Top-quark properties: mass and spin correlations

Markus Cristinziani
Universität Bonn

LHCP@Puebla, México
20–25 May 2019

BMBF-Forschungsschwerpunkt
ATLAS-EXPERIMENT
Physik bei höchsten Energien mit dem ATLAS-Experiment am LHC
FSP 103 ATLAS
Bundesministerium für Bildung und Forschung
erc
UNIVERSITÄT BONN

Top-quark mass

UNIVERSITÄT BONN

Direct top-quark mass measurements at hadron colliders

- based on reconstruction of decay products
- using simulation in the fit to extract the mass
- interpreted as the pole mass

Interpretation uncertainty ~ 0.5–1 GeV

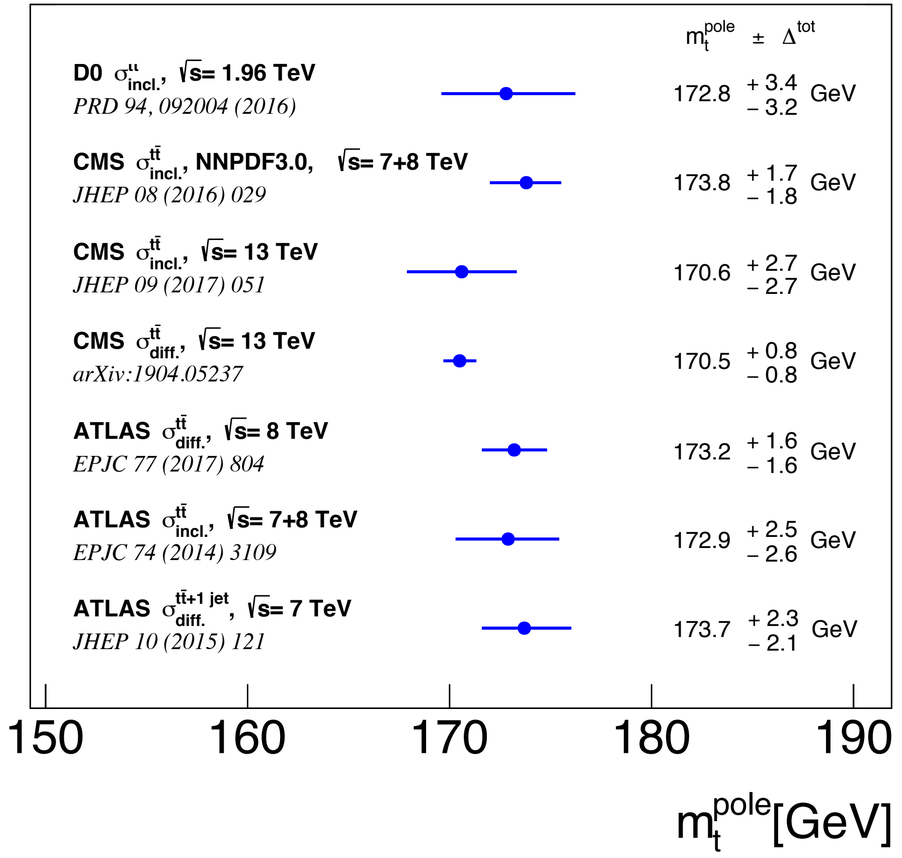
- due to non-perturbative effects
- controversially discussed

G. Corcella, 1903.06574,
M. Buttenschön et al., PRL 117 (2016) 232001,
S. Moch et al., 1405.4781,

A. Juste et al., EPJC 74 (2014) 3119,
P. Nason, 1712.02796,
A. H. Hoang et al., 1412.3649

Alternative top-quark mass measurements

- from cross section, differential distributions
- new result (here): $t\bar{t}$+1 jet



ATLAS EXPERIMENT

Top-quark mass in $t\bar{t}$ + 1 jet

arXiv:1905.02302

UNIVERSITÄT BONN

Observable considered is: $\rho_s = 2m_0/m_{t\bar{t}+1\text{-jet}}$

- m_0 = 170 GeV constant
- $m_{t\bar{t}+1\text{ jet}}$ invariant mass
- presence of one extra jet increases sensitivity to top-quark mass

Then use $\mathcal{R}(m_t^{\text{pole}}, \rho_s) = \frac{1}{\sigma_{t\bar{t}+1\text{-jet}}} \cdot \frac{d\sigma_{t\bar{t}+1\text{-jet}}}{d\rho_s}$

Previous result (ATLAS)

- δm_t = 2.3 GeV using 7 TeV data, JHEP 10 (2015) 121

Simulation and event selection

$t\bar{t}$ nominal samples

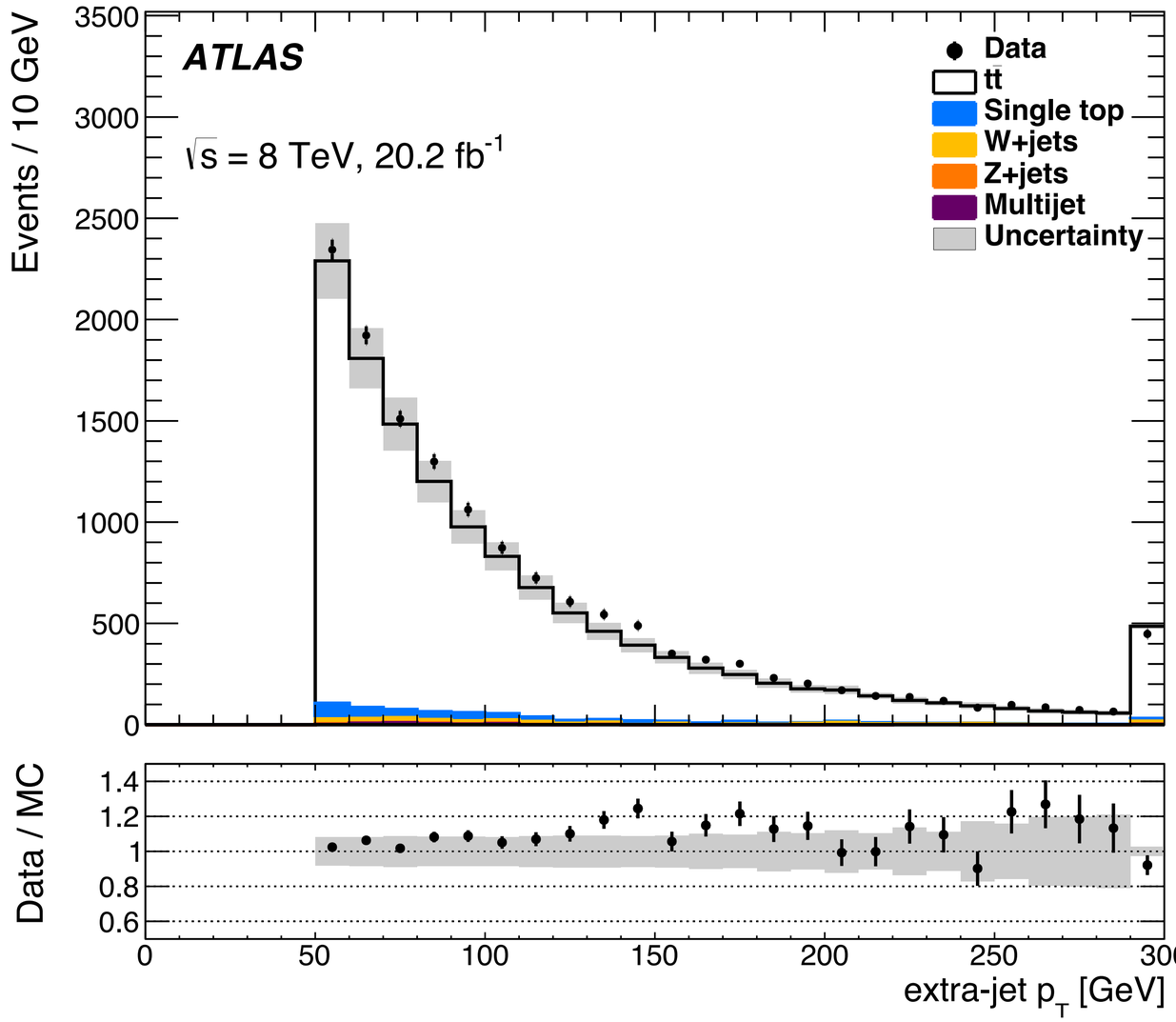
- Powheg-hvq (NLO) + CT10 + Pythia 6
- $h_{damp} = m_t$

$t\bar{t}$ alternative samples

- MC@NLO+Herwig, Powheg+Herwig
- variations of h_{damp}, μ_R, μ_F

ℓ + ≥ 5 jets selection

- event compatible with single lepton $t\bar{t}$
- extra jet $p_T > 50$ GeV
- purity 94–95%



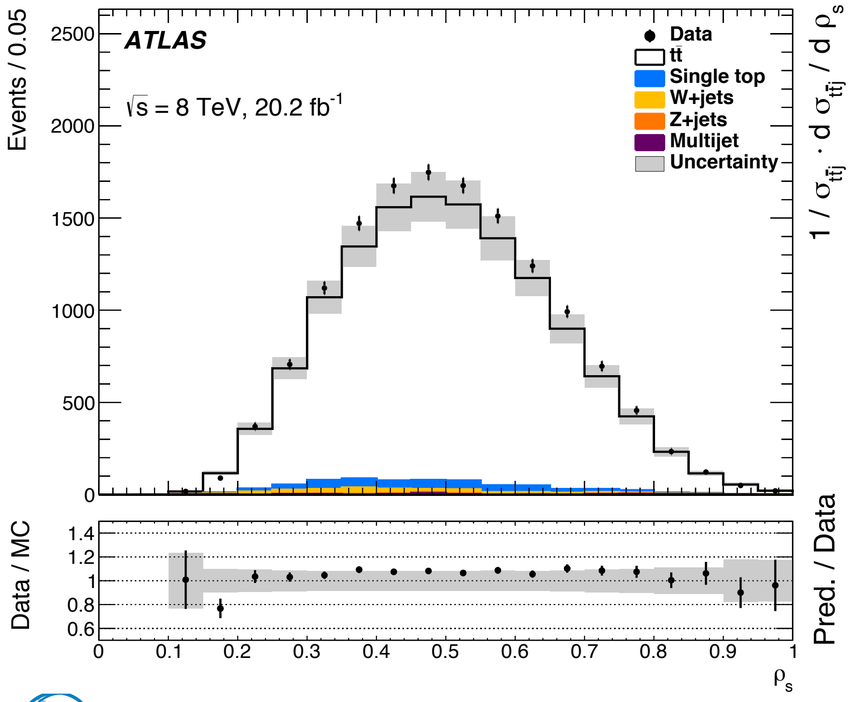
Differential distributions

UNIVERSITÄT BONN

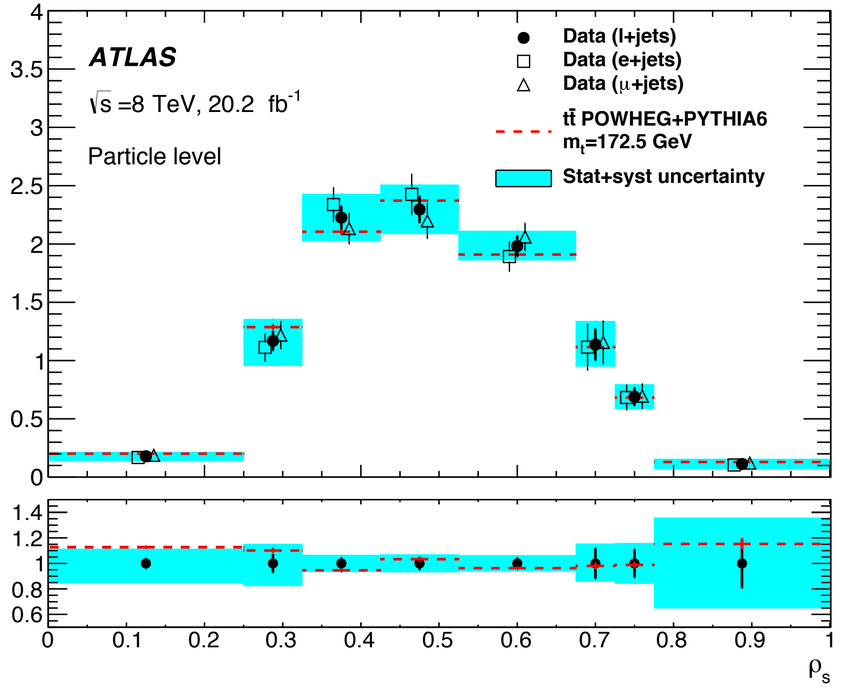
Normalised differential cross section

- as a function of ρ_s
- insensitive to incorrect pairings of W boson and b-jets
- unfolded to particle or parton level

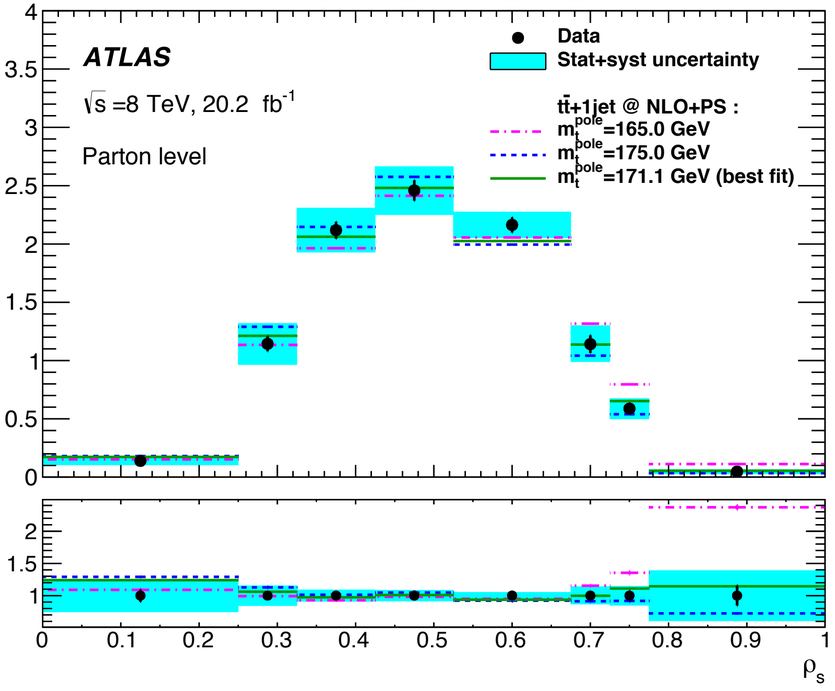
Detector level



Particle level



Parton level

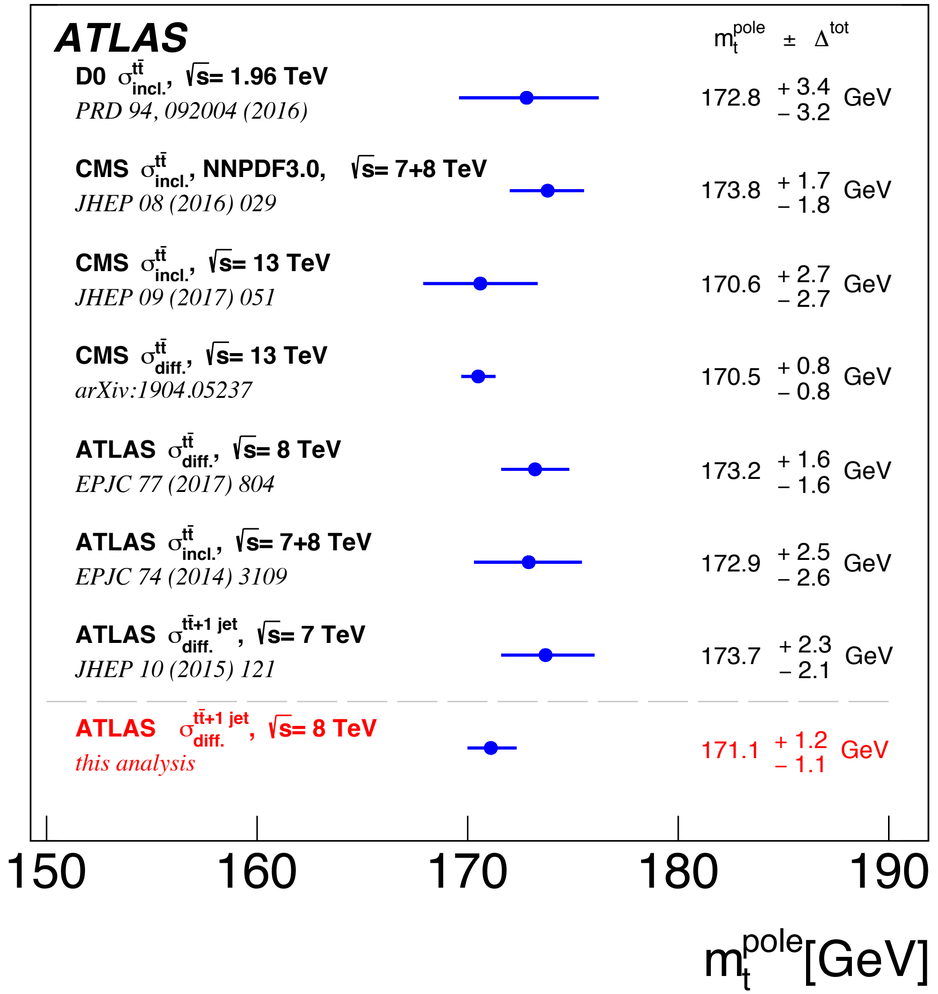


Result

arXiv:1905.02302

UNIVERSITÄT BONN

Mass scheme	m_t^{pole} [GeV]	$m_t(m_t)$ [GeV]
Value	**171.1**	**162.9**
Statistical uncertainty	**0.4**	**0.5**
Simulation uncertainties		
Shower and hadronisation	0.4	0.3
Colour reconnection	0.4	0.4
Underlying event	0.3	0.2
Signal Monte Carlo generator	0.2	0.2
Proton PDF	0.2	0.2
Initial- and final-state radiation	0.2	0.2
Monte Carlo statistics	0.2	0.2
Background	<0.1	<0.1
Detector response uncertainties		
Jet energy scale (including *b*-jets)	0.4	0.4
Jet energy resolution	0.2	0.2
Missing transverse momentum	0.1	0.1
b-tagging efficiency and mistag	0.1	0.1
Jet reconstruction efficiency	<0.1	<0.1
Lepton	<0.1	<0.1
Method uncertainties		
Unfolding modelling	0.2	0.2
Fit parameterisation	0.2	0.2
Total experimental systematic	**0.9**	**1.0**
Scale variations	(+0.6, −0.2)	(+2.1, −1.2)
Theory PDF⊕α_s	0.2	0.4
Total theory uncertainty	**(+0.7, −0.3)**	**(+2.1, −1.2)**
Total uncertainty	**(+1.2, −1.1)**	**(+2.3, −1.6)**

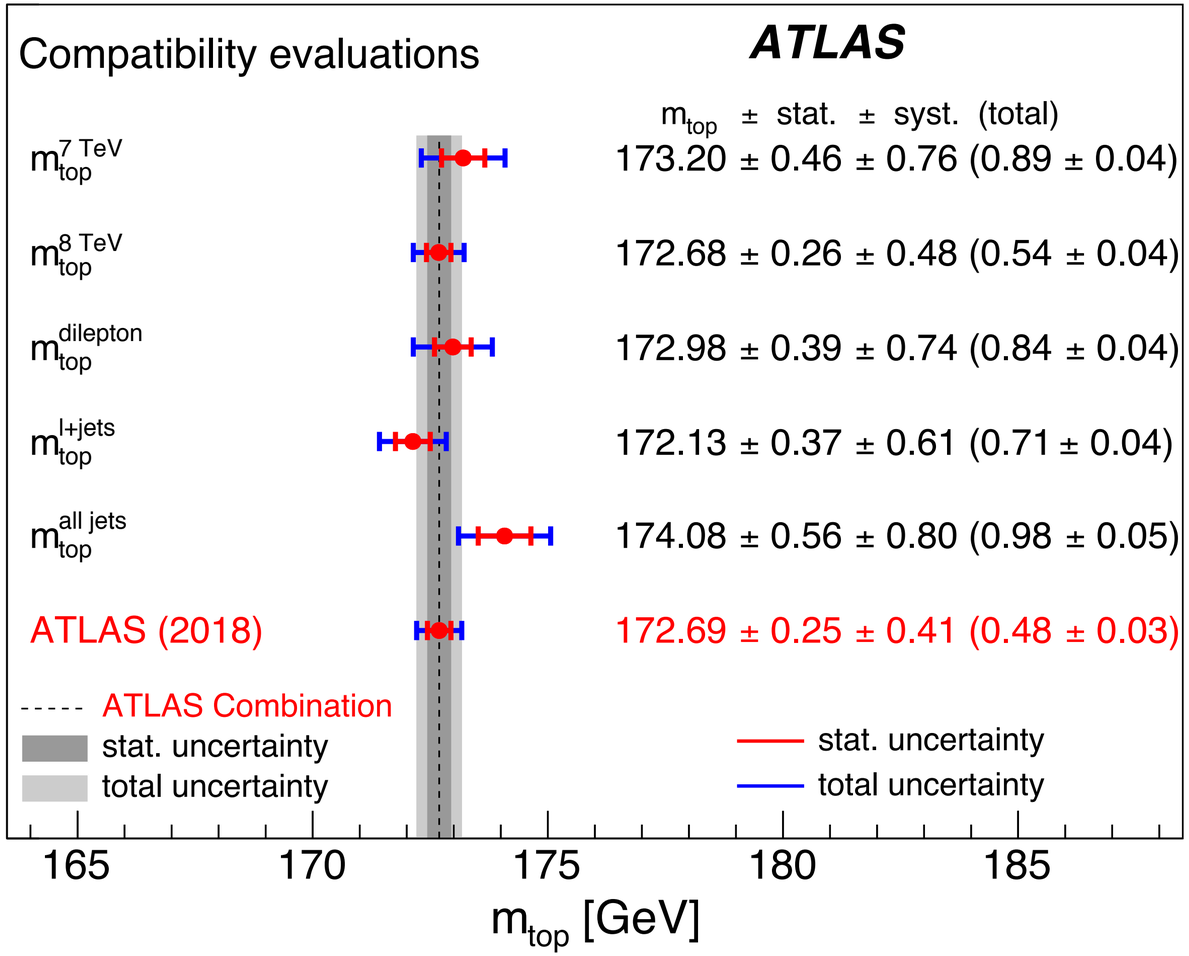


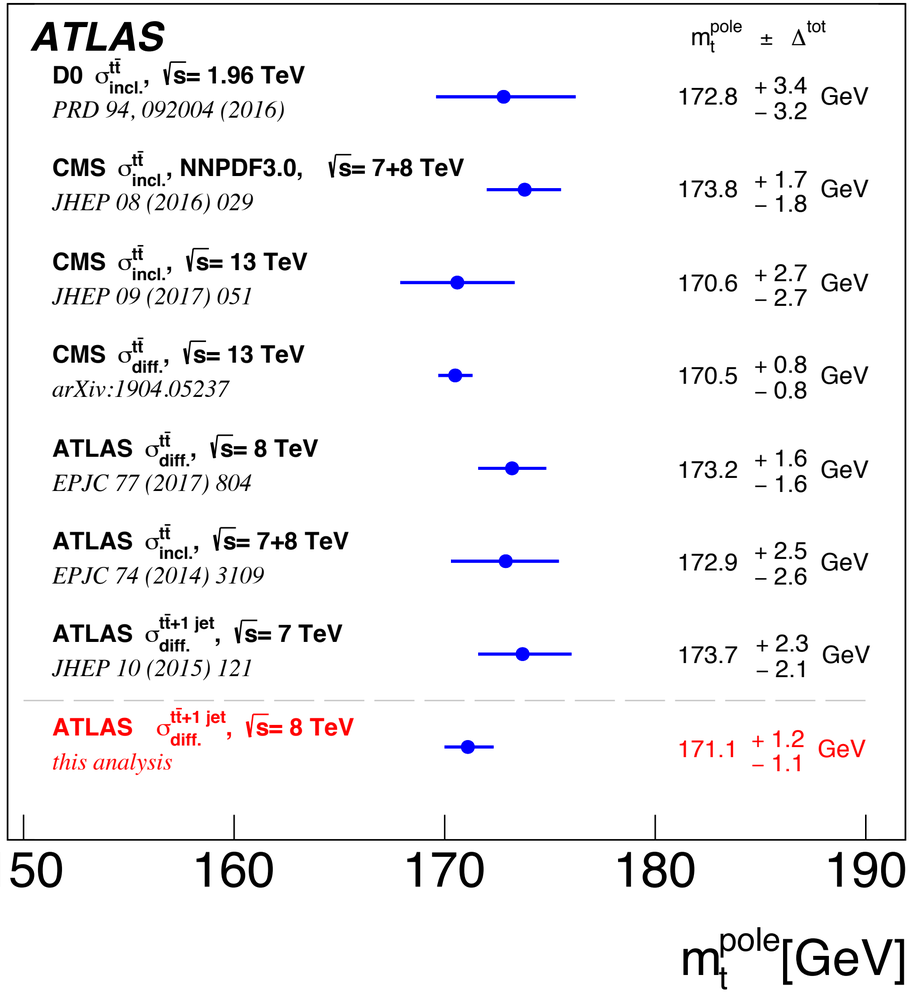
$$m_t^{\text{pole}} = 171.1 \pm 0.4\ (\text{stat}) \pm 0.9\ (\text{syst}) \,^{+0.7}_{-0.3}\ (\text{theo})\ \text{GeV}$$

$$m_t(m_t) = 162.9 \pm 0.5\ (\text{stat}) \pm 1.0\ (\text{syst}) \,^{+2.1}_{-1.2}\ (\text{theo})\ \text{GeV}$$

Comparison direct vs indirect

Eur. Phys. J. C79 (2019) 290





- **Latest ATLAS combination, October 2018**

$t\bar{t}$ spin correlations

arXiv:1903.07570

UNIVERSITÄT BONN

Signature

- 2 isolated OS e/μ, ≥ 2 jets (≥ 1 or ≥ 2 b-jets)

Previous measurements

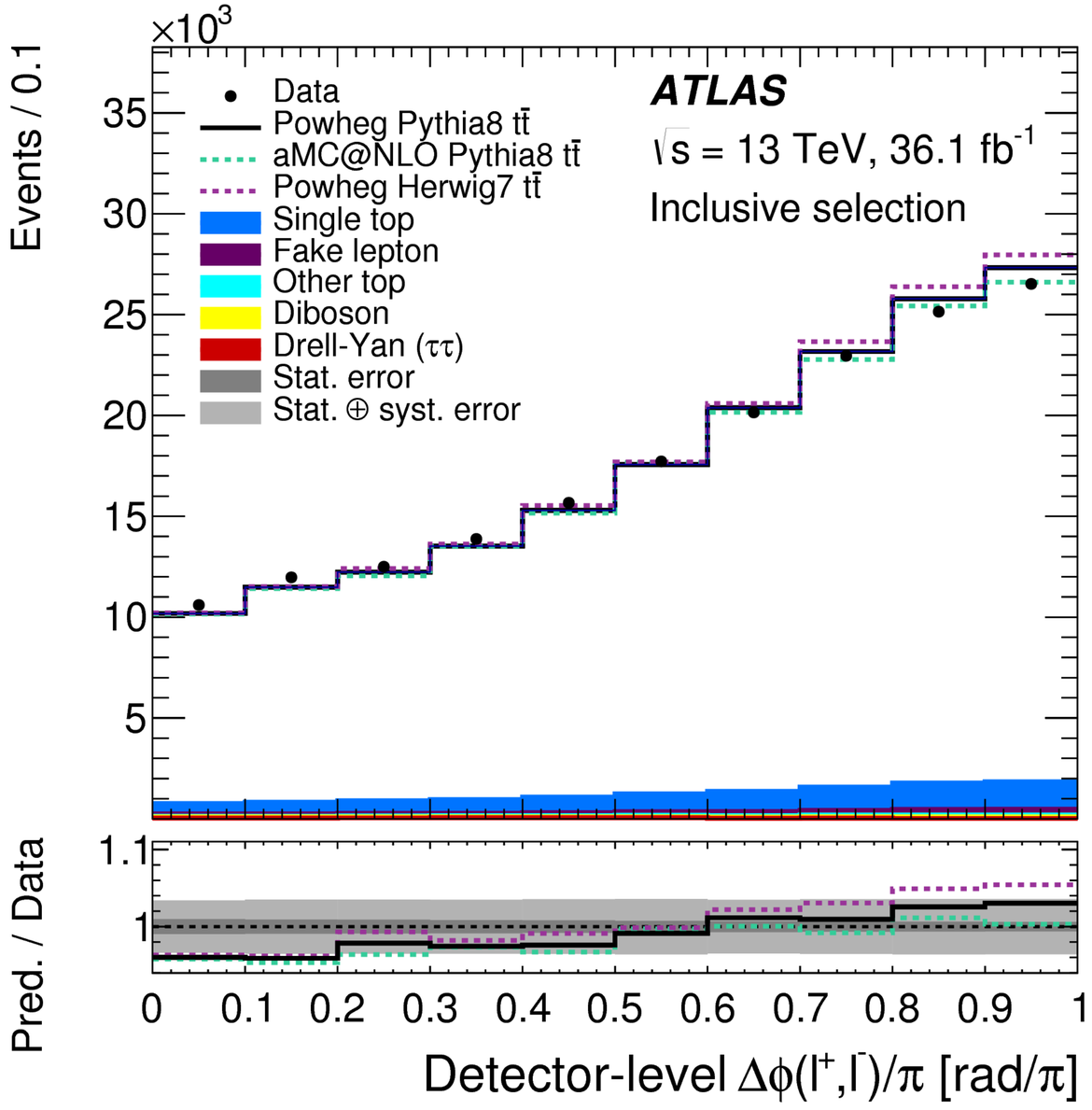
- ATLAS and CMS show slightly stronger spin correlations in Δφ than expected, still compatible with Standard Model
- Here: 13 TeV, 36.1 fb^{-1} data

Selections

- inclusive (≥ 1b)
- $t\bar{t}$-reconstructed (≥ 2b), incl. ν-weighting

Extraction

- differential in $m_{t\bar{t}}$, parton and particle level



$t\bar{t}$ spin correlations

arXiv:1903.07570

UNIVERSITÄT BONN

Signature

- 2 isolated OS e/μ, ≥ 2 jets (≥ 1 or ≥ 2 b-jets)

Previous measurements

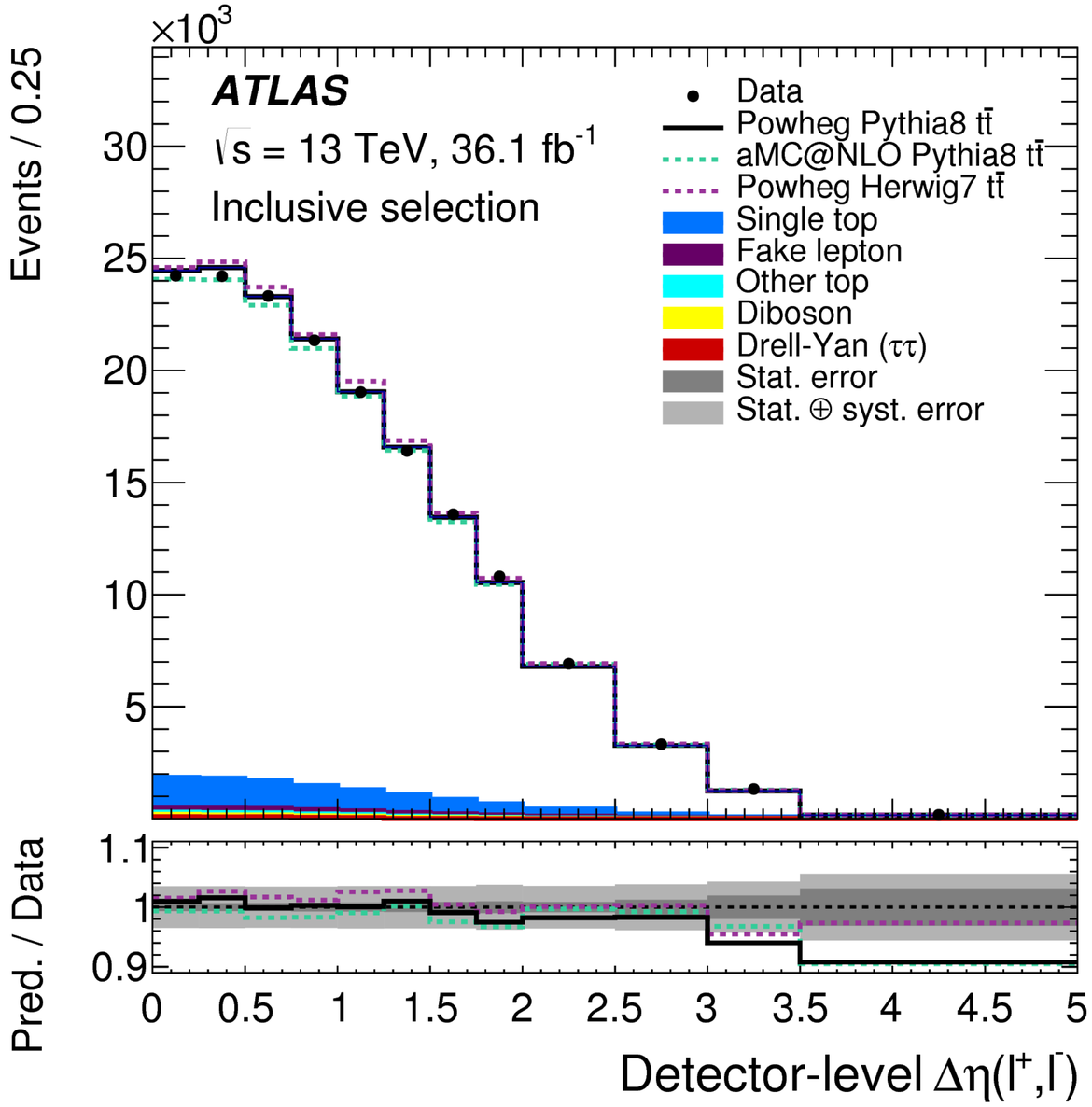
- ATLAS and CMS show slightly stronger spin correlations in Δφ than expected, still compatible with Standard Model
- Here: 13 TeV, 36.1 fb^{-1} data

Selections

- inclusive (≥ 1b)
- $t\bar{t}$-reconstructed (≥ 2b), incl. ν-weighting

Extraction

- differential in $m_{t\bar{t}}$, parton and particle level



$t\bar{t}$ spin correlations: parton level

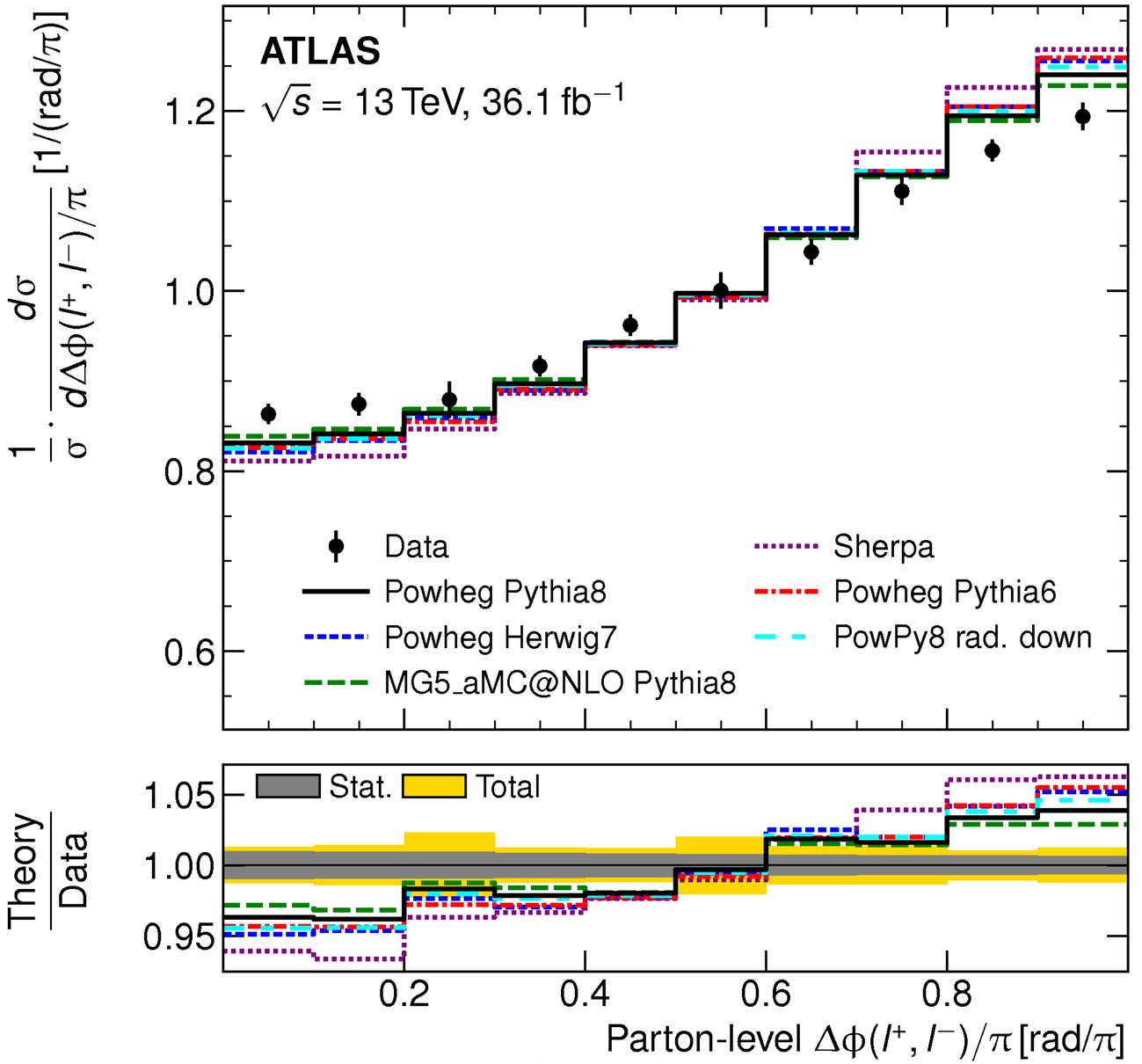
UNIVERSITÄT BONN

Event reconstruction

- want to test $m_{t\bar{t}}$ dependence
- parton-level to full phase space

Systematic uncertainties

- dominated by modelling
- NLO ME generator
- parton shower
- ISR/FSR



$t\bar{t}$ spin correlations: parton level

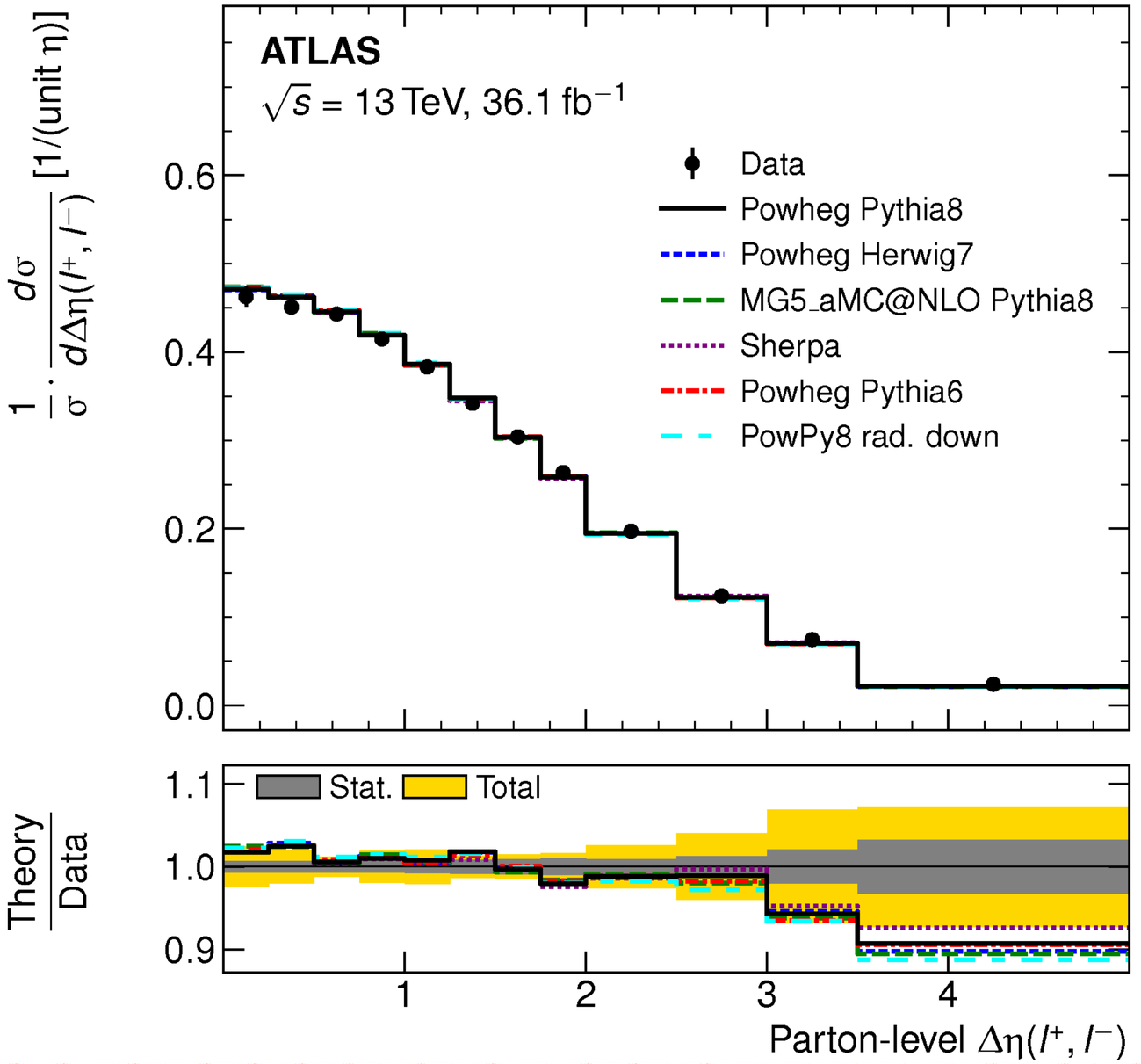
UNIVERSITÄT BONN

Event reconstruction

- want to test $m_{t\bar{t}}$ dependence
- parton-level to full phase space

Systematic uncertainties

- dominated by modelling
- NLO ME generator
- parton shower
- ISR/FSR



$t\bar{t}$ spin correlations: particle level

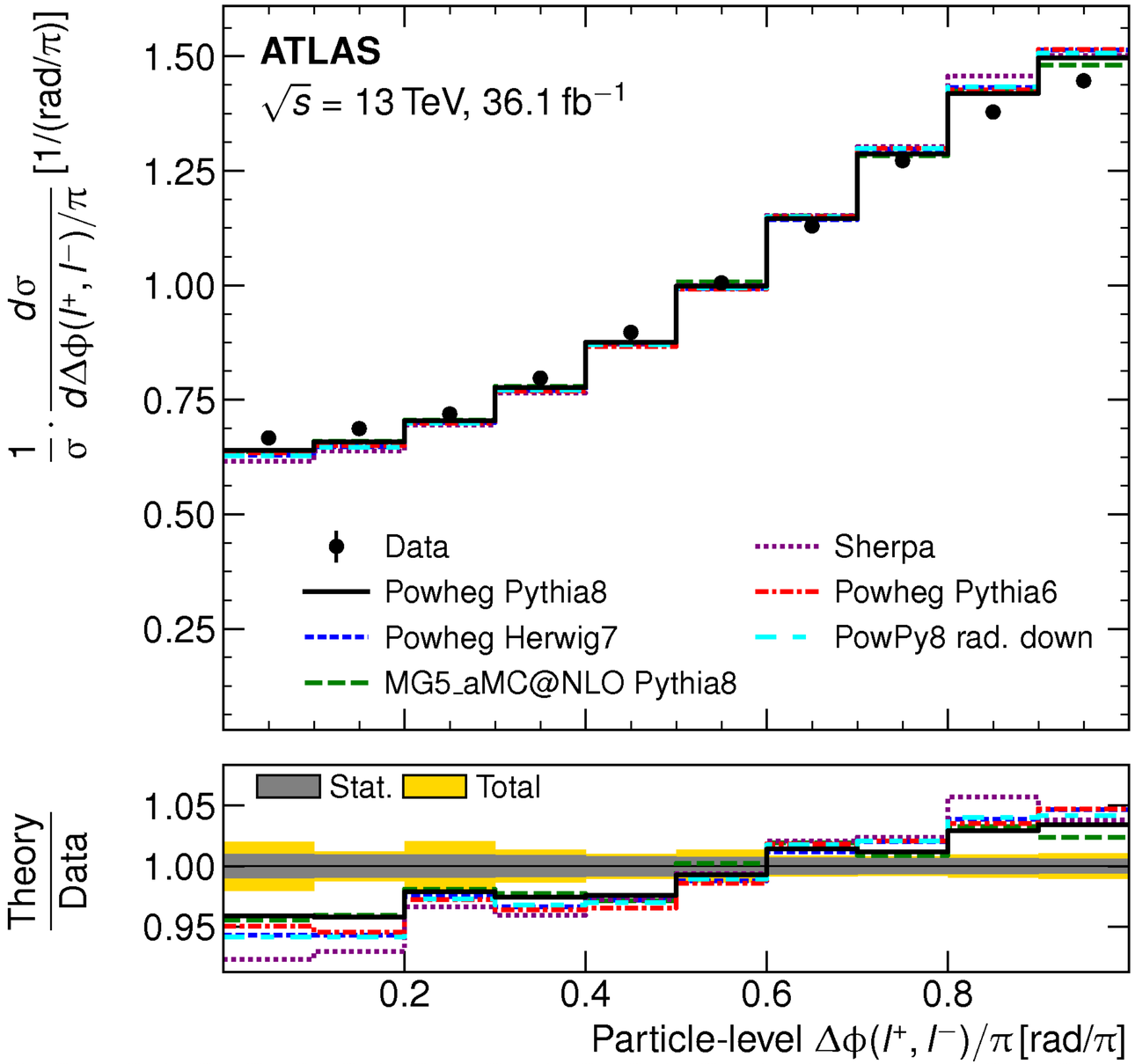
UNIVERSITÄT BONN

Particle-level

- in fiducial "reco-like" phase space

Systematic uncertainties

- dominated by modelling
- NLO ME generator
- parton shower
- ISR/FSR



$t\bar{t}$ spin correlations: particle level

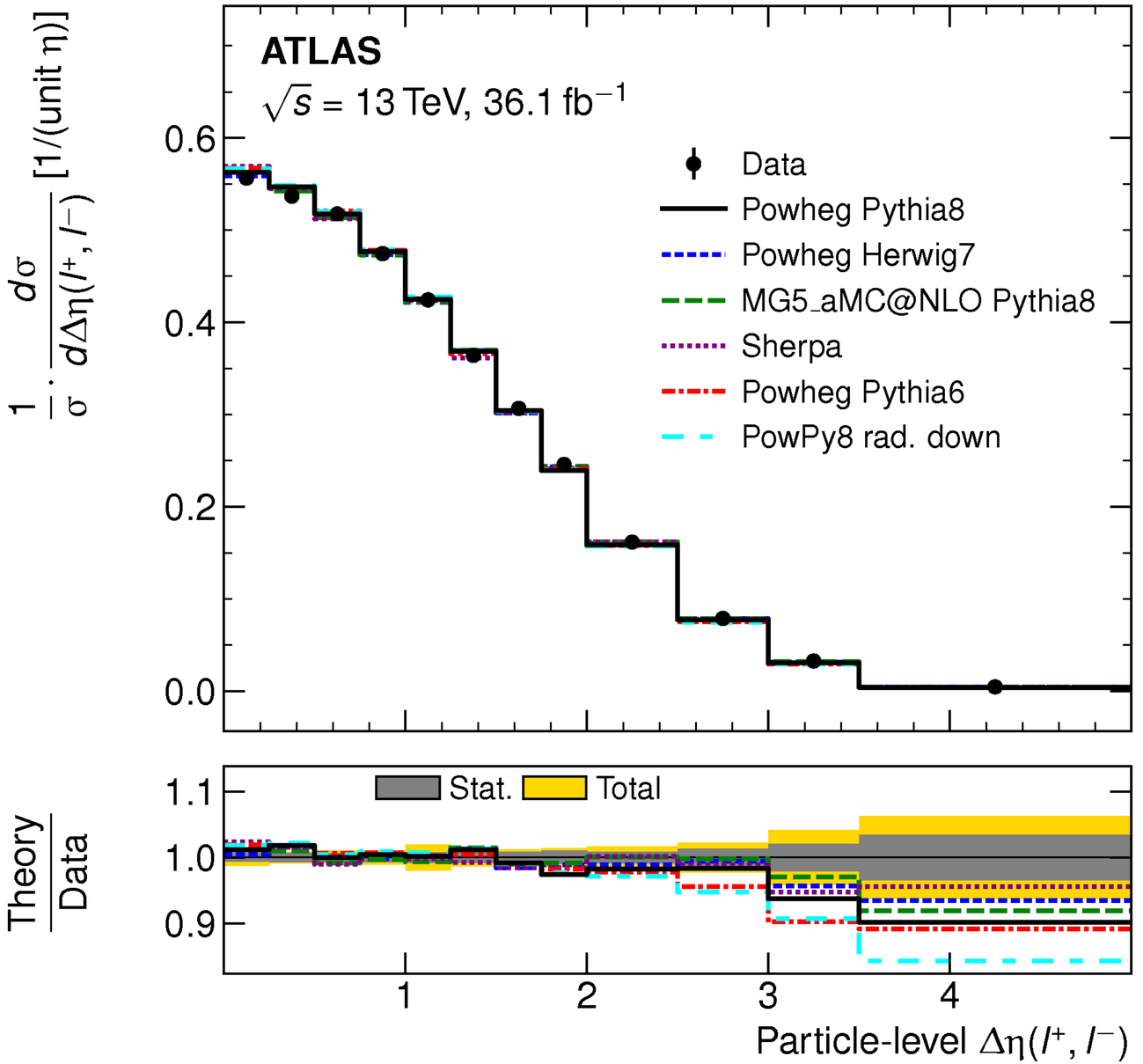
UNIVERSITÄT BONN

Particle-level

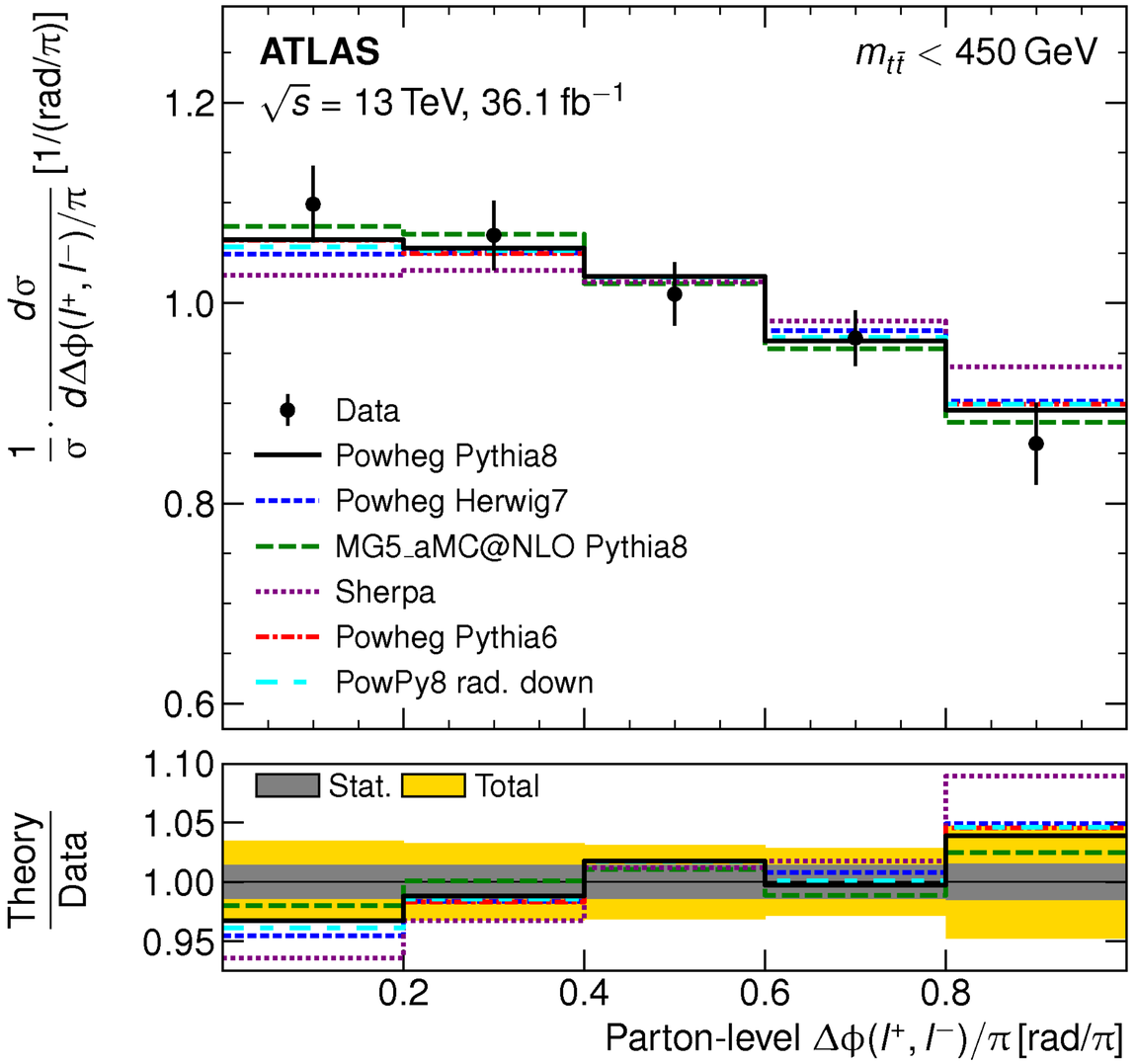
- in fiducial “reco-like” phase space

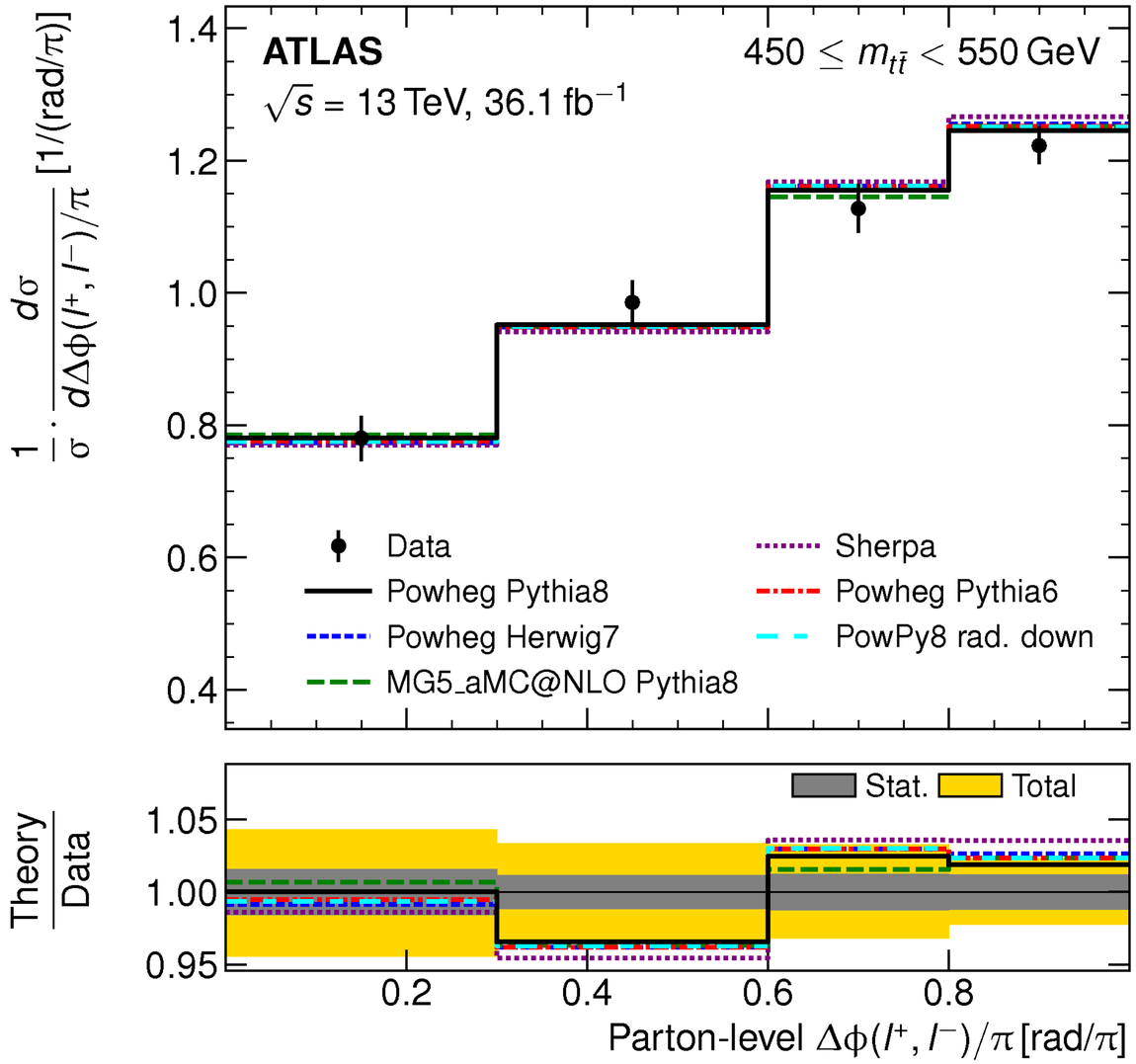
Systematic uncertainties

- dominated by modelling
- NLO ME generator
- parton shower
- ISR/FSR

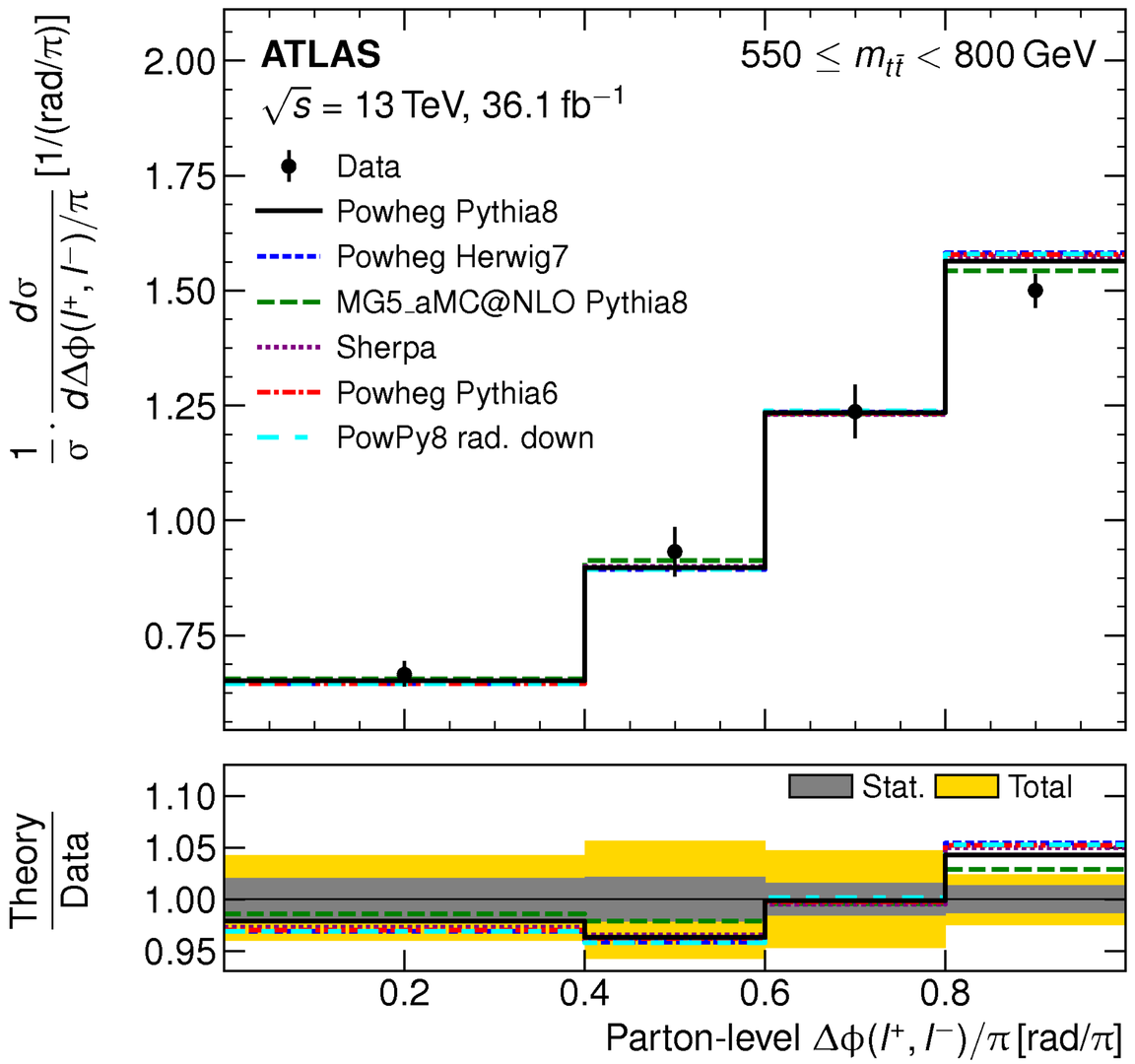


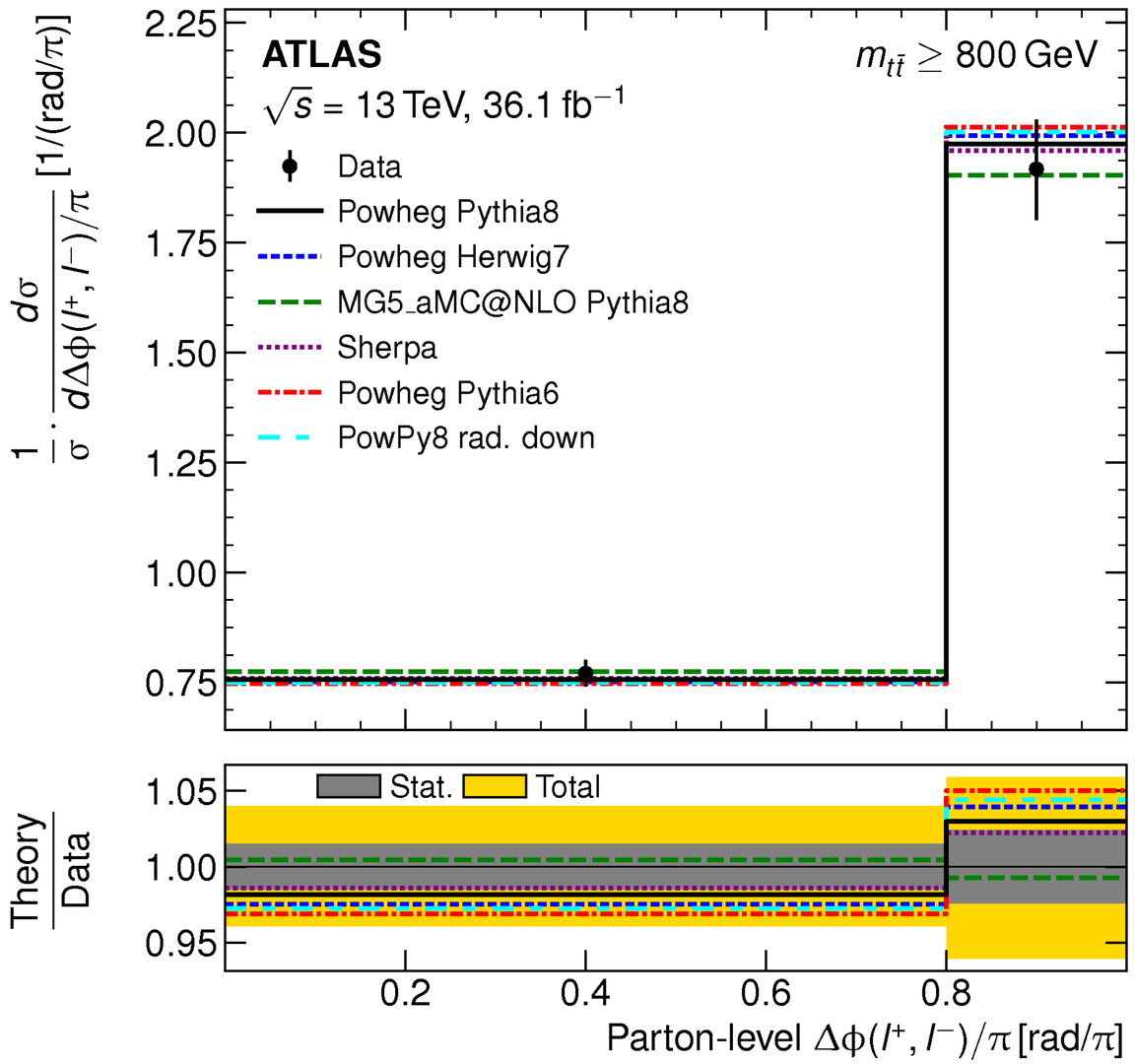
$t\bar{t}$ spin correlations: binned in $m_{t\bar{t}}$





$t\bar{t}$ spin correlations: binned in $m_{t\bar{t}}$





$t\bar{t}$ spin correlations

- **Fraction of SM-like spin correlation**

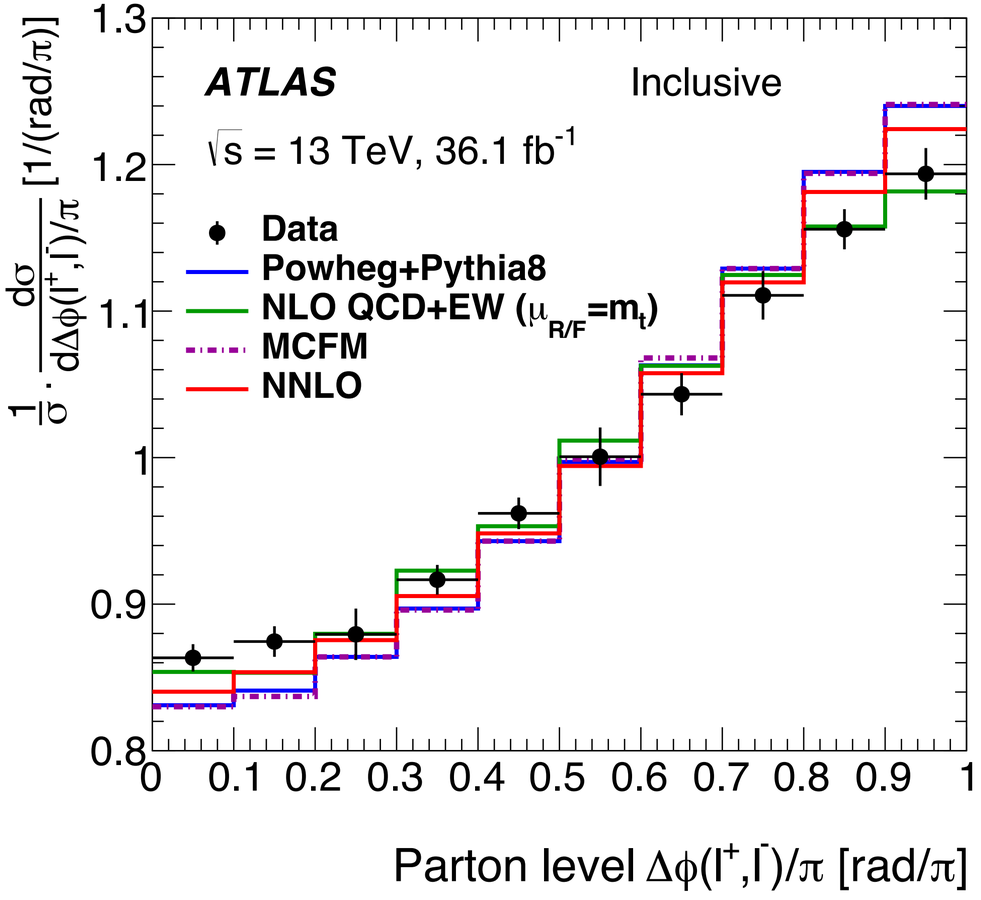
$$x_i = f_{\mathrm{SM}} \cdot x_{\mathrm{spin},\,i} + (1 - f_{\mathrm{SM}}) \cdot x_{\mathrm{nospin},\,i}$$

- **using inclusive and $m_{t\bar{t}}$-binned samples**

Region	$f_{\mathrm{SM}} \pm$ (stat.,syst.,theory)	Significance (excl. theory uncertainties)
Inclusive	$1.249 \pm 0.024 \pm 0.061 \pm 0.040$	3.2 (3.8)
$m_{t\bar{t}} < 450$ GeV	$1.12 \pm 0.04\ ^{+0.12}_{-0.13} \pm 0.02$	0.86 (0.87)
$450 \leq m_{t\bar{t}} < 550$ GeV	$1.18 \pm 0.08\ ^{+0.13}_{-0.14} \pm 0.08$	1.0 (1.1)
$550 \leq m_{t\bar{t}} < 800$ GeV	$1.65 \pm 0.19\ ^{+0.31}_{-0.41} \pm 0.22$	1.3 (1.4)
$m_{t\bar{t}} \geq 800$ GeV	$2.2 \pm 0.9\ ^{+2.5}_{-1.7} \pm 0.7$	0.58 (0.61)

Cross checks

- **H1: LO decay of the top quarks in the nominal hypothesis templates is not a limitation (MCFM check, decay at full NLO)**
- **H2: NWA in the templates is not a limiting factor and does not explain the observed deviation (bb4l $t\bar{t}$+tW)**
- **H3: NNLO in production consistent with scale uncertainties ($p_T(t)$ reweighting to fixed-order calculations and to data; NNLO fixed-order).**



H3: A. Behring, M. Czakon, A. Mitov, A. S. Papanastasiou and R. Poncelet, arXiv: 1901.05407 [hep-ph]

$t\bar{t}$ spin correlations

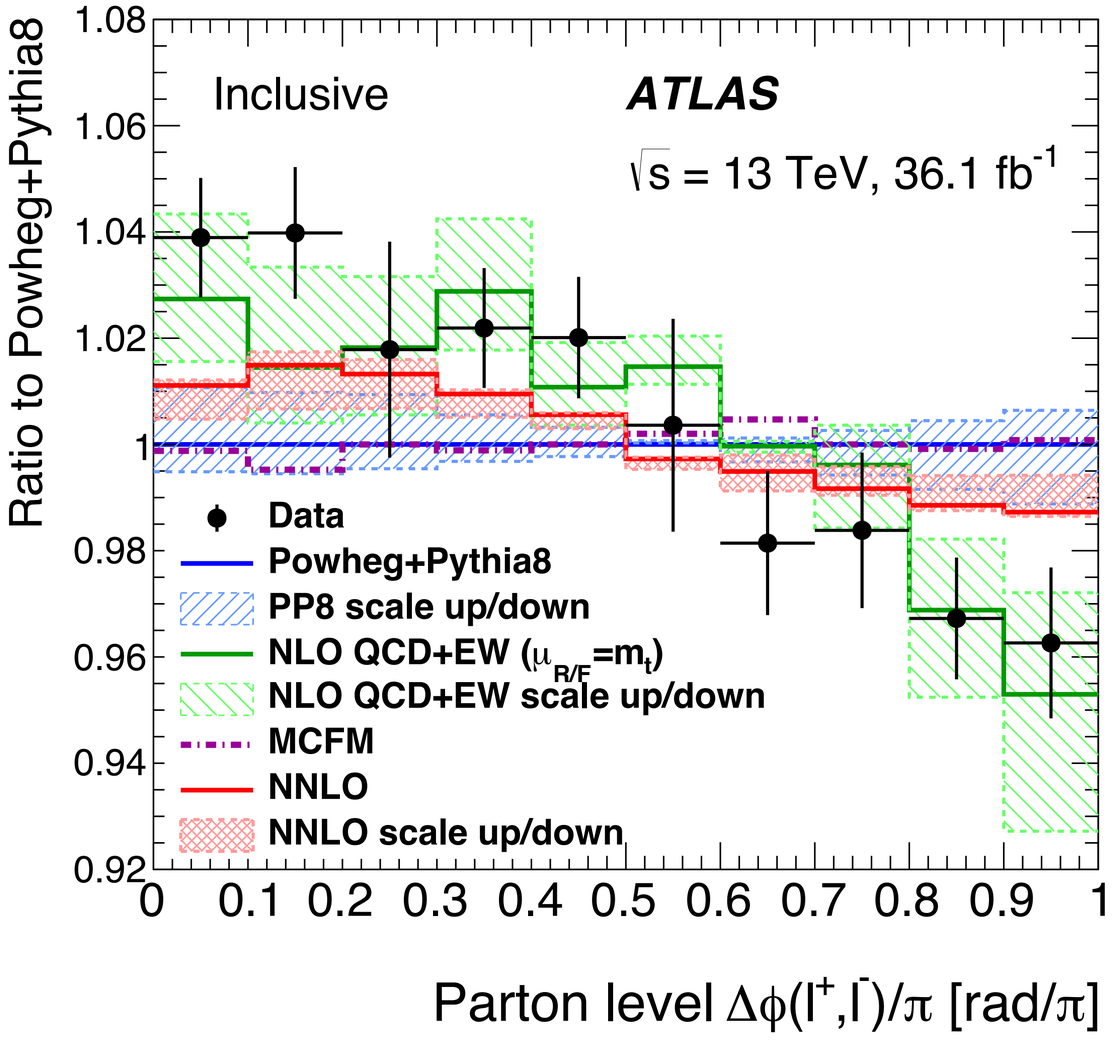
arXiv:1903.07570

UNIVERSITÄT BONN

More cross-checks

- **H4: $\mu_R = \mu_F = m_t$ with NLO expansion in QCD and weak leading to (if used as template) $f_{SM} = 1.03 \pm 0.13$ (scale)**

H4:
W. Bernreuther, D. Heisler and Z.-G. Si, JHEP **12** (2015) 026
W. Bernreuther and Z.-G. Si, Nucl. Phys. B **837** (2010) 90,
W. Bernreuther and Z.-G. Si, Phys. Lett. B **725** (2013) 115, Erratum: Phys. Lett.B744 (2015) 413



Summary

- **spin correlations higher than NLO generators**
- **agree with NLO expanded in QCD and EW couplings, with large uncertainties**
- **increases slightly as a function of $m_{t\bar{t}}$, but no bin with significance more than 1.3σ**

ATLAS top properties summary

ATL-PHYS-PUB-2018-034