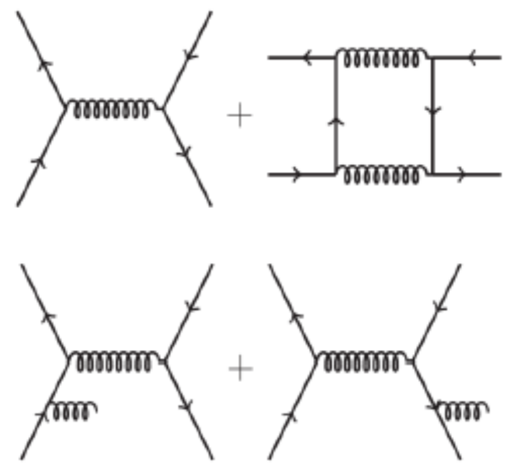
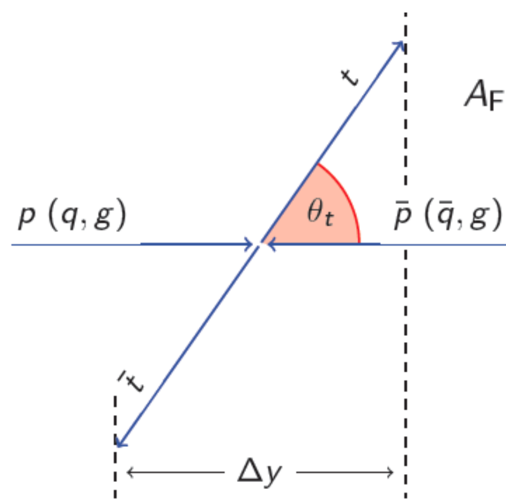
tT asymmetry at the Tevatron

J. Huston
Michigan State University

tT charge asymmetry

- Dominant contribution to charge asymmetry originates from qQ annihilation, namely from asymmetric piece in interference between Born amplitude and one-loop corrections
- Involving an IR divergence that is cancelled in the sum of real and virtual NLO corrections
- The virtual and real corrections to the asymmetry have opposite signs
- At the Tevatron, this charge asymmetry shows up as a forward-backward asymmetry
  - measure in $\Delta y = y_t - y_T$
- Significant EWK corrections
  - AFB (NLO QCD)*1.26 (EWK)
  - Kuhn-Rodrigo, Hollik-Pagani, Manohar-Trott





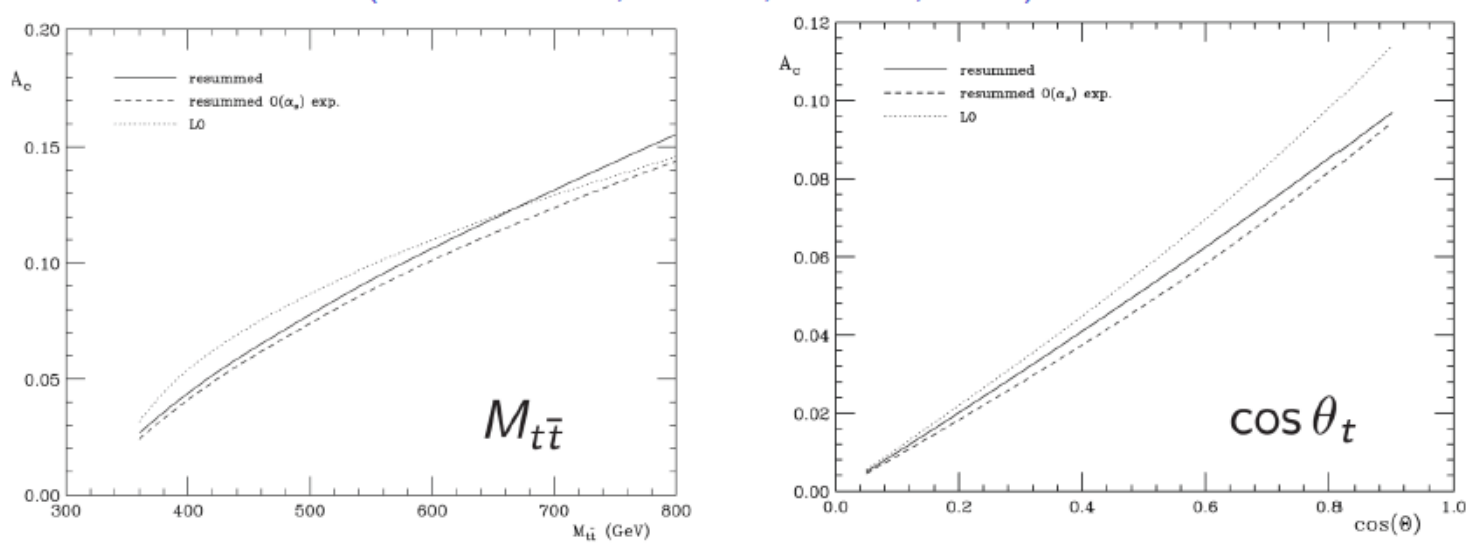
$$A_{FB} \equiv \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$

…expect A_{FB}~6.6%

Asymmetry

- Expect a roughly linear increase in asymmetry with m_{tT} and Δy ($\cos\theta^*$)
- Asymmetry is stable to threshold corrections from soft gluons

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

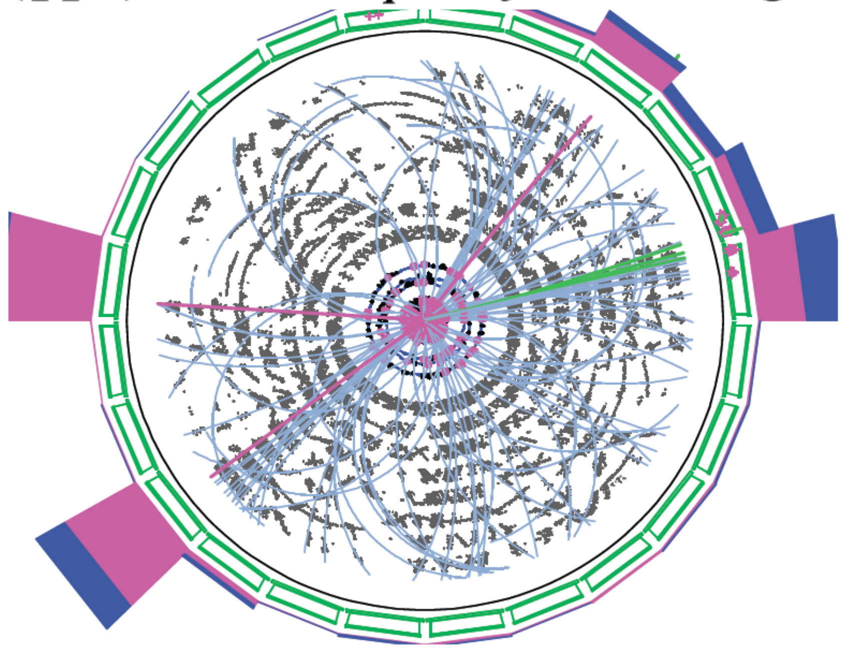


- For comparisons in CDF, we use the Powheg implementation of tT production (which gives a compatible asymmetry to that from MCFM) multiplied by the EWK factor of 1.26
  - note that this effectively is using NLO in as in both the numerator and denominator (which I believe is best, and at least is well-defined)
  - you are free to compare the data to any other prediction

Measurement

$$q\bar{q} \rightarrow g \rightarrow t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (l^+\upsilon b)(q\bar{q}\bar{b}) \rightarrow l^+ + \not{E}_T + 4j + \geq 1\ btag$$

- I will be discussing mostly results from an analysis of 8.7 fb^{-1} from the Run II data set from CDF (2498 events, factor of 2 greater than last analysis)
  - almost full Run II data set
- A_{FB} in ΔY, m_{tT}, p_T (of tT system)
- Multi-bin corrections to parton level
- Lepton-only asymmetry
- A few words about dilepton asymmetry



- 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 reduces QCD background
- 2498 events bkg = 505±123

Note 4:1 signal to background →

Situation as of last summer

prior measurements

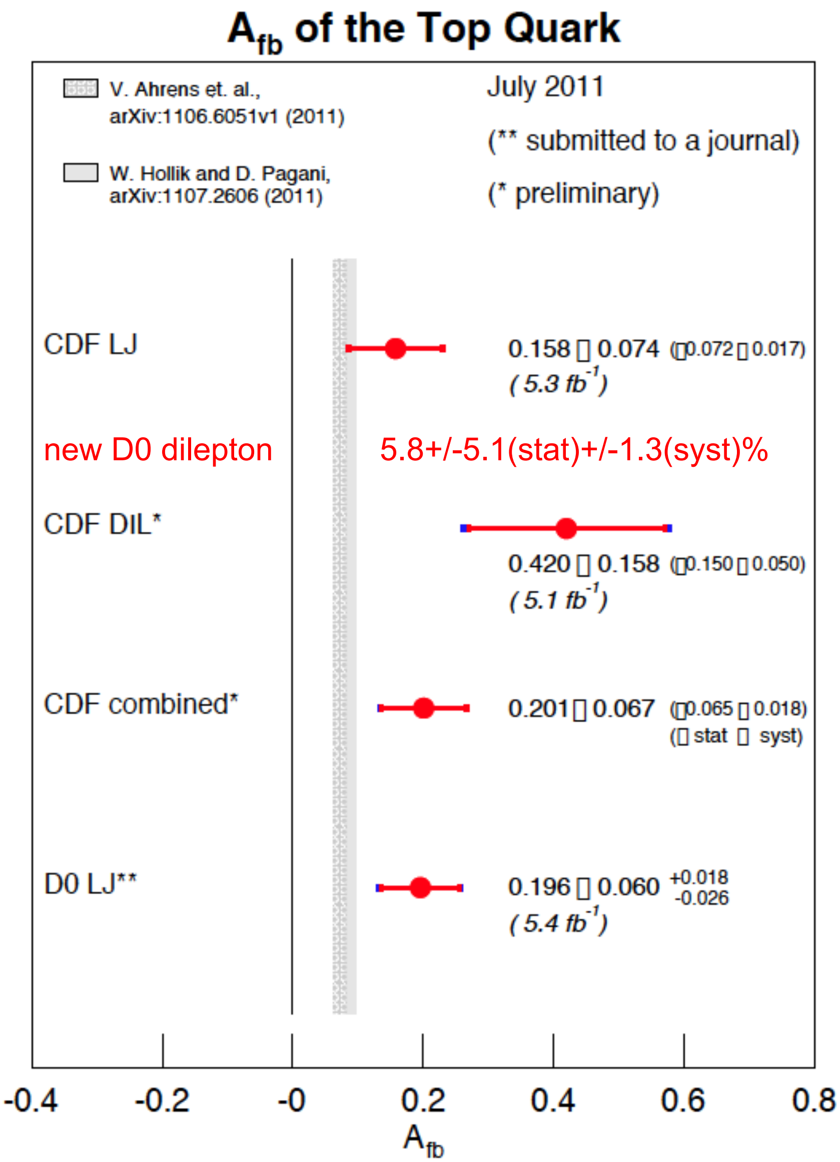
inclusive

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

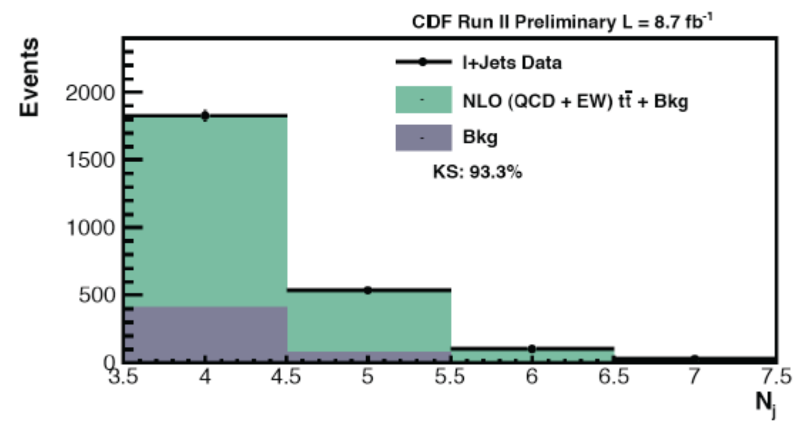
differential (at bkg subtracted data level)

	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
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



Powheg modeling

- Use Pythia for showering
- Provides a good description of the data set
- Agreement, where expected, with MC@NLO and MCFM

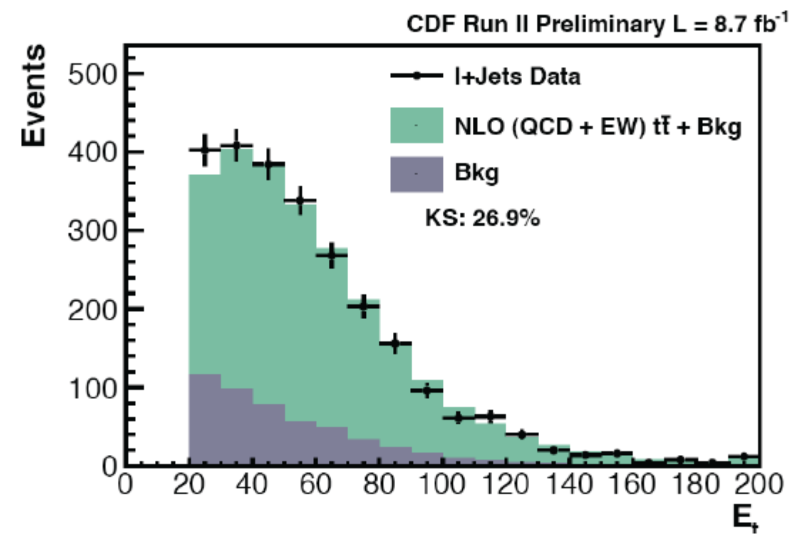


- CDF b-tag background model

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

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

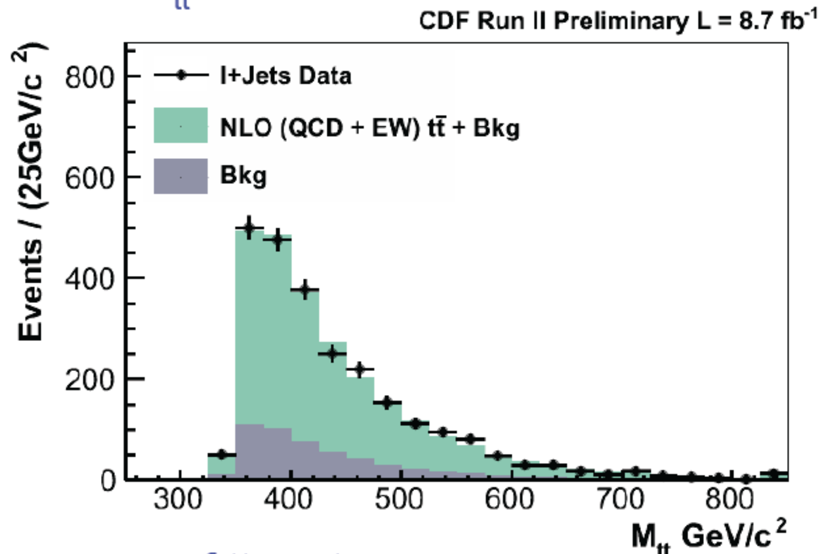
missing E_t



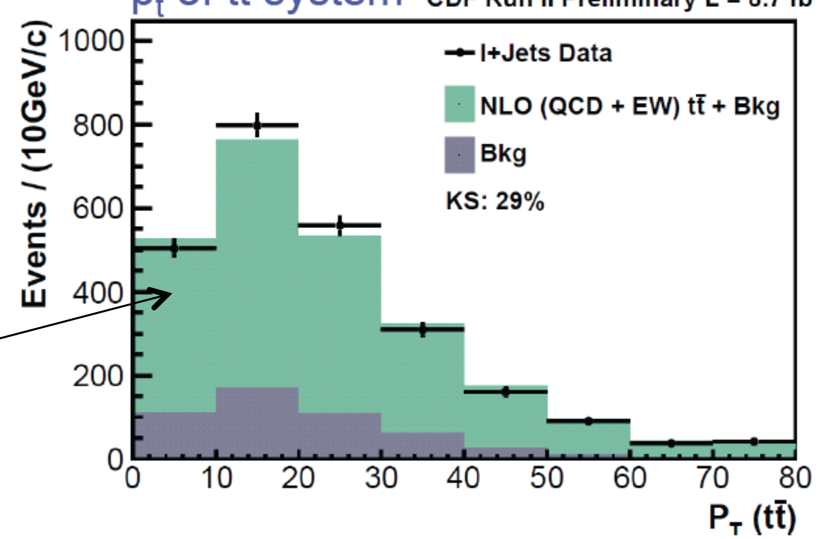
Top reconstruction

- Require lepton + missing E_T + 4 jets (>=1 b tag)
- Apply a jet-parton match and $p_z(\nu)$ solution using simple constraints, choosing best χ^2
  - m_W=80.4 GeV
  - m_t=172.5 GeV
  - b-tag=b jet
  - float jet p_T within errors
- The sign of the lepton gives the sign of the top
- Good agreement between Powheg and data
  - note for p_T of the tT system

M_{tt}

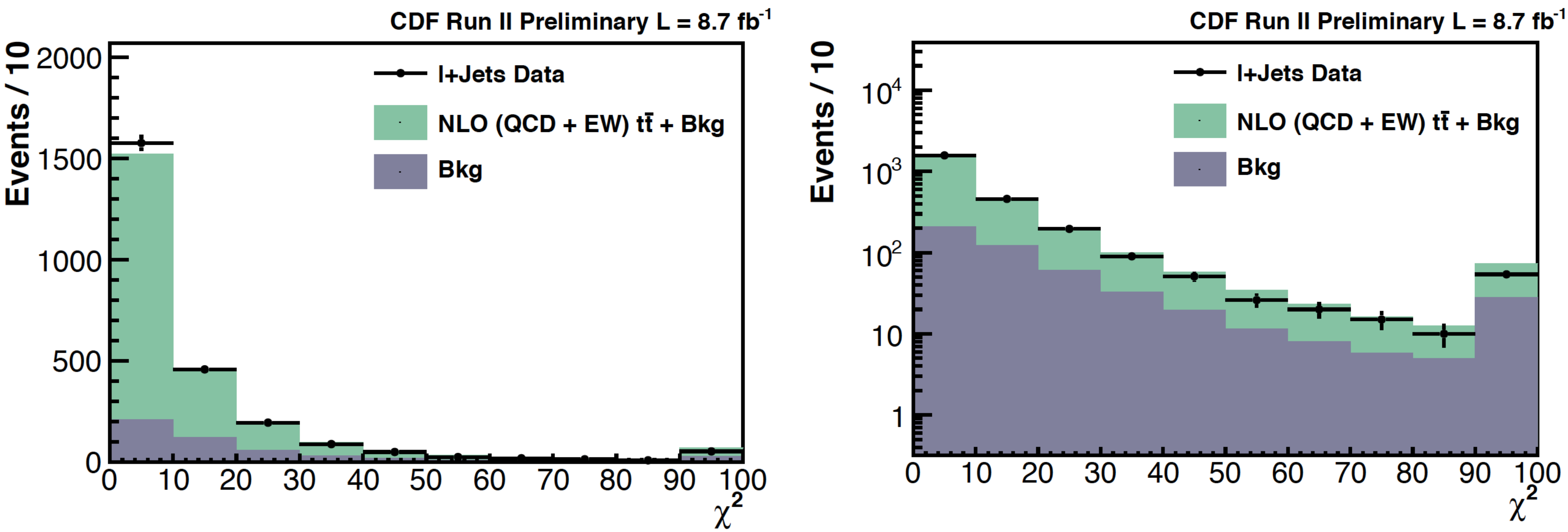


p_t of tt system



Top reconstruction

- Distribution of χ^2 well-described over 2 orders of magnitude
  - and χ^2 is not a real χ^2 in the sense that expect 1 for a good fit



Asymmetry in presence of cuts

The cuts applied for the experimental analysis have the effect of decreasing the measured asymmetry.

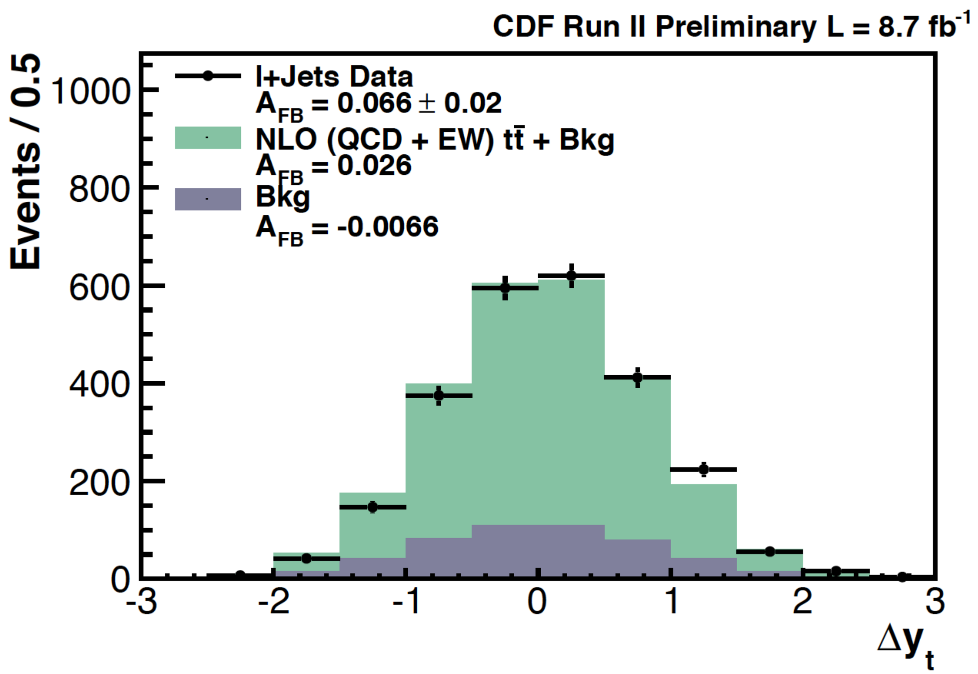
Rapidity range	$A_{FB}^{\text{no cuts}}$(NLO)	A_{FB}^{cuts}(NLO production)	A_{FB}^{cuts}(NLO prod + decay)
inclusive	$0.065^{+0.028}_{-0.014}$	$0.044^{+0.017}_{-0.010}$	$0.045^{+0.021}_{-0.011}$
$0 < \|\Delta y\| < 0.5$	$0.036^{+0.020}_{-0.003}$	$0.017^{+0.005}_{-0.005}$	$0.015^{+0.009}_{-0.004}$
$0.5 < \|\Delta y\| < 1$	$0.062^{+0.013}_{-0.028}$	$0.052^{+0.019}_{-0.012}$	$0.053^{+0.025}_{-0.011}$
$1 < \|\Delta y\| < 1.5$	$0.101^{+0.060}_{-0.006}$	$0.086^{+0.035}_{-0.017}$	$0.092^{+0.039}_{-0.021}$
$\|\Delta y\| > 1.5$	$0.193^{+0.058}_{-0.036}$	$0.142^{+0.059}_{-0.034}$	$0.149^{+0.062}_{-0.036}$

Table 5. Predictions for the top forward-backward asymmetry in the lepton+jets channel at the Tevatron, computed without applying any experimental cuts ($A_{FB}^{\text{no cuts}}$) and also when using the cuts described in the text (A_{FB}^{cuts}). The uncertainties are obtained by varying the scale in the range $(m_t/2, 2m_t)$.

John Campbell and Keith Ellis; arXiv:1204.1513

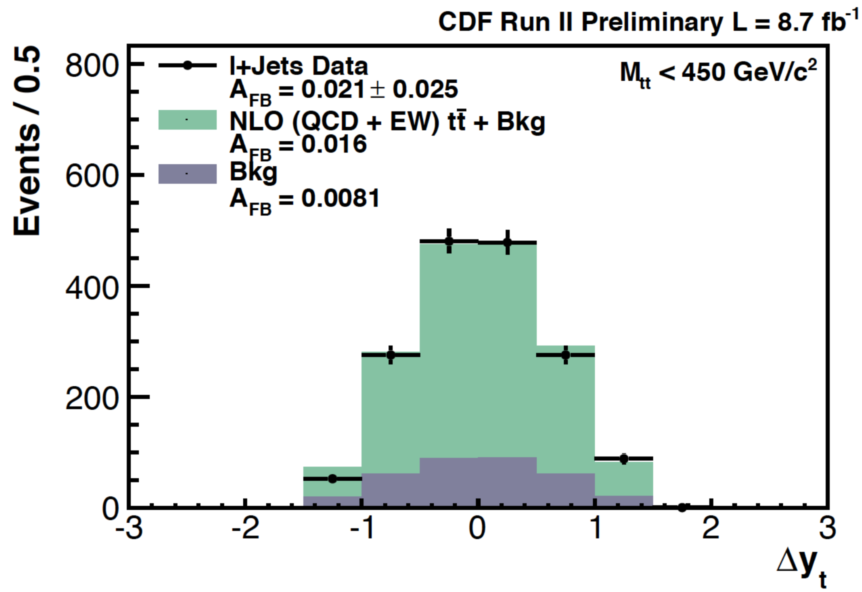
Reconstructed level

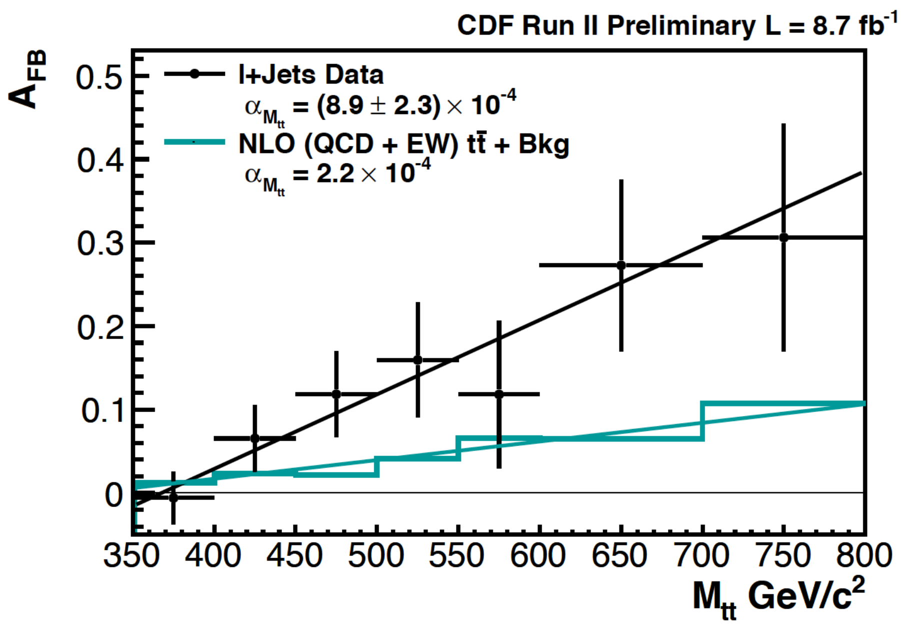
- Expect an asymmetry due to NLO with EWK corrections (plus backgrounds) of 2.6%
- Observe 6.6+/-2.0%
- When sample is separated according to charge of lepton, asymmetries are equal within uncertainties (as expected)

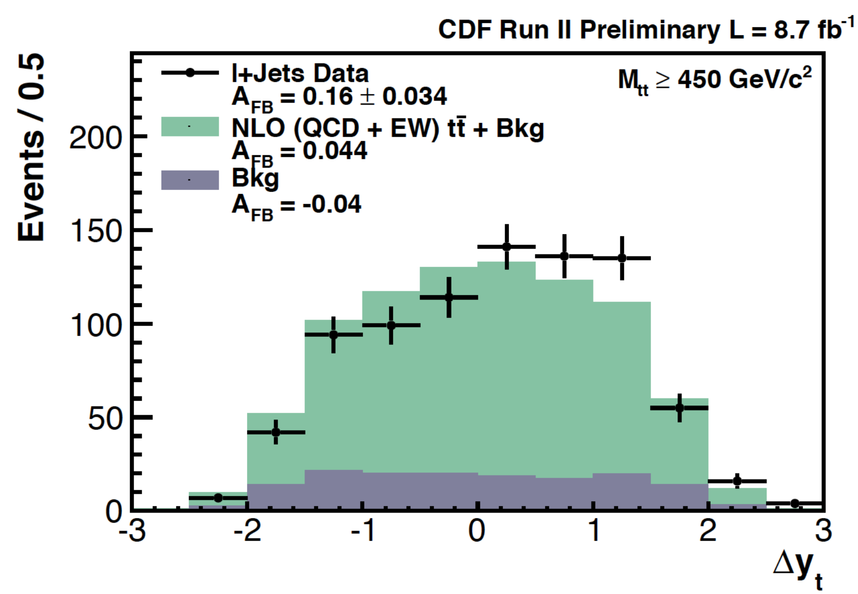


Reconstructed level: mass dependence

- Look at tT masses below and above 450 GeV
- Low mass sample has asymmetry consistent with SM
- High mass sample has A_{FB}=16.0+/-3.4%, expect 4.4%
- No neural net needed here; asymmetry is clearly visible even at reconstructed level

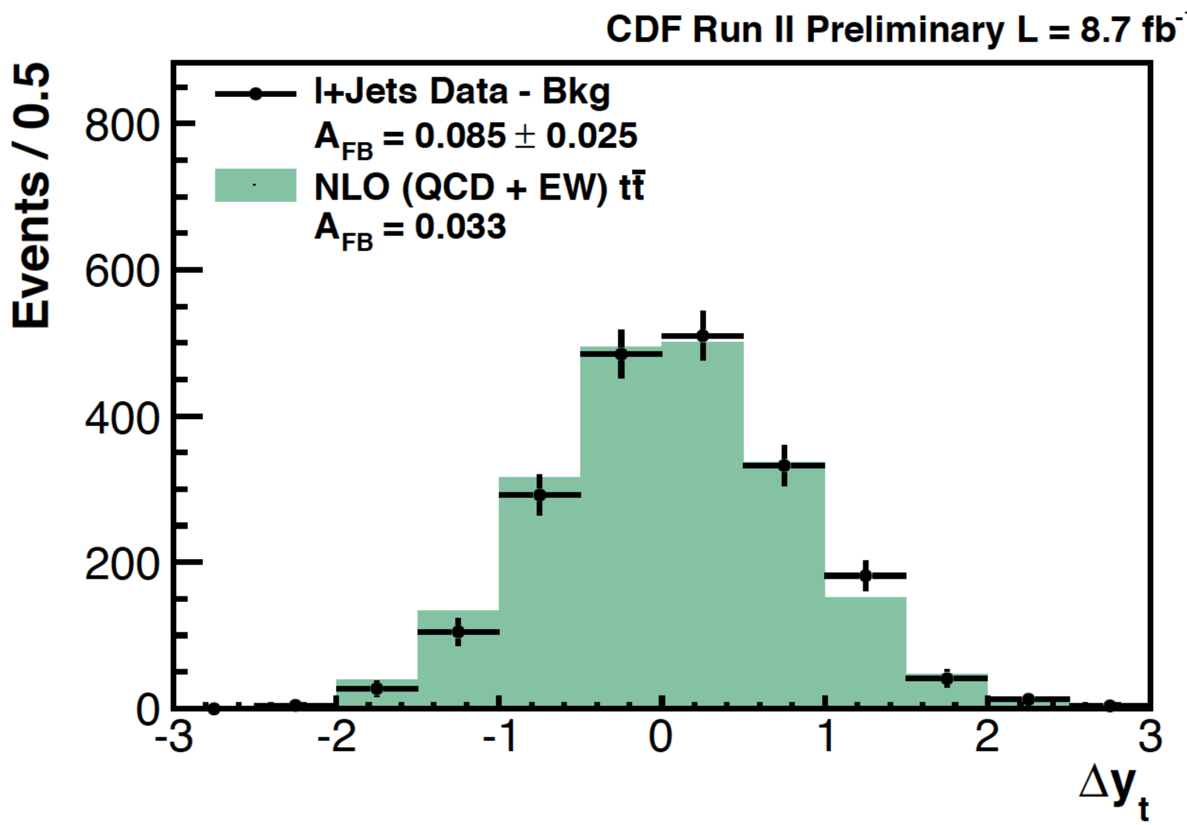






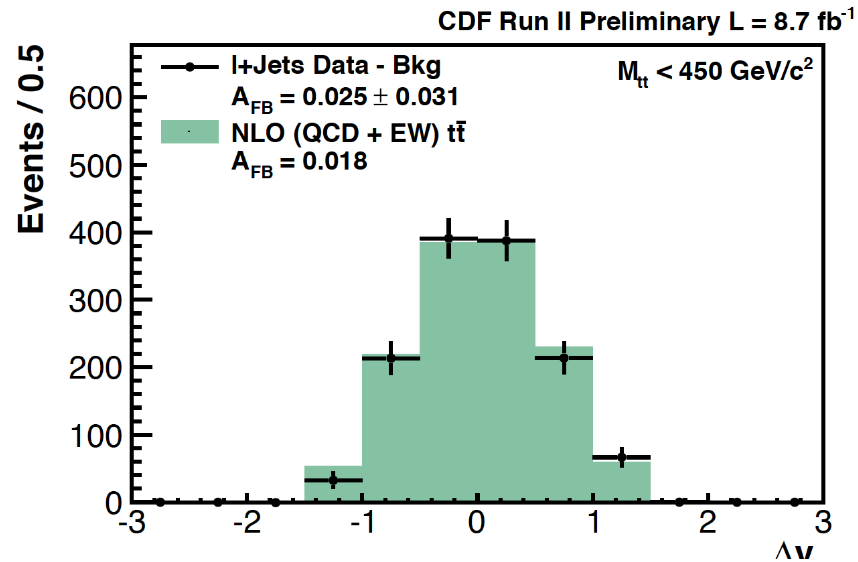
Background subtraction

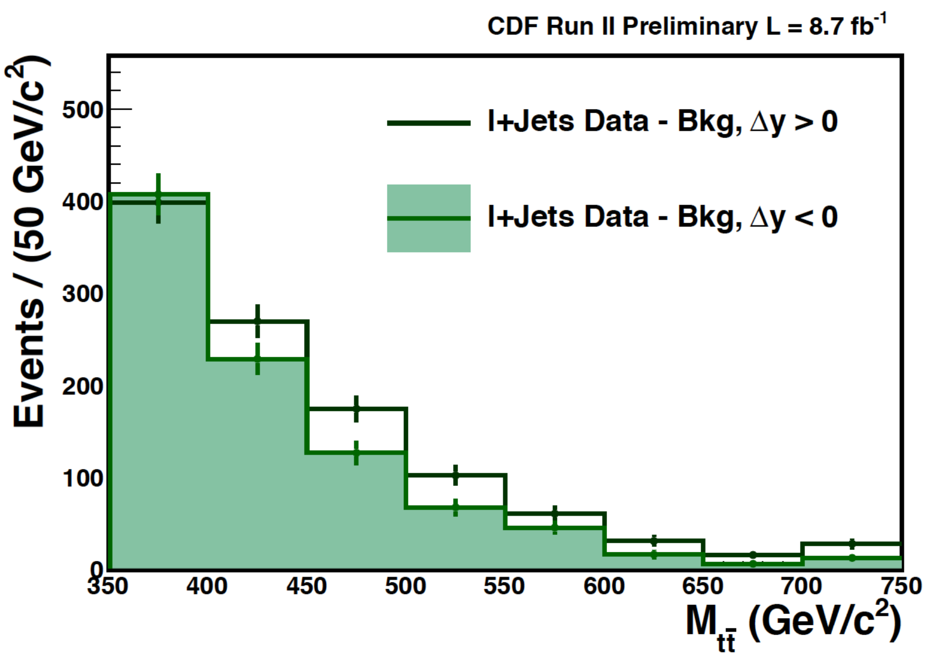
- Now subtract background from sample
- A_{FB}(data)=8.5+/-2.5%
  - A_{FB}(predicted)=3.3%

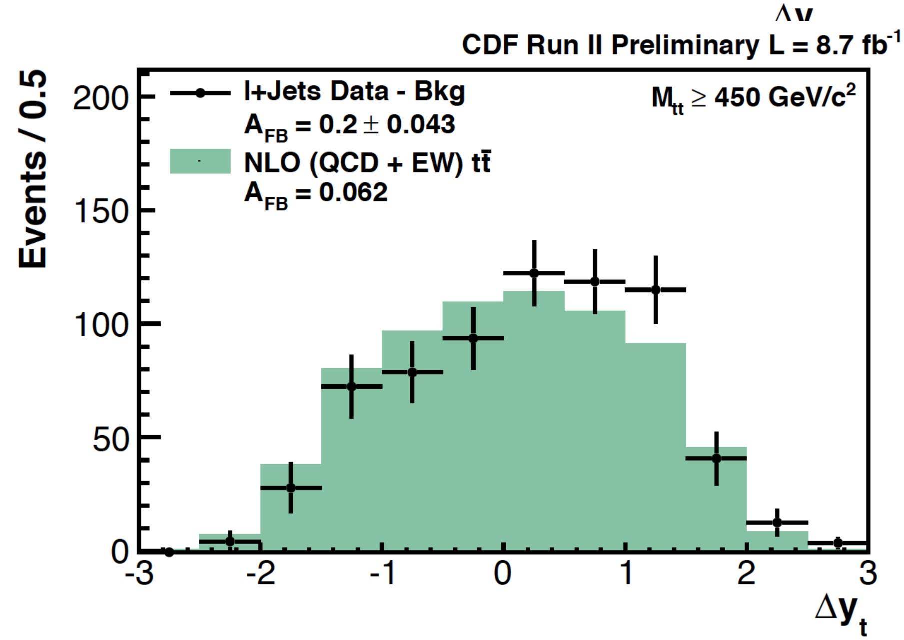


Mass dependence

- Look at mass dependence for background-subtracted data

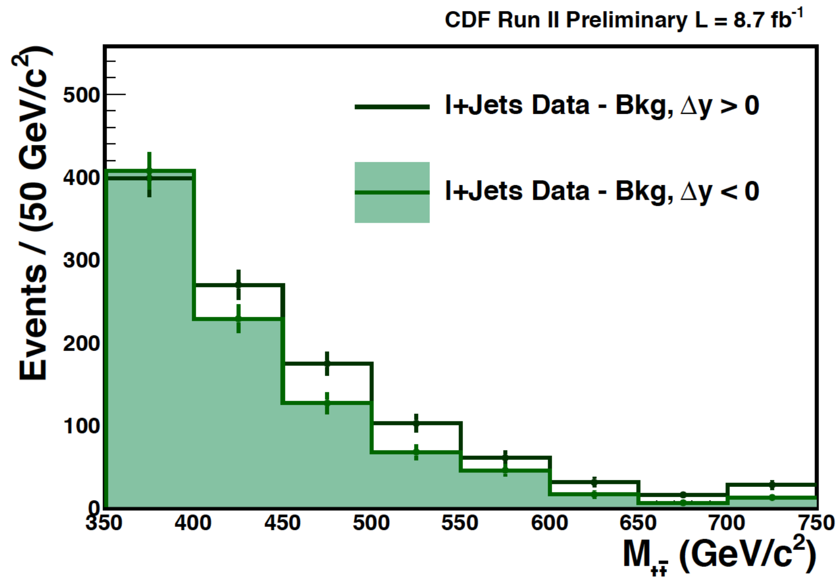


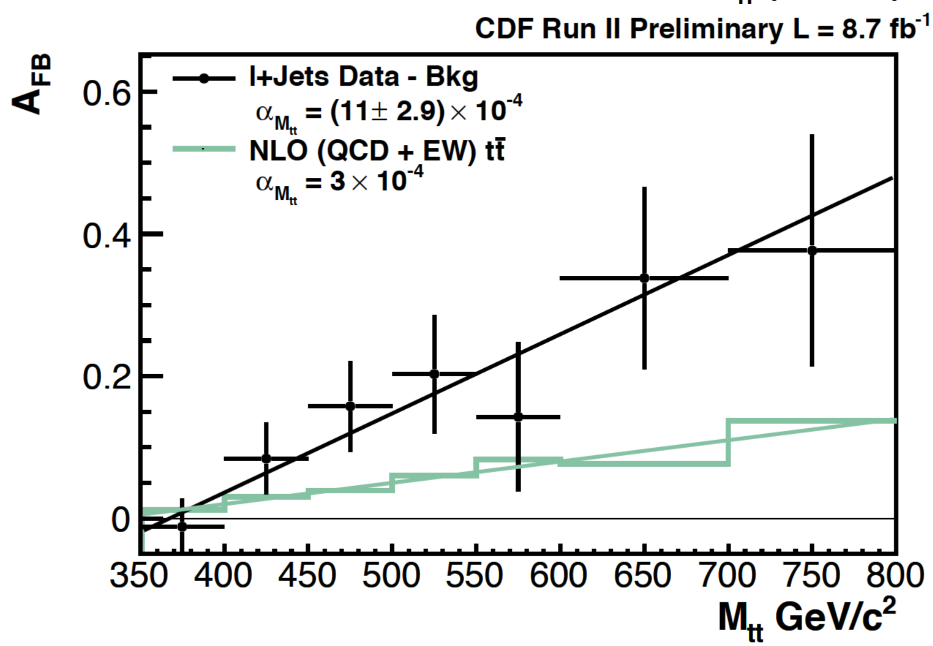




Mass dependence

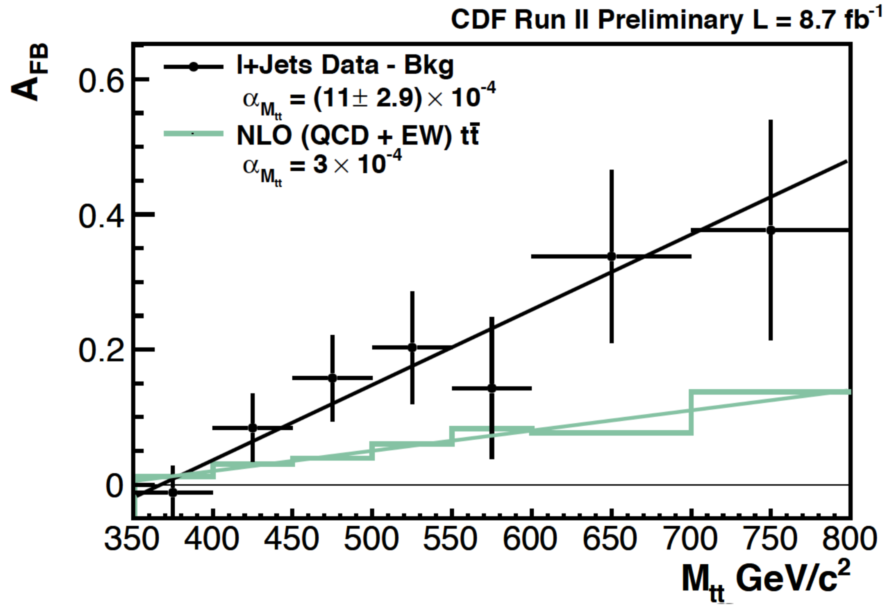
- Look at mass dependence for background-subtracted asymmetry (N(Δy>0)-N(Δy<0)
- SM predicts increase of asymmetry with mass, but not with slope seen in data

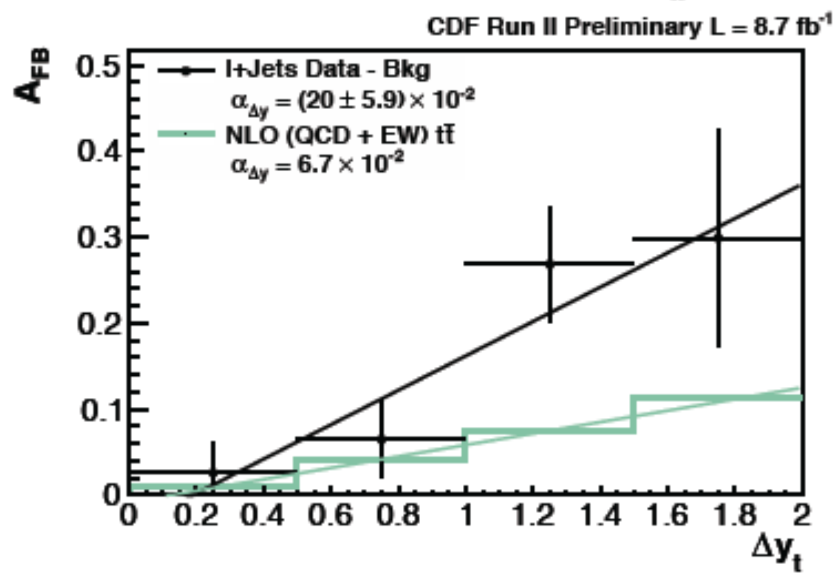




Mass, Δy dependence

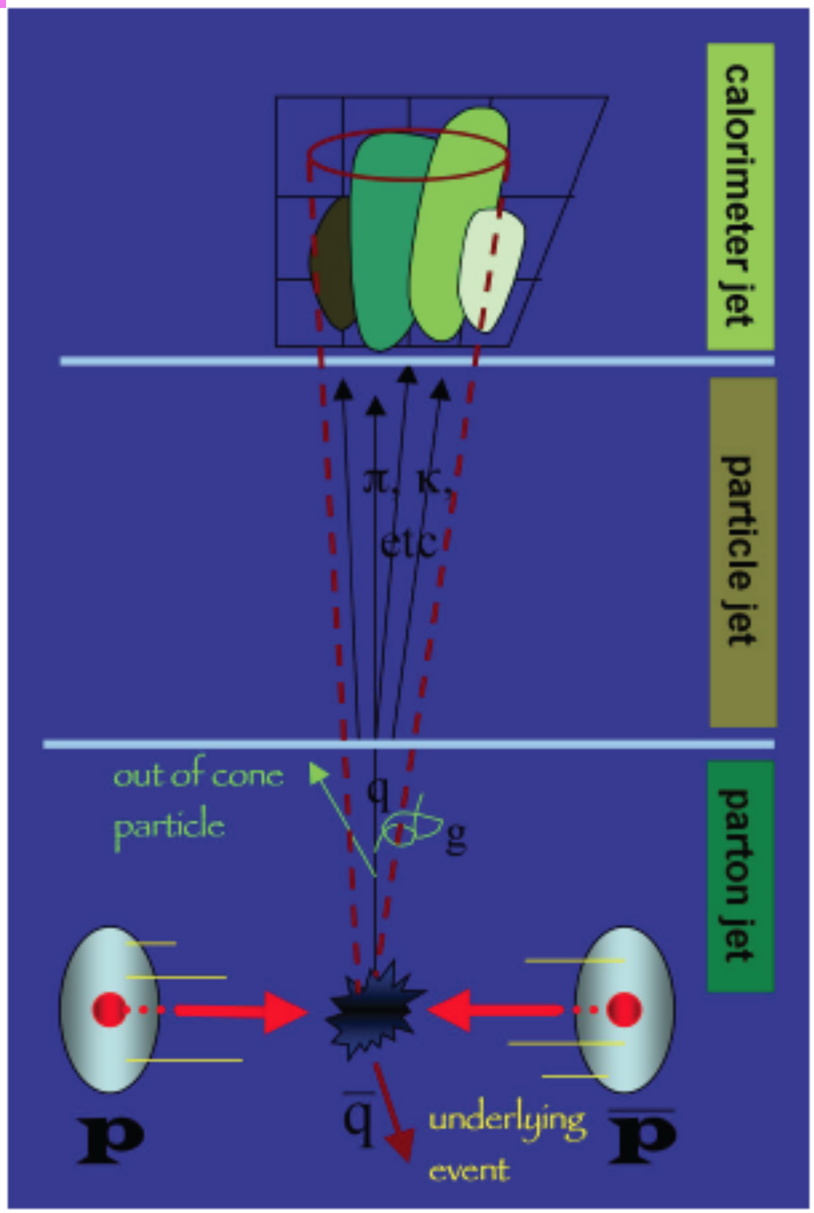
- Mass, Δy dependence, in data and in theory, well-described by linear ansatz
- …but with different slopes for data and theory
- My words: like QCD on steroids
- George Sterman's words: like QCD, only more so





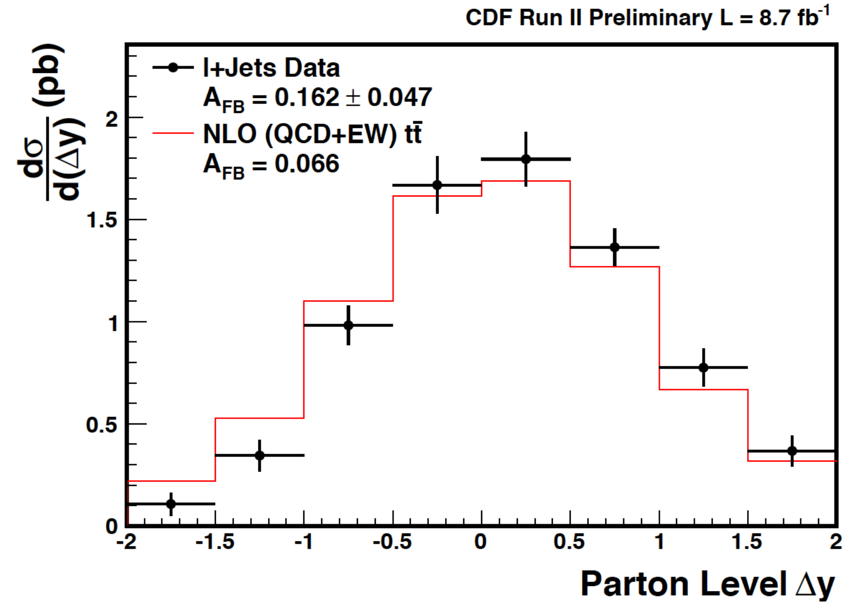
Correct to parton level

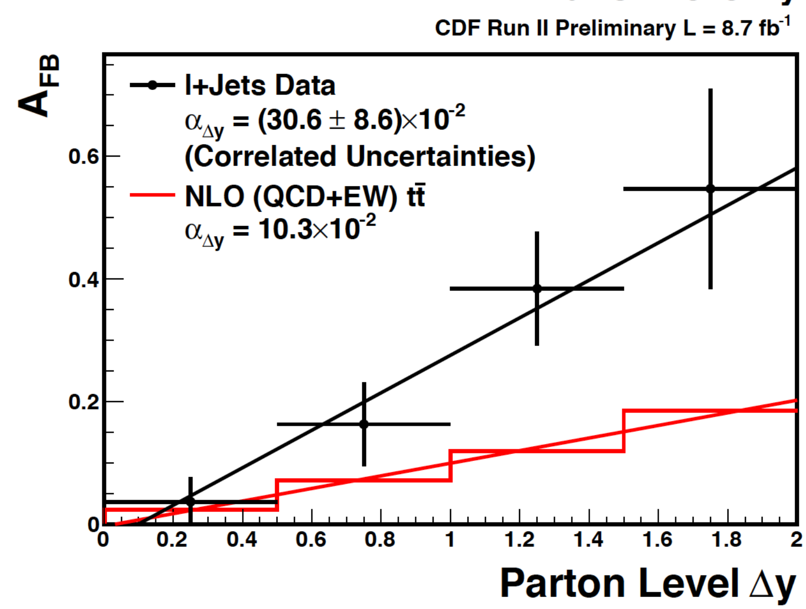
- Must account for
  1. finite detector resolution
  2. smearing due to incorrect reconstruction
  3. effect of selection cuts
  4. geometric acceptance
  5. trigger rate
  6. finite statistics
- First unsmear to correct for 1,2 and 6, and then correct acceptance for 2,4 and 5
  - unsmearing tends to increase asymmetry by removing dilution from mis-reconstructed events
  - acceptance is asymmetric in Δy, with backward events passing selection cuts more often than forward events



Parton level

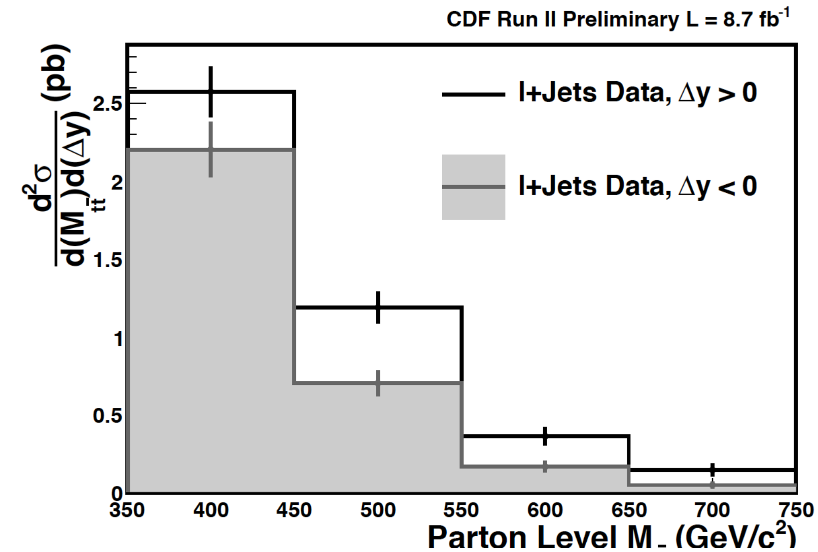
- After correcting to parton level, can again calculate A_{FB}, and again fit linear ansatz
- Similar behavior as before correction, but steeper slopes, for both data and theory

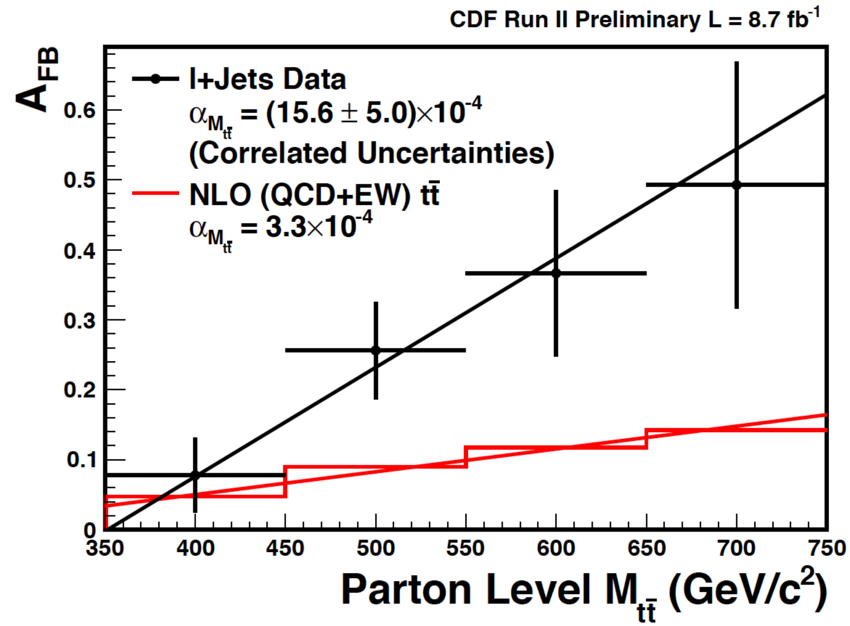




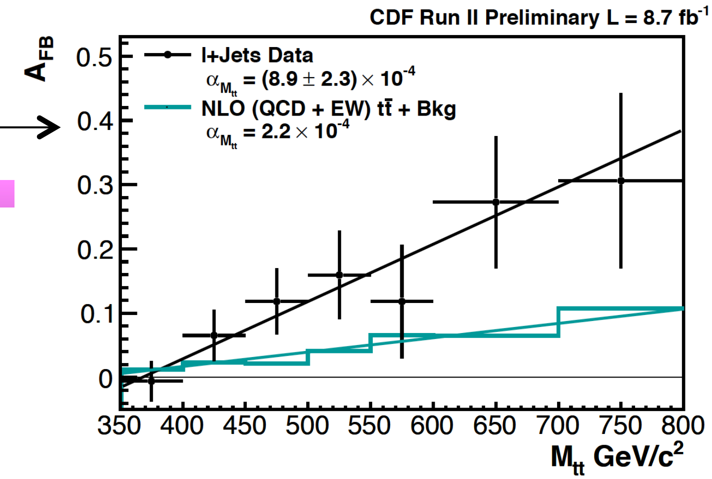
Parton level

- Now as a function of tT mass
- Again, linear ansatz works well for both data and theory
- And again, we have QCD on steroids

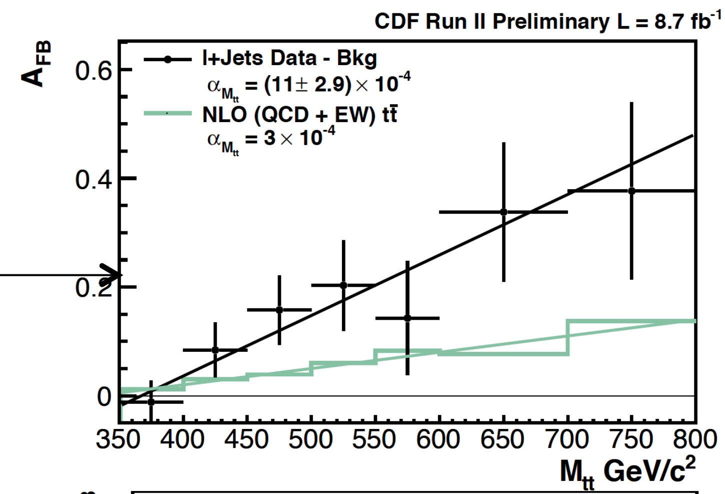




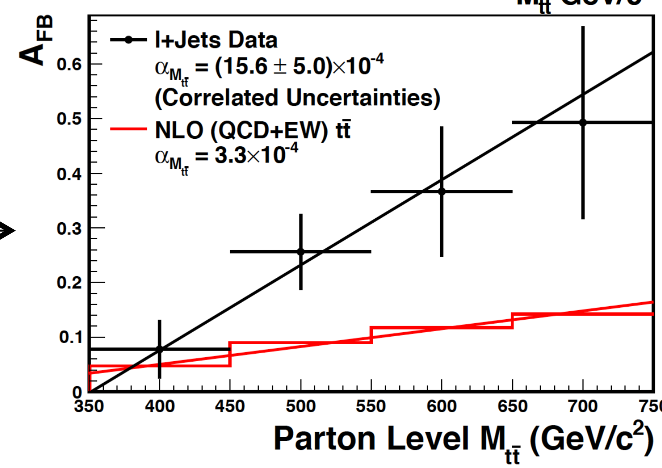
reconstructed level



background-subtracted level

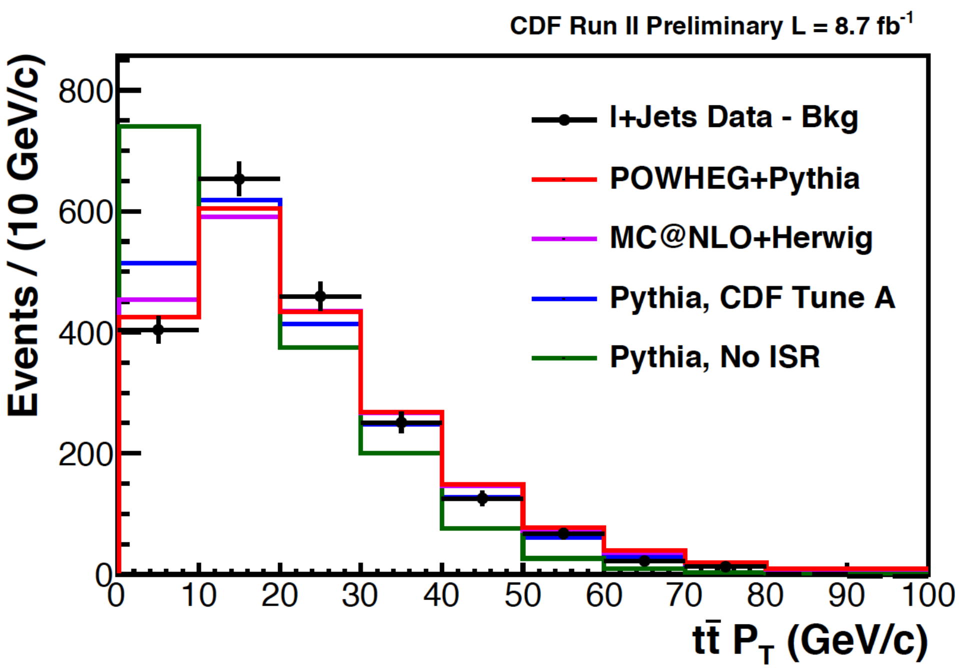


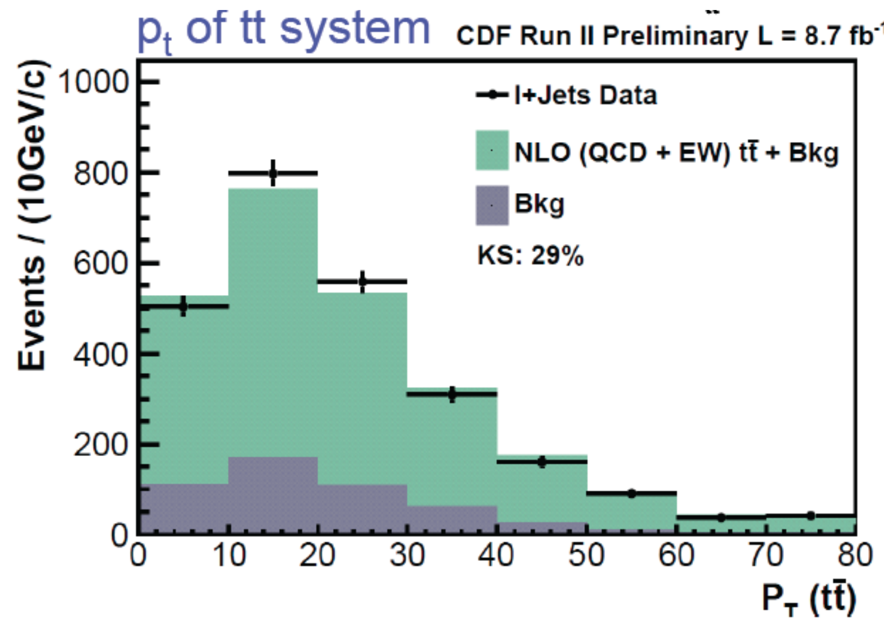
parton level

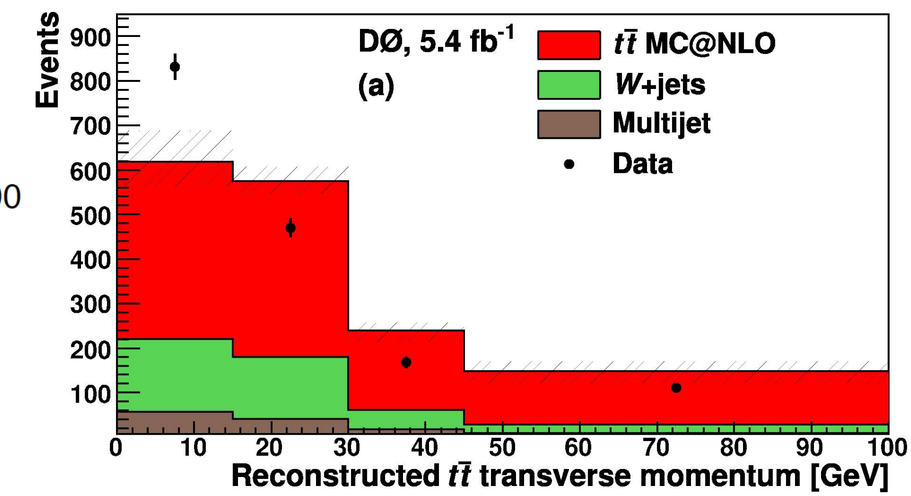


Transverse momentum

- Crucial to correctly describe the tT system p_T
- Powheg does quite a nice job with the CDF data

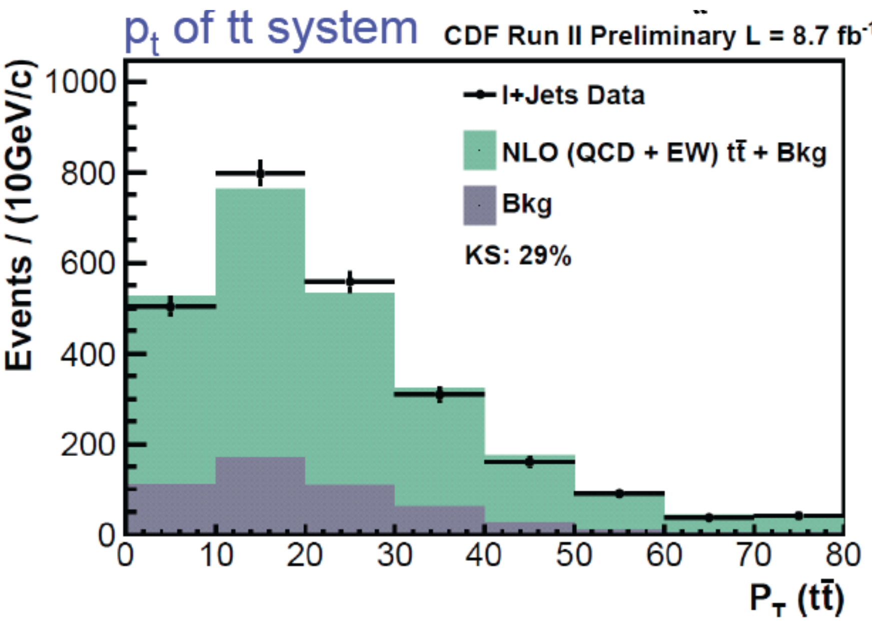


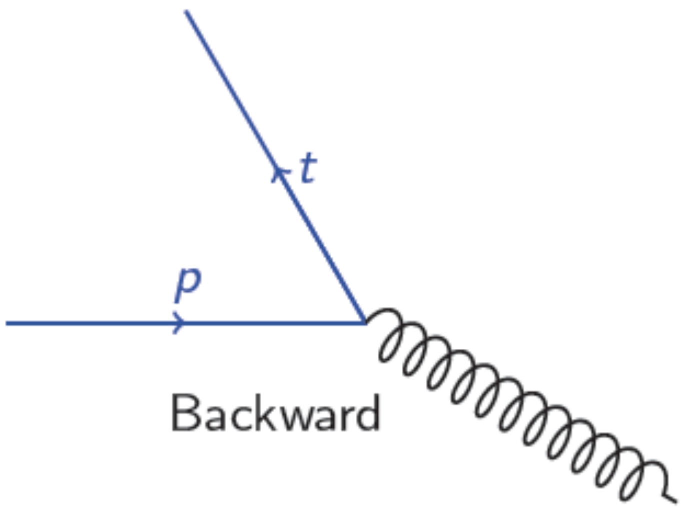




Transverse momentum

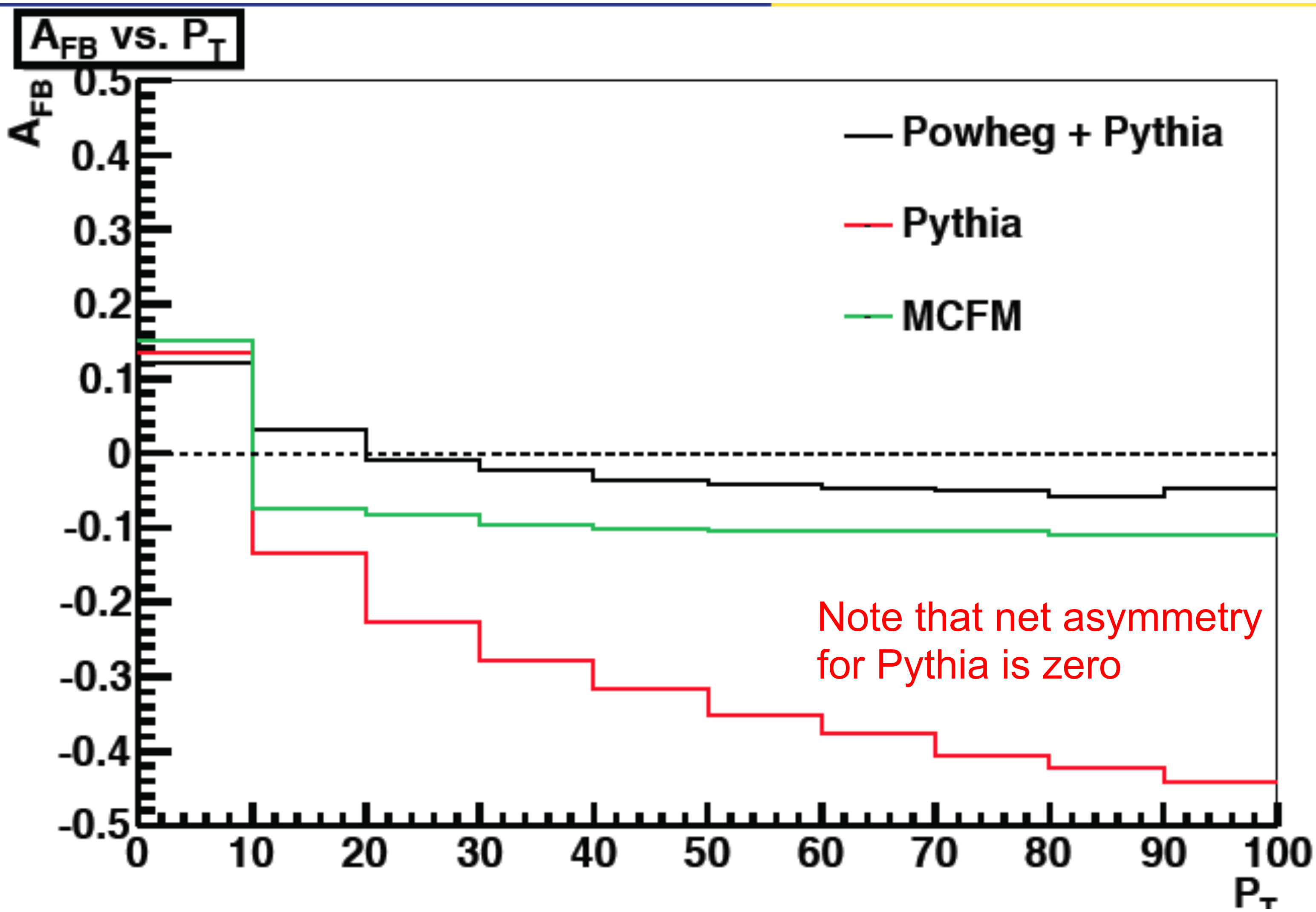
- Crucial to correctly describe the tT system p_T
- Powheg does quite a nice job with the CDF data
- Can also measure the asymmetry as a function of p_T
- Here, at LO, you have a very nice physical picture
  - most likely to radiate an extra gluon (tT->tTj) when color line is 'bent backwards', i.e. a negative asymmetry, opposite in sign to the Born-box interference, but smaller





Some predictions for asymmetry as function of p_T

- So at LO (in asymmetry), expect negative asymmetry



Amazingly enough…

- NLO corrections for tTj asymmetry basically cancel out this effect
- This was a challenge I threw out to the QCD community several years ago, answered by Melnikov and Schulze (**Nucl.Phys. B840 (2010) 129-159**)
  - sorry, Kirill, there was no money prize associated
- tTj is a two-scale problem, m_t and p_T^{jet}
- Hard degrees of freedom as well as soft degrees (as at LO); hard degrees of freedom greatly reduce negative asymmetry from LO
- No implications for tT asymmetry at NNLO since that is not a two-scale problem

$$\sigma(y_t > 0) - \sigma(y_t < 0) \sim \frac{2C_F\alpha_s}{\pi} \ln^2\left(\frac{m_t}{p_{\perp,j}}\right) A_{t\bar{t}}\,\sigma_{t\bar{t}}, \tag{49}$$

where $A_{t\bar{t}}$ is the $p\bar{p} \to t\bar{t}$ *inclusive* asymmetry. Taking the ratio of Eq.(49) and Eq.(47), we find

$$A_{t\bar{t}j}^{\rm hard} \approx A_{t\bar{t}}. \tag{50}$$

The full forward-backward asymmetry at next-to-leading order is given by the sum of the two mechanisms

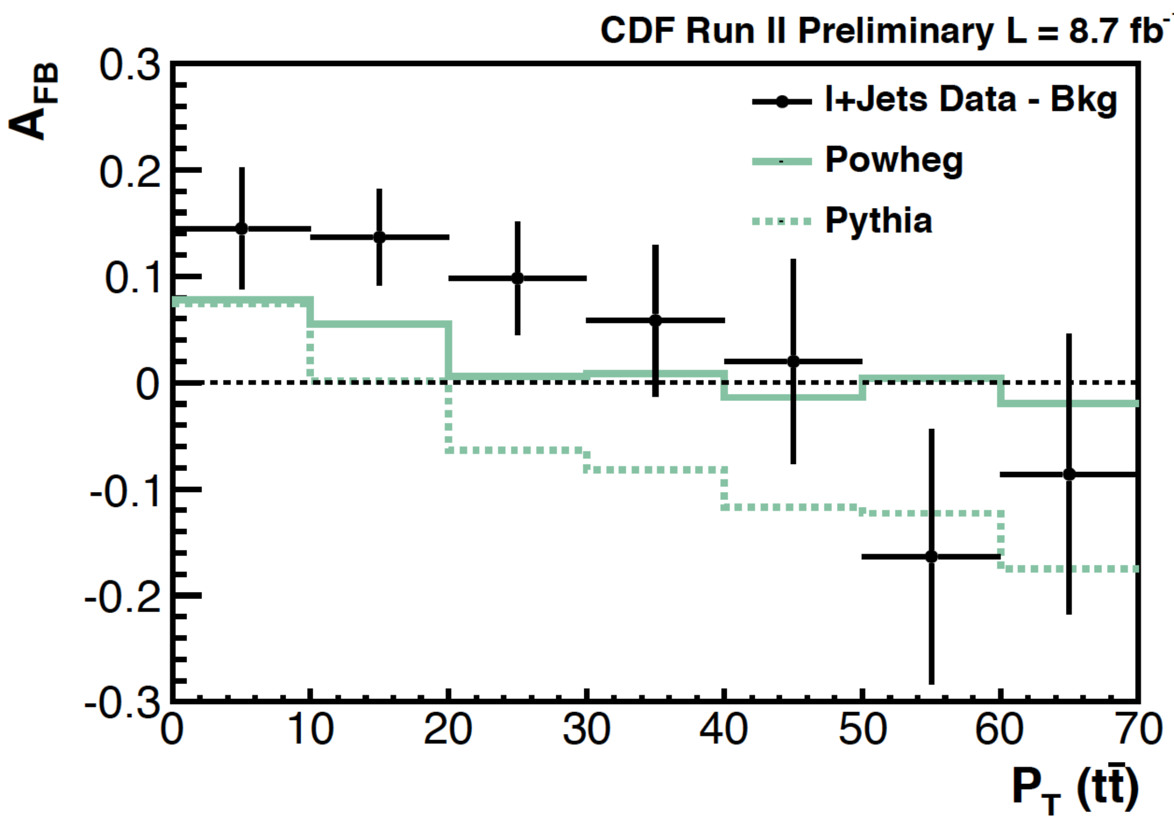
$$A_{t\bar{t}j}^{\rm NLO} \approx A_{t\bar{t}j}^{\rm soft}(p_{\perp,j}) + A_{t\bar{t}j}^{\rm hard}. \tag{51}$$

Following the preceding discussion, we estimate

$$A_{t\bar{t}j}^{\rm soft}(p_{\perp,j}) \sim A_{t\bar{t}j}^{\rm LO}(p_{\perp,j}) \sim \ln^{-1}\left(\frac{m_t}{p_{\perp,j}}\right), \quad A_{t\bar{t}j}^{\rm hard} \approx A_{t\bar{t}}. \tag{52}$$

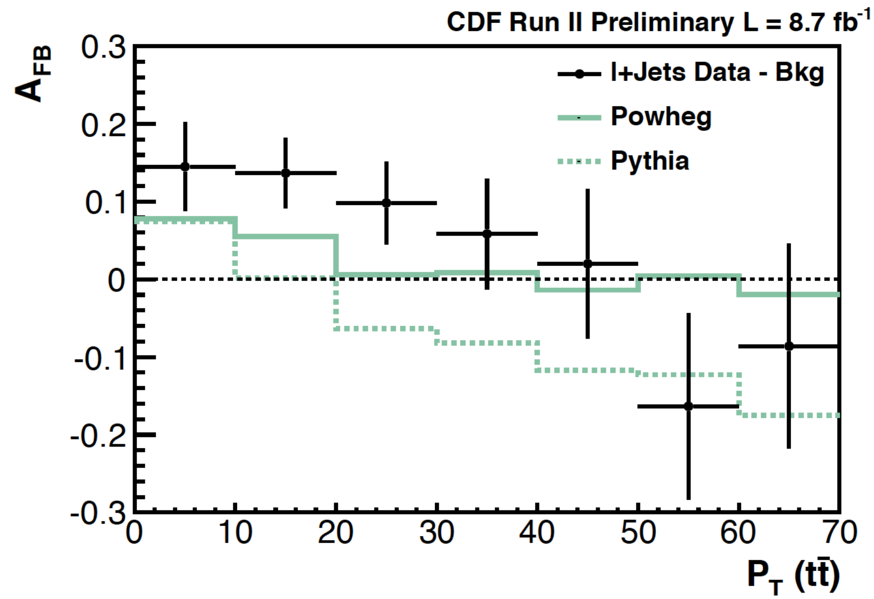
Data

- Asymmetry in data (bckgnd subtracted) has a slope, actually similar to what is observed in Pythia



Data

- The p_T of the tT system is related to the emission of a 5th jet
- We included a table showing the asymmetry for the 4 and 5 jet bins for the 5.3 fb^{-1} paper
- Of course, a caveat is that in some cases the 5th jet is from internal radiation



EVIDENCE FOR A MASS DEPENDENT FORWARD- ...

TABLE XV. MC@NLO predictions for $A^{t\bar{t}}$ in reconstructed $t\bar{t}$ signal (no backgrounds) as a function of $M_{t\bar{t}}$ and jet multiplicity. The uncertainties reflect MC statistics only.

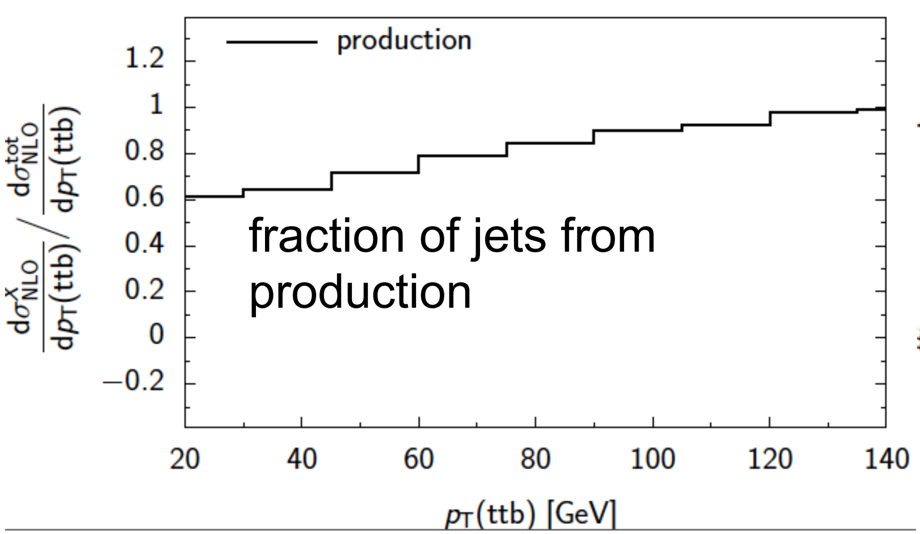
selection	all $M_{t\bar{t}}$	$M_{t\bar{t}} < 450$ GeV$/c^2$	$M_{t\bar{t}} \geq 450$ GeV$/c^2$
inclusive	0.024 ± 0.004	0.015 ± 0.005	0.043 ± 0.007
4-jet	0.048 ± 0.005	0.033 ± 0.006	0.078 ± 0.009
5-jet	-0.035 ± 0.007	-0.032 ± 0.009	-0.040 ± 0.012

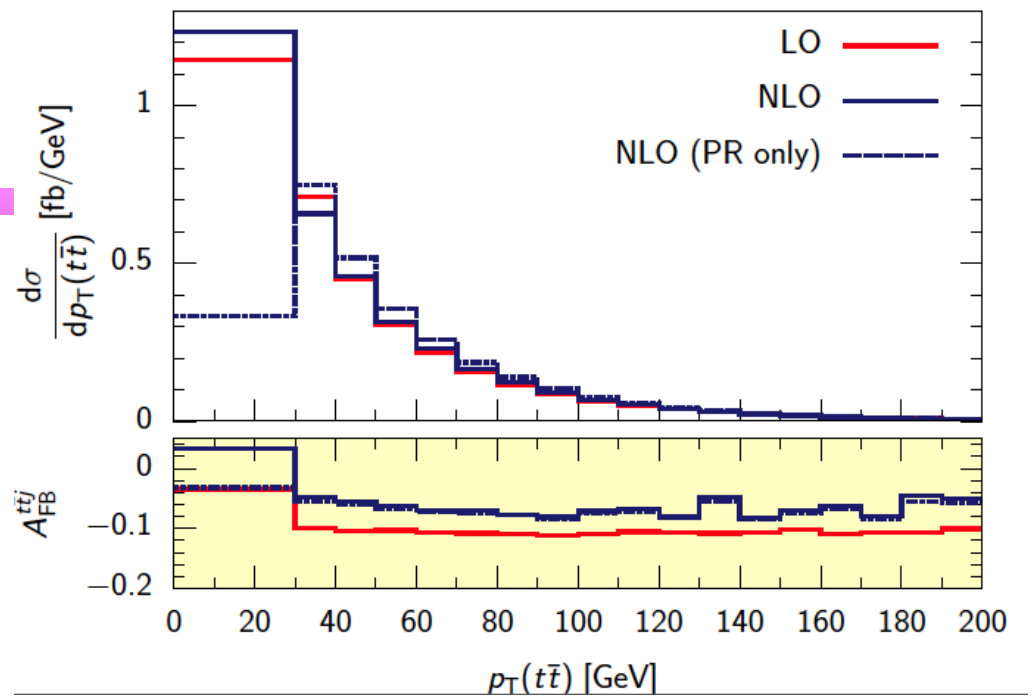
TABLE XVI. Asymmetries $A^{t\bar{t}}$ in the data as a function of jet multiplicity.

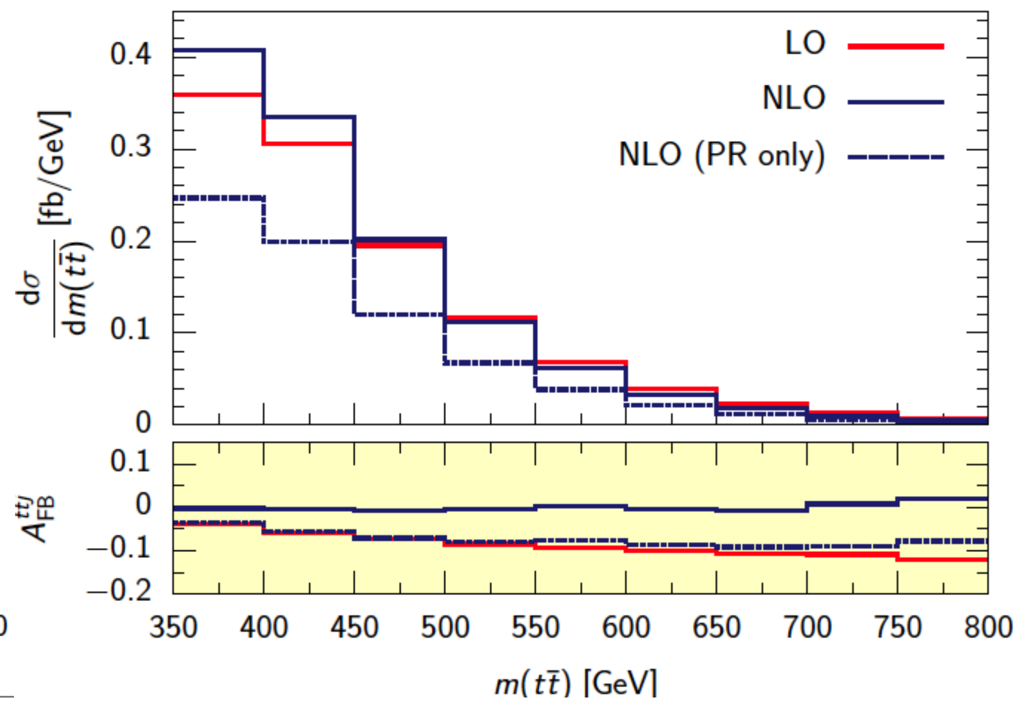
selection	N events	all $M_{t\bar{t}}$	$M_{t\bar{t}} < 450$ GeV$/c^2$	$M_{t\bar{t}} \geq 450$ GeV$/c^2$
inclusive	1260	0.057 ± 0.028	-0.016 ± 0.034	0.212 ± 0.049
4-jet	939	0.065 ± 0.033	-0.023 ± 0.039	0.26 ± 0.057
5-jet	321	0.034 ± 0.056	0.0049 ± 0.07	0.086 ± 0.093

Melnikov, Scharf and Schulze

- Apply CDF cuts to the distributions
- Separate (approximately) into full NLO and NLO with jets from production and not decay
- Asymmetry is reduced both from NLO corrections to production jets, and from inclusion of jets from decay (which have same asymmetry as for inclusive tT production)

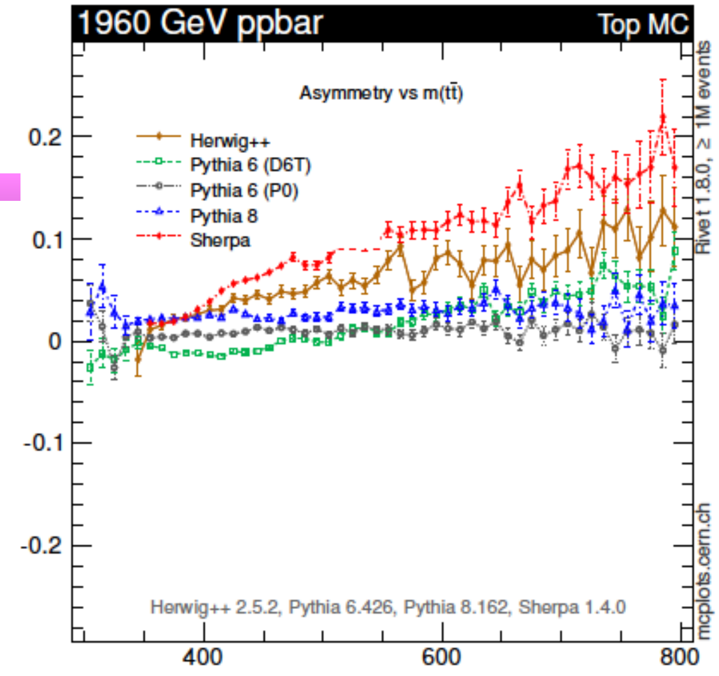


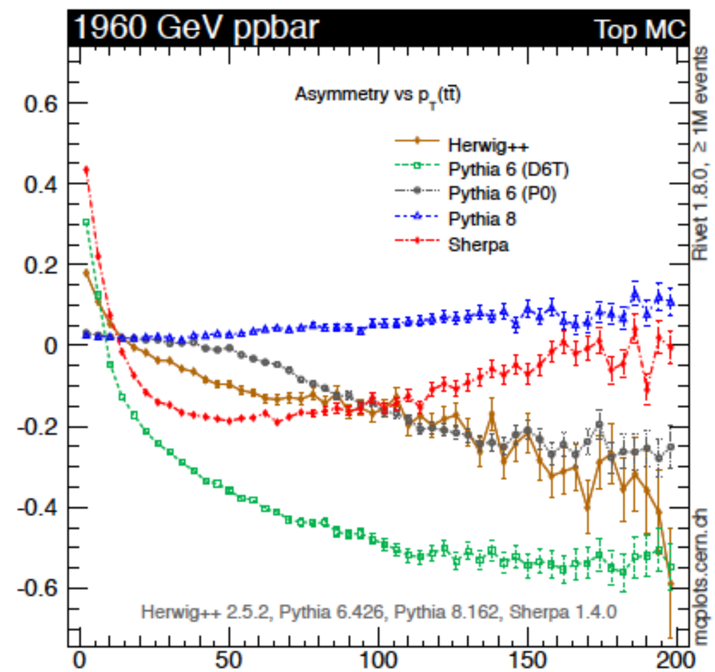




Meanwhile, WTF?

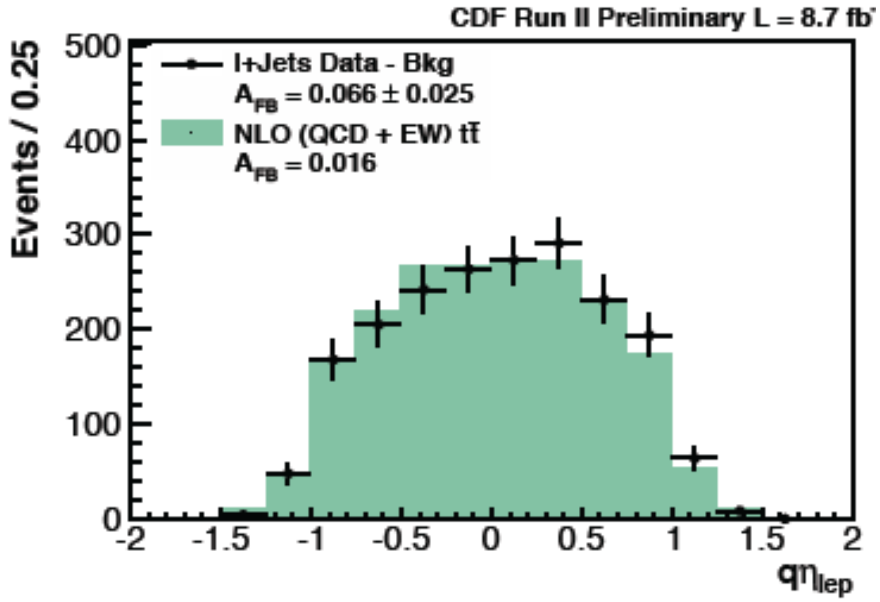
- What conclusions should I draw from the parton shower studies?
- Are these reproductions of the physics in the NLO calculations, or in addition to them?
- Does nature really worry about recoil models?





Lepton asymmetry

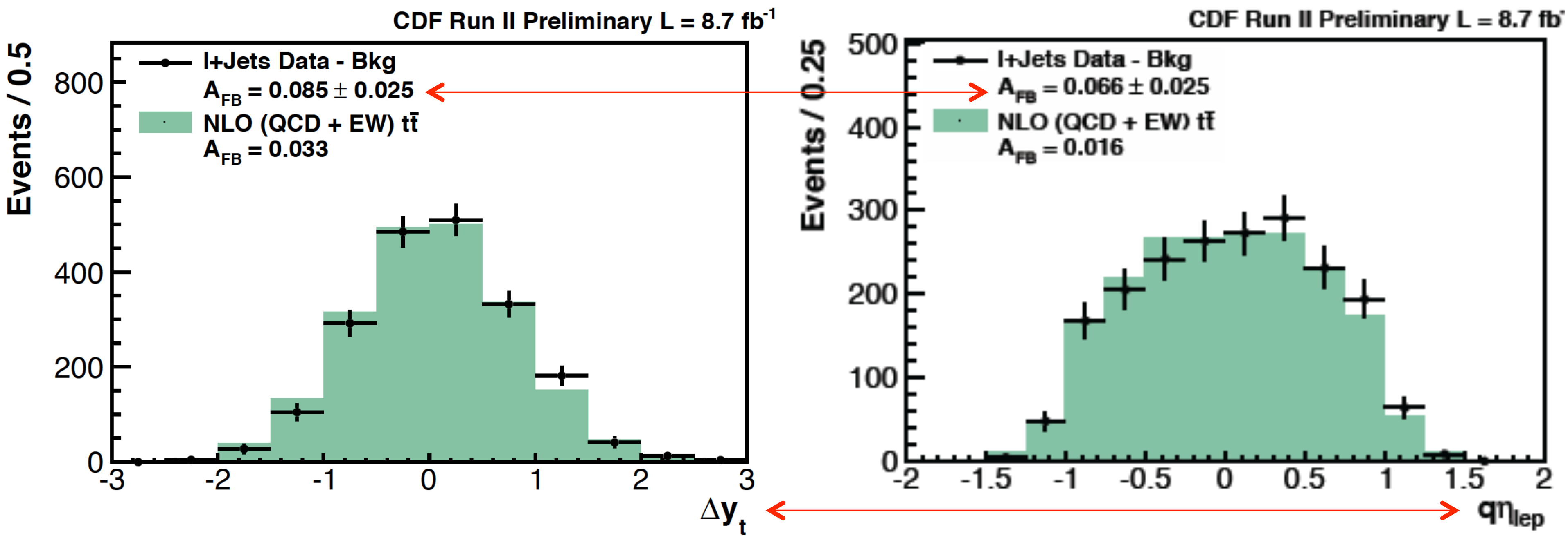
- The lepton asymmetry provides less information, but is independent of the tT reconstruction
- An asymmetry larger than that predicted by the SM is also observed using only the lepton



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

$M_{t\bar{t}}$	Data A_{FB} ($\pm$ [stat.+syst.])	NLO (QCD+EW) $t\bar{t}$ 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

Compare asymmetries



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

	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

Summary

- We have measured the tT asymmetry using the full Run II data sample in a number of kinematic variables
  - 9.4 fb^{-1}; in addition, more data from new data streams
  - paper is in preparation
- The asymmetry observed in earlier data sets has continued, and some of the statistical fluctuations have nicely smoothed out
- The asymmetry 'looks like QCD', only more so
  - could additional QCD effects really be that significant?
- We will continue to try to attack the asymmetry from different angles (such as $\cos\theta^*$)
- Ongoing measurement of the asymmetry in high mass bB production
  - note that there is considerable dilution from gg initial state

Extras

A tale of two cities

The tT asymmetry analysis is centered in Ann Arbor, but they've been kind enough to let me in, despite the (sports) rivalries

prior measurements

inclusive

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

differential (at bkg subtracted data level)

	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
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

New D0 dilepton measurement: 5.8+/-5.1(stat)+/-1.3(syst)%

Asymmetry vs Δy

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

Parton Level $\lvert\Delta y\rvert$	Data A_{FB} ($\pm$ stat. $\pm$ syst.)	NLO (QCD+EW) $t\bar{t}$ A_{FB}
Inclusive	$0.162 \pm 0.041 \pm 0.022$	0.066
< 0.5	$0.037 \pm 0.035 \pm 0.020$	0.023
$0.5 - 1.0$	$0.163 \pm 0.058 \pm 0.036$	0.072
$1.0 - 1.5$	$0.384 \pm 0.084 \pm 0.041$	0.119
≥ 1.5	$0.547 \pm 0.140 \pm 0.085$	0.185
< 1.0	$0.088 \pm 0.042 \pm 0.022$	0.043
≥ 1.0	$0.433 \pm 0.097 \pm 0.050$	0.139
	Data	NLO (QCD+EW) $t\bar{t}$
Slope $\alpha_{\Delta y}$ of Best-Fit Line	$(30.6 \pm 8.6) \times 10^{-2}$	10.3×10^{-2}

Asymmetry vs mass

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

Parton Level $M_{t\bar{t}}$	Data A_{FB} ($\pm$ stat. $\pm$ syst.)	NLO (QCD+EW) $t\bar{t}$ A_{FB}
$< 450 GeV/c^2$	$0.078 \pm 0.048 \pm 0.024$	0.047
$450 - 550 GeV/c^2$	$0.256 \pm 0.063 \pm 0.028$	0.090
$550 - 650 GeV/c^2$	$0.366 \pm 0.085 \pm 0.083$	0.117
$\geq 650 GeV/c^2$	$0.493 \pm 0.159 \pm 0.076$	0.143
$< 450 GeV/c^2$	$0.078 \pm 0.048 \pm 0.024$	0.047
$\geq 450 GeV/c^2$	$0.296 \pm 0.059 \pm 0.031$	0.100
	Data	NLO (QCD+EW) $t\bar{t}$
Slope $\alpha_{M_{t\bar{t}}}$ of Best-Fit Line	$(15.6 \pm 5.0) \times 10^{-4}$	3.3×10^{-4}

Comparison to 5.3 fb^{-1} results

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

Parton Level $\lvert\Delta y\rvert$	NLO (QCD+EW) $t\bar{t}$ A_{FB}	5.3 fb^{-1} A_{FB} ($\pm$[stat.+syst.])	8.7 fb^{-1} A_{FB} ($\pm$[stat.+syst.])
Inclusive	0.066	0.158 $\pm$ 0.074	0.162 $\pm$ 0.047
< 1.0	0.043	0.026 $\pm$ 0.118	0.088 $\pm$ 0.047
≥ 1.0	0.139	0.611 $\pm$ 0.256	0.433 $\pm$ 0.109

Parton Level $M_{t\bar{t}}$	NLO (QCD+EW) $t\bar{t}$ A_{FB}	5.3 fb^{-1} A_{FB} ($\pm$[stat.+syst.])	8.7 fb^{-1} A_{FB} ($\pm$[stat.+syst.])
$< 450\mathrm{GeV}/\mathrm{c}^2$	0.047	-0.116 $\pm$ 0.153	0.078 $\pm$ 0.054
$\geq 450\mathrm{GeV}/\mathrm{c}^2$	0.100	0.475 $\pm$ 0.112	0.296 $\pm$ 0.067