Top differential cross-section and charge asymmetry

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on behalf of the ATLAS collaboration

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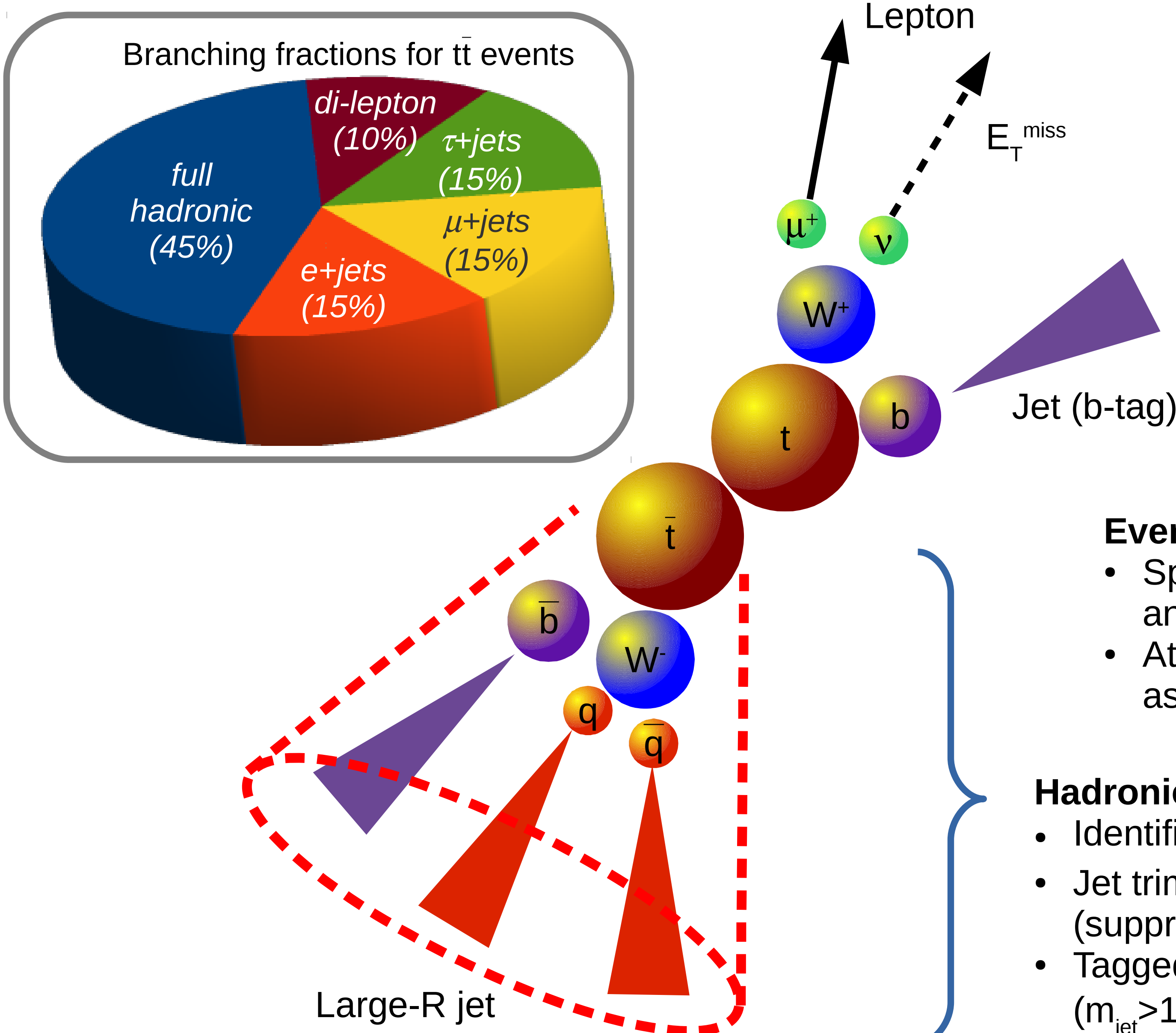
Outline

- Standard Model measurements using boosted top quarks in ATLAS
- Using 20 fb^{-1} of pp collision data at $\sqrt{s}$ = 8 TeV
- **$t\bar{t}$ differential cross section**
  - measurement of $t\bar{t}$ production differential cross section and comparison with NLO Monte Carlo generators
  - evaluate systematic uncertainties associated with the reconstruction techniques
- **$t\bar{t}$ charge asymmetry**
  - measurement of the charge asymmetry in a region with enhanced $q\bar{q}$ production
  - test compatibility with New Physics scenarios

Basic ingredients: l+jets channel



Leptonic top

- Combination of lepton, jet and E_T^{miss}
- Using leading p_T jet in a cone around the lepton (exploit boosted topology)

Event topology

- Spatial separation between hadronic and leptonic top candidates
- At least one b-tagged small-R jet associated with a top candidate

Hadronic top

- Identified with a high-p_T large-R jet
- Jet trimming algorithm applied (suppress pile-up and underlying event)
- Tagged using jet substructure (m_{jet}>100 GeV and $\sqrt{d_{12}}$>40 GeV)

Sample composition

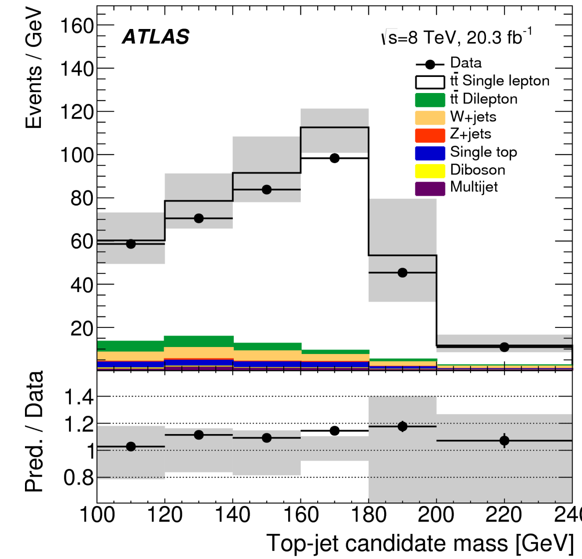
Purity: 85%

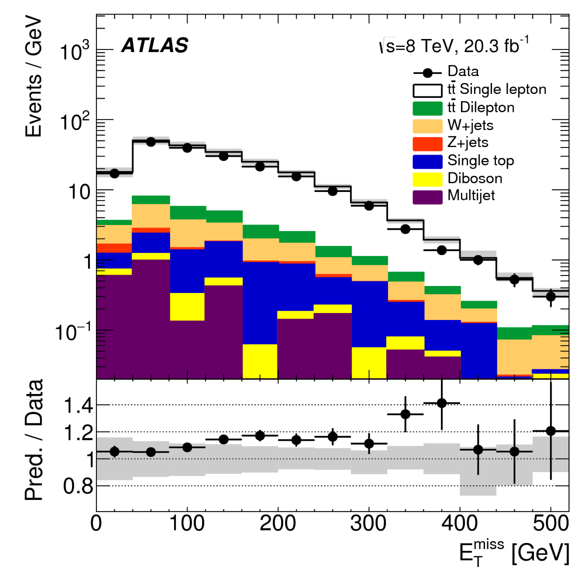
W+jets and multijet yields obtained using data-driven techniques.
Other MC yields normalized to the best theoretical knowledge.
Main background contributions:

- W+jets
- $t\bar{t}$ dilepton
- Single top
- Multijet

Small excess in MC yields (within uncertainties)

	e+jets	μ+jets
$t\bar{t}$ ℓ+jets	3880 ± 430	3420 ± 380
$t\bar{t}$ dilepton	199 ± 27	169 ± 24
W+jets	235 ± 54	226 ± 50
Single top	133 ± 22	134 ± 29
Multijet	91 ± 17	3 ± 1
Z+jets	34 ± 18	14 ± 8
Dibosons	22 ± 12	18 ± 10
Prediction	4600 ± 470	3980 ± 410
Data	4145	3603





Phys. Rev. D93 (2016) 032009

$t\bar{t}$ differential cross-section as a function of the top p_T for boosted top quarks in $\sqrt{s}$=8 TeV pp collisions

Phys. Rev. D93 (2016) 032009

HepData ins1397637
RIVET ATLAS_2015_I1397637

Motivation

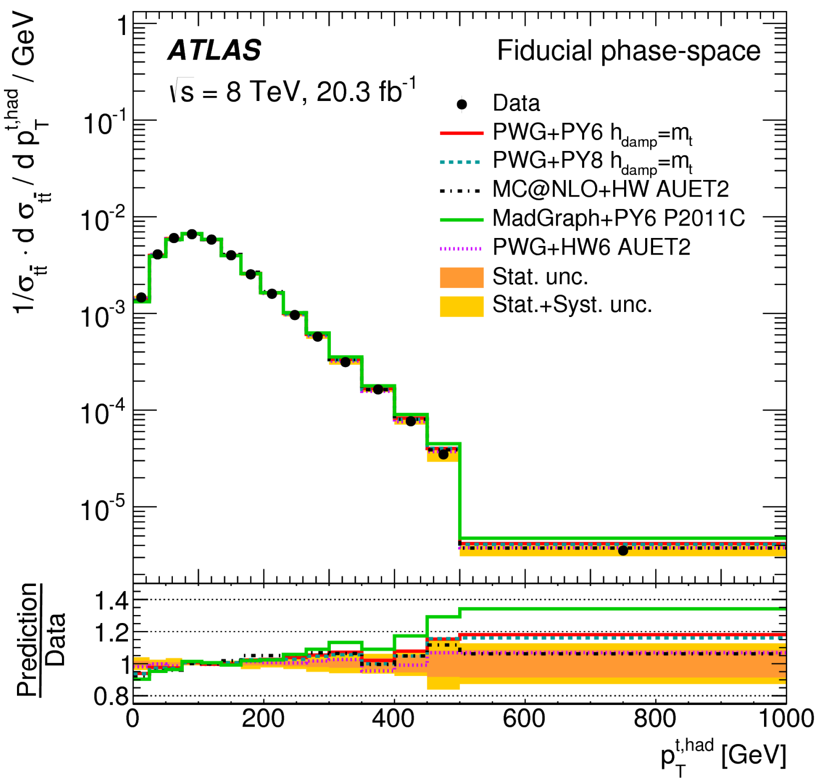
Top quark physics at the LHC allows precision tests of the SM

- $t\bar{t}$ production cross section computed at NNLO
- Recently completed calculations of differential cross sections at NNLO

Test SM prediction for $t\bar{t}$ production in the high-p_T region

- Previous analyses suggest NLO predictions slightly overestimate measurements
- Sensitive to PDFs
- Relevant for BSM physics searches
- Study the performance of boosted object reconstruction and calibration applied to SM measurements

arXiv:1511.04716



Focus on measurement of

$$\frac{d\sigma}{d\,p_{T,had.top}}$$

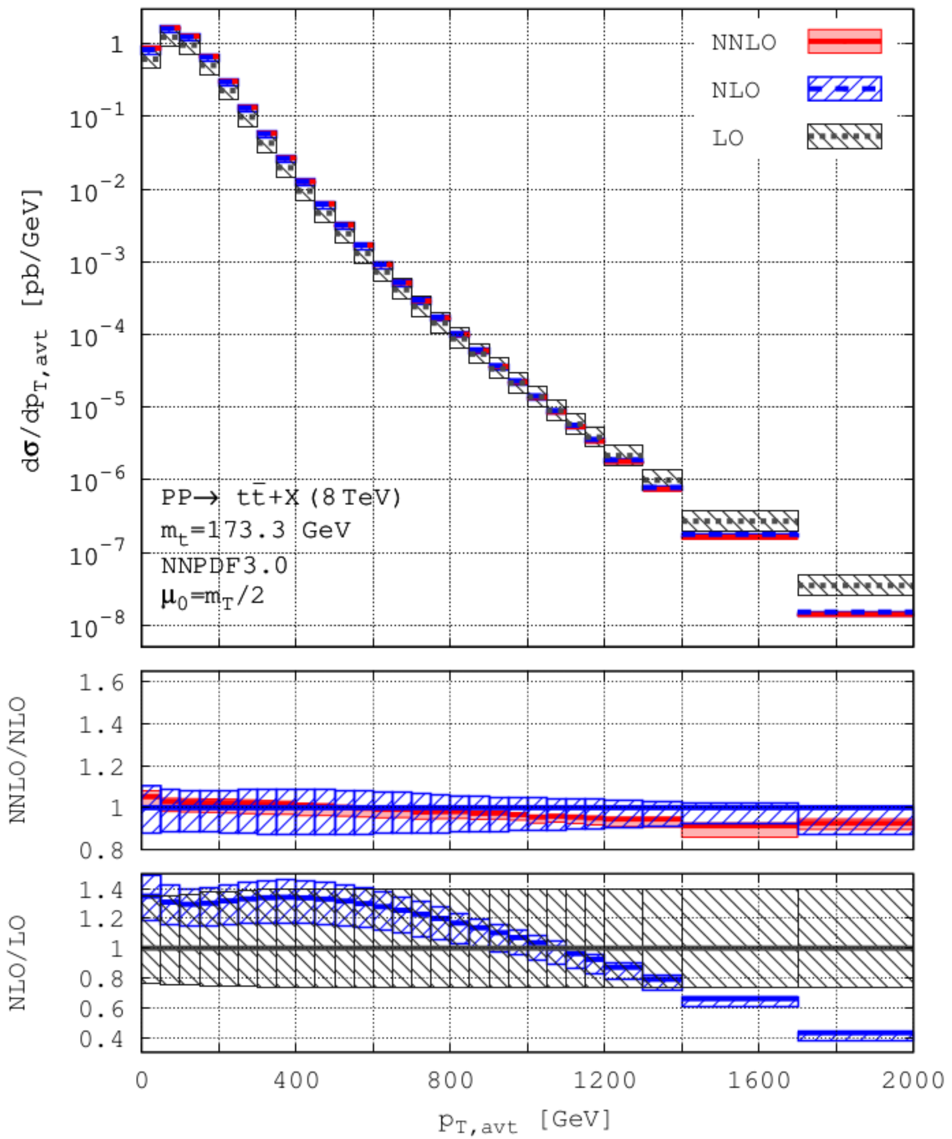
Differential cross sections at NNLO

arXiv:1606.03350

Recent NNLO calculation of $t\bar{t}$ production differential cross section recently available (Czakon, Heymes, Mitov)

Also investigating the role of the PDFs and the choice of the dynamic scale

$p_{T,top}$ slope slightly corrected with respect to NLO

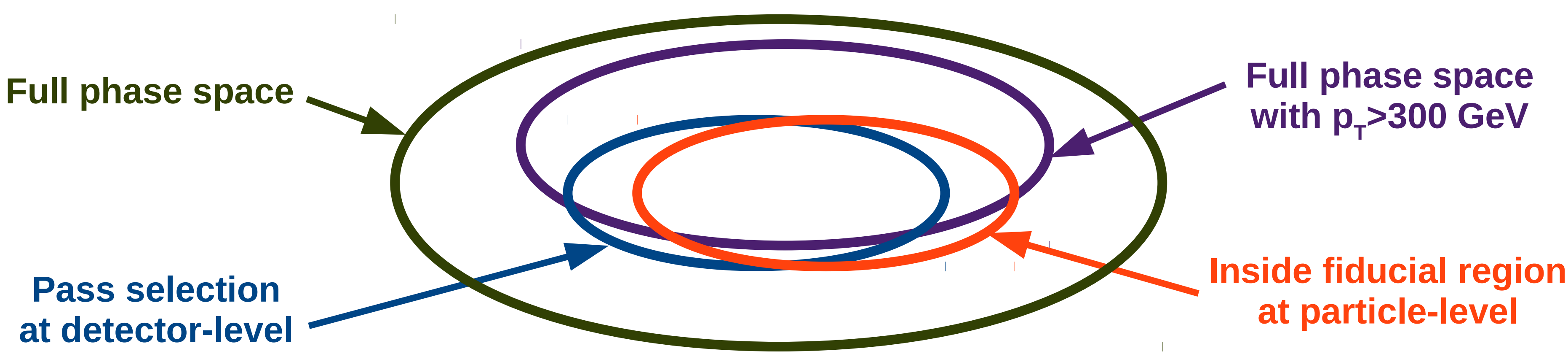


Cross section measurement

Measure $t\bar{t}$ production differential cross section as a function of the p_T of the top quark

- **Particle-level correction:** p_T of tagged particle-level trimmed R=1 jet
  - In a fiducial region defined to closely follow the event selection using “stable” particles ($\tau > 0.3\times10^{-10}$ s)
  - Minimize the extrapolation and the theoretical uncertainty
- **Parton-level correction:** p_T of the top quark just before decay and after radiation
  - In the full phase-space of events with $p_{T,top} > 300$ GeV
  - Allow comparison with NNLO calculations

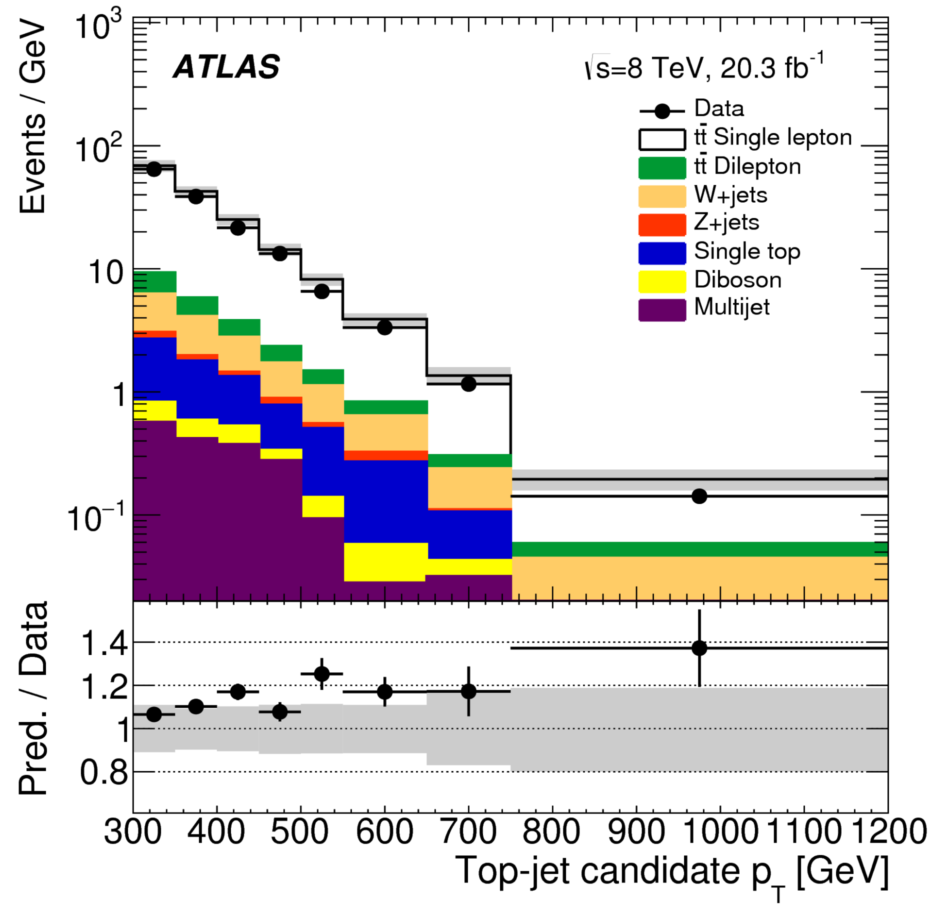
Schematic representation of $t\bar{t}$ event sets



Correction procedure

$$\frac{d\sigma_{t\bar{t}}}{dp_{\mathrm{T,ptcl}}}(p^{i}_{\mathrm{T,ptcl}}) = \frac{1}{\Delta p^{i}_{\mathrm{T,ptcl}}\mathcal{L} f^{i}_{\mathrm{ptcl!reco}}} \cdot \sum_{j} M^{-1}_{ij} f^{j}_{\mathrm{reco!ptcl}} \underbrace{(N^{j}_{\mathrm{reco}} - N^{j}_{\mathrm{reco,bgnd}})}$$

Input:
measured number of events
after subtraction
of the background contributions



Correction procedure

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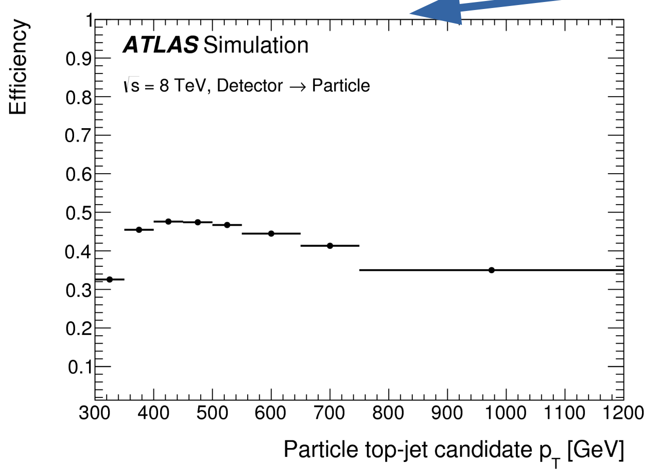
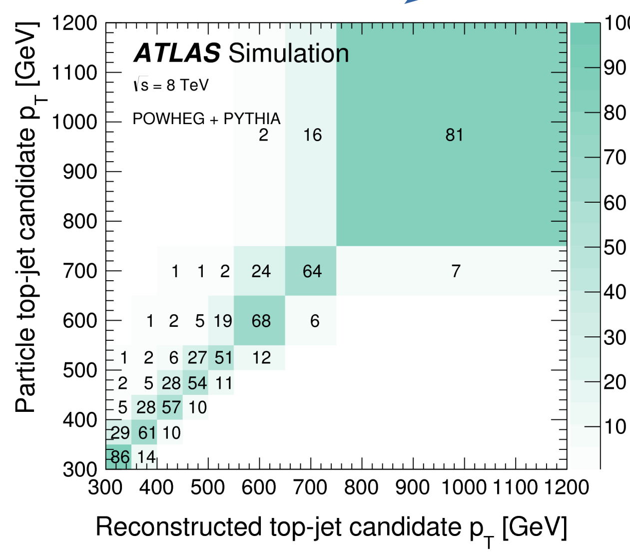
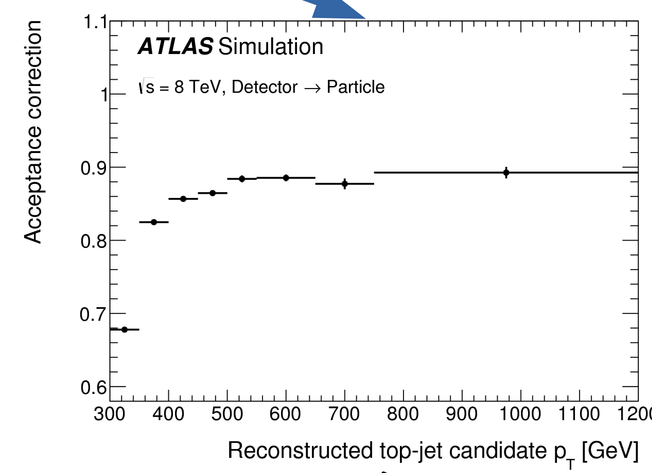






Correct for events in the particle-level fiducial region failing the detector-level cuts

Correct for resolution through inversion of the migration matrix (regularized unfolding technique)

Correct for events passing RECO selection but outside the particle-level fiducial region

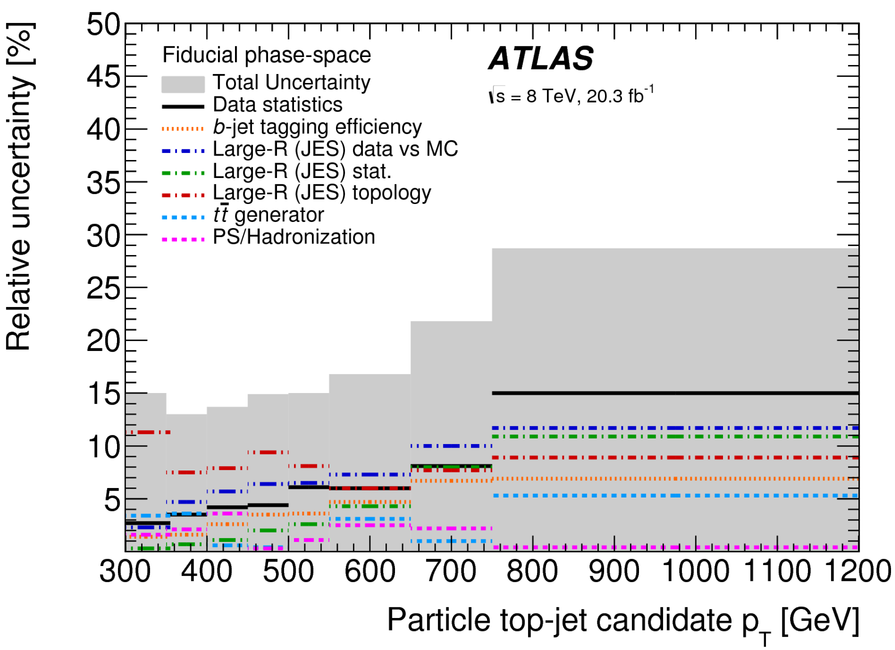
Corrections computed using nominal POWHEG+PYTHIA sample

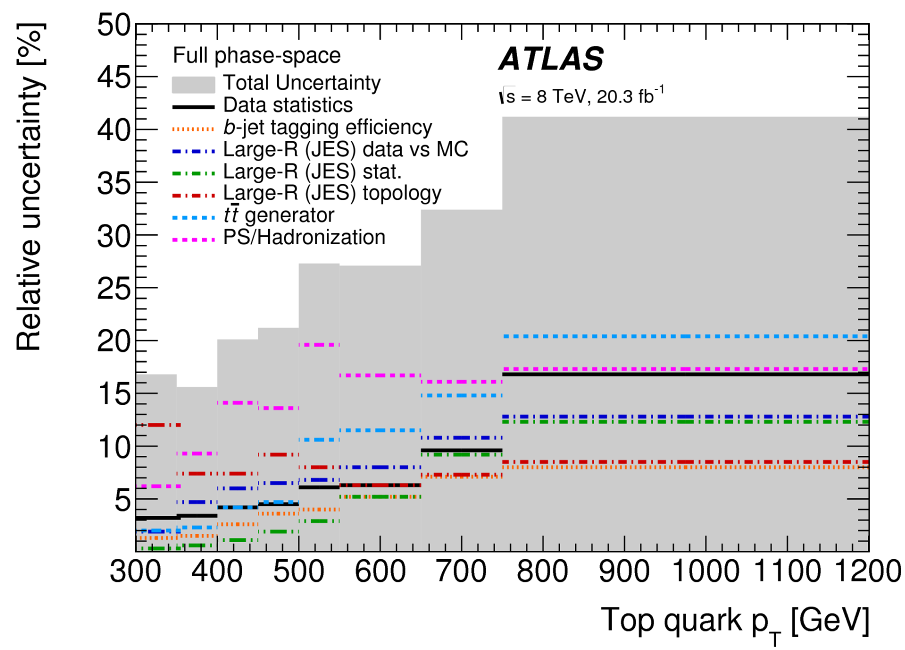
Systematic uncertainties

- **Detector related** systematic uncertainties:
  - Largest contribution from large-R jet energy scale calibration
  - Dominant systematic uncertainty for particle-level cross section

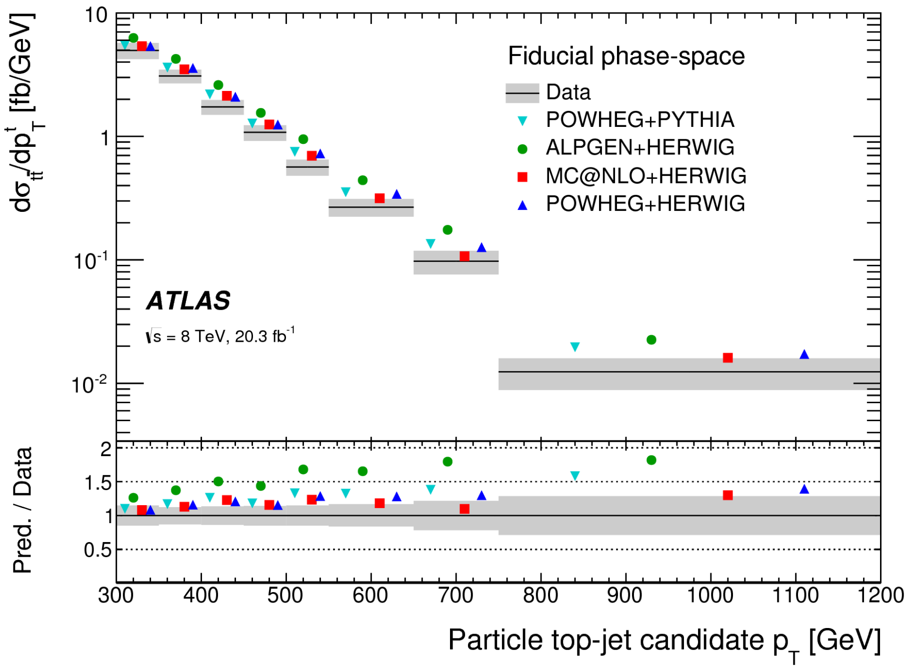
- **Background modeling and normalization**: small

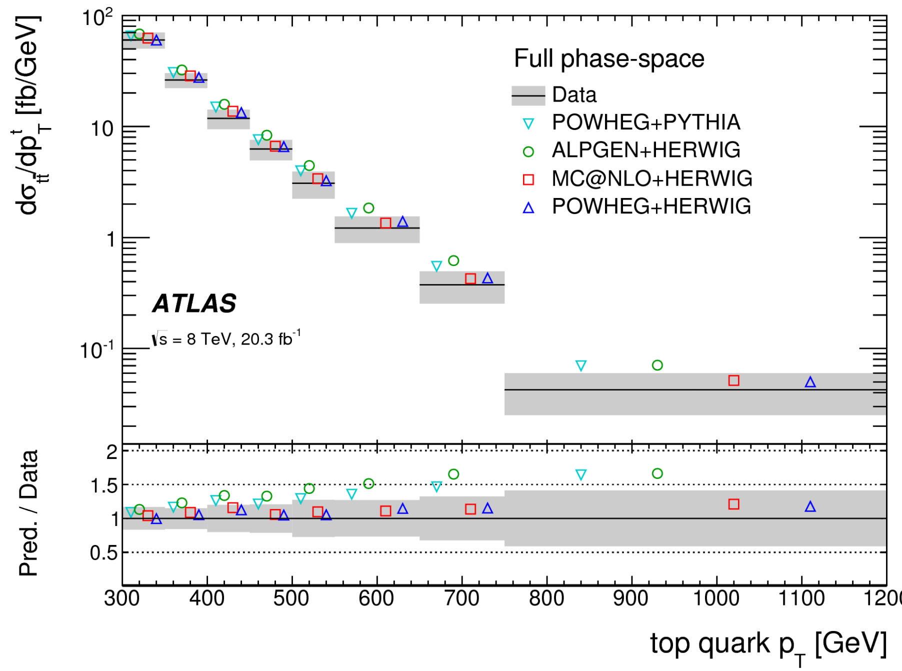
- **MC generator modeling**:
  - Evaluated comparing the effect of the nominal unfolding on different generators
  - Effect of NLO ME generator, PS/hadronization model, ISR/FSR, PDF separately evaluated
  - Dominant systematic uncertainty for parton-level cross section





Results and comparison with theory



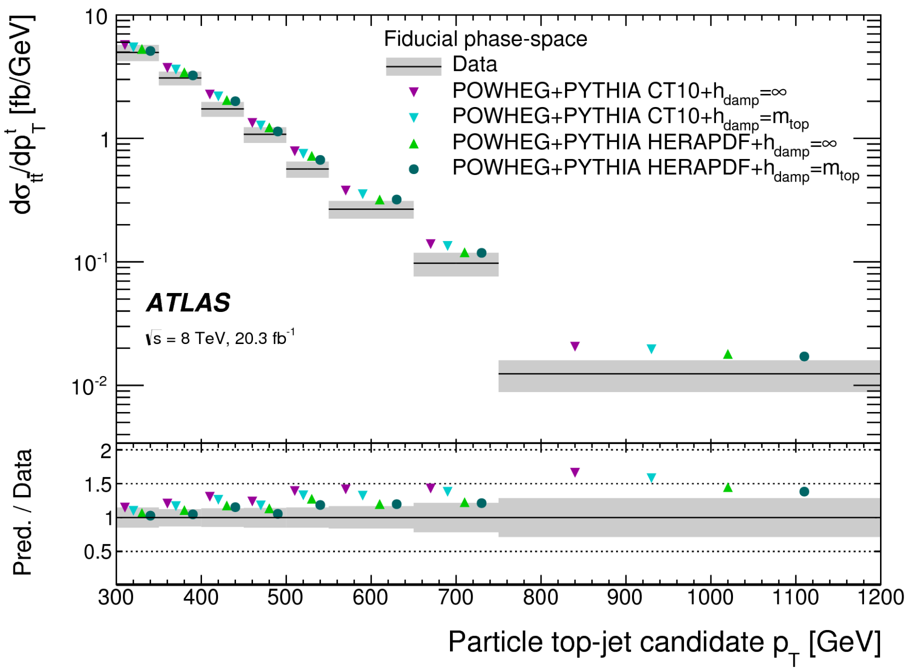


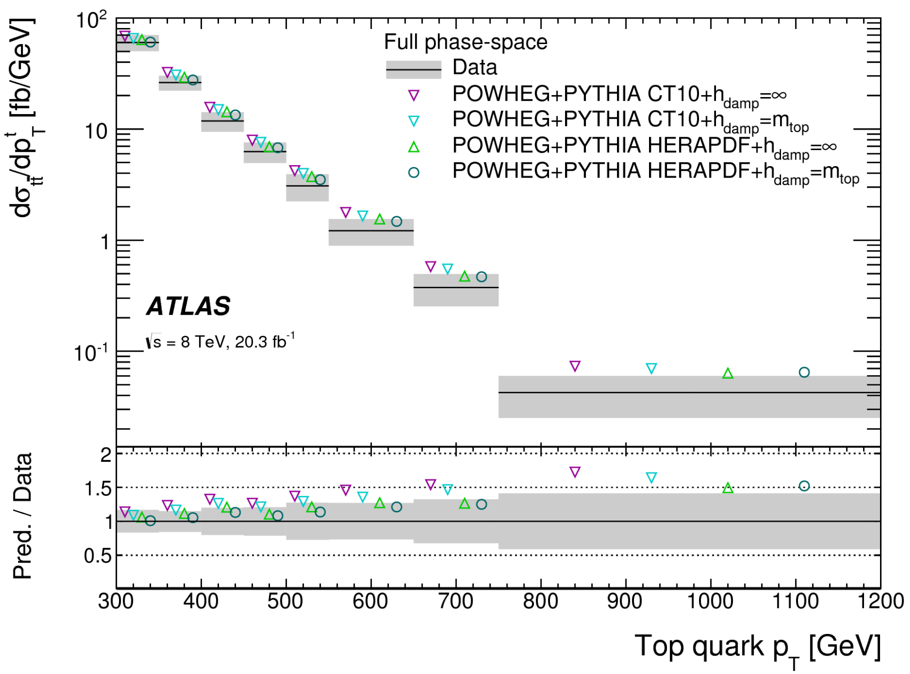
- Total cross section for predictions normalized at NNLO. Theoretical uncertainties not included
- MC generators tend to overestimate the measurement
- Measurement dominated by a few uncertainties correlated between bins

Effect of h_{damp} and PDFs

h_{damp} is a parameter that controls ME/PS matching in POWHEG:

- regulates the amount of high-p_T radiation
- set to m_{top} or ∞ in ATLAS





Data/MC agreement

- Measurement dominated by a few systematic uncertainties → fully correlated between different p_T bins
- Covariance matrix needed to compute the χ^2 and assess the agreement between the tested MC models and the measurement
- Tested at particle-level, less affected by modeling uncertainties

MC generator	PDF	χ^2	p-value
Powheg+Pythia $h_{\mathrm{damp}} = m_{\mathrm{top}}$ + Electroweak corr.	CT10	9.8	0.28
Powheg+Pythia $h_{\mathrm{damp}} = m_{\mathrm{top}}$	CT10	13.0	0.11
Powheg+Pythia $h_{\mathrm{damp}} = \infty$	CT10	15.6	0.05
Powheg+Pythia $h_{\mathrm{damp}} = m_{\mathrm{top}}$	HERAPDF	9.4	0.31
Powheg+Pythia $h_{\mathrm{damp}} = \infty$	HERAPDF	10.9	0.21
Powheg+Herwig	CT10	8.2	0.41
MC@NLO+Herwig	CT10	12.3	0.14
Alpgen+Herwig	CTEQ6	33.1	$5.9 \cdot 10^{-5}$

In general, MC simulations are in reasonable agreement with the measurement

How to test your favorite model?

- Results included in HepData
  - Differential cross-sections at particle and parton level
  - Covariance matrices at particle and parton level
  - Breakdown tables of systematic uncertainties
- RIVET routine to reproduce the fiducial measurement of the differential cross-section at particle level

$t\bar{t}$ charge asymmetry for boosted top quarks in $\sqrt{s}$=8 TeV pp collisions

Phys. Lett. B 756 (2016) 52-71

Motivation

A forward-backward asymmetry (A_{FB}) is expected at $p\bar{p}$ colliders.

A_{FB} observed at the Tevatron is larger than the SM expectations and dependent on $m_{t\bar{t}}$.

Discrepancy reduced to 1.5σ level after inclusion of electroweak effects and NNLO calculation.

A_{FB} cannot be accessed at pp colliders. A related charge asymmetry (A_C) is defined:

$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)} \qquad \text{with:} \qquad \Delta|y| = |y_t| - |y_{\bar{t}}|$$

For $q\bar{q}$ initial states a positive A_C is expected. $t\bar{t}$ production at the LHC is dominated by the gg initial state (~85% of the events).

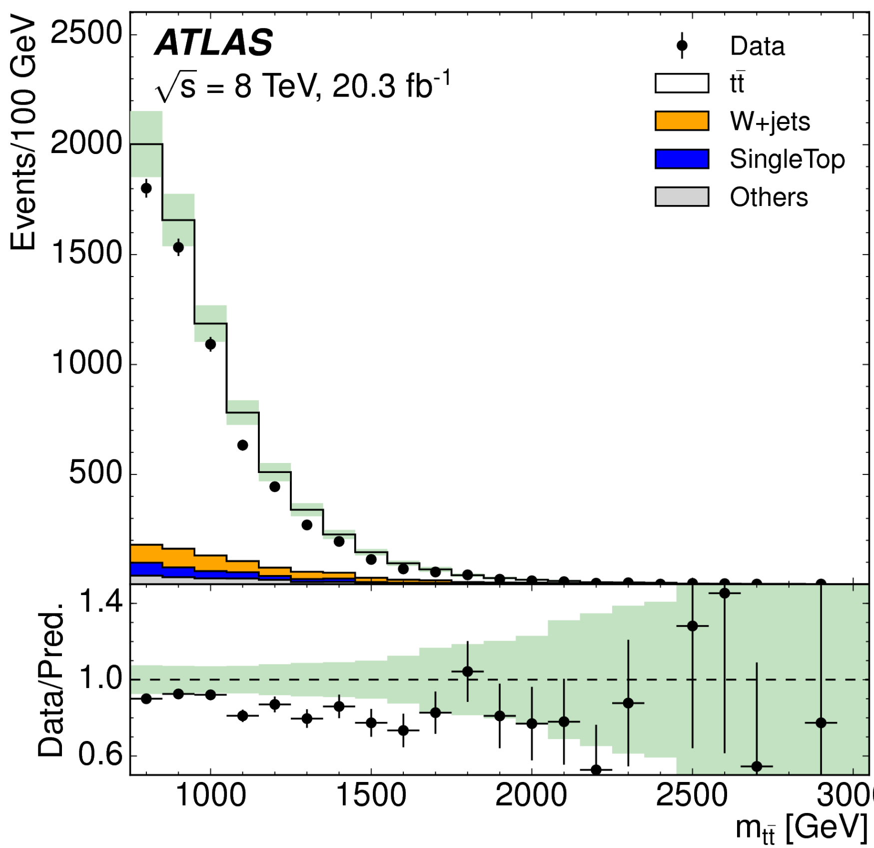
Standard model expectation: $A_C \sim 1\%$. (see arXiv:1109.6830, arXiv:1406.1798, and references therein)

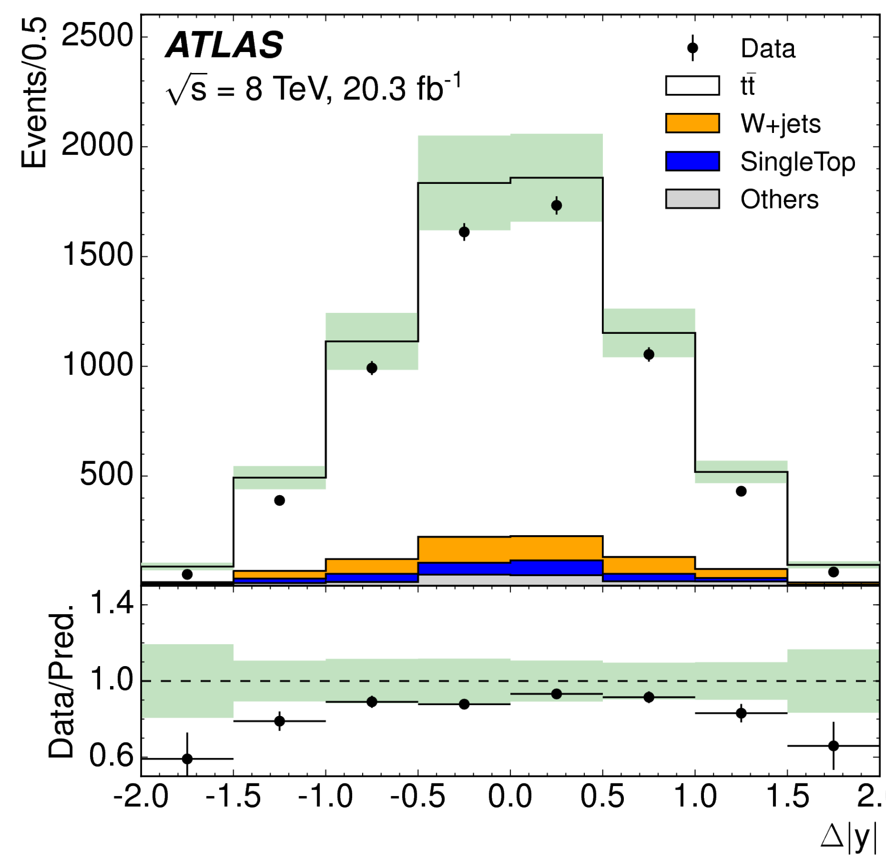
By adopting the boosted approach:

- combinatorial ambiguities in the reconstruction of the $t\bar{t}$ system are reduced
- the fraction of $q\bar{q}$ initiated processes is enhanced, increasing the sensitivity to A_C in the SM
- the sensitivity to possible BSM effects at large invariant mass increases

Event reconstruction

- Only events with reconstructed $m_{t\bar{t}}$ > 750 GeV considered → worse performance in the reconstruction of the boosted top quark at low $m_{t\bar{t}}$
- Mass resolution ~6% over a broad range of $m_{t\bar{t}}$
- Large dilution factor: *D = 2p-1 = 0.75* (p is the probability of wrong Δ|y| sign)

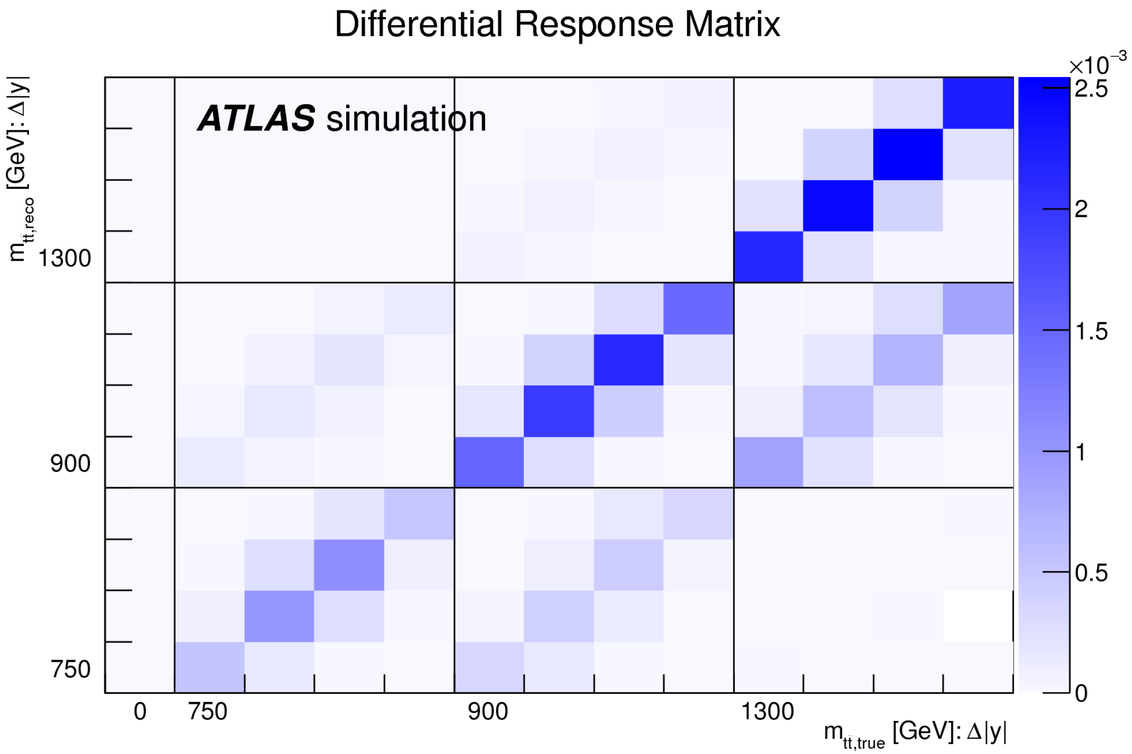




Correction procedure

Unfolding procedure applied to correct the A_C measurement to the parton level in the phase space covered by the measurement ($m_{t\bar{t}}$ > 750 GeV, |Δ|y||<2)

- The asymmetry in the full region is obtained by correcting the content of four Δ|y| bins (boundaries: [-2.0, -0.7, 0, 0.7, 2.0])
- The differential measurement with respect to $m_{t\bar{t}}$ is obtained using the overall migration matrix



Uncertainties

- **Statistical uncertainty**: 2% (full fiducial phase space)
- **Detector related** systematic uncertainties:
  - Largest contributions from jet energy scale and resolution of large-R and small-R jets and from b-tagging
  - Overall limited impact on the result (0.4%)
- **Background normalization**: negligible
- **MC generator modeling**:
  - Evaluated comparing the effect of the nominal unfolding on different generators
  - Effect of NLO ME generator, PS/hadronization model, ISR/FSR, PDF separately evaluated
  - Represent the dominant source of systematic uncertainty (2.5%, all combined)
- **Unfolding uncertainty**: estimated artificially injecting A_C values: small (0.5%)

- **Total uncertainty** in the full fiducial phase space: 3.2%

Results

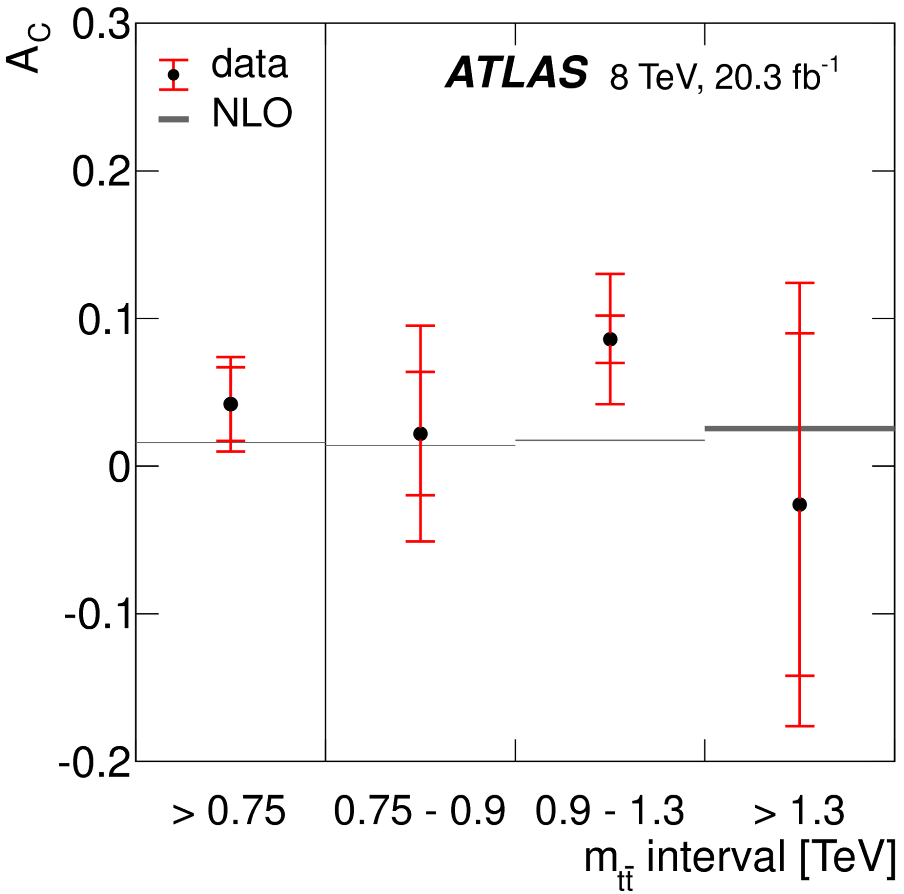
Results compatible with SM calculation at the NLO

For $m_{t\bar{t}} > 0.75$ TeV and $||\Delta|y|| < 2$:

$A_C = (4.2 \pm 3.2)\%$

SM prediction: $A_C = (1.60 \pm 0.04)\%$

Largest discrepancy with the SM prediction observed for $m_{t\bar{t}}$ = 0.9-1.3 TeV is 1.6σ



Interpretation

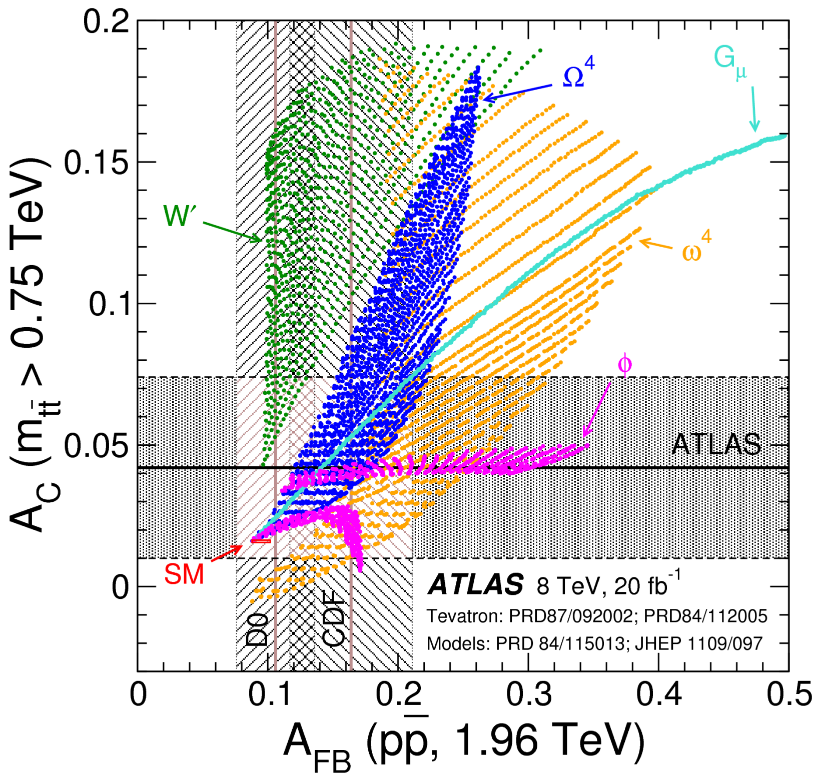
SM extensions including heavy particles can predict an enhanced A_C at the LHC.

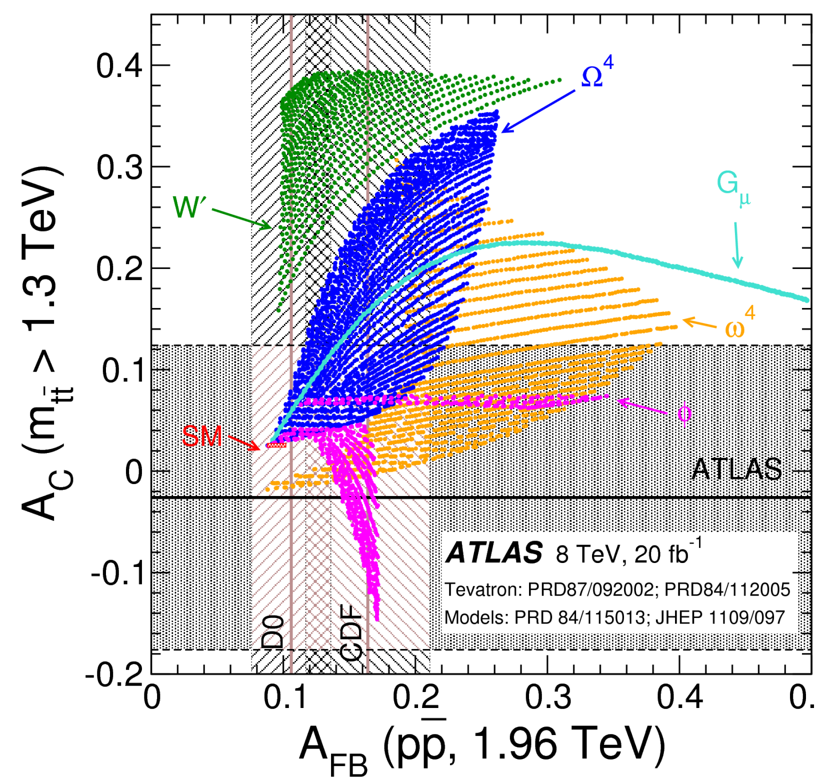
Each dot correspond to a choice of mass (100 GeV - 10 TeV range) and couplings to SM particles.

Models:

- Heavy W' boson exchanged in the t-channel
- Heavy axi-gluon G_μ exchanged in the s-channel
- Doublet ϕ, triplet ω^4 or sextet Ω^4 scalars

t-channel heavy W' disfavored in the highest $m_{t\bar{t}}$ bin.





Summary

- Boosted object reconstruction techniques used to perform top production measurements
- **$t\bar{t}$ differential cross section at high-p_T**
  - NLO MC tend to overestimate measurement at high-p_T: confirm previous observation obtained with different (resolved) event reconstruction technique
  - Systematic uncertainty related to large-R jet calibration dominate the particle-level measurement
  - Modeling uncertainties becomes dominant in the parton-level measurement
  - RIVET routine and HEPDATA including covariance matrix available
- **$t\bar{t}$ charge asymmetry at high-p_T**
  - Investigate region of the phase space where A_C is expected to be enhanced due to SM production mechanism
  - Unambiguous event reconstruction with large dilution factor
  - Small systematic uncertainties related to object reconstruction and calibration. Modeling uncertainties are dominant
  - Sensitivity to BSM physics effects, especially at very large $m_{t\bar{t}}$

THANK YOU!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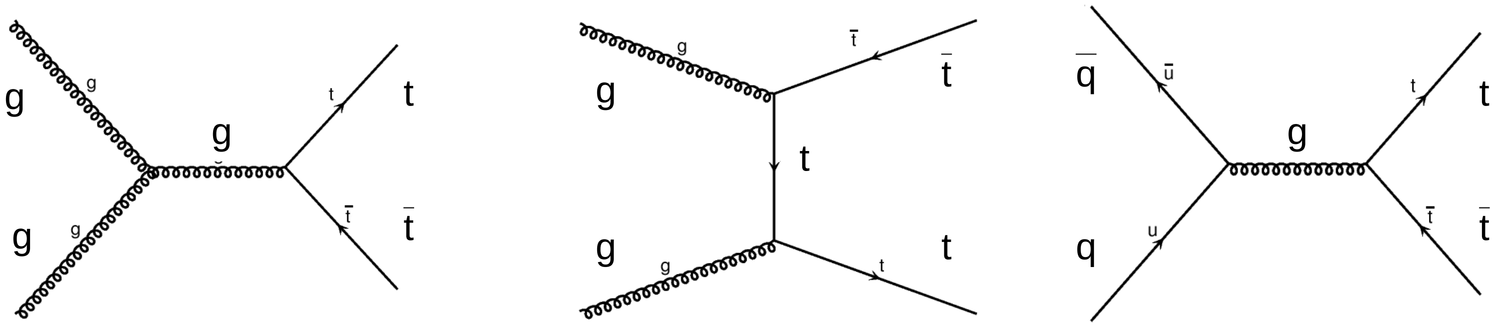
$t\bar{t}$ production at the LHC

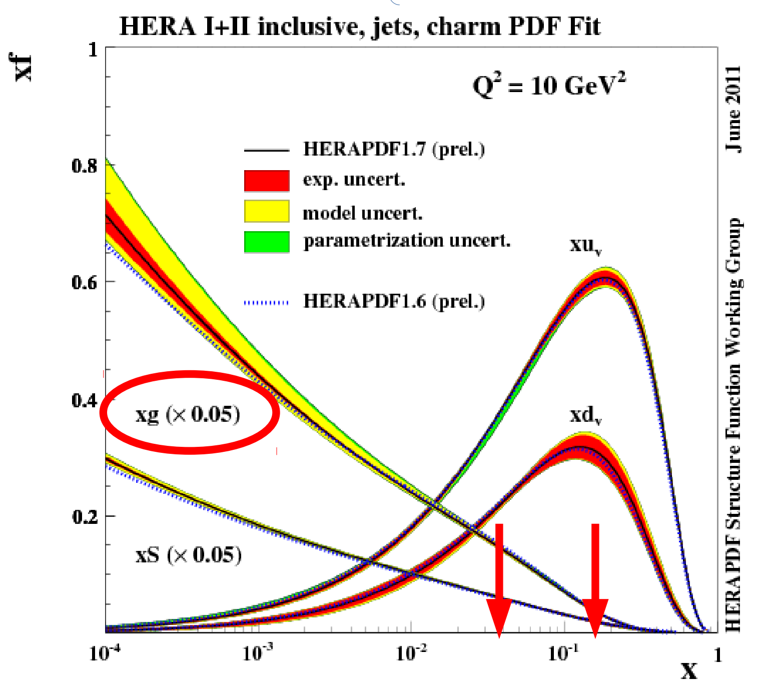


	gg	$q\bar{q}$
Tevatron ($p\bar{p}$ @ 2 TeV)	10%	90%
LHC (pp @ 8 TeV)	85%	15%
LHC (pp @ 14 TeV)	90%	10%

- Theoretical predictions at NNLO+NNLL
  - Uncertainty: ~2% (Tevatron), ~3% (LHC)
  - Comparable with experimental accuracy
- Main theoretical uncertainties: scale uncertainties, PDFs, α_s, m_t
- Sensitivity to PDFs
- $t\bar{t}$ production at the LHC testing large-x gluon PDFs

$$x^2 \approx \hat{s}/s \approx 4\, m_t^2/s$$

x ~ 0.18 (Tevatron)
x ~ 0.04 (LHC 8 TeV)

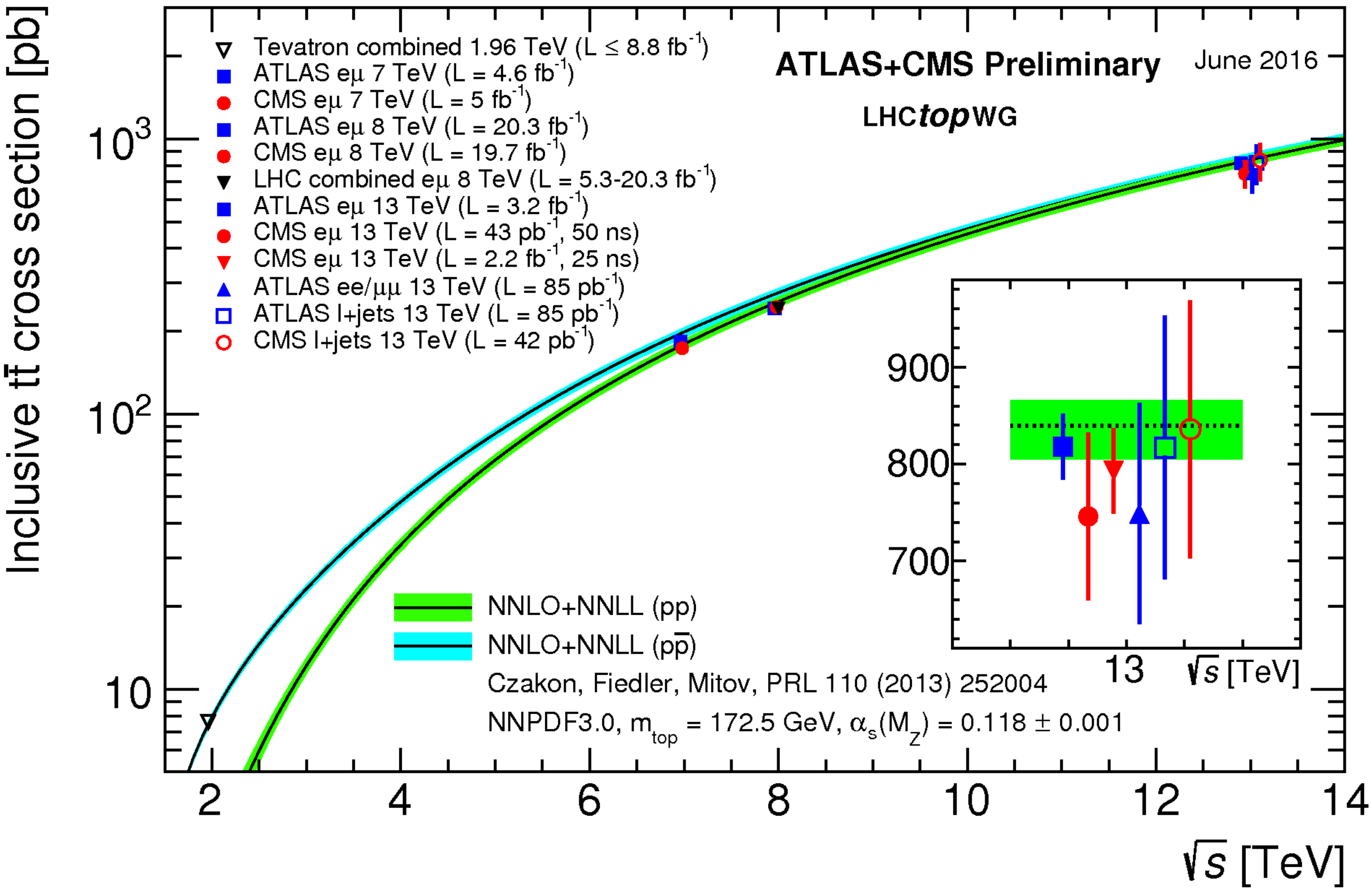


$\sigma(t\bar{t})$ theoretical predictions at NNLO+NNLL

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	+0.110(1.5%) −0.200(2.8%)	+0.169(2.4%) −0.122(1.7%)
LHC 7 TeV	172.0	+4.4(2.6%) −5.8(3.4%)	+4.7(2.7%) −4.8(2.8%)
LHC 8 TeV	245.8	+6.2(2.5%) −8.4(3.4%)	+6.2(2.5%) −6.4(2.6%)
LHC 14 TeV	953.6	+22.7(2.4%) −33.9(3.6%)	+16.2(1.7%) −17.8(1.9%)

Czakon, Fiedler, Mitov, Phys.Rev.Lett 110, 252004 (2013)

$t\bar{t}$ production at the LHC



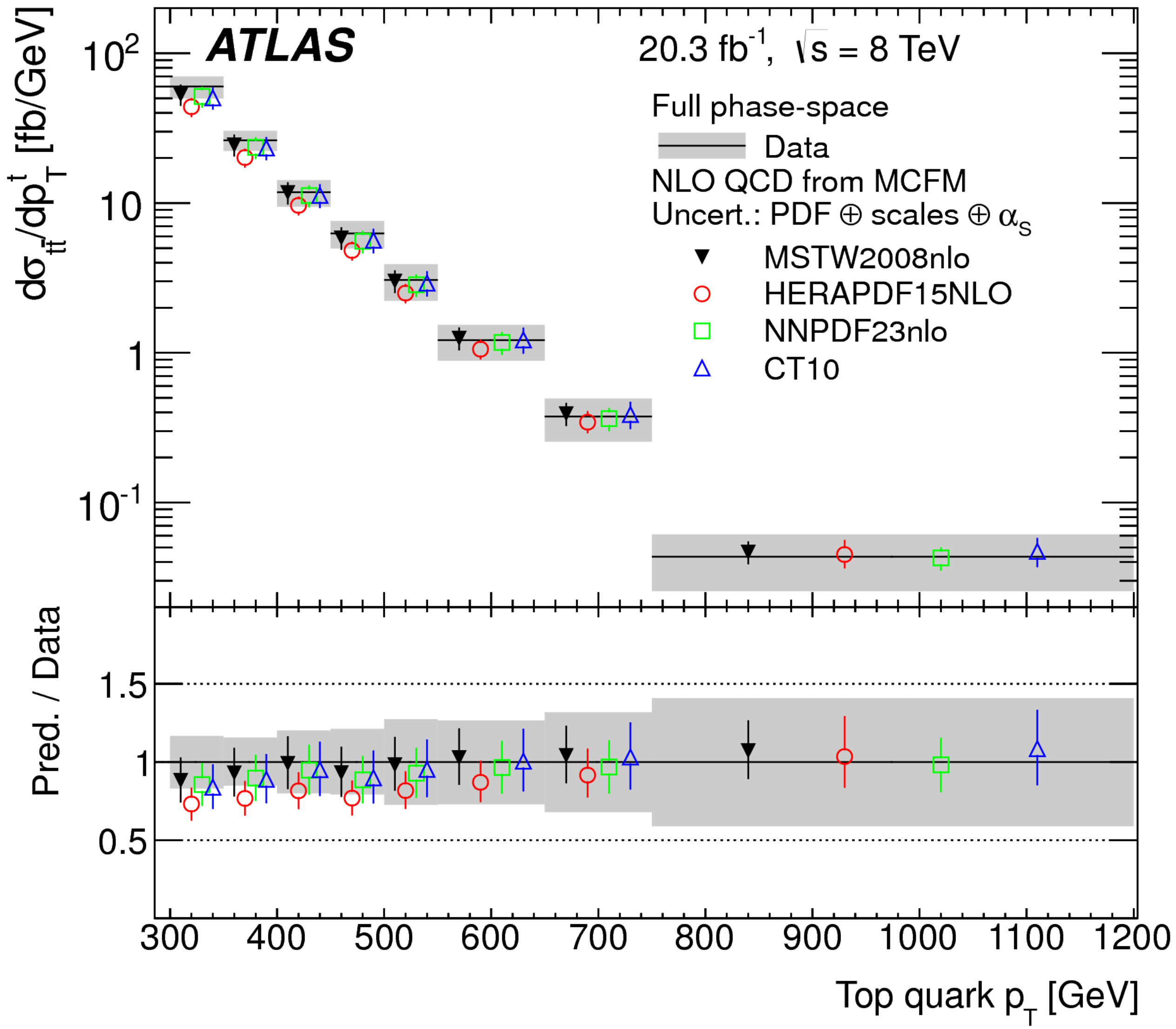
Event selection and fiducial region

Cut	Detector level		Particle level
	$e+$jets	$\mu+$jets	
Leptons	$\|z_0\| < 2$ mm $I_{\mathrm{mini}} < 0.05$ $\|\eta\| <1.37$ or $1.52< \|\eta\| <2.47$ $p_{\mathrm{T}} > 25$ GeV	$\|z_0\| < 2$ mm and $\|d_0/\sigma(d_0)\| < 3$ $I_{\mathrm{mini}} < 0.05$ $\|\eta\| <2.5$ $p_{\mathrm{T}} > 25$ GeV	$\|\eta\| <2.5$ $p_{\mathrm{T}} > 25$ GeV
Anti-k_t $R=0.4$ jets	$p_{\mathrm{T}} > 25$ GeV $\|\eta\| <2.5$ JVF > 0.5 (if $p_{\mathrm{T}} < 50$ GeV and $\|\eta\| < 2.4$)		$\|\eta\| <2.5$ $p_{\mathrm{T}} > 25$ GeV

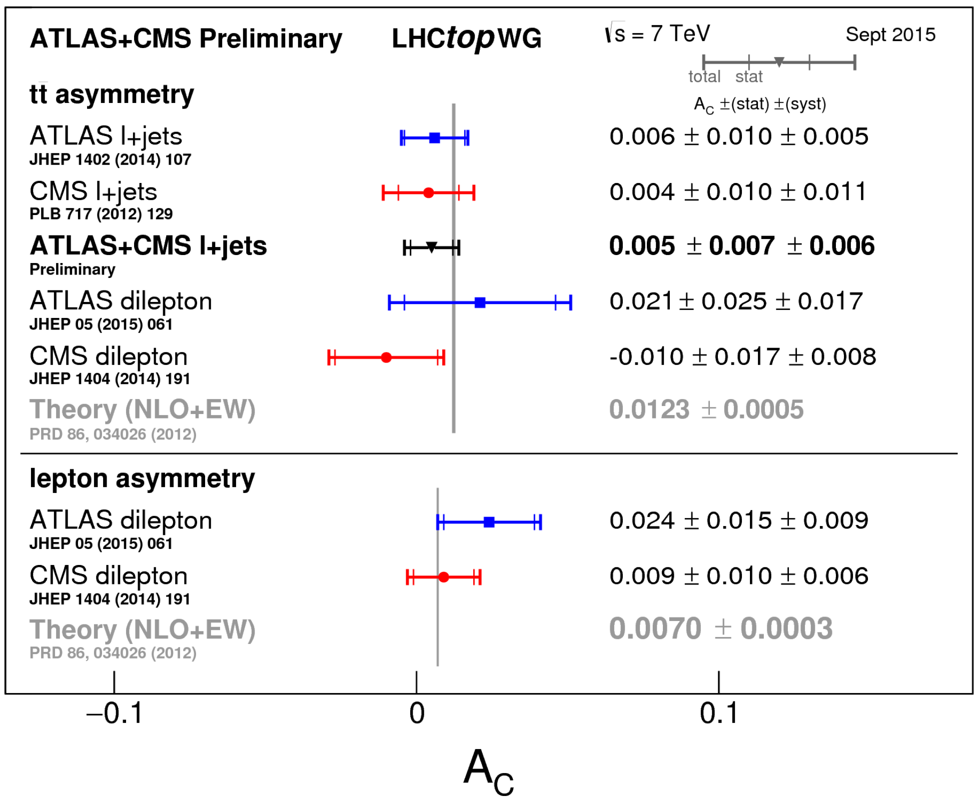
Overlap removal	if $\Delta R(e, \mathrm{jet}_{R=0.4}) <0.4$:
	$\mathrm{jet}'_{R=0.4} = \mathrm{jet}_{R=0.4} - e$
	if $\Delta R(e, \mathrm{jet}'_{R=0.4}) <0.2$:
	e removed and
	$\mathrm{jet}''_{R=0.4} = \mathrm{jet}'_{R=0.4} + e$
		if $\Delta R(\mu, \mathrm{jet}'_{R=0.4}) < 0.04 + 10\ \mathrm{GeV}/p_{\mathrm{T}}(\mu)$:
		μ removed
			None

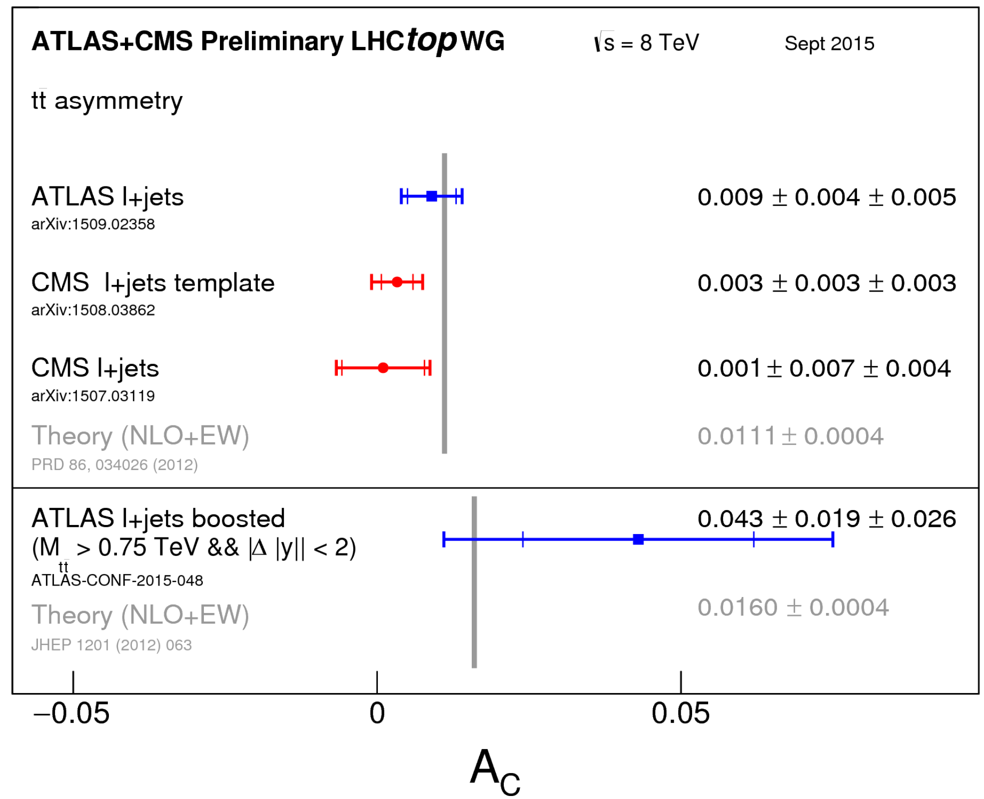
$E_{\mathrm{T}}^{\mathrm{miss}}$,$m_{\mathrm{T}}^{W}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 20$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} + m_{\mathrm{T}}^{W} > 60$ GeV		
Leptonic top	At least one anti-k_t $R=0.4$ jet with $\Delta R(\ell, \mathrm{jet}_{R=0.4}) < 1.5$		
Hadronic top	The leading-p_{T} trimmed anti-k_t $R=1.0$ jet has: $p_{\mathrm{T}} > 300$ GeV, $m > 100$ GeV, $\sqrt{d_{12}} > 40$ GeV $\Delta R(\mathrm{jet}_{R=1.0}, \mathrm{jet}_{R=0.4}) > 1.5$, $\Delta\phi(\ell, \mathrm{jet}_{R=1.0}) > 2.3$		
b-tagging	At least one of: 1) the leading-p_{T} anti-k_t $R=0.4$ jet with $\Delta R(\ell, \mathrm{jet}_{R=0.4}) < 1.5$ is b-tagged 2) at least one anti-k_t $R=0.4$ jet with $\Delta R(\mathrm{jet}_{R=1.0}, \mathrm{jet}_{R=0.4}) < 1.0$ is b-tagged		

Theoretical uncertainties using MCFM



Charge asymmetry: summary





Dilution factor in A_C measurement