Measurements of the top charge asymmetry at the LHC

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Outline

- Introduction: which asymmetries are we measuring?
- $t\bar{t}$ and lepton-based charge asymmetries
- Analyses based on different $t\bar{t}$ final state:

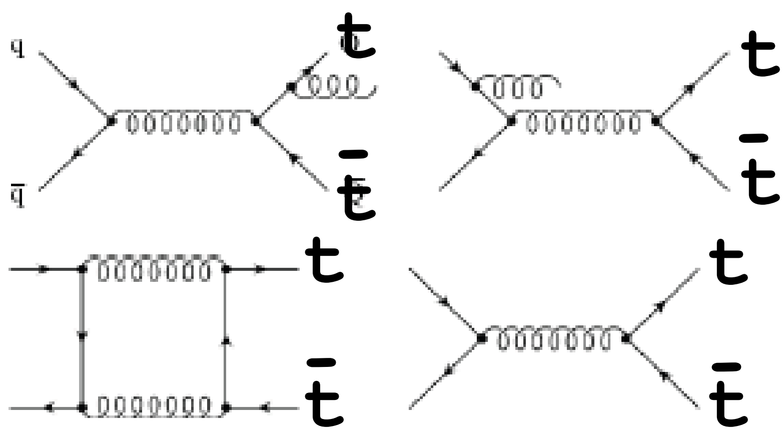
Single lepton channel ***Dilepton channel***

- Object selection
- Unfolding procedures: from reco to parton level
- Results from the two experiments:
  - Inclusive and differential measurements
  - Results vs BSM models predictions

- Conclusions & plans

Forward-backward top asymmetry

- $t\bar{t}$ forward-backward asymmetry is a tiny QCD NLO effect present in $q\bar{q}/qg$ production mechanisms
- It arises from the interference among these diagrams:



→ Negative asymmetry

→ Positive asymmetry

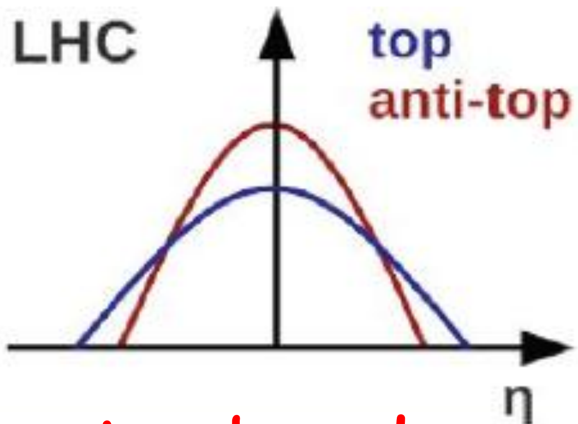
- The net effect is a positive asymmetry, i.e. the top is emitted preferentially in the incoming quark direction
- At hadron colliders it's difficult to reconstruct the parton 4-vectors. Hence lab. frame variables are used, like top/antitop rapidities
- Tevatron choice: $A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$ $\Delta y = y_t - y_{\bar{t}}$

«Forward-backward» asymmetry

Which asymmetries @ LHC ?

- In pp collisions, impossible to distinguish the direction of the quark → Δy symmetric by definition. In addition only 20% of events come from $q\bar{q}$ / qg hard scattering. But still a small asymmetry exists in the $q\bar{q}$ events since valence quarks are more boosted than sea antiquarks.

Charge asymmetry variable: «Forward/backward-central» asymmetry



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

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

Lepton-based asymmetry

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

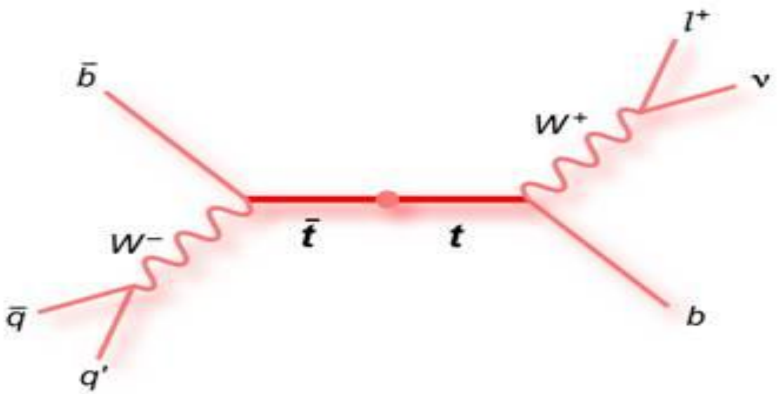
- Advantages: Lepton are very precisely measured; polarization effects
- Drawbacks: Low statistics

Single lepton channel: CMS (1)

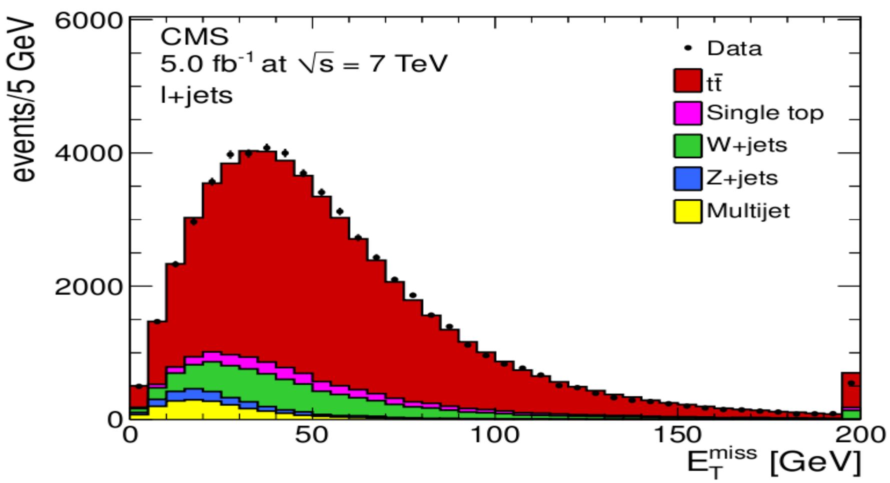
CMS-TOP-11-030; arXiv:1207.0065

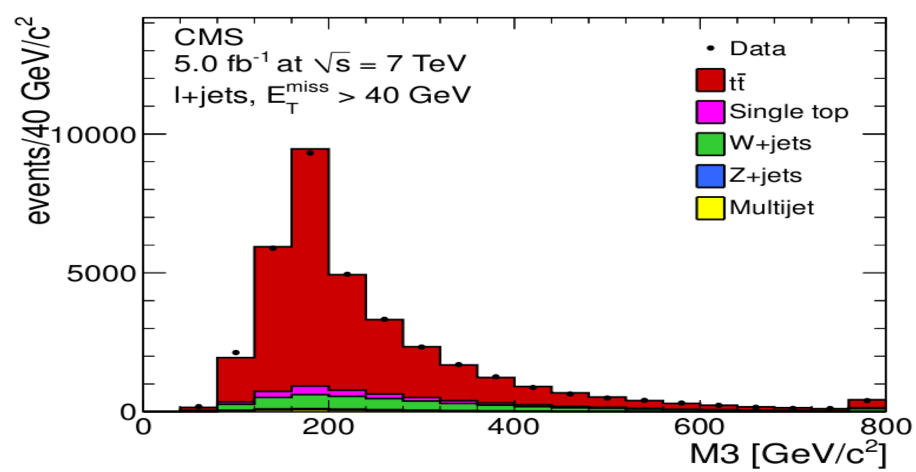
Event selection: 7 TeV, 4.7 fb^{-1}

- One electron (muon) with E_T>30 GeV (20 GeV); |η|<2.5 (2.1)
- Lepton veto: no electron (muon) with E_T>15 GeV (10 GeV)
- ≥ 4 jets with P_T > 30 GeV, |η| < 2.4. At least one b-jet



process	electron+jets	muon+jets	total
single top (t + tW)	1054 ± 319	1358 ± 478	2412 ± 604
W+jets (+)	1839 ± 224	1832 ± 284	3671 ± 362
W+jets (−)	1469 ± 222	1342 ± 270	2811 ± 349
Z+jets	504 ± 145	566 ± 160	1070 ± 216
multijet	1169 ± 221	887 ± 204	2056 ± 301
total BG	6035 ± 521	5985 ± 670	12020 ± 849
$t\bar{t}$	18661 ± 386	26998 ± 464	45659 ± 604
observed data	24705	32992	57697



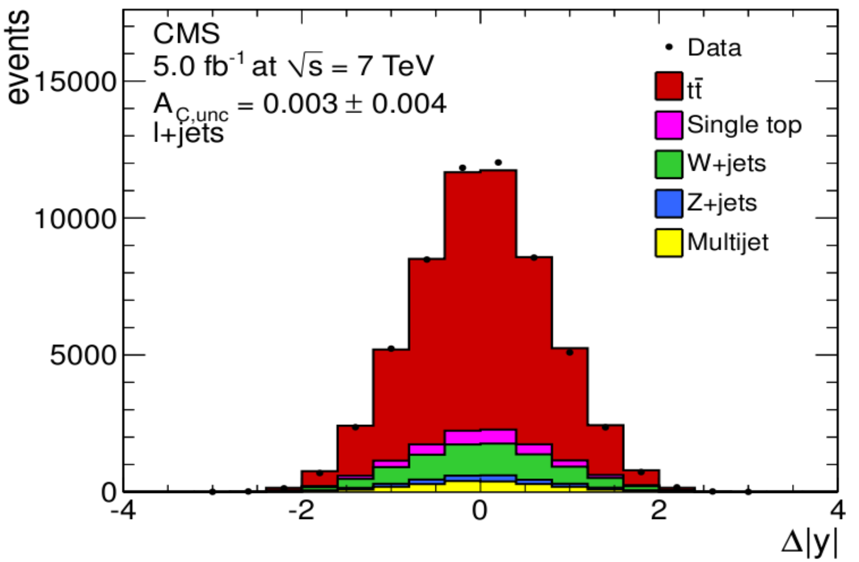


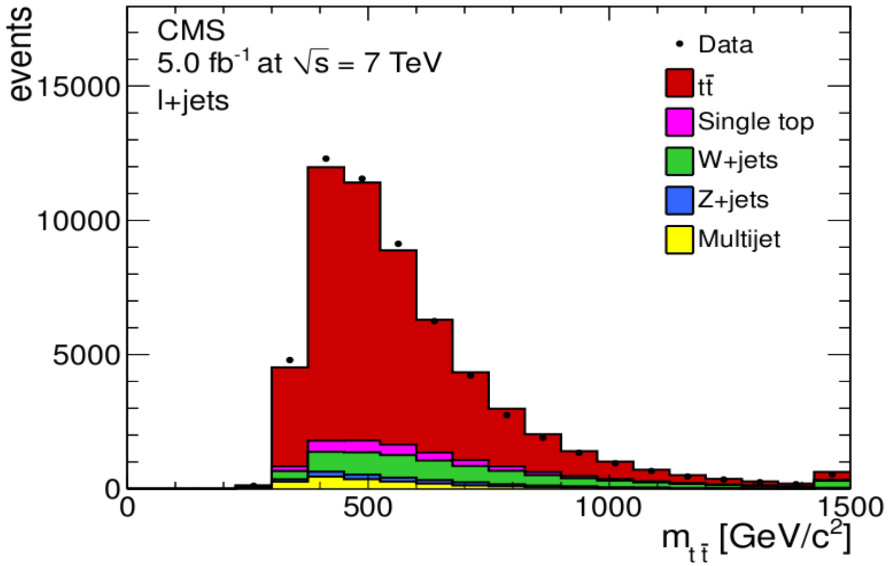
Single lepton channel: CMS (2)

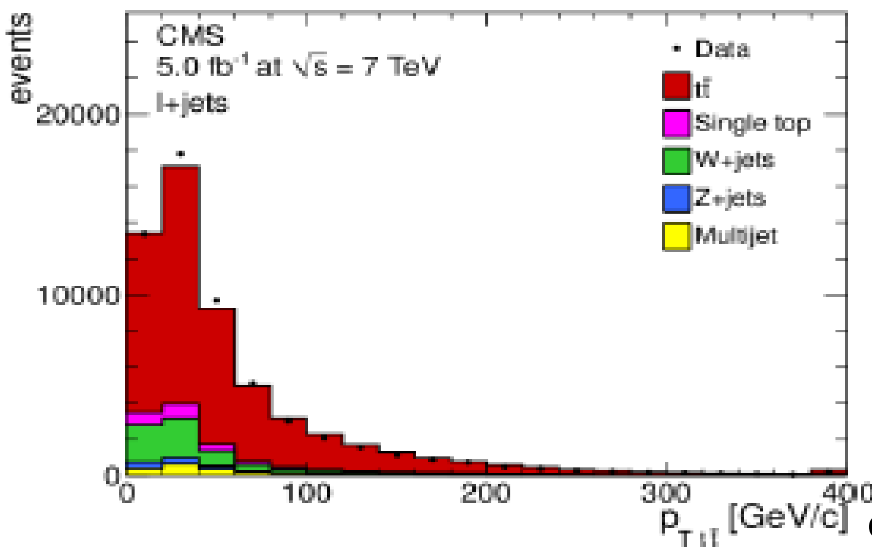
$t\bar{t}$ system reconstruction:

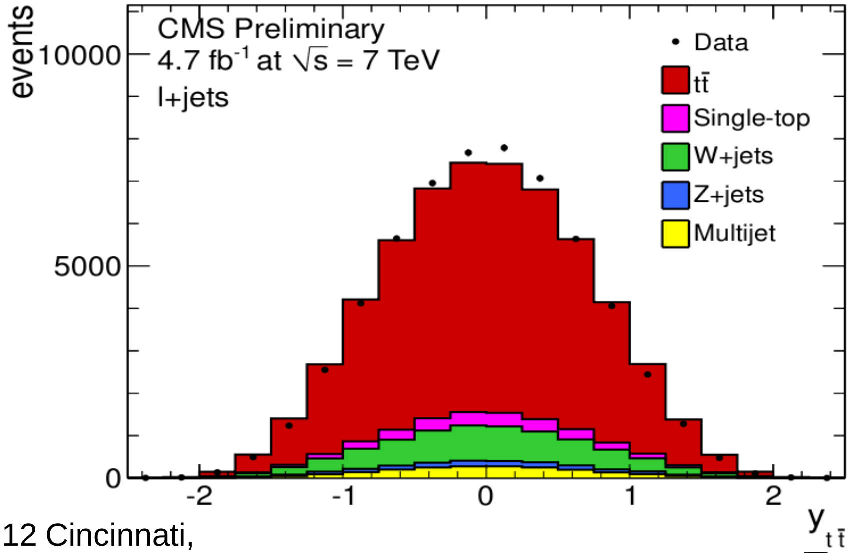
- Reconstruct the top/antitop 4-momenta using: leptons, jets and MET
- $P_Z(\nu)$ from lepton and MET with W-mass constraint
- Consider all jet-quark assignment → several hypotheses
- Build a likelihood to select only 1 hypothesis using the masses of the reconstructed top, W_{HAD} and b-tag/light-tag probablities
- In **72%** of the cases, the $\Delta|y|$ variable is reconstructed with the correct sign

Single lepton channel: CMS (3)









Single lepton channel: CMS (4)

Unfolding: Procedure to pass from reconstructed to partonic quantities.
Main effects to be corrected for:

- Background subtraction to isolate $t\bar{t}$ contribution
- Migration effects due to resolution/reconstruction
- Selection/acceptance effects

Implementation:

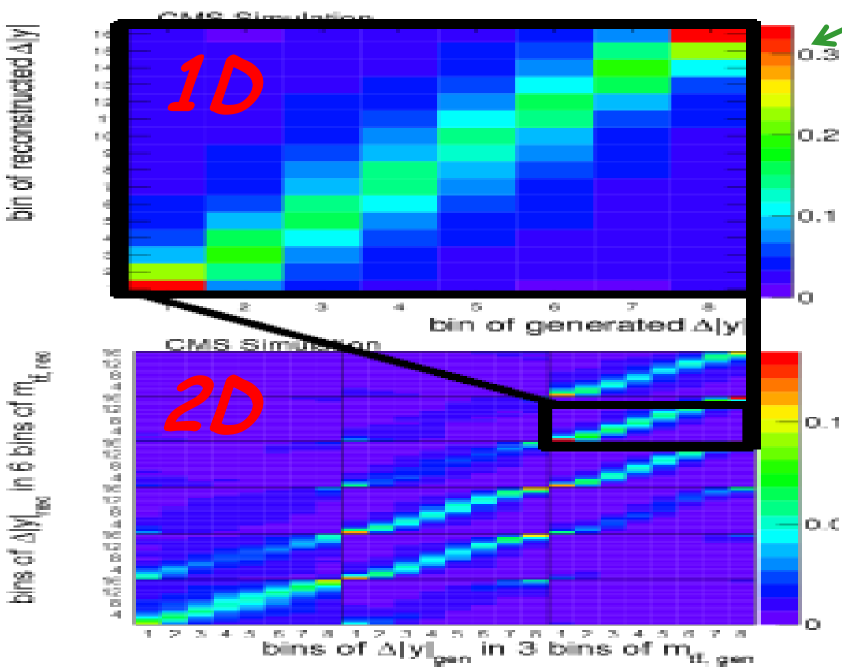
S matrix (from MC)
inversion and regularization

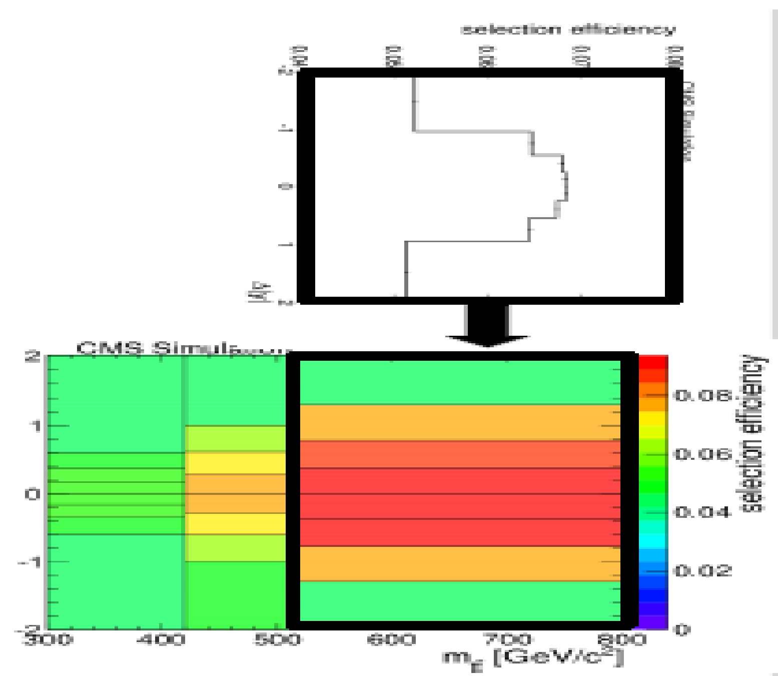
Migration Matrix S

$$\vec{w} = S \cdot \vec{x}$$

Measured spectrum ($\vec{w}$)

True spectrum ($\vec{x}$)



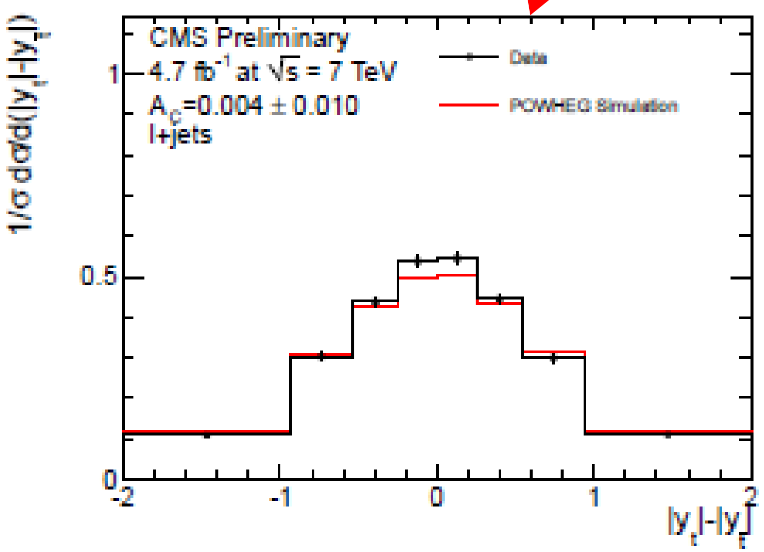


Single lepton channel: CMS (5)

Inclusive asymmetry:

Asymmetry	A_C
Uncorrected	0.003 ± 0.004 (stat.)
BG-subtracted	0.002 ± 0.005 (stat.)
Final corrected	0.004 ± 0.010 (stat.) ± 0.012 (syst.)
Theory prediction (SM)	0.0115 ± 0.0006

[Kühn, Rodrigo, arXiv:1109.6830]



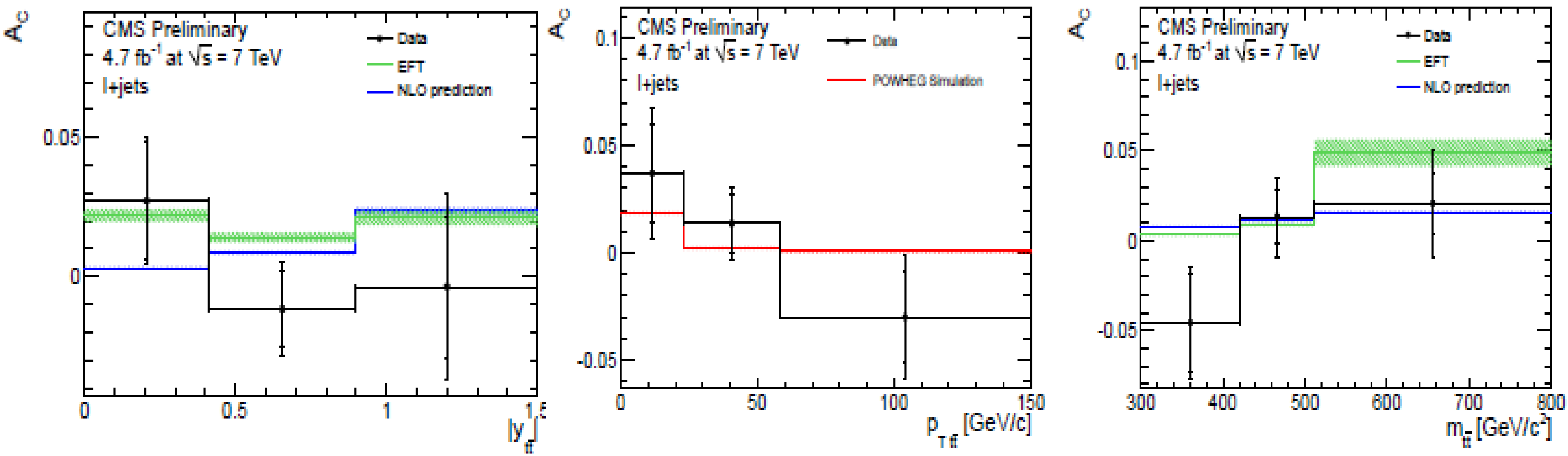
Systematic uncertainty	inclusive A_C
JES	0.002
JER	0.002
Pileup	0.001
Generator	0.001
Migration matrix	0.002
Unfolding	0.008
W+jets	0.004
Multijet	0.001
Lepton ID/sel. efficiency	0.006
Q^2 scale	0.002
Hadronization	0.001
PDF	0.002
Total	0.012

Single lepton channel: CMS (6)

Differential asymmetries

Asymmetries measured as a function of the:

- Rapidity of the $t\bar{t}$ system (left) → A_C increases with $|Y_{tt}|$;
- P_T of the $t\bar{t}$ system (middle); → Born and ISR/FSR contributions;
- Inv. mass of the $t\bar{t}$ system (right) → A_C increases at high m_{tt} values;



No significant hints of New Physics contributions

Single lepton channel: ATLAS (1)

Event selection: 7 TeV, 1.04 fb^{-1}

Eur. Phys. J. C72 (2012) 2039

- Electron(muon) with P_T>25 GeV(20 GeV);|η|<2.47 (|η|<2.5);
- ≥ 4 jets with P_T > 25 GeV; at least one b-jet;
- Electron channel: MET > 35 GeV && M_T(W) > 25 GeV;
- Muon channel: MET > 20 GeV && (MET+MT(W)) > 60 GeV;

Channel	μ + jets pretag	μ + jets tagged	e + jets pretag	e + jets tagged
$t\bar{t}$	7200 ± 600	6300 ± 500	4800 ± 400	4260 ± 350
W+jets	8600 ± 1200	1390 ± 310	5400 ± 800	880 ± 200
Single top	460 ± 40	366 ± 32	320 ± 28	256 ± 22
Z+jets	940 ± 330	134 ± 47	760 ± 270	110 ± 40
Diboson	134 ± 7	22 ± 2	80 ± 5	13 ± 1
Multijets	1500 ± 800	500 ± 500	900 ± 500	250 ± 250
Total background	11700 ± 1400	2400 ± 600	7500 ± 900	1500 ± 320
Signal + background	18900 ± 1600	8800 ± 800	12000 ± 1000	5800 ± 500
Observed	19639	9124	12096	5829

Multijet, **W+jets** backgrounds, estimated from data. Remaining backgrounds from MC simulation.

Single lepton channel: ATLAS (2)

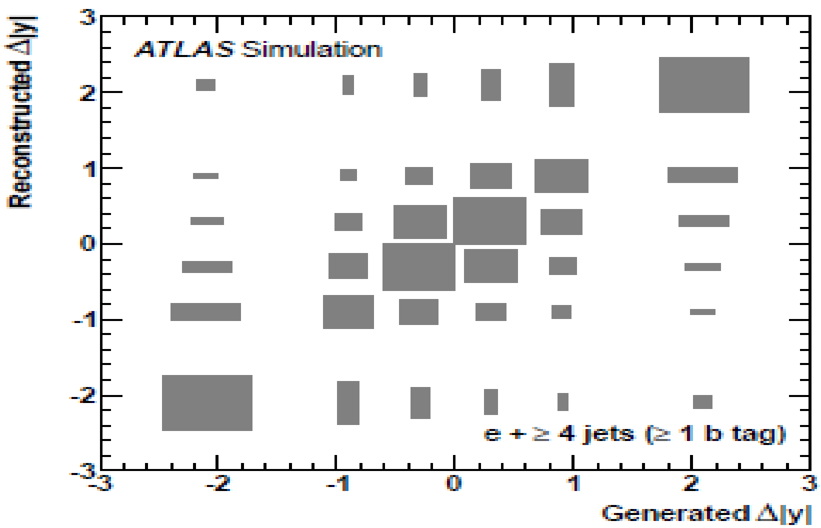
- Full top/antitop kinematic has to be reconstructed to measure the asymmetry.
- Kinematic Likelihood fitter was used for this purpose.
  - Inputs: P_T, η, ϕ for the lepton and the 5 hardest jets in the event, MET
  - Model: $t\bar{t}$ decay from MC. M(W) , M(top) and widths fixed;
  - Breit-Wigner parameterisation of measured vs partonic jet energies
  - Transfer functions to take into account for resolution effects in reconstructing jets from partons derived from MC
  - Assign a btag/rejection probability to each jet in the likelihood
  - Loop over the possible jets combinations assigning a probability to each event. Then choose the best combination
- In the **62%** w/o btag and **74%** with btag of the cases, the reconstructed top/antitop matches the original ones.

Single lepton channel: ATLAS (3)

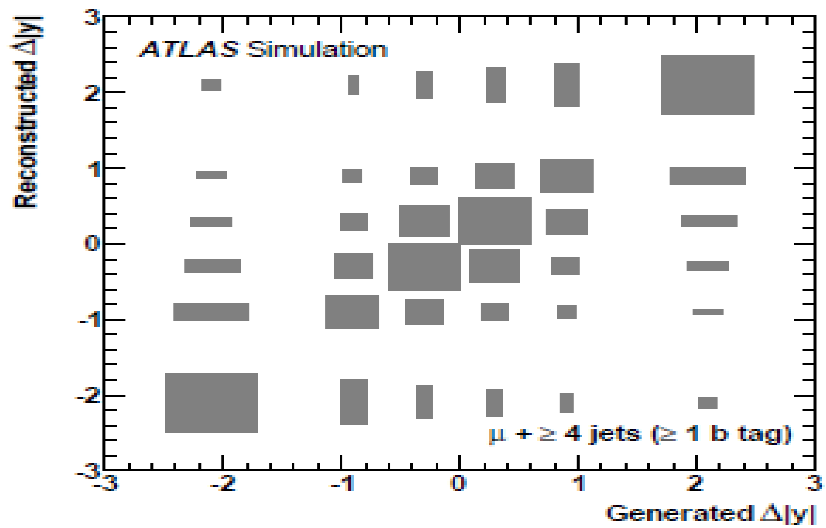
Unfolding procedure:

Observed distrib. → $O_i = \sum_j S_{ij} T_j$ ← Truth distrib.

- The S_{ij} “Response Matrix” is inverted using iteratively the Bayes theorem with the truth $\Delta|y|$ distribution from MC@NLO as prior for the first iteration
- The posterior probability in each iteration is computed and then used to compute the prior for the next iteration
- The regularization is automatically obtained with a small number of iterations



(a) Response Matrix (e+jets)

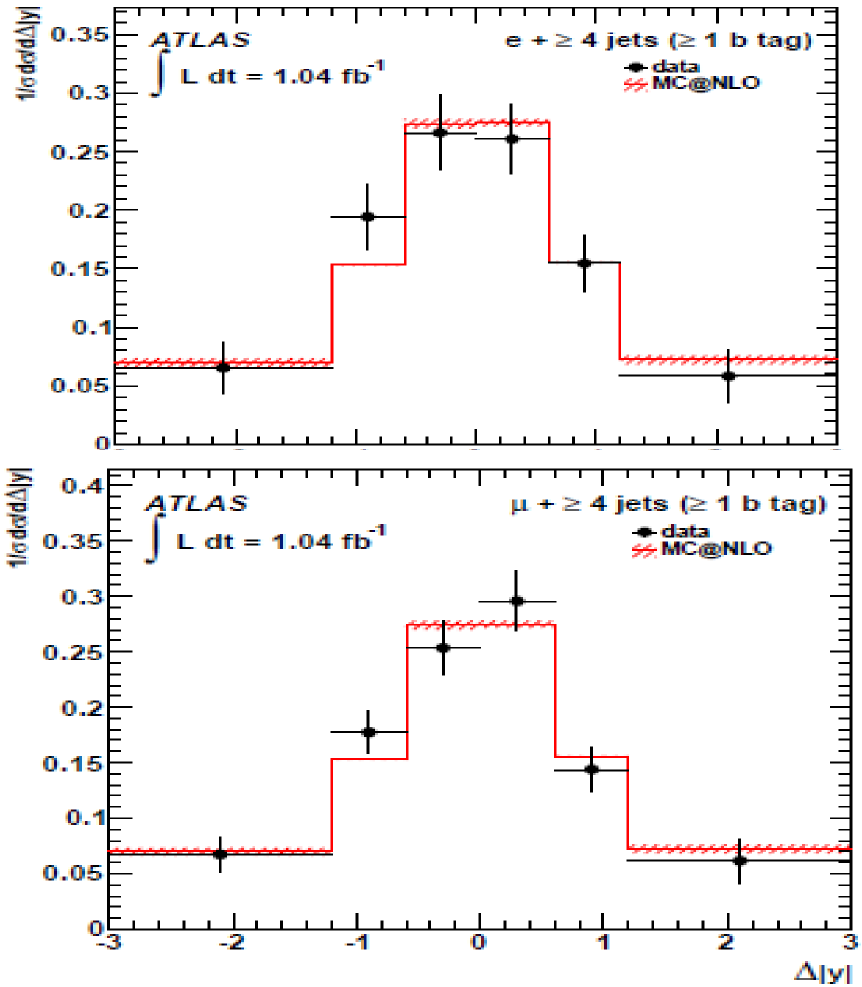


(b) Response Matrix (μ+jets)

Single lepton channel: ATLAS (4)

SM PREDICTION (MC@NLO): A_c=0.006 ± 0.002

Asymmetry	reconstructed	detector and acceptance unfolded
A_C (electron)	-0.034 ± 0.019 (stat.) ± 0.010 (syst.)	-0.047 ± 0.045 (stat.) ± 0.028 (syst.)
A_C (muon)	-0.010 ± 0.015 (stat.) ± 0.008 (syst.)	-0.002 ± 0.036 (stat.) ± 0.023 (syst.)
Combined		-0.018 ± 0.028 (stat.) ± 0.023 (syst.)



Source of systematic uncertainty on A_C	Electron channel	Muon channel
Detector modelling		
Jet energy scale	0.012	0.006
Jet efficiency and resolution	0.001	0.007
Muon efficiency and resolution	<0.001	0.001
Electron efficiency and resolution	0.003	0.001
b-tag scale factors	0.004	0.002
Calorimeter readout	0.001	0.004
Charge mis-ID	<0.001	<0.001
b-tag charge	0.001	0.001
Signal and background modelling		
Parton shower/fragmentation	0.010	0.010
Top mass	0.007	0.007
$t\bar{t}$ modelling	0.011	0.011
ISR and FSR	0.010	0.010
PDF	<0.001	<0.001
W+jets normalization and shape	0.008	0.005
Z+jets normalization and shape	0.005	0.001
Multijet background	0.011	0.001
Single top	<0.001	<0.001
Diboson	<0.001	<0.001
MC Statistics	0.006	0.005
Unfolding convergence	0.001	0.001
Unfolding bias	0.004	<0.001
Luminosity	0.001	0.001
Total systematic uncertainty	0.028	0.023

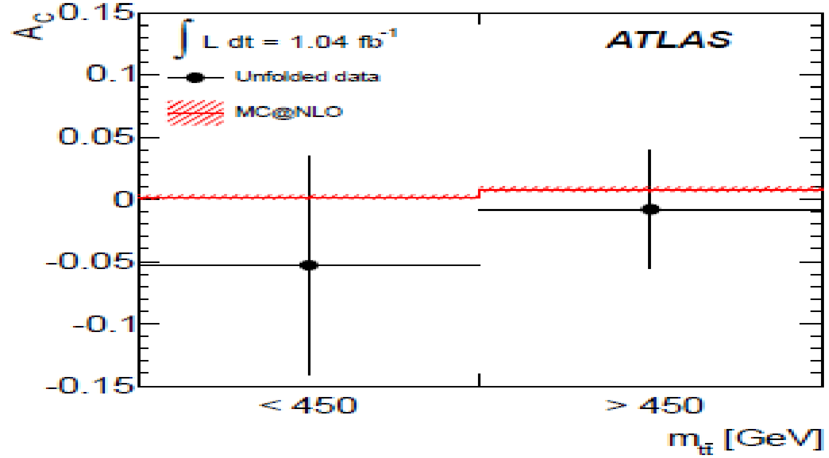
Single lepton channel: ATLAS (5)

Differential asymmetries & Interpretation

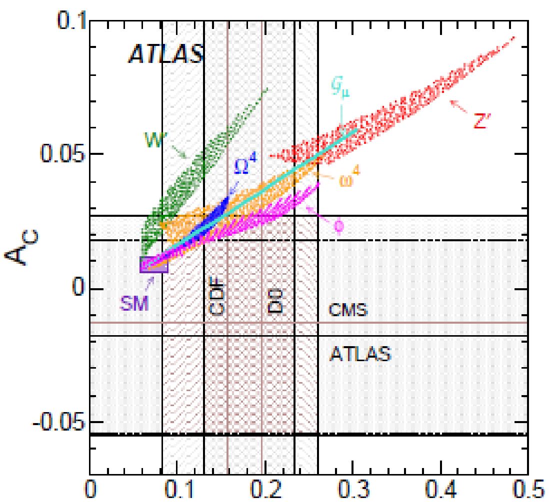
Asymmetries after unfolding measured as a function of m_{tt}:

$$A_C = -0.053 \pm 0.070\,(\text{stat.}) \pm 0.054\,(\text{syst.}) \quad \text{for } m_{t\bar{t}} < 450 \text{ GeV},$$

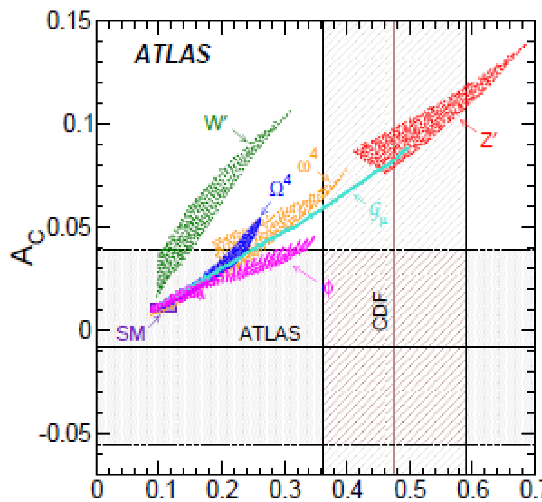
$$A_C = -0.008 \pm 0.035\,(\text{stat.}) \pm 0.032\,(\text{syst.}) \quad \text{for } m_{t\bar{t}} > 450 \text{ GeV}.$$



Combining A_{FB} (CDF) and A_C measurements (inclusive **(a)** and for m_{tt} > 450 GeV **(b)**) for several theoretical models (W',Z',Ω^4,ϕ,$\mathcal{G}_\mu$,ω^4) generated with PROTOS to scan the mass-coupling parameter space. Some models (Z', W') seem to be disfavoured.

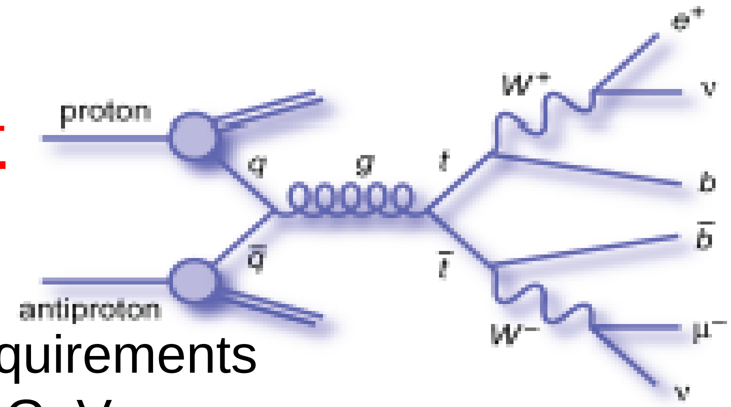


(a) inclusive



(b) m_{tt} > 450 GeV

Dilepton channel: ATLAS (1)



Event selection: 7 TeV, 4,7 fb^{-1}

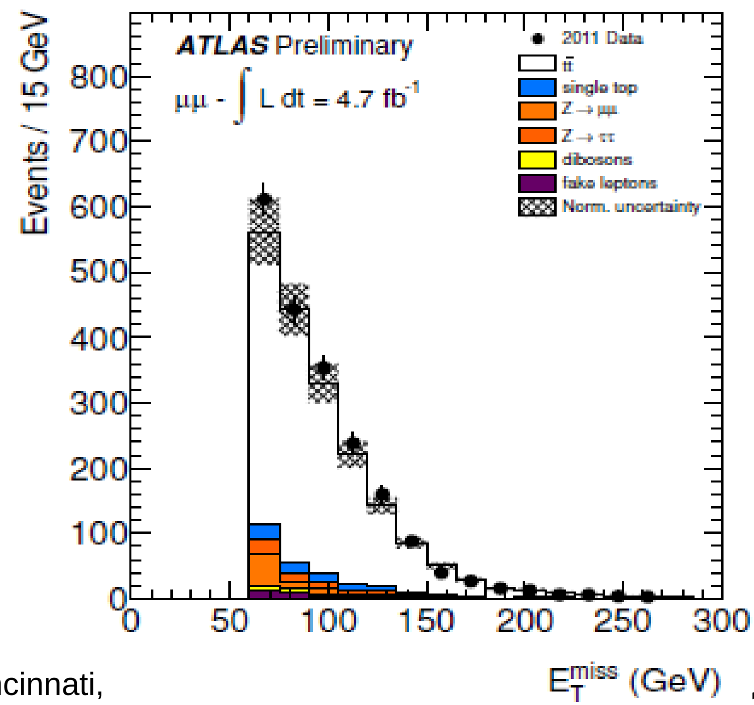
- Exactly two leptons (ee, μμ, eμ)
- E_T(e) > 25 GeV; P_T(μ)>20 GeV
- At least 2 jets with P_T>25 GeV, no b-jet requirements
- ee/μμ channels: MET>60 GeV + m(ll)>15 GeV

+ Z peak veto (± 10 GeV window)

- eμ channel: H_T>130 GeV
- Multijets/W+jets backgrounds estimated

from data

Channel	ee	$e\mu$	$\mu\mu$
$t\bar{t}$	590 ± 60	4400 ± 500	1640 ± 170
$Z \to ee/\mu\mu$	19 ± 7	-	83 ± 29
$Z \to \tau\tau$	19 ± 7	180 ± 60	67 ± 23
Single top	30 ± 2	230 ± 20	82 ± 7
Dibosons	9 ± 1	70 ± 4	23 ± 2
Multijets/W+jets	70 ± 36	250 ± 130	32 ± 17
Total	740 ± 70	5100 ± 500	1930 ± 170
Data	732	5305	2010



Dilepton channel: ATLAS (2)

- $t\bar{t}$ system difficult to reconstruct for the presence of two neutrinos;

The reconstruction method is based on the computing a probability distribution using the $gg \rightarrow t\bar{t}$ LO Matrix Element (ME).

- 22 unknowns (top/antitop, $W^{\pm}$, neutrinos 4-momenta)
- 16 measured quantities: leptons and jets 4-momenta
- Fix m(top) and m(W) + 2 equations to relate $\vec{\mathbf{P}}_{\mathbf{T}}(\nu)$ and $\vec{\mathbf{P}}_{\mathbf{T}}(\mathbf{t\bar{t}})$
- Use transfer function to take into account for jets resolution
- Use MC for $\vec{\mathbf{P}}_{\mathbf{T}}(t\bar{t})$ depending on the number of jets (2 or more)

For each l-j combination a weight is computed proportional to the LO ME, PDF and transfer functions from partonic to reco quantities:

$$\frac{(2\pi)^4}{\varepsilon_1 \varepsilon_2 s} d\varepsilon_1 d\varepsilon_2 f_{PDF}(\varepsilon_1) f_{PDF}(\varepsilon_2) |\mathcal{M}(y)|^2 W(x,y) d\Phi_n$$

gluon momentum fraction

Reco quantity

Partonic quantity

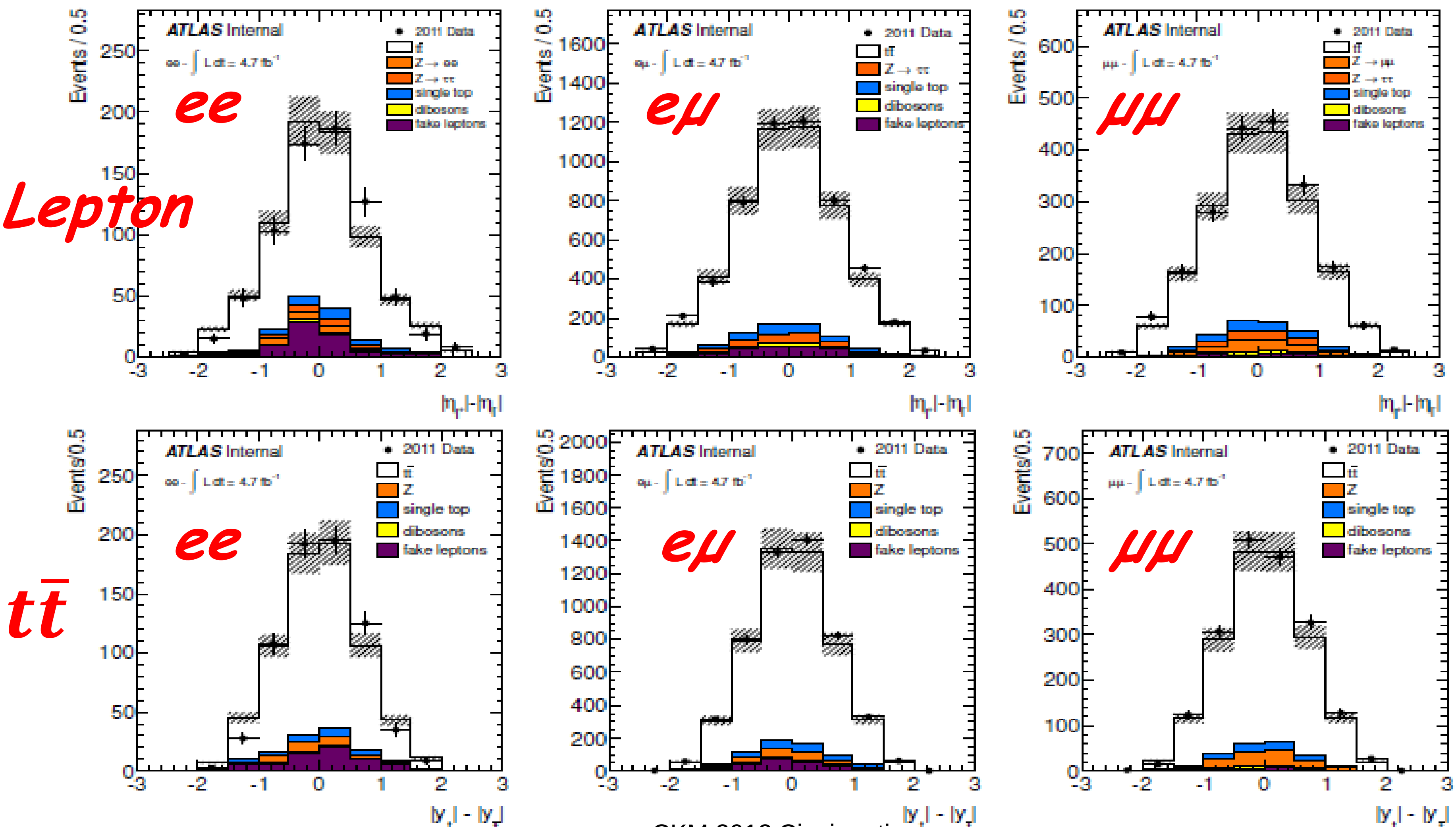
LO matrix element

The combination with the highest weight is finally choosen.

The right lepton-jet combination is found in the 47% of the cases.

Dilepton channel: ATLAS (3)

Δ|y| ($t\bar{t}$) and Δ|η| (leptons) distributions



Dilepton channel: ATLAS (4)

- Calibration is needed to compare the measurement to the theoretical predictions. It corrects for resolution and acceptance effects going back to the parton level asymmetries
- Idea: use MC@NLO $t\bar{t}$ sample to build a calibration curve, i.e. a function that for different parton level injected asymmetries, gives back the correspondant reconstructed asymmetry
- Different asymmetries (from -10% to 10%) obtained artificially reweighting the original MC@NLO sample, are injected at the true level. The correspondant reco asymmetries are then computed and a fit with a straight line is finally performed.
- Measured asymmetries are rescaled by the slope and the offset obtained in the fit.
- Possible effects from New Physics have been tested reweighting the original MC@NLO $t\bar{t}$ sample to describe the various $\Delta|y|$ and $\Delta|\eta|$ distributions at parton level for some New Physics samples (axigluons with different asymmetries)

Dilepton channel: ATLAS (5)

Final asymmetries after background subtraction and calibration:

Main systematics: signal modelling (generator, ISR/FSR) and calibration procedure.

Lepton-based asymmetry

$$A_C^{\ell\ell} = 0.091 \pm 0.041\,(\text{stat.}) \pm 0.029\,(\text{syst.}) \quad (ee\text{ channel})$$
$$A_C^{\ell\ell} = 0.018 \pm 0.014\,(\text{stat.}) \pm 0.009\,(\text{syst.}) \quad (e\mu\text{ channel})$$
$$A_C^{\ell\ell} = 0.026 \pm 0.023\,(\text{stat.}) \pm 0.009\,(\text{syst.}) \quad (\mu\mu\text{ channel})$$

$t\bar{t}$ asymmetry

$$A_C^{t\bar{t}} = 0.079 \pm 0.087\,(\text{stat.}) \pm 0.028\,(\text{syst.}) \quad (ee\text{ channel})$$
$$A_C^{t\bar{t}} = 0.078 \pm 0.029\,(\text{stat.}) \pm 0.017\,(\text{syst.}) \quad (e\mu\text{ channel})$$
$$A_C^{t\bar{t}} = 0.000 \pm 0.046\,(\text{stat.}) \pm 0.021\,(\text{syst.}) \quad (\mu\mu\text{ channel}).$$

Combination

$$A_C^{\ell\ell} = 0.023 \pm 0.012\,(\text{stat.}) \pm 0.008\,(\text{syst.})$$

SM (MC@NLO): 0.004 ± 0.001

$$A_C^{t\bar{t}} = 0.057 \pm 0.024\,(\text{stat.}) \pm 0.015\,(\text{syst.}).$$

SM (MC@NLO): 0.006 ± 0.002

Combination of single lepton and dilepton channel:

$$A_C^{t\bar{t}} = 0.029 \pm 0.018\,(\text{stat.}) \pm 0.014\,(\text{syst.})$$

No significant deviations from SM.

Conclusions & Plans

- The $t\bar{t}$-based charge asymmetry in single lepton and dilepton channel and the lepton-based asymmetry measurements by ATLAS &CMS experiments have been presented
- Both inclusive and differential measurements have been performed by the two experiments
- CMS (single lepton) and ATLAS (dilepton) have measured the asymmetries with the full 2011 statistic at $\sqrt{s}$ =7 TeV
- No significant excess w.r.t. SM expectation have been seen

2012/2013 plans:

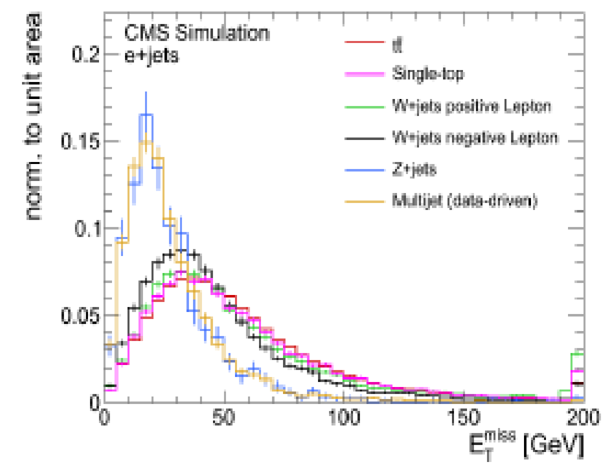
- Roughly 20 fb^{-1} will be collected in 2012 at $\sqrt{s}$ = 8 TeV
- These data will be a great possibility to perform these measurements since the qq fraction is smaller at $\sqrt{s}$ = 14 TeV
- Both experiments plan to analyse these data soon

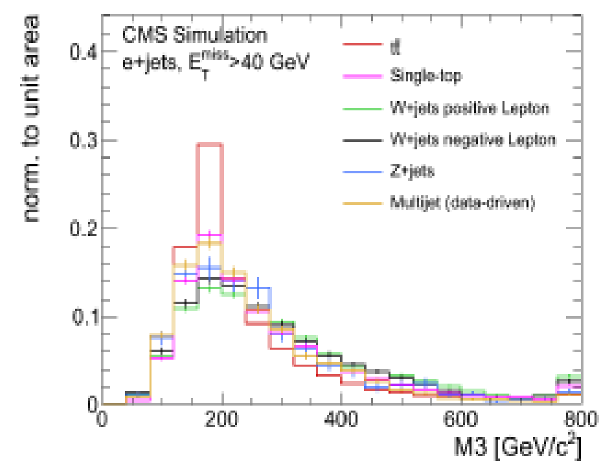
BACKUP

Analysis: BG estimation (1)

For illustration purpose: fit-templates for e+jets channel

- Binned Likelihood-fit
- Fit **MET** in the range **MET<40 GeV**
- Fit **M3** in events with **MET>40 GeV**
- Fit **electron+jets** and **muon+jets separately**
- MC-Templates, except for QCD:
  - Data-driven QCD template, from events with non-isolated charged leptons
- Constrain single top and Z+jets to the theory prediction using Gauss constraints (width: 30%)





M3: Invariant mass of the three jets with the highest vectorially summed p_T

Analysis: Unfolding (3)

Courtesy of T.Chwalek

- **Regularized unfolding** through a **generalized matrix inversion** method
- TUnfold package
  - Least-square problem:

Covariance matrix of the measured spectrum

$$F_{\mathrm{LS}}(\vec{x}) = (S\vec{x} - \vec{w})^{\mathrm{T}} V_w^{-1} (S\vec{x} - \vec{w})$$

  - Solution:

$$\vec{x}_{\mathrm{LS}} = S^{\#}\vec{w} \text{ with } S^{\#} = (S^{\mathrm{T}} V_w^{-1} S)^{-1} S^{\mathrm{T}} V_w^{-1}$$

Generalized inverse matrix

    - In general: unstable, huge fluctuations
  - Regularization:

$$F(\vec{x},\kappa) = F_{\mathrm{LS}}(\vec{x}) + \tau ||L(\vec{x} - \vec{x}_{\mathrm{bias}})||^2 + \kappa\left(N_{\mathrm{obs}} - \sum_{i=1}^{n} (S\vec{x})_i\right)^2$$

Regularization term

Normalization term

Proportional to 2^{nd} **derivatives of x - x_{bias}**

    - Bias distribution: from default MC sample → Curvature of difference between unfolded and default MC distribution is used for regularization
  - For τ we choose the value that minimizes the global correlation between the data points of the unfolded spectrum (Minimum of Global Correlation Method)

Courtesy of T.Chwalek

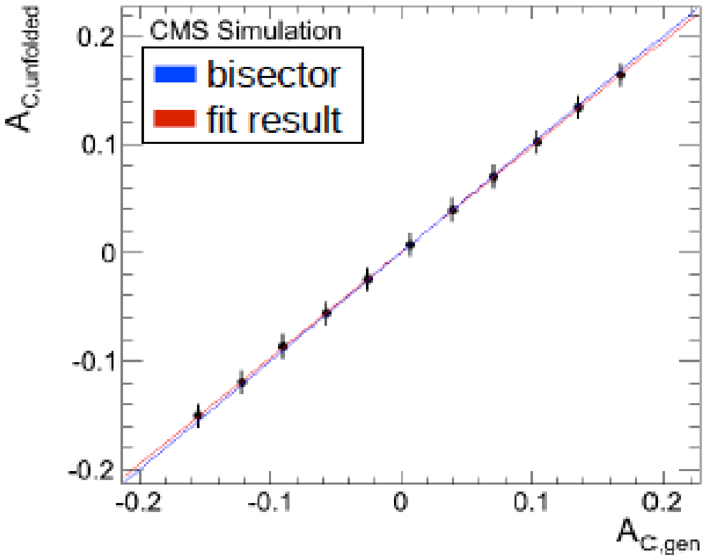
Analysis: Cross Checks

- Unfolding method is checked for stability using pseudo experiments
- Measured A_c is compared to generated A_c
- Samples are re-weighted to artificially generate different asymmetries

$$w = k \cdot \Delta|y| + 1$$

- For inclusive measurement as well as for single bins of the differential measurements

Linearity check for the inclusive measurement

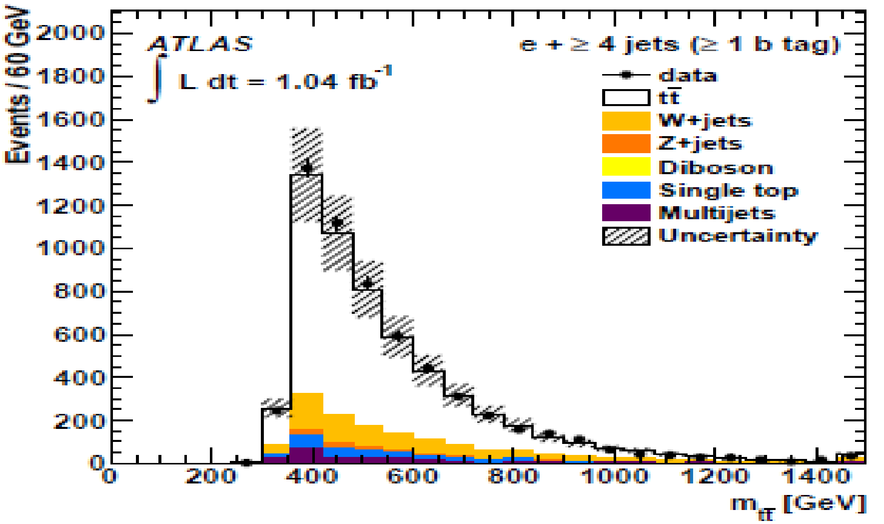


- To test the model-independence of the unfolding procedure:
  - Produced asymmetries depending on the kinematic variables V

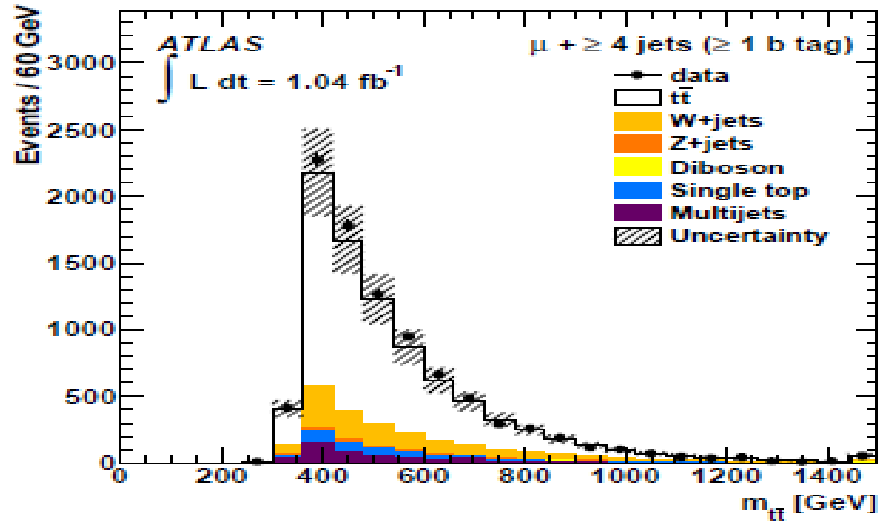
$$w = k(V) \cdot \Delta|y| + 1$$

Single lepton channel: ATLAS

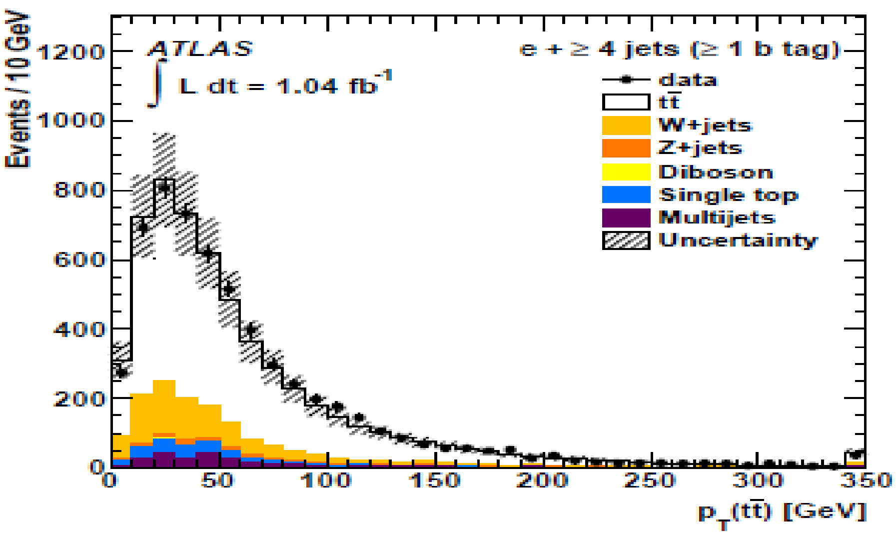
Stat. + syst. uncertainties



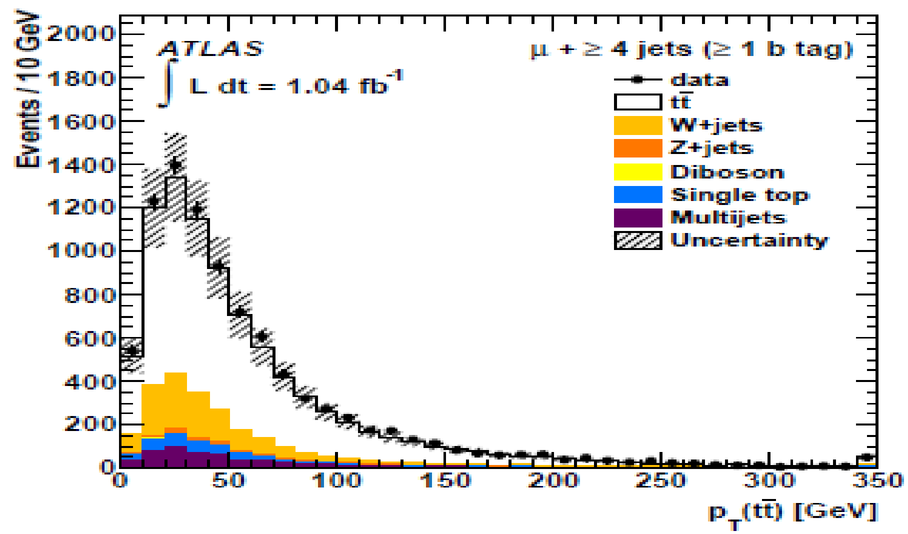
(a)



(b)



(c)



(d)

Systematic uncertainties: Lepton asymm.

	ee	$e\mu$	$\mu\mu$
signal and background modeling			
signal generator	0.011	0.003	0.002
ISR and FSR	0.004	0.004	0.006
parton shower/fragmentation	0.001	0.004	0.003
PDF	<0.001	<0.001	<0.001
Z+jets	0.005	0.004	0.001
diboson	<0.001	<0.001	<0.001
single top	<0.001	<0.001	<0.001
multijet background	0.014	0.002	<0.001
Detector modeling			
jet efficiency and resolution	0.008	0.001	0.003
jet energy scale	0.006	0.001	0.002
muon efficiency and resolution	<0.001	0.001	0.002
electron efficiency and resolution	0.005	0.003	<0.001
calibration	0.019	0.002	0.004
luminosity	0.002	<0.001	<0.001
Total	0.029	0.009	0.009

- eμ and μμ channels show a lower overall systematic uncertainty w.r.t ee channel
- Dominat syst. in ee channel is the QCD data-driven estimate and the calibration (i.e. error propagation from fit parameters)
- If the syst affects the background → perform subtraction, recompute the asymmetry and calibrate
- If the syst affects the signal → redo the calibration curves

Systematic uncertainties: $t\bar{t}$ asymm.

	ee	$e\mu$	$\mu\mu$
Signal and background modeling			
signal generator	0.014	0.009	0.002
ISR and FSR	0.008	0.002	0.018
parton shower/fragmentation	0.001	0.001	0.001
PDF	0.001	<0.001	<0.001
Z+jets	0.001	0.006	0.002
diboson	<0.001	<0.001	<0.001
single top	<0.001	<0.001	<0.001
multijet background	0.012	0.010	0.001
Detector modeling			
jet efficiency and resolution	0.007	0.001	0.005
jet energy scale	0.003	0.002	0.006
muon efficiency and resolution	0.004	0.003	0.005
electron efficiency and resolution	0.013	0.006	0.002
calibration	0.004	0.001	0.002
luminosity	<0.001	0.001	<0.001
Total	0.028	0.017	0.021

- The three channels show similar overall systematic uncertainty
- Some fluctuation in some systematic (ISR/FSR, $t\bar{t}$ generator) especially in the ee channel is due to limited available statistics
- If the syst affects the background → perform subtraction, recompute the asymmetry and calibrate
- If the syst affects the signal → redo the calibration curves

Dilepton channel: ATLAS

➢ Multijet background estimation: Matrix Method

- Define “loose” and “tight” lepton selection criteria
- Real efficiencies measured in Z→ℓℓ events
- Fake rate estimation measured in control region with low MET and $M_T(W)$ for muons, in low MET for electrons

➢ Other backgrounds:

Single top, Dibosons, Z→ℓℓ + jets for normalization and shapes from MC