Karlsruher Institut für Technologie

ATLAS and CMS $t\bar{t}$ charge asymmetry measurements at 8 TeV

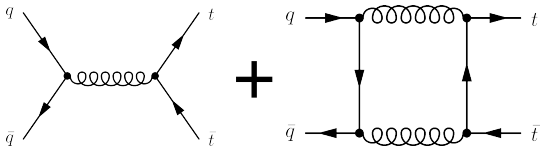
Thorsten Chwalek, Frederic Deliot

Institut für Experimentelle Kernphysik, Karlsruher Institut für Technologie

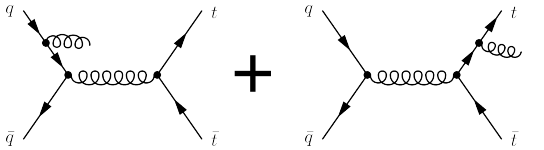
Charge asymmetry

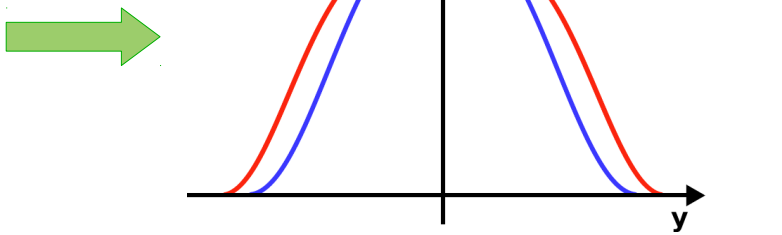
- Interference of diagrams in NLO

positive contribution



negative contribution





Sensitive variables

- Top-quarks

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

- Leptons

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

Asymmetry

$$A_C = \frac{N_+ - N_-}{N_+ + N_-}$$

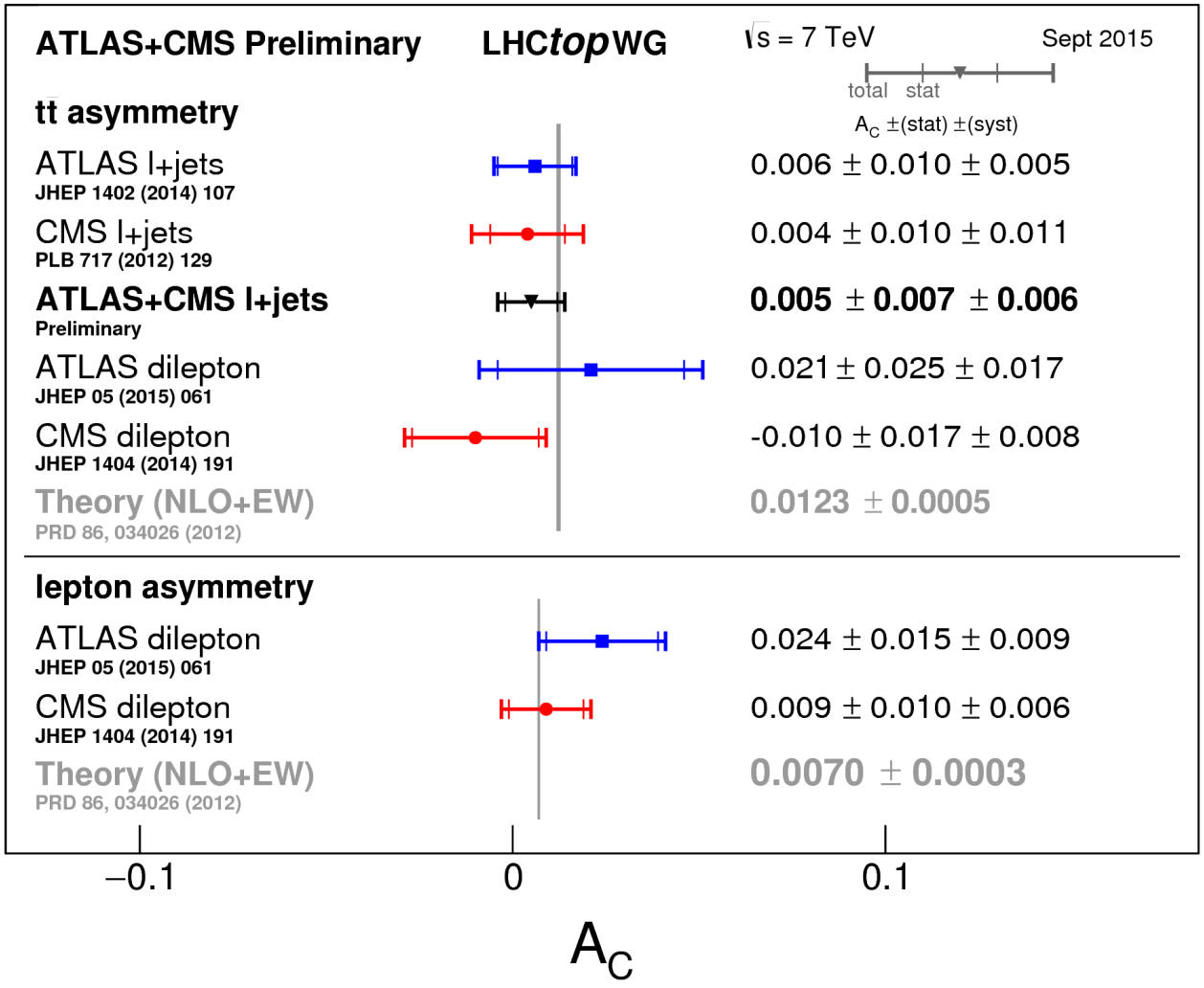
Theory predictions

$A_C = +0.0102 \pm 0.0005$ [Kühn, Rodrigo]

$A_C = +0.0111 \pm 0.0004$ [Bernreuther, Si]

$A_C^{lep} = +0.0064 \pm 0.0003$ [Bernreuther, Si]

ATLAS and CMS measurements at 7 TeV



Public ATLAS and CMS results at 8 TeV

- **ATLAS** inclusive and differential measurements [submitted to EPJC]
- **ATLAS** inclusive and differential measurements in highly boosted top-pair production [ATLAS-CONF-2015-048]
- **CMS (unfolding analysis)** inclusive and differential measurements [submitted to PLB]
- **CMS (template analysis)** inclusive measurement [submitted to PRD]

All publicly avilable 8 TeV results are from measurements in the ***lepton+jets channel***

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All publicly avilable 8 TeV results are from measurements in the ***lepton+jets channel***

ATLAS analysis arXiv:1509.02358v2 [hep-ex]

- Luminosity: 20.3/fb
- Event selection:
  - 1 isolated electron or muon *(p_T > 25 GeV, |η|< 2.5)*
  - ≥ 4 jets *(p_T > 25 GeV, |η|< 2.5)*
  - Control (0 b-tag) and signal regions (1 b-tag, 2+ b-tags)
  - MET + MTW > 60 GeV for 0 or 1 b-tag
  - MET > 40 (20) GeV for 0(1) b-tag
- BG normalization:
  - W+jets: fitted **in situ** exploiting the W charge asymmetry
  - QCD multijet: determined using a matrix method
    - *Determine the number of QCD events with tight leptons (signal region) from the number of events with loose leptons and the efficiencies for real and fake leptons that satisfy the loose criteria to also pass the tight ones.*
  - Single top, diboson: normalized to NNLO prediction


EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: EPJC

CERN-PH-EP-2015-217
7th October 2015

Measurement of the charge asymmetry in top-quark pair production in the lepton-plus-jets final state in pp collision data at $\sqrt{s} = 8$ TeV with the ATLAS detector

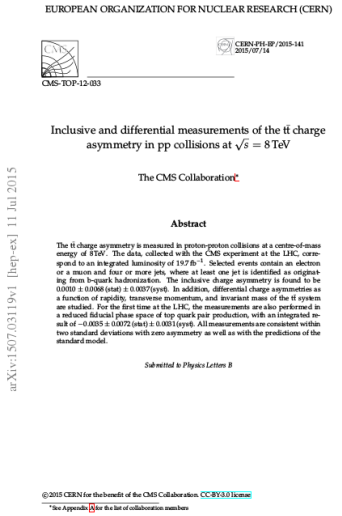
The ATLAS Collaboration

Abstract

This paper reports inclusive and differential measurements of the $t\bar{t}$ charge asymmetry A_C in 20.3 fb^{-1} of $\sqrt{s} = 8$ TeV pp collisions recorded by the ATLAS experiment at the Large Hadron Collider at CERN. Three differential measurements are performed as a function of the invariant mass, transverse momentum and longitudinal boost of the $t\bar{t}$ system. The $t\bar{t}$ pairs are selected in the single-lepton channels (e or μ) with at least four jets, and a likelihood fit is used to reconstruct the $t\bar{t}$ event kinematics. A Bayesian unfolding procedure is performed to infer the asymmetry at parton level from the observed data distribution. The inclusive $t\bar{t}$ charge asymmetry is measured to be $A_C = 0.009 \pm 0.005$ (stat.+syst.). The inclusive and differential measurements are compatible with the values predicted by the Standard Model.

CMS analysis arXiv:1507.03119v1 [hep-ex]

- Luminosity: 19.7/fb
- Event selection:
  - 1 isolated electron or muon *(p_T > 30 (26) GeV, |η|< 2.5 (2.1))*
  - ≥ 4 jets *(p_T > 30 GeV, |η|< 2.5)*
  - ≥ 1b-tag
- BG normalization:
  - Fit to MTW and m_3 distributions to determine BGs
  - W+jets, QCD, $t\bar{t}$ left free in the fit
  - Single top and Z+jets constrained to SM prediction


EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-PH-EP/2015-141
2015/07/14

CMS-TOP-12-033

Inclusive and differential measurements of the $t\bar{t}$ charge asymmetry in pp collisions at $\sqrt{s} = 8$ TeV

The CMS Collaboration*

Abstract

The $t\bar{t}$ charge asymmetry is measured in proton-proton collisions at a centre-of-mass energy of 8 TeV. The data, collected with the CMS experiment at the LHC, correspond to an integrated luminosity of 19.7 fb^{-1}. Selected events contain an electron or a muon and four or more jets, where at least one jet is identified as originating from b-quark hadronization. The inclusive charge asymmetry is found to be 0.010 ± 0.006 (stat) ± 0.007(syst). In addition, differential charge asymmetries as a function of rapidity, transverse momentum, and invariant mass of the $t\bar{t}$ system are studied. For the first time at the LHC, the measurements are also performed in a reduced fiducial phase space of top quark pair production, with an integrated result of −0.035 ± 0.0072 (stat) ± 0.0031(syst). All measurements are consistent within two standard deviations with zero asymmetry as well as with the predictions of the standard model.

Submitted to Physics Letters B

arXiv:1507.03119v1 [hep-ex] 11 Jul 2015

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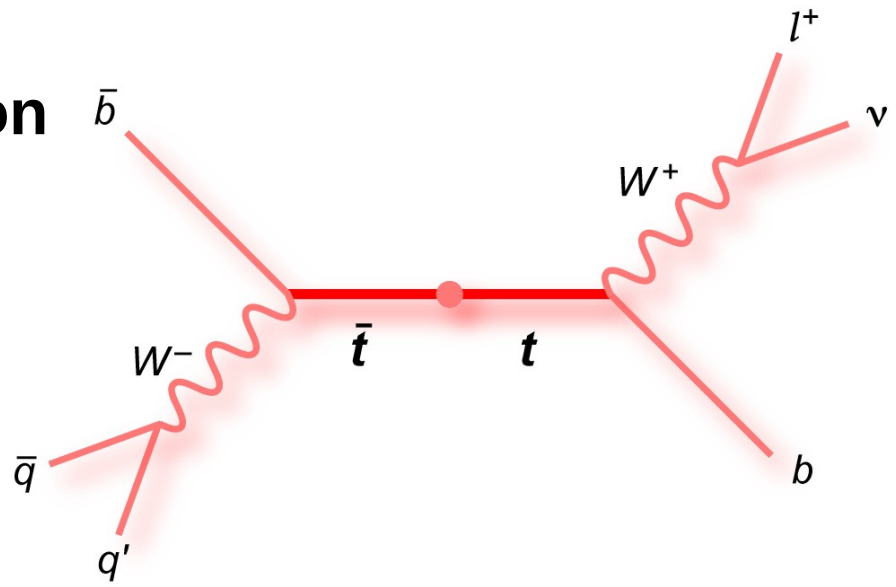
*See Appendix A for the list of collaboration members

ATLAS and CMS use similar event selection criteria, the main difference is in the determination of the largest BG (W+jets)

Event reconstruction



- **Kinematic fit** with fourvectors of the four jets, the lepton and MET as inputs, top and W masses as constraints

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

- Consider all possible mappings of jets to partons and chose the one that yields the best agreement with top and W masses and b-probabilities

$$\psi = L_1(m_1)L_2(m_2)L_3(m_3)$$
$$P_b(x_{b1})P_b(x_{b2})(1 - P_b(x_{q1}))(1 - P_b(x_{q2}))$$

Unfolding

- **Fully Bayesian Unfolding** technique
- No explicit matrix inversion
- In situ handling of systematics

True parton level distribution

Distribution as measured in **D**ata

$$p(T|D) \propto L(D|T) \cdot \pi(T)$$

Likelihood function of D given T and M (response matrix)

Prior probability density for T

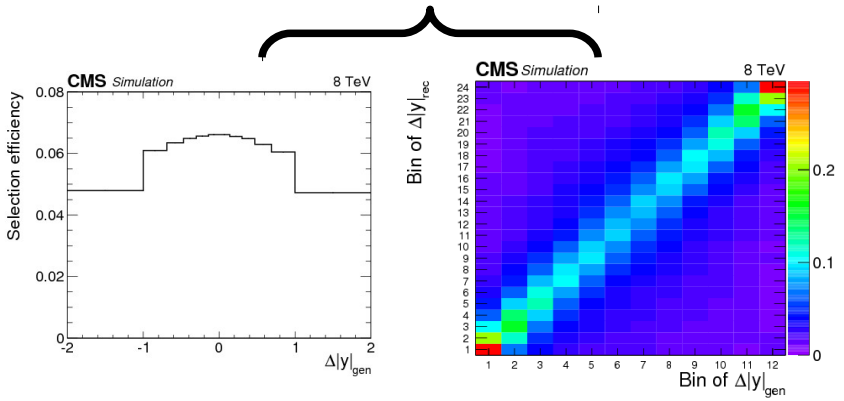
- **Regularized unfolding** based on generalized **matrix inversion**
- Systematics are determined separately

Reconstructed distribution

True parton level distribution

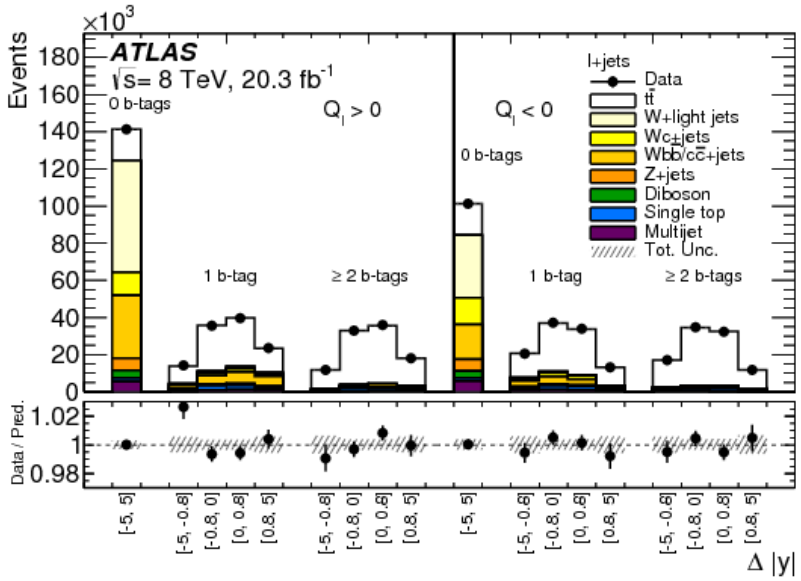
$$R = M \cdot T$$

Response-**M**atrix (selection efficiency and migration effects)



Unfolding

- **Fully Bayesian Unfolding** technique
- No explicit matrix inversion
- In situ handling of systematics
- **In situ estimation of W+jets BG**



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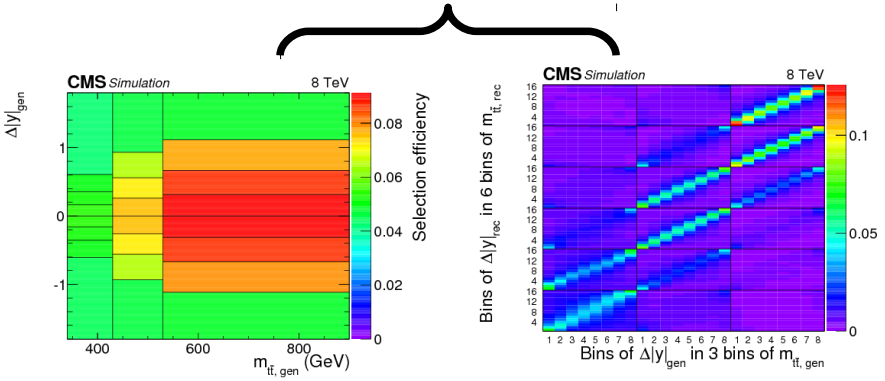
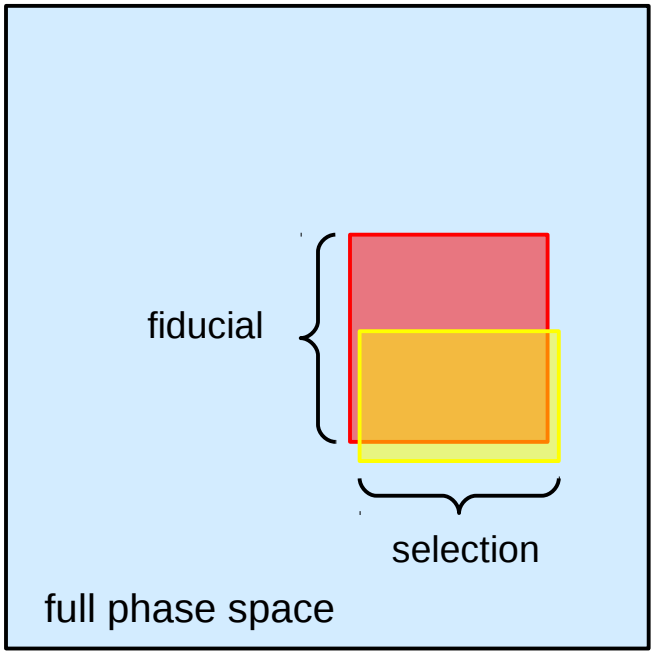
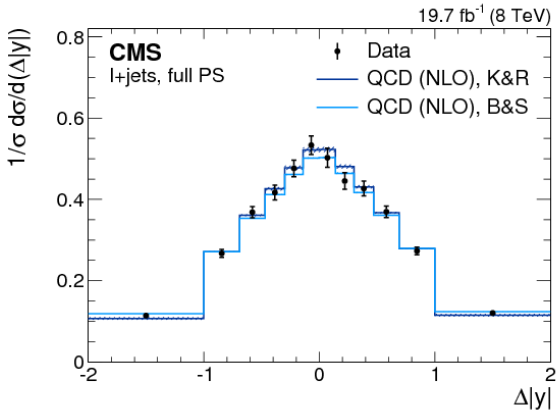


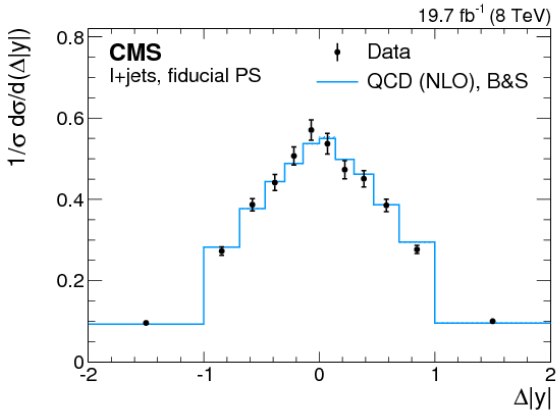
Unfolding (fiducial phase space)

- In addition to the full unfolding (extrapolation into the full phase space) CMS provides an unfolding into a fiducial phase space
- Fiducial phase space:
  - P_T and η cuts on generated leptons
  - P_T and η cuts on GenJets
  - ΔR(jet,lepton) > 0.4 to emulate isolation
- Affects **only the selection efficiency** and its inversion
- Migration effects are the same as in the unfolding into the full phase space



Results ATLAS and CMS: inclusive measurements





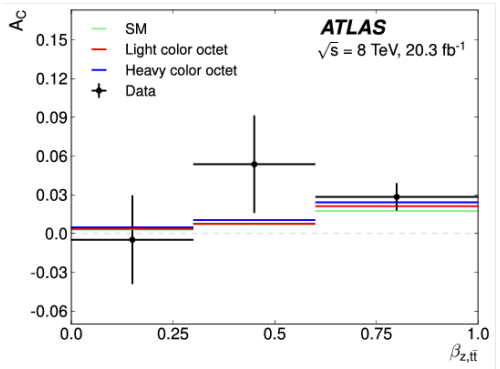
Full phase space

ATLAS	0.0090 ±0.005 (stat. + syst.)
CMS (Unfolding)	0.0010 ±0.0068 (stat.) ±0.0037 (syst.)
QCD NLO [Kühn, Rodrigo]	0.0102 ±0.0005
QCD NLO [Bernreuther, Si]	0.0111 ±0.0004

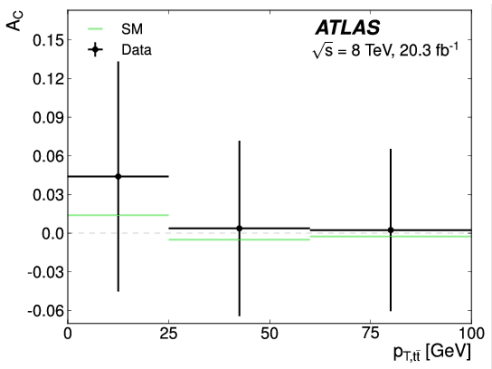
Fiducial phase space

CMS (Unfolding)	-0.0035 ±0.0072 (stat.) ±0.0031 (syst.)
QCD NLO [Bernreuther, Si]	0.0101 ±0.0010

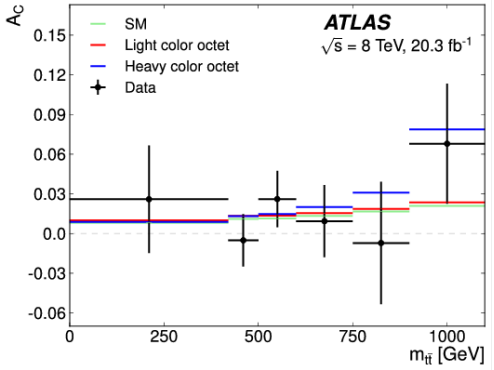
Results ATLAS and CMS: differential measurements



Boost of the $t\bar{t}$ system in z-direction

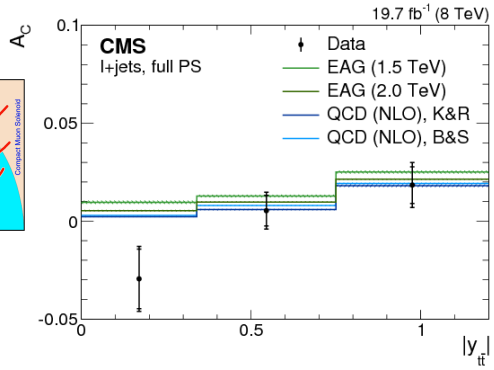


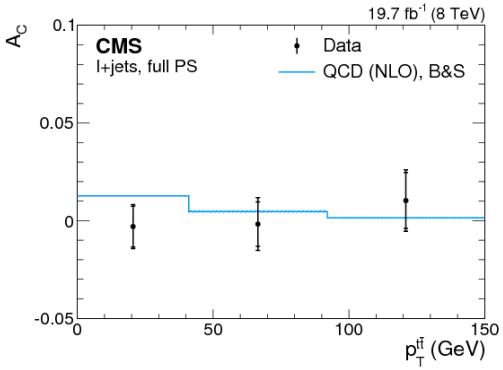
Transverse momentum of the $t\bar{t}$ system

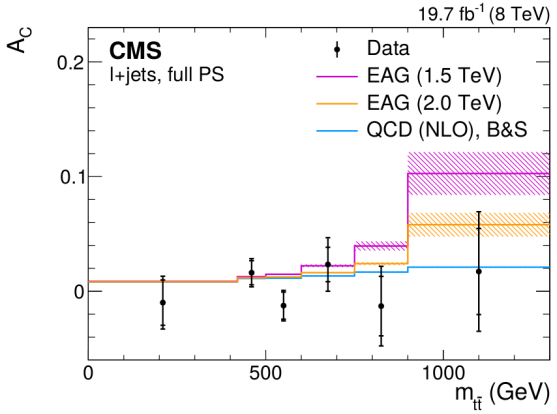


Invariant mass of the $t\bar{t}$ system

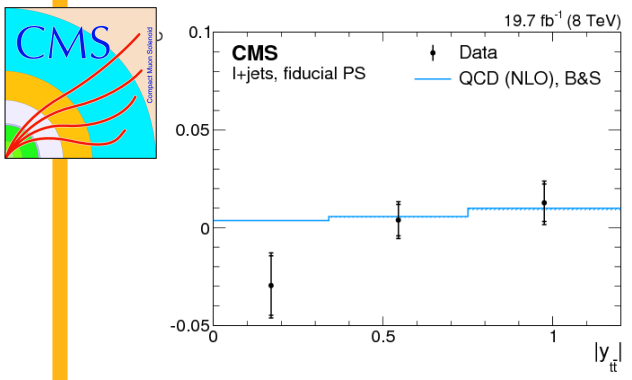
Rapidity of the $t\bar{t}$ system



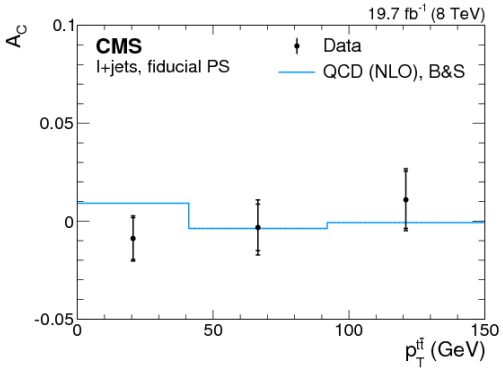




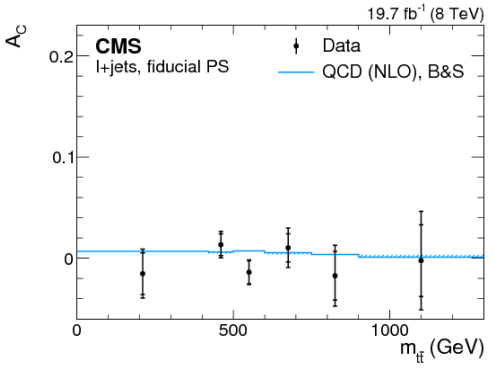
Results CMS: differential measurements in fiducial PS



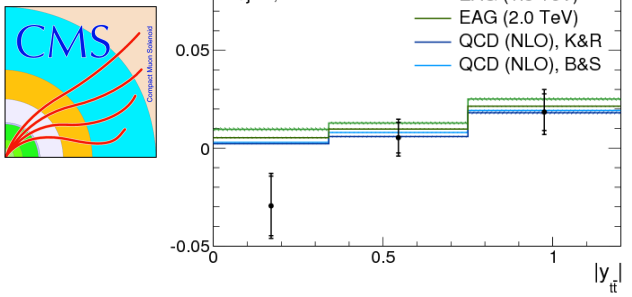
Rapidity of the $t\bar{t}$ system

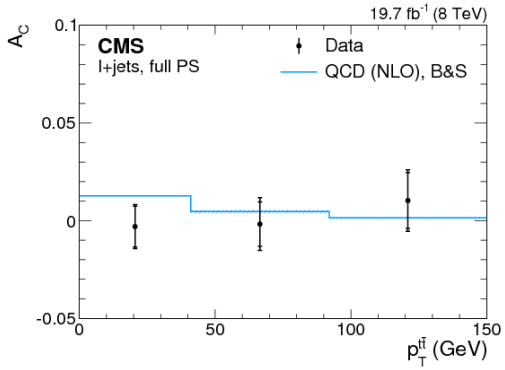


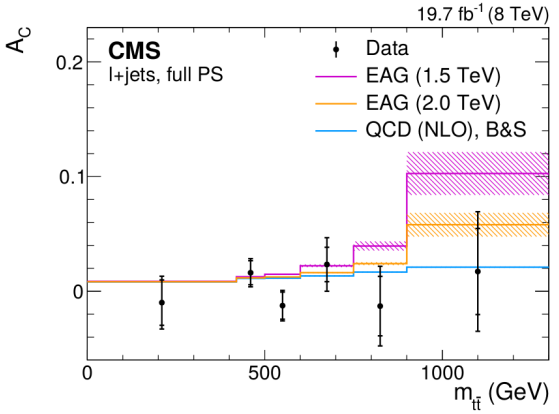
Transverse momentum of the $t\bar{t}$ system



Invariant mass of the $t\bar{t}$ system







CMS (template analysis) arXiv:1508.03862v1

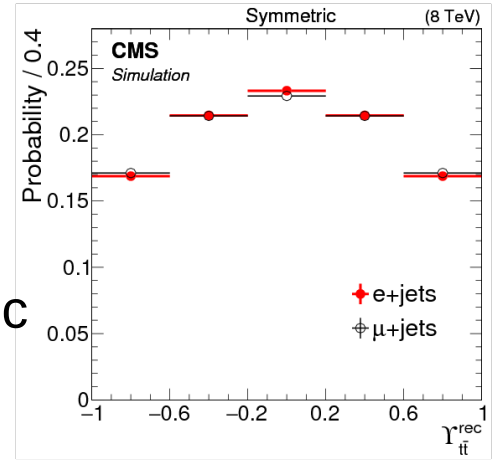
- Luminosity: 19.6/fb
- Event selection:
  - 1 isolated electron or muon *(p_T > 30 (26) GeV, $|\eta|$< 2.5 (2.1))*
  - ≥ 4 jets *(p_T > 20 GeV, $|\eta|$< 2.5)*
  - ≥ 1b-tag
- BG normalization:
  - Contributions from $t\bar{t}$, W+jets and QCD are fitted simultaneously
  - Single top and Z+jets are normalized to the SM predictions
- Reconstruction:
  - Analytic solution of missing z-component of neutrino vector
  - All jet-parton assignments are considered
  - Jet energies are corrected using scale factors (obtained from simulation) according to the assignment
  - In each event one assignment is chosen based on a likelihood criterion

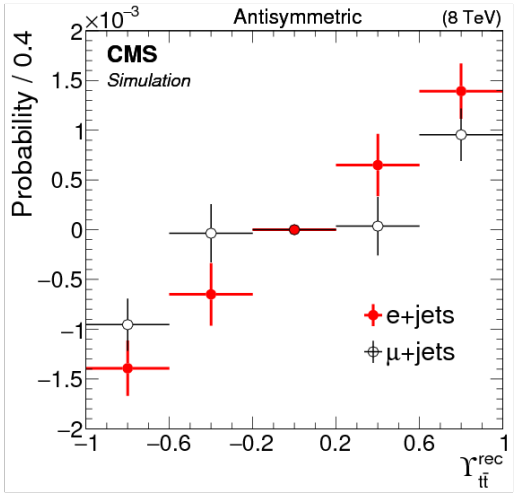
CMS (template analysis)

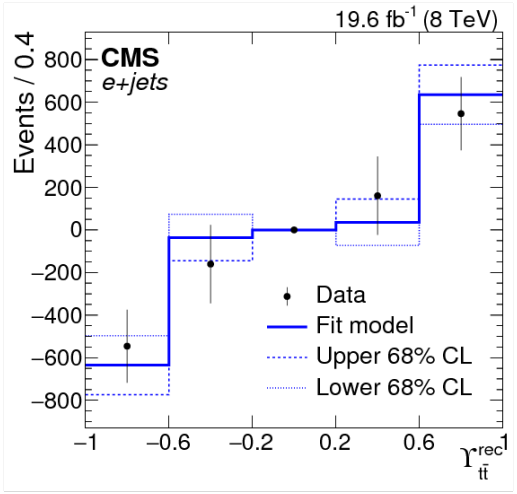
- Sensitive variable

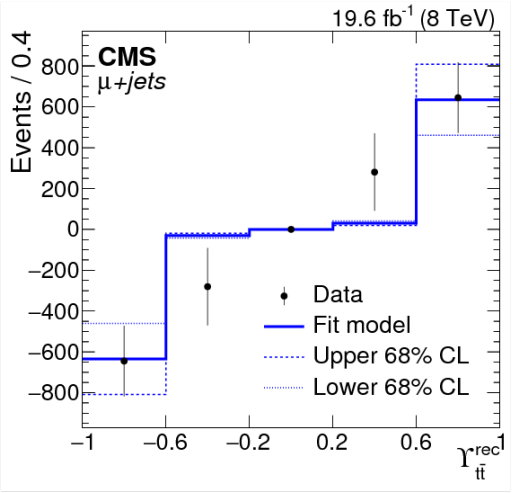
$$Y_{t\bar{t}} = \tanh\left(\Delta|y|\right)$$

- Construct templates symmetric and antisymmetric in this variable
- Measure the ratio after the fit to get the asymmetry at parton level









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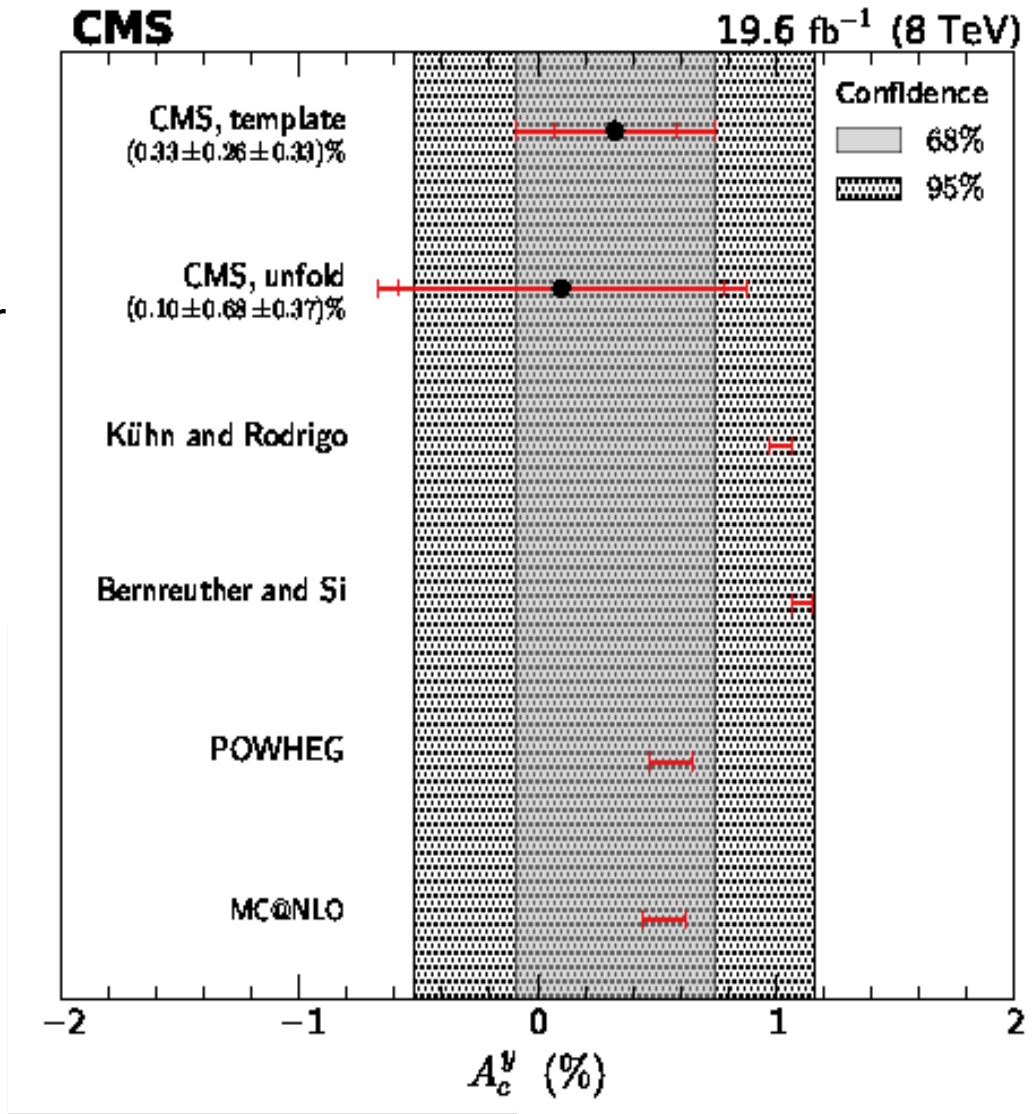
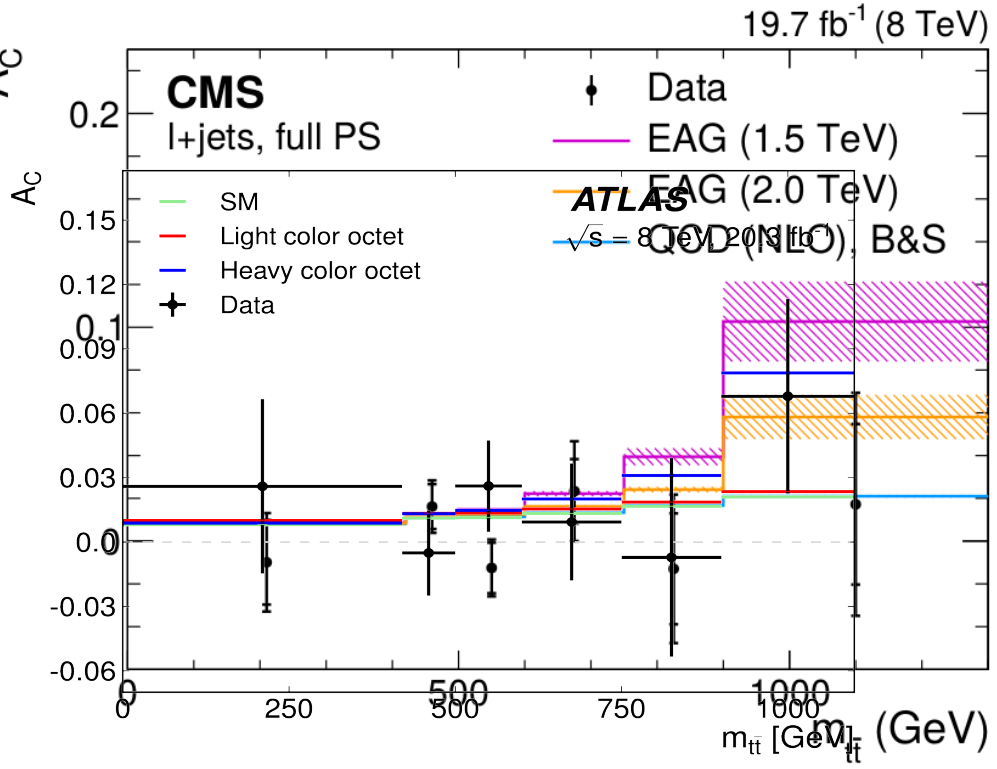


Combination – status and plans (1)

- Combination of inclusive results
  - Inputs are the two most precise results
  - **ATLAS** 0.005 total uncertainty
  - **CMS (template)** 0.004 total uncertainty
  - Combination is performed using BLUE
- Status of the combination
  - Mapping of systematic uncertainties **done**
  - Correlation assumptions **done**
  - Combination **done**
  - Approval in ATLAS and CMS and publication **on the way**

Combination – status and plans (2)

- Combination of differential results
  - Inputs are the ATLAS and CMS (unfolding) measurements of A_c as a function of the invariant mass of the $t\bar{t}$ system in six bins
- Status:
  - Mapping of systematics **done**
  - 2 dimensional combination and bin-by-bin correlations **is being worked on**
- Plan:
  - Approval and publication together with the inclusive combination



Combination of differential measurements

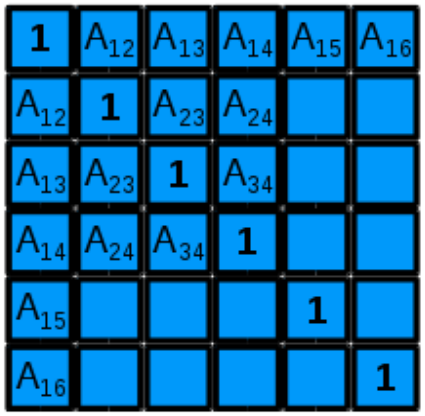
- For the combination of differential results we have to take into account: **the correlation between ...**
  - ... **different bins** in **one analysis (*)**
  - ... the **same bins** in **different analyses (**)**
  - … **different bins** in **different analyses (***)**

(*): can be estimated by each analysis group

(**): correspond to the assumed correlation (ρ) for the inclusive combination

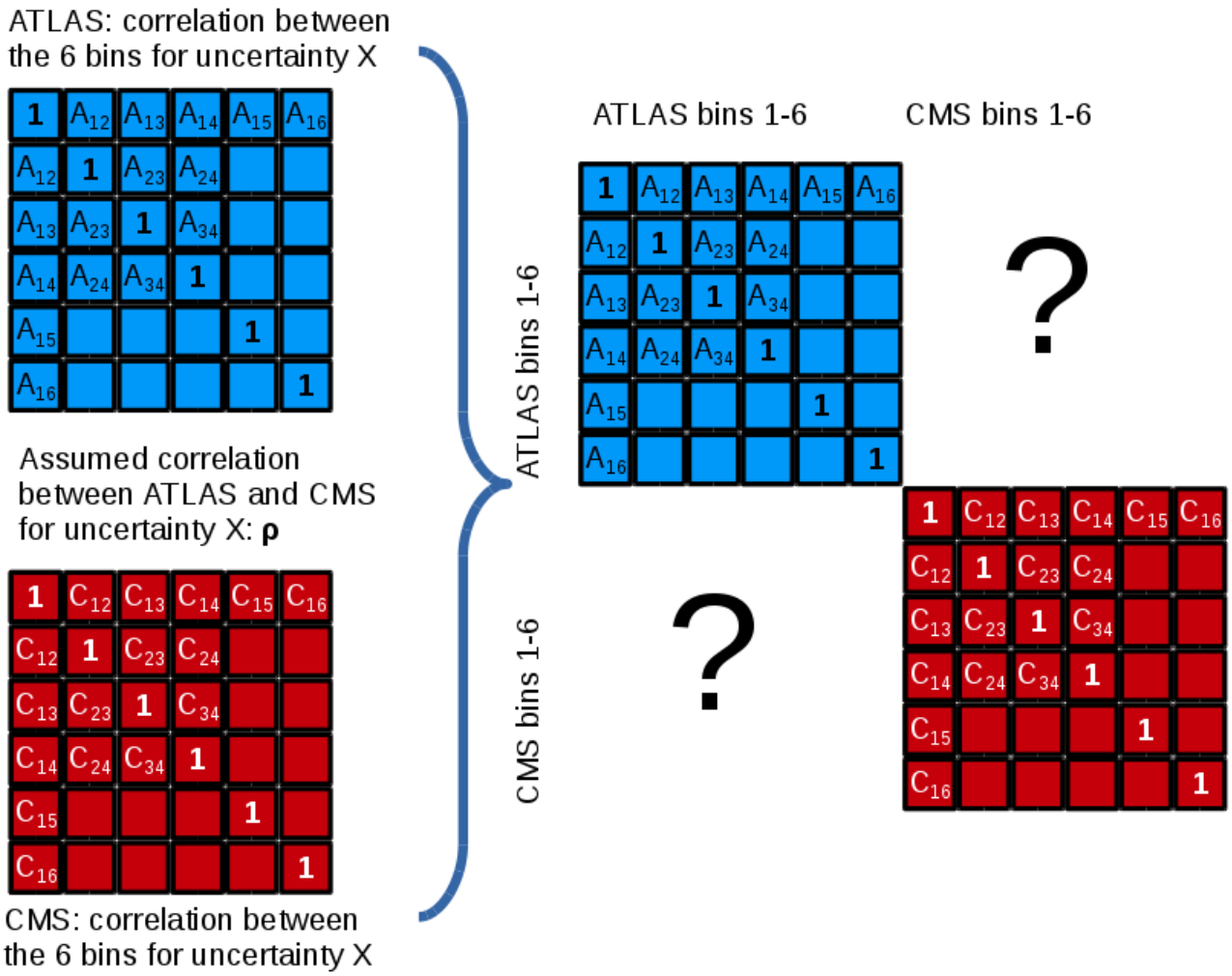
(***): have to be estimated

Different bins in one analysis



- For each uncertainty source the correlations between different bins are estimated separately for each analysis
- In most cases the correlations are either 1 or -1
- In some cases also values between 1 and -1 are possible

Different bins in one analysis



Same bins in different analyses

ATLAS: correlation between the 6 bins for uncertainty X

1	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}
A_{12}	1	A_{23}	A_{24}		
A_{13}	A_{23}	1	A_{34}		
A_{14}	A_{24}	A_{34}	1		
A_{15}				1	
A_{16}					1

Assumed correlation between ATLAS and CMS for uncertainty X: **ρ**

1	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
C_{12}	1	C_{23}	C_{24}		
C_{13}	C_{23}	1	C_{34}		
C_{14}	C_{24}	C_{34}	1		
C_{15}				1	
C_{16}					1

CMS: correlation between the 6 bins for uncertainty X

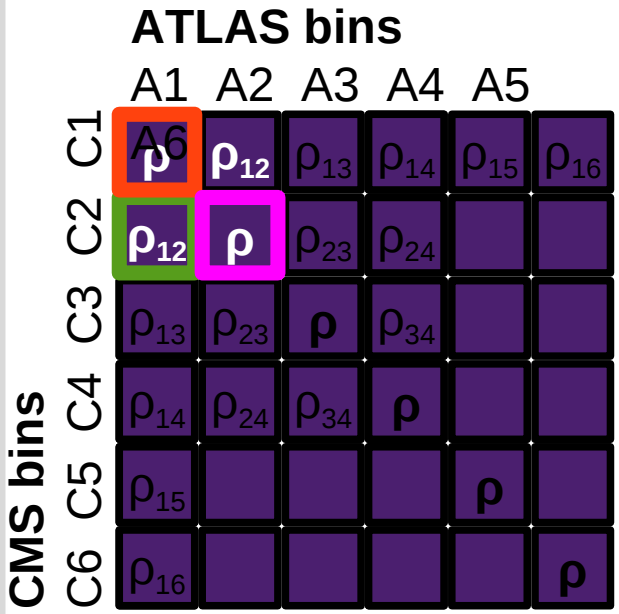
ATLAS bins 1-6 / CMS bins 1-6

ATLAS bins 1-6 \ CMS bins 1-6						
1	A_{12}	A_{13}	A_{14}	A_{15}	A_{16}	ρ	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}	ρ_{16}
A_{12}	1	A_{23}	A_{24}			ρ_{12}	ρ	ρ_{23}	ρ_{24}		
A_{13}	A_{23}	1	A_{34}			ρ_{13}	ρ_{23}	ρ	ρ_{34}		
A_{14}	A_{24}	A_{34}	1			ρ_{14}	ρ_{24}	ρ_{34}	ρ		
A_{15}				1		ρ_{15}				ρ	
A_{16}					1	ρ_{16}					ρ
ρ	ρ_{12}	ρ_{13}	ρ_{14}	ρ_{15}	ρ_{16}	1	C_{12}	C_{13}	C_{14}	C_{15}	C_{16}
ρ_{12}	ρ	ρ_{23}	ρ_{24}			C_{12}	1	C_{23}	C_{24}		
ρ_{13}	ρ_{23}	ρ	ρ_{34}			C_{13}	C_{23}	1	C_{34}		
ρ_{14}	ρ_{24}	ρ_{34}	ρ			C_{14}	C_{24}	C_{34}	1		
ρ_{15}				ρ		C_{15}				1	
ρ_{16}					ρ	C_{16}					1

CMS bins 1-6

Same correlation assumptions as for combination of inclusive measurements

Different bins in different analyses



- Diagonal elements: assumed correlation between ATLAS and CMS w.r.t. uncertainty X: **ρ(=0/0.5/1)**
- **Off-diagonal elements**: no information available, we have to make an estimation.
  - **Example: ATLAS bin 1 (A1) and CMS bin 2 (C2)**
  - **Two possibilities:**
    - Start from **A1C1 = ρ** and multiply with C_{12}
    - Start from **A2C2 = ρ** and multiply with A_{12}
    - Both options are valid, take the average of the two

      $$A1C2 = (\rho C_{12} + \rho A_{12})/2 = \rho_{12}$$

    - **As a result, A1C2 = A2C1 and the matrix is symmetric**

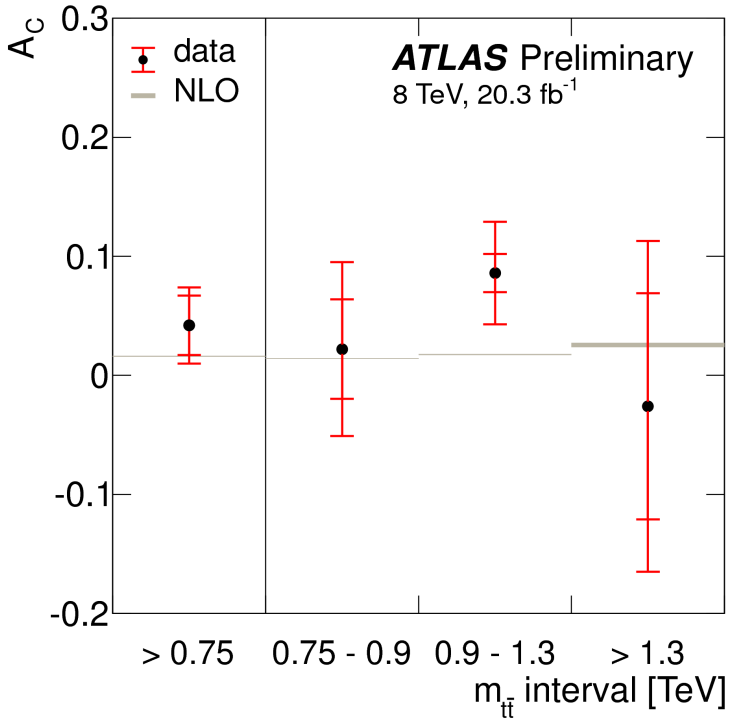
ATLAS charge asymmetry in boosted events

- Luminosity: 20.3/fb
- Event selection:
  - 1 isolated electron or muon *(p_T > 25 GeV, $|\eta|$< 2.5)*
  - ≥ 1 default (R = 0.4) jet *(p_T > 25 GeV, $|\eta|$< 2.5)*
  - 1 large (R = 1.0) jet (p_T > **300** GeV, ΔΦ(l,jet) > 2.3, ΔR(large jet, default jet), substructure quality criteria)
  - MET + MTW > 60 GeV for 0 or 1 b-tag
  - MET > 40 (20) GeV for 0(1) b-tag
- BG normalization: Same as in the “standard” ATLAS analysis
- Reconstruction:
  - Hadronically decaying top: large, high-momentum jet
  - Leptonically decaying top: default jet with hightest p_T added to lepton and neutrino
- Unfolding: Same as in the “standard” ATLAS analysis

ATLAS charge asymmetry in boosted events

- Measurement in a fiducial region with $m_{t\bar{t}} > 750$ GeV and $-2 < \Delta|y| < 2$

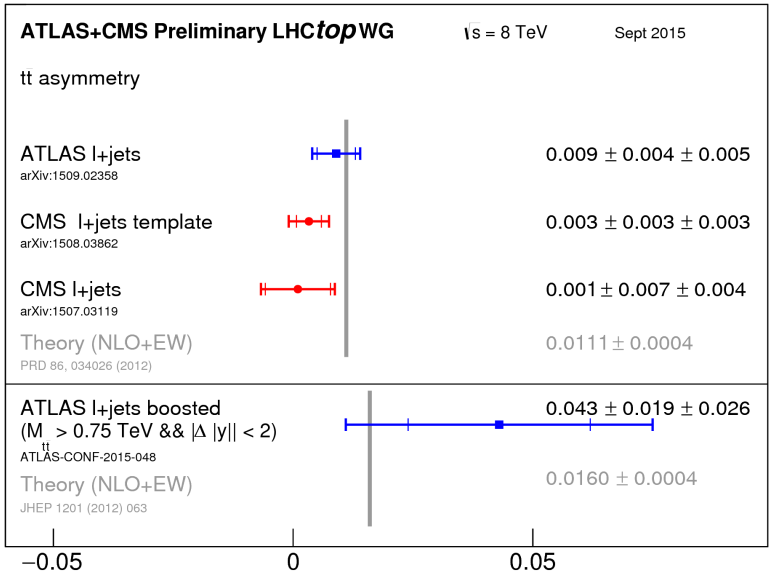
$m_{t\bar{t}}$ interval	> 0.75 TeV	$0.75 - 0.9$ TeV	$0.9 - 1.3$ TeV	> 1.3 TeV
measurement	4.2 ± 3.2 %	2.2 ± 7.3 %	8.6 ± 4.3 %	$-2.6\% \pm 13.9$ %
SM prediction	1.60 ± 0.04 %	1.42 ± 0.04 %	1.75 ± 0.05 %	2.55 ± 0.18 %



CMS and ATLAS dilepton analyses

- Top quark charge asymmetry
  - Statistically limited
  - Precision is not compatible with lepton+jets results
- Lepton charge asymmetry
  - Advantage: Lepton reconstruction is very precise, resolution and migration effects due to reconstruction are negligible
- ATLAS and CMS groups work on finalizing the measurements of the top charge asymmetry and the lepton charge asymmetry in the dilepton channels

Summary and Outlook



- 8 TeV
  - Dilepton results will be finalized soon
  - Combination of lepton+jets results will be finalized soon
- 13 TeV
  - Challenge: A_c gets smaller
  - Advantage: Will get a lot more $t\bar{t}$ events in Run II (not yet...)
    - Measure in phase spaces that enhance the asymmetry
    - Explore new observables
- “Gold rush” is over
  - Tevatron discrepancy decreased
  - LHC results support the SM predictions
- Still interesting to measure this effect as precisely as possible in order to get a better understanding of the top quark and its production