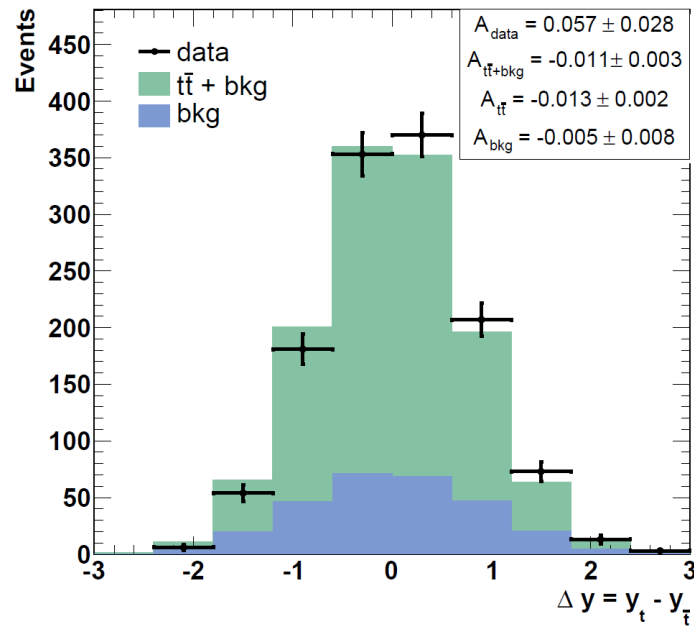




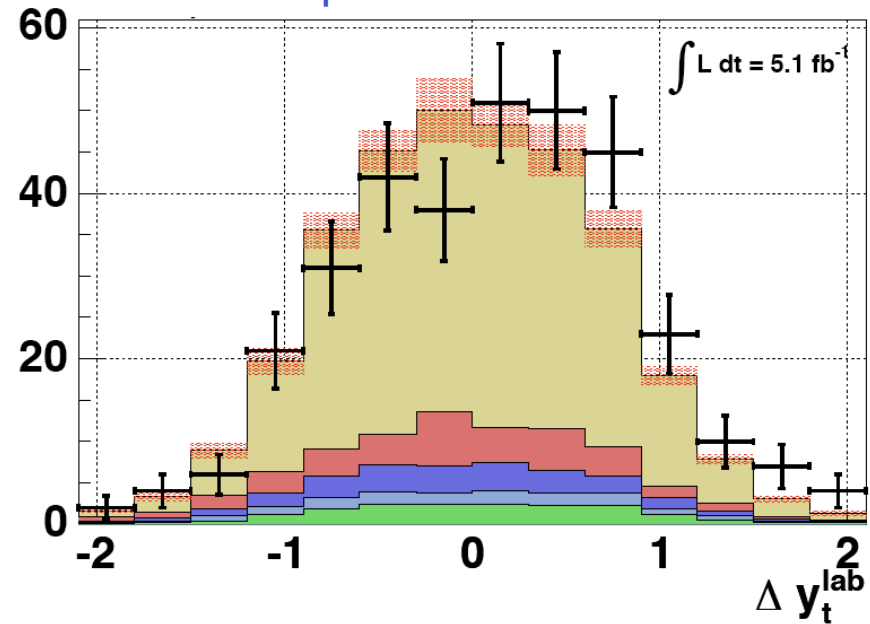
A Forward-Backward Asymmetry in Top Quark Pair Production

The CDF Collaboration
D. Amidei, University of Michigan

lepton + jets mode



dilepton mode



top quark pair production

- hard scatter cm-frame generically

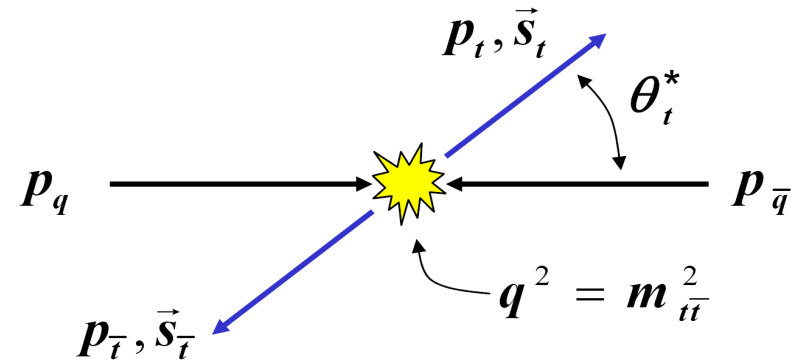
$$\sigma \sim \frac{\alpha_s^2}{q^2} \left[1 + \cos^2 \theta^* + f(q^2) \cos \theta^* \right] \cdot g(\vec{s})$$

– specified by α , q^2 , θ^* , \vec{s}

- α , q^2 well measured in σ and $M_{t\bar{t}}$ spectrum. SM-like.

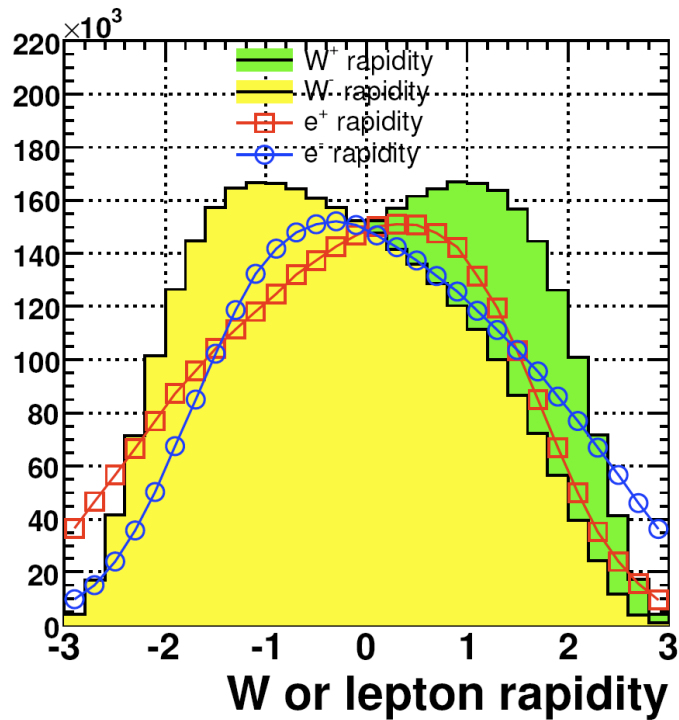
- here: the production angle θ^*

– in particular: asymmetry in production angle with respect to proton direction
– forward-backward asymmetry



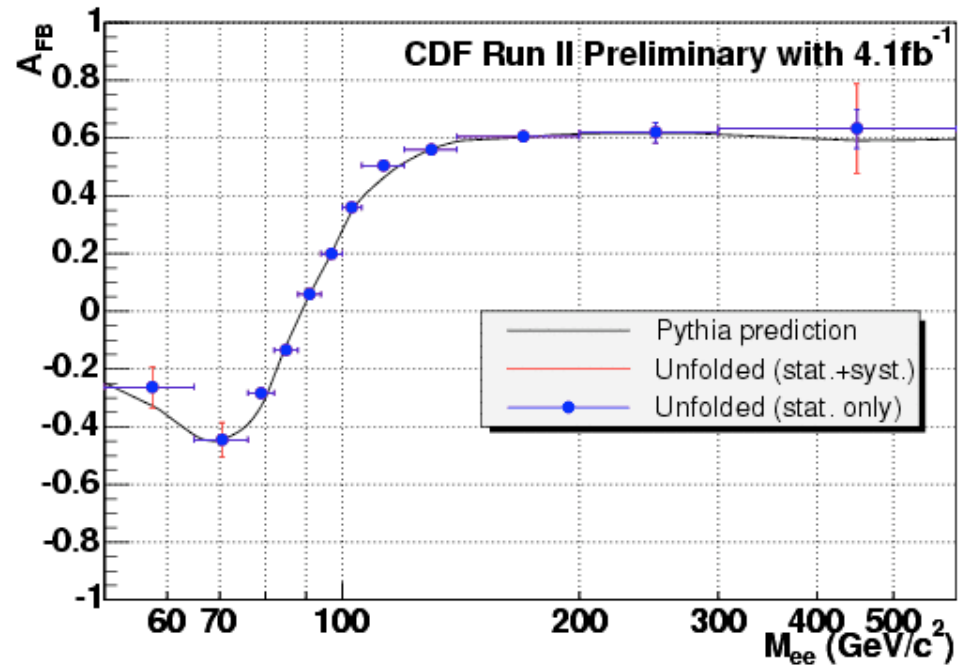
some other asymmetries at the Tevatron

- W boson charge asymmetry
 - from asymmetry of initial state (u/d PDFs)



n.b. hadron collisions $\theta^* \rightarrow y$

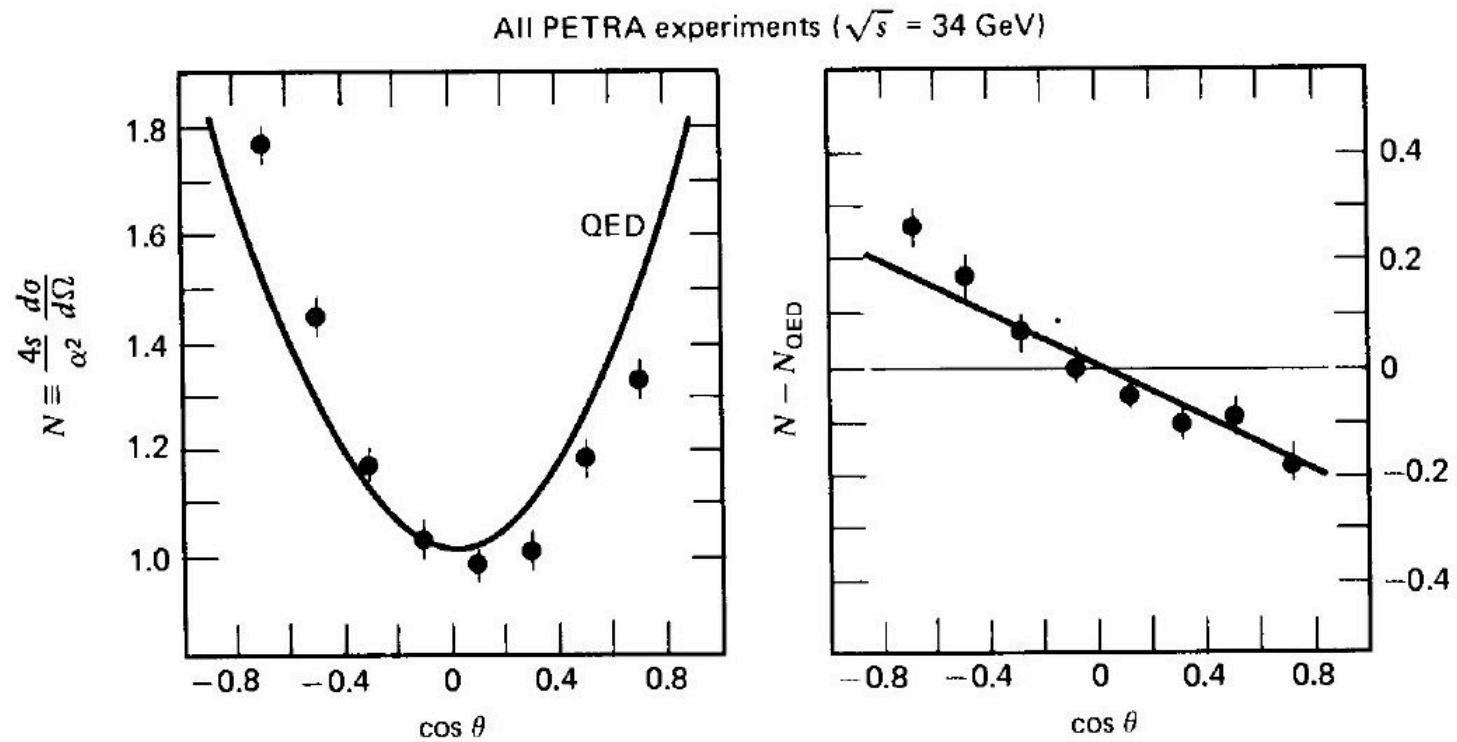
- A_{fb} in $p\bar{p} \rightarrow Z/\gamma^* \rightarrow e^+e^-$
 - from weak current couplings



n.b. q^2 dependence is of interest

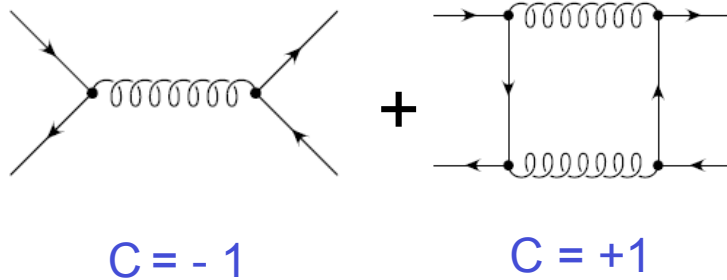
wisdom from history

- A_{fb} in $e^+e^- \rightarrow Z/\gamma^* \rightarrow \mu^+\mu^-$ observed at PETRA $E_{\text{cm}} \sim 35$ GeV
- evidence for Z, well below the pole



tt charge asymmetry in NLO QCD

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



asymmetry in $\Delta y = y_t - y_{\bar{t}}$
prediction: $A_{fb} \sim 0.06 \pm 0.015$

- verified for QED in $e^+e^- \rightarrow \mu^+\mu^-$
- strong interaction C tests at high energy? difficulty of jet charge
- reconstructed top pair system has accessible information on charge flow
 - test C in strong interactions at large q^2

prior measurements (lepton + jets)

- CDF, 1.9 fb⁻¹ , inclusive, corrected to “parton-level”

- tt rest frame $A^{\bar{t}\bar{t}} = 0.24 \pm 0.14$

PRL 101, 202001 (2008)

- NLO QCD $A^{\bar{t}\bar{t}} = 0.06 \pm 0.01$

- D0, inclusive, background subtracted “data-level”

- tt rest frame $A^{\bar{t}\bar{t}} = 0.12 \pm 0.08$ 0.9 fb⁻¹

PRL 100, 142002 (2008)

- $A^{\bar{t}\bar{t}} = 0.08 \pm 0.04$ 4.3 fb⁻¹

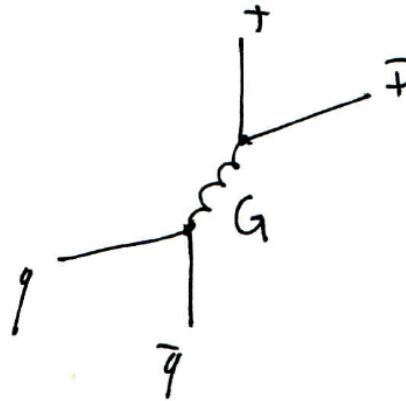
ICHEP 2010

- NLO QCD $A^{\bar{t}\bar{t}} = 0.02 \pm 0.01$

theoretical interest

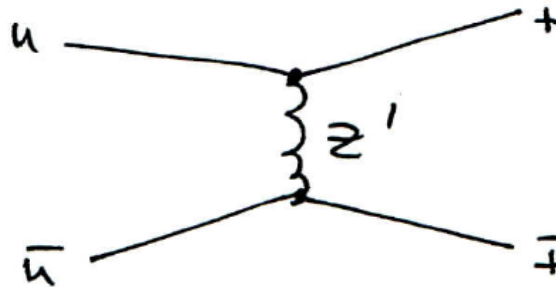
- s-channel

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



- FV t-channel

- $W'Z'$
- color triplets, sextets

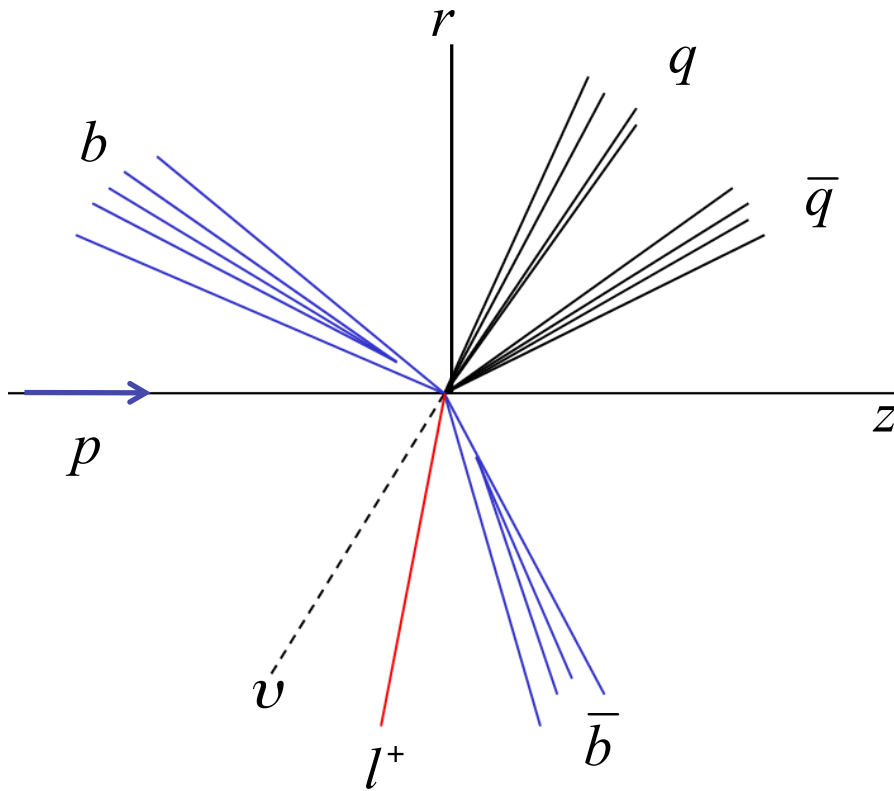


- model building must contend with

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

lepton + jets: selection and reconstruction

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



r-z view

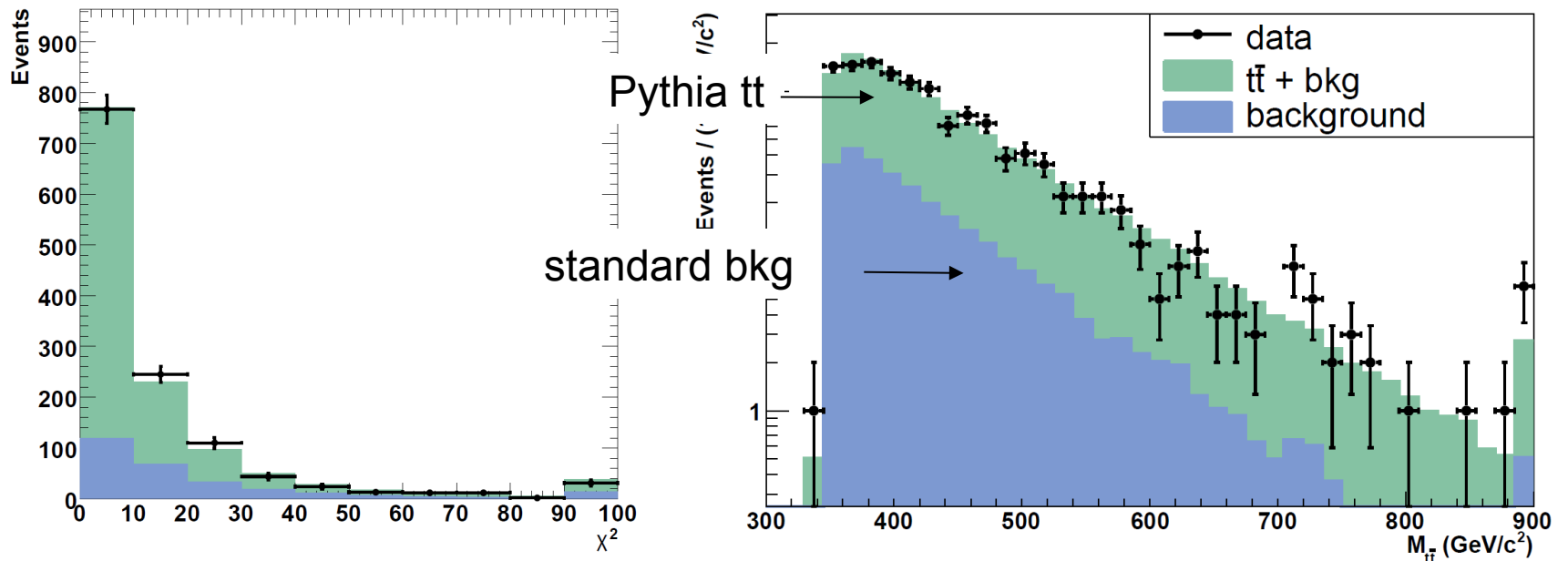
- 5.3 fb⁻¹
- lepton (e/μ) E_t/p_t > 20 GeV (/c)
- missing E_t > 20 GeV
- .g.e. 4 jets E_t > 20 GeV
 - at least one b-tagged jet
- 1260 events bkg = 283±50

top reconstruction

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

- jet-parton assignment, $p_z(\nu)$ via minimum of simple χ^2
 - Constraints: $M_W = 80.4 \text{ GeV}/c^2$, $M_t = 175 \text{ GeV}/c^2$, btag = b
 - Float jet p_t within errors
- sign of lepton fixes charge of tops and decay products

$$\chi^2 = \sum_{lep, jets} \frac{(p_t^{i, meas} - p_t^{i, fit})^2}{\sigma_i^2} + \sum_{j=x, y} \frac{(p_j^{UE, meas} - p_j^{UE, fit})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{top})^2}{\Gamma_t^2} + \frac{(M_{blv} - M_{top})^2}{\Gamma_t^2}$$



top pair rapidity difference

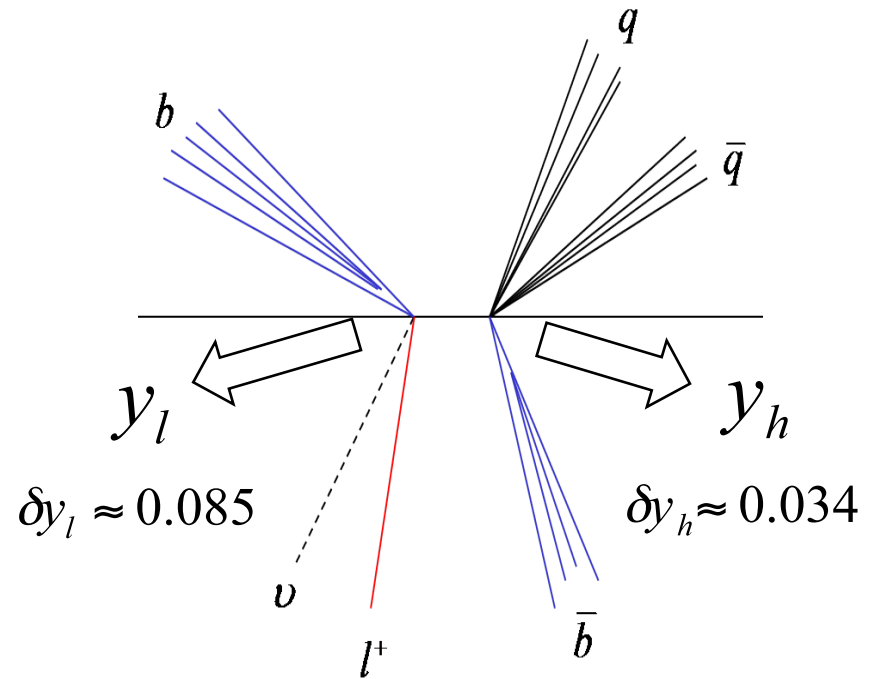
- frame invariant variables

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

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

- interpretation

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



- asymmetry in Δy equals asymmetry in top quark production angle in $t\bar{t}$ rest frame

$$\begin{aligned}
 A^{t\bar{t}} &= \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \\
 &= \frac{N(\cos \theta^* > 0) - N(\cos \theta^* < 0)}{N(\cos \theta^* > 0) + N(\cos \theta^* < 0)}
 \end{aligned}$$

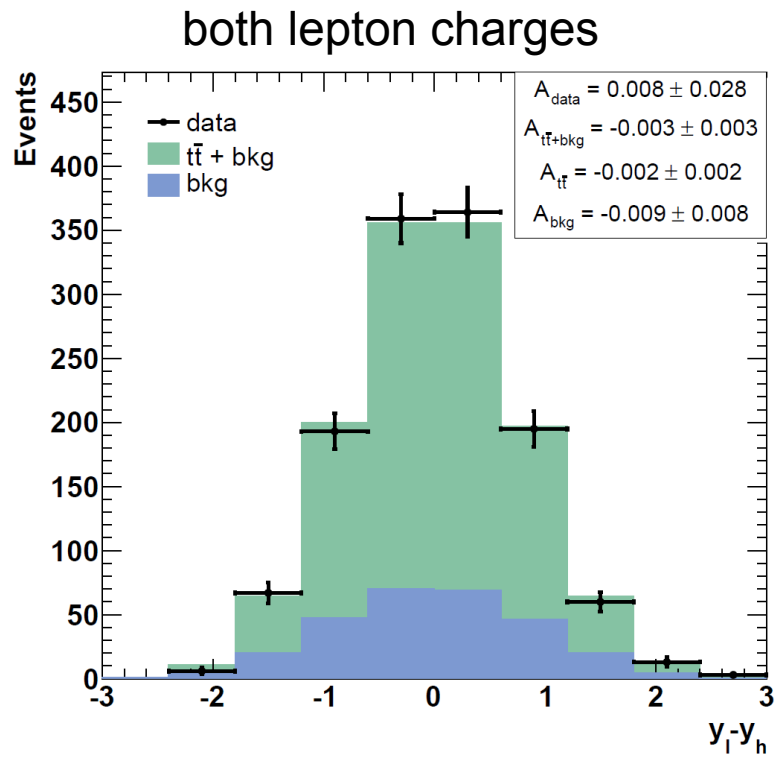
expected QCD asymmetries

- 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	$t\bar{t} + \text{bkg}$	0.017 ± 0.004	sim + reco + bkg

- n.b.
 - prediction for data level asymmetry < stat precision (0.028)
 - LO Pythia $t\bar{t}$ model remains good approximation of SM

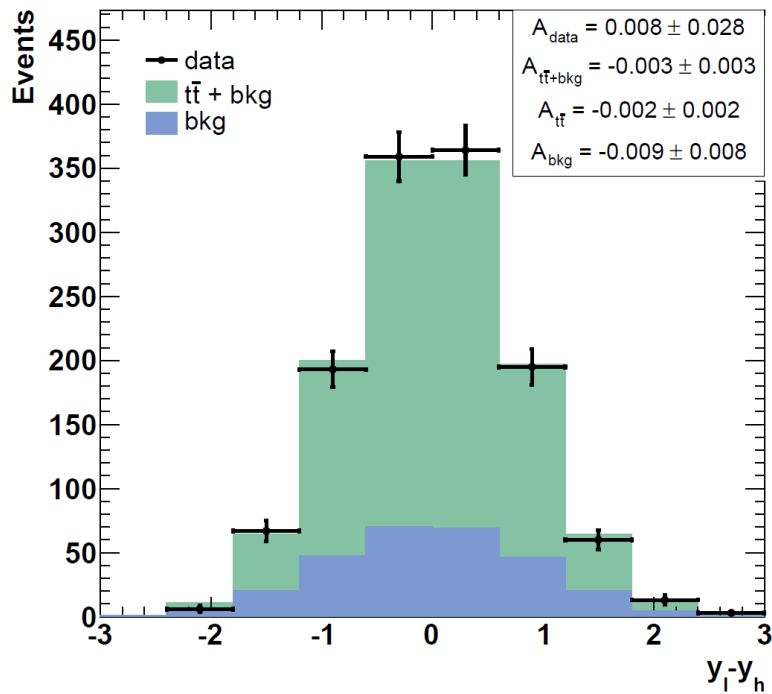
inclusive $y_l - y_h$ distributions



- $A_{\text{FB}} = 0.008 \pm 0.028$
- “uncharged” distribution is symmetric

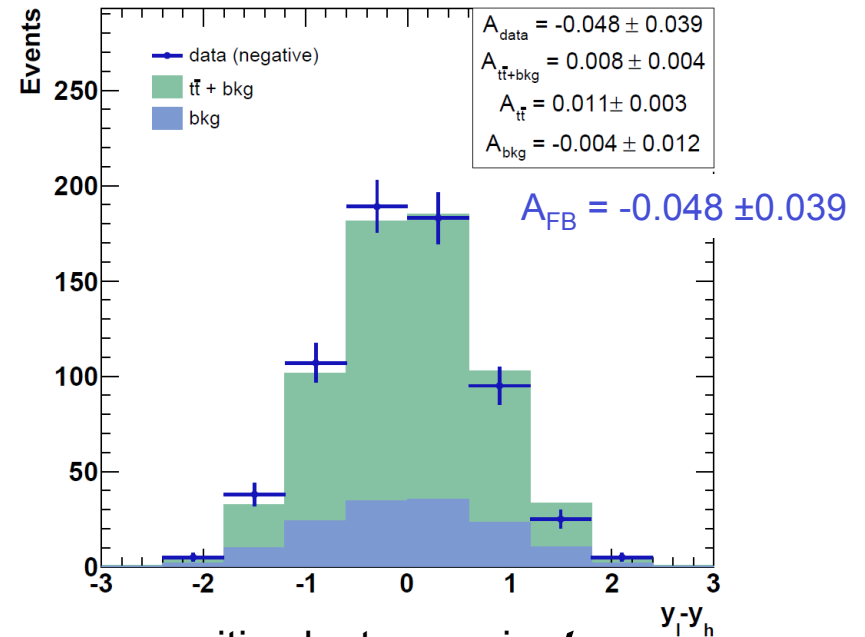
inclusive $y_l - y_h$ distributions

both lepton charges

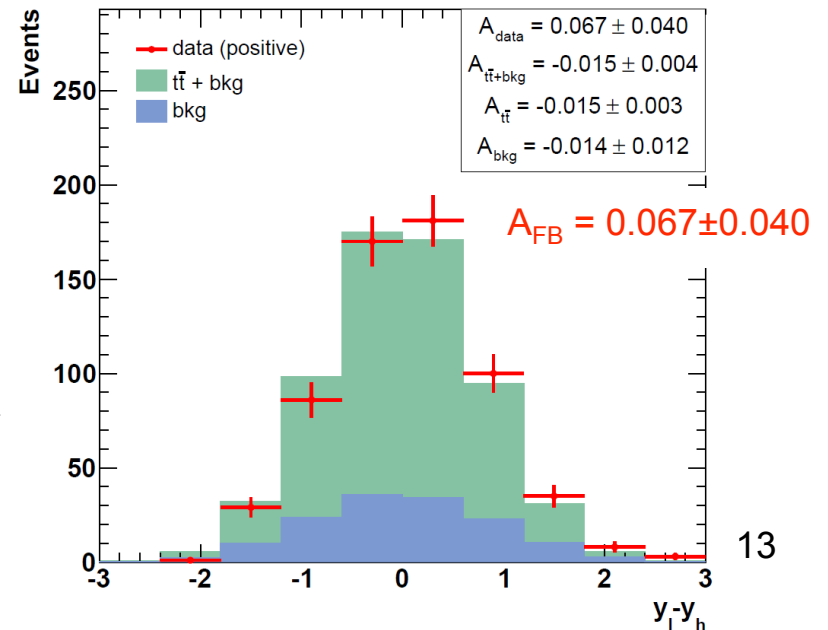


- $A_{\text{FB}} = 0.008 \pm 0.028$
- “uncharged” distribution is symmetric
- but if separate by lepton charge →
- see charge asymmetry
- CP conserving

negative leptons: y_l is \bar{t}

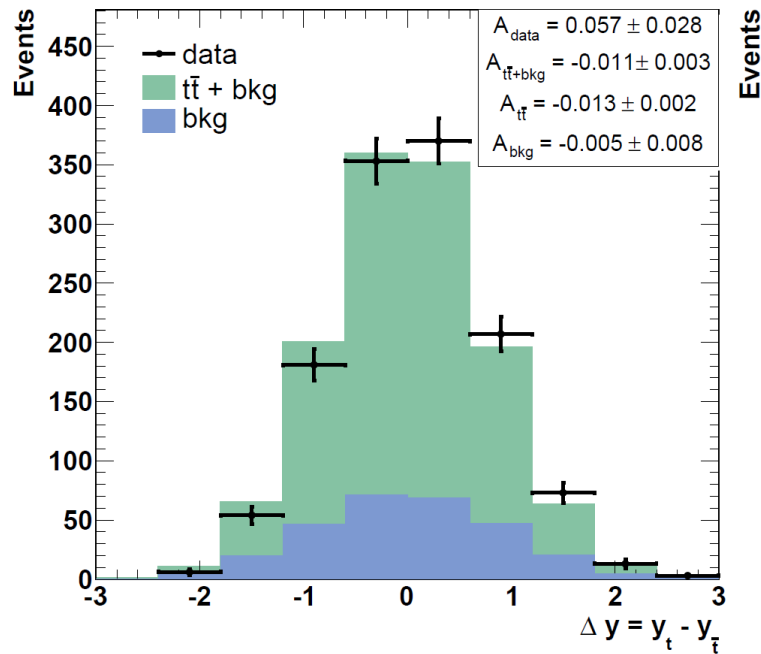


positive leptons: y_l is t



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

data level

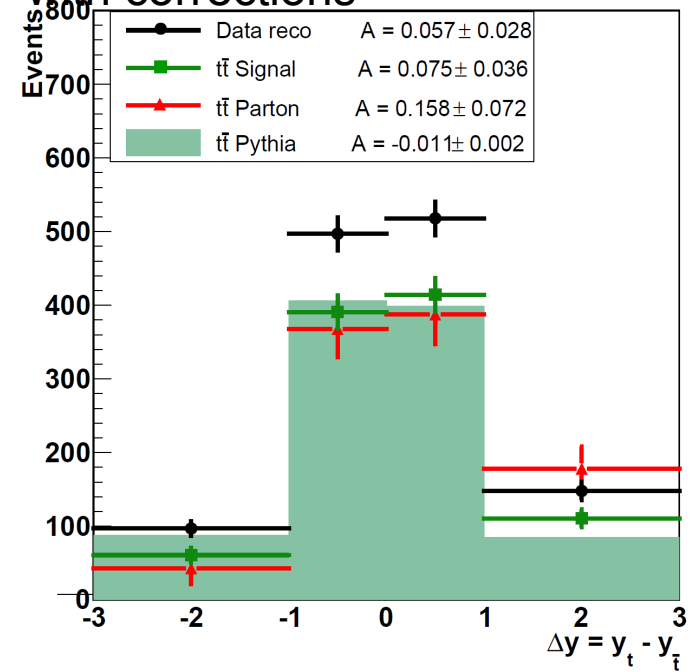


sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t} + \text{bkg}$	0.017 ± 0.004

then

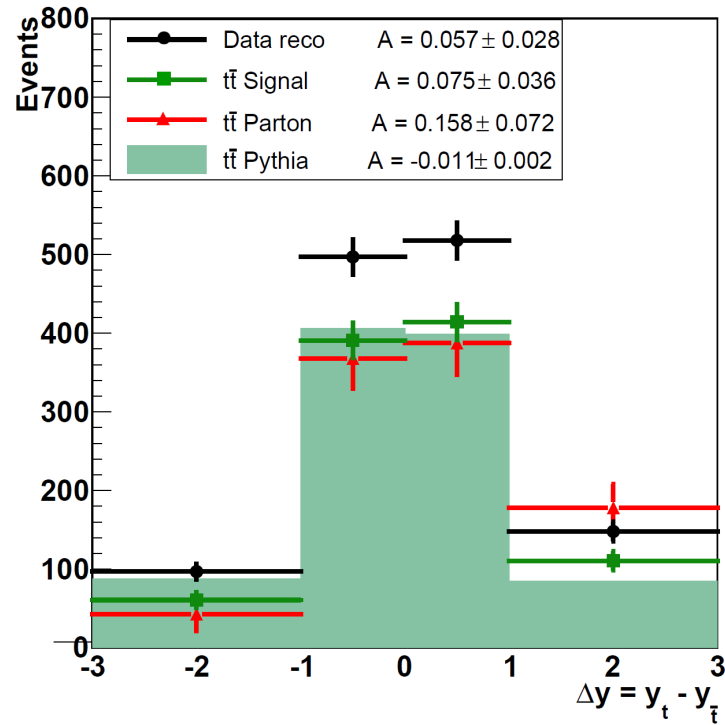
- **bkg subtract**
 - yields tt “signal” at reco level
- **correct acceptance & unfold resolution**
 - yields tt at “parton level”

with corrections



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

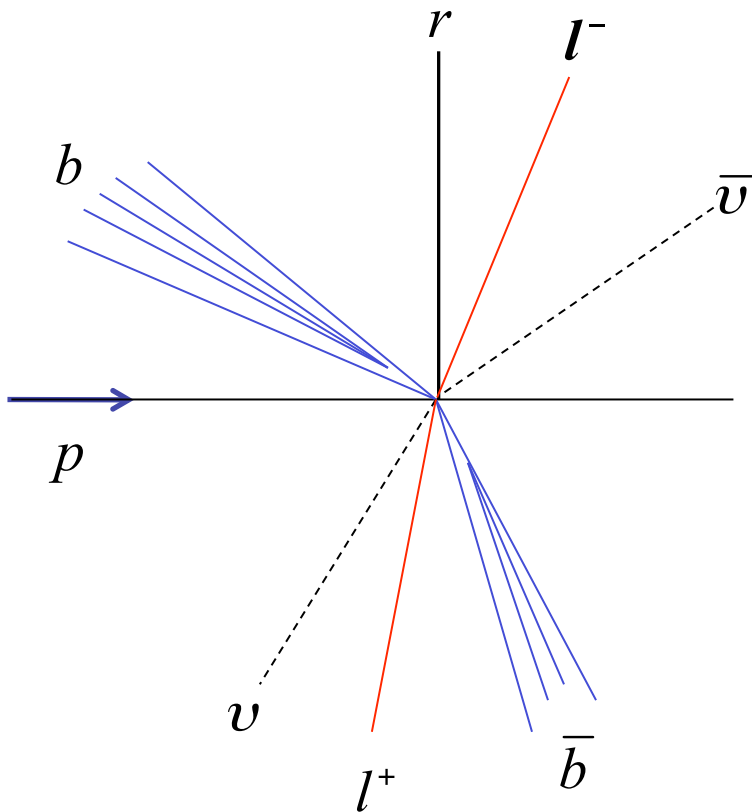
A(Δy), parton level, data



sample level	$ \Delta y < 1.0$	$ \Delta y \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

dilepton mode selection

$$q\bar{q} \rightarrow g \rightarrow t\bar{t} \rightarrow (W^+b)(W^-\bar{b}) \rightarrow (l^+\nu b)(l^-\bar{\nu}\bar{b}) \rightarrow l^+ + l^- + E_T + 2j$$



r-z view

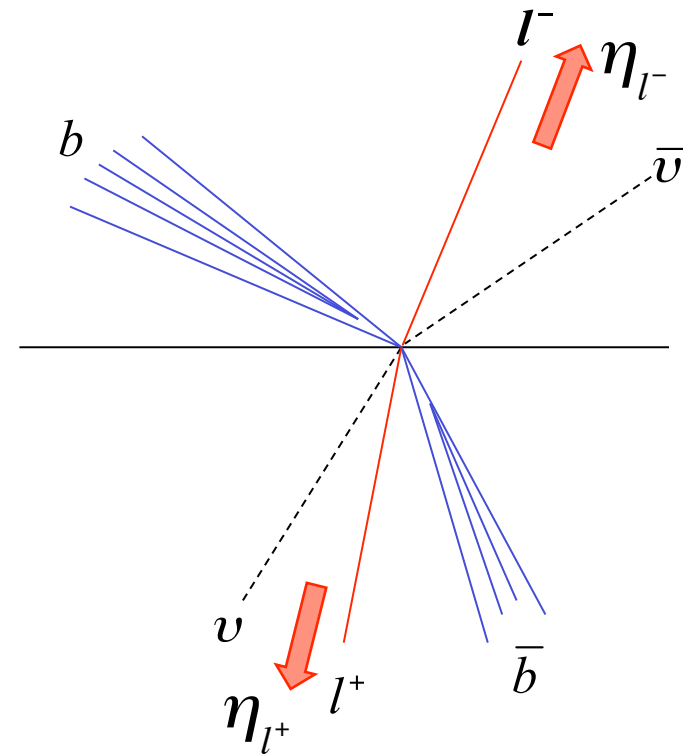
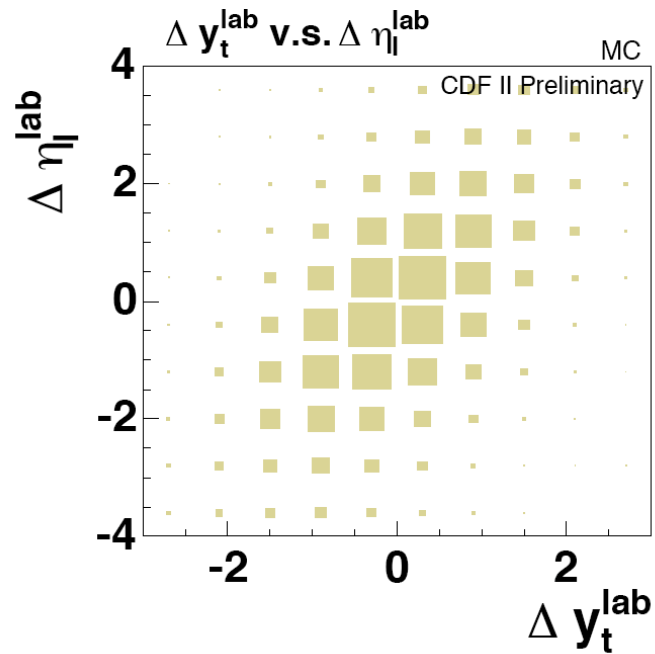
selection and reconstruction

- 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



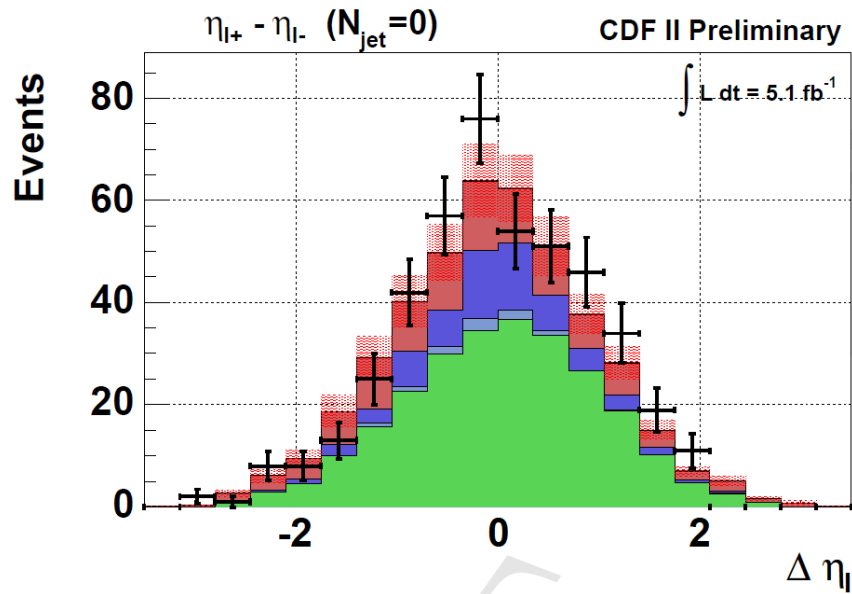
$$A^{\Delta\eta_l} = \frac{N(\Delta\eta_l > 0) - N(\Delta\eta_l < 0)}{N(\Delta\eta_l > 0) + N(\Delta\eta_l < 0)}$$

lepton rapidity difference in Z control samples

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

lepton rapidity difference in top dilepton control samples

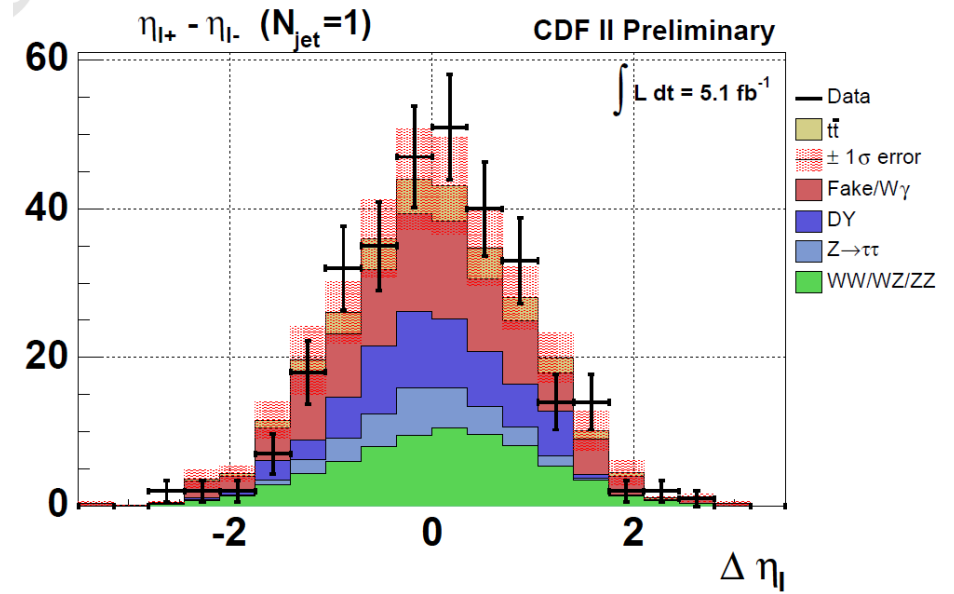
dilepton + MET+ 0 jets



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

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

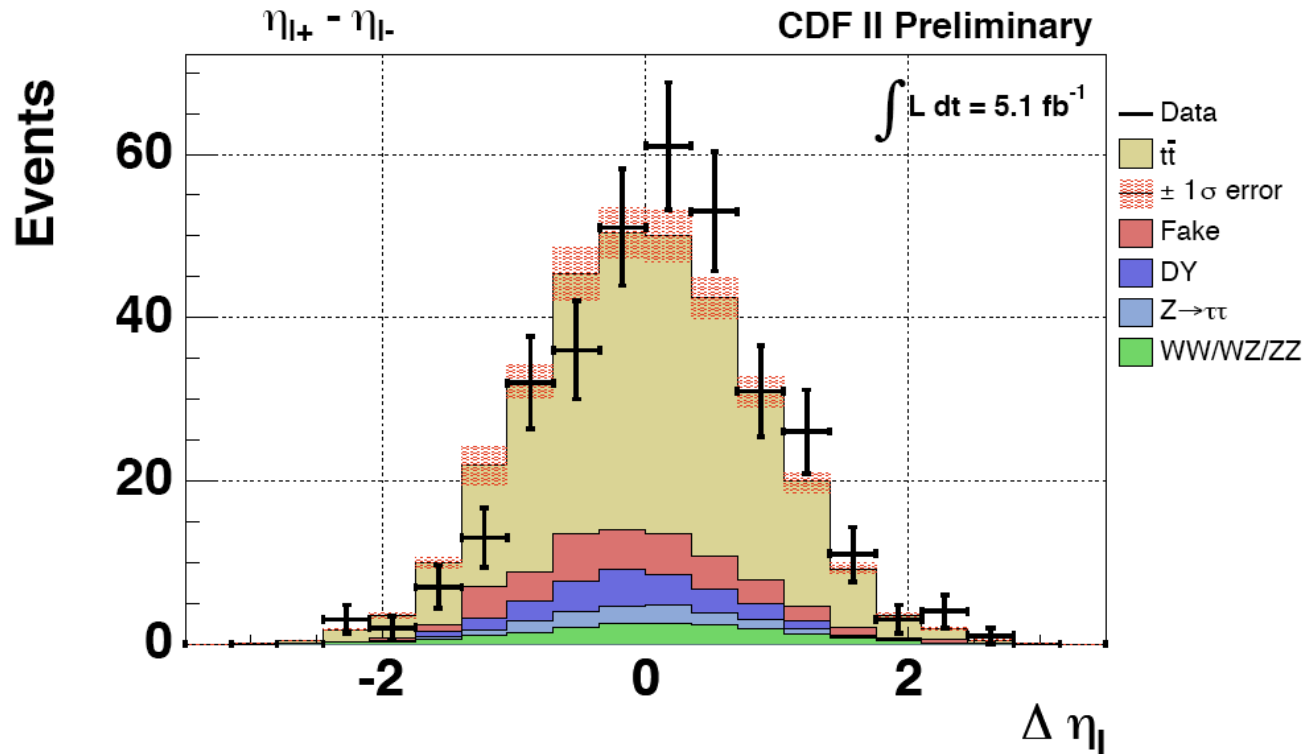
dilepton + MET+ 1 jet



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

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

lepton rapidity difference in dilepton top signal



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

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

KS = 0.8%

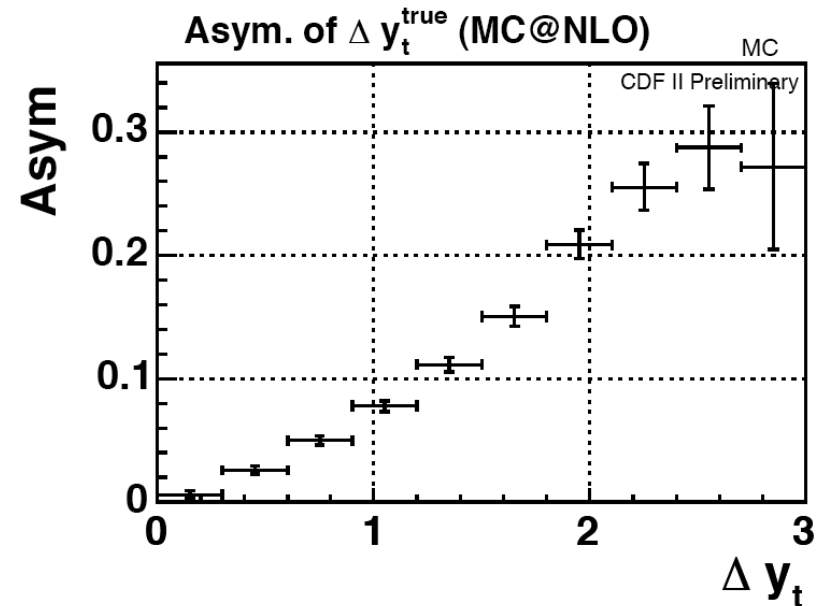
correcting to the parton level

- sub bkg: $A_{fb} = 0.205 \pm 0.073$
- parton level:
 - minimal model assumptions
 1. $A(\Delta y) = \alpha \Delta y$
 2. Pythia Δy is true at $A=0$
 - reweight Pythia by $1 + \alpha \Delta y$
 - find truth level A_{true}
 - find reco level A_{obs}
 - for ensemble of α , find $A_{true} = k A_{obs}$
- parton level in data:

$$A_{fb} \text{ (DIL)} = 0.417 \pm 0.156$$

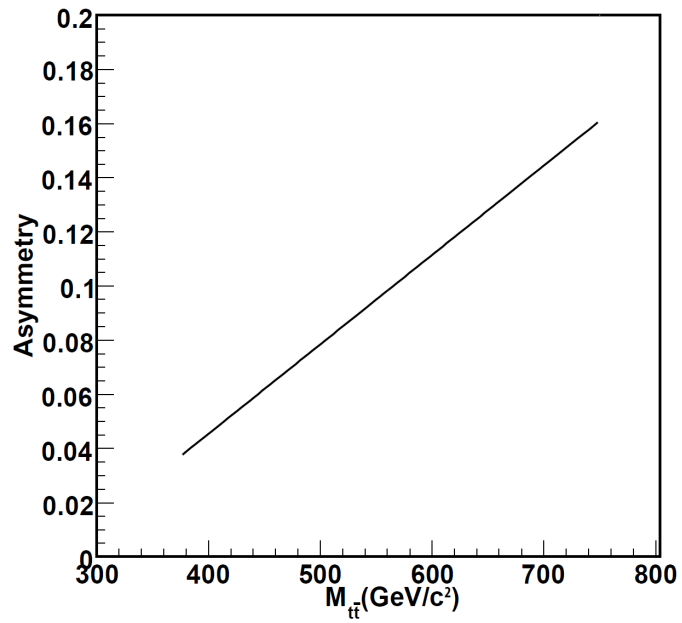
- compare:

$$A_{fb} \text{ (ljets)} = 0.158 \pm 0.074$$

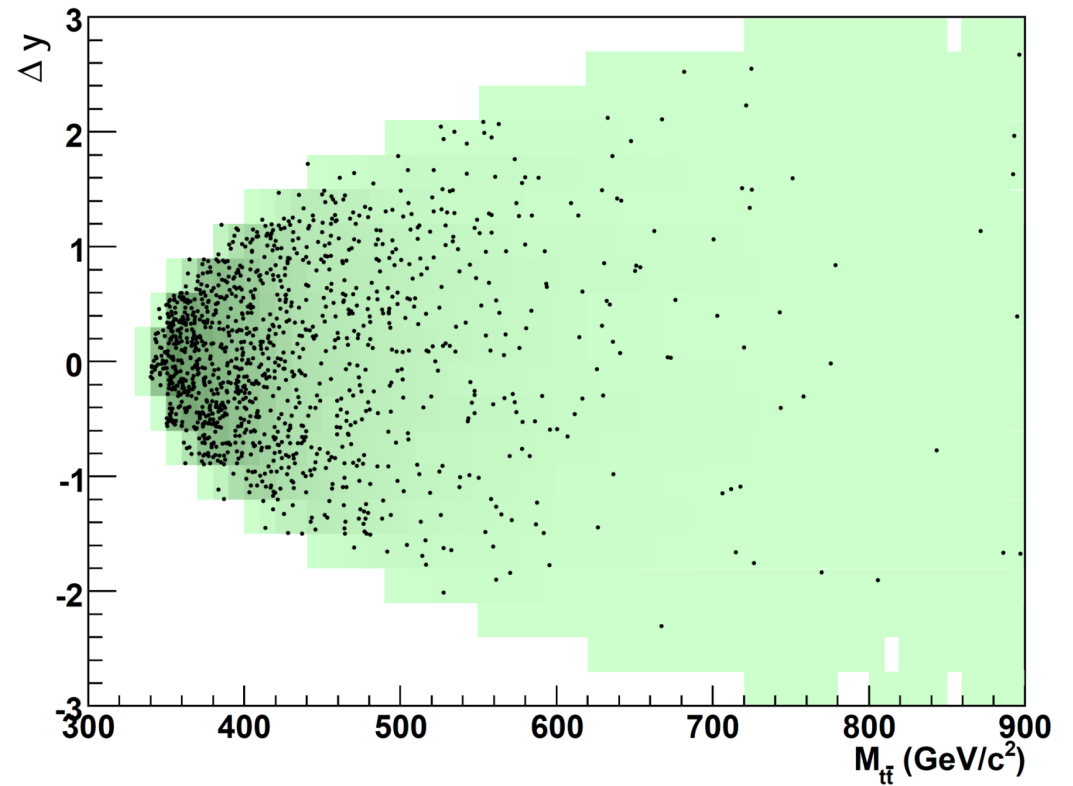


M_{tt} dependence of the asymmetry

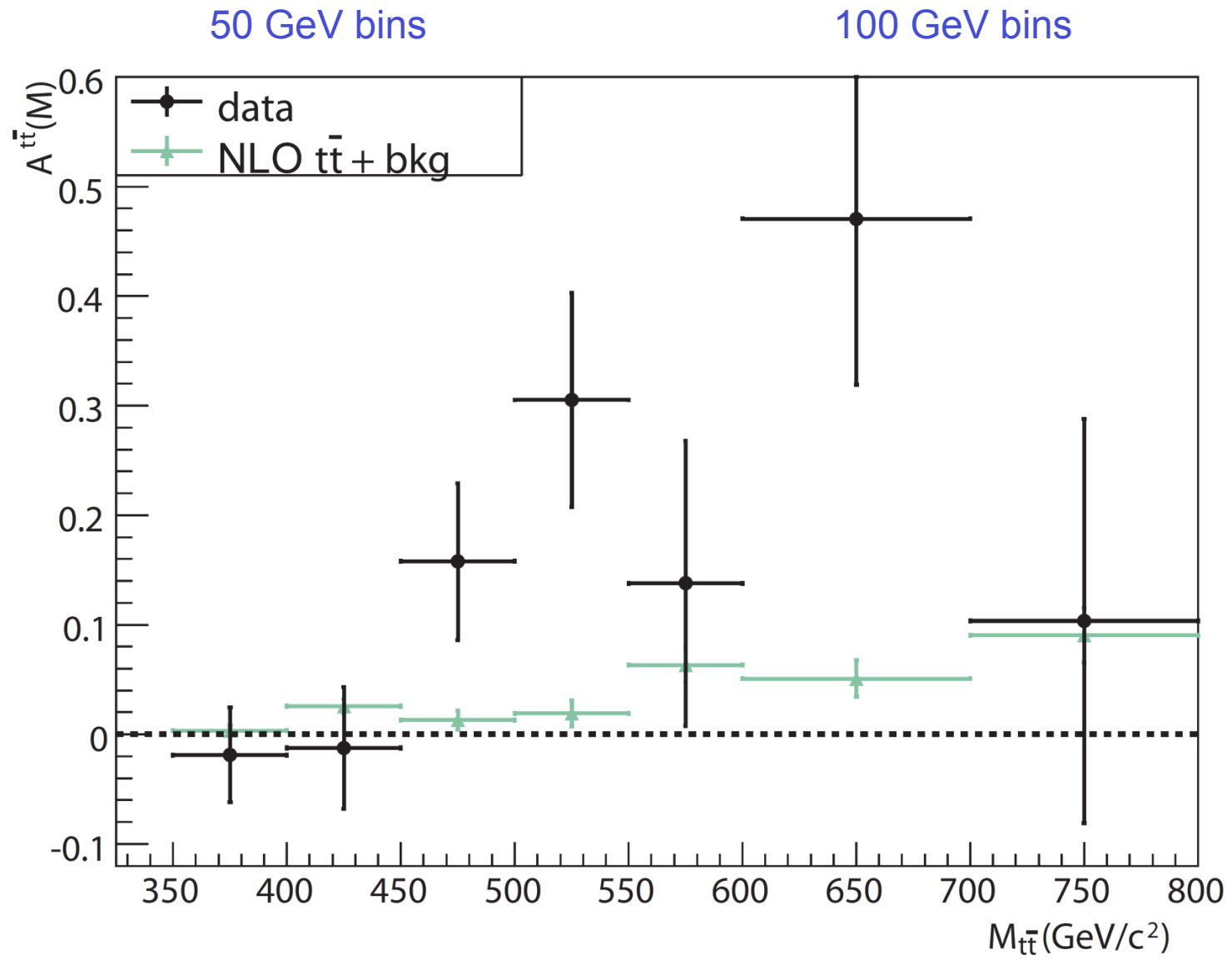
MCFM: $A(M_{tt})$



data: Δy vs M_{tt}

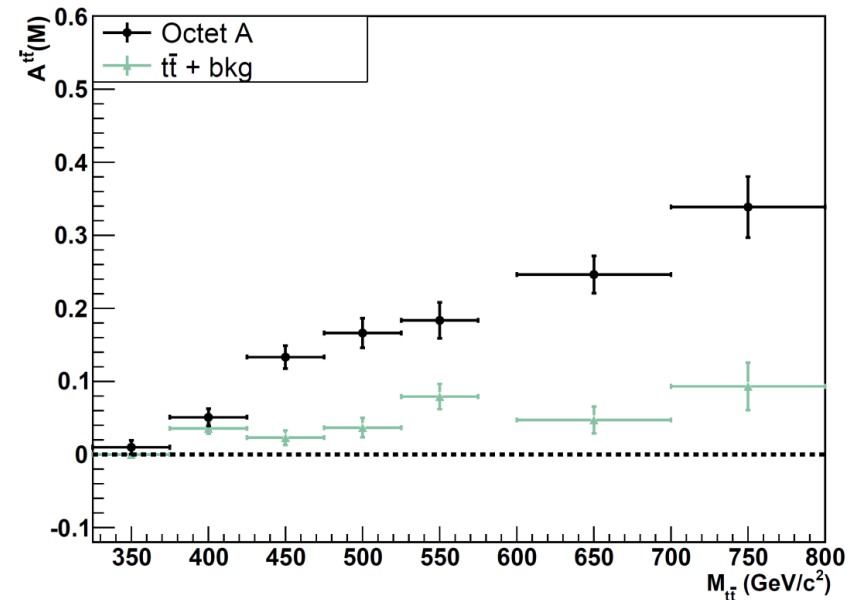
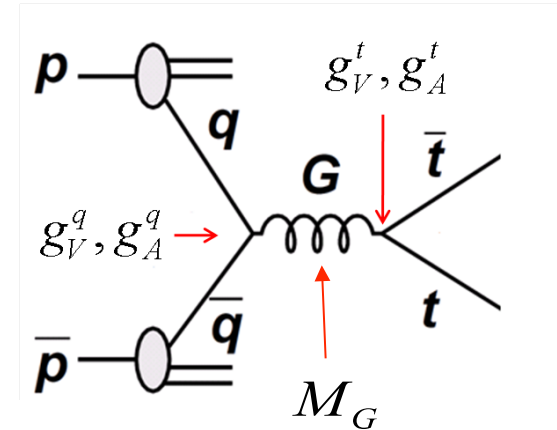


$A^{t\bar{t}}(M_{t\bar{t}, i})$



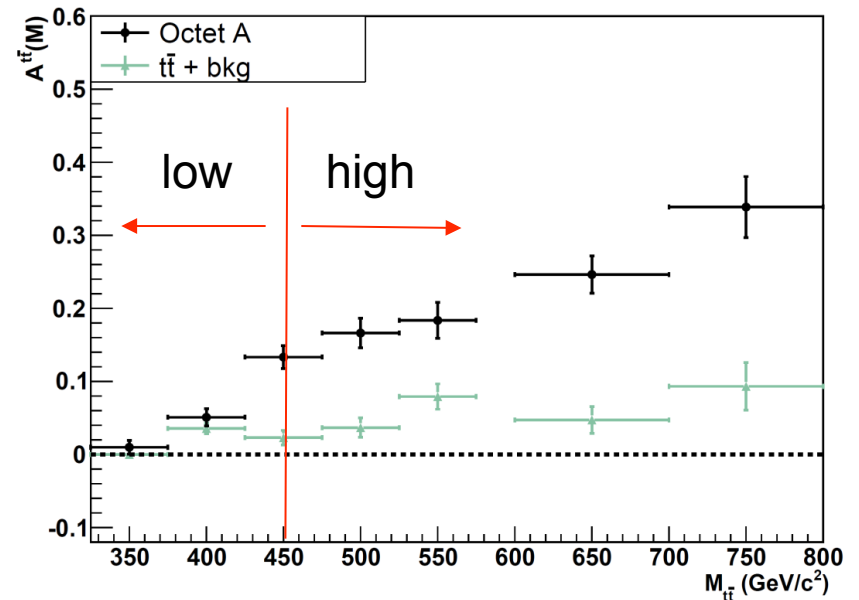
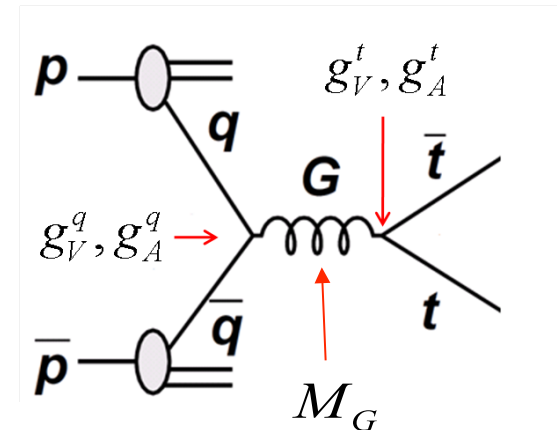
color octet model

- 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”
 - $g_V = 0, |g_A = 3|$
 - $g_A^q = -g_A^t$
 - $M_G = 2.0$ TeV
- good match to data
 - xsec ratio: $\sigma/\sigma_{sm} = 1.02$
 - M_{tt} spectrum minimal high mass tail
 - model: Parton $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
 - data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$
- study treatment of mass dependence
 - 2-bin $A(M_{tt})$

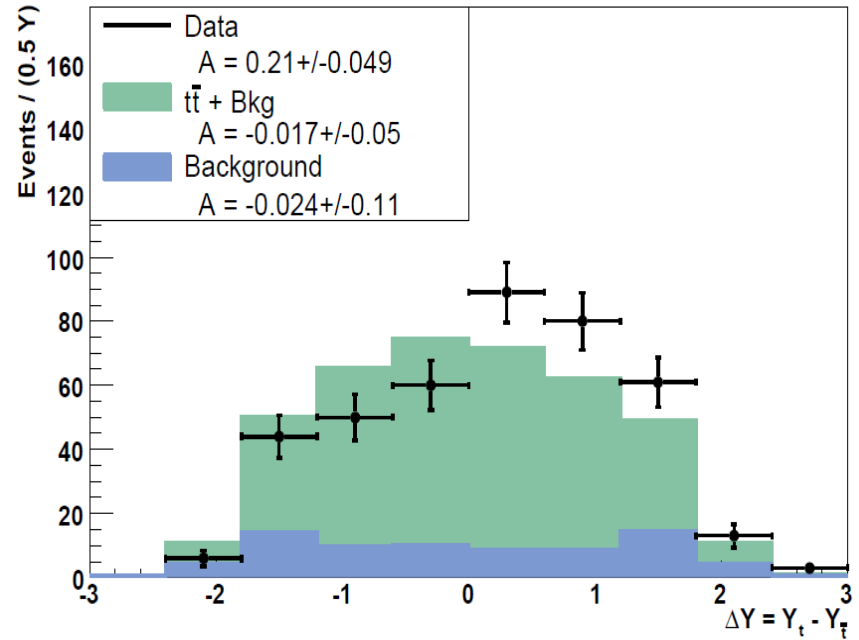
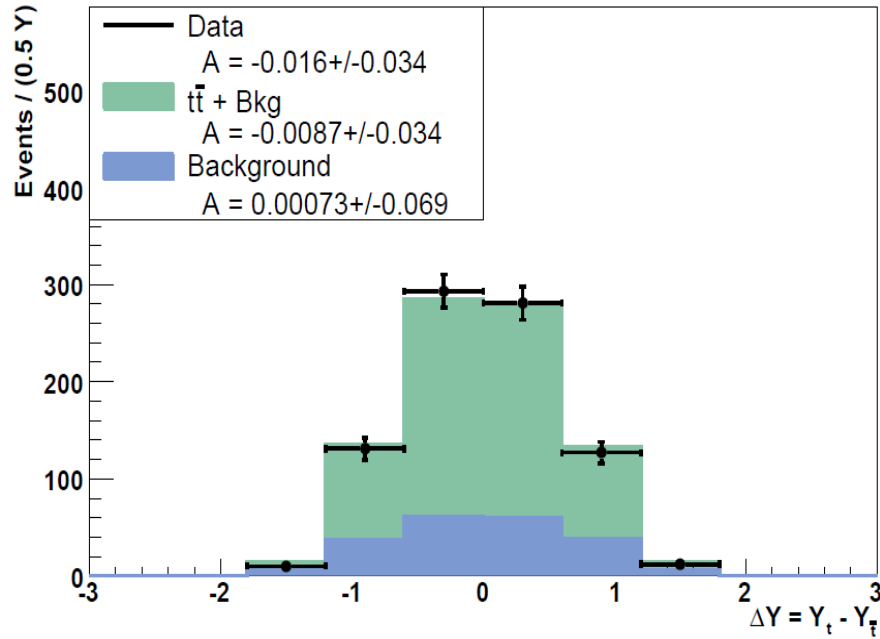


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 - data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$
- study treatment of mass dependence
 - 2-bin $A(M_{tt})$
 - optimal partition at $M_{tt} = 450$ GeV/c²

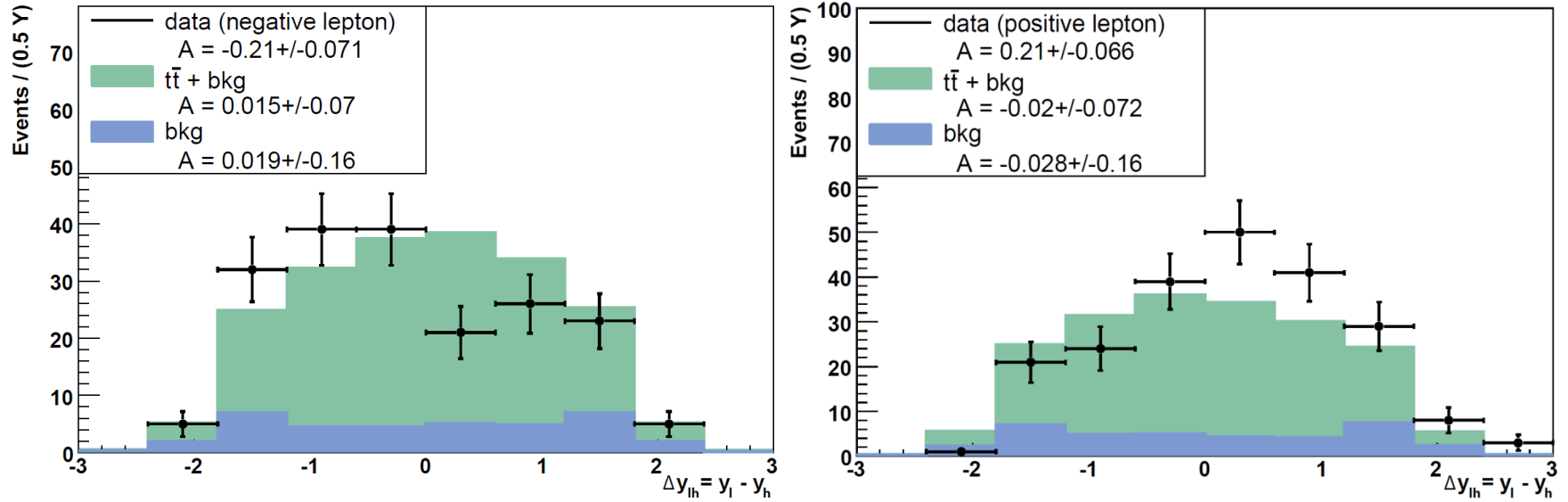


Δy at low and high mass



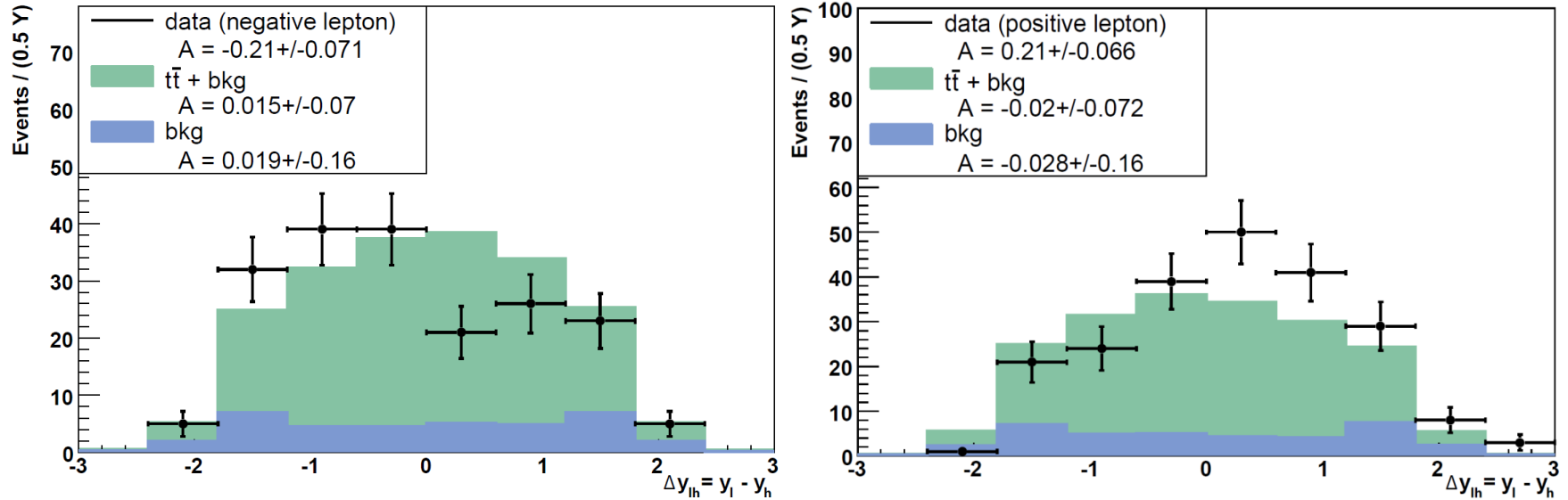
selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
reco data	0.057 ± 0.028	-0.016 ± 0.034	0.212 ± 0.049
MC@NLO	0.017 ± 0.004	0.012 ± 0.006	0.030 ± 0.007

Δy_{lh} at high mass by lepton charge



selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
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



selection	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
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

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

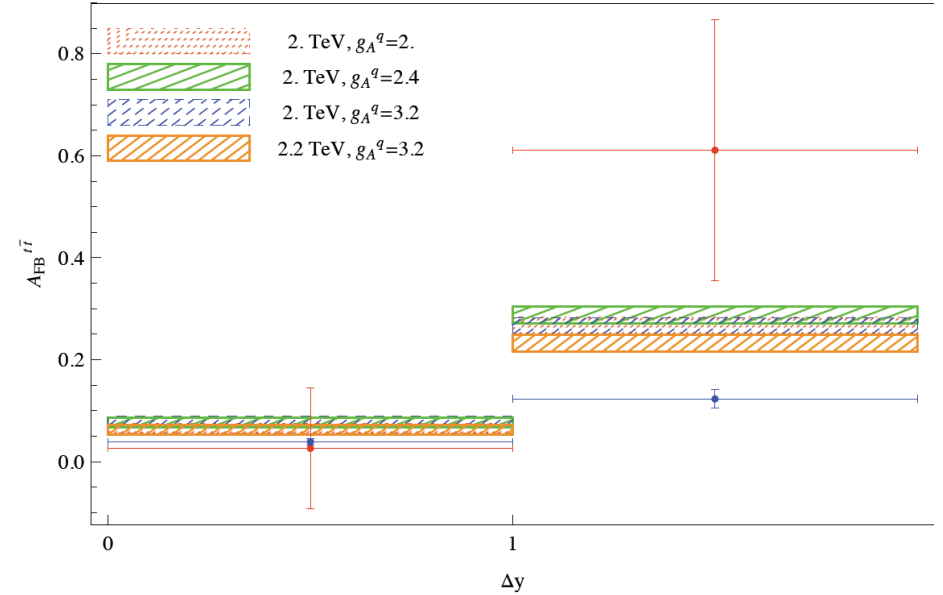
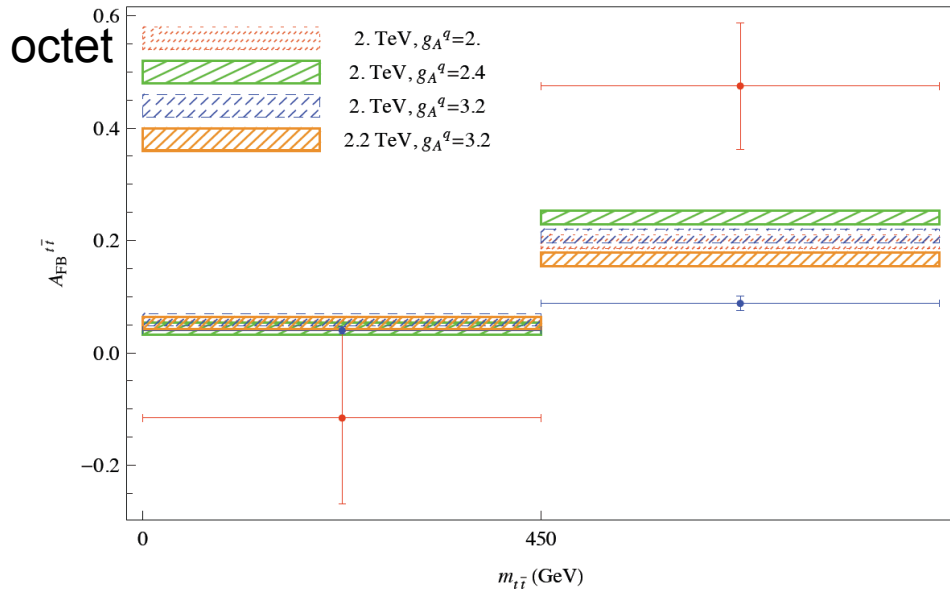
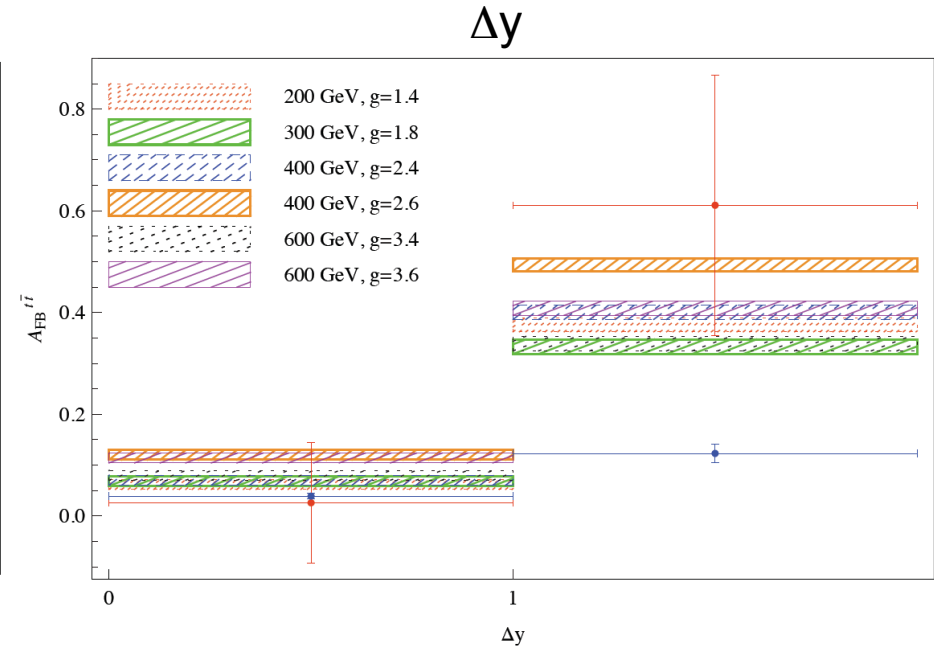
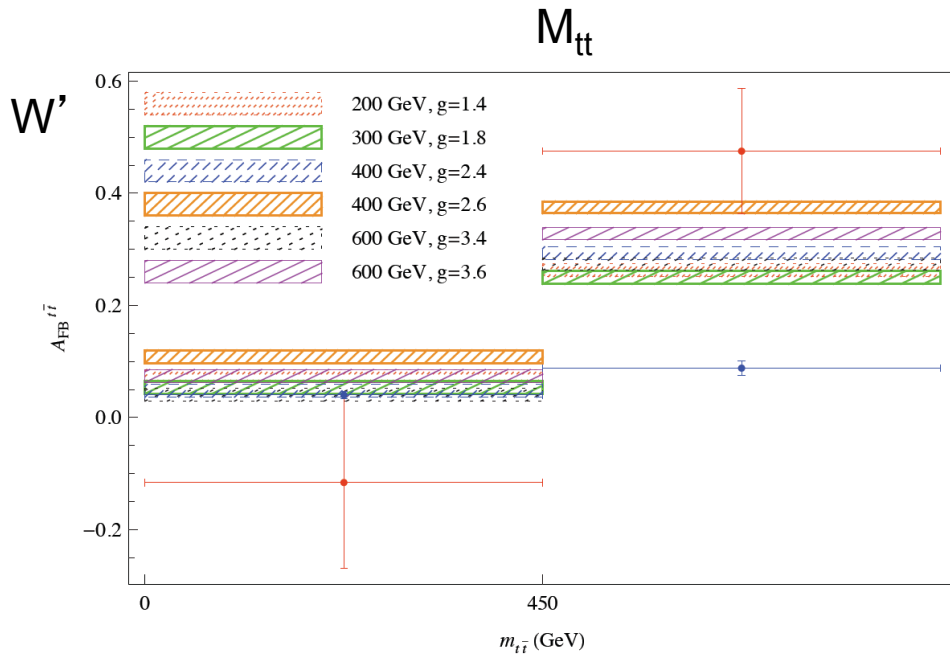
correction to parton level

- background subtraction
- unfold in 4 bins in Δy and $M_{t\bar{t}}$
 - low mass forward
 - low mass backward
 - high mass forward
 - high mass backward

selection	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
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

A(M) and A(Δy) for representative theories

Gresham, Kim, Zurek ArXiv:1103.3501



frame dependence

- a selection of cross-checks in the lab frame using $-qy_h = y_t^{p\bar{p}}$

selection	all $M_{t\bar{t}}$	$M_{t\bar{t}} < 450 \text{ GeV}/c^2$	$M_{t\bar{t}} \geq 450 \text{ GeV}/c^2$
data reco	0.073 ± 0.028	0.059 ± 0.034	0.103 ± 0.049
MC@NLO	0.001 ± 0.003	-0.008 ± 0.005	0.022 ± 0.007
A_h^+	-0.070 ± 0.040	-0.028 ± 0.050	-0.148 ± 0.066
A_h^-	0.076 ± 0.039	0.085 ± 0.047	0.053 ± 0.072
single b -tags	0.095 ± 0.032	0.079 ± 0.034	0.130 ± 0.057
double b -tags	-0.004 ± 0.060	-0.023 ± 0.076	0.028 ± 0.097

- the high mass asymmetry is less significant in the lab frame
 - like QCD ?
- the high mass double tag asymmetry is low in the lab frame
 - statistics?
 - $|\eta| < 1.0$ for b -tags. acceptance + physics?

summary

- significant inclusive $A_{fb}(\Delta y)$ is observed in two decay modes

	lepton + jets	dilepton
– data	0.054 ± 0.028	0.138 ± 0.054
– bkg sub	0.075 ± 0.037	0.205 ± 0.076
– parton level	0.158 ± 0.074	0.417 ± 0.157
– MCFM	0.058 ± 0.009	

- in dileptons, well understood $A_{fb}(\eta_{ll})$ is consistent with $A_{fb}(\Delta y)$
- in lepton+jets, $A_{fb}(\Delta y)$ is observed to depend on Δy and M_{tt}

	$M_{tt} < 450 \text{ GeV}/c^2$	$M_{tt} \geq 450 \text{ GeV}/c^2$
– data	-0.016 ± 0.034	0.210 ± 0.049
– parton level	-0.116 ± 0.153	0.475 ± 0.112
– MCFM	0.040 ± 0.006	0.088 ± 0.013

- A_{fb} reverses sign under interchange of lepton (top) charge: CP conservation
- various data puzzles remain.
- interesting theoretical suggestions
- lots of work still to do

Backup

studies of A^{tt} at the data level

selection	N events	all M	$M < 450 \text{ GeV}/c^2$	$M \geq 450 \text{ GeV}/c^2$
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

bonus question

- Highest Q^2 prior test of C in strong interactions ?

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Test of charge-conjugation invariance in $\bar{p}p$ interactions

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Using $\bar{p}p$ interactions at $\sqrt{s} = 5.44$ GeV we have tested for evidence of C noninvariance through a comparison of the transverse-momentum distributions of particle and antiparticle produced at 90° in the center of mass. We found an average charge asymmetry for pions with p_\perp between 0.5 and 2.7 GeV/ c of $\Delta = (N_+ - N_-)/(N_+ + N_-) = 0.006 \pm 0.009$. This corresponds to a limit on the magnitude of the C -violating (relative to C -conserving) amplitude of $\text{Re}\alpha \leq 0.0045$.