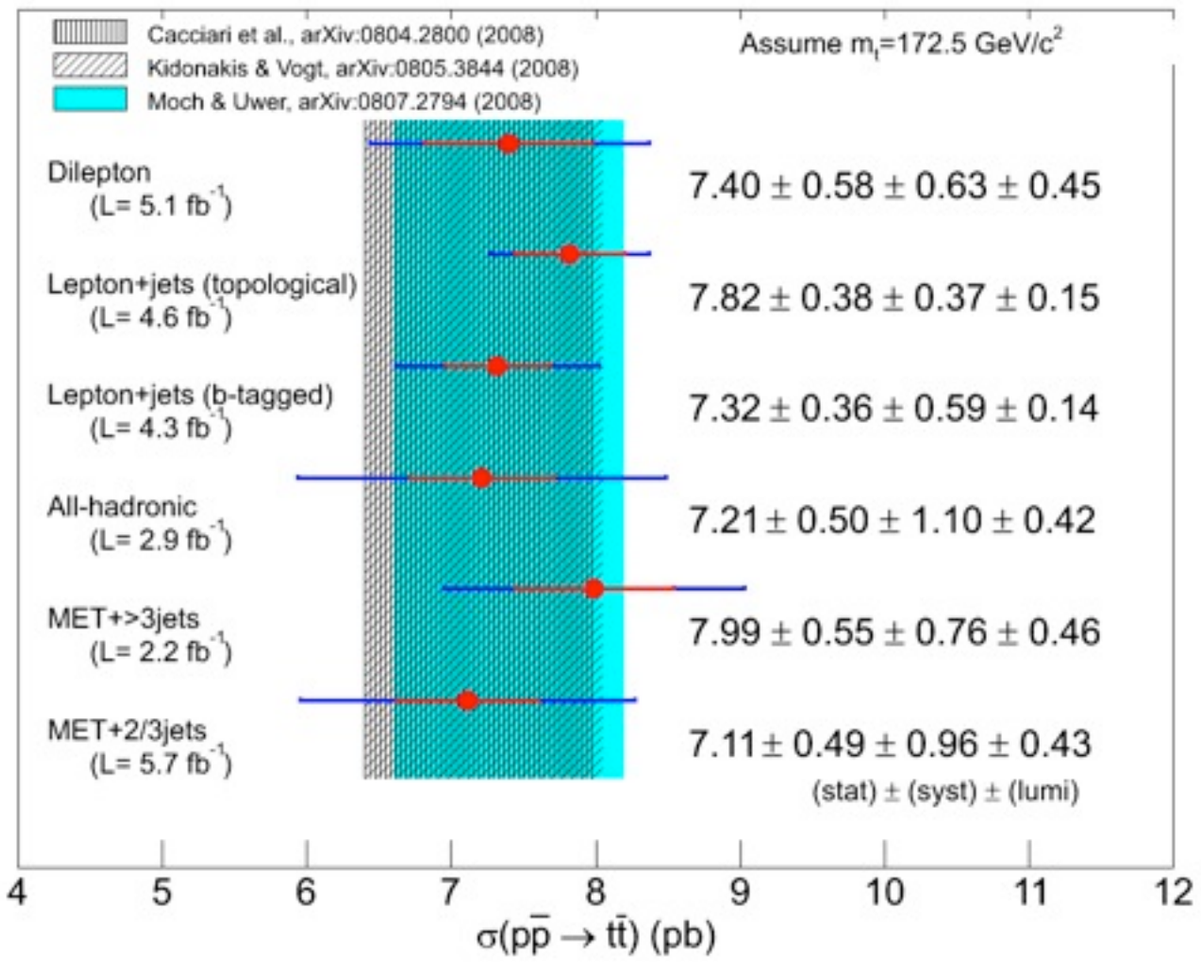
$A_{FB} = 48 \pm 11_{stat+syst}$ %

5.3 fb^{-1}

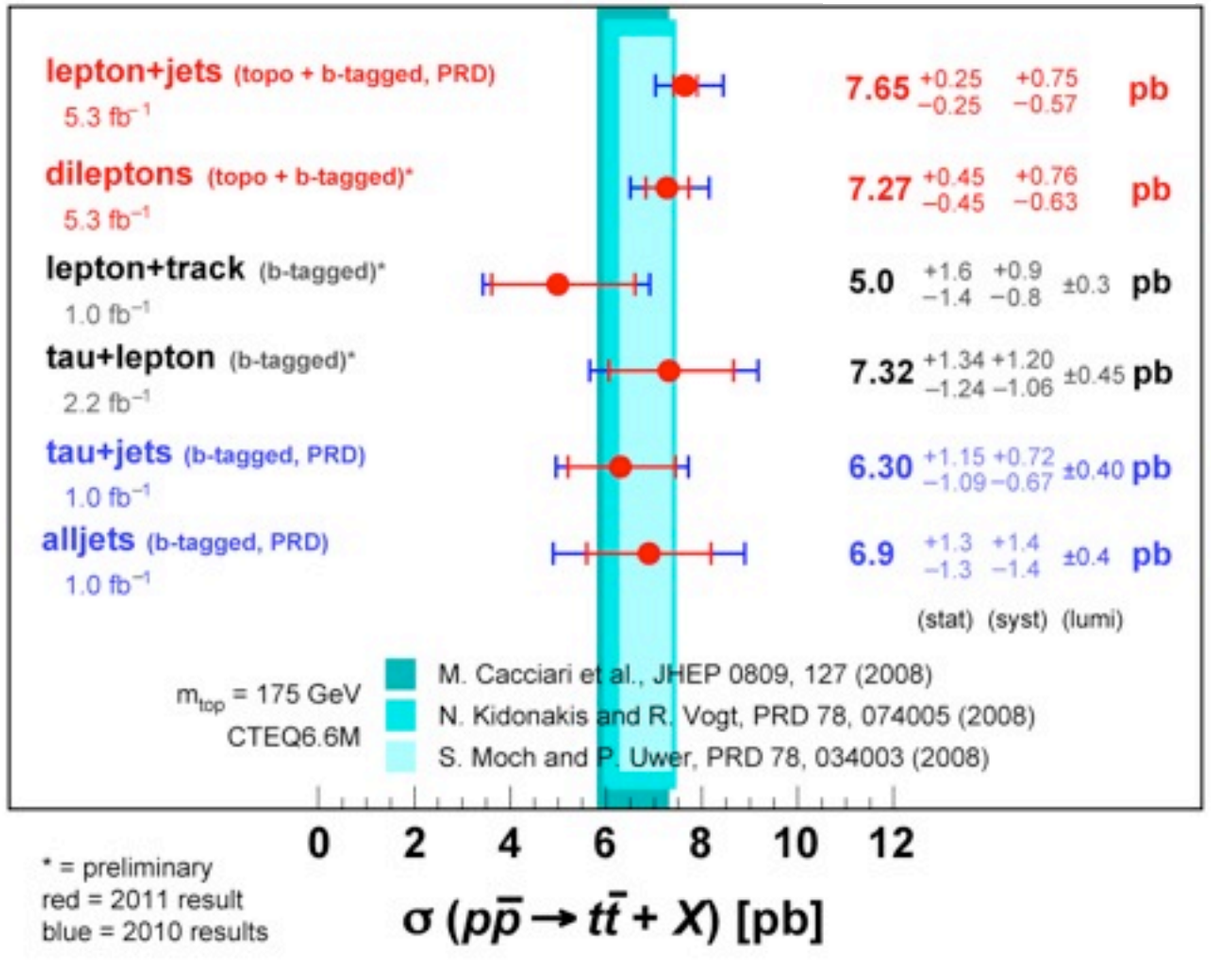
$A_{FB}^{Theory} = 9 \pm 1$ %

Rate of Top Production

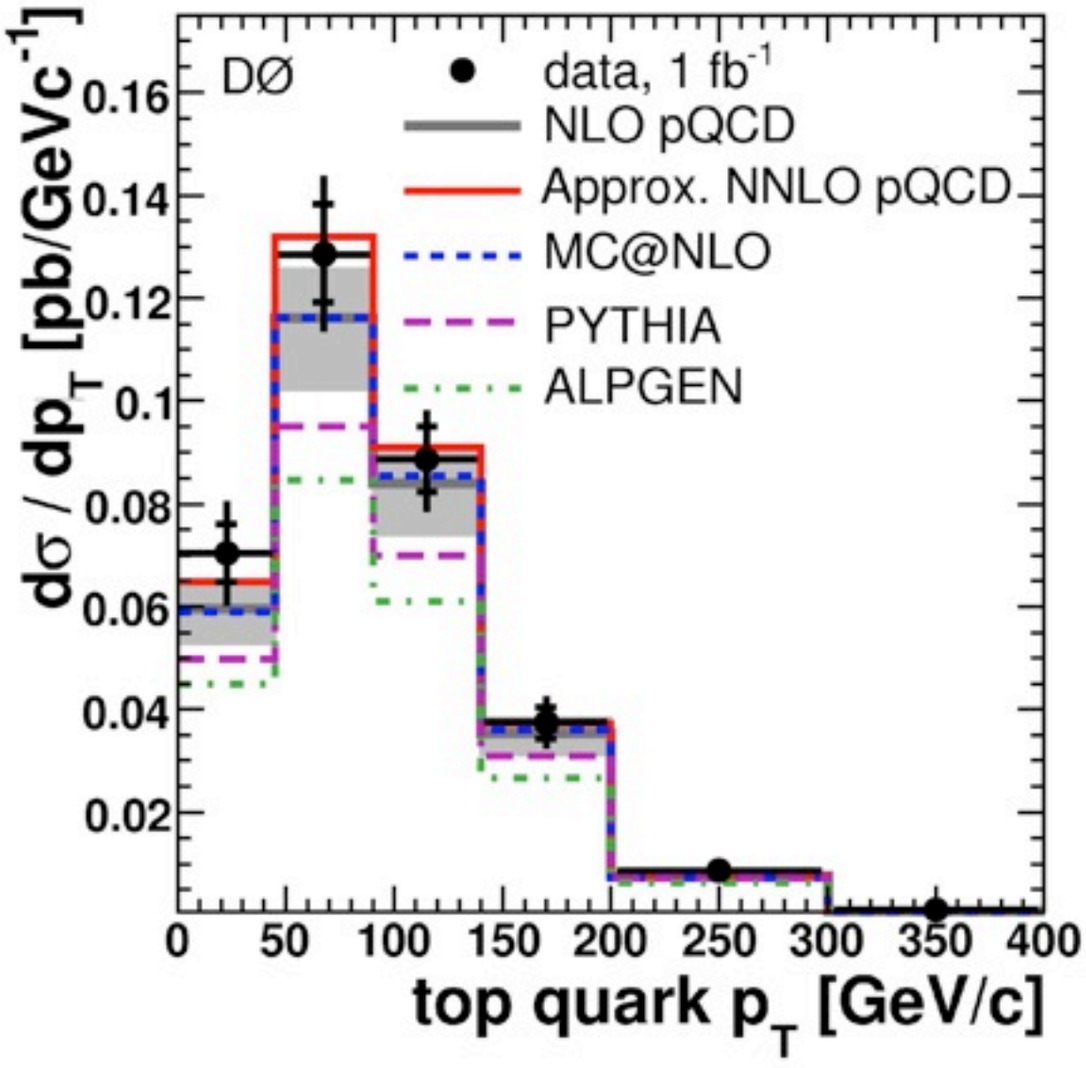
CDF Run II

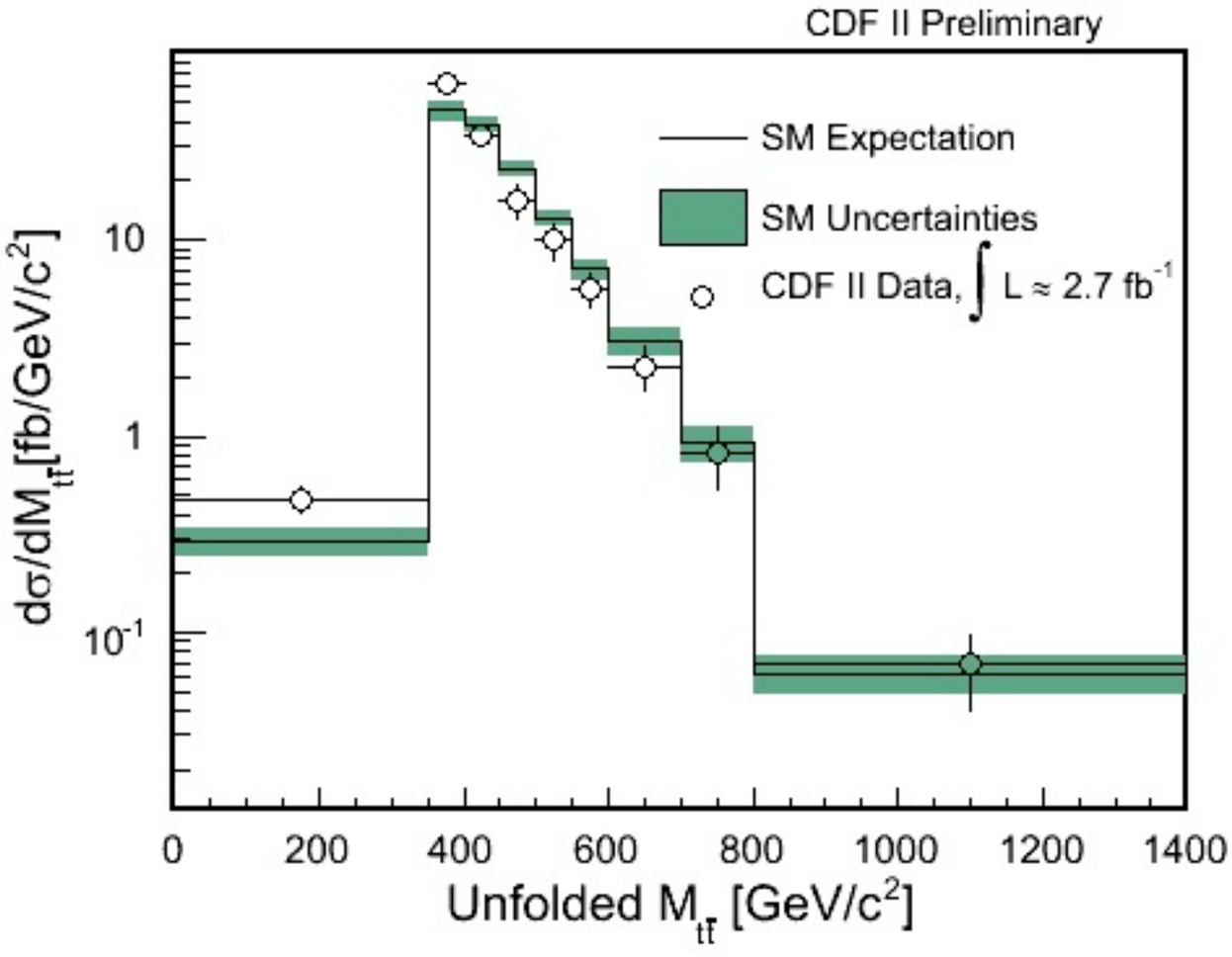


D0 Run II



Top Kinematics





Boosted Top

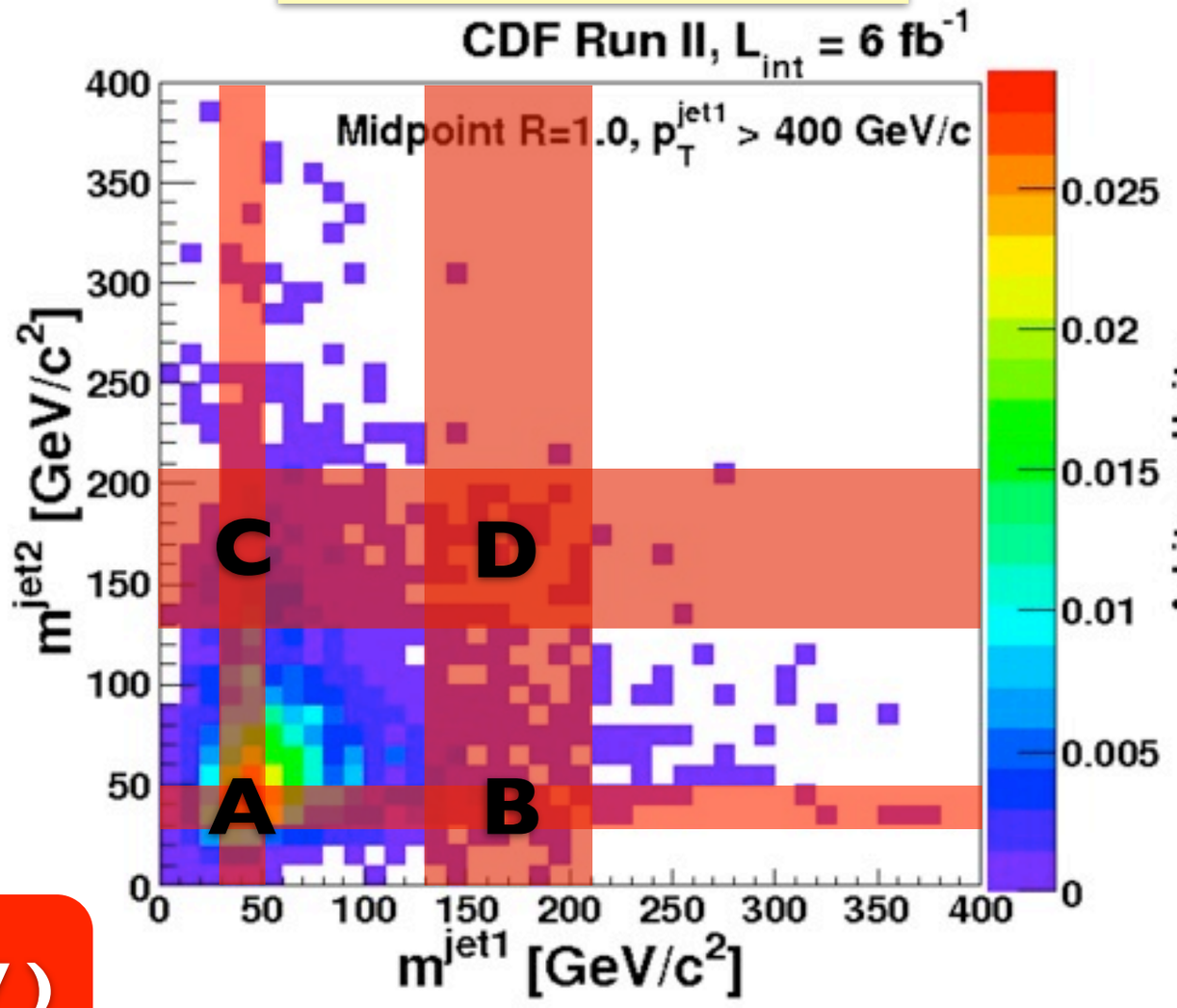
- **Look for top events at very high Pt (P_t > 400 GeV)**

$$\sigma_{tt}^{sm} \sim 4 \text{ fb}$$

- **Decay products merge together due to boost**
- **Use mass of top 'jets' to distinguish events**
- **Expect 44 ±16 events, observe 58**

σ_{tt} < 40 fb @ 95%CL (p_t > 400 GeV)

ABCD Method



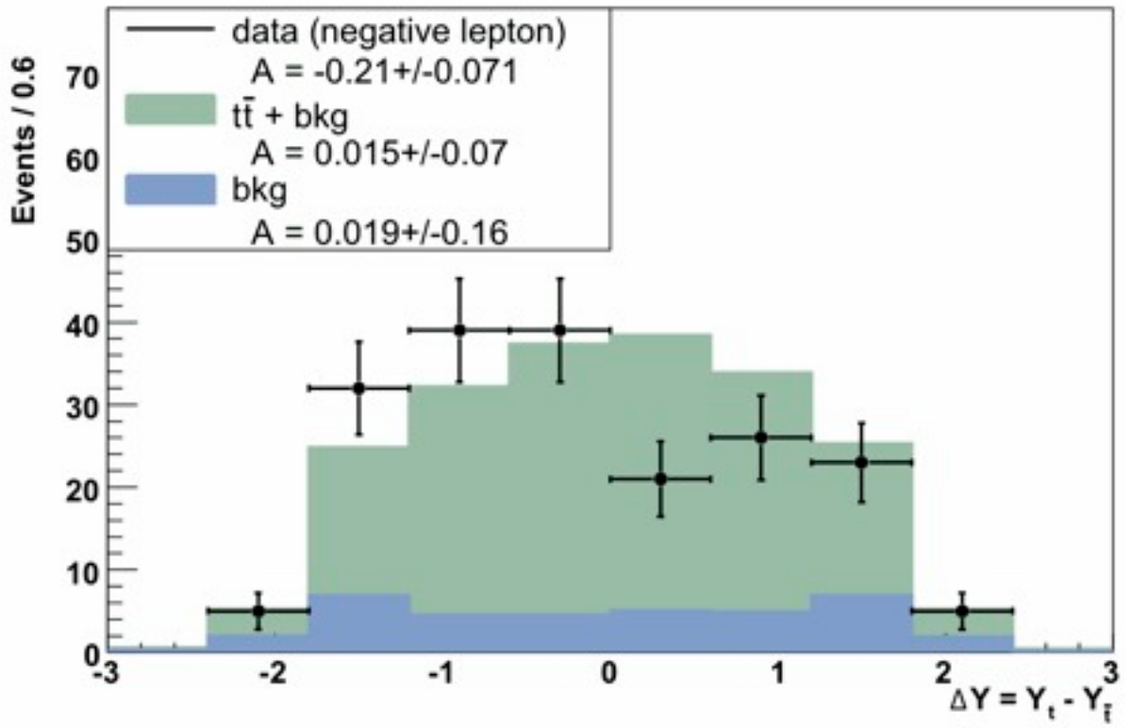
What's Next for A_{FB}

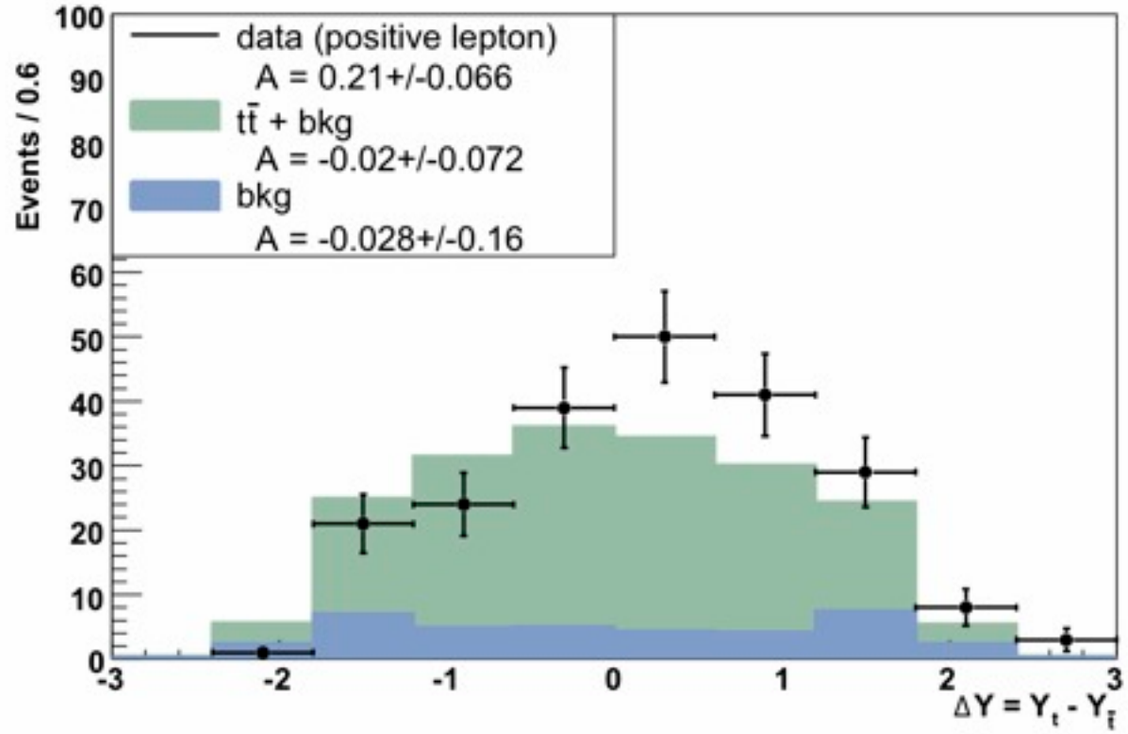
- **Time and data - really need 4-5σ before we're sure it's not statistics**
- **D0 will tell us more - comparable results, study mass dependence, combination**
- **Correlated to other observables → LHC needs to see something**

STAY TUNED!

Thanks!!!

$M_{t\bar{t}}$ Dependence

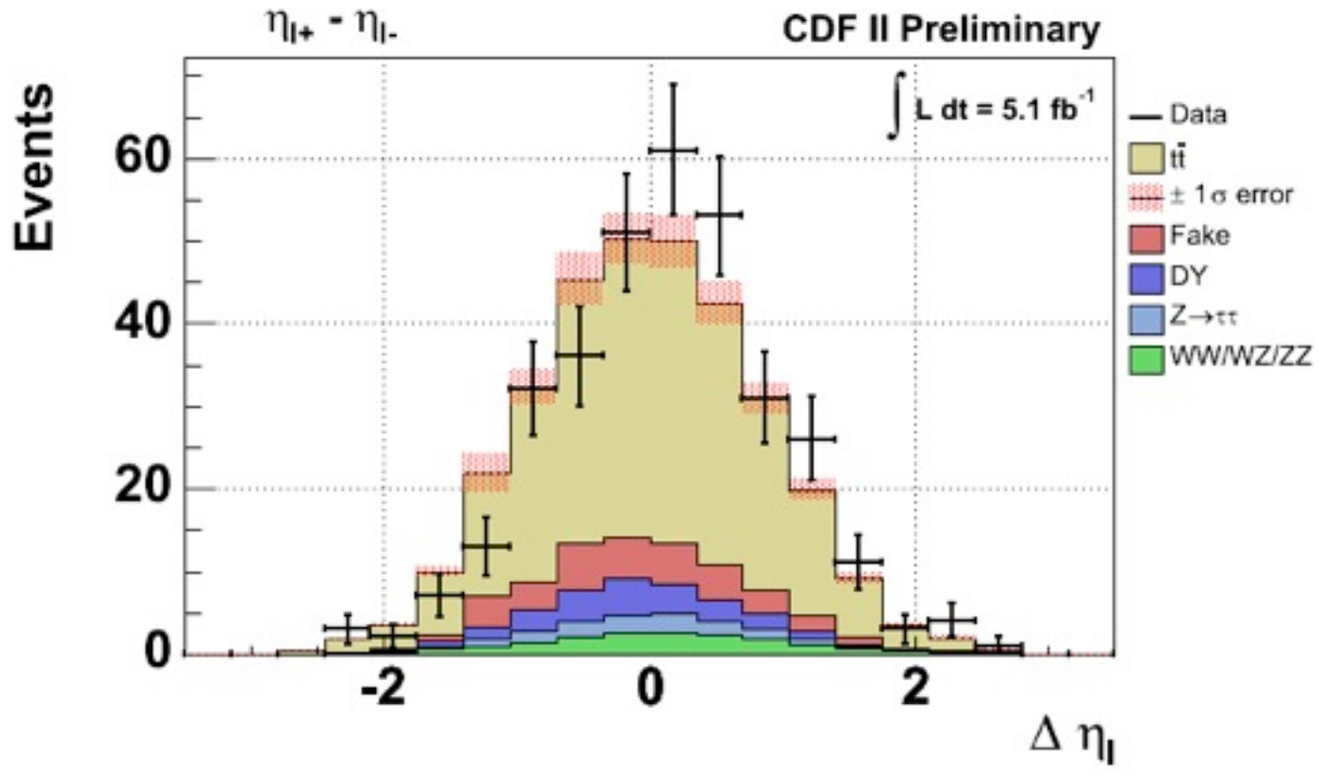




	Inclusive	M < 450 GeV	M > 450 GeV
AFB +	6.7 ± 4 %	-1 ± 5 %	21 ± 7 %
AFB -	-5 ± 4 %	2 ± 5 %	-21 ± 7 %

A_{FB} in Dileptons

- **Top direction correlated with two leptons**
- **Much simpler than reconstruction algorithm - though correlated**
- **Significance remains**



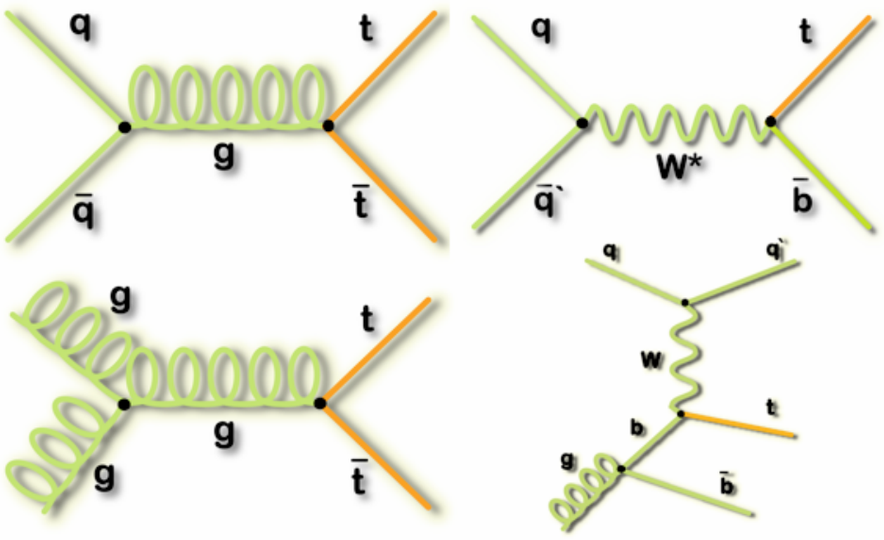
$A_{FB}^{ll} = 14 \pm 5_{stat}\ \%$

$5.1\ fb^{-1}$

$A_{FB}^{Pred} = -2 \pm 2\ \%$

Tevatron Top Physics

How is Top Produced



- **Strong Force**
  $\sigma_{tt} \sim 7.5$ pb
- **Electroweak**
  $\sigma_{s+t} \sim 3$ pb

How Does Top Decay

- **V-A**
  $F_0 \sim 0.7$, $F_+ \sim 0$
- $V_{TB} \sim 1$

What are Top's Intrinsic Properties

- **Mass**
- **Spin** 1/2
- **Charge** +2/3

Tevatron Top Physics

How is Top Produced	How Does Top Decay	What are Top's Intrinsic Properties
$\sigma_{tt} = 7.70$ $\delta \sim 6\ \%$	$F_0 = 0.88$ $\delta \sim 10\ \%$	$M_t = 173.3$ $\delta \sim 0.6\ \%$
$\sigma_{s+t} = 2.8$ $\delta \sim 19\ \%$	$F_+ = -0.15$ $\delta \sim 10\ \%$	$\Gamma_t \sim 2.1$ @ 25%CL
$\sigma_t = 3.1$ $\delta \sim 30\ \%$	$V_{tb} = 0.88$ $\delta \sim 9\ \%$	$\kappa = 0.7$ sig ~ 1 σ
		$q \neq -4/3$ @ 95%CL
• Strong Force $\sigma_{tt} \sim 7.5$ pb • Electroweak $\sigma_{s+t} \sim 3$ pb	• V-A $F_0 \sim 0.7$, $F_+ \sim 0$ • $V_{TB} \sim 1$	• Mass • Spin 1/2 • Charge +2/3

What you shouldn't worry about

- **Backgrounds**
  - **Too small, and the predicted asymmetry in backgrounds goes in the opposite direction**
- **Reconstruction**
  - **If it's broken, it's broken for MANY precision measurements that agree with the SM and other well-vetted techniques**
- **Unfolding**
  - **The significance of the result is present before the acceptance/reconstruction corrections - they only scale the result**

Questions...

- **Why do muons have a larger asymmetry than electrons?**
- **Why is the lab frame asymmetry stronger, yet less dependent on M_{tt} ?**
- **Why is the result in dileptons so much larger?**

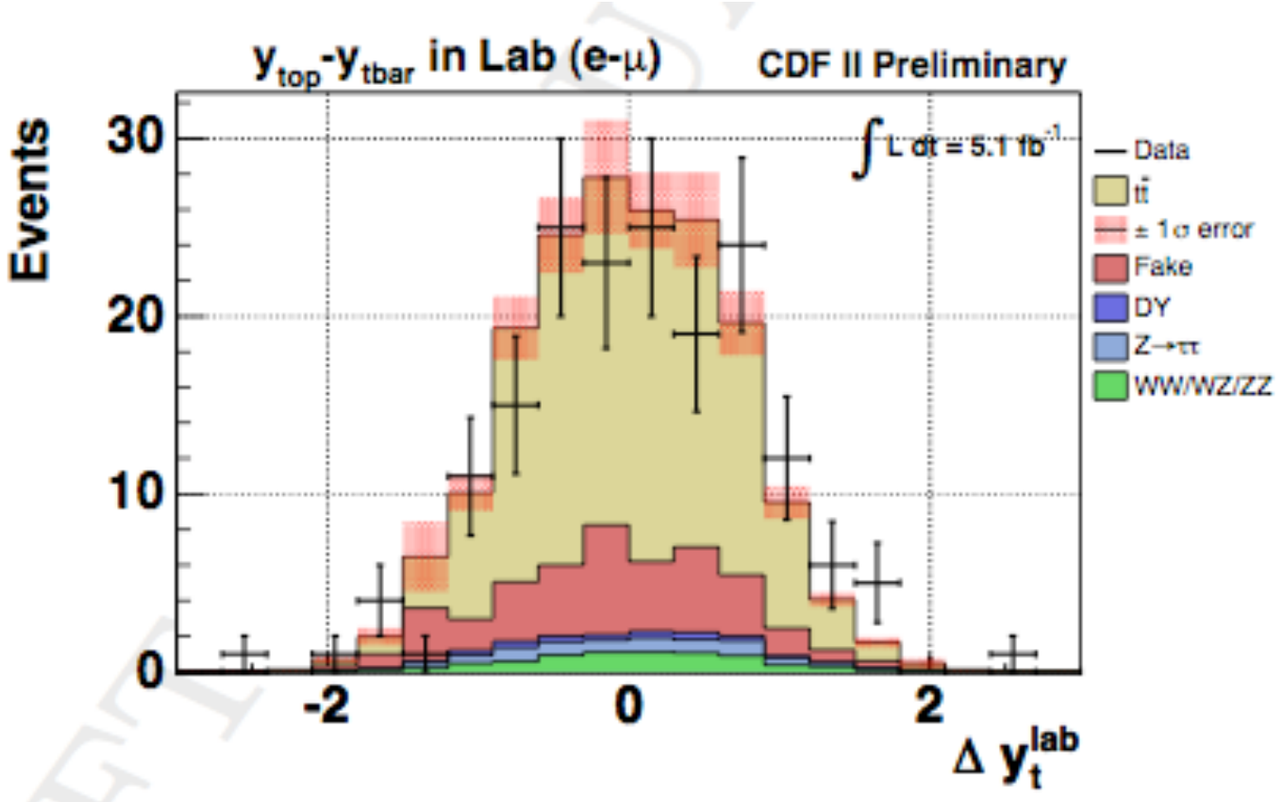
Muons vs Electrons

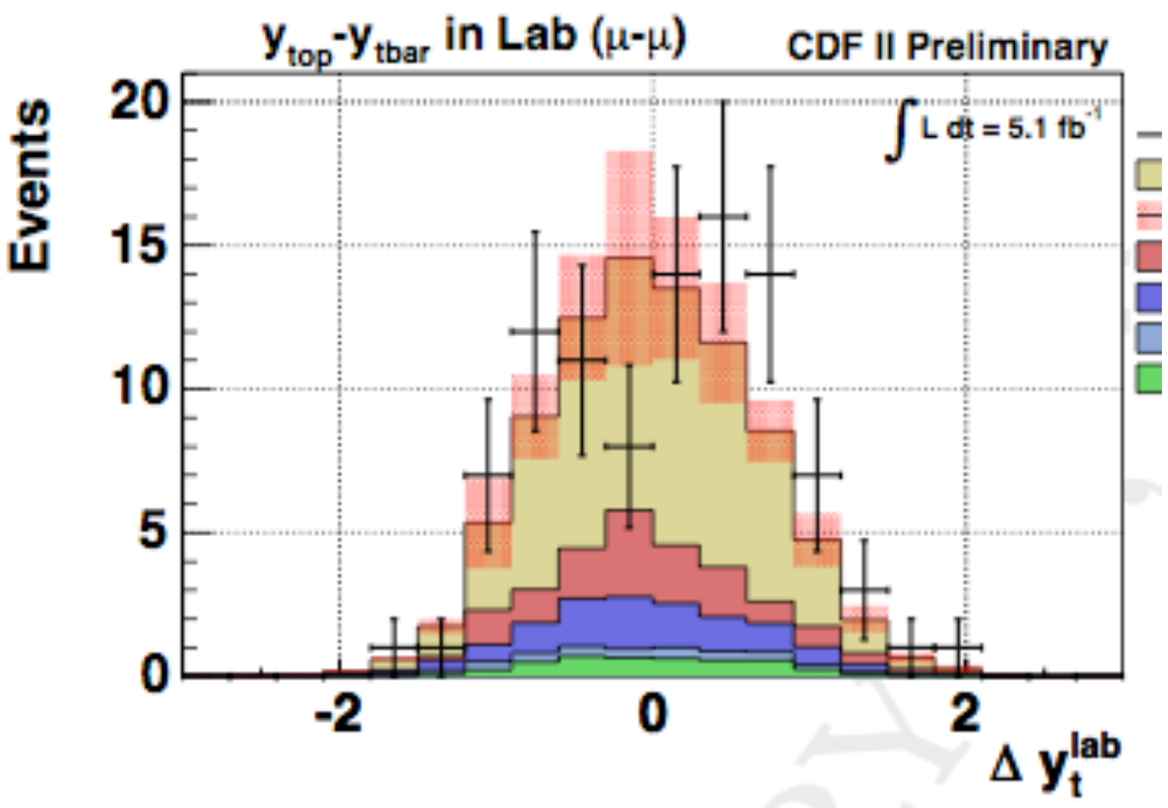
**** before corrections***

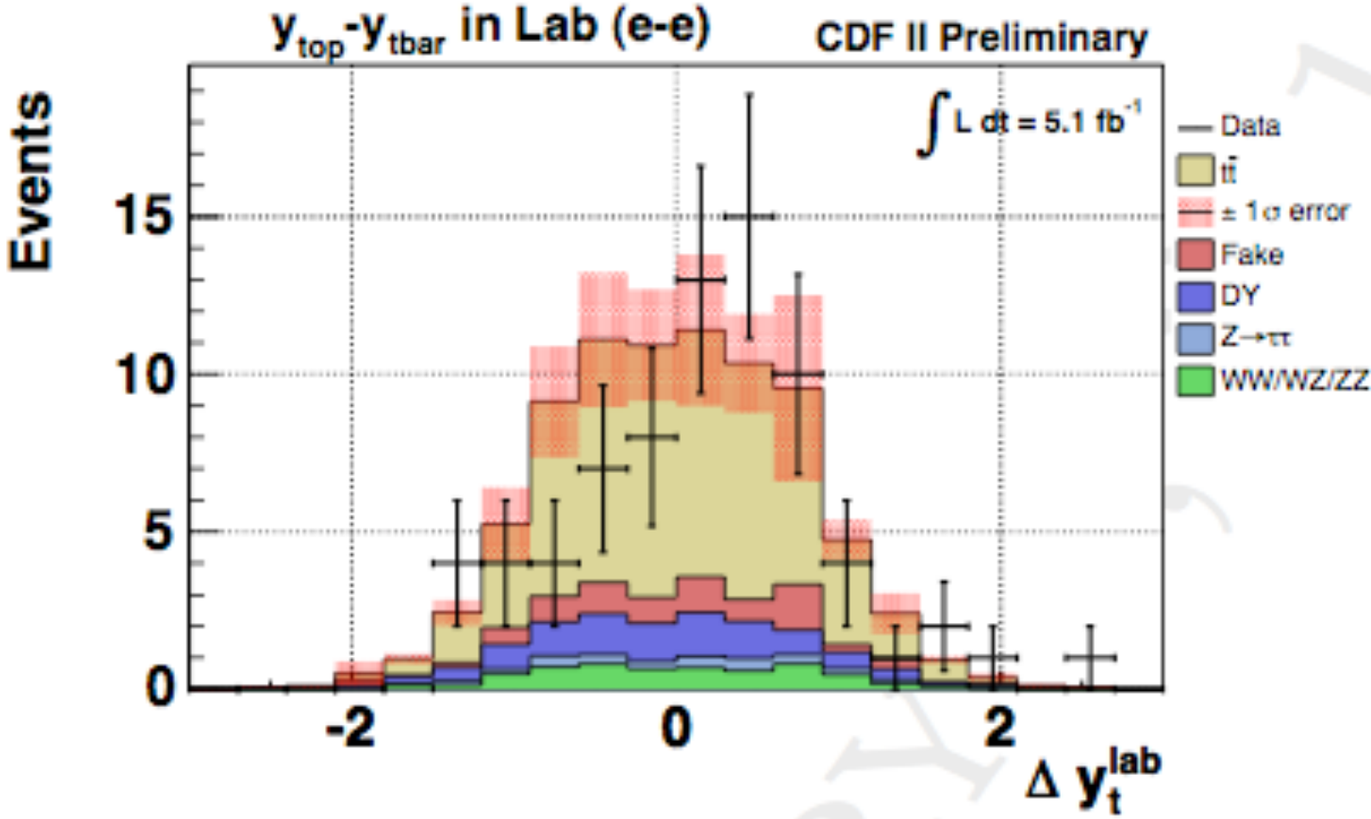
selection	N events	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
standard	1260	0.057±0.028	-0.016±0.034	0.212±0.049
electrons	735	0.026±0.037	-0.020±0.045	0.120±0.063
muons	525	0.105±0.043	-0.012±0.054	0.348±0.080
data $\chi^2 < 3.0$	338	0.030±0.054	-0.033 ± 0.065	0.180 ± 0.099
data no-b-fit	1260	0.062±0.028	0.006 ± 0.034	0.190 ± 0.050
data single b-tag	979	0.058±0.031	-0.015±0.038	0.224±0.056
data double b-tag	281	0.053±0.059	-0.023±0.076	0.178±0.095
data anti-tag	3019	0.033±0.018	0.029±0.021	0.044±0.035
pred anti-tag	-	0.010±0.007	0.013±0.008	0.001±0.014
pre-tag	4279	0.040±0.015	0.017±0.018	0.100±0.029
pre-tag no-b-fit	4279	0.042±0.015	0.023±0.018	0.092±0.029

What about the di-lepton result?

Flavor	Asymmetry
Inclusive	14 ± 5 %
e-e	27 ± 11 %
e-u	6.4 ± 7.6 %
u-u	17 ± 10 %

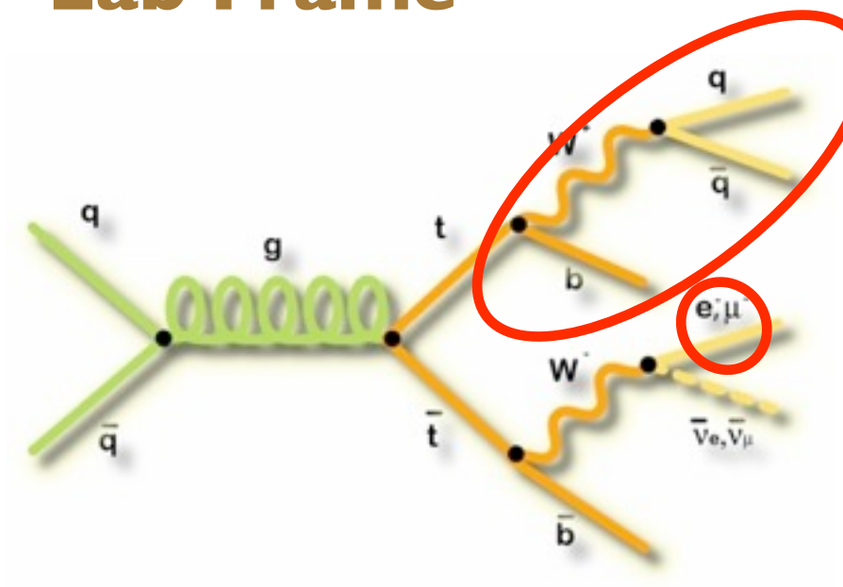


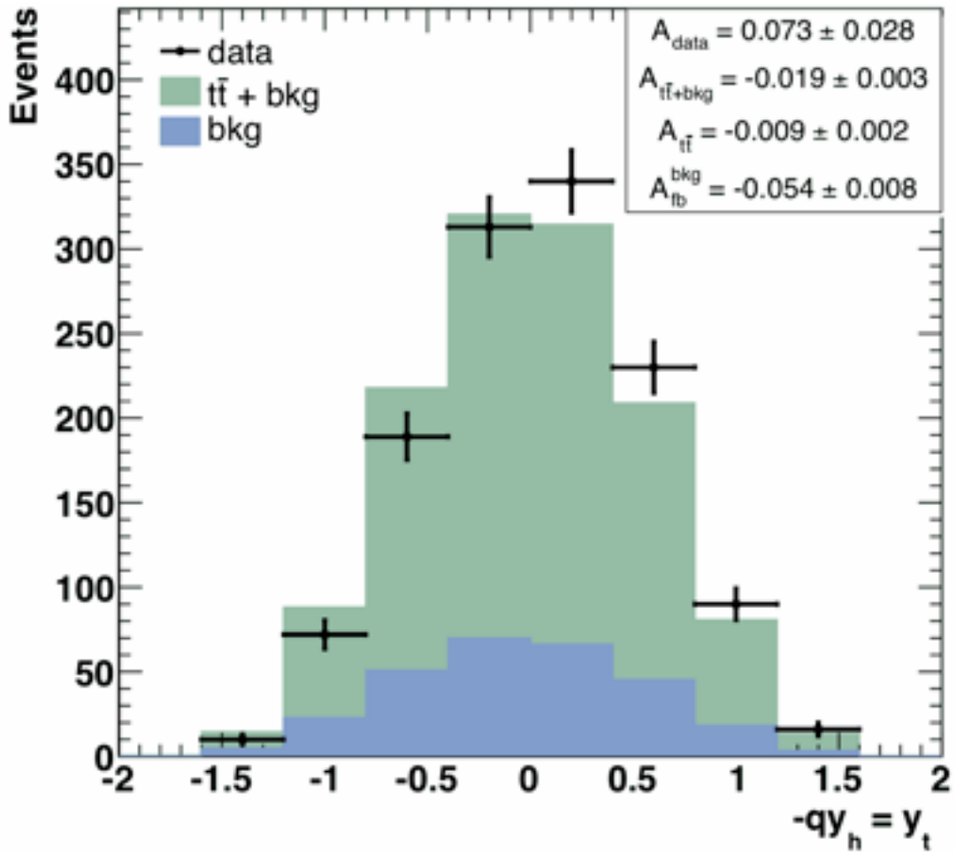




Lab Frame

- **Alternative method**
  - **Lab Frame**





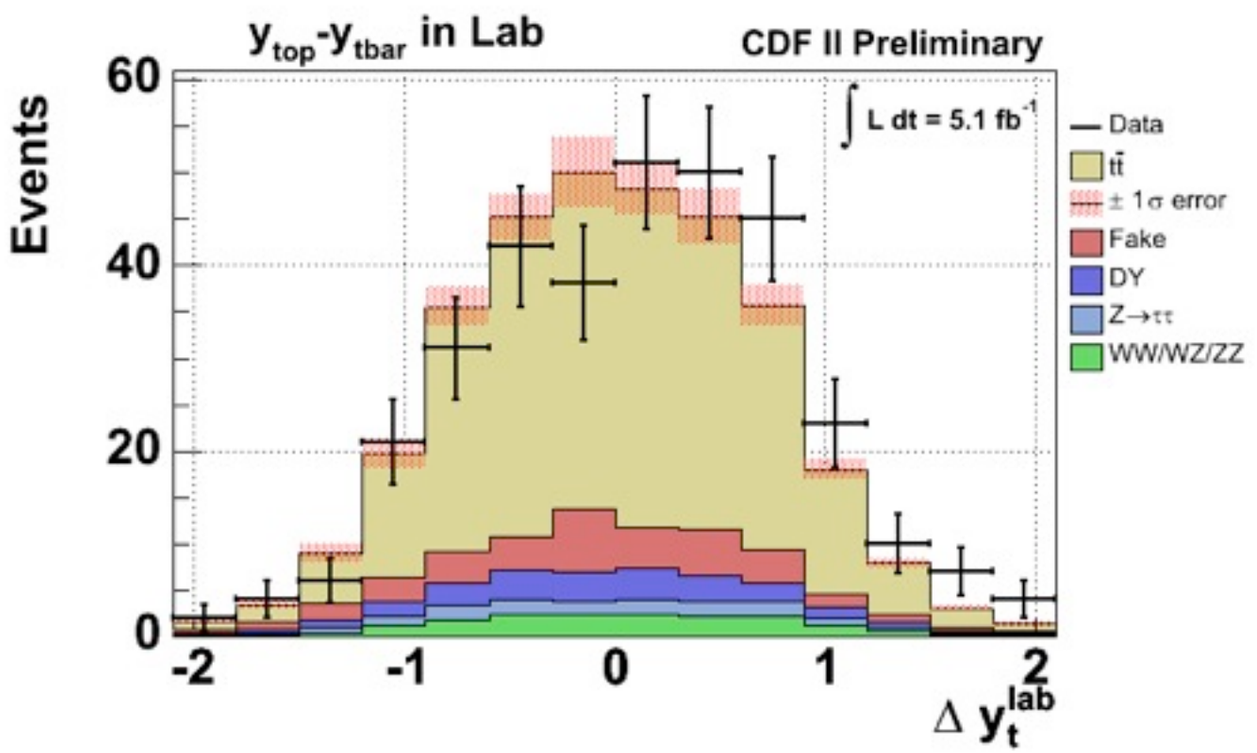
- **Takes the Lepton Pt and Neutrino out of it, still depend on lepton charge**

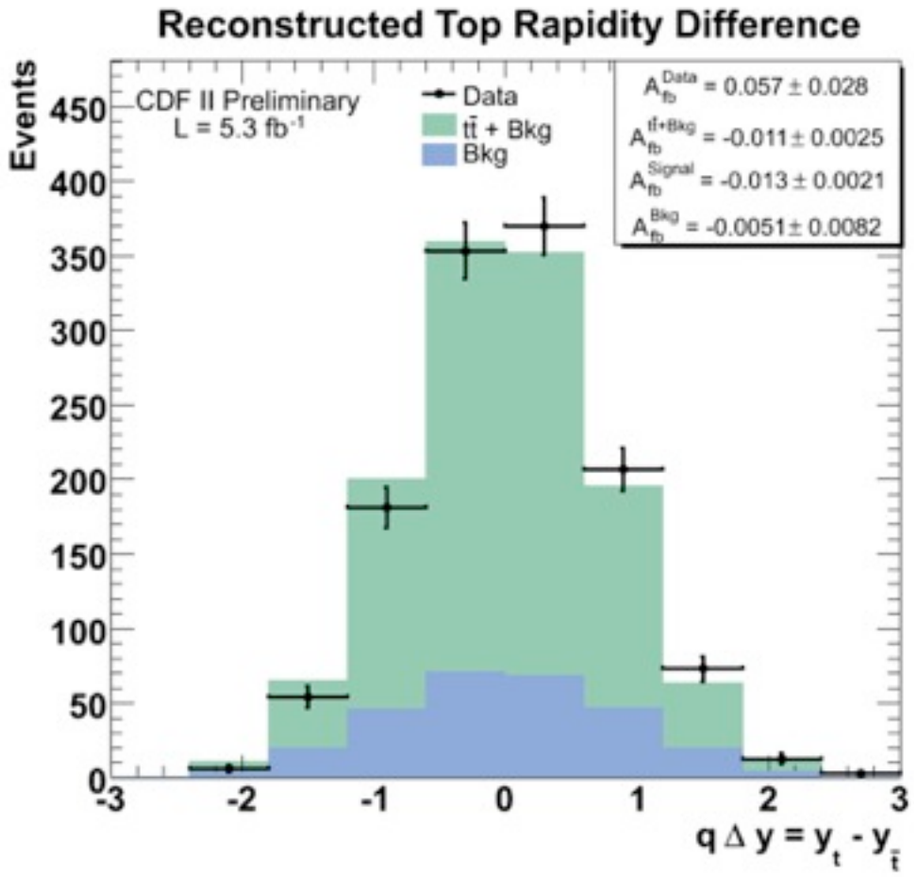
A_{FB} = 15 ± $5_{stat+syst}$ %

Lab Frame

	Inclusive	M < 450 GeV	M > 450 GeV
Data - tt Frame	5.7 ± 2.8 %	-1 ± 3 %	21 ± 5 %
SM Prediction	2 ± 0.4 %	1 ± 0.6 %	3 ± 0.7 %
Data - pp Frame	7.3 ± 2.8 %	5.9 ± 3.4 %	10.3 ± 4.9 %
SM Prediction	2 ± 0.4 %	-1 ± 0.5 %	2 ± 0.7 %

Dileptons vs L+Jets





A_{FB} = 42 ± 15$_{stat}$ ± 5$_{syst}$ %

5.1 fb^{-1}

A_{FB} = 16 ± 7$_{stat}$ ± 2$_{syst}$ %

5.3 fb^{-1}

$M_{t\bar{t}}$ Dependence

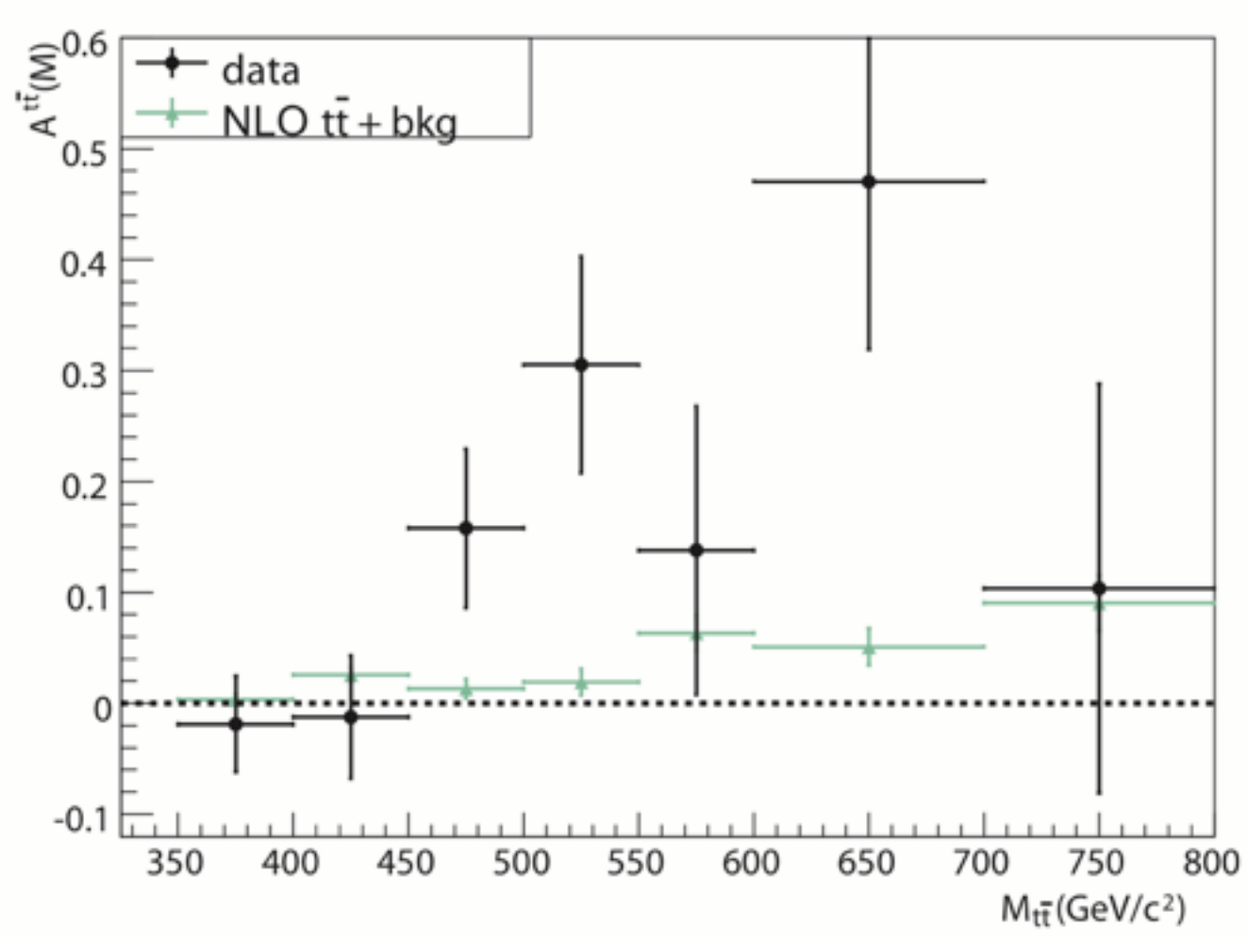
- **What is the optimal high/low bin-edge (based on MC) ?**

	OctetA		OctetB	
bin-edge (GeV/c^2)	A^{tt}	significance	A^{tt}	significance
345	0.082 ± 0.028	2.90	0.168 ± 0.028	5.99
400	0.128 ± 0.036	3.55	0.235 ± 0.035	6.74
450	0.183 ± 0.047	3.91	0.310 ± 0.044	7.08
500	0.215 ± 0.060	3.60	0.369 ± 0.054	6.81
550	0.246 ± 0.076	3.25	0.425 ± 0.066	6.43
600	0.290 ± 0.097	2.97	0.460 ± 0.081	5.70

Models provided by Tim Tait

$M_{t\bar{t}}$ Dependence

- **Interesting effect**
- **Want to correct this now to compare directly to SM - unfolding**
- **450 GeV choice though lies on a weird spot**
- **We're stuck with what we chose, but this demonstrates the limits of 4-bin unfolding**

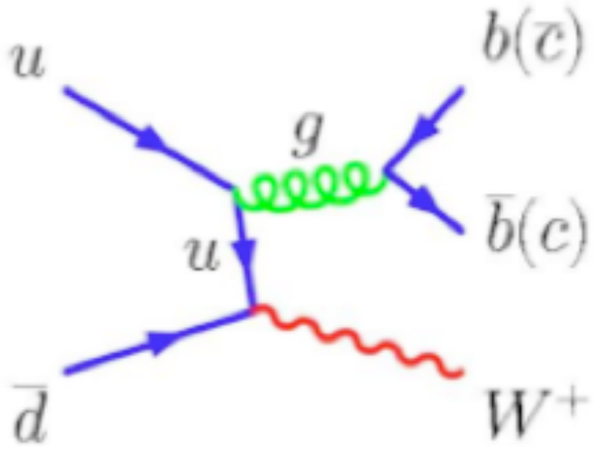


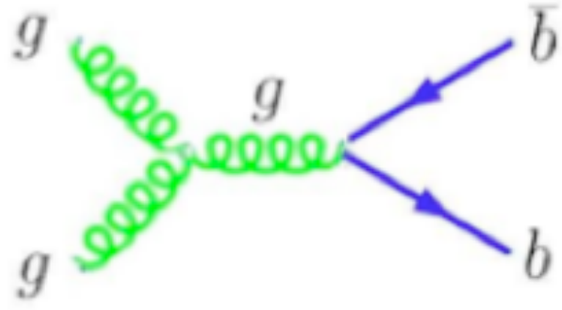

Reconstruction and
Corrections

Backgrounds

- Select 1260 Events
- Predict ~ 1287
- ~ 20% background

Process	Prediction
W+Jets	181
QCD	67
Other	35
$t\bar{t}$	1004
Data	1260





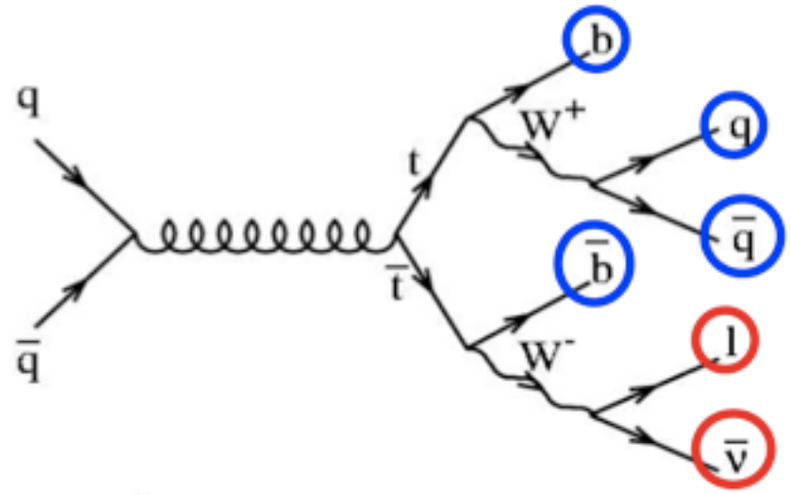
Event Reconstruction

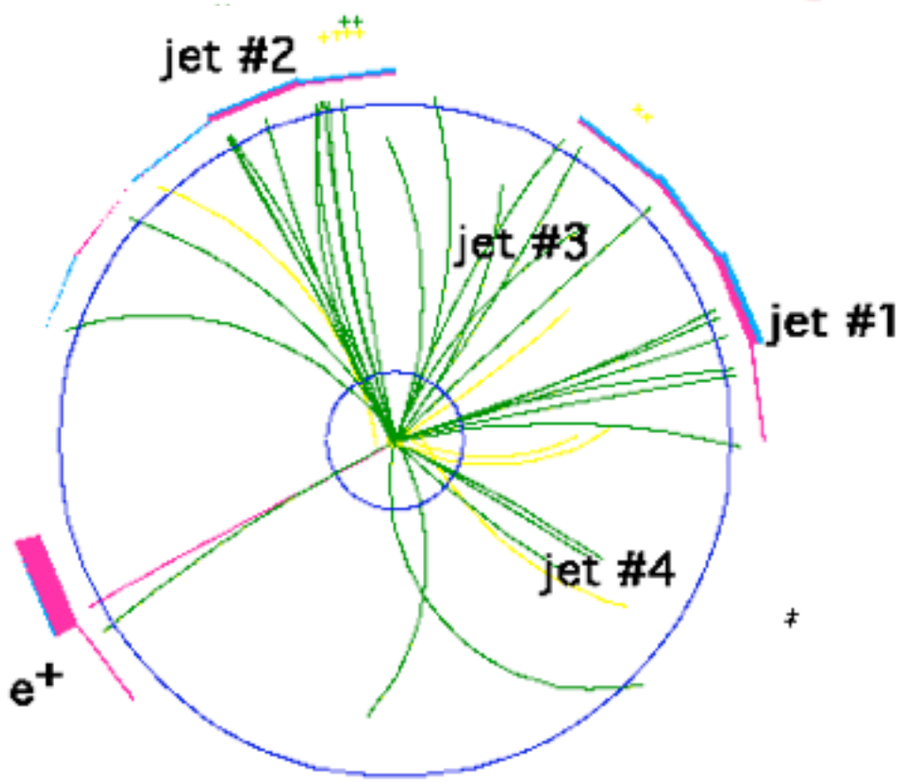
- Reconstruct the top direction from the observables in the detector

- Biggest problem is to match the jets in the detector to the "true" decay products of t and $\bar{t}$?

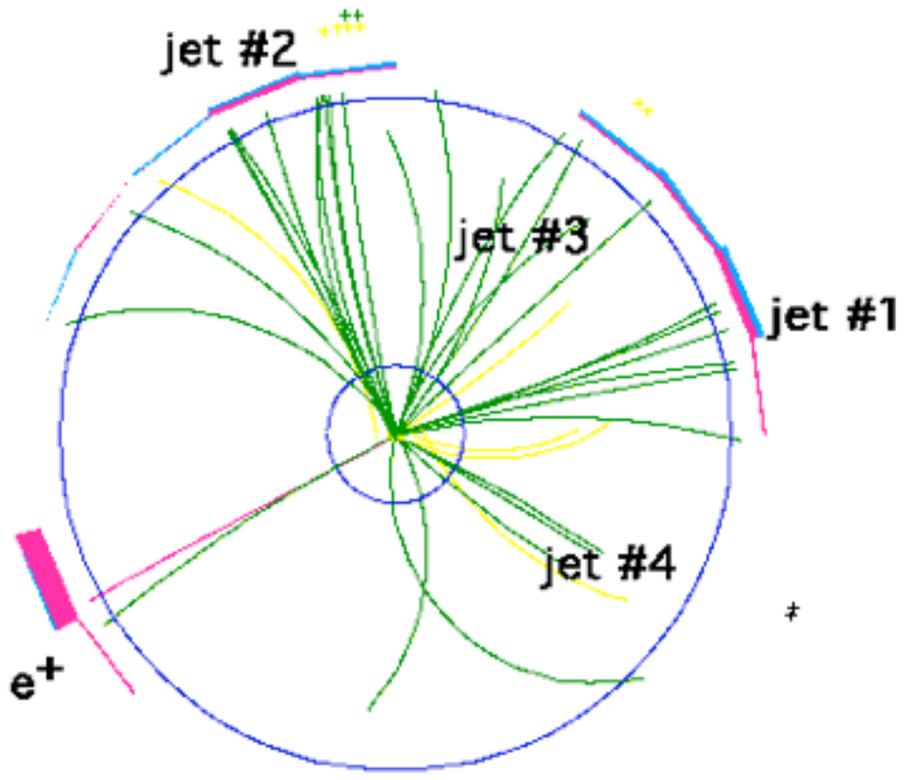
- 4 Jets to match to 4 quarks leads to 24 combinations

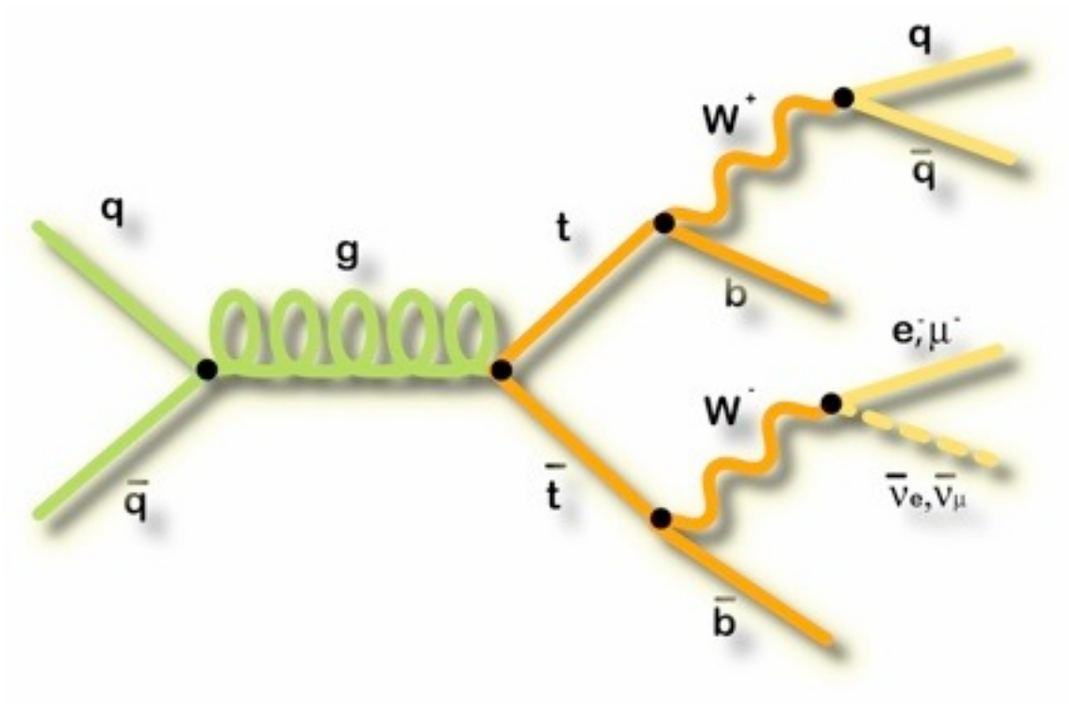
- Use the event topology to build an algorithm!





Event Reconstruction

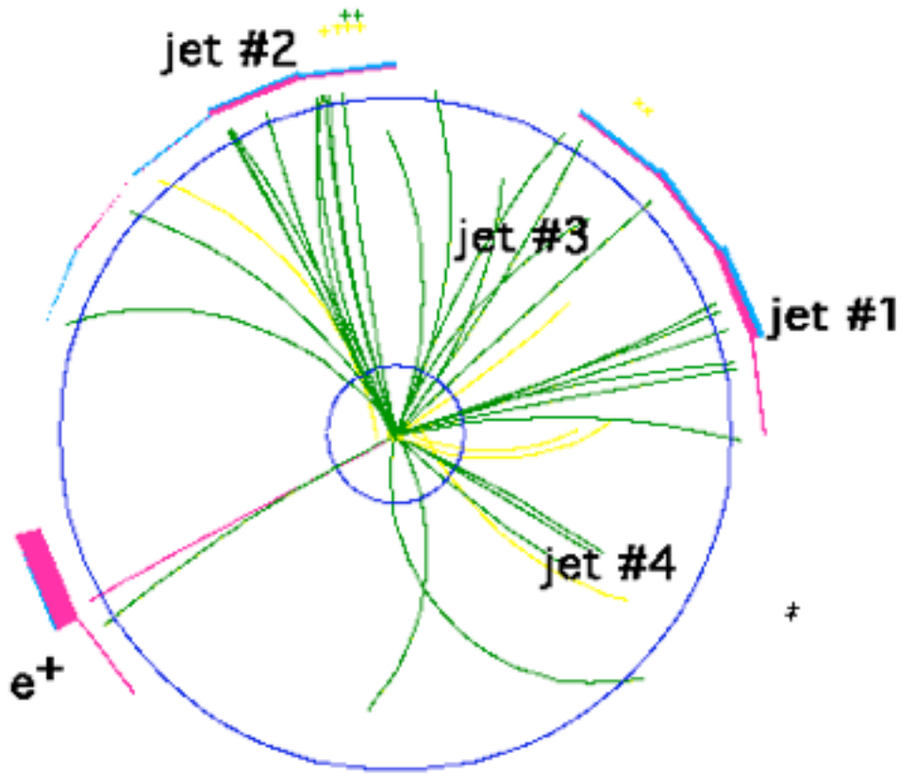


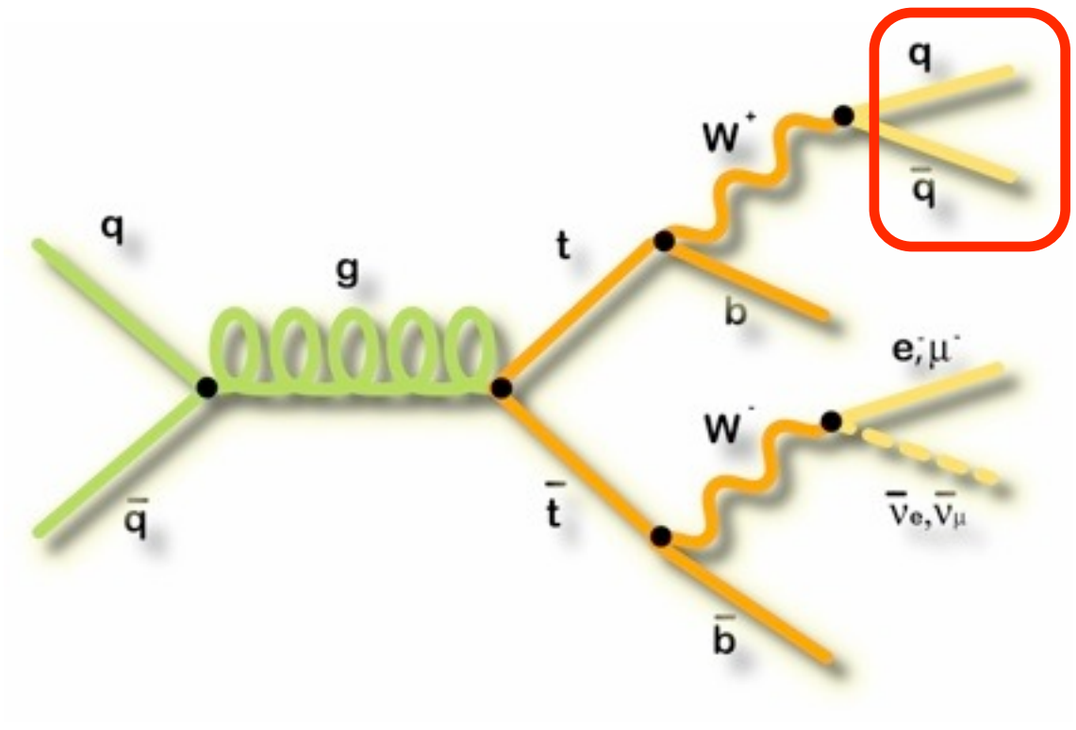


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{fit})^2}{\Gamma_t^2}$$

Event Reconstruction





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

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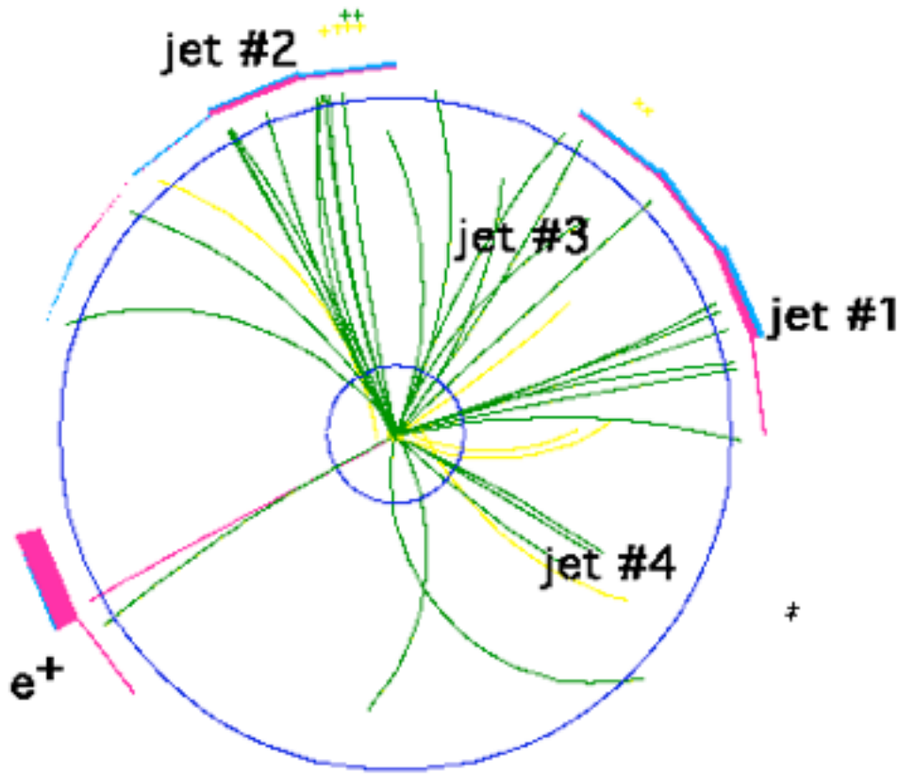
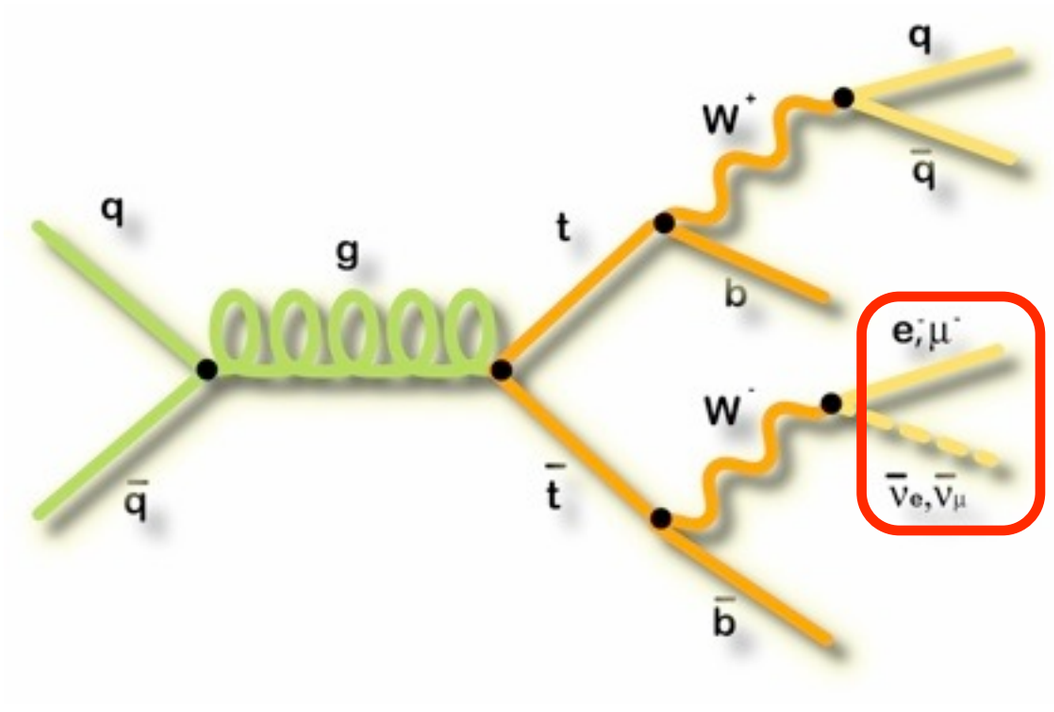
Event Reconstruction





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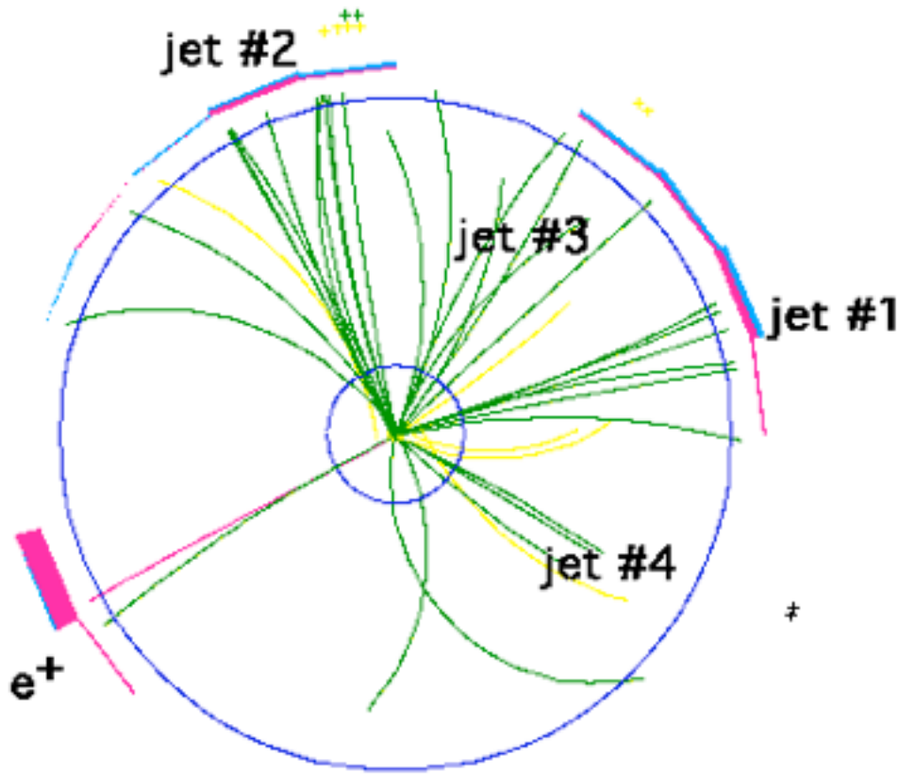
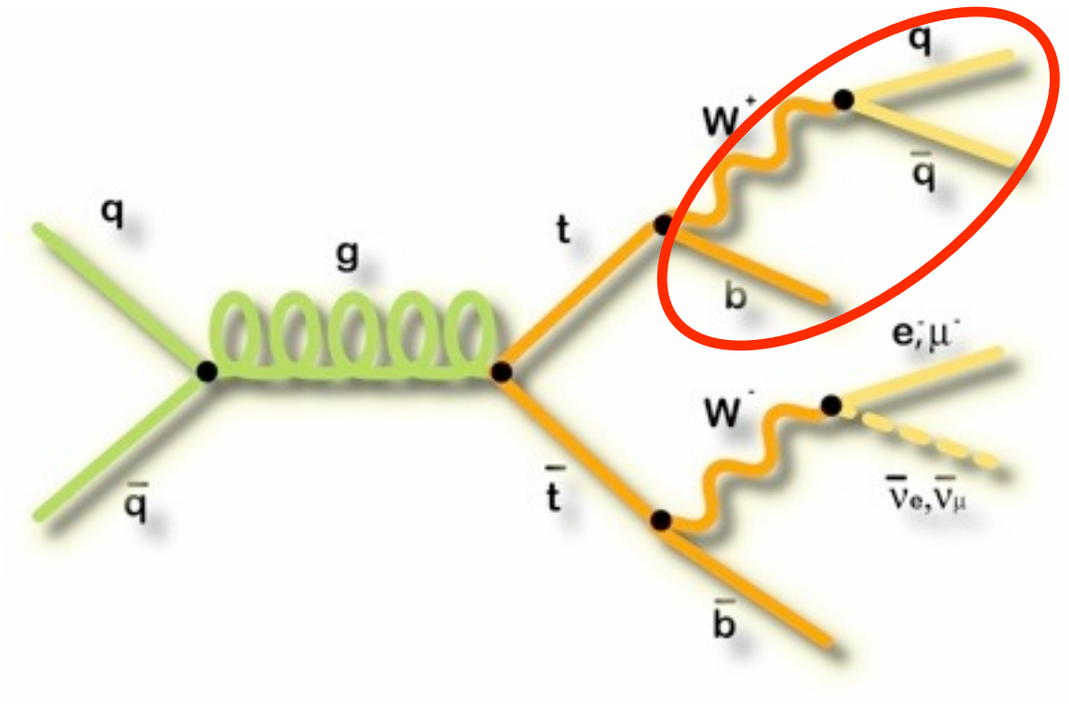
$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

Event Reconstruction

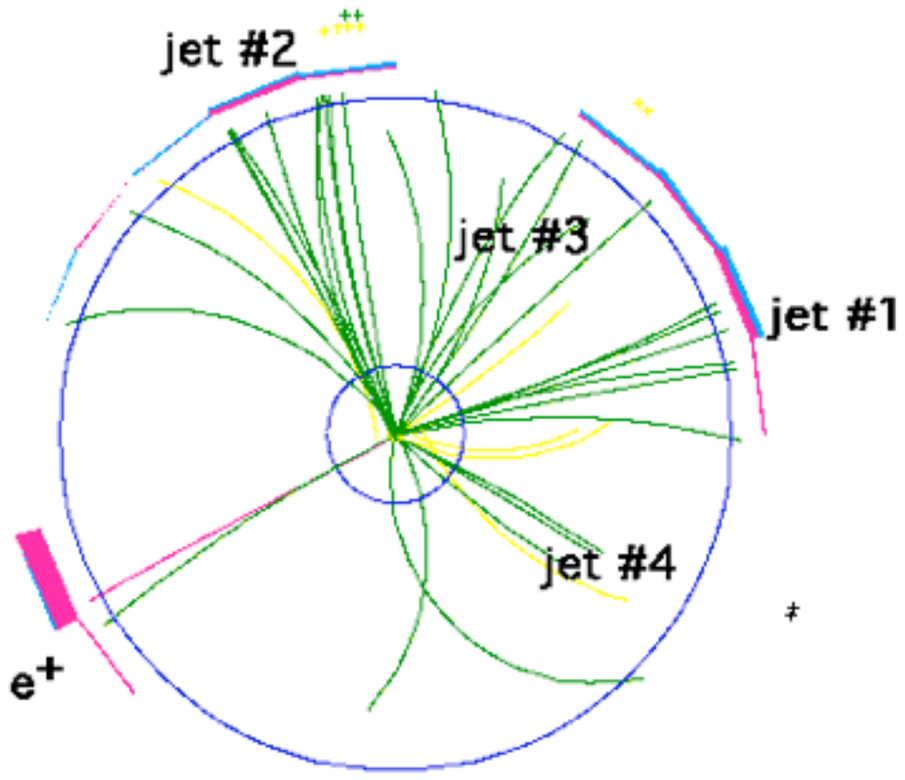


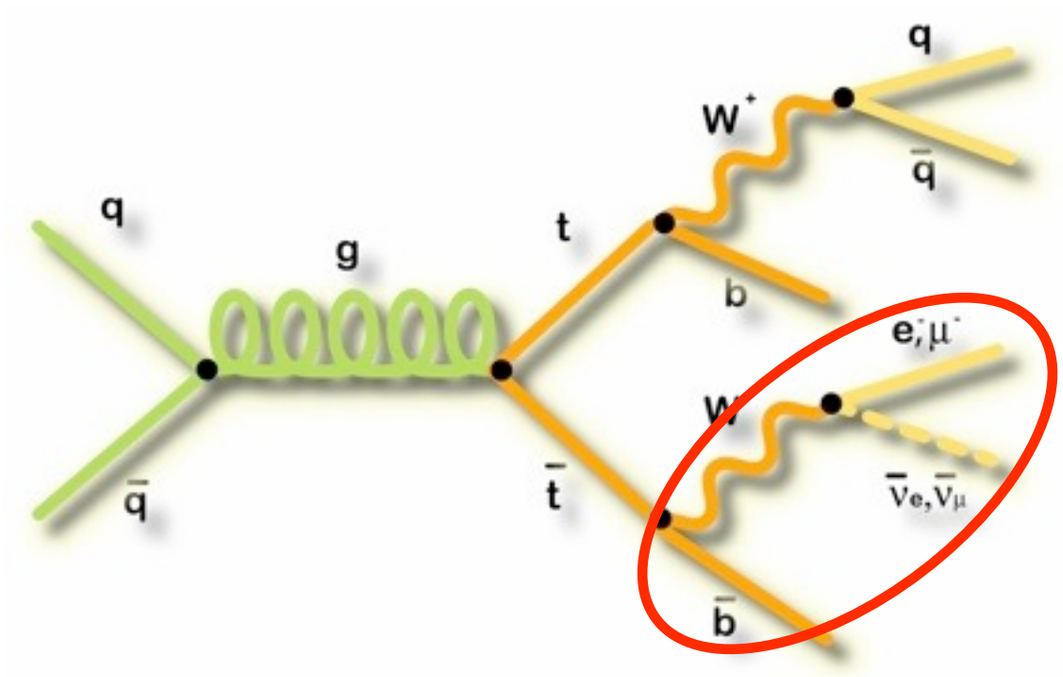


$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{fit})^2}{\Gamma_t^2}$$

Event Reconstruction

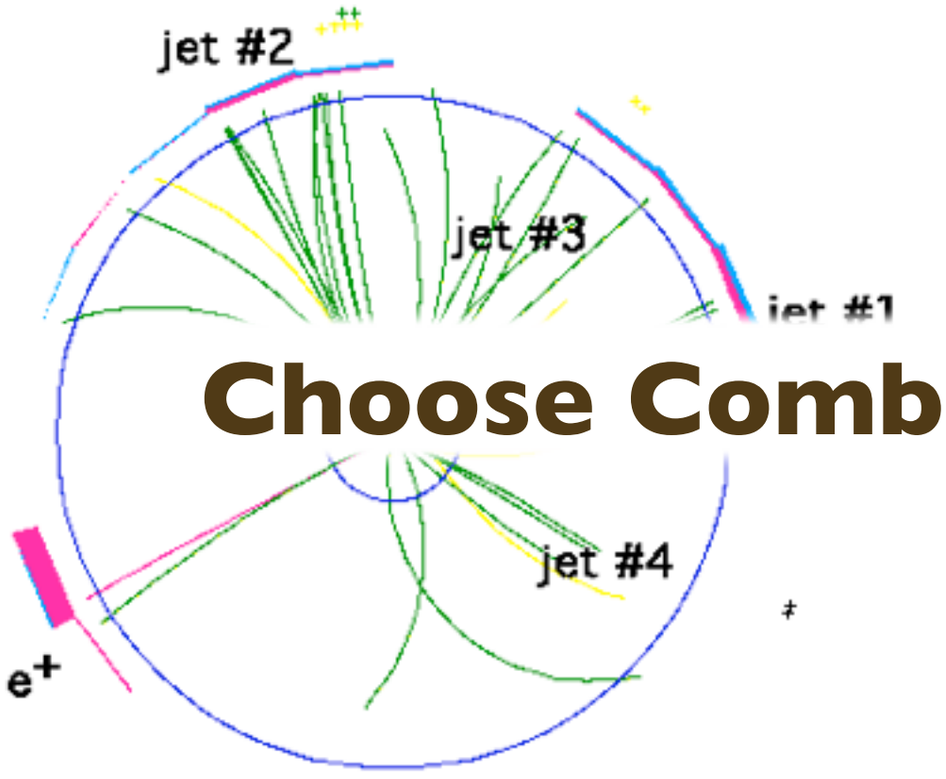




$$\chi^2 = \sum_{i=l,jets} \frac{(p_t^{i,meas} - p_t^{i,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,meas} - p_j^{UE,fit})^2}{\sigma_j^2}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{fit})^2}{\Gamma_t^2}$$

Event Reconstruction

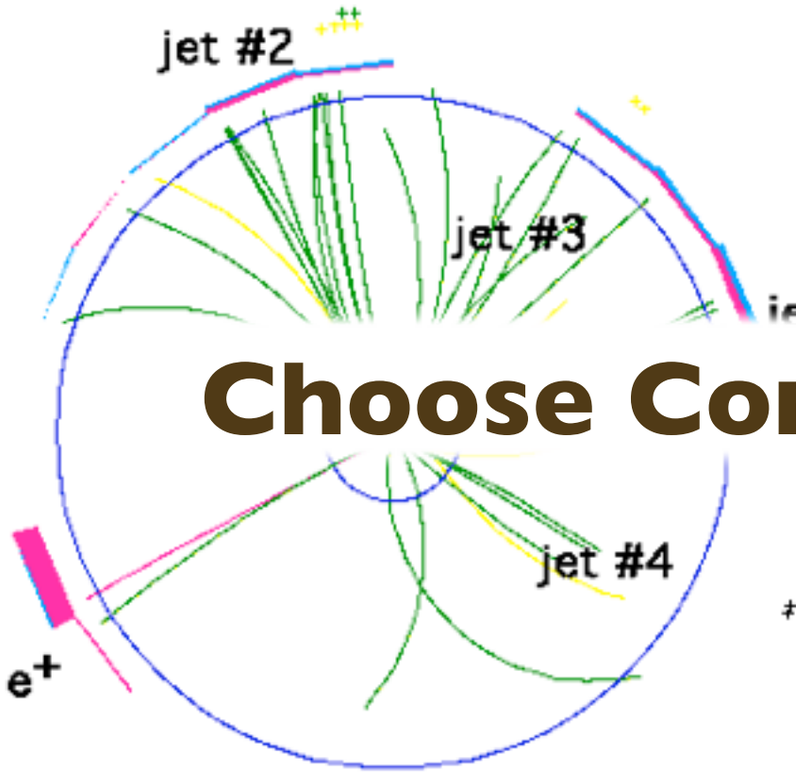


Choose Combination with Best χ^2

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

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{fit})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{fit})^2}{\Gamma_t^2}$$

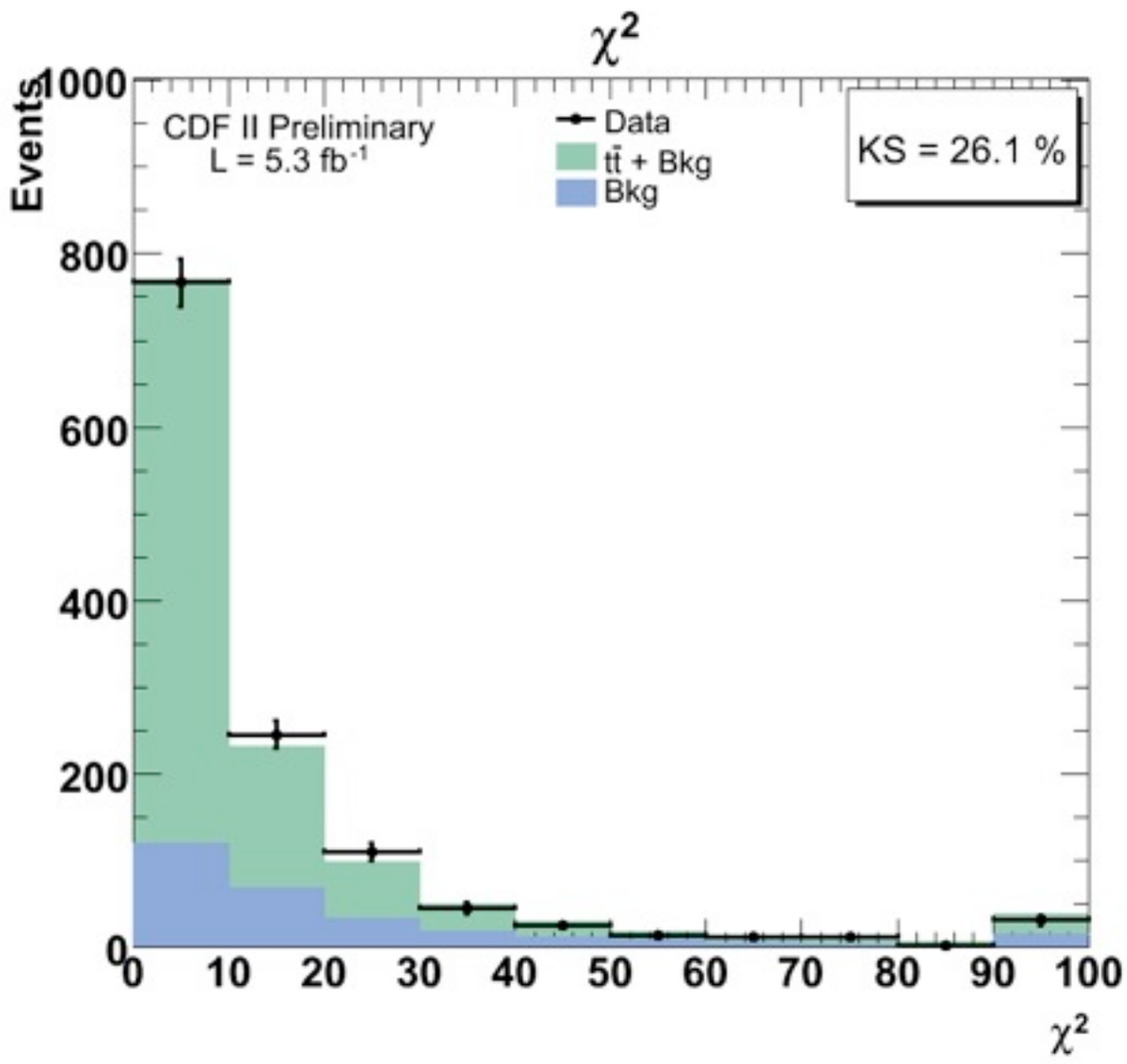
Event Reconstruction

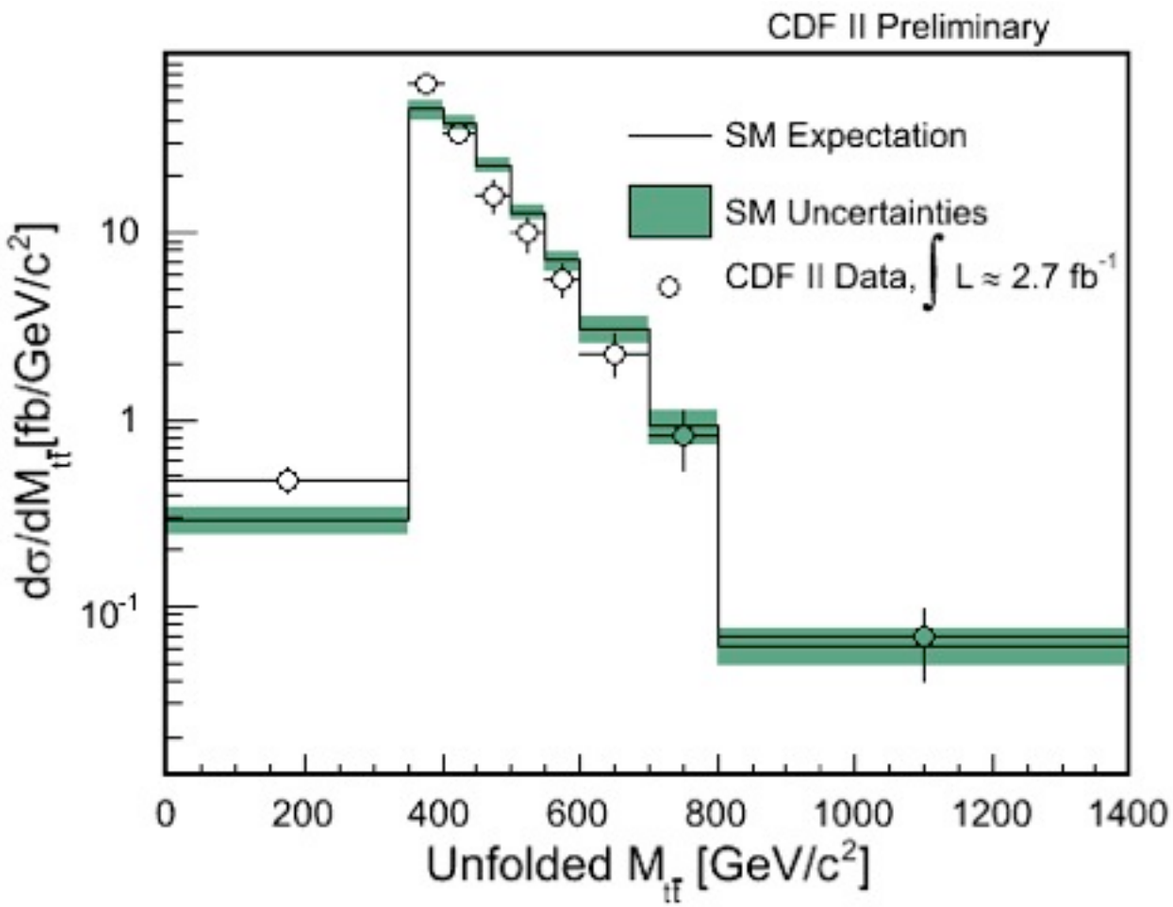


Choose Combination with Best χ^2

All particle energies and angles are available after reconstruction

Event Reconstruction

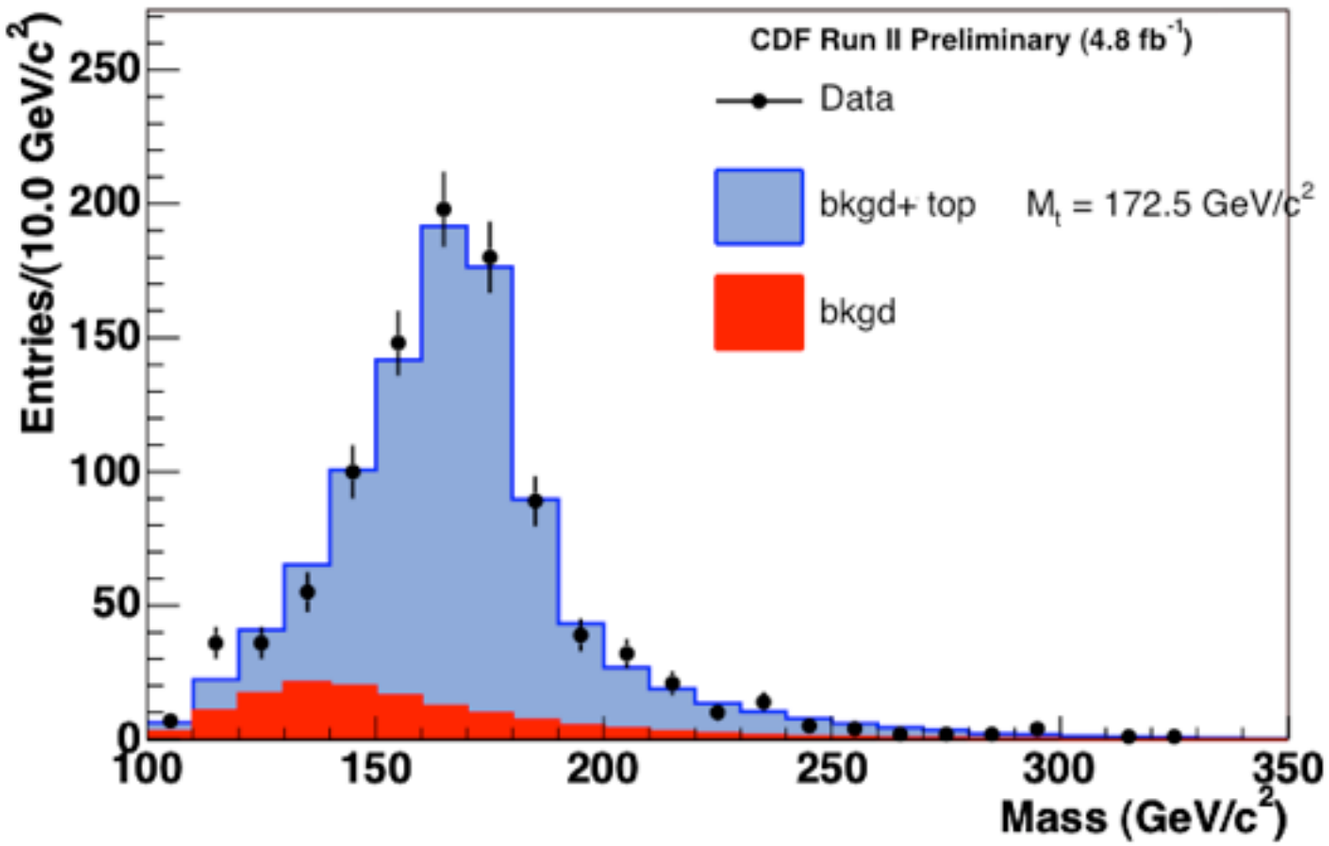




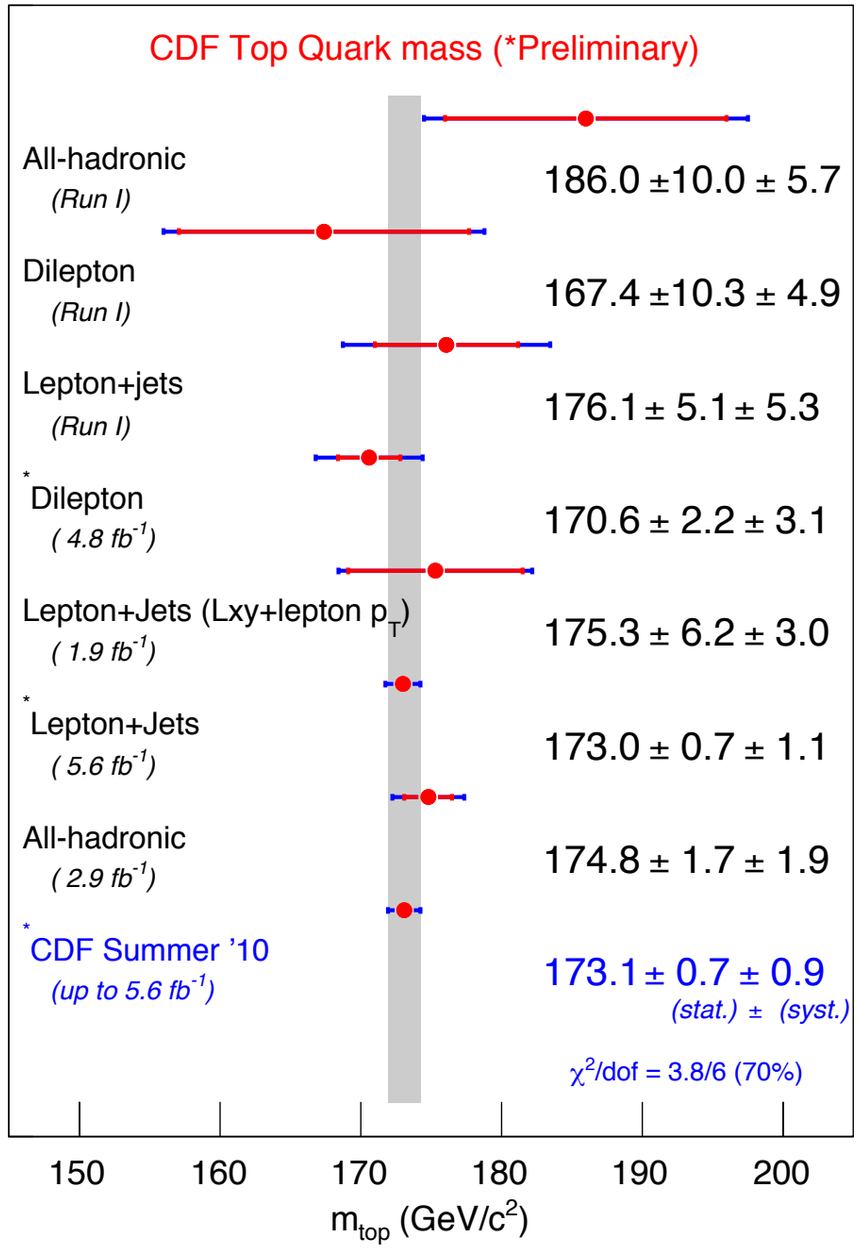
http://www-cdf.fnal.gov/physics/new/top/2010/tprop/Afb/validation.html

Reconstructed Mass

Used in CDF Top Mass Measurement



M_T = 172.0 ± 1.5 GeV



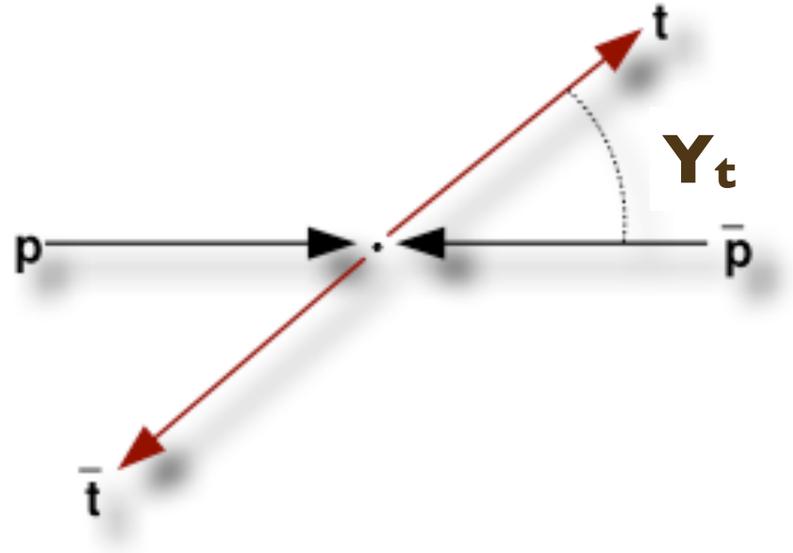
Top Angle

- **Use the top rapidity (Y_t) to measure the asymmetry**

- **Unfortunately, we do not reconstruct top or antitop, rather t→lvb and t→jjb**

- **Rapidity difference (ΔY) of t and $\bar{t}$ is proportional to Y_t in $t\bar{t}$ rest frame**

- **Measure A_{FB} using ΔY**

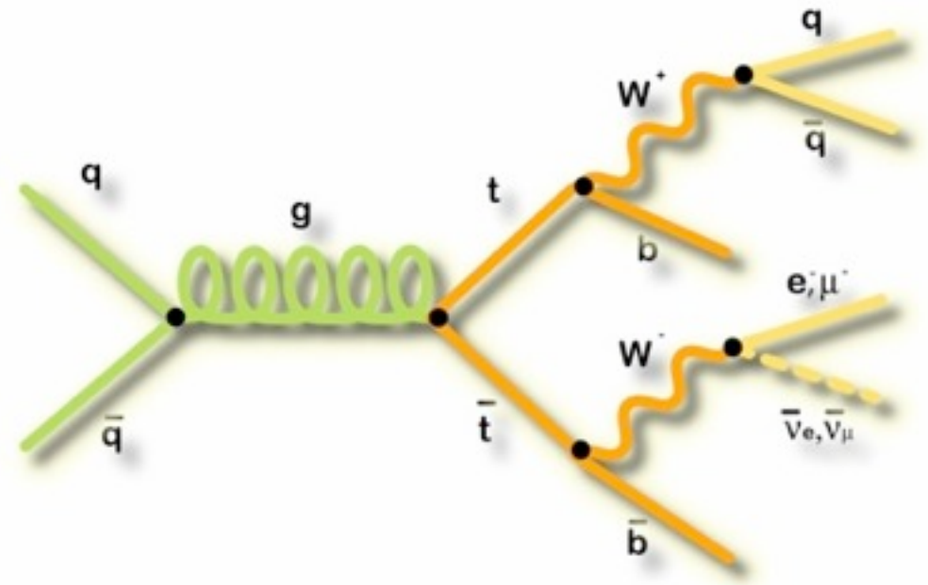


$$\Delta Y = q_{lep} \cdot (Y_{lep} - Y_{had})$$

Top Angle

- **Use the top rapidity (Y_t) to measure the asymmetry**

- **Unfortunately, we do not reconstruct top or antitop, rather t→lvb and t→jjb**



- **Rapidity difference (ΔY) of t and $\bar{t}$ is proportional to Y_t in $t\bar{t}$ rest frame**

$$\Delta Y = q_{lep} \cdot (Y_{lep} - Y_{had})$$

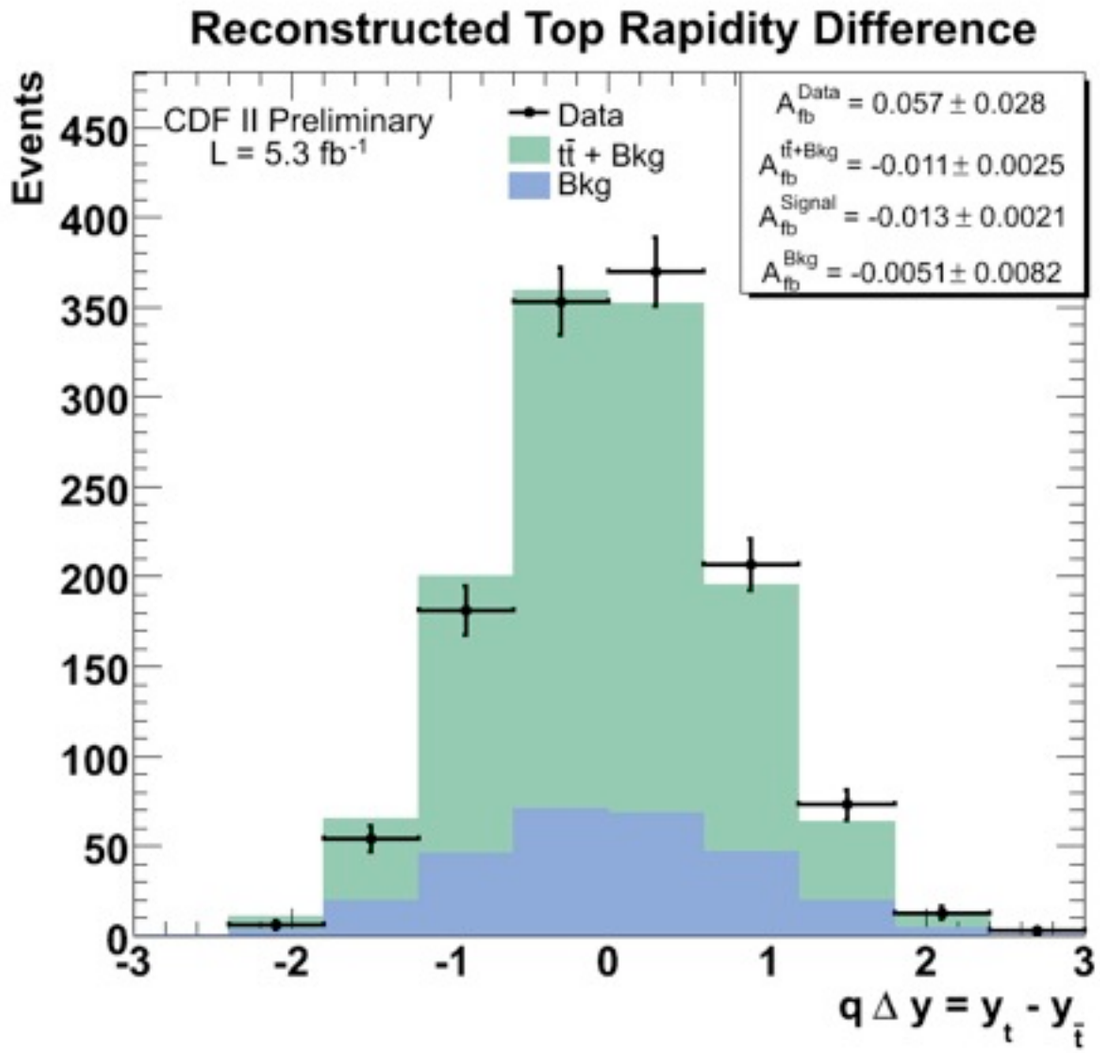
- **Measure A_{FB} using ΔY**

Top Angle

Uncorrected

A_{FB} = 5.7 ± 2.8 %

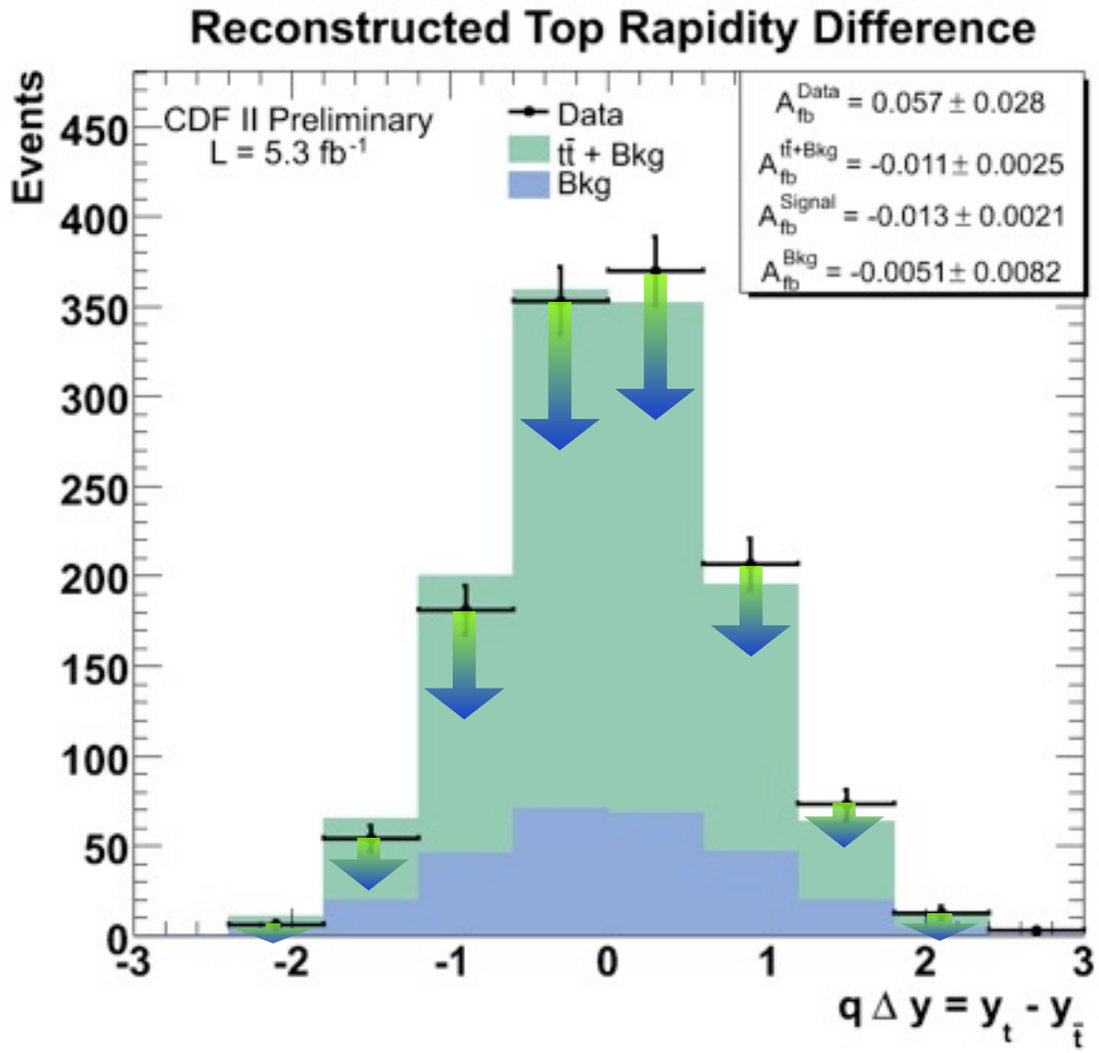
- The shape in data can be biased and diluted by backgrounds, acceptance, and poor reconstruction
- Each effect has to be corrected to compare our measurement to theory



Backgrounds

- **Subtract predicted background shape from data**

- **Resulting distribution is the $t\bar{t}$ production angle after selection and reconstruction**



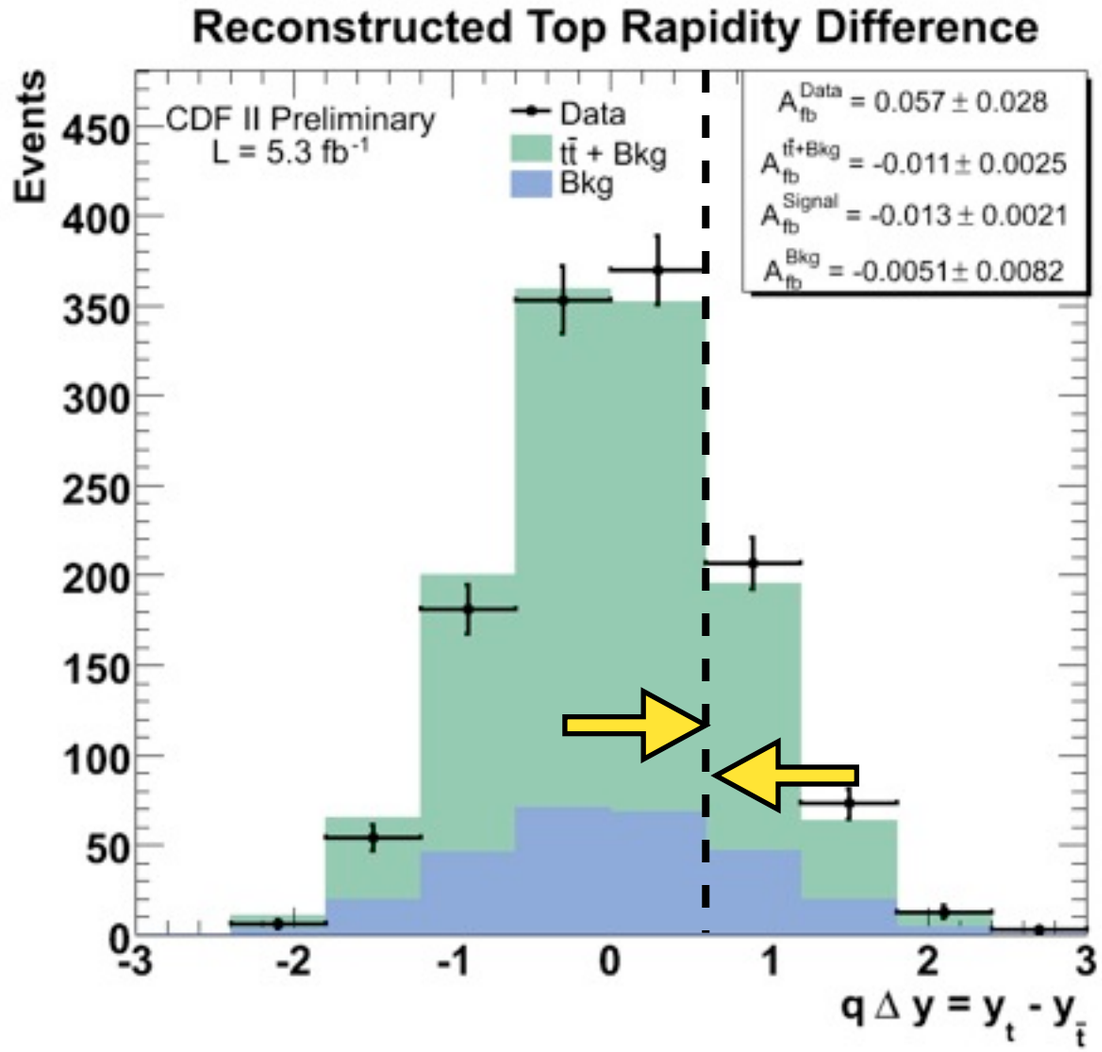
Bkg Corrected

$A_{FB} = 7.5 \pm 3.7\ \%$

Correcting Reconstruction

- **Mis-reconstruction of the top production angle will dilute or skew the true asymmetry**

- **Can correct for this by simulating smearing in Monte Carlo and applying to data**

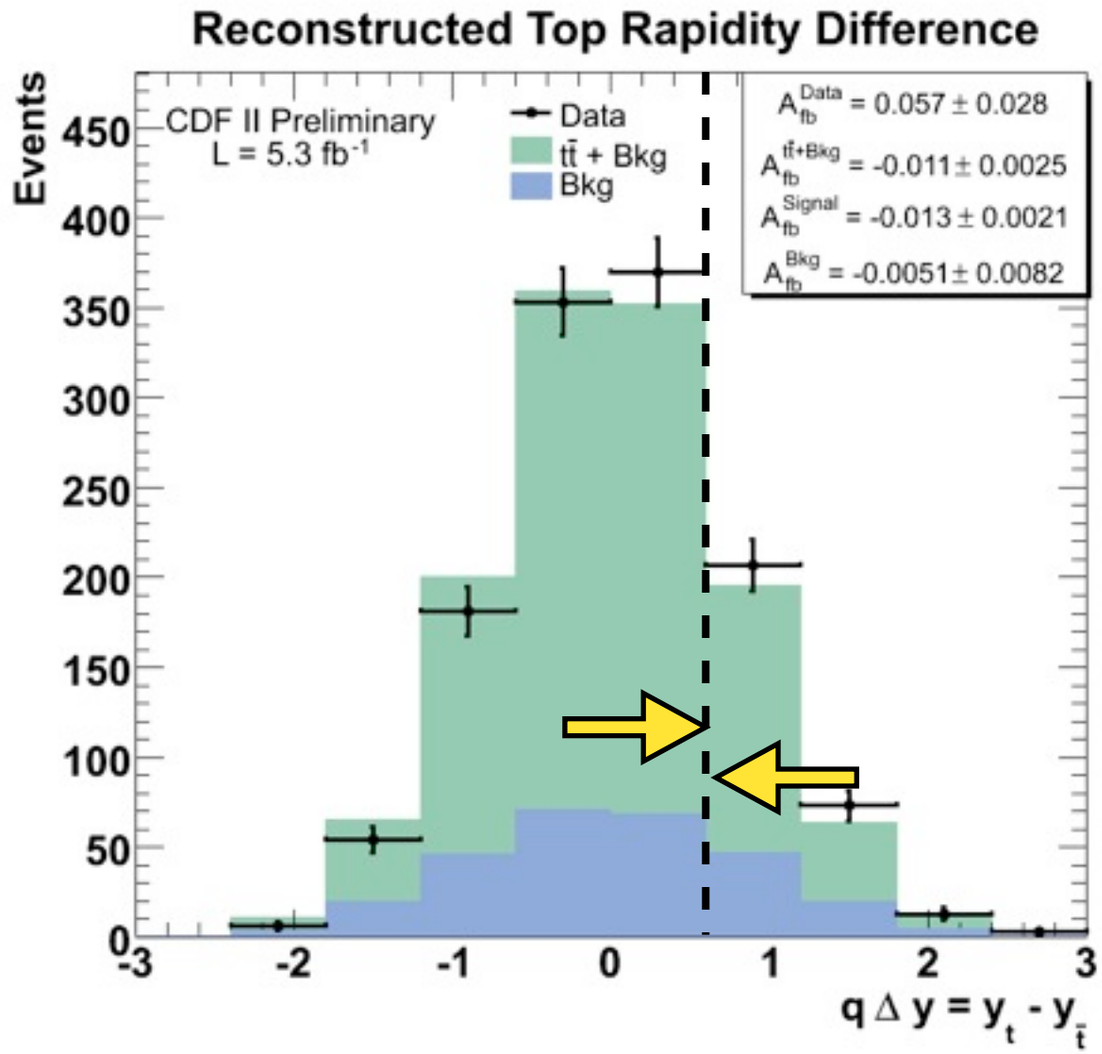


Correcting Reconstruction

- **Derive smearing matrix (S) from MC**

$$[Recon] = \begin{bmatrix} s_{0,0} & s_{0,1} & \cdots & s_{0,nbins} \\ s_{1,0} & s_{1,1} & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ s_{nbins0} & \cdots & \cdots & s_{nbins,nbins} \end{bmatrix} [True]$$

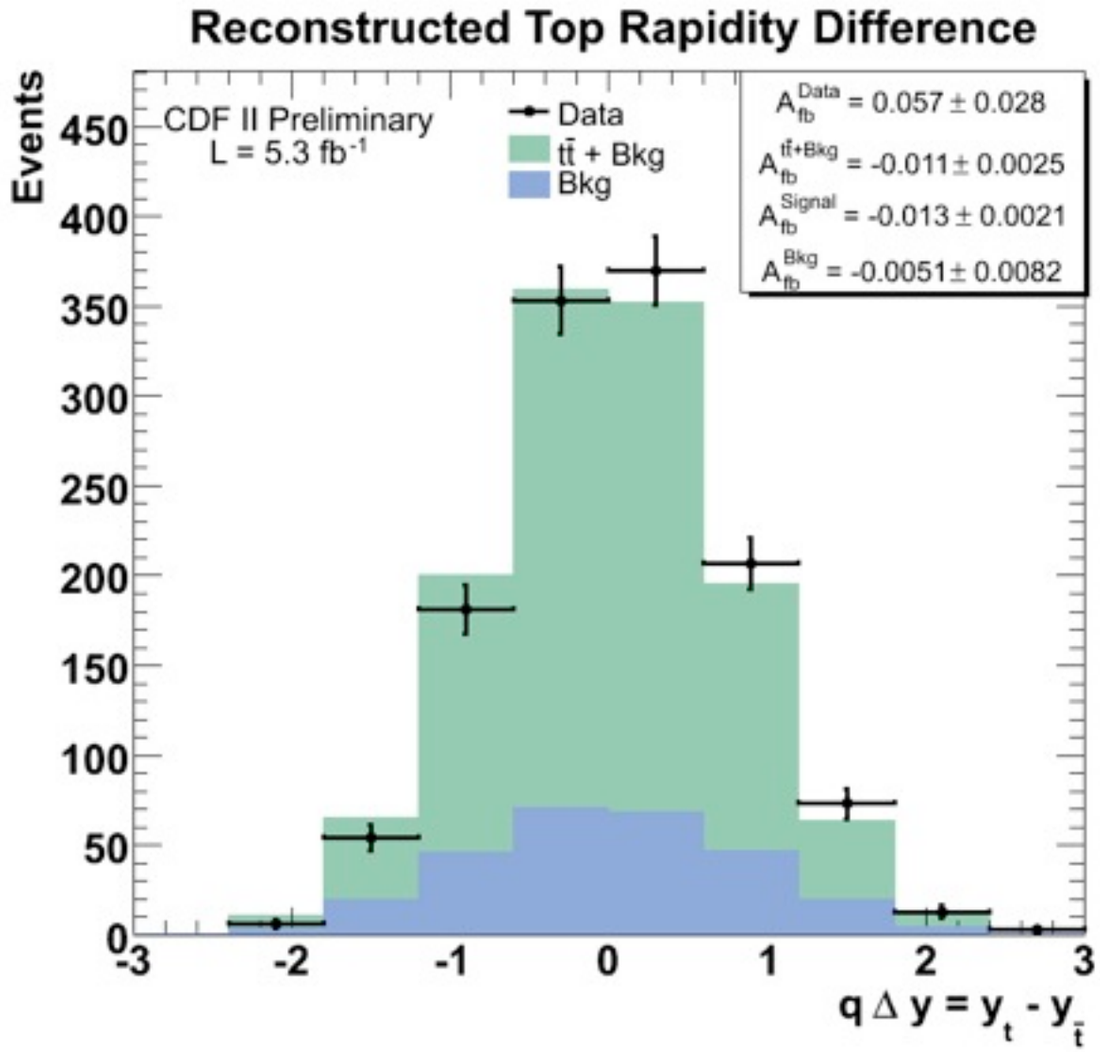
- **The matrix is inverted to correct for smearing**



Correcting Acceptance

- **Similarly, detector acceptance is represented as a matrix (A)**

$$[Selected] = \begin{bmatrix} \epsilon_0 & 0 & 0 & 0 \\ 0 & \epsilon_1 & 0 & 0 \\ 0 & 0 & ... & 0 \\ 0 & 0 & 0 & \epsilon_{nbins} \end{bmatrix} [True]$$



Putting it All Together

- Cascade correction matrices and apply to the background corrected data

- Result can then be directly compared to the Standard Model

$$\mathbf{Corrected} = \mathbf{A}^{-1} \cdot \mathbf{S}^{-1} \cdot (\mathbf{Data} - \mathbf{Bkg})$$

Bin-to-Bin Oscillations

- **Simple Example of a smearing matrix**

$$\begin{bmatrix} d_1 \\ d_2 \end{bmatrix} = \frac{1}{2} \cdot \begin{bmatrix} 1+\epsilon & 1-\epsilon \\ 1-\epsilon & 1+\epsilon \end{bmatrix} \cdot \begin{bmatrix} t_1 \\ t_2 \end{bmatrix}$$

- **Inverted to solved for truth, you get**

$$\begin{bmatrix} t_1 \\ t_2 \end{bmatrix} = \frac{d_1+d_2}{2} \cdot \begin{bmatrix} 1 \\ 1 \end{bmatrix} + \frac{d_1-d_2}{2\epsilon} \cdot \begin{bmatrix} 1 \\ -1 \end{bmatrix}$$

- **If d1 - d2 are not statistically distinct, then bad smearing can dominate the solution! Need a way to dampen these terms...**

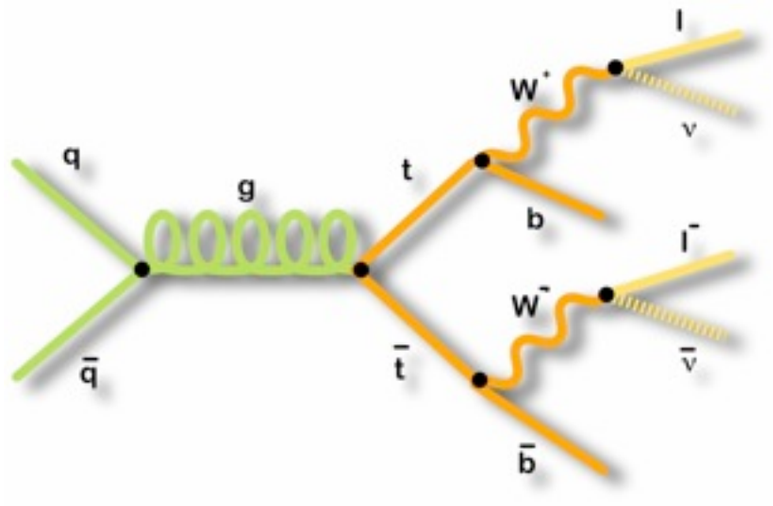
A_{FB} in Dileptons

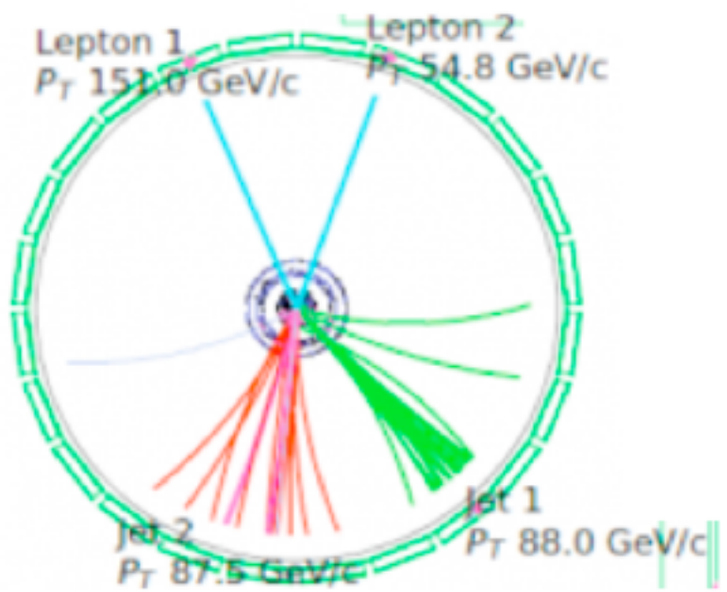
- **Leptons well measured, but missing two neutrino momenta and match jets to b quarks**

- **Energy, momentum constraints lead to 4 possible solutions**

- **Best solution chosen from likelihood based on PDF's for P_z^{tt}, P_T^{tt}, and M_{tt}**

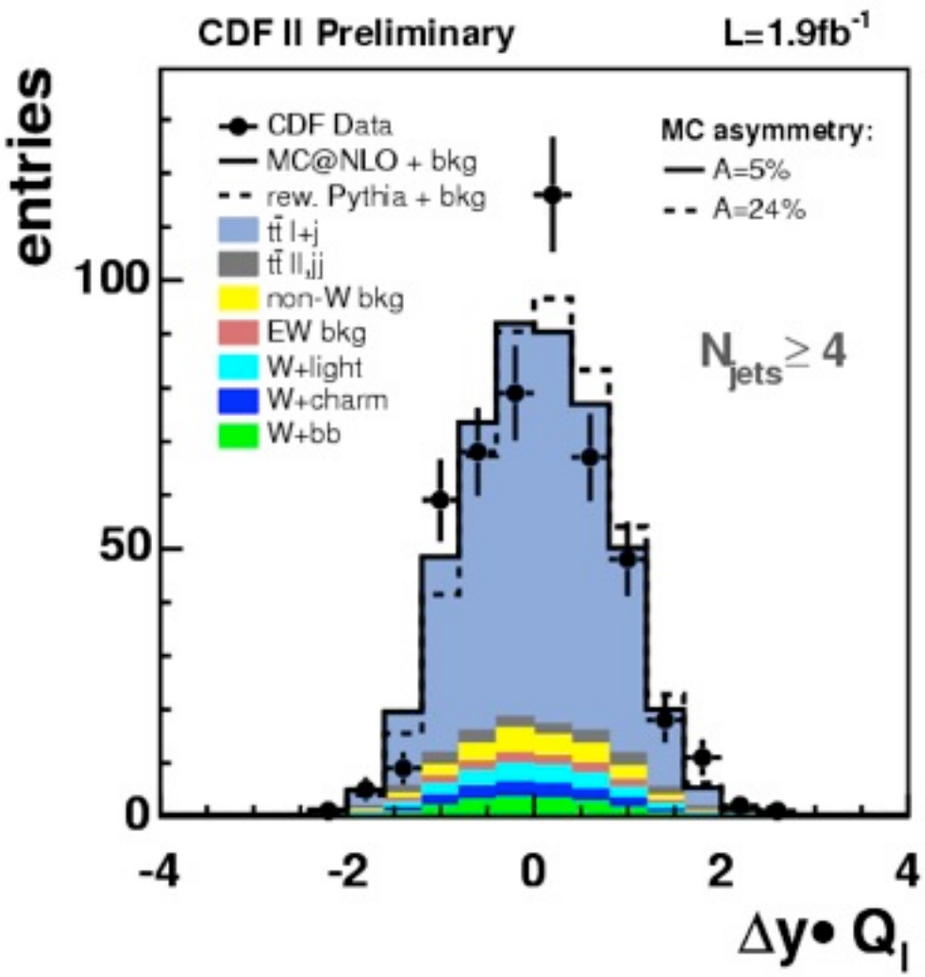
- **Top and anti-top direction both fully reconstructed**





Other Signs?

- **Alternative measurement at CDF (Karlsruhe)**
- **Measured in $t\bar{t}$ rest frame**
- **Performed with 1.9 fb^{-1}**



$A_{FB} = 24 \pm 14_{stat+sys}$ %

$A_{FB}^{SM} = 7 \pm 2$ %