Top quark pair property measurements using the ATLAS detector at the LHC

EPS 2019, Ghent

Jay Howarth, on behalf of the ATLAS collaboration

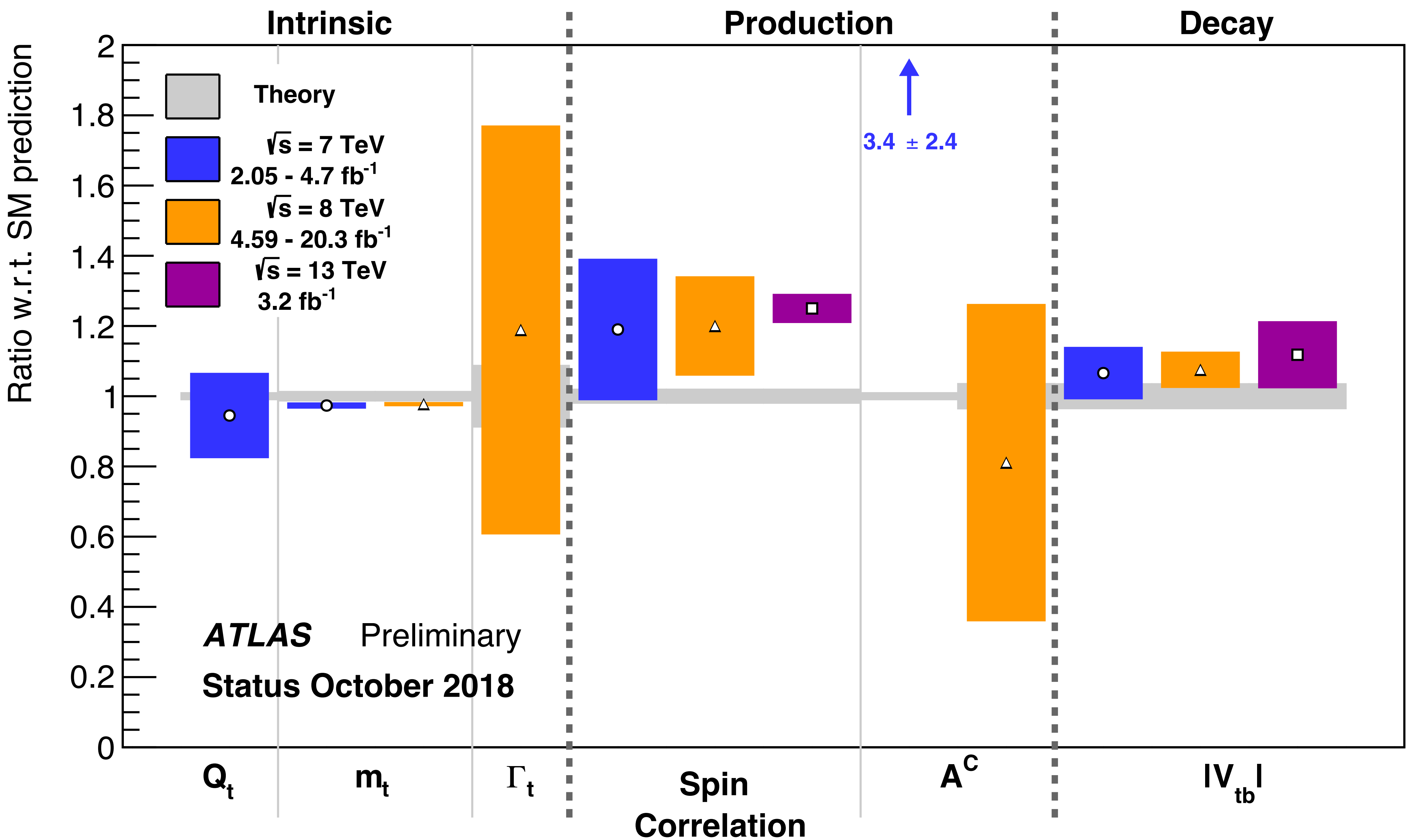
Top Quark Properties

Production time		Decay time		Hadronisation time		Spin-Decor. time
$\frac{1}{m_t}$	$<$	$\frac{1}{\Gamma_t}$	$<$	$\frac{1}{\Lambda}$	$<$	$\frac{m_t}{\Lambda}$
$\sim 10^{-27}$ s		$\sim 10^{-25}$ s		$\sim 10^{-23}$ s		$\sim 10^{-22}$ s

- Top quark is the heaviest particle in the SM, which leads to unique features:
  - ➡ Decay timescale is orders of magnitude shorter than the hadronisation or spin de-correlation timescale → **top acts like bare quark.**
  - ➡ Top yukawa term ~1 → **possibly plays a special role in EWSB?**
  - ➡ Very clear signal with little background and high production cross-section at the LHC → **possible to make precision measurements.**

Top Quark Properties

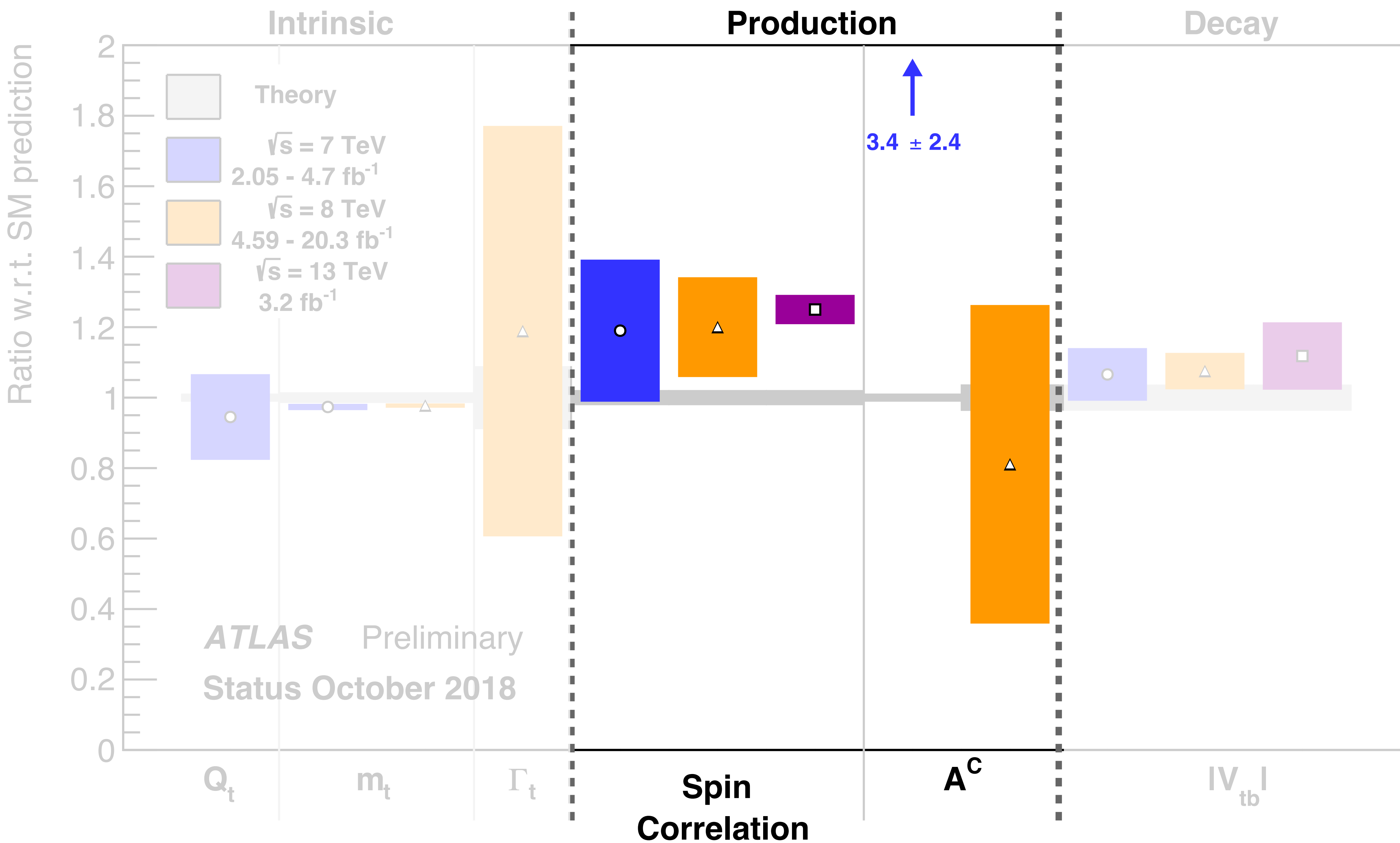
ATLAS Summary Plots



- Large suite of measurements from ATLAS probing the top quark's properties

Top Quark Properties

ATLAS Summary Plots



- Today, I'll focus on production properties of $t\bar{t}$ pairs.

Spin Correlation

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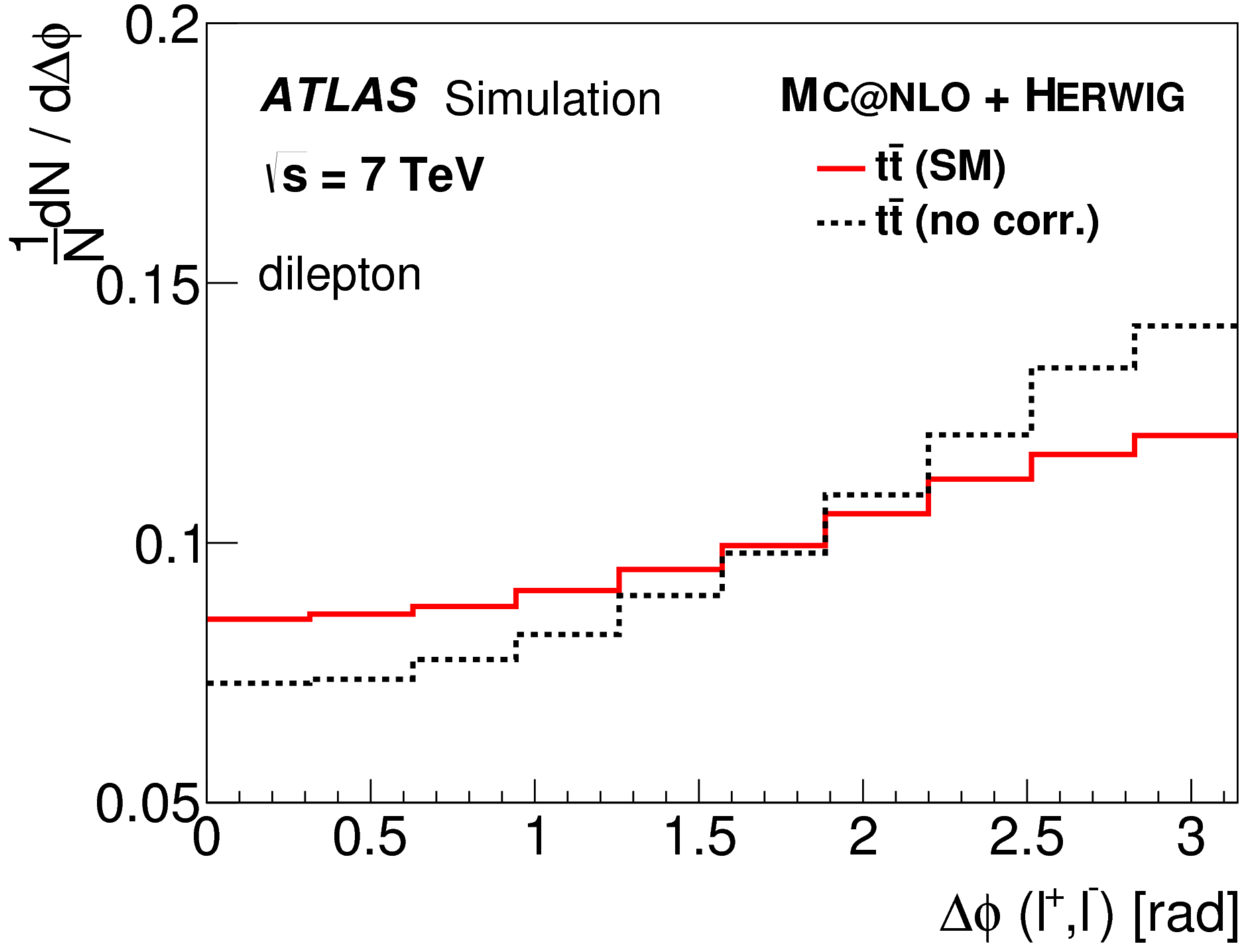
$$C = A\alpha_1\alpha_2 = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\uparrow\downarrow) - N(\downarrow\uparrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\uparrow\downarrow) + N(\downarrow\uparrow)}$$

- Tops produced via QCD are not intrinsically polarised, but spins between top pairs are correlated.
- Tops decay before they can hadronise:
  - ➡ Spin information is transferred directly to decay particles.
  - ➡ Leptons carry the full spin information ($\alpha_\ell \sim 1$)
  - ➡ Dilepton $t\bar{t}$ decays are the best choice for accessing spin information.
- Can be measured directly using complex observables involving the angles between the tops and their decay products:
  - ➡ Incurs large top reconstruction uncertainties in dilepton channel due to ν's.

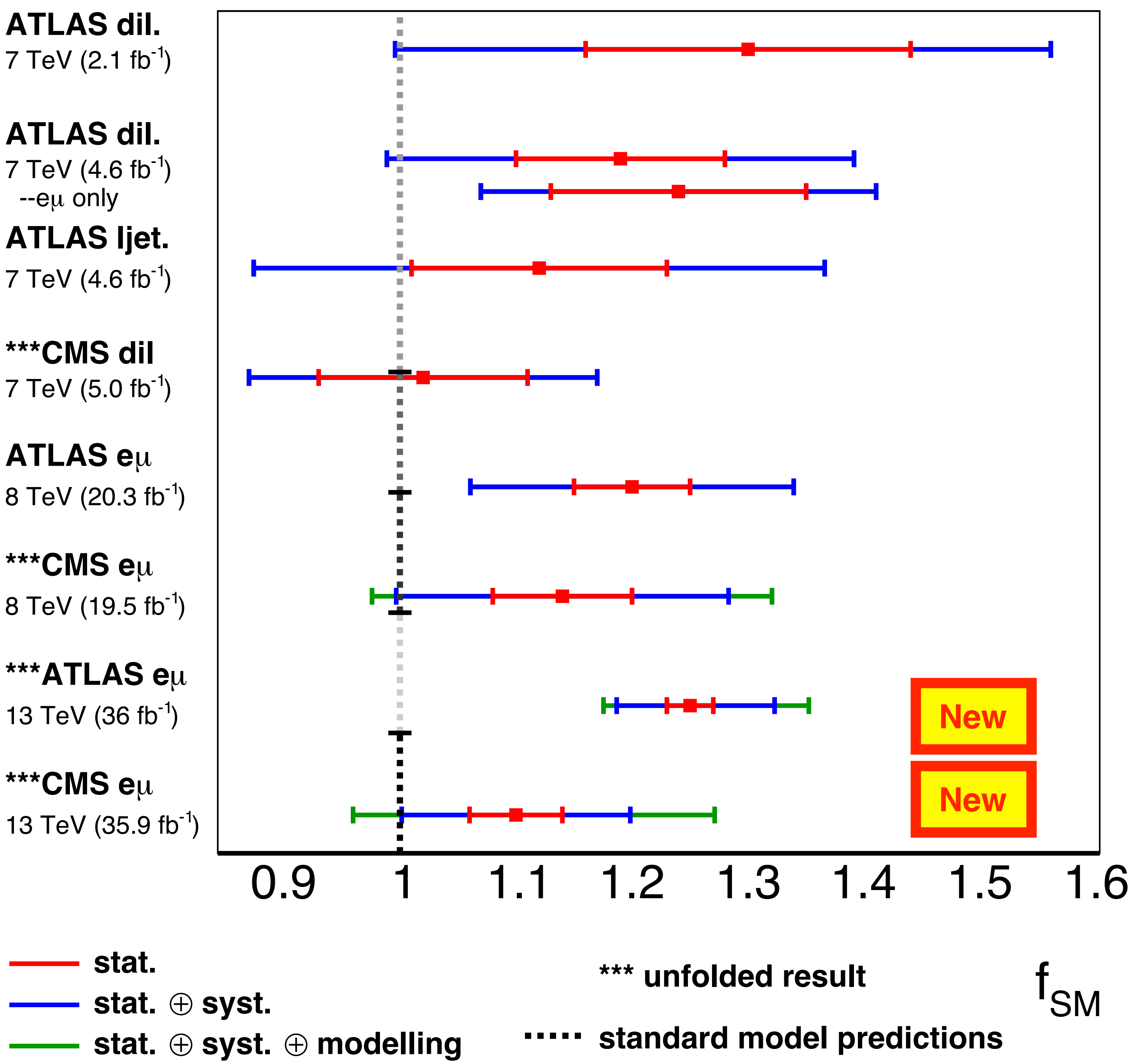
Spin Correlation

Phys. Rev. D90 (2014) 112016



- Fortunately, there is a lab-frame observable that does not require any top reconstruction that is sensitive to spin correlation:
  - ➡ The difference in the azimuthal angle between the leptons from the top decay
  - ➡ Usually, spin is extracted using a template fit using a SM spin and NoSpin hypothesis.

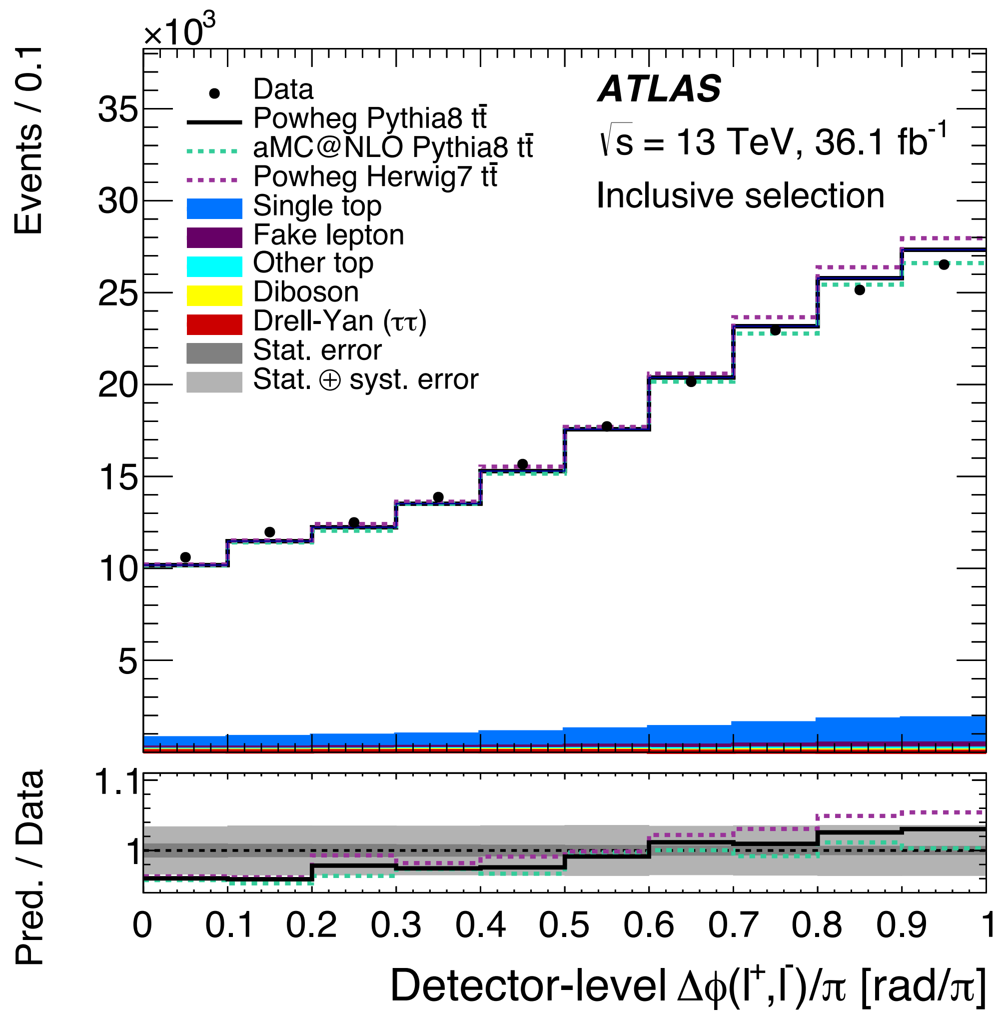
Spin Correlation

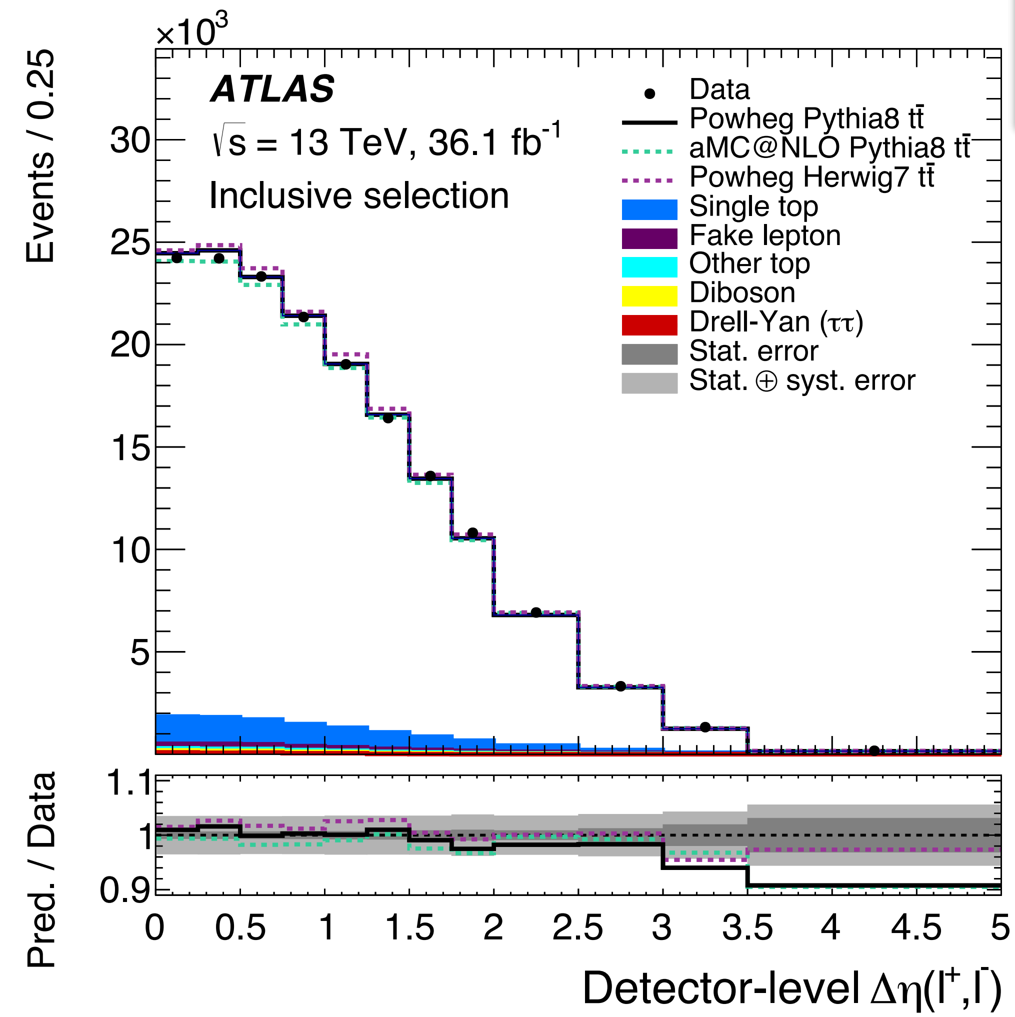


- This property has been measured many times by ATLAS and CMS, at each collision energy.
- f_{SM} is *"fraction of SM-like spin correlation"*:
  - ➡ f_{SM} = 1 is SM-like
  - ➡ f_{SM} = 0 is uncorrelated
- Both ATLAS and CMS consistently measure stronger than SM spin correlations using the $|\Delta\phi_{\ell\ell}|$ observable.

ATLAS result

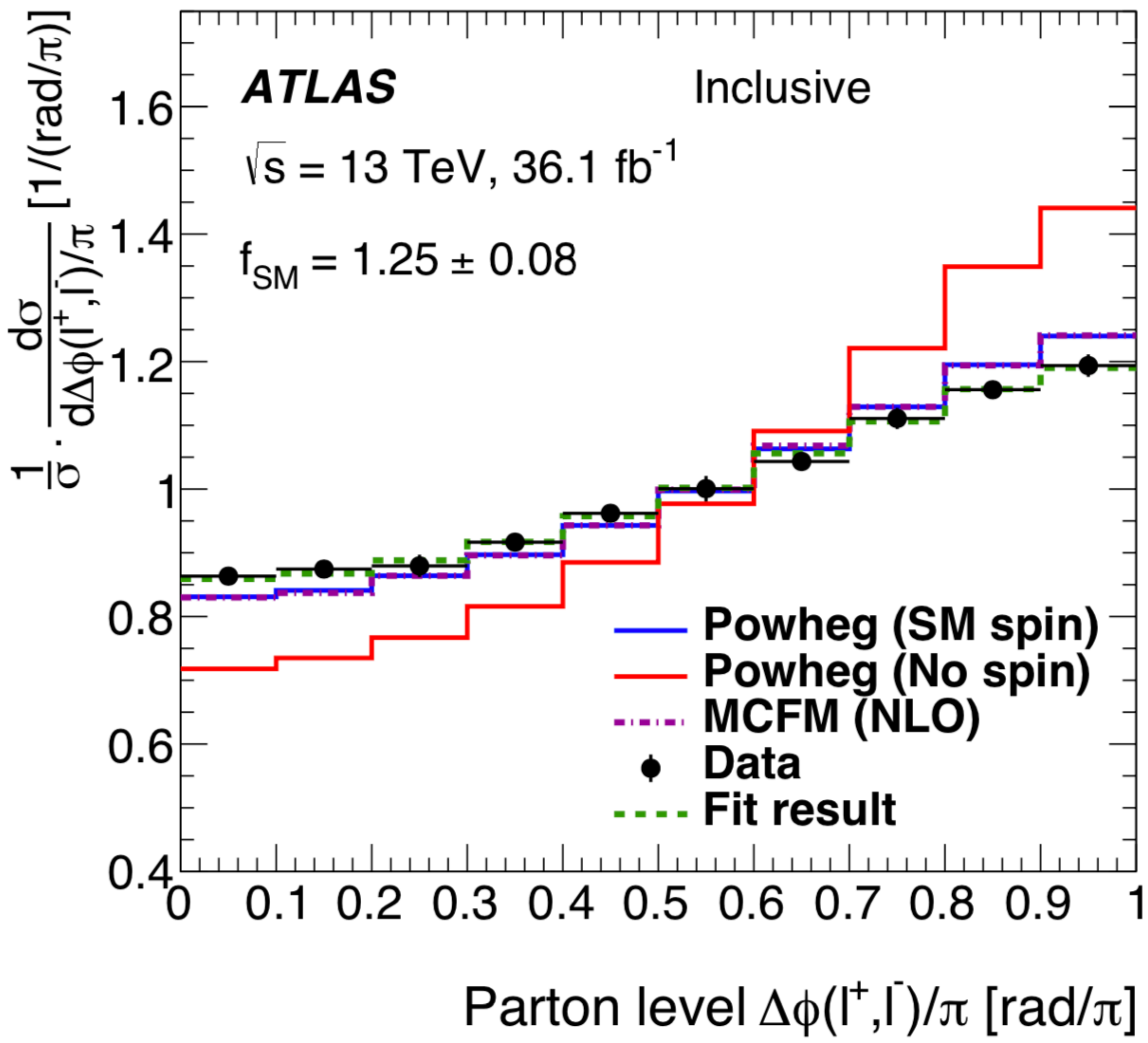
Submitted to EPJC





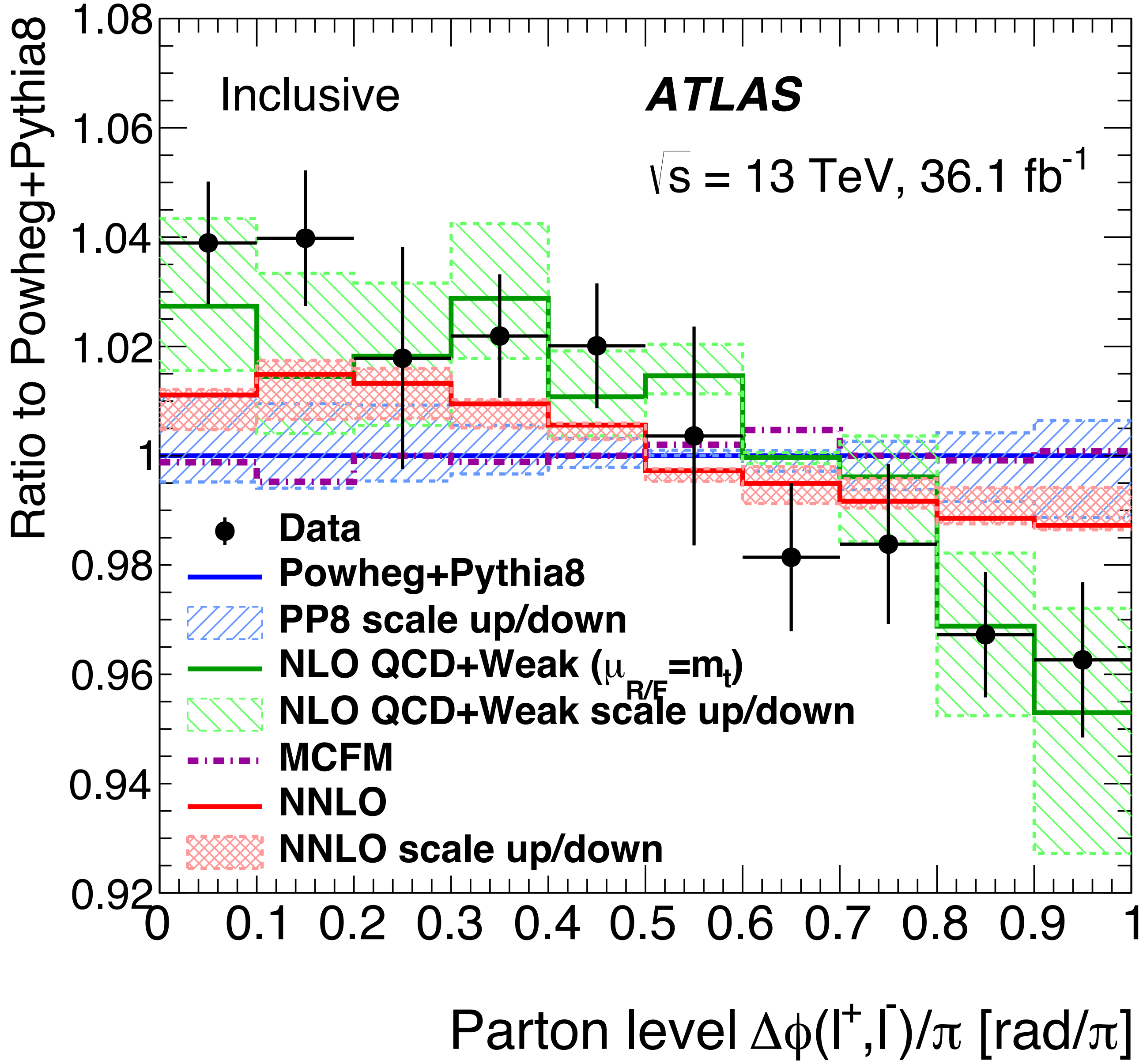
- Measured the $|\Delta\phi_{\ell\ell}|$ using 36 fb^{-1} of 13 TeV Run2 data and a eμ + 2b selection.
  ➡ Also measured differentially vs. m($t\bar{t}$)
- Also measured the $|\Delta\eta_{\ell\ell}|$ observable, which is sensitive to SUSY production.
- All results unfolded to **fiducial particle level** and **full phase-space parton level** using Bayesian Iterative Unfolding.

ATLAS result



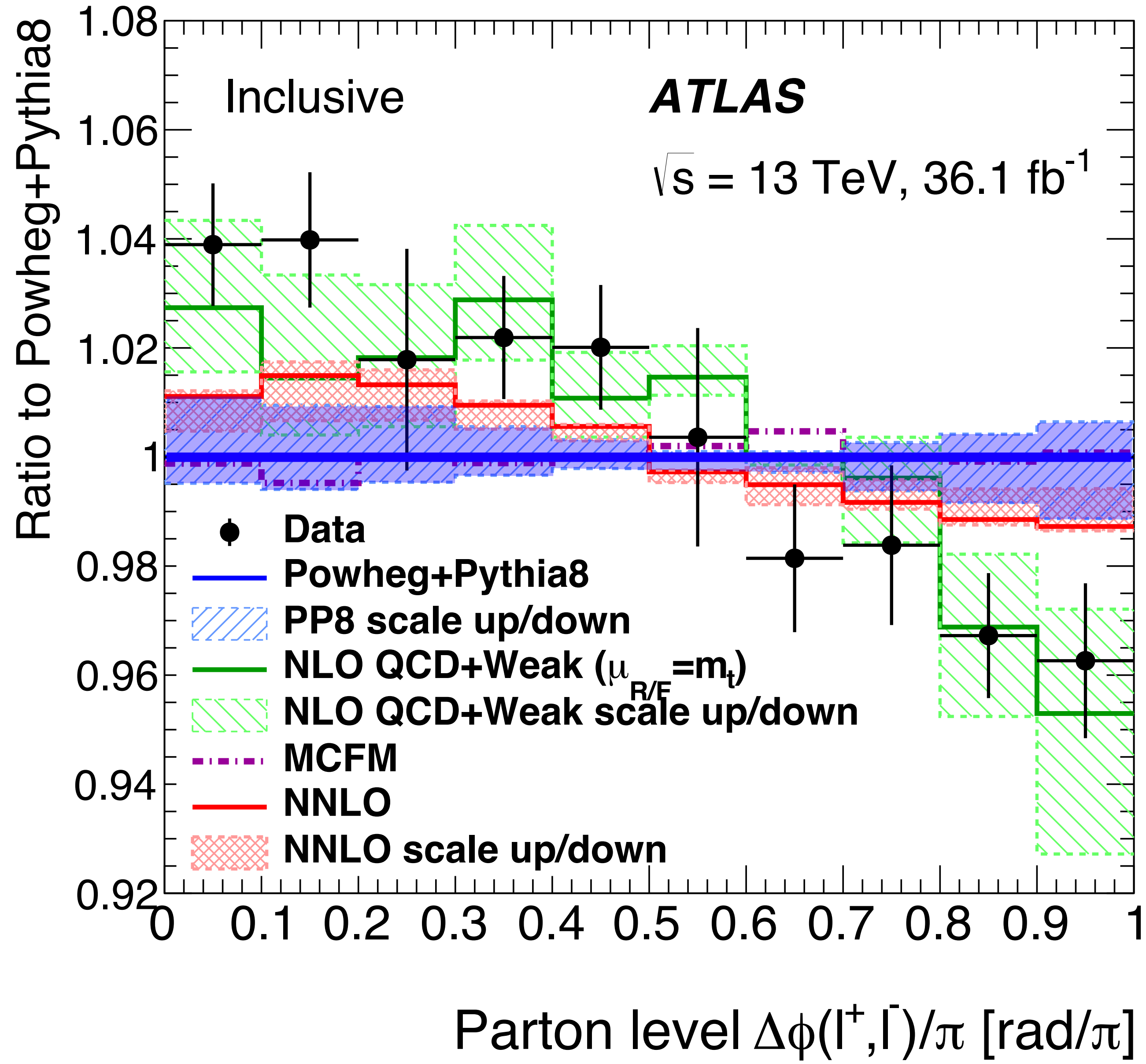
- As with previous results, the $|\Delta\phi_{\ell\ell}|$ shows a stronger slope than the data, and we measure f_{SM} = 1.25 +/- 0.08, relative to NLO predictions.
  ➡ This is more than 3σ discrepant from what we expect from the SM at NLO.

ATLAS result



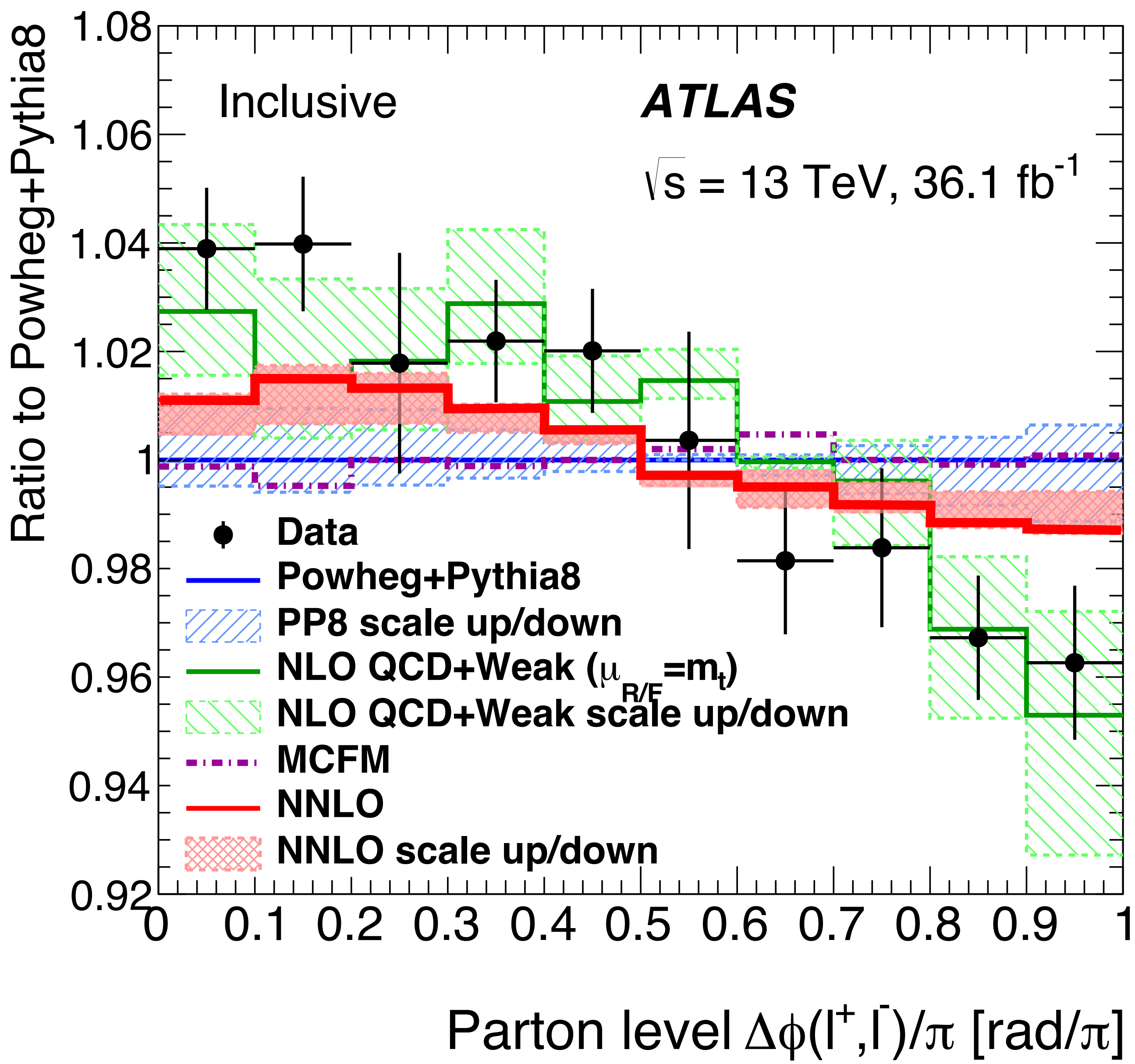
- Lots of discussions in the theory community after the CONF note for this result.
- ATLAS focused on understanding the assumptions involved in the template hypotheses.

ATLAS result



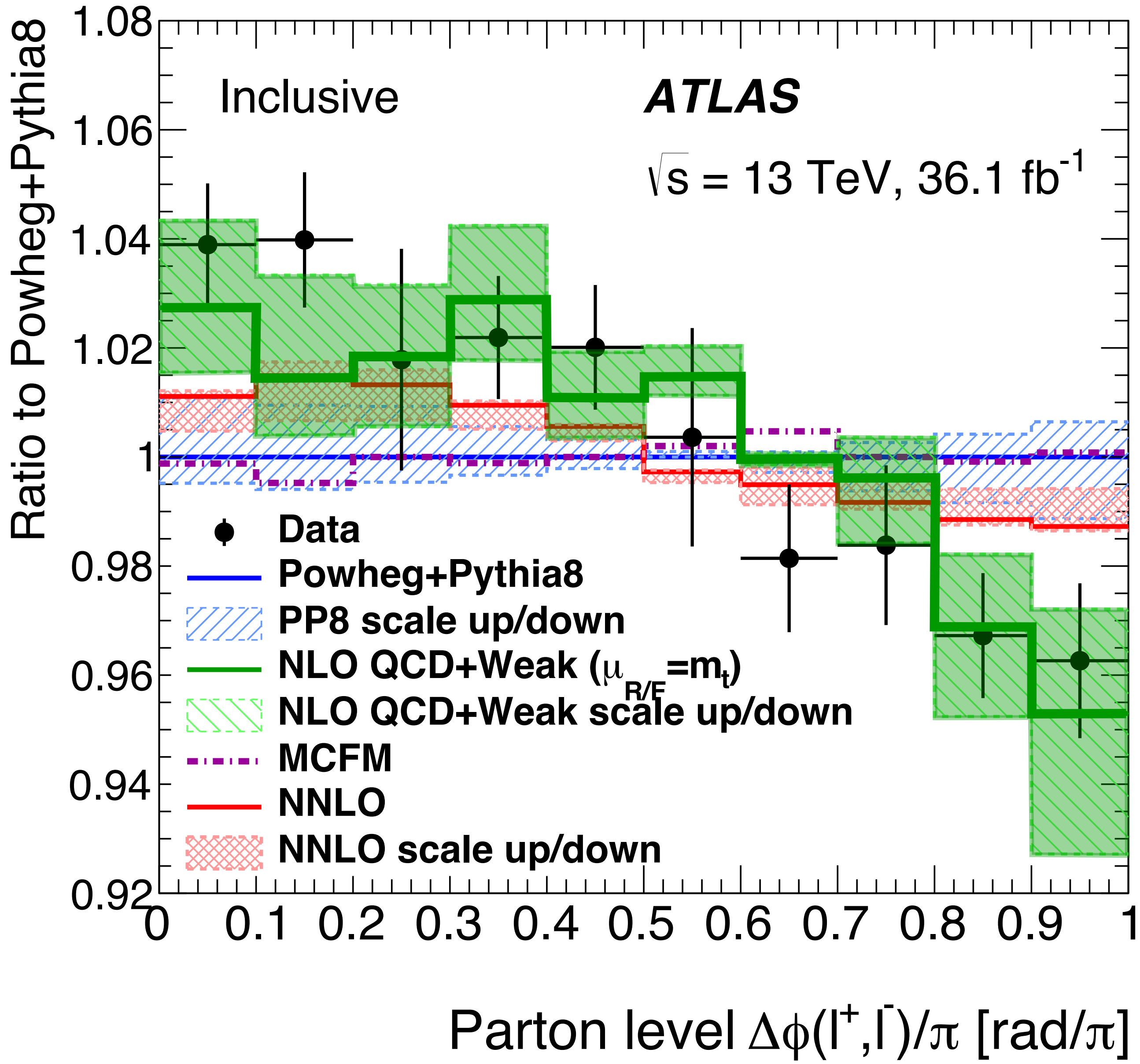
- **NLO + Parton** shower MC consistent with fixed-order calculations from **MCFM**.
- We also tested assumptions such as LO vs. NLO top decays and the use of the narrow-width approximation, none were significant shifts.

ATLAS result



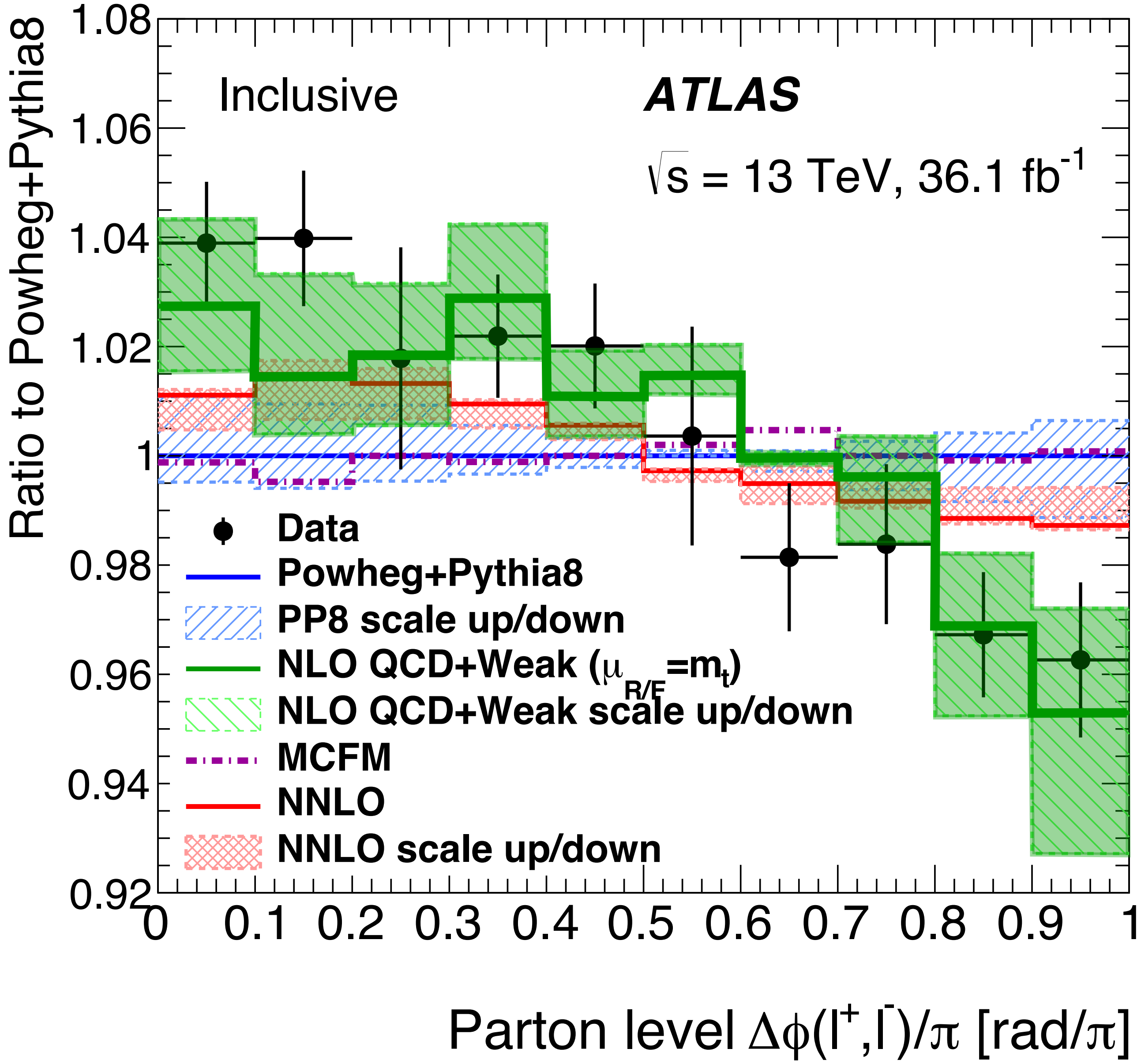
- ATLAS investigated alternative predictions, including bespoke state-of the art **NNLO-QCD** predictions (Brun et. al.).
- These are closer to the data, but not all the way (significance would be 2.2 sigma).

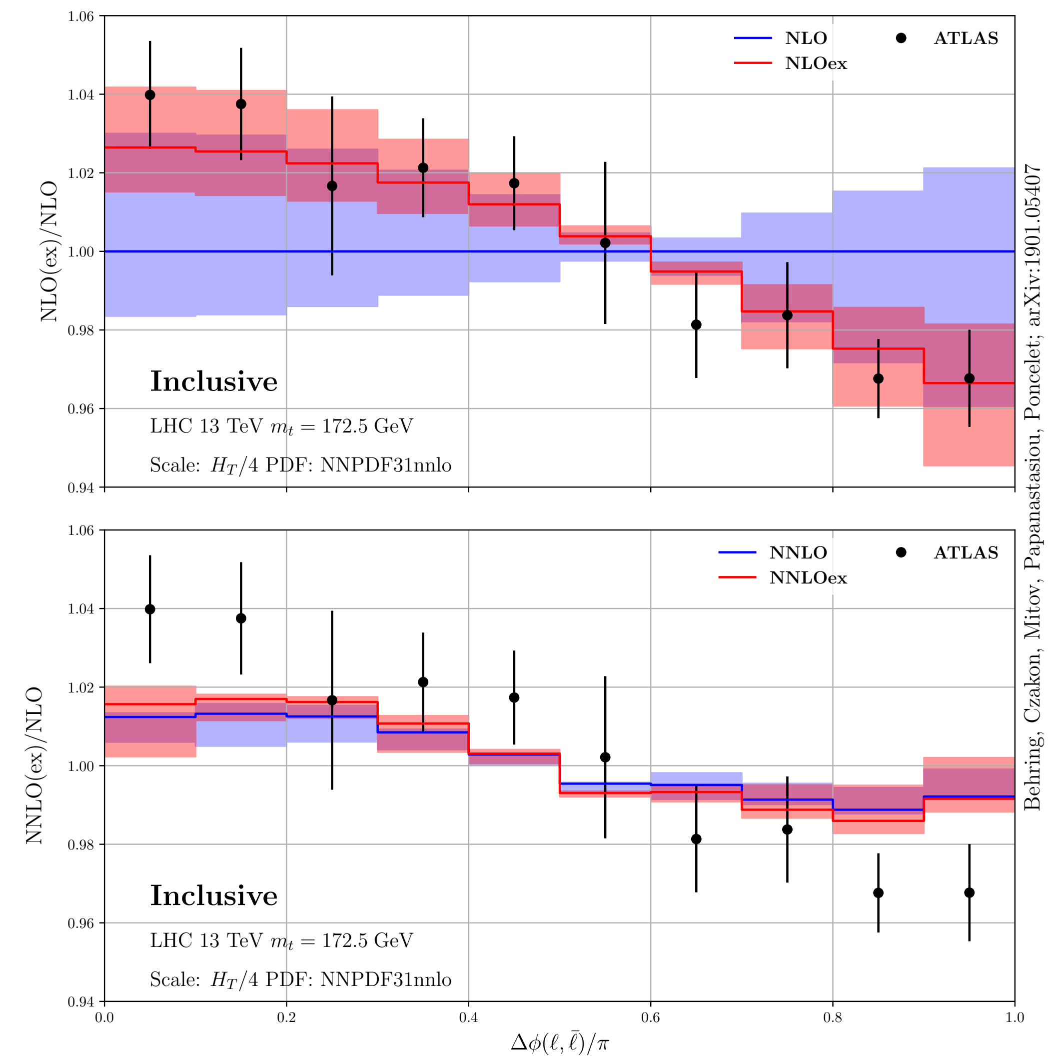
ATLAS result



- A **NLO-QCD + Weak Ratio-Expanded** prediction was also available.
- Agrees with the data but with large scale uncertainties.
- Further studies imply that the Weak corrections are not driving the agreement but rather the ratio expansion method. However, at NNLO, this may not be true…

ATLAS result

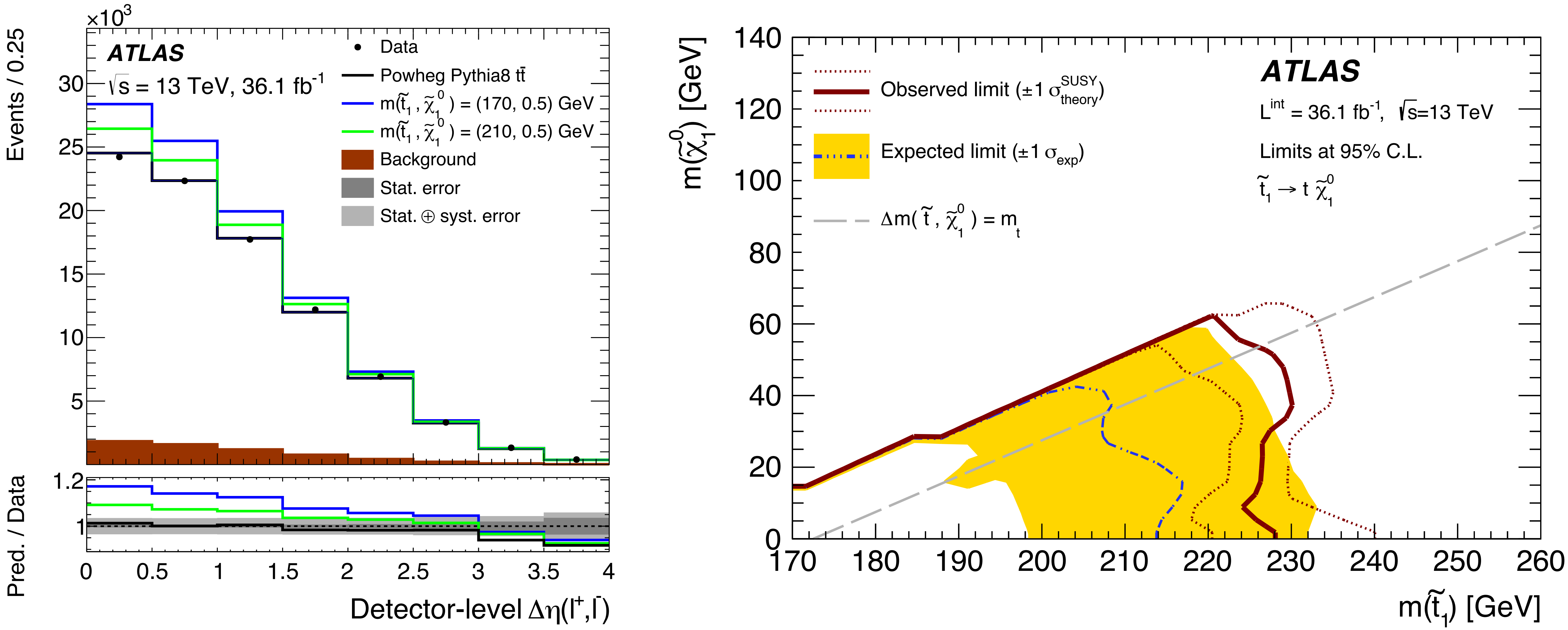




Paper: :1901.05407
Extension: Web Page

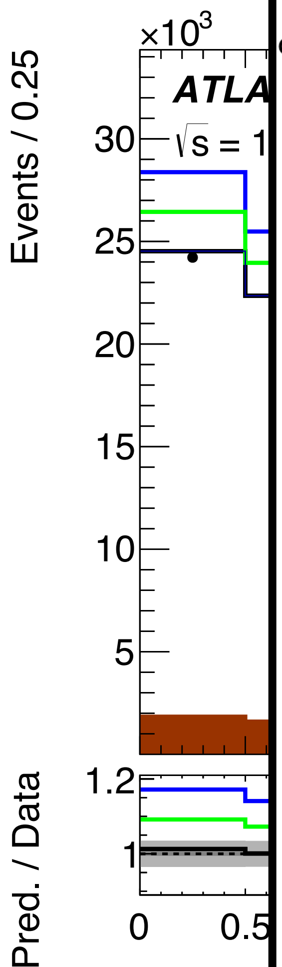
- It appears that when the ratio is expanded at NNLO, the agreement disappears.
- Discrepancy remains unresolved, but is stimulating state-of-the-art predictions and development in the theory community.

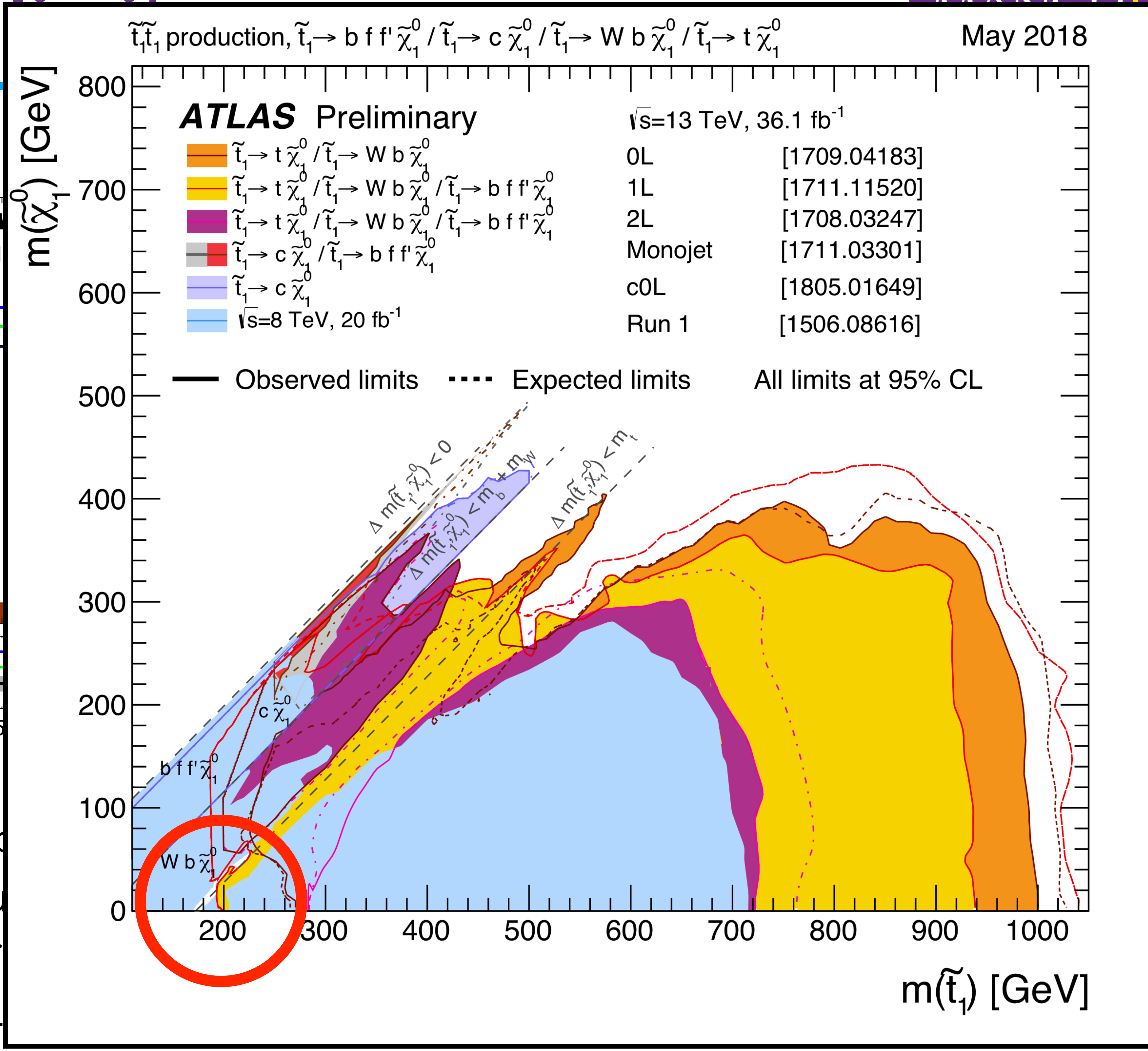
SUSY limits

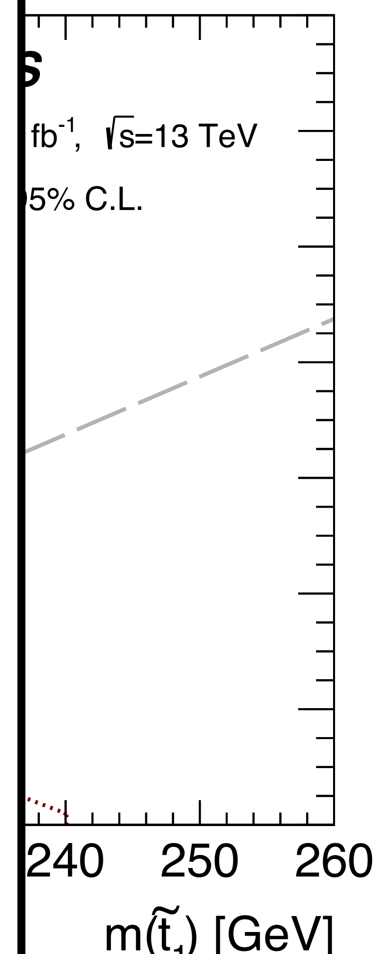


- Use both the $|\Delta\phi_{\ell\ell}|$ and $|\Delta\eta_{\ell\ell}|$ to set limits on SUSY stop production.
- Exclude Stops with a mass below ~ 220 GeV for all kinematically-allowed neutralino masses:
  - ➡ Limit is driven by $|\Delta\eta_{\ell\ell}|$ but additional modelling uncertainties are included to account for the Data/Prediction disagreement in $|\Delta\phi_{\ell\ell}|$.

SUSY li...



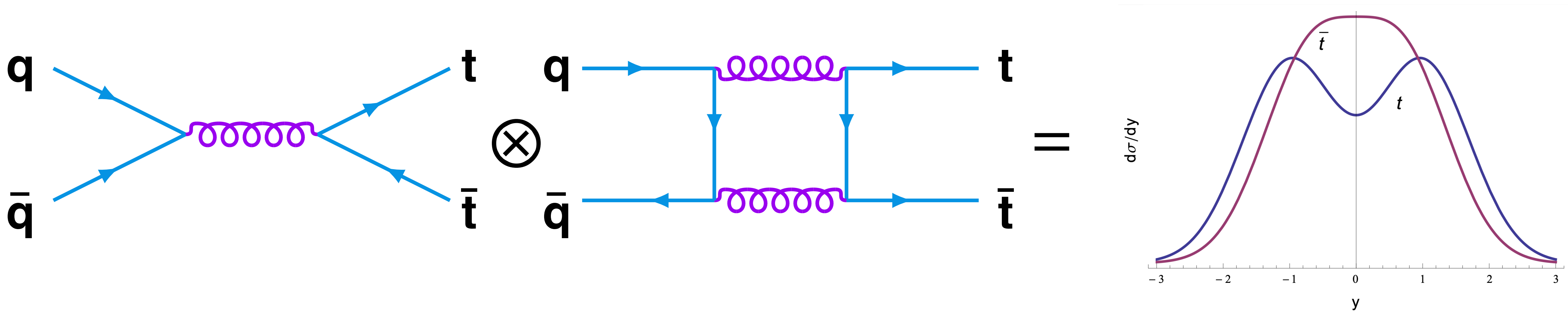




- Use b...
- Exclu... d
  neutr...

➡ L... ncluded to account for the Data/Prediction disagreement in $|\Delta\phi_{\ell\ell}|$.

Charge Asymmetry



- Interference between Born and Box diagrams, and to a lesser extent ISR and FSR, induce an asymmetry in the direction of top and anti-top quarks:
  - ➡ Top quarks produced more forward than anti-top quarks.
  - ➡ (mention Tevatron ppbar asym.)
- This *"charge asymmetry"* only exists in higher-order qqbar production, gg-fusion is symmetric to all orders:
  - ➡ Extremely challenging to measure at the LHC (qqbar ~10% of production fraction at 13 TeV).

$$A_C^{t\bar{t}} = \frac{N(\Delta|y| > 0) \; - \; N(\Delta|y| < 0)}{N(\Delta|y| > 0) \; + \; N(\Delta|y| < 0)} \qquad \Delta|y| = |y(t)| - |y(\bar{t})|$$

Charge Asymmetry

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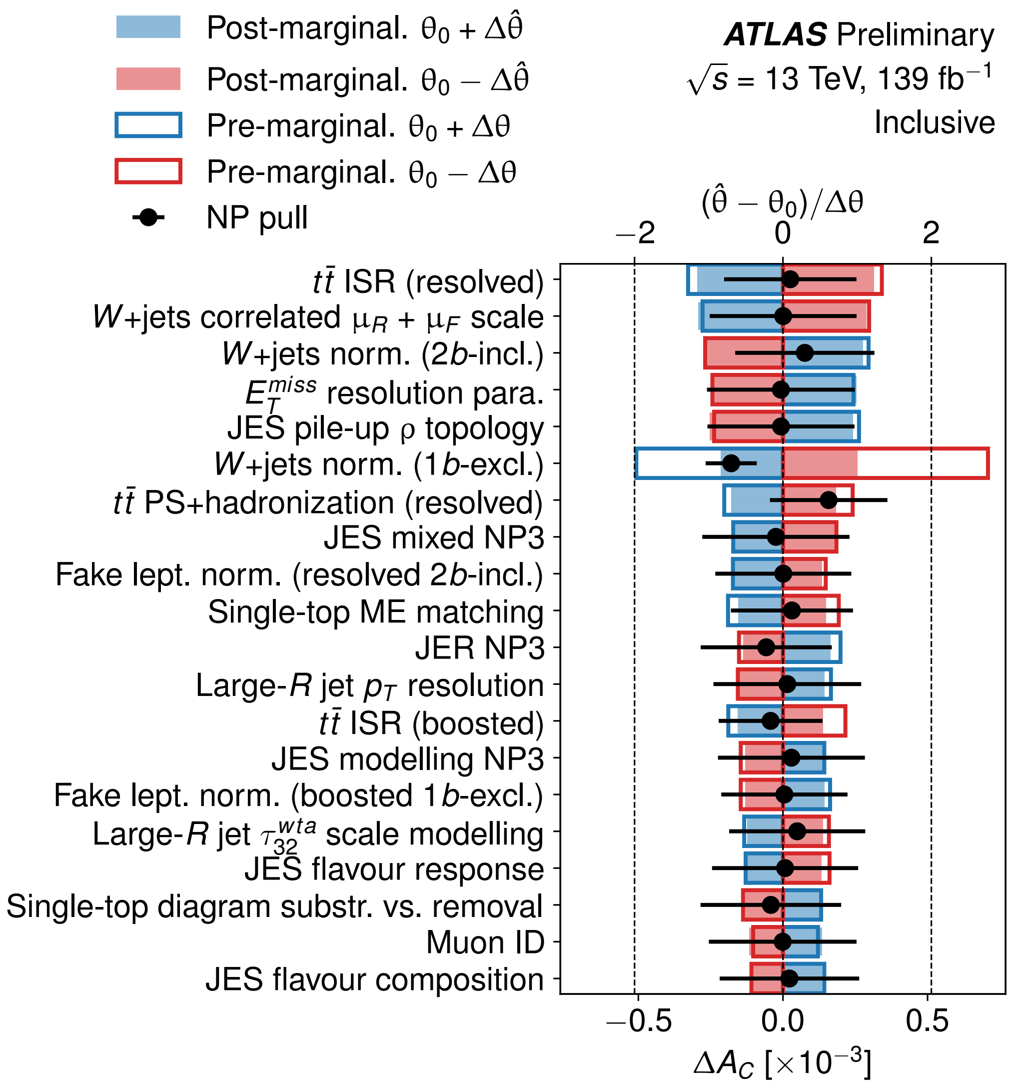
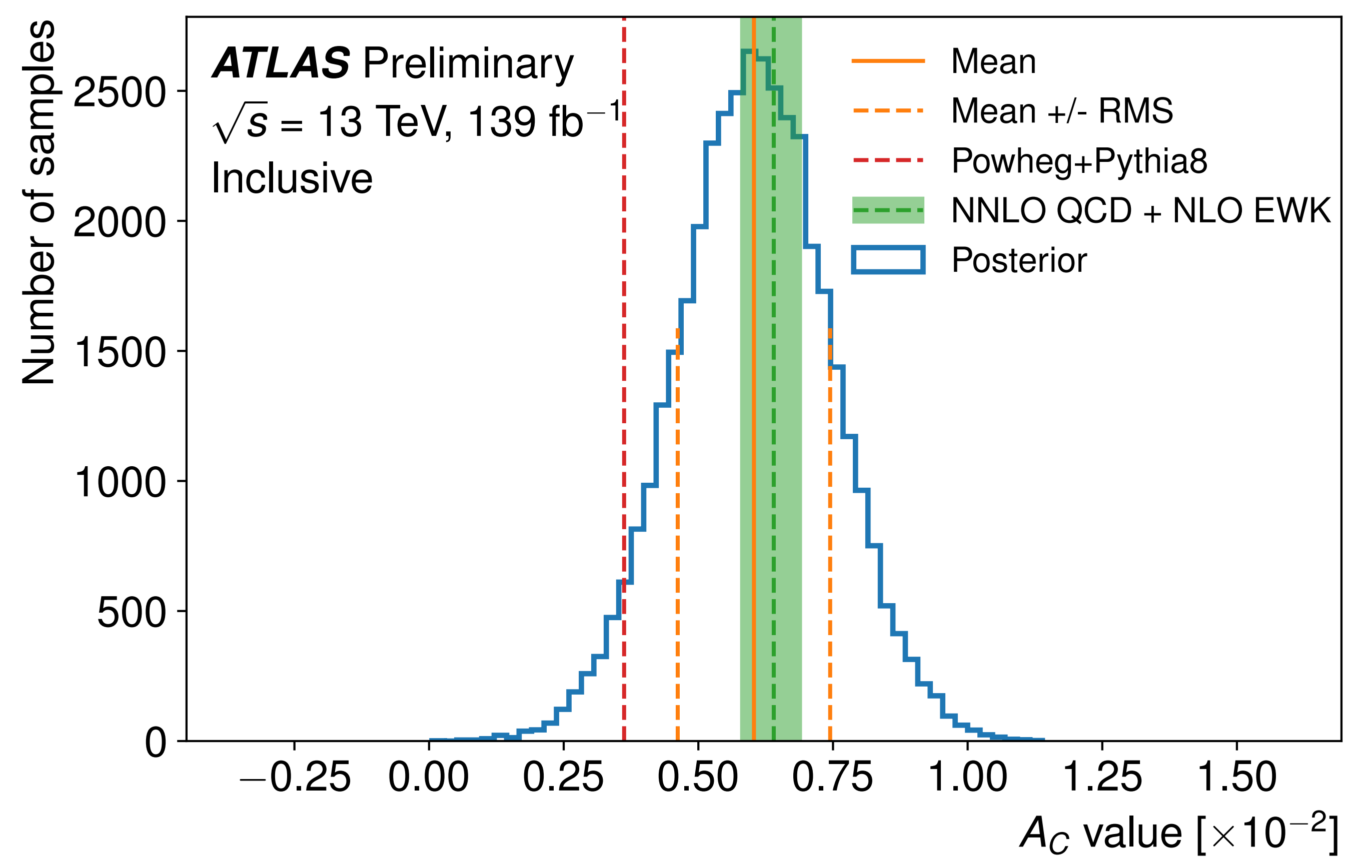
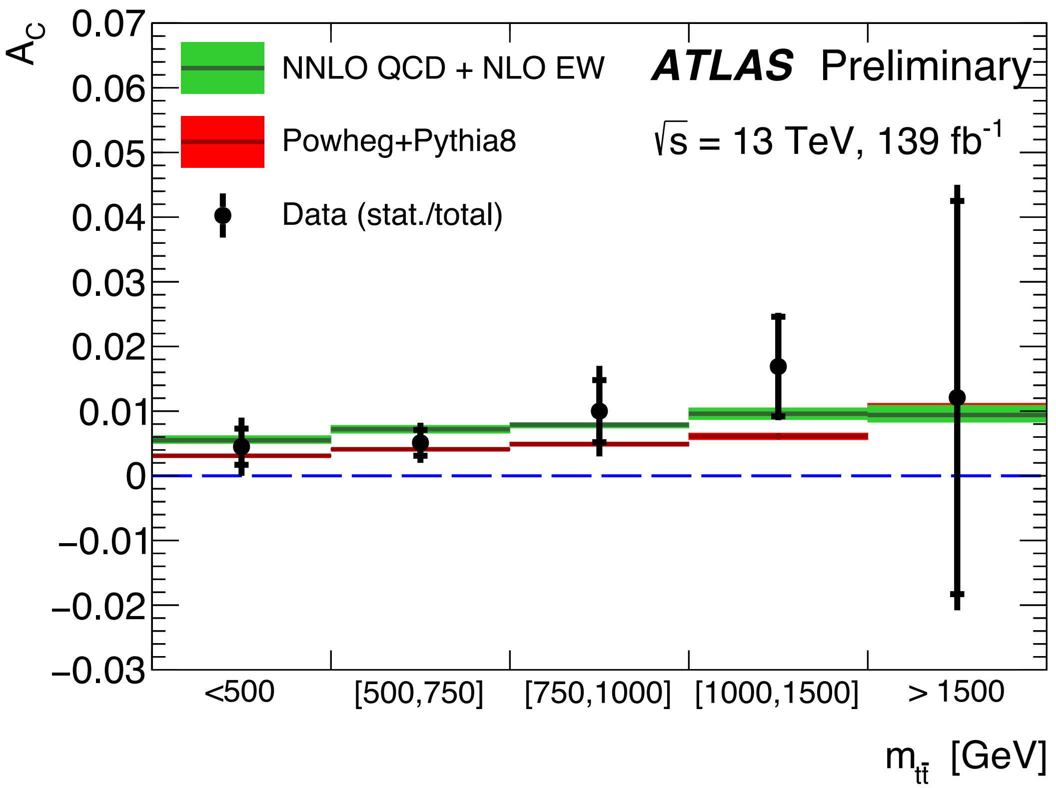
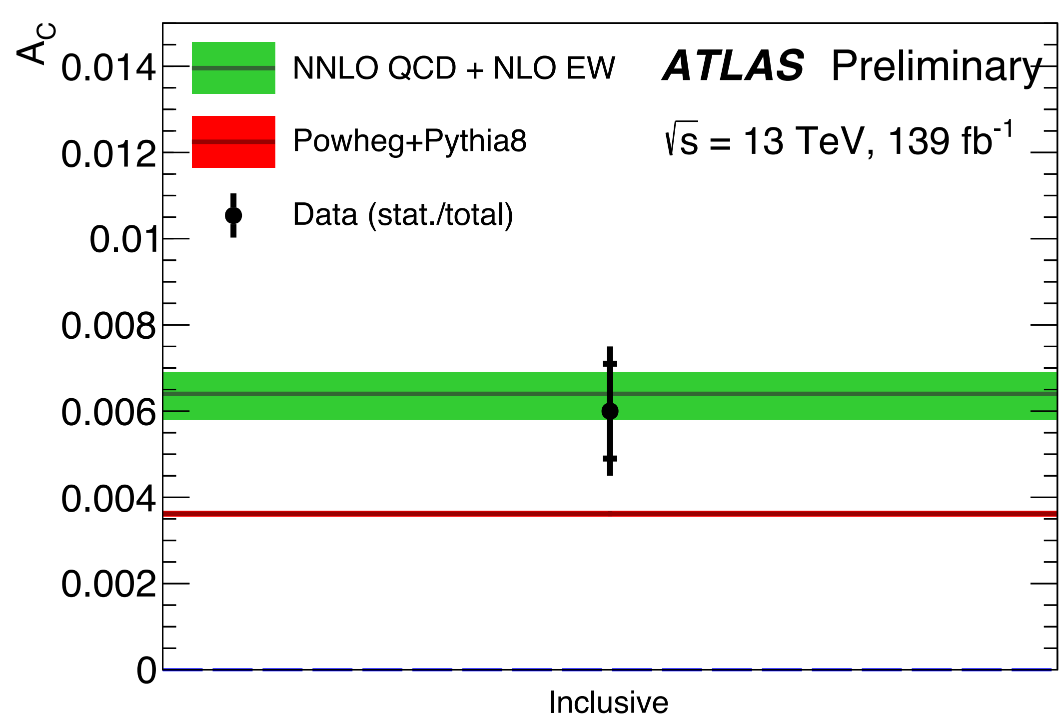


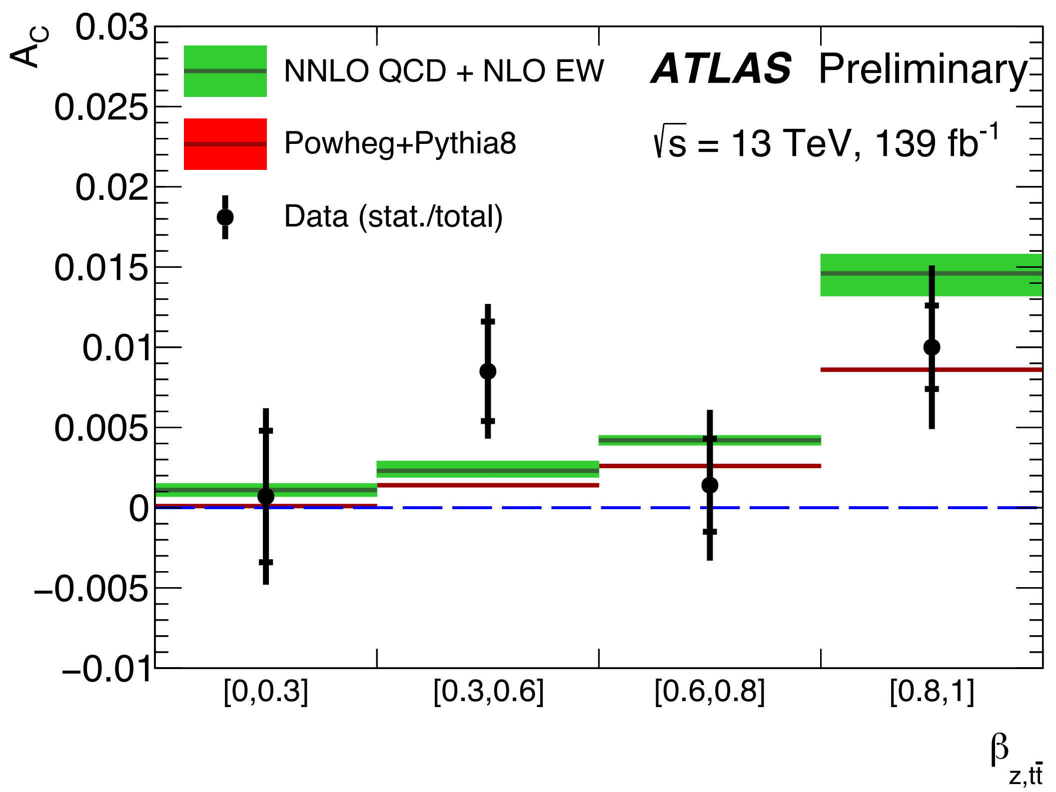


- Charge asymmetry is extracted from 139 fb^{-1} of 13 TeV data, using a resolved (pT(t) < 400 GeV) and boosted (p_T(t) > 400) single lepton (e/μ) selection.
- The $|\Delta y|$ distribution is unfolded using a likelihood-based technique called *"fully bayesian unfolding"* **[ref]**.
  - ➡ Systematic uncertainties are profiled as nuisance parameters.

Charge Asymmetry

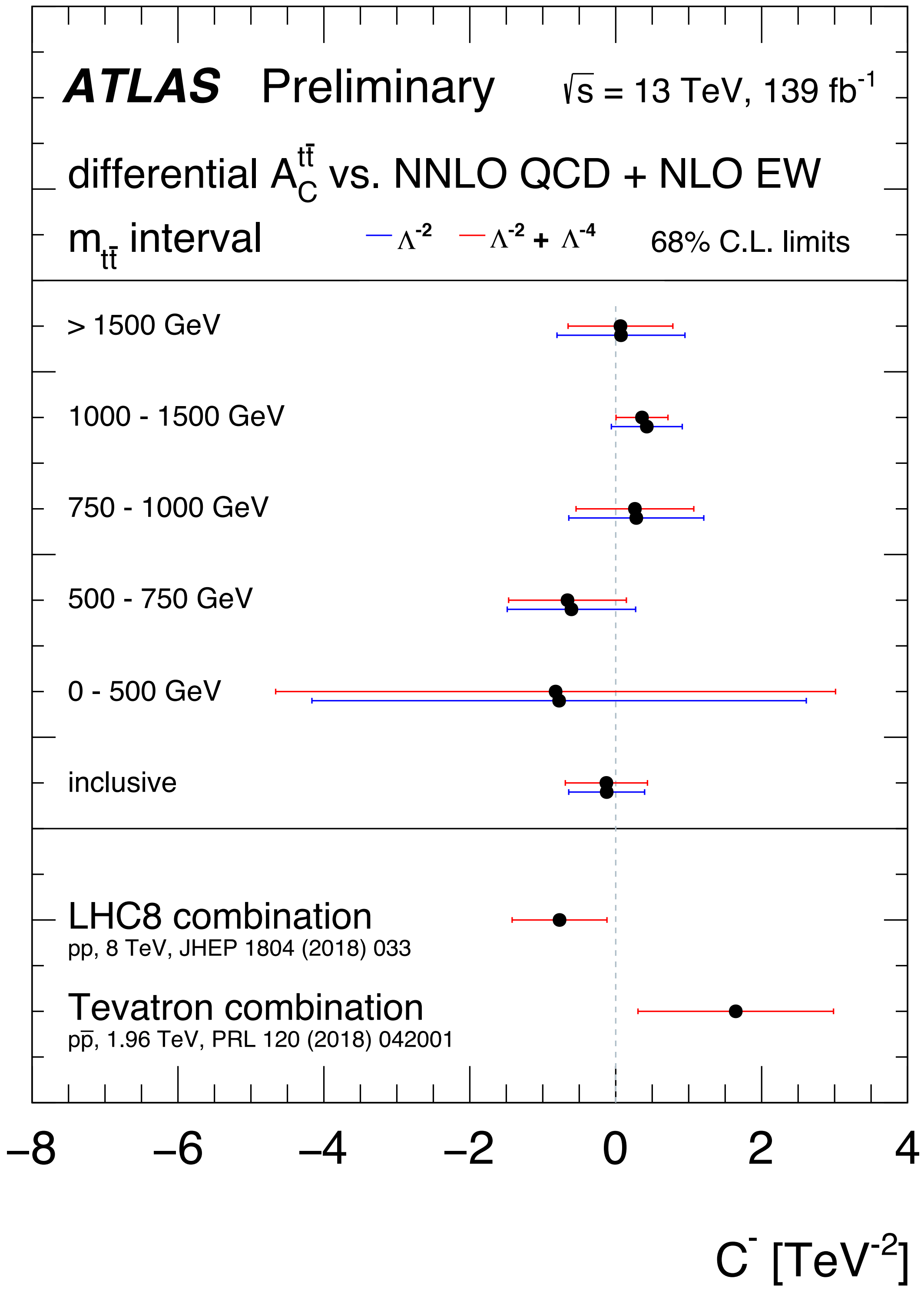






- Charge Asymmetry measured inclusively to be 0.6% +/- 0.15%, in agreement with the NNLO QCD + NLO EW predictions and 4σ from 0.
  ➡ **First evidence for charge asymmetry in pp collisions.**
- Also measured as a function of $m(t\bar{t})$ and the boost of the $t\bar{t}$ system.

Charge Asymmetry



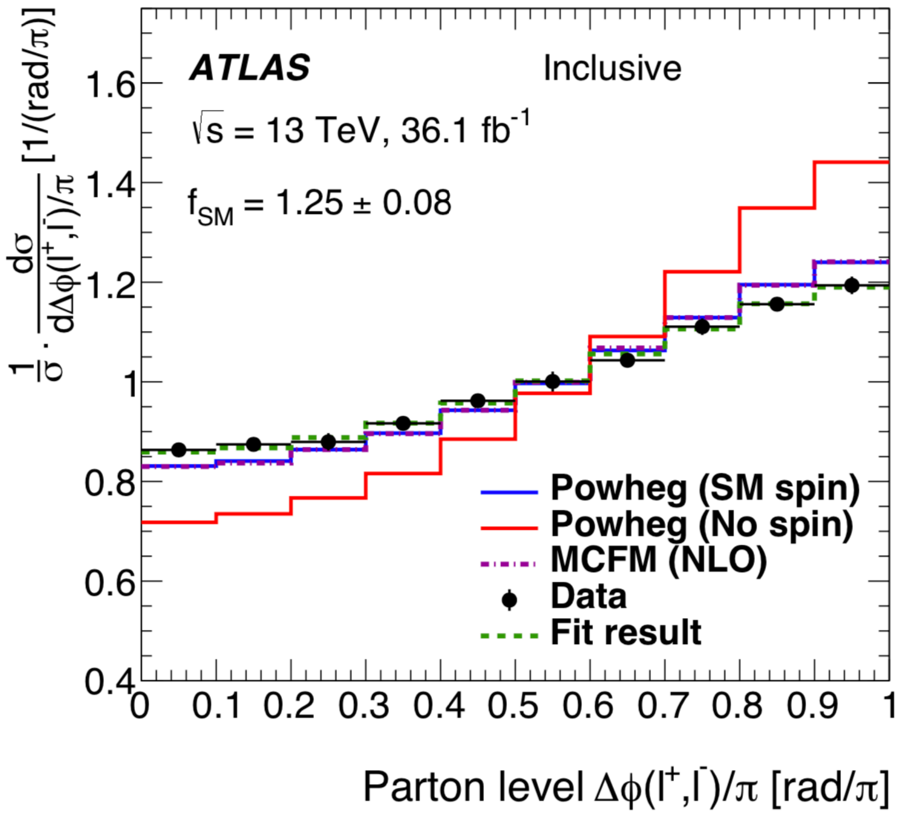
- These measurements can also be used to set limits on EFT operators:

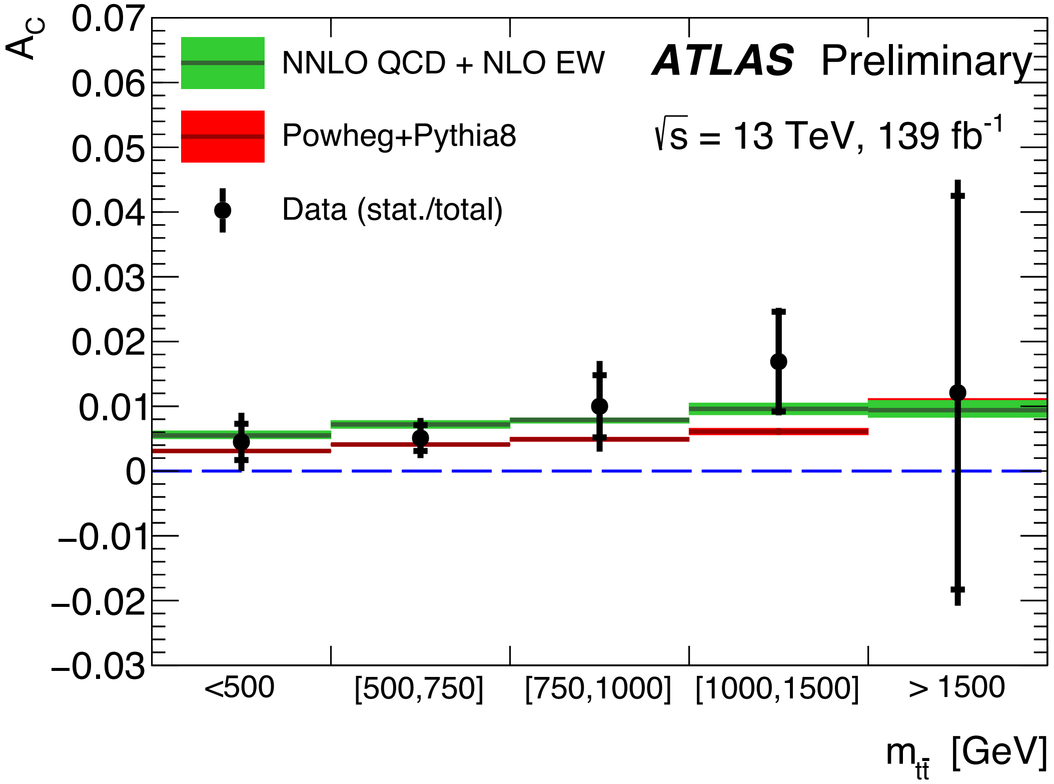
  C^- = four fermion operator assuming flavour conservation and equal up-down type couplings (simple axion model).

- Inclusive and differential results are surpassing those set via ATLAS+CMS combination in Run1.

- Not a large dependence on quadratic terms:
  ➡ dimension 6 approach is stable and appropriate.

Conclusion





- ATLAS has a large suite of top properties measurements that are probing the SM's heaviest particle to ever-greater precision.
- We are now encountering significant tensions between data and predictions:
  - ➡ Perhaps this is highlighting the limitations in our understanding of $t\bar{t}$ production and decay.
  - ➡ Perhaps it's something more interesting…
- We are now also able to see subtle higher-order effects.

Backup

NLO Expansion