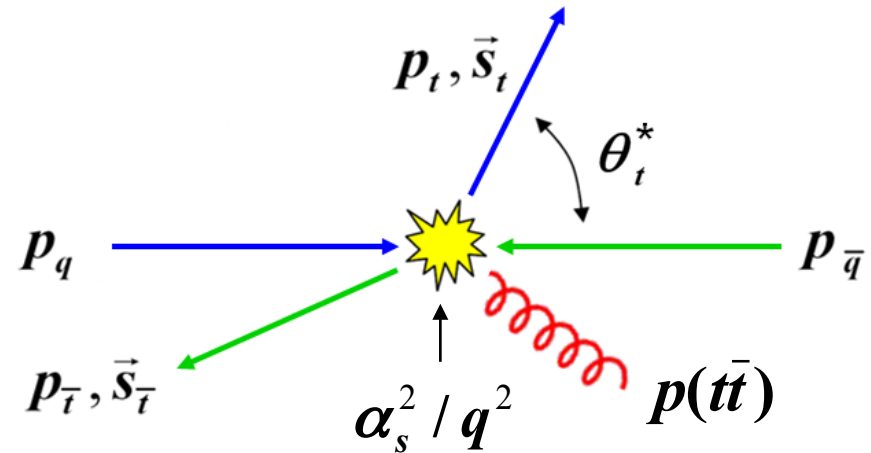# Top Production Asymmetry at the Tevatron

The CDF and D0 Collaborations
presented by

Dan Amidei

University of Michigan

top pair production at Tevatron

- is specified by m_t, pdf's, and
  - α_s implicit in $\sigma_{tt} \sim$ SM
  - q^2 in $d\sigma/dM_{tt} \sim$ SM, no bumps
  - spin in κ ~ correlated a la SM
  - $p_t(tt)$ in extra jets ok

- and…the production angle

  - CDF &D0 observe consistent large
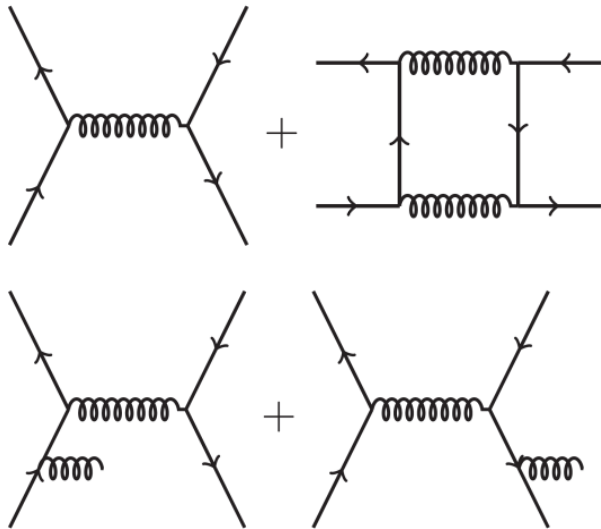 $$A^{tt}_{FB} \sim (19 \pm 4)\%$$
    (informal average)

  - compared to NLO QCD+EWK
    $$A^{tt}_{FB} \sim (6.6 \pm 2.0)\%$$

$$p_t, \vec{s}_t$$

$$\theta_t^*$$

$$p_q \qquad p_{\bar{q}}$$

$$p_{\bar{t}}, \vec{s}_{\bar{t}}$$

$$\alpha_s^2 / q^2 \qquad p(t\bar{t})$$

- this talk
  - physics context
  - inclusive Δy A_{FB}'s
  - Δy and M_{tt} dependence
  - P_t dependence
  - lepton asymmetries
  - summary

top A_{FB} in QCD
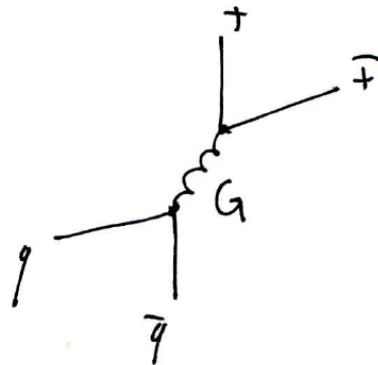

- **recent work**
  - EWK corrections
  - lepton asymmetries
  - $p_t(tt)$ dependence
  - parton-shower asymmetries
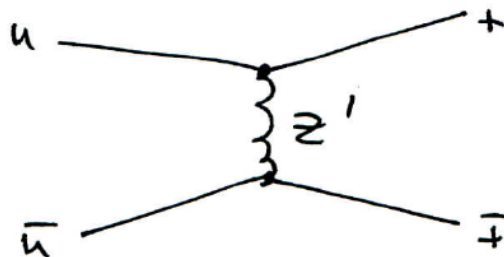 - denominators
  - factorization
  - NNLO is coming

- **at NLO:**
  - C = -1 & C = +1 → A_C
  - at Tevatron this is an A_{FB}
  - measure in $\Delta y = y_t - y_{\bar{t}}$

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

  - inclusive NLO prediction (QCD+EWK):
    A_{FB} = (6.6 ± 2.0)%

BSM ideas

- ## s-channel
  - – massive chiral color octets
  - – RS gluon

- ## t-channel
  - – W´Z´
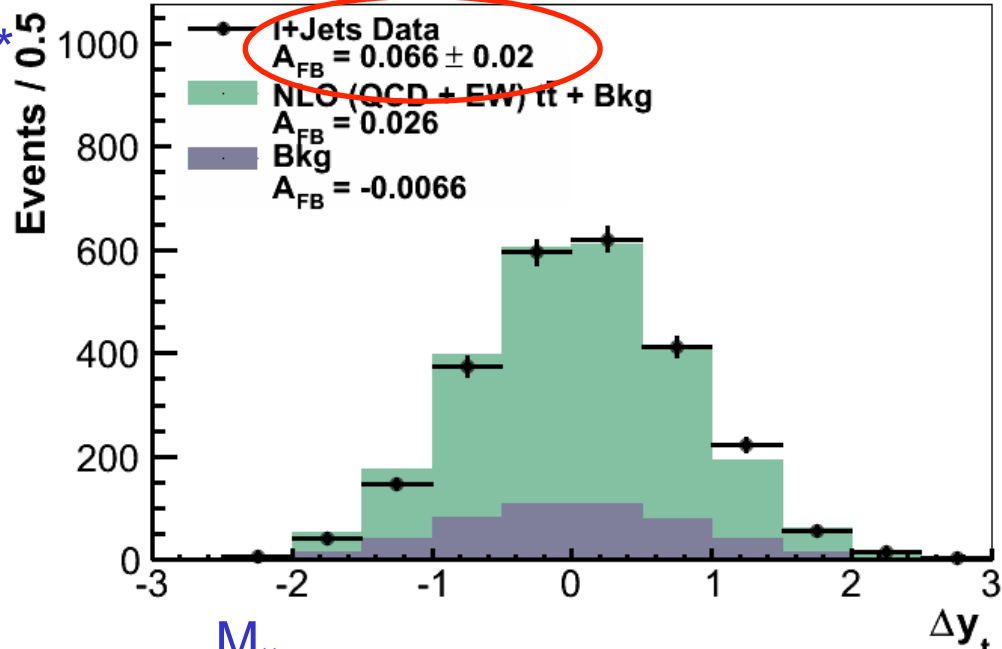 - – color triplets, sextets

- ## BSM model building must contend with
  - – total σ, $d\sigma/dM_{tt}$ in good agreement with SM at Tevatron, LHC
  - – small A_C at LHC
  - – absence of other indirect indications
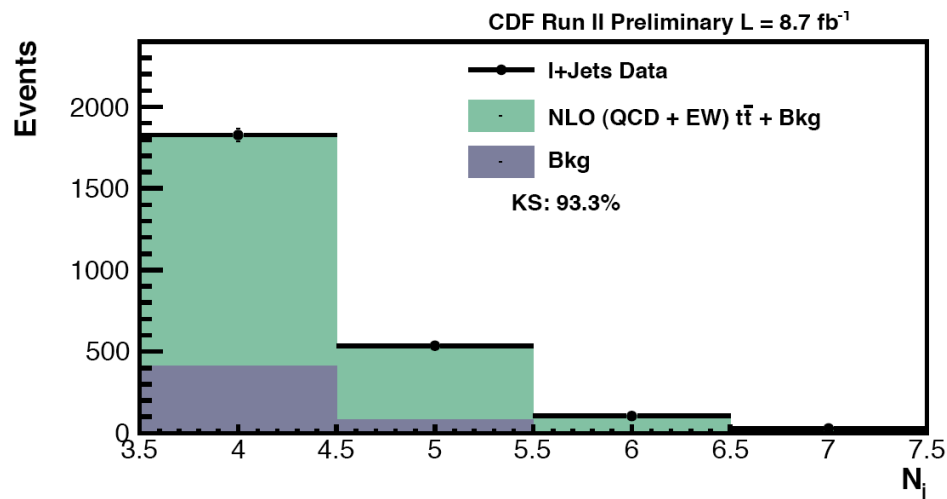
top Δy asymmetry in CDF l+jets
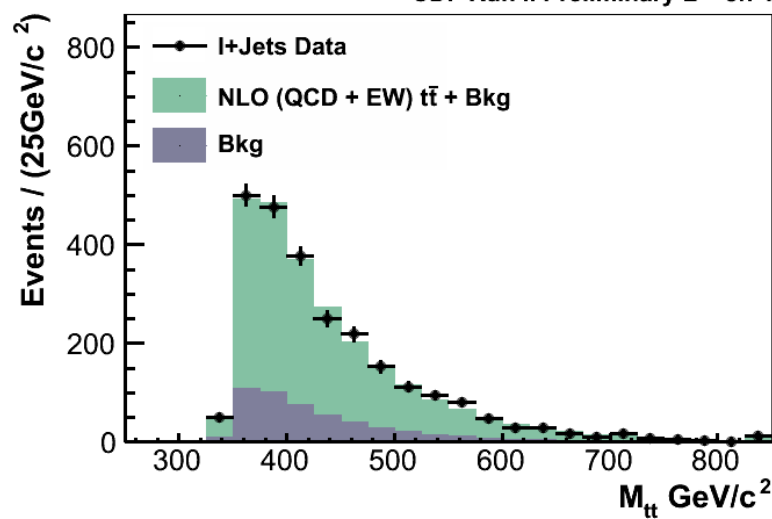
- 8.7 fb^{-1} lepton+met +ge4 jets+btg*
- btg counting bkgs
- 2498 events, bkg = 505 ± 123
- full tt reconstruction
  - M_W, M_t constraints, best χ^2
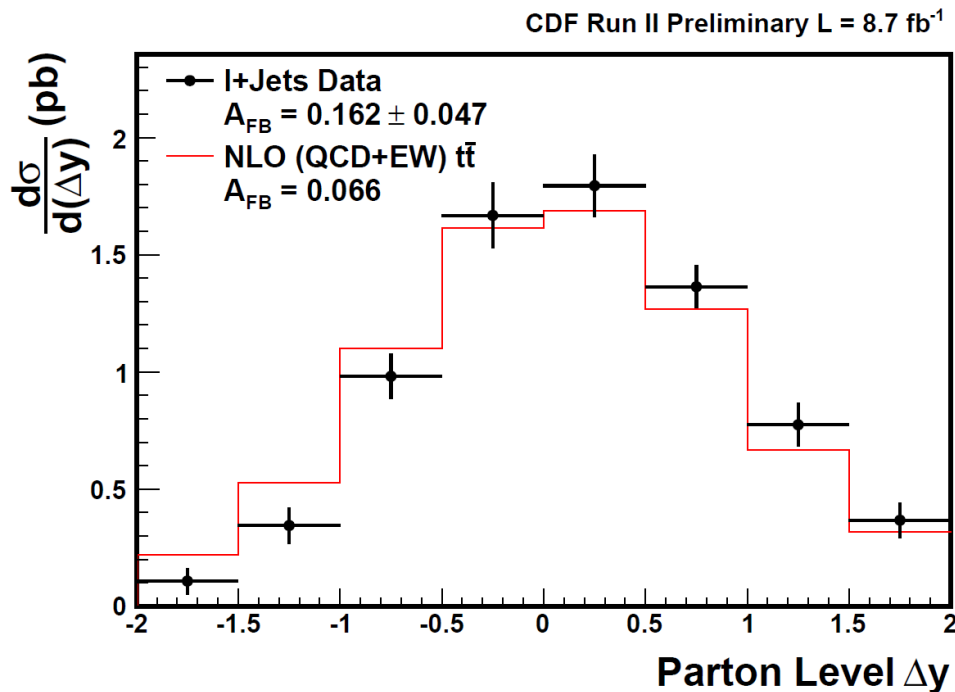- NLO model
  - (powheg + EWK A_{FB}) ±30%

Δy

CDF Run II Preliminary L = 8.7 fb^{-1}

l+Jets Data
A_{FB} = 0.066 ± 0.02
NLO (QCD + EW) tt + Bkg
A_{FB} = 0.026
Bkg
A_{FB} = -0.0066

jet multiplicity

CDF Run II Preliminary L = 8.7 fb^{-1}

l+Jets Data
NLO (QCD + EW) t$\bar{t}$ + Bkg
Bkg
KS: 93.3%

M_{tt}

CDF Run II Preliminary L = 8.7 fb^{-1}

l+Jets Data
NLO (QCD + EW) tt + Bkg
Bkg

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top Δy asymmetry in CDF l+jets

- SVD unfold to parton level
- differential xsec in Δy

Source	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

- A_{fb} parton = (16.2 ± 4.7)%
- A_{fb} NLO   = (6.6 ± 2.0)%

top Δy asymmetry in D0 l+jets

- PRD84, 112005 (2011), arXiv:1110.2062
- 5.4 fb-1, lepton+met +ge4 jets+btag
- neural net S:B normalization
- 1581 events, bkg = 455 ± 39
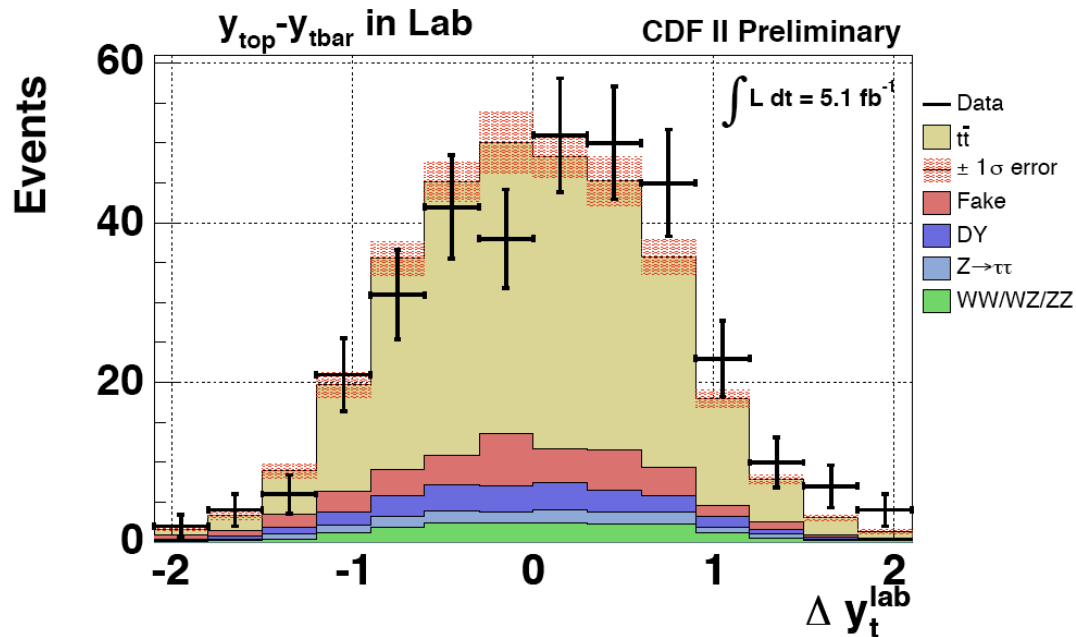- kinematic reconstruction
- unfold to parton level
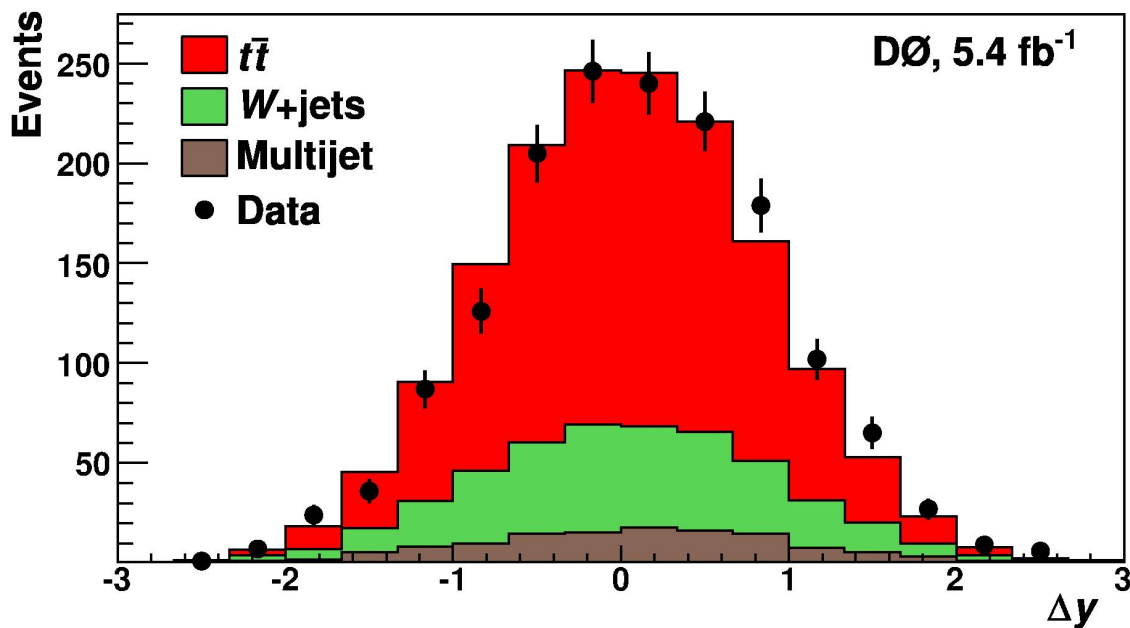
A_{FB} obs = (9.2 ± 3.7)%

A^l_{fb} parton = (19.6 ± 6.5)%

top Δy asymmetry in CDF dileptons

- http://www-cdf.fnal.gov/physics/new/top/2011/DilAfb/
- 2 OS leptons (M.ne.Z) + met + 2 jets
- 5.1 fb^{-1}, 337 events bkg = 87±17
- kinematic reconstruction w mass contraints and pt pz likelihood
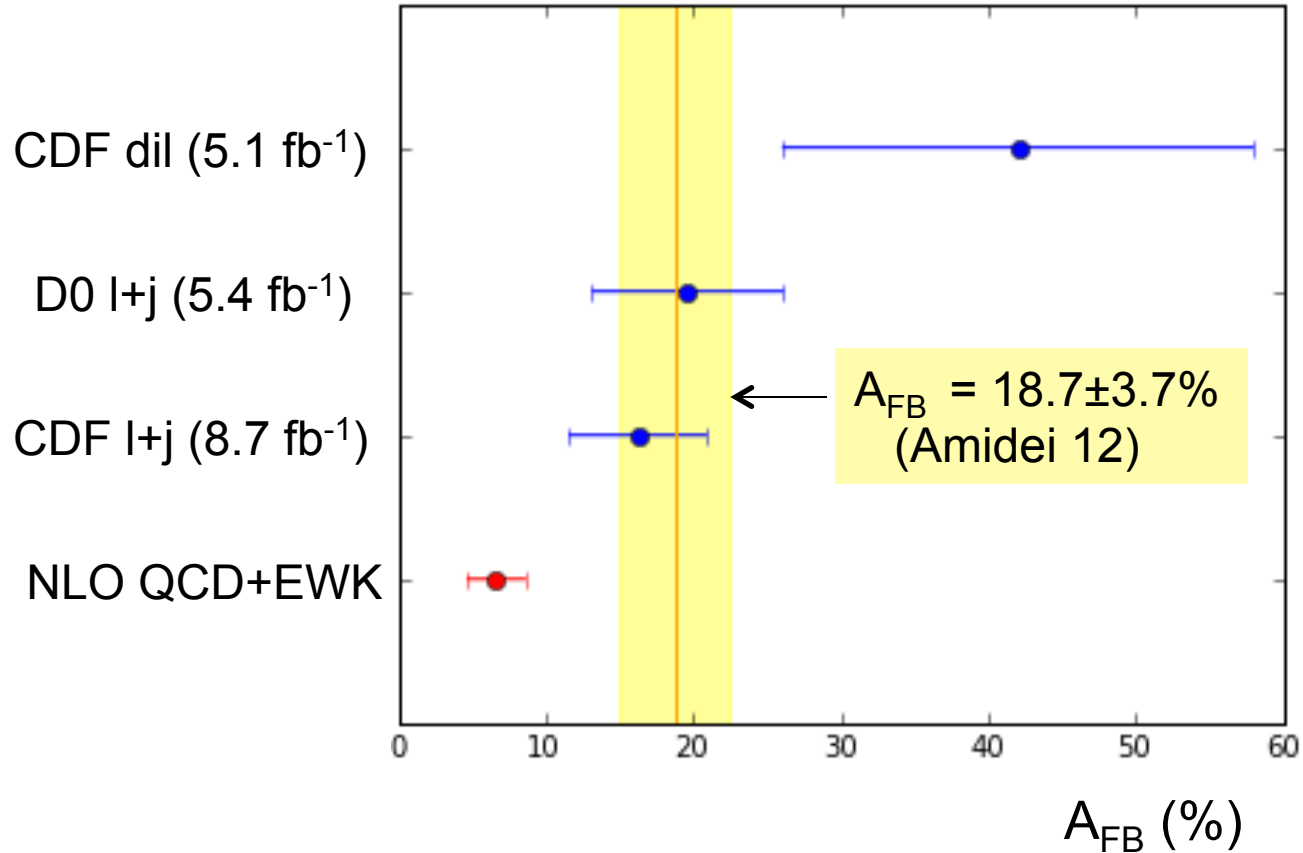- parton level via templates assuming $A(\Delta y) = \alpha \Delta y$

A_{FB} obs = (13.8 ± 5.4)%

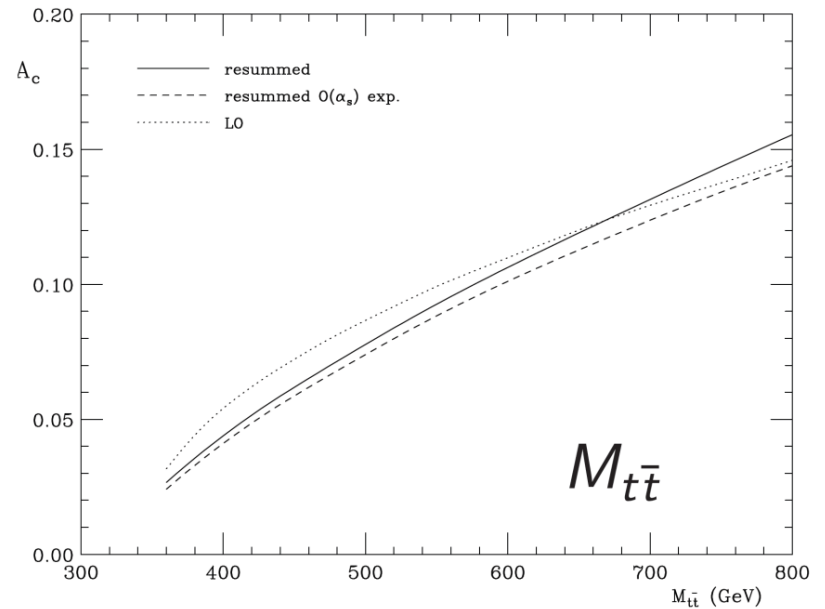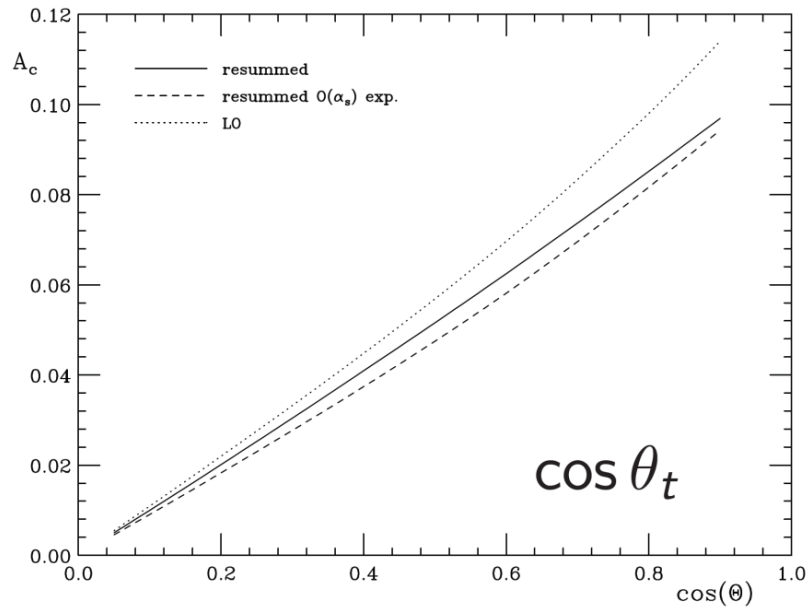A^l_{fb} parton = (41.7 ± 15.7)%

comparison of tevatron top Δy A_{FB} results Sept. 2012

- including private average

  simple weighted, neglect correlations

A$_{FB}$ functional dependence

resummed NLO (Almeida et al., PRD87, 014008, 2008)

rapidity dependence

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

- linear ansatz
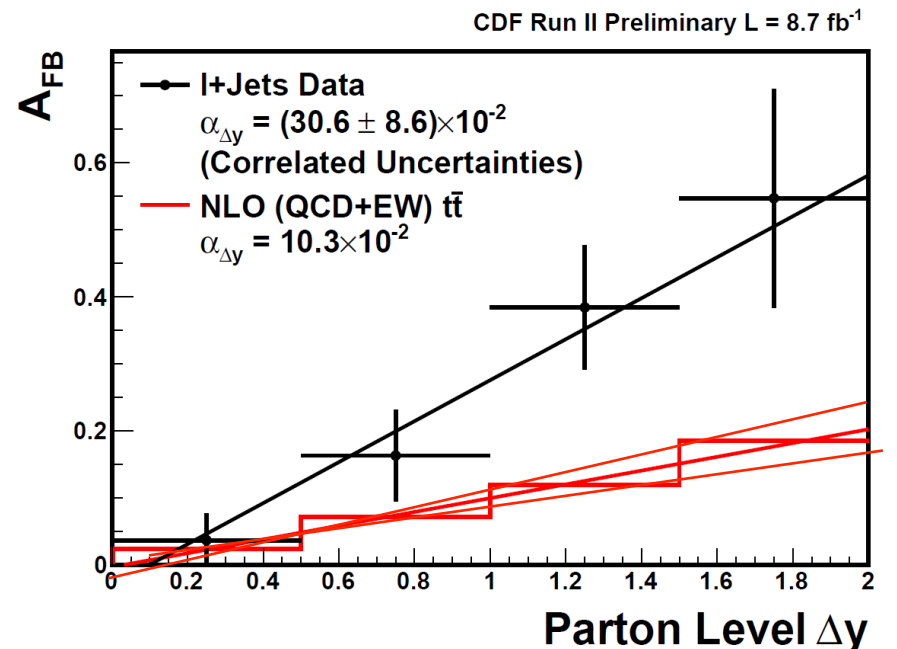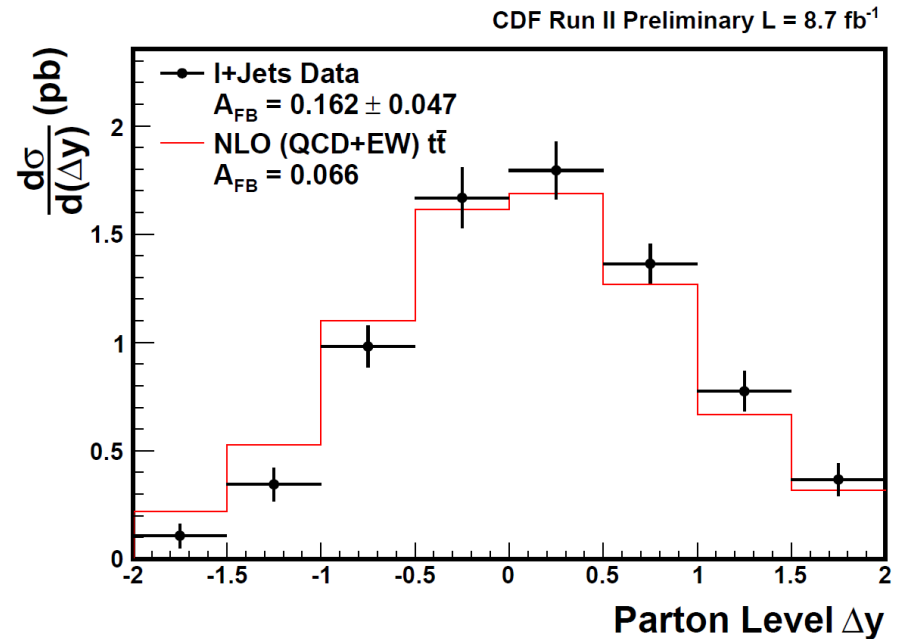 - $\chi^2_{\text{p.d.f.}}$ = 1.0

- line measures correlated significance
  - slope > 3σ from 0
  - PE how often $\alpha_{NLO} \geq \alpha_{data}$
  - use background sub data
  - p_{NLO} = 0.00892

- A_{FB} depends ~linearly on Δy
  - slope is 2.4σ from SM

mass dependence

- 2D unfold M_{tt} and Δy
  - double differential xsec
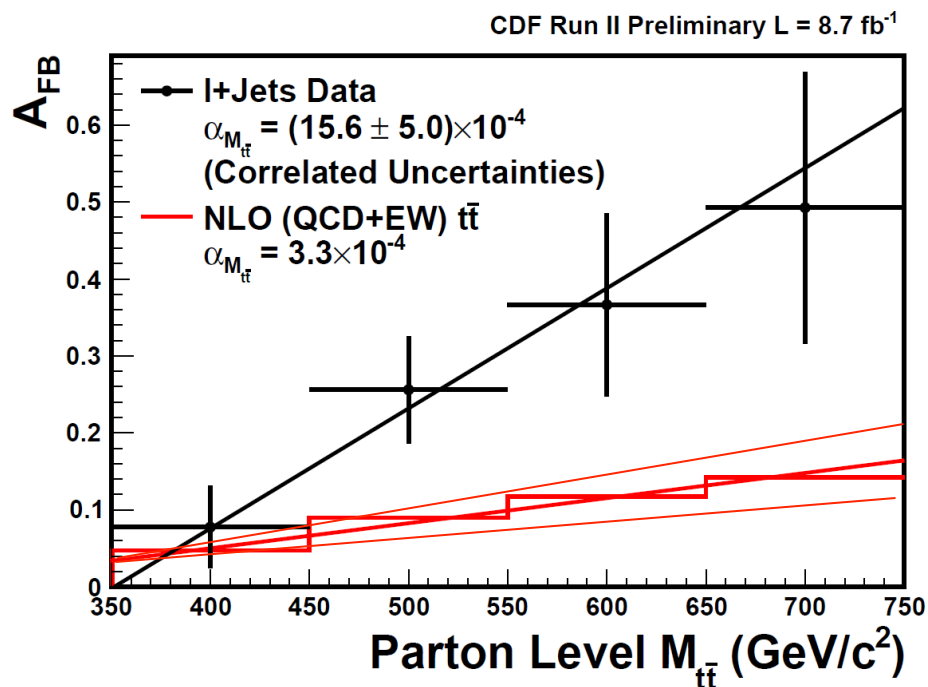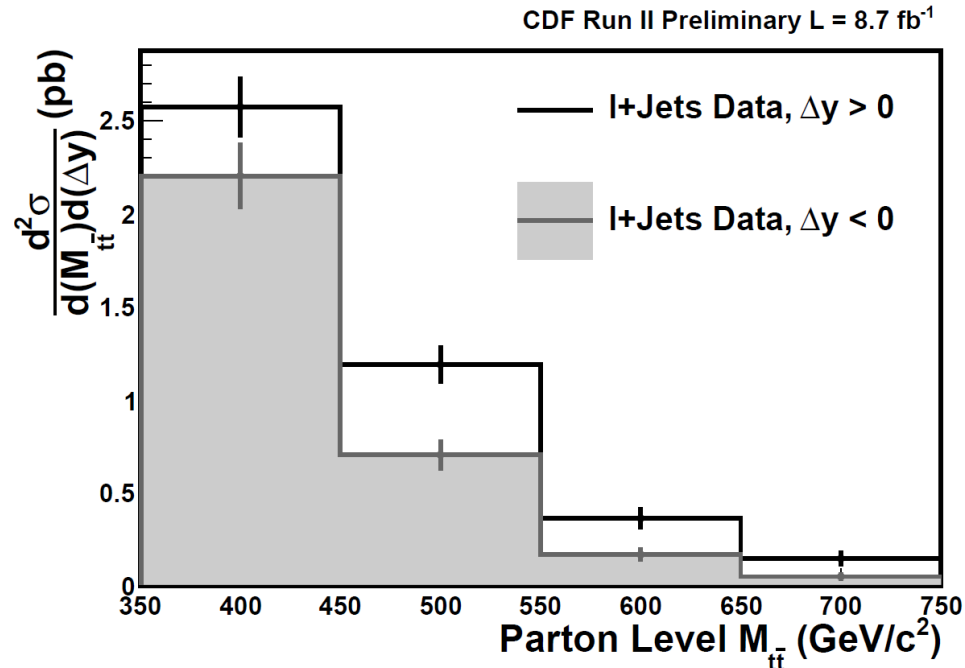
- mass dependent asymmetry

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

- lin fit in obs bkg sub sample
  - slope is >3σ from 0
  - fit $\chi^2_{p.d.f.}$ = 0.3
  - p_{NLO} = 0.00646

- A_{FB} depends ~linearly on M_{tt}
  - slope is 2.5σ from SM

CDF Run II Preliminary L = 8.7 fb⁻¹

I+Jets Data, $\Delta y > 0$

I+Jets Data, $\Delta y < 0$

$\frac{d^2\sigma}{d(M_{t\bar{t}})d(\Delta y)}$ (pb)

Parton Level $M_{t\bar{t}}$ (GeV/c²)

CDF Run II Preliminary L = 8.7 fb⁻¹

A_{FB}

I+Jets Data
$\alpha_{M_{tt}}$ = (15.6 ± 5.0)×10⁻⁴
(Correlated Uncertainties)
NLO (QCD+EW) $t\bar{t}$
$\alpha_{M_{tt}}$ = 3.3×10⁻⁴

Parton Level $M_{t\bar{t}}$ (GeV/c²)

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p_t (tt) dependence of the asymmetry

- noted in D0 l+jet analysis
- color coherence
  - top kicked backwards when w/ $p_t \neq 0$

MC truth:

NLO (Melnikov, Scharf, Schulze)

NLO

LO +PS +tunes
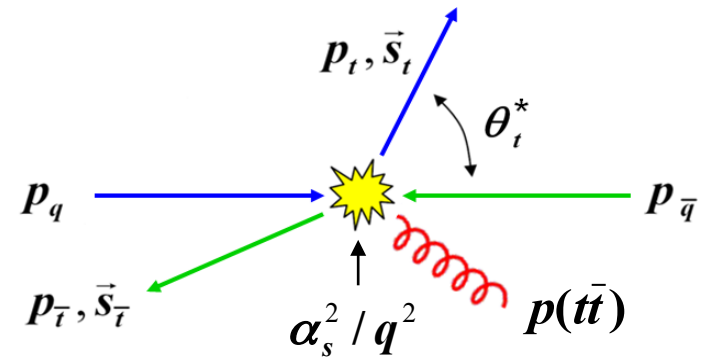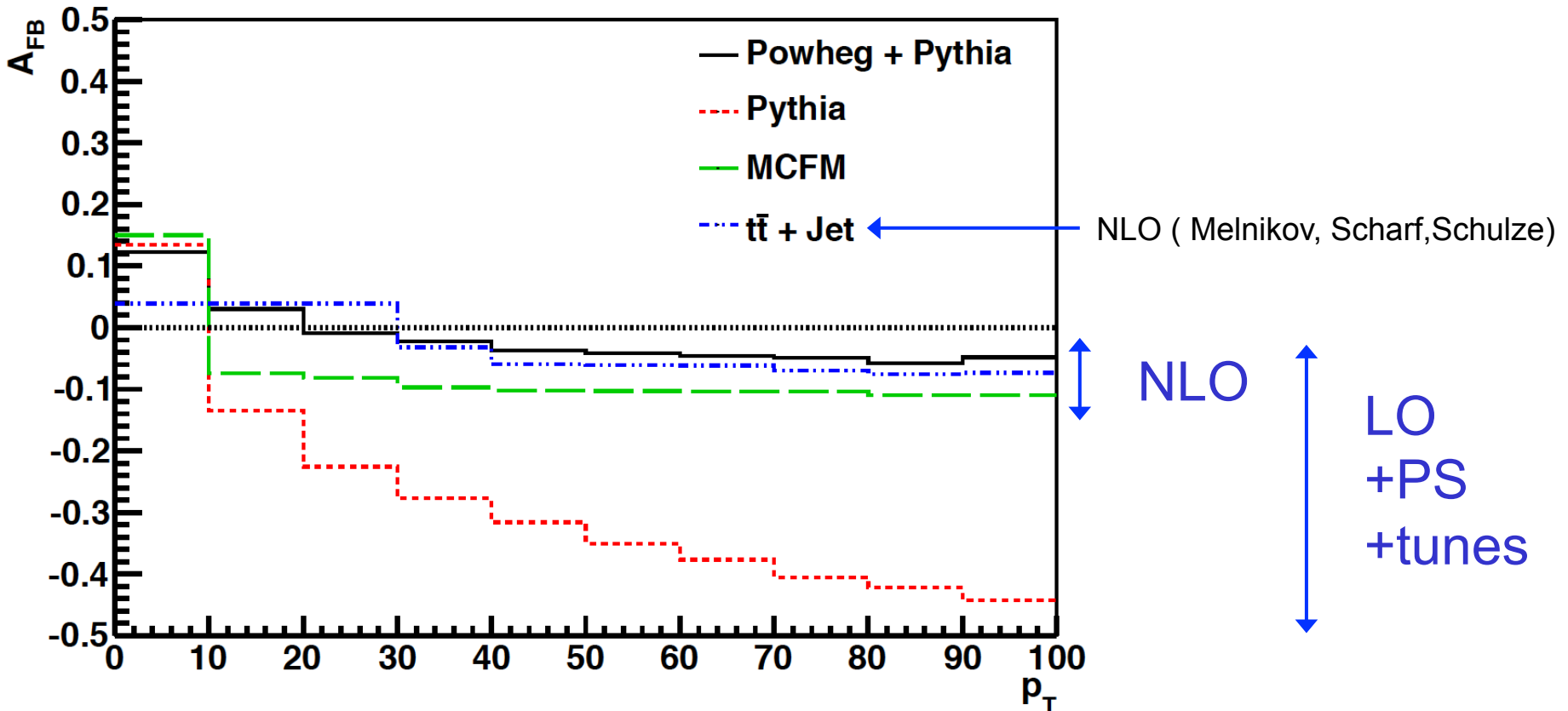
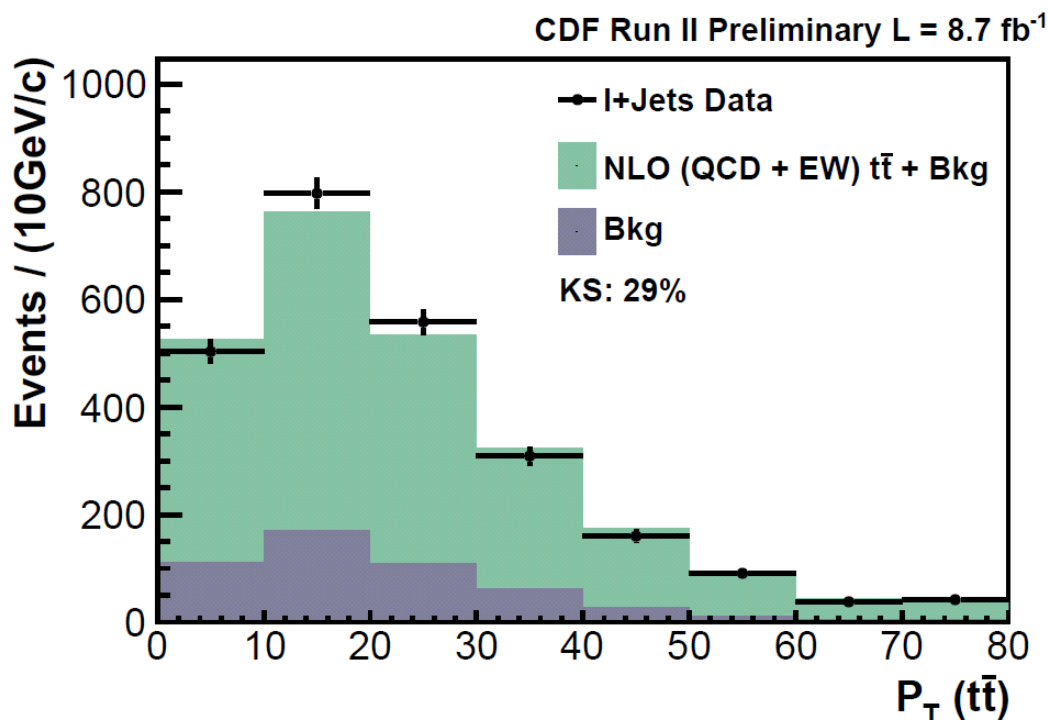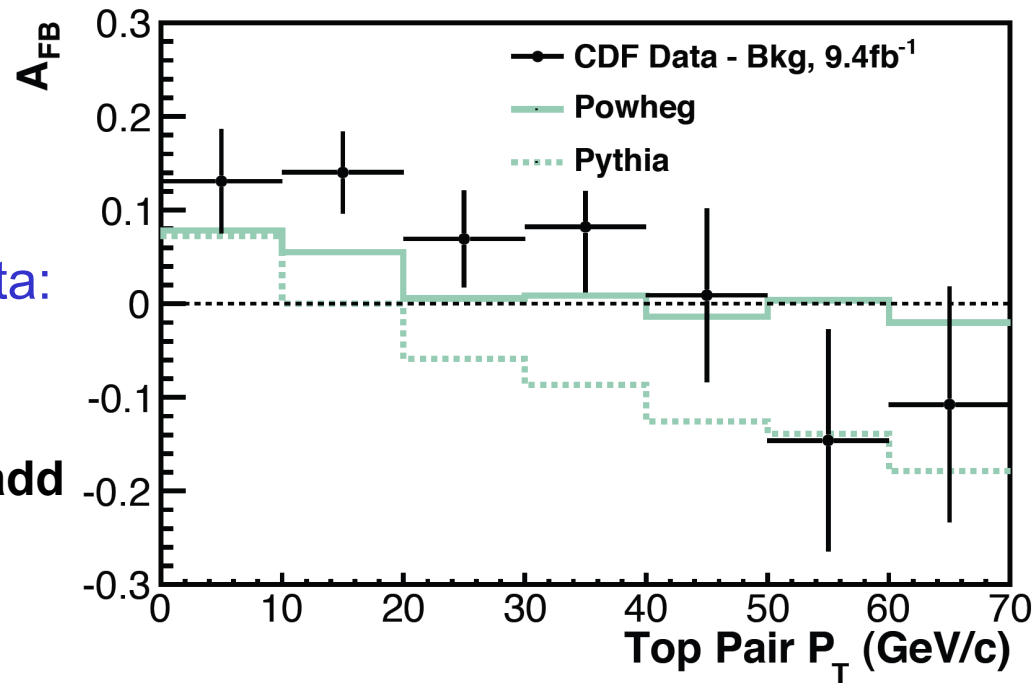# p_t (tt) dependence of the asymmetry at CDF

- a experimentally difficult variable
  - extra jets
  - unclustered energy

- modeling is good

CDF Run II Preliminary L = 8.7 fb^{-1}

l+Jets Data

NLO (QCD + EW) $t\bar{t}$ + Bkg

Bkg

KS: 29%

p_t (tt) dependence of the asymmetry at CDF

- **examine at bkg-sub obs level**
  - pythia and powheg follow expected trend
  - CDF 8.7 fb^{-1} l+jets
  - data above predictions

- **to normalize predictions to the data:**
  - assume additional source of asymmetry A^a_{FB}
  - since independent asymmetries **add**
  - each bin of data contains
    $$A^{Pt}_{FB} + \text{inclusive } A^a_{FB}$$
  - to norm: offset by difference of inclusive asymmetries ΔA_{FB}

p$_t$ (tt) dependence of the asymmetry at CDF

- **examine at obs bkg-sub level**
  - pythia and powheg follow expected trend
  - CDF 8.7 fb^{-1} l+jets
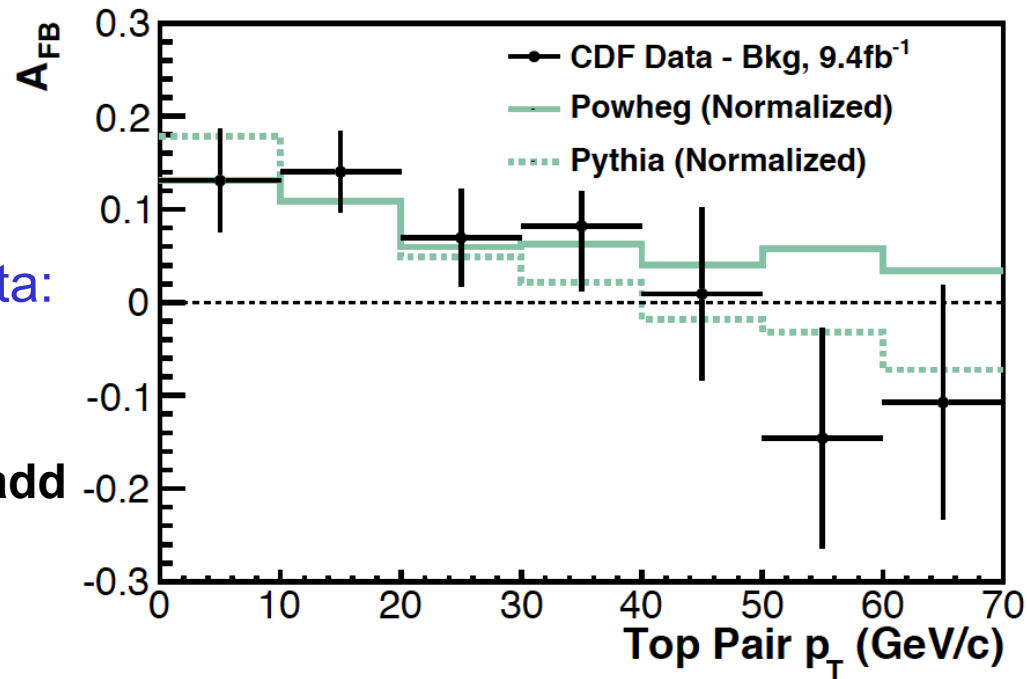 - data above predictions

- **to normalize predictions to the data:**
  - assume additional source of asymmetry A^a_{FB}
  - since independent asymmetries **add**
  - each bin of data contains
    $$A^{Pt}_{FB} + \text{inclusive } A^a_{FB}$$
  - to norm: offset by difference of inclusive asymmetries ΔA_{FB}

- **good agreement with both predictions**

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lepton asymmetries

- lepton follows top
  - independent of asymmetry mechanism if P=0
- reconstructed lepton η is systematically unencumbered
- "bias free" asymmetry indicator

single lepton

$$A_{FB}^{l^\pm} = \frac{N_{l^\pm}(\eta > 0) - N_{l^\pm}(\eta < 0)}{N_{l^\pm}(\eta > 0) + N_{l^\pm}(\eta < 0)}$$

$$A_{FB}^{l} = \frac{N_l(Q \cdot \eta > 0) - N_l(Q \cdot \eta < 0)}{N_l(Q \cdot \eta > 0) + N_l(Q \cdot \eta < 0)}$$

two lepton

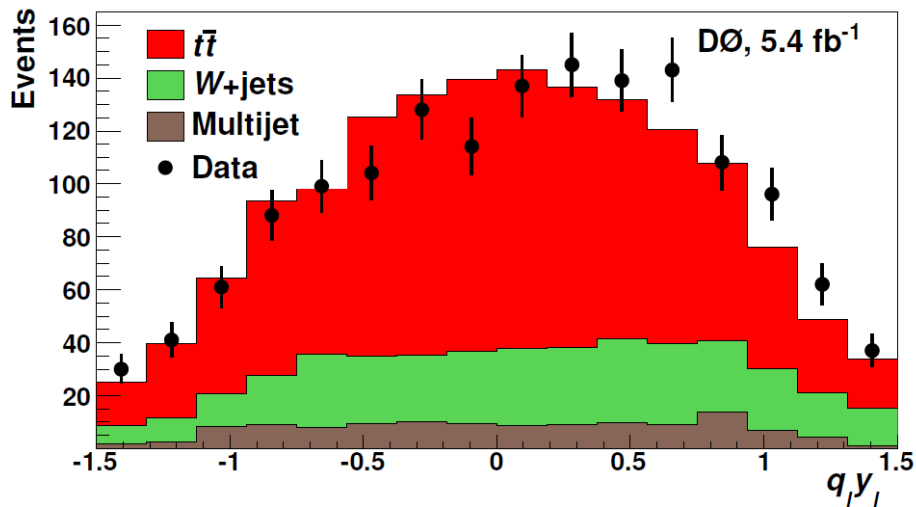$$A^{ll} = \frac{N(\Delta\eta > 0) - N(\Delta\eta < 0)}{N(\Delta\eta > 0) + N(\Delta\eta < 0)}$$

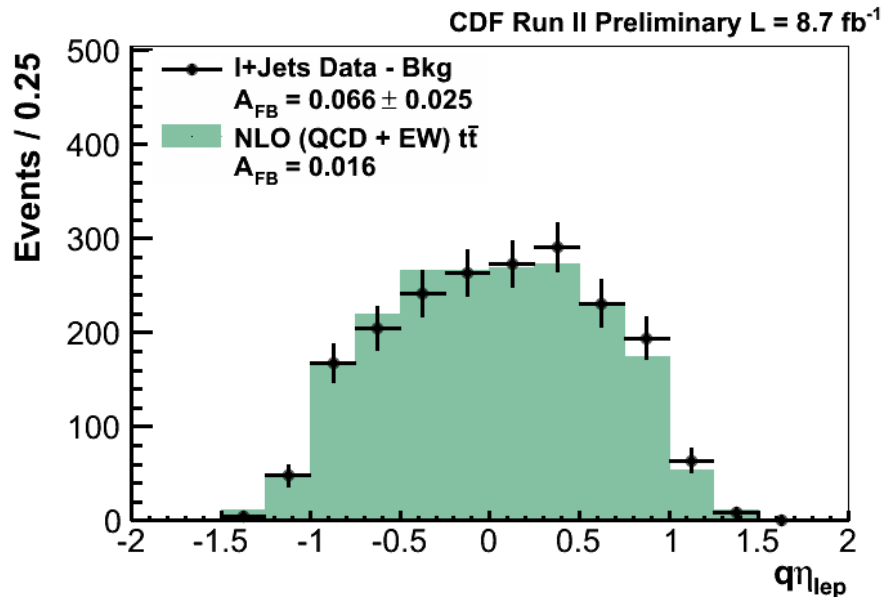$$A_{CP}^{l} = \frac{N_{l^+}(\Delta\eta > 0) - N_{l^-}(\Delta\eta < 0)}{N_{l^+}(\Delta\eta > 0) + N_{l^-}(\Delta\eta < 0)}$$

single lepton in l+jets

$$q \cdot y_l$$

D0 5.4 fb^{-1} l+jets,1532 leptons

Legend:
- $t\bar{t}$
- W+jets
- Multijet
- Data

D∅, 5.4 fb^{-1}

A_{fb}^l obs. $(14.2 \pm 3.8)\%$
      pred. $(0.8 \pm 0.6)\%$

A_{fb}^l parton $(15.2 \pm 4.0)\%$
      pred. $(2.1 \pm 0.1)\%$

significant

CDF 8.4fb^{-1} l+jets 2498 leptons

CDF Run II Preliminary L = 8.7 fb^{-1}

- l+Jets Data - Bkg
  $A_{FB} = 0.066 \pm 0.025$
- NLO (QCD + EW) $t\bar{t}$
  $A_{FB} = 0.016$

A_{fb}^l obs bkg-sub. $(6.6 \pm 2.5)\%$
      pred. $(1.6 \pm 0.5)\%$

A_{fb}^l obs bkg-sub. $(3.7 \pm 3.1)\%$ M<450
      pred. $(0.7 \pm 0.2)\%$
A_{fb}^l obs bkg-sub. $(11.6 \pm 4.2)\%$ M>450
      pred. $(3.2 \pm 1.0)\%$

mass dependent

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lepton-top asymmetry ratio

- $R^l_{FB} = A^l_{FB}/A^{tt}_{FB}$
  - independent of denominator
  - independent of asymmetry mechanism if P = 0

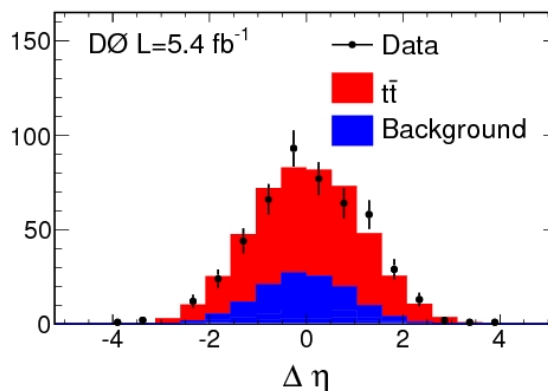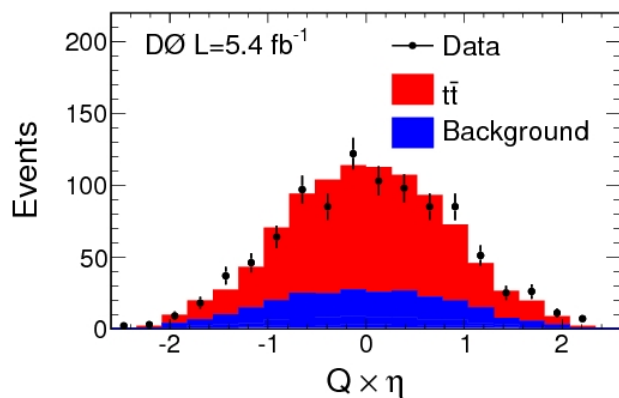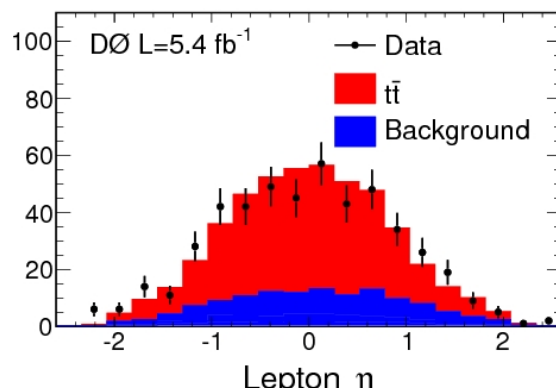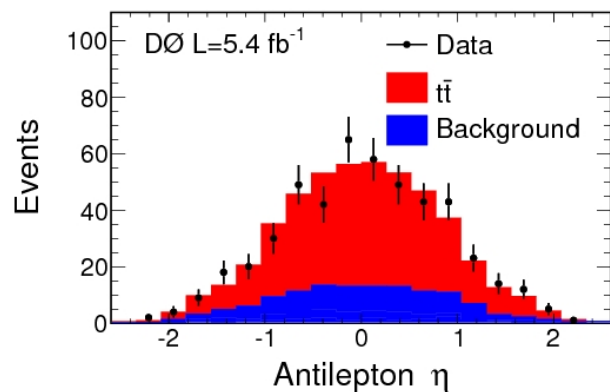- $R^l_{FB} = (0.3\text{-}0.4) \pm 0.05$ (Bernreuter-Si,Campbell-Ellis)

informal suggestion of the D0 5.4fb-1 l+jets numbers

(neglecting correlations)
- $R^l_{FB} \sim (15.2 \pm 4.0)/(19.6 \pm 6.5) \sim 0.78 \pm 0.3$

D0 dilepton rapidity asymmetries

- arXiv:1207.0364
- 5.4 fb^{-1}, 2 OS leptons (M.ne.Z) + met + 2 jets + Ht
- 649 events bkg = 244±18
- no tt reconstruction: it's the leptons

D0 dilepton rapidity asymmetries

- inclusive

	Raw	Unfolded	Predicted	
A^ℓ	$2.9 \pm 6.1 \pm 0.9$	$2.5 \pm 7.1 \pm 1.4$	4.7 ± 0.1	A_C
$A^{\ell^+}_{\mathrm{FB}}$	$4.5 \pm 6.1 \pm 1.1$	$4.1 \pm 6.8 \pm 1.1$	4.4 ± 0.2	+ charge leptons
$A^{\ell^-}_{\mathrm{FB}}$	$-1.2 \pm 6.1 \pm 1.3$	$-8.4 \pm 7.4 \pm 2.4$	-5.0 ± 0.2	- charge leptons
A^{ℓ}_{FB}	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	4.7 ± 0.1	both charges (q.η)
$A^{\ell\ell}$	$3.3 \pm 6.0 \pm 1.1$	$5.3 \pm 7.9 \pm 2.9$	6.2 ± 0.2	Δy leptons
A^{ℓ}_{CP}	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	-0.3 ± 0.1	CP violating

- no excursions

D0 dilepton rapidity asymmetries

- inclusive

	Raw	Unfolded	Predicted	
A^ℓ	$2.9 \pm 6.1 \pm 0.9$	$2.5 \pm 7.1 \pm 1.4$	4.7 ± 0.1	A_C
$A^{\ell+}_{\mathrm{FB}}$	$4.5 \pm 6.1 \pm 1.1$	$4.1 \pm 6.8 \pm 1.1$	4.4 ± 0.2	+ charge leptons
$A^{\ell-}_{\mathrm{FB}}$	$-1.2 \pm 6.1 \pm 1.3$	$-8.4 \pm 7.4 \pm 2.4$	-5.0 ± 0.2	- charge leptons
A^{ℓ}_{FB}	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	4.7 ± 0.1	both charges (q.η)
$A^{\ell\ell}$	$3.3 \pm 6.0 \pm 1.1$	$5.3 \pm 7.9 \pm 2.9$	6.2 ± 0.2	Δy leptons
A^{ℓ}_{CP}	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	-0.3 ± 0.1	CP violating

- no excursions
- how does single lepton compare to same in l+jets?

D0 combined lepton asymmetry

- A^l_{FB} DIL   = (5.8 ± 5.3) %   pred (4.7 ± 0.1)%
- A^l_{FB} l+jets = (15.2 ± 4.0)%   pred (2.1 ± 0.1)%

- combination $A^l = (11.8 \pm 3.2)$%   (BLUE LJ:DIL = 64:36)

informal suggestion of the combined D0 numbers

- R^l_{FB} ~ $(11.8 \pm 3.2)/(19.6 \pm 6.5)$ ~ 0.6 ± 0.3

- recall we expect ~ 0.3-0.4

- picture is hanging together?

- but! CDF large DIL A^{tt}_{FB} : (41.7 ± 15.7)%
  - must be reconciled with small A^l_{FB} in D0 DIL

summary

in l+jets

- inclusive asymmetry in agreement CDF+D0
  - informal combo $A^{tt}_{FB} \sim (19 \pm 4)\%$
  - eventual combined $\delta A_{FB} \sim 3.0\%$
- linear M_{tt} and Δy dependence of A_{fb} in tt system (CDF)
  - slopes 3σ from zero and 2σ larger than NLO prediction
- measured $2\text{-}3\sigma$ asymmetry in the lepton alone (D0 parton, CDF obs.)
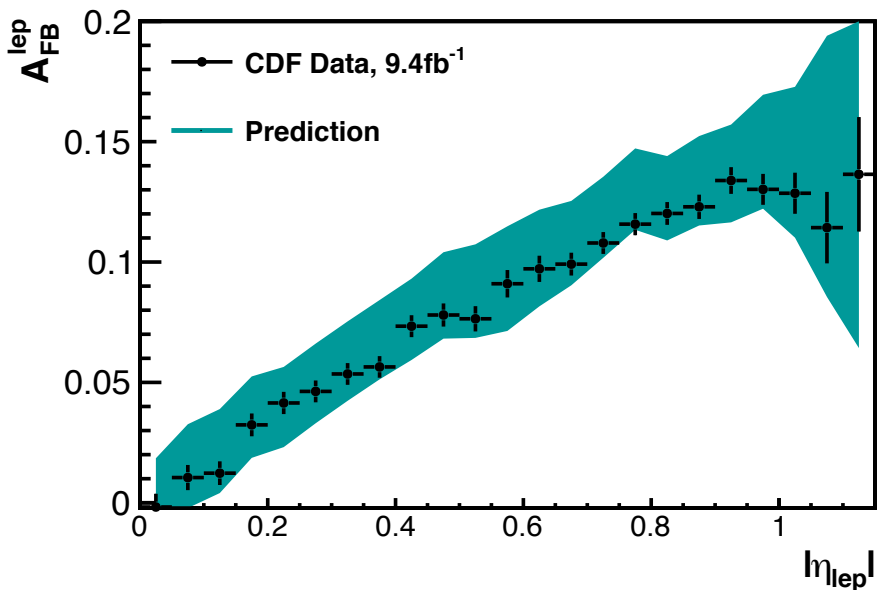- $p_t(tt)$ dependence agrees with Poweg/Pythia + offset

in dileptons

- no significant A_{FB} in any lepton variable (D0)

  - tension in A^l_{FB}? but combined A^l_{FB} agrees with expected R

- significant A_{FB} in reco tt Δy (CDF)

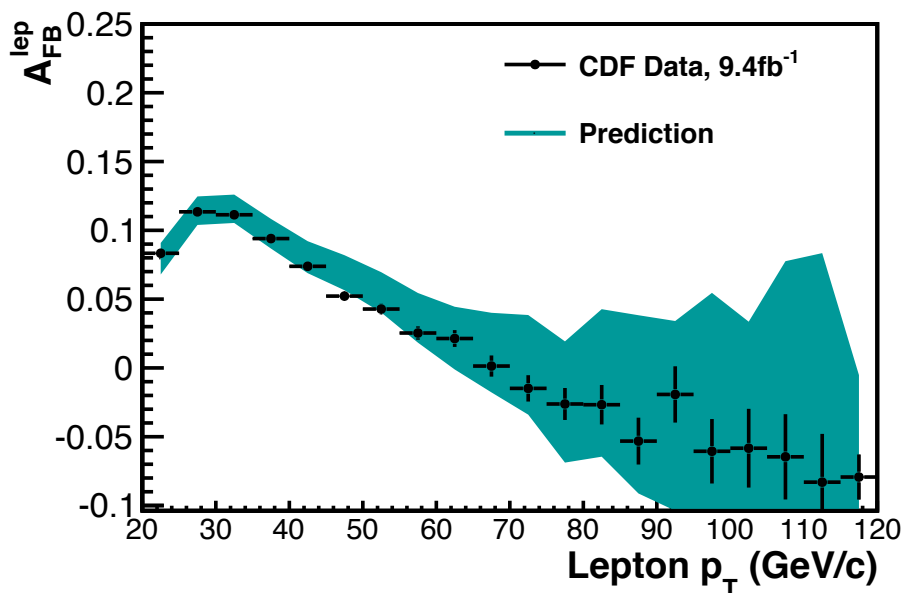 - tension w D0 dil leptons?

something is there ?

- picture still incomplete, much work still to do

additional material

# lepton A_{FB} performance in the W+1 jet sample (CDF)

	$|\eta_{lep}| < 0.75$	$|\eta_{lep}| \geq 0.75$
Observed Data	0.059 ± 0.001	0.124 ± 0.002
SM Prediction	0.063 ± 0.005	0.134 ± 0.008
Data Minus Prediction	-0.004 ± 0.005	-0.010 ± 0.008

	$p_T < 60\mathrm{GeV}/c$	$p_T \geq 60\mathrm{GeV}/c$
Observed Data	0.083 ± 0.001	-0.009 ± 0.004
SM Prediction	0.089 ± 0.004	-0.001 ± 0.013
Data Minus Prediction	-0.006 ± 0.004	-0.008 ± 0.014

lepton asymmetry

- CDF lepton at reco level
- A^l_{FB} = (6.6
- parton level coming
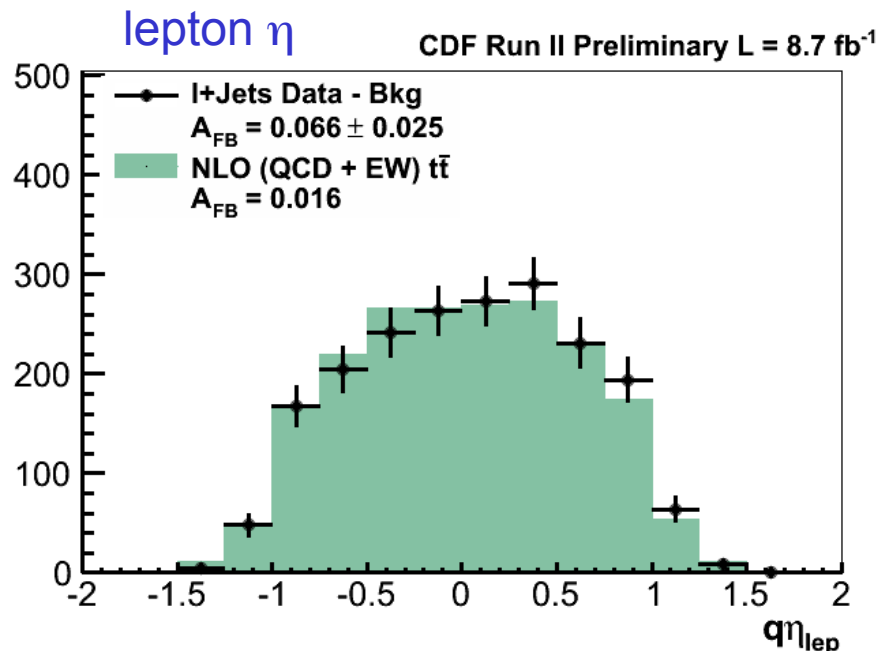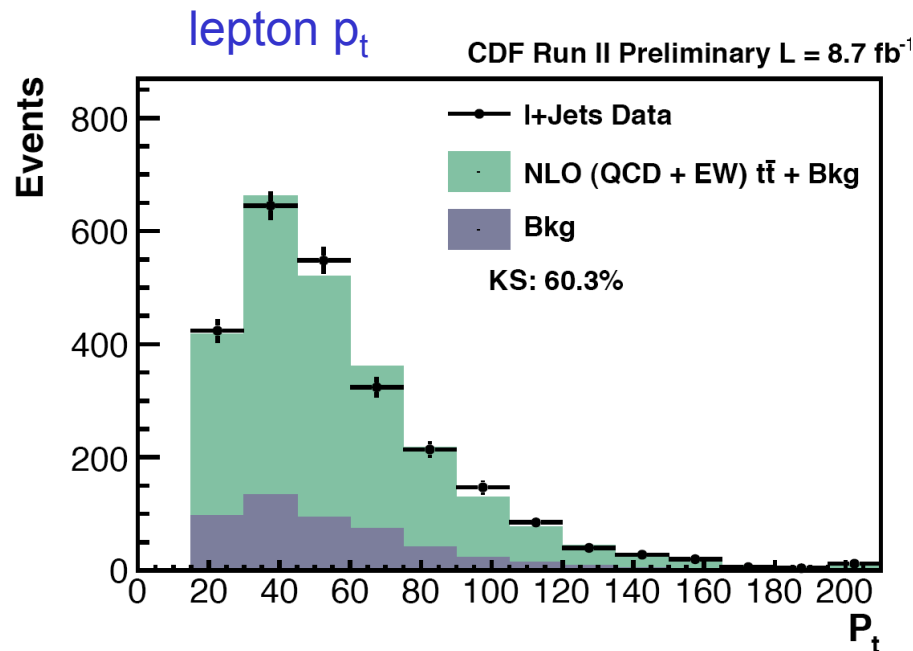
lepton p_t

lepton η

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

CDF vs D0 lepton rapidity difference in dilepton top signal

$$A_{obs}^{\Delta\eta_l} = 0.138 \pm 0.054$$

$$A_{pred}^{\Delta\eta_l} = -0.022 \pm 0.022$$
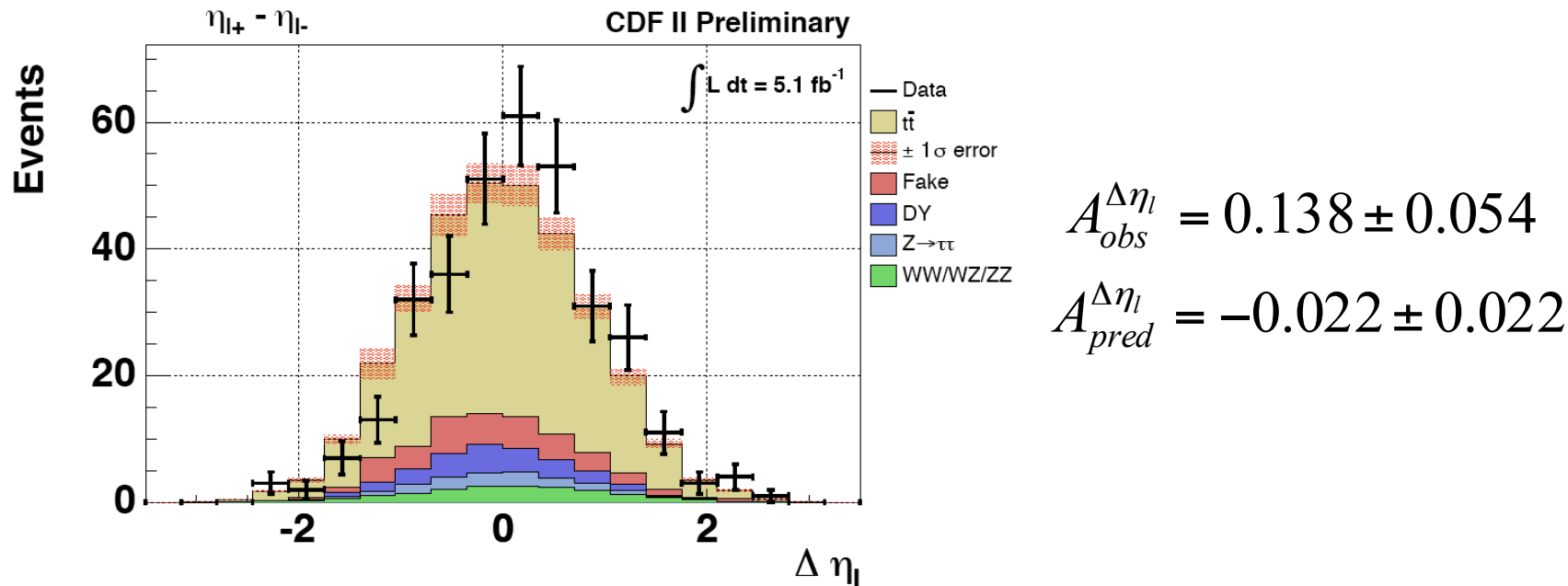
	Raw	Unfolded	Predicted	
A^ℓ	$2.9 \pm 6.1 \pm 0.9$	$2.5 \pm 7.1 \pm 1.4$	4.7 ± 0.1	
$A_{FB}^{\ell^+}$	$4.5 \pm 6.1 \pm 1.1$	$4.1 \pm 6.8 \pm 1.1$	4.4 ± 0.2	
$A_{FB}^{\ell^-}$	$-1.2 \pm 6.1 \pm 1.3$	$-8.4 \pm 7.4 \pm 2.4$	-5.0 ± 0.2	
A_{FB}^{ℓ}	$3.1 \pm 4.3 \pm 0.8$	$5.8 \pm 5.1 \pm 1.3$	4.7 ± 0.1	
$A^{\ell\ell}$	$3.3 \pm 6.0 \pm 1.1$	$5.3 \pm 7.9 \pm 2.9$	6.2 ± 0.2	?????
A_{CP}^{ℓ}	$1.8 \pm 4.3 \pm 1.0$	$-1.8 \pm 5.1 \pm 1.6$	-0.3 ± 0.1	

new CDF l+jets

$$q\bar{q} \to g \to t\bar{t} \to (W^+ b)(W^- \bar{b}) \to (l^+ \nu b)(q\bar{q}\bar{b}) \to l^+ + \not{E}_T + 4j + \geq 1 \, btag$$
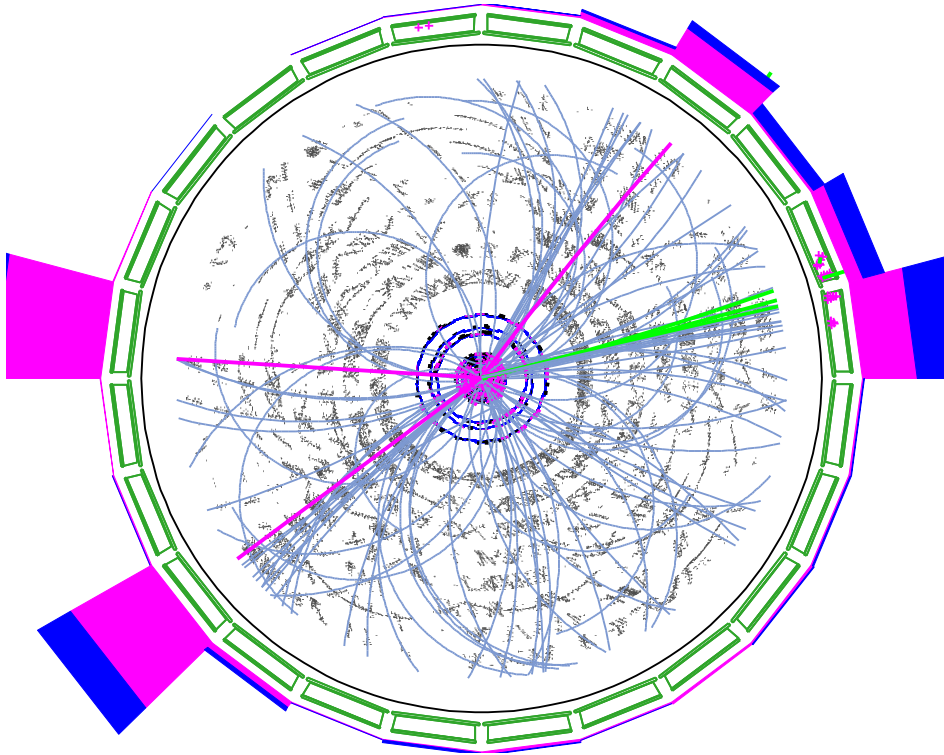
- **full Run II data set**
  - 8.7 fb^{-1} (soon to be 9.4 fb^{-1})
  - add new muon trigger stream
  - require

    - 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

  - find 2498 events
  - bkg = 505 ± 123

top reconstruction χ^2
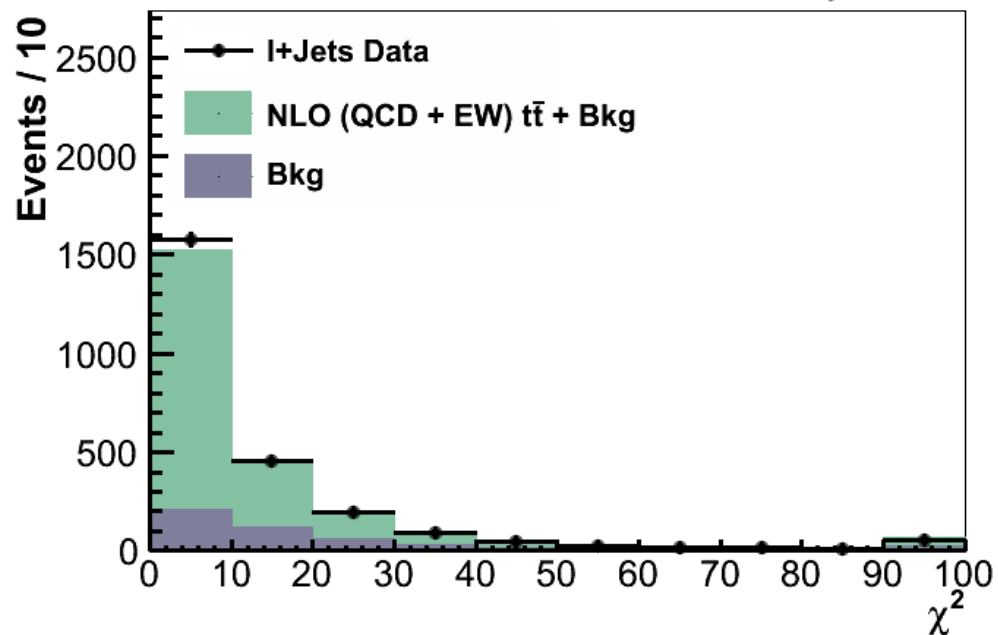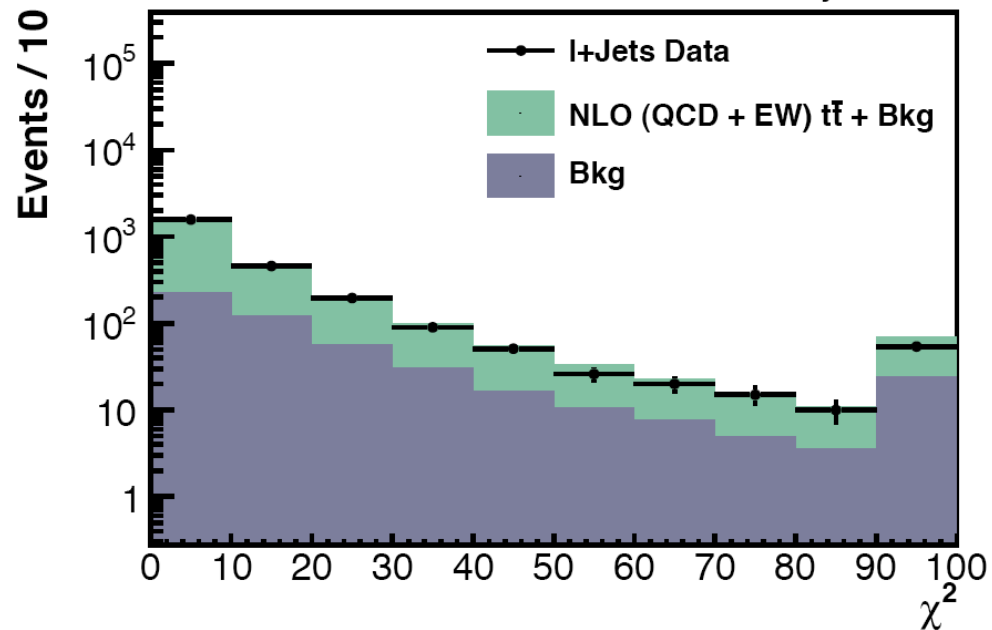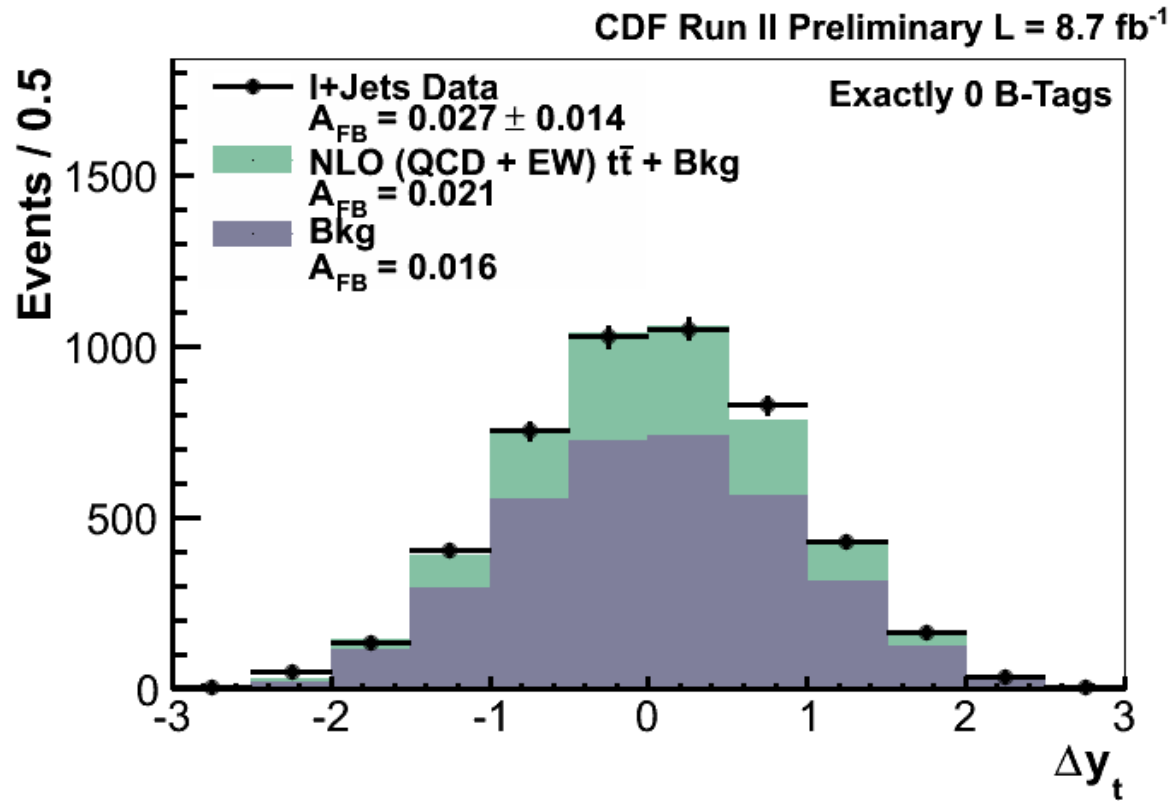
top reconstruction $p_t(t\bar{t})$

- **a difficult variable**
  - extra jets
  - unclustered energy
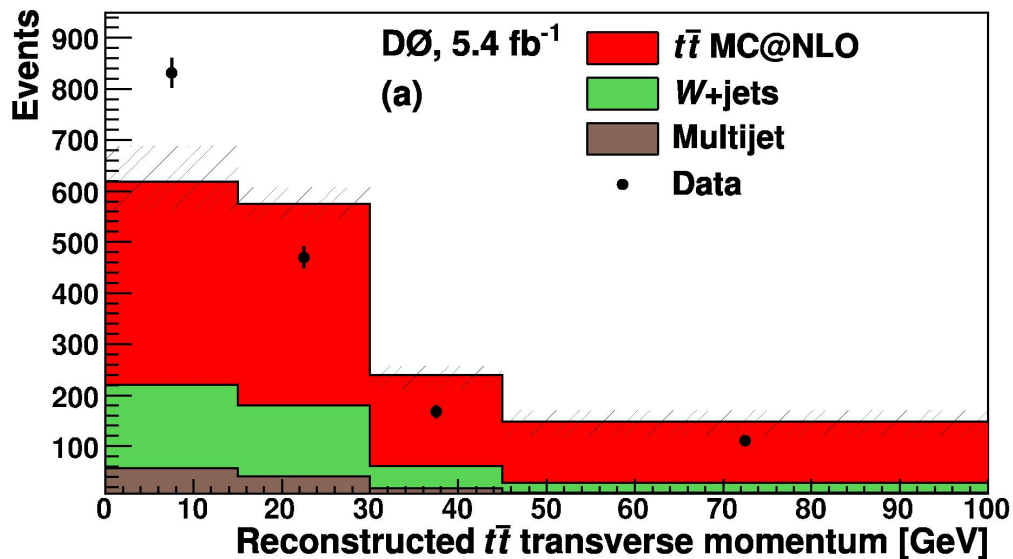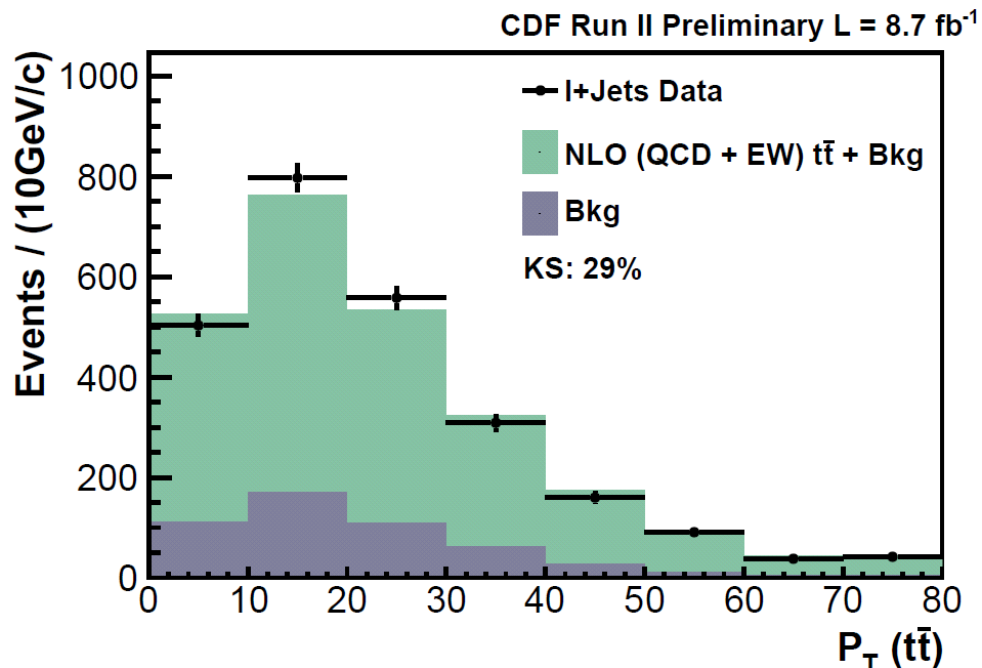
backgrounds

- **check in 0-btag sample**
  - ~ 80% non-tt

- A_{fb} **data = (2.7 ± 1.4)%**

- A_{fb} **pred. = 2.1%**

- **suggests**
  - bkgs well modeled
  - bkgs not source of A_{fb}

- **subtract 'em**

CDF Run II Preliminary L = 8.7 fb^{-1}

Exactly 0 B-Tags

l+Jets Data
$A_{FB} = 0.027 \pm 0.014$

NLO (QCD + EW) $t\bar{t}$ + Bkg
$A_{FB} = 0.021$

Bkg
$A_{FB} = 0.016$

Events / 0.5

Δy_t

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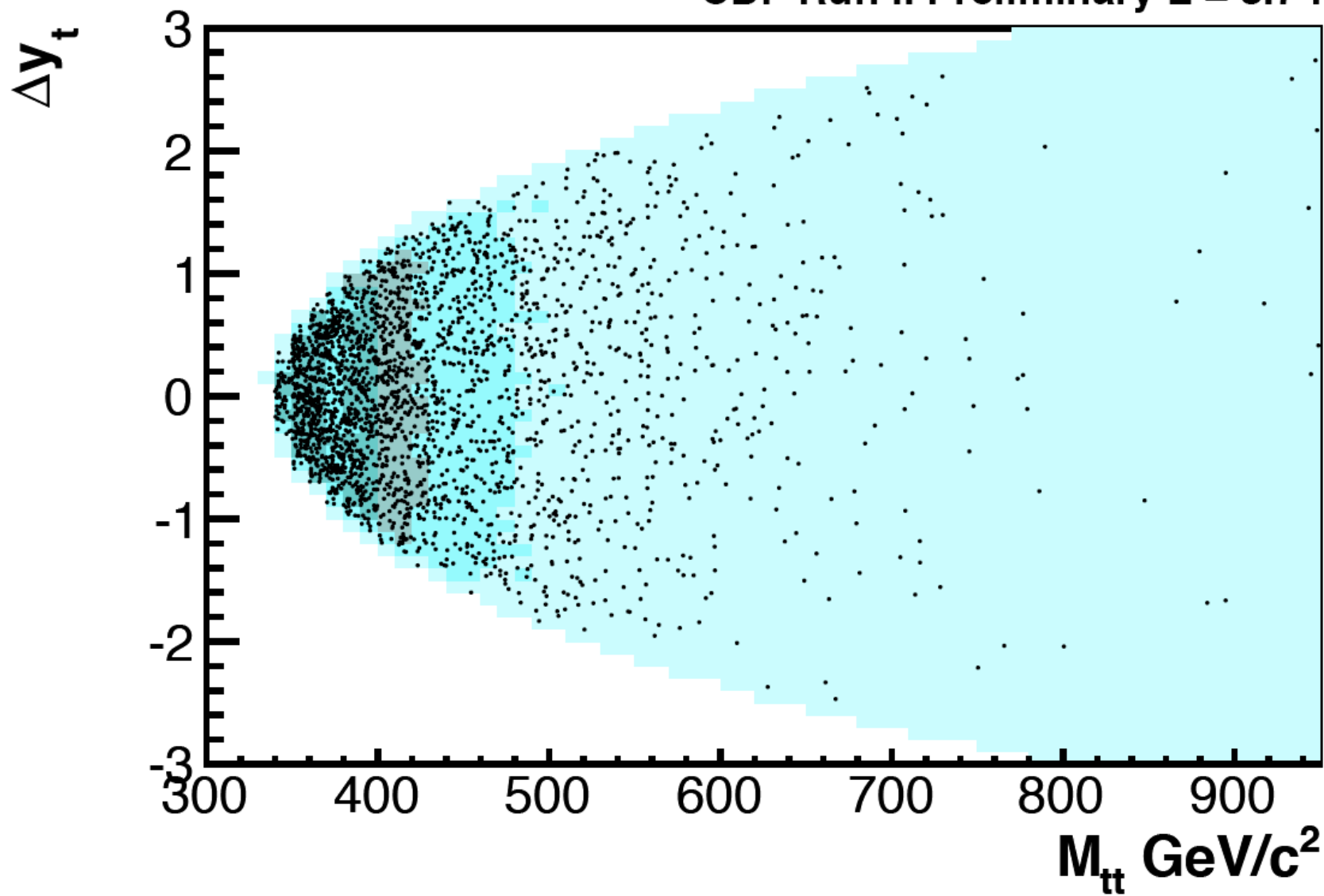
mass dependence

$M_{tt} < 450$ GeV/c^2

$M_{tt} > 450$ GeV/c^2
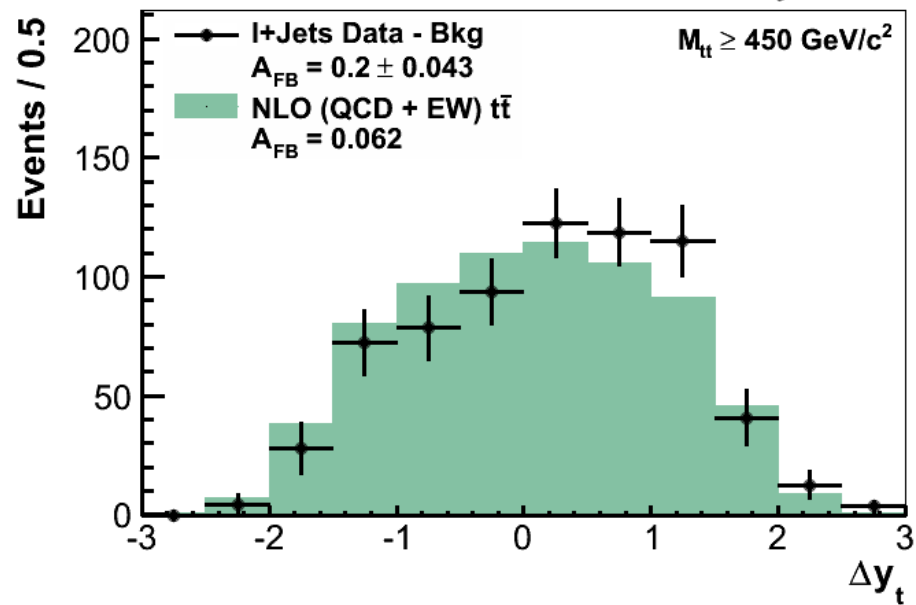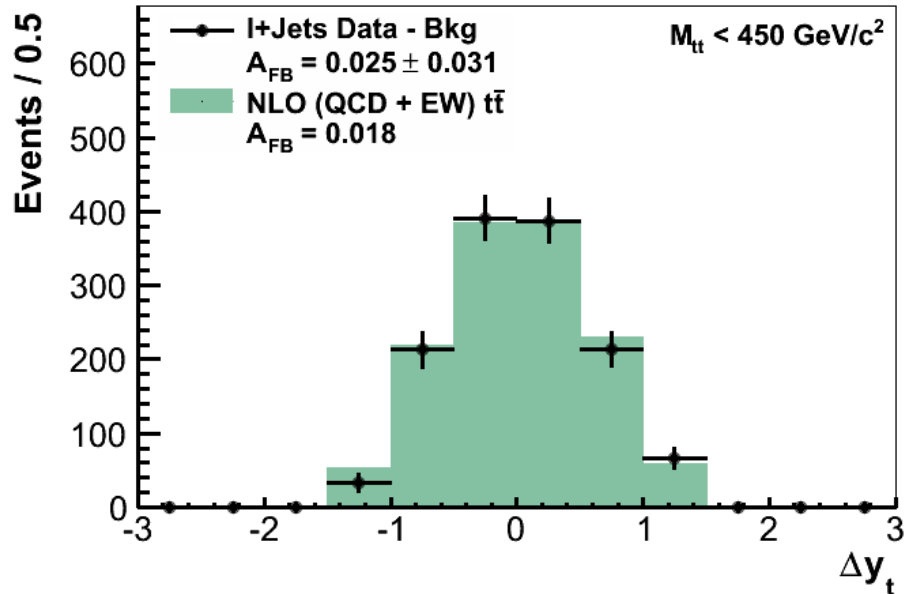
mass dependence

- **M_{tt} for forward and backward**
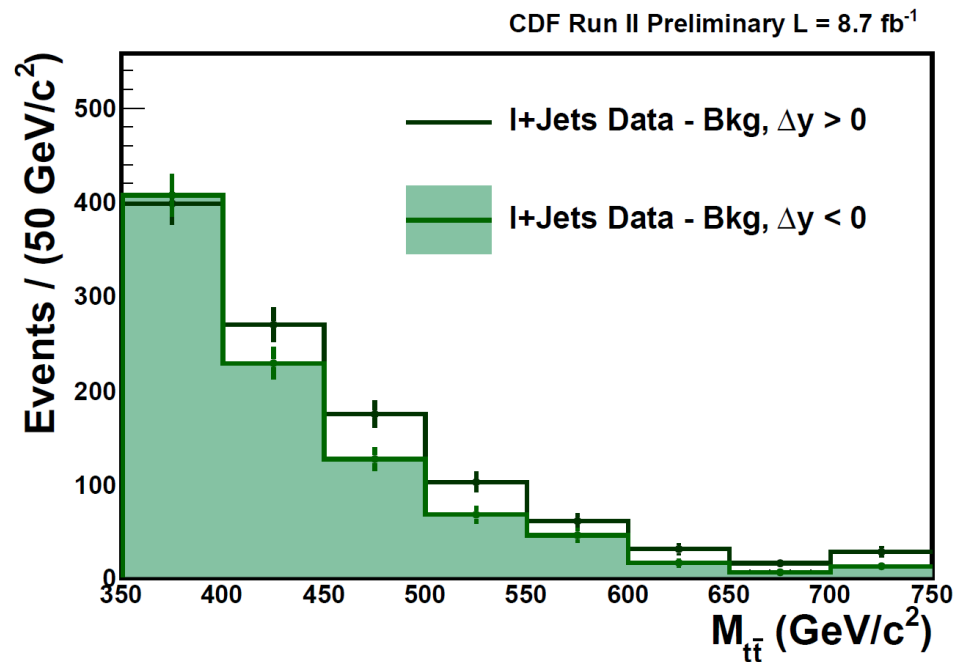
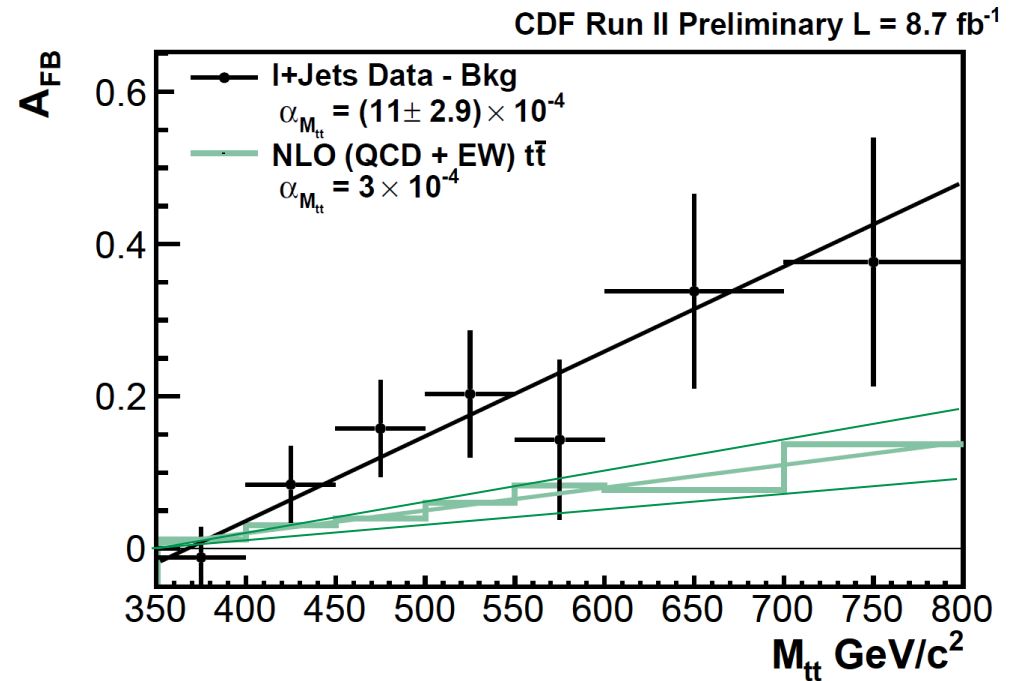- **mass dependent asymmetry**

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

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

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Asymmetry in various selections

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

CDF Run II Preliminary $L = 8.7$ fb^{-1}

backgrounds
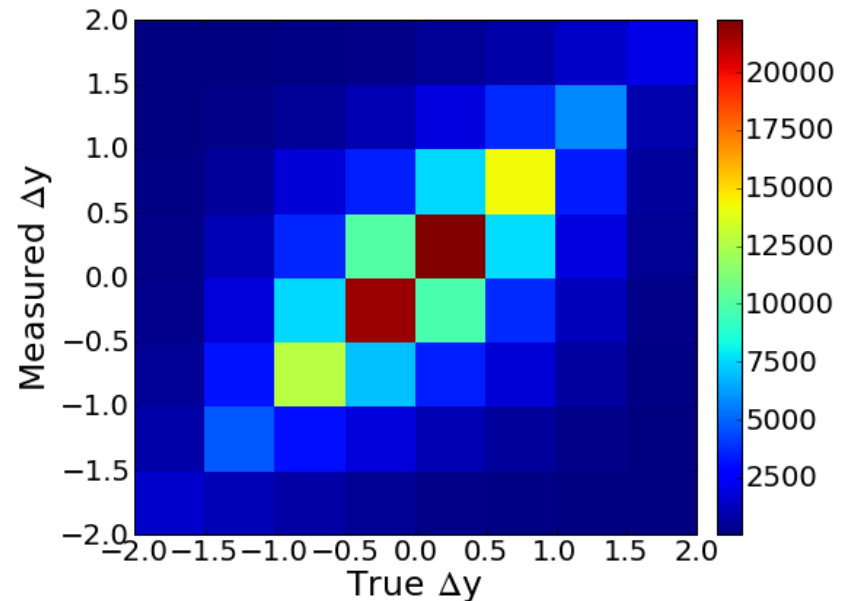
- 0 b-tags with *top subtracted*
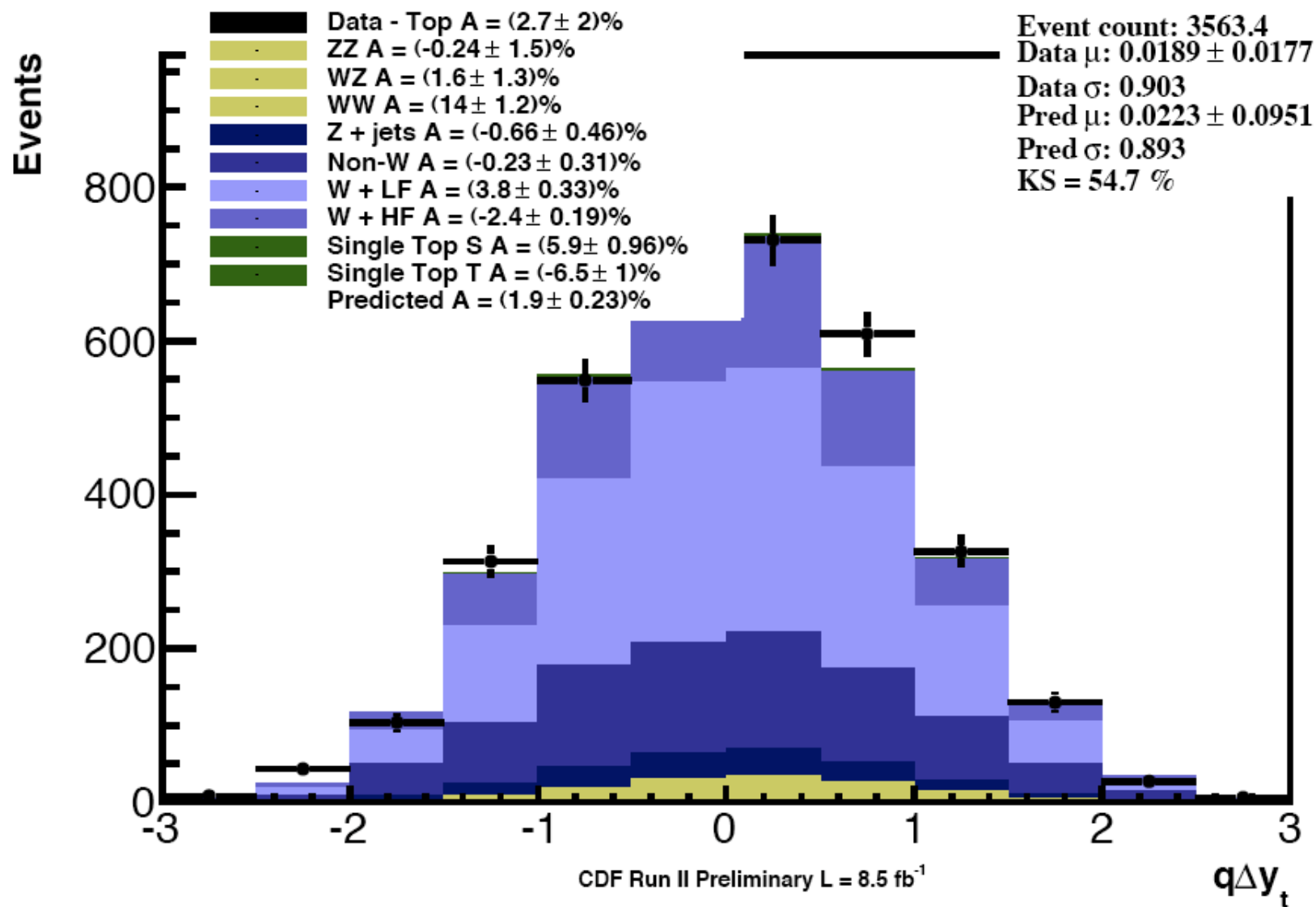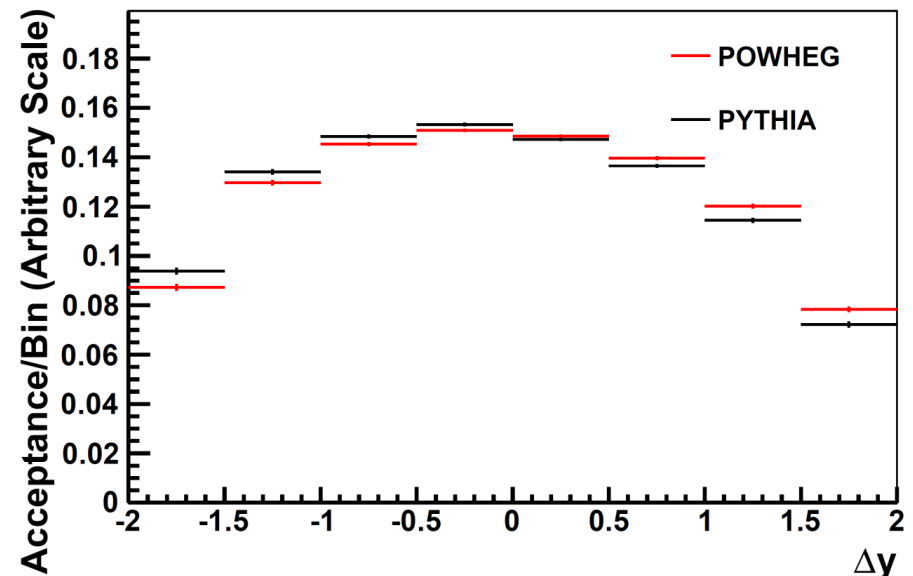
parton level

- binned data

- correct for smearing S
  - finite resolution
  - incorrect reconstruction

- and acceptance   A
  - detector coverage
  - trigger selection
  - selection cuts

$$x_i^{Parton} = A_{ij}^{-1} S_{jk}^{-1} x_k^{Data}$$
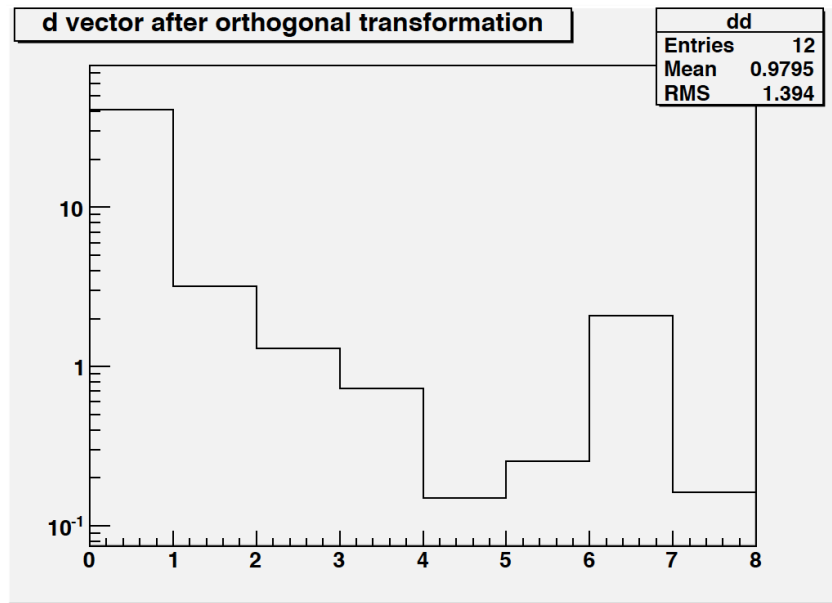
- SVD unsmear (Hocker-Kartvelshvili)

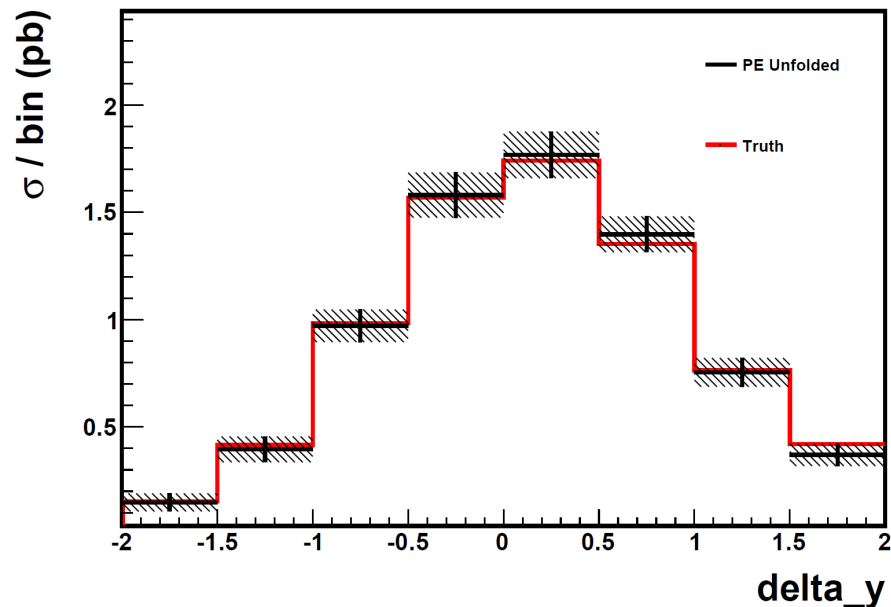

CDF Run II Preliminary L = 8.7 fb⁻¹

SVD unfold

"d vector"

bias studies with "Octet A"

d vector after orthogonal transformation	dd	
	Entries	12
	Mean	0.9795
	RMS	1.394

- choose k =4

$|\Delta y|$	Found Asymmetry	Uncertainty
Inclusive	0.162	0.039
$0.0 \leq |\Delta y| < 0.5$	0.056	0.036
$0.5 \leq |\Delta y| < 1.0$	0.180	0.056
$1.0 \leq |\Delta y| < 1.5$	0.313	0.081
$|\Delta y| \geq 1.5$	0.431	0.132

mass dependence old vs new

CDF Run II Preliminary L = 8.7 fb^{-1}

l+Jets Data

NLO (QCD + EW) t$\bar{t}$ + Bkg

A_{FB}

M_{tt} GeV/c^2
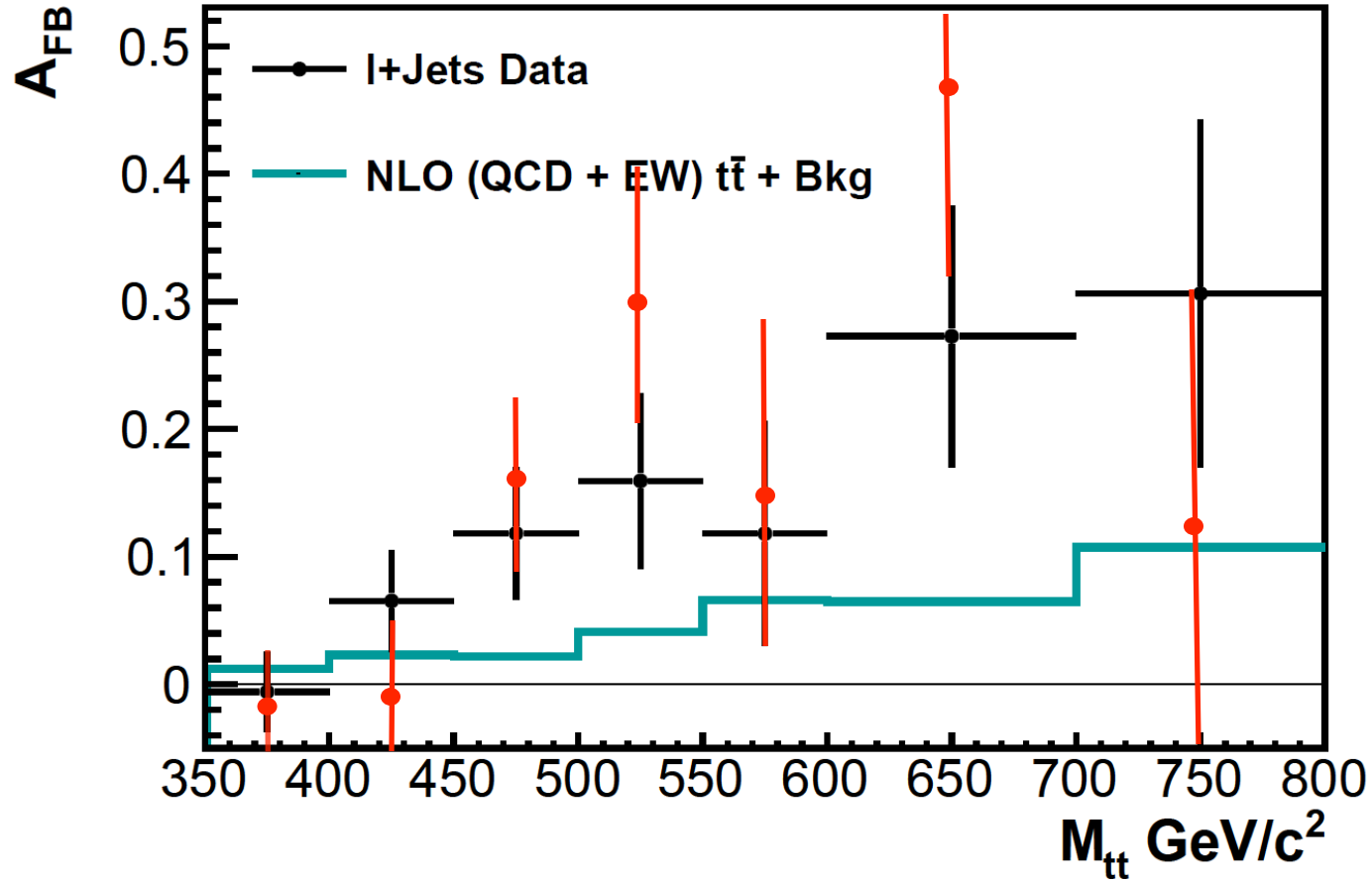
prior measurements of A(Δy) (%)

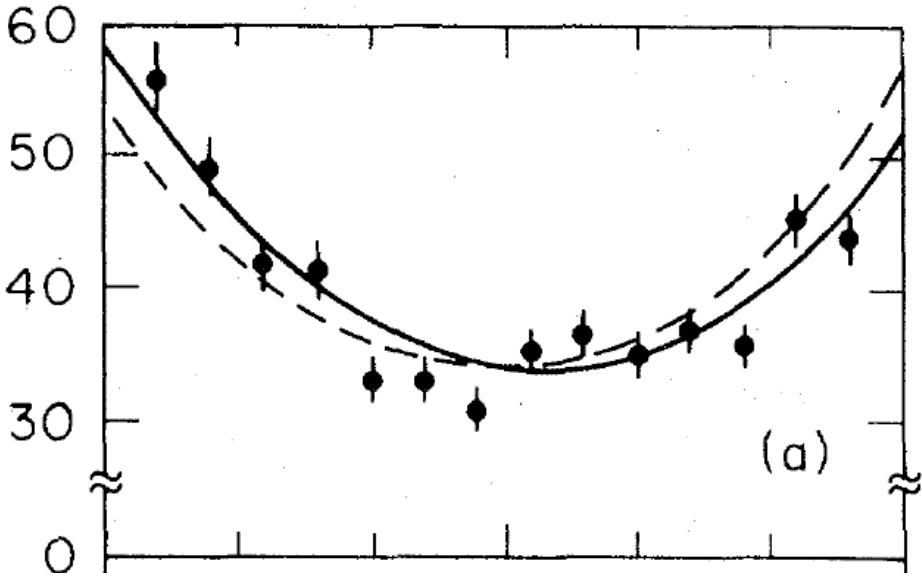|	
CDF l+jet 5.3 fb^{-1}	15.8 ± 7.4
CDF DIL 5.1 fb^{-1}	42.0 ± 16.0
CDF combo	20.1 ± 6.7
D0 l+jet 5.4 fb^{-1}	19.6 ± 6.5
informal combo	19.8 ± 4.7

NLO 6.6±2.0

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

this talk: new CDF l+jets, lepton only, $A_{FB}(p_T(tt))$

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Historical perspective

e+e- 29 GeV

Z discovered below pole, 1983