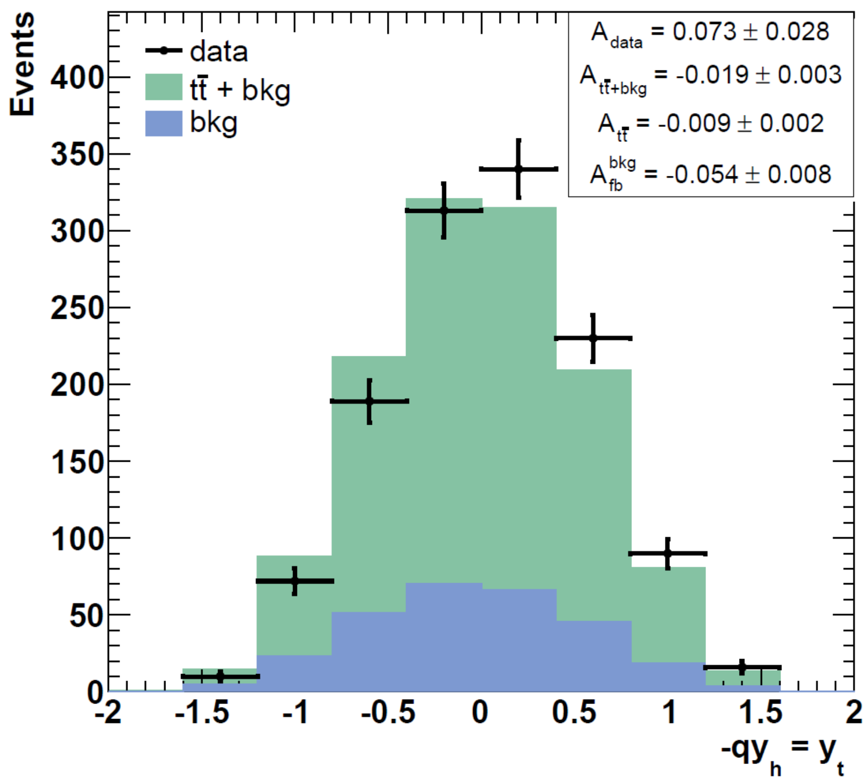
Forward-Backward Asymmetry in $t\bar{t}$ Pair Production

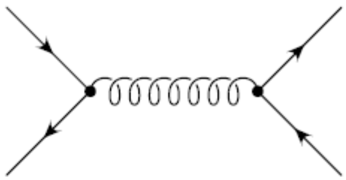
The CDF Collaboration



charge asymmetry in QCD

- Halzen, Hoyer, Kim; Brown, Sadhev, Mikaelian; Kuhn, Rodrigo; Almeida, Sterman, Vogelsang; Bowen, Ellis, Rainwater; Dittmaier, Uwer, Weinzier

$t\bar{t}$



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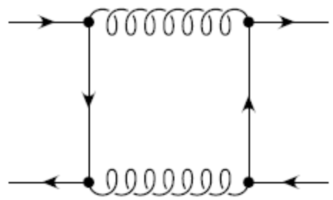


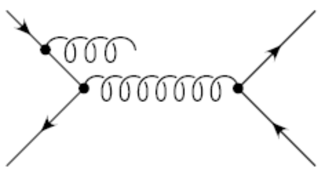
C = - 1

C = +1

tt frame asymmetries

A_{FB} ~ +10-12 % NLO

$t\bar{t}j$



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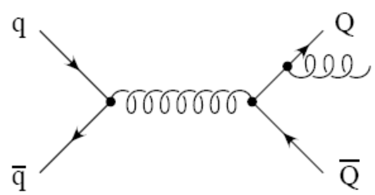


C = + 1

C = -1

A_{FB} ~ -7 % NLO

A_{FB} ~ 6 +- 1.0 % net

theoretical investigations

- Exotic gluons
  - massive chiral color
  - RS gluon
  - color sextets, anti-triplets
- IVB′
  - Z′
  - FV W′Z′ t-channel
- FV scalars
- Effective Lagrangians

- Nice summary by Cao et al. arXiv:1003.3461

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

prior measurements

- 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)

  - lab (pp) frame $A^{p\bar{p}} = 0.17 \pm 0.08$
  - NLO QCD $A^{p\bar{p}} = 0.04 \pm 0.01$

- 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} ICEHP 2010

this analysis

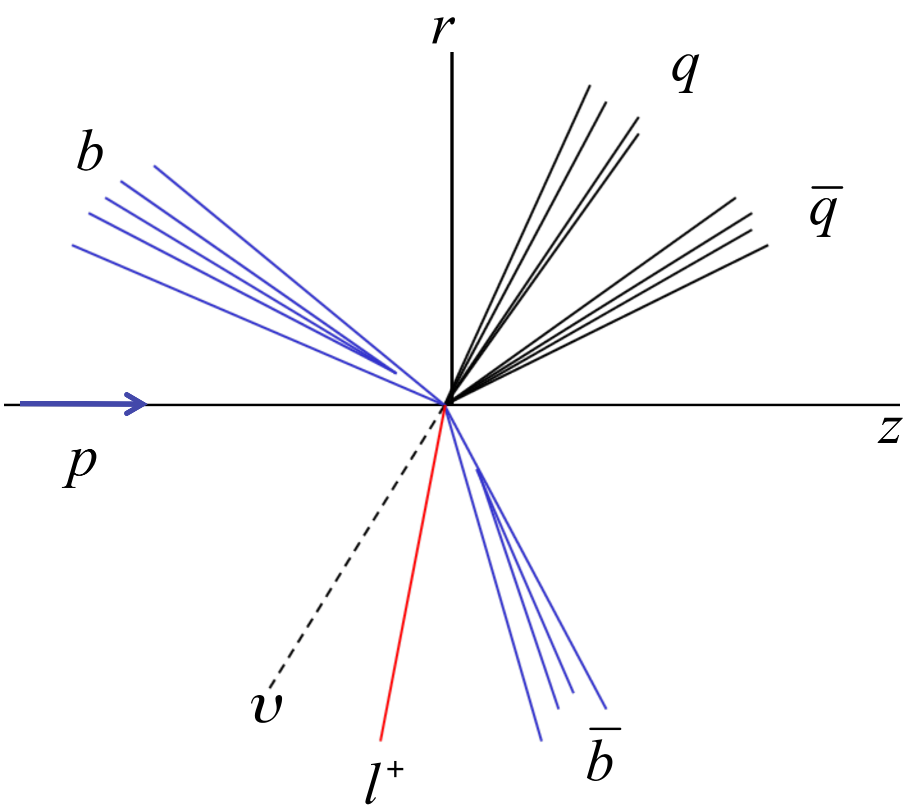
- 5.3 fb^{-1}
- Standard “lepton+jets” selection, reconstruction
- Establish rapidity variables, A_{fb} definitions, in tt frame and lab frame
- Models
  - LO
  - QCD charge asymmetry
  - color-octet
- Correct the rapidity distributions for
  - backgrounds
  - selection efficiency
  - reconstruction smearing

  to find the model independent A_{fb} to compare to theory
- Inclusive in tt and lab frame
- Rapidity dependence in tt frame
- M_{tt} dependence in lab frame

top pair production and decay

lepton + jets mode

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



r-z view

event selection

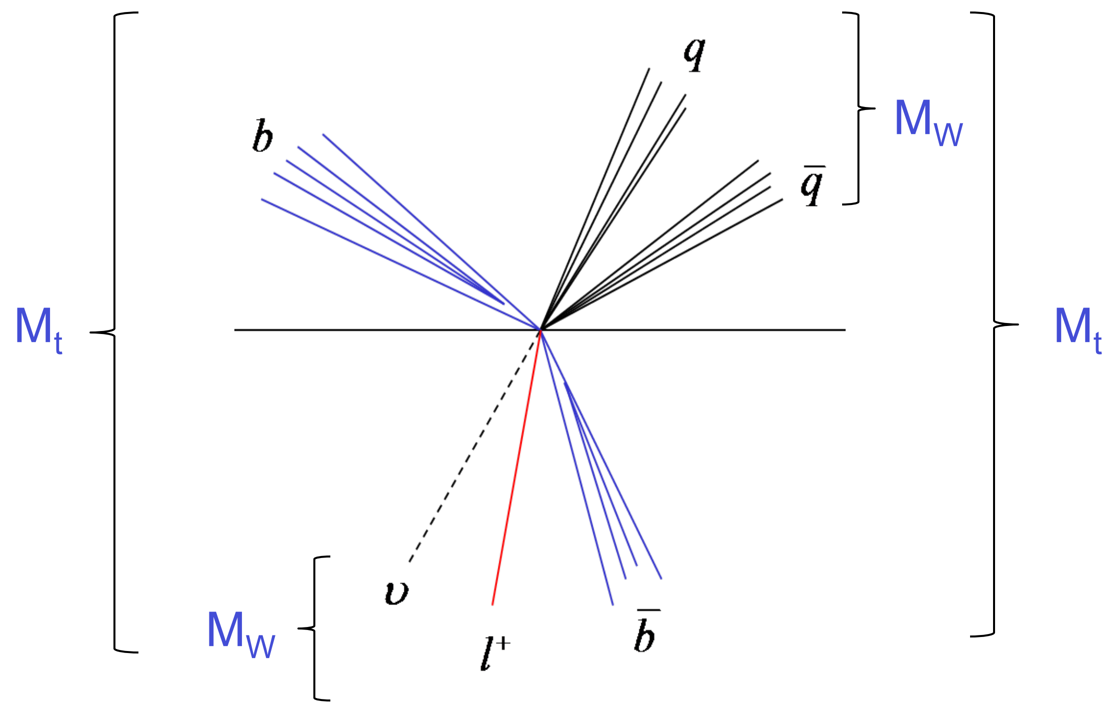
- high p_t lepton (e/μ)
  - $E_t/p_t > 20$ GeV (/c)
  - $|\eta| < 1.0$
- missing $E_t > 20$ GeV
- four jets
  - $E_t > 20$ GeV
  - $|\eta| < 2.0$
- at least one b-tagged jet
  - $|\eta| < 1.0$
- 1260 events
- 283±50 non-tt background
  - standard technique
  - mostly W+jets

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

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



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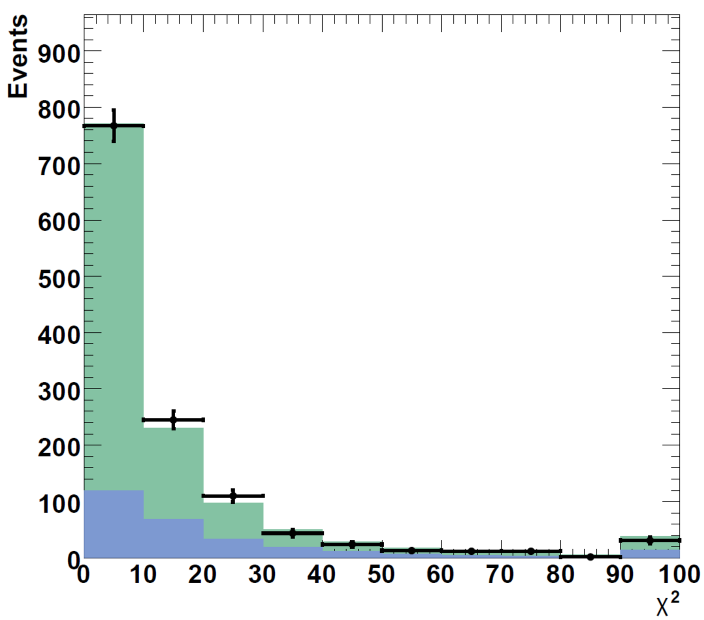
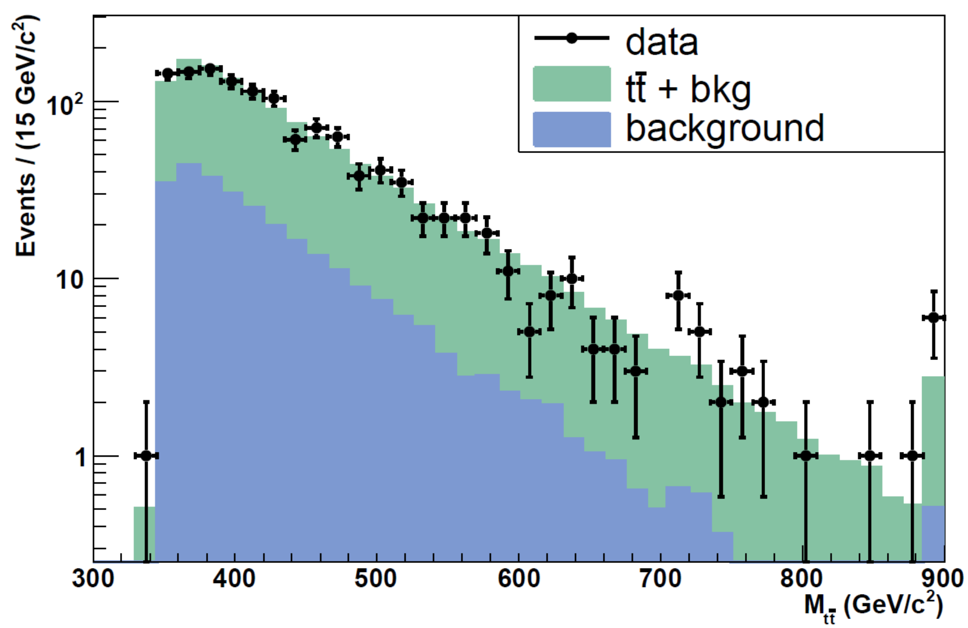
$$\chi^2 = \sum_{lep,\,jets} \frac{(p_t^{i,\,meas} - p_t^{i,\,fit})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,\,meas} - p_j^{UE,\,fit})^2}{\sigma_j^2} + \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_{top})^2}{\Gamma_t^2} + \frac{(M_{bl\nu} - M_{top})^2}{\Gamma_t^2}$$

$$\chi^2$$



$$M_{t\bar{t}}$$



rapidity : lab frame

- each event has a t_{lep} and t_{had} decay

$$+q_l \Rightarrow t_{leptonic} + \bar{t}_{hadronic}$$

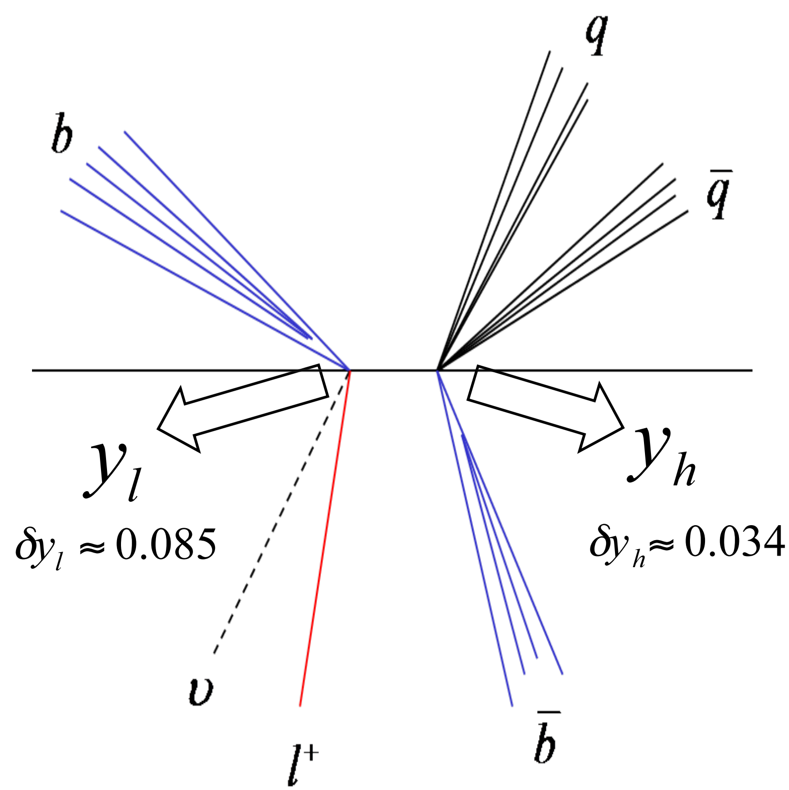
$$-q_l \Rightarrow t_{hadronic} + \bar{t}_{leptonic}$$

- and a rapidity for each

$$y_{leptonic} = y_l$$

$$y_{hadronic} = y_h$$

- simple rapidity variable in lab frame: y_h
  - better measured than y_l
  - acceptance out to $|\eta| < 2.0$

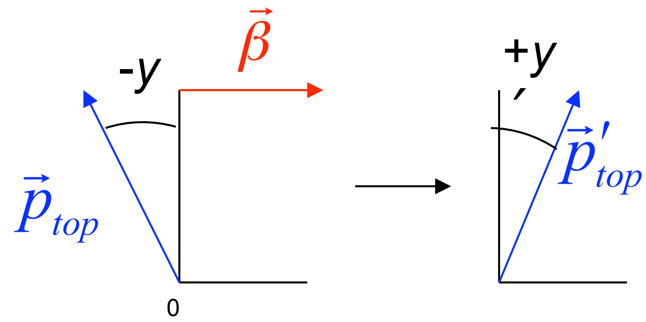


- charge tag:
  - assign charge with lepton from t_{lep}
  - interchange of lepton charge ⟷ interchange of t and $\bar{t}$
  - If assume CP can combine

$$-q \cdot y_h = y_t^{p\bar{p}}$$

rapidity : tt frame

- a longitudinal boost can change the direction of the top quark
  - A_{fb} is frame dependent!



- a frame invariant variable
  - rapidity difference

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

  - good : decreased dilution from boost

$$A_{FB}^{t\bar{t}} \approx 1.5 \times A_{FB}^{p\bar{p}}$$

  - bad: decreased precision $\delta \Delta y \approx 0.100$
  - great: ease of interpretation:

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

→ asymmetry in Δy_{tt} is equal to asymmetry in top quark production angle in tt rest frame

asymmetries

- lab frame asymmetry in $-qy_h$

$$A_{FB}^{p\bar{p}} = \frac{N(-qy_h > 0) - N(-qy_h < 0)}{N(-qy_h > 0) + N(-qy_h < 0)}$$

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

- tt rest frame asymmetry in Δy:

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

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

- also of interest: uncharged asymmetries in y_h and y_l-y_h

expected QCD asymmetries

- MCFM NLO calculation at "parton level"
- MC@NLO + CDFSIM

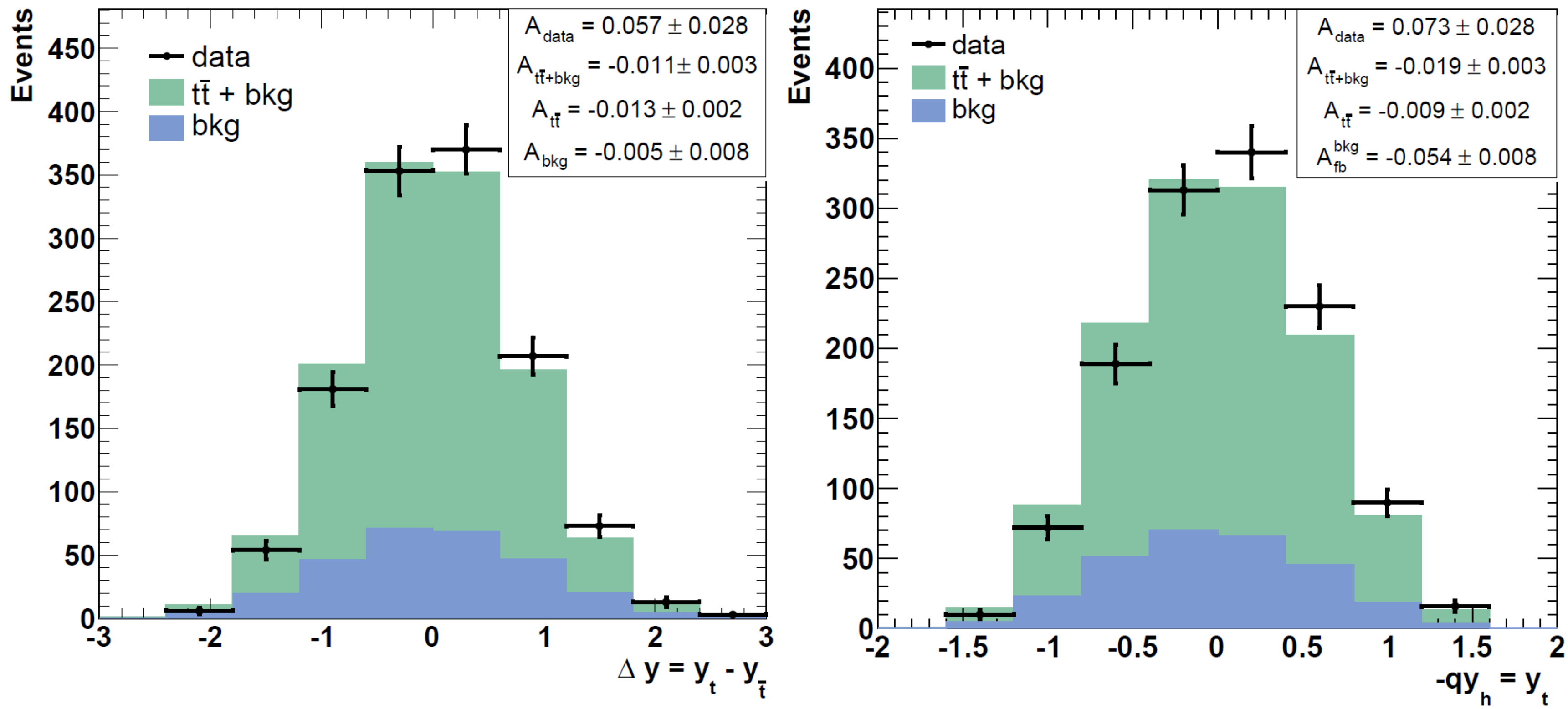
model	level	$A^{\mathrm{p\bar{p}}}$	$A^{\mathrm{t\bar{t}}}$	
MCFM	parton	0.038 ± 0.006	0.058 ± 0.009	
MC@NLO	parton	0.032 ± 0.005	0.052 ± 0.008	truth
MC@NLO	$t\bar{t}$	0.018 ± 0.005	0.024 ± 0.005	sim + reco
MC@NLO	$t\bar{t}$+bkg	0.001 ± 0.003	0.017 ± 0.004	sim + reco +bkg

- MC@NLO:
  - prediction for data level asymmetry in rest frame is zero!
  - prediciton for data level asymmetrry in tt frame < stat precision (0.028)

- Pythia remains good approximation of SM

Combine charges

$\Delta y \sim$ tt frame



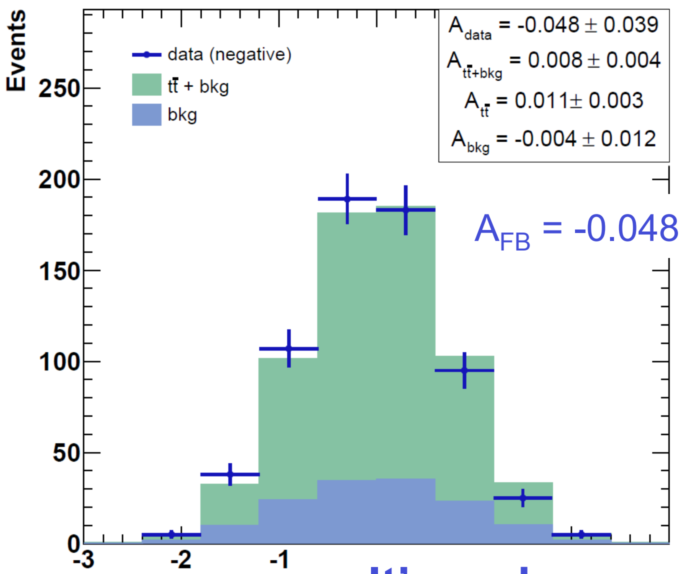
- Combined Δy:
  A_{FB} = 0.057 ±0.028
- Compare to mc@nlo
  A_{FB} = 0.024

- Combined $-q*y_h$:
  A_{FB} = 0.073 ±0.028
- Compare to mc@nlo
  A_{FB} = 0.001

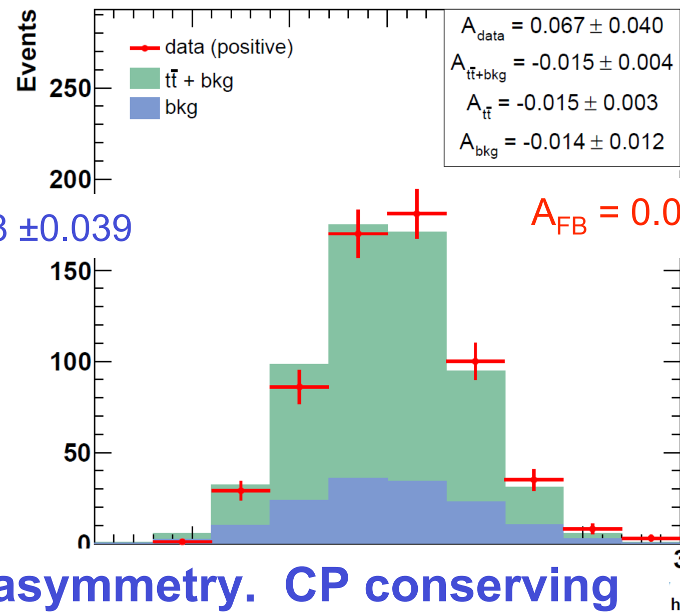
Separate by lepton charge

negative leptons | positive leptons

Δy



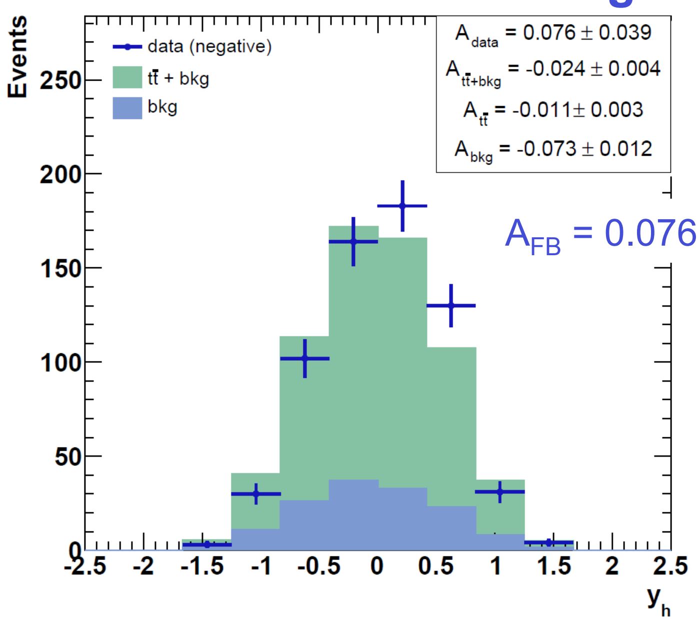
A_{FB} = -0.048 ±0.039



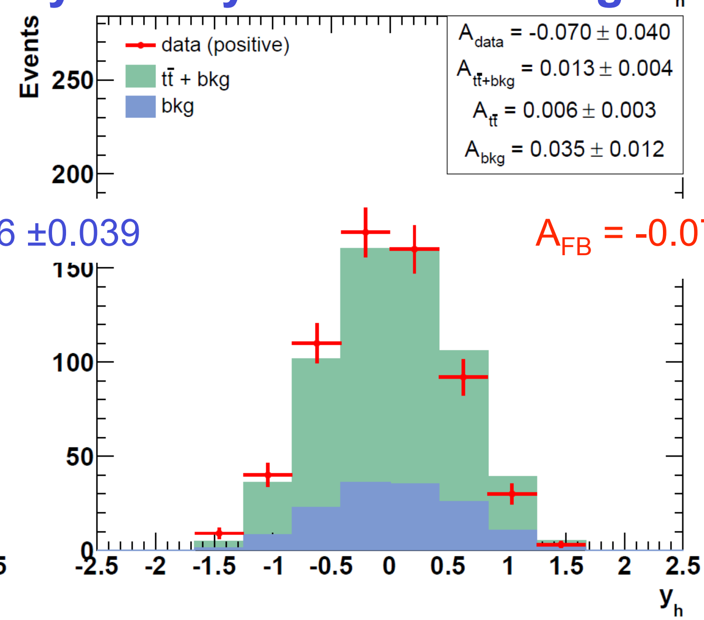
A_{FB} = 0.067±0.040

It's a charge asymmetry. CP conserving

y_h



A_{FB} = 0.076 ±0.039

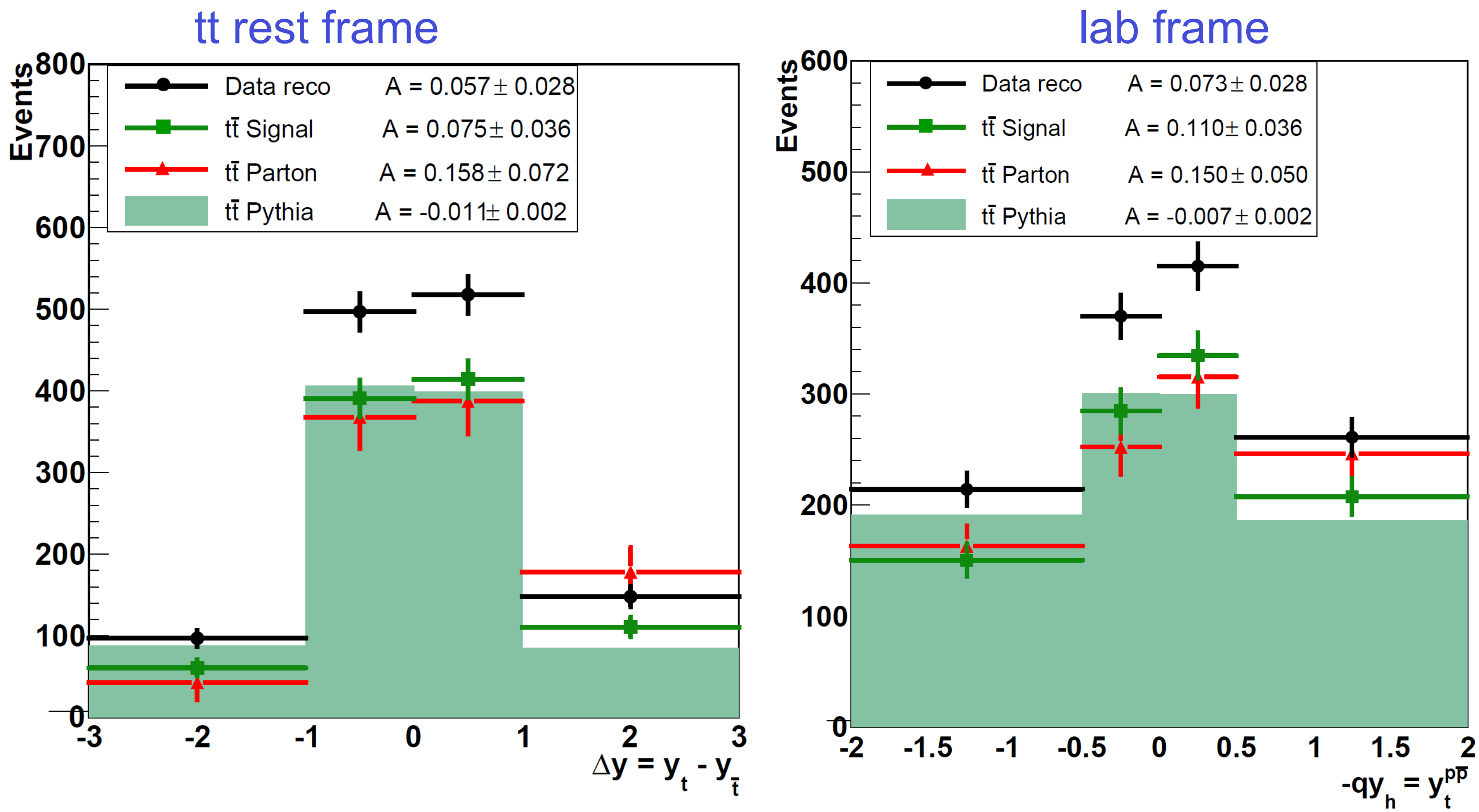


A_{FB} = -0.070±0.040

Unfold to the parton level

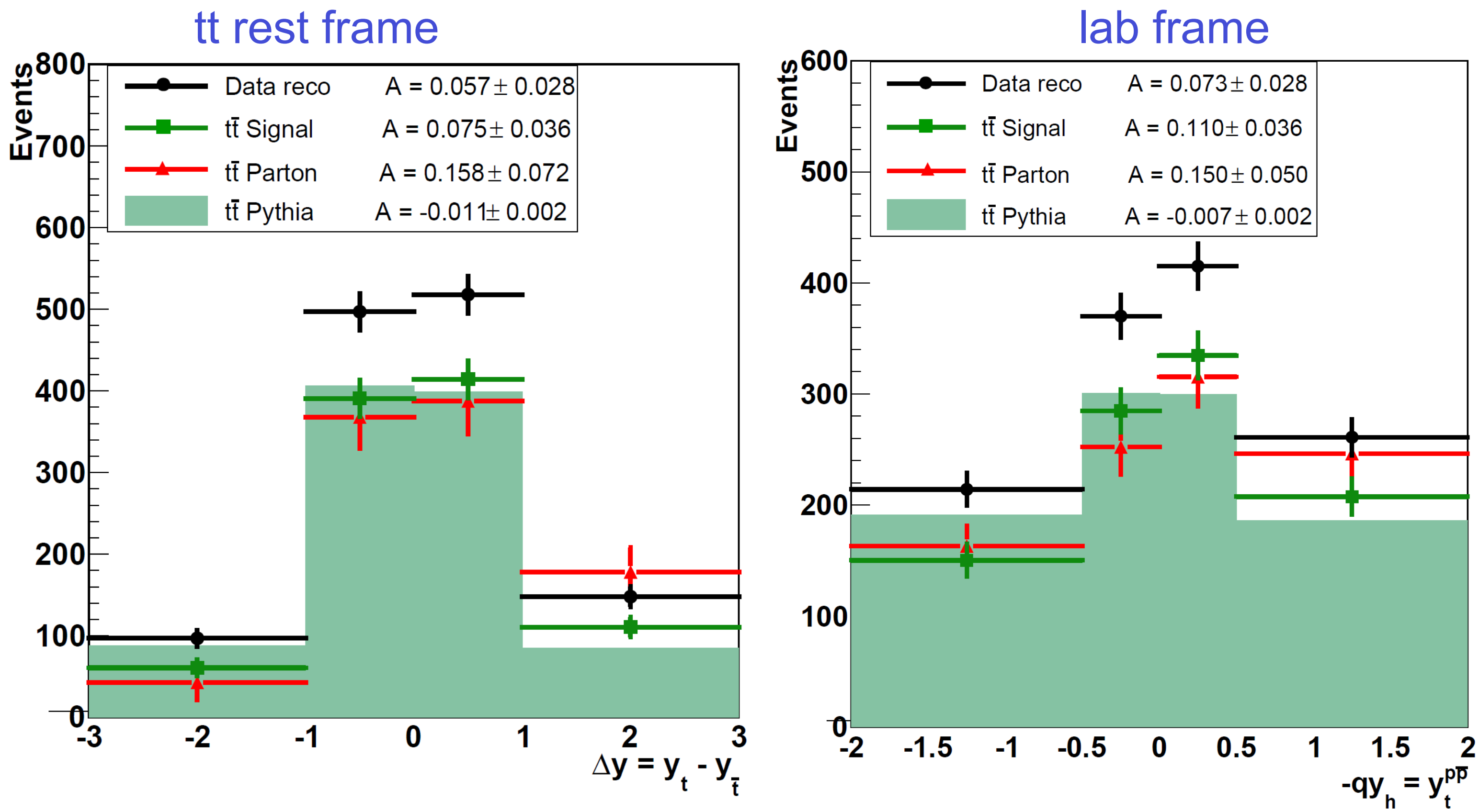
- dN/dy parton level histogram
  - parton level bins j w/ contents P_j
- the top data signal
  - $T_i = S_{ij} \times A_j \times P_j$
- where
  - the A_j are the acceptances for each bin
  - the S_{ij} are the bin-to-bin migration ratios
  - both measured with symmetric Pythia
- dN/dy data level histogram
  - 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

4-bin measurements



sample	level	$A^{t\bar{t}}$	$A^{p\bar{p}}$
data	data	0.057 ± 0.028	0.073 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004	0.001 ± 0.003
data	signal	0.075 ± 0.037	0.110 ± 0.039
MC@NLO	$t\bar{t}$	0.024 ± 0.005	0.018 ± 0.005
data	parton	0.158 ± 0.074	0.150 ± 0.055
MCFM	parton	0.058 ± 0.009	0.038 ± 0.006

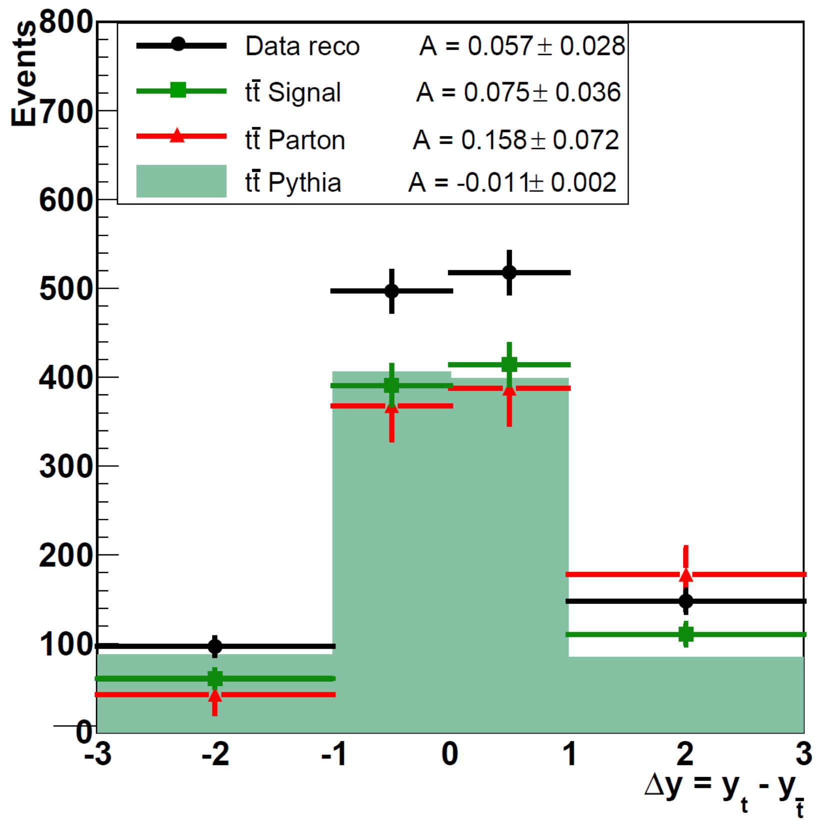
4-bin measurements

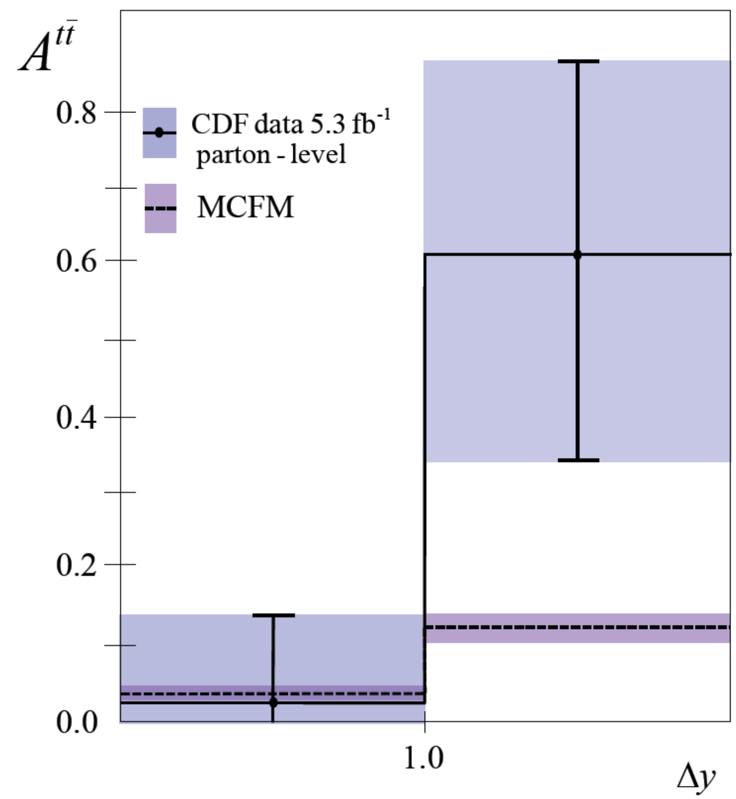


sample	level	$A^{t\bar{t}}$
data	data	0.057 ± 0.028
MC@NLO	$t\bar{t}$+bkg	0.017 ± 0.004
data	signal	0.075 ± 0.037
MC@NLO	$t\bar{t}$	0.024 ± 0.005
data	parton	0.158 ± 0.074
MCFM	parton	0.058 ± 0.009

D0 signal level 4.3 fb^{-1}
0.08±0.04

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

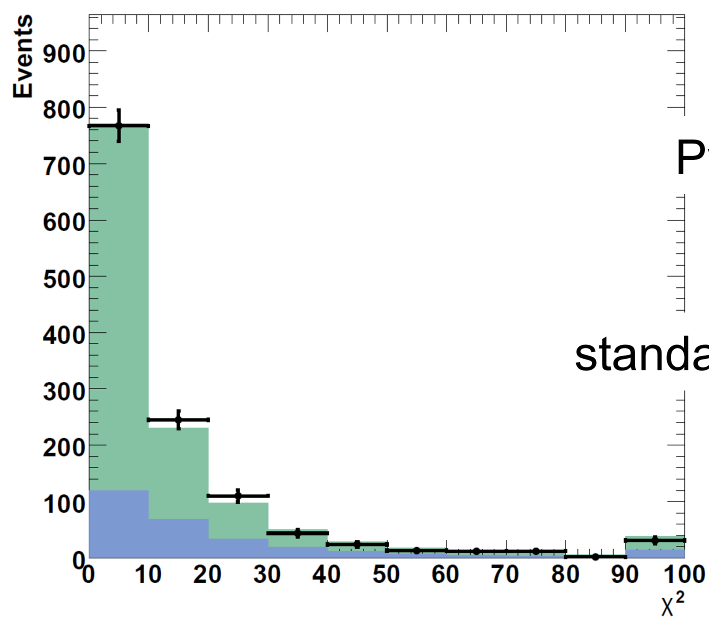
top reconstruction

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

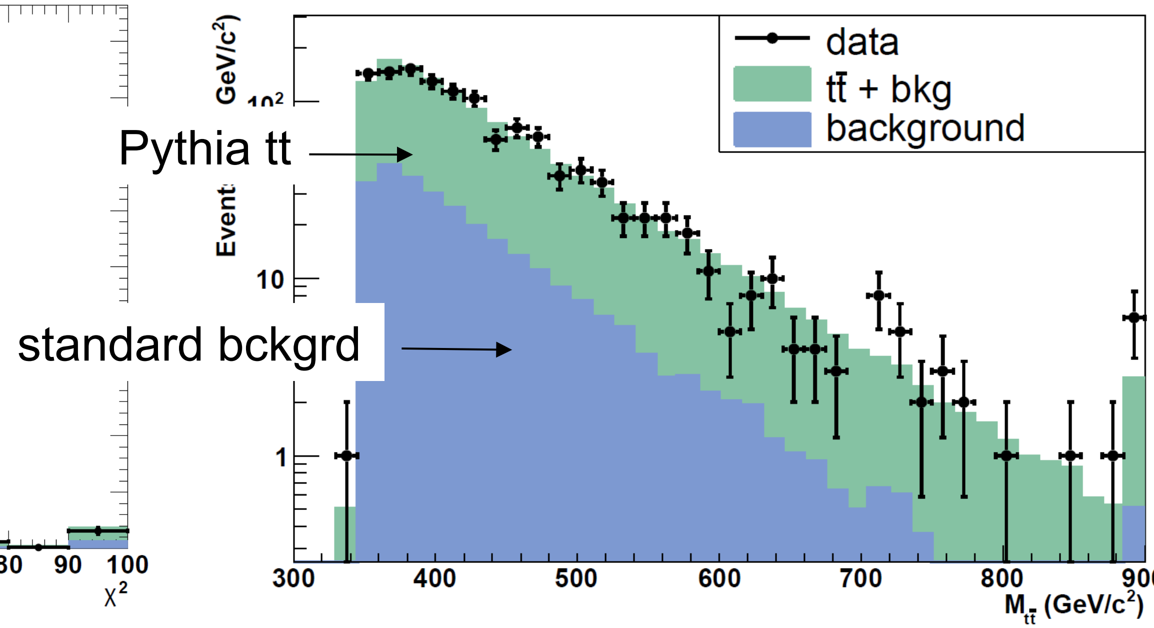
- Jet-parton assignment, $p_z(\nu)$ via minimum of simple χ^2
  - Constraints: M_W = 80.4 GeV/c2, Mt = 175 GeV/c^2, btag = b
  - Float jet p_t within errors

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

χ^2

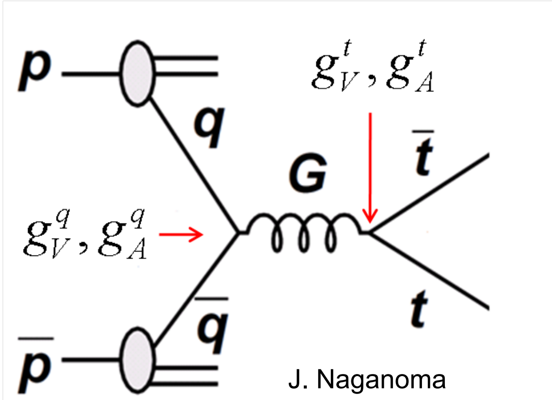


$M_{t\bar{t}}$



color octet model

- need to test methodology on large asymmetry
- model: color octets with axial couplings
- this is a test sample. **not a hypothesis**



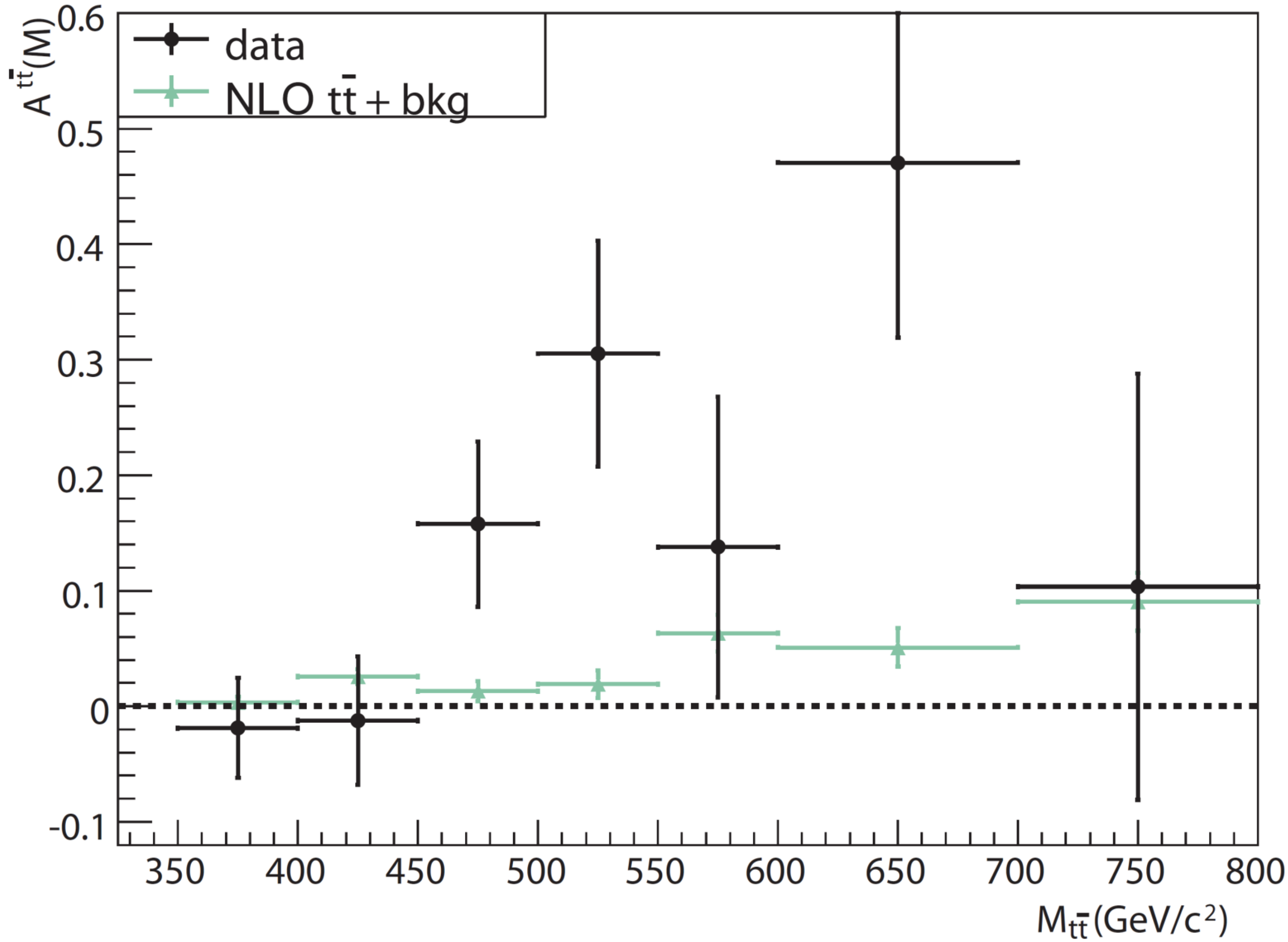
- after Ferrario and Rodrigo arXiv:0906.5541
  - thanks to T. Tait for Madgraph
- If $g_A^q = -g_A^t$ get positive asymmetry
- Octet A
  - $g_V = 0$, $|g_A = 3/2|$
  - $M_G = 2.0$ TeV
  - $\sigma/\sigma_{sm} = 1.02$
  - ~ M_{tt} spectrum compares to Pythia
  - Model: True $A_{tt} = 0.16$ Reco $A_{tt} = 0.08$
  - Data: Parton $A_{tt} = 0.15$, Reco $A_{tt} = 0.06$
- Octet B
  - MG = 1.8 TeV. asymmetries bigger; σ, M_{tt} disrepancies bigger

the two-bin boundary

- simplest A(M): two bins
- high and low mass
- where to put boundary?
- look at significance at high mass vs boundary
- ➢ best boundary: 450 GeV/c^2

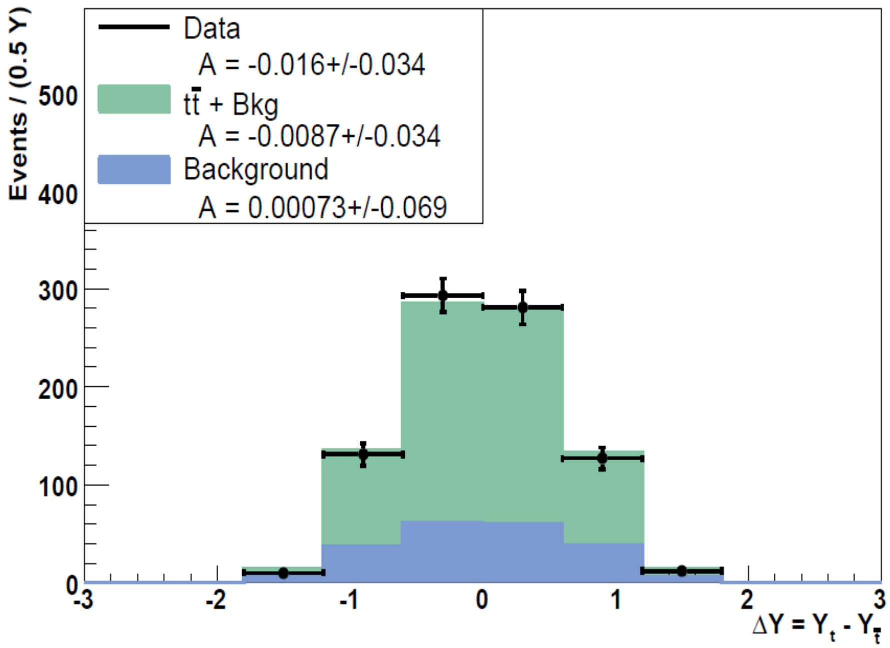
	Octet A		Octet B	
bin-edge (GeV/c^2)	A^{tt}	significance	A^{tt}	significance
345	0.082 ± 0.028	2.90	0.168 ± 0.028	5.99
400	0.128 ± 0.036	3.55	0.235 ± 0.035	6.74
450	0.183 ± 0.047	3.91	0.310 ± 0.044	7.08
500	0.215 ± 0.060	3.60	0.369 ± 0.054	6.81
550	0.246 ± 0.076	3.25	0.425 ± 0.066	6.43
600	0.290 ± 0.097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

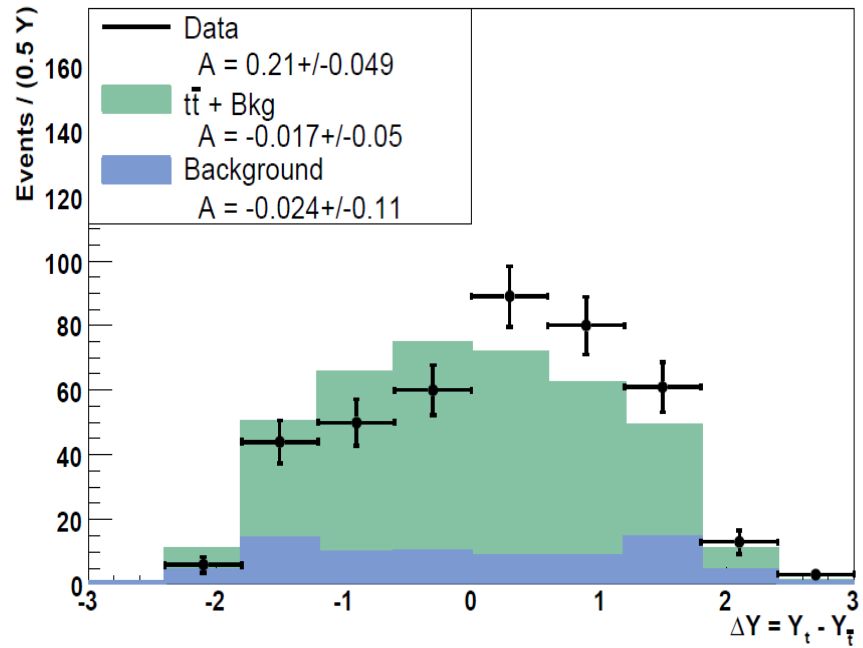
$A^{tt}(M_{tt,\,i})$



- 50 /100 GeV bins below/above 600 GeV/c2

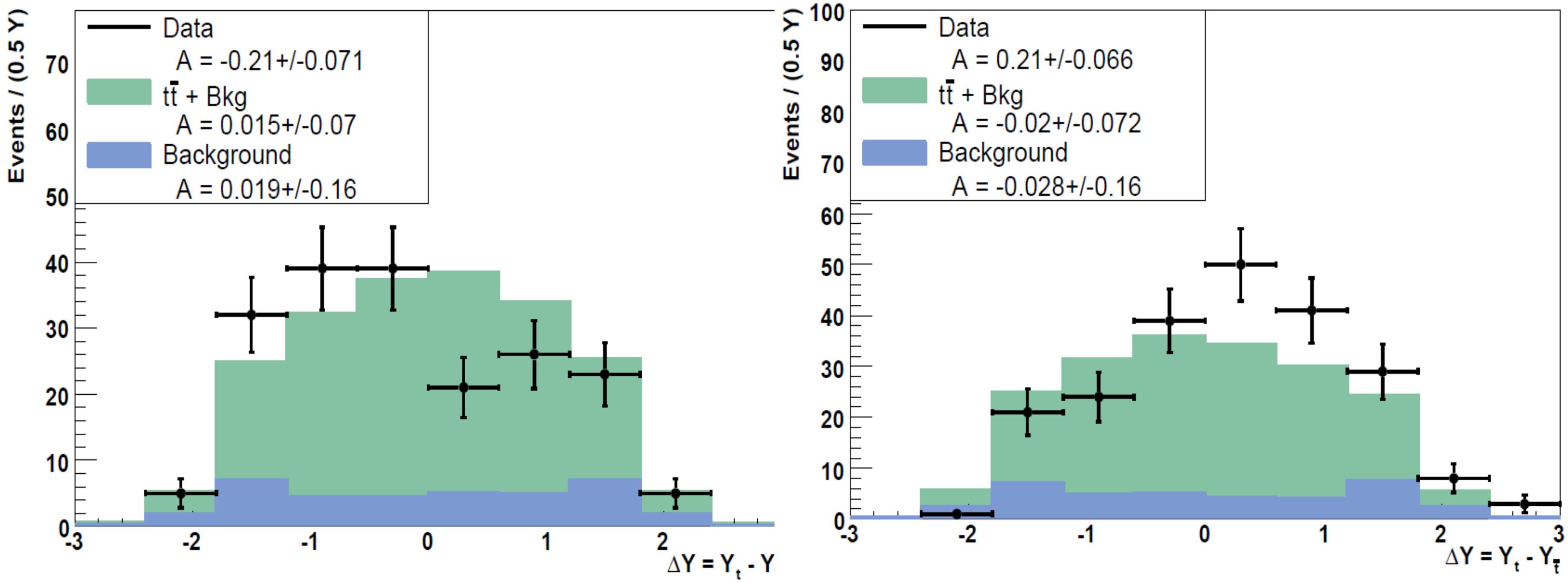
data: Δy at low and high mass





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 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 conserving charge asymmetry.

unfold to the parton level

- dN/dy parton level histogram
  - parton level bins j w/ contents Pj
- 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 measured with symmetric Pythia
- dN/dy data level histogram
  - parton level bins j w/ contents Pj
  - data: in bins i w/ contents $D_i=T_i+B_i$
- 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

BUT NOW:

4 bins in Δy and M_{tt}

low mass forward
low mass backward
high mass forward
high mass backward

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

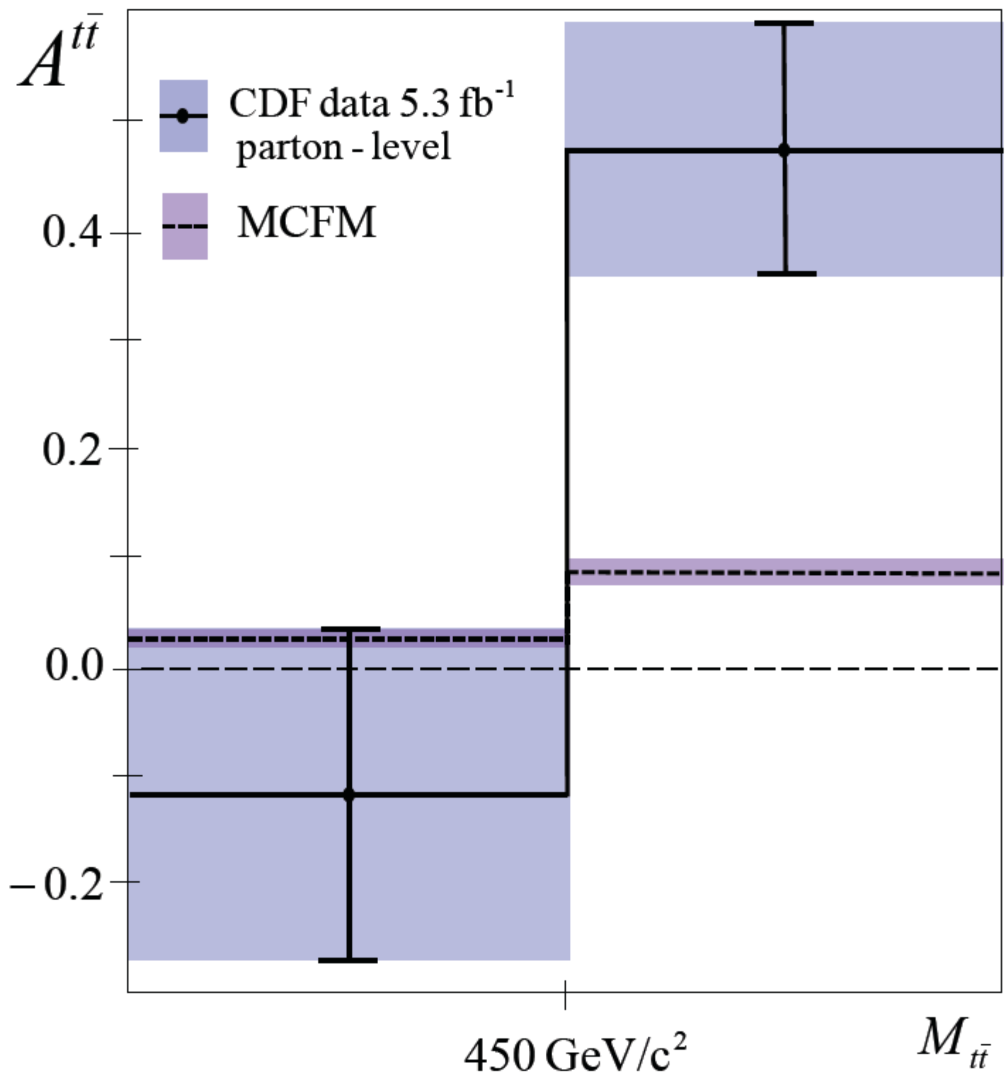
TABLE XII: Systematic uncertainties in the two-mass bin unfold

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

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

TABLE XIII: Asymmetry $A^{t\bar{t}}$ at high and low mass compared to prediction.

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



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

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?

Summary

- Inclusive A in lab and tt frames in 2 sigma excess over SM
- Consistent with CP conservation

- A in the tt frame has a strong dependence on Δy, M_{tt}
- For M_{tt} > 450 GeV/c^2

$$A^{tt}_{reco} = 0.210 \pm 0.049, \quad A^{tt}_{parton} = 0.475 \pm 0.112$$

$$A^{tt}_{NLO\ reco} = 0.043 \pm 0.006 \quad A^{tt}_{MCFM} = 0.088 \pm 0.013$$

- The asymmetry at high mass is consistent with CP conservation
- Most cross-checks rule out non-physics, although a few puzzles

➢ The modest inclusive asymmetry originates with a significant effect at large Δy, M_{tt}

- There is a lot more work to do!