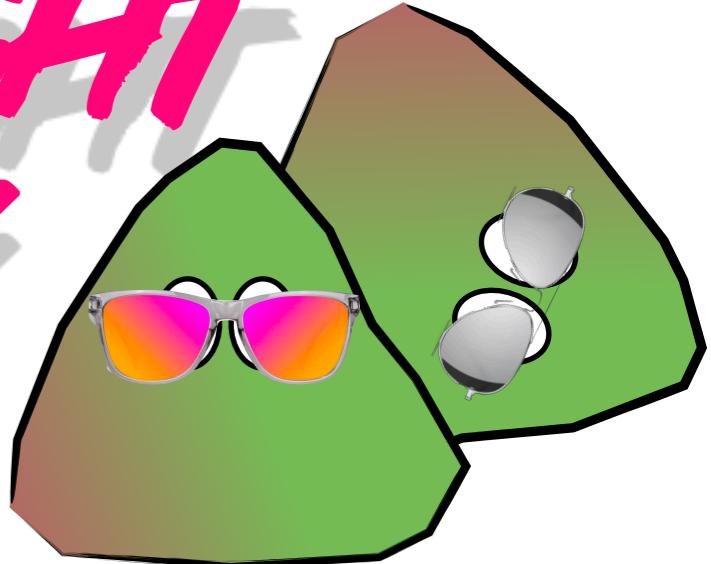
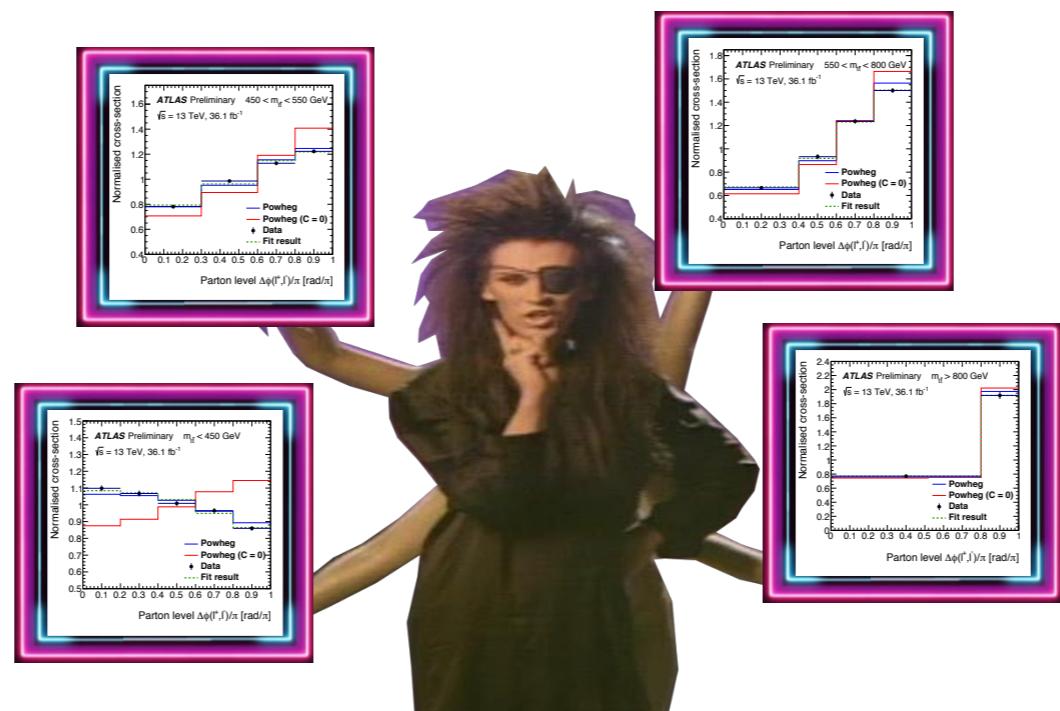


# YOU SPIN ME RIGHT ROUND BABY

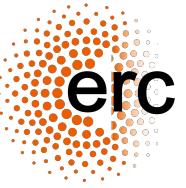


**Jay Howarth:** On behalf of the ATLAS experiment

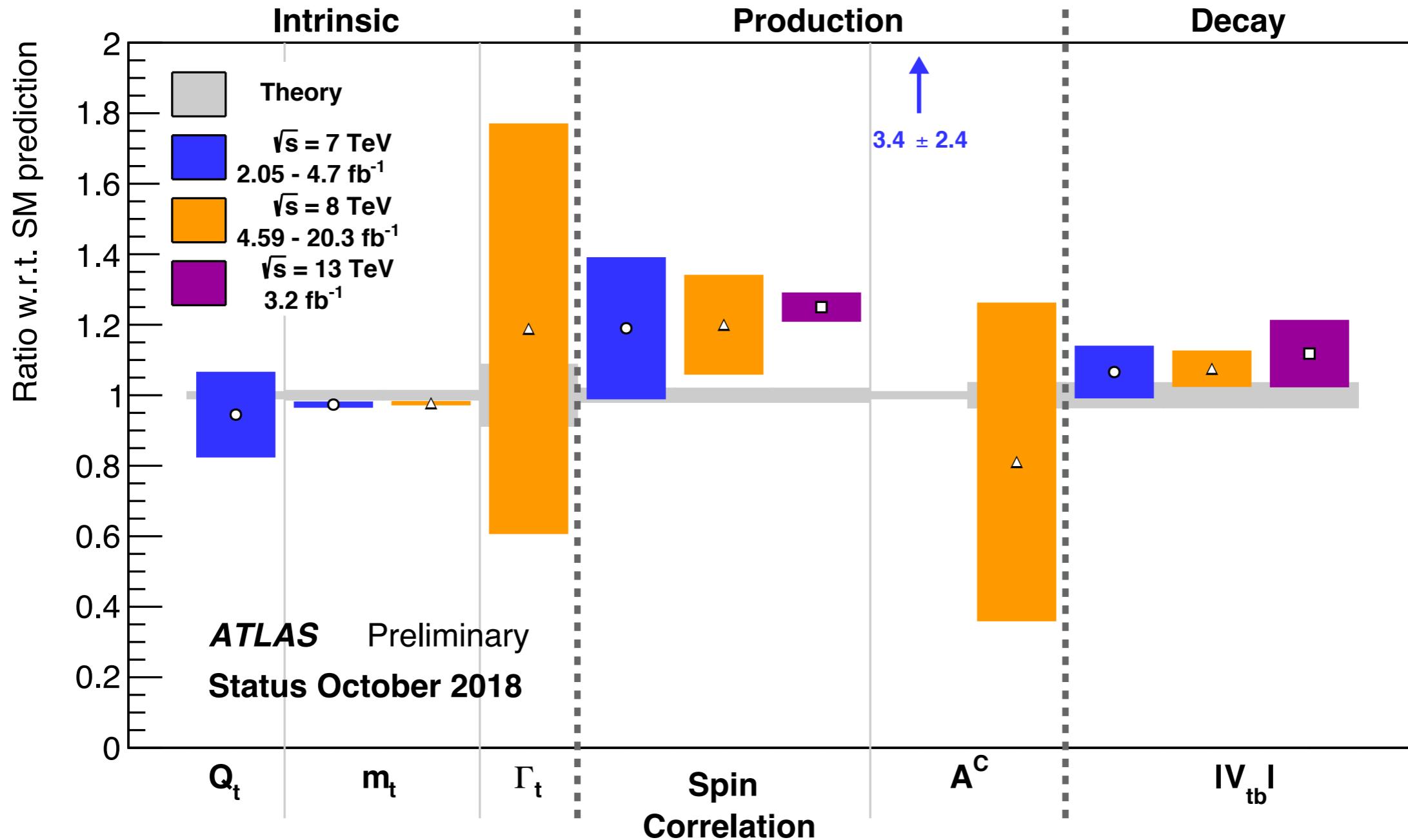


# Top Quark Properties

MANCHESTER  
1824



ATL-PHYS-PUB-2018-034/



- In the last 10 years we've learned an awful lot about the top quark, including some things that had never been measured before.

# What is Spin Correlation?

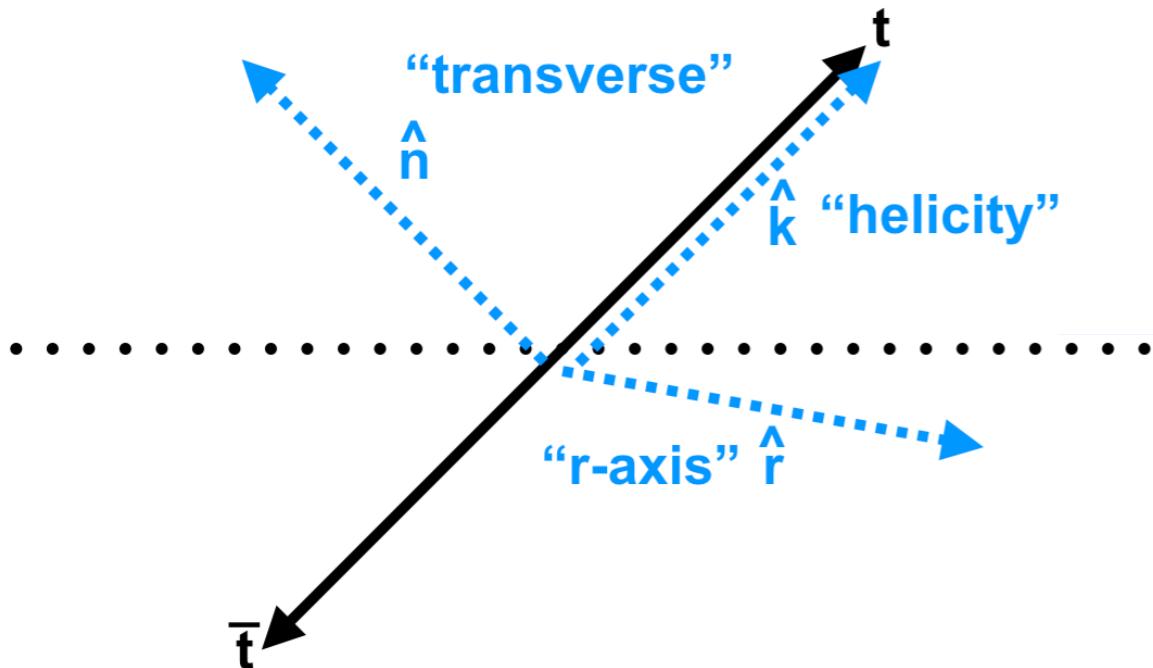
MANCHESTER  
1824



- Spin correlation in  $t\bar{t}$  is:

$$C = \alpha_1 \cdot \alpha_2 \cdot \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- Where  $\alpha$  is the “**spin analysing power**” of some decay particle from a top quark ( $\sim 1$  for charged leptons so we won’t mention it again for dilepton analyses).
- $\uparrow$  and  $\downarrow$  are the direction of  $t$  and  $\bar{t}$  spin, in some chosen “**spin analysing basis**”



- There are three orthogonal bases that are most commonly used:
  - ➡ The “**Helicity**” basis: direction of the  $t$  in the  $t\bar{t}$  rest frame.
  - ➡ The “**Transverse basis**”: orthogonal to the plane formed by the  $t$  and beam line in  $t\bar{t}$  rest frame.
  - ➡ The “**R-axis**”: basis orthogonal to the other two.

# How do we measure it?

- Sensitive observables can be readily seen by examining the double differential cross-section as a function of the angular distribution of  $t$  and  $\bar{t}$  decay products:

Double diff. xsec

Polarisation (0 in SM)

Spin Correlation

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

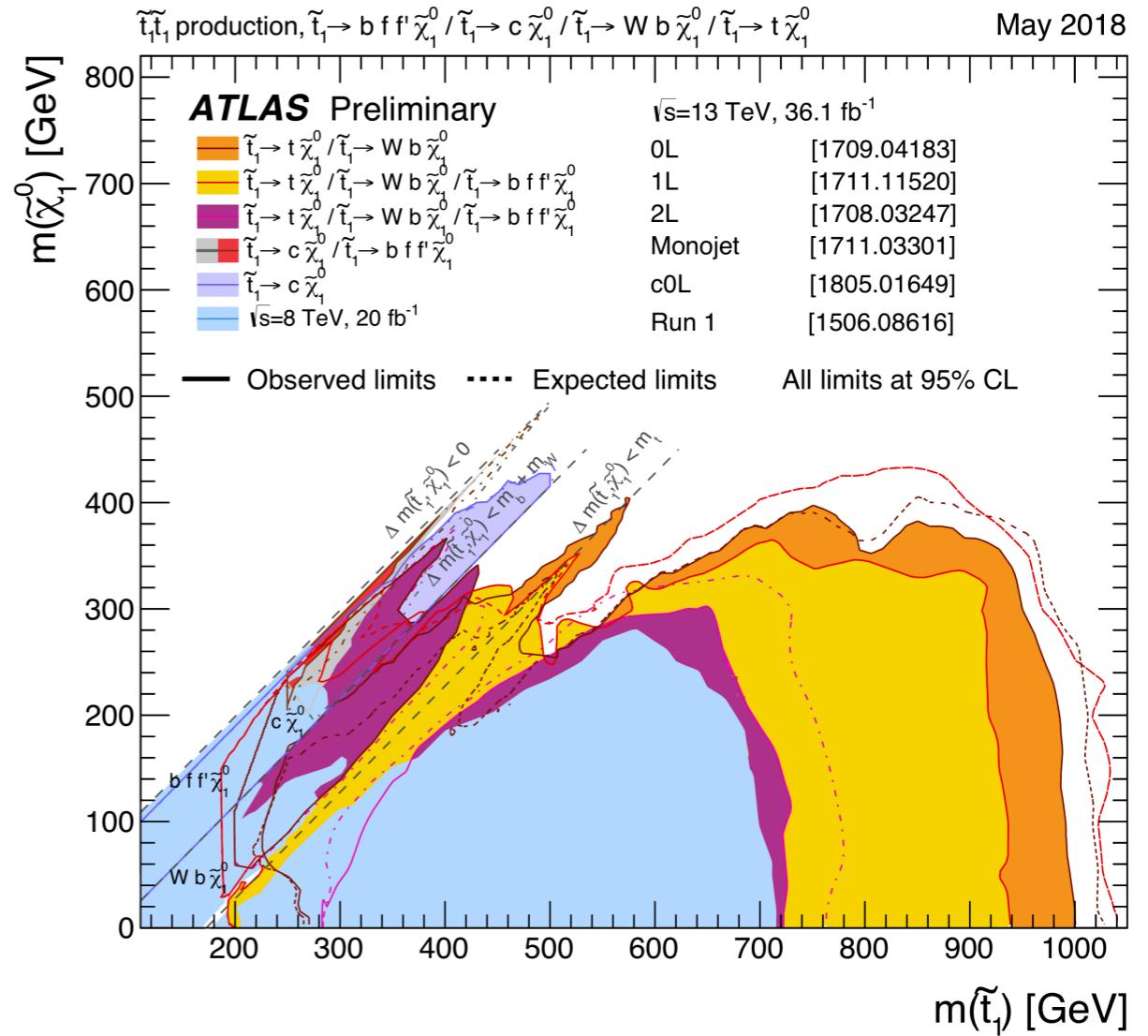
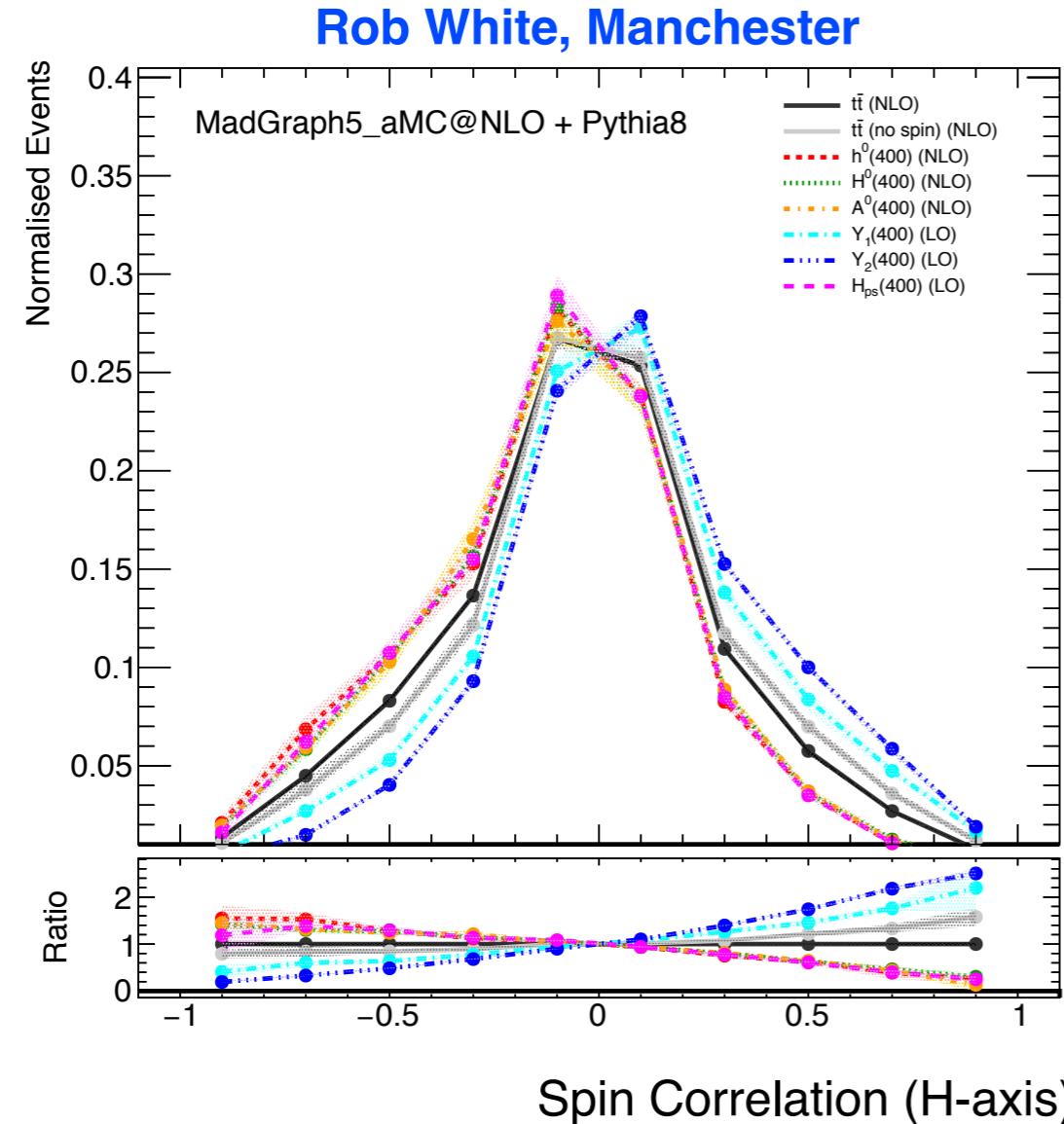
- By measuring the  $\cos(\theta)$  angles (usually with leptons) we can directly extract the spin correlation parameter  $C$ :

$$B_+ = 3 \cdot \langle \cos(\theta_+) \rangle$$

$$C = -9 \cdot \langle \cos(\theta_+) \cos(\theta_-) \rangle$$

- ATLAS measured the spin correlation parameter,  $C$ , the polarisation parameters  $B$ , and cross-correlations ( $\cos(\theta_+)$  and  $\cos(\theta_-)$ ) using different spin analysing bases) in an 8 TeV paper: [Link](#).
- But these direct measurements require full  $t\bar{t}$  reconstruction in dilepton events and therefore suffer from significant systematic uncertainties and resolution effects.

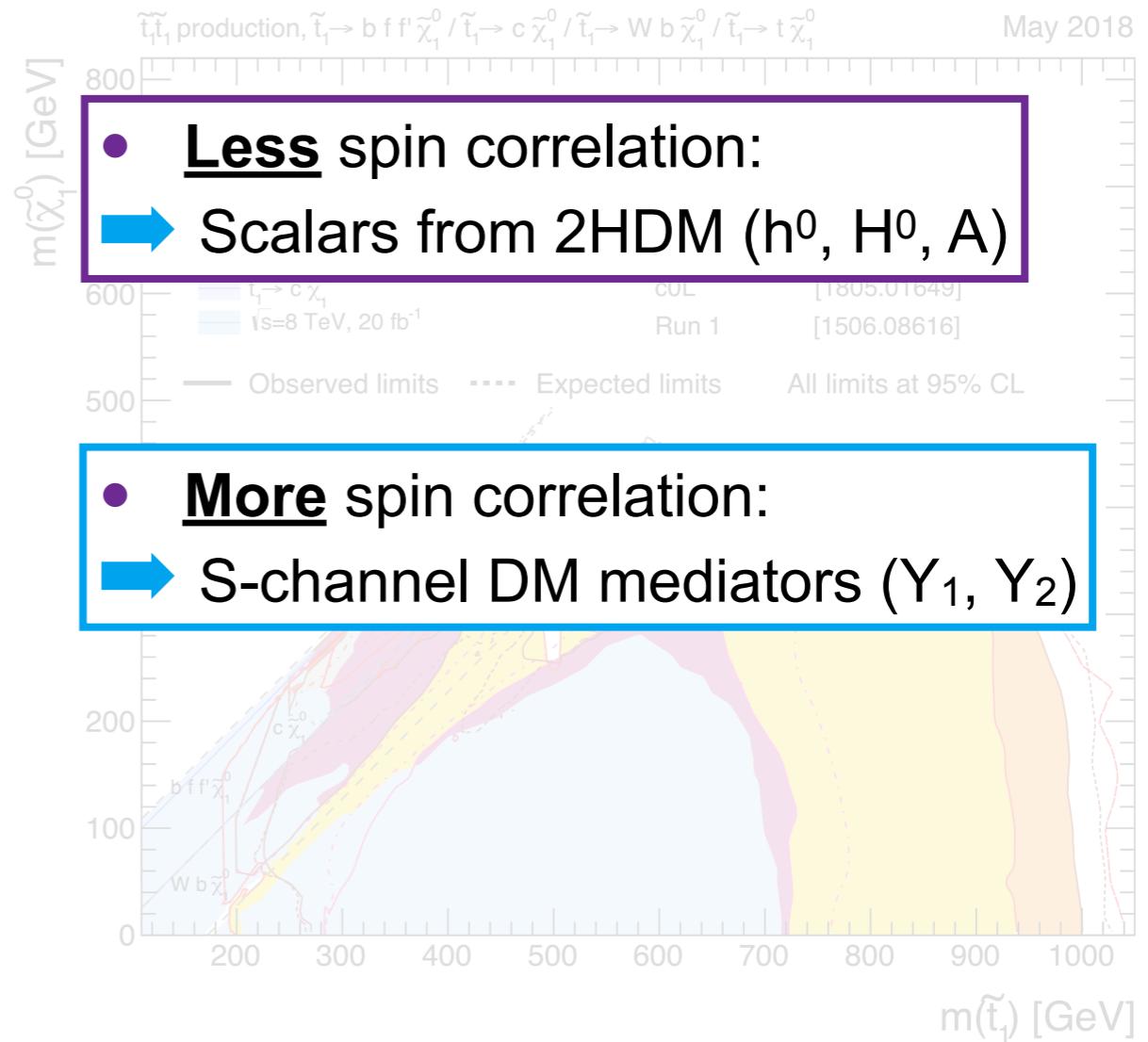
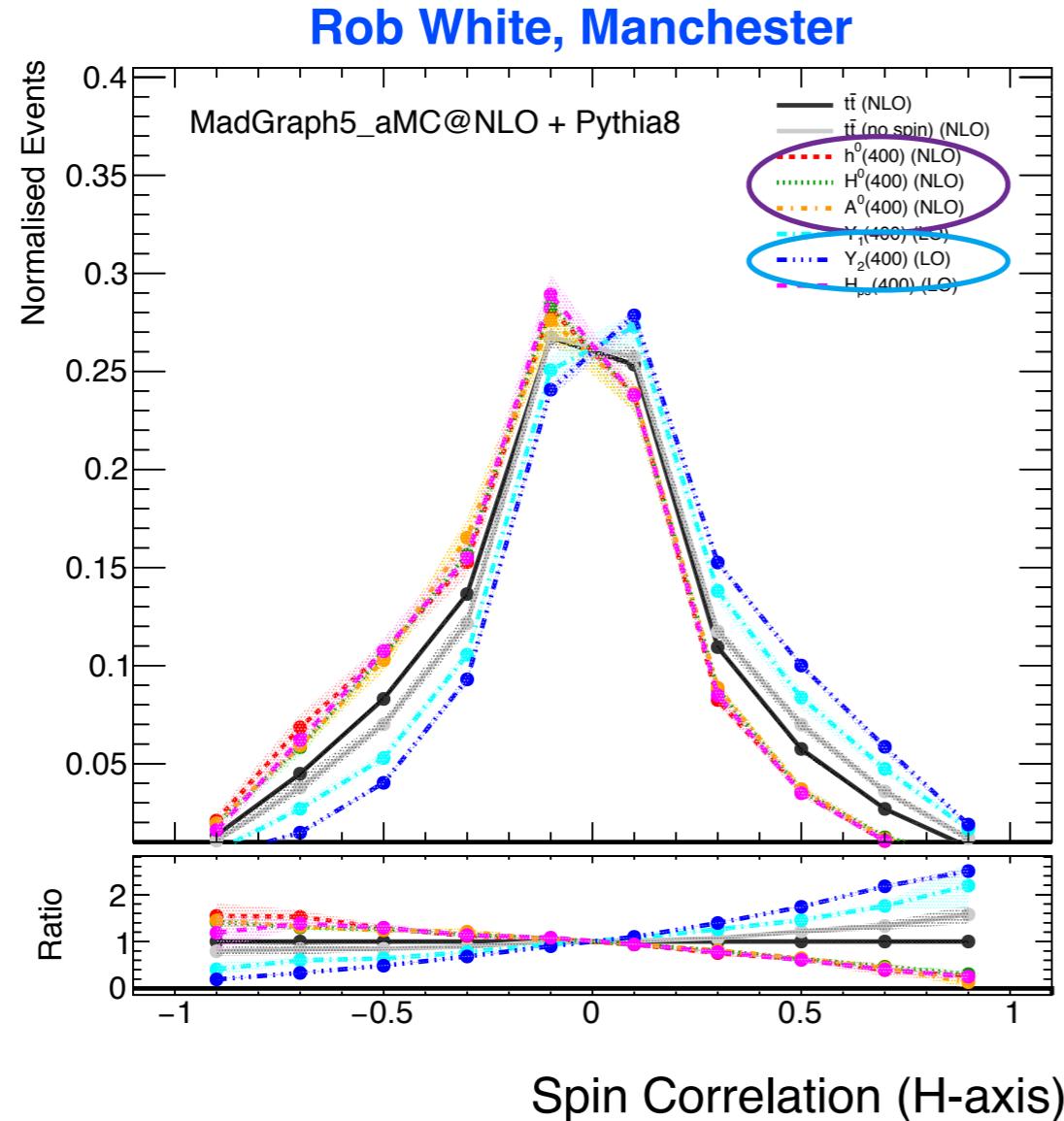
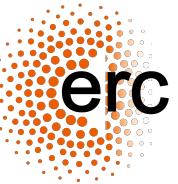
# Why do we measure it?



- Spin correlation observables are sensitive to new mediators in production and to “degenerate” new physics models that appear top like (low mass Stop, for example).
- Used at 8 TeV to set limits in kinematically difficult region.

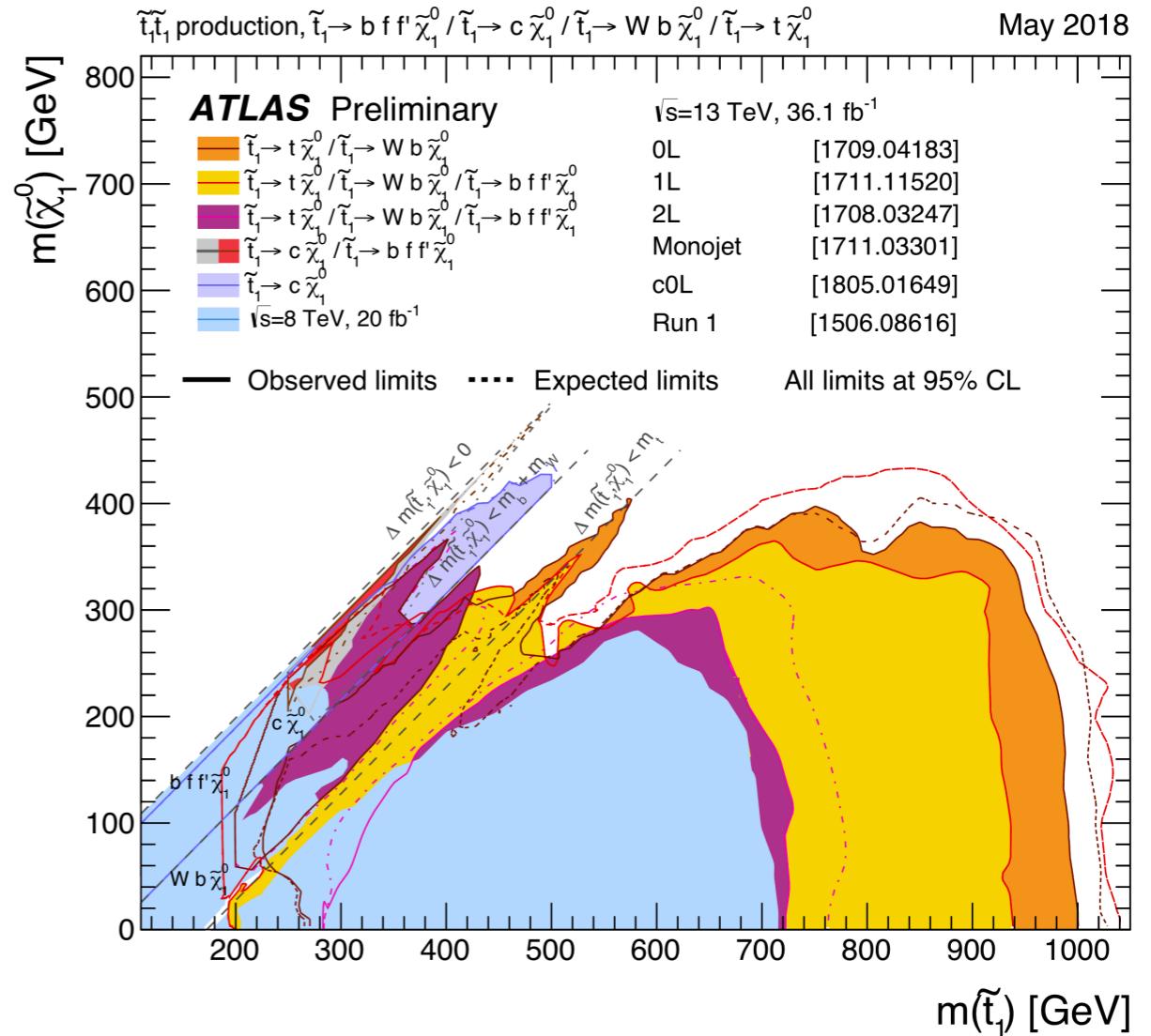
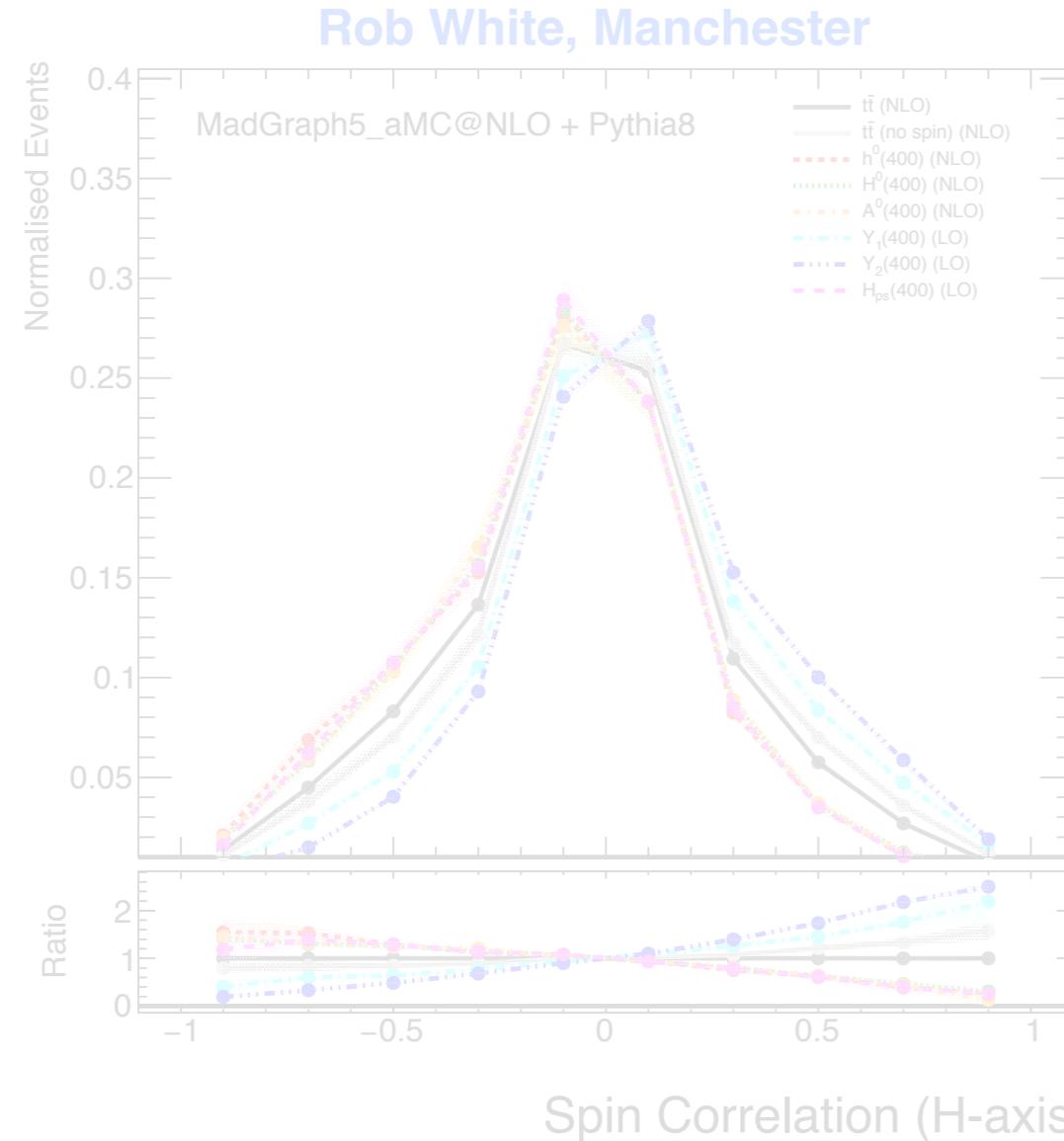
# Why do we measure it?

MANCHESTER  
1824



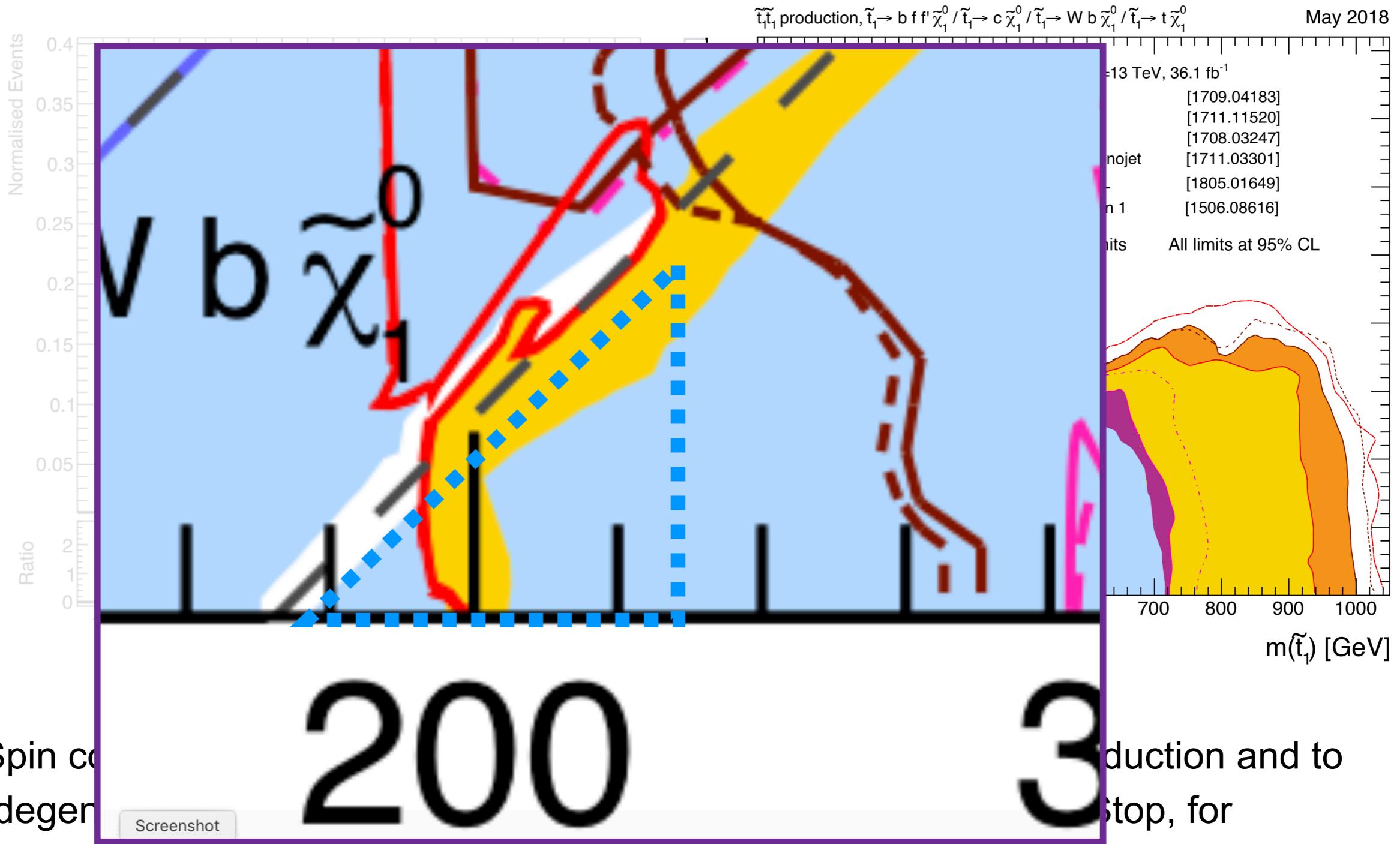
- Spin correlation observables are sensitive to new mediators in production and to “degenerate” new physics models that appear top like (low mass Stop, for example).
- Used at 8 TeV to set limits in kinematically difficult region.

# Why do we measure it?



- Spin correlation observables are sensitive to new mediators in production and to “degenerate” new physics models that appear top like (low mass Stop, for example).
- Used at 8 TeV to set limits in kinematically difficult region.

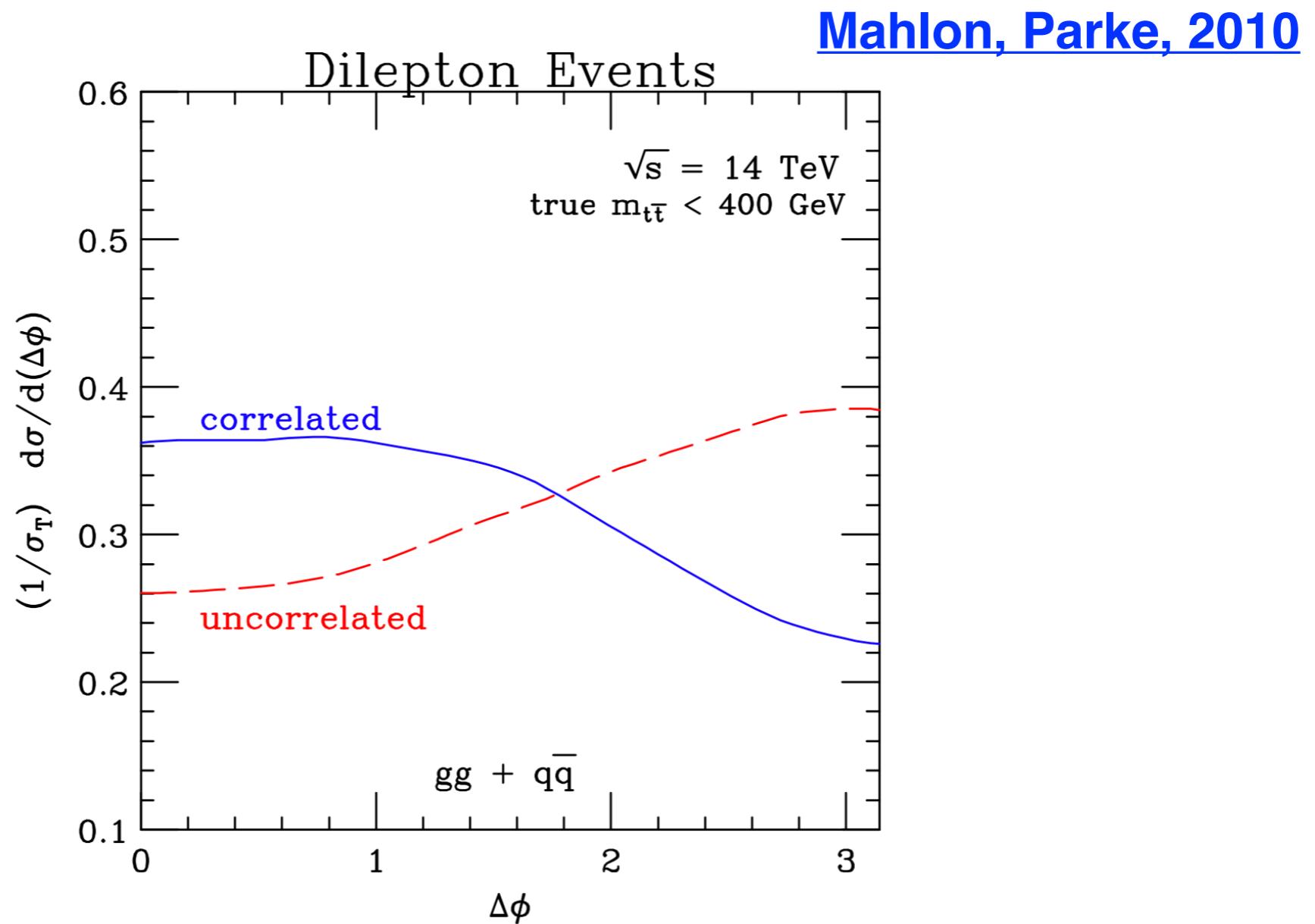
# Why do we measure it?



- Spin conservation can lead to “degenerate” states (e.g. the example).
- Used at 8 TeV to set limits in kinematically difficult region.

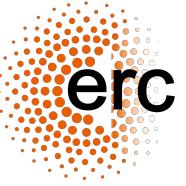
# An easier observable

- Though it cannot be directly translated in to the **C** parameter, spin correlation can be inferred from the difference between the azimuthal angle between the two charged leptons in the lab frame ( $\Delta\phi$ ).

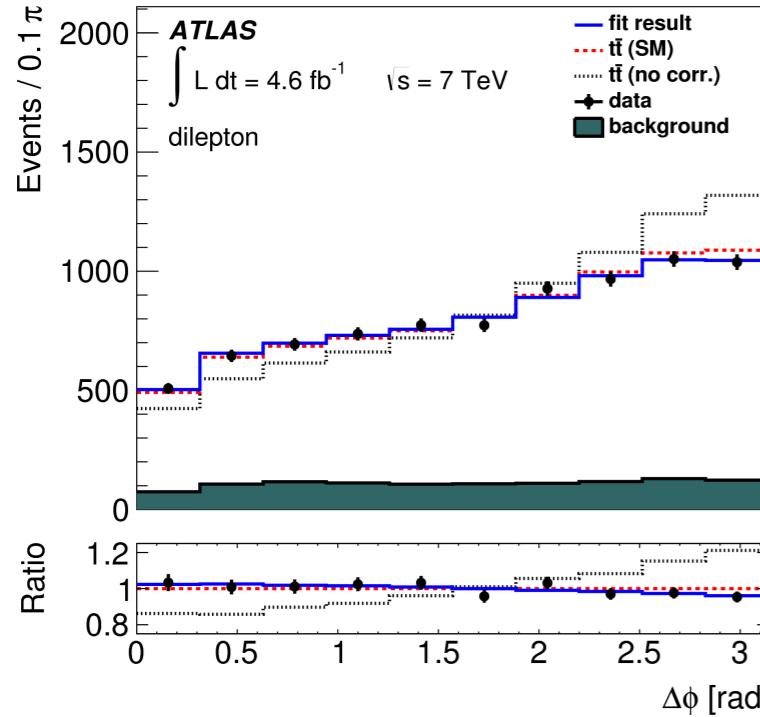


# Previous Measurements

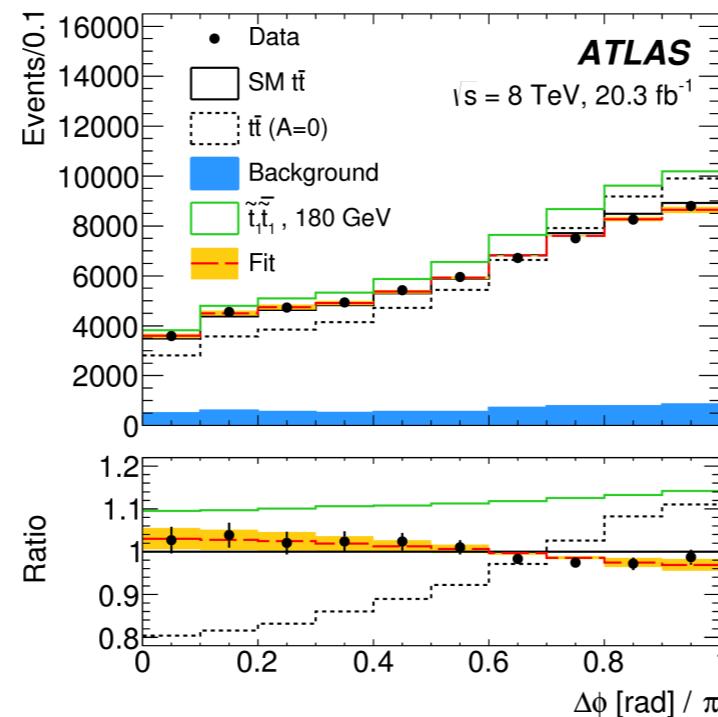
MANCHESTER  
1824



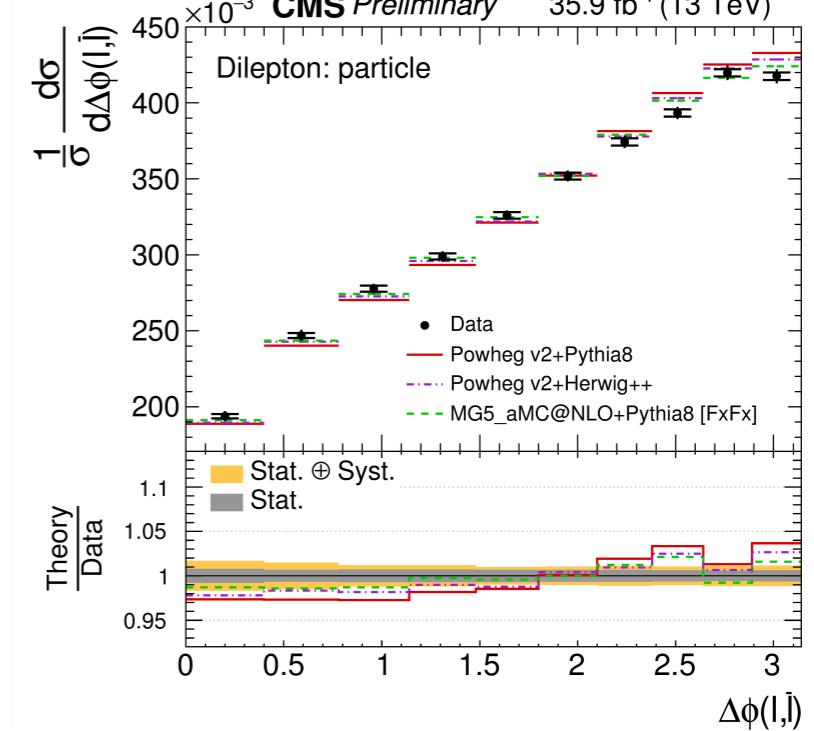
## ATLAS Reco-level



## ATLAS Reco-level



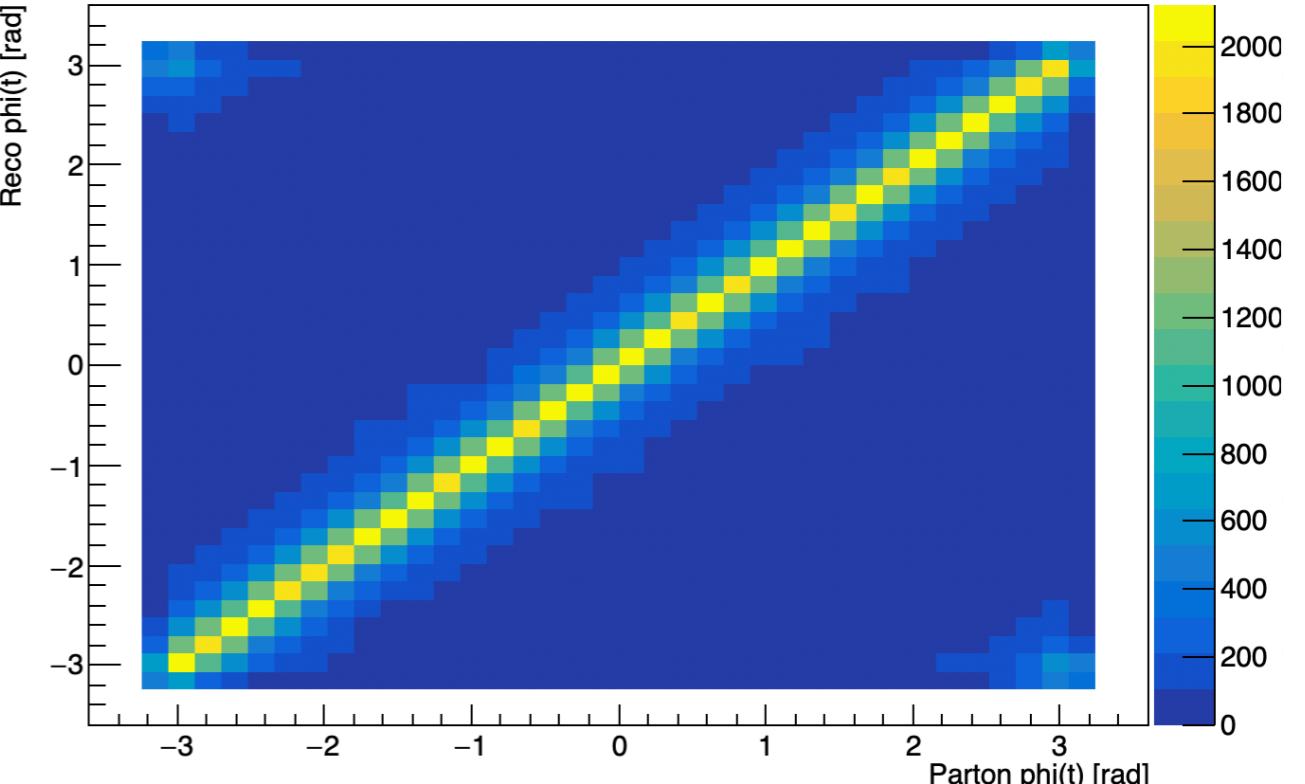
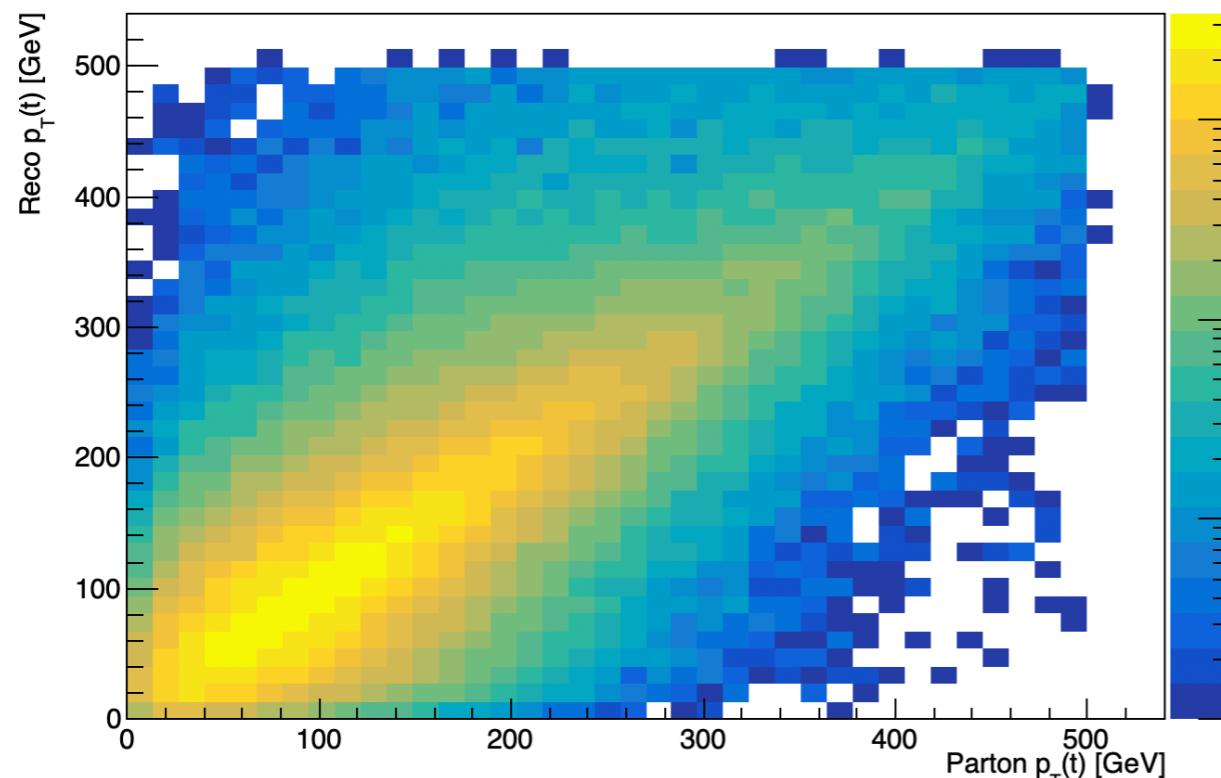
## CMS Particle-level [Link](#)



- ATLAS used this observable to obtain first evidence for spin correlation during Run1.
- ATLAS and CMS have since both measured spin correlation using this observable at multiple collision energies.
- Both experiments have observed (at all collision energies) that the  $|\Delta\phi|$  spectra in our simulations is “steeper” than the data.
- Until now this has been covered by systematic uncertainties but for 13 TeV this is no longer the case.

- We use 2015 + 2016 data with a standard dilepton **e $\mu$  selection**:
  - exactly 2 opposite-sign leptons (27, 25 GeV)
  - At least one b-jet;  $\geq 2$  jets  $pT > 25$  GeV.
  - No cuts on MET or on  $m(l\bar{l})$
- We measure the  **$\Delta\phi$**  inclusively and in bins of  **$m(t\bar{t})$** , and unfold to both particle and parton level:
  - Iterative Bayesian Unfolding.
  - Tops and leptons are defined as after radiation (i.e the last particle in the decay chain at parton level before decay).
  - Using dressed leptons at particle level (electrons and muon).
  - Anti- $k_T$  0.4 jets with ghost-matching for b-tagging.
  - Same fiducial selection as reco level.

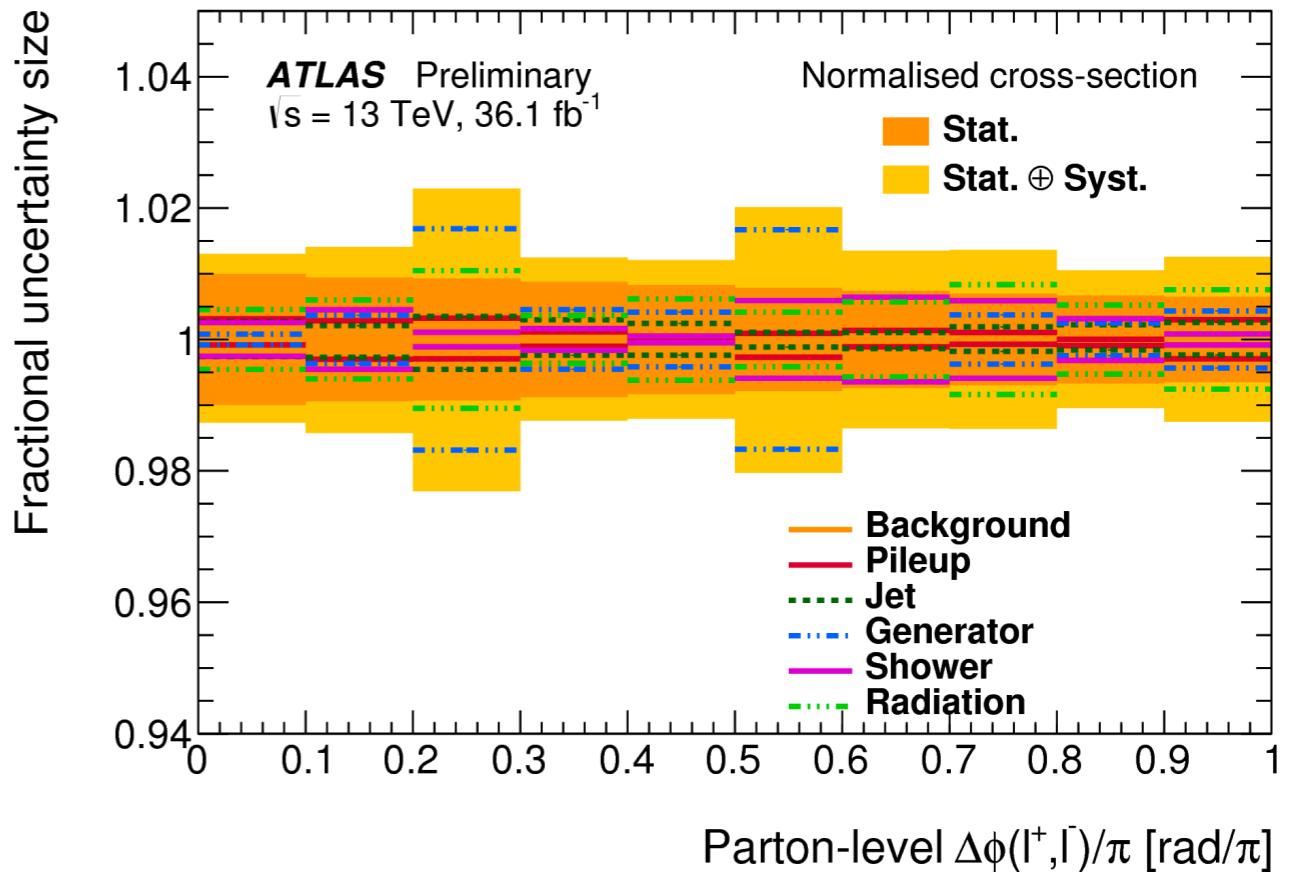
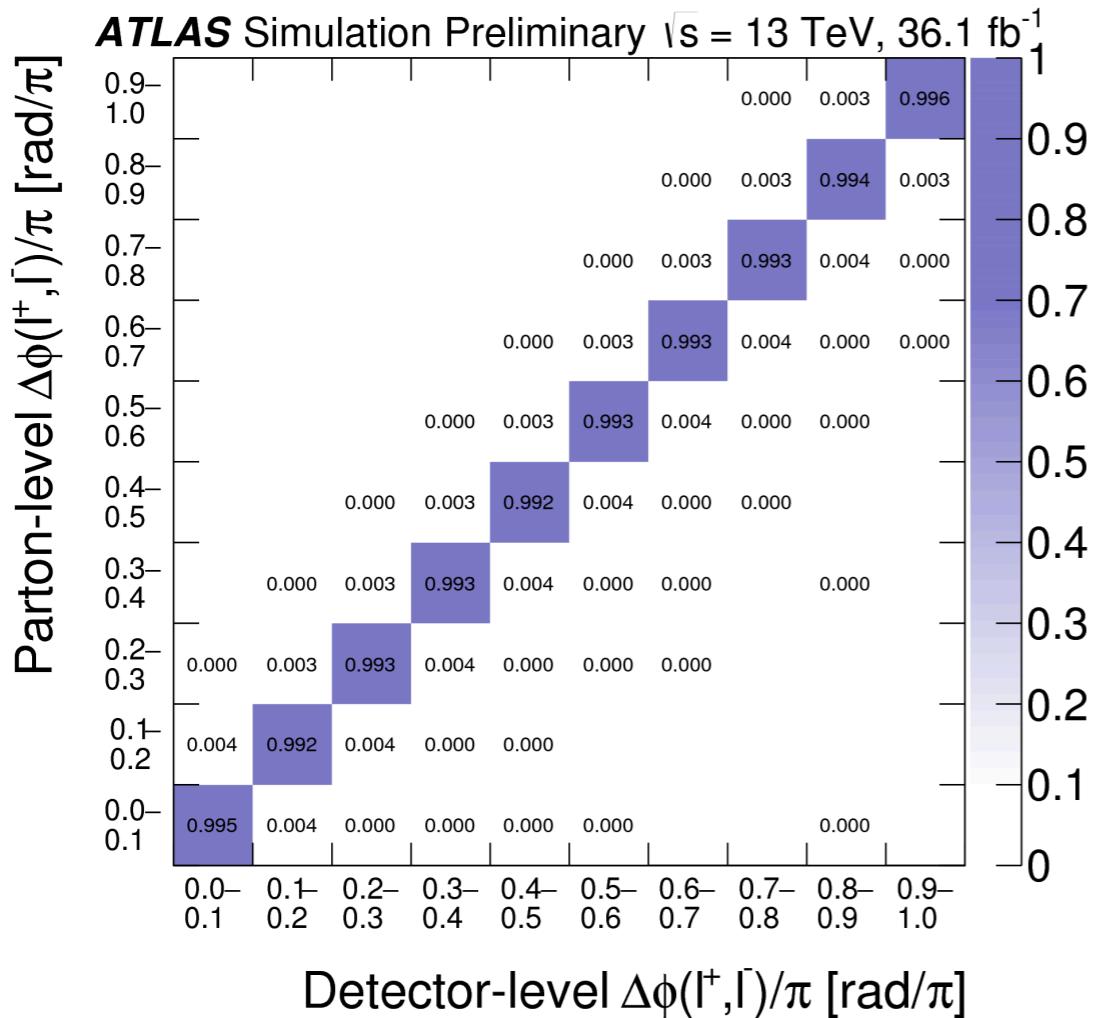
# Full ttbar Reconstruction



- This analysis uses Neutrino Weighting to reconstruct the dileptonic  $t\bar{t}$  final state.
- Well-known and uncontroversial technique, used in many published analyses.
- Excels at angular resolution, does a decent job of momenta and energy resolutions.

# Systematics and Unfolding

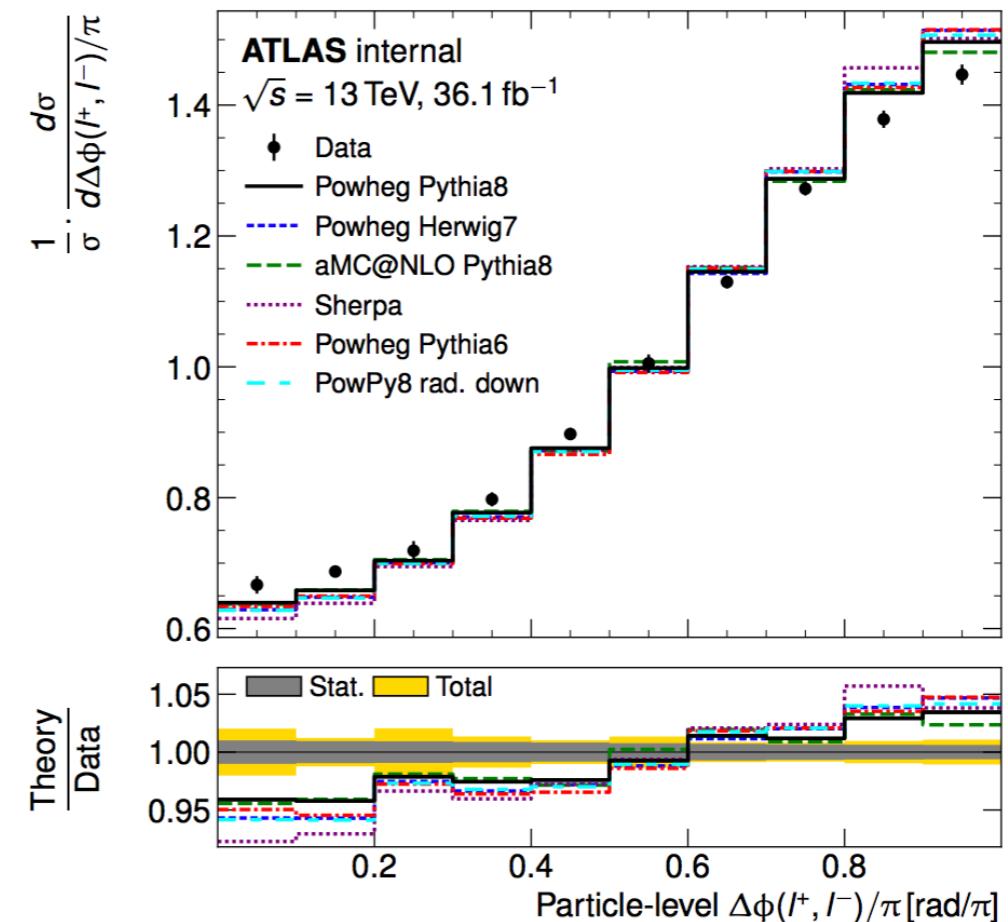
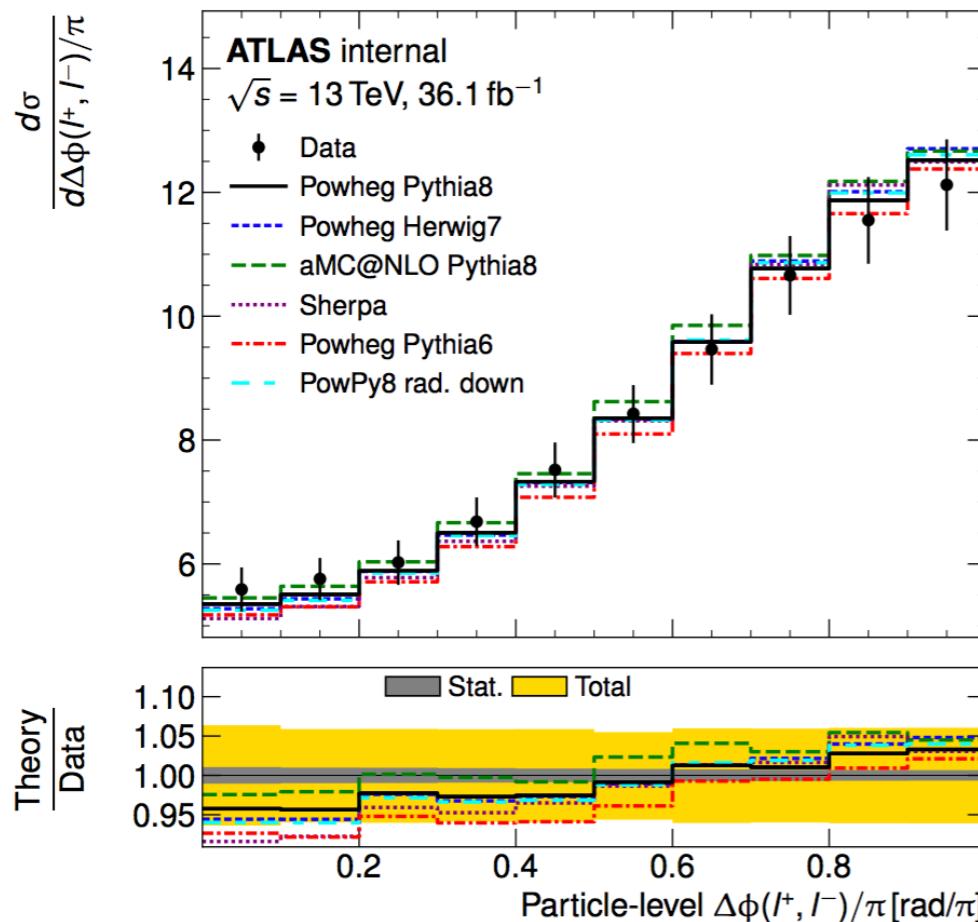
MANCHESTER  
1824



- Iterative Bayesian Unfolding is used to correct the data to Parton level.
- Systematic uncertainties are evaluated by unfolding a systematic shifted MC sample with the nominal unfolding procedure and comparing to it's truth spectra.
- Dominant uncertainties are from **Generator** (`MG5_aMC@NLO` unfolded with Powheg) and **Shower** (`Powheg + Herwig7` unfolded with Powheg + Pythia8).

# Results

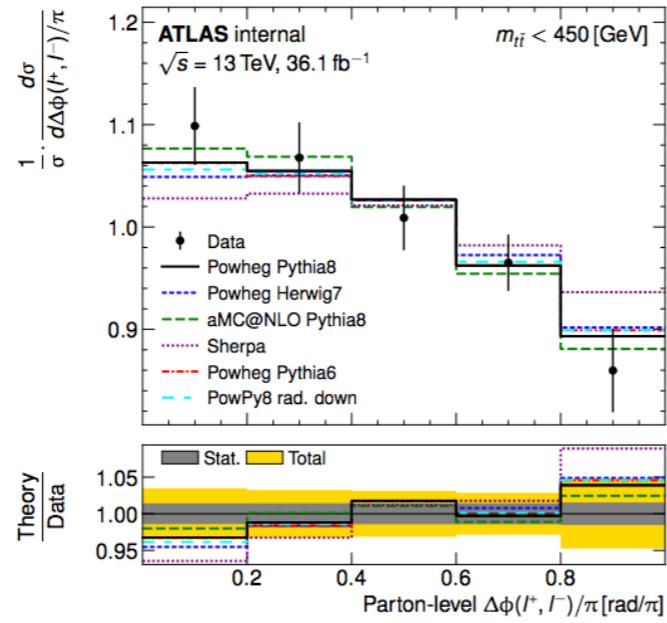
- Inclusive results show a clear slope in the data relative to the MC predictions (varying slightly depending on which prediction, Powheg + Pythia8 is closest in general).
- Relative cross-sections shift due to acceptance effects when normalising, but shape remains the same.



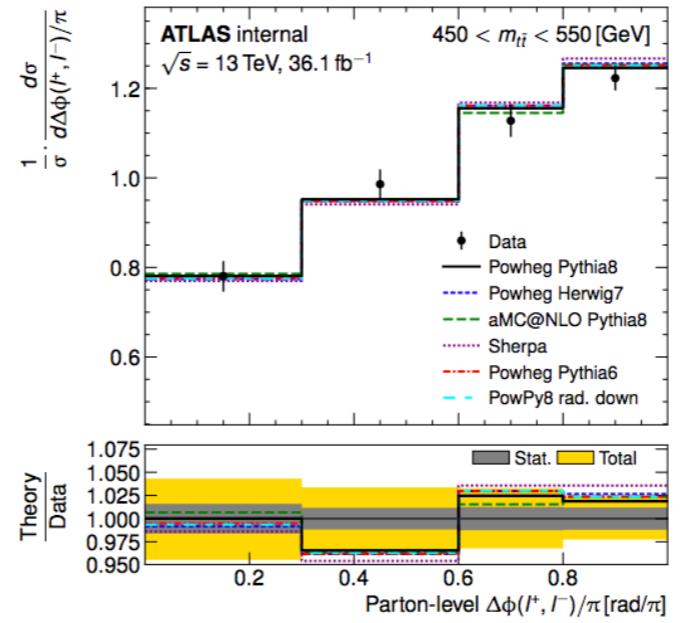
- In most bins the systematics are dominant, but statistics have a relatively large contribution (though uncertainties are small overall).

# Results

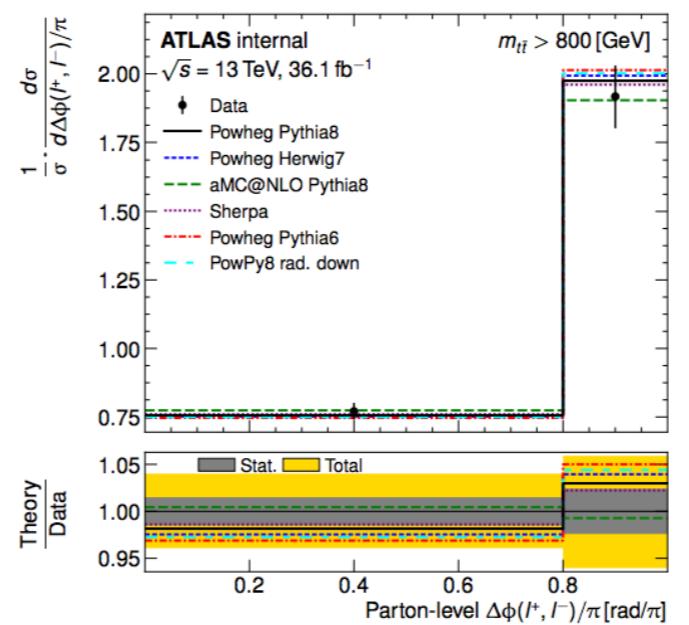
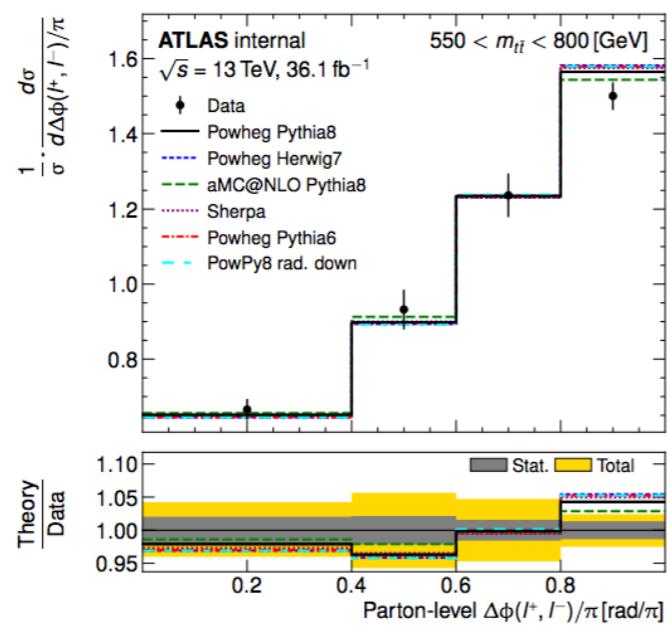
- Similar story for the double differential. The behaviour of the observable as it moves from low  $m(t\bar{t})$  to high  $m(t\bar{t})$  is clearly seen.



(a)

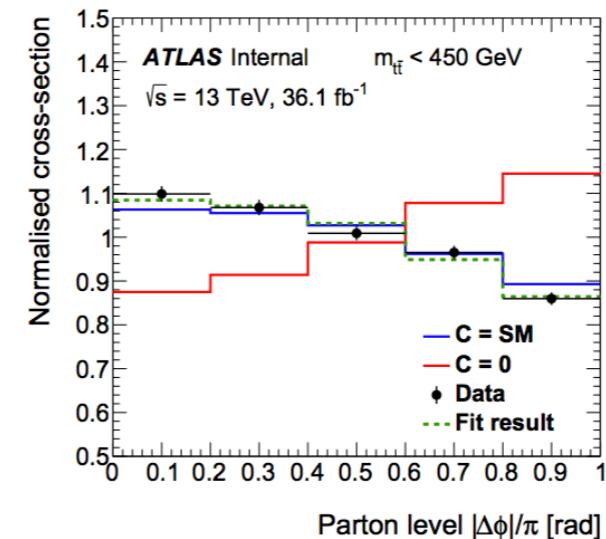
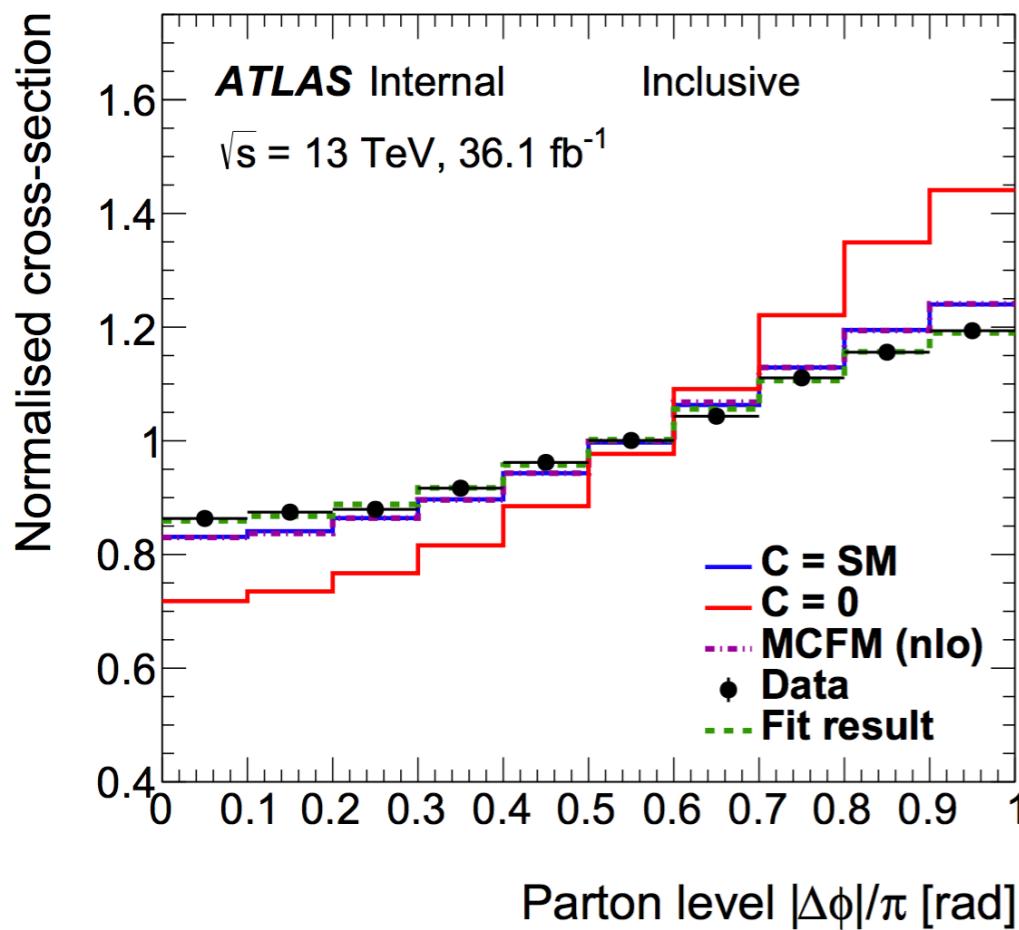


(b)

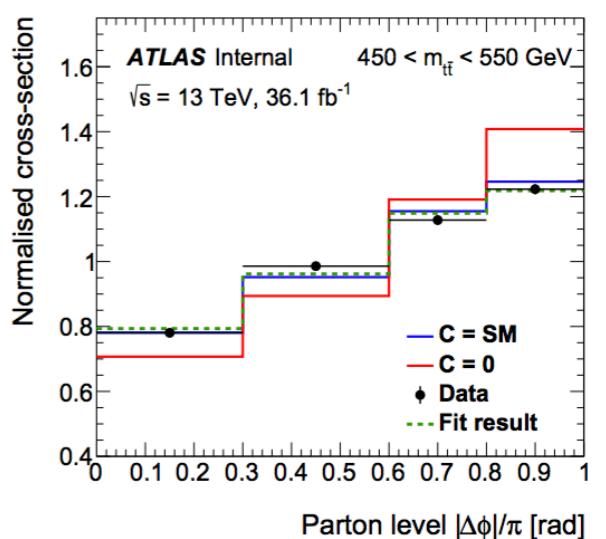


# Results

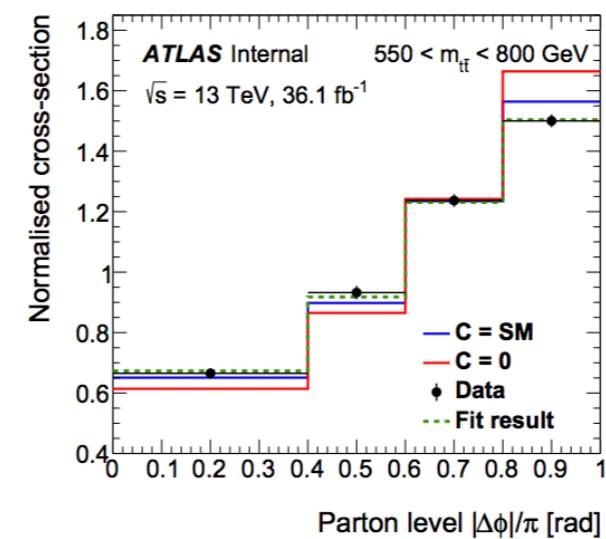
- The fraction of SM spin correlation ( $f_{SM}$ ) is extracted using a binned maximum likelihood fit with two templates:



(b)



(c)



- Statistical uncertainties are calculate using pseudo-data generated with poisson variations of the unfolded data.
- Full systematic shapes accounted for.

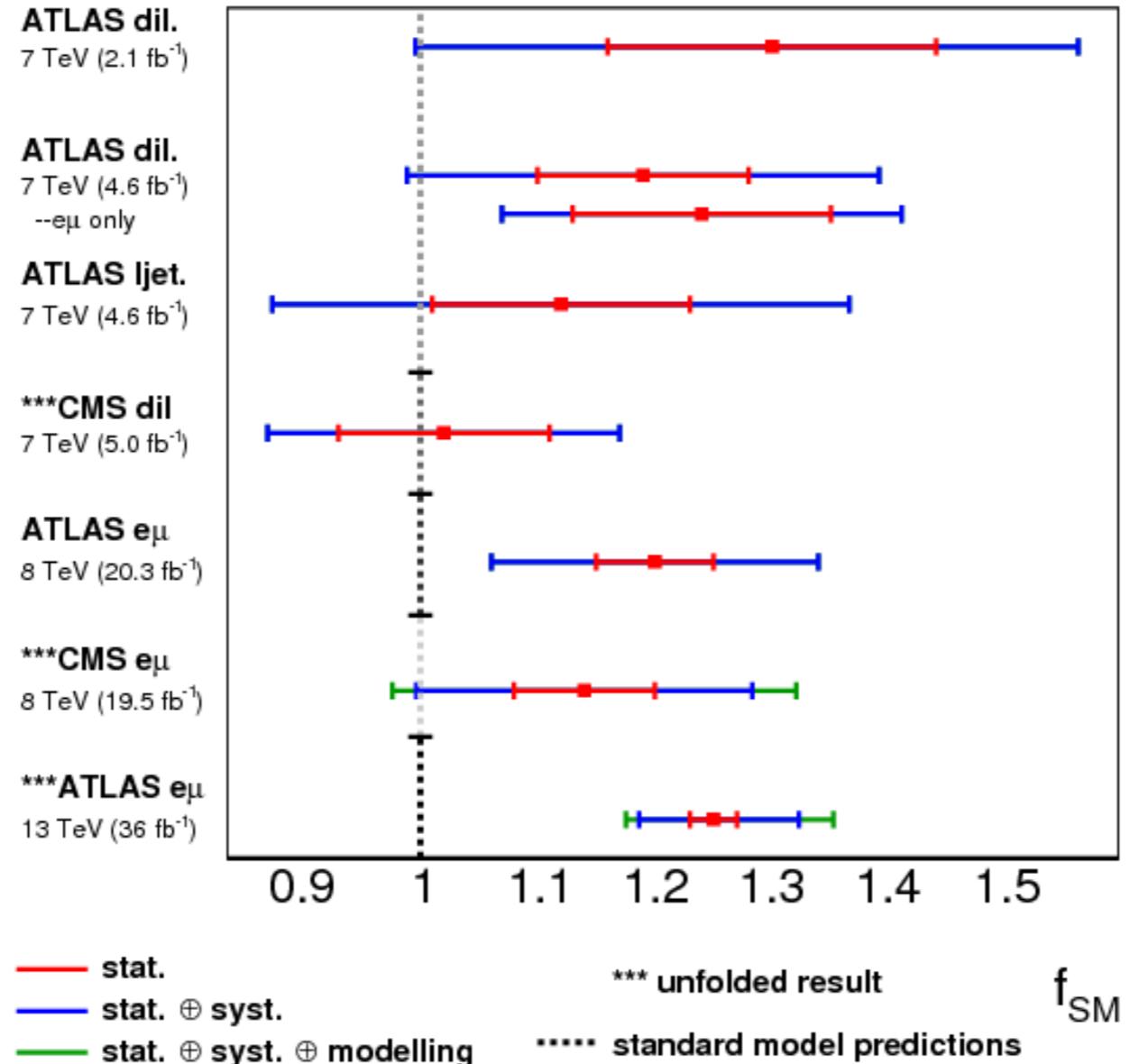
# Results

- The significance of the  $f_{SM}$ , relative to the SM template, is calculated using a  $CL_{s+b}$  method (though since no uncertainties are profiled, fitted, or floated, this is effectively the same as counting the number of s.d. away from  $f_{SM} = 1$ )

Region	$f_{SM}$	Consistency with SM (incl. theory uncertainties)
$m(t\bar{t}) < 450 \text{ GeV}$	$1.11 \pm 0.04^{+0.13}_{-0.13}$	0.85 (0.84)
$450 < m(t\bar{t}) < 550 \text{ GeV}$	$1.17 \pm 0.09^{+0.14}_{-0.14}$	1.00 (0.91)
$550 < m(t\bar{t}) < 800 \text{ GeV}$	$1.60 \pm 0.24^{+0.34}_{-0.35}$	1.40 (1.40)
$m(t\bar{t}) > 800 \text{ GeV}$	$2.2 \pm 1.8^{+2.4}_{-2.3}$	0.67 (0.67)
inclusive	$1.250 \pm 0.026^{+0.064}_{-0.063}$	3.70 (3.20)

- Two results are quoted; the extracted  $f_{SM}$  relative to the Powheg + Pythia8 prediction and the  $f_{SM}$  relative to the SM prediction (Powheg + Pythia8 with scale and PDF uncertainties).
- The  $f_{SM}$  increases as a function of  $m(t\bar{t})$ , though the uncertainties are too large to make a definitive statement on this.
- The inclusive  $f_{SM}$  significantly deviates from the SM prediction.

# Results



- When interpreted as spin correlation, this results in ~20% more than the spin correlation expectation of the SM, has been observed in many other results.

# Things we have already checked

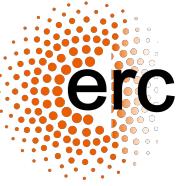
MANCHESTER  
1824



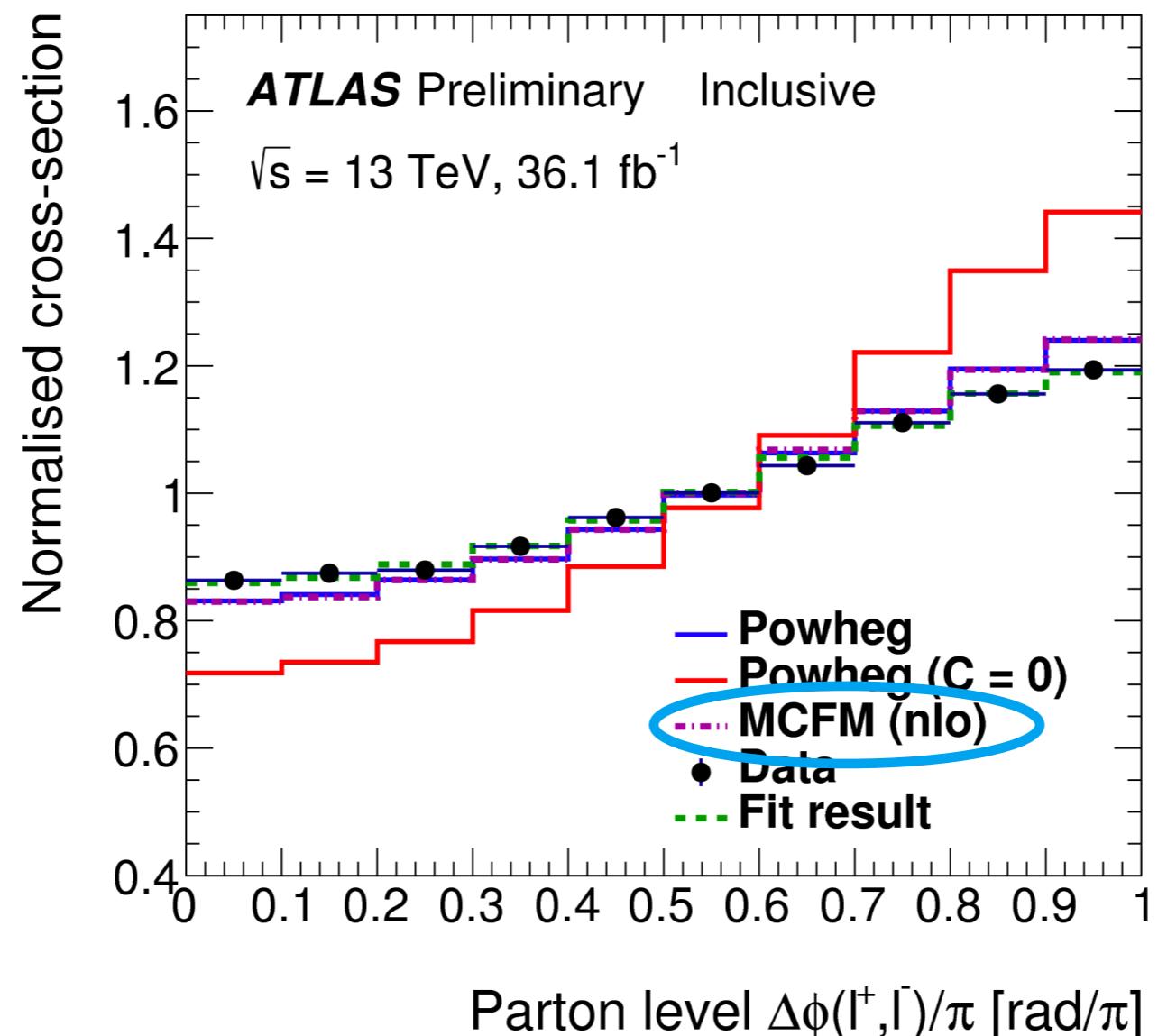
- Questions have naturally arisen about the templates we are using to extract spin correlation, and if some modelling effects may be missing?
- Thus far we have ruled-out the following:
  - **NLO effects in the decays of the top quarks:** Powheg (hvq) + Pythia8 is only NLO in production, but no difference were observed when comparing the  $\Delta\phi$  distribution with MCFM (which included NLO decays).
  - **Effect of NNLO in production:** We checked this by reweighing the top pT to match the NNLO prediction. The effect stays within the uncertainties we already consider.
  - **Effect of top pT modelling:** We checked this by reweighing to the top pT to match the unfolded data of several analyses that measure this quantity. The results agreed almost exactly with the NNLO test.
  - **Modelling of the underlying spin correlation:** Powheg agrees perfectly with the NLO predictions for Spin Correlation from Bernreuther, Heisler, and Si. MG5\_aMC@NLO is close, Sherpa 2.2.1 is completely off (and is therefore not used anywhere in the analysis, is apparently fixed in newer version).

# Things we have already checked

MANCHESTER  
1824



- **NLO effects in the decays of the top quarks:** Powheg (hvq) + Pythia8 is only NLO in production, but no difference were observed when comparing the  $\Delta\phi$  distribution with MCFM (which included NLO decays).

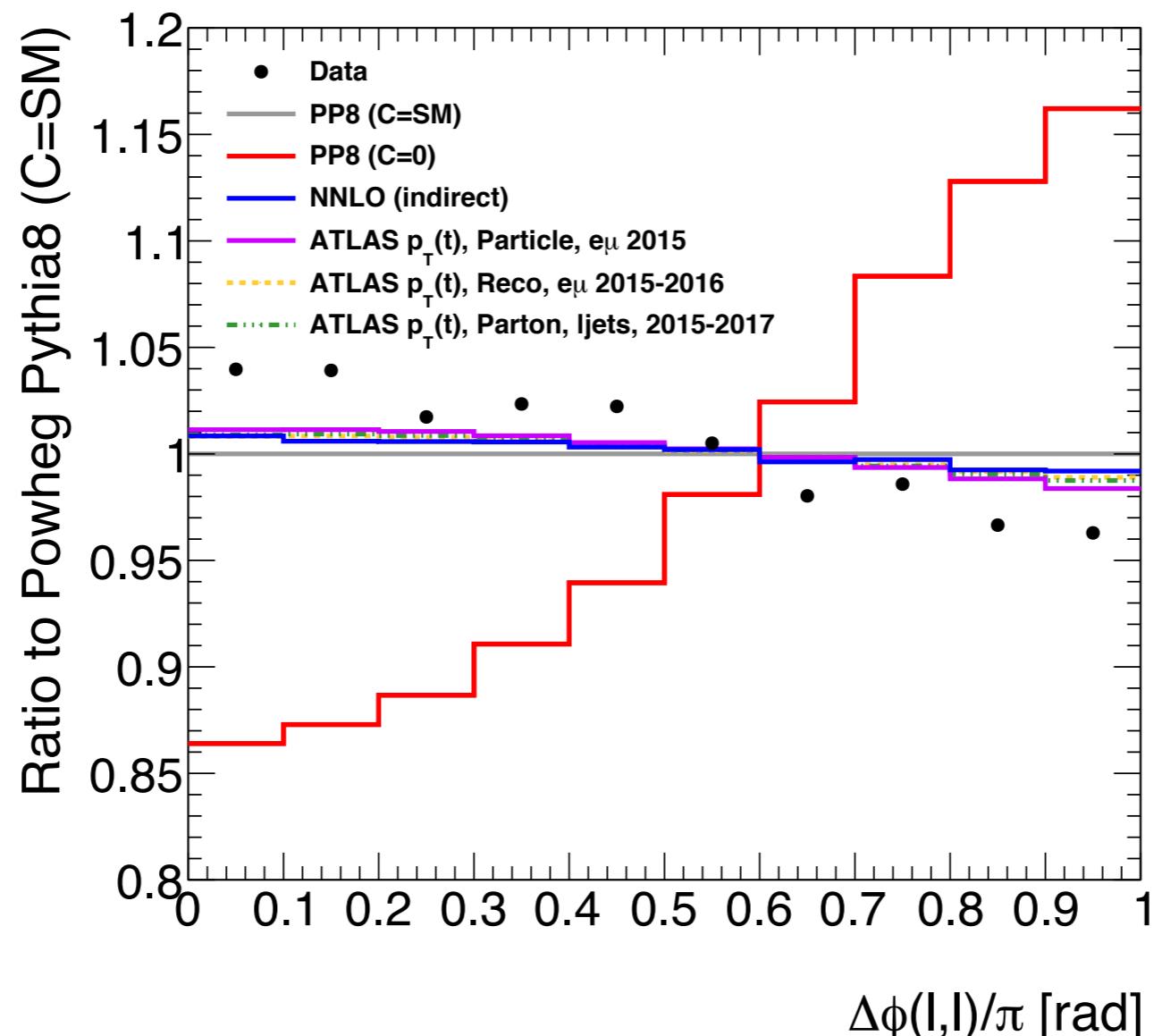


# Things we have already checked

MANCHESTER  
1824

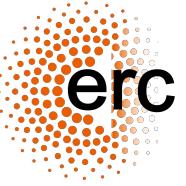


- **Effect of NNLO in production:** We checked this by reweighting the top pT to match the NNLO prediction. The effect stays within the uncertainties we already consider.

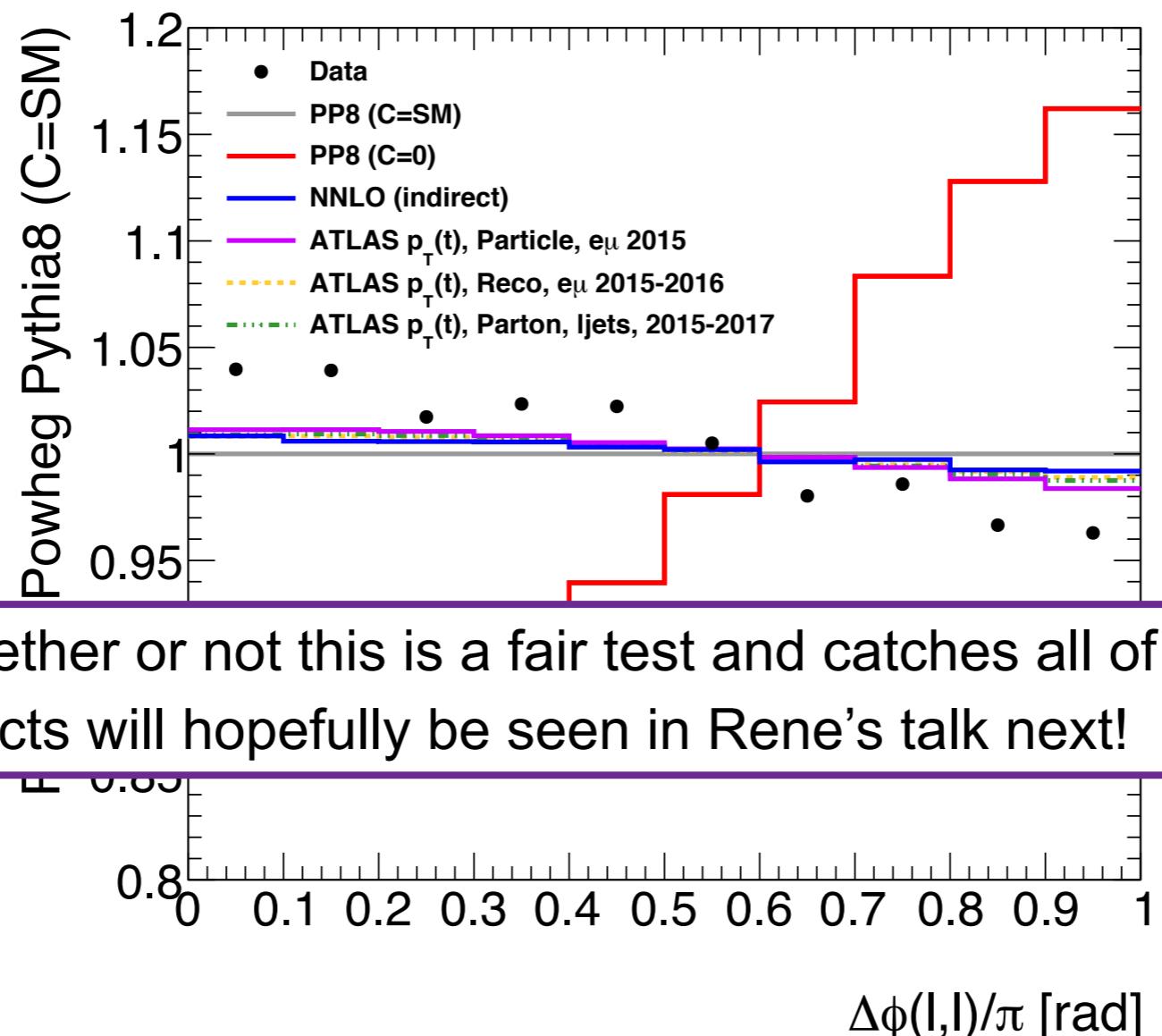


# Things we have already checked

MANCHESTER  
1824



- **Effect of NNLO in production:** We checked this by reweighting the top pT to match the NNLO prediction. The effect stays within the uncertainties we already consider.



- Whether or not this is a fair test and catches all of the NNLO effects will hopefully be seen in Rene's talk next!

# Things we have already checked

MANCHESTER  
1824

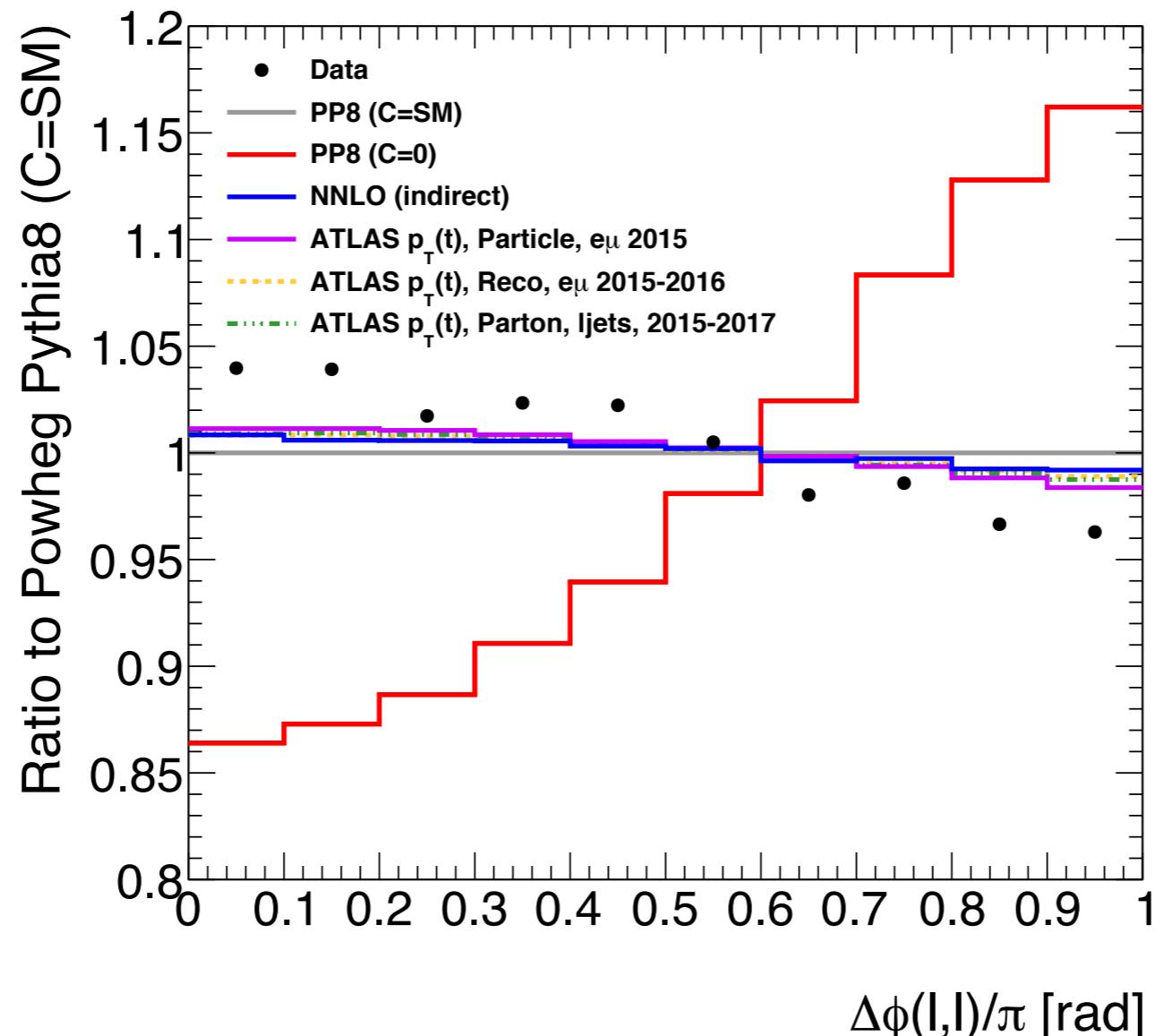


# Things we have already checked

MANCHESTER  
1824

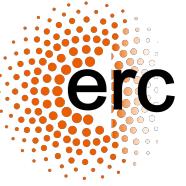


- **Effect of top pT modelling:** We checked this by reweighing to the top pT to match the unfolded data of several analyses that measure this quantity. The results agreed almost exactly with the NNLO test.



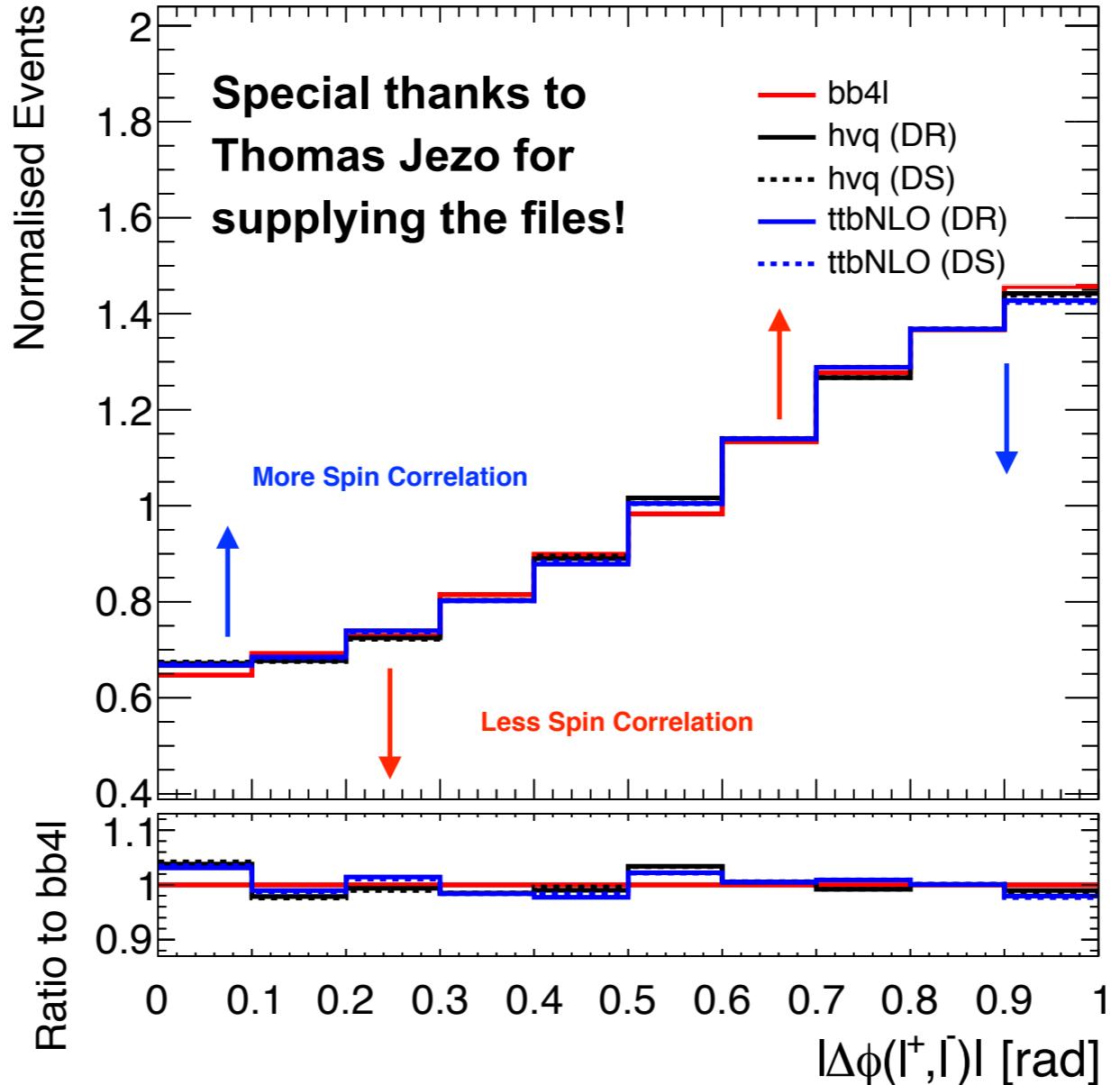
# Things we have already checked

MANCHESTER  
1824



- **Modelling of the underlying spin correlation:** Powheg agrees perfectly with the NLO predictions for Spin Correlation from Bernreuther, Heisler, and Si. MG5\_aMC@NLO is close, Sherpa 2.2.1 is completely off (and is therefore not used anywhere in the analysis, fixed in newer version).

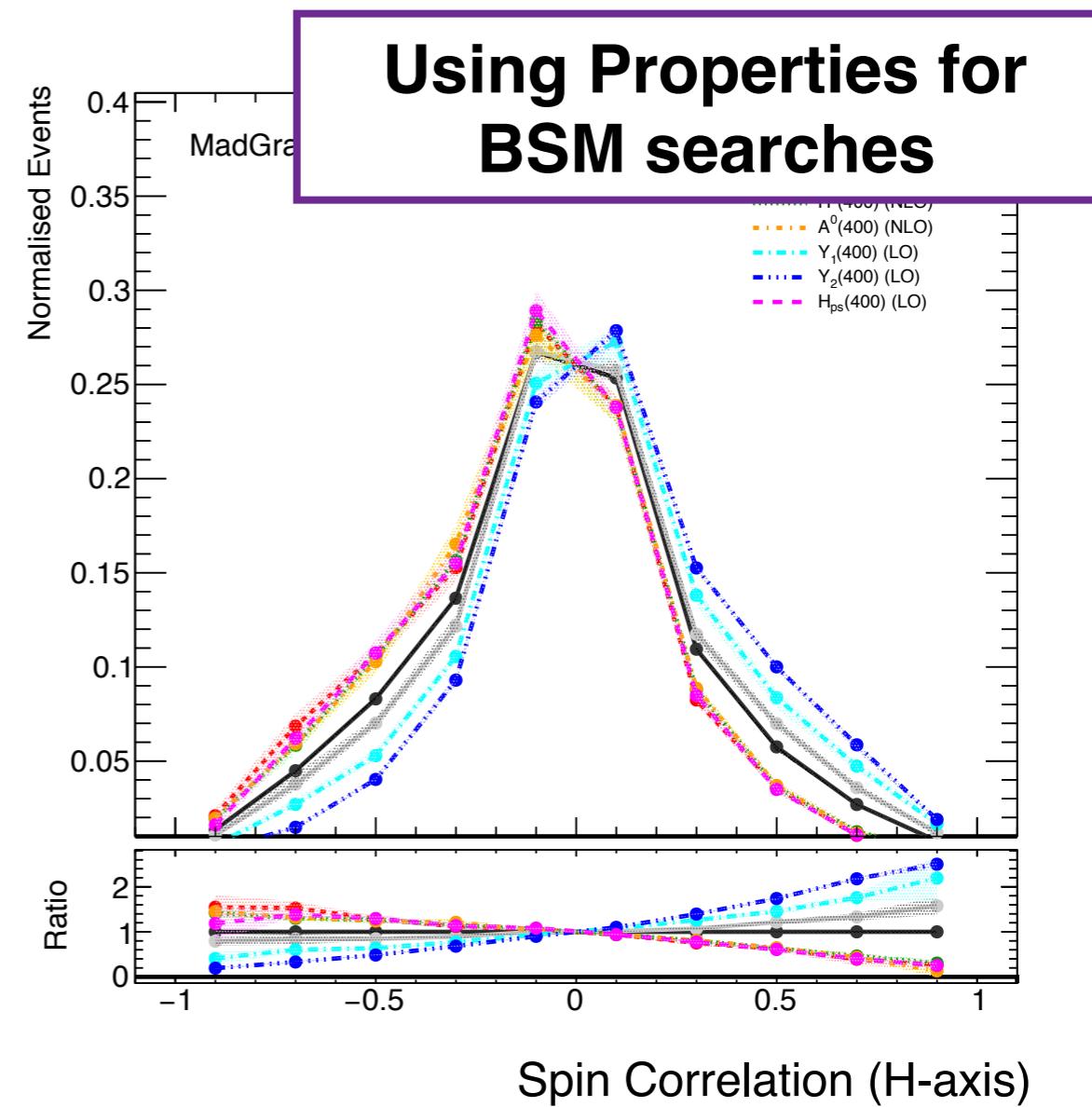
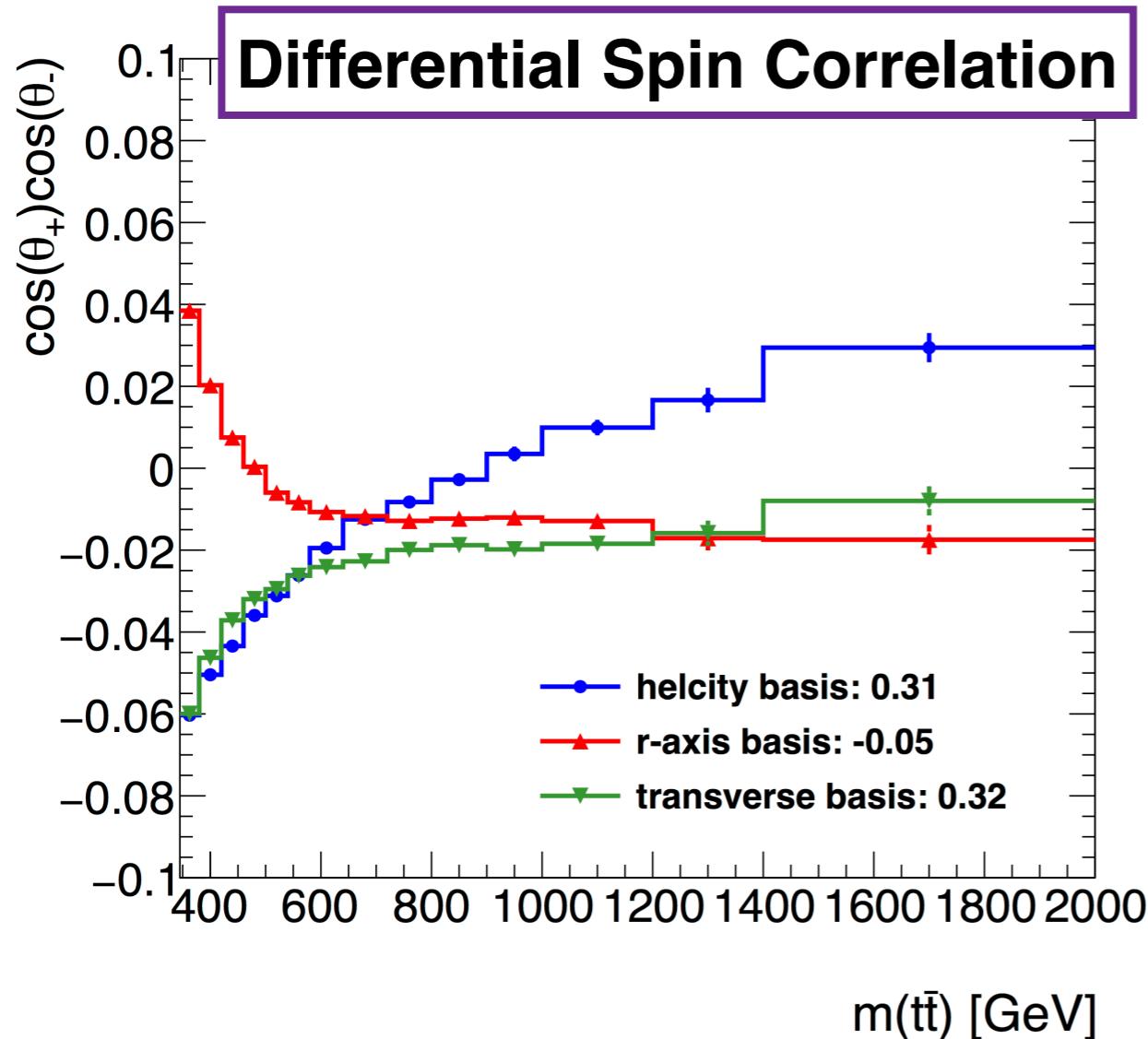
Sample	$C_{\text{helicity}}$	$C_{\text{raxis}}$	$C_{\text{transverse}}$
Bernreuther, Heisler & Si (NLO 13 TeV)	$0.318 \pm 0.003$	$0.055 \pm 0.009$	$0.332 \pm 0.002$
POWHEG + PYTHIA8 (dil.)	$0.314 \pm 0.002$	$-0.050 \pm 0.002$	$0.320 \pm 0.002$



- **This is not a  $t\bar{t}$  comparison!** It is the leptonic  $WbWb$  final state ( $t\bar{t} + Wt$ , or  $bb4l$ )
- bb4l, hvq, and ttbNLO\_dec all agree very well for the delta phi observable.
- Type of overlap handling between ttbar and Wt also not a large effect here.

# Future Work

- Although  $|\Delta\phi|$  was necessary for first observation and due to statistics, we're explicitly hiding any possible CP effects. We have the statistics now, any future use of the observable should utilise a  $-\pi \rightarrow +\pi$  binning!



# Conclusions

- ATLAS have measured spin correlation using the delta phi observable that disagrees with the SM prediction by 3.2 sigma.
- Largest systematic uncertainties come from modelling of the  $t\bar{t}$  system.
- All of our efforts to explain the deviation in the context of limited MC precision or MC assumptions have failed, systematic prescription is quite conservative.
- We have also investigated spin correlations as a function of the invariant mass of the  $t\bar{t}$  system, but uncertainties are large.



# BACKUP

## Andrew Papanasatiou's Top2017 talk

Two mainstream ways of calculating, when top decay is included:

- ▶ Narrow-width approximation (NWA),  $p(t)^2 = m_t^2$ ,  $\Gamma_t \rightarrow 0$  limit
  - ▶ NLO: [Bernreuther, Si; Melnikov, Schulze; Campbell, Ellis (MCFM)]
  - ▶ production / decay of **onshell** tops completely factorize
  - ▶ compute higher-order corrections to prod. & decay separately
  - ▶ for large class of observables NWA is an **excellent** approx (error  $\sim \mathcal{O}(\Gamma_t/m_t)$ )
- ▶ Offshell,  $p(t)^2 \neq m_t^2$ 
  - ▶ NLO: [Bevilaqua et al, Denner et al, Falgari et al, Heinrich et al, Frederix, Cascioli et al]
  - ▶ diagrams involving top quarks only form a subset of all required contributions
  - ▶ since there are both resonant and non-resonant contributions, notion of a physical, onshell top-quark parton loses meaning
  - ▶ finite-width effects **vital** in certain regions of phase space, e.g. edge of  $M_{bl}$  distribution!

## Andrew Papanasatiou's Top2017 talk

Two mainstream ways of calculating, when top decay is included:

- ▶ Narrow-width approximation (NWA),  $p(t)^2 = m_t^2$ ,  $\Gamma_t \rightarrow 0$  limit
  - ▶ NLO: [Bernreuther, Si; Melnikov, Schulze; Campbell, Ellis (MCFM)]
  - ▶ production / decay of **onshell** tops completely factorize
  - ▶ compute higher-order corrections to prod. & decay sepa
  - ▶ for large class of observables NWA is an **excellent approx** (error  $\sim \mathcal{O}(\Gamma_t/m_t)$ )
- ▶ Offshell,  $p(t)^2 \neq m_t^2$ 
  - ▶ NLO: [Bevilacqua et al, Denner et al, Falgari et al, Heinrich et al, Frederix, Cascioli et al]
  - ▶ diagrams involving top quarks only form a subset of all required contributions
  - ▶ since there are both resonant and non-resonant contributions, notion of a physical, onshell top-quark parton loses meaning
  - ▶ finite-width effects vital in certain regions of phase space, e.g. edge of  $M_{bl}$  distribution!

All of our top MC in  
ATLAS uses the  
NWA.

## Andrew Papanasatiou's Top2017 talk

Two mainstream ways of calculating, when top decay is included:

- ▶ Narrow-width approximation (NWA),  $p(t)^2 = m_t^2$ ,  $\Gamma_t \rightarrow 0$  limit
  - ▶ NLO: [Bernreuther, Si; Melnikov, Schulze; Campbell, Ellis (MCFM)]
  - ▶ production / decay of onshell tops completely factorize
  - ▶ compute higher-order corrections to prod. & decay separately
  - ▶ for large class of observables NWA is an excellent approximation (error  $\sim \mathcal{O}(\Gamma_t/m_t)$ )
- ▶ Offshell,  $p(t)^2 \neq m_t^2$ 
  - ▶ NLO: [Bevilacqua et al, Denner et al, Falgari et al, Heinrich et al, Frederix, Casalderrey-Solana et al]
  - ▶ diagrams involving top quarks only form a subset of all contributions
  - ▶ since there are both resonant and non-resonant contributions, notion of a physical, onshell top-quark parton loses meaning
  - ▶ finite-width effects vital in certain regions of phase space, e.g. edge of  $M_{bl}$  distribution!

The off-shell effects are not expected to be large in an inclusive phase-space (like the one used in this analysis)

## Tomas Jezo's Top2017 talk

- hvq [Frixione, Nason, Ridolfi, 2007], ST\_wtch\_DR(S) [Re, 2010]
  - ▶ Production at NLO
  - ▶ Decays at LO
  - ▶ Radiation from FS  $b$ 's only with PS
  - ▶ Includes hadronic  $W$  decays
- ttb\_NLO\_dec [Campbell, Ellis, Nason, Re, 2014]
  - ▶ Production at NLO
  - ▶ Decays at NLO
  - ▶ Radiation from FS  $b$ 's with ME (thanks to allrad)
  - ▶ Includes hadronic  $W$  decays,  $Wt$  contribution at LO
- bb4l [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]
  - ▶  $pp \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b \bar{b}$  production at NLO (production and decay at NLO)
  - ▶ Radiation from FS  $b$ 's with ME (thanks to allrad)
  - ▶ No hadronic  $W$  decays, Includes  $Wt$  contribution



## Tomas Jezo's Top2017 talk

- hvq [Frixione, Nason, Ridolfi, 2007], ST\_wtch\_DR(S) [Re, 2010]
  - ▶ Production at NLO
  - ▶ Decays at LO
  - ▶ Radiation from FS  $b$ 's only with PS
  - ▶ Includes hadronic  $W$  decays
- ttb\_NLO\_dec [Campbell, Ellis, Nason, Re, 2014]
  - ▶ Production at NLO
  - ▶ Decays at NLO
  - ▶ Radiation from FS  $b$ 's with ME (thanks to allrad)
  - ▶ Includes hadronic  $W$  decays,  $Wt$  contribution at LO
- bb4l [TJ, Lindert, Nason, Oleari, Pozzorini, 2016]
  - ▶  $pp \rightarrow \ell^+ \nu_\ell \ell^- \bar{\nu}_\ell b \bar{b}$  production at NLO (production and decay at NLO)
  - ▶ Radiation from FS  $b$ 's with ME (thanks to allrad)
  - ▶ No hadronic  $W$  decays, Includes  $Wt$  contribution

So the question is,  
how does spin  
correlation look in  
each of these  
processes?

