

ATLAS spin correlations update

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on behalf of the ATLAS Collaboration

Top LHC WG Meeting
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UNIVERSITY OF
BIRMINGHAM

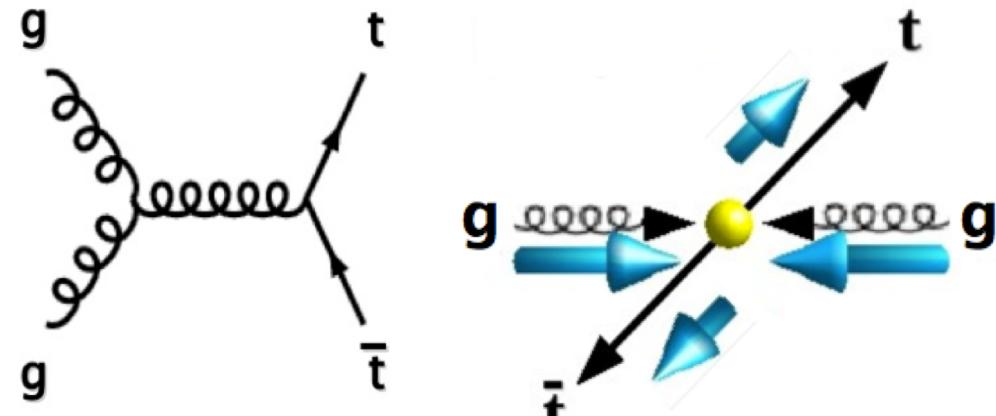
Spin correlation: overview

- LHC (pp): top quarks produced ~unpolarised, but...
- ...expect correlations between spins of top and anti-top in the SM

- Top quarks decay before hadronisation & top lifetime shorter than decorrelation time

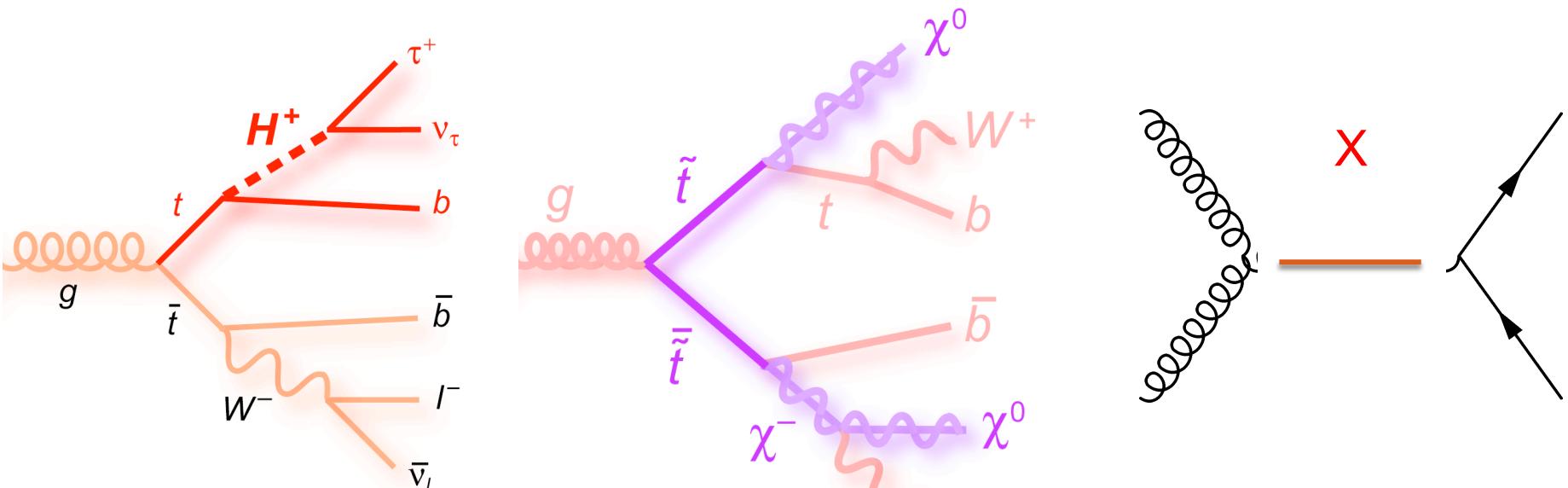
→ Spin information passed directly to decay products

→ Measure spin information from angular distributions



Spin correlation: beyond the Standard Model

- Measured spin correlation can alter due to
 - Different decays
 - Different production
- Spin correlation: test full chain from production to decay

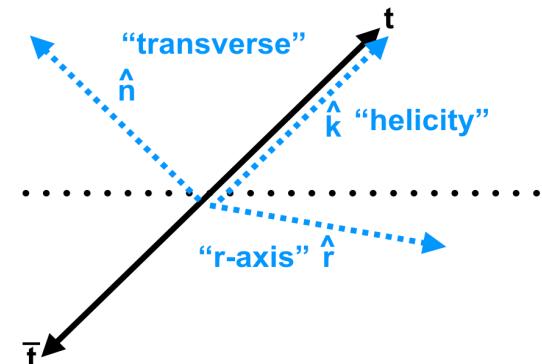


- Decays: charged Higgs, b' ,...

- Production: stop pairs, KK gravitons, Z' , Higgs...

“Direct” spin correlation measurements

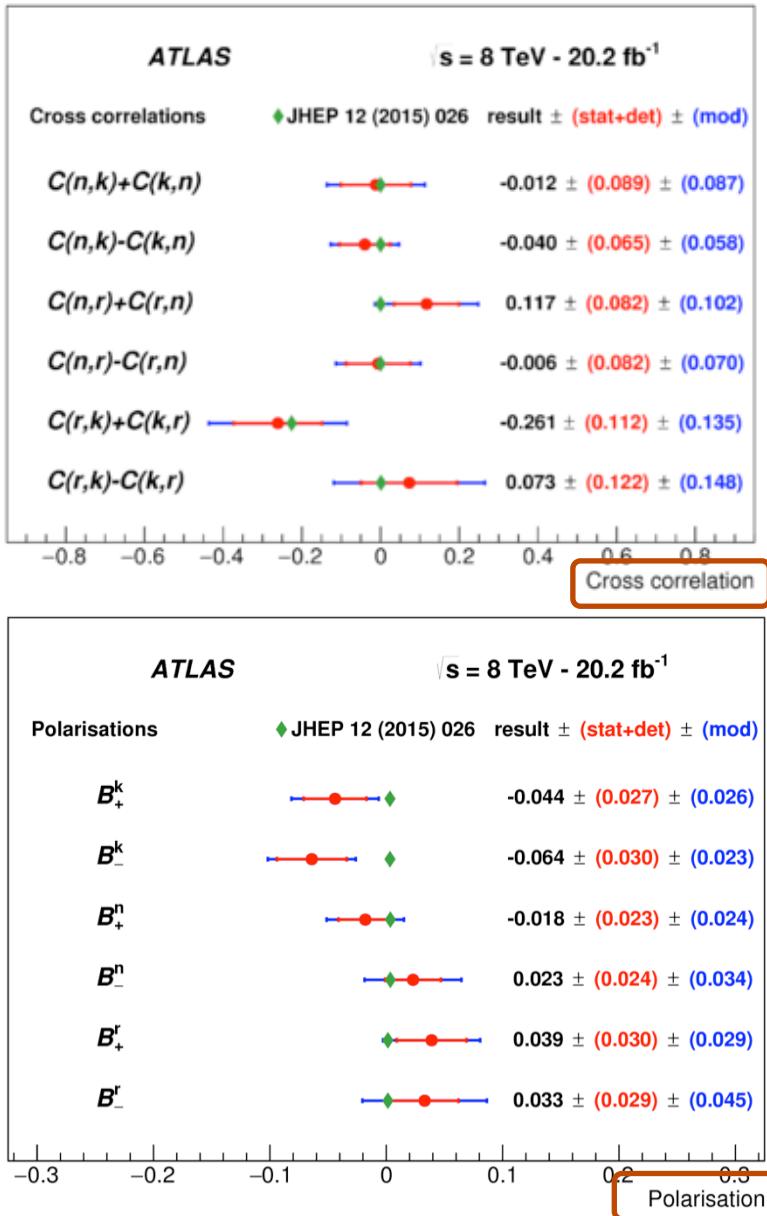
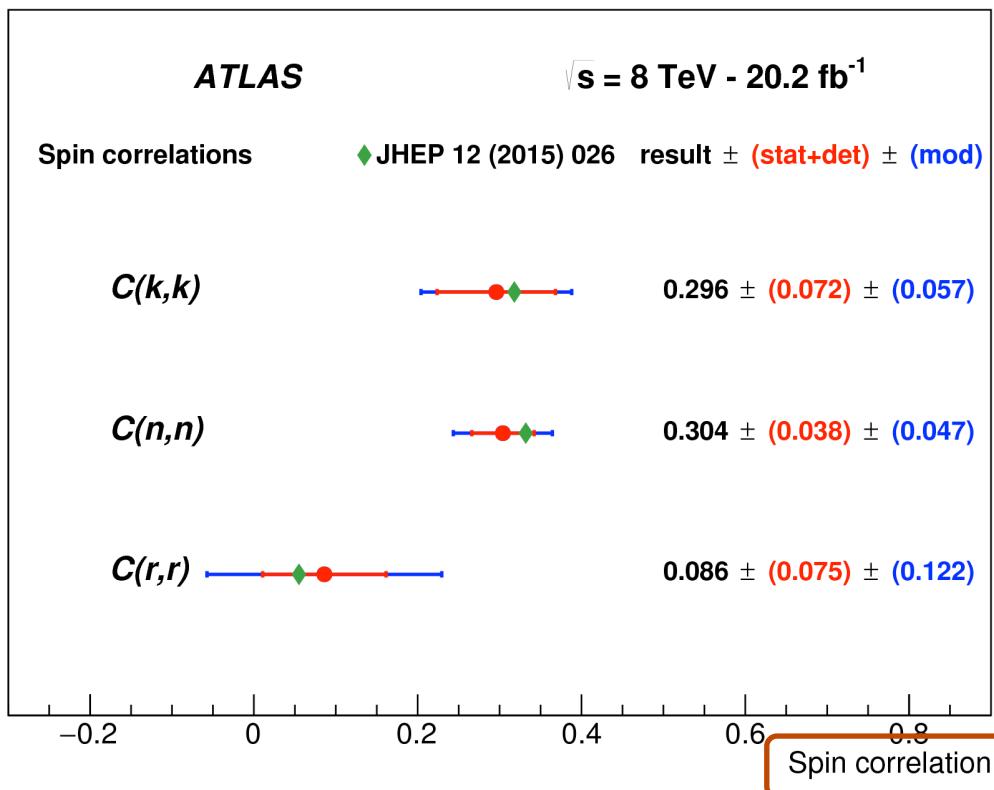
- Extract parameters from the angular distribution of t and \bar{t} decay products in the parent top quark's rest frame (various axes)



$$\frac{1}{\sigma} \frac{d^2\sigma}{d \cos \theta_+^a d \cos \theta_-^b} = \frac{1}{4} (1 + B_+^a \cos \theta_+^a + B_-^b \cos \theta_-^b - C(a, b) \cos \theta_+^a \cos \theta_-^b)$$

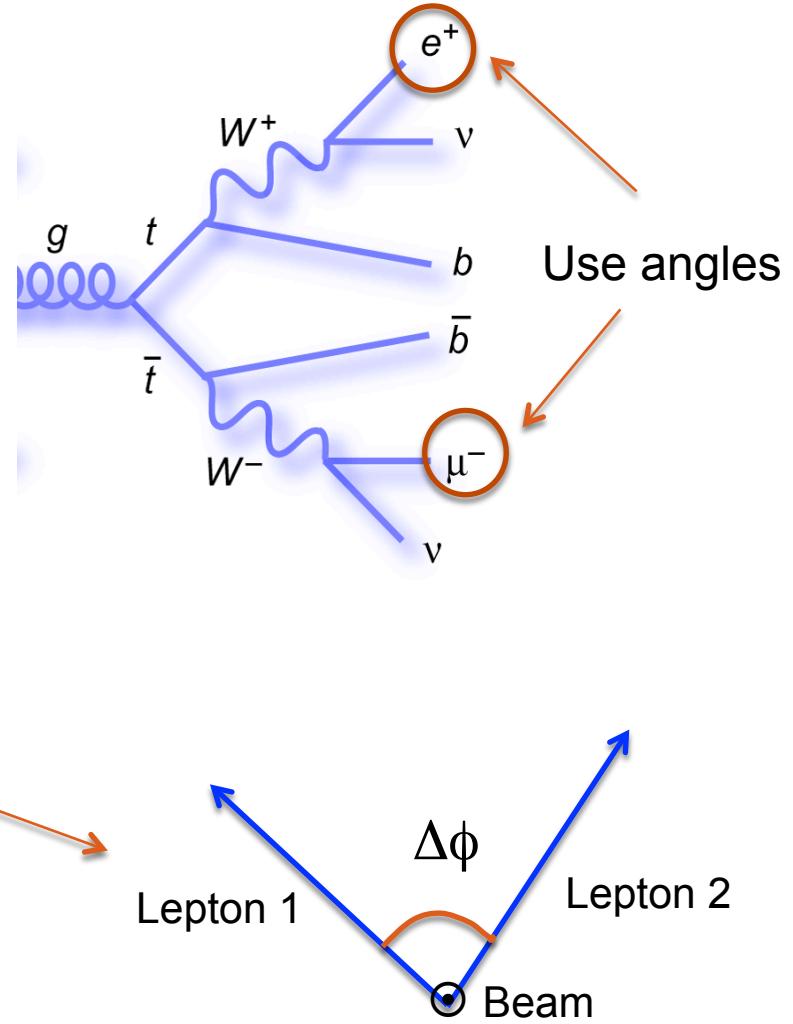
- Requires full $t\bar{t}$ reconstruction in dilepton events → significant systematic uncertainties and resolution effects

- 15 observables corrected to particle and parton level
- Compared to NLO predictions
- No significant deviation from the SM

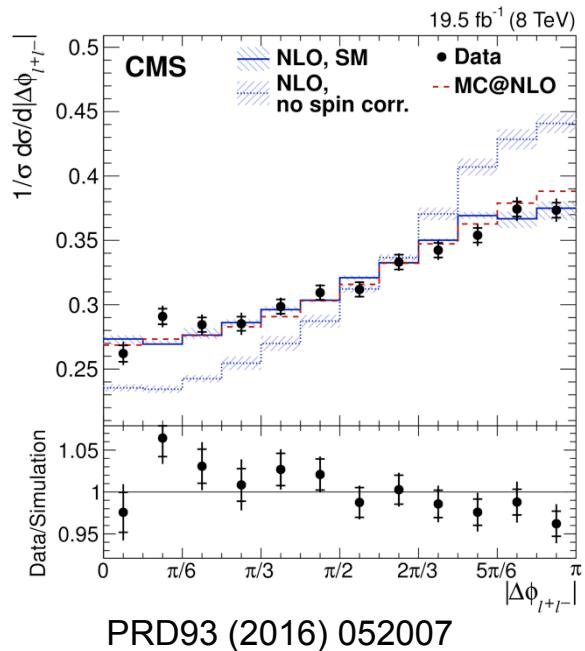
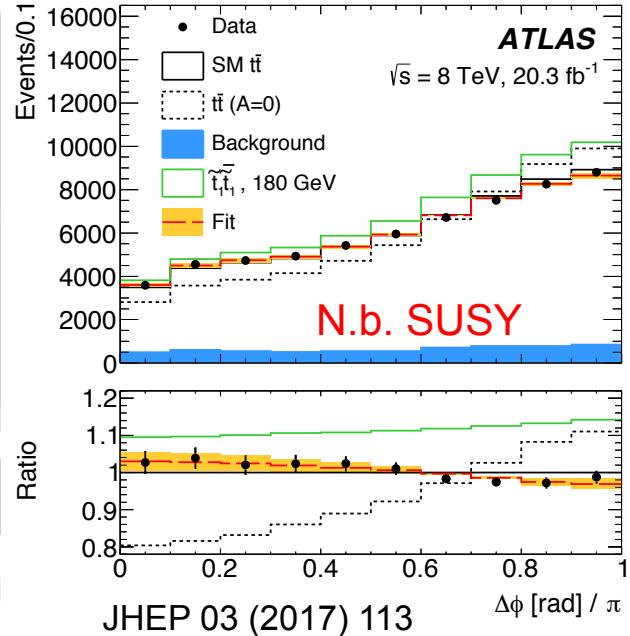
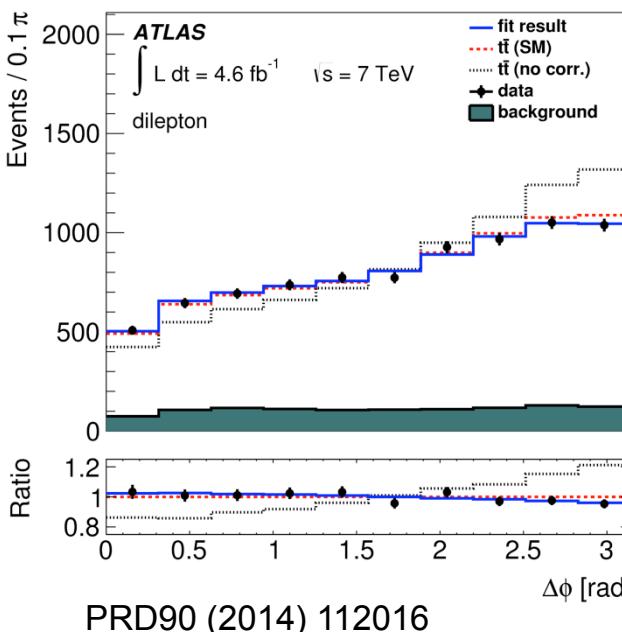


Spin correlation: $\Delta\phi$ observable

- Highest spin analysing power:
leptons from top decay
- Use **dileptonic** $t\bar{t}$ events
- Very clean samples
- Spin correlation can be inferred
from the $\Delta\phi$ distribution:
 - $\Delta\phi$: difference in azimuthal angle
between the leptons, lab frame
- No event reconstruction required
- Excellent lepton resolution



Previous results at 7 TeV and 8 TeV

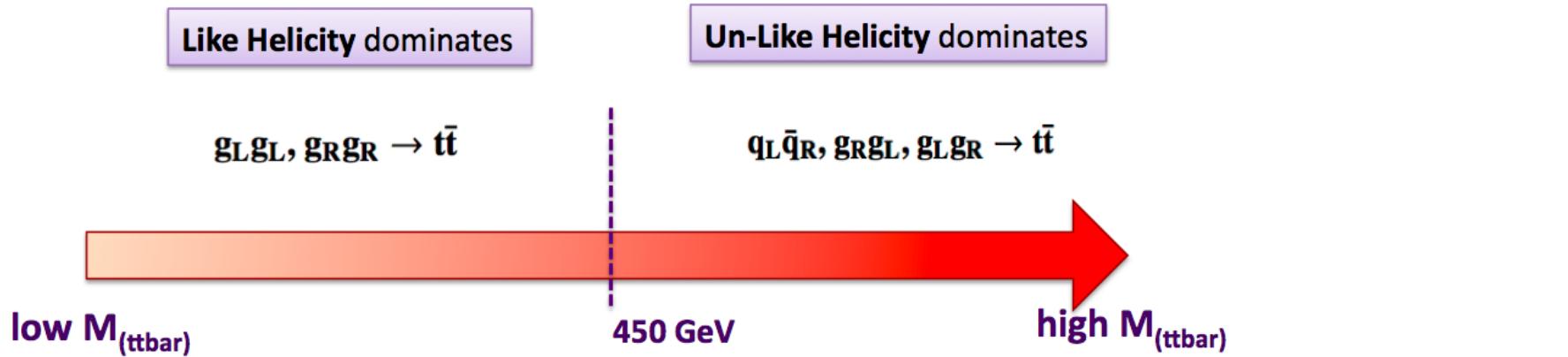


- Several measurements by ATLAS and CMS at various \sqrt{s}
- First exclusion of zero spin correlation at $>5\sigma$ by ATLAS at 7 TeV
- Observed $\Delta\phi$ to be “steeper” in predictions than the data
- Covered by systematic uncertainties at 7 and 8 TeV

PRL108
(2012)
212001

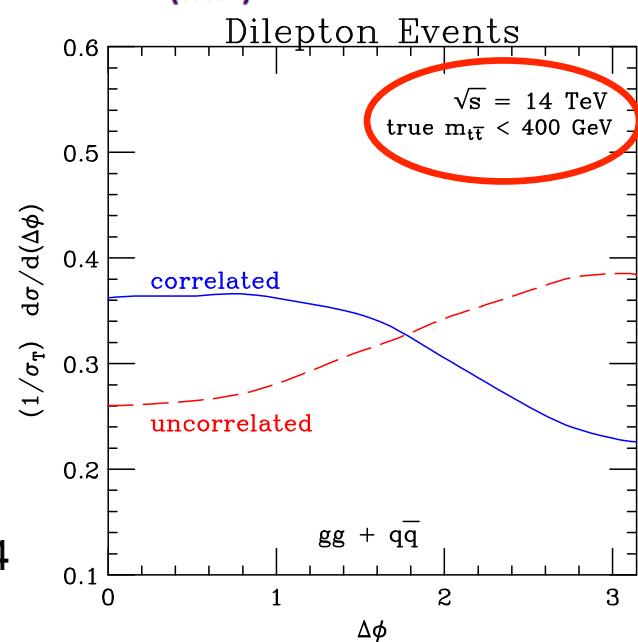
Double-differential measurement

- SM spin correlation varies as a function of $m_{t\bar{t}}$
- Dominated by gluon-gluon fusion at LHC

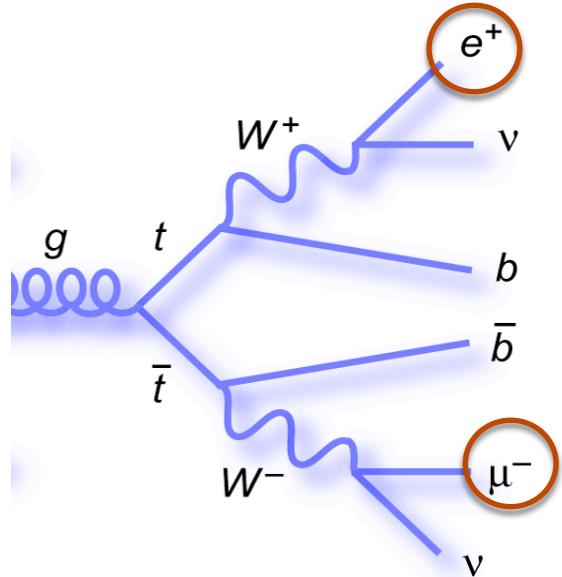


- Double-differential cross-section ($\Delta\phi, m_{t\bar{t}}$)
 - Expect higher sensitivity to SM spin correlations at low $m_{t\bar{t}}$
 - New physics at higher $m_{t\bar{t}}$?
 - Requires $t\bar{t}$ event reconstruction

Mahlon and Parke
Phys. Rev. D 81, 074024

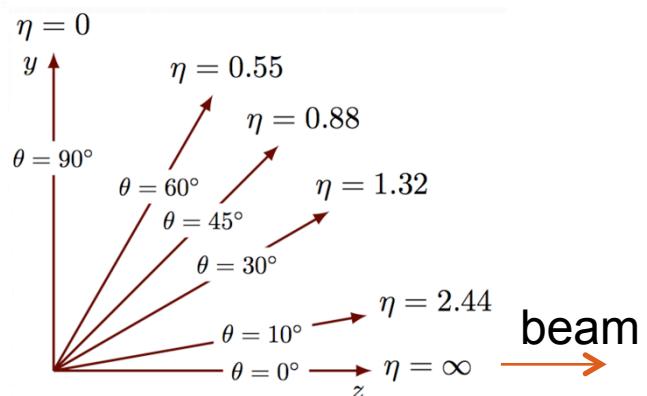


- 2015 + 2016 data (36 fb^{-1}) with a standard dilepton $e\mu$ selection:
 - Exactly 2 opposite-sign leptons (27, 25 GeV)
 - At least one b-jet; ≥ 2 jets $pT > 25 \text{ GeV}$
 - No cuts on E_T^{miss} or on $m(\text{ll})$
- Fiducial particle level:
 - Stable particles in generator record
 - “Dressed” leptons with radiated photons
 - Anti- k_T $R=0.4$ jets with “ghost-matching” of intermediate B-hadrons for b-tagging
 - Same kinematic cuts as above
- Parton level, full phase space:
 - Tops defined after radiation but before decay
 - Leptons are taken before radiation (i.e. Born level)
 - $e\mu$ channel only (no tau decays)

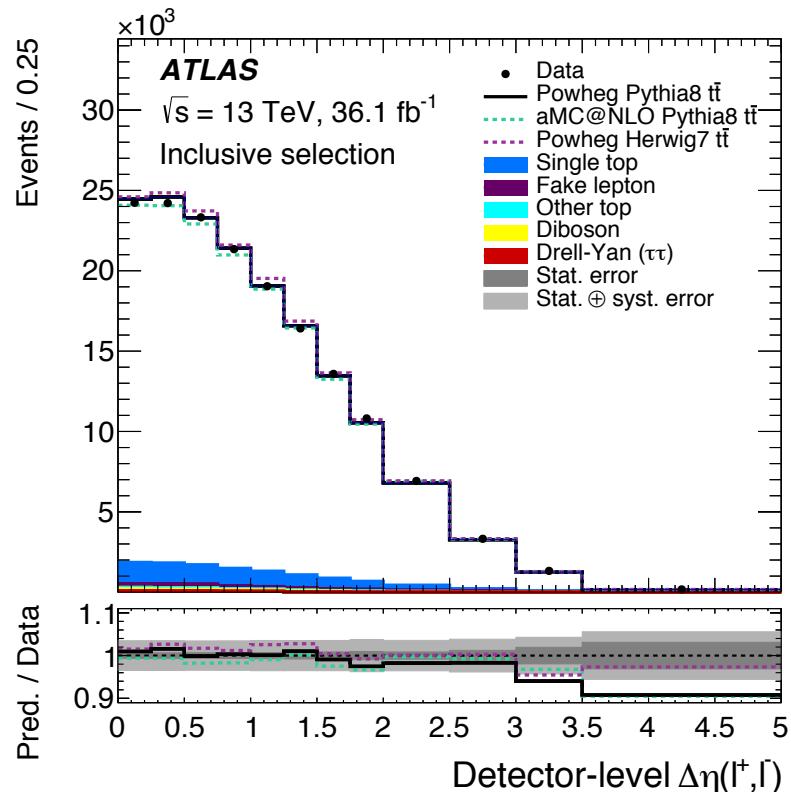
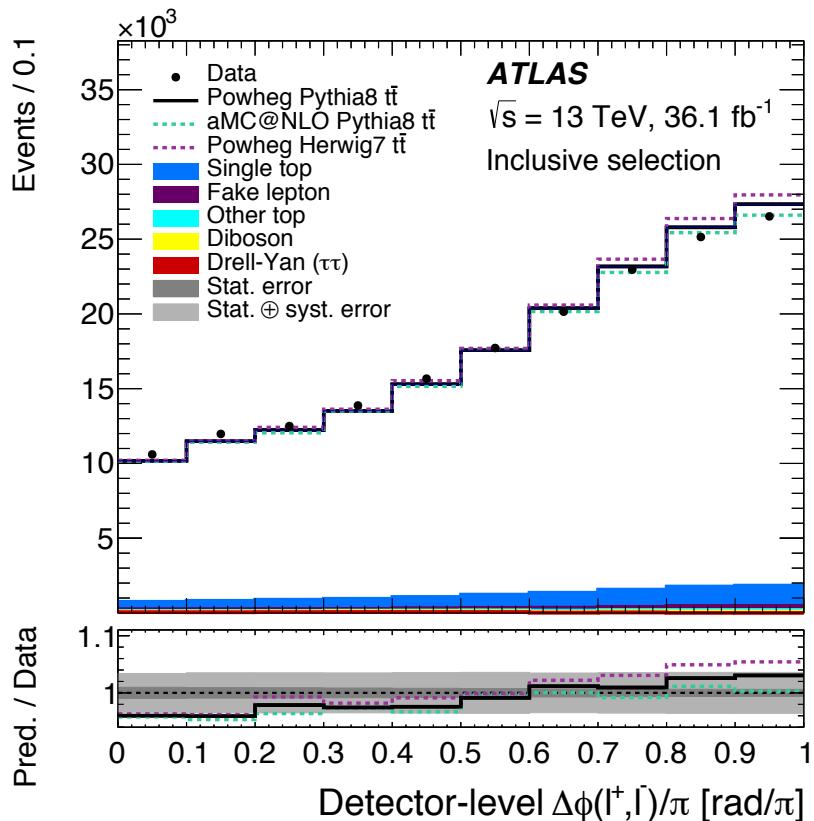


$\Delta\phi$: in lab. frame

$|\Delta\eta|$: abs. difference in η of leptons



Measured distributions: $\Delta\phi$, $\Delta\eta$



- Inclusive selection for simple angular distributions (note: hint of disagreement)
- For $\Delta\phi$ as a function of $m_{t\bar{t}}$:
 - Require $t\bar{t}$ event reconstruction
 - Use Neutrino Weighting

Event reconstruction (for $m_{t\bar{t}}$ dependence) and unfolding

- Reconstruct dilepton $t\bar{t}$ system:
 - Constrain system using values of top mass and W mass
 - Test many different assumptions for η for the two neutrinos
 - Select highest weight based on observed E_T^{miss} (“Neutrino Weighting”)
- Iterative Bayesian Unfolding to correct data to fiducial particle or parton level
- Nominal $t\bar{t}$ Monte Carlo:
 - Powheg-Box next-to-leading order (NLO) matrix-element
 - Pythia8 for parton shower and fragmentation
 - NNPDF3.0 NLO PDF

Kinematic constraints

$$(\ell_{1,2} + \nu_{1,2})^2 = M_W^2 = 80.2^2$$

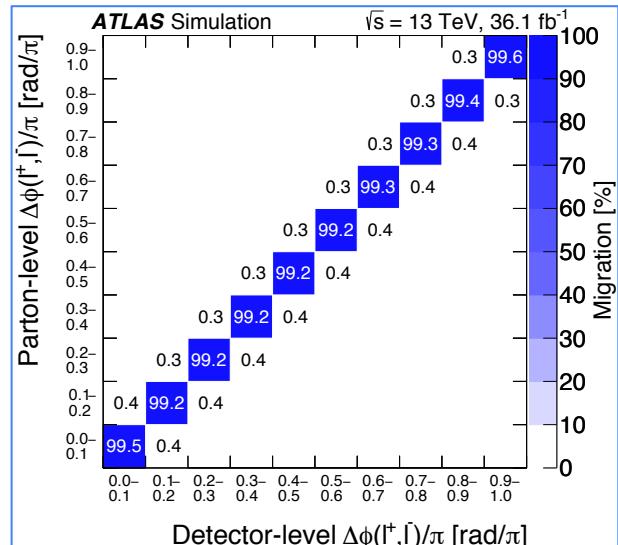
$$(\ell_{1,2} + \nu_{1,2} + b_{1,2})^2 = M_t^2 = 172.5^2$$

Require 2 b-tagged jets

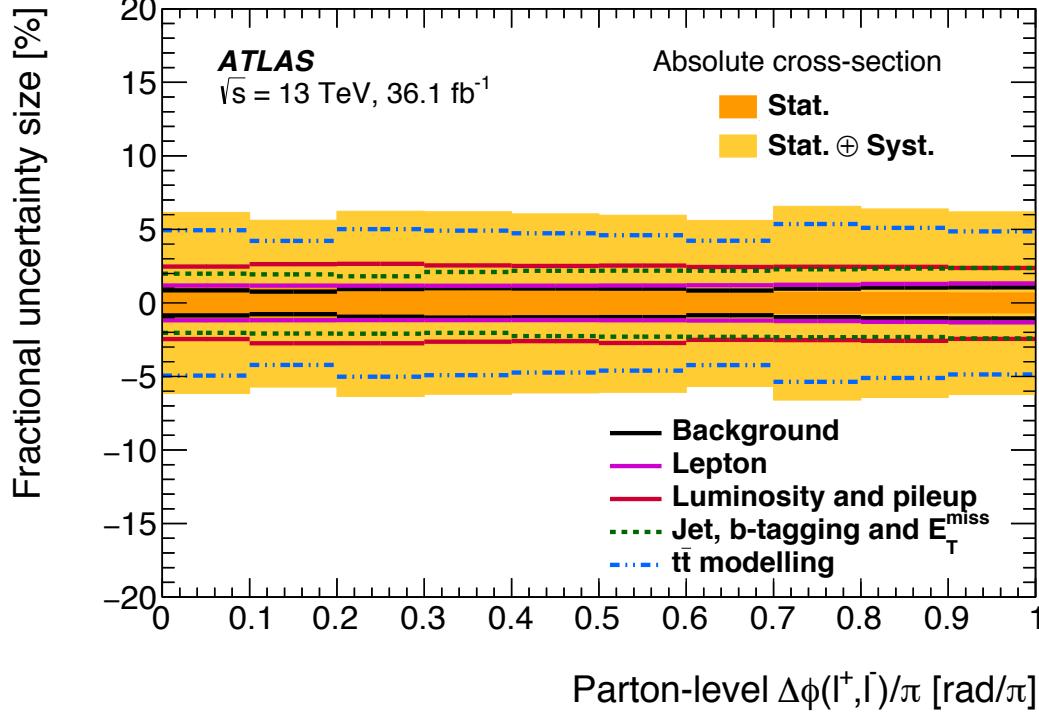
Weight function

$$w_i = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right)$$

E_T^{miss} resolution factor

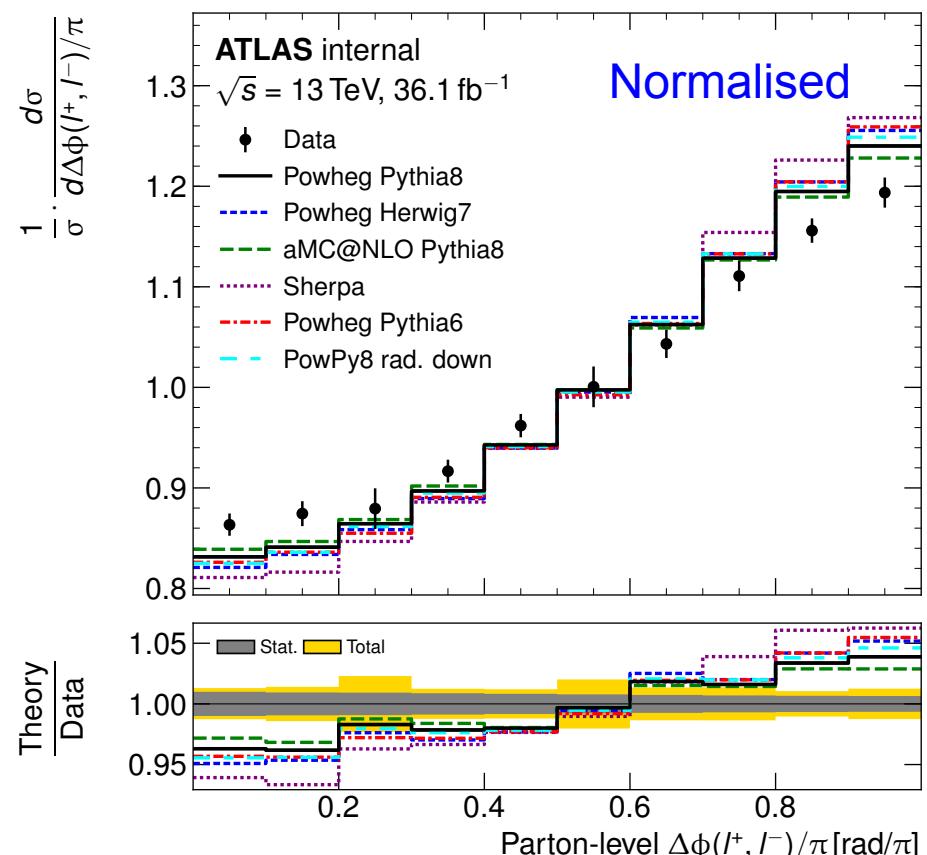
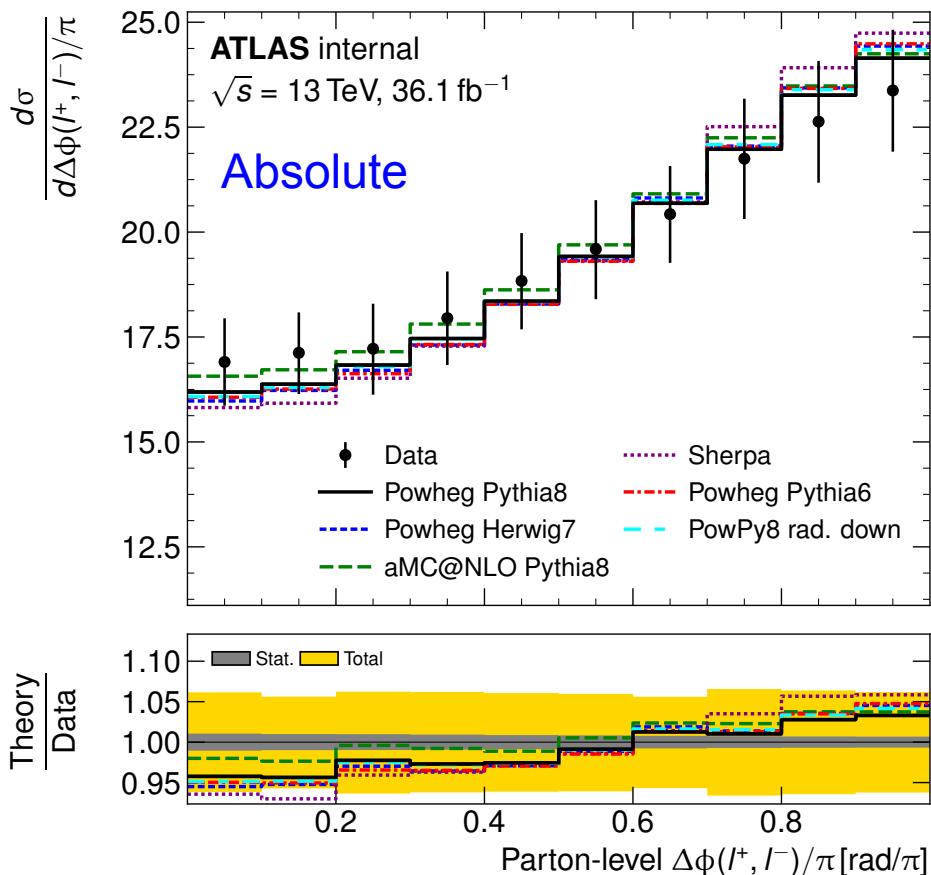


Systematic uncertainties



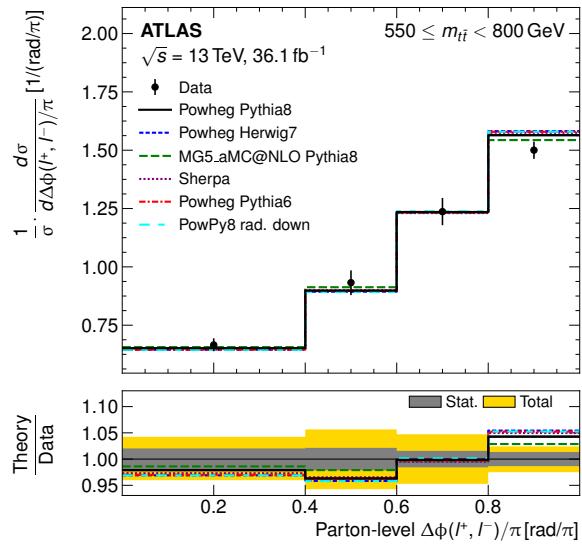
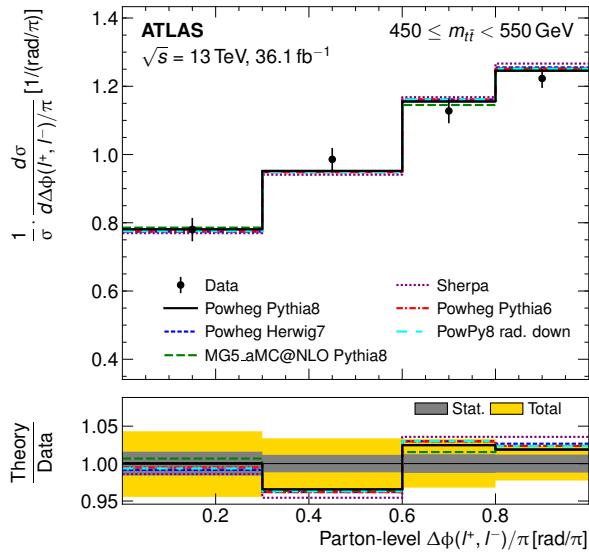
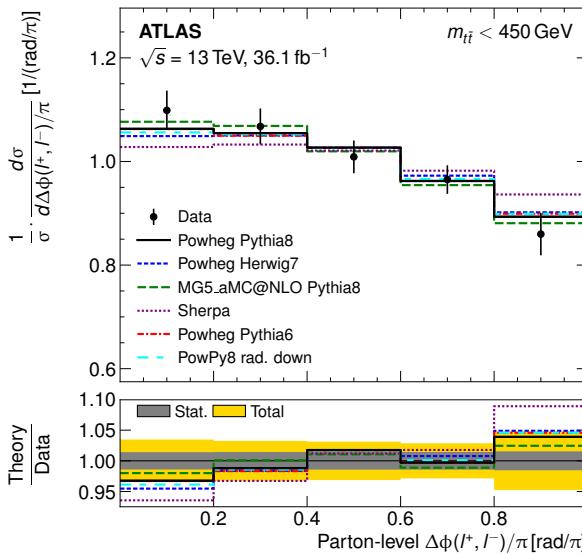
- **General method:** *unfold shifted sample with nominal response matrix, compare to nominal sample*
- Detector modelling
- Background and luminosity
- Signal modelling (dominant):
 - Parton shower: Pythia8 or Herwig7
 - NLO model: Powheg or MG5_aMC@NLO
 - Initial and final state radiation
 - PDF variation

Results: $\Delta\phi$ parton level

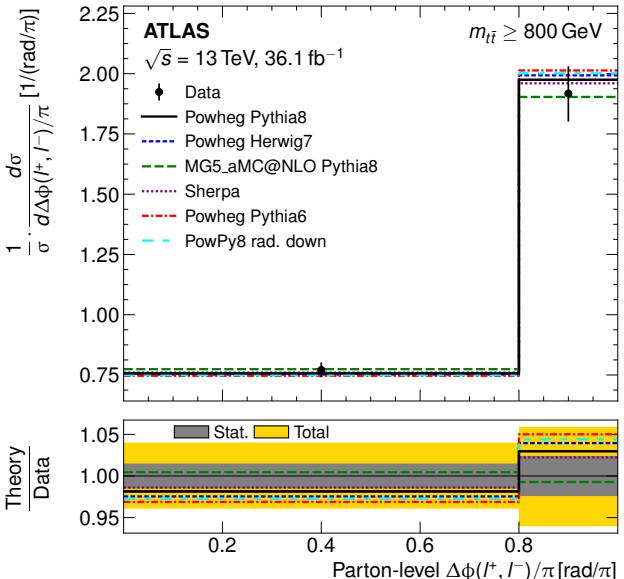


- Clear slope in the data relative to the MC predictions: none agree well
- Systematics are dominant in most bins

Unfolded distributions: double differential

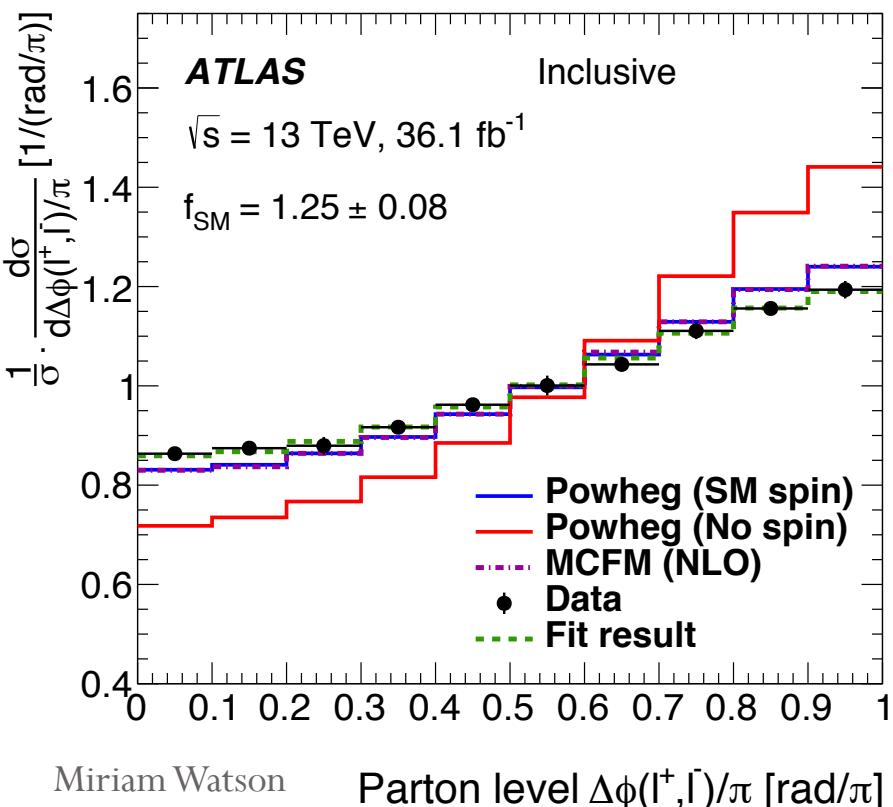


- The behaviour of the $\Delta\phi$ observable from low $m_{t\bar{t}}$ to high $m_{t\bar{t}}$ is clearly seen
- Uncertainties are larger here due to the $t\bar{t}$ reconstruction (jets and E_T^{miss} become important)



Results: extracting spin correlation

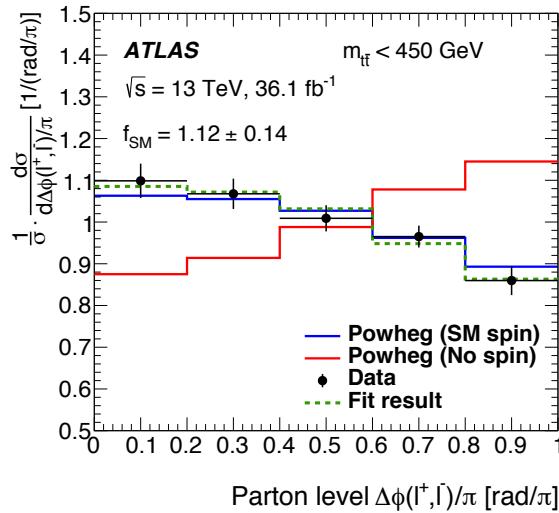
- Fraction of SM-like spin correlation (f_{SM}) is extracted using a binned maximum likelihood fit with two templates
- With-spin template: nominal MC (Powheg+Pythia8) with SM spin $\rightarrow f_{\text{SM}} = 1$
- No-spin template: same MC settings, but top quarks decayed using MadSpin with top spin correlations disabled $\rightarrow f_{\text{SM}} = 0$



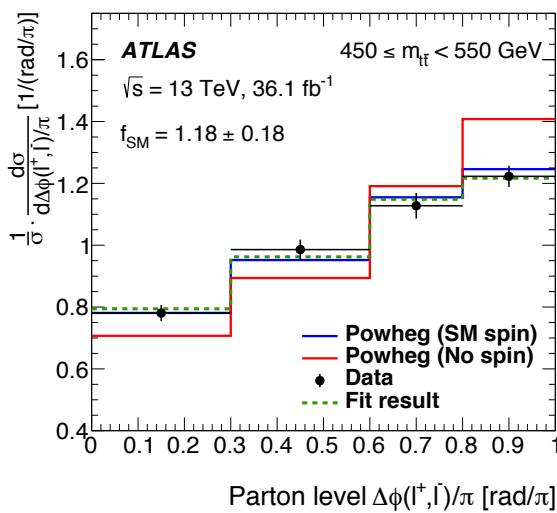
$$x_i = f_{\text{SM}} \cdot x_{\text{spin}, i} + (1 - f_{\text{SM}}) \cdot x_{\text{nospin}, i}$$

- Shallower slope in data is visible

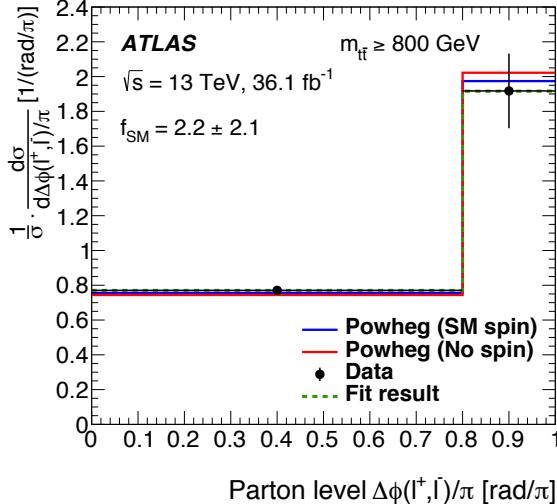
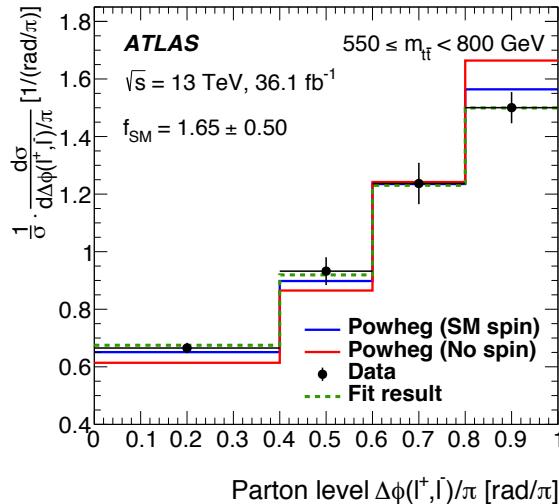
Results: extracting spin correlation vs. $m_{t\bar{t}}$



(a)



(b)



- Separation between spin and no-spin templates reduces with $m_{t\bar{t}}$

- Significant shape difference at low $m_{t\bar{t}}$

Results: f_{SM} values

- The significance of the f_{SM} , relative to the SM template, is calculated using a $\text{CL}_{\text{s+b}}$ method

c.f. Powheg + Pythia8 with/without scale and PDF uncertainties on templates

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

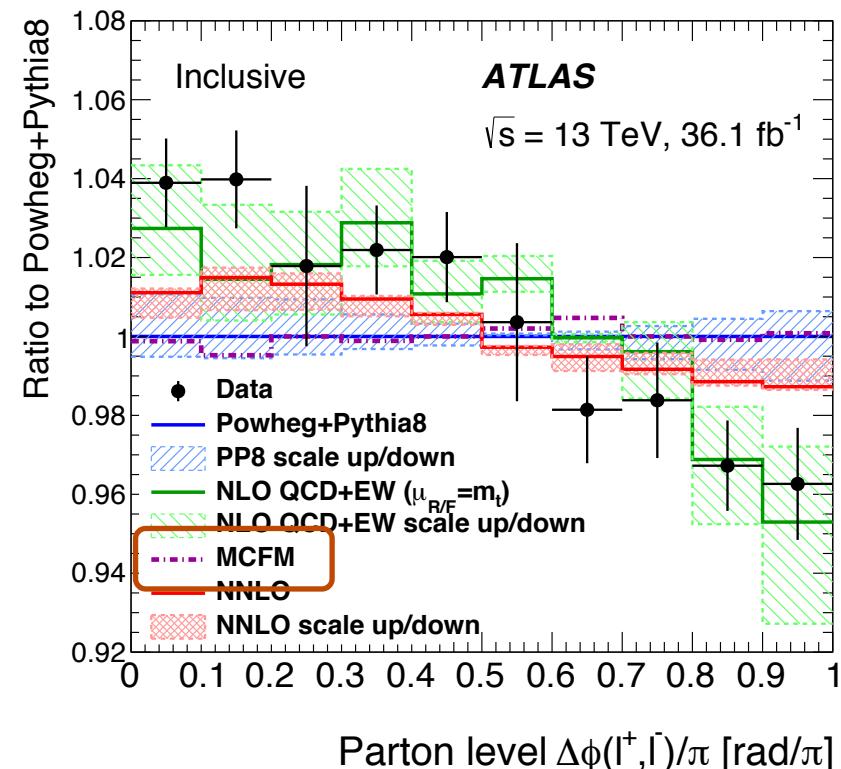
- Slight (but insignificant) increase in f_{SM} as a function of $m_{t\bar{t}}$
- The inclusive f_{SM} deviates significantly from the SM prediction in NLO MC

Further checks

- NLO generators used here (e.g. Powheg + Pythia8):
 - NLO in production
 - Not full NLO in top quark decays
 - Use Narrow Width Approximation (NWA) to factorise production and decay: interference effects neglected between initial + final state

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- **NLO effects in the decays of the top quarks:** compare the $\Delta\phi$ distribution with MCFM (full NLO, including NLO decays) → very close to nominal template

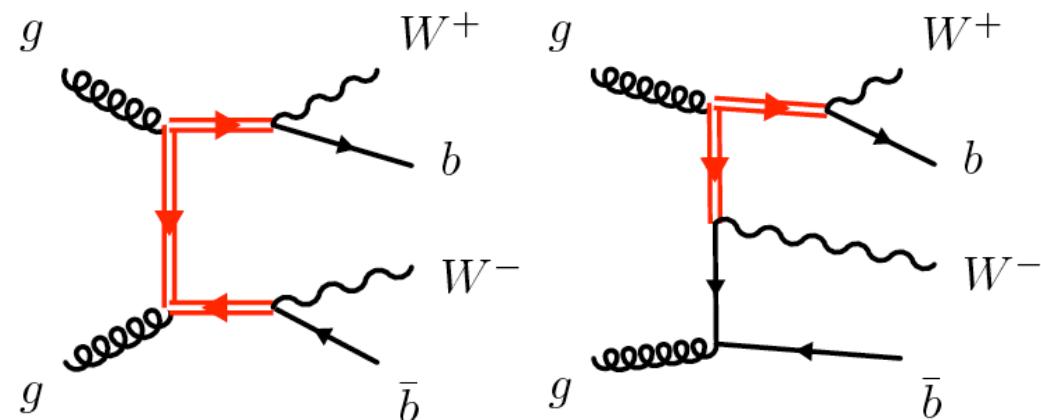


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- **NWA in the templates:**

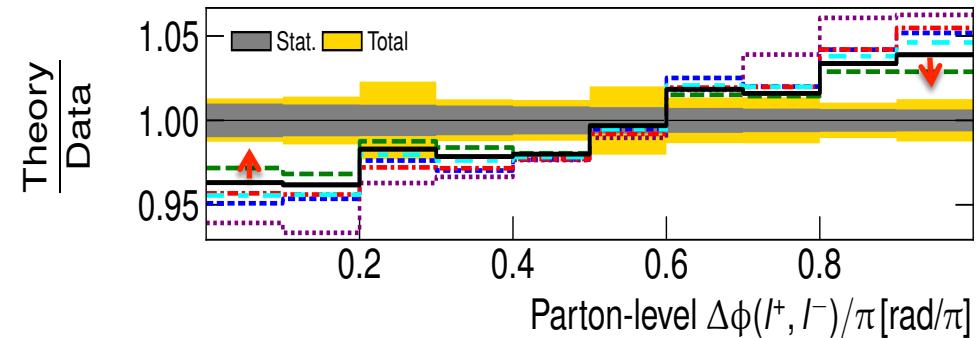
Powheg-Box-Res bb4I
without NWA, full NLO in production and decay
- Compare full $t\bar{t}+tW$ process with nominal $t\bar{t}$ and tW

→ no significant differences



Further checks

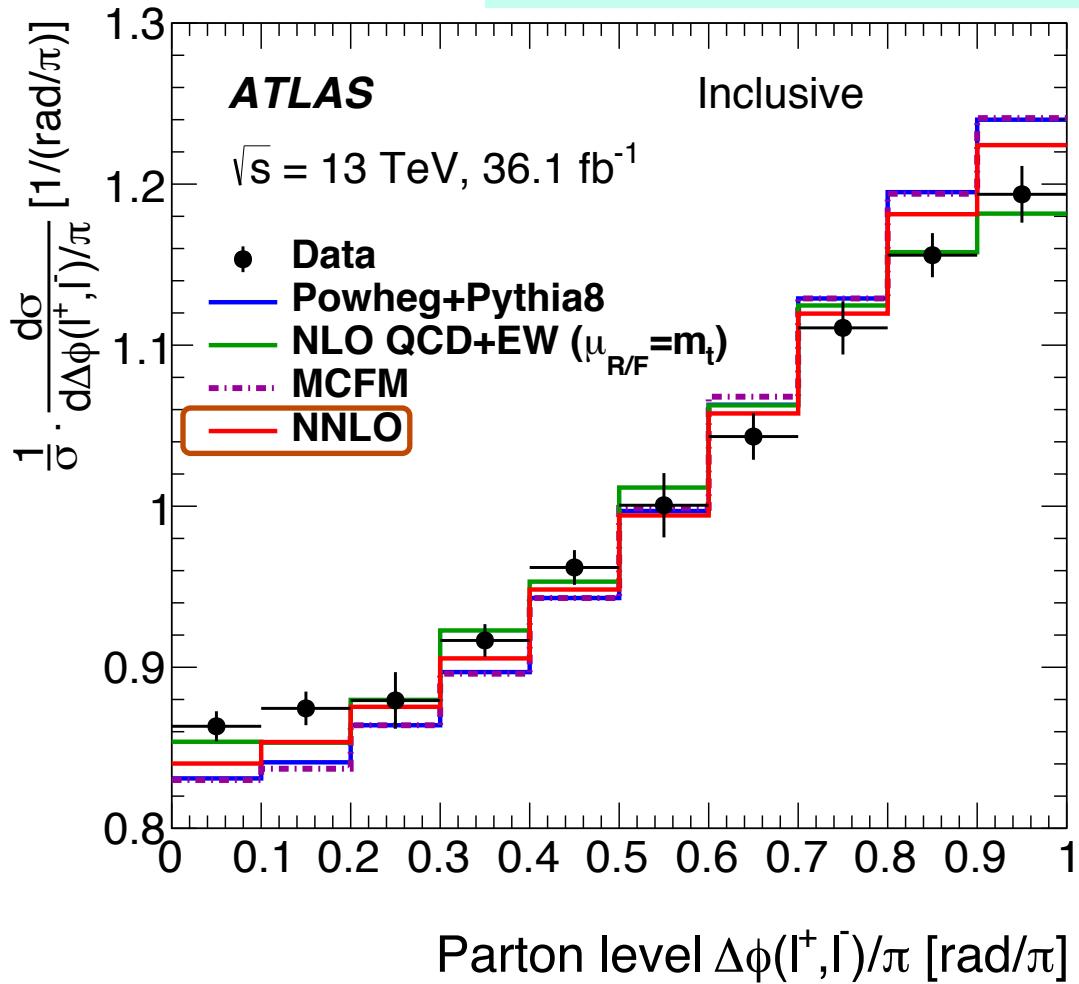
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- **Effect of NNLO in production:**
Reweight the **top p_T** to match
fixed-order NNLO predictions or
unfolded data from several
previous ATLAS measurements
- Deviations reduced slightly but
consistent within scale
uncertainties already considered



New theoretical predictions: NNLO

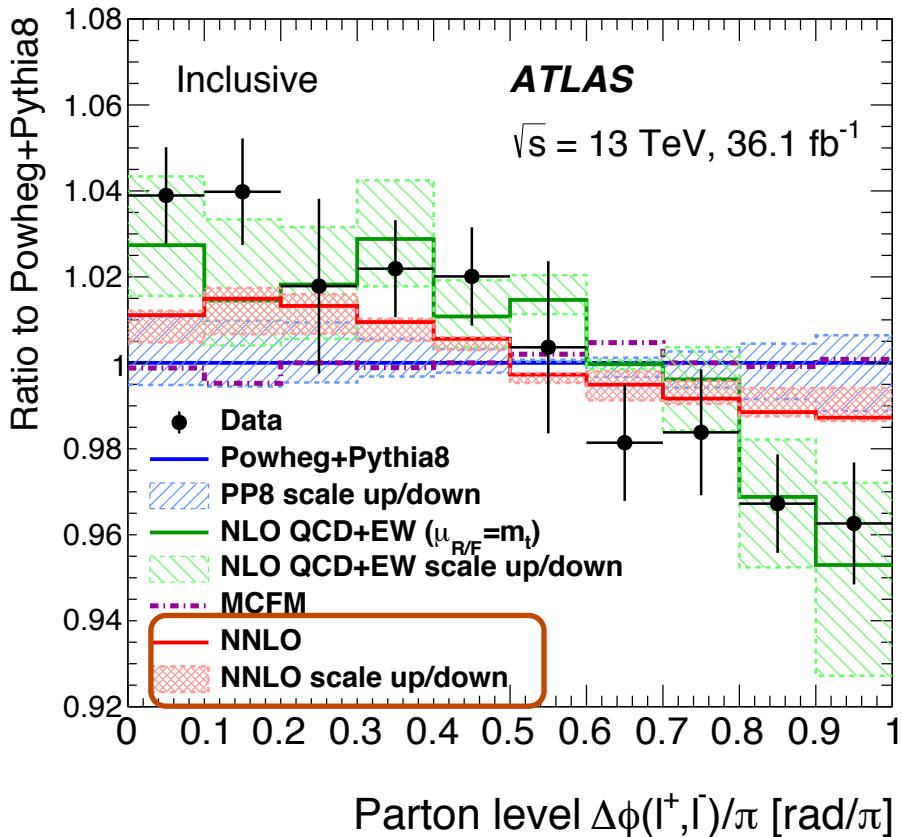
Behring, Czakon, Mitov,
Papanastasiou and Poncelet,
arXiv:1901.05407

- New fixed-order NNLO predictions for $\Delta\phi$ and $\Delta\eta$ directly, with renormalisation and factorisation scale uncertainties
- Closer to parton-level unfolded data, but does not cover observed discrepancy



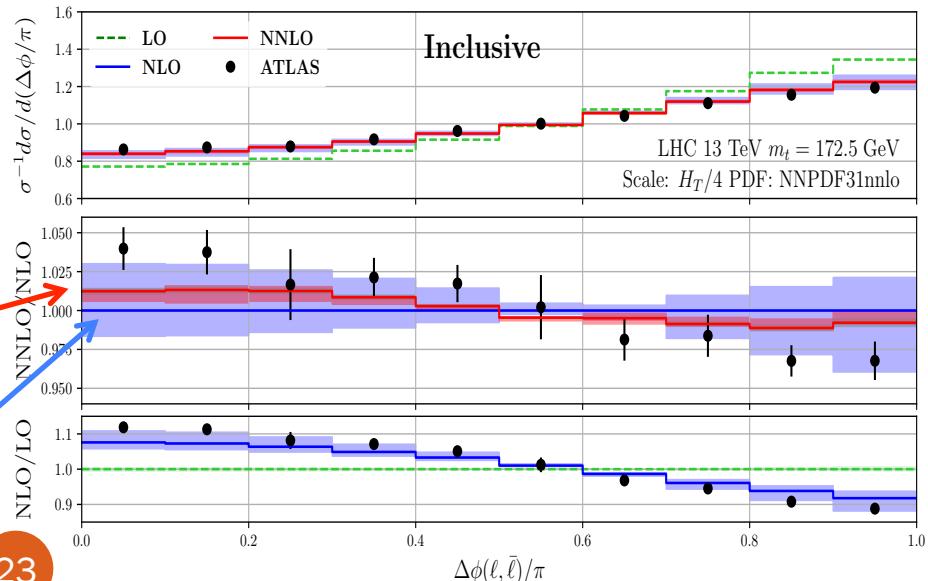
New theoretical predictions: NNLO inclusive

Behring, Czakon, Mitov,
Papanastasiou and Poncelet,
arXiv:1901.05407



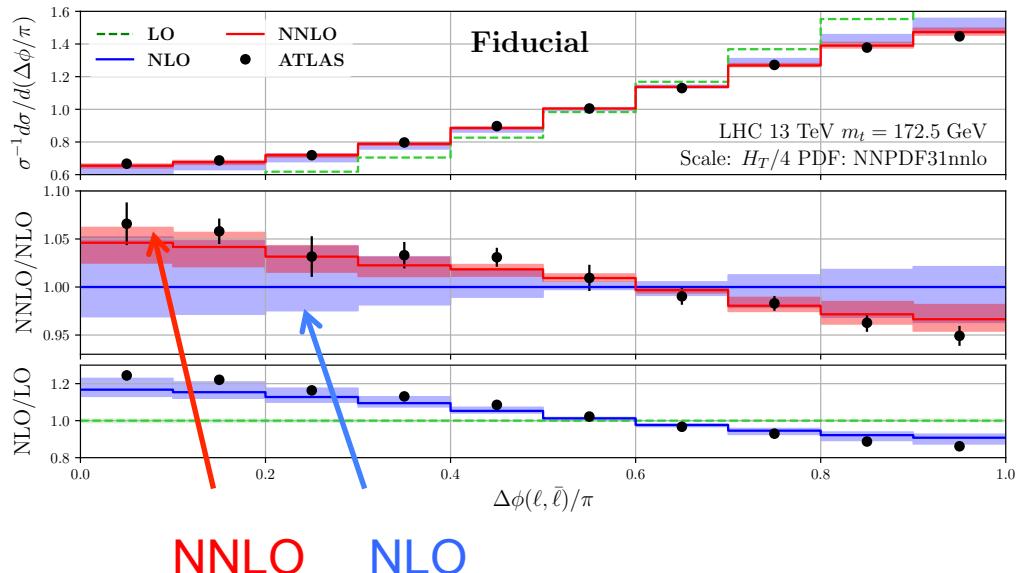
- Closer to parton-level unfolded data, but does not cover observed discrepancy
- Similar to our results with reweighting to top p_T for NNLO^(*) or data

(*) Also to **NNLO QCD + NLO EW**
top p_T in JHEP 10 (2017) 186



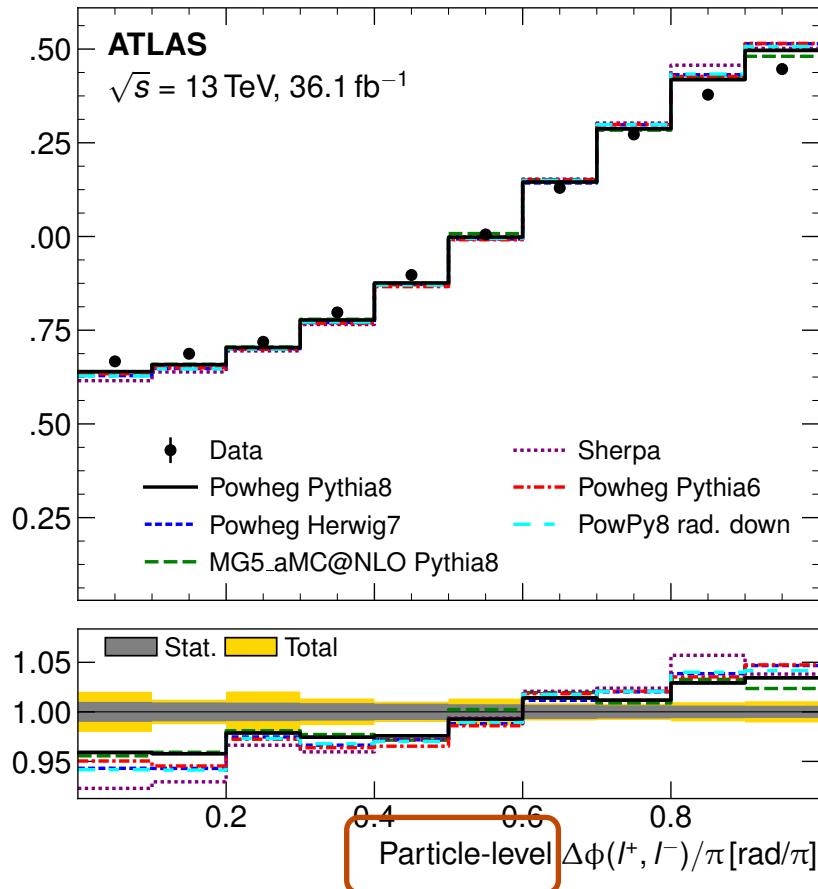
New theoretical predictions: NNLO fiducial

Behring, Czakon, Mitov,
Papanastasiou and Poncelet,
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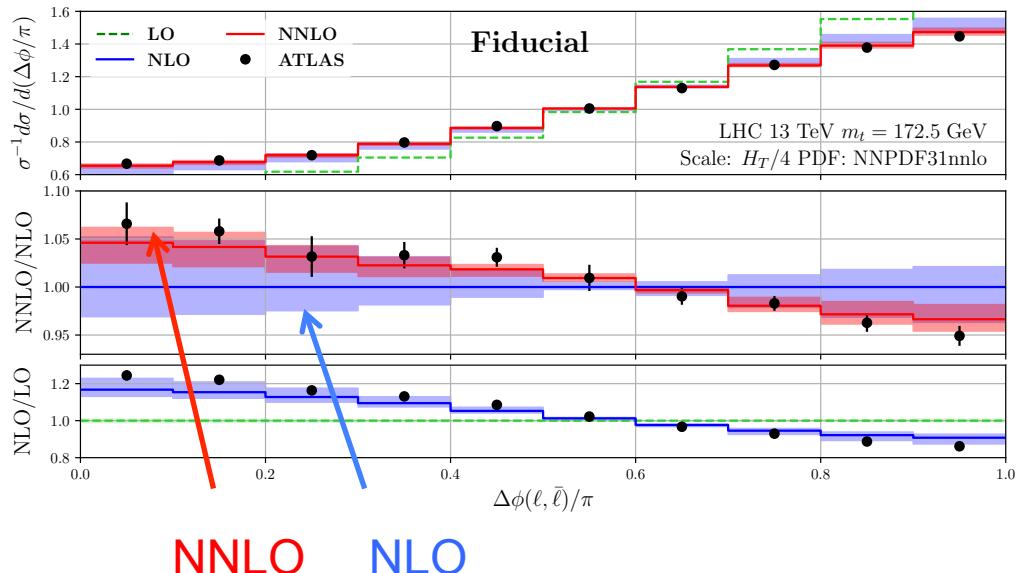
NNLO NLO

- The NNLO authors perform a **fiducial** fixed order calculation, similar to ATLAS particle level, by clustering the b-quarks with radiation into jets (but not with any parton shower, hadronisation, b-decays etc)
- Larger scale uncertainties, but better agreement with data



New theoretical predictions: NNLO fiducial

Behring, Czakon, Mitov,
Papanastasiou and Poncelet,
arXiv:1901.05407



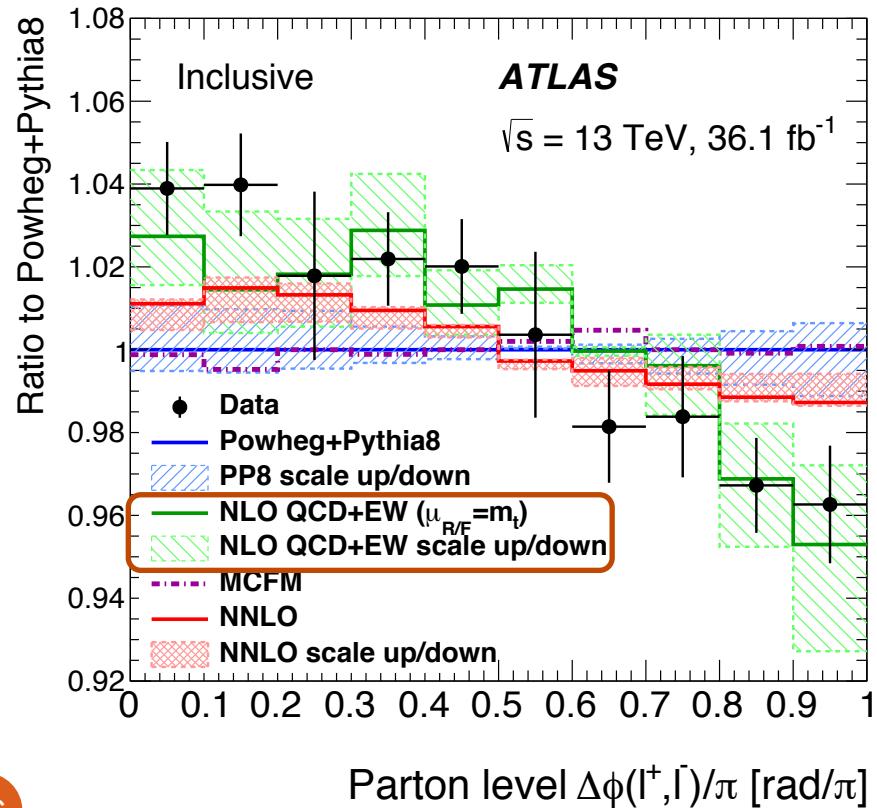
- **Authors' suggestion:** There could be a problem with the extrapolation of the ATLAS fiducial data to the full phase space with NLO MC
- **Comment:** Fiducial cuts are applied to the ‘b-jets’ ($p_T > 25$ GeV, $|n| < 2.5$). These are unlikely to be the same for ATLAS *particle* level jets and fixed-order *partons* → could sculpt the shape

More theoretical predictions: NLO QCD + weak corrections

- **NLO QCD+weak (NLOW):** previous calculation now produced for our binning at 13 TeV

- NLO QCD including weak interaction corrections
- Expanded as a ratio to fixed order (c.f. computation of cross-section numerator/denominator)
- Fixed scale choice: $\mu_{R/F} = m_{top}$
- PDF set CT10 (NLO)
- Better agreement with data, but large scale uncertainties
- Gives $f_{SM} = 1.03 \pm 0.13$ (scale)

Bernreuther, Heisler & Si, JHEP **12** (2015) 026
Bernreuther and Si, Nucl. Phys. B **837** (2010) 90,
Bernreuther and Si, Phys. Lett. B **725** (2013)
115, Erratum: Phys. Lett.B744 (2015) 413



$\Delta\phi$ and f_{SM} summary

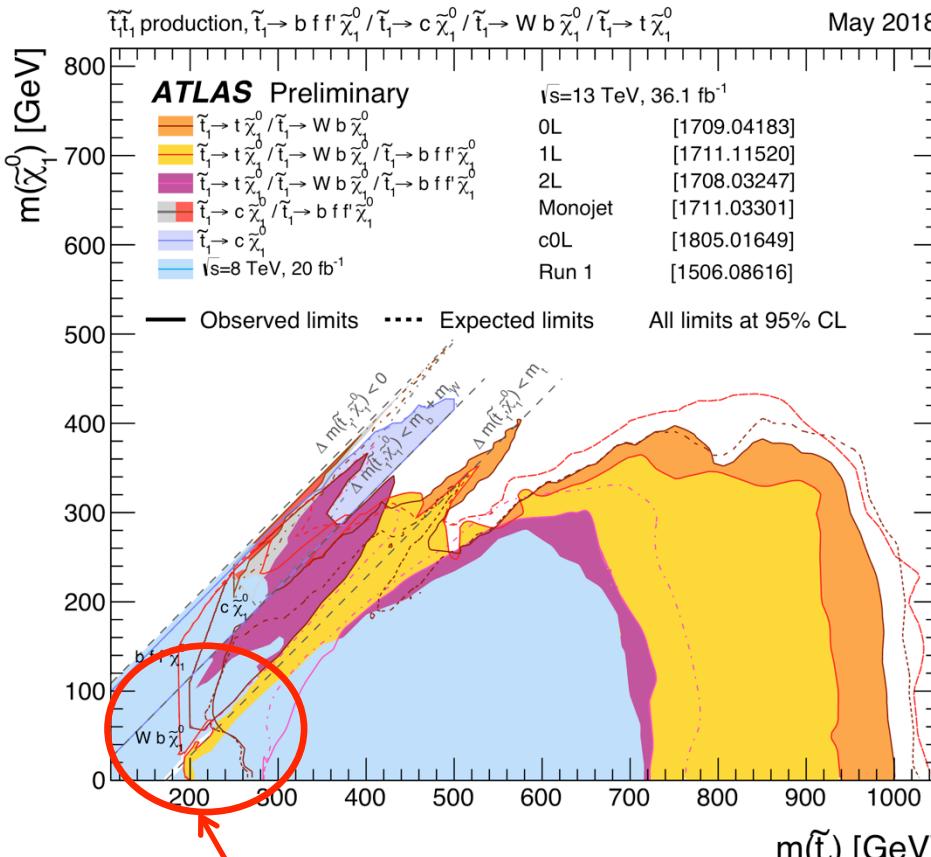
f_{SM} with alternative templates: remain >1

Table 7: Summary of the extracted spin correlation values in the inclusive $\Delta\phi$ observable using different hypothesis templates.

Generator	Inclusive	$m_{t\bar{t}} < 450 \text{ GeV}$	$450 \leq m_{t\bar{t}} < 550 \text{ GeV}$	$550 \leq m_{t\bar{t}} < 800 \text{ GeV}$	$m_{t\bar{t}} \geq 800 \text{ GeV}$
f_{SM} values					
Powheg + Pythia 8	1.25	1.12	1.18	1.65	2.2
Powheg + Pythia 8 (2.0 μ_F , 2.0 μ_R)	1.29	1.14	1.23	1.79	2.0
Powheg + Pythia 8 (0.5 μ_F , 0.5 μ_R)	1.18	1.09	1.11	1.40	1.3
Powheg + Pythia 8 (PDF variations)	1.26	1.13	1.25	1.76	2.2
Powheg + Pythia 8 RadLo tune	1.29	1.15	1.23	1.79	2.0
Powheg + Herwig 7	1.32	1.17	1.25	1.79	2.0
MADGRAPH5_aMC@NLO + Pythia 8	1.20	1.06	1.18	1.40	0.7
NLO (QCD + EW expanded) [35, 81, 82]	1.03	-	-	-	-
NNLO QCD [80]	1.16	-	-	-	-

- This is not a “simple” observable: a lot of effects can affect the $\Delta\phi$ shape:
 - Choice of functional form of $\mu_{R/F}$ e.g. fixed or dynamic scale
 - Parton shower matching/merging
 - Effect of hard radiation (i.e. hdamp setting in generators like Powheg)
 - Weak/EW corrections and how they are included
 - Choice of PDF
 - Higher-order NNLO QCD corrections and extrapolation to full phase-space
 - Interplay between kinematic effects and higher order corrections
 - Could also be new physics...

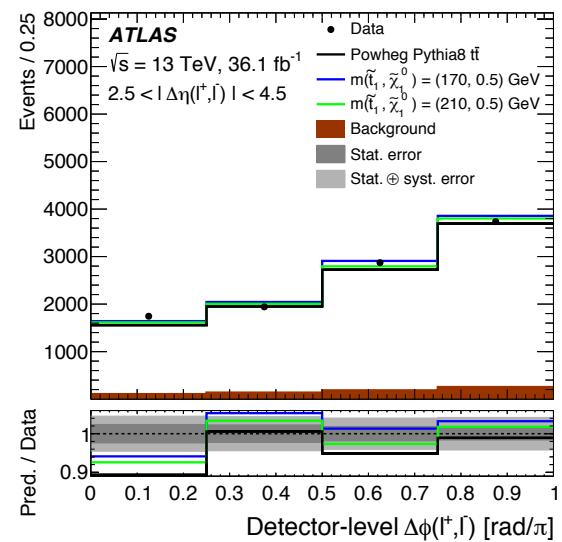
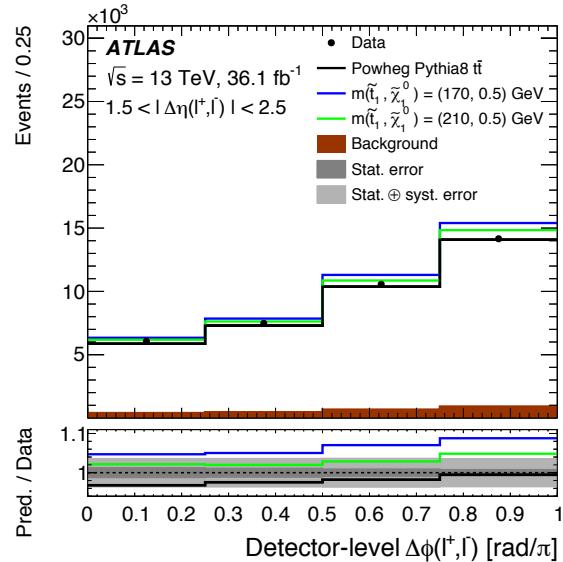
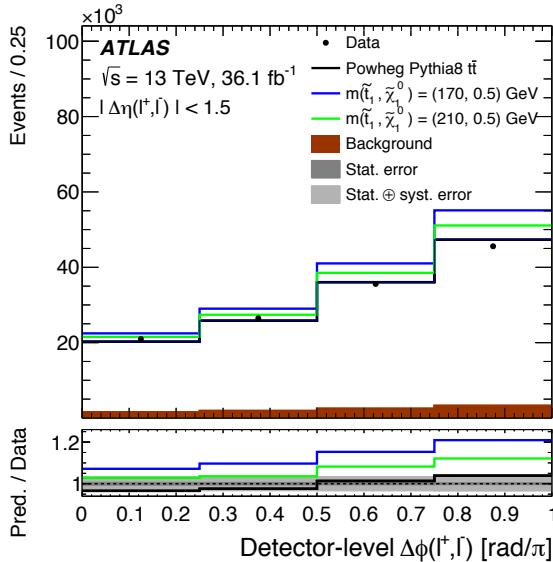
Supersymmetric top squark pair production



Small region with $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \approx m_t$
difficult to access
in direct searches

Exclusion contours as a function of
 $m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1}$

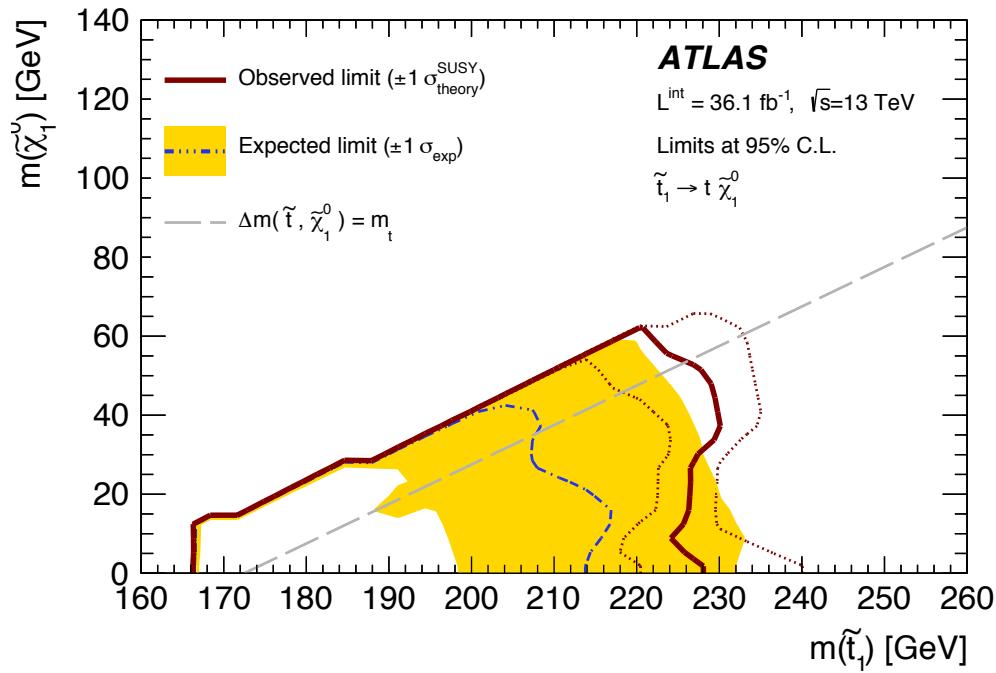
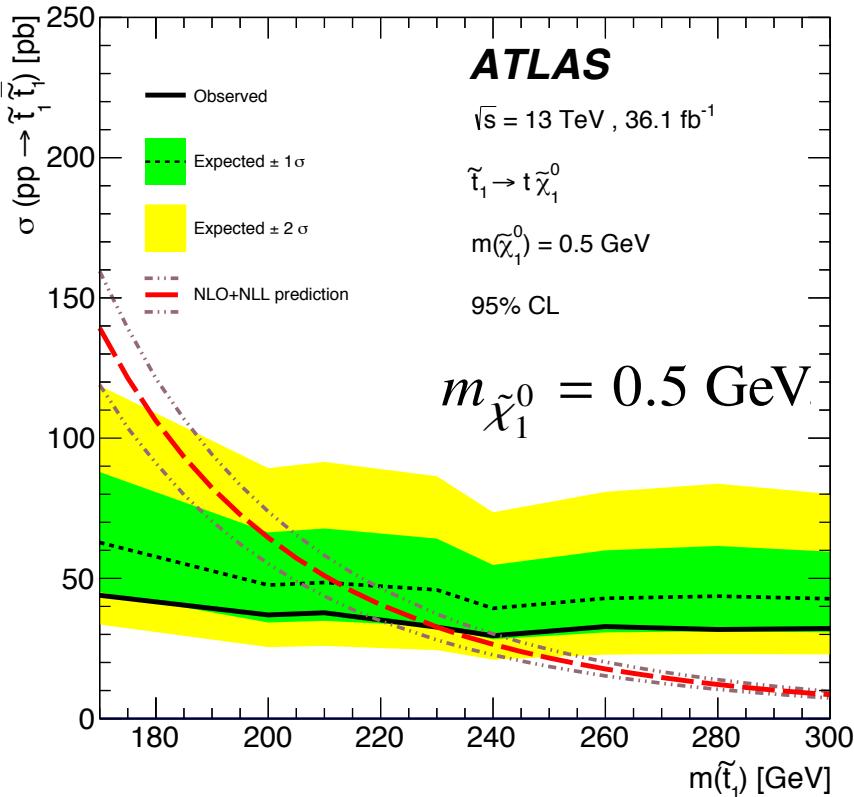
Supersymmetric top squark pair production



- Use double differential $Δϕ$ in 3 regions of $Δη$ to set limits on **SUSY stop production**
- More exclusion power comes from $Δη$ than $Δϕ$
- Additional theory uncertainty to allow for variation of $t\bar{t}$ background predictions

$(\tilde{t}_1 \tilde{\chi}_1^0)$ with
 $\tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$

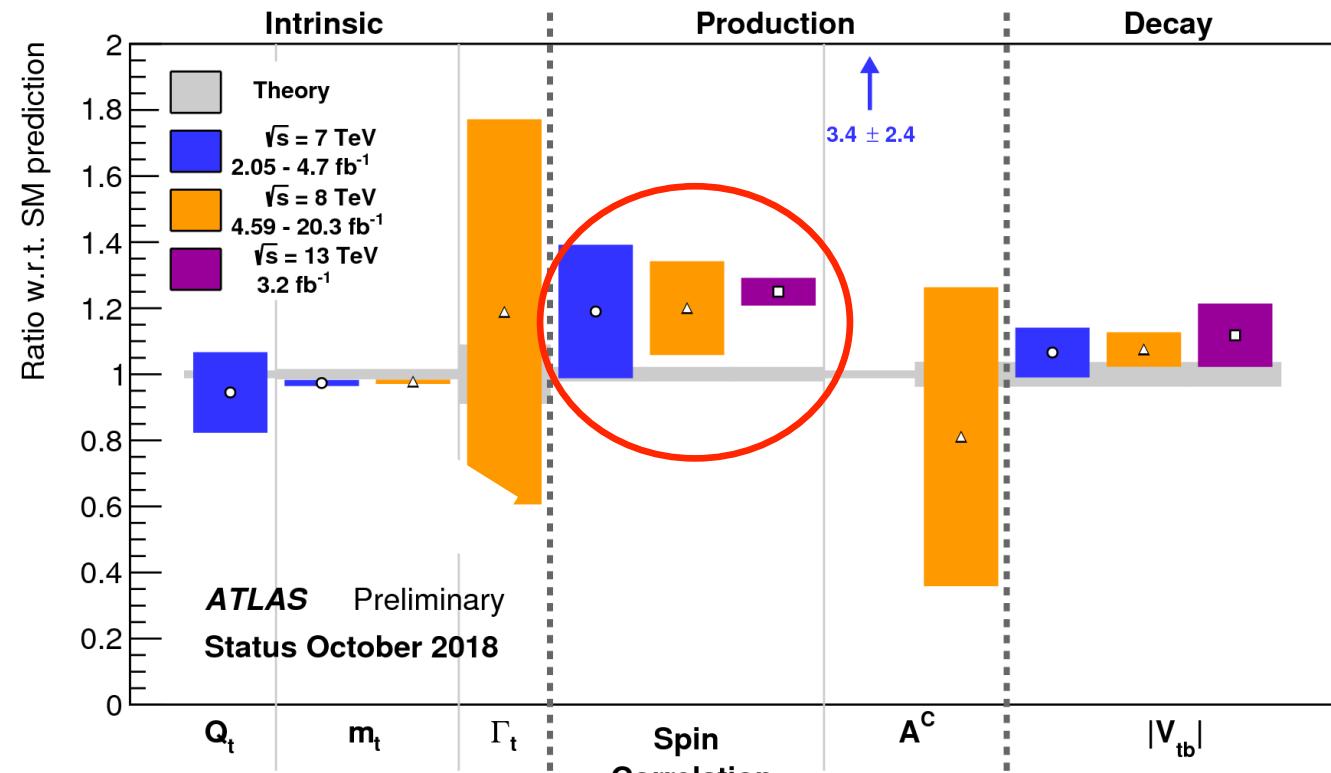
Expected and observed cross-section limits



- Observed (expected) limits on top squarks with masses between 170 (170) GeV and 230 (217) GeV
- Closes off last hiding place for “stealth stops” with $\Delta m(\tilde{t}, \tilde{\chi}_1^0) \approx m_t$

Summary

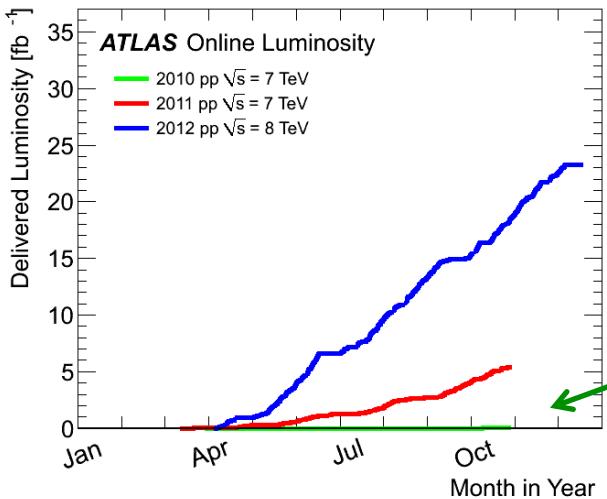
- Still more to do to understand $t\bar{t}$ spin correlations and QCD!
- Interplay between kinematics, higher order corrections, PDFs and experimental techniques is complicated
- Some hints in calculations (e.g. NNLO, weak corrections, fiducial corrections) but no simple solution
- We can exploit the full Run 2 data (4x the current data), study multi-differential distributions, investigate phase space corrections
- Watch this space!



MC samples

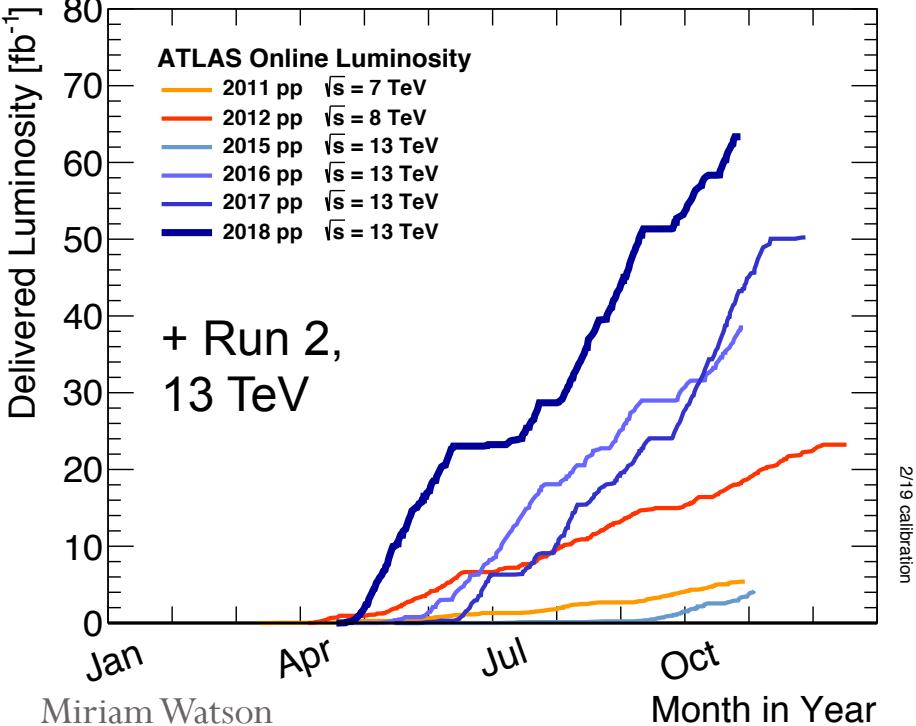
- Dilepton signal ($t\bar{t}$):
 - Nominal sample: Powheg+Pythia8
 - Radiation high/low: Powheg+Pythia8
 - Parton shower: Powheg+Herwig7
 - Alt. NLO: aMC@NLO+Pythia8
- Backgrounds:
 - Z+jets: Sherpa 2.2.1
 - W+jets: Sherpa 2.2.1
 - Diboson: Sherpa 2.2.1 + 2.1
 - Single top: Powheg+Pythia6
 - $t\bar{t}W$, $t\bar{t}Z$, tWZ : aMC@NLO + Pythia8
 - tZ , $t\bar{t}WW$, $t\bar{t}\bar{t}t$: MadGraph + Pythia8
 - Fakes from MC (l+jets $t\bar{t}$, W+jets, single top, $t\bar{t}V$, other), cross-checked with like-sign leptons

Data-taking at ATLAS 2010-2018



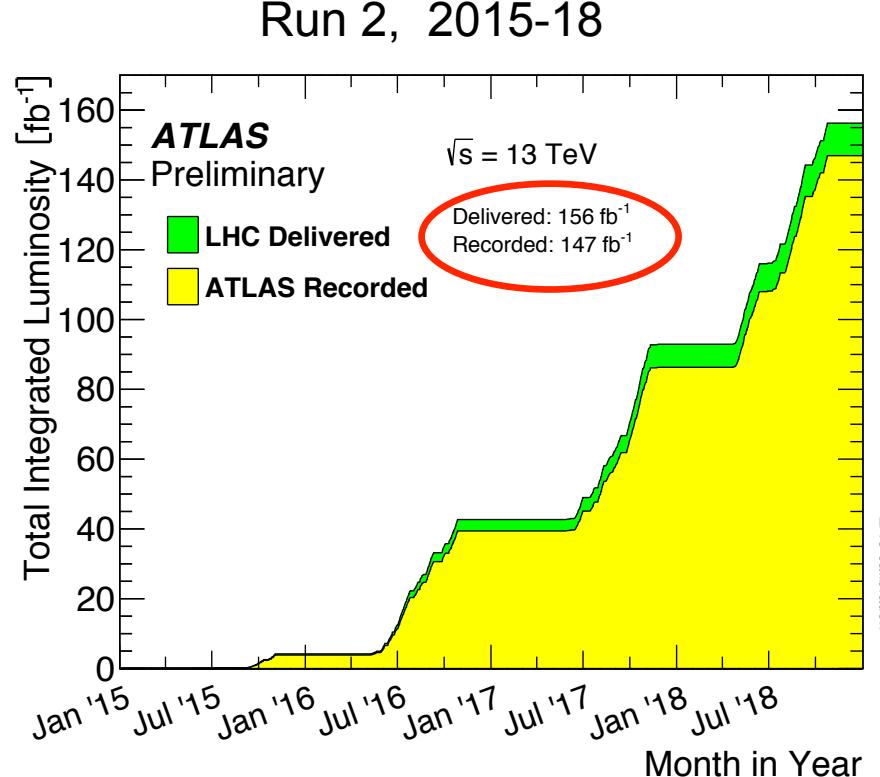
Run 1,
7+8 TeV

2010 data!



+ Run 2,
13 TeV

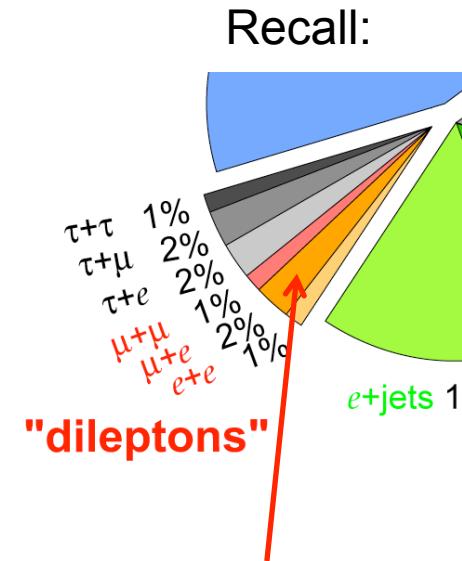
33



Today: mostly 2015-16 data, 36 fb^{-1}

Selected candidates

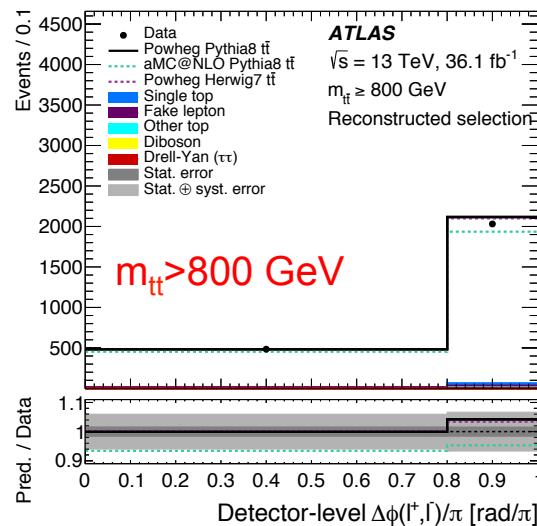
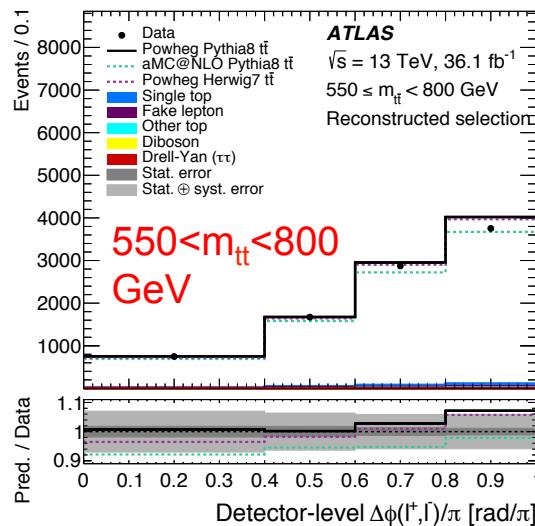
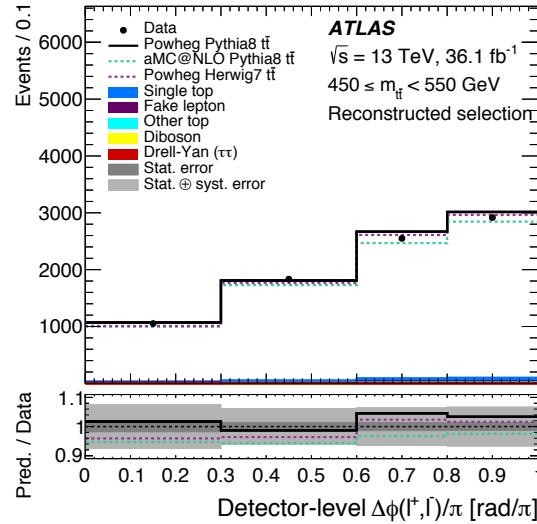
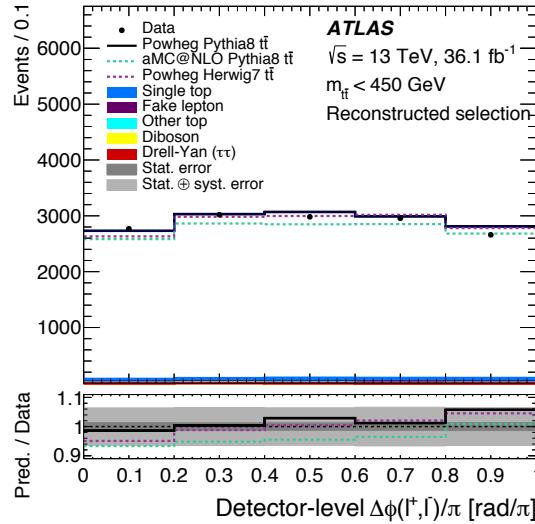
Process	Inclusive selection		Reconstructed selection	
	≥ 1 b-tag		≥ 2 b-tags +NW	
$t\bar{t}$	165 000	\pm 5000	75 000	\pm 4000
tW	8900	\pm 1400	1550	\pm 170
$t\bar{t}V$ and others	670	\pm 60	233	\pm 22
Diboson	580	\pm 60	15.1	\pm 2.8
$Z/\gamma^* \rightarrow \tau^+\tau^-$	420	\pm 70	26	\pm 17
Fake Lepton	1800	\pm 700	630	\pm 250
Expected	177 000	\pm 6000	78 000	\pm 4000
Observed	177 113		75 885	



This segment,
and only 25%
of run 2 data

- Nominal tt Monte Carlo:
 - Powheg-Box next-to-leading order (NLO) matrix-element
 - Pythia8 for parton shower and fragmentation
 - NNPDF3.0 NLO parton distribution function (PDF)

Measured distributions in 4 mass bins



- Shape differences apparent
- Binning determined by statistical precision and resolution on $m_{t\bar{t}}$, not $\Delta\phi$

Event reconstruction for $m_{t\bar{t}}$ dependence

- Reconstruct dilepton $t\bar{t}$ system
 - Two unknowns: η of neutrinos
- Constrain system using values of top mass and W mass
- Test many different assumptions for η for the two neutrinos
- Give each solution a weight based on observed E_T^{miss} in the event
- Select solution based on **highest weight** (“Neutrino Weighting”)
- Improving resolution:
 - M_t sampling, jet p_T smearing

Kinematic constraints

$$(\ell_{1,2} + \nu_{1,2})^2 = M_W^2 = 80.4^2$$

$$(\ell_{1,2} + \nu_{1,2} + b_{1,2})^2 = M_t^2 = 172.5^2$$

Require 2 b-tagged jets

Weight function

$$w_i = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right)$$

E_T^{miss} resolution factor

Unfolding for detector effects

- Iterative Bayesian Unfolding is used to correct the data to fiducial Particle or Parton level.

Data



Subtract backgrounds estimated using MC

Data - Background



Bayesian iterative unfolding with n iterations

Unfolded data



Correct for fiducial phase-space acceptance

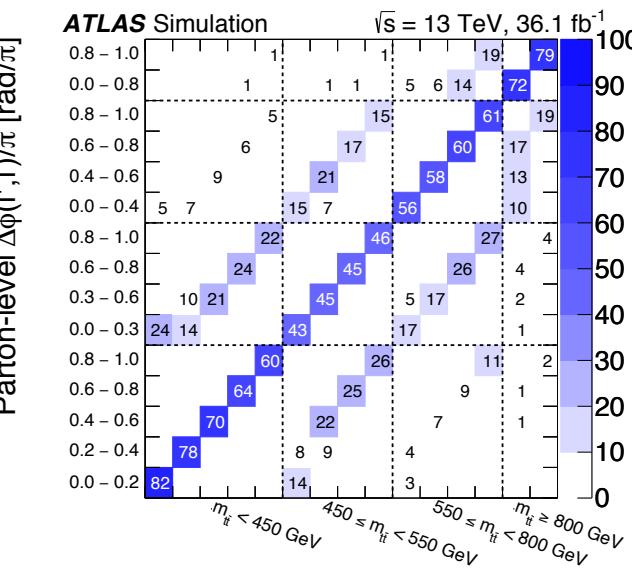
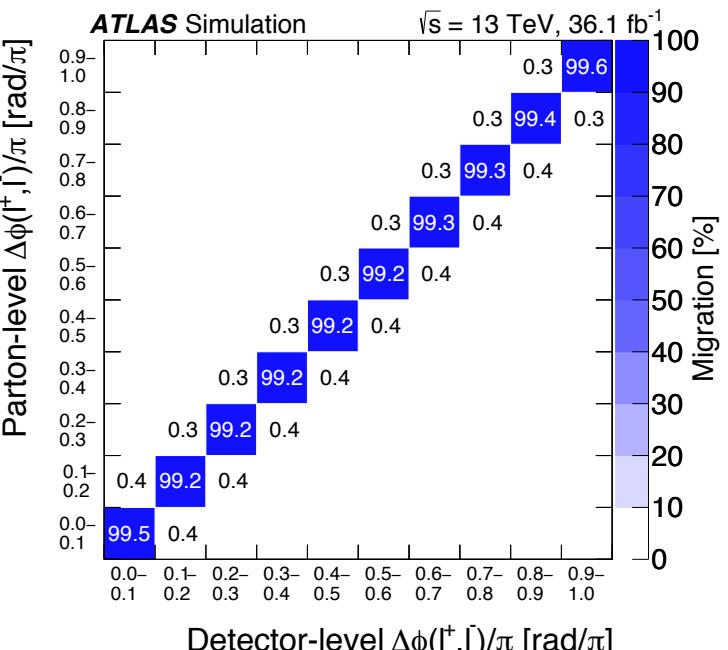
Fiducial data

or full phase-space



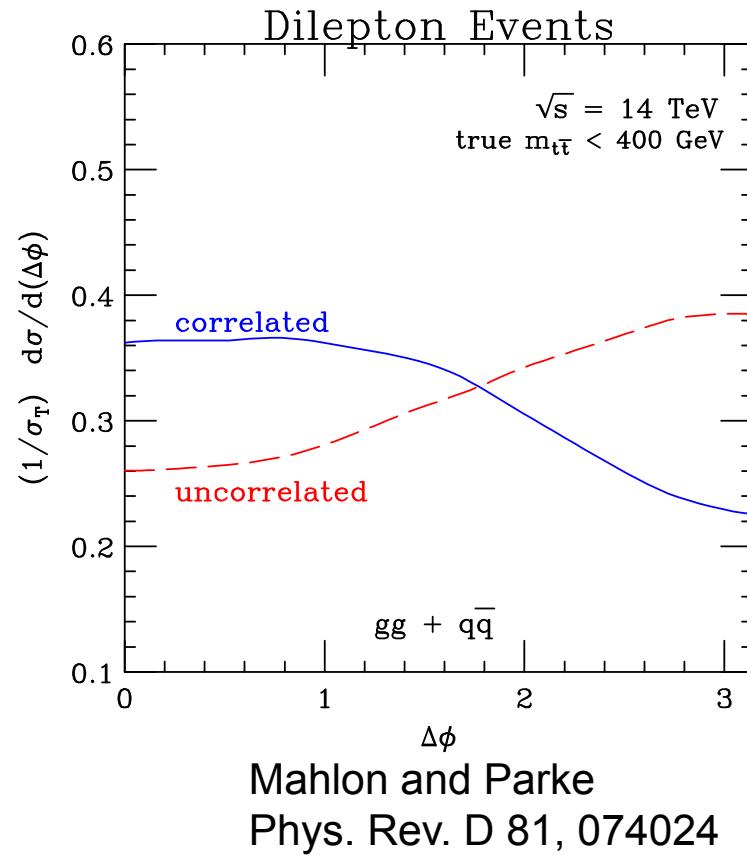
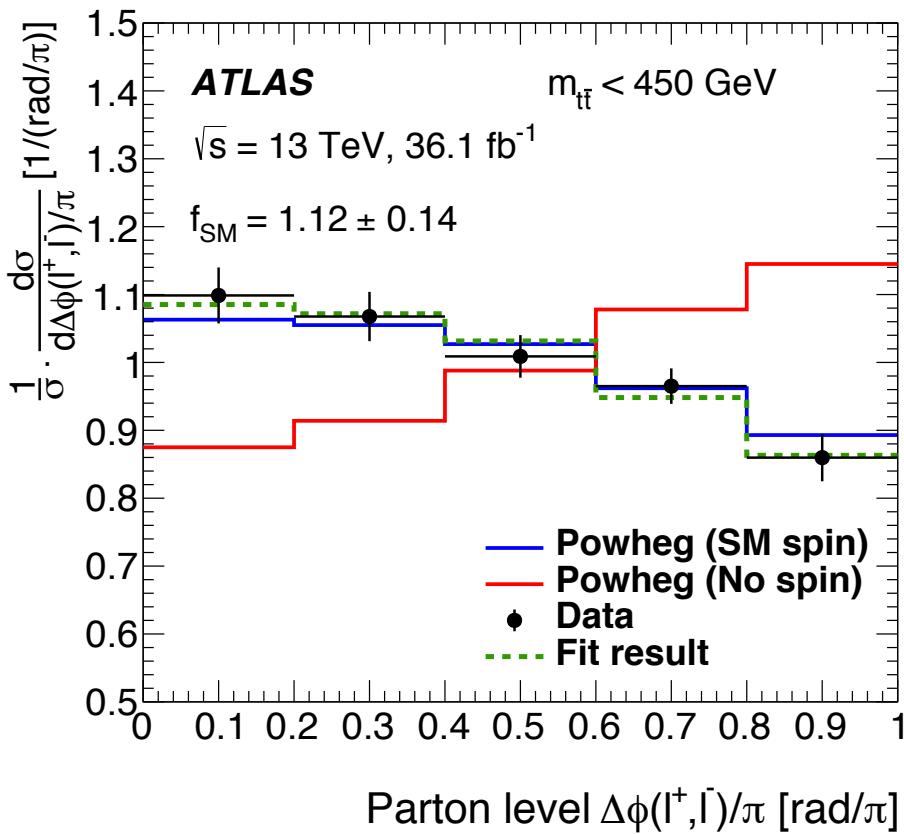
Determine cross-section, absolute or normalised

Result



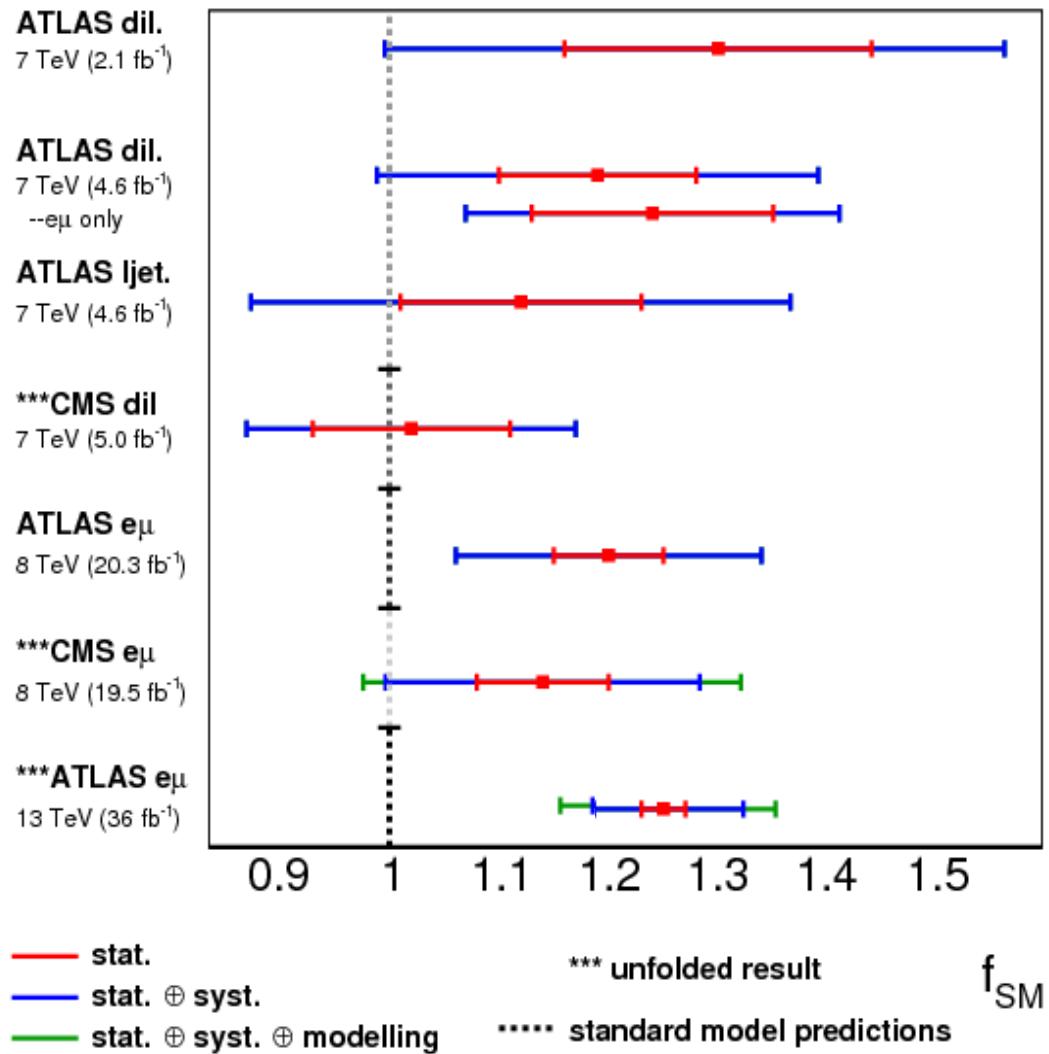
Results: extracting spin correlation vs. $m_{t\bar{t}}$

- MC parton-level distributions follow theoretical predictions at low $m_{t\bar{t}}$



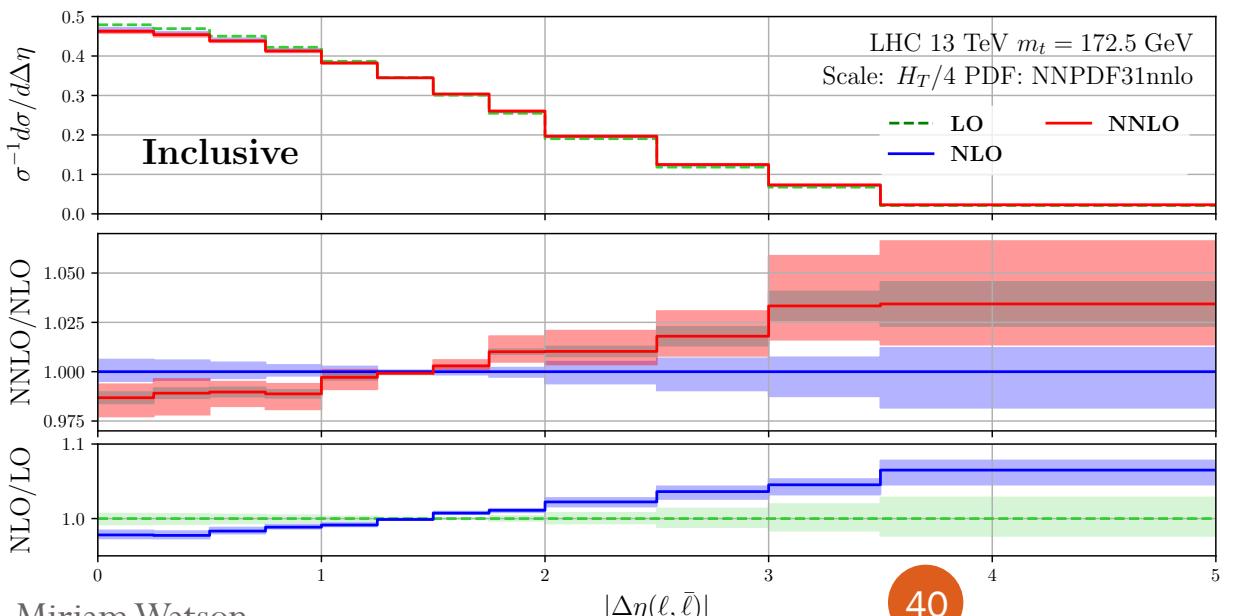
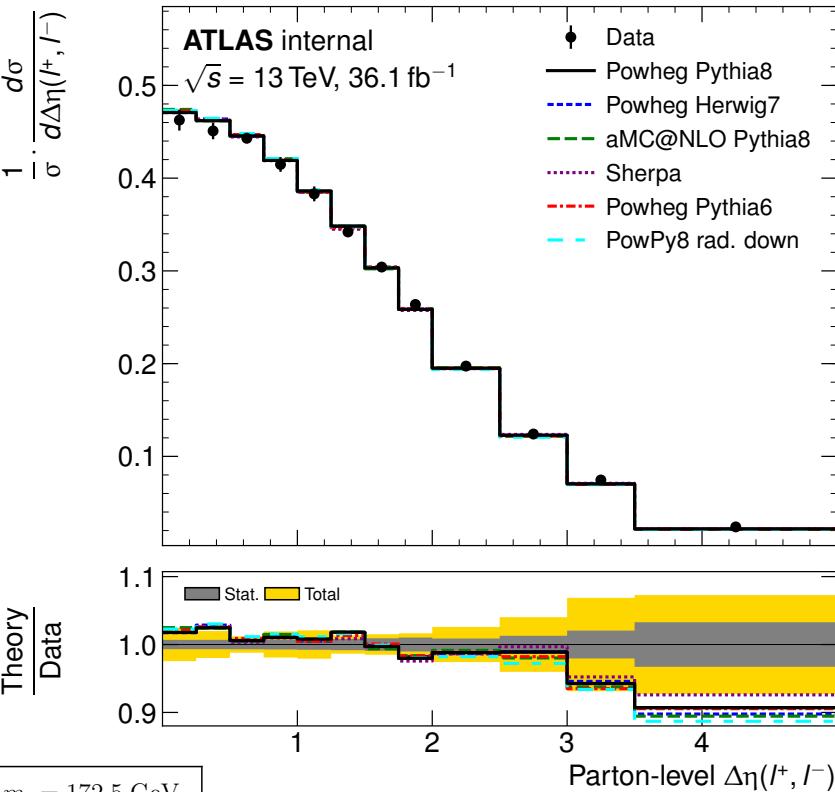
Comparison of f_{SM} values

- When interpreted as spin correlation, shows $\sim 20\%$ more than the spin correlation expectation of the SM (in NLO MC)
- Observed in many other results, with larger uncertainties
- Main differences here:
 - Improved MC generators
 - Improved MC tuning
 - Larger dataset to constrain systematic uncertainties



ATLAS and NNLO $\Delta\eta$

- Unfolded parton-level distribution
- NNLO corrections appear to follow data trends



Aside: renormalisation and factorisation scale choice

$$\mu_0 \sim m_t, \quad \text{NLO+Weak}$$

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2}, \quad \text{Powheg+Pythia8}$$

$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2},$$

$$\mu_0 \sim H'_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} + \sum_i p_{T,i},$$

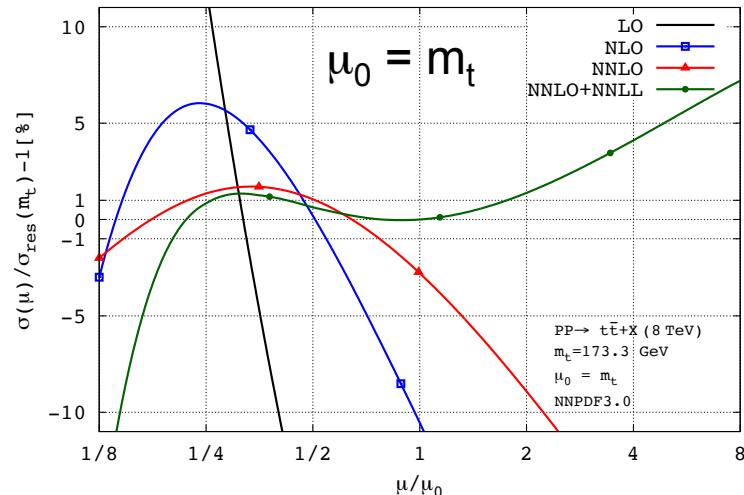
$$\mu_0 \sim E_T = \sqrt{\sqrt{m_t^2 + p_{T,t}^2} \sqrt{m_t^2 + p_{T,\bar{t}}^2}},$$

$$\mu_0 \sim H_{T,\text{int}} = \sqrt{(m_t/2)^2 + p_{T,t}^2} + \sqrt{(m_t/2)^2 + p_{T,\bar{t}}^2},$$

$$\mu_0 \sim m_{t\bar{t}},$$

$$\mu_0 = \begin{cases} \frac{m_T}{2} & \text{for : } p_{T,t}, p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}, \\ \frac{H_T}{4} & \text{for : all other distributions} \end{cases}$$

Czakon, Heymes, Mitov
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Preferred