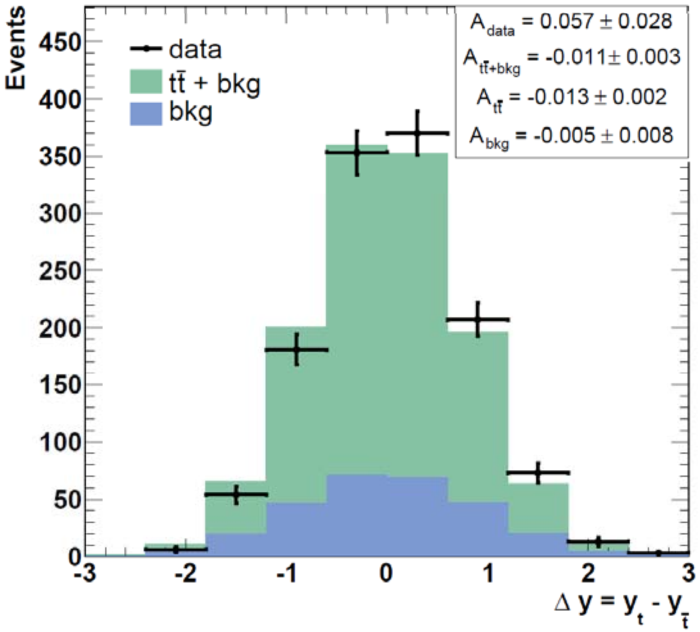
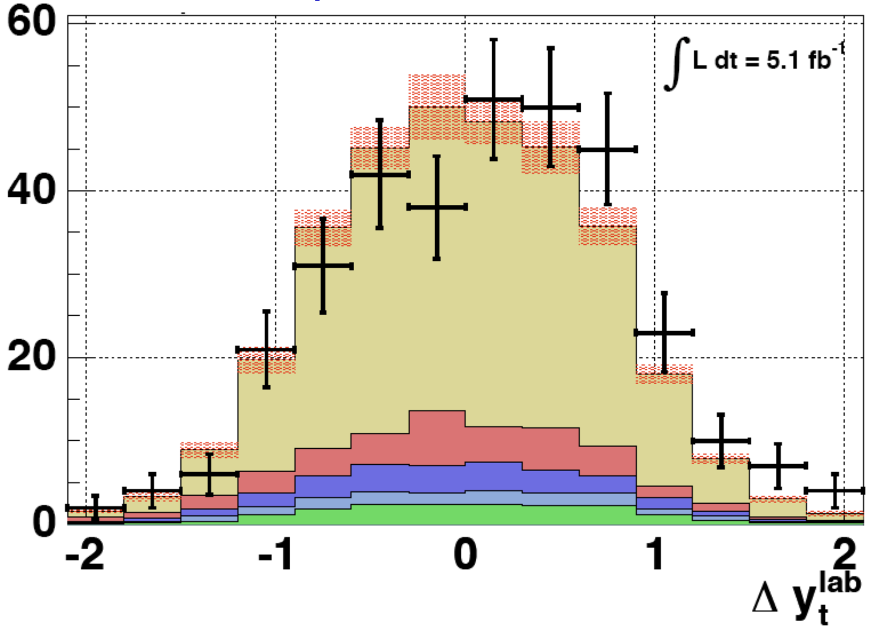
A Forward-Backward Asymmetry in Top Quark Pair Production

The CDF Collaboration
D. Amidei, University of Michigan

lepton + jets mode



dilepton mode

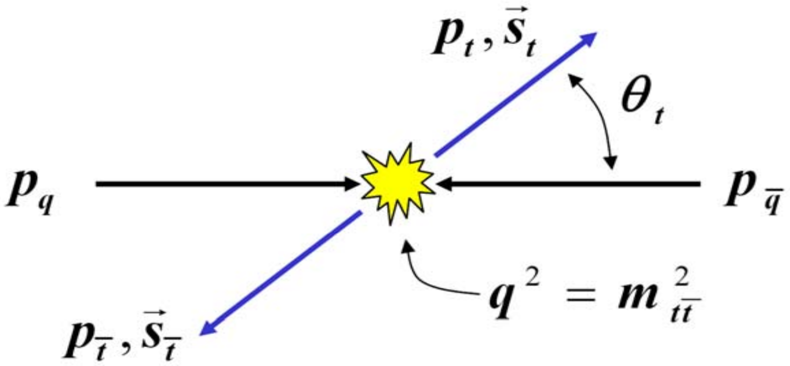


LaThuile, Feb. 28, 2011

top quark pair production

- hard scatter cm-frame cross-section

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



  – 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: asymmetry in production angle with respect to beamline

$$A = \frac{F - B}{F + B}$$

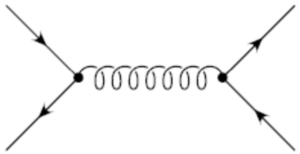
  – also of interest: q^2 dependence

- hadron collisions:
  – $\theta \to \Delta y$

tt charge asymmetry in NLO QCD

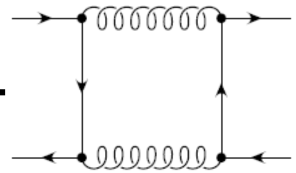
- Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Ellis, Dawson, Nason; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater

$t\bar{t}$



C = - 1

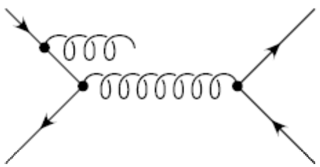
+



C = +1

$A_{FB} \sim$ +10-12 %

$t\bar{t}j$



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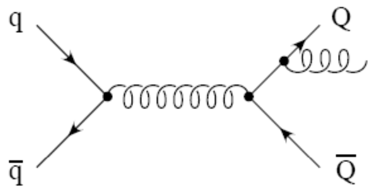
+



C = +1

$A_{FB} \sim$ -7 %

$A_{FB} \sim$ 6 +- 1.0 %   net

- verified for QED in $e^+e^- \rightarrow \mu^+\mu^-$

- strong interaction C tests at high energy have been confounded by 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 $A^{t\bar{t}} = 0.24 \pm 0.14$
  - NLO QCD $A^{t\bar{t}} = 0.06 \pm 0.01$

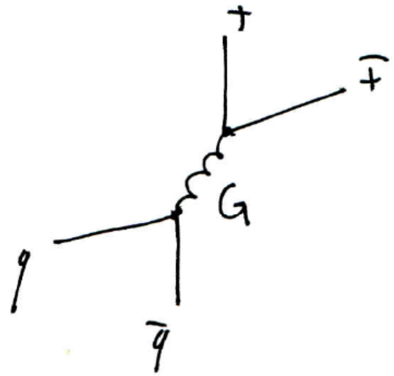
PRL 101, 202001 (2008)

- D0, inclusive, background subtracted "data-level"
  - tt rest frame $A^{t\bar{t}} = 0.12 \pm 0.08$ 0.9 fb^{-1} PRL 100, 142002 (2008)

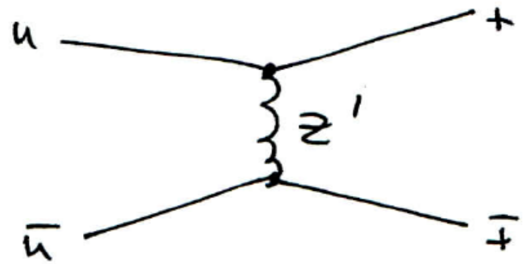
    $A^{t\bar{t}} = 0.08 \pm 0.04$ 4.3 fb^{-1} ICHEP 2010
  - NLO QCD $A^{t\bar{t}} = 0.02 \pm 0.01$

theoretical interest

- exotic gluons
  - massive chiral color
  - RS gluon
  - color sextets, anti-triplets



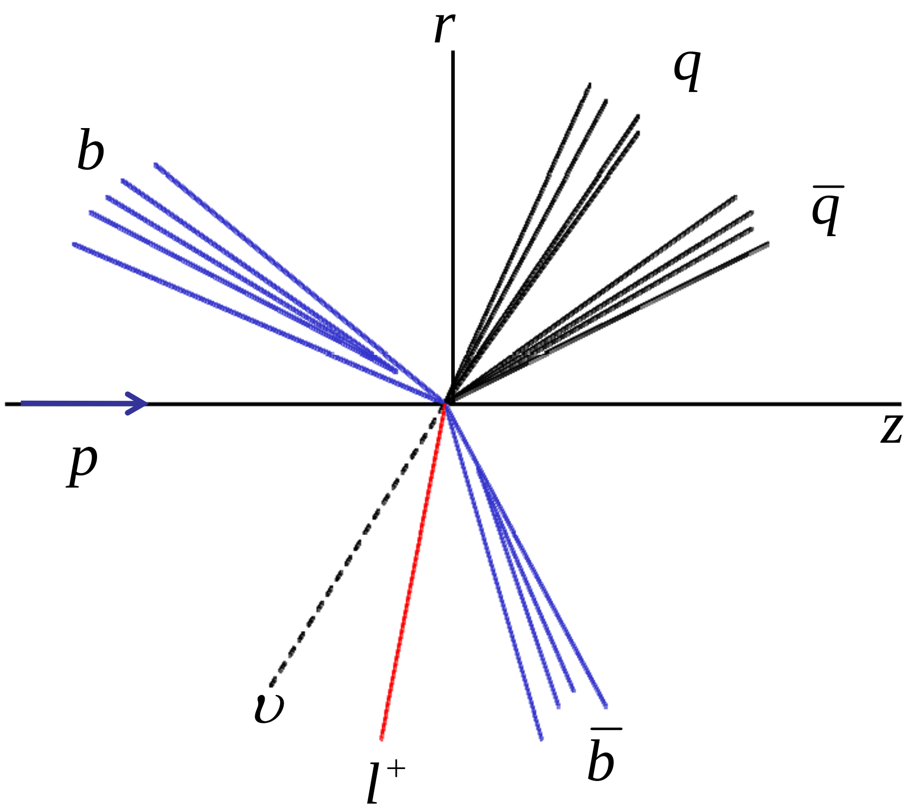
- FV IVB´
  - Z´
  - FV W´Z´ t-channel
- FV scalars



- 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

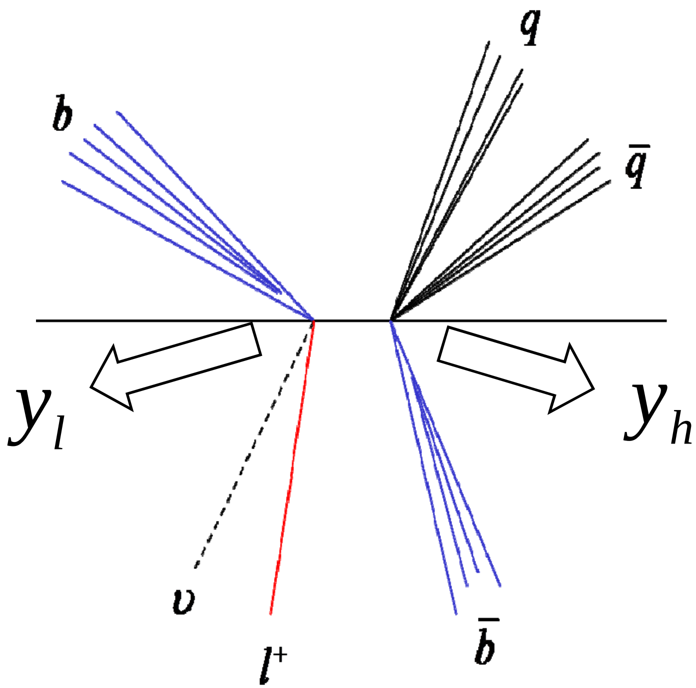
$$q\bar{q} \to g \to t\bar{t} \to (W^+b)(W^-\bar{b}) \to (l^+\upsilon b)(q\bar{q}\bar{b}) \to l^+ + \not{E}_T + 4j + \geq 1\ btag$$



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
- jet-parton match and top reconstruction via M_W, M_t constraints and simple χ^2

top pair rapidity difference



- a frame invariant variable
  - rapidity difference

$$\Delta y = q \cdot (y_l - y_h)$$
$$= y_t - y_{\bar{t}}$$

  - interpretation

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

➢ asymmetry in Δy_{tt} equals asymmetry in top quark production angle in tt rest frame

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

expected QCD asymmetries

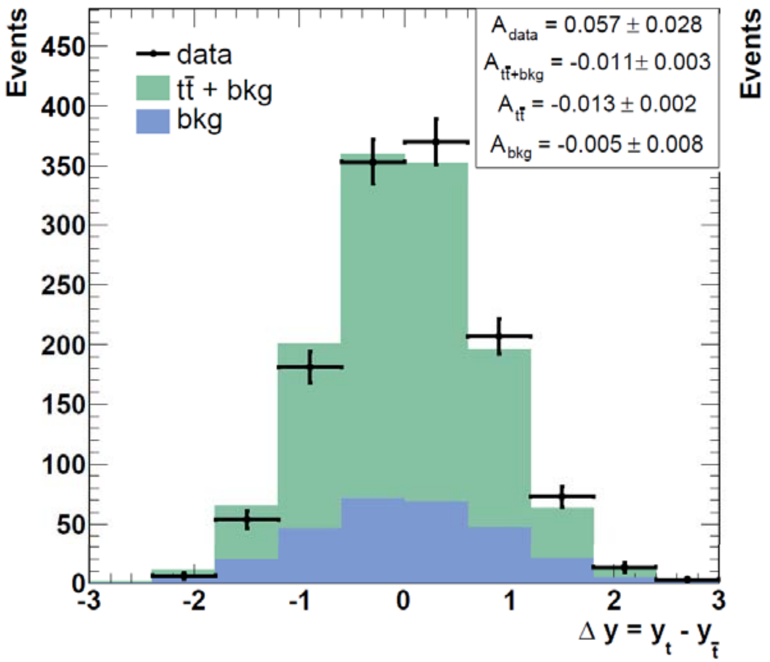
- three different calculations for expectation:
  - Pythia: LO simulated sample
  - MCFM: NLO calculation at "parton level"
  - MC@NLO + CDFSIM: simulated sample for input the analysis

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)
  - Pythia tt model remains good approximation of SM

inclusive Δy

data level

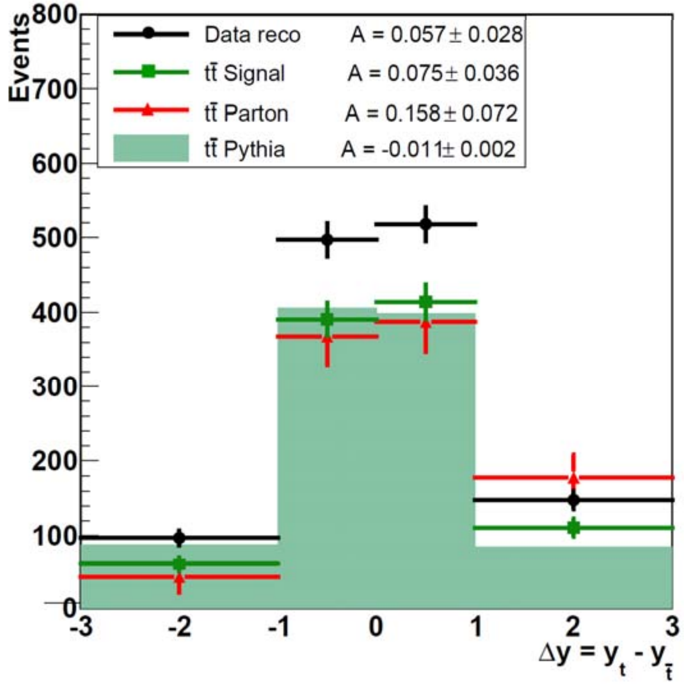


sample	level	A^{tt}
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004

then

- bkg subtract
  - yields tt "signal" at reco level
- unfold acceptance & resolution
  - yields tt at "parton level"

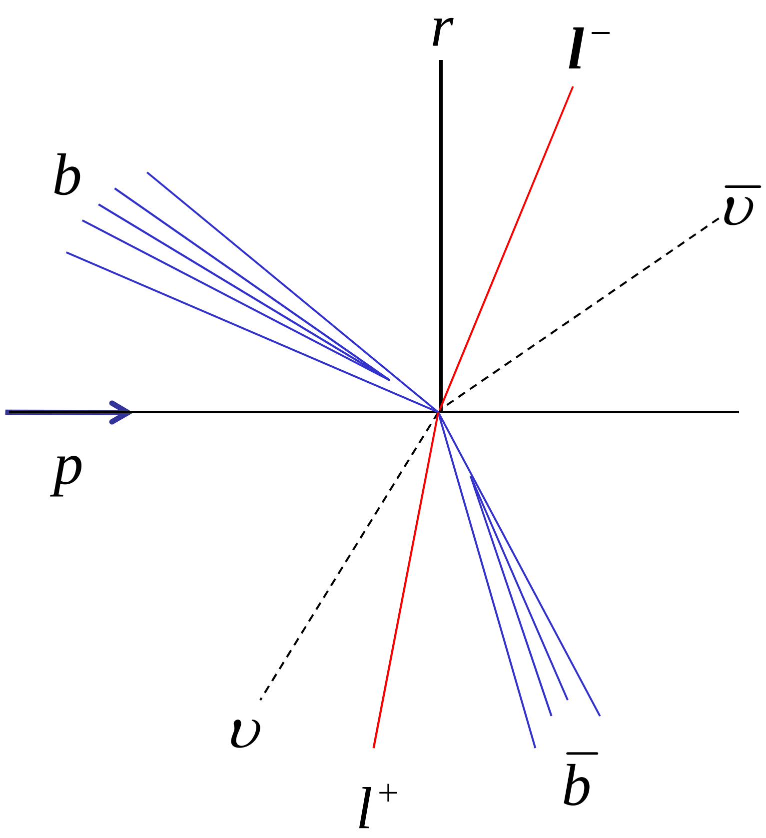
with corrections



sample	level	A^{tt}
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

dilepton 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$\pm$17

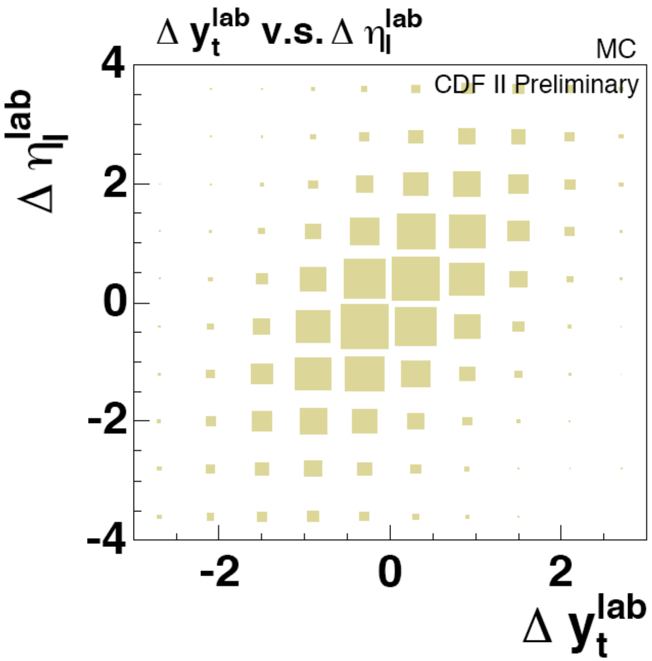
two rapidity differences

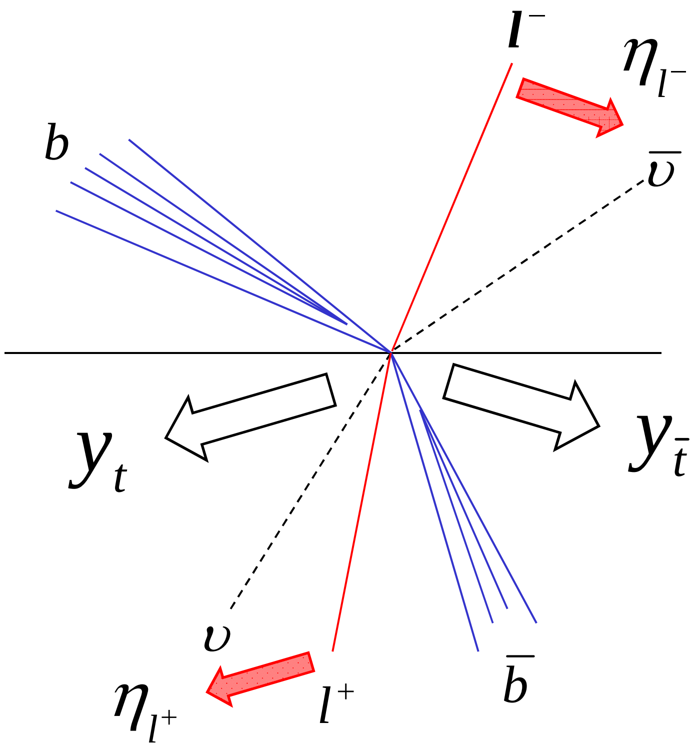
- frame invariant variables
  - rapidity difference

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

  - lepton rapidity difference!

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



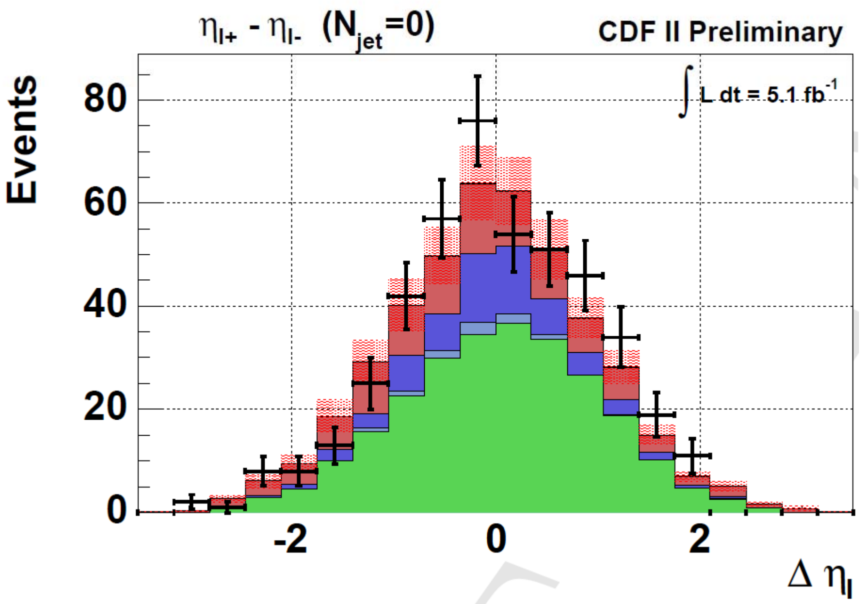


$$A^{\Delta y_t} = \frac{N(\Delta y_t > 0) - N(\Delta y_t < 0)}{N(\Delta y_t > 0) + N(\Delta y_t < 0)}$$

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

lepton rapidity difference in dilepton control samples

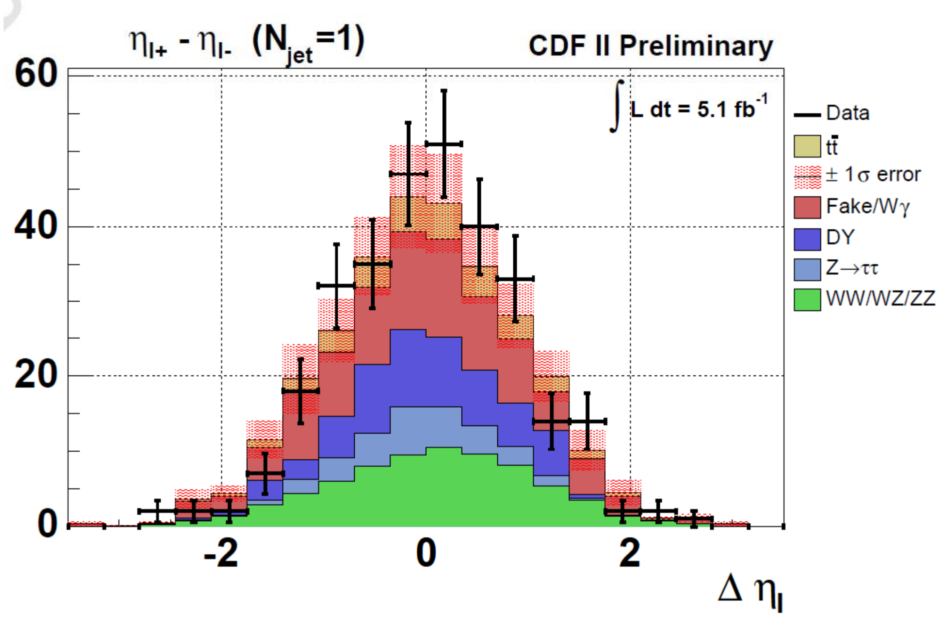
dilepton + MET+ 0 jets



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

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

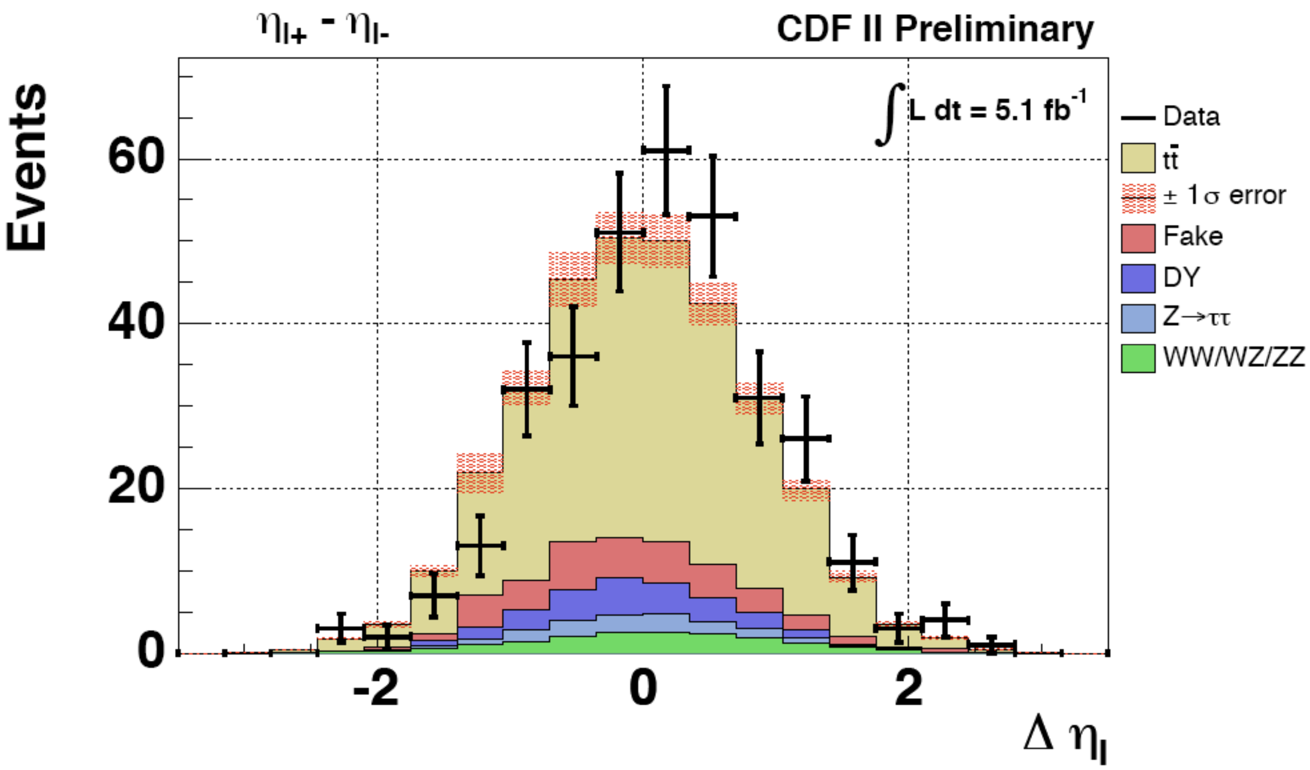
dilepton + MET+ 1 jet



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

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

lepton rapidity difference in dilepton top signal



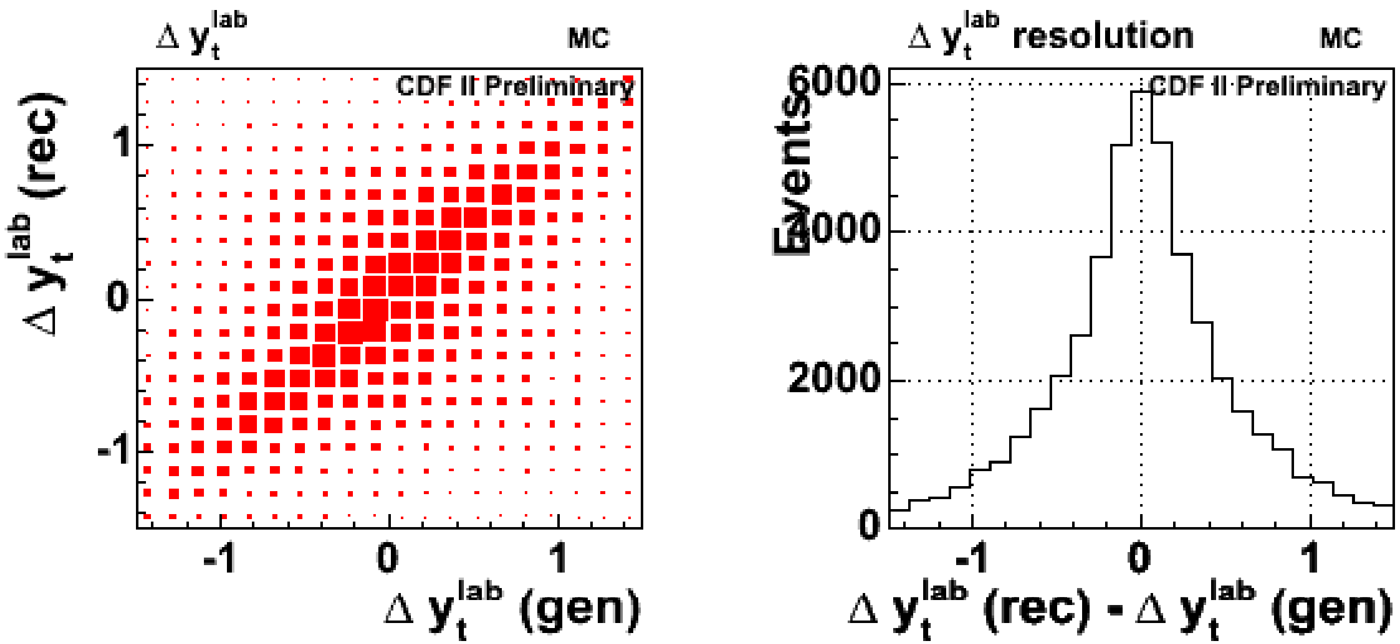
$$A_{obs}^{\Delta\eta_l} = 0.138 \pm 0.054$$

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

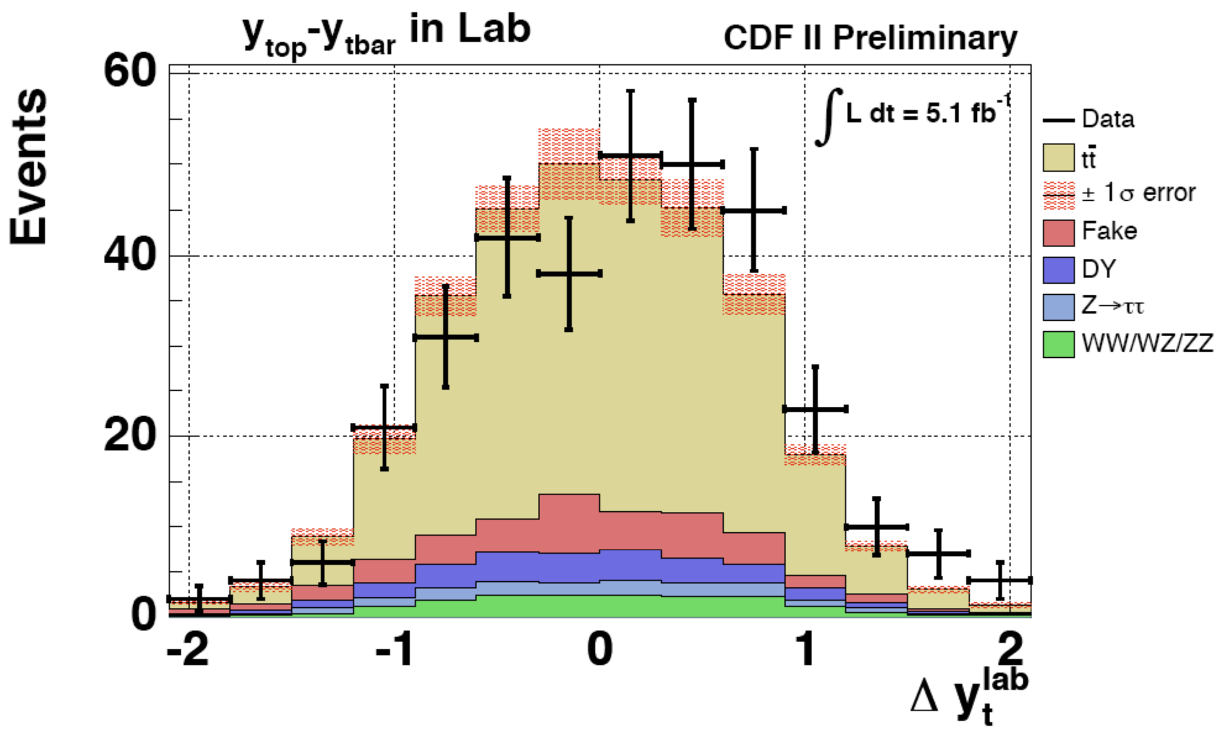
KS = 0.8%

top reconstruction in the dilepton sample

- jet-parton match and top reconstruction via
  - M_W, M_t constraints
  - and likelihoods of $p_T^{t\bar{t}}, p_z^{t\bar{t}}, M_{t\bar{t}}$



top rapidity difference in dilepton sample

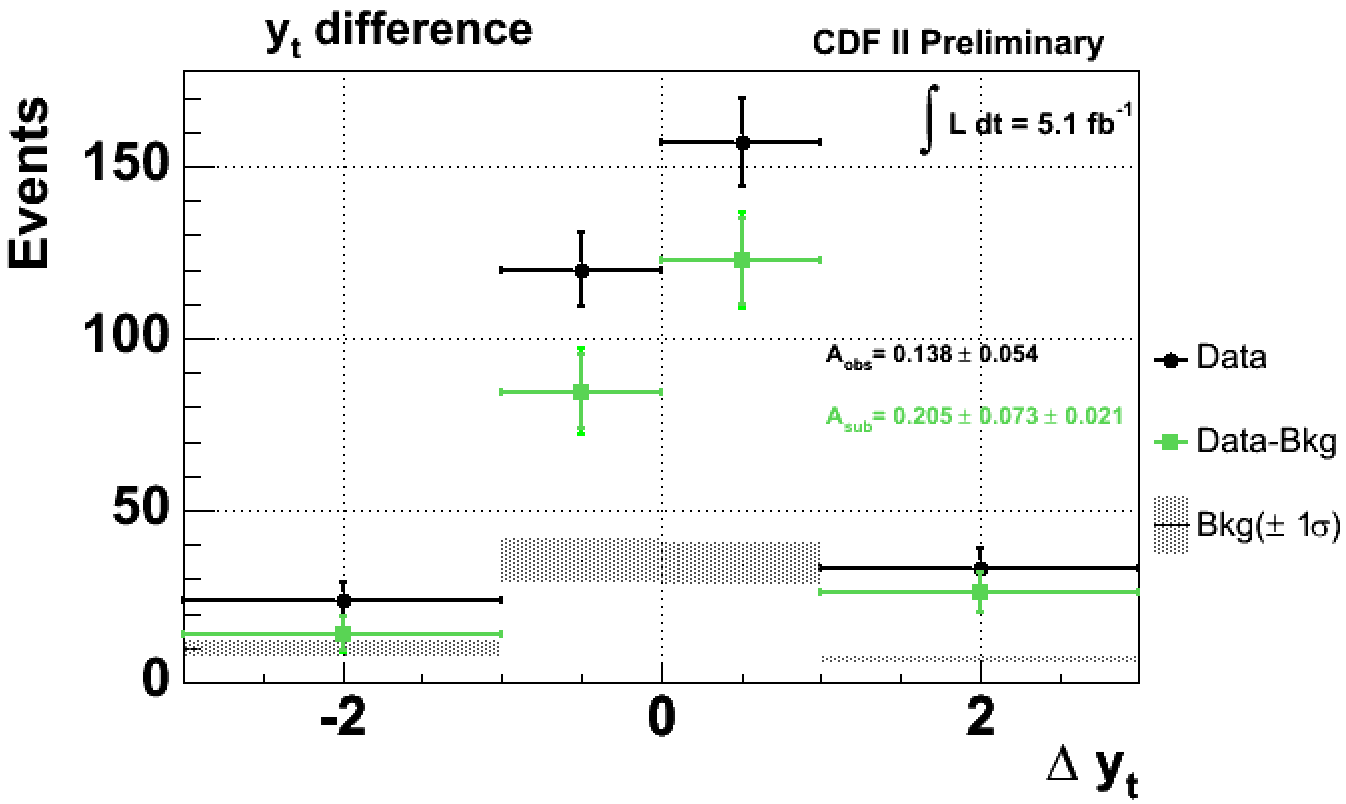


$$A_{obs}^{\Delta y_t} = 0.138 \pm 0.054$$

$$A_{pred}^{\Delta \eta_l} = -0.015 \pm 0.023$$

KS = 1.4%

top rapidity difference in dilepton sample w/ bkg subtraction



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

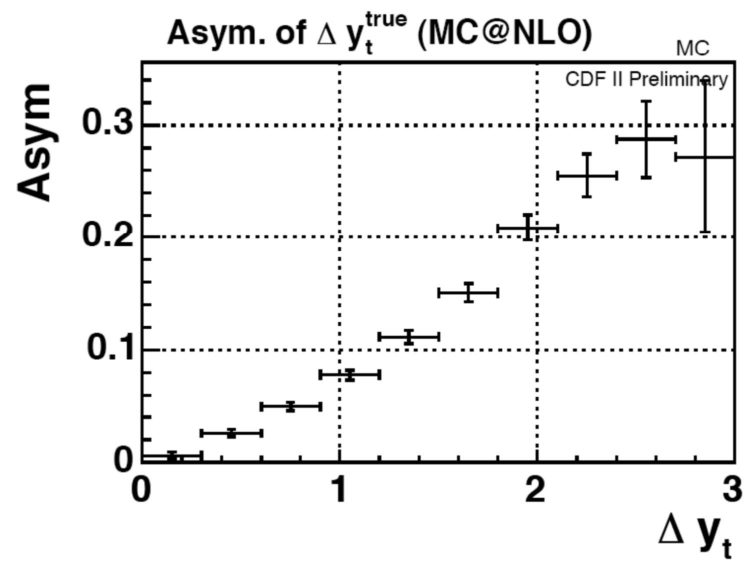
$$A_{sub}^{\Delta y_t} = 0.205 \pm 0.073 \pm 0.021$$

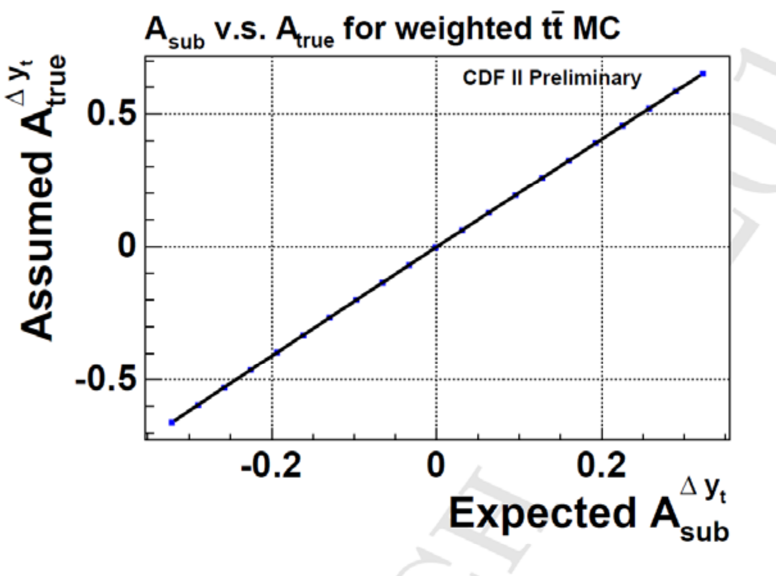
correcting to the parton level

- not an unfold
- minimal model assumptions
  1. $A(\Delta y) = \alpha \Delta y$
     - consistent with MC@NLO
  2. Pythia Δy is true at A=0
- for each α
  - reweight Pythia by $1+\alpha\Delta y$
  - find truth level A_{true}
  - find reco level A_{obs}
- for ensemble of α
  - $A_{true} = k\, A_{obs}$
- data

$$A_{sub}^{\Delta y_t} = 0.205 \pm 0.073$$

$$\Rightarrow A_{true}^{\Delta y_t} = 0.417 \pm 0.148 \pm 0.053$$

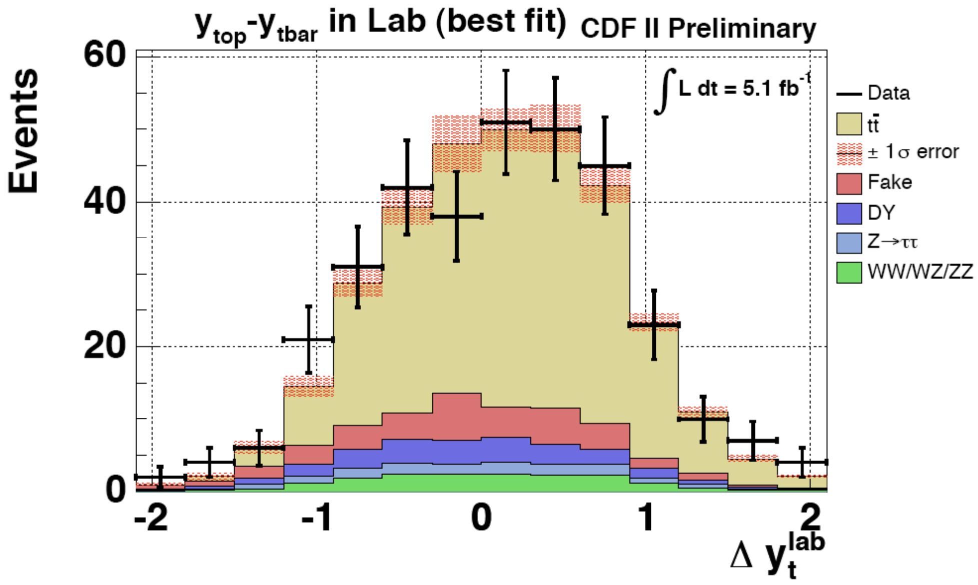




compare to best fit model

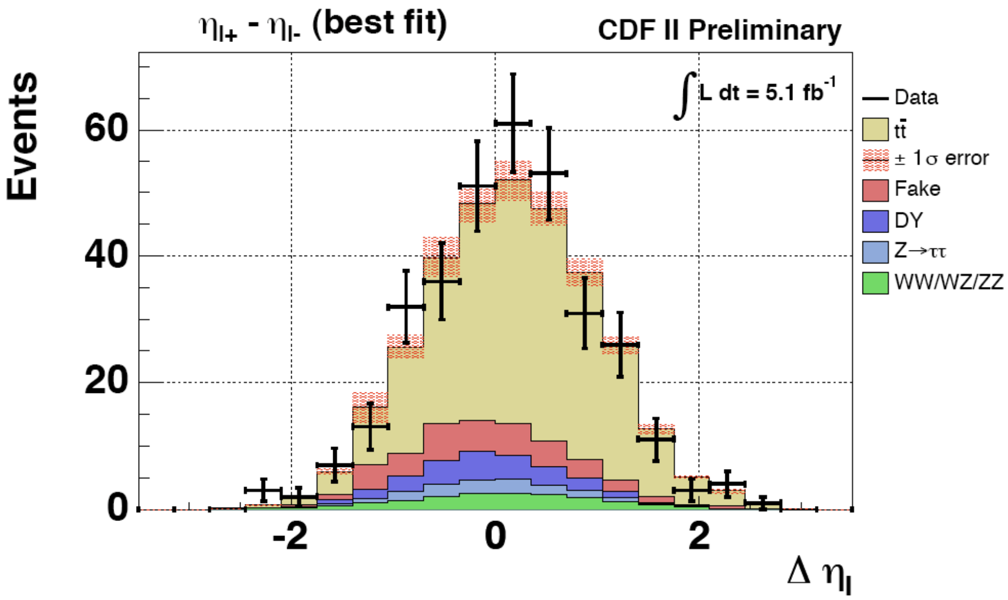
- top rapidity difference

  KS = 51.2 %



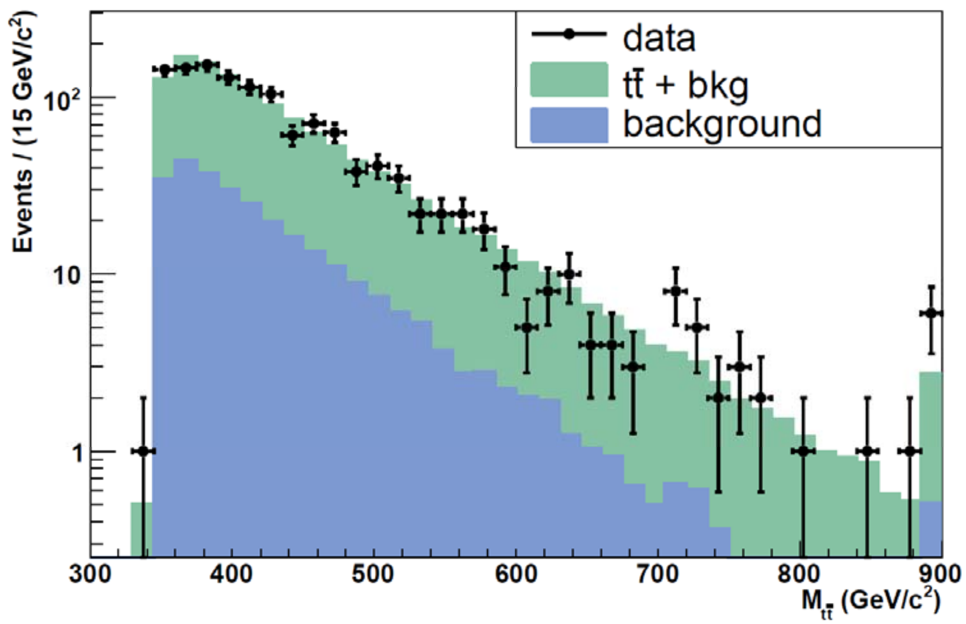
- lepton rapidity difference

  KS = 44.8%

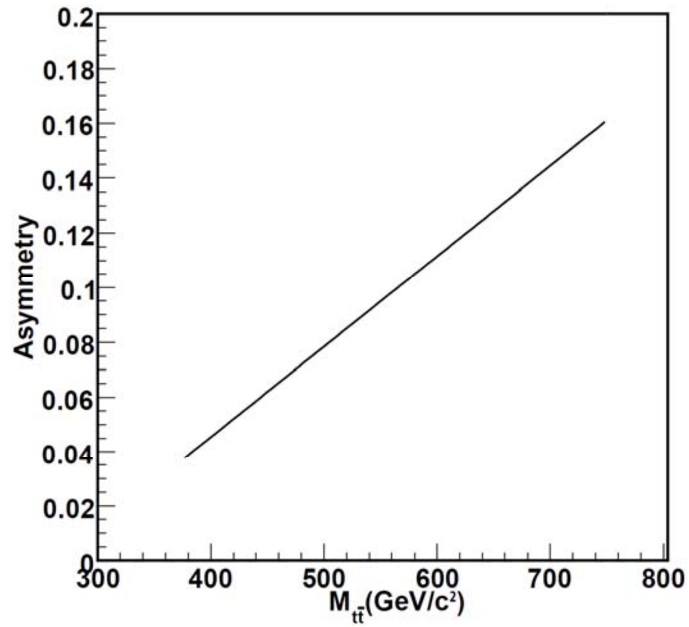


M_{tt} dependence of the asymmetry

M_{tt} Spectrum

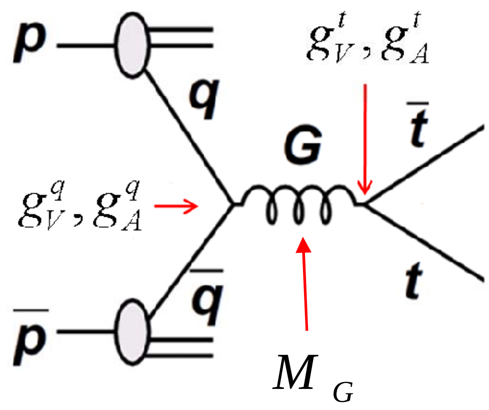


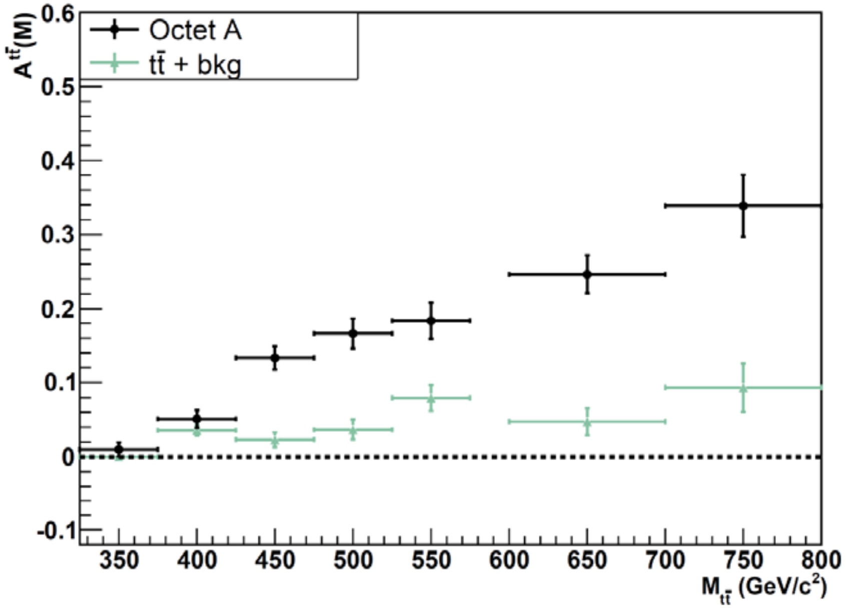
$A(M_{tt})$ from MCFM



- $A(M_{tt})$ of interest in QCD and in other theories color octet model

- to test methodology on large asymmetry
- 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
  - xsec ratio: $\sigma/\sigma_{sm} = 1.02$
  - M_{tt} spectrum ~ compares to Pythia
  - Model: True $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
  - Data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$





- a test sample. **not a hypothesis**
- use to study parton level corrections and treatment of mass dependence
  - 2-bin $A(M_{tt})$
  - optimal partition at M = 450 GeV/c^2

color octet model

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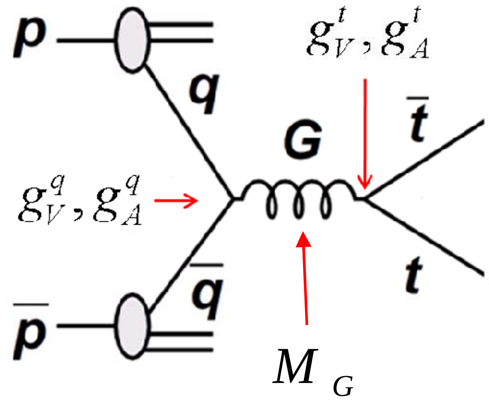

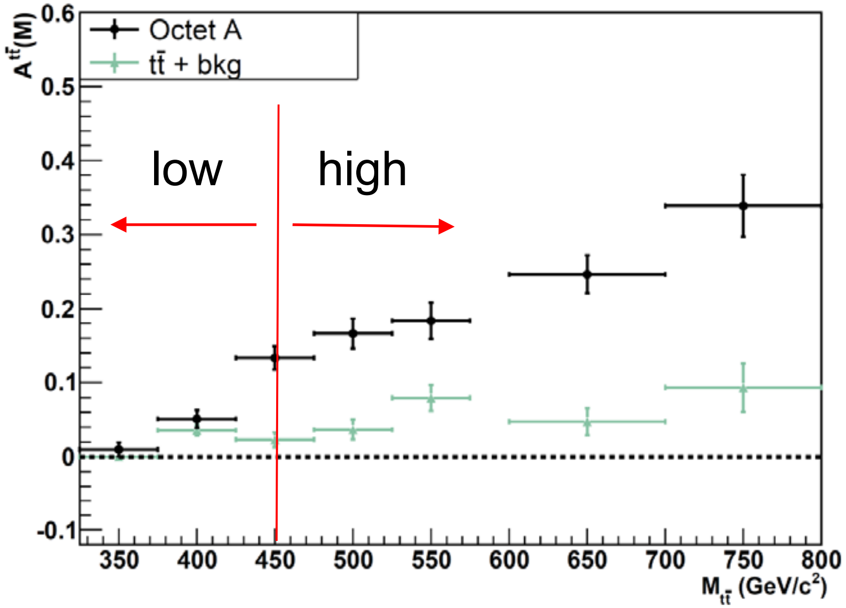

- a test sample. **not a hypothesis**
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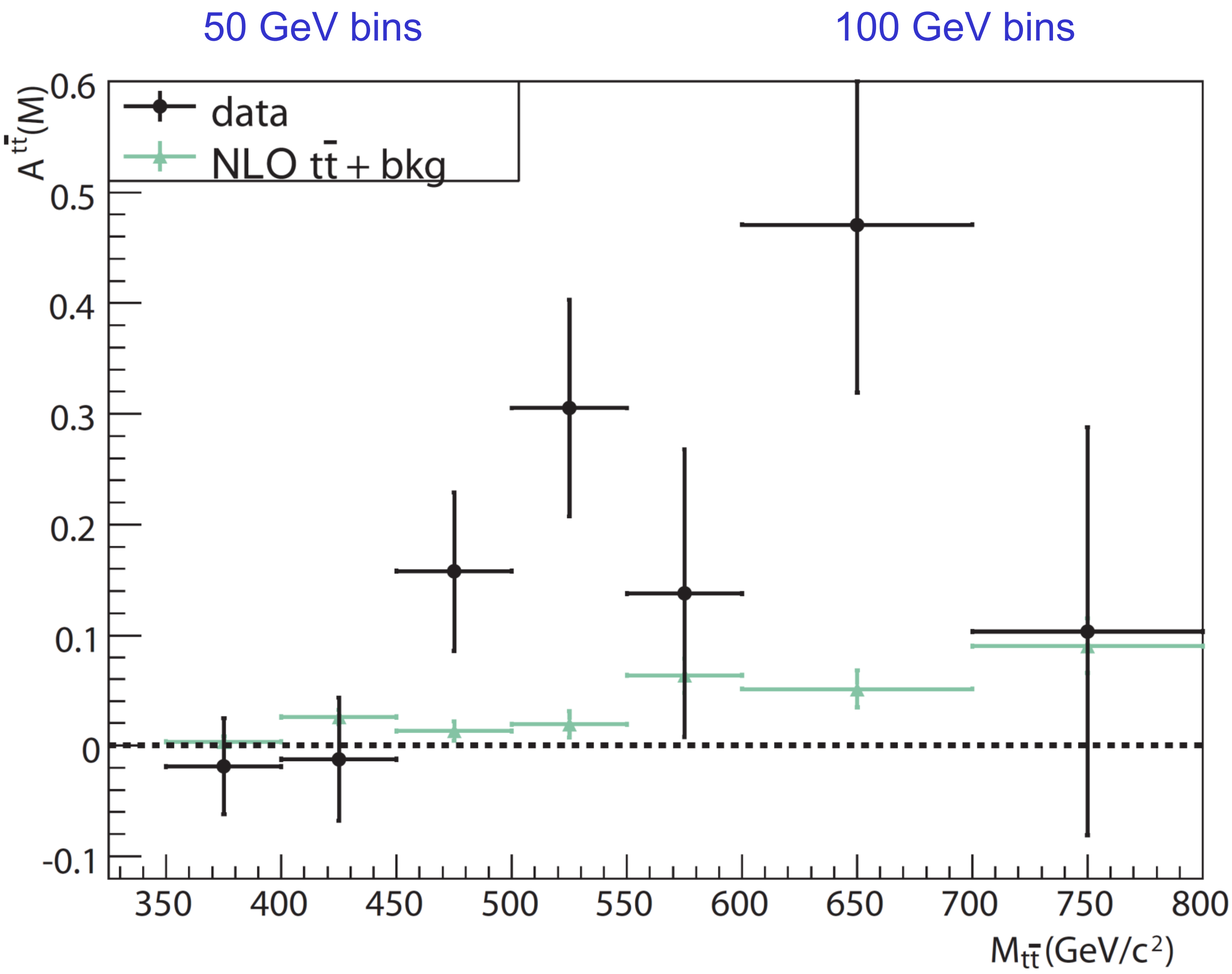
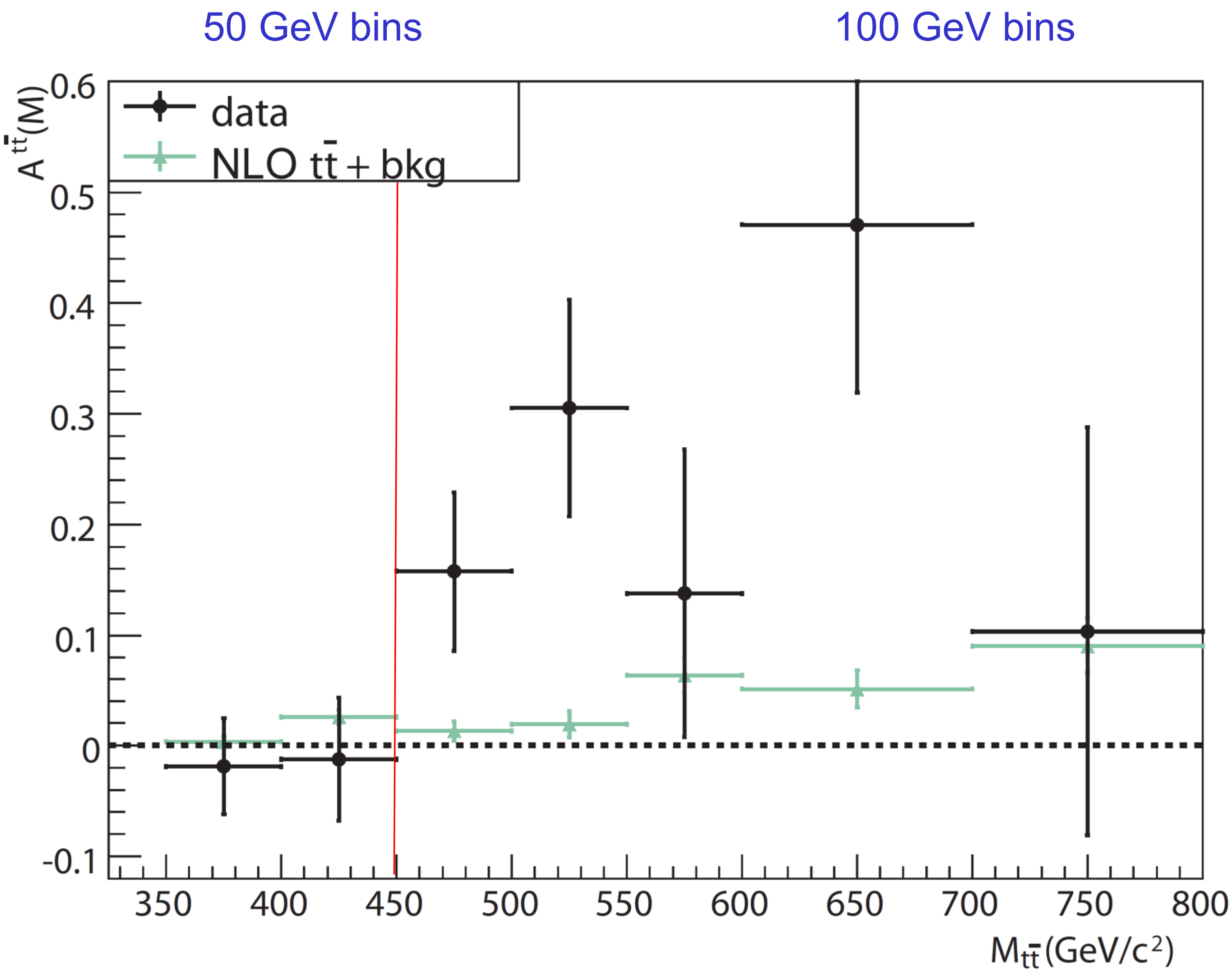
  - optimal partition at M = 450 GeV/c^2

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

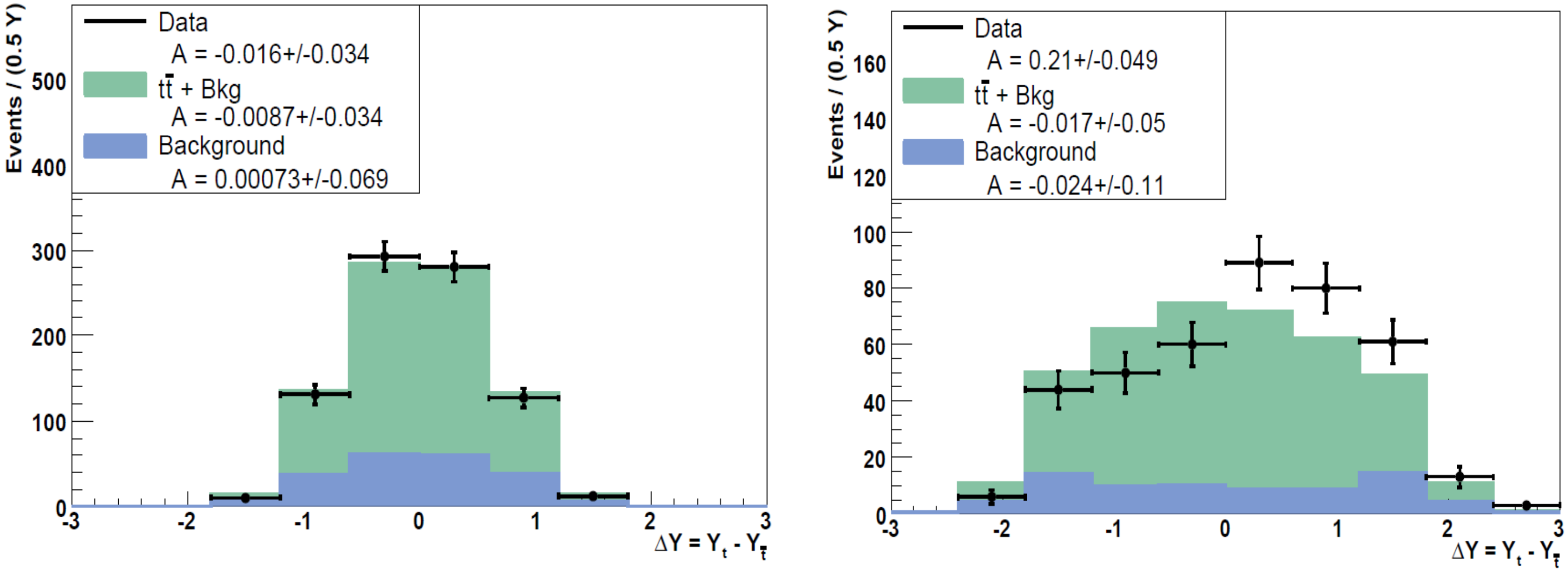


50 GeV bins
100 GeV bins
data
NLO $t\bar{t}$ + bkg
$A^{t\bar{t}}(M)$
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
350
400
450
500
550
600
650
700
750
800
$M_{t\bar{t}}$ (GeV/c^2)

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

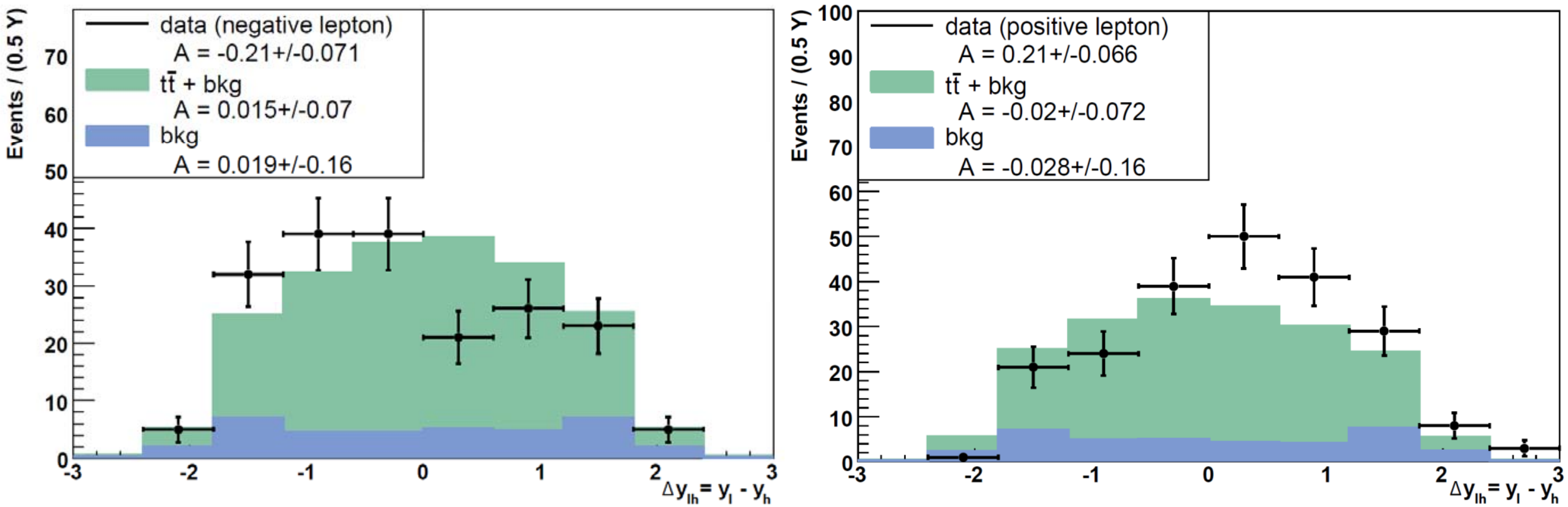

50 GeV bins
100 GeV bins
data
NLO $t\bar{t}$ + bkg
$A^{t\bar{t}}(M)$
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
350
400
450
500
550
600
650
700
750
800
$M_{t\bar{t}}(GeV/c^2)$

data: Δy at low and high mass



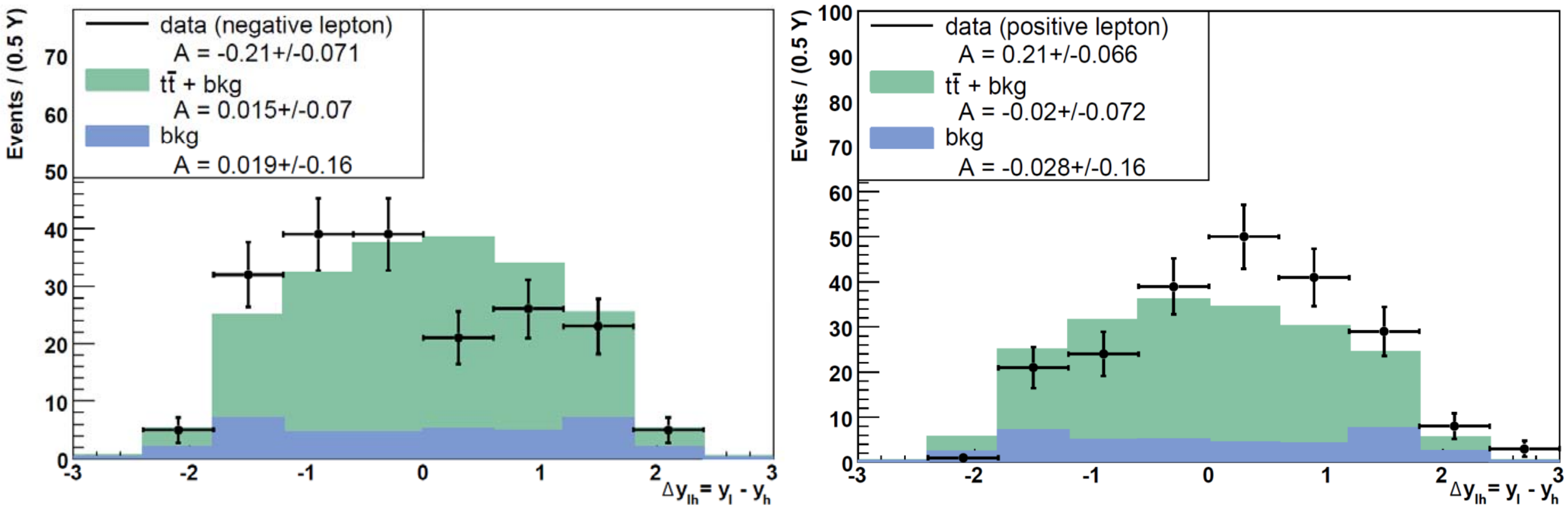
selection	all M	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$
reco data	0.057±0.028	-0.016±0.034	0.212±0.049
MC@NLO	0.017±0.004	0.012±0.006	0.030±0.007

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



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

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

corrected asymmetries

- background subtraction
- unfold to parton level 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

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 $A_{fb}(\eta_{ll})$ is consistent with $A_{fb}(\Delta y)$
  - this variable very well verified with Z
  - top 0 and 1 jet control regions consistent with prediction

- in lepton+jets, $A_{fb}(\Delta y)$ is observed to depend on M_{tt}

	M_{tt} < 450 GeV/c^2	M_{tt} ≥ 450 GeV/c^2
– data	-0.016 ± 0.034	0.210 ± 0.049
– parton level	-.116 ± 0.153	0.475 ± 0.112
– MCFM	0.040 ± 0.006	0.088 ± 0.013

  - reverses sign under interchange of lepton (top) charge: CP conservation

- there is a lot more work to do

Backup

bonus question

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

PHYSICAL REVIEW D VOLUME 17, NUMBER 7 1 APRIL 1978

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

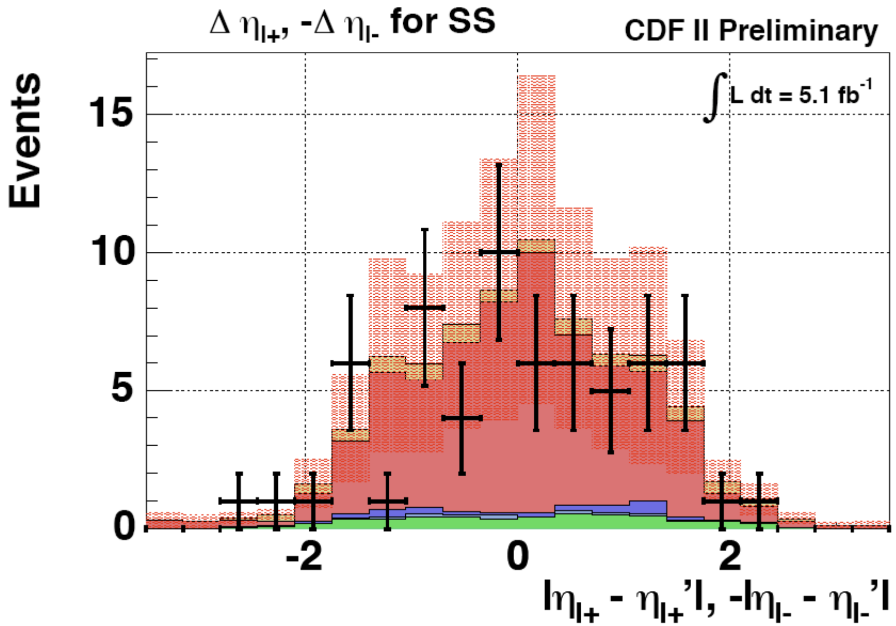
R. Cester, V. L. Fitch, R. W. Kadel,* R. C. Webb, J. D. Whittaker, and M. S. Witherell
Department of Physics, Princeton University, Princeton, New Jersey 08540

M. May
Brookhaven National Laboratory, Upton, L.I., New York 11973
(Received 12 December 1977)

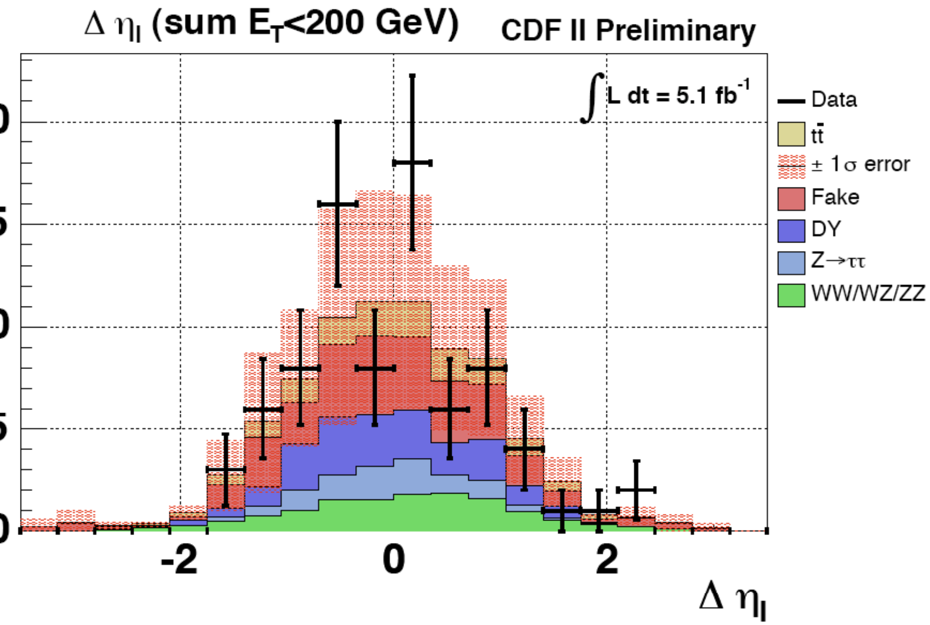
Using $\bar{p}p$ interactions at $\sqrt{s} = 5.44$ GeV we have tested for evidence of C noninvariance through a comparison of the transverse-momentum distributions of particle and antiparticle produced at 90° in the center of mass. We found an average charge asymmetry for pions with $p_\perp$ between 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 $\text{Re}\,\alpha \leq 0.0045$.

lepton rapidity difference in dilepton control samples

SS + MET+ 2 jets



candidates with H_t < 200 GeV



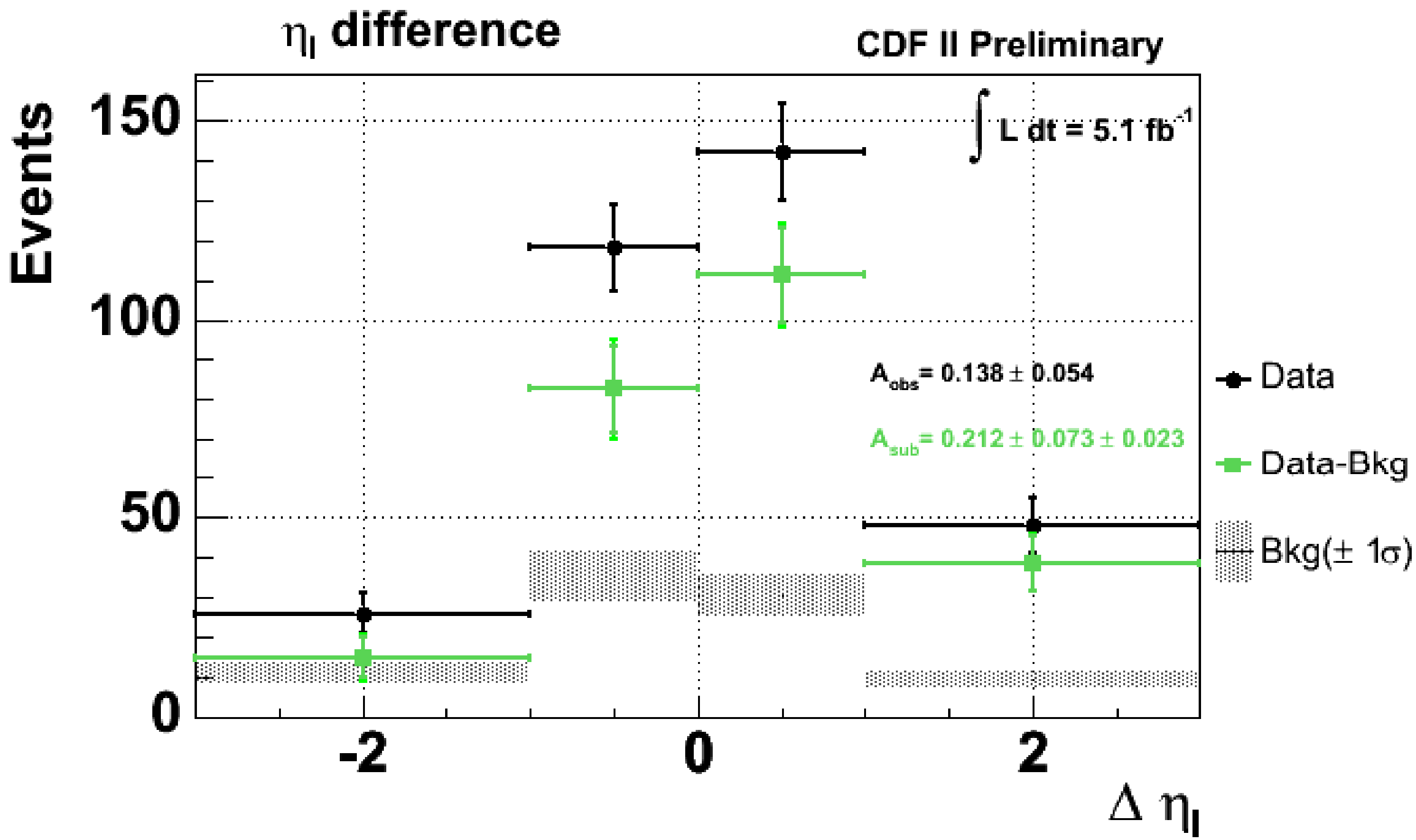
$$A_{obs}^{\Delta\eta_l} = -.012 \pm 0.111$$

$$A_{pred}^{\Delta\eta_l} = -0.02 \pm 0.165$$

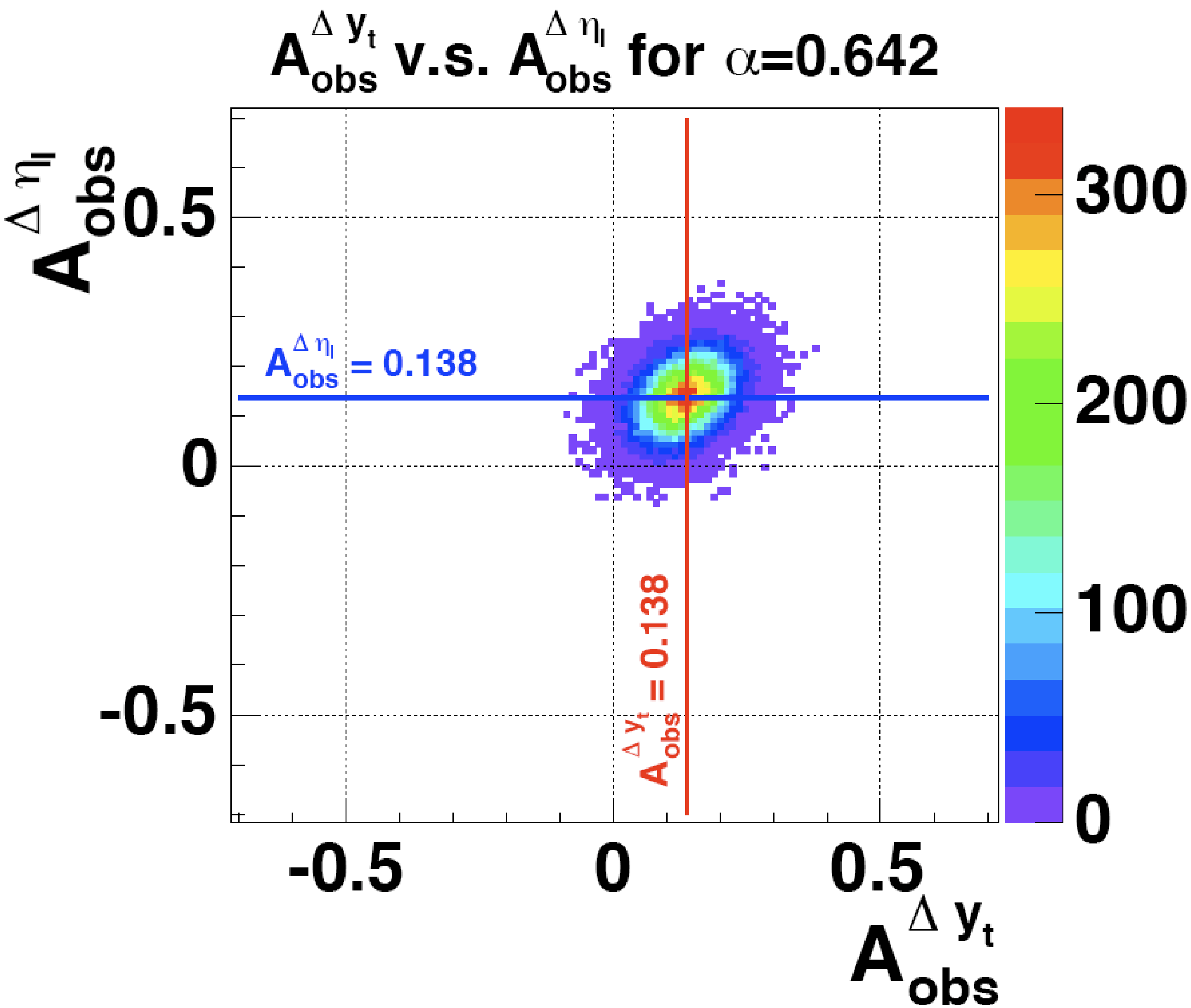
lepton rapidity difference in Z control samples

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

top rapidity difference in dilepton sample w/ bkg subtraction

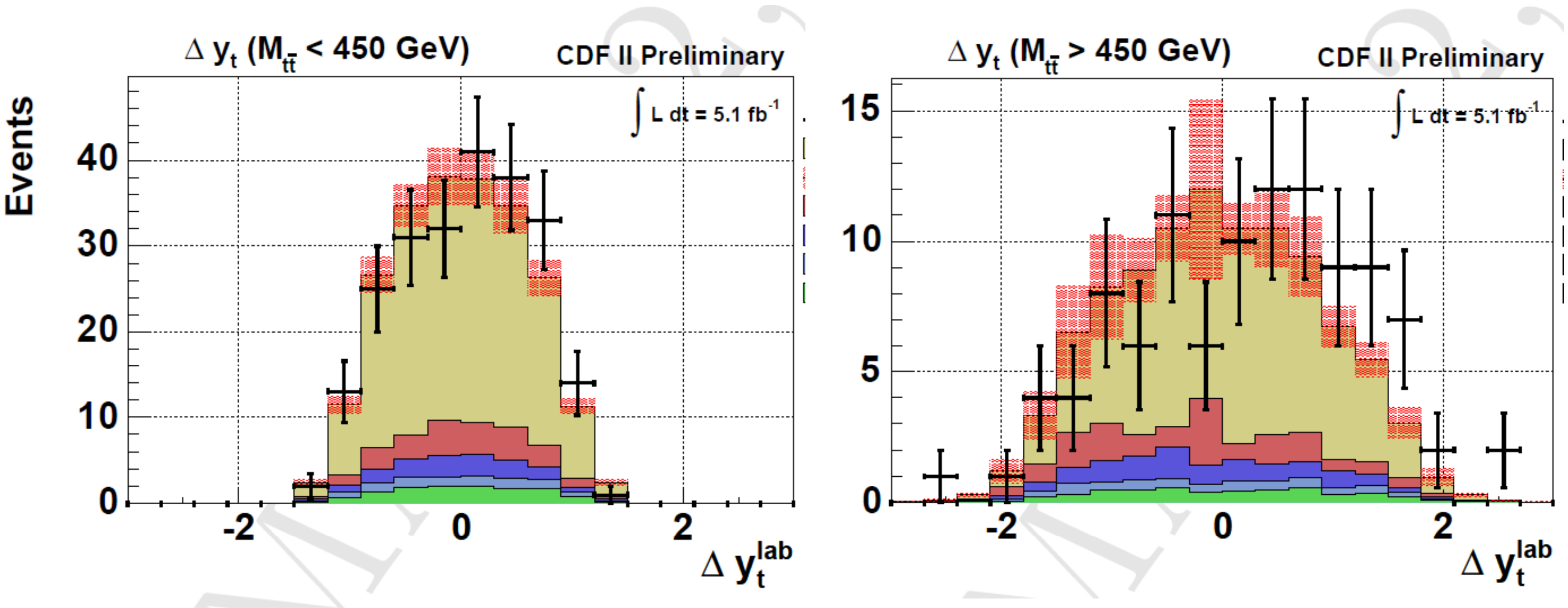


expected correlation of Δη and Δy for best fit



Asymmetry in Dileptons

- High and and low mass



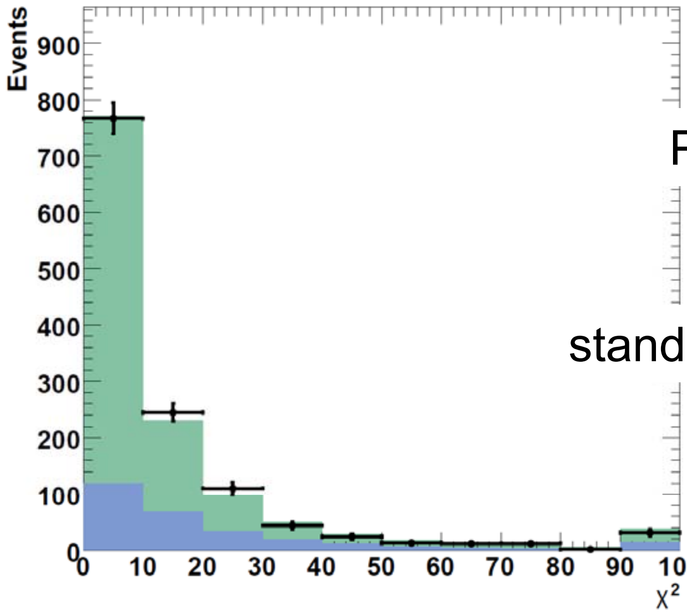
top reconstruction

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

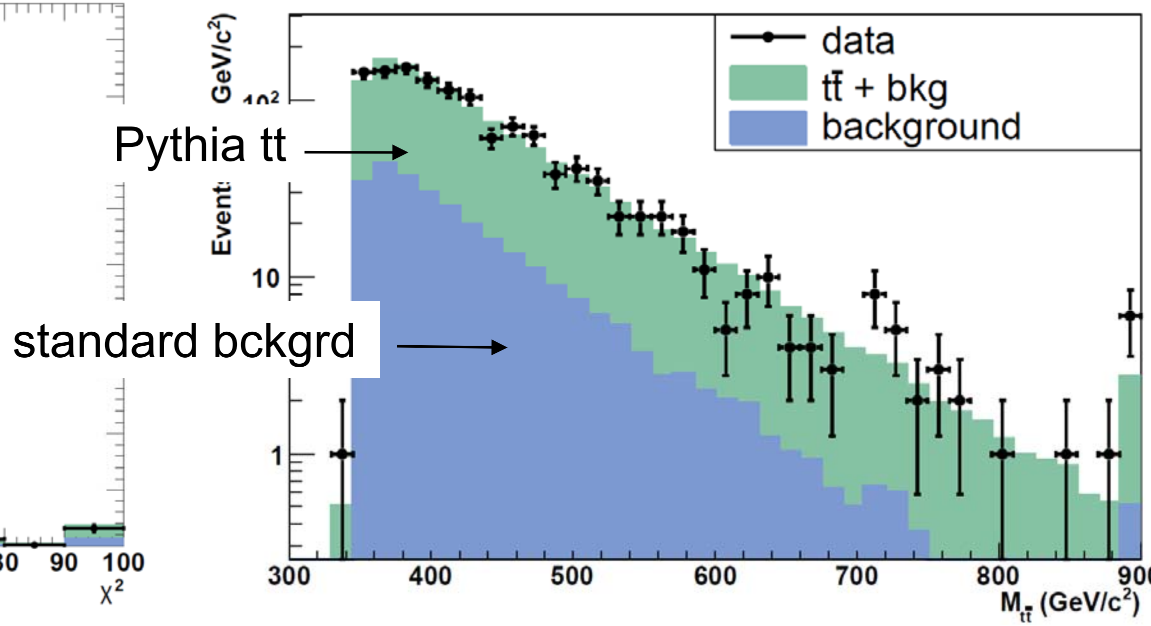
- Jet-parton assignment, $p_z(\nu)$ via minimum of simple χ^2
  - Constraints: M_W = 80.4 GeV/c2, Mt = 175 GeV/c^2, btag = b
  - Float jet p_t within errors

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

χ^2

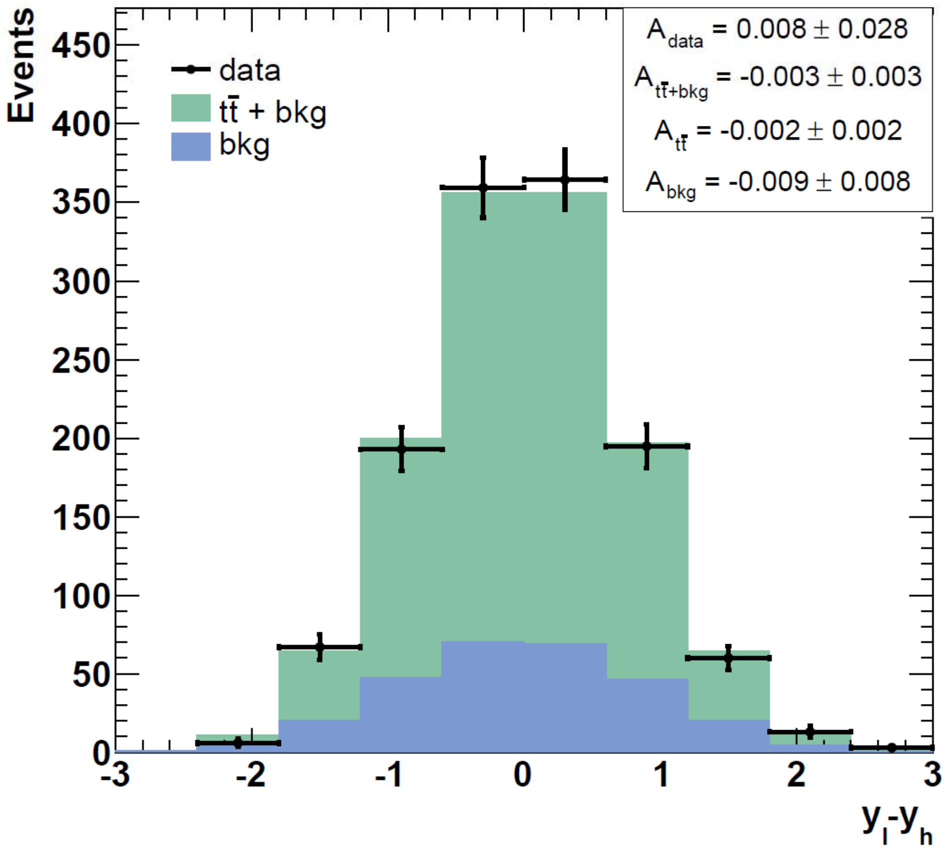


$M_{t\bar{t}}$

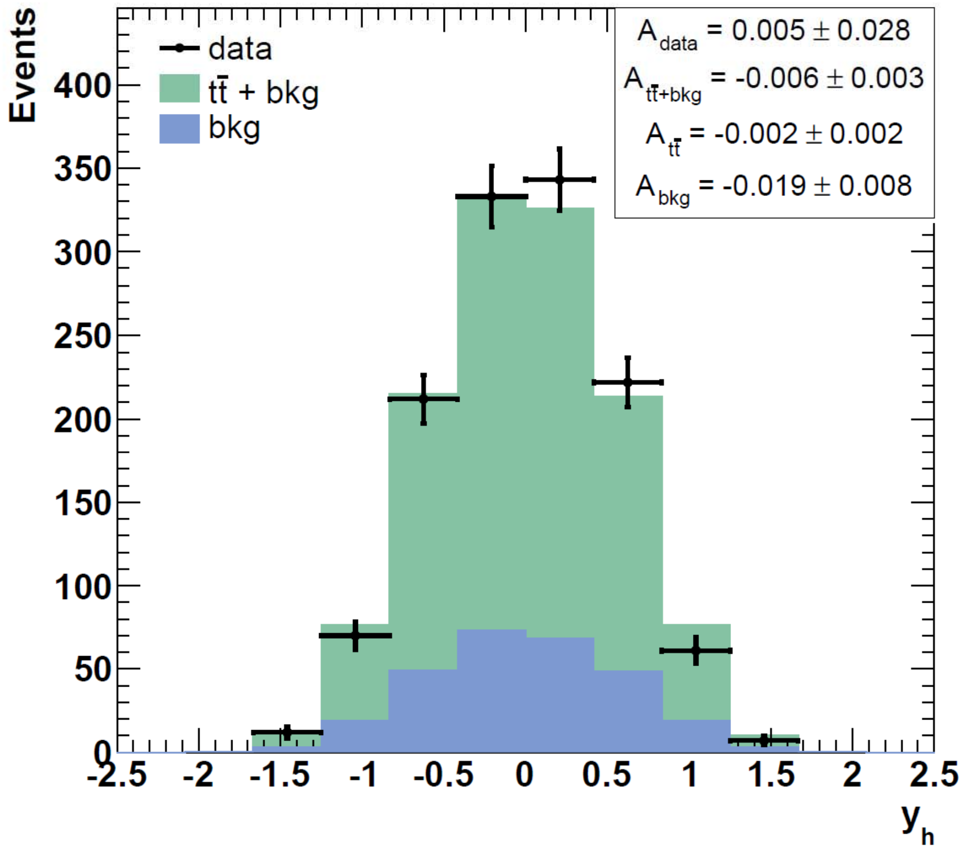


inclusive distributions (both lepton charges)

Δy



y_h



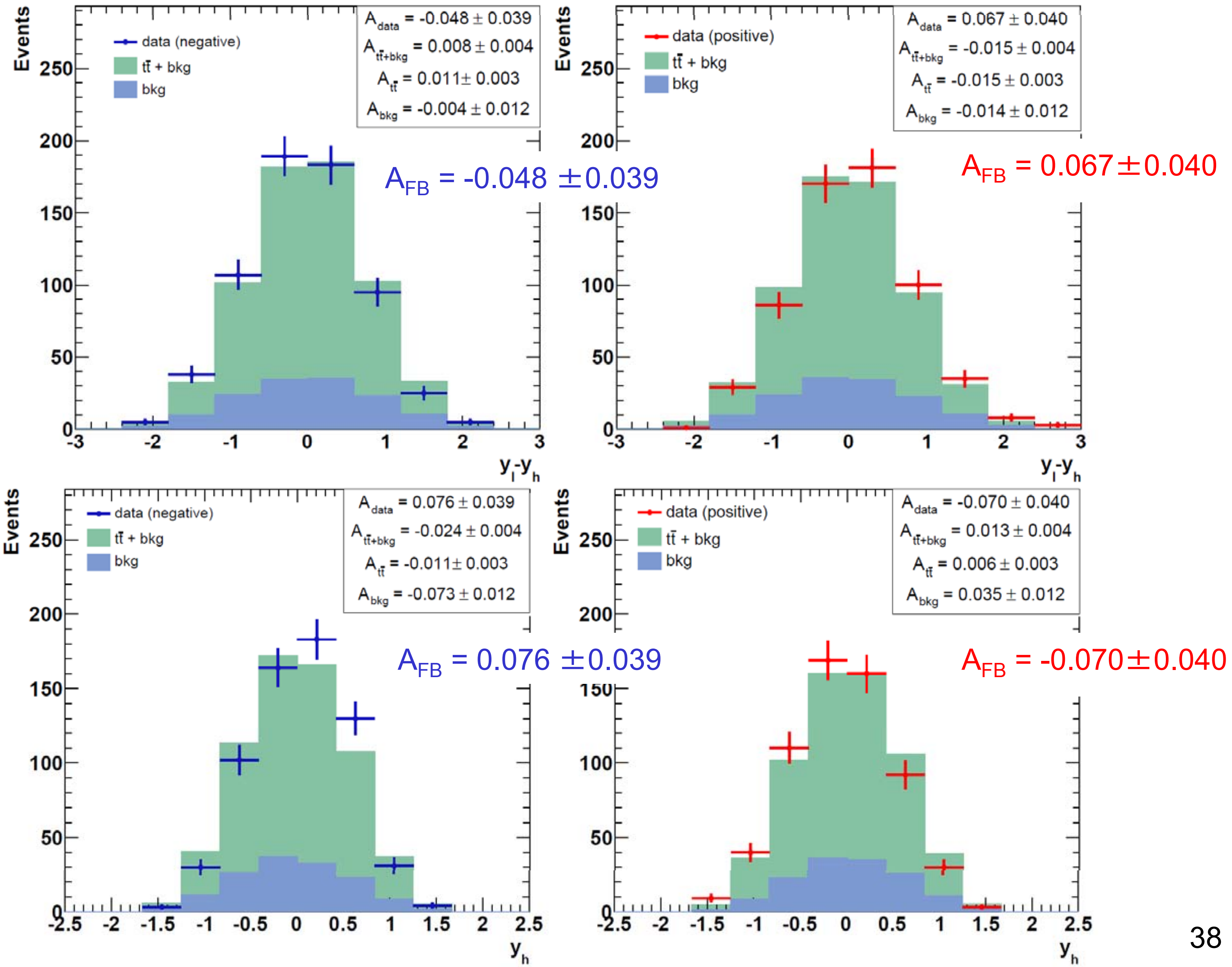
- symmetric!

separate by lepton charge

negative leptons | positive leptons

Δy

y_h



separate by lepton charge

negative leptons

positive leptons

Δy

A_{FB} = -0.048 ±0.039

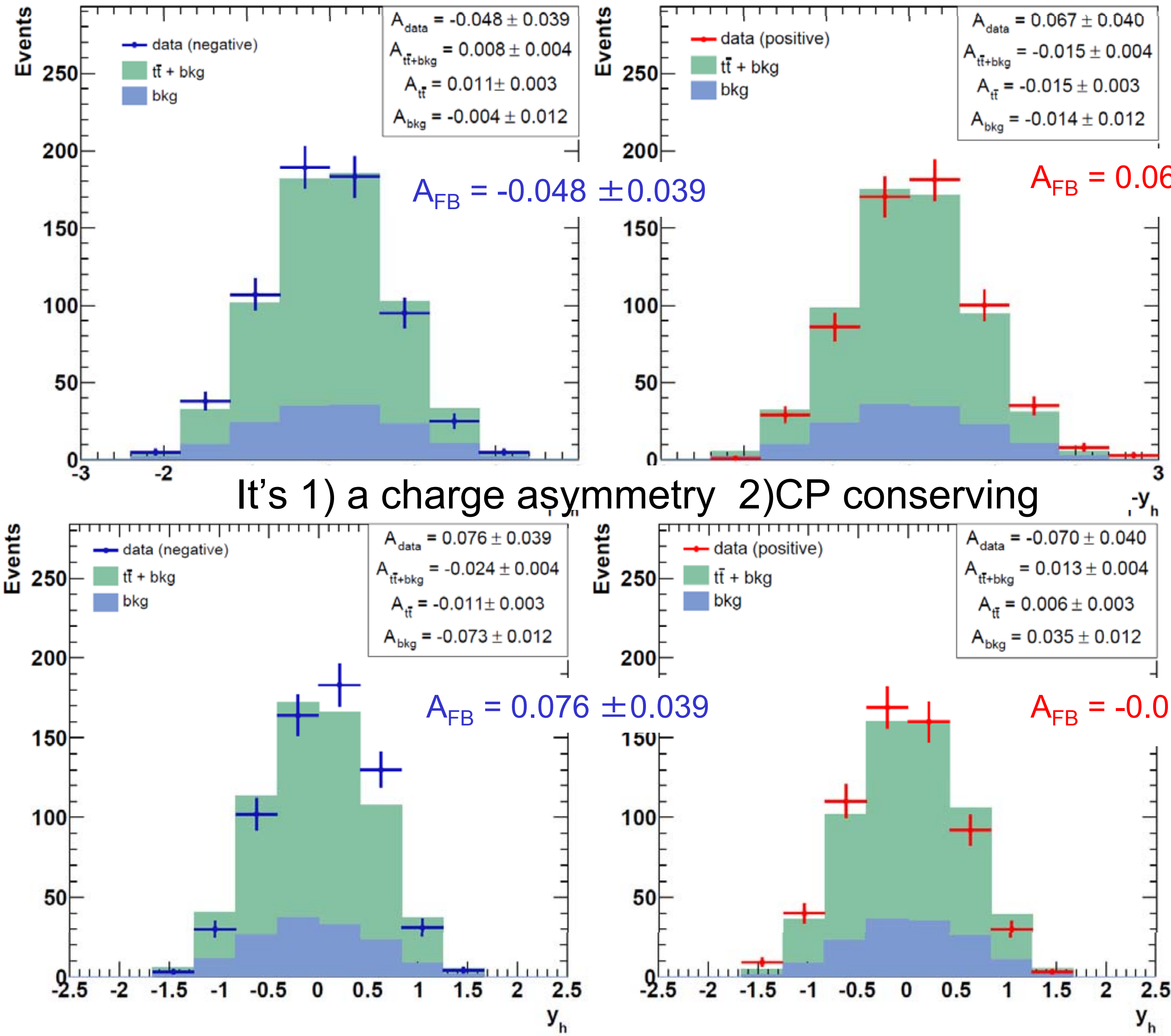
A_{FB} = 0.067±0.040

It's 1) a charge asymmetry 2)CP conserving

y_h

A_{FB} = 0.076 ±0.039

A_{FB} = -0.070±0.040



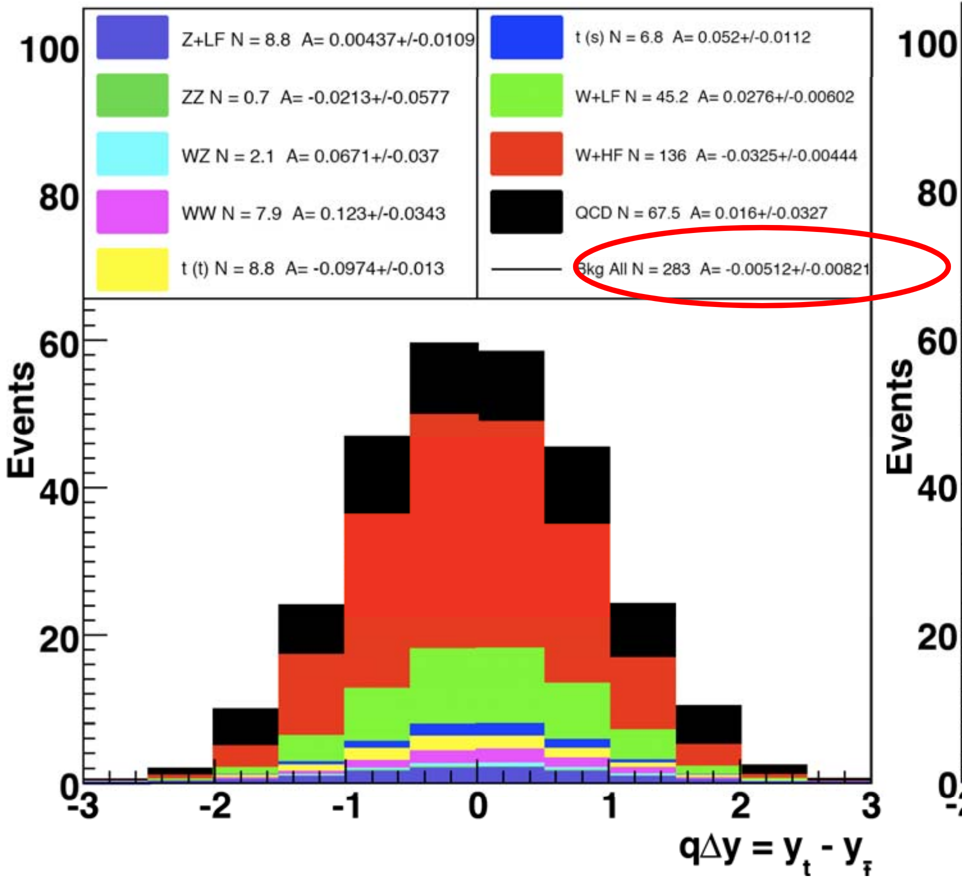
correct to the parton level

- dN/dy parton level histogram
  - parton level bins j w/ contents P_j
- the top data signal
  - $T_i = S_{ij} \times A_j \times P_j$
- where
  - the A_j are the acceptances for each bin
  - the S_{ij} are the bin-to-bin migration ratios
  - both are estimated with Pythia
- dN/dy data level histogram
  - data level bins i w/ contents D_i
  - Sum of top and bkgrd: $D_i=T_i+B_i$
- to propagate data to parton level:
  - $P_j = A_j^{-1} \times S_{ji}^{-1} \times (D_i-B_i)$
- result is optimized when number of bins = 4

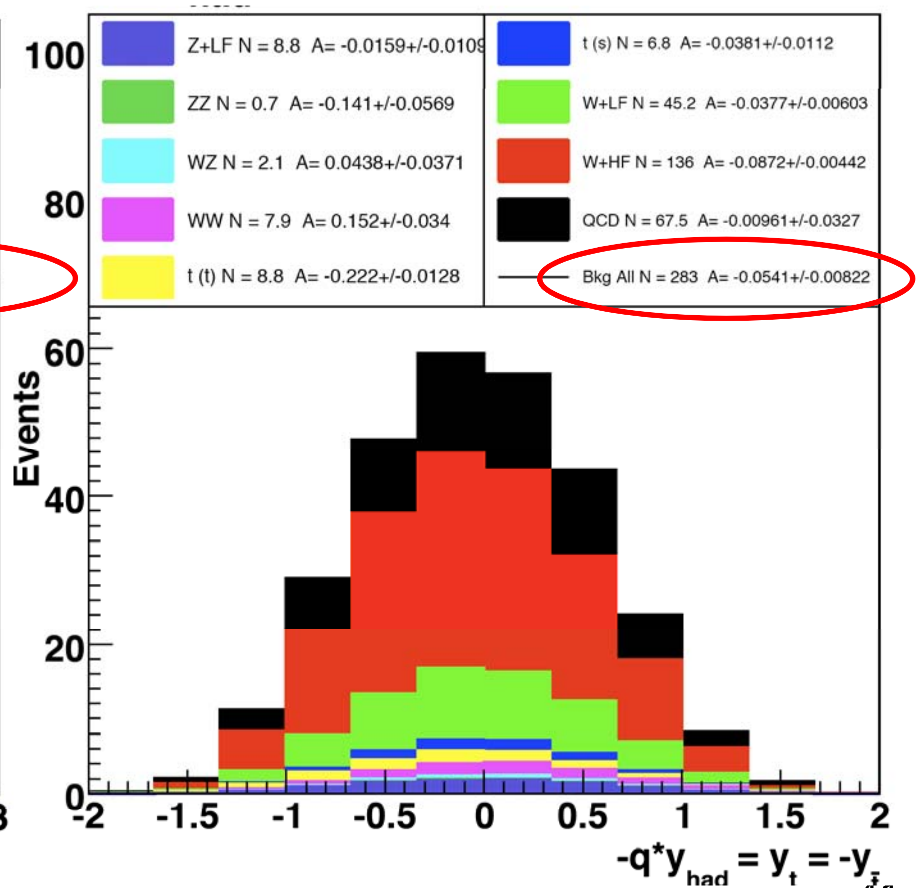
backgrounds

- detailed model for all background components
- fully simulated model samples are reconstructed like data
- asymmetries small (but not zero)

tt rest frame



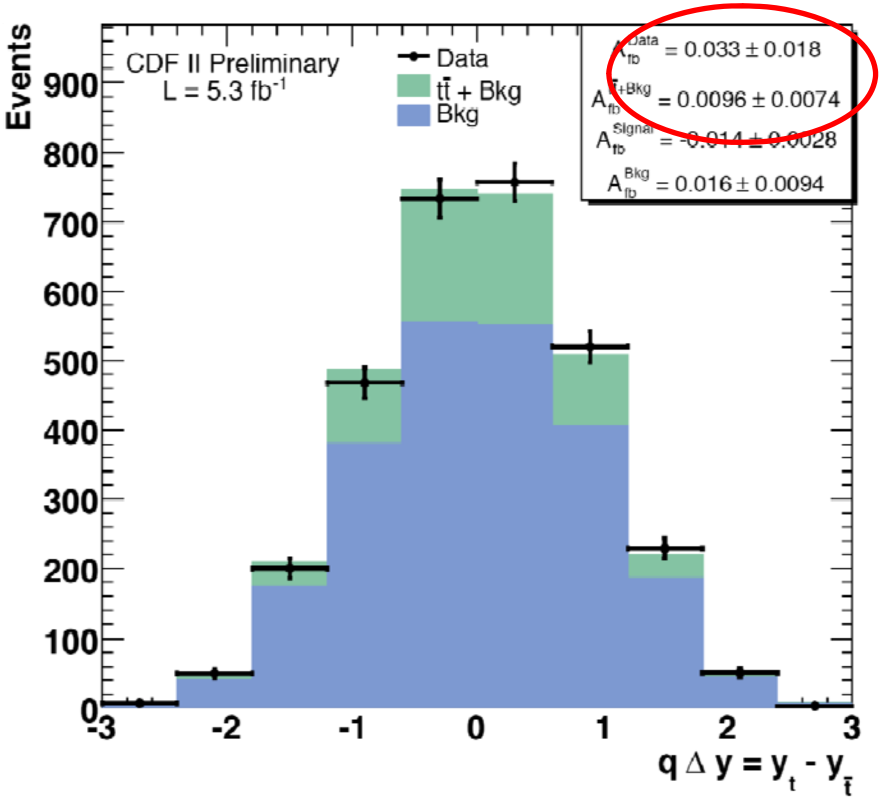
lab frame



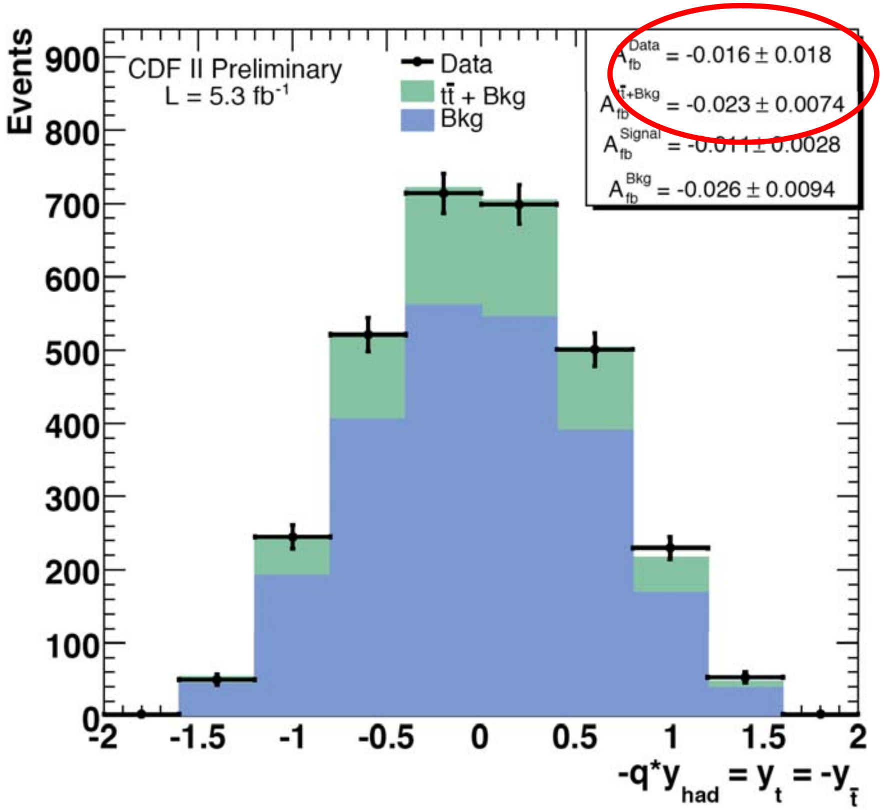
backgrounds

- can be checked in events without b-tags. S:B = 0.3
- data and predictions in good agreement

tt rest frame



lab frame

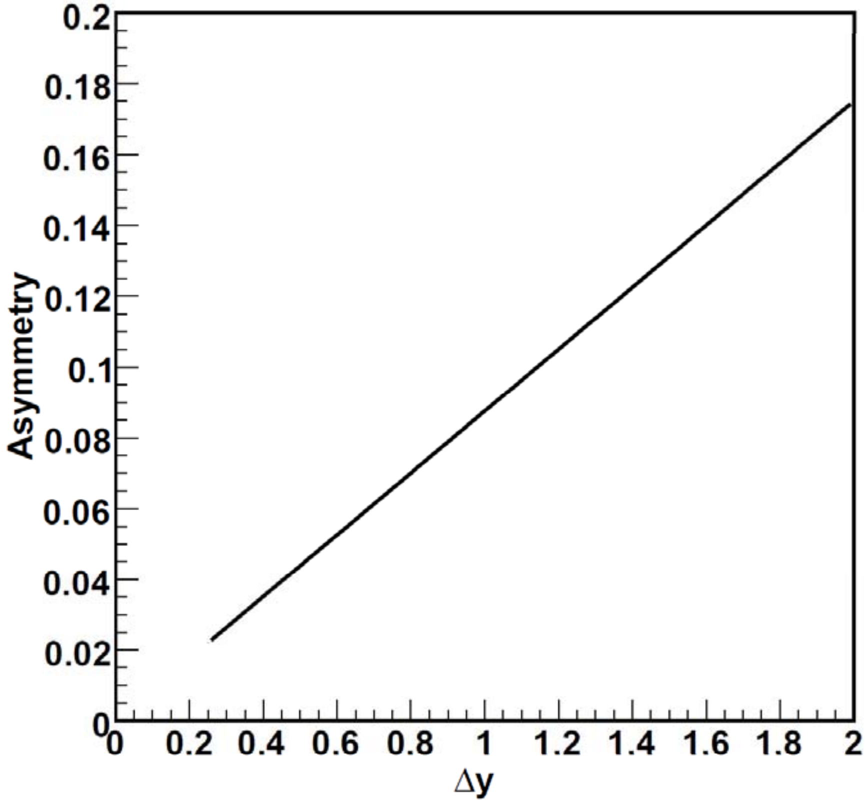


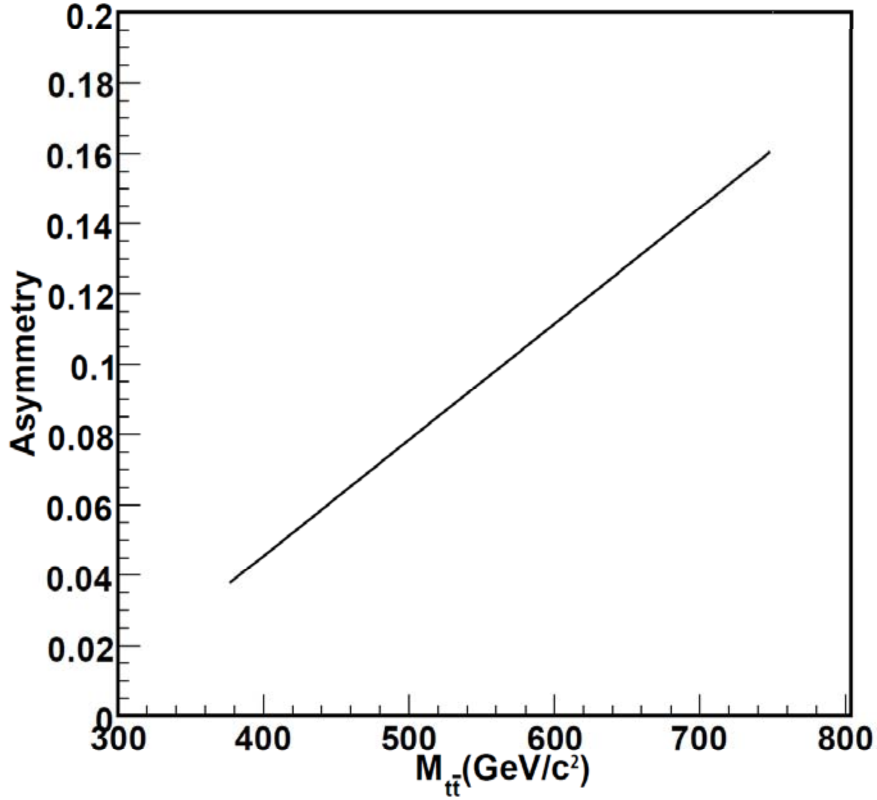
Systematic Uncertainties Inclusive

effect	$\delta A^{\mathrm{p\bar{p}}}$	$\delta A^{\mathrm{t\bar{t}}}$
background magnitude	0.015	0.011
background shape	0.014	0.007
ISR/FSR	0.010	0.001
JES	0.003	0.007
PDF	0.005	0.005
color reconnection	0.001	0.004
LO MC generator	0.005	0.005
total	0.024	0.017

Asymmetry is a function of Δy and M_{tt}

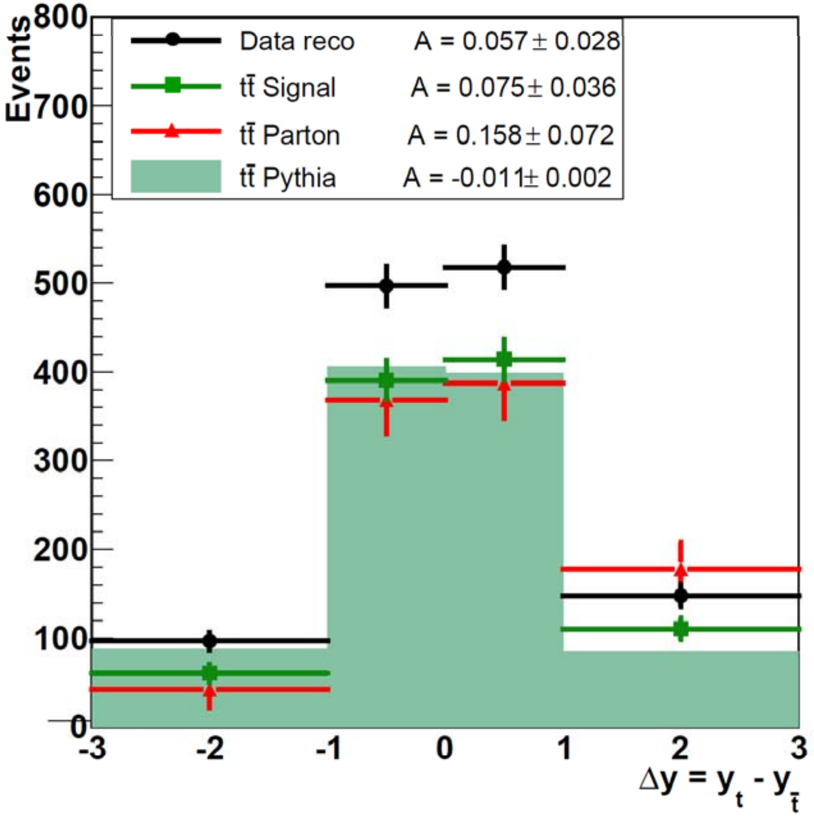
- in tt frame, QCD asymmetry has linear dependence on $\Delta y,\ M_{t\bar{t}}$
- NLO prediction from MCFM

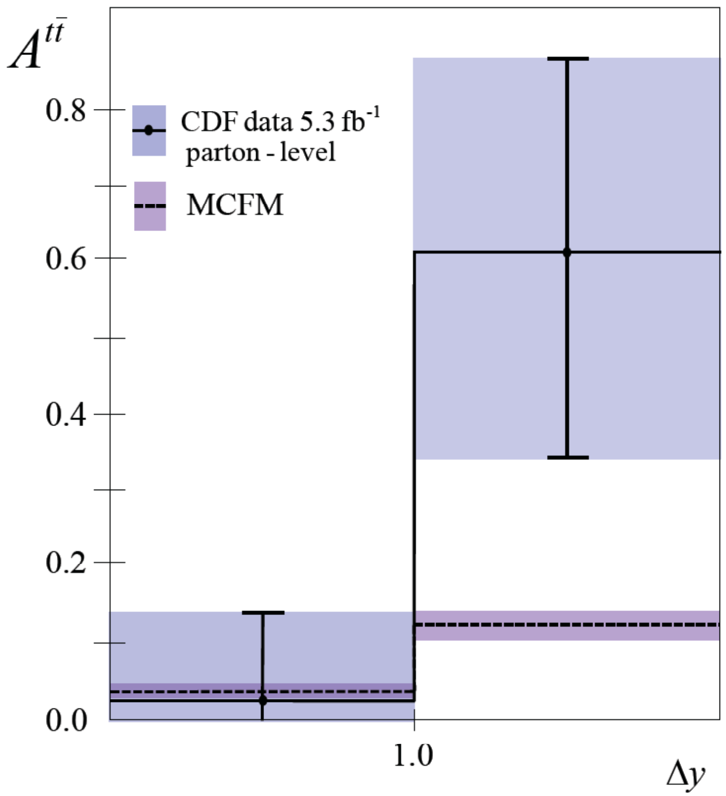




- $\Delta y,\ M_{t\bar{t}}$ dependence generally of interest in other theories

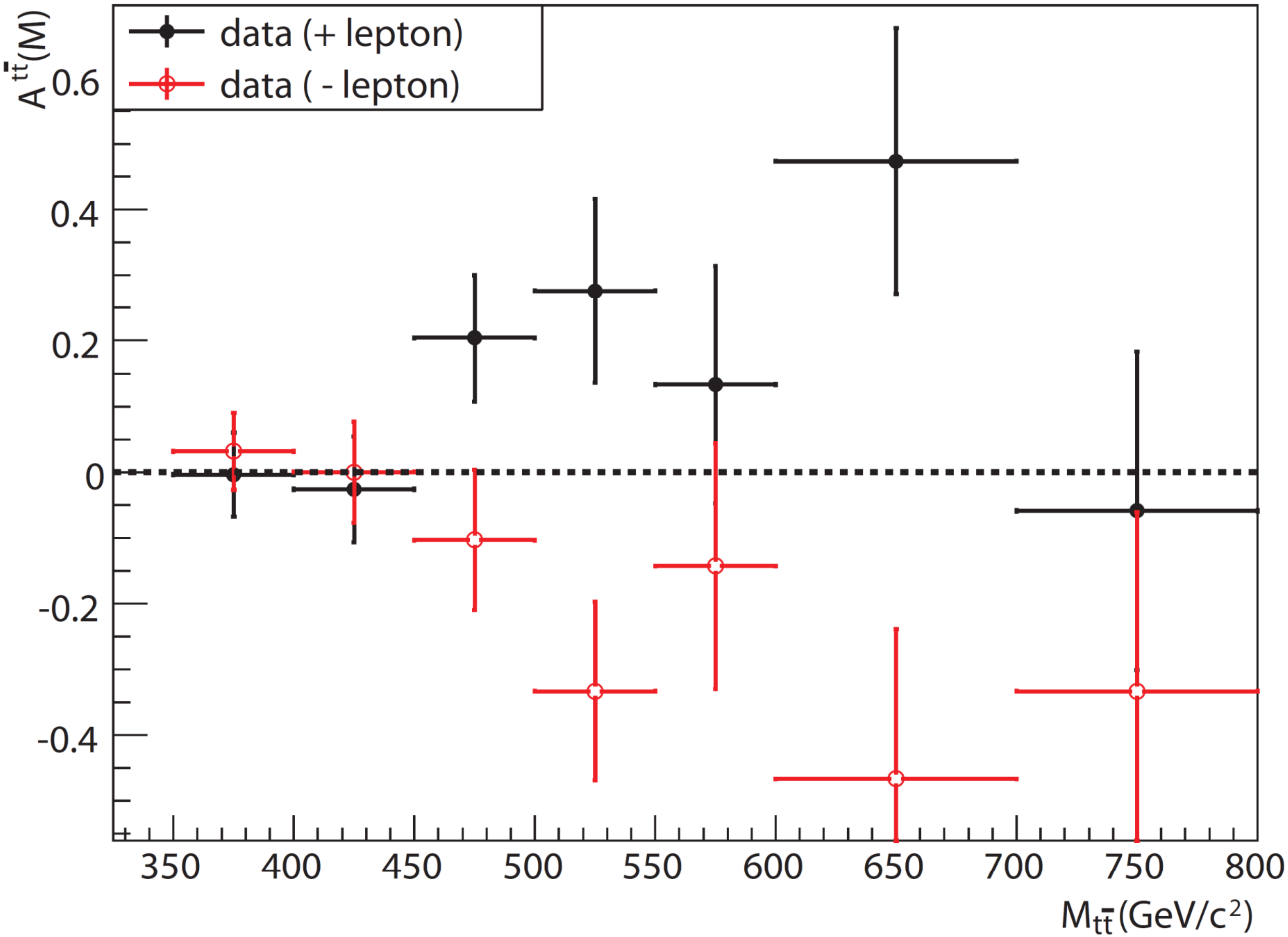
A(Δy), parton level, data





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

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



the two-bin boundary

- simplest A(M): two bins
- high and low mass
- where to put boundary?
- look at significance $S_A = \frac{A}{\delta A}$ at high mass vs. boundary

➢ best boundary: 450 GeV/c^2

	OctetA		OctetB	
bin-edge (GeV/c^2)	A^{tt}	significance	A^{tt}	significance
345	0.082 ± 0.028	2.90	0.168 ± 0.028	5.99
400	0.128 ± 0.036	3.55	0.235 ± 0.035	6.74
450	0.183 ± 0.047	3.91	0.310 ± 0.044	7.08
500	0.215 ± 0.060	3.60	0.369 ± 0.054	6.81
550	0.246 ± 0.076	3.25	0.425 ± 0.066	6.43
600	0.290 ± 0.097	2.97	0.460 ± 0.081	5.70

the two-bin boundary

- simplest A(M): two bins
- high and low mass
- where to put boundary?
- look at significance $S_A = \dfrac{A}{\delta A}$ at high mass vs. boundary

➢ best boundary: 450 GeV/c^2

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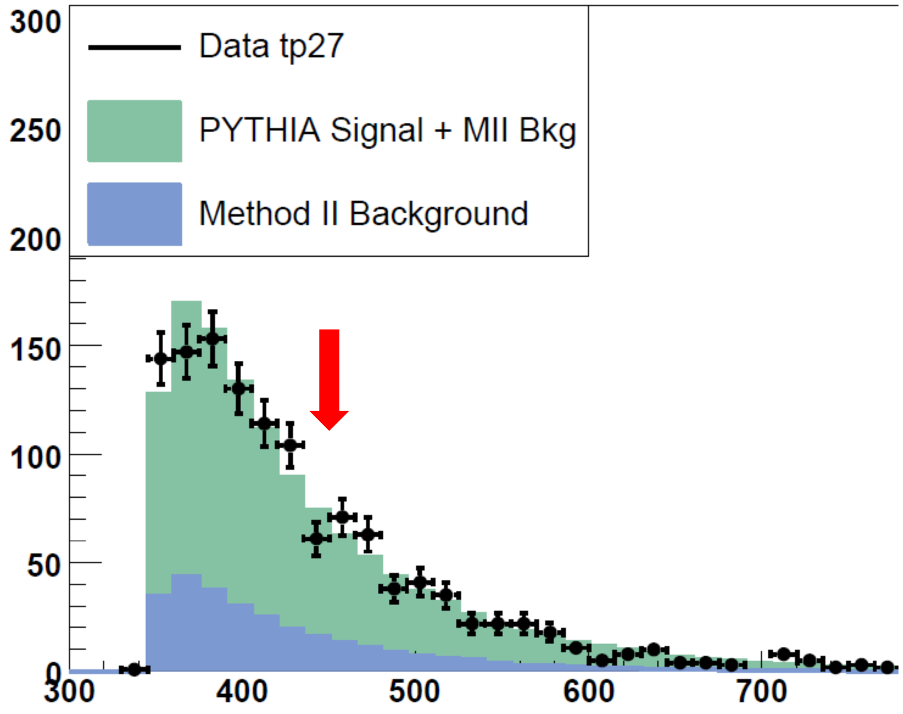
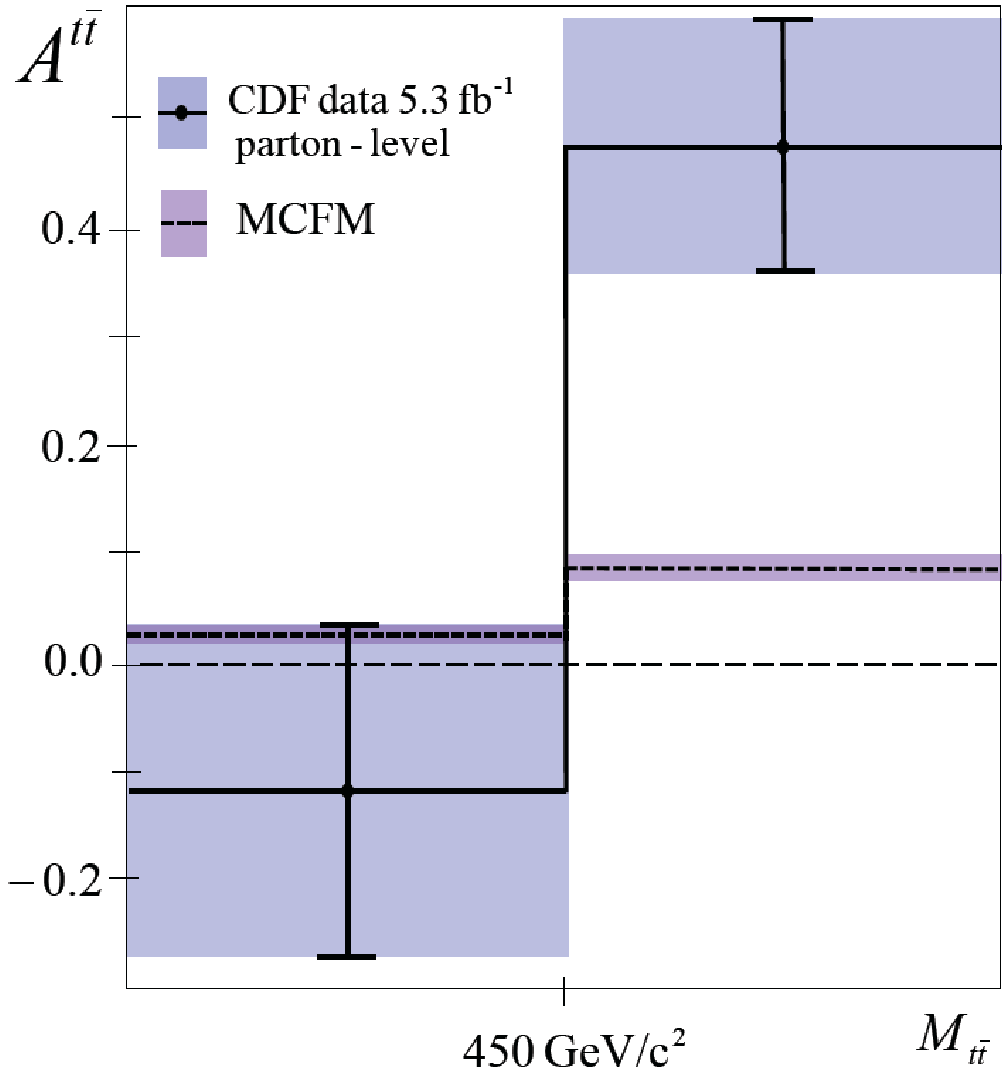
600	0.290 ± 0.097	2.97



A^{tt} at high and low mass: parton level



tests of unfold procedure

Sample	$A^{t\bar{t}}$ level	$M_{t\bar{t}} < 450$ GeV/c^2	$M_{t\bar{t}} \geq 450$ GeV/c^2
PYTHIA	MC truth	0.002	0.001
	reconstructed	-0.011 ± 0.006	-0.013 ± 0.008
	corrected	0.001 ± 0.018	0.006 ± 0.014
MC@NLO	MC truth	0.043	0.070
	reconstructed	0.015 ± 0.006	0.043 ± 0.009
	corrected	0.066 ± 0.014	0.086 ± 0.011
Octet A	MC truth	0.081	0.276
	reconstructed	0.024 ± 0.035	0.183 ± 0.010
	corrected	0.054 ± 0.022	0.308 ± 0.016
Octet B	MC truth	0.150	0.466
	reconstructed	0.078 ± 0.036	0.310 ± 0.009
	corrected	0.187 ± 0.024	0.476 ± 0.015

sys uncertainty of unfold procedure

Source	$M < 450$ GeV/c^2	$M \geq 450$ GeV/c^2
background size	0.017	0.032
background shape	0.003	0.003
JES	0.005	0.012
ISR/FSR	0.012	0.008
color reconnection	0.009	0.004
PDF	0.018	0.004
physics model	0.035	0.035
total	0.047	0.049

TABLE XII: Systematic uncertainties in the two-mass bin unfold

studies of A^{tt} at the data level

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

jet multiplicity dependence

- the NLO QCD asymmetry has a strong N_{jet} dependence

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

- data: the high mass asymmetry is significantly reduced for 5 jet events

selection	N events	all M	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$
data 4-jet	939	0.065±0.033	-0.023±0.039	0.26±0.057
data 5-jet	321	0.034±0.056	0.0049±0.07	0.086±0.093

- need to study other models, color flow, asymmetry reco in ttj

frame dependence

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

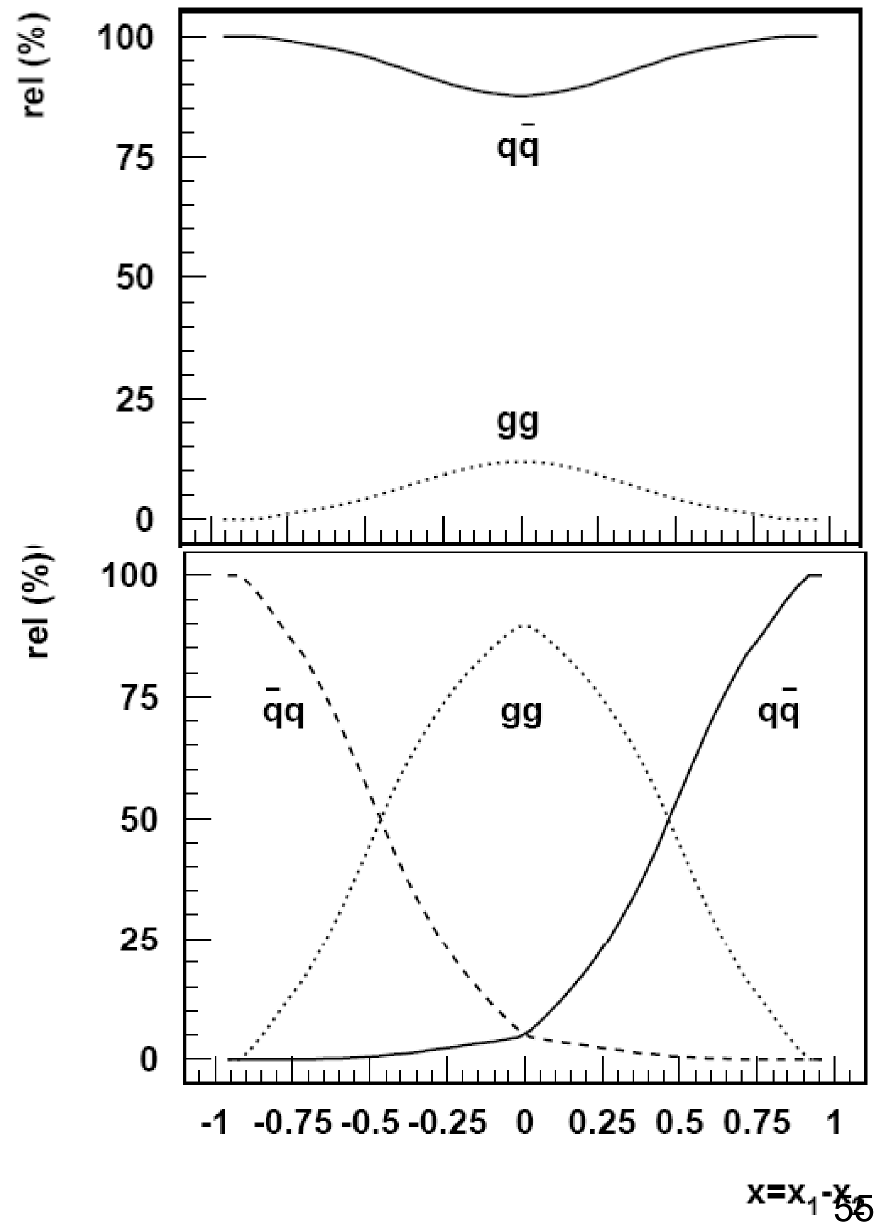
selection	all M	$M < 450$ GeV$/c^2$	$M \geq 450$ GeV$/c^2$
data reco	0.073±0.028	0.059±0.034	0.103±0.049
MC@NLO	0.017±0.004	-0.008±0.005	0.022±0.007
A_h^+	-0.076±0.039	-0.085±0.047	-0.053±0.072
A_h^-	0.070±0.040	0.028±0.050	0.148±0.066
single b-tags	0.095±0.032	0.079±0.034	0.130±0.057
double b-tags	-0.004±0.060	-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?

Tevatron vs LHC (from Kuhn and Rodrigo)

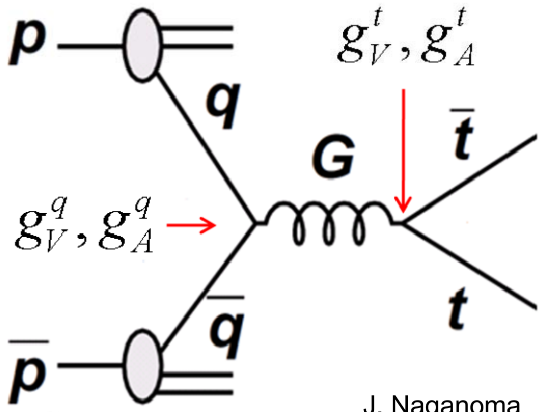
- Tevatron dominated by $q\overline{q}$

- at LHC, work at large x



Model

- Color-Octet
- after Ferrario and Rodrigo
  arXiv:0906.5541
- If $g_A^q = -g_A^t$ get positive asymmetry



$$\frac{d\sigma^{q\bar{q}\to t\bar{t}}}{d\cos\hat{\theta}} = \alpha_S^2 \frac{T_F C_F}{N_C} \frac{\pi\beta}{2\hat{s}} \{1 + c^2 + 4m^2$$

$$+ \frac{2\hat{s}(\hat{s} - m_G^2)}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [g_V^q\, g_V^t\, (1 + c^2 + 4m^2) + 2\, g_A^q\, g_A^t\, c]$$

$$+ \frac{\hat{s}^2}{(\hat{s} - m_G^2)^2 + m_G^2\Gamma_G^2} [((g_V^q)^2 + (g_A^q)^2)$$

$$\times ((g_V^t)^2(1 + c^2 + 4m^2) + (g_A^t)^2(1 + c^2 - 4m^2))$$

$$+8\, g_V^q\, g_A^q\, g_V^t\, g_A^t\, c]\} \;, \qquad (1)$$

Production Angle →Rapidity

- from qq to lab
  - black = SM
  - red = SM +0.34cosθ