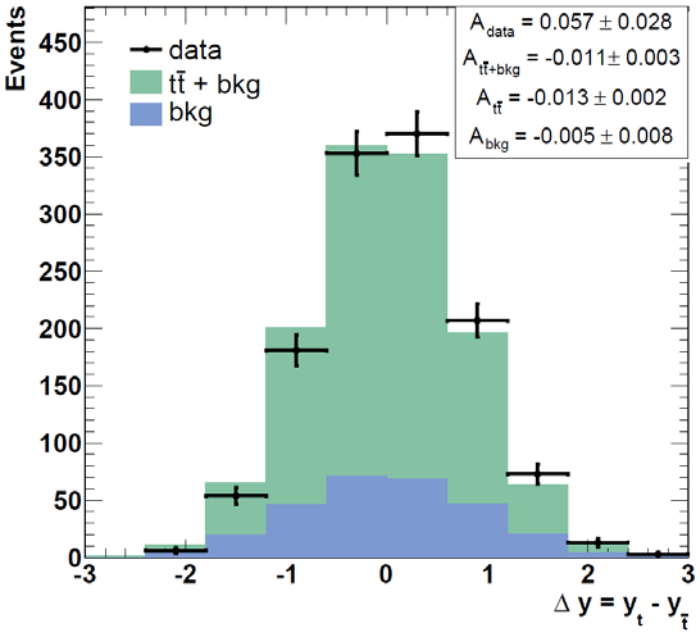
A Forward-Backward Asymmetry in Top Quark Pair Production

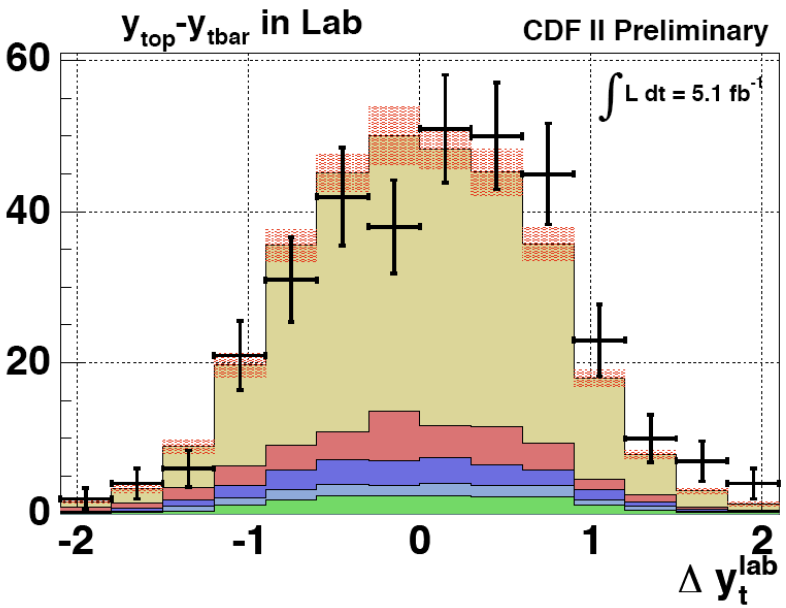
The CDF Collaboration

D. Amidei, University of Michigan

lepton + jets mode



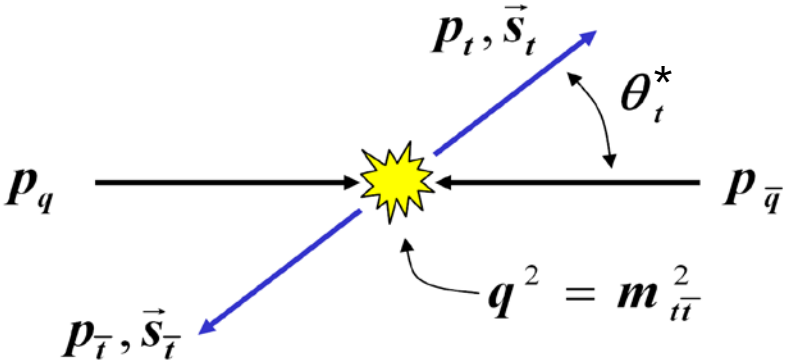
dilepton mode



top quark pair production

- hard scatter cm-frame generically

$$\sigma \sim \frac{\alpha_s^2}{q^2}\left[1+\cos^2\theta^* + f(q^2,\cos\theta^*)\right]\cdot g(\vec{s})$$



- specified by $\alpha,\ q^2, \theta^*, \vec{s}$

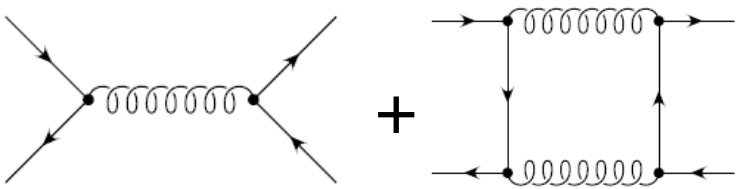
- $\alpha,\ q^2$ well measured in σ and M_{tt} spectrum. SM-like.

- here: the production angle θ^*
  - in particular: forward-backward asymmetry of production angle with respect to proton direction

$$A_{FB} = \frac{N_F - N_B}{N_F + N_B}$$

tt charge asymmetry in NLO QCD

- Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Ellis, Dawson, Nason; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater



C = - 1 C = +1

asymmetry in $\Delta y = y_t - y_{\bar{t}}$

prediction: $A_{fb} \sim 0.06 \pm 0.015$

- not particular to QCD!
- verified for QED in $e^+e^- \rightarrow \mu^+\mu^-$ (T. Himel et al., 1978)

- strong interaction C tests at high energy?
  - difficulty of jet charge
  - now: charge flow info in reconstructed tt system

prior measurements (lepton + jets)

- CDF, 1.9 fb^{-1} , inclusive, corrected to “parton-level”
  - tt rest frame $A^{t\bar{t}} = 0.24 \pm 0.14$
  - NLO QCD $A^{t\bar{t}} = 0.06 \pm 0.01$

PRL 101, 202001 (2008)

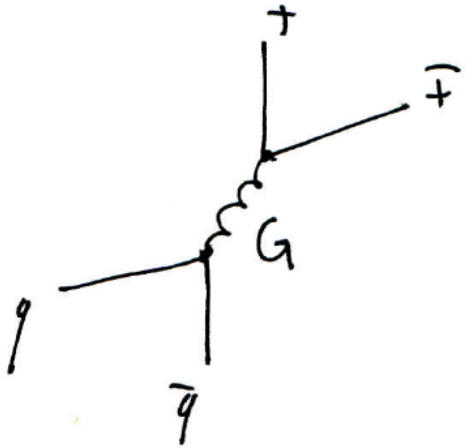
- D0, 0.9 fb^{-1} inclusive “signal-level” (data after bkg subtract)
  - tt rest frame $A^{t\bar{t}} = 0.12 \pm 0.08$
  - NLO QCD $A^{t\bar{t}} = 0.02 \pm 0.01$

PRL 100, 142002 (2008)

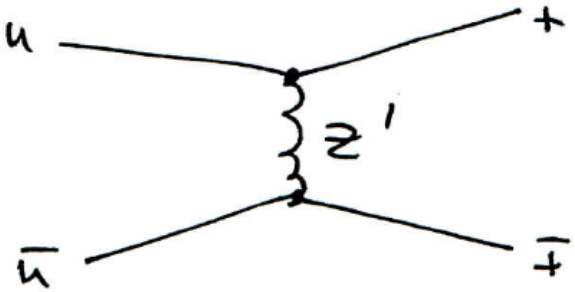
- Recent D0 result with 5 fb^{-1} to be discussed shortly…

theoretical interest

- s-channel
  - massive chiral color octets
  - “axigluon”
  - RS gluon



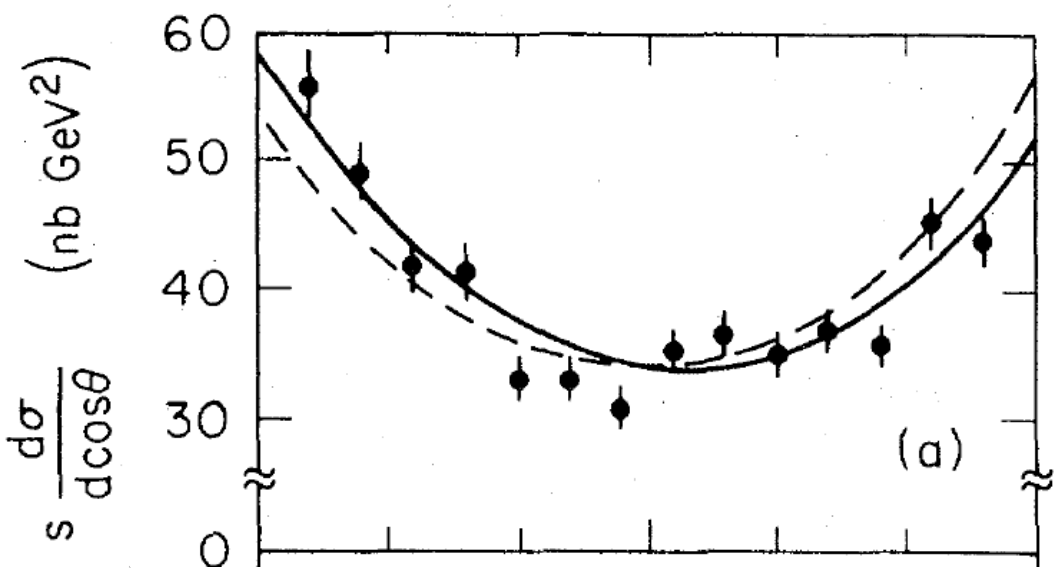
- FV t-channel
  - W´Z´
  - color triplets, sextets



- model building must contend with
  - total σ in good agreement with SM
  - $d\sigma/dM_{tt}$ in good agreement with SM

wisdom from history

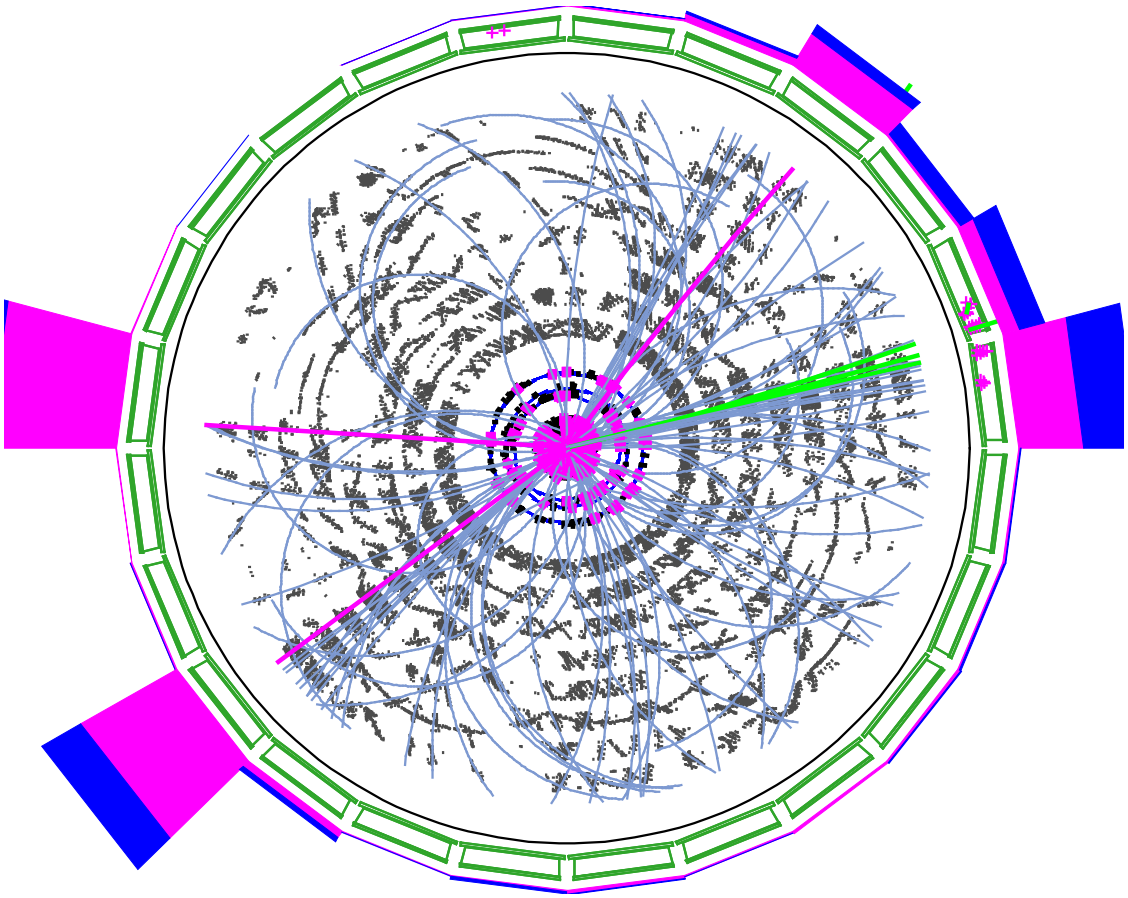
- A_{fb} in $e^+e^- \to Z/\gamma^* \to \mu^+\mu^-$ observed at PEP E_{cm} ~ 29 GeV
- evidence for Z, well below the pole



M.Levi et al Nov 1983

lepton + jets: selection and reconstruction

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



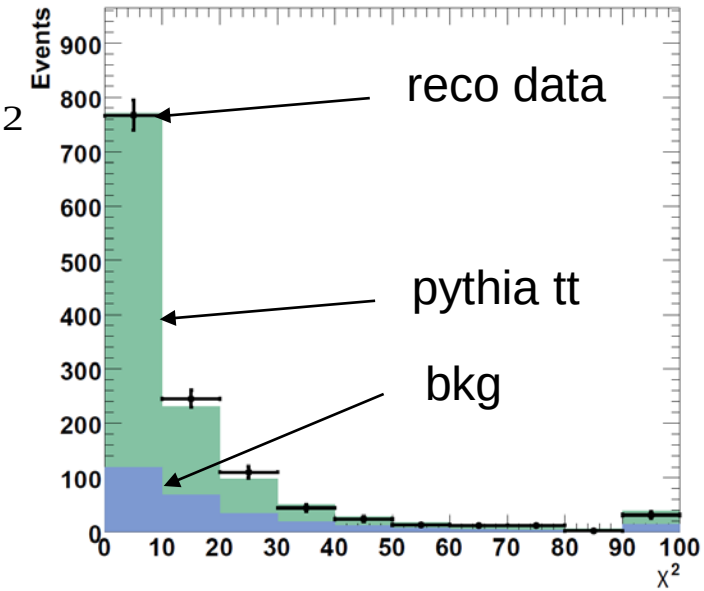
- 5.3 fb^{-1}
- lepton (e/μ) E_t/p_t > 20 GeV (/c)
- missing E_t > 20 GeV
- .g.e. 4 jets E_t > 20 GeV
  - at least one b-tagged jet
- 1260 events bkg = 283±50

top reconstruction

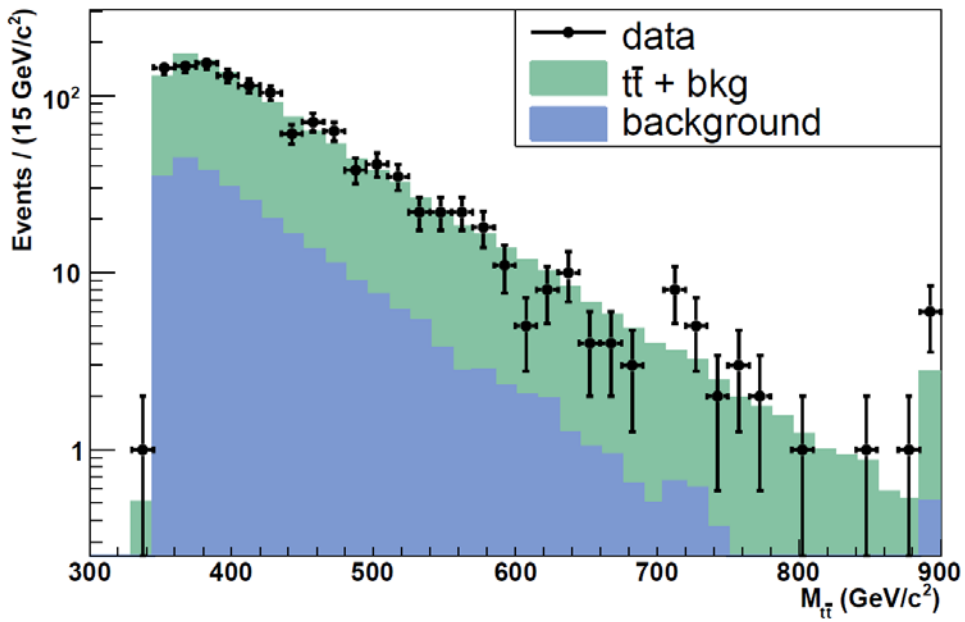
$$l^+ + E_T + 4j + \geq 1\ btag \rightarrow t\bar{t}$$

- tt reconstruction
- jet parton, $p_z(\nu)$ minimize simple χ^2
  - fix: $M_W = 80.4$ GeV/c^2
    $M_t = 172.5$ GeV/c^2
    btag = b
  - float jet p_t within errors
- sign of lepton → charge of tops

χ^2



$M_{t\bar{t}}$



top pair rapidity difference

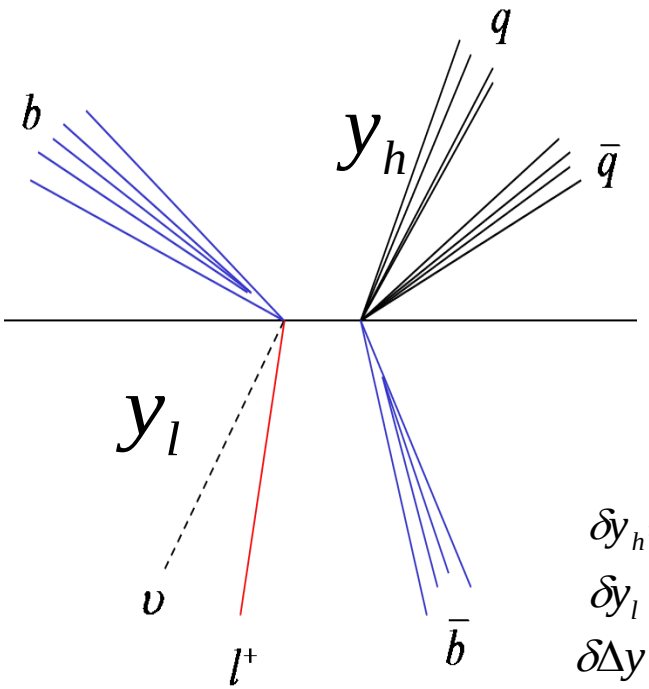
- frame invariant variable

$$\Delta y_{lh} = y_l - y_h$$

$$\Delta y = q \cdot \Delta y_{lh} = y_t - y_{\bar{t}}$$

  – interpretation

$$\Delta y = 2 y_t^{t\bar{t}}$$



$\delta y_h \approx 0.034$

$\delta y_l \approx 0.085$

$\delta \Delta y \approx 0.104$

- asymmetry in Δy

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

equals asymmetry in top quark production angle in tt rest frame

expected QCD asymmetries

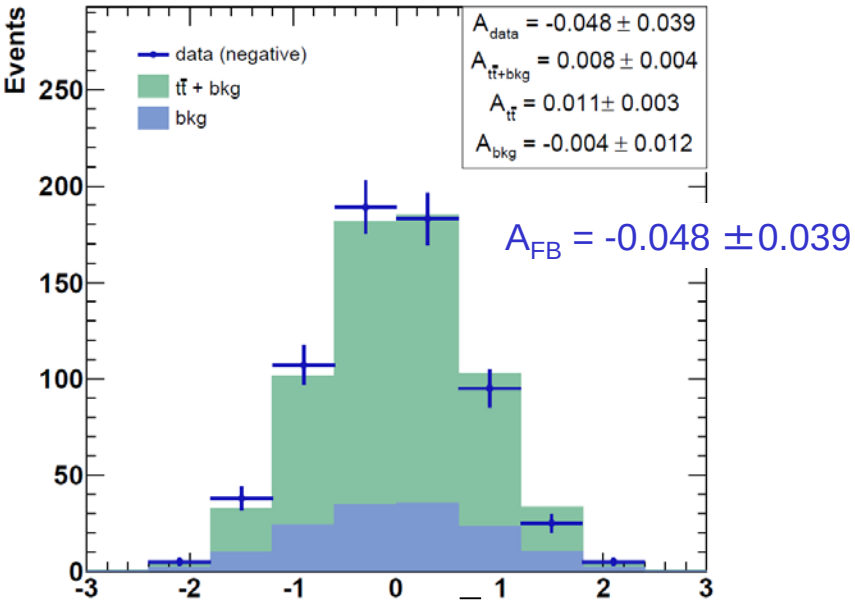
- two calculations for NLO expectation
  - MCFM: NLO calculation at “parton level”
  - MC@NLO + CDFSIM: simulated sample for input the analysis

model	level	$A^{t\bar{t}}$	
MCFM	parton	0.058 ± 0.009	truth
MC@NLO	parton	0.052 ± 0.008	truth
MC@NLO	$t\bar{t}$	0.024 ± 0.005	sim + reco
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004	sim + reco +bkg

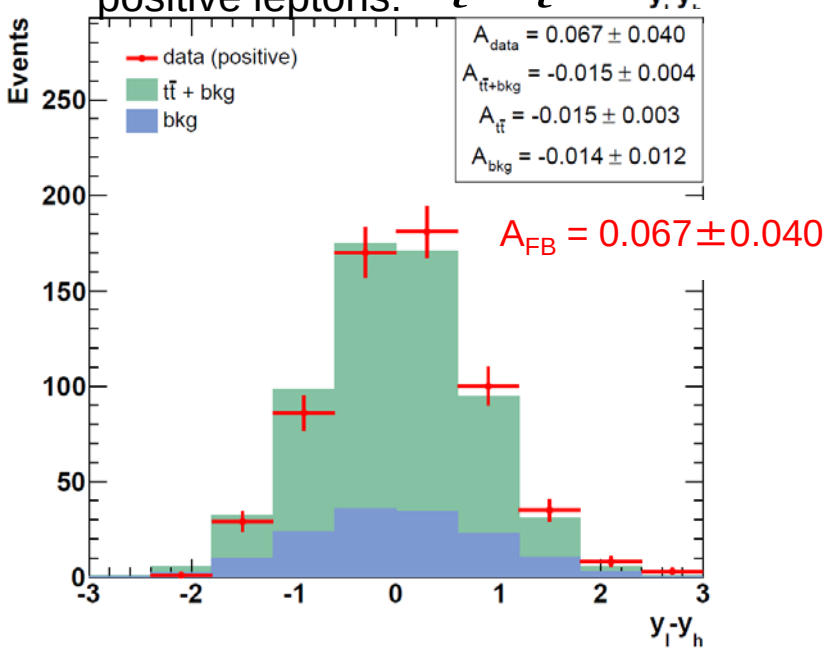
- n.b.
  - prediction for data level asymmetry < stat precision (0.028)
  - LO Pythia tt model remains good approximation of SM

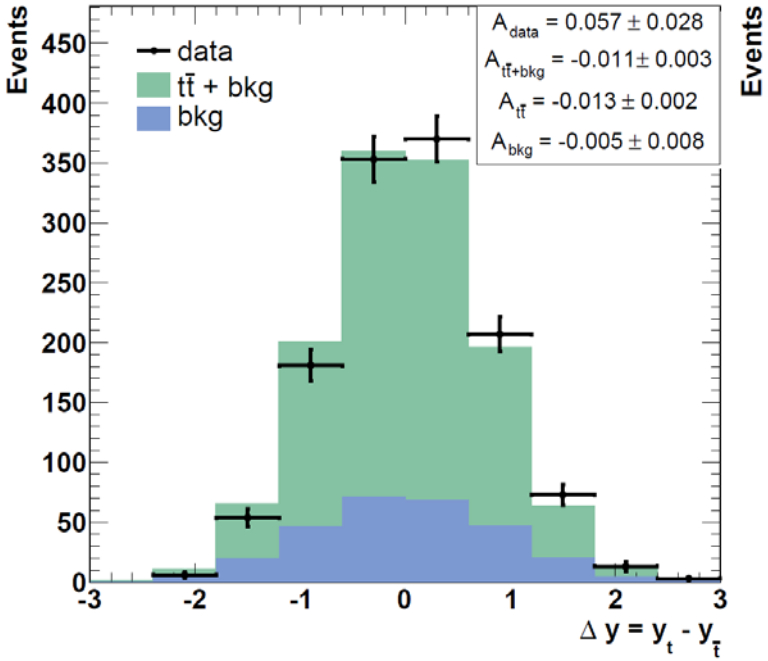
data $y_l - y_h$ $\Delta y = q \cdot (y_l - y_h)$

negative leptons: $\bar{t} - t$



positive leptons: $\bar{t} - t$

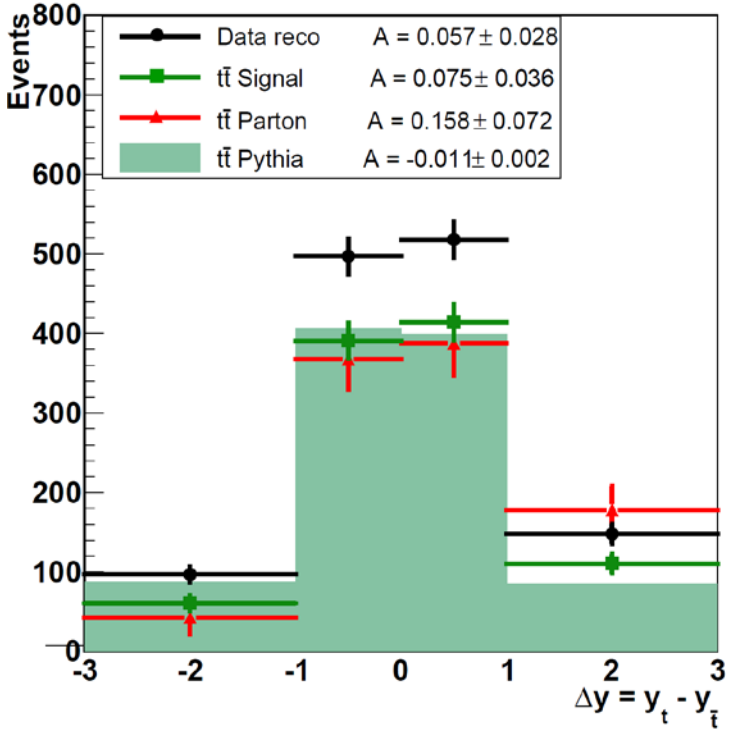




sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004

parton level asymmetry

sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009



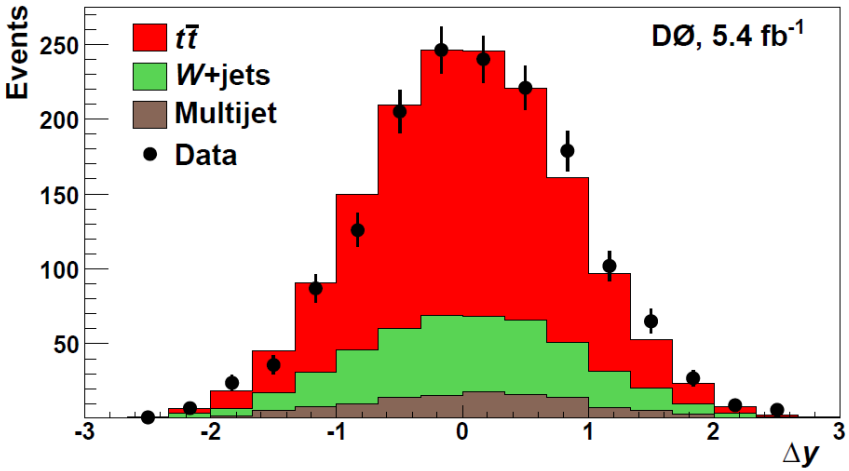
simple rapidity dependence

sample	level	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
data	data	0.021 ± 0.031	0.208 ± 0.062
data	parton	$0.026 \pm 0.104 \pm 0.056$	$0.611 \pm 0.210 \pm 0.147$
MCFM	parton	0.039 ± 0.006	0.123 ± 0.018

a new result from D0

analysis

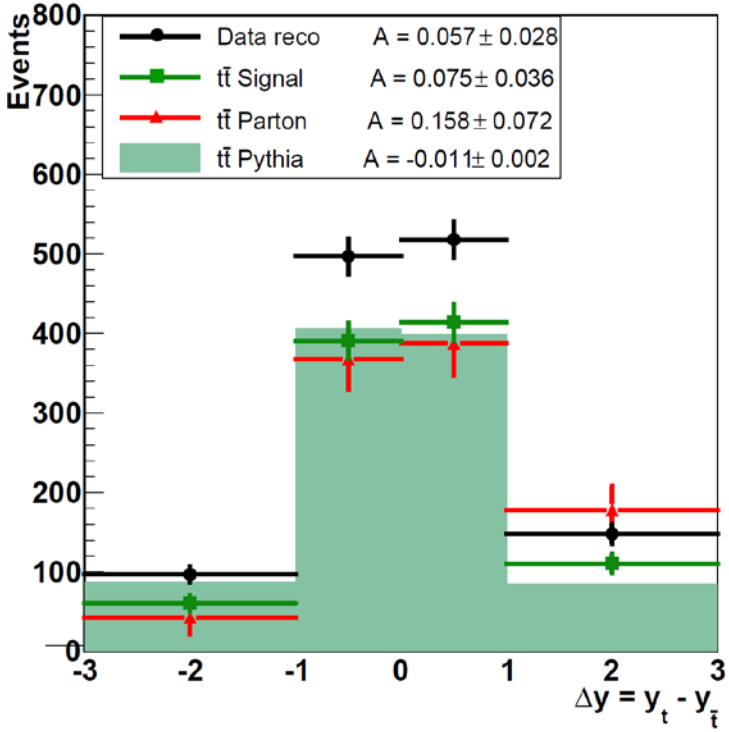
- 5.4 fb^{-1}
- lepton (e/μ) $E_t/p_t > 20$ GeV (/c)
  (muons out to $|\eta| < 2$)
- missing $E_t > 20$ GeV
- 1 jet Et > 40 GeV 3 jets $E_t > 20$ GeV
  - at least one b-tagged jet
- 1581 events bkg = 455±39
- similar kinematic reconstruction
- likelihood based signal/background/A_{fb}
- regularized unfold to parton level
- identical MC@NLO predictions as CDF



parton level asymmetry

D0

sample	level	$A^{t\bar{t}}$	
data	data	0.057 ± 0.028	0.074±0.025
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004	
data	signal	0.075 ± 0.037	0.092±0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005	
data	parton	0.158 ± 0.074	0.196±0.065
MCFM	parton	0.058 ± 0.009	

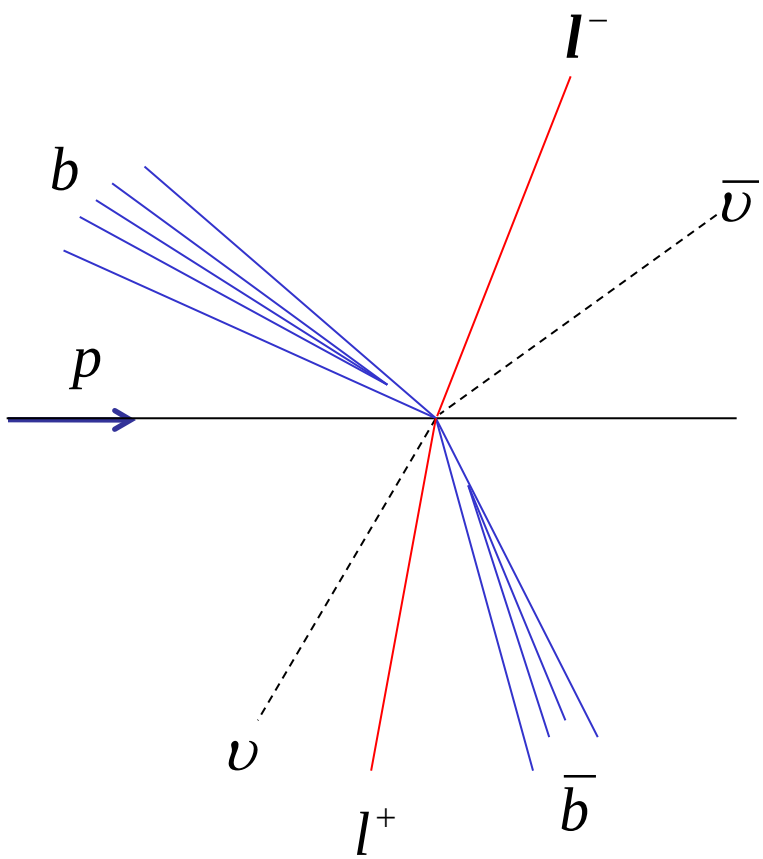


simple rapidity dependence

sample	level	$\lvert\Delta y\rvert < 1.0$	$\lvert\Delta y\rvert \geq 1.0$
data	data	0.021 ± 0.031	0.208 ± 0.062
D0	data	0.061± 0.041	0.213±0.097

CDF dilepton (DIL) mode selection

$$q\bar{q} \to g \to t\bar{t} \to (W^+b)(W^-\bar{b}) \to (l^+\upsilon b)(l^-\bar{\upsilon}\bar{b}) \to l^+ + l^- + \not{E}_T + 2j$$



r-z view

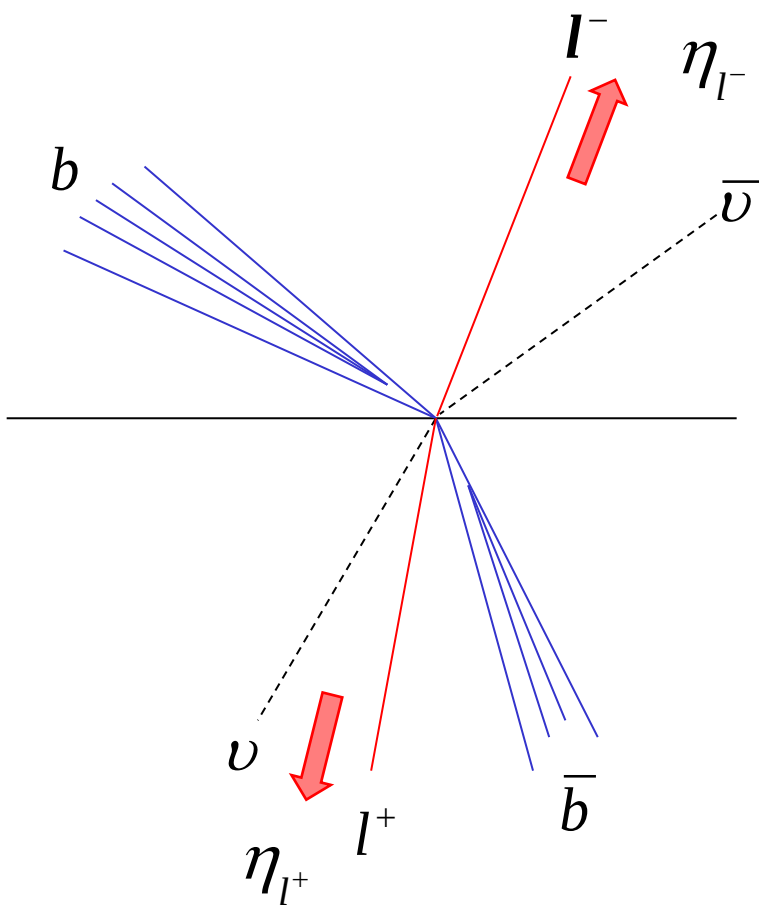
selection and reconstruction

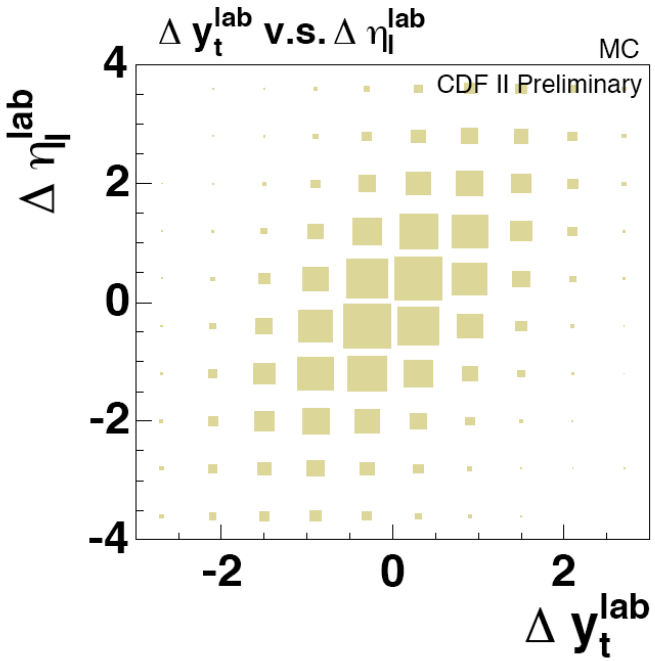
- 5.1 fb^{-1}
- 2 OS lepton (e/μ) E_t/p_t > 20 GeV (/c)
  - M_{ll}.ne. M_Z
- missing E_t > 25 GeV
- .g.e. 2 jets E_t > 15 GeV
- H_t > 200 GeV
- 334 events bkg = 87±17

lepton rapidity difference

$$\Delta\eta_l = \eta_{l^+} - \eta_{l^-}$$

- experimentally robust
- correlated with Δy





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

lepton rapidity difference in control samples

Z + n jets

$A_{\rm obs}^{\Delta\eta_\ell, Z\to\ell\ell+n \text{ jets}}$	Data	Prediction
$Z(\to ee) + 0$ jet	$-0.045 \pm 0.003(\text{stat.})$	-0.046 ± 0.002
$Z(\to \mu\mu) + 0$ jet	$-0.034 \pm 0.003(\text{stat.})$	-0.032 ± 0.002
$Z(\to ee) + 1$ jet	$-0.037 \pm 0.006(\text{stat.})$	-0.048 ± 0.004
$Z(\to \mu\mu) + 1$ jet	$-0.031 \pm 0.007(\text{stat.})$	-0.030 ± 0.003
$Z(\to ee) + \geq 2$ jet	$-0.065 \pm 0.012(\text{stat.})$	-0.056 ± 0.008
$Z(\to \mu\mu) + \geq 2$ jet	$-0.058 \pm 0.014(\text{stat.})$	-0.025 ± 0.007

DIL with MET+ 0 jets

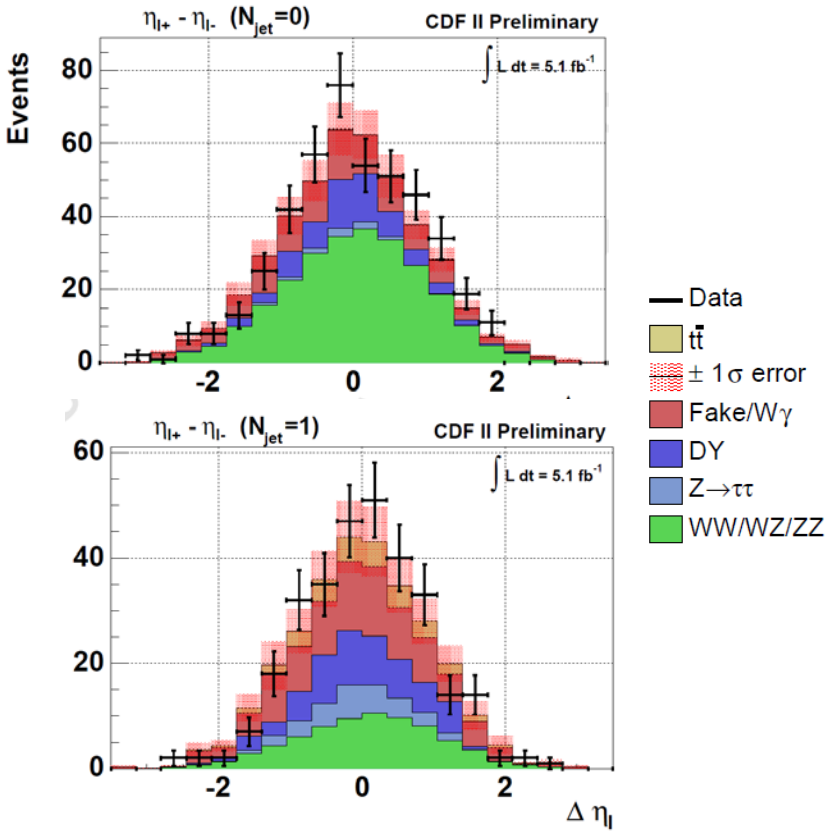
$$A_{obs}^{\Delta\eta_l} = -0.038 \pm 0.047$$

$$A_{pred}^{\Delta\eta_l} = -0.026 \pm 0.037$$

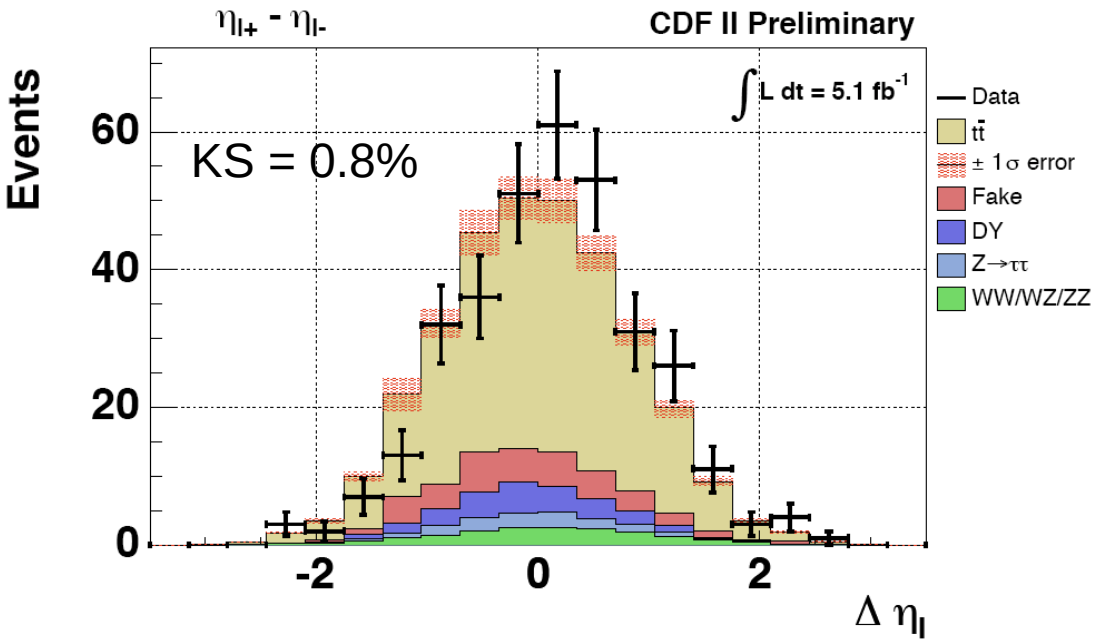
DIL with MET+ 1 jets

$$A_{obs}^{\Delta\eta_l} = 0.040 \pm 0.057$$

$$A_{pred}^{\Delta\eta_l} = -0.009 \pm 0.053$$



lepton rapidity difference in dilepton top signal



- data:

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

$$A_{pred}^{\Delta\eta_l} = -0.022 \pm 0.022$$

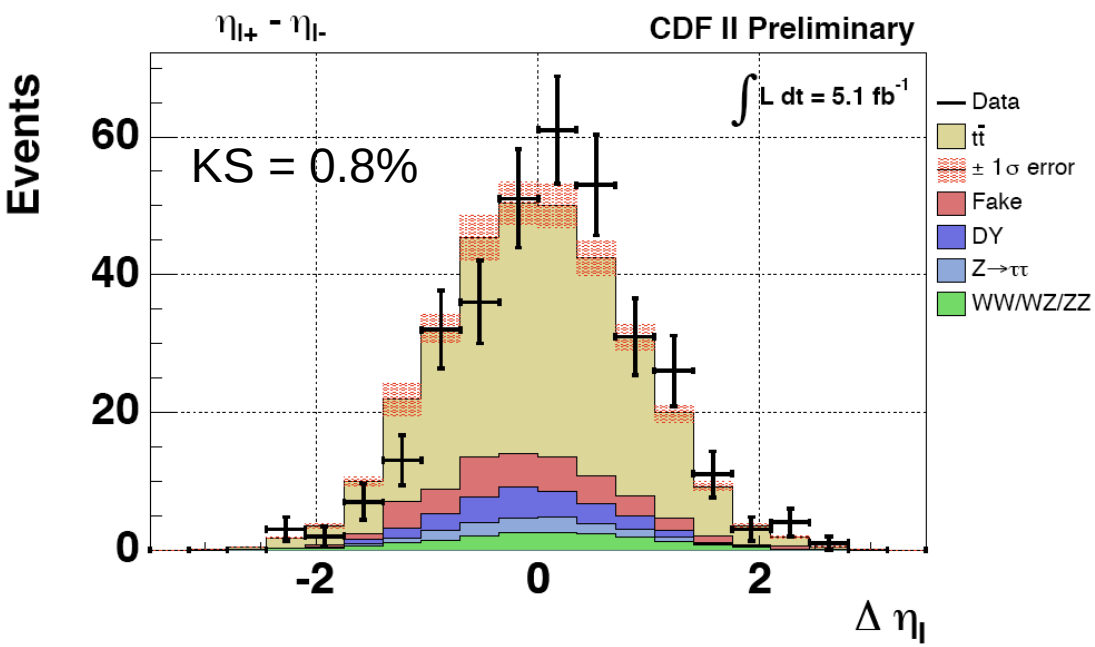
- subtract bkg

$$A_{signal}^{\Delta\eta_l} = 0.205 \pm 0.073$$

- parton level

$$A_{parton}^{\Delta y} = 0.417 \pm 0.156$$

lepton rapidity difference in dilepton top signal



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- recall l+jets result

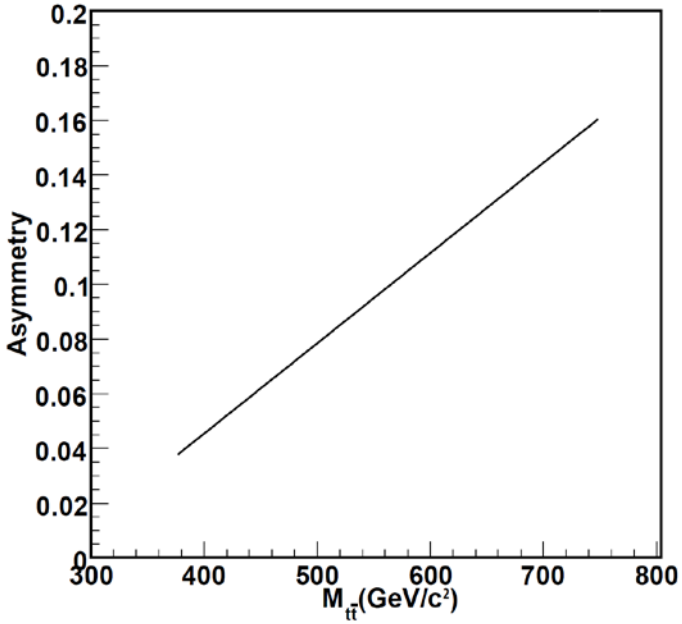
$$A_{parton}^{\Delta y} = 0.158 \pm 0.074$$

- **combined CDF top A_{fb} (5 fb^{-1})**

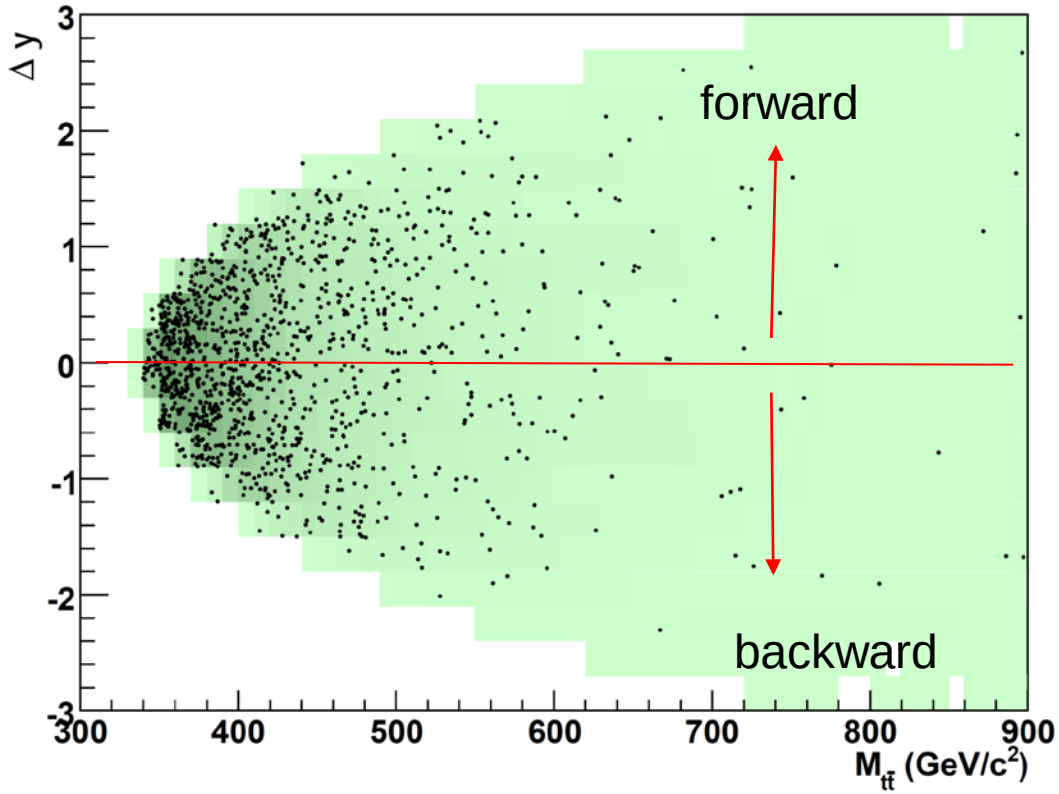
$$A_{parton}^{\Delta y} = 0.20 \pm 0.07$$

M_{tt} dependence of the asymmetry

MCFM: $A(M_{tt})$

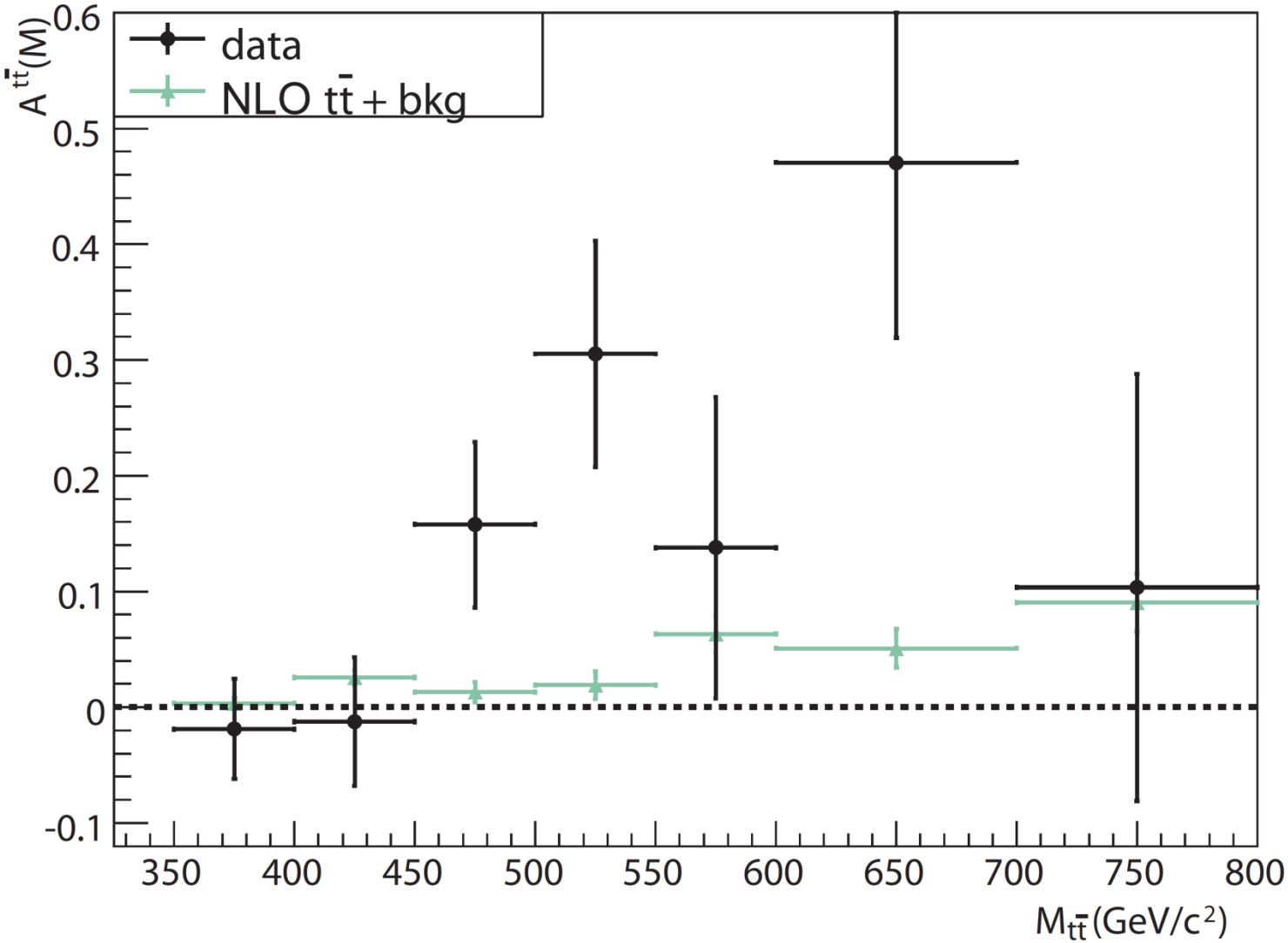


data: Δy vs M_{tt}



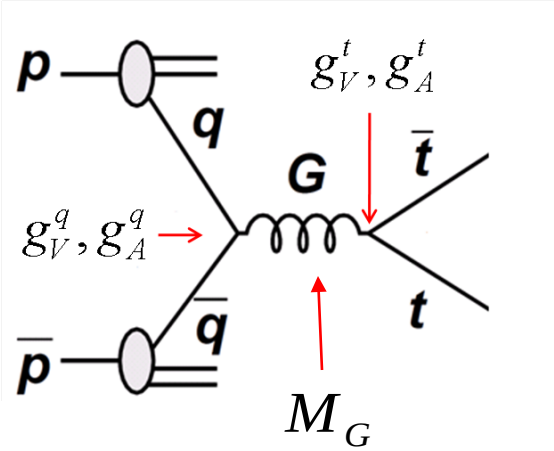
$A^{tt}(M_{tt,\,i})$

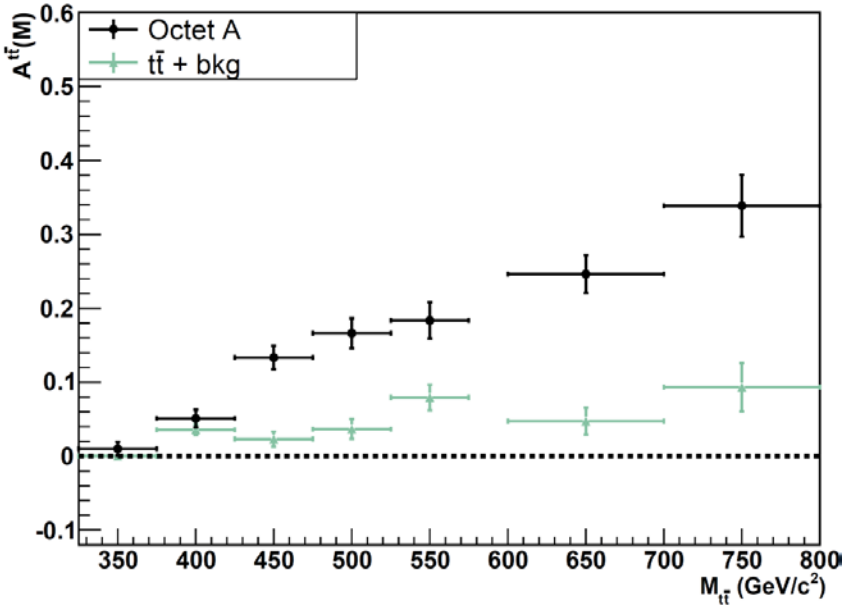
50 GeV bins 100 GeV bins



color octet model

- to test methodologies on
  - large asymmetry, mass dependence
  - **not a hypothesis**
- color octets with axial couplings
  - after Ferrario and Rodrigo arXiv:0906.5541
  - thanks to T. Tait for Madgraph
- sample "Octet A"
  - $g_v = 0$, $|g_A = 3|$
  - $g^q_A = - g^t_A$
  - $M_G = 2.0$ TeV
- good match to data
  - xsec ratio: $\sigma/\sigma_{sm} = 1.02$
  - M_{tt} spectrum ~ SM
  - parton $A_{tt} = 0.16$
  - reco $A_{tt} = 0.08$
- study treatment of mass dependence





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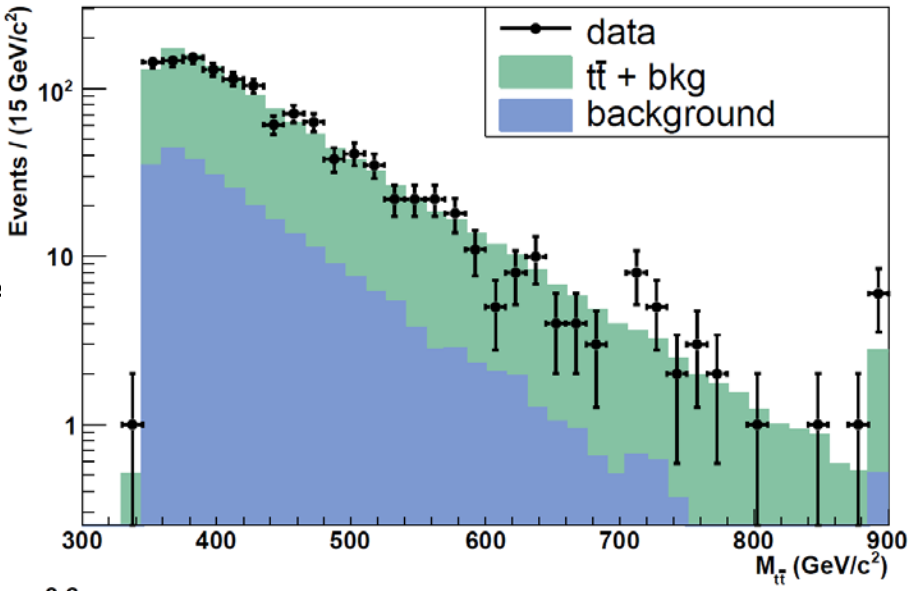

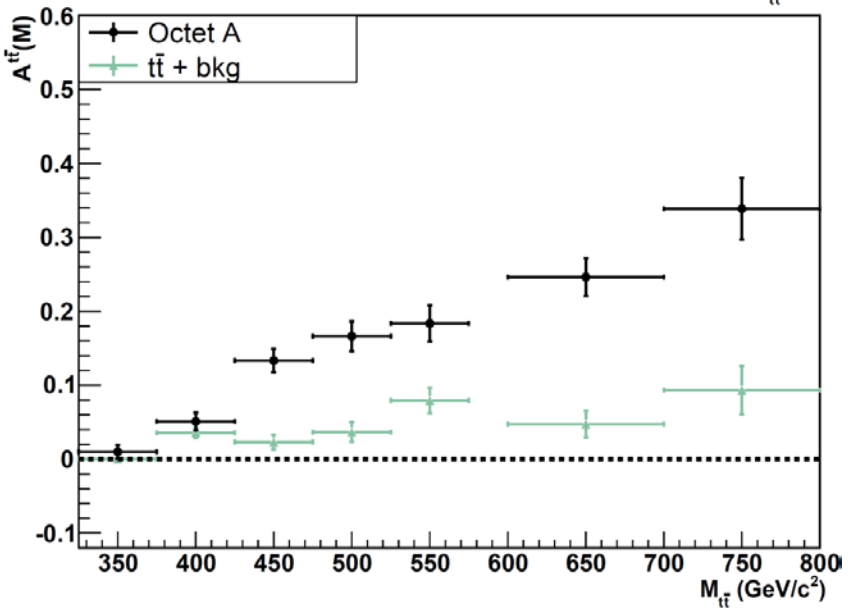

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  - parton $A_{tt} = 0.16$
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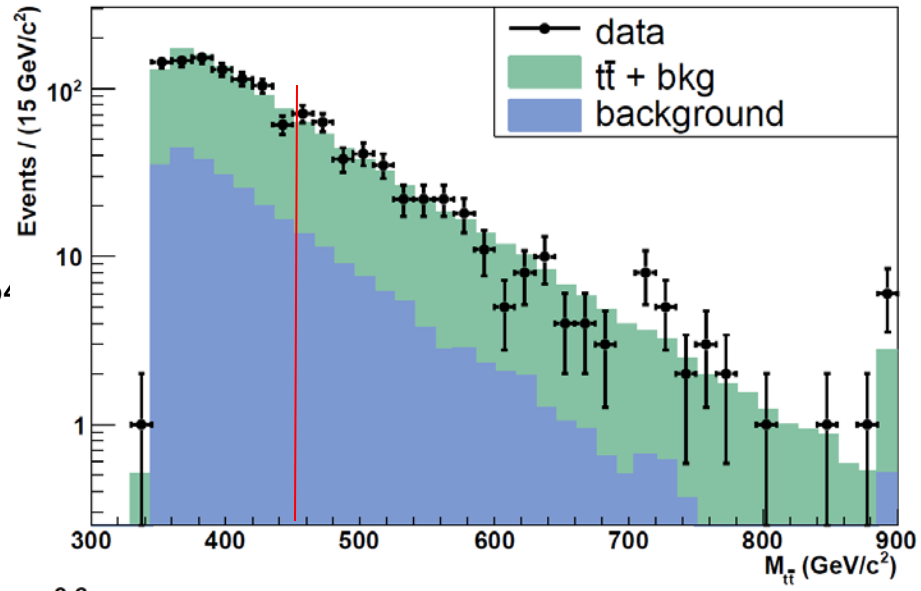
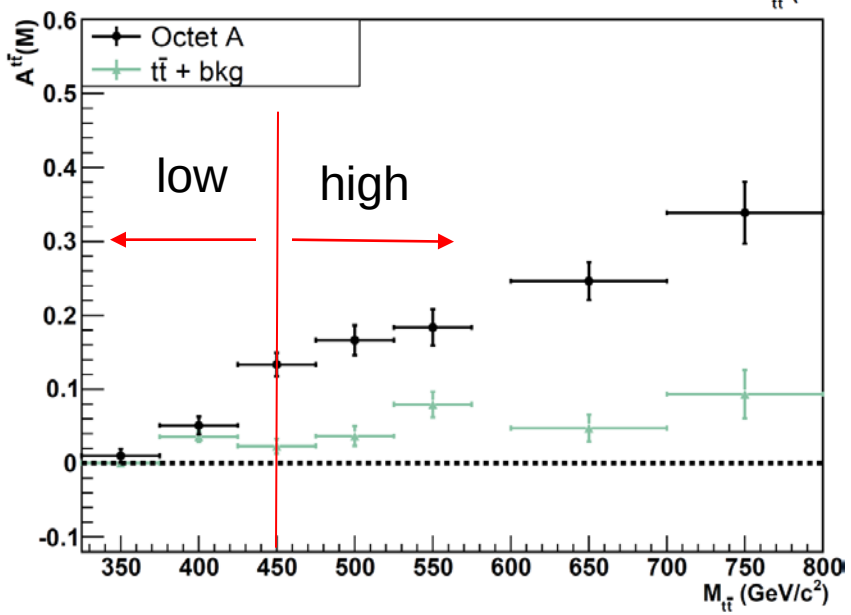
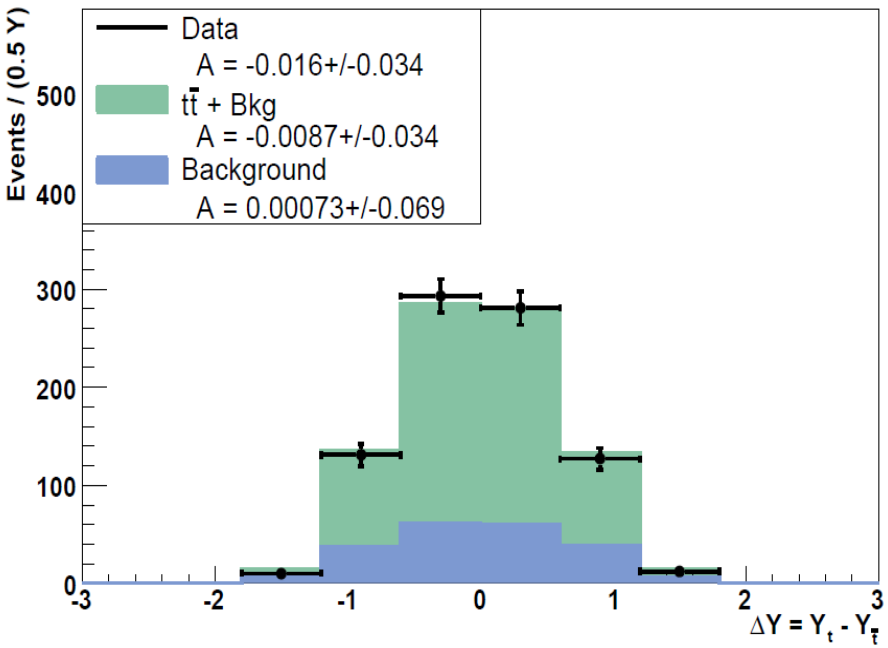
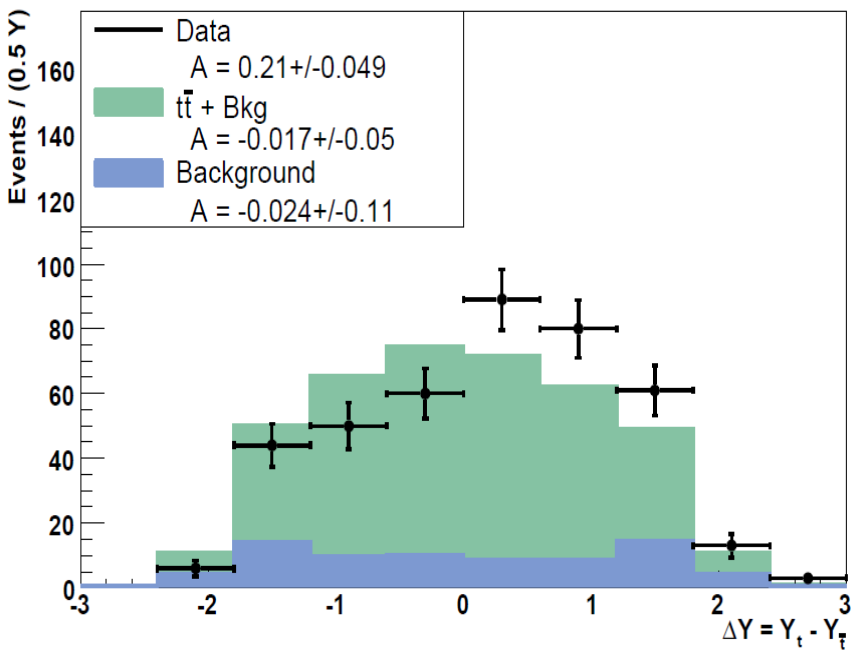
- study treatment of mass dependence
  - 2-bin $A(M_{tt})$
  - optimal partition at $M_{tt} = 450$ GeV/c^2





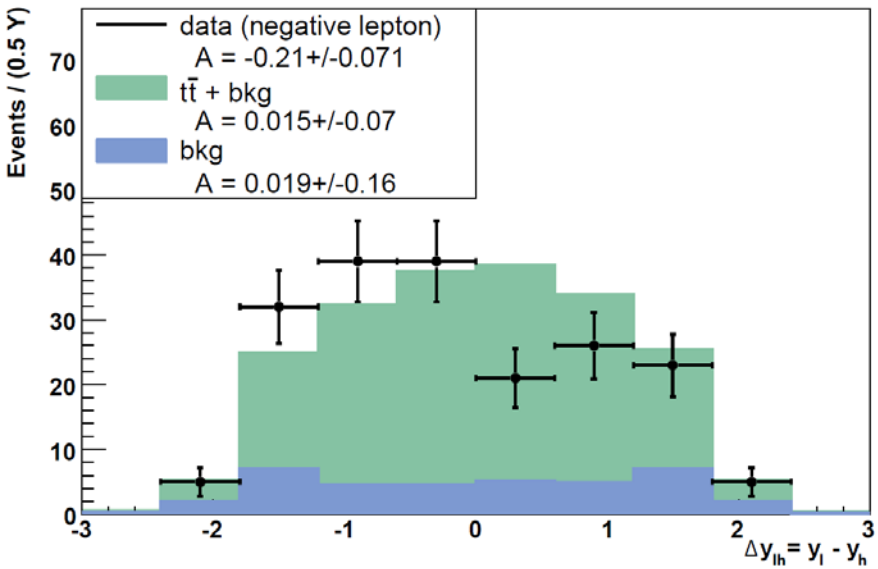
Δy at low and high mass

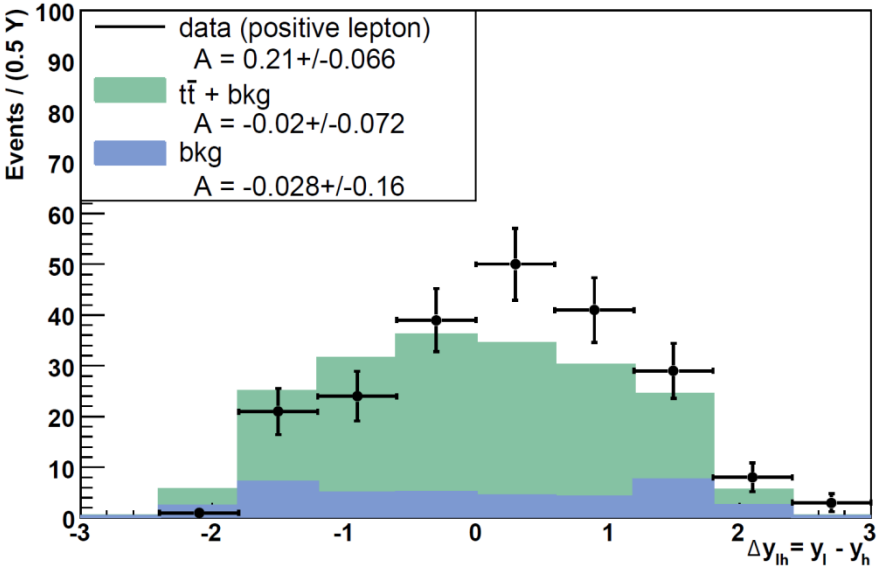




selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
reco data	0.057±0.028	-0.016±0.034	0.212±0.049
MC@NLO	0.017±0.004	0.012±0.006	0.030±0.007

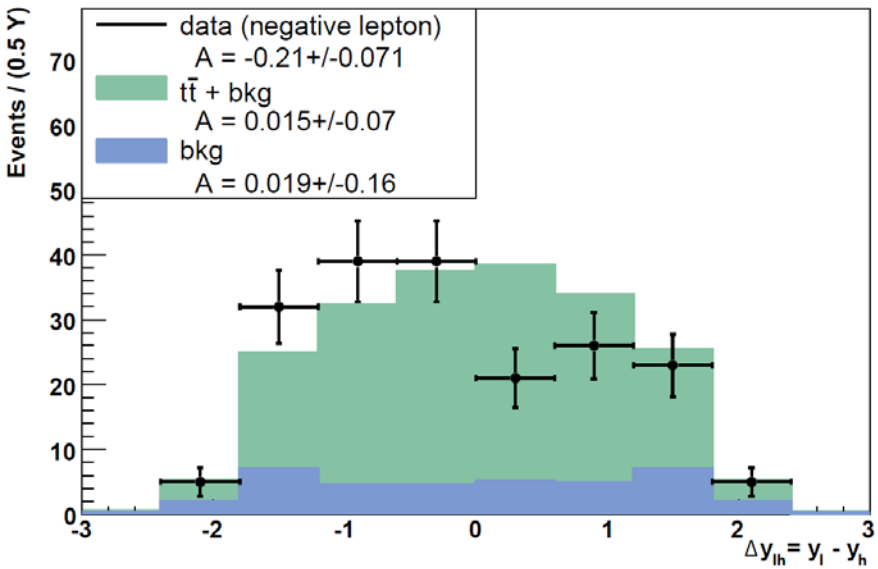
Δy_{lh} at high mass by lepton charge

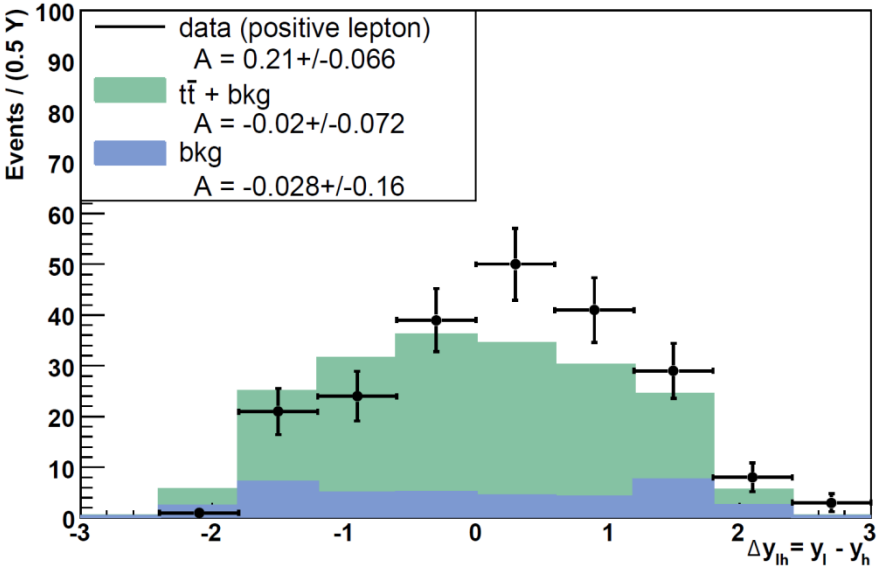




selection	all M	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
A^+_{lh}	0.067±0.040	-0.013±0.050	0.210±0.066
A^-_{lh}	-0.048±0.039	0.020±0.047	-0.210±0.071

Δy_{lh} at high mass by lepton charge





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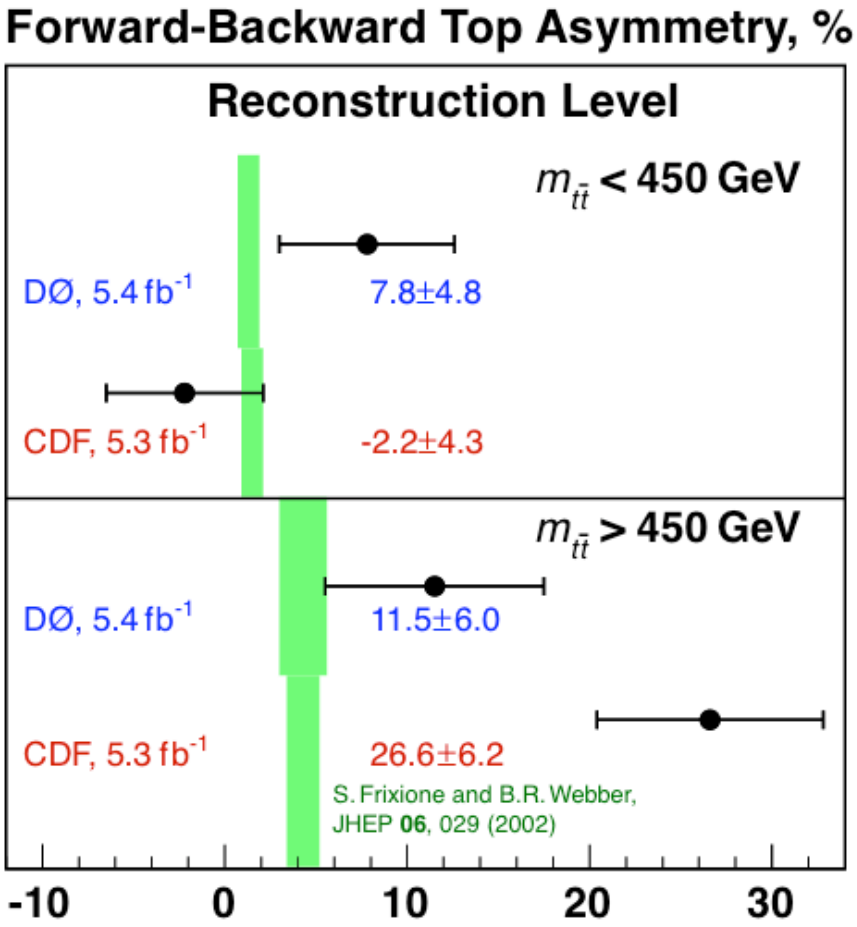
- consistent with CP conservation
- argues against experimental artifact, as detection/reconstruction are sign independent

correction to parton level

- background subtraction
- unfold in 4 bins in Δy and M_{tt}
  - low mass forward
  - low mass backward
  - high mass forward
  - high mass backward

selection	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
data	-0.016 ± 0.034	0.210 ± 0.049
MC@NLO $t\bar{t}$+bkg	$+0.012 \pm 0.006$	0.030 ± 0.007
data signal	$-0.022 \pm 0.039 \pm 0.017$	$0.266 \pm 0.053 \pm 0.032$
MC@NLO $t\bar{t}$	$+0.015 \pm 0.006$	0.043 ± 0.009
data parton	$-0.116 \pm 0.146 \pm 0.047$	$0.475 \pm 0.101 \pm 0.049$
MCFM	$+0.040 \pm 0.006$	0.088 ± 0.013

CDF vs D0 Mass dependence

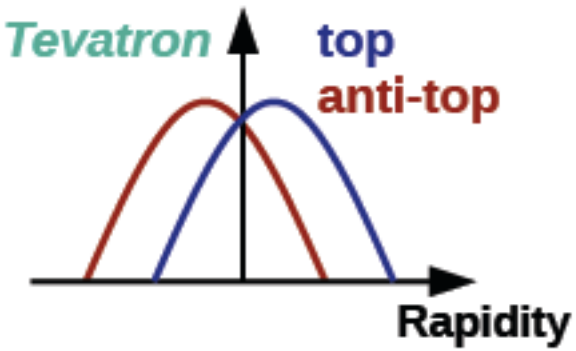


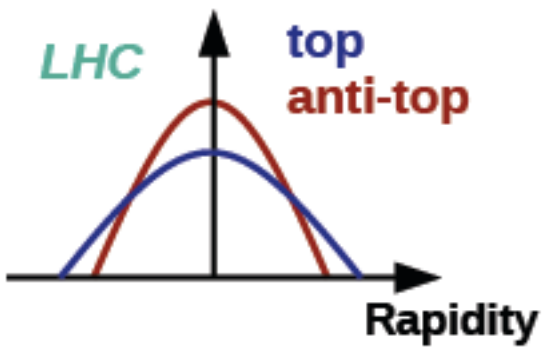
D0 does not seem to see strong mass dependence

but all numbers nevertheless statistically consistent

at the LHC

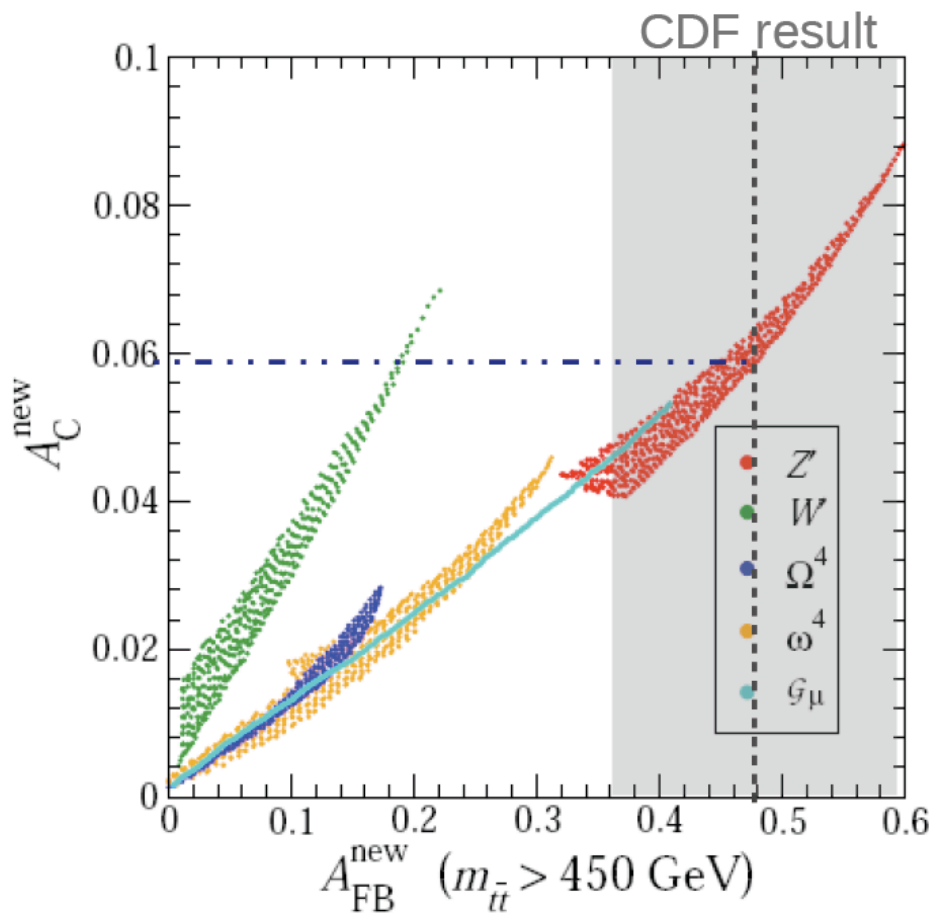
LHC-Tevatron complementarity





$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

J. Aguilar-Saavedra, M. Perez-Victoria, arXiv:1105.4606



$$A_C^y = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

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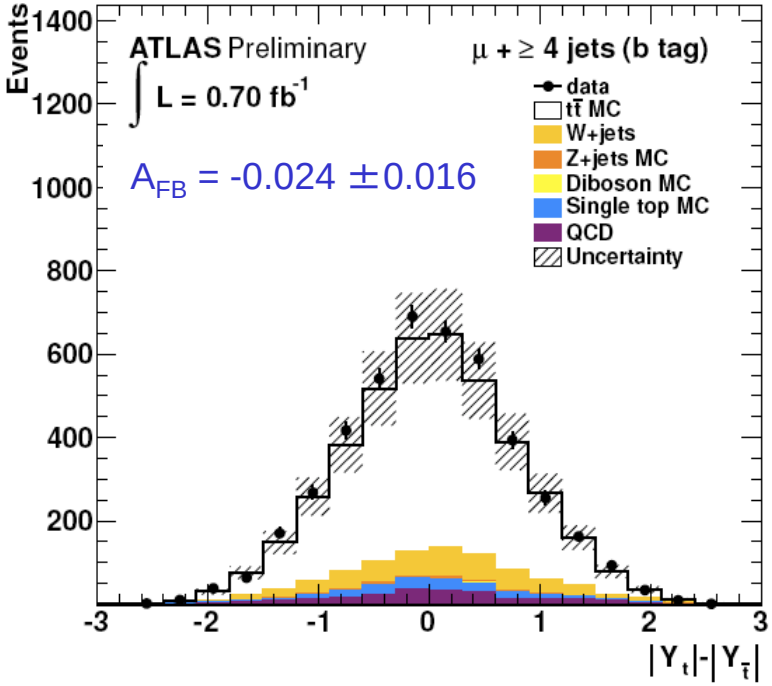
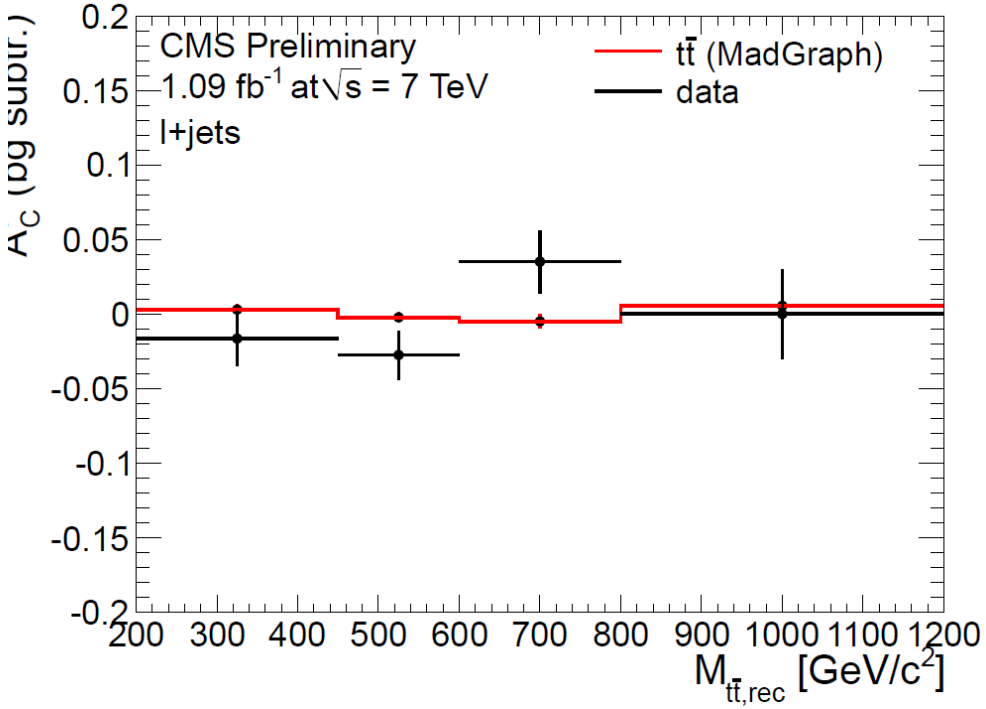
inclusive



A_{FB} = -0.024 ±0.016

CMS PAS TOP-11-014

mass dependent



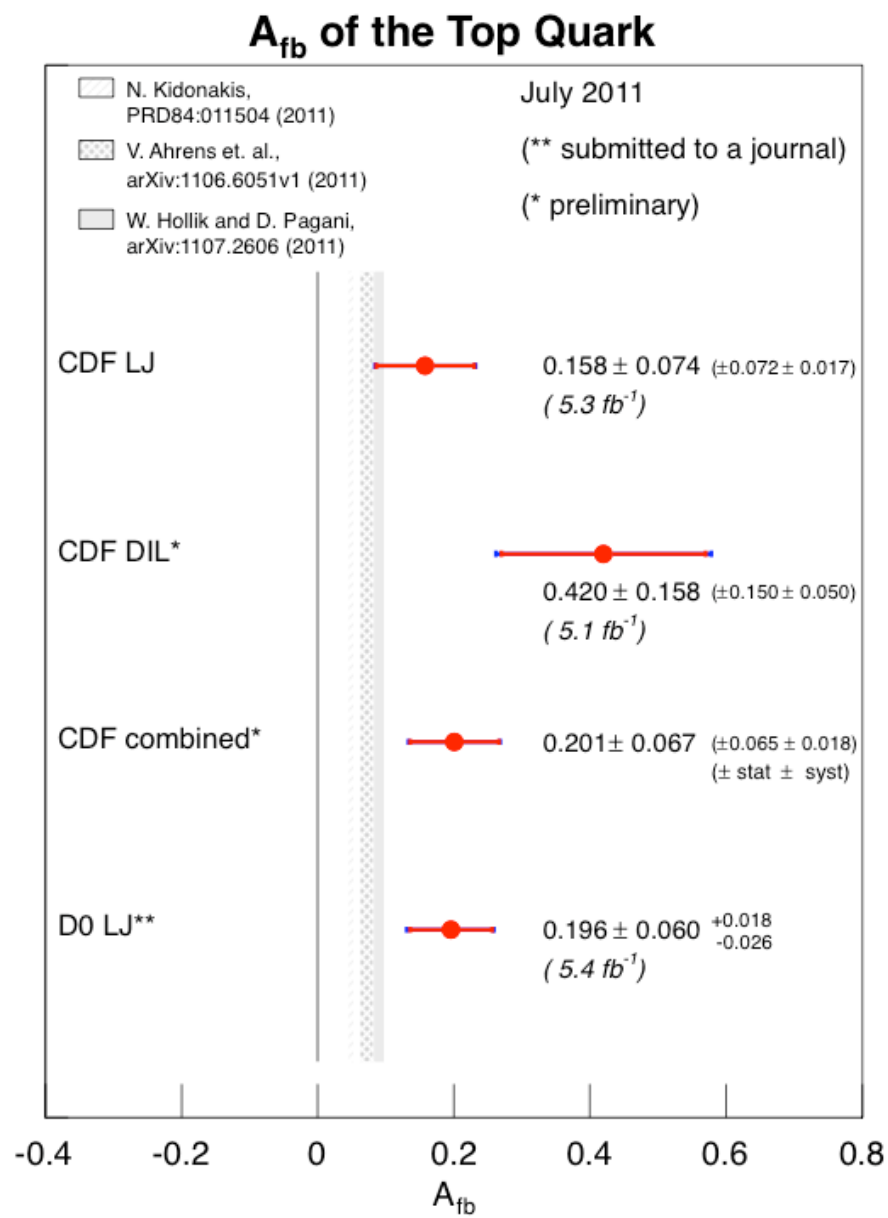
jury still out?

summary

- significant $A_{fb}(\Delta y)$ in two decay modes
  - in DIL, A_{fb} in robust lepton $\Delta\eta$
  - in l+jets

    A_{fb} depends on Δy and M_{tt}

    A_{fb} reverses sign when $t \rightarrow \bar{t}$

- D0 confirms $A_{fb}(\Delta y)$ in l+jets

- interesting theoretical suggestions
- LHC analyses underway
- more than double TeV data
- lots of work still to do