THE TOP PAIR FORWARD-BACKWARD ASYMMETRY IN THE FULL CDF DATASET

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On Behalf of the CDF Collaboration
THE TOP ASYMMETRY

- Very large top mass → intriguing possibilities for top quark interactions
  - Special role in EWSB? Enhanced couplings to new physics?
  - Precision top property measurements can provide the answers

- Previous measurements: large forward-backward asymmetry ($A_{FB}$) in the production angle
  - Equivalent to a charge asymmetry

- Use $\Delta y$ as a proxy for production angle
  - Invariant to boosts along the beamline
    - $A_{FB}$ measured in top pair rest frame
    - Inclusive $A_{FB}$ is the same in $\Delta y$ and $\cos \theta$

- $A_{FB}$ measurement is unique to the Tevatron
  - LHC experiments can see a charge asymmetry
  - But it requires different techniques and the expected magnitude is much smaller
The Standard Model Prediction

- **Leading order:** no asymmetry
- **Next-to-leading order:** small positive asymmetry
- Some uncertainty regarding theory predictions
  - E.g., use LO or NLO cross-section for $A_{FB}$ denominator?
- Predictions shown today are from NLO Monte Carlo generator POWHEG
  - Flat correction of 26% in $\Delta y$ asymmetries for electroweak contributions

\[ A_{FB}^{NLO} = 6.6\% \]

**POWHEG:**

**EW Corrections:**
Kuhn and Rodrigo, JHEP **1201**, 063 (2012)
**A_{FB} Functional Dependencies**

- Expected standard model dependence of $A_{FB}$ on $\cos \theta$ (top) and $M_{tt}$ (bottom)
The Asymmetry in ~5 fb$^{-1}$

- Both CDF and D0 measure large inclusive $A_{FB}$
  - $\sim 3\sigma$ from no asymmetry
  - $\sim 1.5-2\sigma$ above SM prediction
  - Good consistency between measurements

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Parton Level $A_{FB}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$CDF Lep+Jets, 5.3 fb$^{-1}$</td>
<td>15.8 ± 7.4</td>
</tr>
<tr>
<td>$^2$CDF Dilepton, 5.1 fb$^{-1}$</td>
<td>42 ± 16</td>
</tr>
<tr>
<td>$^3$CDF Combined</td>
<td>20.1 ± 6.7</td>
</tr>
<tr>
<td>$^4$D0 Lep+Jets, 5.4 fb$^{-1}$</td>
<td>19.6 ± 6.5</td>
</tr>
<tr>
<td>Informal Combination*</td>
<td>19.8 ± 4.7</td>
</tr>
<tr>
<td>NLO (QCD+EW)</td>
<td>6.6</td>
</tr>
</tbody>
</table>

*NOT an official result – just a simple weighted average of the D0 lepton+jets and the combined CDF results (correlations of systematics NOT included)

MASS AND RAPIDITY DEPENDENCE
- Mass and rapidity dependence studied in only 2 bins of $M_{tt}$ and $\Delta y$ – results are somewhat ambiguous
  - Large mass dependence at CDF, no significant effect at D0
    - Consistent at $\sim 1.7\sigma$ level
  - CDF observes large rapidity dependence, smaller at D0
    - Consistent within $1\sigma$

<table>
<thead>
<tr>
<th>Background-Subtracted $A_{FB}$ (%)</th>
<th>D0 Lep+Jet, 5.4 fb$^{-1}$</th>
<th>CDF Lep+Jet, 5.3 fb$^{-1}$</th>
<th>Informal Combination*</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{tt} &lt; 450$ GeV/$c^2$</td>
<td>7.6 ± 4.8</td>
<td>−2.2 ± 4.3</td>
<td>2.1 ± 3.2*</td>
</tr>
<tr>
<td>$M_{tt} \geq 450$ GeV/$c^2$</td>
<td>11.5 ± 6.0</td>
<td>26.6 ± 6.2</td>
<td>18.6 ± 4.3*</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>&lt; 1.0$</td>
<td>6.1 ± 4.1</td>
</tr>
<tr>
<td>$</td>
<td>\Delta y</td>
<td>\geq 1.0$</td>
<td>21.3 ± 9.7</td>
</tr>
</tbody>
</table>

*NOT an official result – just a simple weighted average of the D0 and CDF lepton+jets results
**Theoretical Responses to a Large $A_{FB}$**

- Some deviation from SM in 5 fb\(^{-1}\) results
  - Largest (CDF, high mass) > 3 $\sigma$
  - Much theoretical work followed
- Do we need better understanding of SM?
  - Refined calculations
    - EW corrections
    - NNLO calculations in progress
  - SM prediction increased, but not yet enough to match observed data
- Could it be new physics?
  - Two main classes of models:
    - s-channel mediator (e.g., axigluon)
    - t-channel flavor changing mediator (e.g., $W'$, $Z'$)
  - Mass/rapidity dependence can untangle new physics from QCD
Overview of the CDF Analysis

- Full CDF dataset (8.7 fb\(^{-1}\) with full detector working)
  - New data stream also added
  - Lepton+jets selection: 1 lepton, \(\geq 4\) jets (\(\geq 1\) \(b\)-tag), large missing \(E_T\)
  - 2498 candidate events – doubles the 5.3 fb\(^{-1}\) dataset (1260)
  - 505 predicted background events

- Events reconstructed with \(\chi^2\)-based kinematic fit
  - Lepton charge fixes the charge of all final state objects

- NLO generator POWHEG for signal modeling
  - 5.3 fb\(^{-1}\) analysis used PYTHIA (LO)

- New regularized unfolding method for correction to parton level
THREE MEASUREMENT LEVELS

- $A_{FB}$ at three levels of correction (focus on 2 and 3):
  1. Reconstruction (Raw Data) Level:
     - Observed data, no corrections
     - Includes background contributions
     - *NLO $A_{FB}$ (with backgrounds): 2.6%
  2. Background Subtracted (Signal) Level:
     - Remove predicted backgrounds
     - Pure top sample, but includes selection and reconstruction effects
     - *NLO $A_{FB}$: 3.3%
  3. Parton Level:
     - Correct for acceptances and reconstruction
     - Direct comparison to theory models
     - *NLO $A_{FB}$: 6.6%

*NLO predictions in this talk always include flat 26% correction to POWHEG for electroweak contributions
**RECONSTRUCTION LEVEL $\Delta y$ IN 8.7 fb$^{-1}$**

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

- **I+Jets Data**
  - $A_{FB} = 0.066 \pm 0.02$

- **NLO (QCD + EW) $t\bar{t}$ + Bkg**
  - $A_{FB} = 0.026$

- **Bkg**
  - $A_{FB} = -0.0066$

- **Blue: background prediction**
- **Green: NLO POWHEG signal**
- **Stacked with backgrounds**
- **Black: observed data**

- **NLO signal plus backgrounds predict $A_{FB} = 2.6%$**
  - Signal prediction includes reweighting for electroweak contributions

- **Observed inclusive asymmetry is (6.6 ± 2.0)%**
  - $> 3 \sigma$ from no asymmetry
REMOMING THE BACKGROUNDS

- ~20% of selected sample is composed of events from background sources
  - Dominant sources: W+jets, QCD multi-jet events
  - Backgrounds have small inherent asymmetry, but dilute any $A_{FB}$ in top events
- Subtract predicted backgrounds from the observed data to yield the pure top signal
Observed asymmetry after background subtraction is $(8.5 \pm 2.5)\%$

- NLO POWHEG predicts 3.3\%
  - Observation is $3.4 \sigma$ from no $A_{FB}$, $2.1 \sigma$ from prediction
**RAPIDITY-DEPENDENT DIFFERENTIAL A_{FB}**

Observed \( A_{FB} \) as a function of \(|\Delta y|\) well-described by linear ansatz

\[
A_{FB}(|\Delta y|) = \frac{N(|\Delta y|) - N(-|\Delta y|)}{N(|\Delta y|) + N(-|\Delta y|)}
\]

- **Observed \( A_{FB} \) as a function of \(|\Delta y|\) well-described by linear ansatz**
  - Determine best-fit slope — easily compare data to prediction
  - \( \chi^2 / \text{d.o.f.} = 1.0 \), significant non-zero slope
  - Slope is not a specific theoretical parameter
    - Linear fit motivated by approximate linearity of SM prediction
**Mass-Dependent Differential $A_{FB}$**

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

$A_{FB}(M_{tt}) = \frac{N_F(M_{tt}) - N_B(M_{tt})}{N_F(M_{tt}) + N_B(M_{tt})}$

- Determine $A_{FB}$ as a function of $M_{tt}$ with finer binning
- Again well-described by linear ansatz
  - Determine best-fit slope for data and prediction
  - $\chi^2$/d.o.f. = 0.3
Determining the Significance

- How significant is the discrepancy between the POWHEG SM prediction and observed differential $A_{FB}$?
  - Evaluate at background-subtracted level – avoid complications from correction procedure
- Quantify by comparing best-fit slopes to find p-value
- Perform simulated experiments with Poisson fluctuations on nominal POWHEG prediction
  - No theory uncertainty included – compare specifically to the NLO POWHEG calculation (with EW corrections)
- p-value: fraction of experiments where $\alpha_{NLO} \geq \alpha_{data}$
**P-VALUES FOR DATA SLOPES VS. PREDICTION**

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

**$\alpha (M_{tt})$ p-value:** $6.46 \times 10^{-3}$

**$\alpha (\Delta y)$ p-value:** $8.92 \times 10^{-3}$
**BACKGROUND-SUBTRACTED LEPTONIC A_{FB}**

- Lepton allows independent measurement of the asymmetry
  - Direction of motion correlated with parent top quark
  - Measurement of lepton direction does not require event reconstruction

- Measure asymmetry in \( q \times \eta_{lep} \)

### Table: Predicted vs. Observed

<table>
<thead>
<tr>
<th>Sample</th>
<th>Predicted ( A_{FB} ) (%)</th>
<th>Observed ( A_{FB} ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>1.6</td>
<td>6.6 ± 2.5</td>
</tr>
<tr>
<td>( M_{tt} &lt; 450 ) GeV/c^2</td>
<td>0.7</td>
<td>3.7 ± 3.1</td>
</tr>
<tr>
<td>( M_{tt} \geq 450 ) GeV/c^2</td>
<td>3.2</td>
<td>11.6 ± 4.2</td>
</tr>
</tbody>
</table>
CORRECTING TO THE PARTON LEVEL

- Background-subtracted results use pure top sample
- Data cannot be directly compared to theoretical predictions
  - Limited acceptance
  - Finite detector resolution
  - Need full detector simulation to compare theory to background-subtracted data
- Correct to parton level in two steps:
  1. Unsmearing Correction (bin migration)
     - Regularized singular value decomposition unfolding algorithm
       - ROOUNFOLD software package
  2. Acceptance Correction
     - Multiplicative correction to each bin based on POWHEG
- Test by correcting distributions created from SM and various BSM Monte Carlo samples
- Final results: differential cross-section and parton-level $A_{FB}$ measurement
Parton-level $\Delta y$ distribution normalized to $\sigma_{\text{tot}} = 7.4$ pb

- Result is $d\sigma/d(\Delta y)$

- Measured inclusive asymmetry is $(16.2 \pm 4.7)\%$
  - $3.4\sigma$ from null asymmetry
  - NLO prediction: 6.6%
Linear ansatz applies also to parton level $A_{FB}$ as a function of $|\Delta y|$.

- $\chi^2/\text{d.o.f.} = 0.3$

After correction, bins are correlated – use full covariance matrix in performing the $\chi^2$ fit.
Mass-Dependent Differential \( A_{FB} \)

- Parton level \( A_{FB} \) vs. \( M_{tt} \) well-described by a line with slope larger than NLO prediction
  - \( \chi^2 \)/d.o.f = 0.1
CONCLUSIONS

- CDF has updated the top pair $A_{FB}$ measurement using the full dataset
- Inclusive $A_{FB}$ remains significant
  - Parton level $A_{FB} = (16.2 \pm 4.7)\%$
    - $3.4 \sigma$ from no asymmetry, $2 \sigma$ from NLO POWHEG prediction
- Mass and rapidity dependence from 5.3 fb$^{-1}$ confirmed in full dataset at background-subtracted and parton levels
  - Behavior is well-described by a linear ansatz
    - Slopes are non-zero at $>3 \sigma$ level
    - p-values (after background subtraction) relative to POWHEG of $6.46 \times 10^{-3}$ for $A_{FB}$ vs. $M_{tt}$ and $8.92 \times 10^{-3}$ for $A_{FB}$ vs. $|\Delta y|$
- CDF has several additional $A_{FB}$ analyses coming soon
  - Exploring new kinematic variables in the lepton+jets analysis
  - Analyzing the full CDF dataset in the dilepton channel
  - Measuring $A_{FB}$ in bottom-antibottom pairs
Backup Slides
SAMPLE COMPOSITION

- Top signal modeled with NLO POWHEG
- Electroweak backgrounds from Monte Carlo
- W+jets shape from Monte Carlo
- QCD shape from data
- W+jets and QCD normalizations determined from fit to the missing $E_T$ spectrum
- 505 predicted background events
  - S:B ratio ~4:1

<table>
<thead>
<tr>
<th>Source</th>
<th>Predicted Event Count, 8.7 fb$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>W + Heavy Flavor</td>
<td>241 ± 78</td>
</tr>
<tr>
<td>Non-W (QCD)</td>
<td>98 ± 51</td>
</tr>
<tr>
<td>W + Light Flavor</td>
<td>96 ± 29</td>
</tr>
<tr>
<td>Single Top</td>
<td>33 ± 2</td>
</tr>
<tr>
<td>Diboson</td>
<td>19 ± 3</td>
</tr>
<tr>
<td>Z + Jets</td>
<td>18 ± 2</td>
</tr>
<tr>
<td>Total Background</td>
<td>505 ± 123</td>
</tr>
<tr>
<td>Top Pairs (7.4 pb)</td>
<td>2037 ± 277</td>
</tr>
<tr>
<td>Total Prediction</td>
<td>2542 ± 303</td>
</tr>
<tr>
<td>Data</td>
<td>2498</td>
</tr>
</tbody>
</table>
RECONSTRUCTING TOP PAIR EVENTS

- Match observed jets to top decay products: $\chi^2$-based kinematic fit to top-antitop hypothesis
  - $M_t = 172.5$ GeV/$c^2$
  - $M_W = 80.4$ GeV/$c^2$

$$\chi^2 = \sum_{i=l,\text{jets}} \frac{(p_{T,i,\text{fit}} - p_{T,i,\text{meas}})^2}{\sigma_i} + \sum_{j=x,y} \frac{(p_{j,\text{Unc.Energy,fit}} - p_{j,\text{Unc.Energy,meas}})^2}{\sigma_j}$$

$$+ \frac{(M_{jj} - M_W)^2}{\Gamma_W^2} + \frac{(M_{lv} - M_W)^2}{\Gamma_W^2} + \frac{(M_{bjj} - M_t)^2}{\Gamma_t^2} + \frac{(M_{blv} - M_t)^2}{\Gamma_t^2}$$

- Four leading jets enter the fit
- Measured energies float within uncertainties
- Choose solution with the smallest $\chi^2$
- Determine top and antitop four-vectors from decay product momenta
- Lepton charge used to assign the charge of all final state objects
**The \( \chi^2 \) and \( M_{tt} \) Distributions**

- \( M_{tt} \) and \( \chi^2 \) of the kinematic reconstruction
  - Sensitive checks of reconstruction method
- Well-modeled by signal + background prediction
  - Even for events with large \( \chi^2 \)

**Graphs: CDF Run II Preliminary \( L = 8.7 \text{ fb}^{-1} \)**

- **Blue**: background prediction
- **Green**: NLO POWHEG signal
  - Stacked with backgrounds
- **Black**: observed data
**The Top Pair $P_T$**

- Transverse momentum of top pair is a good check of background model, event reconstruction
  - Sensitive to soft jets
  - Correlated with $A_{FB}$
    - ISR/FSR give negative contribution to asymmetry

- Good agreement between data and NLO MC + background prediction
THE TOP PAIR $P_T$

- D0 $5.4 \text{ fb}^{-1}$ analysis observed mis-modeling at low $P_T$ (top)
- CDF finds agreement with NLO predictions of POWHEG and MC@NLO (bottom)
Check background prediction in background-dominated region

Events pass all selection requirements except they do not have any $b$-tagged jets

Good agreement between data and expectation
**Reconstruction Level $\Delta y$ at High and Low Mass**

- $\Delta y$ distribution for $M_{tt}$ above and below 450 GeV/c$^2$
  - Cut-off defined in 5.3 fb$^{-1}$ analysis
- Low mass consistent with expectation
- Large asymmetry at high mass: $(15.5 \pm 3.4\%)$
  - $4.5\sigma$ from no asymmetry, $3.3\sigma$ from prediction
  - Consistent in events with positive $(15.5 \pm 4.8\%)$ and negative $(15.6 \pm 4.8\%)$ leptons
Linear ansatz holds even at reconstruction level before any background subtraction

- $\chi^2$/d.o.f. = 1.1
**Reconstruction Level Mass Dependence**

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

- $A_{FB}$ as a function of $M_{tt}$ at reconstruction level also well-described by linear ansatz
  - $\chi^2$/d.o.f. = 0.2

\[ \alpha_{M_{tt}} = (8.9 \pm 2.3) \times 10^{-4} \]

\[ \alpha_{M_{tt}} = 2.2 \times 10^{-4} \]
Could the asymmetry result from a temporary detector effect, mis-calibration, etc.?

- Measure $A_{FB}$ as a function of the total number of observed events in the data sample
- $A_{FB}$ constant within uncertainties through the entire course of Run II data taking
**Background-Subtracted $\Delta y$ at High and Low Mass**

- $\Delta y$ distribution for $M_{tt}$ above and below 450 GeV/c$^2$
  - Cut-off defined in 5.3 fb$^{-1}$ analysis
- Low mass distribution consistent with NLO prediction
- The large asymmetry predominantly arises at high mass – (19.8 ± 4.3)%
  - 4.6 $\sigma$ from no asymmetry
  - NLO POWHEG predicts 6.2% at high mass
COMPARISON TO PREVIOUS BACKGROUND-SUBTRACTED MASS-DEPENDENT RESULTS

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<thead>
<tr>
<th>Background-Subtracted $A_{FB}$ (%)</th>
<th>D0 Lep+Jet, 5.4 fb$^{-1}$</th>
<th>CDF Lep+Jet, 5.3 fb$^{-1}$</th>
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<td>$M_{tt} \geq 450$ GeV/c$^2$</td>
<td>11.5 ± 6.0</td>
<td>26.6 ± 6.2</td>
<td>18.6 ± 4.3*</td>
<td>19.8 ± 4.3</td>
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- Two-bin mass dependence statistically consistent among the D0 measurement and both CDF results
  - Very good agreement of new CDF data with simple weighted average of previous CDF and D0 results

*NOT an official result – just a simple weighted average of the D0 and CDF lepton+jets results
THE INVARIANT MASS DISTRIBUTION FOR FORWARD AND BACKWARD EVENTS

- Compare the $M_{tt}$ distributions for events with positive and negative $\Delta y$
  - Approximately equal at lowest masses, but excess of forward events at higher mass
P-VALUE DETERMINATION

- Plots show slopes for $A_{FB}$ vs. $M_{tt}$ (top) and $A_{FB}$ vs. $\Delta y$ (bottom) measured from fluctuations on NLO prediction at the background-subtracted level.

- p-value: fraction of experiments in which $\alpha_{NLO} \geq \alpha_{Data}$
**SYSTEMATIC UNCERTAINTIES**

- Correction procedure introduces systematic uncertainties related to the signal model, in addition to the background uncertainties discussed previously.
  - Total is small compared to the statistical uncertainty

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background Shape</td>
<td>1.4</td>
</tr>
<tr>
<td>Background Normalization</td>
<td>1.1</td>
</tr>
<tr>
<td>Parton Showering</td>
<td>1.0</td>
</tr>
<tr>
<td>Jet Energy Scale</td>
<td>0.5</td>
</tr>
<tr>
<td>Initial/Final State Radiation</td>
<td>0.5</td>
</tr>
<tr>
<td>Color Reconnection</td>
<td>0.1</td>
</tr>
<tr>
<td>Parton Distribution Functions</td>
<td>0.1</td>
</tr>
<tr>
<td>Correction Procedure</td>
<td>0.3</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>2.2</td>
</tr>
<tr>
<td>Statistical Uncertainty</td>
<td>4.1</td>
</tr>
<tr>
<td>Total Uncertainty</td>
<td>4.7</td>
</tr>
</tbody>
</table>
Mass Distributions for Forward and Backward Events

- Parton-level $M_{tt}$ distributions for events with positive and negative $\Delta y$
- These distributions are then combined to find the differential asymmetry
**Comparison to the 5 fb\(^{-1}\) Results**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Prediction</th>
<th>CDF, 5.3 fb(^{-1})</th>
<th>D0, 5.4 fb(^{-1})</th>
<th>CDF, 8.7 fb(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inclusive</td>
<td>6.6</td>
<td>15.8 ± 7.4</td>
<td>19.6 ± 6.5</td>
<td>16.2 ± 4.7</td>
</tr>
<tr>
<td>(M_{tt} &lt; 450) GeV/c(^2)</td>
<td>4.7</td>
<td>−11.6 ± 15.3</td>
<td>7.8 ± 4.8 (Bkg. Subtracted)</td>
<td>7.8 ± 5.4</td>
</tr>
<tr>
<td>(M_{tt} \geq 450) GeV/c(^2)</td>
<td>10.0</td>
<td>47.5 ± 11.2</td>
<td>11.5 ± 6.0 (Bkg. Subtracted)</td>
<td>29.6 ± 6.7</td>
</tr>
<tr>
<td>(</td>
<td>\Delta y</td>
<td>&lt; 1.0)</td>
<td>4.3</td>
<td>2.6 ± 11.8</td>
</tr>
<tr>
<td>(</td>
<td>\Delta y</td>
<td>\geq 1.0)</td>
<td>13.9</td>
<td>61.1 ± 25.6</td>
</tr>
</tbody>
</table>

- Parton level asymmetries in two bins of \(M_{tt}\) and \(|\Delta y|\) for direct comparison to previous results
The Detector Response Matrix

- Plot shows detector response matrix used for regularized unfold of $\Delta y$
  - Box sizes proportional to bin contents
  - Does not include acceptances (acceptance matrix is diagonal, simply a multiplicative correction to each bin)
- Predominantly diagonal (good resolution) and symmetric (no bias for forward or backward events)
**Bias Tests**

- Check the correction procedure in simulated experiments based on Monte Carlo samples
- Plots show average corrected results compared to true MC distributions in POWHEG (left) and an example new physics (axigluon) sample (right)
The Leptonic Asymmetry

- Could $A_{FB}$ be an artifact of the reconstruction?
- Lepton allows independent measurement of the asymmetry
  - Direction of motion correlated with parent top quark
  - Measurement of lepton direction does not require event reconstruction
- Find asymmetry in $q \times \eta_{lep}$
- $A_{FB}$ exceeds signal + background prediction
  - Significance similar to that of $\Delta y A_{FB}$

Sample | Predicted $A_{FB}$ (%) | Observed $A_{FB}$ (%)
--- | --- | ---
Inclusive | 2.5 | 6.5 ± 2.0
$M_{tt} < 450$ GeV/c$^2$ | 2.3 | 4.7 ± 2.5
$M_{tt} \geq 450$ GeV/c$^2$ | 3.3 | 10.1 ± 3.4