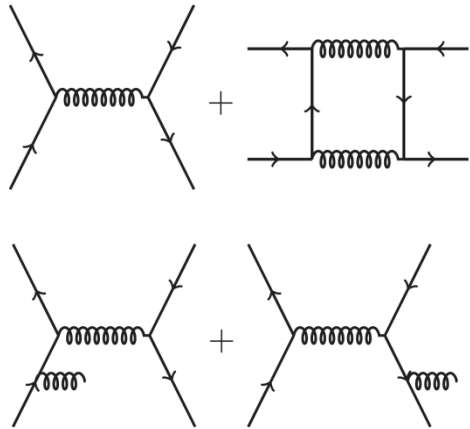




# Top Quark Forward-Backward Asymmetry in the Lepton+Jets Channel

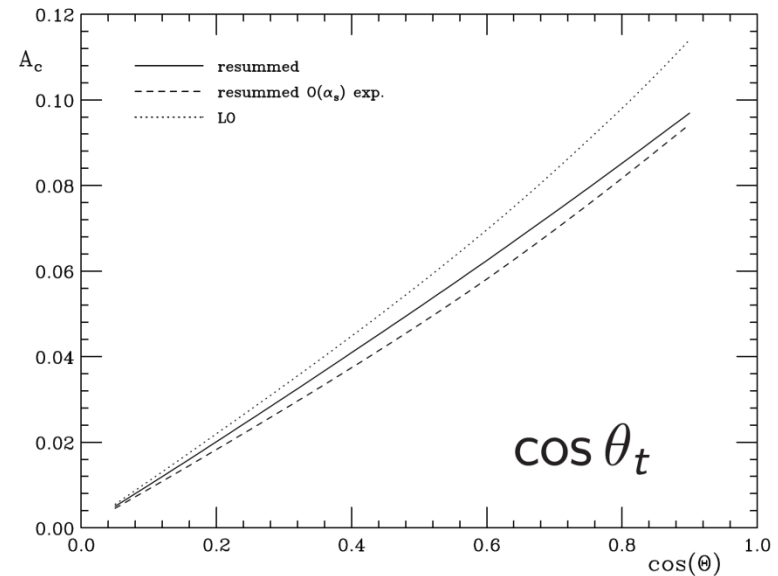
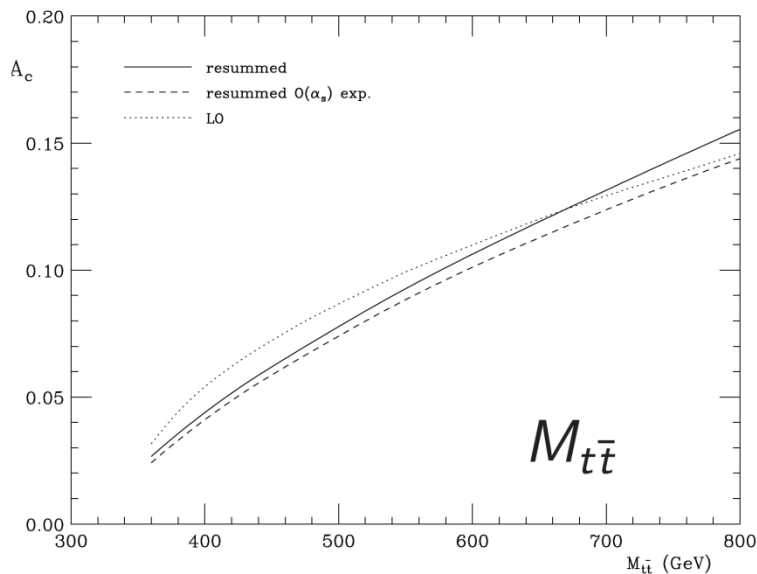
The CDF Collaboration  
presented by  
D. Amidei  
University of Michigan

# tt charge asymmetry in NLO QCD



- $C = -1$  &  $C = +1 \rightarrow A_C$
- at Tevatron this is an  $A_{FB}$
- measure in  $\Delta y = y_t - y_{\bar{t}}$
- prediction now includes EWK part  
(Kuhn-Rodrigo, Hollik-Pagani, Manohar-Trott)
- $A_{FB}(\text{total}) = A_{FB}(\text{QCD}) \times 1.26 = 0.066$   
(our Powheg model)

differential behavior (Almeida et al., PRD87, 014008, 2008)



# prior measurements

## inclusive

CDF l+jet 5.3 fb <sup>-1</sup>	15.8 ± 7.4	
CDF DIL 5.1 fb <sup>-1</sup>	42.0 ± 16.0	
CDF combo	20.1 ± 6.7	
D0 l+jet 5.4 fb <sup>-1</sup>	19.6 ± 6.5	
informal combo	19.8 ± 4.7	NLO 6.6

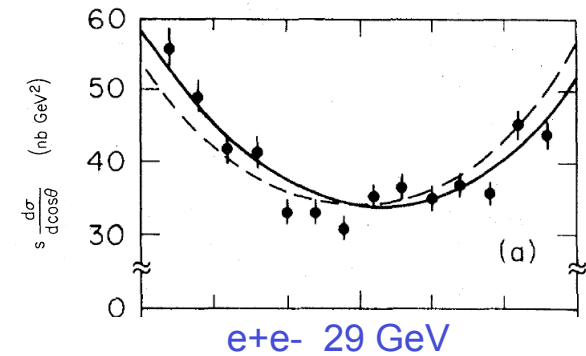
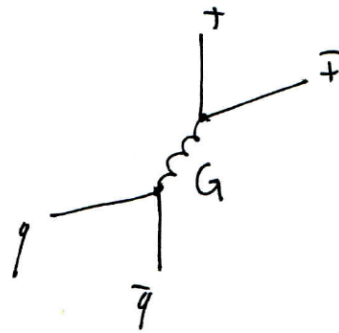
## differential (at bkg subtracted data level)

	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$	$ \Delta y  < 1.0$	$ \Delta y  \geq 1.0$
CDF l+jets	-2.2 ± 4.0	26.6 ± 6.2	2.9 ± 4.0	29.1 ± 9.0
D0 l+jets	7.8 ± 4.8	11.5 ± 6.2	6.1 ± 4.1	21.3 ± 9.7
informal combo	2.8 ± 3.3	19.0 ± 4.4	4.5 ± 2.8	25.2 ± 6.6
NLO + EWK	1.5 ± 0.3	4.9 ± 1.0	1.6 ± 0.3	7.2 ± 1.4

# BSM ideas

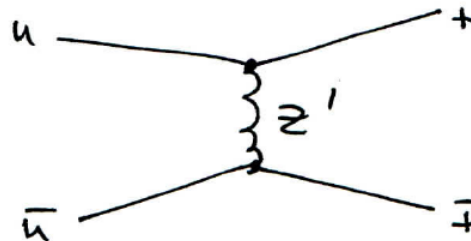
- s-channel

- massive chiral color oct
- “axigluon”
- RS gluon



- t-channel

- W'Z'
- color triplets, sextets



- BSM model building must contend with

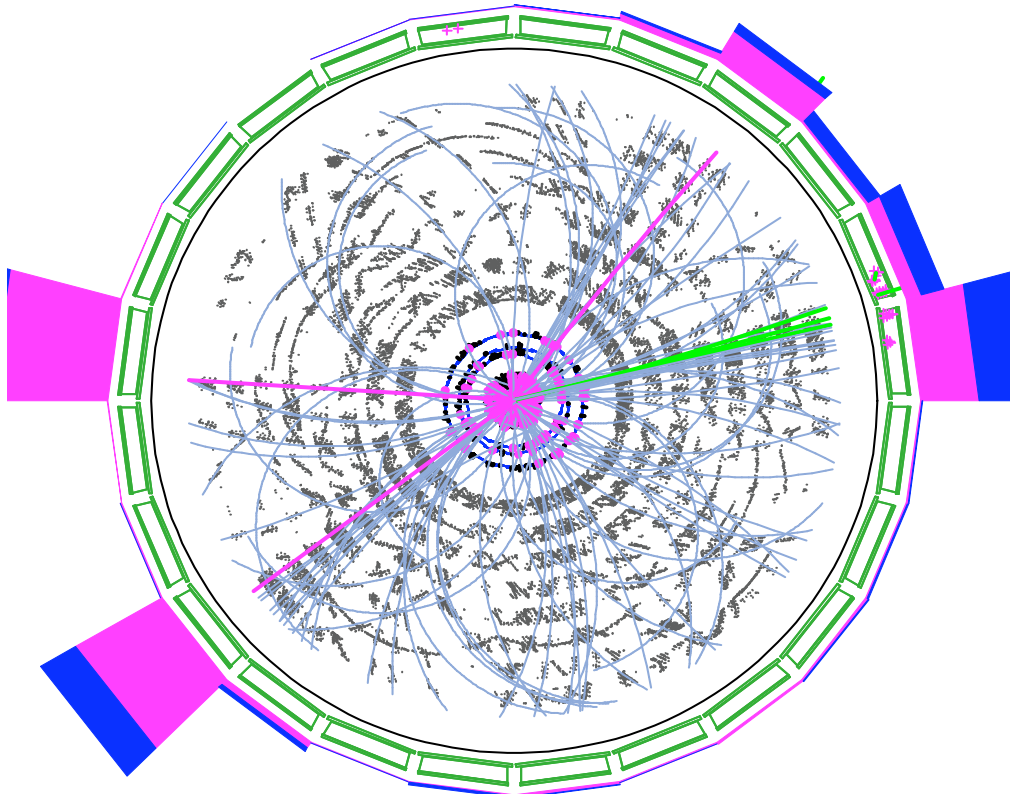
- total  $\sigma$ ,  $d\sigma/dM_{tt}$  in good agreement with SM at Tevatron, LHC
- absence of other indirect indications

# new CDF analysis

- full Run II data set
  - 8.7 fb<sup>-1</sup>
  - add new muon trigger stream
  - 2498 events (x2 last analysis)
- NLO ttbar model
  - Powheg + EWK corrections
  - inc. tt p<sub>t</sub> dependence a la NLO
- multi-bin differential A<sub>fb</sub>'s
  - A<sub>fb</sub>(Δy), A<sub>fb</sub>(M<sub>tt</sub>)
  - linear fits, p-values
  - multi-bin correction to parton level
- lepton only asymmetry
- p<sub>t</sub> dependence of the asymmetry

## selection and reconstruction

$$q\bar{q} \rightarrow g \rightarrow t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (l^+\nu b)(q\bar{q}\bar{b}) \rightarrow l^+ + \cancel{E}_T + 4j + \geq 1 \text{ btag}$$

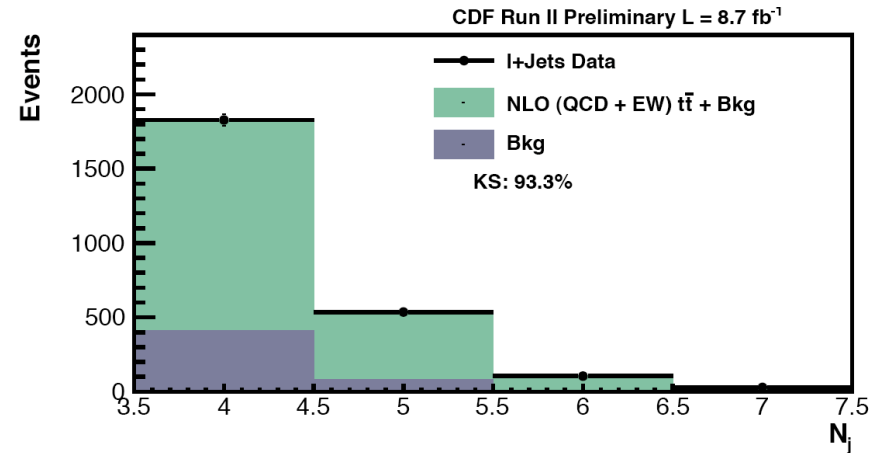


- lepton (e/μ)  $E_t/p_t > 20$  GeV (/c)
- missing  $E_t > 20$  GeV
- .g.e. 4 jets  $E_t > 20$  GeV
  - at least one b-tagged jet
- $H_t > 220$  GeV
- 2498 events    bkg =  $505 \pm 123$

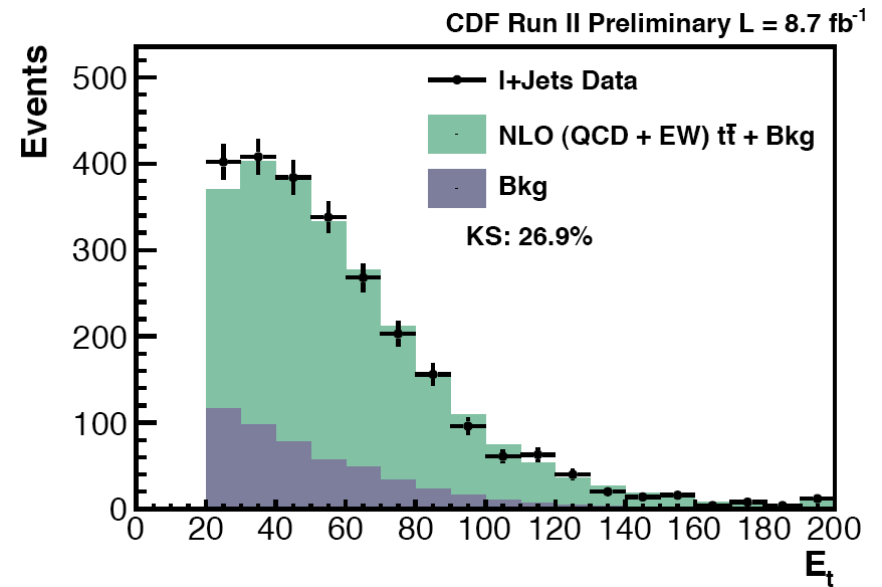
# modeling

- $t\bar{t}$ : POWHEG NLO
  - good agreement with mc@nlo, mcfm
  - pythia showers + CDF simulation
  - asymmetries
    - use Powheg denominator
    - use Powheg central value
    - x 1.26 for EWK

## jet multiplicity



## missing $E_t$



## CDF b-tag background model

CDF Run II Preliminary L = 8.7 fb<sup>-1</sup>

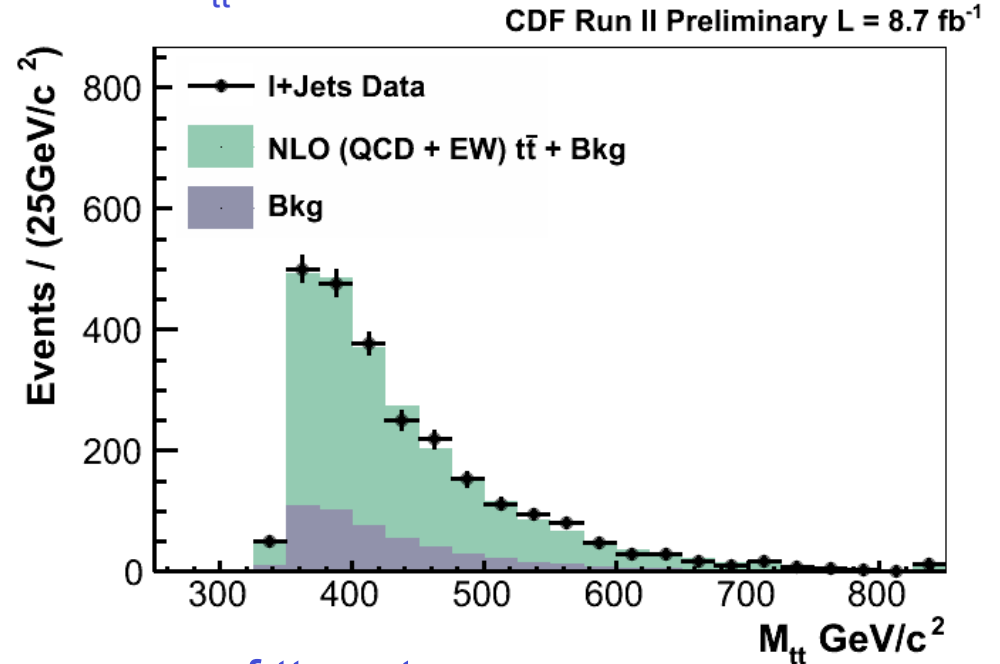
	$\geq 4$ jets	
W+HF	241 ± 78	
Non-W	98 ± 51	
W+LF	96 ± 29	
Single Top	33 ± 2	
Diboson	19 ± 3	
Z+Jets	18 ± 2	
Total Background	505 ± 123	
$t\bar{t}$ 7.4pb	2037 ± 277	
Total Prediction	2542 ± 303	
Data	2498	

# top reconstruction

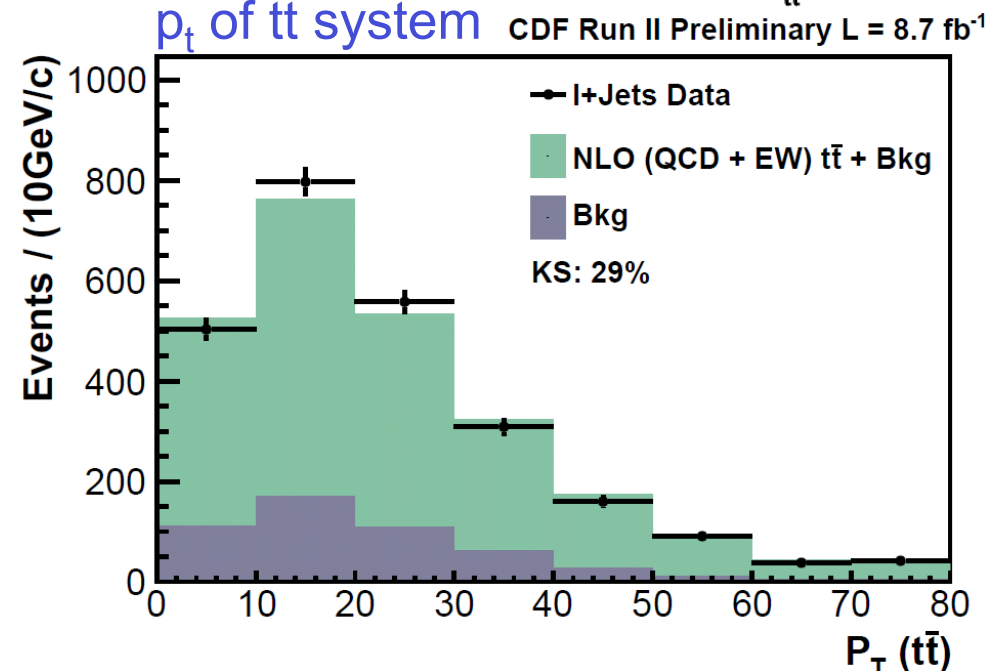
$$l^+ + \mathbf{E}_T + 4\mathbf{j} + \geq 1 \text{ btag} \rightarrow t\bar{t}$$

- jet parton match and  $p_z(\nu)$  solution using simple constraints and  $\chi^2$ 
  - $M_W = 80.4 \text{ GeV}/c^2$
  - $M_t = 172.5 \text{ GeV}/c^2$
  - btag = b
  - float jet  $p_t$  within errors
- sign of lepton  $\rightarrow$  charge of tops

$M_{t\bar{t}}$

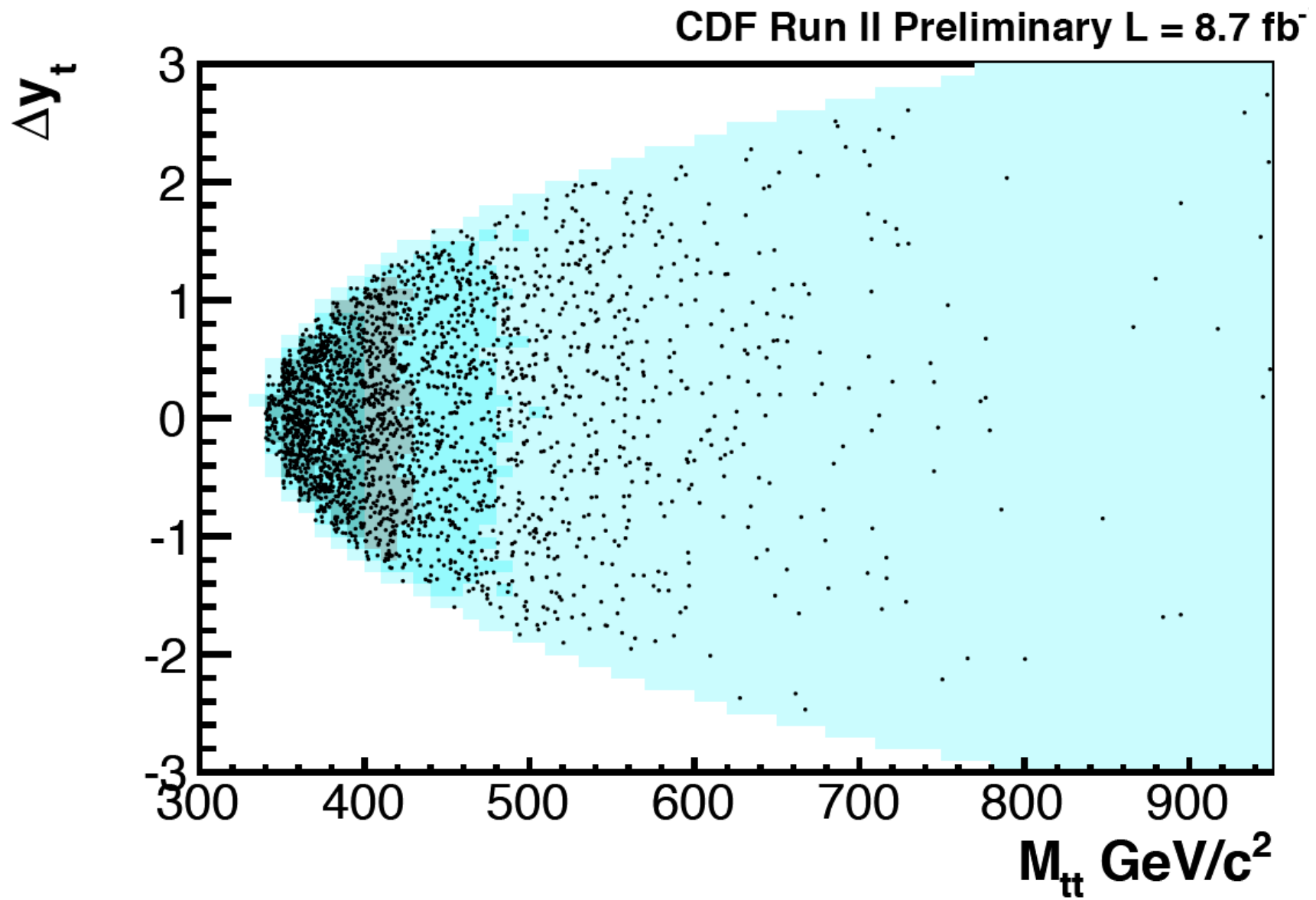


$p_t$  of  $t\bar{t}$  system





the  $\Delta y - M_{tt}$  plane

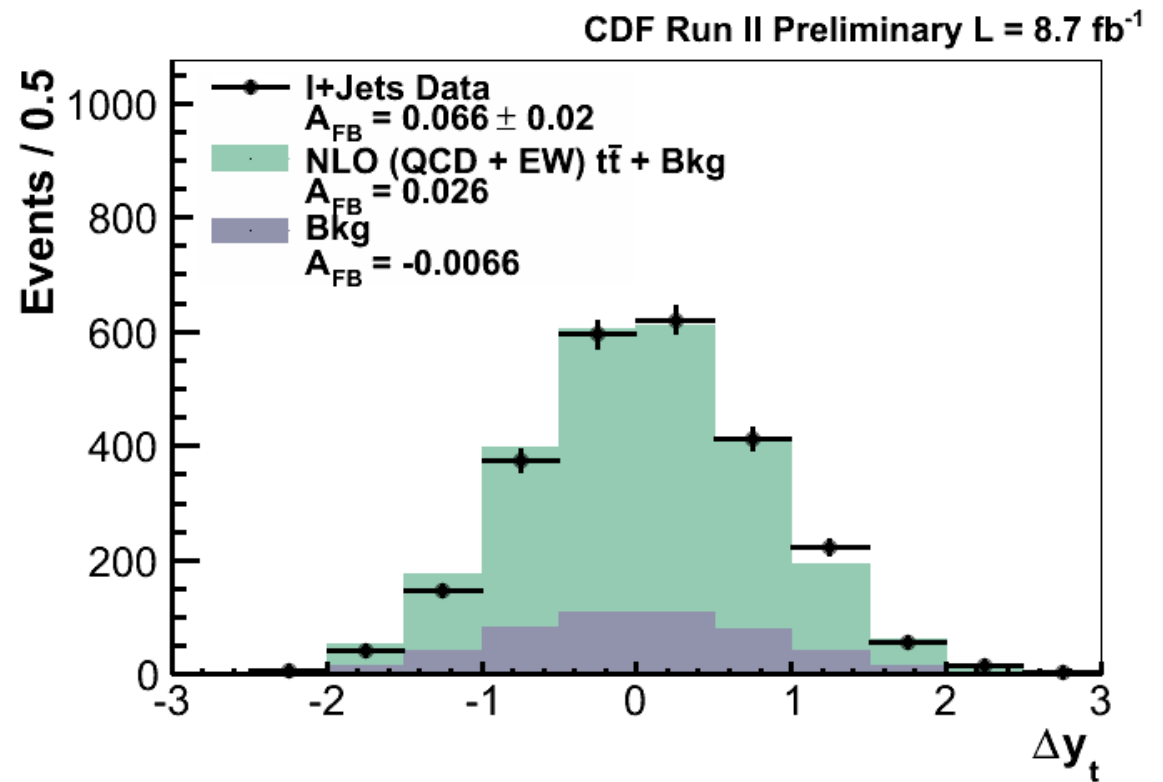


# rapidity

$$\begin{aligned}\Delta y &= q \cdot (y_{t\ell} - y_{t\bar{h}}) \\ &= y_t - y_{\bar{t}} \\ &= 2y_t^{\bar{t}\bar{t}}\end{aligned}$$

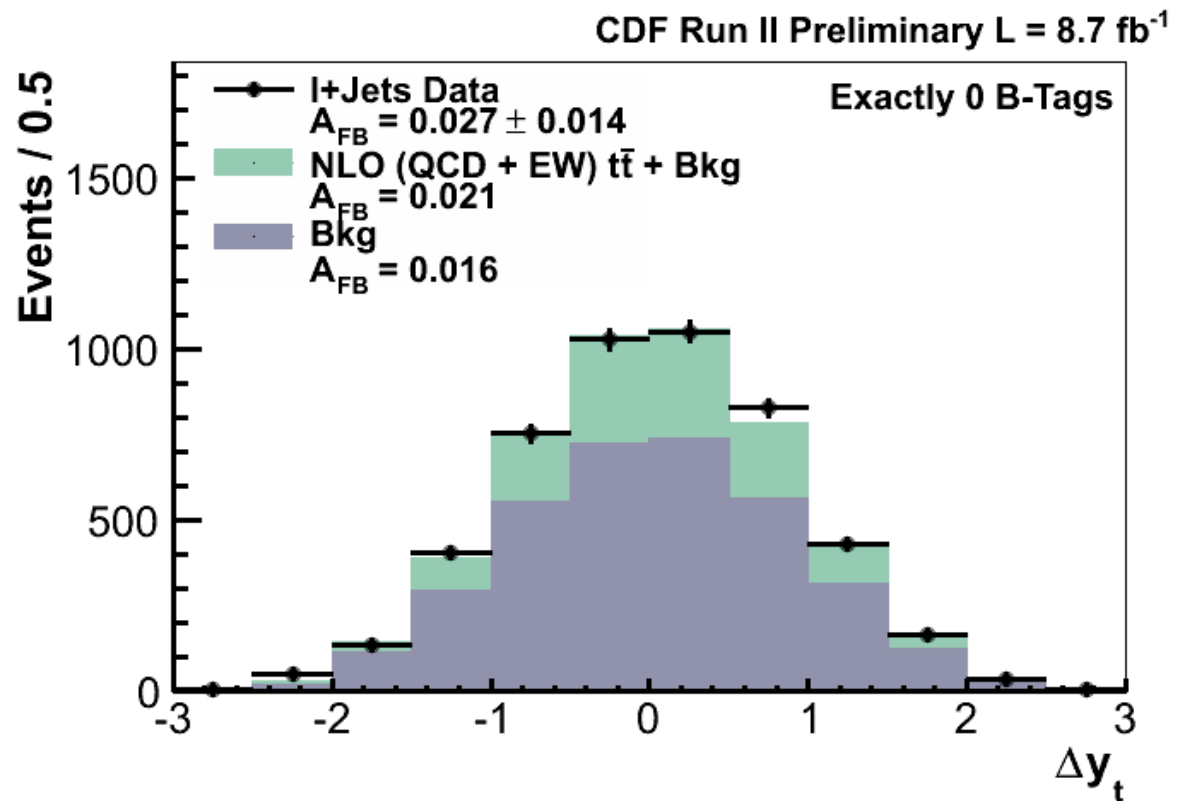
$$A^{\bar{t}\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

- $A_{\text{fb}}$  data =  $(6.6 \pm 2.0)\%$
- $A_{\text{fb}}$  pred. = 2.6%



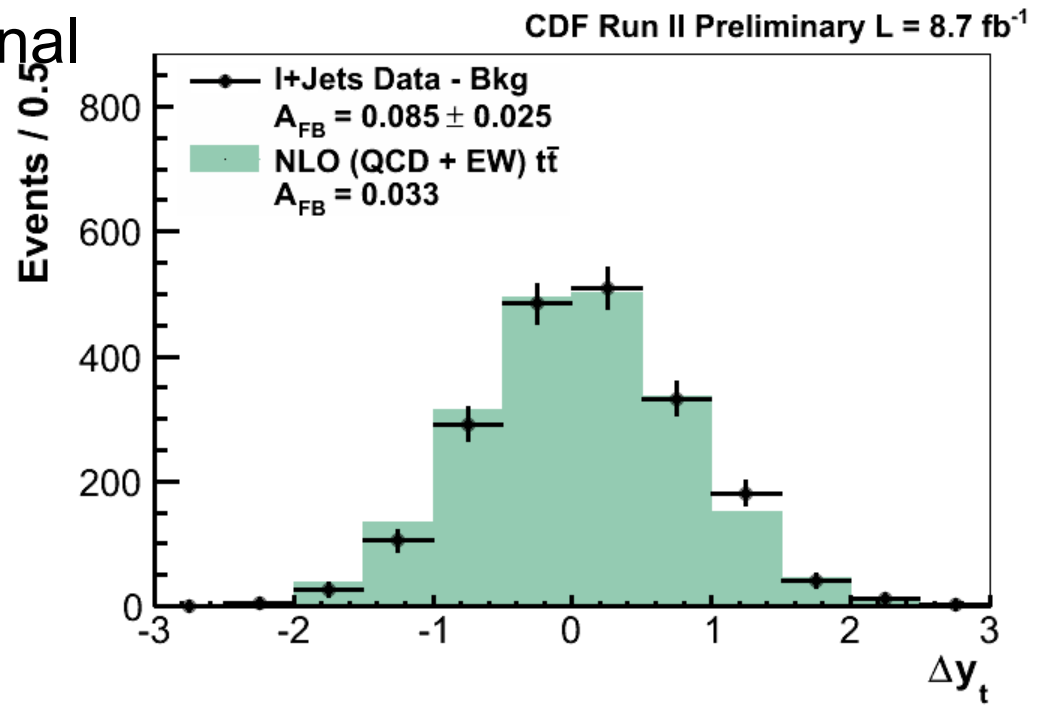
# backgrounds

- check in 0-btag sample  
~ 80% non-tt
- $A_{fb}$  data =  $(2.7 \pm 1.4)\%$
- $A_{fb}$  pred. = 2.1%
- suggests
  - bkg well modeled
  - bkg not source of  $A_{fb}$  !



# $\Delta y$ of reconstructed $t\bar{t}$ signal

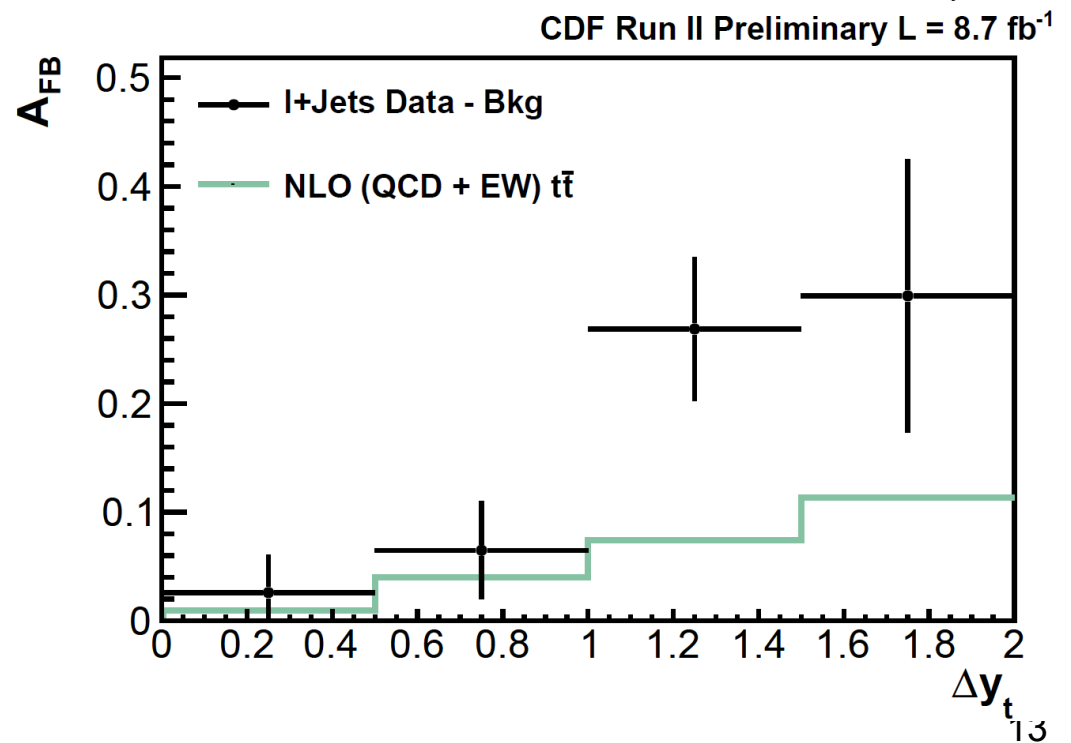
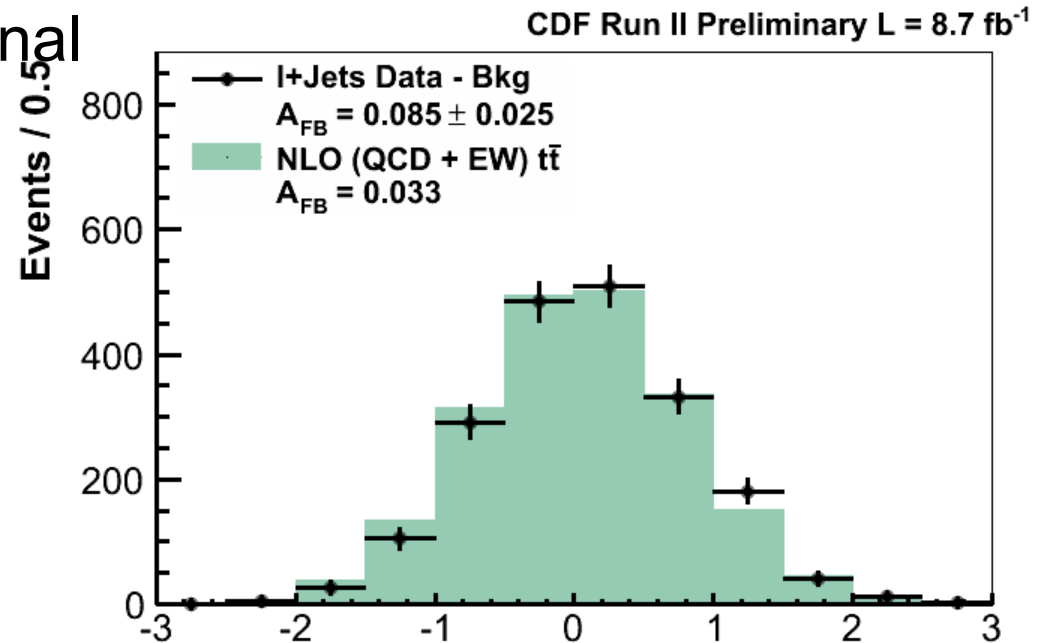
- subtract background
  - sys uncertainties included
    - bkg model  $\delta A_{fb} \sim 0.008$
    - bkg norm  $\delta A_{fb} \sim 0.005$
- $A_{fb}$  data =  $(8.5 \pm 2.5)\%$
- $A_{fb}$  pred = 3.3%



# $\Delta y$ of reconstructed $t\bar{t}$ signal

- subtract background
  - sys uncertainties included
    - bkg model  $\delta A_{fb} \sim 0.008$
    - bkg norm  $\delta A_{fb} \sim 0.005$
- $A_{fb}$  data =  $(8.5 \pm 2.5)\%$
- $A_{fb}$  pred = 3.3%
- rapidity dependence

$$A_{FB}(|\Delta y|) = \frac{N(|\Delta y|) - N(-|\Delta y|)}{N(|\Delta y|) + N(-|\Delta y|)}$$

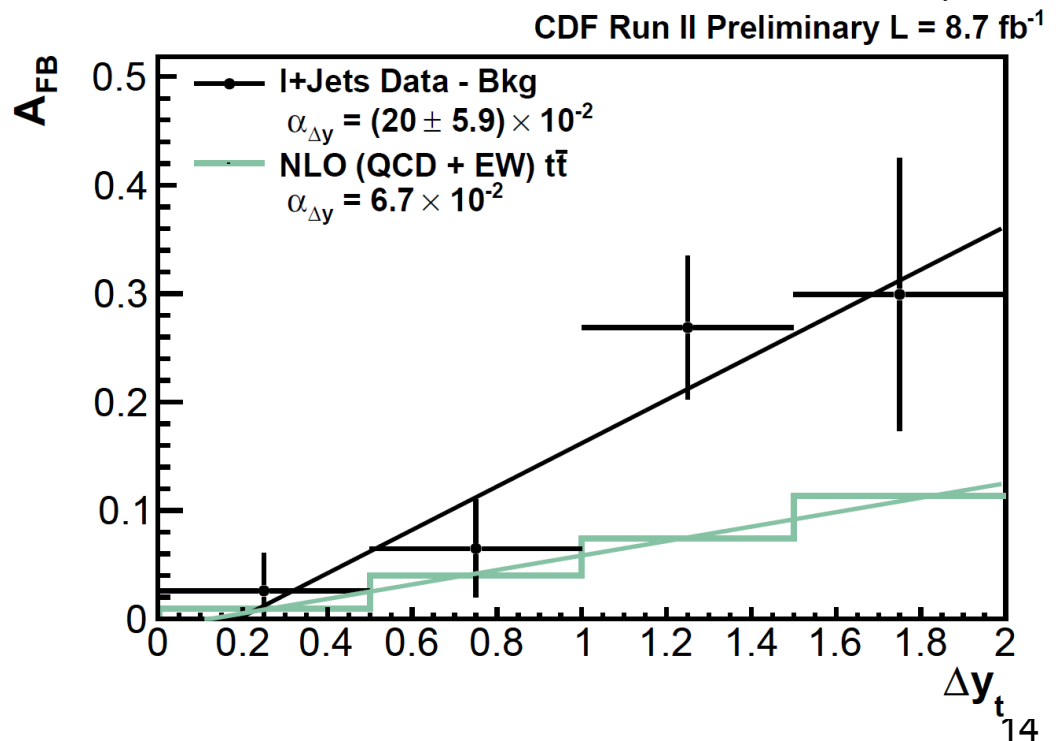
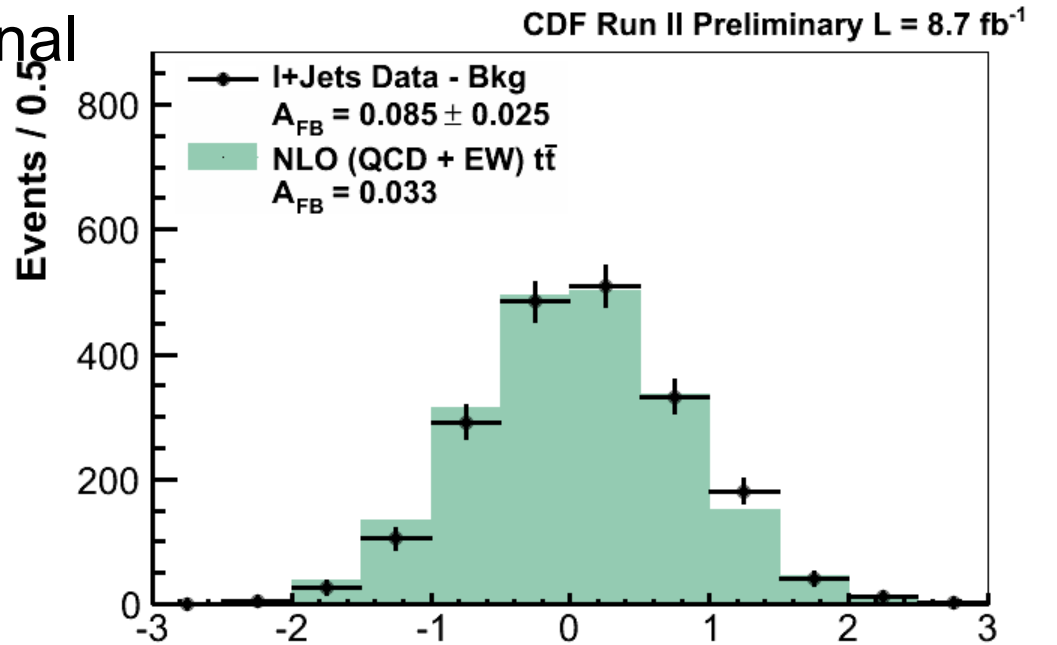


# $\Delta y$ of reconstructed $t\bar{t}$ signal

- subtract background
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    - bkg model  $\delta A_{fb} \sim 0.008$
    - bkg norm  $\delta A_{fb} \sim 0.005$
- $A_{fb}$  data =  $(8.5 \pm 2.5)\%$
- $A_{fb}$  pred = 3.3%
- rapidity dependence

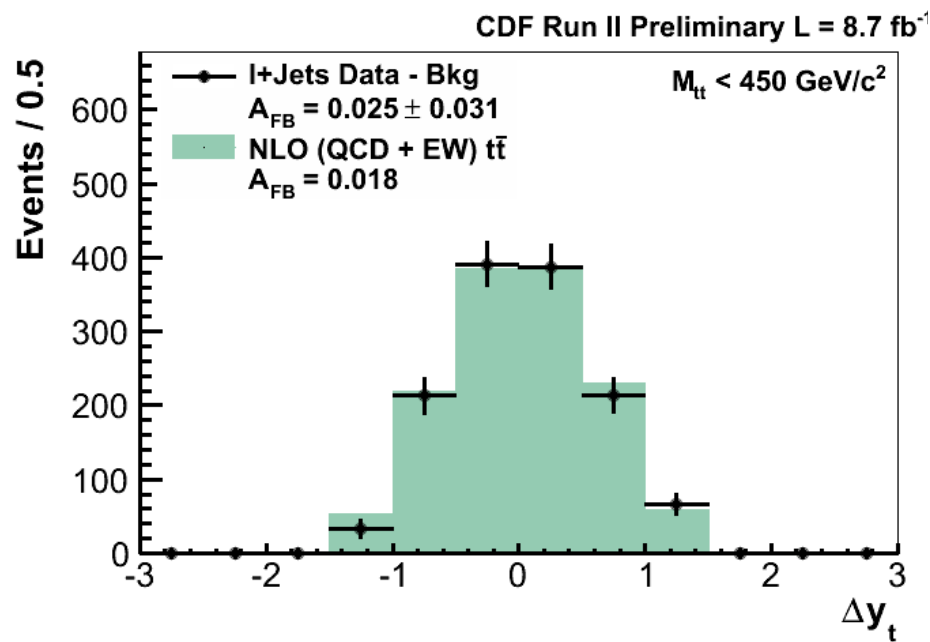
$$A_{FB}(|\Delta y|) = \frac{N(|\Delta y|) - N(-|\Delta y|)}{N(|\Delta y|) + N(-|\Delta y|)}$$

- $A(\Delta y)$  linear form, slope  $\alpha$
- fit  $\chi^2$  p.d.f. of data = 1.0
- significance
  - slope is  $> 3\sigma$  from 0
  - PE how often  $\alpha_{NLO} \geq \alpha_{data}$
  - $p_{NLO} = 0.00892$

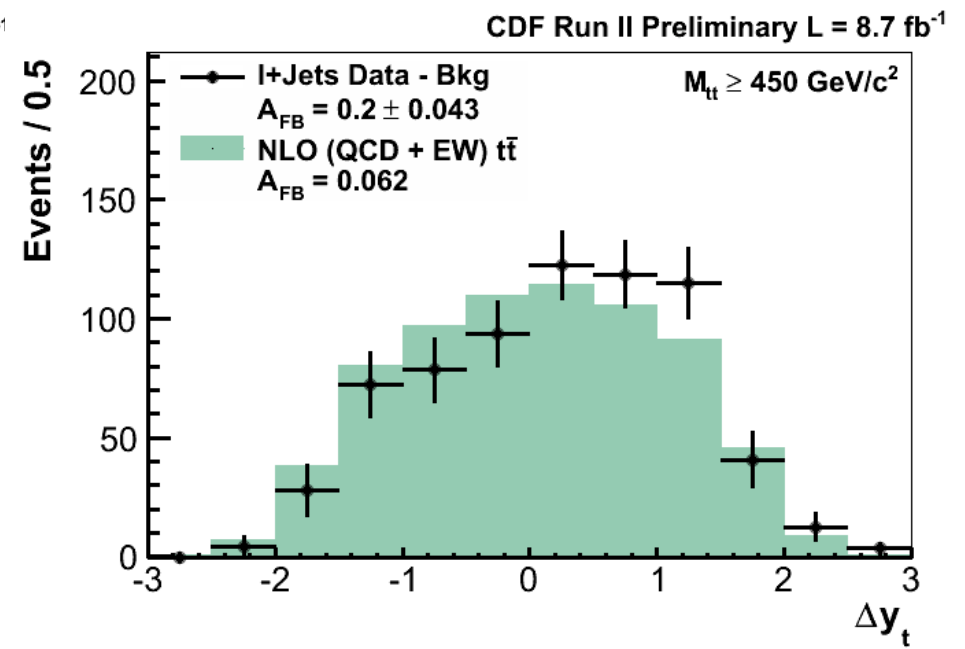


# mass dependence

$M_{t\bar{t}} < 450 \text{ GeV}/c^2$



$M_{t\bar{t}} > 450 \text{ GeV}/c^2$

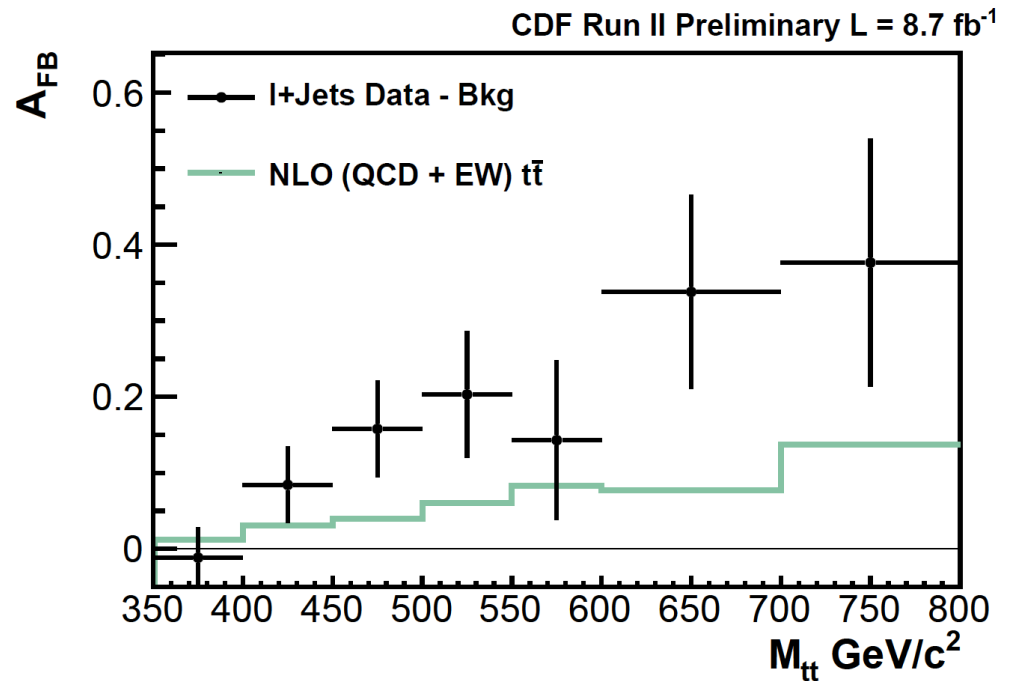
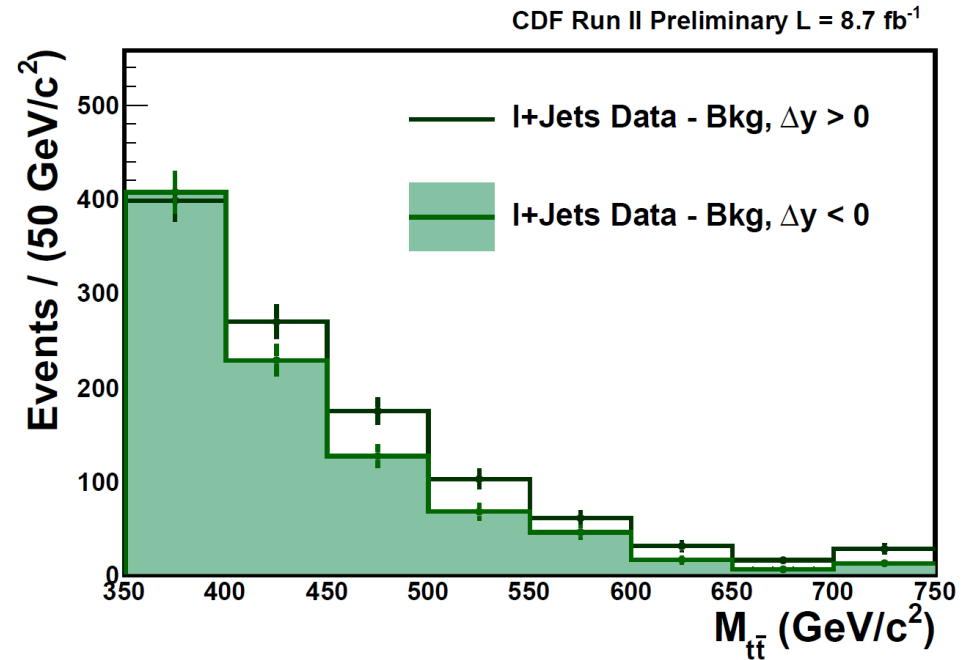


# mass dependence

- $M_{t\bar{t}}$  for forward and backward

- mass dependent asymmetry

$$A_{FB}(M_{t\bar{t}}) = \frac{N_F(M_{t\bar{t}}) - N_B(M_{t\bar{t}})}{N_F(M_{t\bar{t}}) + N_B(M_{t\bar{t}})}$$





# mass dependence

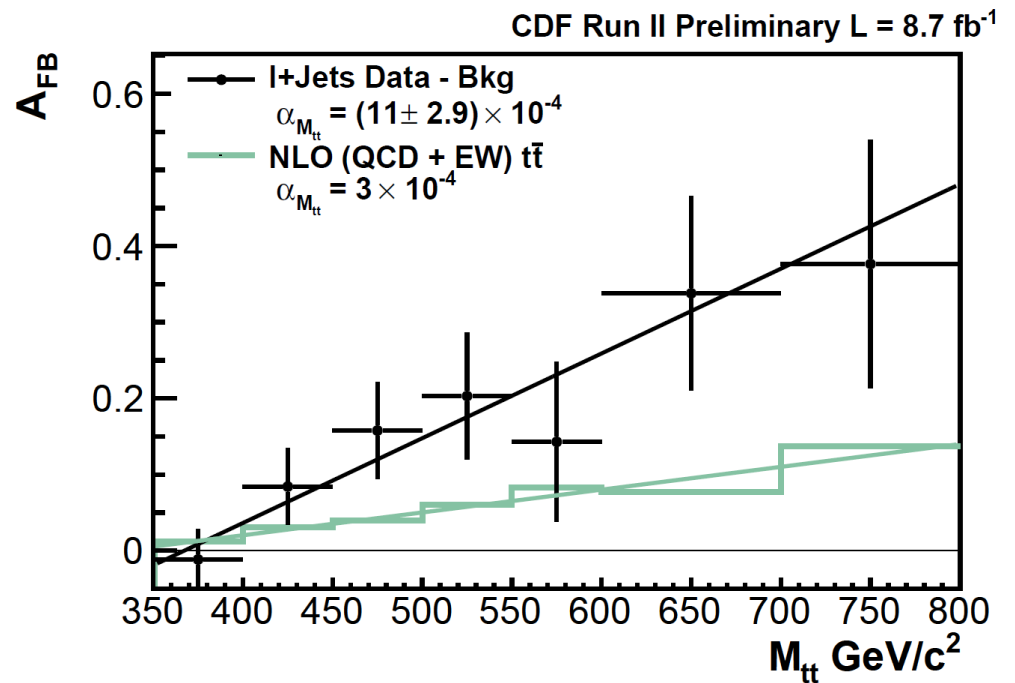
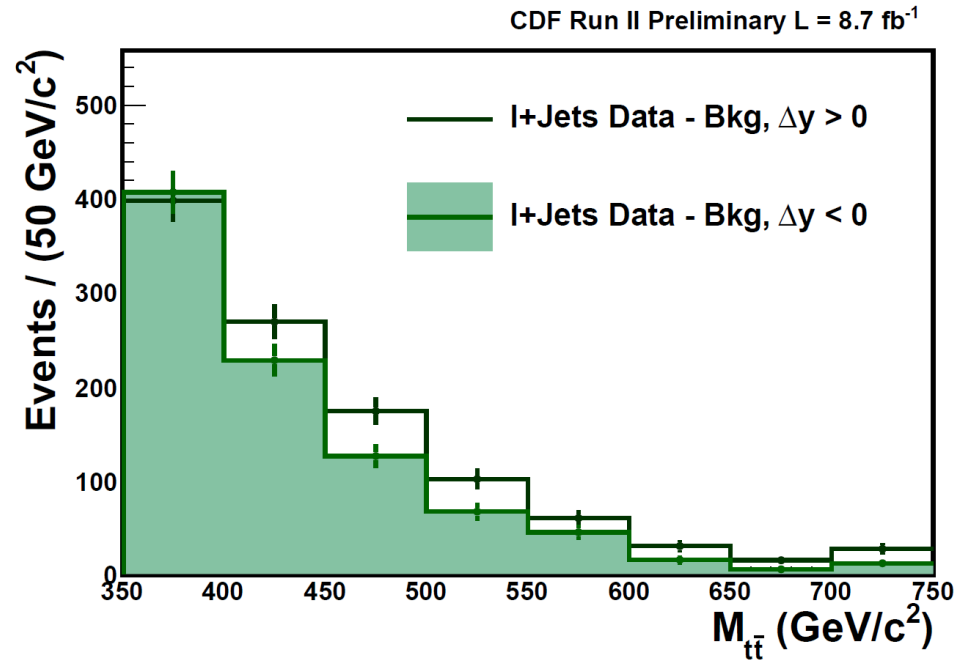
- $M_{t\bar{t}}$  for forward and backward

- mass dependent asymmetry

$$A_{FB}(M_{t\bar{t}}) = \frac{N_F(M_{t\bar{t}}) - N_B(M_{t\bar{t}})}{N_F(M_{t\bar{t}}) + N_B(M_{t\bar{t}})}$$

- linear fit

- slope is  $>3\sigma$  from 0
- fit  $\chi^2_{\text{p.d.f.}} = 0.3$
- $p_{\text{NLO}} = 0.00646$

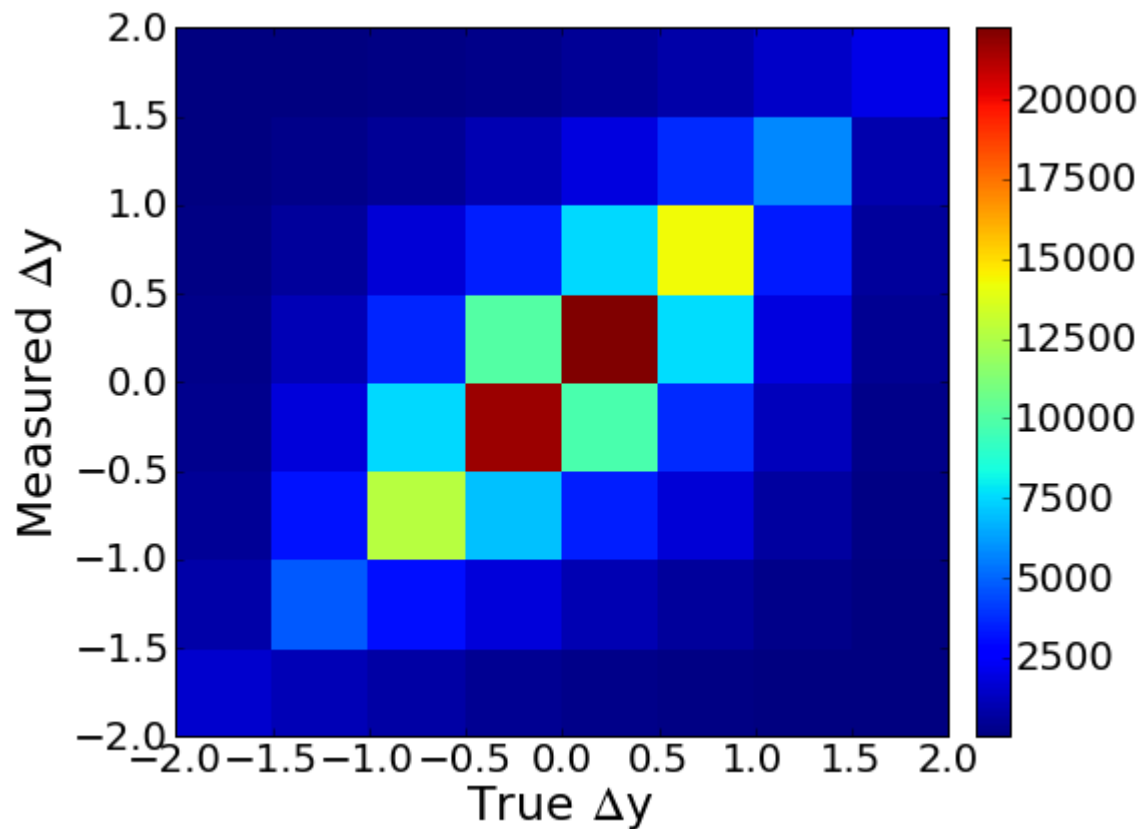


## parton level

- correct smearing and acceptance

$$x_i^{Parton} = A_{ij}^{-1} S_{jk}^{-1} x_k^{Bkg.Sub.}$$

- $S^{-1}$  unsmear uses SVD (Hocker-Kartvelishvili, 1995)

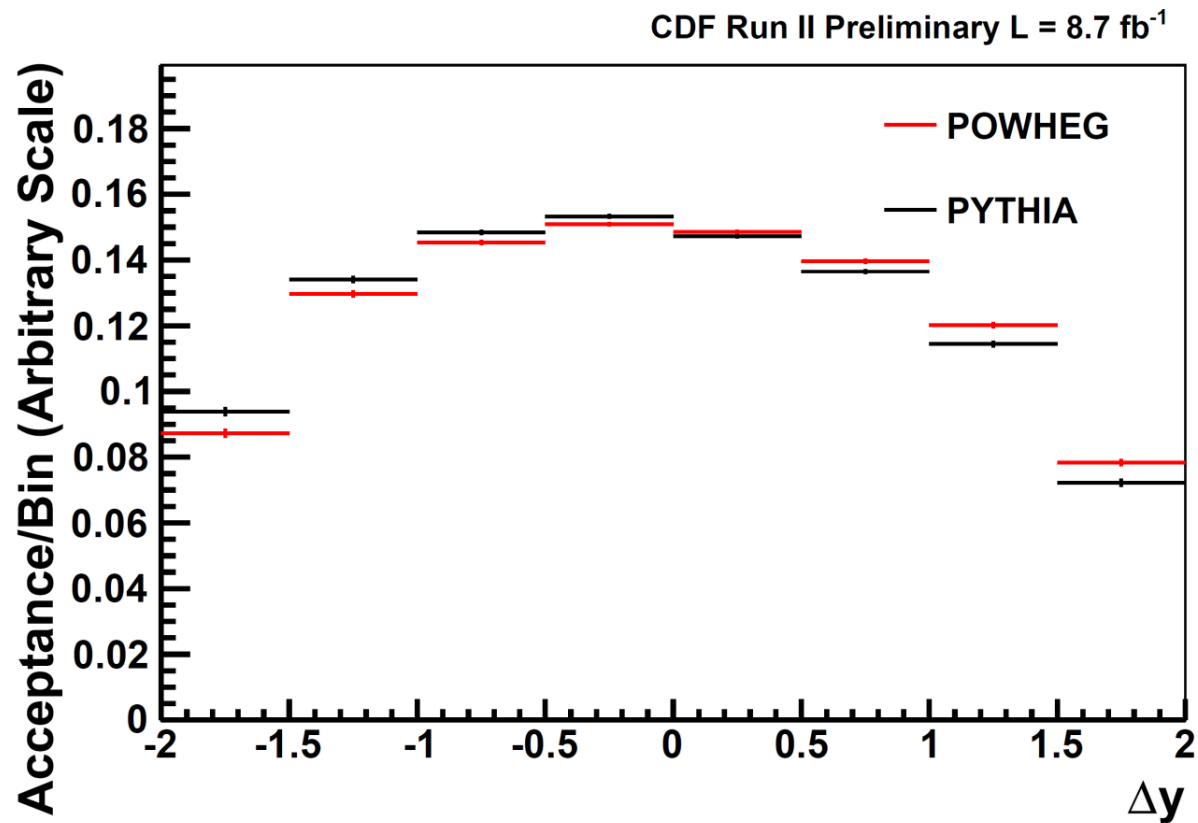


## parton level

- correct smearing and acceptance

$$x_i^{Parton} = A_{ij}^{-1} S_{jk}^{-1} x_k^{Bkg.Sub.}$$

- $A^{-1}$  acceptance correction uses powheg model



## parton level

- correct smearing and acceptance

$$x_i^{Parton} = A_{ij}^{-1} S_{jk}^{-1} x_k^{Bkg.Sub.}$$

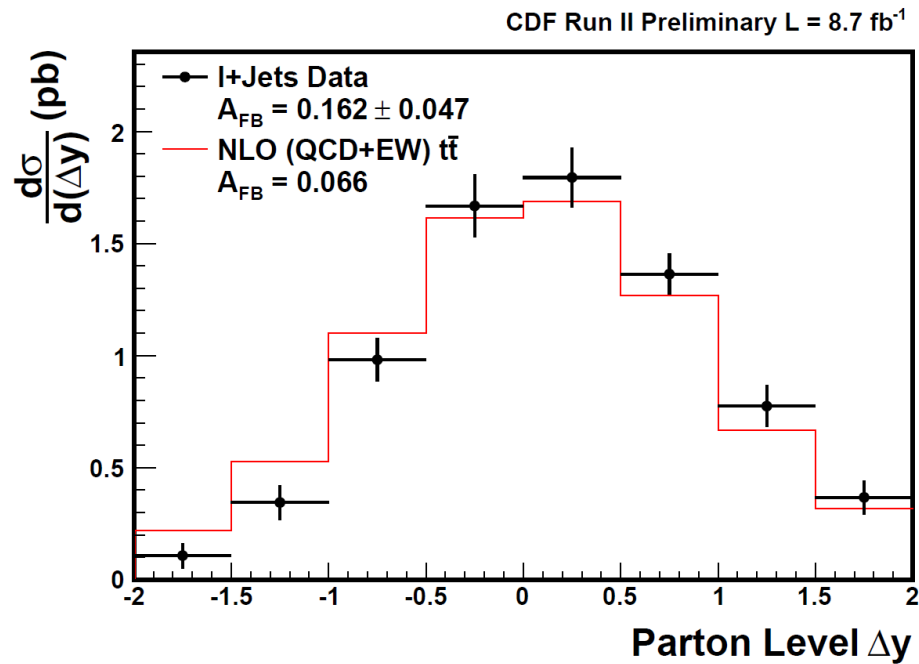
- systematic uncertainties

CDF Run II Preliminary L = 8.7 fb<sup>-1</sup>

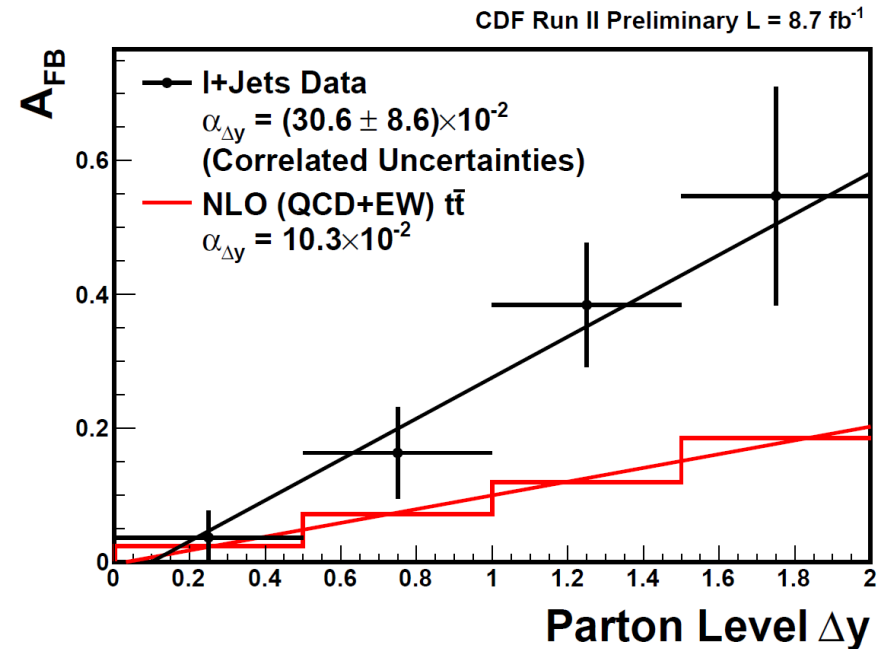
Source	Systematic Uncertainty
Background Shape	0.014
Background Normalization	0.011
Parton Showering	0.010
Jet Energy Scale	0.005
Initial and Final State Radiation	0.005
Color Reconnection	0.001
Parton Distribution Functions	0.001
Correction Procedure	0.003
Total Systematic Uncertainty	0.022
Statistical Uncertainty	0.041
Total Uncertainty	0.047

- n.b. model bias is not included

# differential cross-section and asymmetry in $\Delta y$

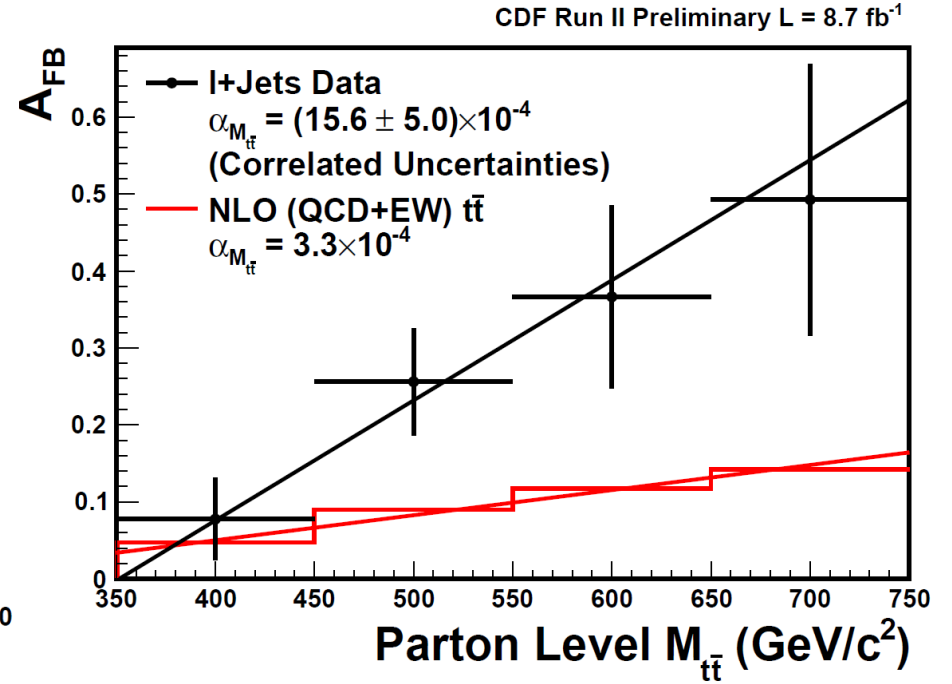
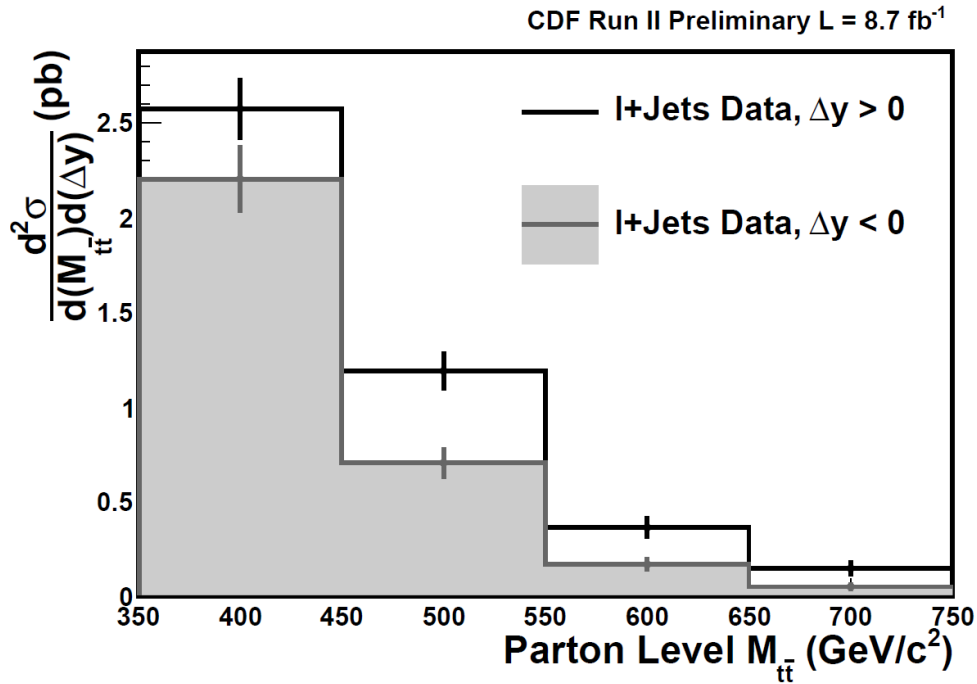


- $A_{fb}$  data =  $(16.2 \pm 4.7)\%$
- $A_{fb}$  pred. = 6.6%



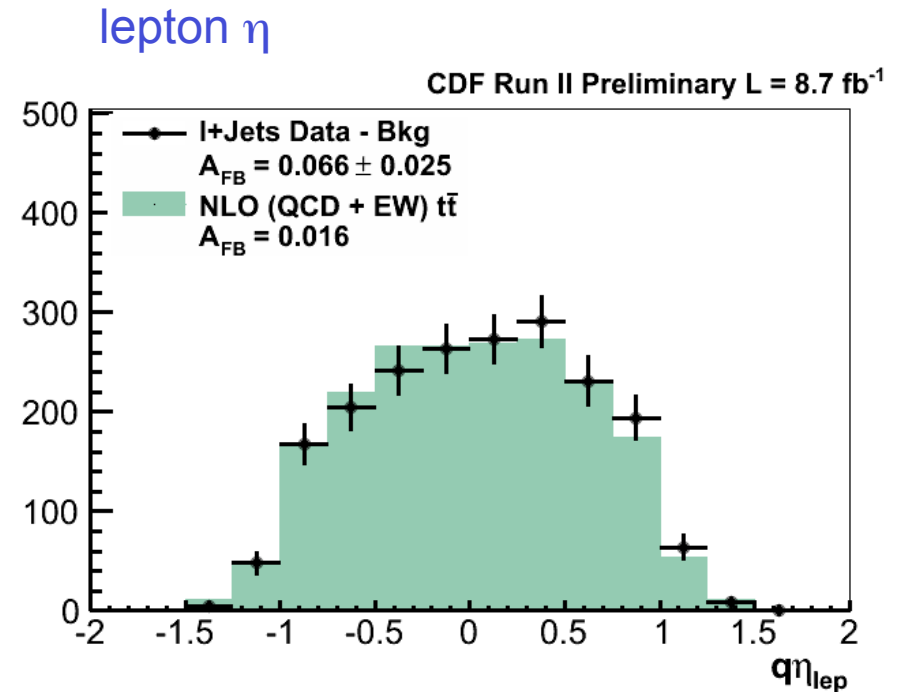
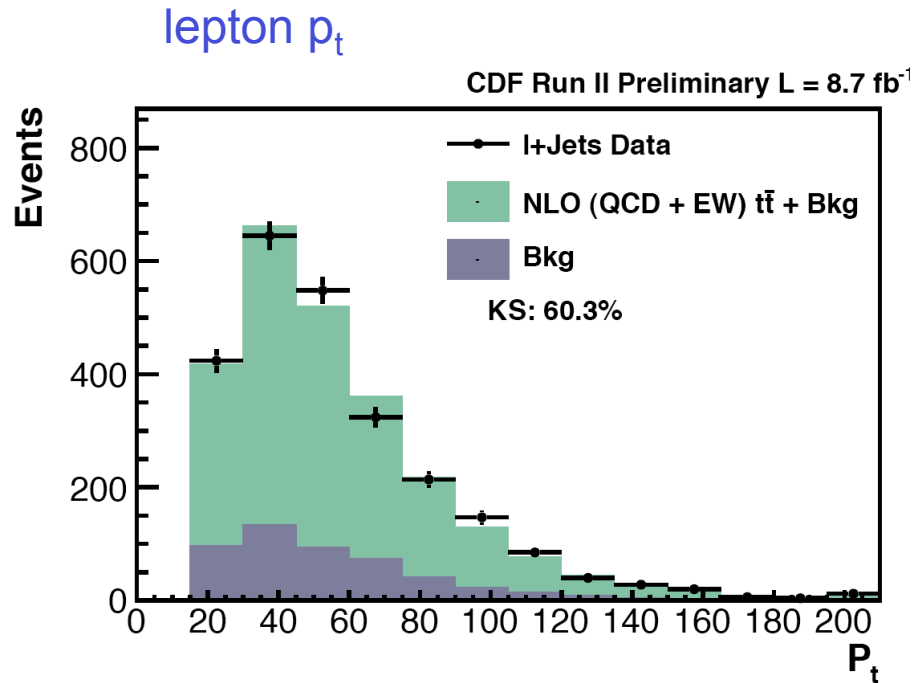
- linear form works again
- slope
  - uses full covariance
  - $>3\sigma$  from 0
  - $>2\sigma$  from powheg

# double differential cross-section and asymmetry in $M_{t\bar{t}}$ and $\Delta y$



# lepton asymmetry

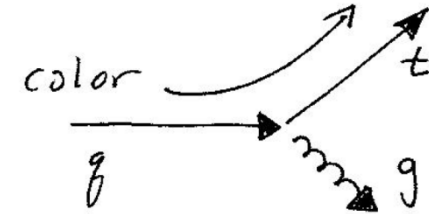
- lepton follows top
- reconstructed lepton  $\eta$  is systematically unencumbered



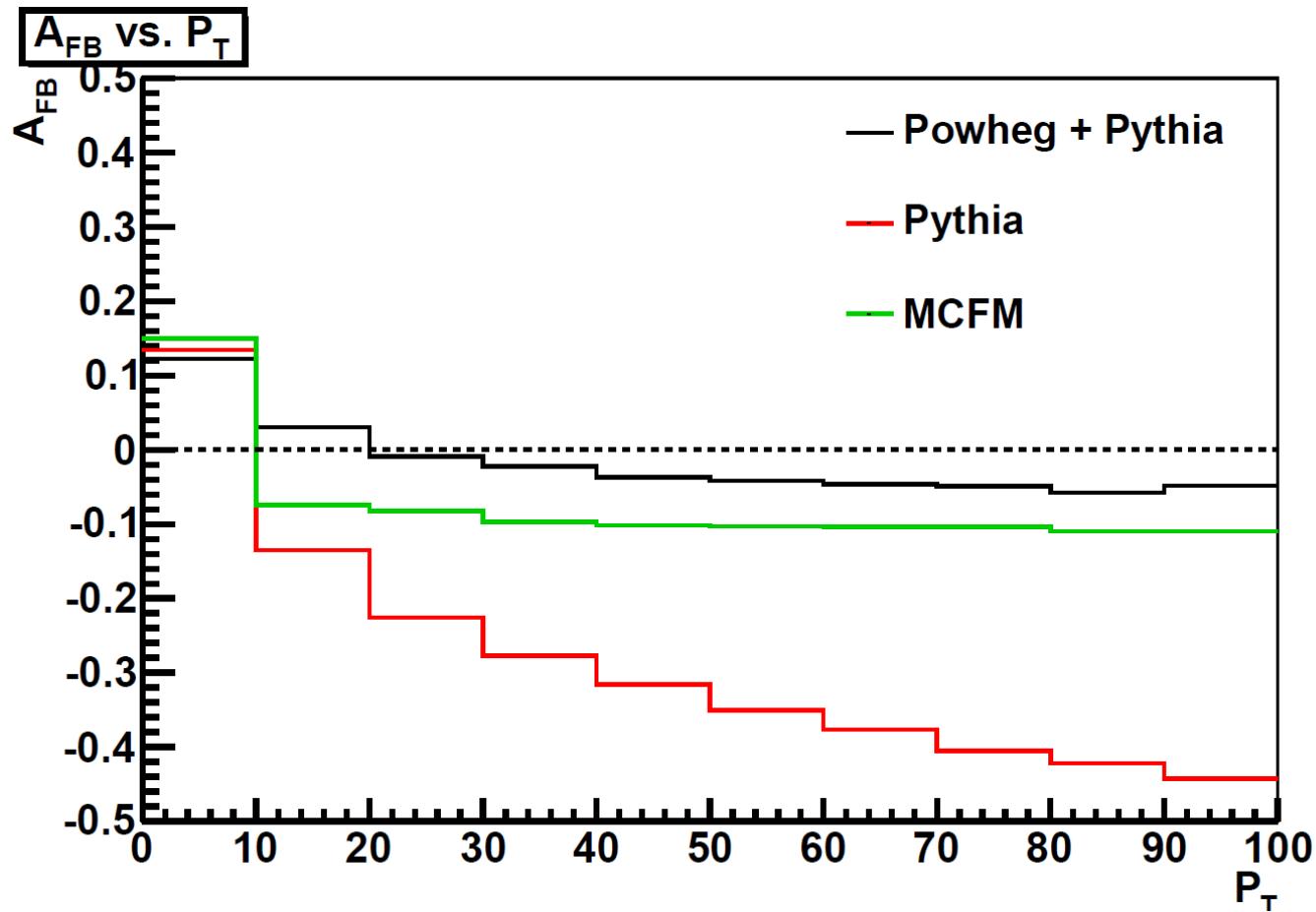
	Data	NLO (QCD+EW) $t\bar{t}$
$M_{t\bar{t}}$	$A_{FB} (\pm [\text{stat.}+\text{syst.}])$	$A_{FB}$
Inclusive	$0.066 \pm 0.025$	0.016
$< 450\text{GeV}/c^2$	$0.037 \pm 0.031$	0.007
$\geq 450\text{GeV}/c^2$	$0.116 \pm 0.042$	0.032

# $p_t$ (t $\bar{t}$ bar) dependence of the asymmetry

- 1) color coherence  $\rightarrow$  backwards top correlated w/  $p_t \neq 0$
- 2) NLO tt+j has negative  $A_{fb}$



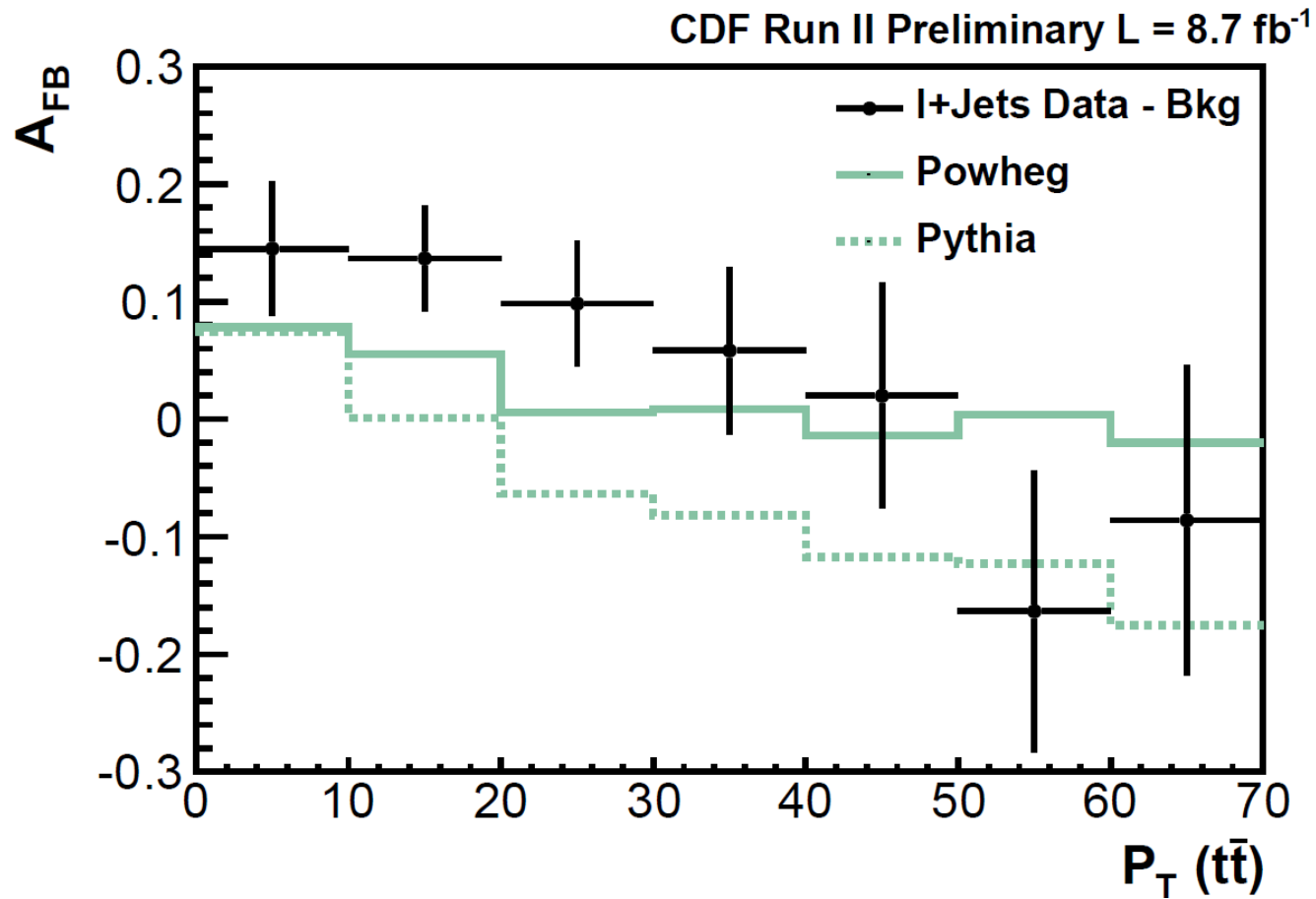
expectation @ MC truth:





## $p_t$ ( $t\bar{t}$ ) dependence of the asymmetry

- examine at background subtracted level
- data vs powheg/pythia shower vs pythia neat



## conclusions

in the l+jets top sample in the full Run II Tevatron dataset we have:

- measured a  $M_{tt}$  and  $\Delta y$  dependent  $A_{fb}$  in tt system
- found the  $A_{fb}$  is
  - approximately linear in both variables
  - slopes are  $3\sigma$  from zero and larger than NLO prediction
- corrected the  $M_{tt}$  and  $\Delta y$  spectra to derive
  - differential cross sections
  - $A_{fb}$ ,  $A_{fb}(\Delta y)$ , and  $A_{fb}(M_{tt})$  at the parton level
- verified the asymmetry and mass dependence in the lepton alone
- measured the dependence of  $A_{fb}$  on the tt  $p_t$

this is the *start* of a program of further study....

additional material

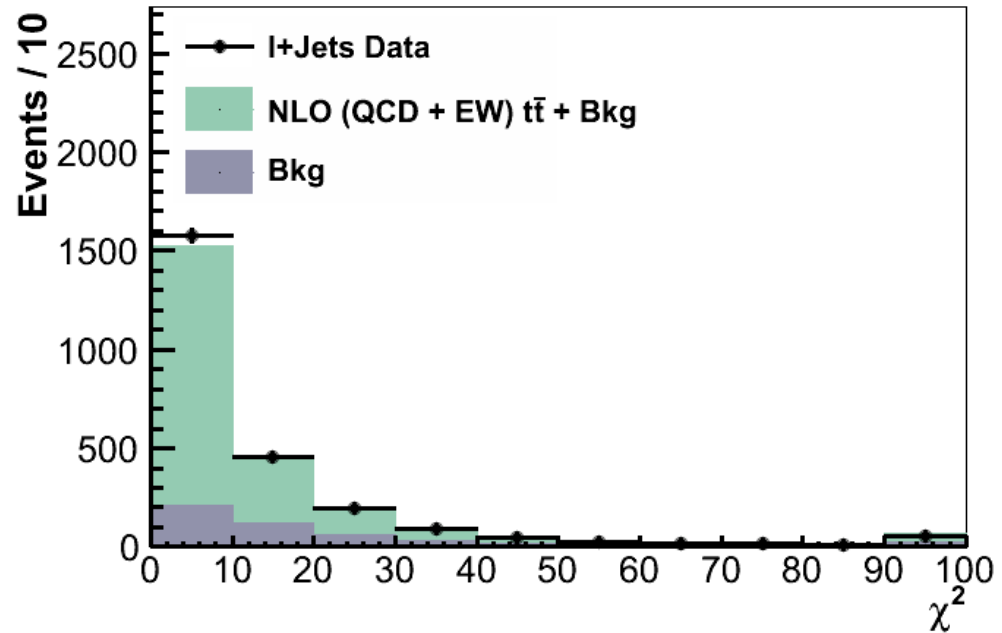
# Asymmetry in various selections

CDF Run II Preliminary L = 8.7 fb<sup>-1</sup>

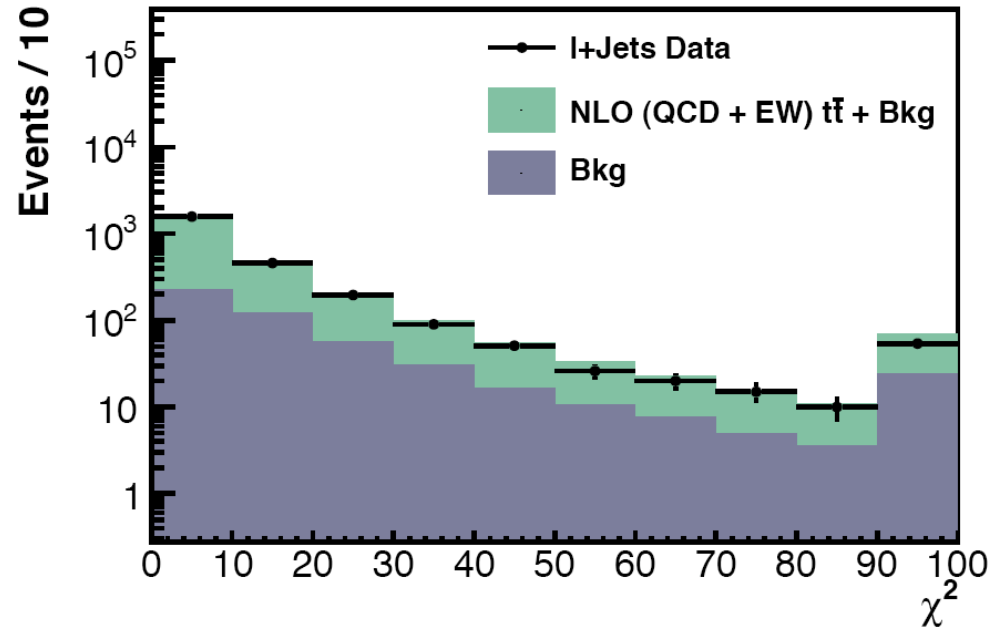
Sample	$A_{\text{FB}} (\pm [\text{stat.}+\text{syst.}])$	$A_{\text{FB}} (\pm [\text{stat.}+\text{syst.}])$	$A_{\text{FB}} (\pm [\text{stat.}+\text{syst.}])$
	Inclusive	$M_{t\bar{t}} < 450\text{GeV}/c^2$	$M_{t\bar{t}} \geq 450\text{GeV}/c^2$
All Data	$0.085 \pm 0.025$	$0.025 \pm 0.031$	$0.198 \pm 0.043$
Positive Leptons	$0.100 \pm 0.037$	$0.044 \pm 0.046$	$0.198 \pm 0.060$
Negative Leptons	$0.071 \pm 0.035$	$0.008 \pm 0.043$	$0.198 \pm 0.059$
Exactly 0 <i>b</i> -tags	$0.056 \pm 0.052$	$0.079 \pm 0.066$	$0.005 \pm 0.085$
Exactly 1 <i>b</i> -tags	$0.103 \pm 0.030$	$0.039 \pm 0.037$	$0.226 \pm 0.050$
At least 2 <i>b</i> -tags	$0.034 \pm 0.046$	$-0.014 \pm 0.057$	$0.122 \pm 0.077$
Electron Events	$0.058 \pm 0.038$	$-0.018 \pm 0.048$	$0.199 \pm 0.062$
Muon Events	$0.107 \pm 0.034$	$0.060 \pm 0.041$	$0.197 \pm 0.057$

# top reconstruction $\chi^2$

CDF Run II Preliminary L = 8.7 fb<sup>-1</sup>

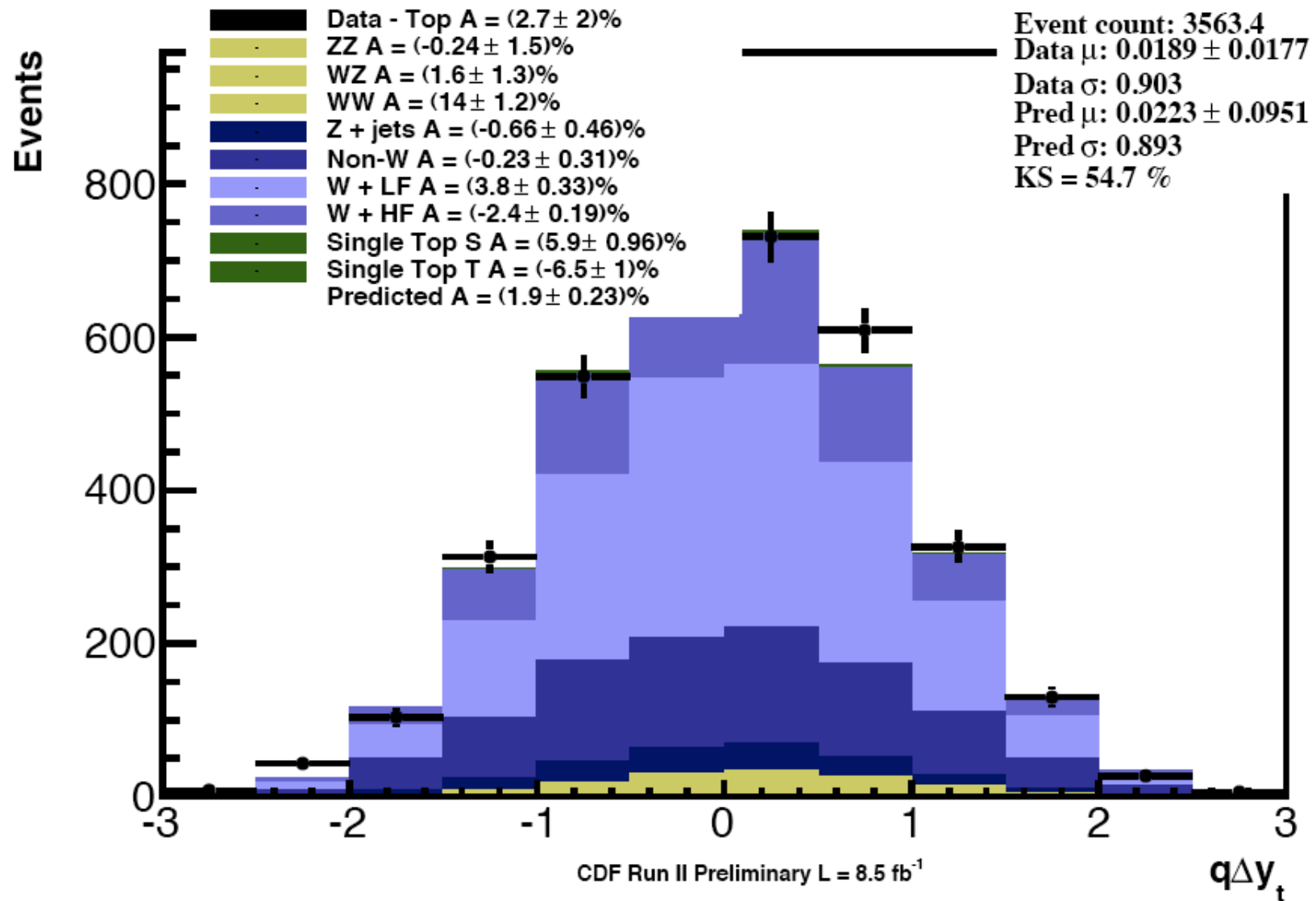


CDF Run II Preliminary L = 8.7 fb<sup>-1</sup>



# backgrounds

- 0 b-tags with *top subtracted*



## Comparison to Previous Background-Subtracted Mass-Dependent Results

Background-Subtracted $A_{FB}$ (%)	D0 Lep+Jet, 5.4 fb <sup>-1</sup>	CDF Lep+Jet, 5.3 fb <sup>-1</sup>	CDF Lep+Jet, 8.7 fb <sup>-1</sup>
$M_{tt} < 450 \text{ GeV}/c^2$	$7.6 \pm 4.8$	$-2.2 \pm 4.3$	$2.5 \pm 3.1$
$M_{tt} \geq 450 \text{ GeV}/c^2$	$11.5 \pm 6.0$	$26.6 \pm 6.2$	$19.8 \pm 4.3$

- Mass dependence somewhat moderated compared to previous CDF result, larger than D0 result
  - All results statistically compatible

## Comparison to the 5 fb<sup>-1</sup> Results

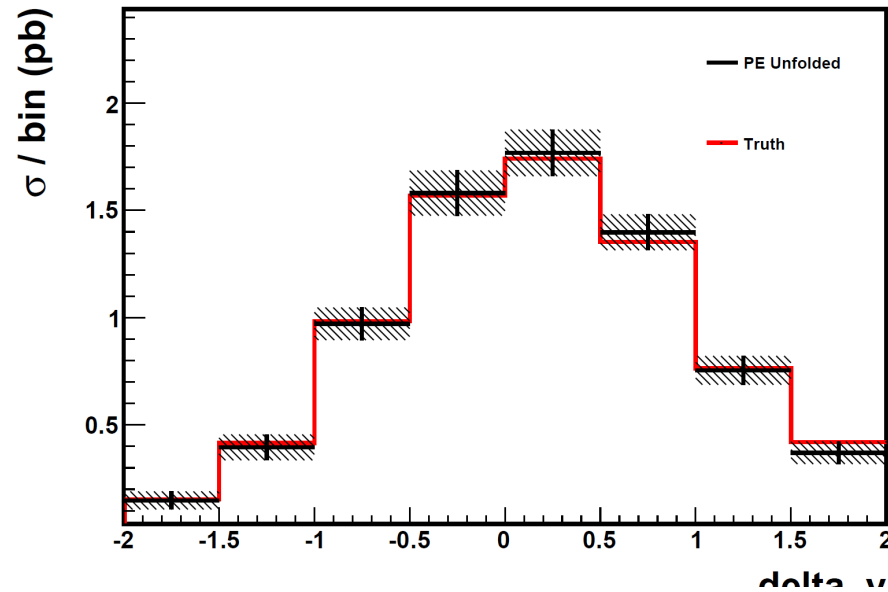
Selection	Prediction	CDF, 5.3 fb <sup>-1</sup>	D0, 5.4 fb <sup>-1</sup>	CDF, 8.7 fb <sup>-1</sup>
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
$M_{tt} < 450 \text{ GeV}/c^2$	4.7	-11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
$M_{tt} \geq 450 \text{ GeV}/c^2$	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7
$ \Delta y  < 1.0$	4.3	2.6 ± 11.8	6.1 ± 4.1 (Bkg. Subtracted)	8.8 ± 4.7
$ \Delta y  \geq 1.0$	13.9	61.1 ± 25.6	21.3 ± 9.7 (Bkg. Subtracted)	43.3 ± 10.9

- Measure the parton level asymmetries in two bins of  $M_{tt}$  and  $|\Delta y|$  for direct comparison to previous results



# parton level

- bias studies with “Octet A”



$ \Delta y $	Found Asymmetry	Uncertainty	Truth
Inclusive	0.162	0.039	0.156
$0.0 \leq  \Delta y  < 0.5$	0.056	0.036	0.052
$0.5 \leq  \Delta y  < 1.0$	0.180	0.056	0.158
$1.0 \leq  \Delta y  < 1.5$	0.313	0.081	0.295
$ \Delta y  \geq 1.5$	0.431	0.132	0.468

# mass dependence old vs new

