Measurement of the charge asymmetry in top quark pair production in 8 TeV *pp* collision data collected by the ATLAS experiment

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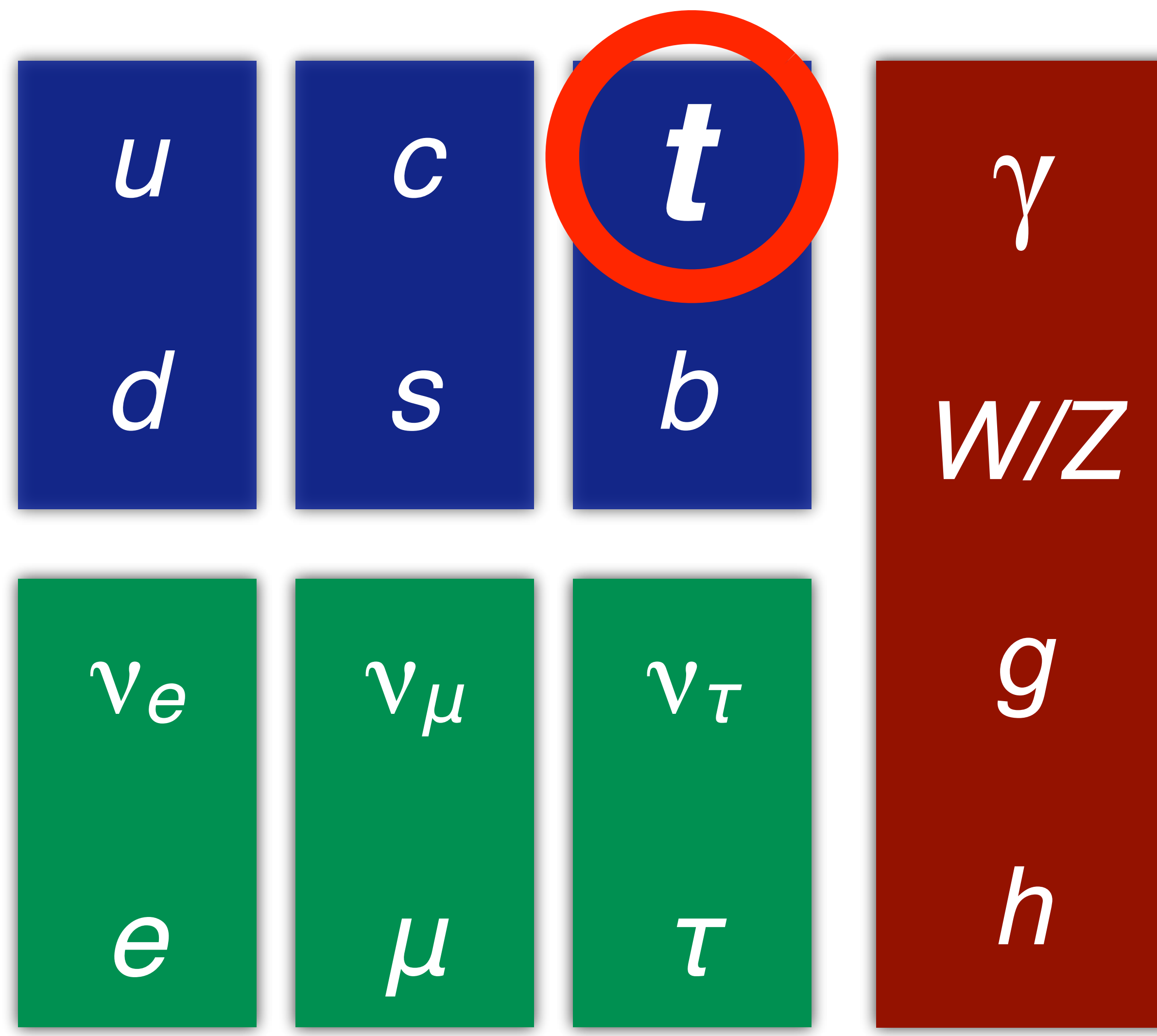
ATLAS EXPERIMENT

Outline

- Top Quark Charge Asymmetry
  - Overview
- Resolved ℓ+jets Analysis
- Boosted ℓ+jets Analysis

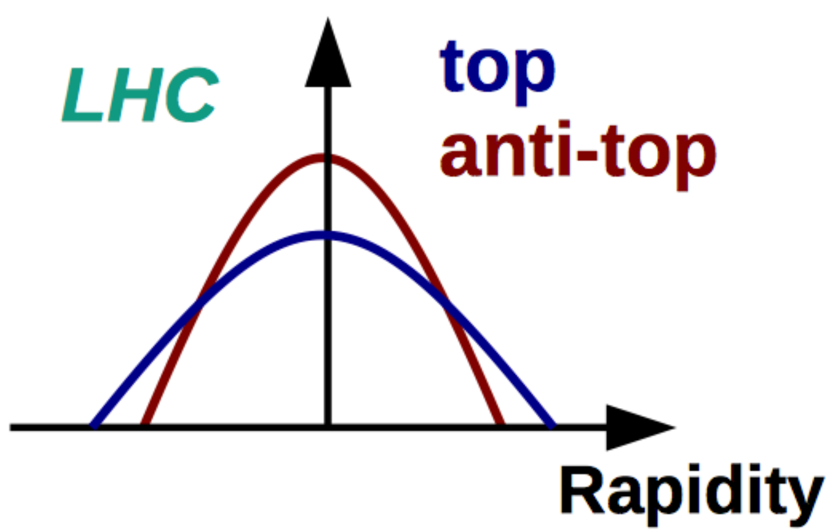


Charge Asymmetry

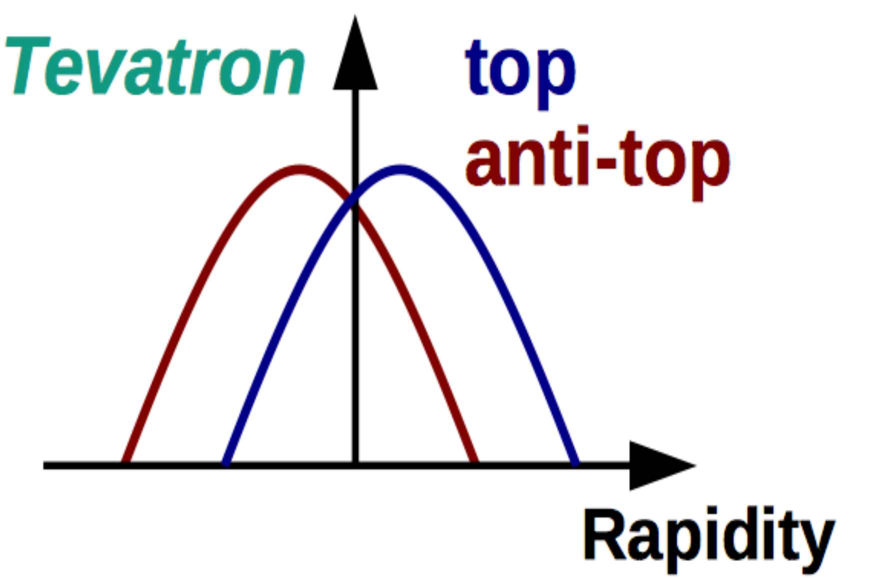
- The Tevatron and LHC are both sensitive to a difference in rapidity distributions of top and anti-top quarks

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

$A_C : \Delta|y| \equiv |y_t| - |y_{\bar{t}}|$

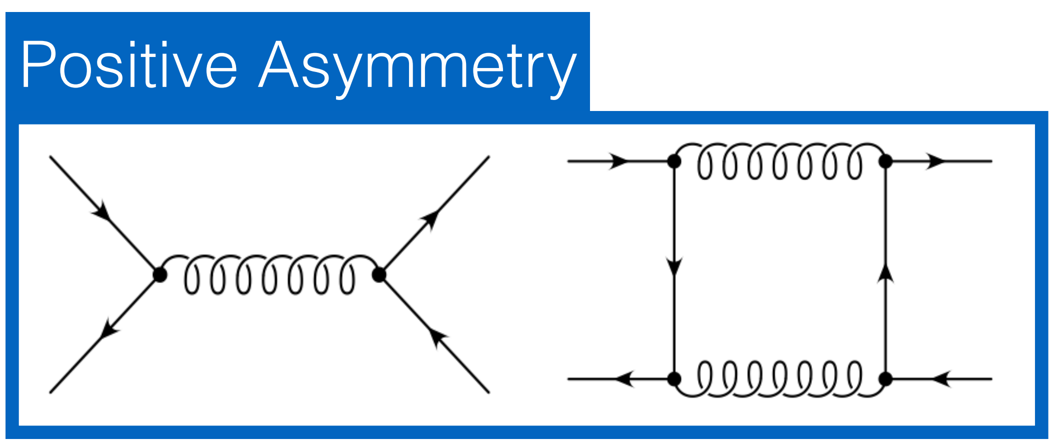


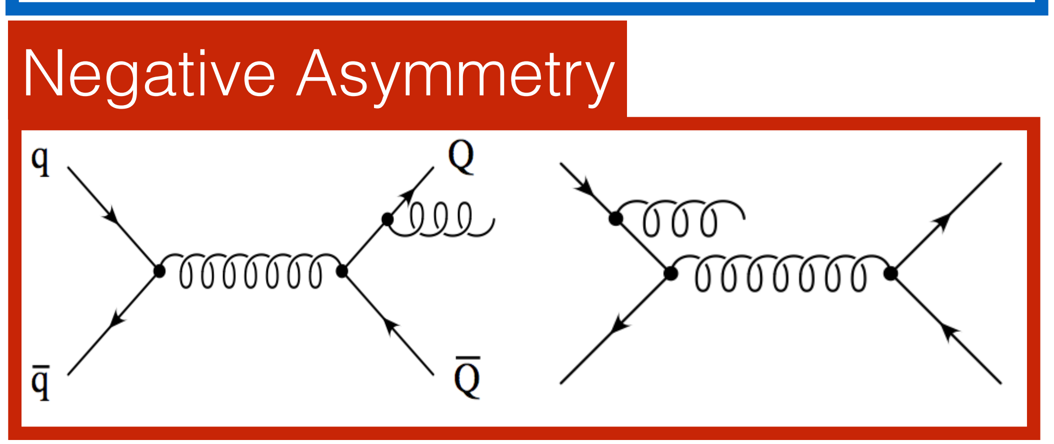
$A_{fb} : \Delta|y| \equiv y_t - y_{\bar{t}}$

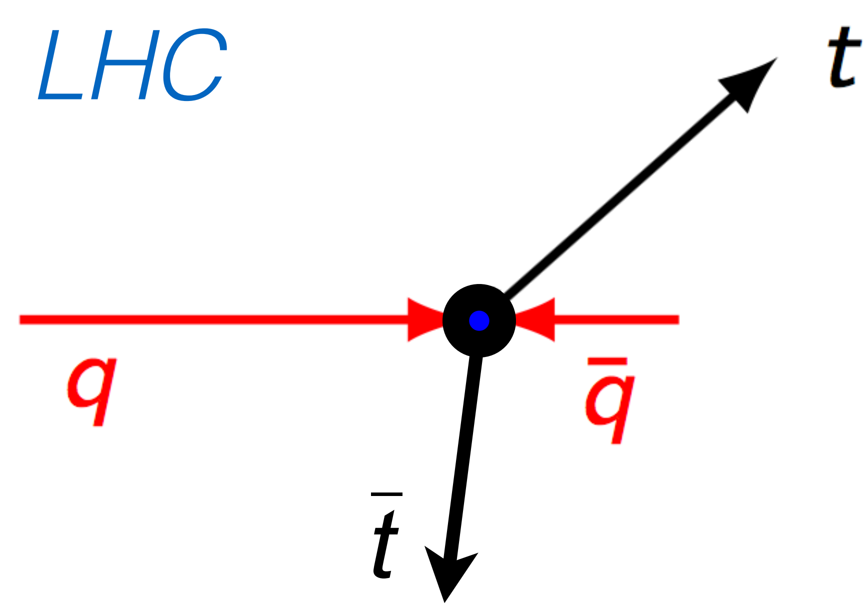


Charge Asymmetry

- The charge asymmetry is generated from correlations between the incoming quark (anti-quark) and top (anti-top)
- Charge symmetric production (*gg*-fusion) does not produce an asymmetry

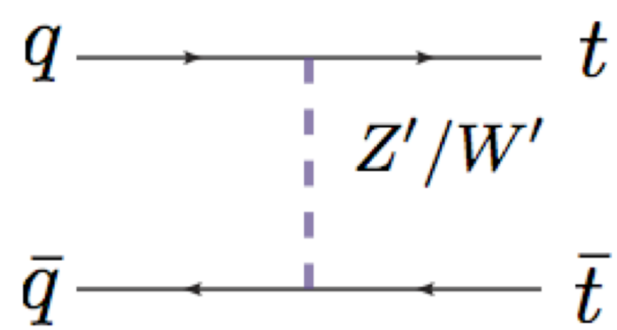


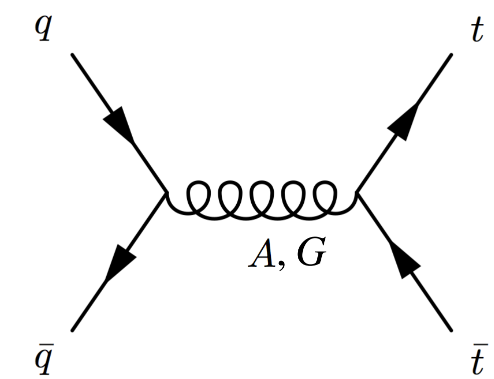


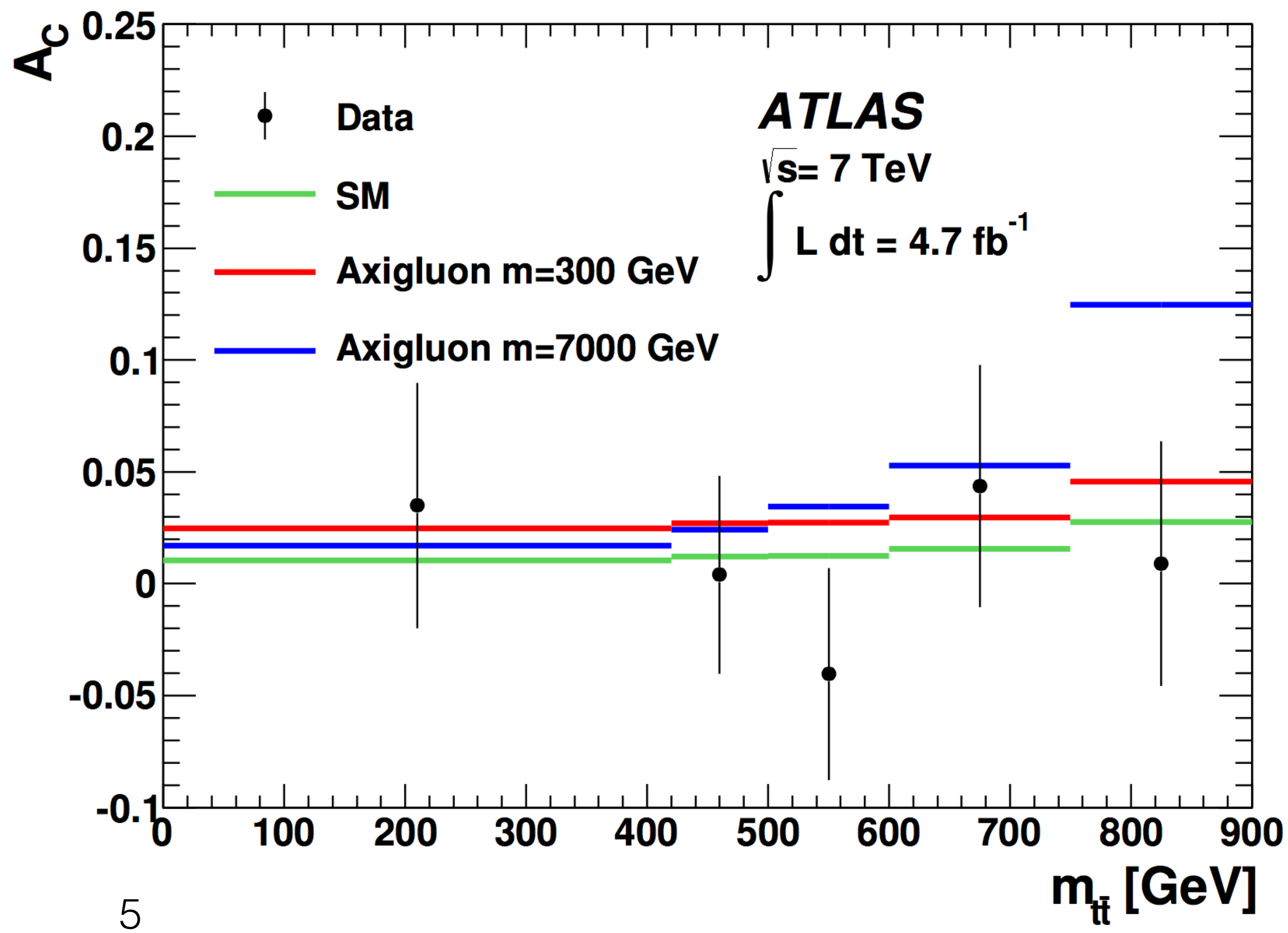


Motivation

- Discrepancy between measurements and theory has reduced recently
- However, now we have: High Statistics & Boosted Tops!
  - Able to do *precise* measurements and investigate high m_{tt} events





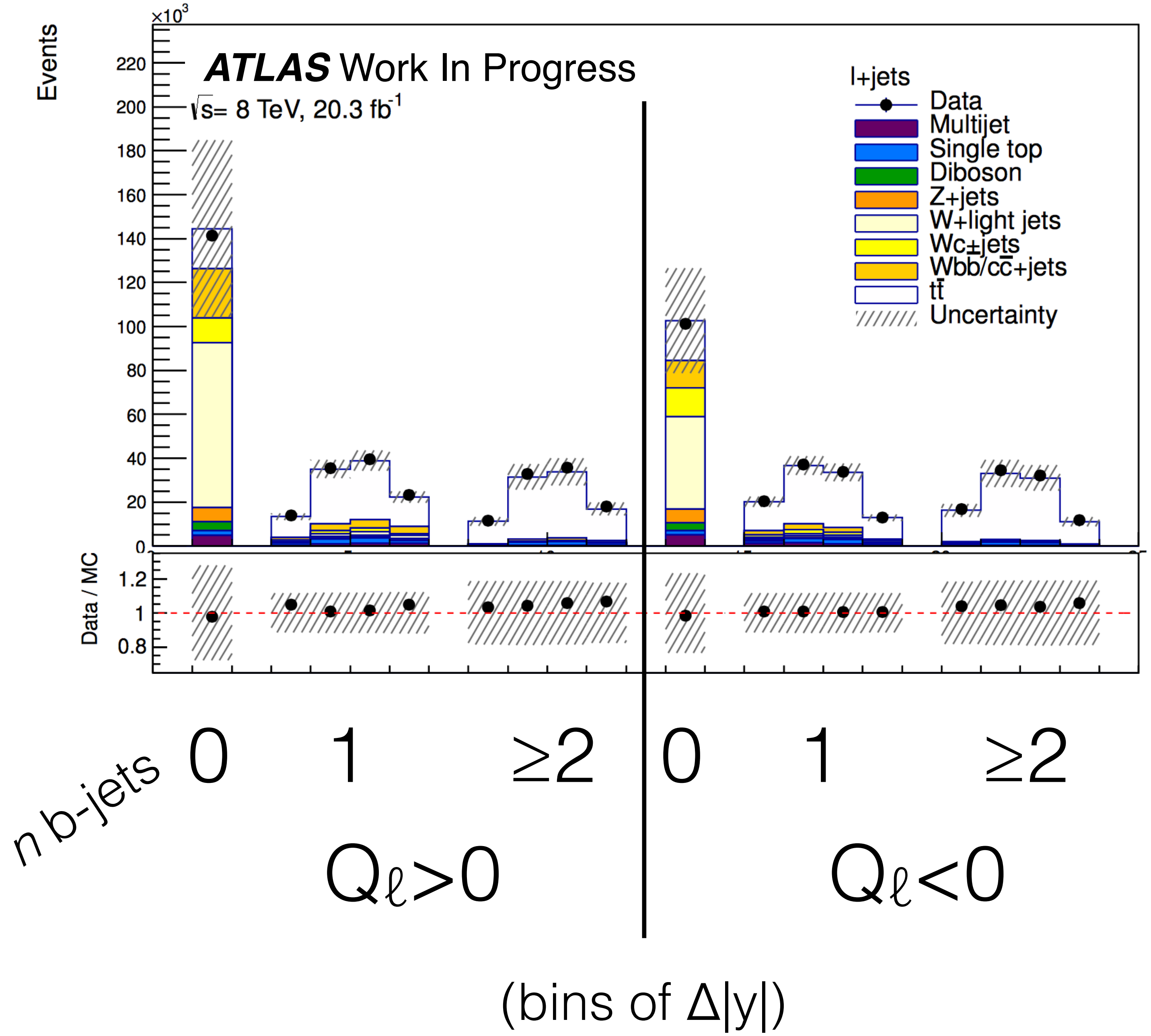


ATLAS (7TeV): JHEP 02 (2014) 107

Resolved ℓ+jets

Analysis Strategy

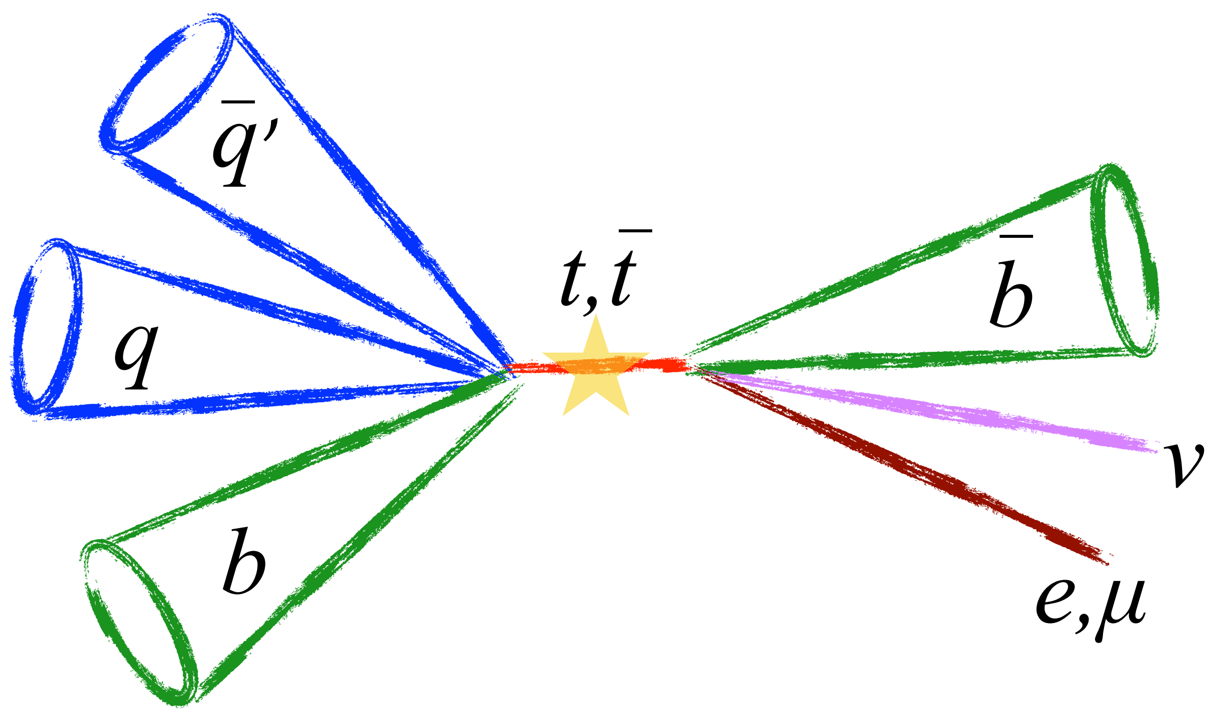
- Enriched ttbar sample
  Event Selection
- ttbar reconstruction
  Likelihood fit
- Background estimation
  in-situ calibration of W+Jets
- Estimate of parton-level A_C
  Unfolding



Event Selection

- ~Standard **ℓ+jets** selection
  - 1 lepton (e/μ, p_T>25 GeV)
  - ≥4 jets (p_T>25 GeV)
  - MET > 60 (40) GeV
    MET+MTW > 60 (0) GeV

} If 0 (1) b-tag in the event



$$MTW = \sqrt{2 p_T E_T^{\text{miss}} \left(1 - \cos\phi_{\ell\nu}\right)}$$

Reconstruction

- The ttbar system is fully reconstructed using a likelihood fit

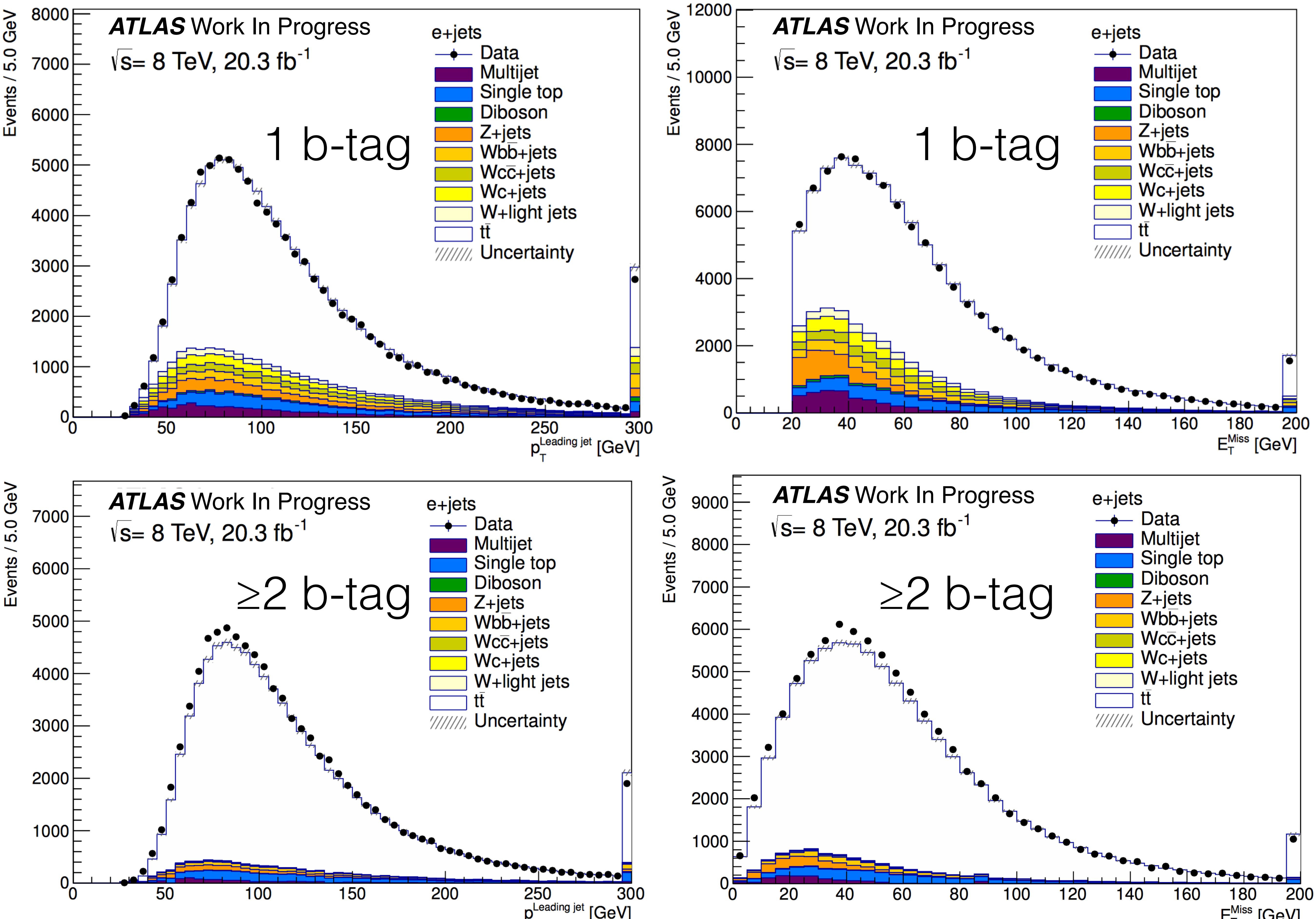
$$L \propto \mathcal{B} \times \mathcal{W}$$

$\mathcal{B}$ | Breit-Wigner constraints on the leptonic/hadronic W and top masses (4 terms)

$\mathcal{W}$ | Transfer functions that map the response of objects to particles (7 terms)

- Each jet permutation is calculated, and the most probable configuration is chosen

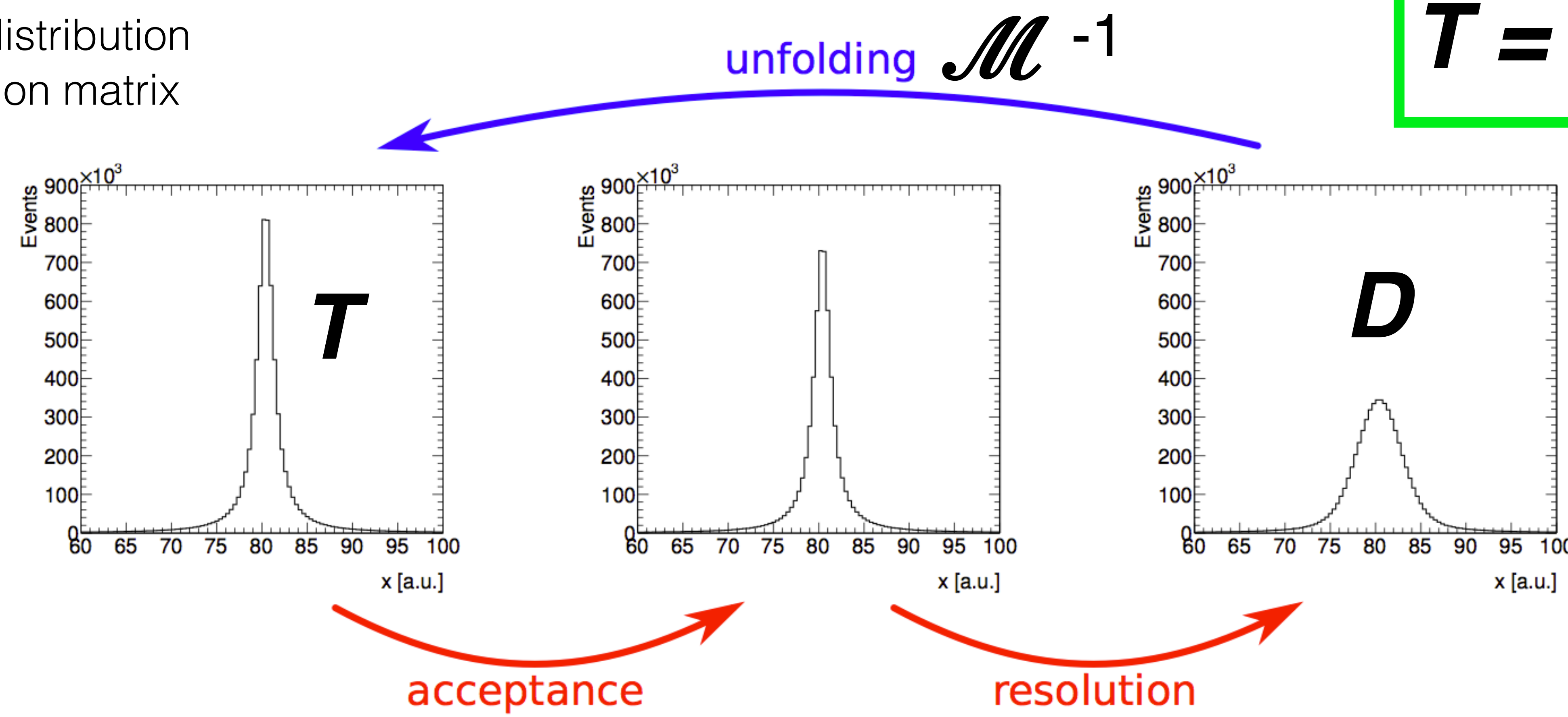
Likelihood Fit: Nuclear Instruments and Methods in Physics Research Section A 748 (2014) 18-25


ATLAS Work In Progress
√s= 8 TeV, 20.3 fb^-1
1 b-tag
e+jets
Data
Multijet
Single top
Diboson
Z+jets
Wbb̄+jets
Wcc̄+jets
Wc+jets
W+light jets
tt̄
Uncertainty
Events / 5.0 GeV
p_T^Leading jet [GeV]
ATLAS Work In Progress
√s= 8 TeV, 20.3 fb^-1
1 b-tag
e+jets
Events / 5.0 GeV
E_T^Miss [GeV]
ATLAS Work In Progress
√s= 8 TeV, 20.3 fb^-1
≥2 b-tag
e+jets
Events / 5.0 GeV
p_T^Leading jet [GeV]
ATLAS Work In Progress
√s= 8 TeV, 20.3 fb^-1
≥2 b-tag
e+jets
Events / 5.0 GeV
E_T^Miss [GeV]

Unfolding

$\boldsymbol{T}$ = “true” distribution
$\boldsymbol{D}$ = “data” distribution
$\mathscr{M}$ = Migration matrix

$$\boldsymbol{T} = \mathscr{M}^{-1}\,\boldsymbol{D}$$



- To correct for acceptance and resolution effects, we unfold our final result
- Result is unfolded to parton-level
  - Allows us to compare our measurement with other experimental and theoretical results

Fully Bayesian Unfolding

- Bayes' Theorem is directly applied to the problem of unfolding
    - Avoid the problem of matrix inversion!

$$p\left(\boldsymbol{T}|\boldsymbol{D},\mathcal{M}\right) \propto \mathcal{L}\left(\boldsymbol{D}|\boldsymbol{T},\mathcal{M}\right) \cdot \pi\left(\boldsymbol{T}\right)$$

- **Posterior probability** of the true spectrum, **T**, given data, **D**
- **Likelihood** of **D**, given **T** and response matrix
- **Prior probability density** of **T** (our prior knowledge about **T**)

Implemented using open source pyFBU

FBU: arXiv:1201.4612

Fully Bayesian Unfolding

- Calculate A_C given the posterior probability density in each bin of $\Delta|y|$

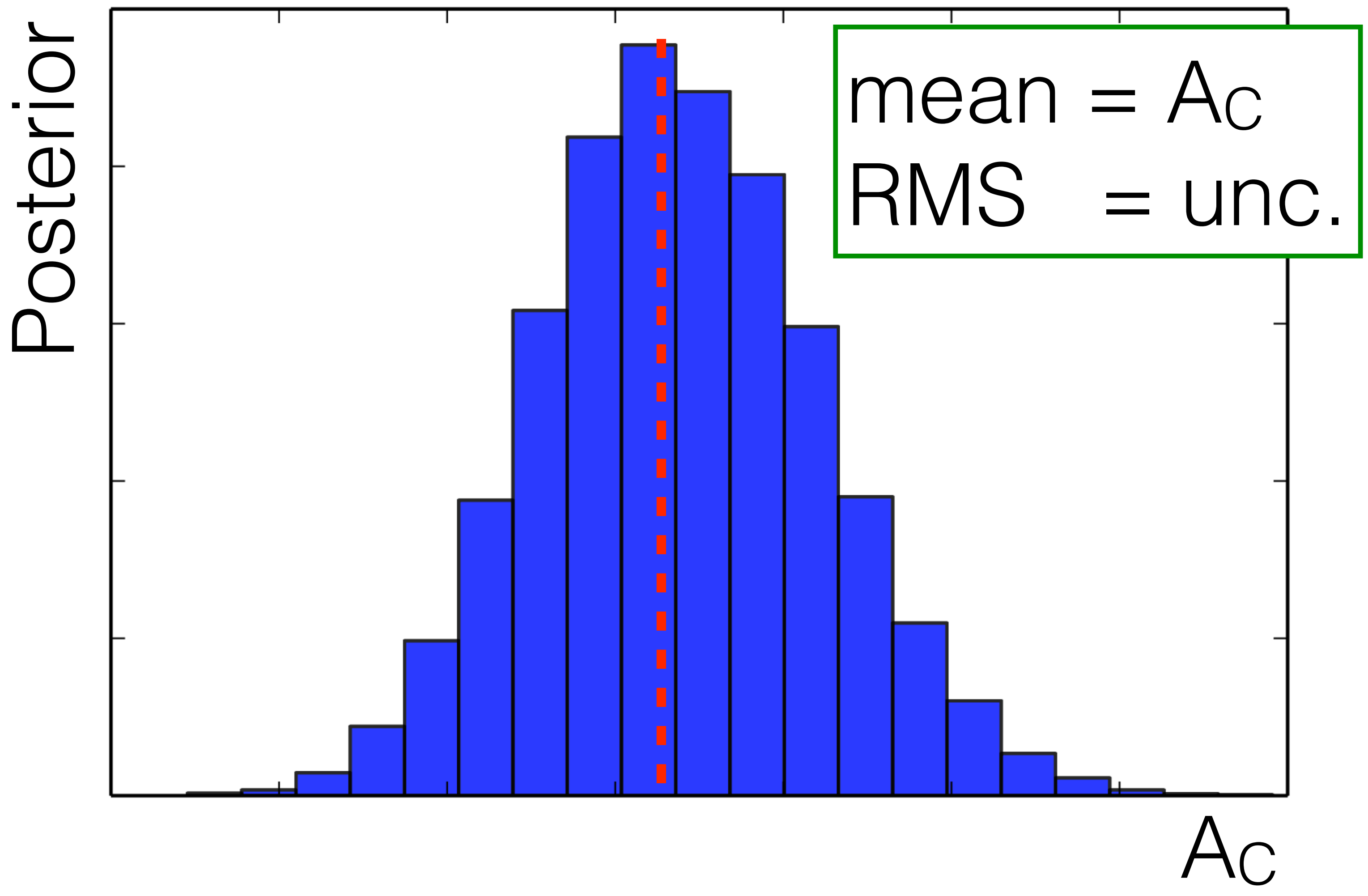


image: pyFBU

Systematic Uncertainties

- Detector-related systematic uncertainties are included in our unfolding procedure (a)
- Other systematic uncertainties are studied independently and added in quadrature to the total uncertainty (b)

	Source of systematic uncertainty	δA_C
(a)	Jet energy scale and resolution	0.0016
	Multijet background normalisation	0.0005
(b)	Initial-/final-state radiation	0.0009
	Monte Carlo statistics	0.0010
	PDF	0.0007
	Statistical uncertainty	0.0044
	Total uncertainty	0.0049

***Expected* uncertainty** (work in progress)

statistically limited!

Inclusive measurement

Differential Measurements

- Three differential measurements are presented (measure A_C in bins of differential variable)
  - A_C vs $p_{T,tt}$: Sensitivity to ISR/FSR generated asymmetry
  - A_C vs $\beta_{z,tt}$: Increase the fraction of quark-antiquark initiated events to enhance the asymmetry
  - A_C vs m_{tt}: Different behavior for various BSM physics at high m_{tt}; enhance quark-antiquark initiated events

$\beta_{z,tt}$: Phys. Lett. B 707 (2012) 92-98

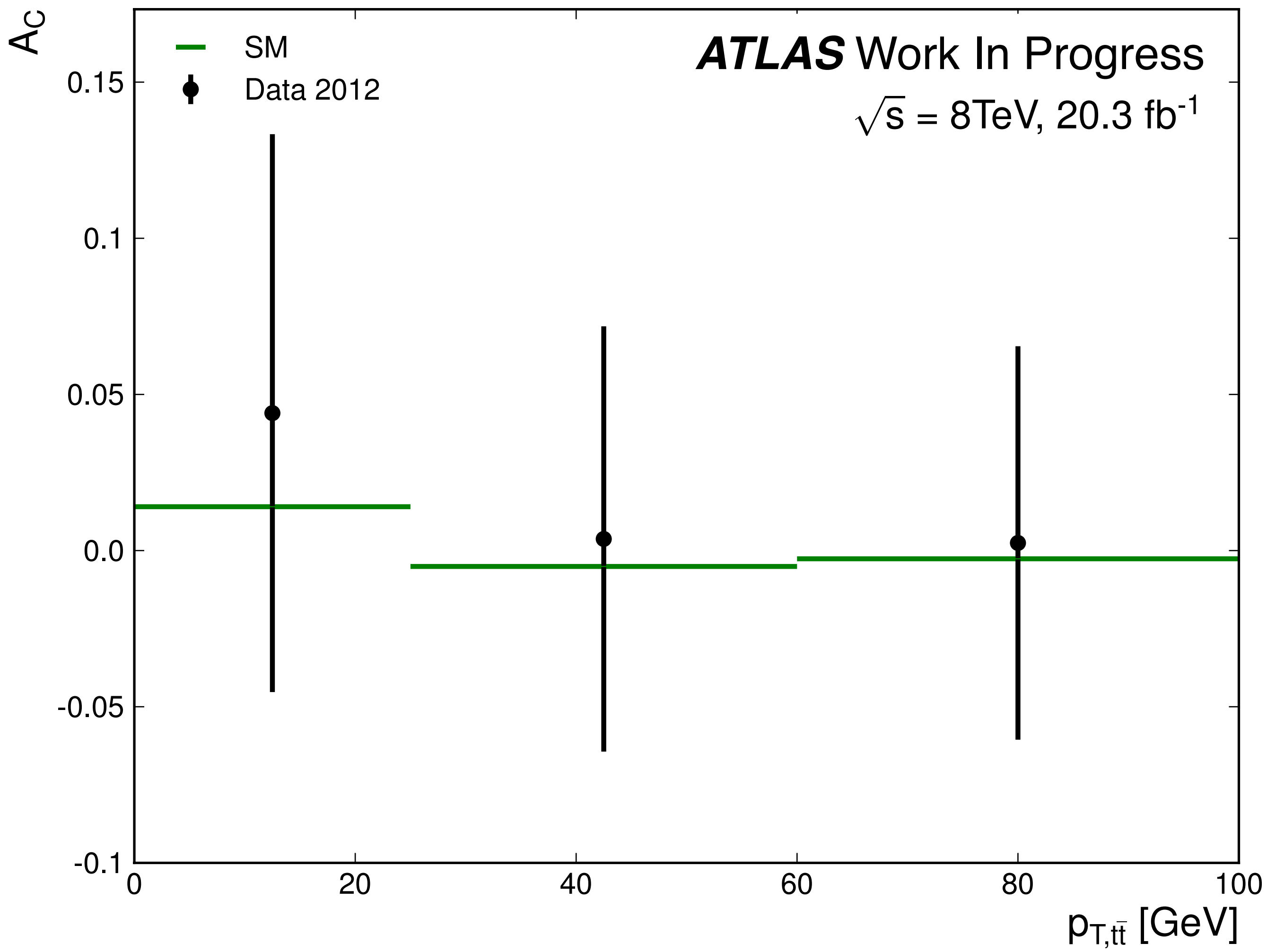
Results

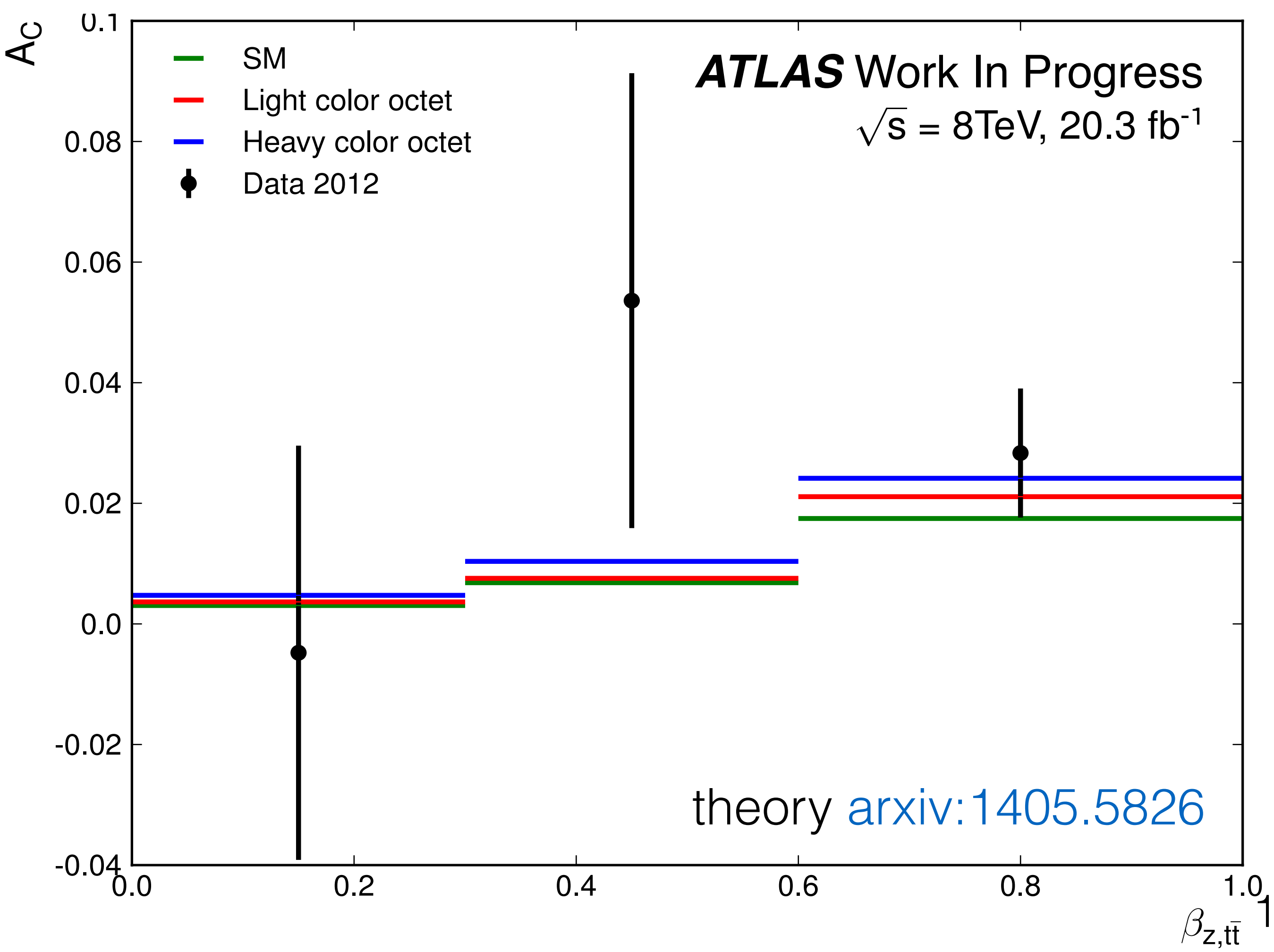
Inclusive:

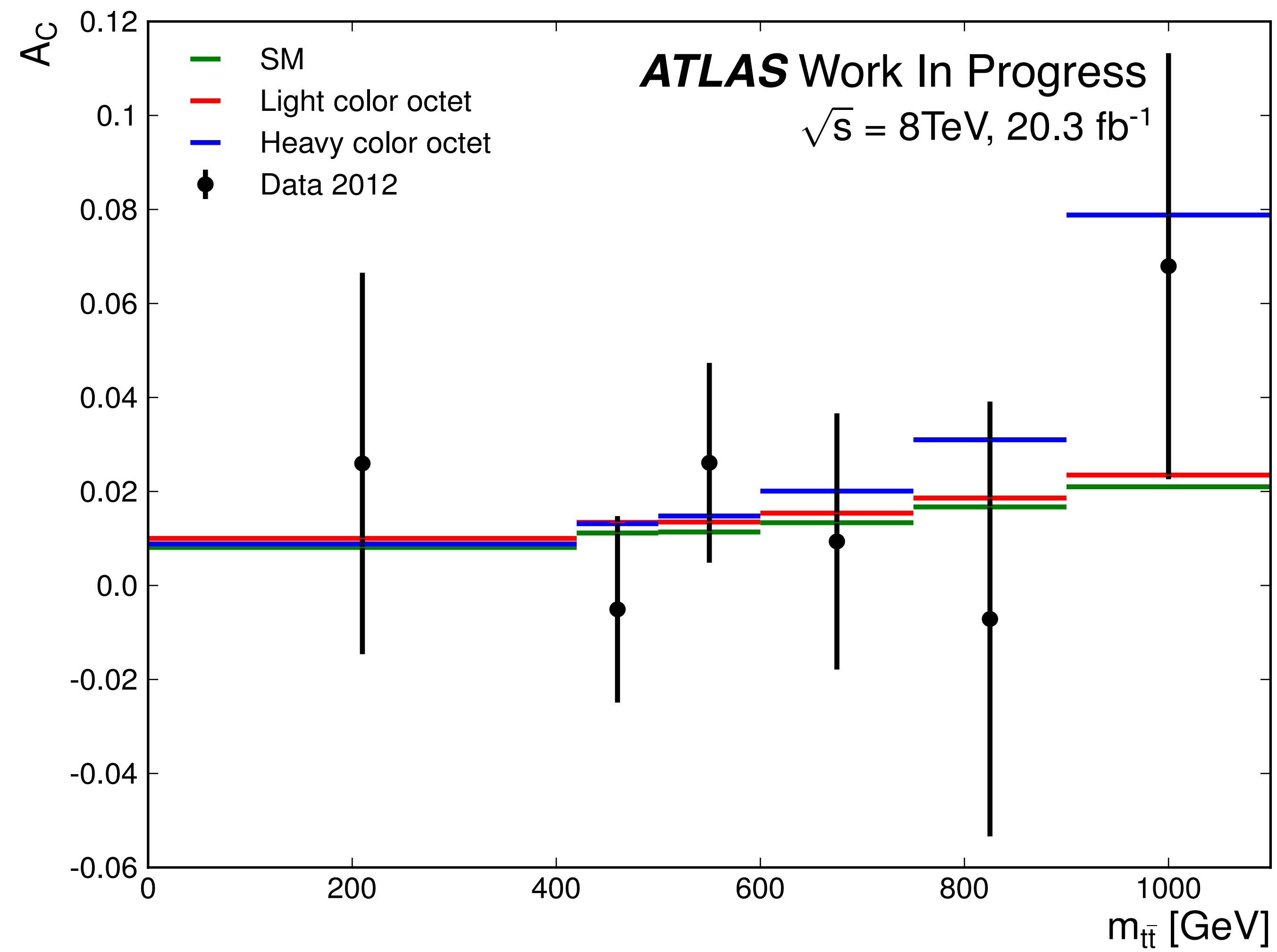
$A_C = 0.009 \pm 0.005$

CMS: 0.0010 ± 0.008

SM: 0.0111 ± 0.0004



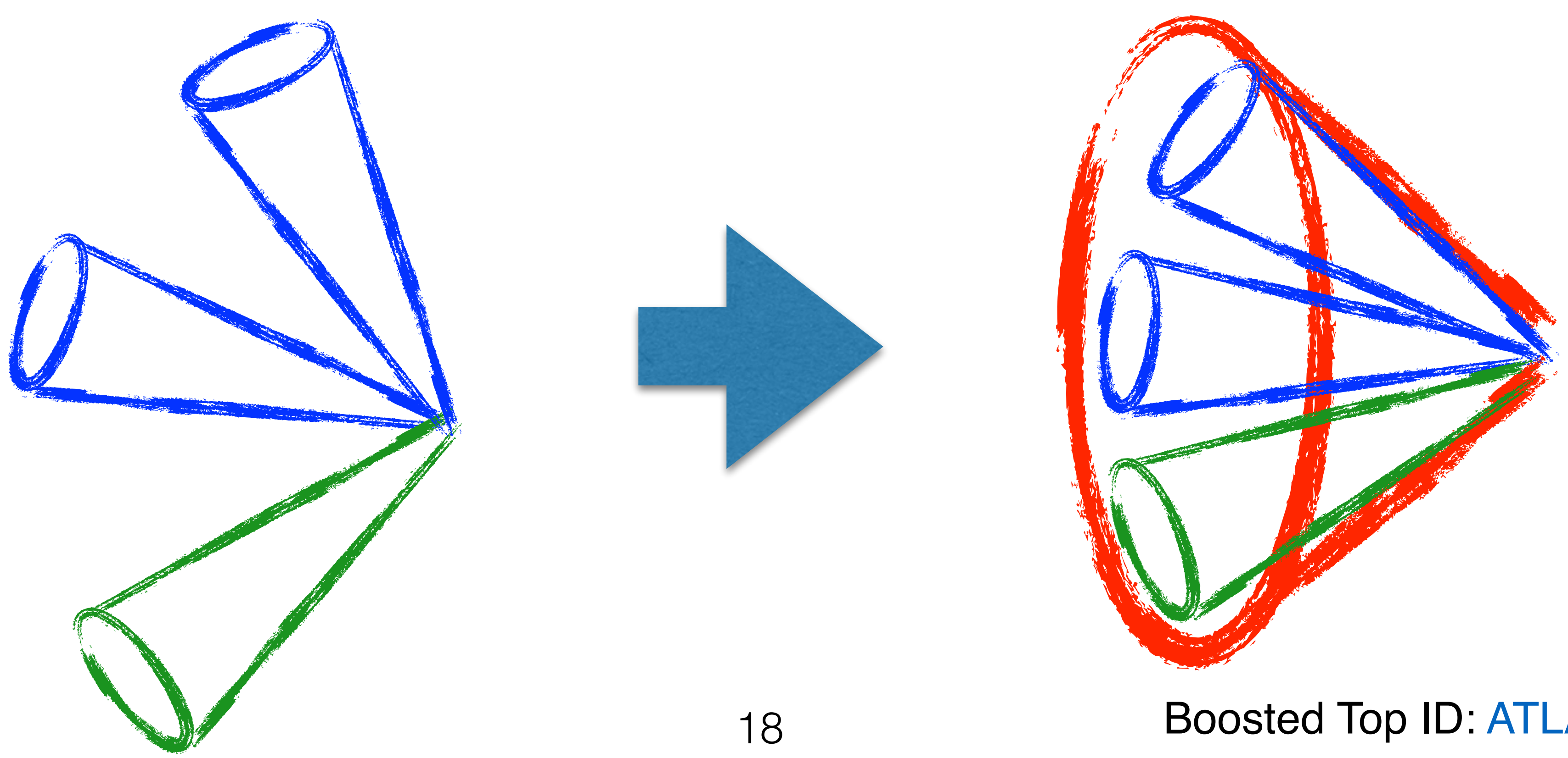




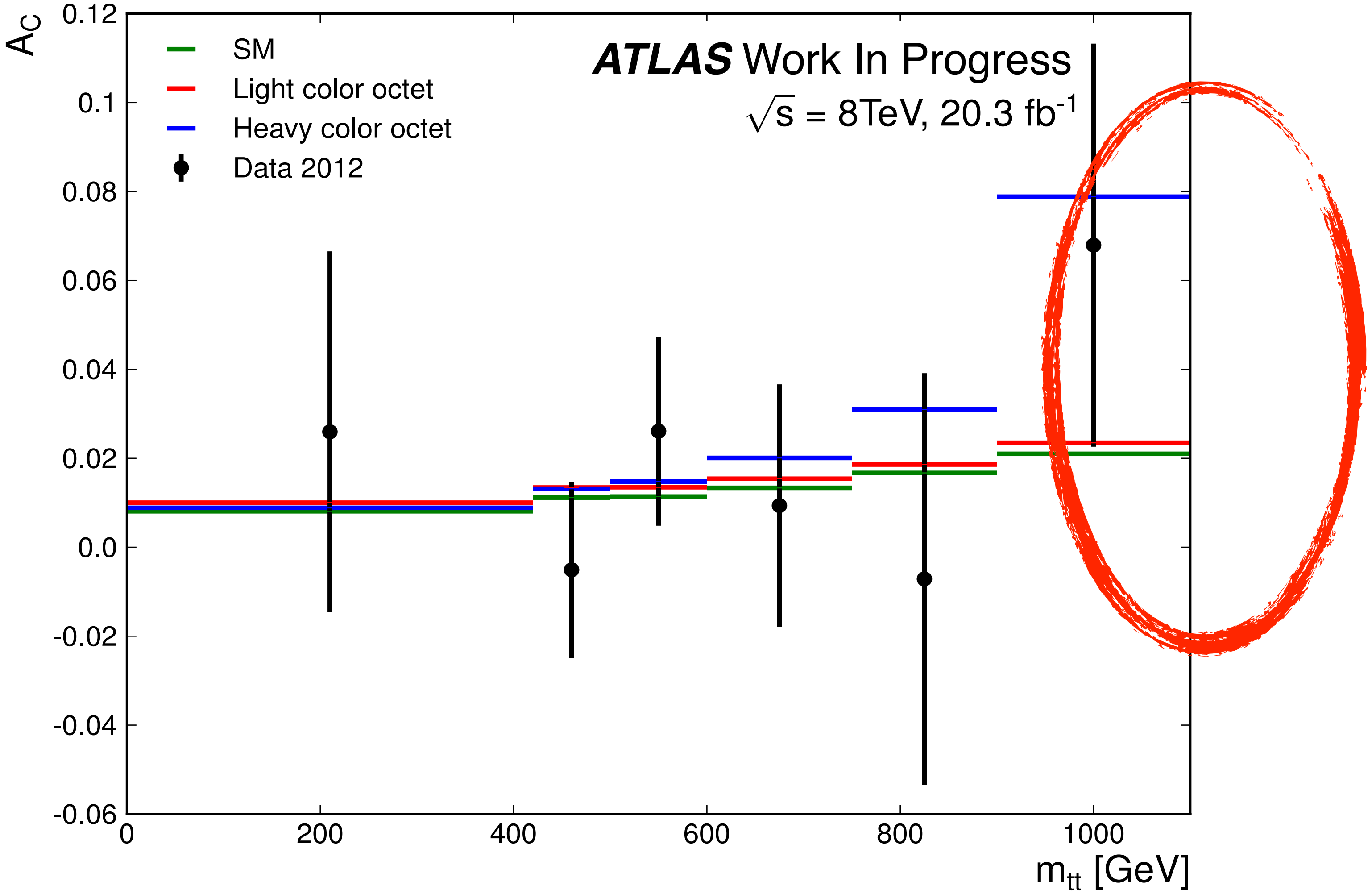
Boosted ℓ+jets

Boosted Top Quarks

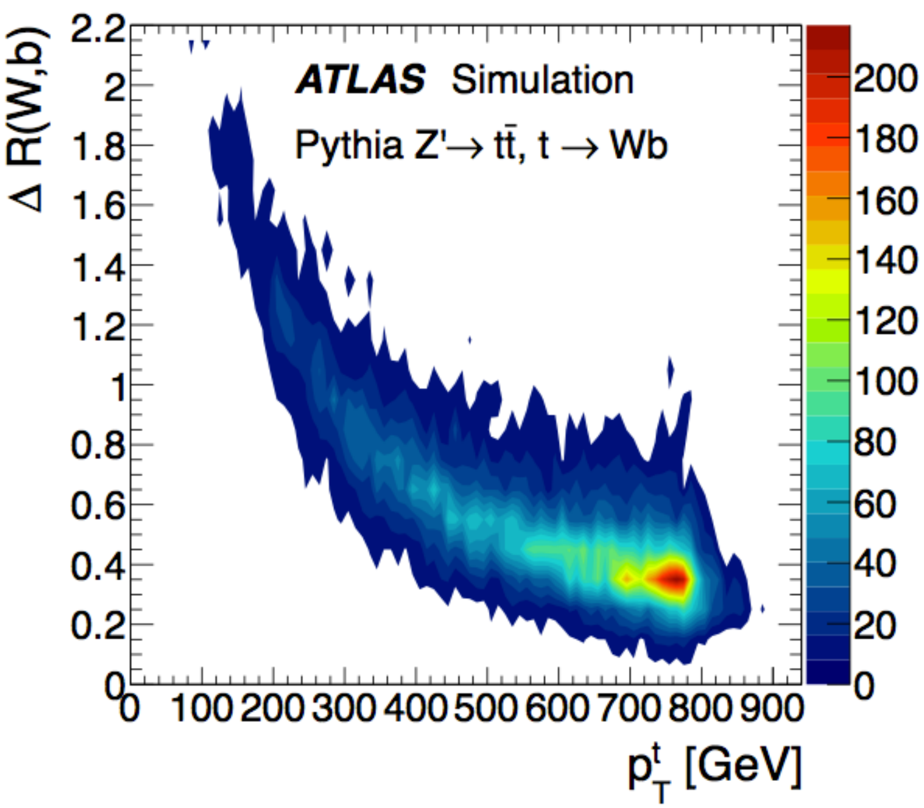
- Top quarks that are produced with high-p_T have their decay products collimated (p_T>300 GeV)
- At 8TeV, nearly 20,000 boosted top quarks were produced
- New techniques applying jet substructure on large-radius jets are used to reconstruct & identify hadronically-decaying boosted top quarks



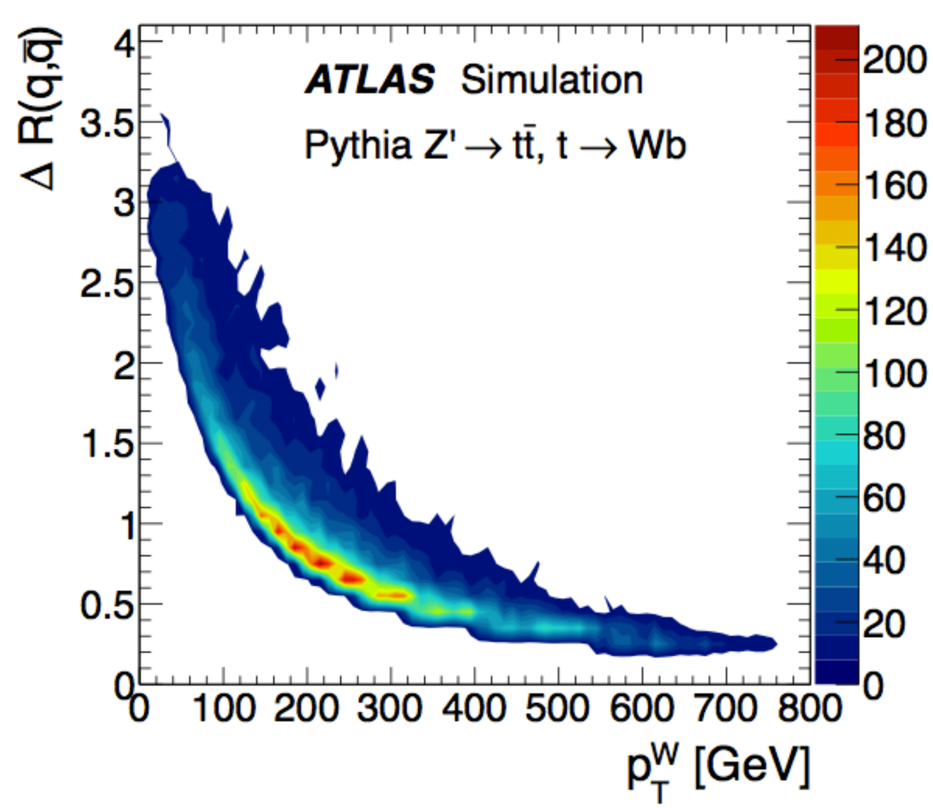
Boosted Top ID: ATLAS-CONF-2013-084



- Interested in high mass region that extends the reach of the resolved measurements
- Using Large-R Jets and jet substructure!



(a) $t \to Wb$



(b) $W \to q\bar{q}$

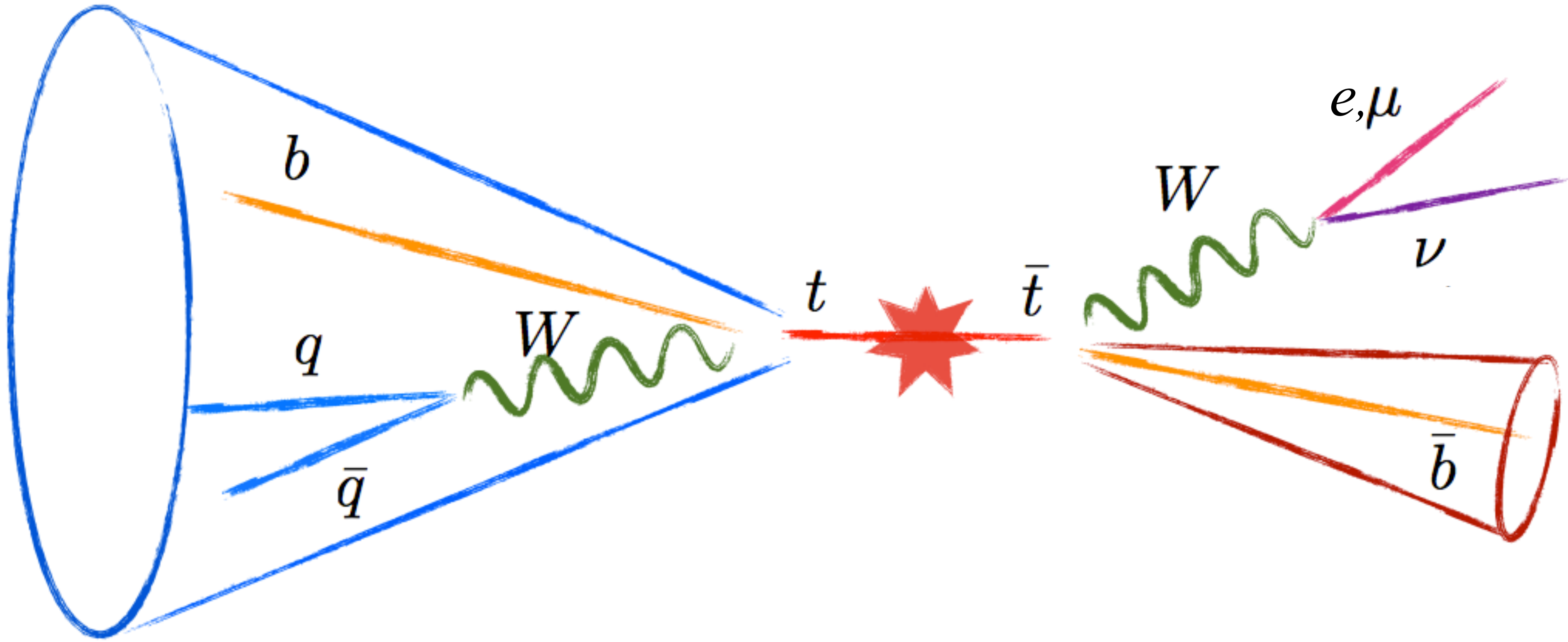
$$R \sim \frac{2m}{p_T}$$

arXiv:1306.4945

Analysis Strategy

- Following the strategy set by ttbar resonances search and the resolved charge asymmetry measurement
  - Select events enriched in boosted top quarks
    - *Not orthogonal to resolved A_C analysis*
  - Apply large-R jet substructure techniques to reduce backgrounds and improve boosted top quark identification

ttbar Resonances: arXiv:1505.07018

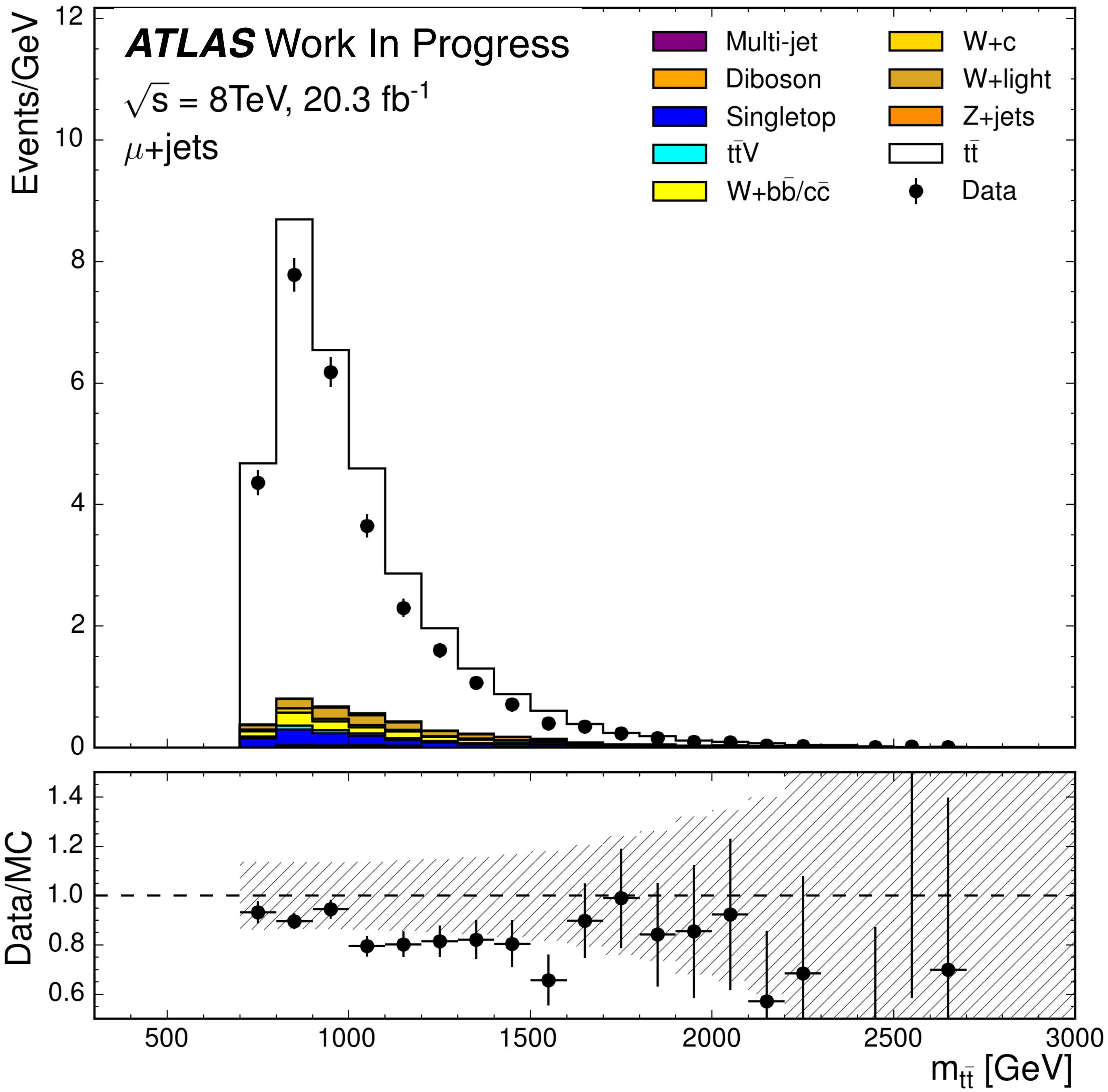


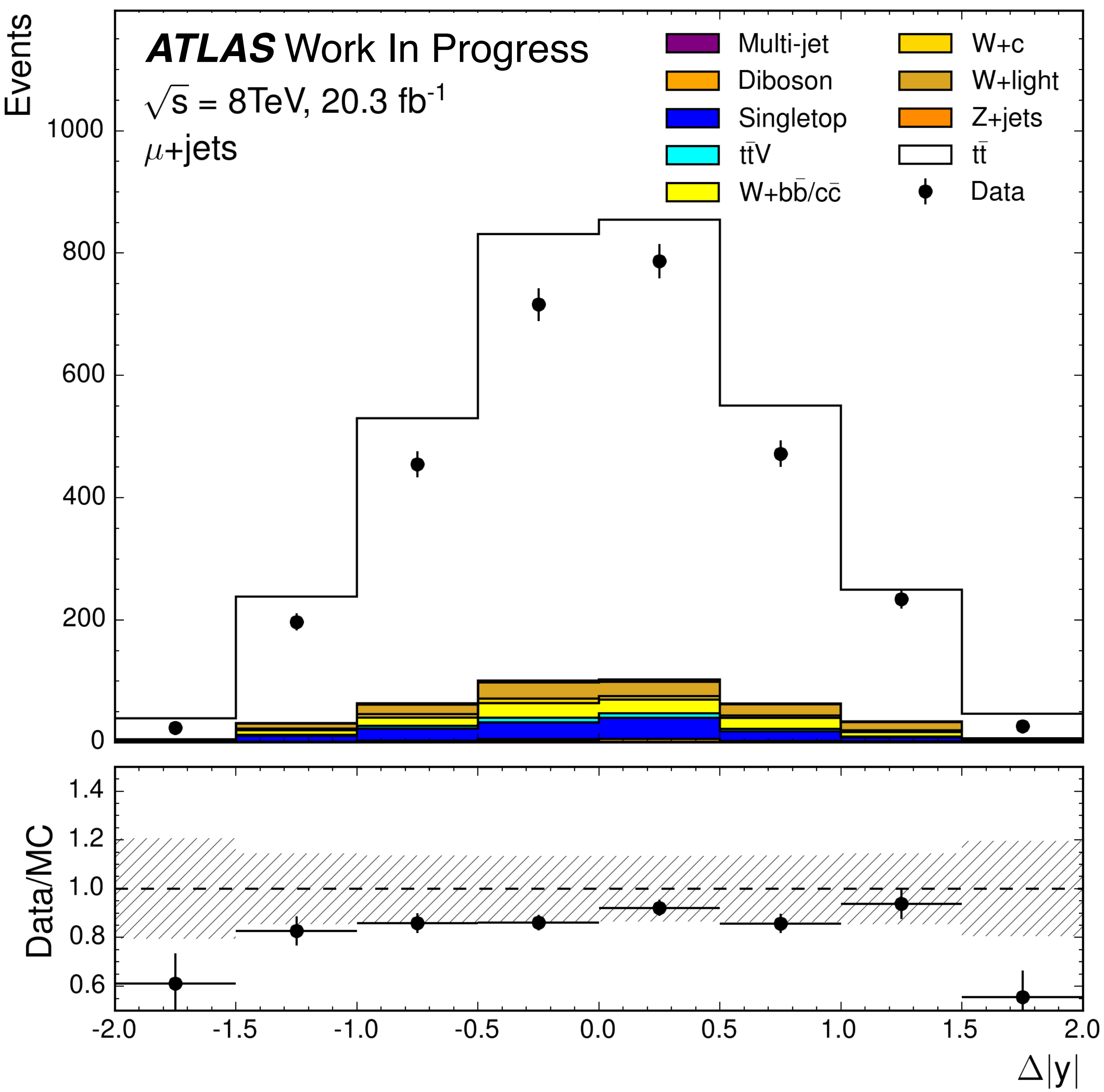
- ~Standard *boosted top* selection
  - 1 lepton (e/μ, p_T>25 GeV)
    +
    1 “near-by” small-r jet (p_T>25 GeV)
  - 1 Large-R Jet (p_T>300 GeV, m>100 GeV, $\sqrt{d_{12}}$ > 40 GeV)
  - MET > 20 GeV; MET+MTW > 60 GeV

Event Selection

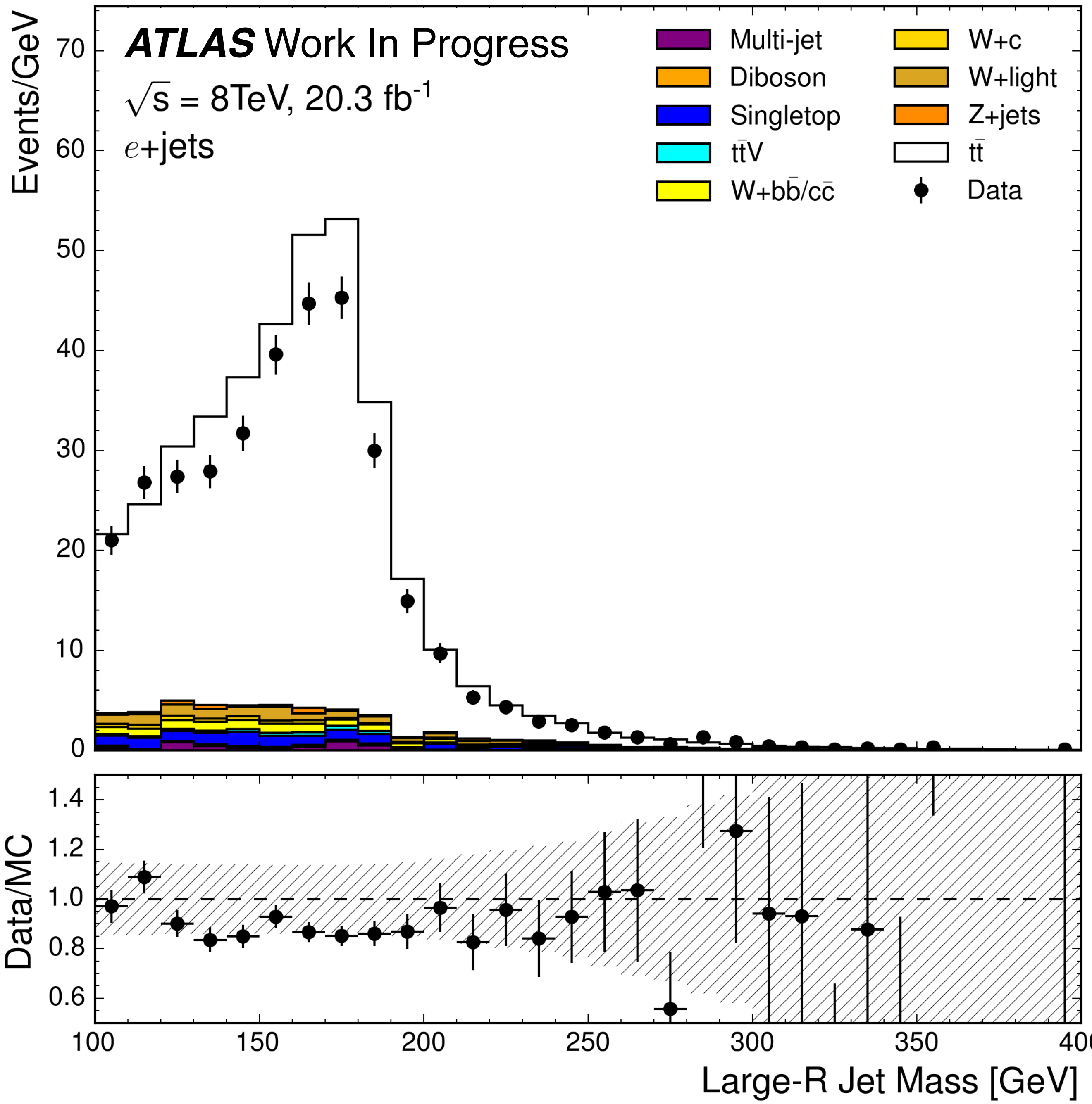
- We further limit the selection for parton-level top quarks to
  - $-2 < \Delta|y| < 2$
  - 750 GeV $< m_{tt} < 4000$ GeV
- This removes large uncertainties from extrapolating forward regions of the detector and low m_{tt} events where the reconstruction is poorest

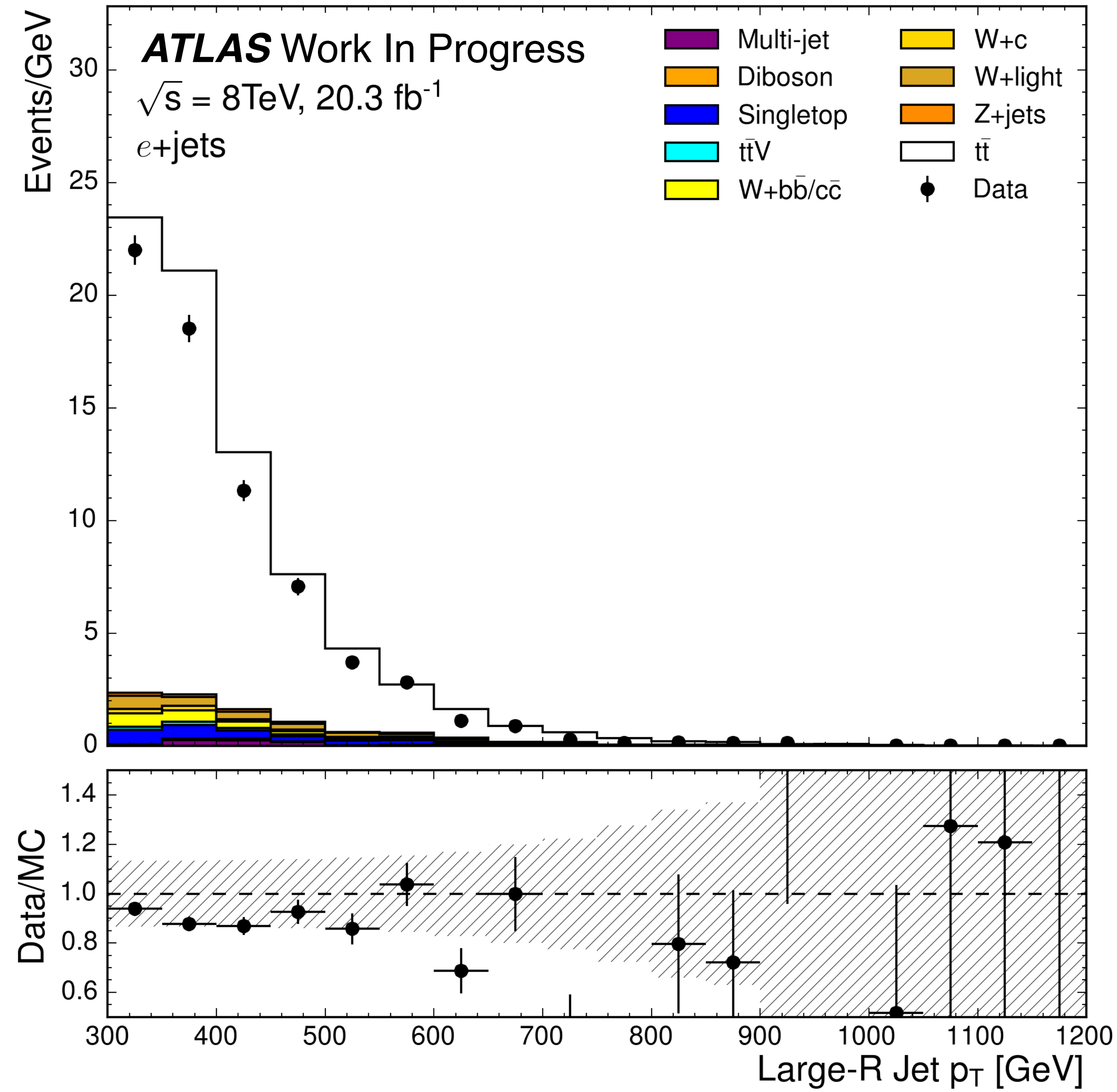
Control Plots





Control Plots





Unfolding

- Implementing the same procedure as the resolved asymmetry: Fully Bayesian Unfolding

$$p\left(\boldsymbol{T}\middle|\boldsymbol{D},\mathcal{M}\right) \propto \mathcal{L}\left(\boldsymbol{D}\middle|\boldsymbol{T},\mathcal{M}\right) \cdot \pi\left(\boldsymbol{T}\right)$$

- Differences with resolved A_C analysis:
    - No in-situ W+Jets calibration
    - One signal region defined for Likelihood

Systematic Uncertainties

- Treatment of systematic uncertainties follows the same prescription as the resolved measurement
- New systematics (compared to the resolved analysis) include high-p_T b-tagging and large-R jets

source of uncertainty	δA_C (%)
signal modeling - PS	± 0.8
singal modeling - ME	± 1.5
signal modeling - ISR/FSR	± 0.1
signal modeling - m_t	± 0.1
signal modeling - PDF	± 0.4
signal modeling - total	± 1.7
background norm.	± 0.10
jet energy and resolution - $R = 0.4$ jets	± 0.11
jet energy and mass scale - $R = 1.0$ jets	± 0.32
b-tag/mis-tag efficiency	± 0.18
lepton reco/id/scale	± 0.09
missing tranverse energy (E_T^{miss})	± 0.05
unfolding & MC stat.	± 0.60

Modeling

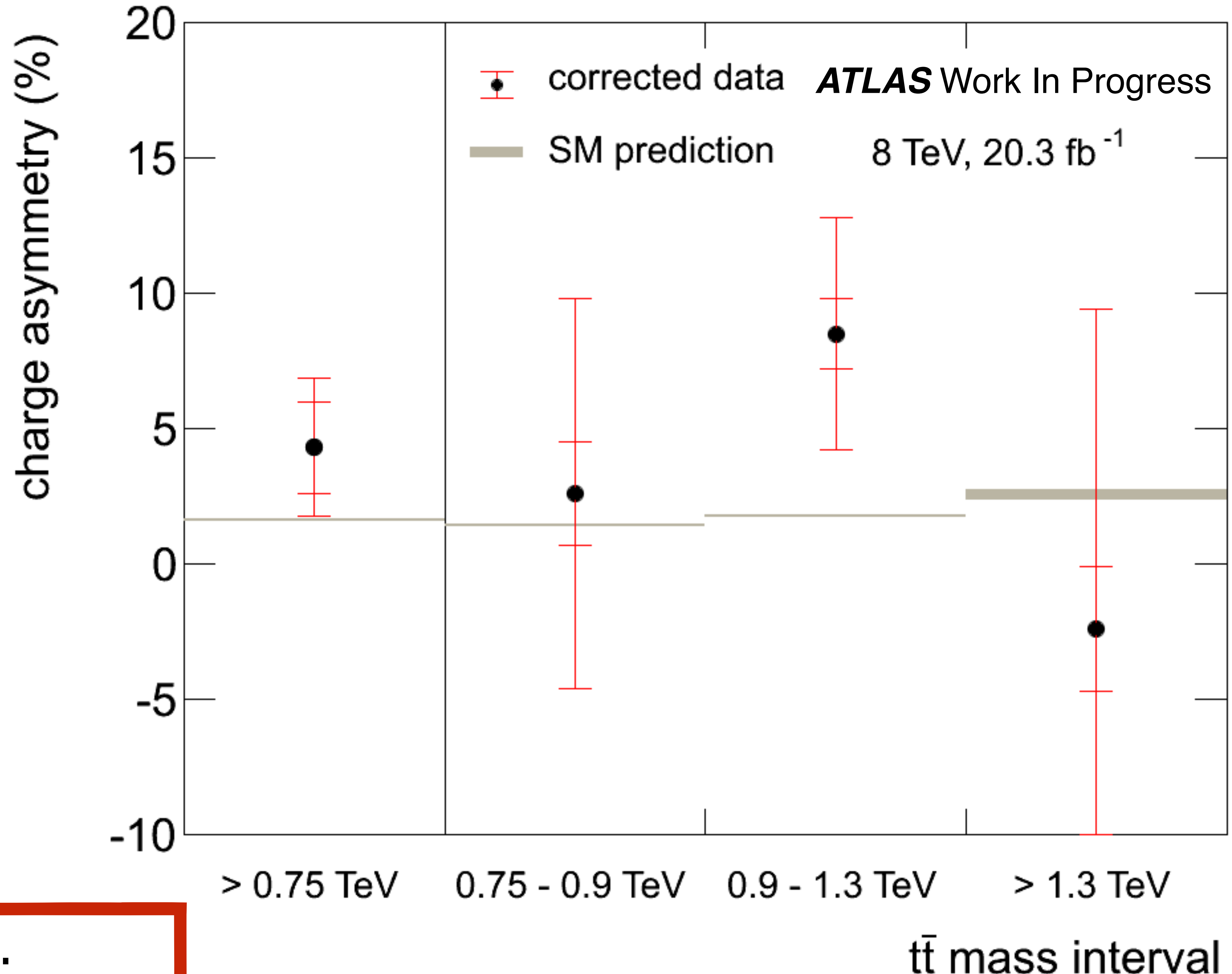
Detector-level

Expected **uncertainty** (work in progress)

Inclusive measurement

Results

- Results for the inclusive and differential measurement are shown.
- All results are consistent with the Standard Model



Inclusive:

$A_C = 0.043 \pm 0.026$

Small error bars show the modeling and unfolding uncertainties. The large error bars show the full uncertainty

SM: G. Rodrigo, IFIC (UVEG/CSIC) Valencia, private communication.

Summary of Results

- Recent measurements (CMS, ATLAS) are shown below for the ℓ+jets channel
  - All results are consistent with Standard Model predictions

	7 TeV	8 TeV
Theory	0.0123±0.0005	0.0111±0.0004
CMS	0.004±0.010(stat)±0.011(syst)	0.0010±0.0068(stat)±0.0037(syst)
ATLAS	0.006±0.010(stat+syst)	0.009±0.005 (stat+syst) (resolved) 0.043±0.026 (stat+syst) (boosted)

Theory: Phys.Rev. D86 (2012) 034026

ATLAS (7TeV): JHEP 02 (2014) 107

CMS (7TeV): Phys. Lett. B 717 (2012) 129

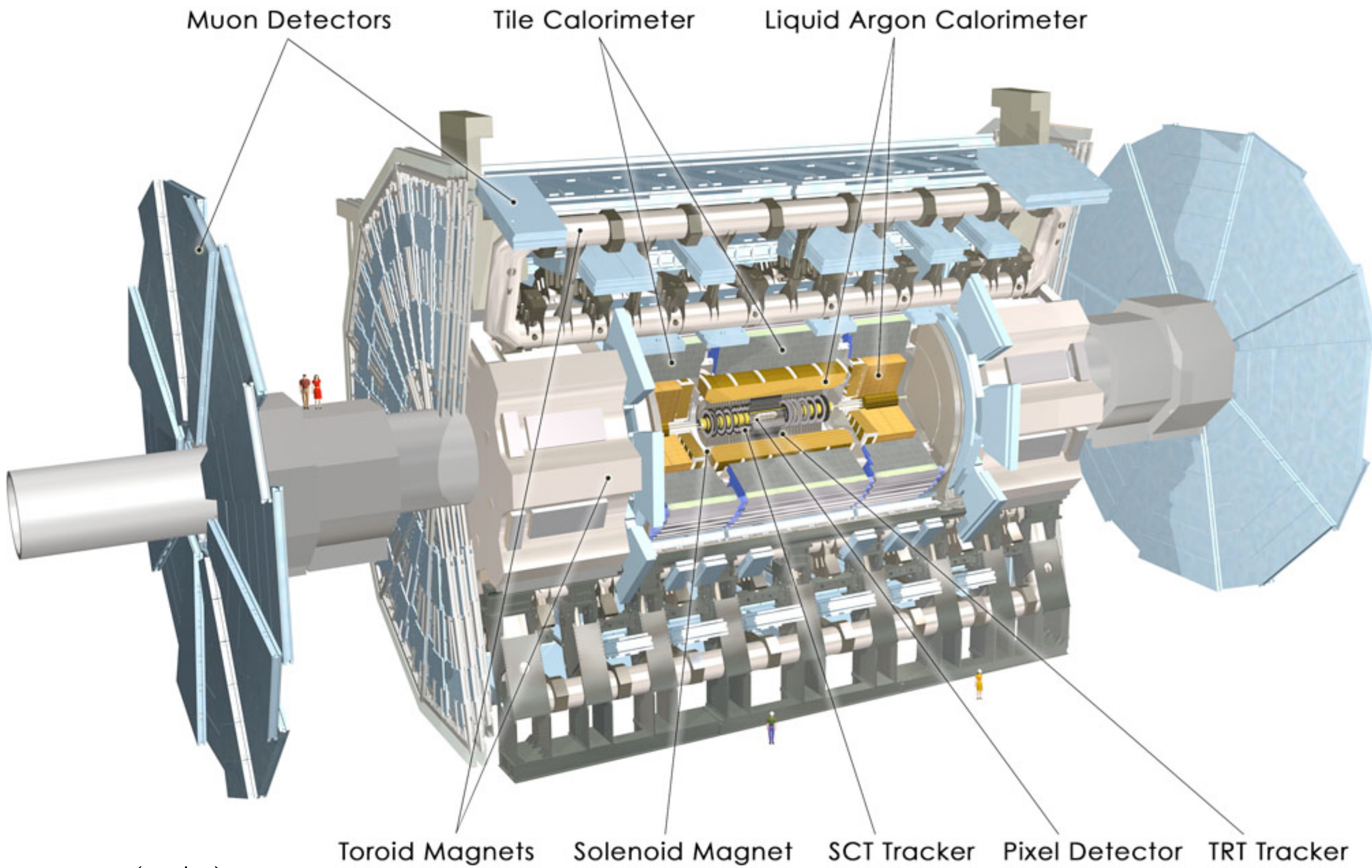
CMS (8TeV): arXiv:1507.03119

Conclusions

- ATLAS Top Charge Asymmetry has been measured in the ℓ+jets channel for both *resolved* and *boosted* topologies
- Results are consistent with Standard Model predictions
- 8 TeV ATLAS results are being finalized internally with results aimed for **Top2015**
- Asymmetry at 13 TeV is on the horizon!

Backup

ATLAS Detector



$$\eta \equiv -\ln\tan(\theta/2)$$

$$y \equiv \tfrac{1}{2} - \ln\tan\left(\frac{E-p_z}{E+p_z}\right)$$

JINST 3 (2008) S08003

Object Reconstruction

- Electrons:
    - Electron candidates are required to have a transverse energy $E_T > 25$ GeV and $|\eta_{cluster}| < 2.47$, except for $1.37 < |\eta_{cluster}| < 1.52$, where $\eta_{cluster}$ is the pseudorapidity of the cluster of energy deposited in the electromagnetic calorimeter, computed with respect to the centre of ATLAS detector and matched to the candidate.
- Muons:
    - Muon candidates are required to have $p_T > 25$ GeV and $|\eta| < 2.5$. The matching of the muon to the collision vertex is imposed by the requirements that the longitudinal impact parameter relative to the collision vertex be less than 2 mm and that the transverse impact parameter relative to the collision vertex divided by its uncertainty, $|d0/\sigma_{d0}|$, be less than 3.0.

ttbar Resonances: arXiv:1505.07018

Object Reconstruction

- Jets
  - Jets are reconstructed using the anti-k_T algorithm applied to clusters of calorimeter cells that are topologically connected and calibrated to the hadronic energy scale using a local calibration scheme. Small-radius jets (radius parameter R = 0.4) as well as large-radius jets (R = 1.0) are used. The energies of all jets and the masses of the large-radius jets have been calibrated to their values at particle level. Small-radius jets are required to satisfy $p_T > 25$ GeV and $|\eta| < 2.5$, while large-radius jets are required to satisfy $p_T > 300$ GeV and $|\eta| < 2.0$. Low-p_T central small-radius jets ($p_T < 50$ GeV, $|\eta| < 2.4$) are required to have a jet vertex fraction greater than 0.5. The jet vertex fraction is defined as the total transverse momentum (using a scalar sum) of tracks in the jet that are associated with the primary vertex divided by the scalar sum of the transverse momentum of all tracks in the jet. This variable suppresses jets arising from pile-up effects. Large-radius jets have jet trimming applied. In trimming, subjets are formed by applying a jet algorithm with smaller radius parameter, R_{sub}, and then soft subjets with less than a certain fraction, f_{cut}, of the original jet pT are removed. The properties of the trimmed jet are then calculated using the surviving subjets. This procedure mitigates the effect of pile-up. The trimming parameters used in this search are $f_{cut} = 0.05$ and $R_{sub} = 0.3$, and the inclusive k_T algorithm is used to form the subjets.

Anti-k_T:JHEP 0804 (2008)

b-tagging & MET

- b-tagging:
  - Only small-radius jets are considered for b-jet identification (b-tagging). The b-tagging algorithm uses a multivariate approach with inputs taken from the results of separate impact parameter, secondary vertex and decay topology algorithms. The operating point of the algorithm is chosen such that the b- tagging efficiency for simulated ttbar events is 70%. In MC simulation, factors are applied to correct for the differences between the b-tagging efficiency in simulated events and that measured in data. The factors are adapted to be appropriate for b-jets from high-p_T top quarks, for which the b-tagging efficiencies are lower.
- Missing E_T
  - The MET is calculated from the vector sum of the transverse energy of topological clusters in the calorimeter. The clusters associated with the reconstructed electrons and small-radius jets are replaced by the calibrated energies of these objects. Muon transverse momenta determined from the ID and the muon spectrometer are also included in the calculation.

Overlap Removal

- Overlap in identification of the relevant physics objects is possible and a procedure is implemented to remove duplication. Electrons and small-radius jets are considered for overlap removal if the cluster associated with the electron is within $\Delta R = 0.4$ of the nearest jet. In such cases, the jets have their four- momentum and jet vertex fraction recalculated after subtracting the electron four-momentum and then are removed if the recalculated values do not satisfy the original jet selection criteria. If the distance ΔR between the electron and the recalculated jet is < 0.2, the electron candidate is likely to be from the hadronic jet. Therefore the electron is removed from the electron candidate list and its four-momentum is added to that of the recalculated jet. Muons are removed from the muon candidate list if the distance ΔR between the muon and small-radius jet is less than $0.04 + 10$ GeV/p_T. This criterion exploits the anti-correlation between the muon p_T and its angular distance from the b-quark, in an approach similar to the isolation variable. The parameters are tuned based on signal MC simulations in order to provide a constant high efficiency as a function of resonance mass.

Jet Substructure

- k_T splitting scale ($\sqrt{d_{12}}$)
  - Defined by re-clustering the constituents of a jet with the k_T recombination algorithm. At the final step of the jet recombination procedure, the k_T distance measure for the remaining two jets (i=1,j=2) is

$$\sqrt{d_{ij}} = \min(p_{\mathrm{T}i}, p_{\mathrm{T}j}) \times \Delta R_{ij},$$

k_T Algorithm: Phys. Lett. B 269 (1991) 432., Phys. Rev. D 48 (1993) 3160, Nucl. Phys. B 406 (1993) 187.

JHEP09 (2013) 076

FBU – likelihood

$$\mathcal{L}(\mathbf{D}|\mathbf{T}) = \prod_{i=1}^{n} Poisson(d_i, r_i(\mathbf{T}, \mathcal{M}))$$

$$r_i(\mathbf{T}, \mathcal{M}) = \sum_{j=0}^{n} \epsilon(t_j) p(r_i|t_j)$$

- where d_i,r_i and t_i are the i-th bins of $\mathbf{D}$,$\mathbf{R}$ and $\mathbf{T}$.
- $\epsilon(t_i)$: acceptance for i-th bin.
- $p(r_i|t_j)$: probability for event in t_j to be reconstructed in r_i.

FBU – background

The background prediction is included in the likelihood definition
→NO background subtraction from distribution of data.

$$\mathcal{L}(\mathbf{D}|\mathbf{T}, \mathbf{B}) = \prod_{i=1}^{n} Poisson(d_i, r_i(\mathbf{T}, \mathcal{M}) + b_i)$$

Marginalization in FBU

In the Bayesian framework systematic uncertainties are treated as nuisance parameters which are integrated out of the likelihood.

$$\mathcal{L}(\mathbf{D}|\mathbf{T}) = \int \mathcal{L}(\mathbf{D}|\mathbf{R}(\mathbf{T},\theta),\mathbf{B}(\eta,\theta)) \cdot Gaus(\eta)\, Gaus(\theta)\, \mathrm{d}\theta \mathrm{d}\eta$$

We consider two types of nuisance parameters:

- background normalizations η , which affect only the background prediction.
- object definition/calibration uncertainties θ, which affect the overall reco-level prediction (**R**)