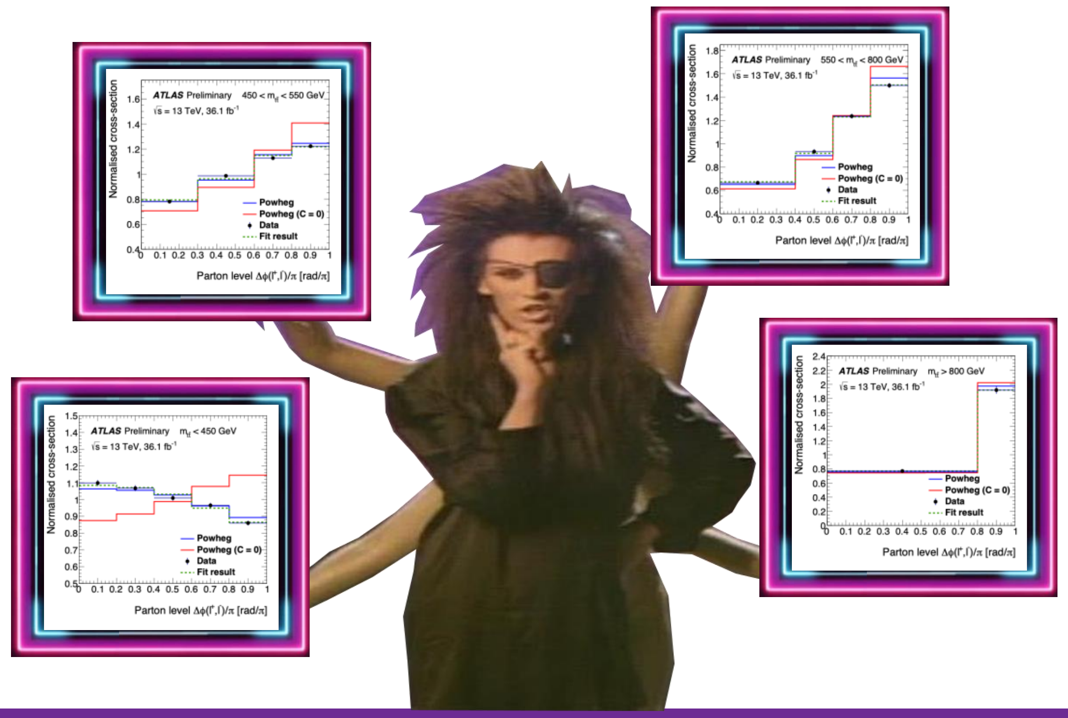
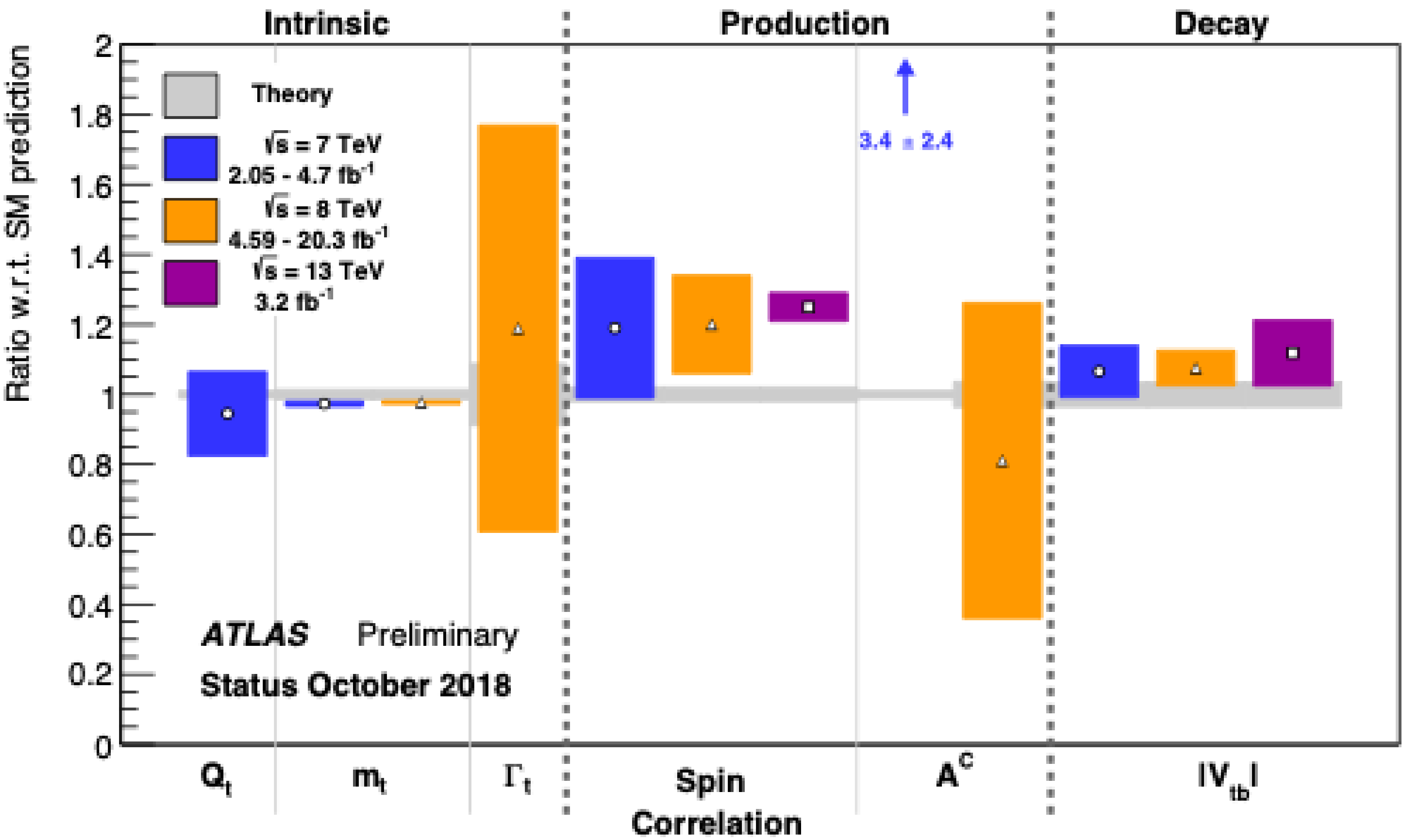
You spin me right round baby

Jay Howarth: On behalf of the ATLAS experiment



Top Quark Properties

ATL-PHYS-PUB-2018-034/



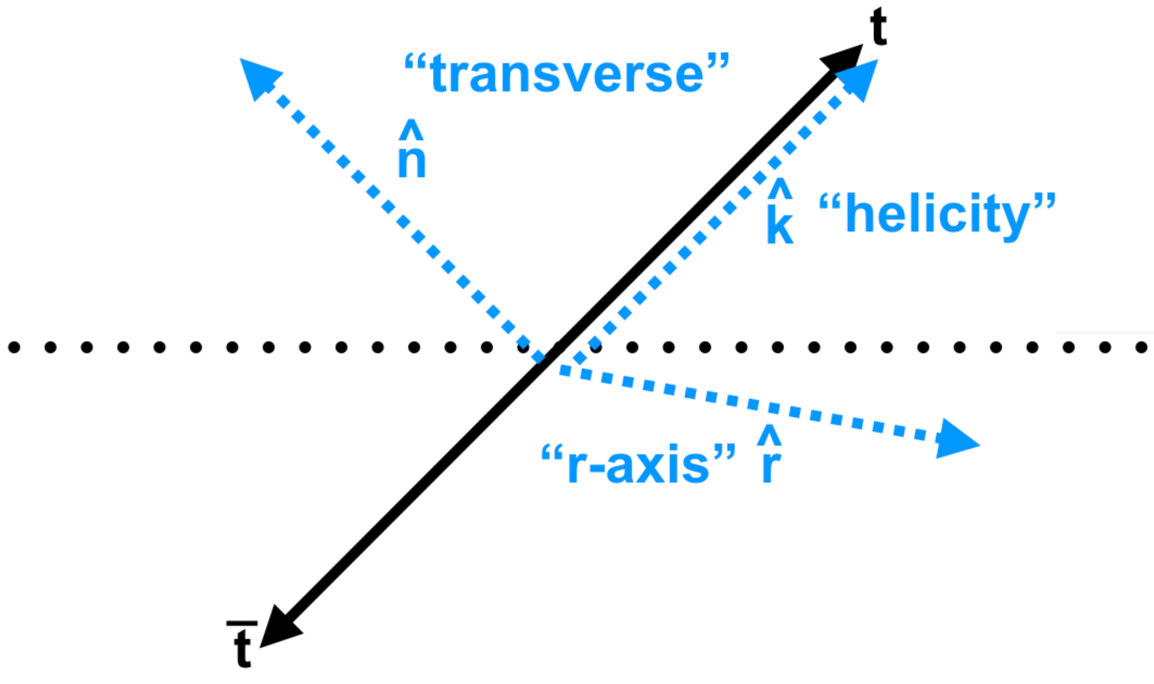
- In the last 10 years we've learned an awful lot about the top quark, including some things that had never been measured before.

What is Spin Correlation?

- 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 α is the "**spin analysing power**" of some decay particle from a top quark (~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**

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

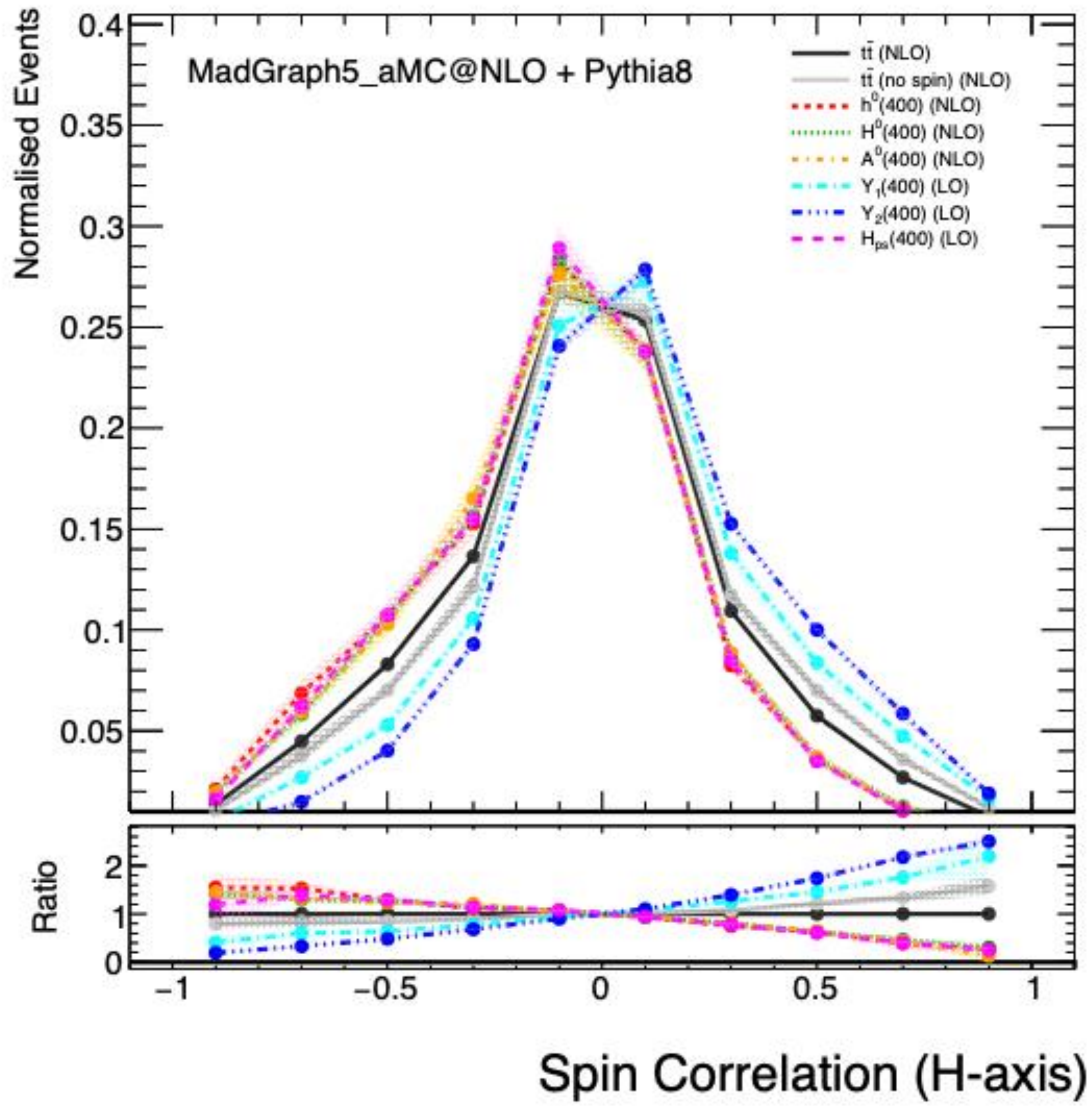
- By measuring the cos(θ) angles (usually with leptons) we can directly extract the spin correlation parameter C:

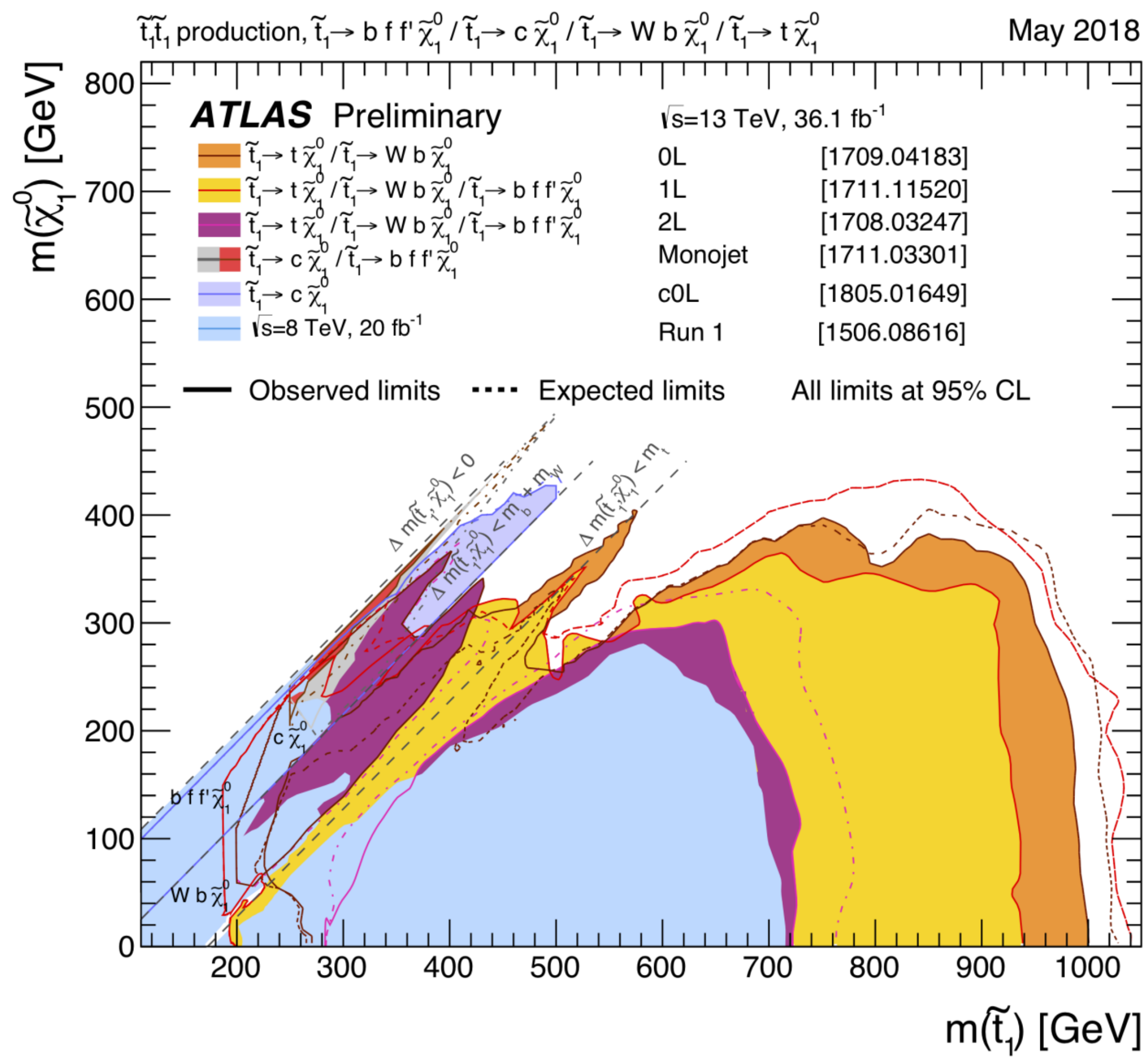
$$B_+ = 3 \cdot < cos(\theta_+) > \qquad C = -9 \cdot < cos(\theta_+) cos(\theta_-) >$$

- ATLAS measured the spin correlation parameter, **C**, the polarisation parameters **B**, and cross-correlations (cos(θ+) and cos(θ-) 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?

Rob White, Manchester





- 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.

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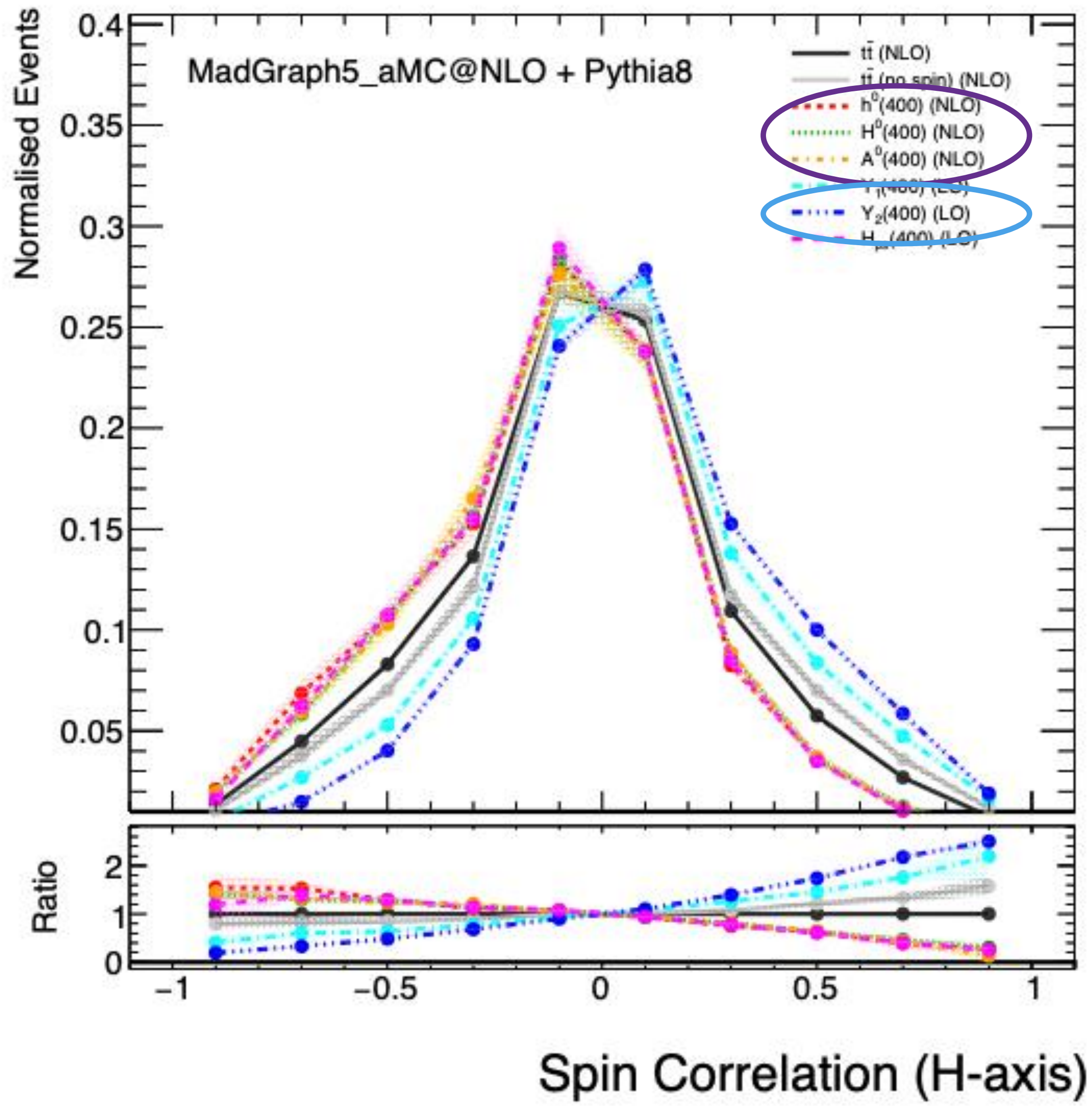

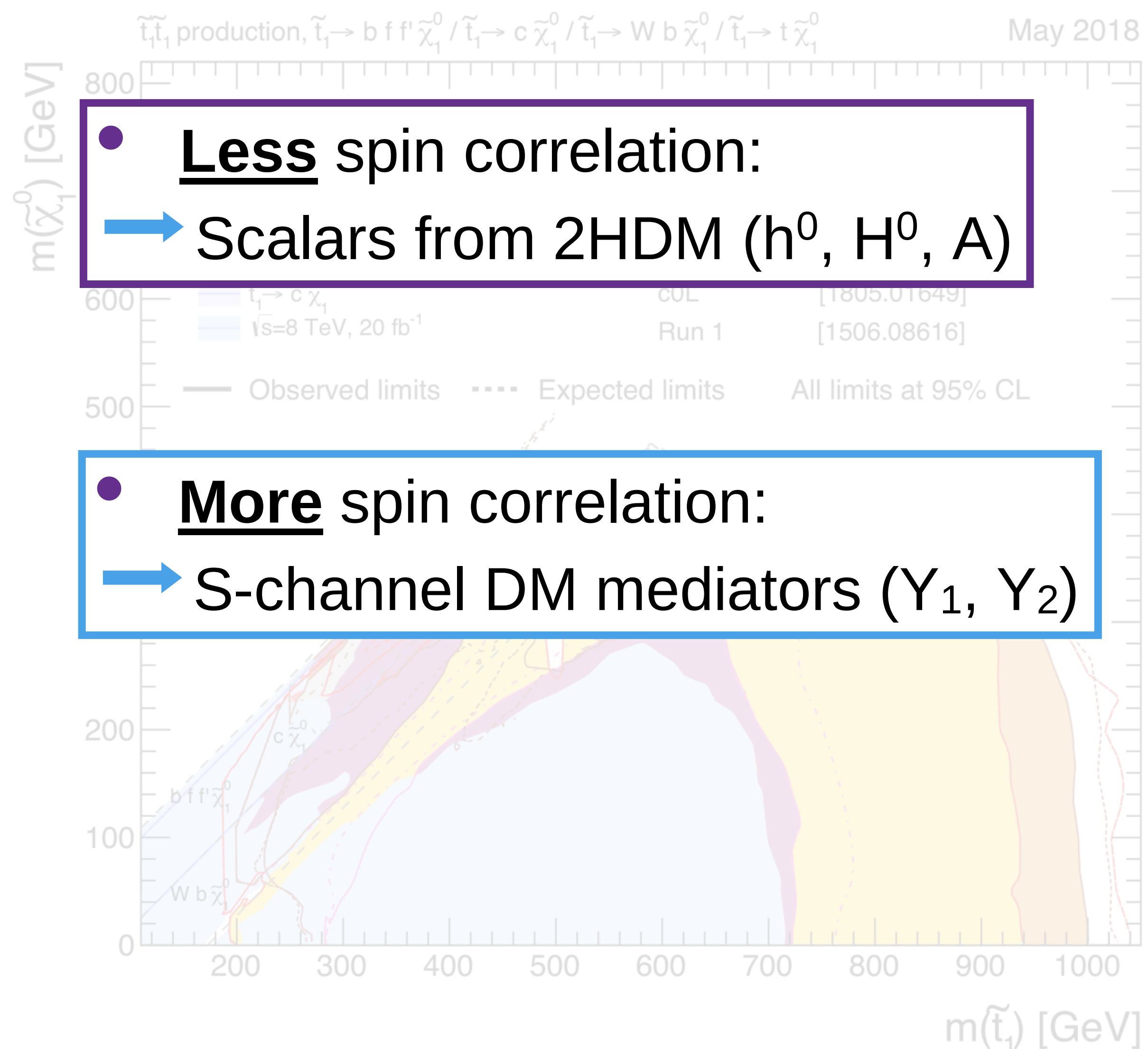

- **<u>Less</u>** spin correlation:
  ➡ Scalars from 2HDM (h^0, H^0, A)

- **<u>More</u>** spin correlation:
  ➡ S-channel DM mediators (Y_1, Y_2)

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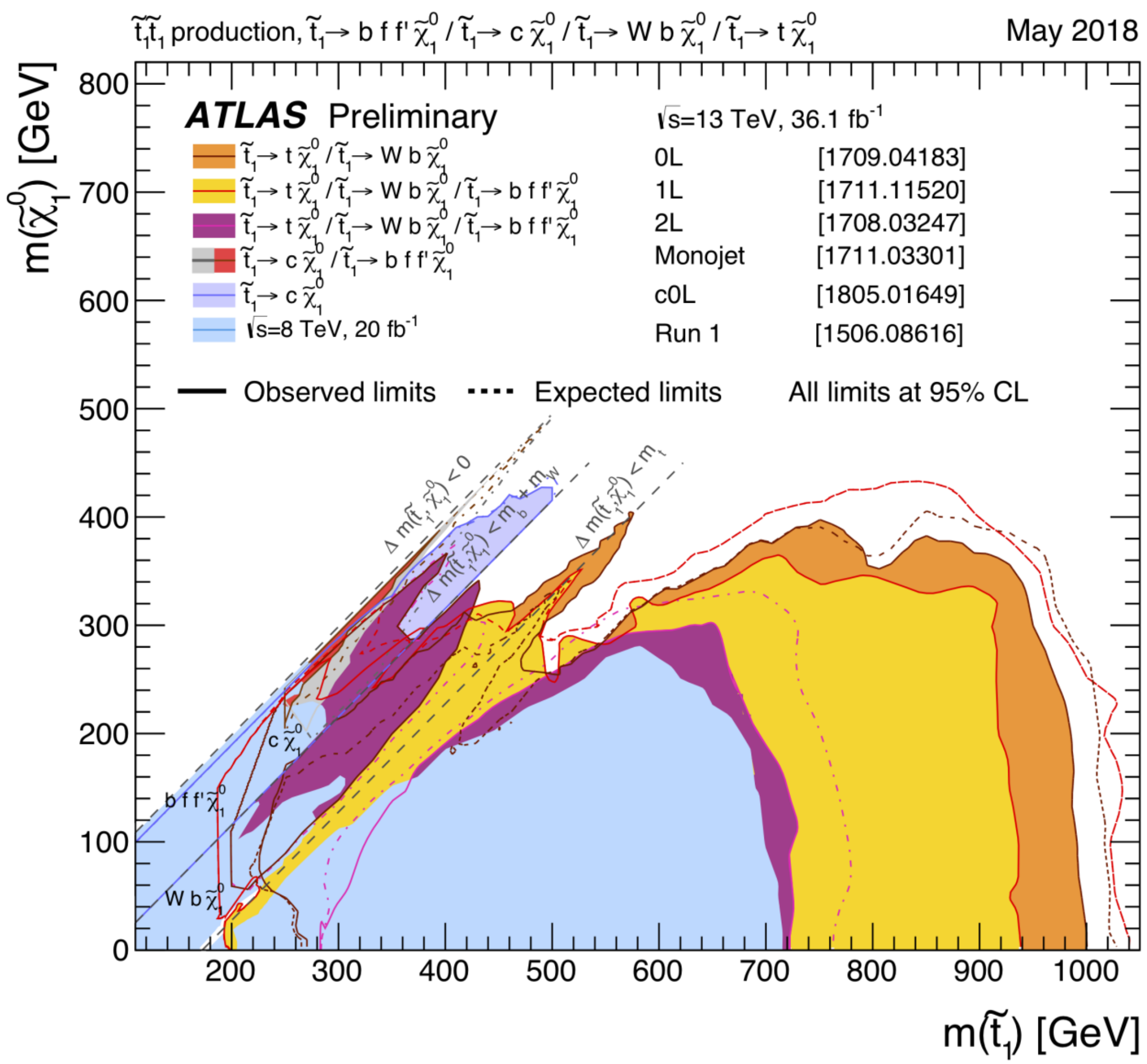

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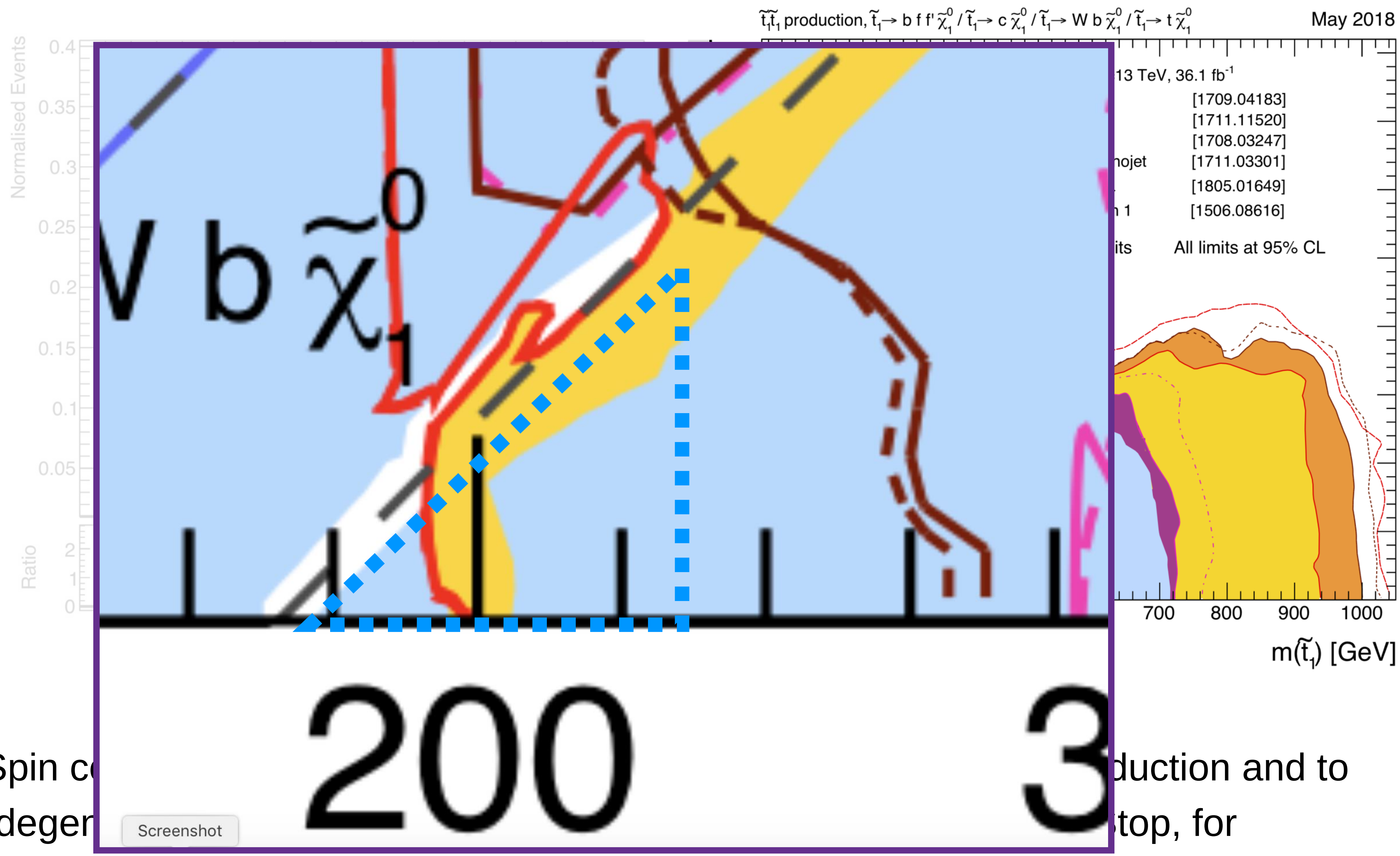
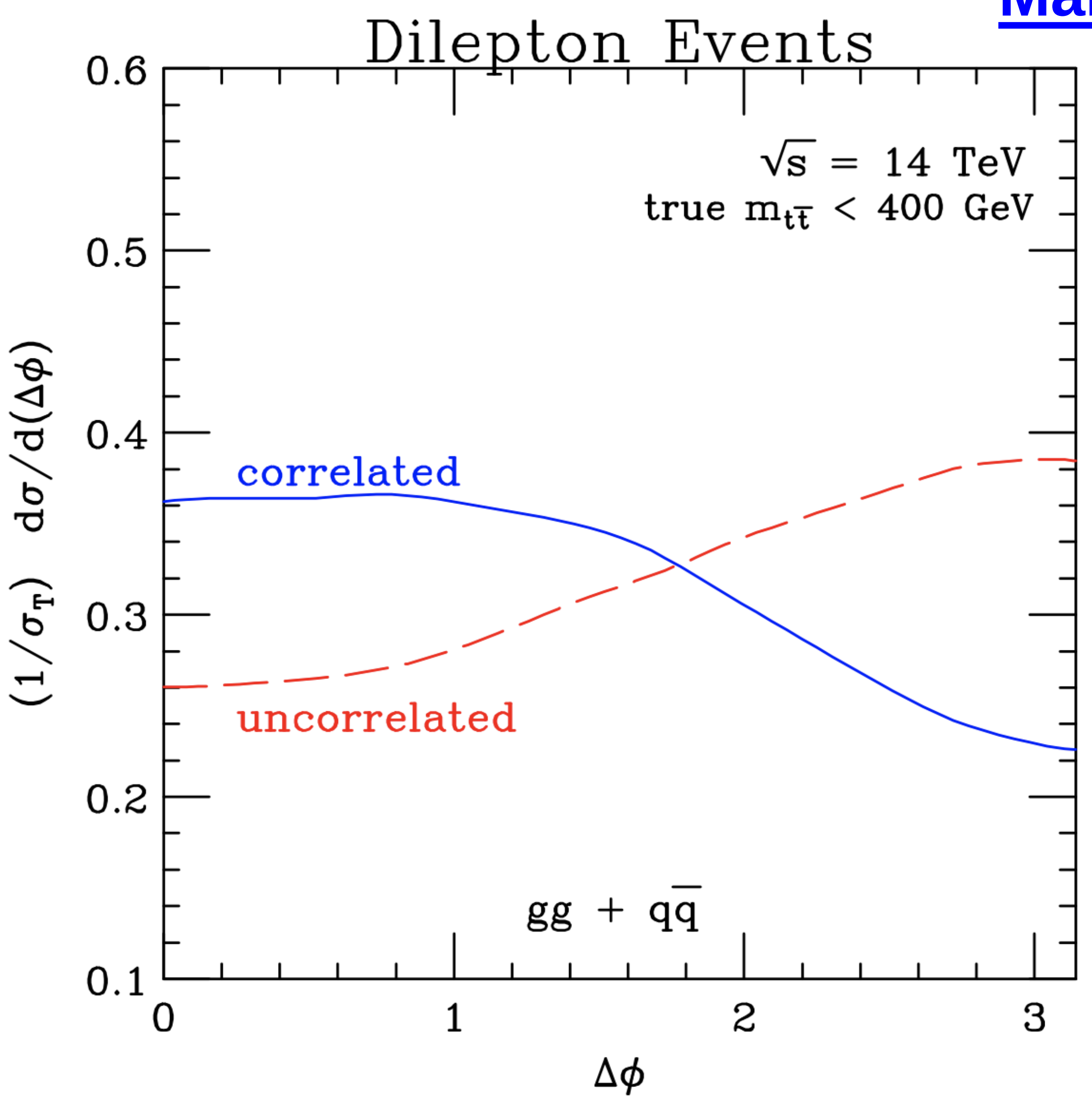


- Spin c… …duction and to "degen… …top, for example).
- Used at 8 TeV to set limits in kinematically difficult region.

An easier observable

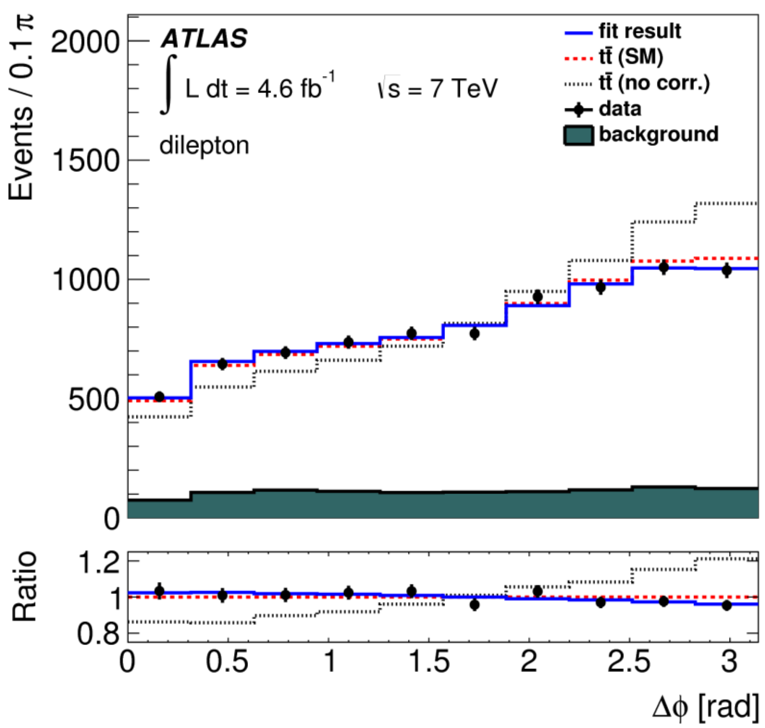
- Though it cannot be directly translated in to the **C** parameter, spin correlation can be inferred from the difference between the azimuthal angle between the two charged leptons in the lab frame (**Δϕ**).

[Mahlon, Parke, 2010]

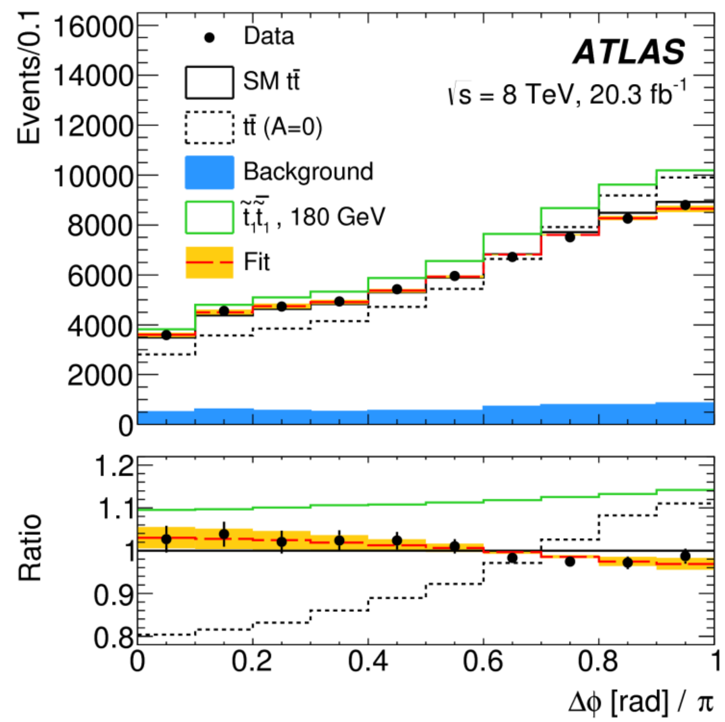


Previous Measurements

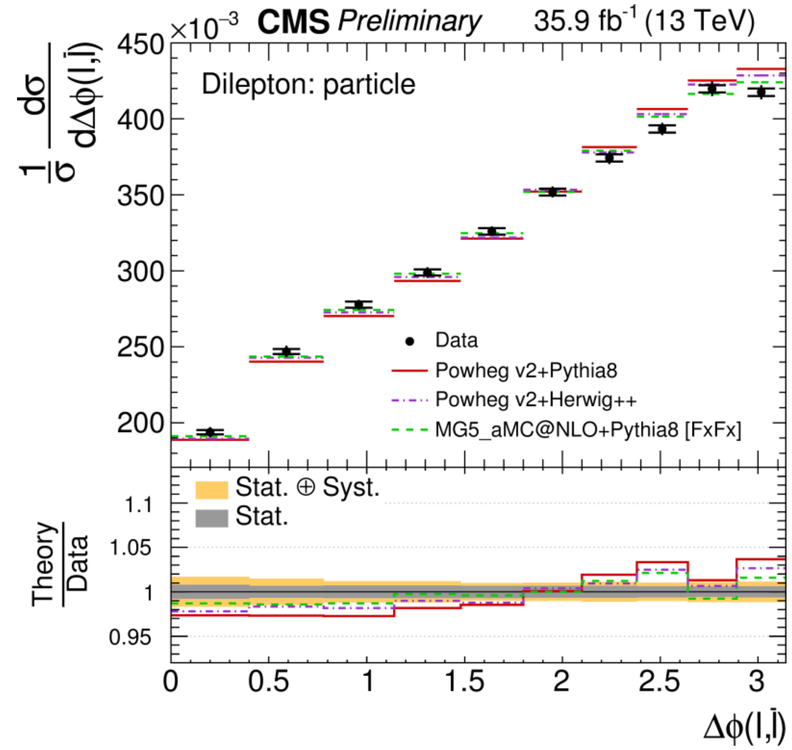
ATLAS Reco-level



ATLAS Reco-level



CMS Particle-level Link



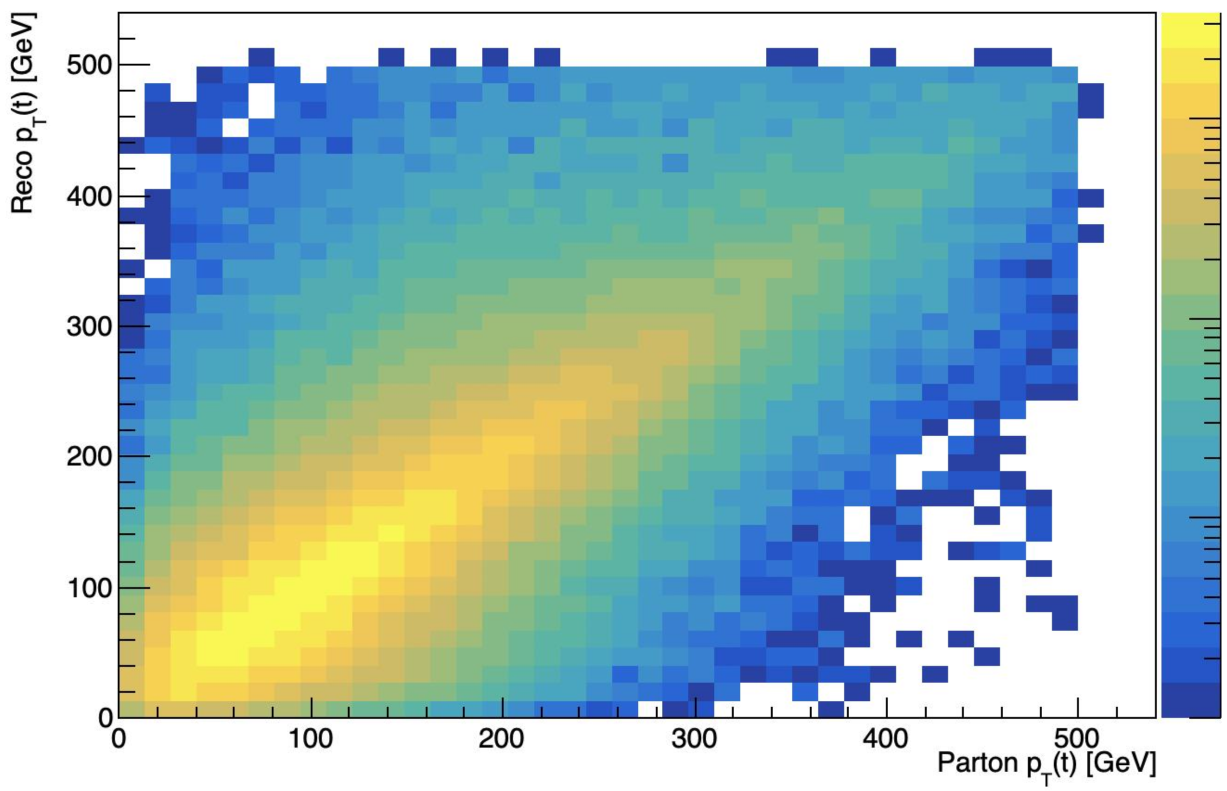
- ATLAS used this observable to obtain first evidence for spin correlation during Run1.
- ATLAS and CMS have since both measured spin correlation using this observable at multiple collision energies.
- Both experiments have observed (at all collision energies) that the |Δϕ| spectra in our simulations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

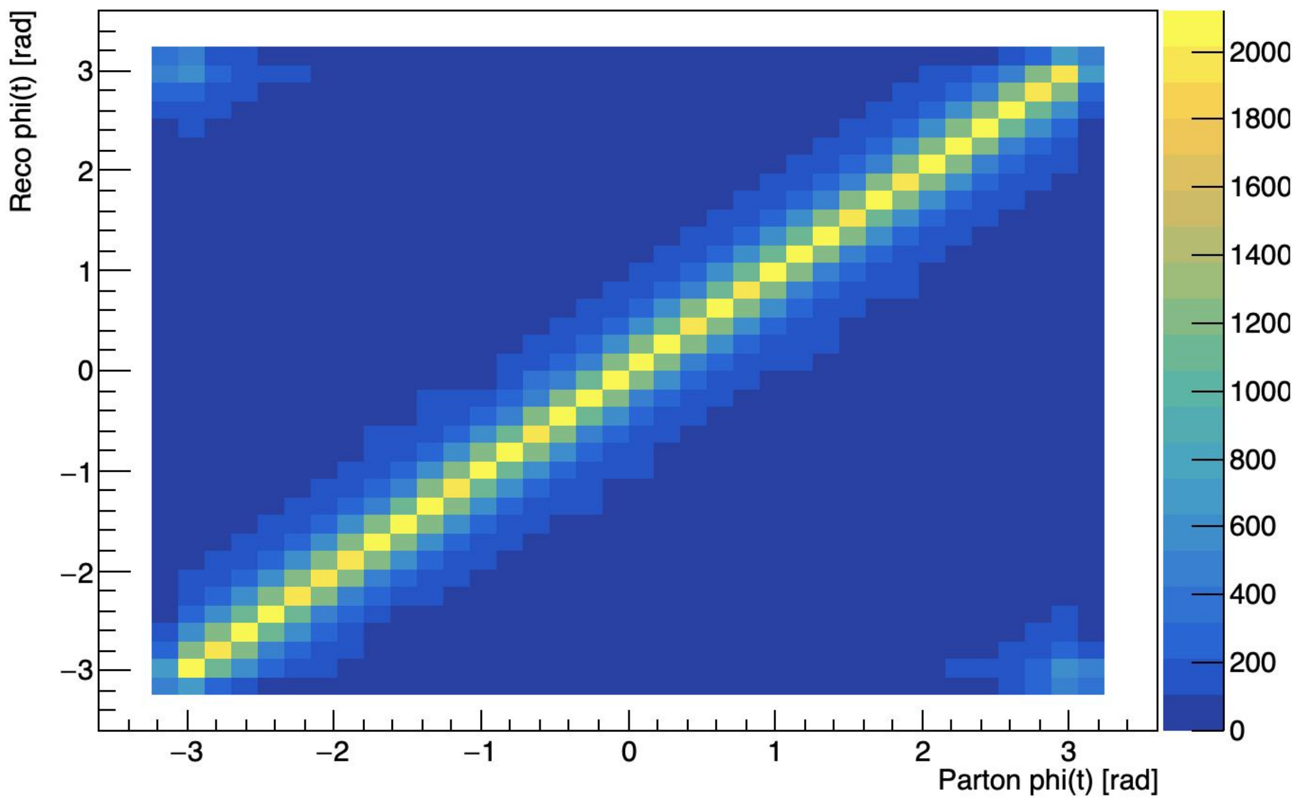
ATLAS 13 TeV measurement

- We use 2015 + 2016 data with a standard dilepton **eμ selection**:
  - → exactly 2 opposite-sign leptons (27, 25 GeV)
  - → At least one b-jet; >= 2 jets pT > 25 GeV.
  - → No cuts on MET or on m(ll)

- We measure the **Δϕ** 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-kT 0.4 jets with ghost-matching for b-tagging.
  - → Same fiducial selection as reco level.

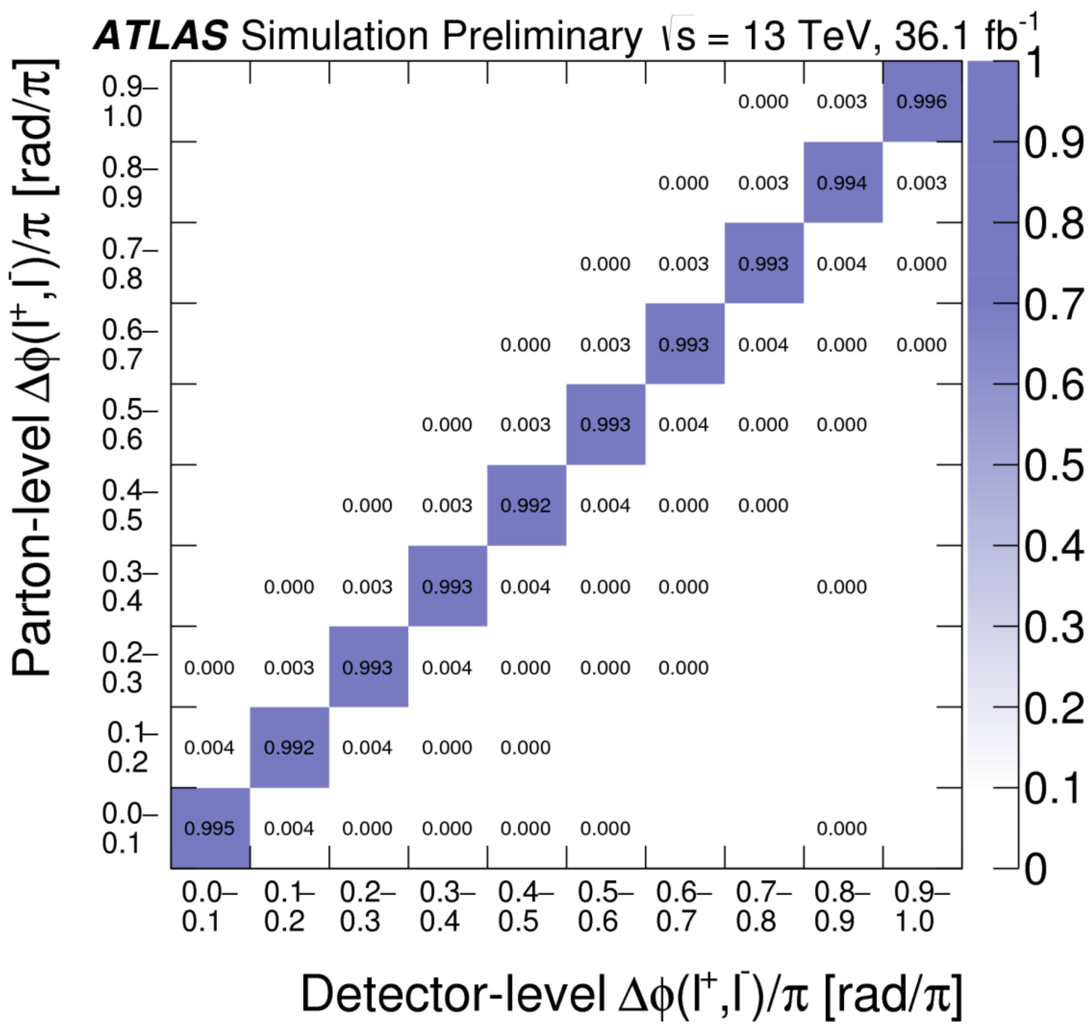
Full ttbar Reconstruction

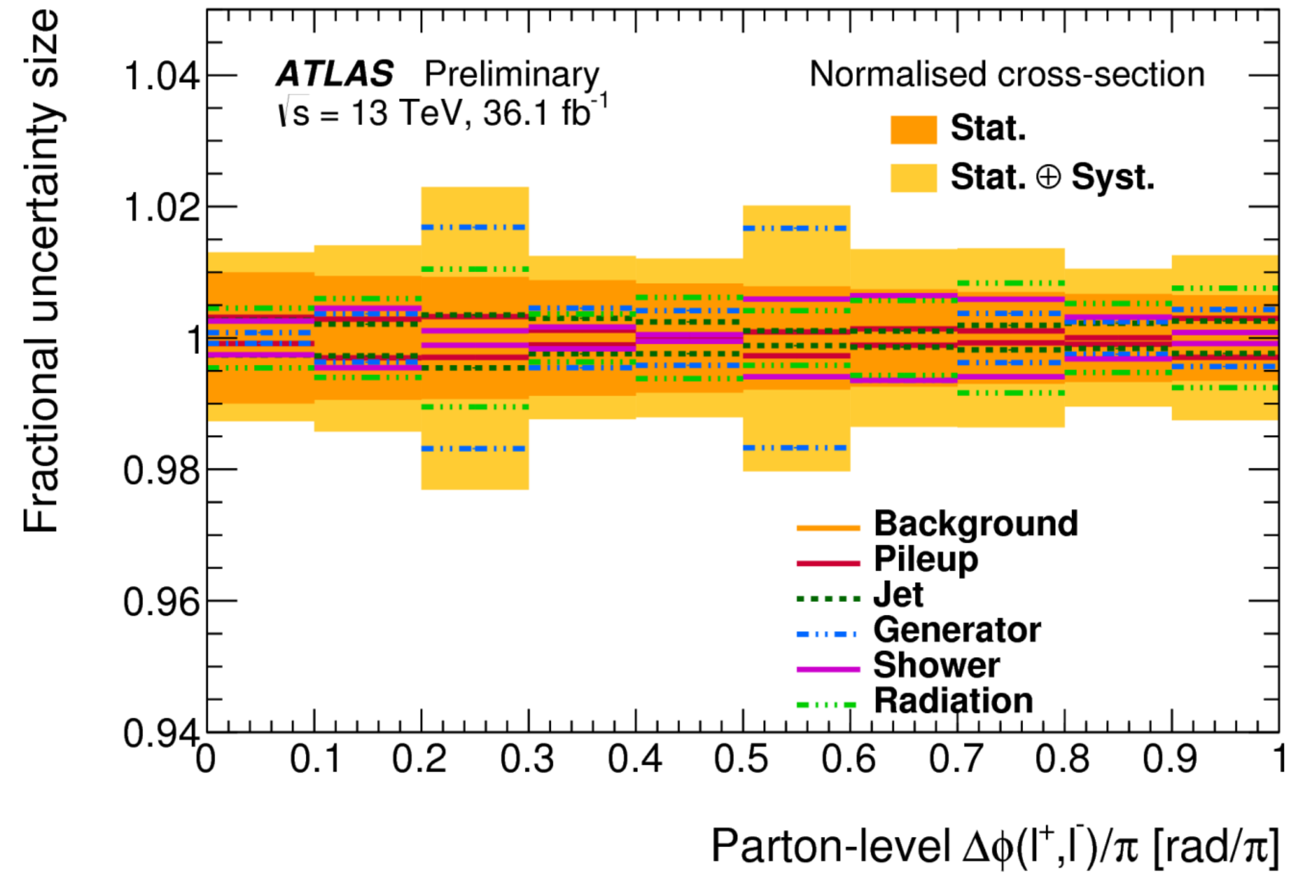




- This analysis uses Neutrino Weighting to reconstruct the dileptonic $t\bar{t}$ final state.
- Well-known and uncontroversial technique, used in many published analyses.
- Excels at angular resolution, does a decent job of momenta and energy resolutions.

Systematics and Unfolding

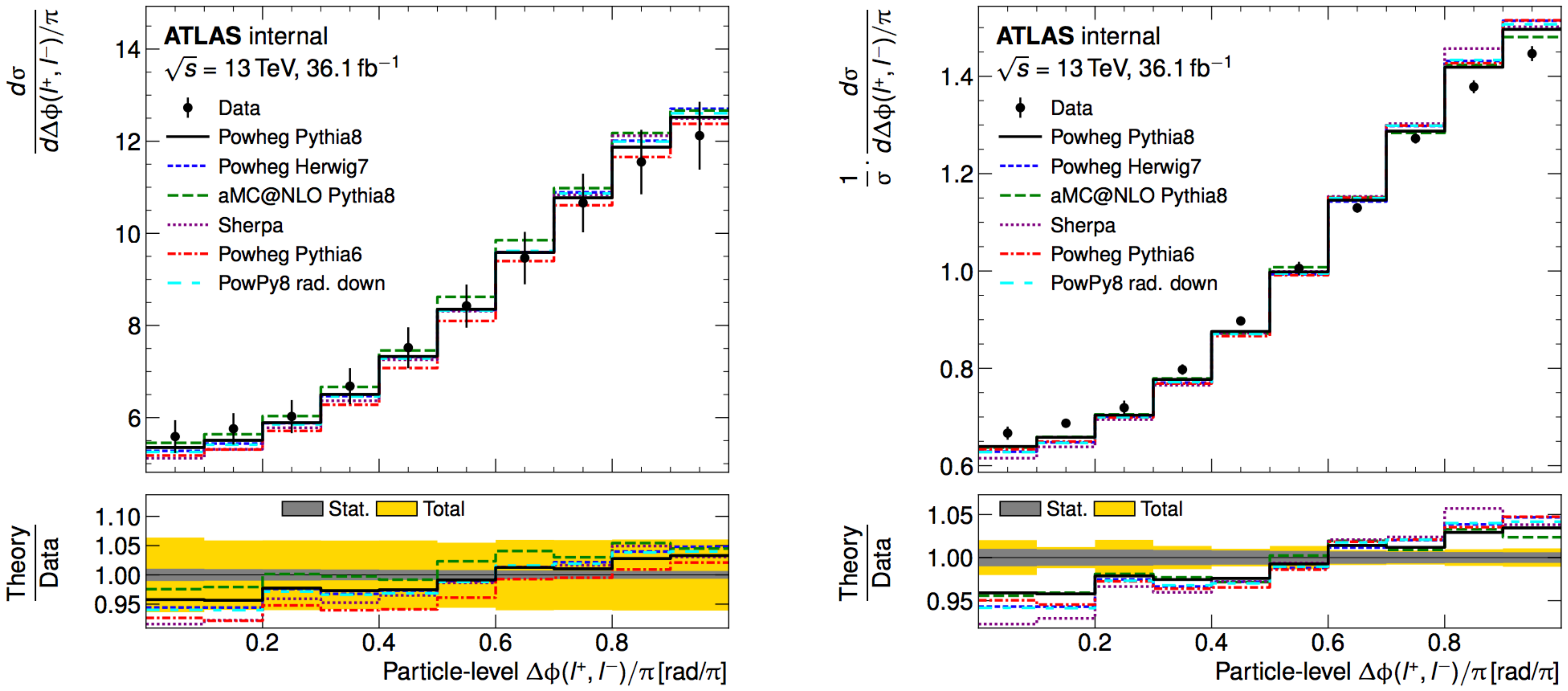




- Iterative Bayesian Unfolding is used to correct the data to Parton level.
- Systematic uncertainties are evaluated by unfolding a systematic shifted MC sample with the nominal unfolding procedure and comparing to it’s truth spectra.
- Dominant uncertainties are from **Generator** (MG5_aMC@NLO unfolded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

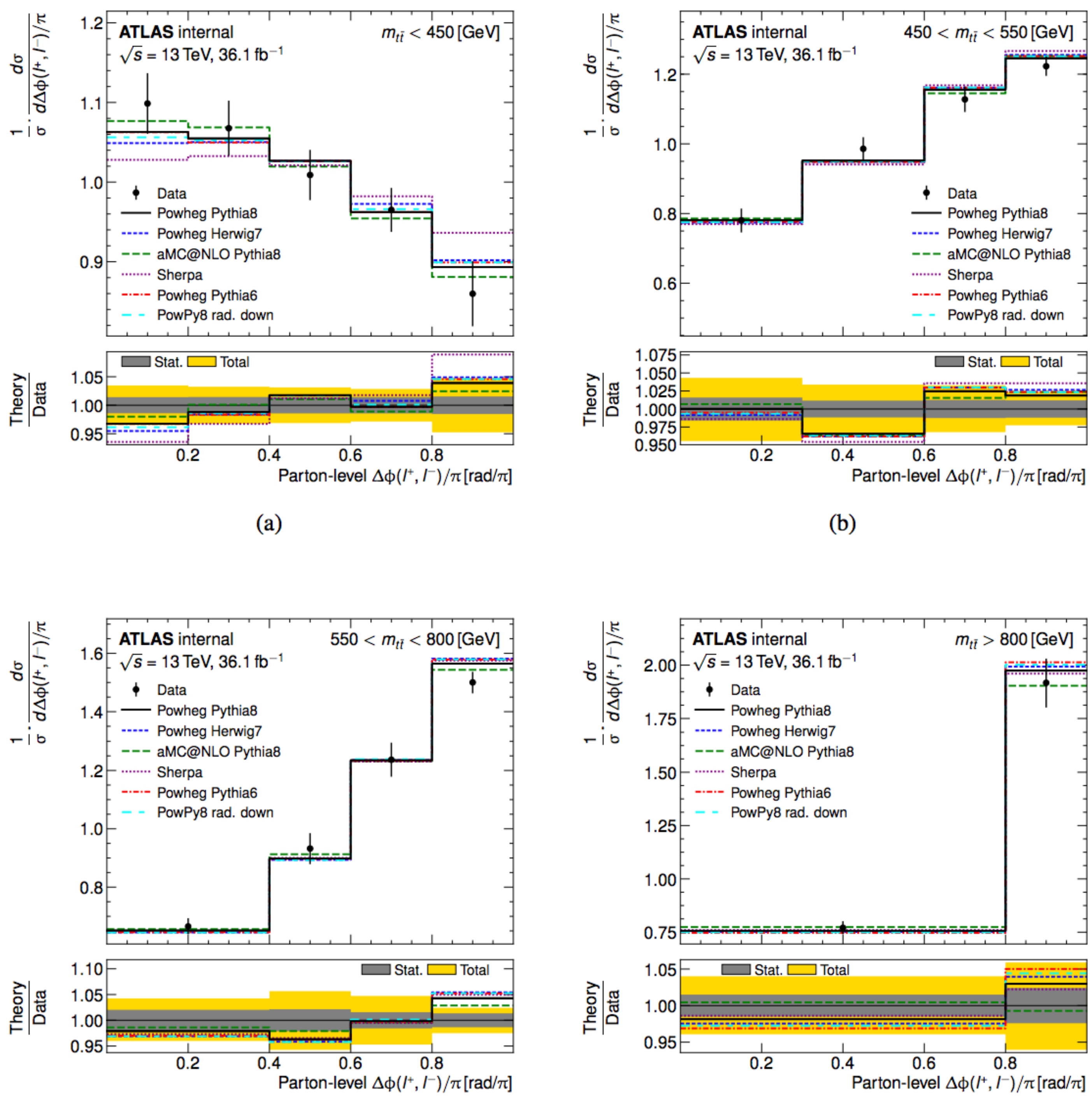
Results

- 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.



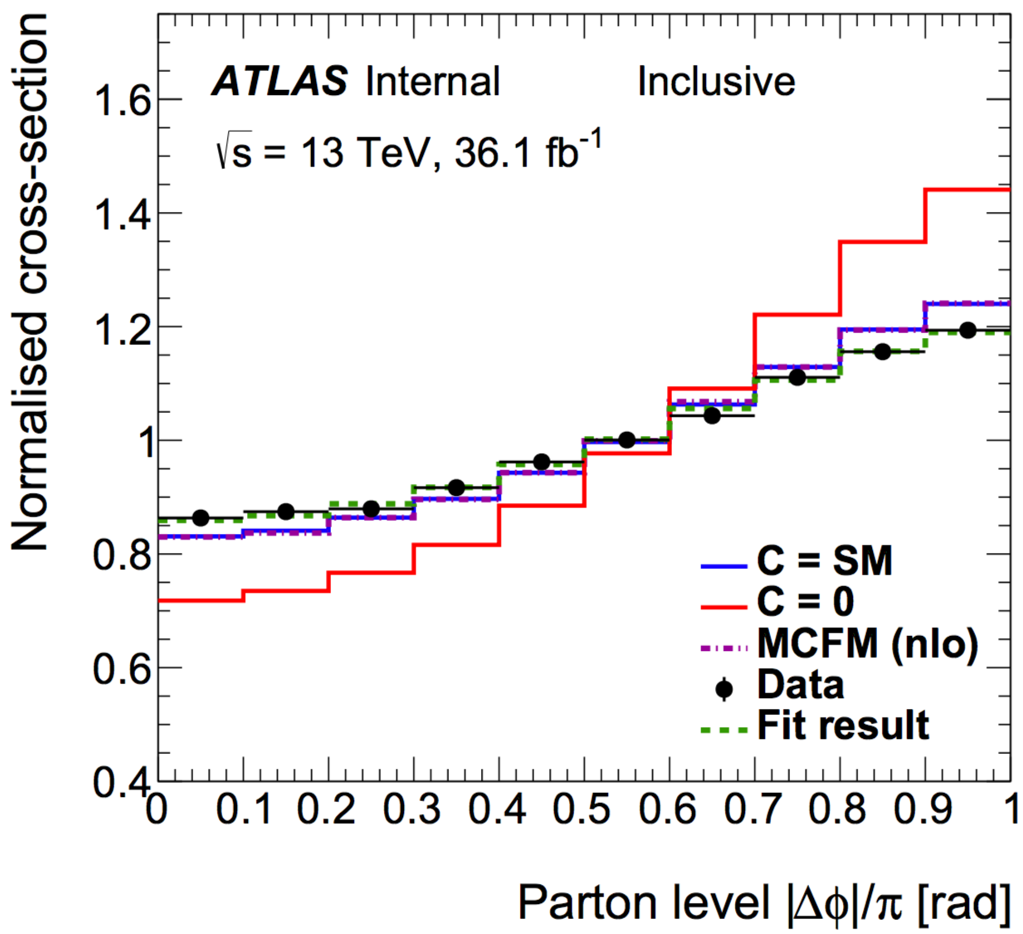
- In most bins the systematics are dominant, but statistics have a relatively large contribution (though uncertainties are small overall).

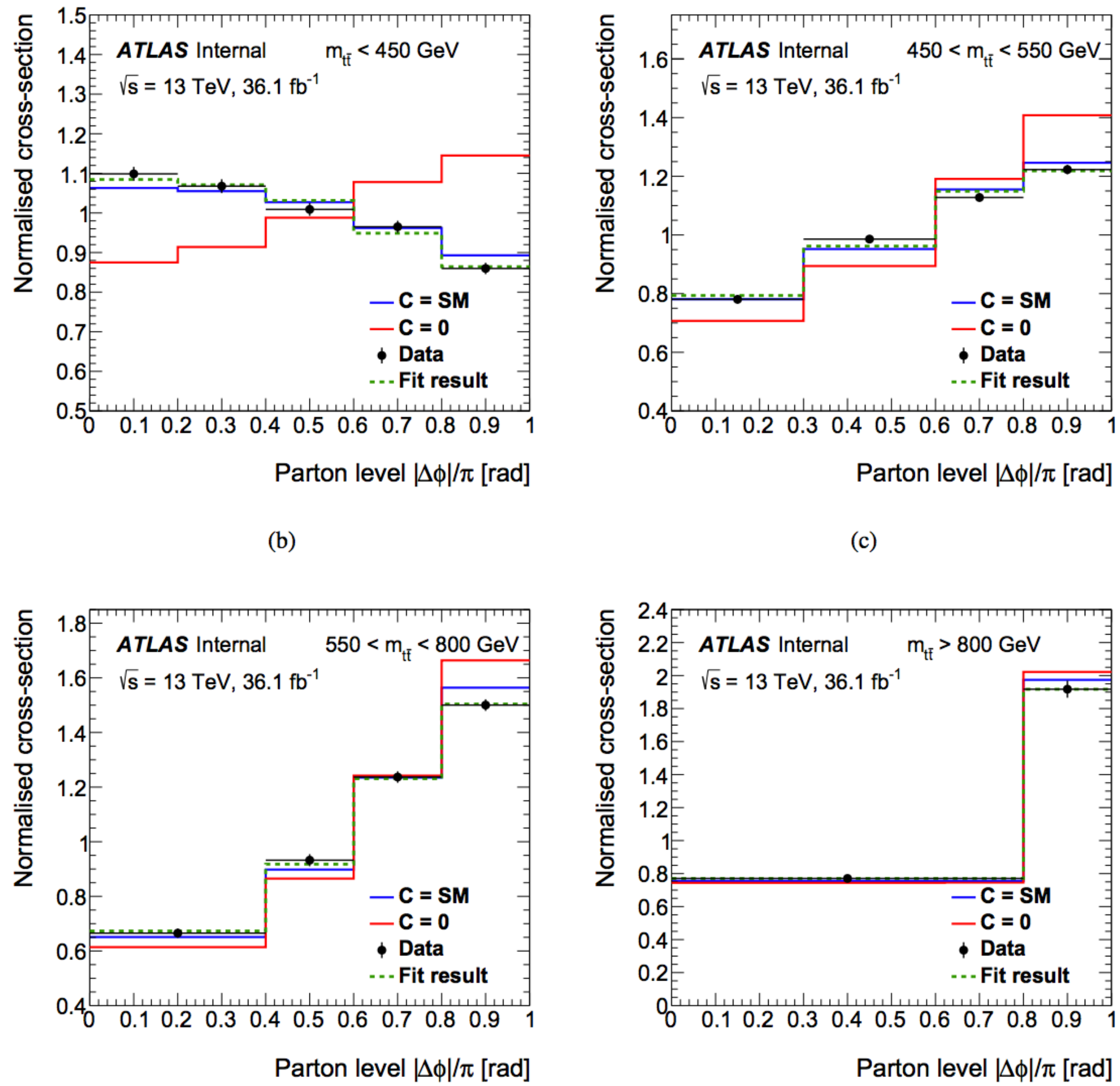
- Similar story for the double differential. The behaviour of the observable as it moves from low m($t\bar{t}$) to high m($t\bar{t}$) is clearly seen.



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.

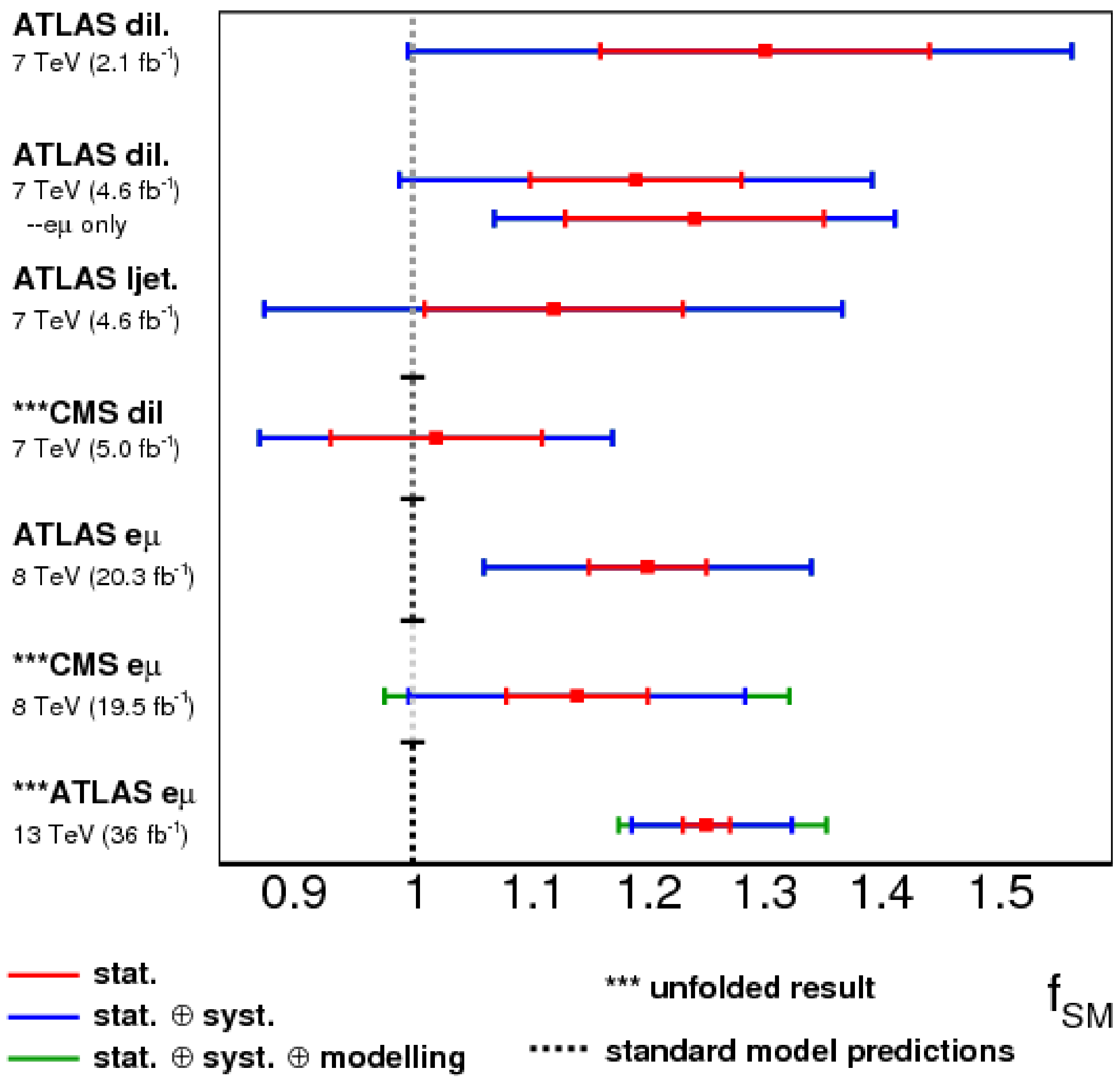
Results

- 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)
$m(t\bar{t}) < 450$ GeV	$1.11 \pm 0.04\,^{+0.13}_{-0.13}$	0.85 (0.84)
$450 < m(t\bar{t}) < 550$ GeV	$1.17 \pm 0.09\,^{+0.14}_{-0.14}$	1.00 (0.91)
$550 < m(t\bar{t}) < 800$ GeV	$1.60 \pm 0.24\,^{+0.34}_{-0.35}$	1.40 (1.40)
$m(t\bar{t}) > 800$ 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

- 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 Δϕ 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).

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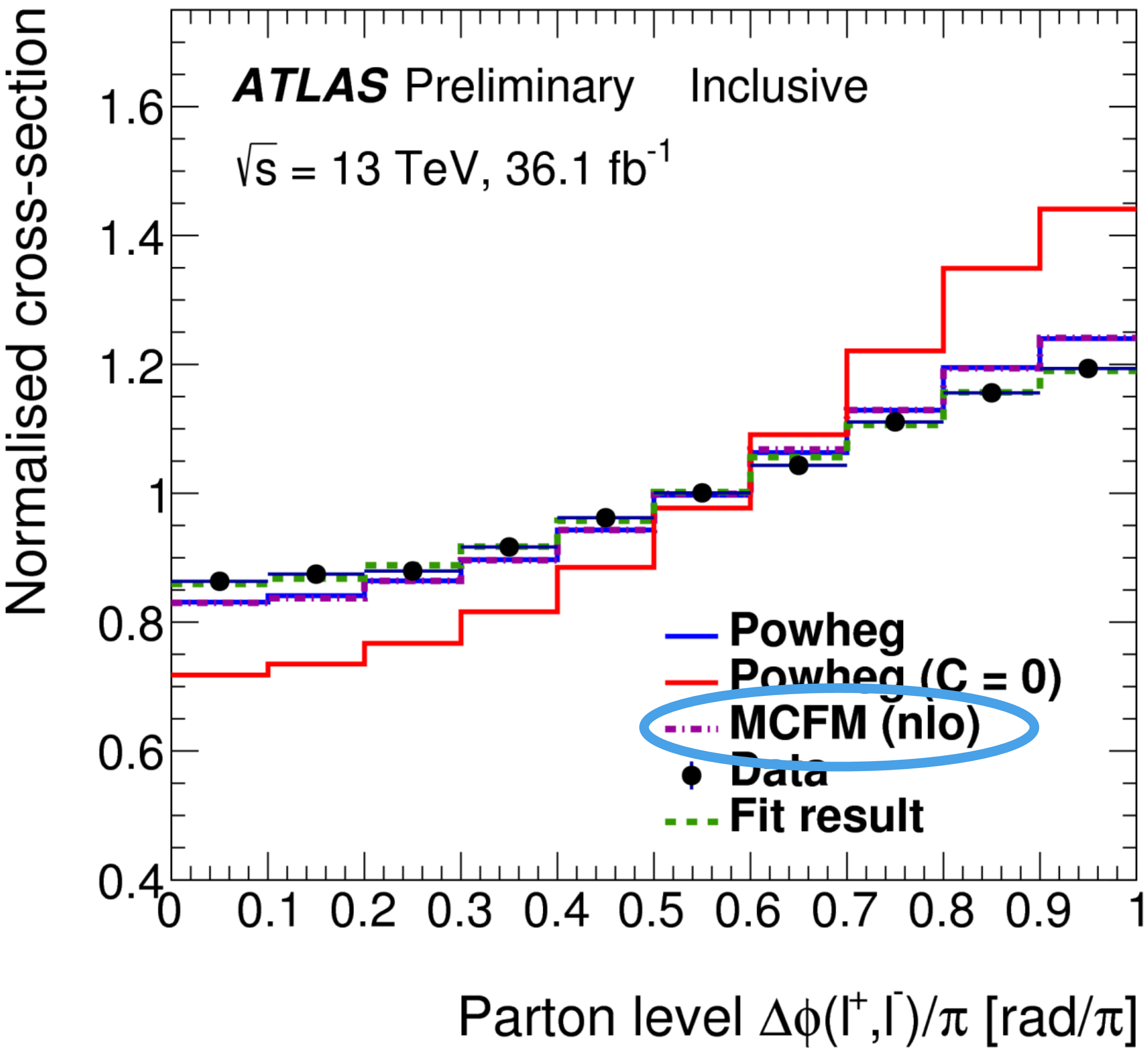

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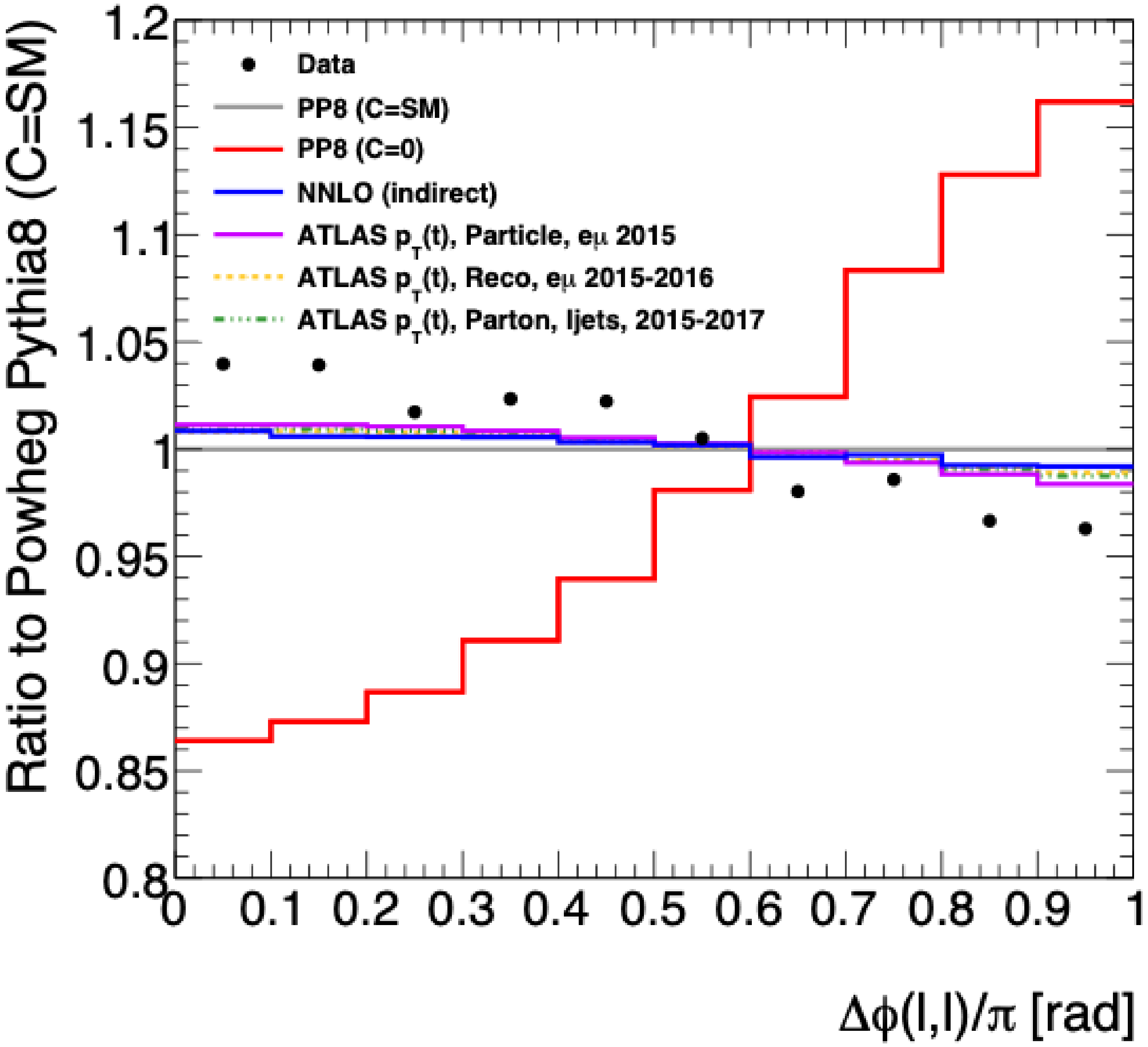

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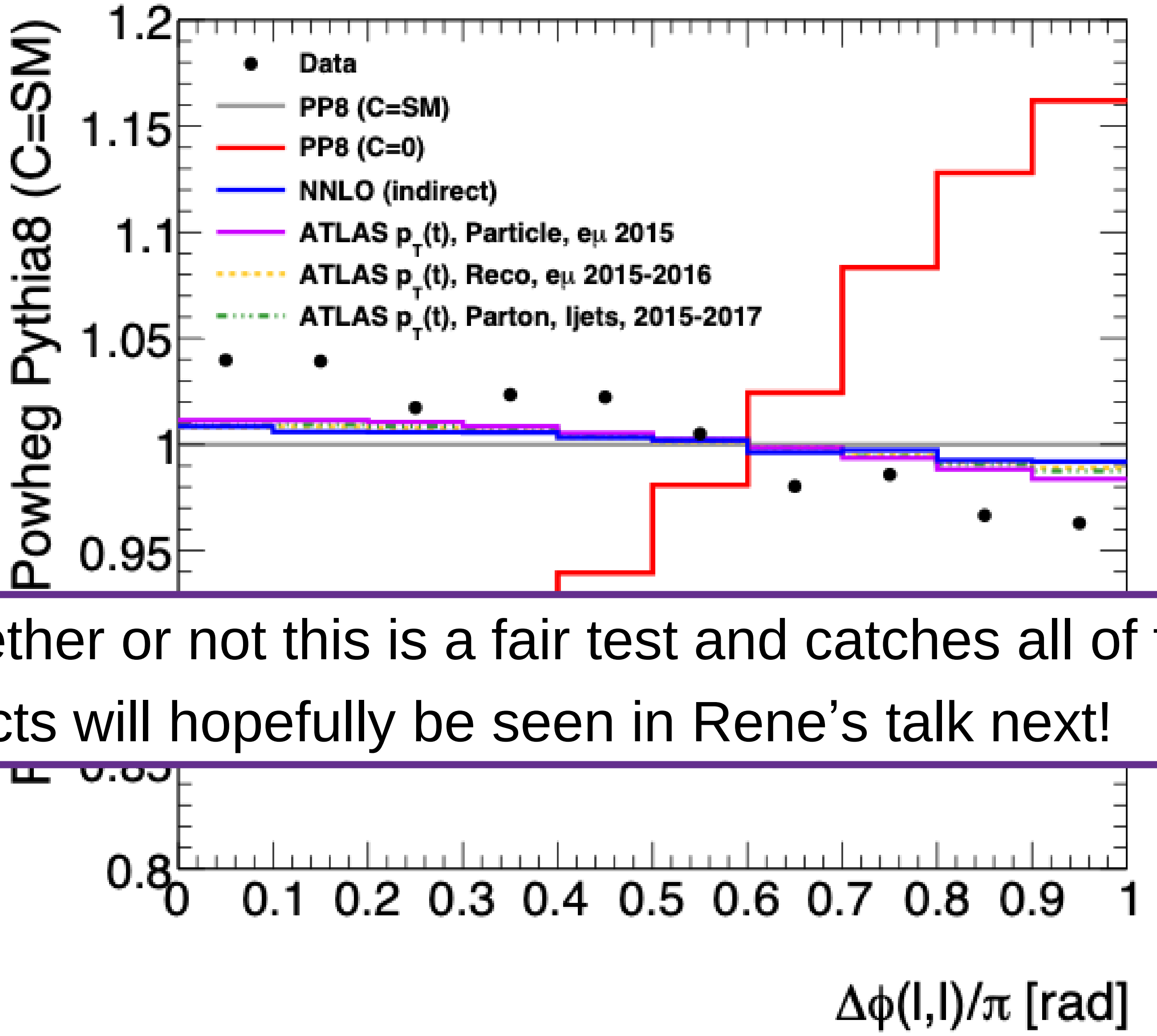

- Whether or not this is a fair test and catches all of the NNLO effects will hopefully be seen in Rene's talk next!

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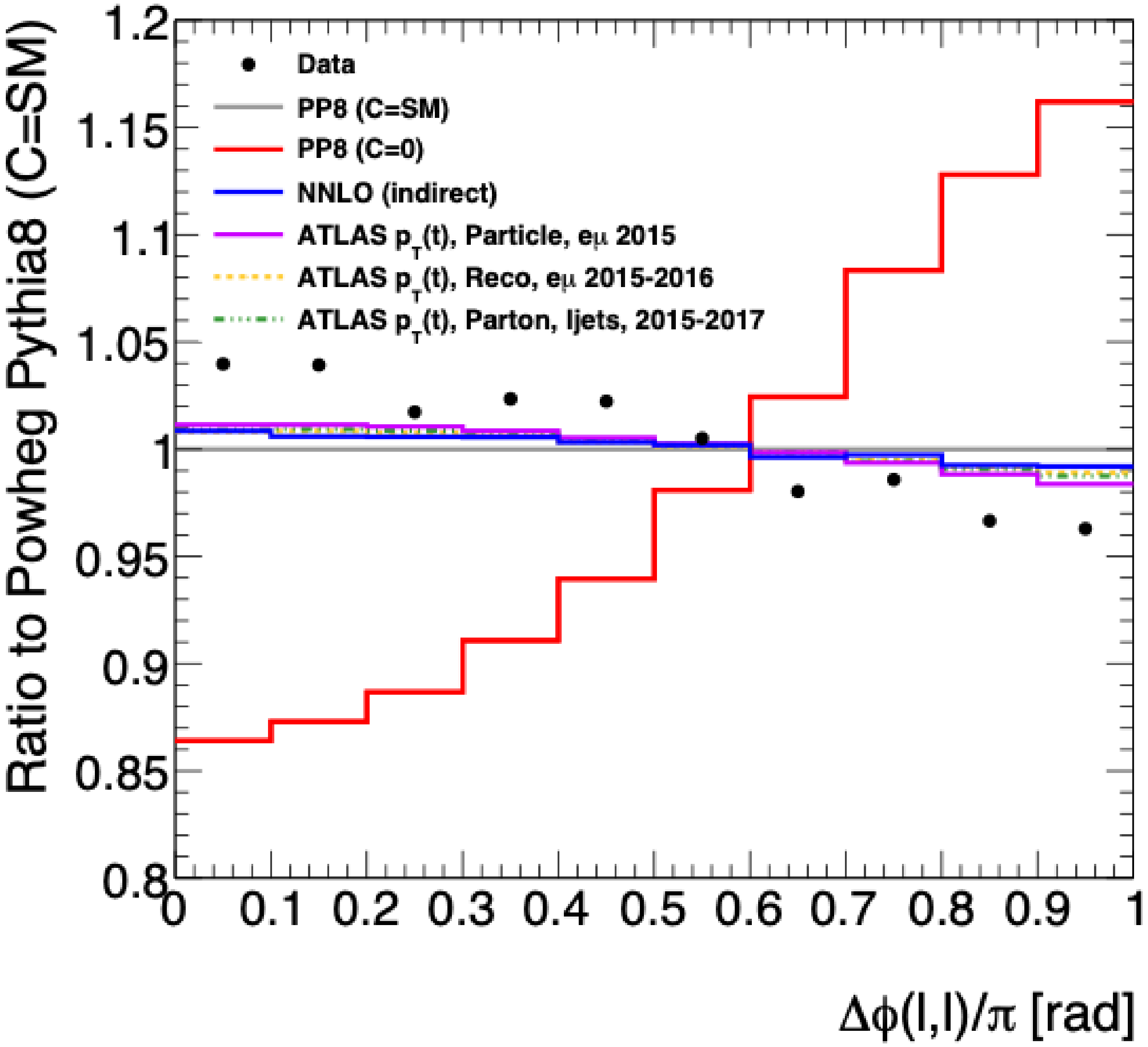

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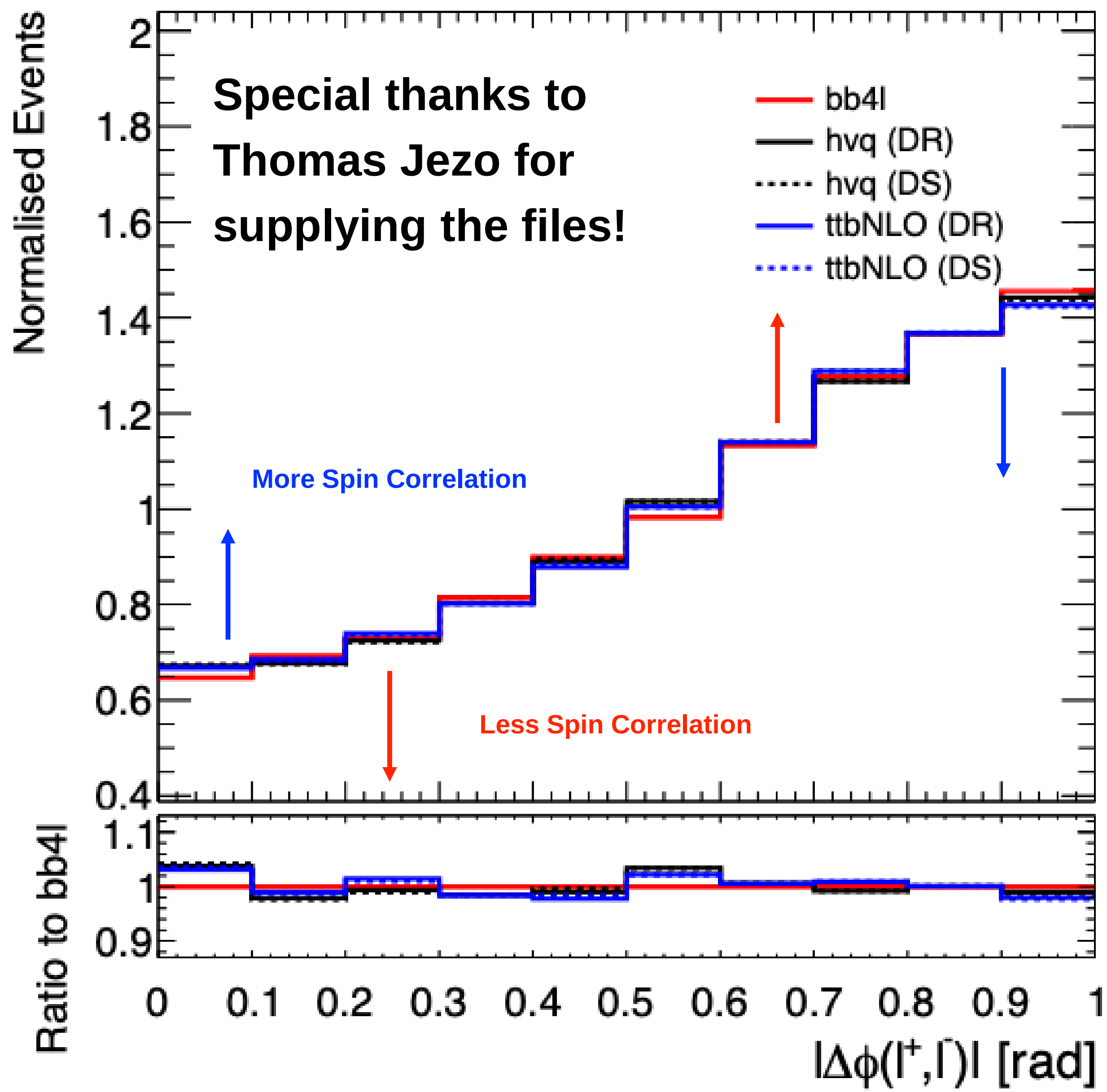
Sample	$C_{helicity}$	C_{raxis}	$C_{transverse}$
Bernreuther, Heisler & Si (NLO 13 TeV)	0.318 ± 0.003	0.055 ± 0.009	0.332 ± 0.002
POWHEG + PYTHIA8 (dil.)	0.314 ± 0.002	-0.050 ± 0.002	0.320 ± 0.002

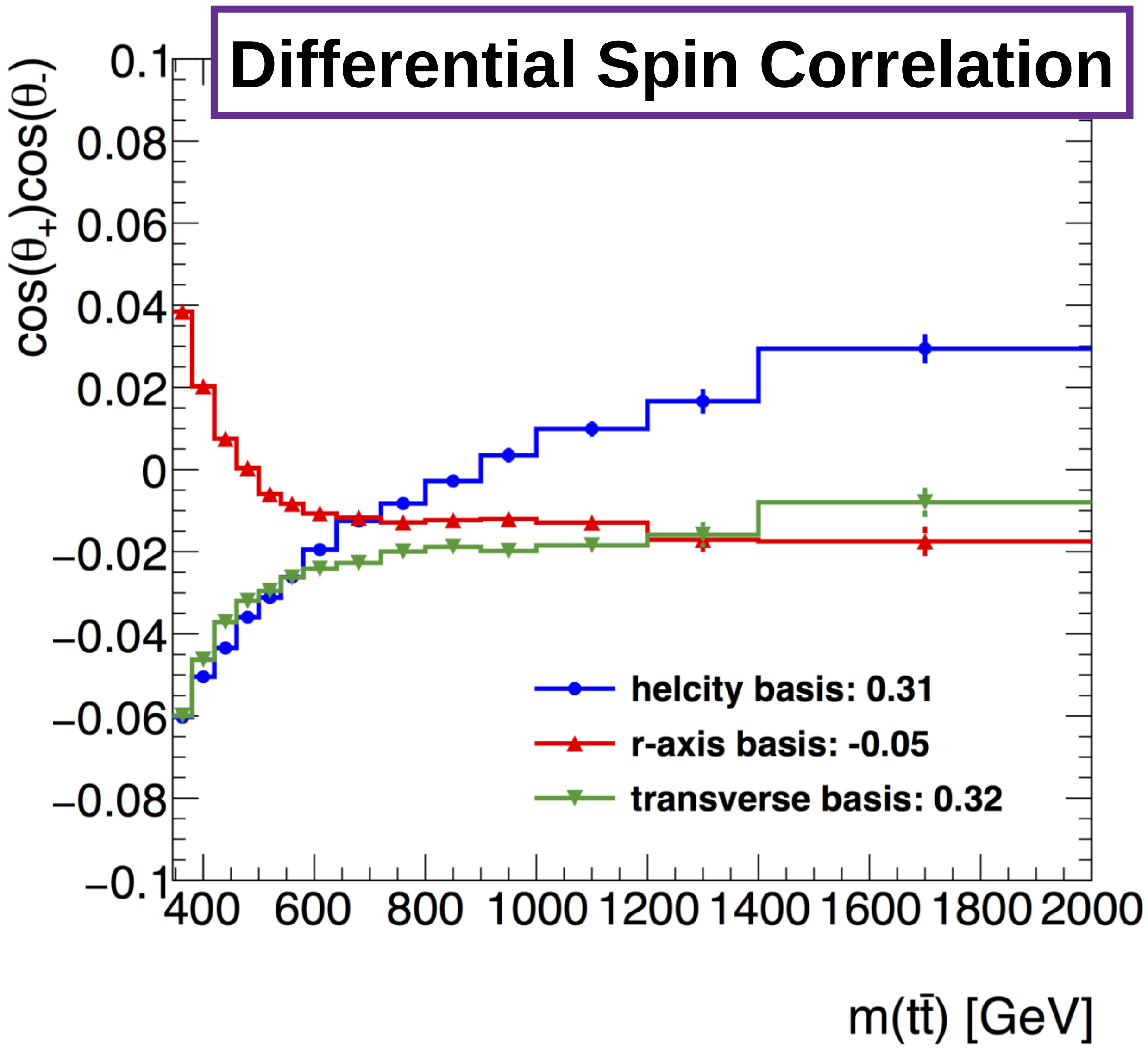
Powheg bb4l

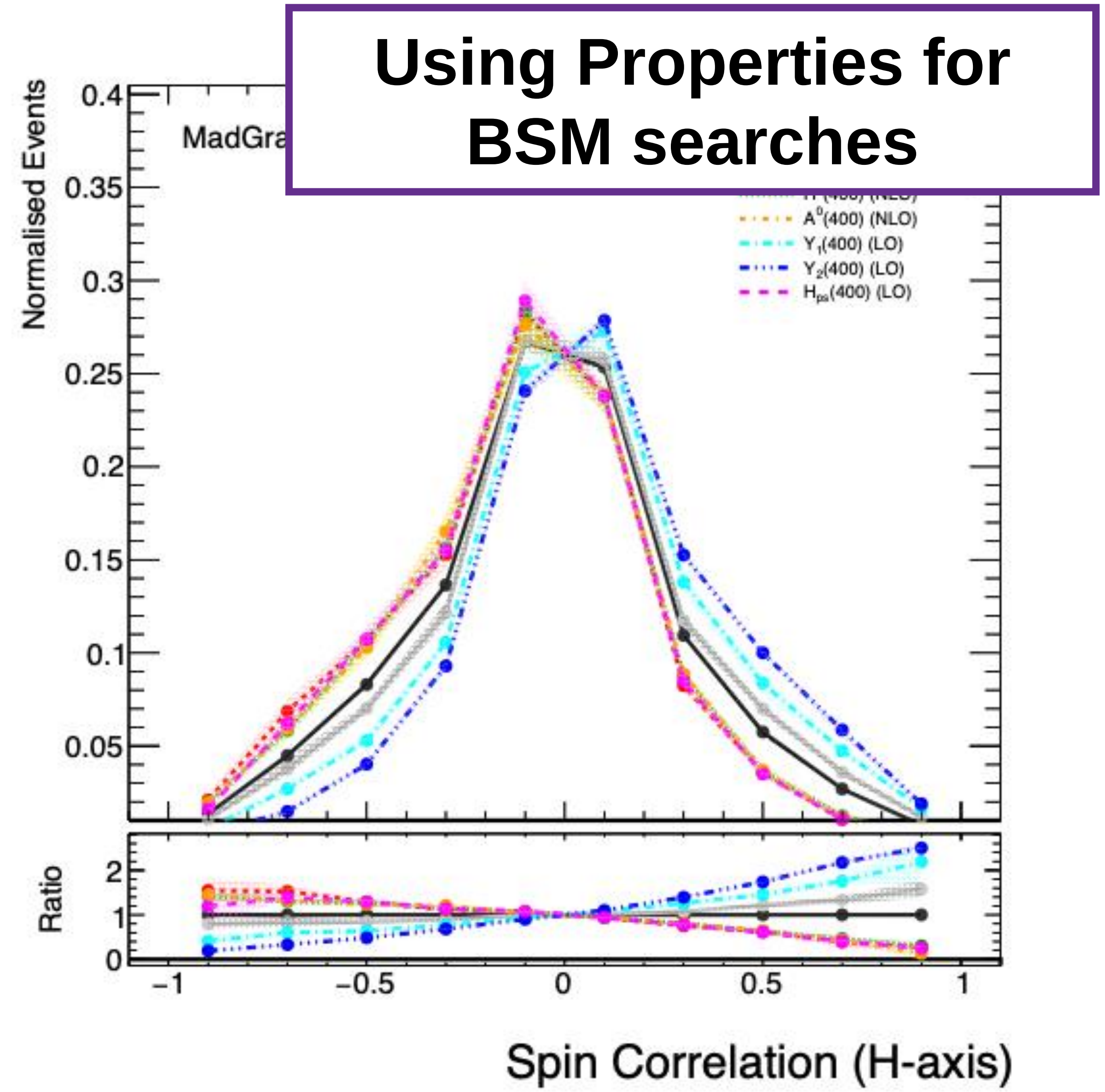


- **<u>This is not a $t\bar{t}$ comparison!</u>** It is the leptonic WbWb final state ($t\bar{t}$ + Wt, or bb4l)
- bb4l, hvq, and ttbNLO_dec all agree very well for the delta phi observable.
- Type of overlap handling between ttbar and Wt also not a large effect here.

Future Work

- Although |Δϕ| 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 **-π → +π** 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

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Narrow Width Approximation

Andrew Papanasatiou's Top2017 talk

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

- Narrow-width approximation (NWA), $p(t)^2 = m_t^2$, $\Gamma_t \to 0$ 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!

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All of our top MC in ATLAS uses the NWA.

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

Narrow Width Approximation

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]
  - $pp \rightarrow \ell^+ \nu_\ell l^- \bar{\nu}_l b \bar{b}$ 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

Narrow Width Approximation

[Tomas Jezo's Top2017 talk]

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