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Charge Asymmetry Measurements at the LHC

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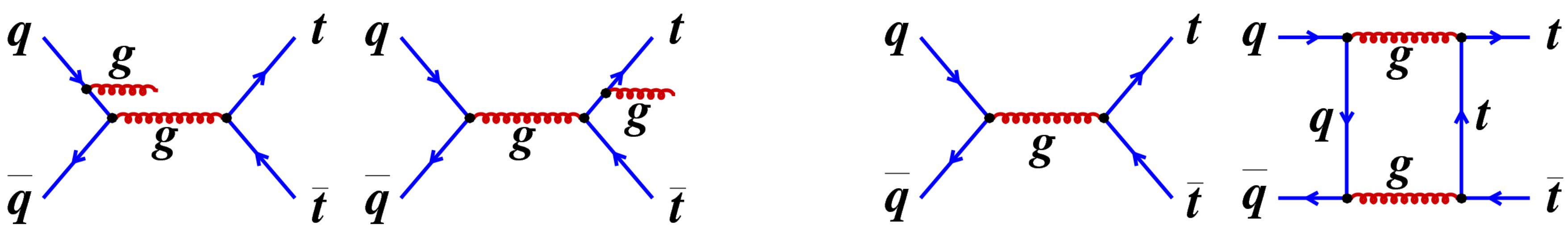
Overview

Charge Asymmetry in General:

- In $q\bar{q} \rightarrow t\bar{t}$: Top quarks are preferably emitted in the direction of the incoming quark, anti-top quarks in the direction of the incoming anti-quark.
- No asymmetry in $gg \rightarrow t\bar{t}$.

In SM:

Only small asymmetry expected from interference effects between ISR and FSR processes and between LO and box diagrams in $q\bar{q} \rightarrow t\bar{t}$.



New Physics:

Top quark production mechanisms with new exchange bosons could enhance the charge asymmetry.

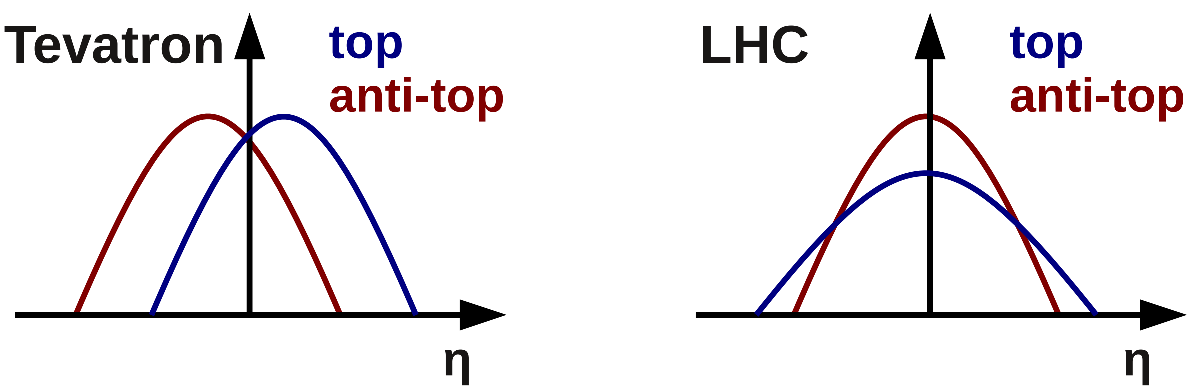
Charge Asymmetry at LHC

LHC: symmetric proton-proton collisions

→ charge asymmetry cannot result in a forward-backward asymmetry as at Tevatron

Visible effects at LHC:

- **Proton-PDF:** Quarks in initial state have on average larger momentum than anti-quarks.
- Charge Asymmetry transfers boost difference to top-antitop final state.

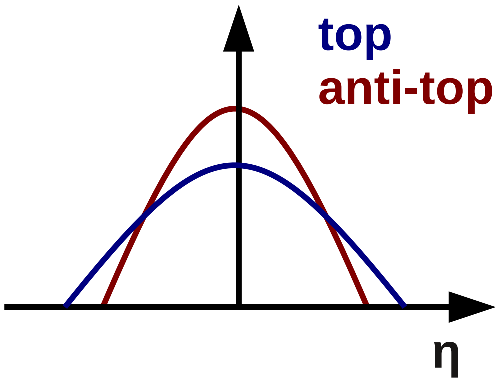


→ expected effects at LHC smaller due to larger $gg \rightarrow t\bar{t}$ contribution

Sensitive Variables

Variables sensitive to the asymmetry are:

- $\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$
- $\Delta|y| = |y_t| - |y_{\bar{t}}|$
- $\Delta y^2 = y_t^2 - y_{\bar{t}}^2 = (y_t - y_{\bar{t}}) \times (y_t + y_{\bar{t}})$ Tevatron variable boosted into $t\bar{t}$ rest frame
  (as proposed in Phys Rev D83 (2011) 114039)



The charge asymmetry can be defined as asymmetry in these variables:

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

$$A_C^y = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} = \frac{N(\Delta y^2>0) - N(\Delta y^2<0)}{N(\Delta y^2>0) + N(\Delta y^2<0)}$$

SM prediction: $A_C \approx 0.01$ (G. Rodrigo)

Measurements Overview

ATLAS (ATLAS-CONF-2011-106)**:**

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

CMS (CMS PAS TOP-11-014)**:**

- used variables: $\Delta|\eta| = |\eta_t| - |\eta_{\bar{t}}|$ and $\Delta y^2 = y_t^2 - y_{\bar{t}}^2$

Common analysis strategy:

- Select top quark pair events in e+jets/μ+jets channel.
- Determine background contributions.
- Reconstruct the top quark momenta.
- Perform an unfolding of the sensitive variable to correct for selection/reconstruction inefficiencies.
- Measure the asymmetry in the corrected spectrum.

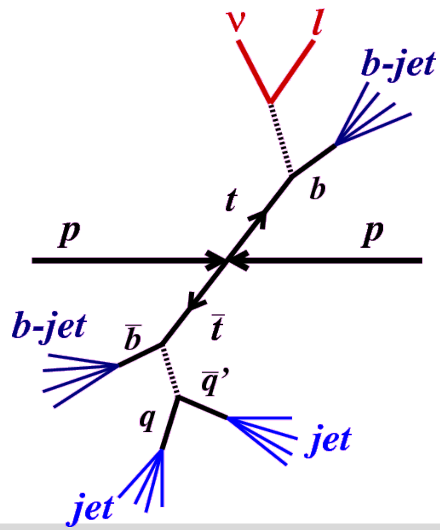
Event Selections

ATLAS:

- single lepton triggers
- exactly one isolated electron (muon) with p_T>25 (20) GeV/c, $|\eta|<2.5$
- at least 4 jets with p_T>25 GeV/c and $|\eta|<2.5$
- one secondary vertex b-tag
- additional cuts against QCD:
  - e+jets: E_T^{miss}>35 GeV and $m_T(W)$>25 GeV
  - μ+jets: E_T^{miss}>20 GeV and $E_T^{miss}+m_T(W)$>60 GeV

CMS:

- lepton+3 jets triggers
- exactly one isolated electron (muon) with E_T>30 GeV, $|\eta|<2.5$ (p_T>20 GeV/c, $|\eta|<2.1$)
- at least 4 jets with p_T>30 GeV/c and $|\eta|<2.4$
- one b-tag (IP significance of 2[nd] track)
- Using particle flow algorithm to define all objects.



Background Estimation ATLAS

- QCD background from matrix method:
  - define loose lepton selection requirements with relaxed isolation cuts

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake} \qquad N^{tight} = \epsilon_{real} N^{loose}_{real} + \epsilon_{fake} N^{loose}_{fake}$$

  - estimate ε_{real} from Z data and ε_{fake} from side-band regions with inverted QCD cuts

    → allows for determination of number of fake leptons in tight selection region

- Determine W+jets rate from asymmetry between positively (D^+) and negatively charged leptons (D^-) in the pretag sample:

$$N_{W^+} + N_{W^-} = \frac{r_{MC}+1}{r_{MC}-1}\left(D^+ - D^-\right)$$

  - W^+/W^- ratio r_{MC} taken from MC corrected for heavy flavor fractions from data
  - extrapolate W+jets rate to tagged sample using tagging efficiency from MC

- Z+jets, diboson and single top rates from MC prediction

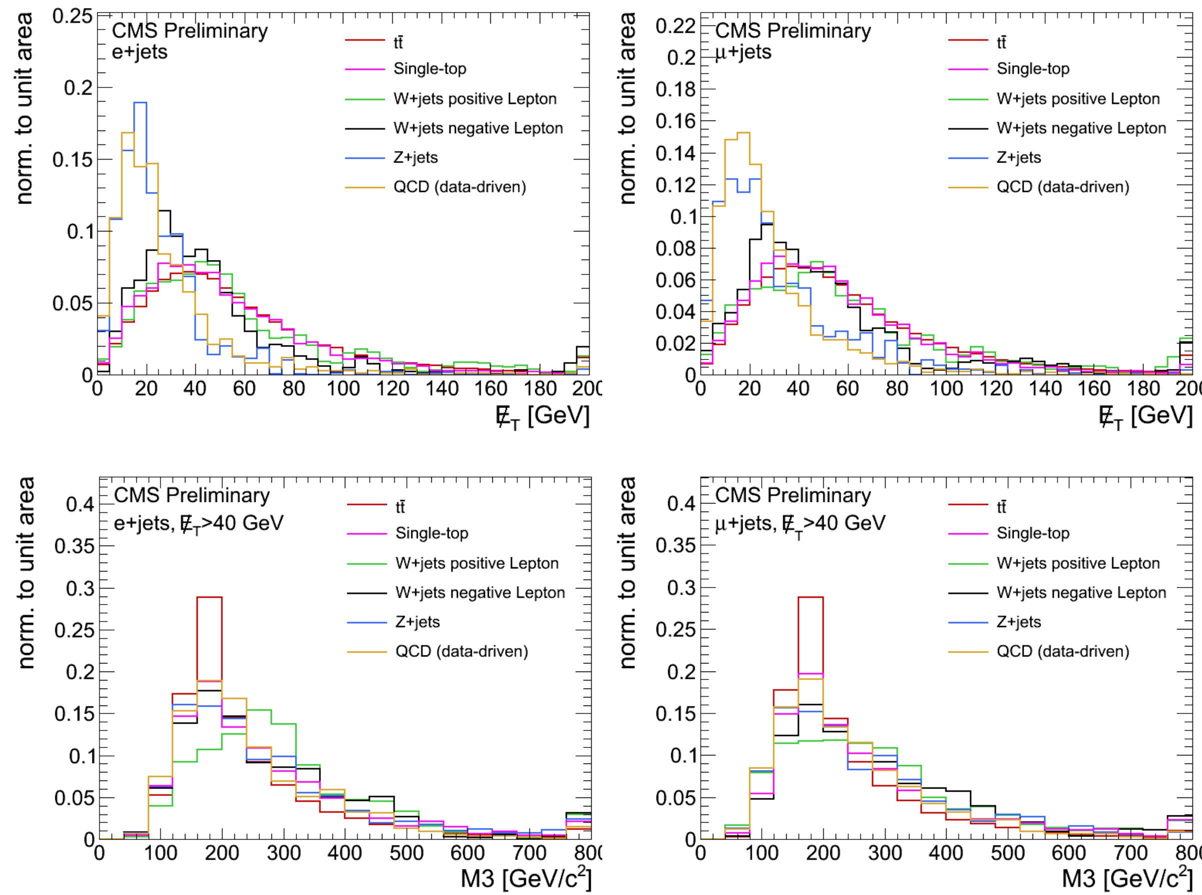
Background Estimation CMS

Estimate sample composition from likelihood fits:

- fit E_T^{miss} for E_T^{miss}<40 GeV
- fit M3 for E_T^{miss}>40 GeV

Fit individually the rates of tt, W^++jets, W^-+jets, QCD e, QCD μ, Z+jets and single top.

Z+jets and single top constrained to SM prediction.



QCD template from data with less-well isolated leptons.

Event Yields

Channel	μ + jets pretag	μ + jets tagged	e + jets pretag	e + jets tagged
$t\bar{t}$	4784 ± 5	3247 ± 4	3293 ± 4	2218 ± 4
Single top	306 ± 2	171 ± 2	219 ± 2	124 ± 2
Z+jets	632 ± 7	43 ± 2	535 ± 7	35 ± 1
Diboson	90 ± 2	8 ± 1	56 ± 1	5 ± 0
W+jets	5741 ± 915	494 ± 234	3436 ± 628	309 ± 144
QCD	1103 ± 552	227 ± 227	665 ± 332	84 ± 84
Total background	7871 ± 1068	943 ± 326	4910 ± 711	557 ± 167
Signal + background	12655 ± 1068	4189 ± 326	8203 ± 711	2775 ± 167
Observed	12705	4392	8193	2997

ATLAS

L_{int}=0.7 fb^{-1}

process	electron+jets	muon+jets	total
$t\bar{t}$	4401 ± 165	5835 ± 199	10236 ± 258
single top (t + tW)	213 ± 58	293 ± 81	507 ± 99
W^++jets	313 ± 84	404 ± 106	718 ± 135
W^-+jets	299 ± 90	245 ± 109	544 ± 141
Z+jets	81 ± 24	85 ± 26	165 ± 35
QCD	355 ± 71	232 ± 79	587 ± 106
total fit result	5663 ± 226	7094 ± 276	12757 ± 357
observed data	5665	7092	12757

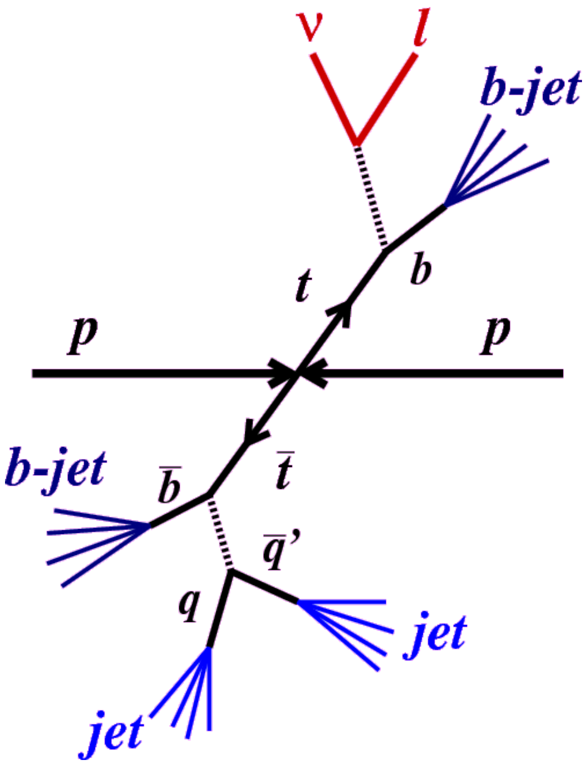
CMS

L_{int}=1.1 fb^{-1}

Several thousand top pair events selected with a purity of >70%

Reconstruction

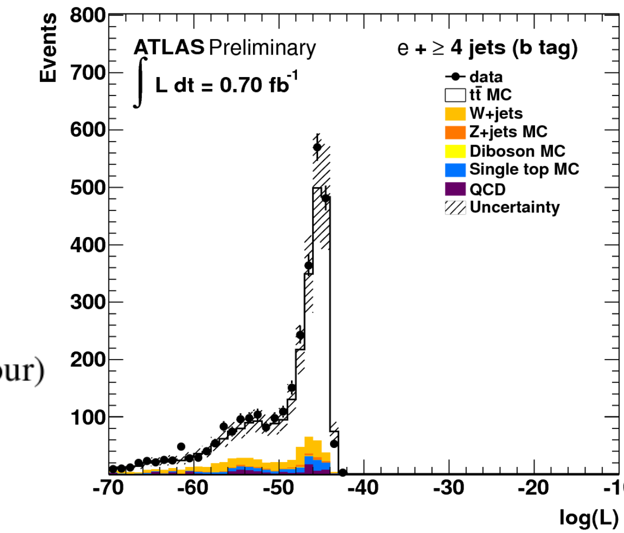
- Measurement of charge asymmetry requires full reconstruction of the top quark 4-momenta.
- Accessible objects: jets, leptons, E_T^{miss}
- Create list of hypotheses for assignment of jets and leptons to top quark decay products
- Jet assignment is ambiguous.
- Find a criterion to select a reconstruction hypothesis which describes the momenta of top quarks best.



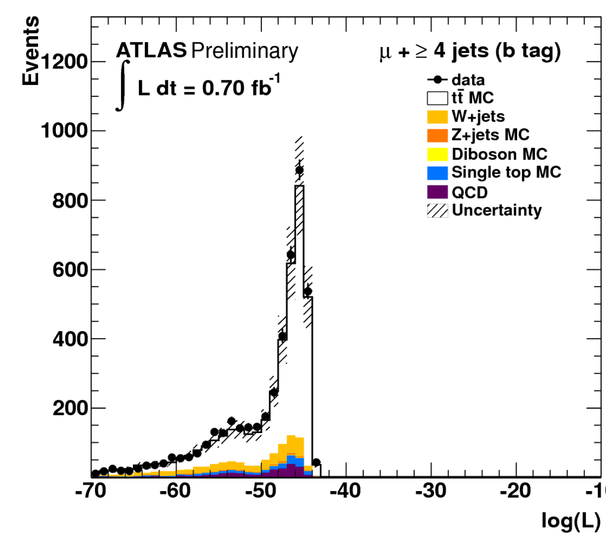
Reconstruction ATLAS

- Construct kinematic likelihood to select one reconstruction hypothesis:

$$
\begin{aligned}
L \;=\; & \mathcal{B}(\widetilde{E}_{\mathrm{p},1},\widetilde{E}_{\mathrm{p},2}|m_W,\Gamma_W)\cdot\mathcal{B}(\widetilde{E}_{\mathrm{lep}},\widetilde{E}_{\nu}|m_W,\Gamma_W)\cdot \\
& \mathcal{B}(\widetilde{E}_{\mathrm{p},1},\widetilde{E}_{\mathrm{p},2},\widetilde{E}_{\mathrm{p},3}|m_t,\Gamma_t)\cdot\mathcal{B}(\widetilde{E}_{\mathrm{lep}},\widetilde{E}_{\nu},\widetilde{E}_{\mathrm{p},4}|m_t,\Gamma_t)\cdot \\
& \mathcal{W}(\widetilde{E}_x^{miss}|\hat{p}_{x,\nu})\cdot\mathcal{W}(\widetilde{E}_y^{miss}|\hat{p}_{y,\nu})\cdot\mathcal{W}(\widetilde{E}_{\mathrm{lep}}|\hat{E}_{\mathrm{lep}})\cdot \\
& \prod_{\mathrm{i}=1}^{4}\mathcal{W}(\widetilde{E}_{\mathrm{p,i}}|\hat{E}_{\mathrm{jet,i}})\cdot\prod_{\mathrm{i}=1}^{4}\mathcal{W}(\widetilde{\eta}_{\mathrm{p,i}}|\hat{\eta}_{\mathrm{jet,i}})\cdot\prod_{\mathrm{i}=1}^{4}\mathcal{W}(\widetilde{\phi}_{\mathrm{p,i}}|\hat{\phi}_{\mathrm{jet,i}})\cdot\prod_{\mathrm{i}=1}^{4}P(\text{tagged}\mid\text{parton flavour})
\end{aligned}
$$



- $\mathcal{B}$: Breit-Wigner functions for top and W mass peaks
- $\mathcal{W}$: transfer functions between partonic and measured quantities
- P: b-tagging probabilities



- Method finds correct event topology in 74% of all matchable events (l+jets events where every parton can be matched to a reconstructed object).

Reconstruction CMS

- No fit of reconstructed momenta, tops directly reconstructed from adding 4-momenta of jets and leptons
- Neutrino momentum from E_T^{miss} and W mass constraint
- Select reconstruction hypothesis with largest ψ:

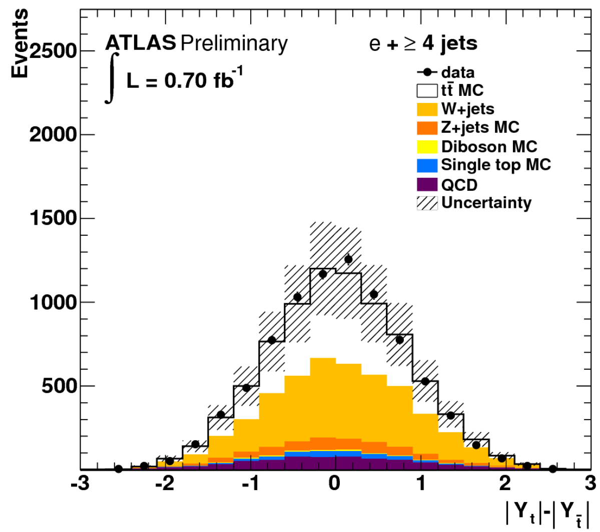
$$\psi = L(m_1)L(m_2)L(m_3)P_b(x_{b,lep})P_b(x_{b,had})(1 - P_b(x_{q1}))(1 - P_b(x_{q2}))$$

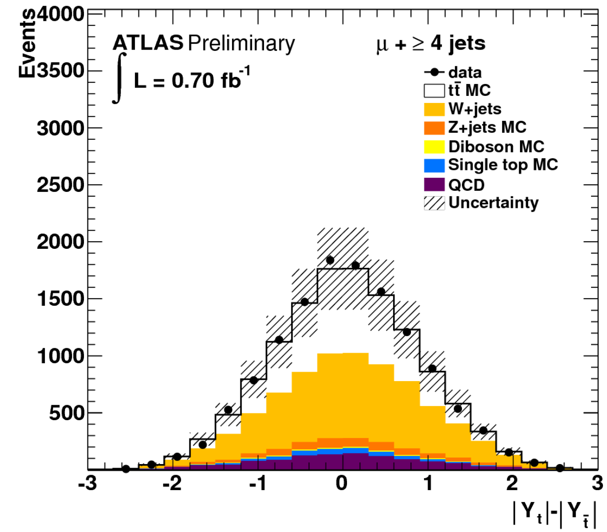
- $L(m_i)$: likelihood of the reconstructed mass m_i to be compatible with the best possible reconstruction hypothesis in MC
- m_1, m_2, m_3: de-correlated masses of tops and hadronically decaying W
- $P_b(x)$: probability of a jet with b tagger output x to be assigned to a b quark in the best possible hypothesis.

- Reconstruction method finds best possible solution in >50% of all matchable events (but using looser matching criteria than ATLAS).

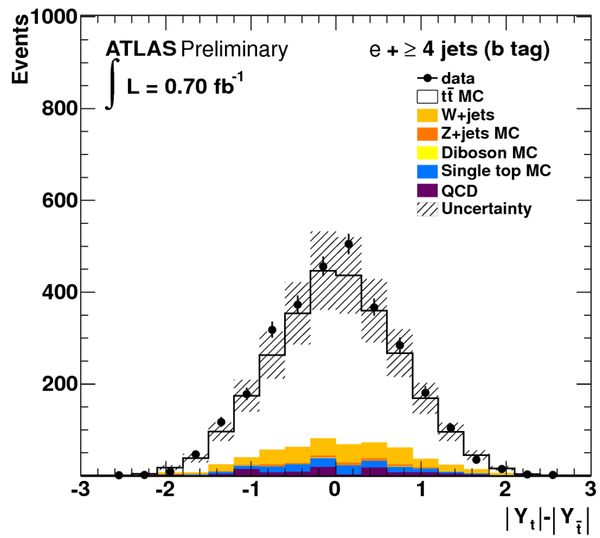
Raw Results ATLAS

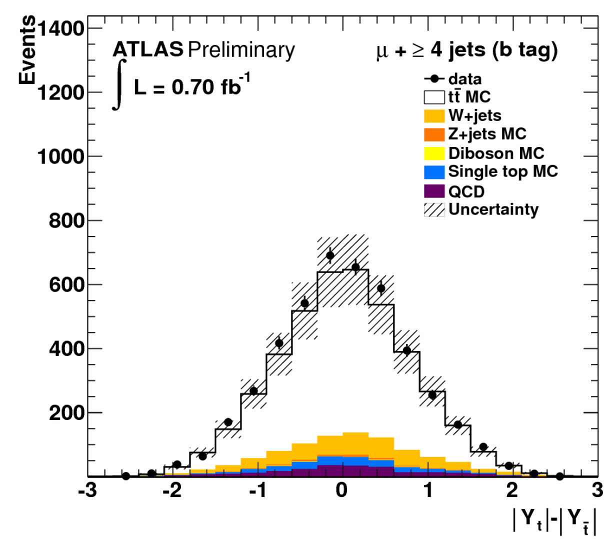
Pretag sample:



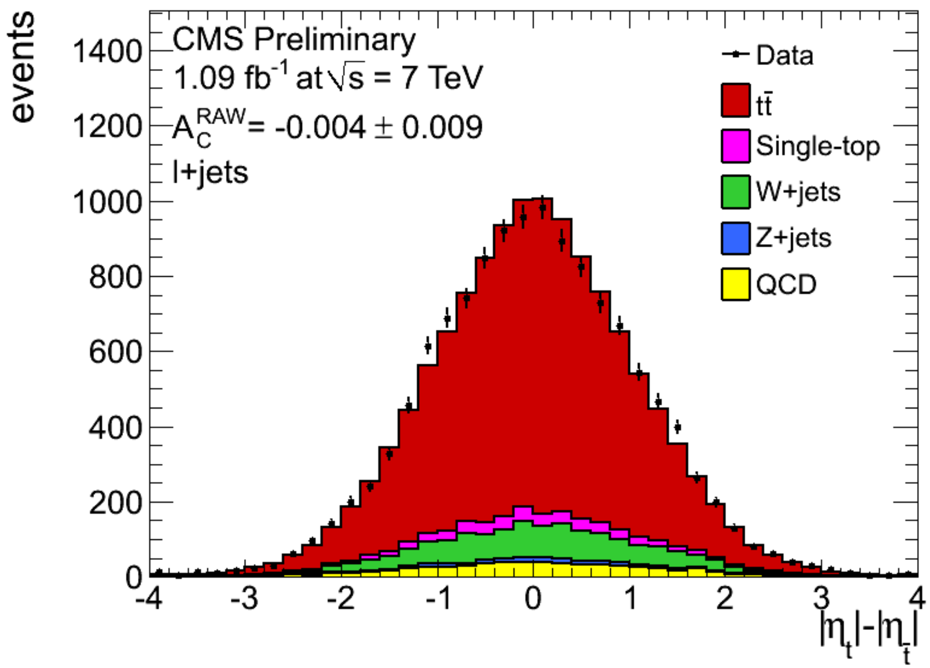


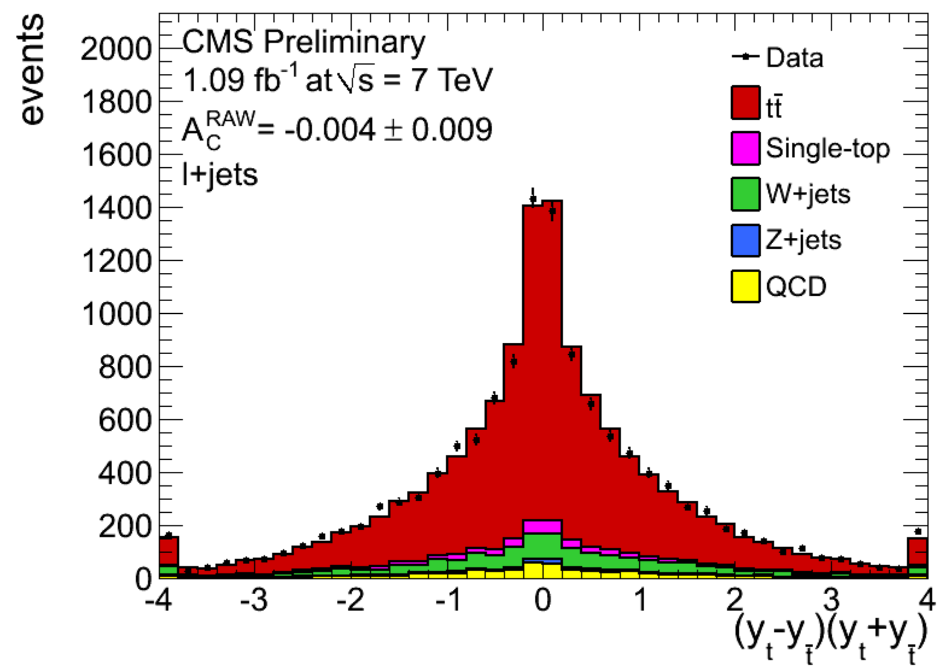
Tagged sample:





Raw Results CMS



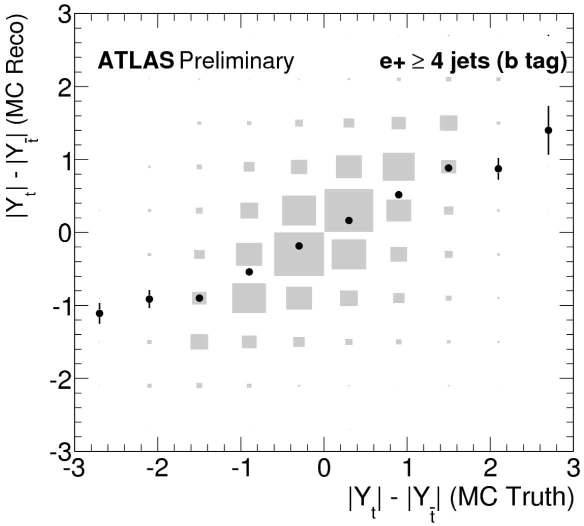


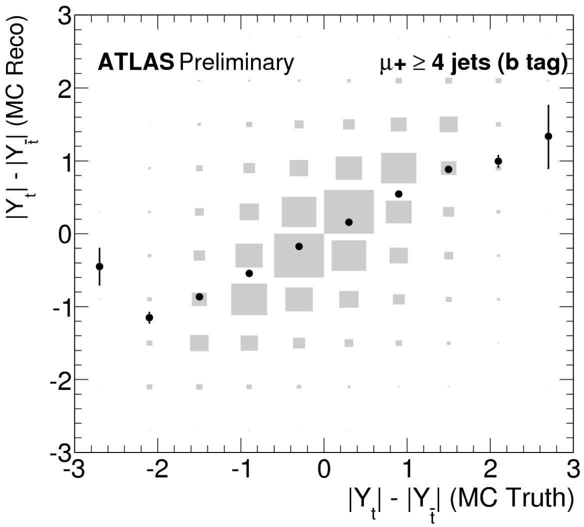
Reconstructed asymmetry is not directly comparable with theory prediction:

- background contributions
- smearing due to imperfect reconstruction
- non-flat selection efficiency

→ correction techniques required

Unfolding



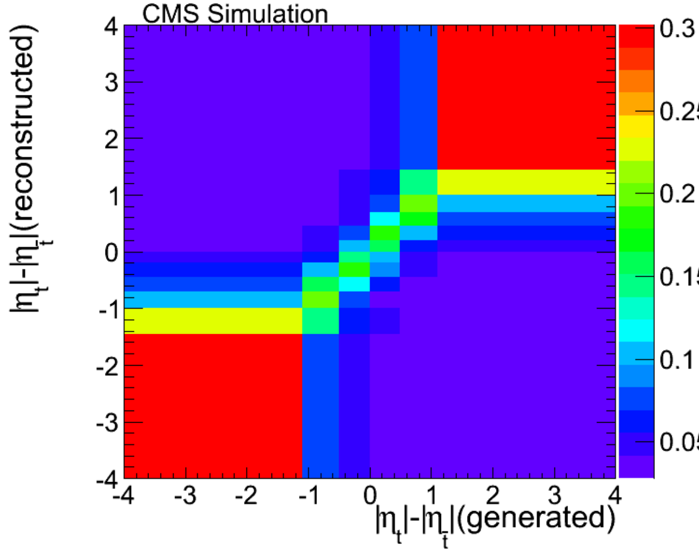


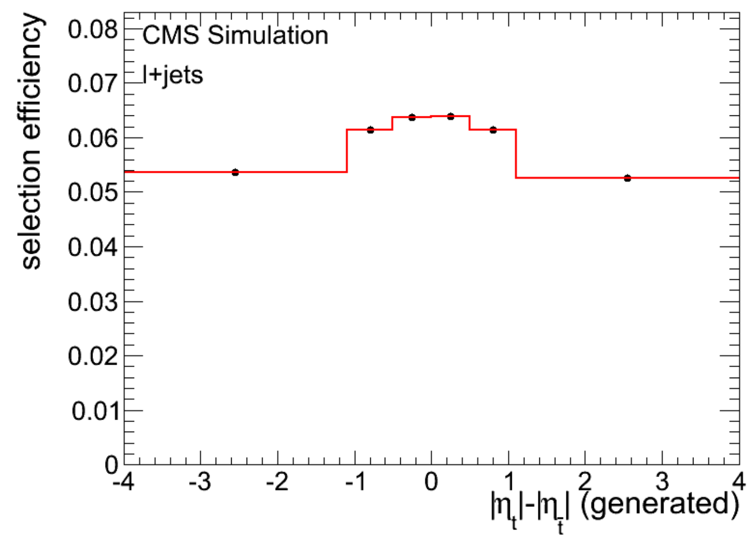
ATLAS:

- Iterative Bayesian unfolding
- Separate unfolding in e+jets and μ+jets
- Response matrix from MC@NLO

CMS:

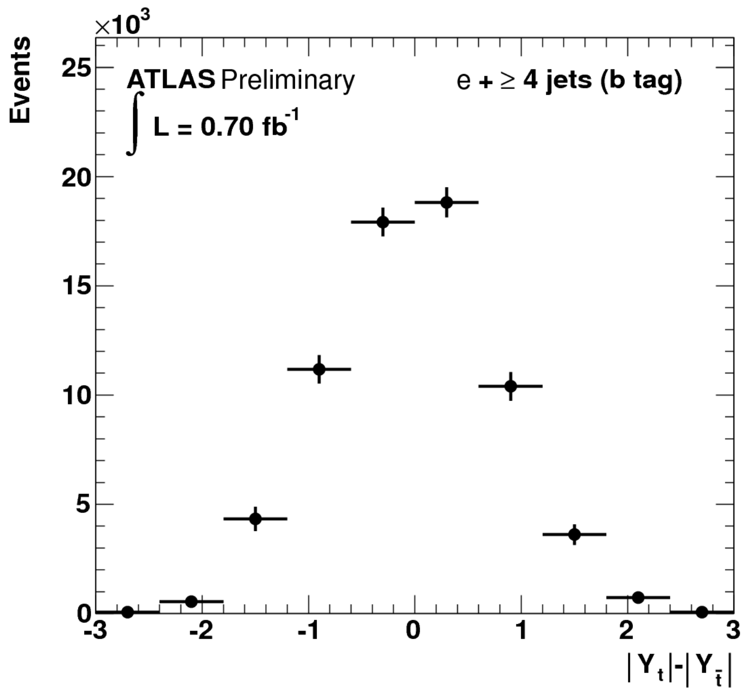
- Regularized unfolding based on generalized matrix inversion
- Combined unfolding of e+jets and μ+jets
- Response matrix from MadGraph MC





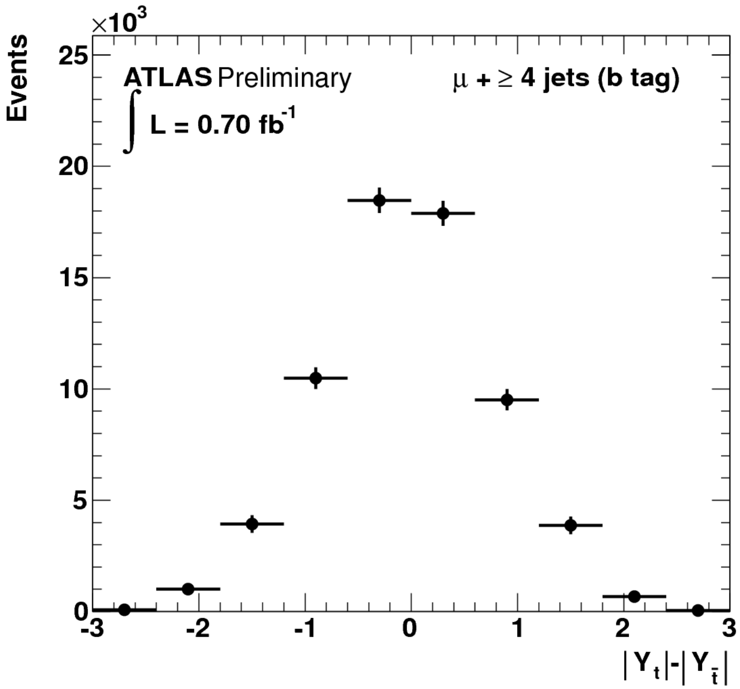
Unfolded Results ATLAS

Electron channel:



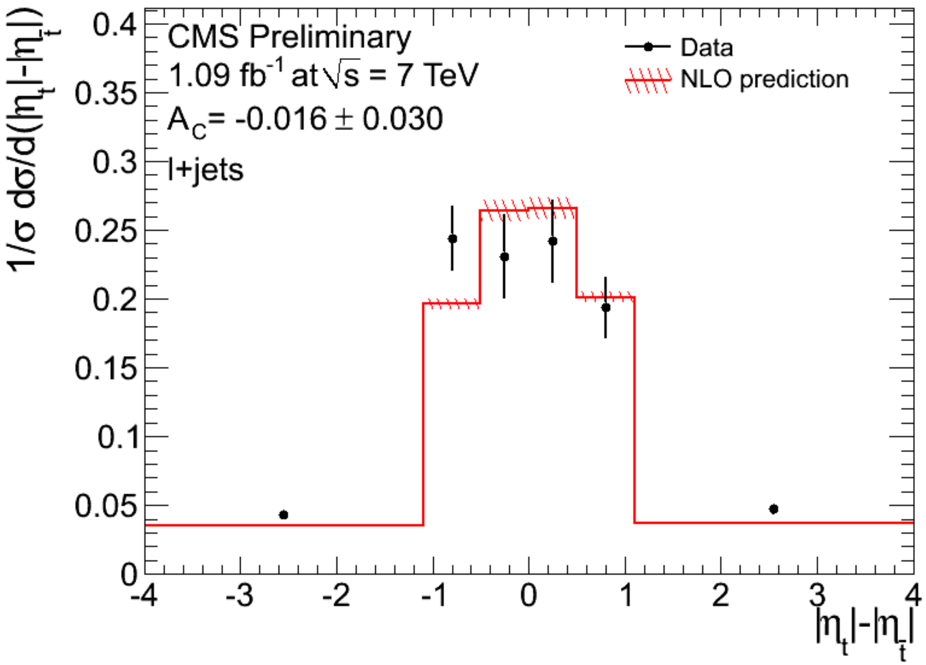
$$A_C^y = -0.009 \pm 0.023 (stat.)$$

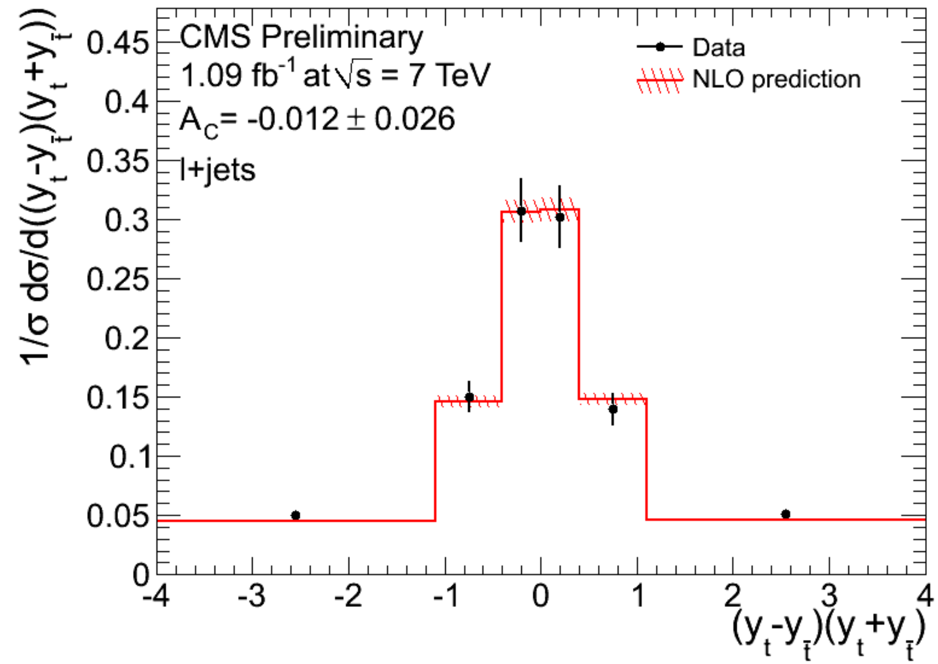
Muon channel:



$$A_C^y = -0.028 \pm 0.019 (stat.)$$

Unfolded Results CMS





$$A_C^{\eta} = -0.016 \pm 0.030 (stat.)$$

$$A_C^{y} = -0.013 \pm 0.026 (stat.)$$

Systematics

ATLAS

	Electron channel	Muon channel
Source of systematic uncertainty	ΔA_C	
Signal and background modelling		
$t\bar{t}$ generator	0.0243	0.0100
Parton shower/fragmentation	0.0108	0.0079
ISR/FSR	0.0074	0.0074
PDF uncertainty	0.0008	0.0008
Top mass	0.0059	0.0059
QCD normalisation	0.0062	0.0059
W+jets normalisation	0.0054	0.0097
W+jets shape	0.0043	0.0043
Z+jets normalisation	0.0002	0.0002
Z+jets shape	0.0010	0.0010
Single Top normalisation	0.0002	0.0002
Diboson normalisation	0.00001	0.00001
MC sample sizes	0.0043	0.0029
Detector modelling		
Muon efficiencies	(n.a.)	0.0002
Muon momentum scale and resolution	0.0004	0.0004
Electron efficiencies	0.0004	(n.a.)
Electron energy scale and resolution	0.0004	0.0004
Lepton charge misidentification	0.0002	0.0002
Jet energy scale	0.0041	0.0046
Jet energy resolution	0.0105	0.0040
Jet reconstruction efficiency	0.0003	0.0003
b-tagging scale factors	0.0038	0.0038
Charge asymmetry in b-tagging efficiency	0.0007	0.0007
Calorimeter readout	0.0015	0.0029
Combined uncertainty	0.032	0.022

CMS

	A_C^{η}		A_C^{y}	
Source of Systematic	− Variation	+ Variation	− Variation	+ Variation
JES	−0.003	0.000	−0.007	0.000
JER	−0.002	0.000	−0.001	0.001
Q^2 scale	−0.014	0.000	−0.013	+0.003
ISR/FSR	−0.006	+0.003	0.000	+0.024
Matching threshold	−0.006	0.000	−0.013	+0.006
PDF	−0.001	+0.001	−0.001	+0.001
b tagging	−0.001	+0.003	0.000	0.001
Lepton ID/sel. efficiency	−0.002	+0.004	−0.002	0.003
QCD model	−0.008	+0.008	−0.006	+0.006
Pileup	−0.002	+0.002	0.000	0.000
Overall	−0.019	+0.010	−0.021	+0.026

- **ATLAS:** perform unfolding on data using alternative MC samples for smearing matrix/background subtraction
- **CMS:** draw pseudo experiments from systematically shifted samples and evaluate shifts of the asymmetry when doing the unfolding with the standard templates.

Final Results

ATLAS:

- e+jets: $A_C^y = -0.009 \pm 0.023\,(stat.) \pm 0.032\,(syst.)$
- μ+jets: $A_C^y = -0.028 \pm 0.019\,(stat.) \pm 0.022\,(syst.)$

- Combined using BLUE method:

$$A_C^y = -0.024 \pm 0.016\,(stat.) \pm 0.023\,(syst.)$$

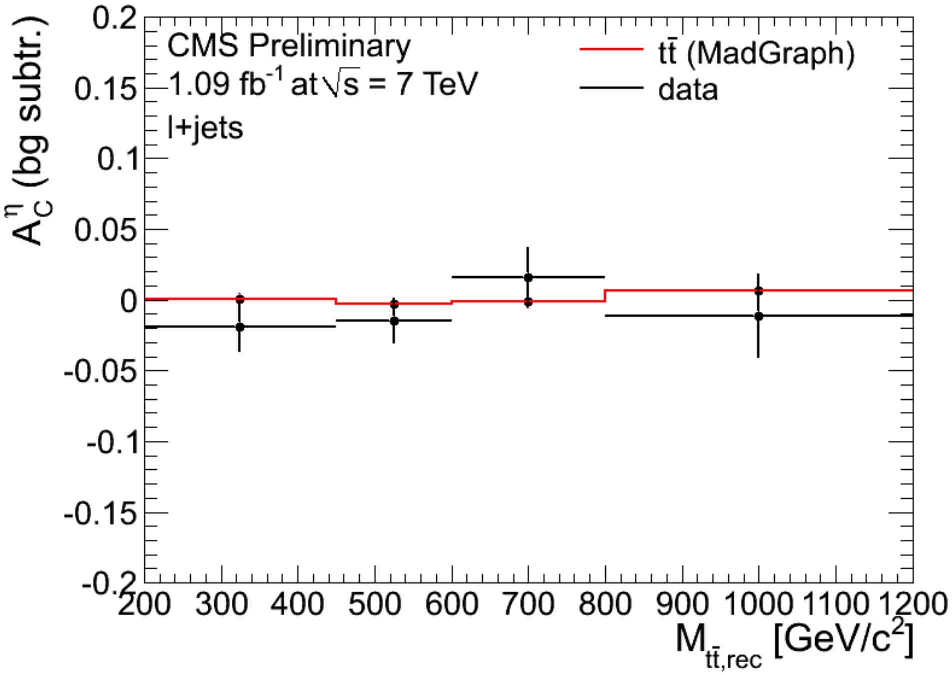
CMS:

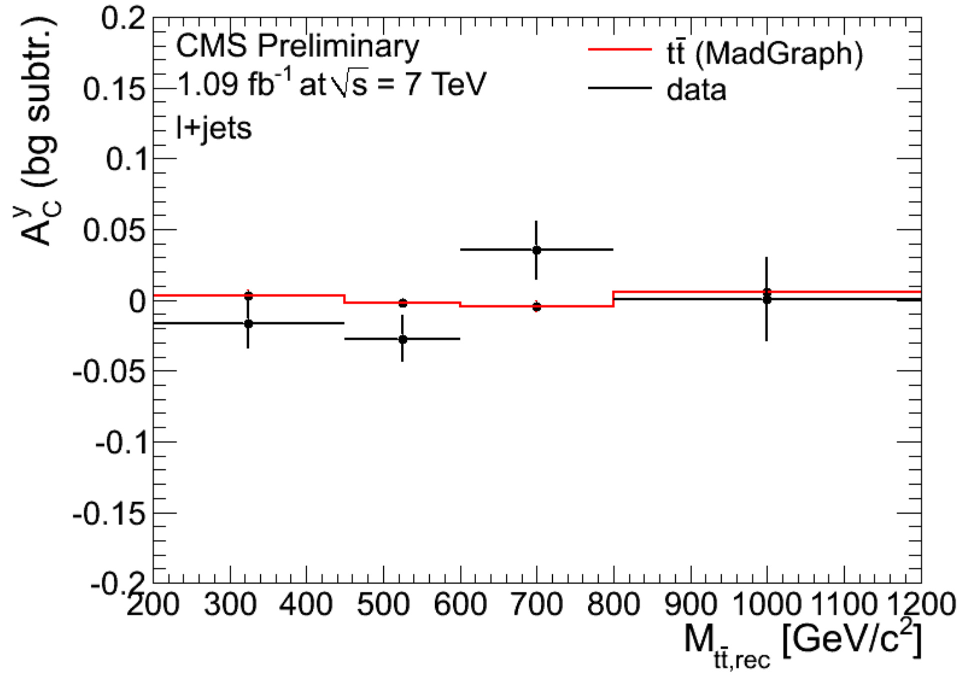
$$A_C^\eta = -0.016 \pm 0.030\,(stat.)^{+0.010}_{-0.019}\,(syst.)$$

$$A_C^y = -0.013 \pm 0.026\,(stat.)^{+0.026}_{-0.021}\,(syst.)$$

M_{tt} Dependence

- CMS measures the charge asymmetry differentially in M_{tt}.
- Results only corrected for background contributions, no full unfolding yet.





- Not directly comparable with theory predictions, but no tendency visible.

Conclusion

- Different sensitive variables but similar techniques used by CMS and ATLAS to measure the charge asymmetry in proton-proton collisions.
- Measured charge asymmetries have slight tendency to negative values but are still consistent with SM prediction of ~1%.
- More detailed studies of charge asymmetry in differential distribution might show hints for new physics in top quark pair production.