Spinning Tops: Top quark spin correlations in the dilepton channel at ATLAS (and CMS)

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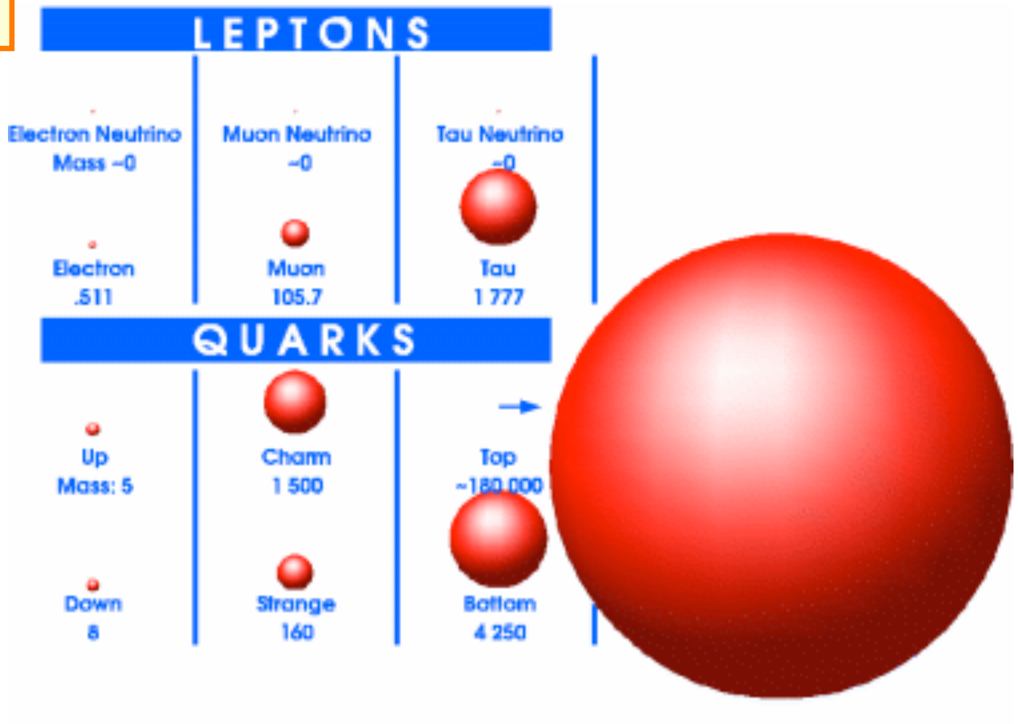
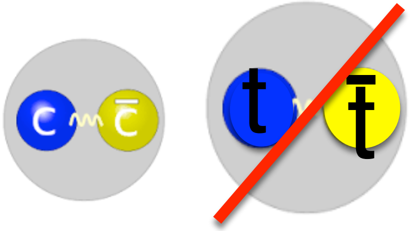
23/05/19

Introduction to top quarks

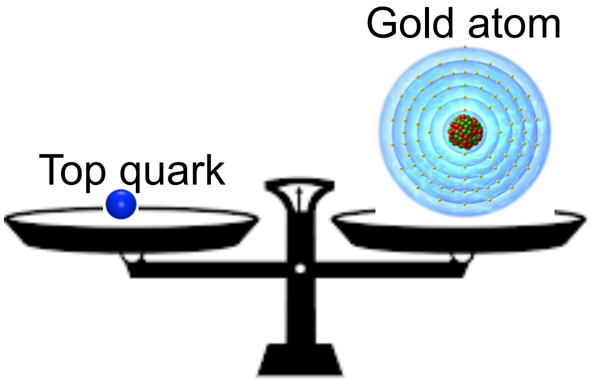
- Discovered by CDF and DØ collaborations at the Tevatron in 1995



- A unique quark:
  - Lifetime ~5×10^{-25} s
  - Decays before it hadronises
  - No bound states (mesons)

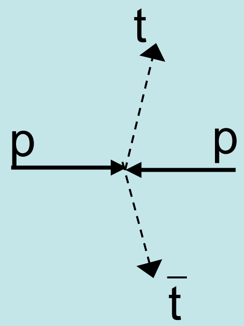


  - Largest mass of any fundamental particle
  - Yukawa coupling ~ 1



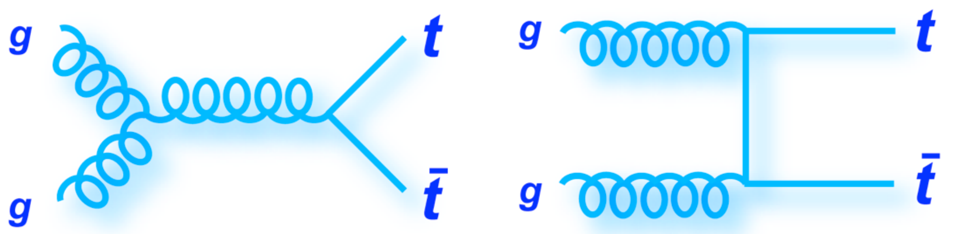
Top quark production at the LHC

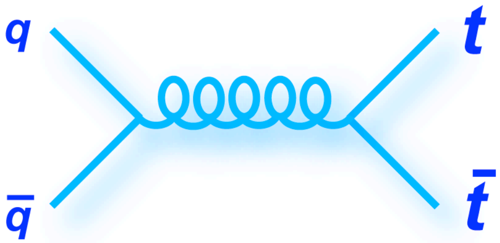
Top pairs



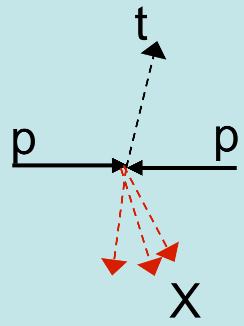
QCD pair production: gg-fusion and $q\bar{q}$ annihilation

~90 %



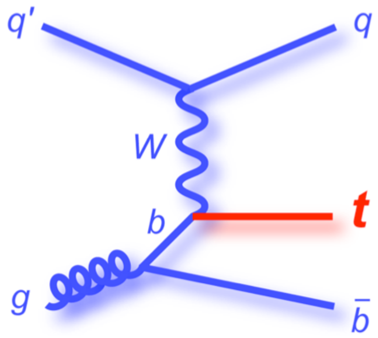


Single top



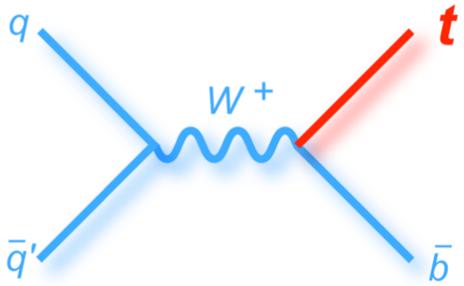
EW production of single top quarks

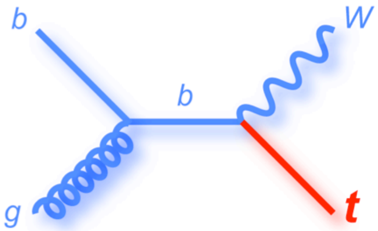
t-channel



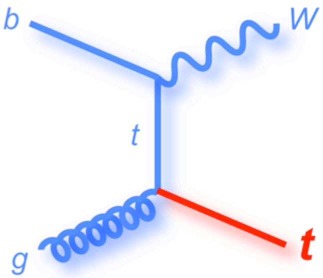
Dominant

s-channel





associated tW



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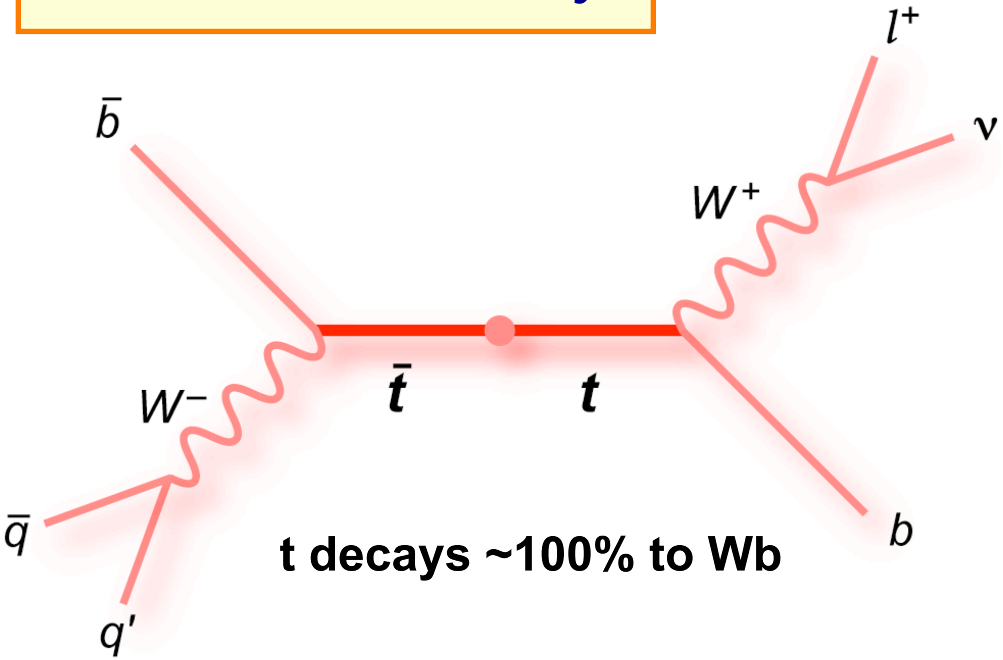
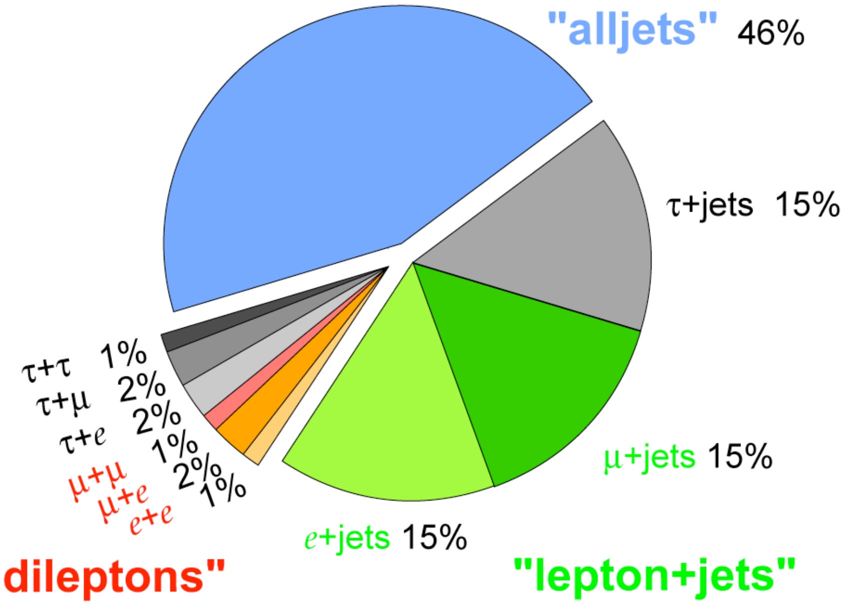
Overview of $t\bar{t}$ decays



t decays ~100% to Wb



	BR	Background	b jets	Light jets	Leptons	Neutrinos
Fully hadronic	High	Very high	2	4	0	0
Semi-leptonic	High	Fairly high	2	2	1	1
Dileptonic	Low	Low	2	0	2	2

What we would like to know about top

Production cross section

Resonant production?

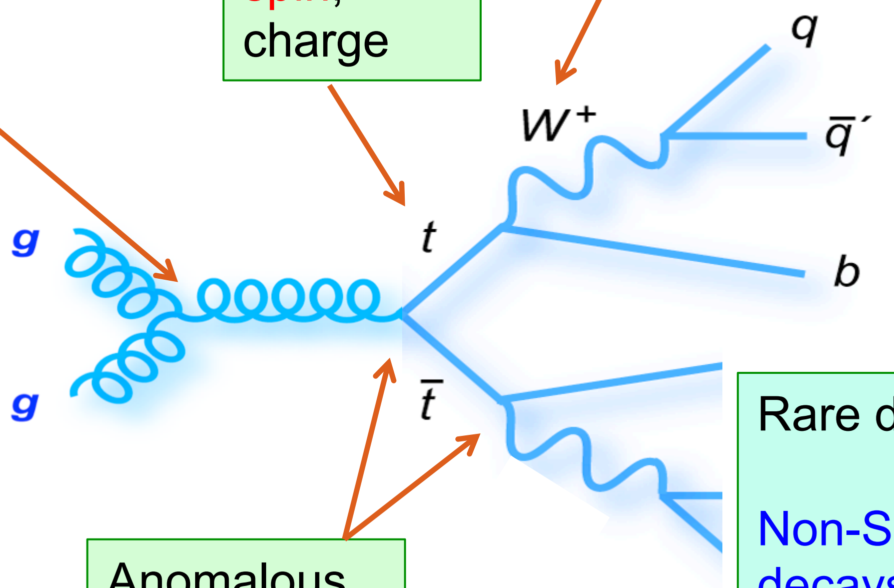
Production kinematics

Spin/polarisation

Top mass, width, spin, charge

Wtb coupling, $|V_{tb}|$

W helicity



+ more!

Anomalous couplings?

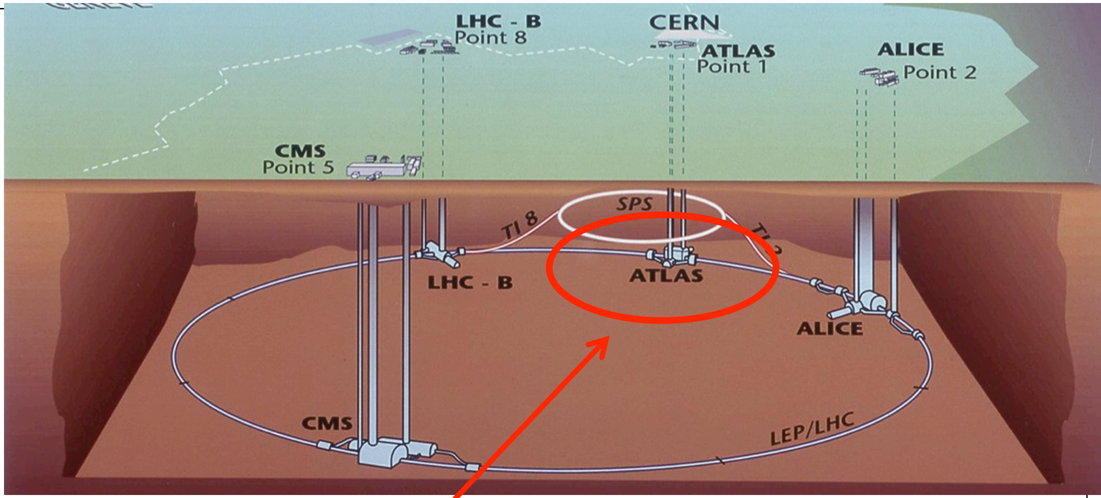
Yukawa coupling?

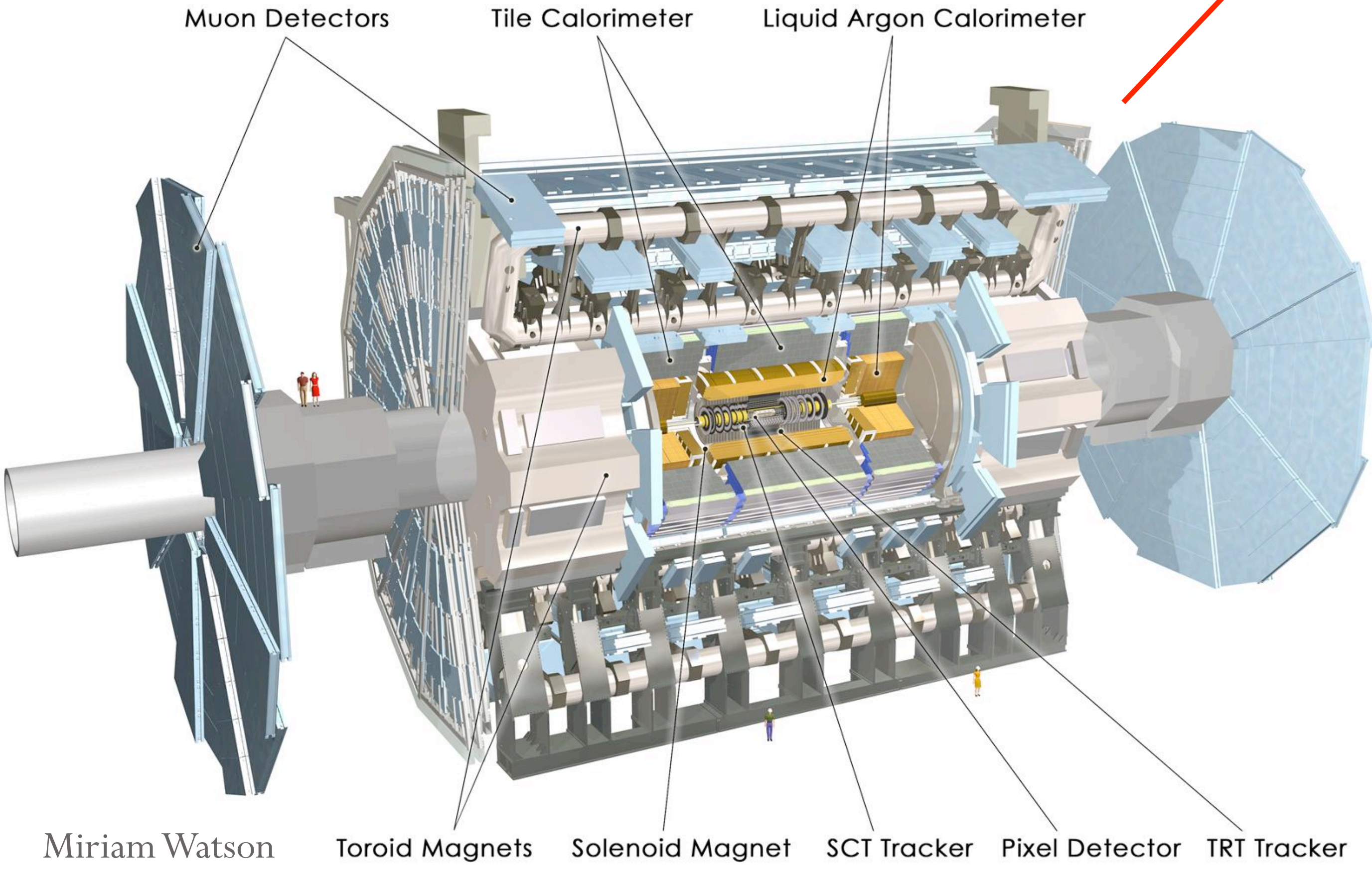
Rare decays

Non-SM decays?

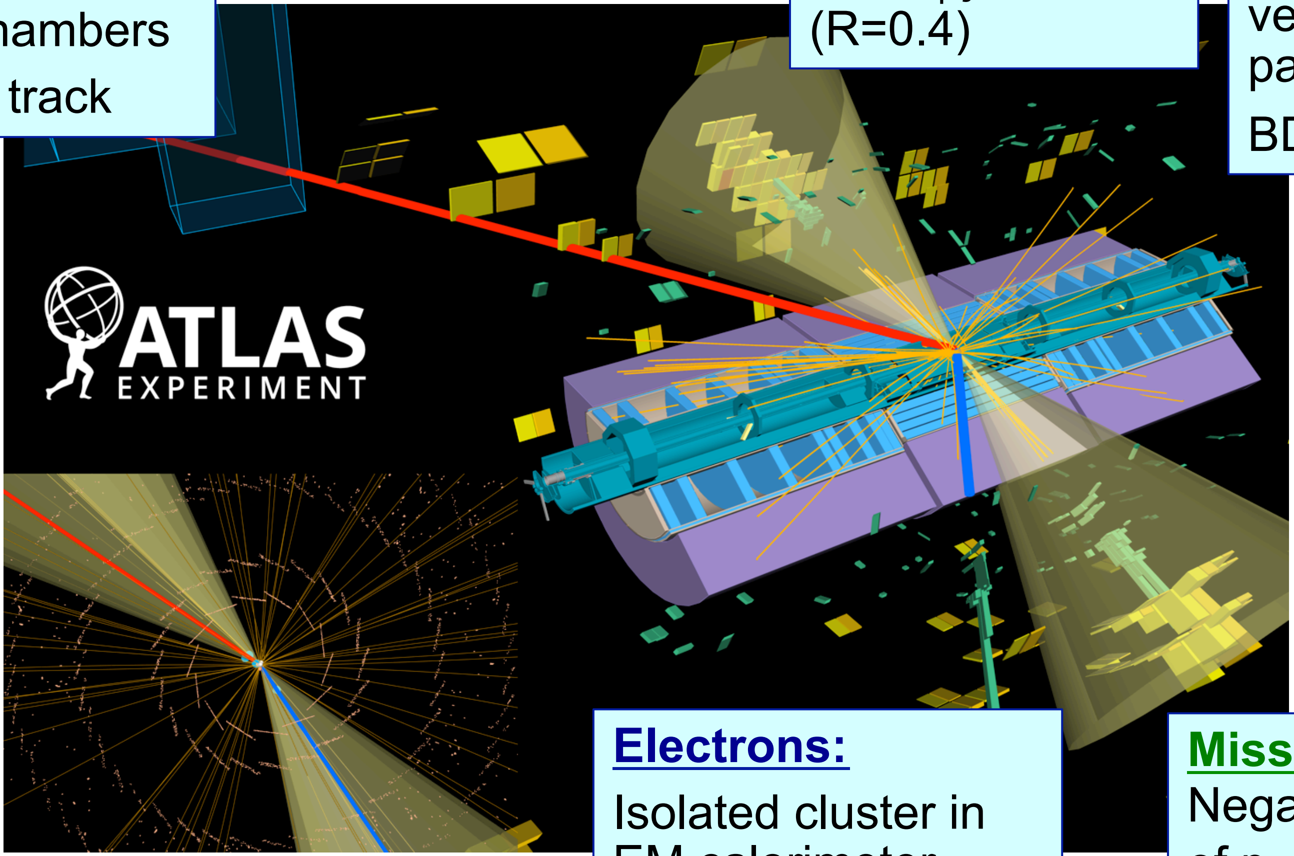
Branching fractions

The ATLAS detector





Selection of top events (example)



Muons:

Segments in tracker and muon chambers

Isolated track

Jets:

Topological calorimeter clusters

Anti-k_T jet finder ($R=0.4$)

B-tagged jets:

Displaced tracks, secondary vertex, impact parameters etc.

BDT algorithms

Electrons:

Isolated cluster in EM calorimeter

Matched to track

Missing E_T:

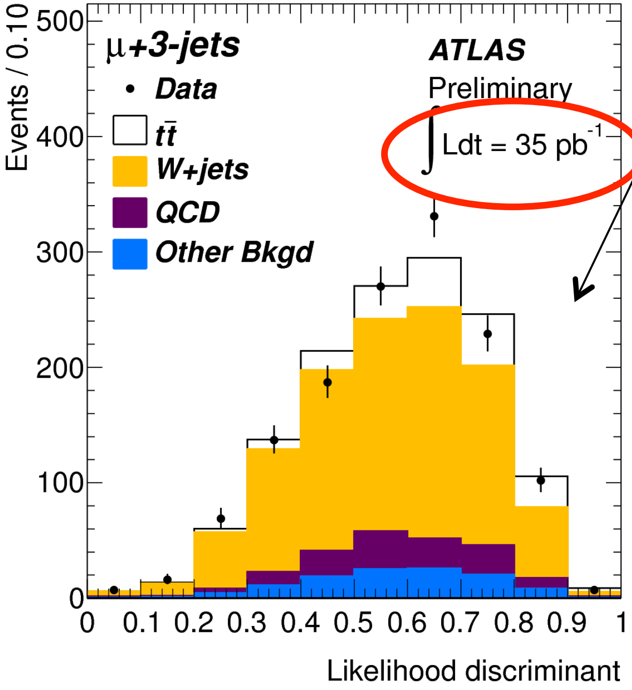
Negative vector sum of p_T for all reconstructed, calibrated objects

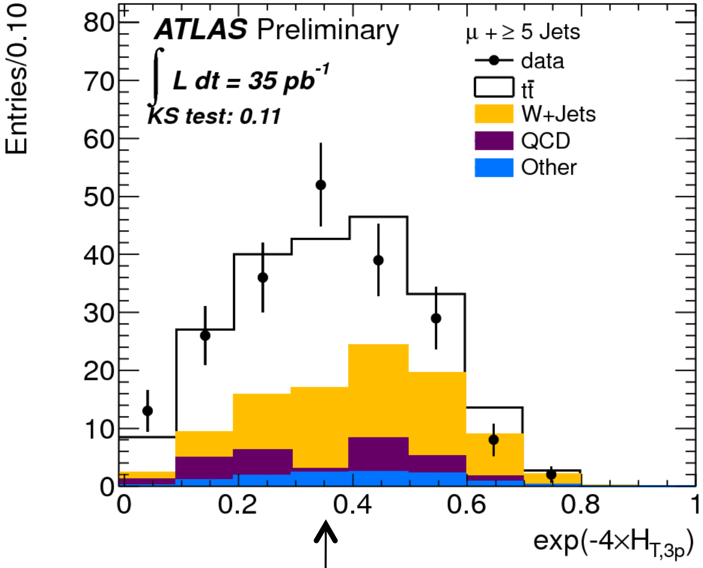
Top pair cross-section (lepton+jets)

- Use binned likelihood fit to kinematic distributions

- Selection:
  - Lepton trigger
  - Lepton
  - Jets
  - Missing E_T

No b-tagging





With b-tagging

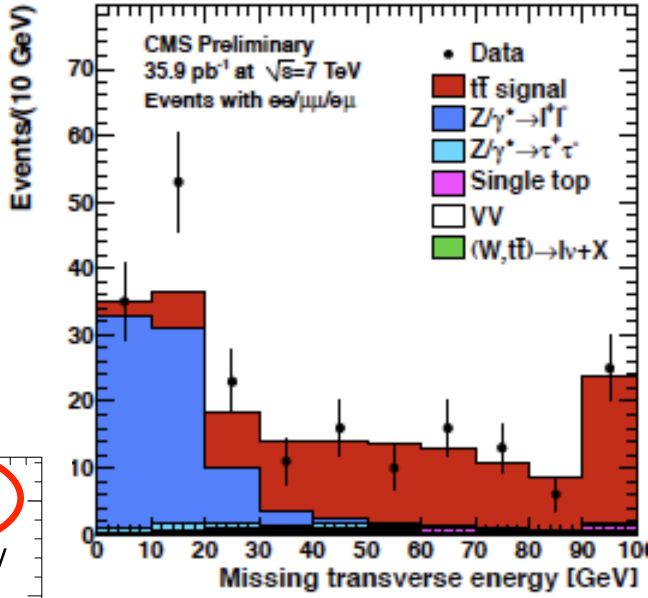
- Jet energy scale and reconstruction uncertainties dominate
- Most backgrounds determined from data
- Larger background w/o b-tagging, but no tagging uncertainties

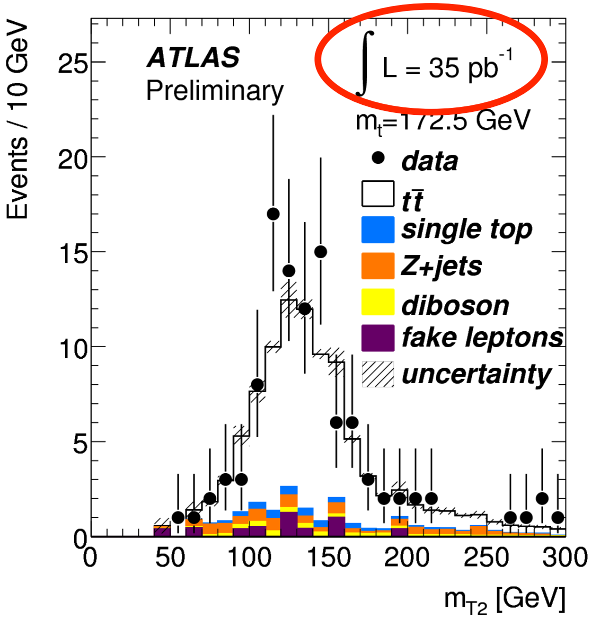
Top pair cross-section (dilepton)

- Cut-based methods
  - 2 leptons (opp.sign)
  - 2 jets
  - Missing E_T, total E_T

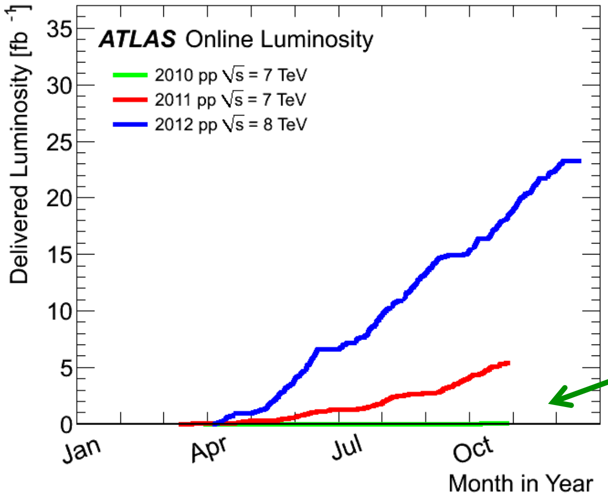
- Main systematics
  - JES
  - Parton shower
  - Fakes

ee, μμ, eμ channels



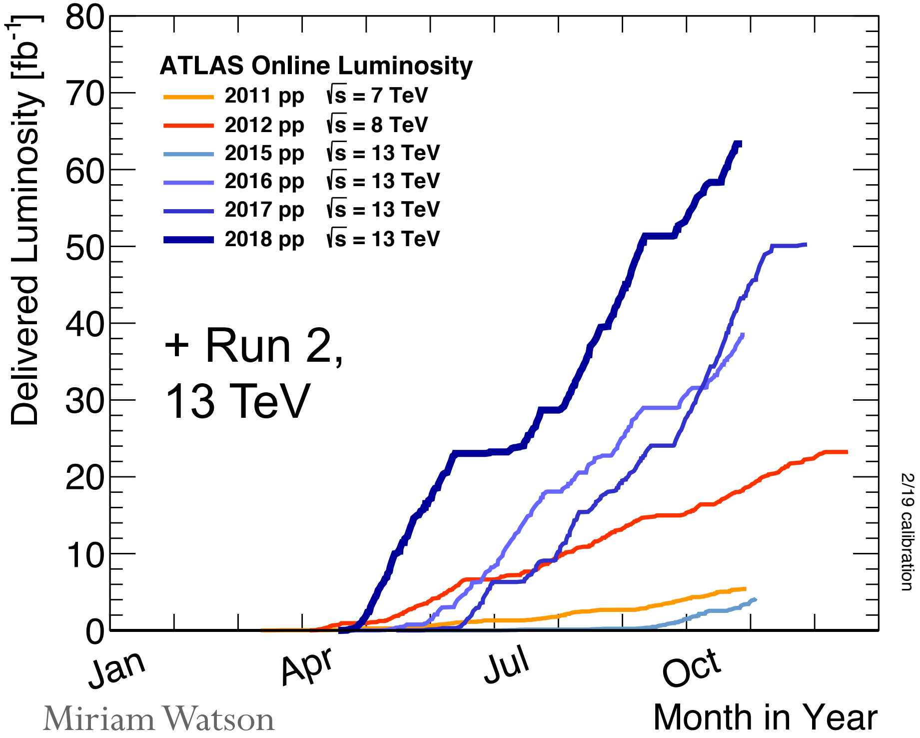


Data-taking at ATLAS 2010-2018



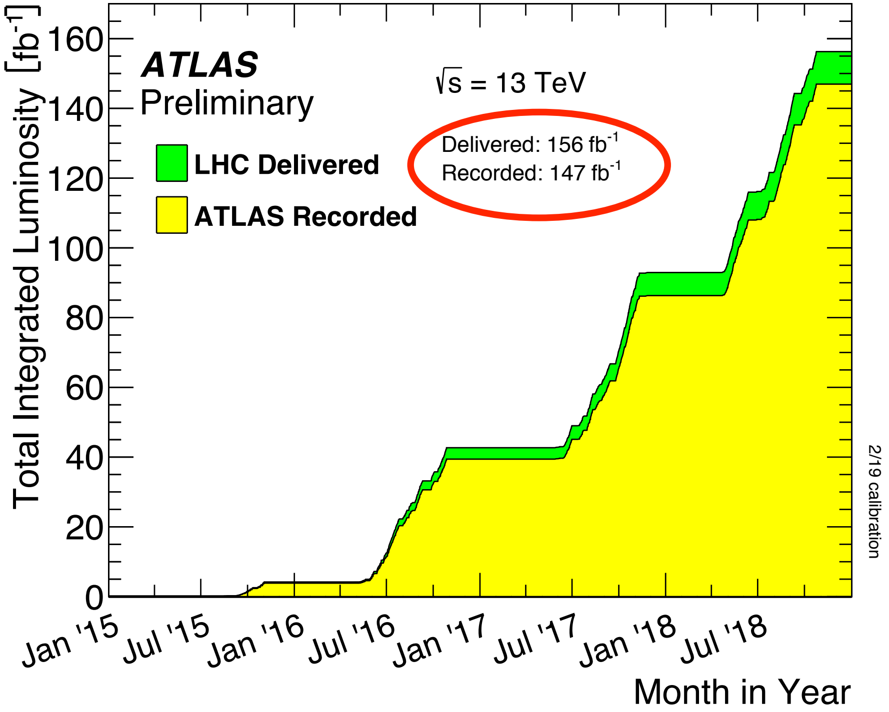
Run 1,
7+8 TeV

2010 data!



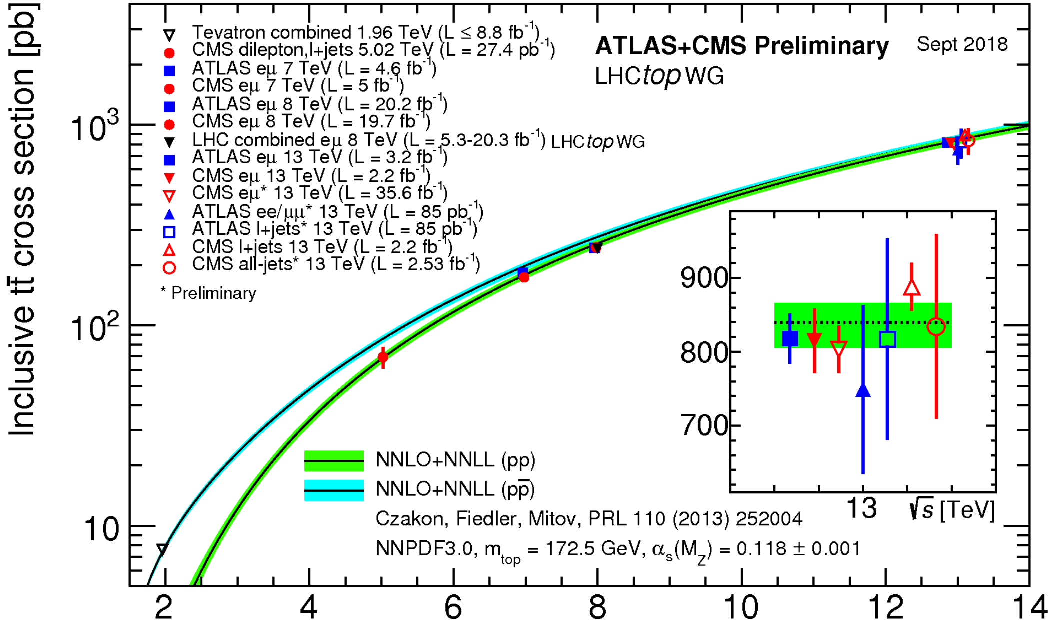
+ Run 2,
13 TeV

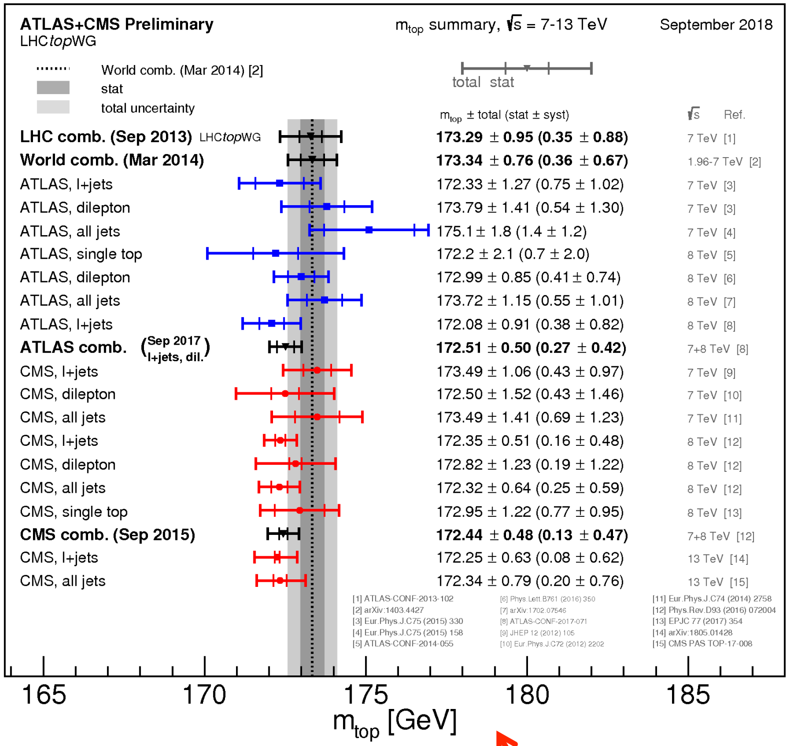
Run 2, 2015-18



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

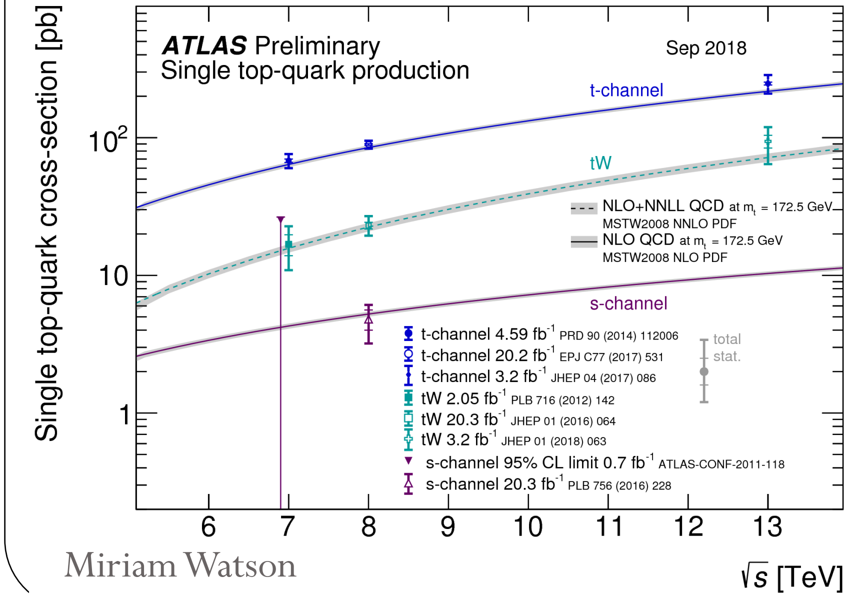
Top physics summary plots: 7, 8 and 13 TeV





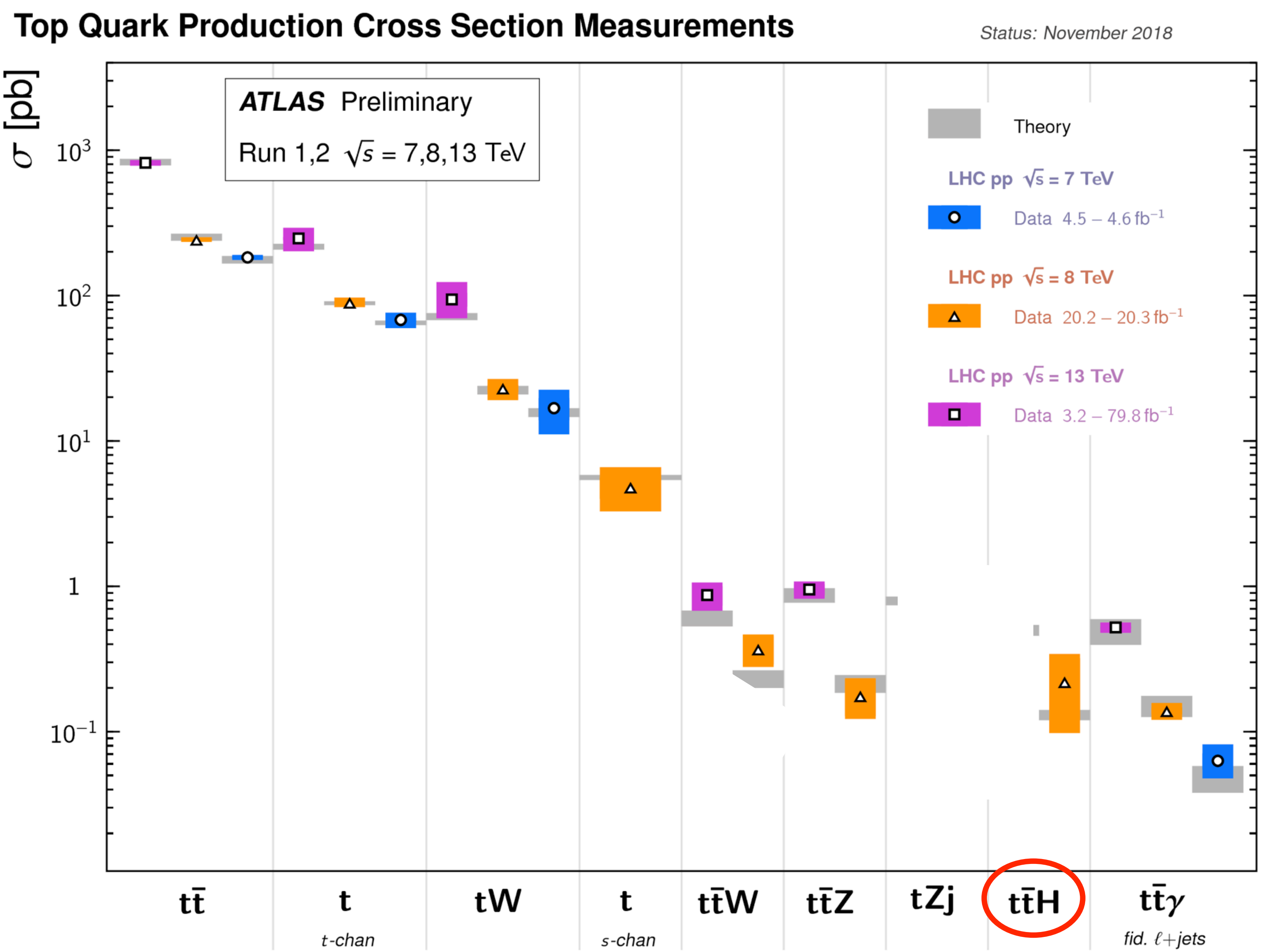
Top pair cross-sections (note increase with √s)

Top quark mass



Single top cross-sections: t-channel, tW production and s-channel

Top quark cross-sections

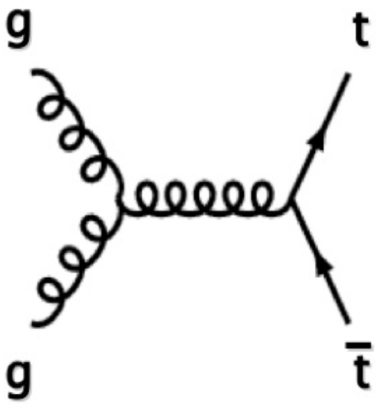


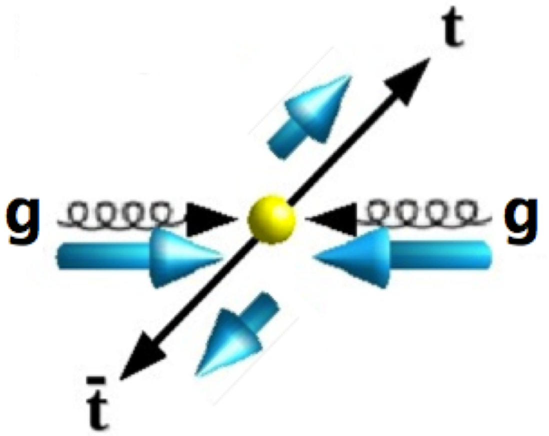
Now a “background” to consider!

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



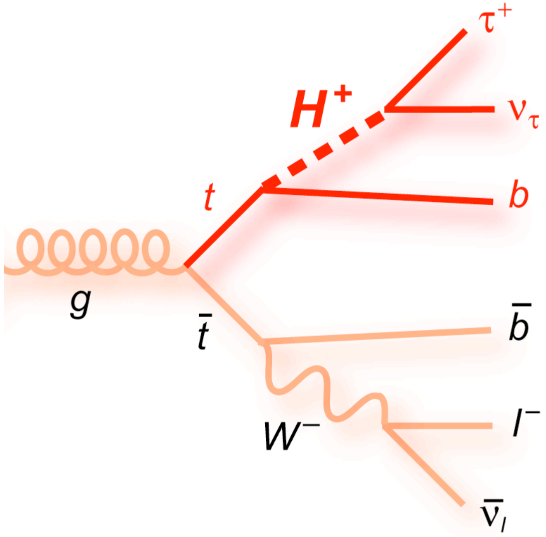


➡ Spin information passed directly to decay products

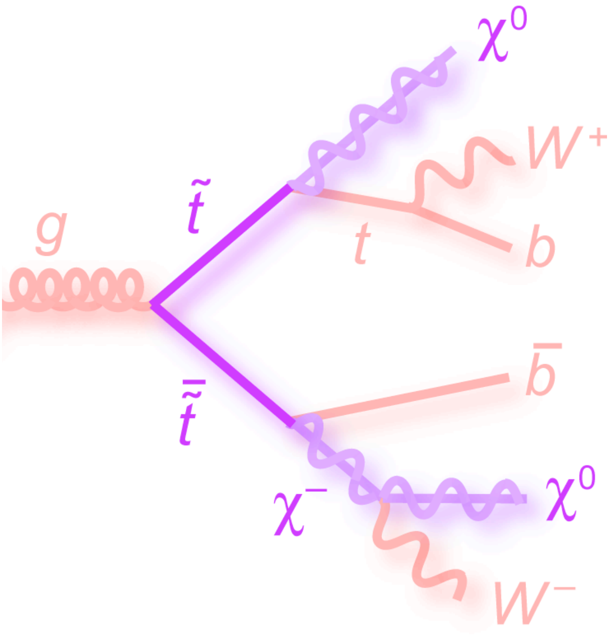
➡ Measure spin information from angular distributions

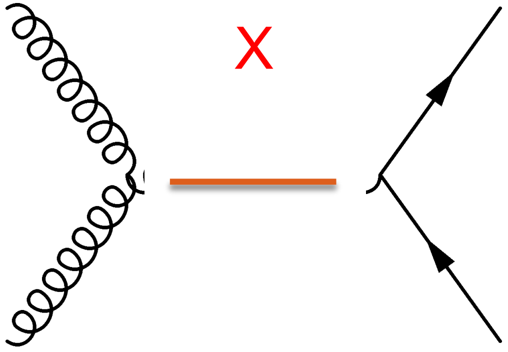
Spin correlation: beyond the Standard Model

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



- Decays: charged Higgs, b',…

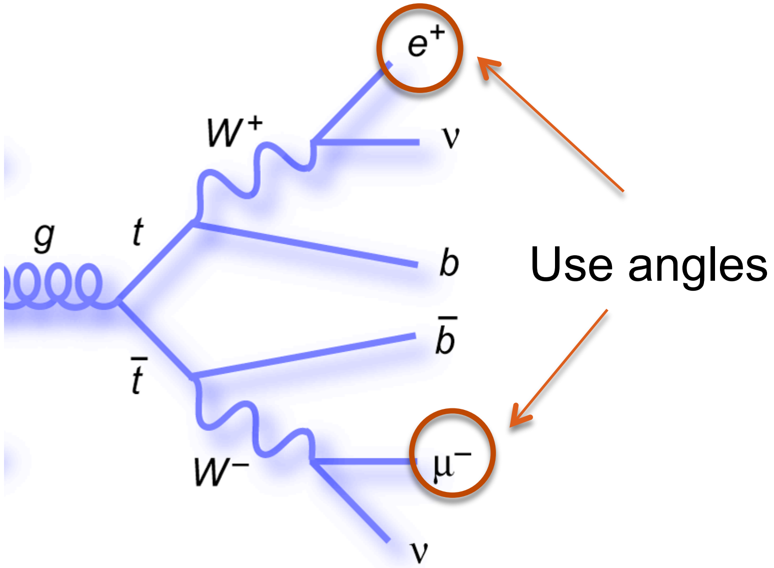




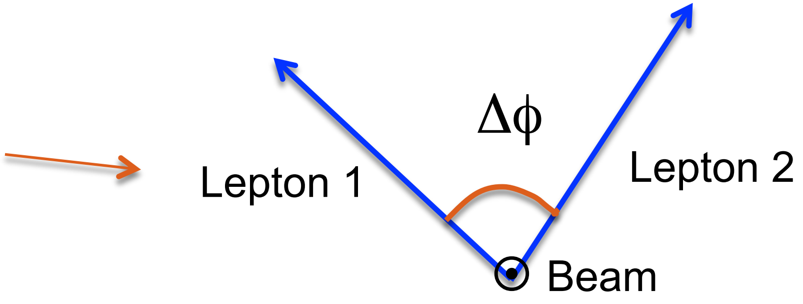
- Production: stop pairs, KK gravitons, Z', Higgs…

Spin correlation: Δϕ observable

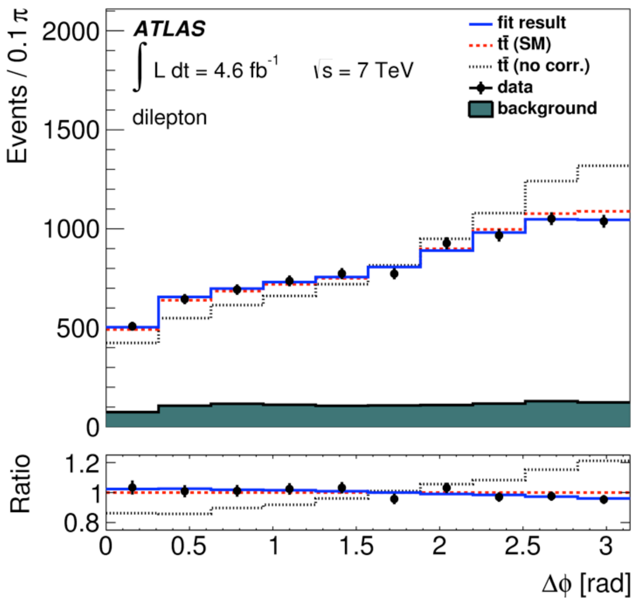
- Highest spin analysing power: leptons from top decay
- Use dileptonic tt events
- Very clean samples



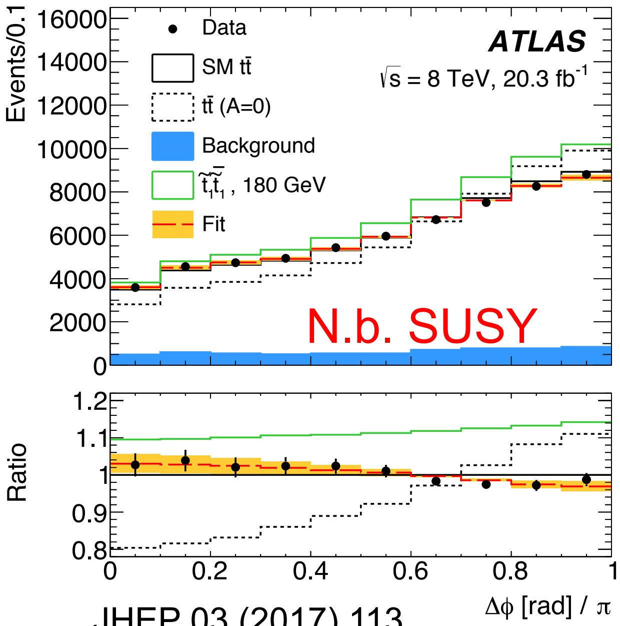
- Measure spin correlation using angular distributions of decay products (leptons here)
- Spin correlation can be inferred from the Δϕ distribution:
  - Δϕ: difference in azimuthal angle between the leptons, lab frame
- No event reconstruction required
- Excellent lepton resolution



Previous results at 7 TeV and 8 TeV

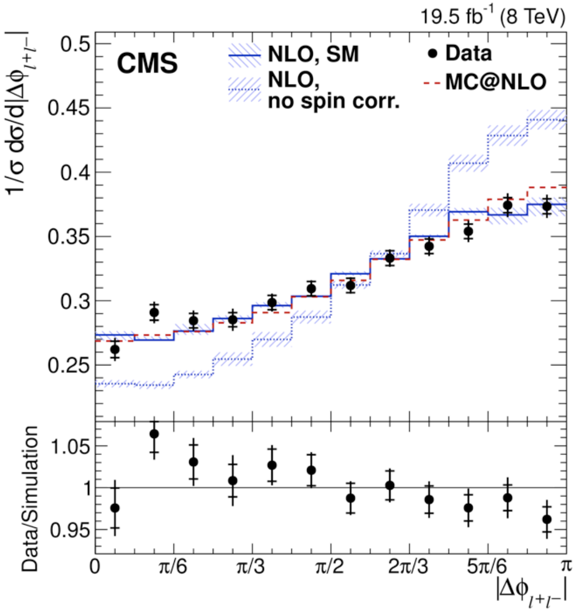


PRD90 (2014) 112016



N.b. SUSY

JHEP 03 (2017) 113



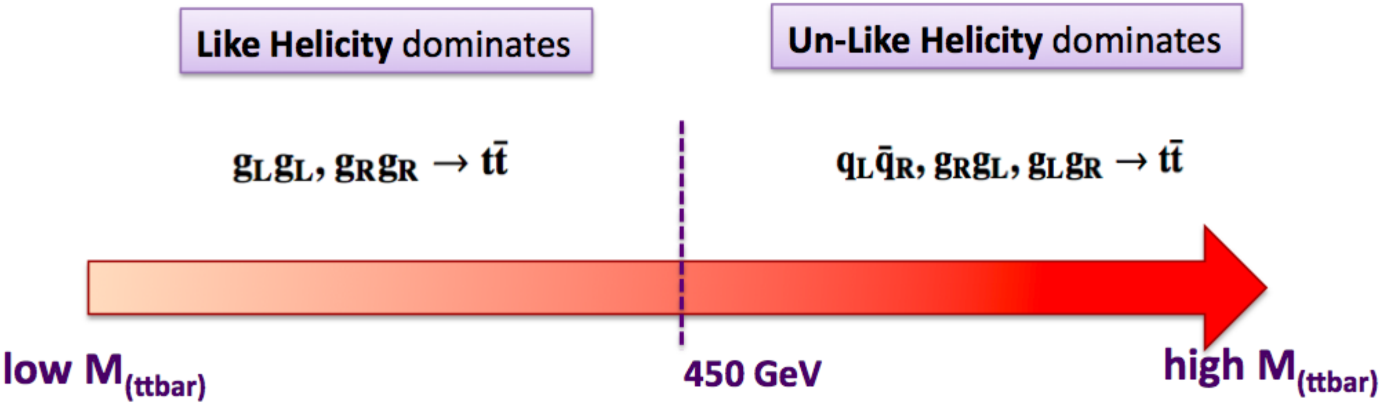
PRD93 (2016) 052007

- Several measurements by ATLAS and CMS at multiple collision energies
- First exclusion of <u>zero spin correlation</u> at >5σ by ATLAS at 7 TeV
- Both experiments have observed Δϕ 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_{tt}
- Dominated by gluon-gluon fusion at LHC



Like Helicity dominates

Un-Like Helicity dominates

$g_L g_L, g_R g_R \to t\bar{t}$

$q_L \bar{q}_R, g_R g_L, g_L g_R \to t\bar{t}$

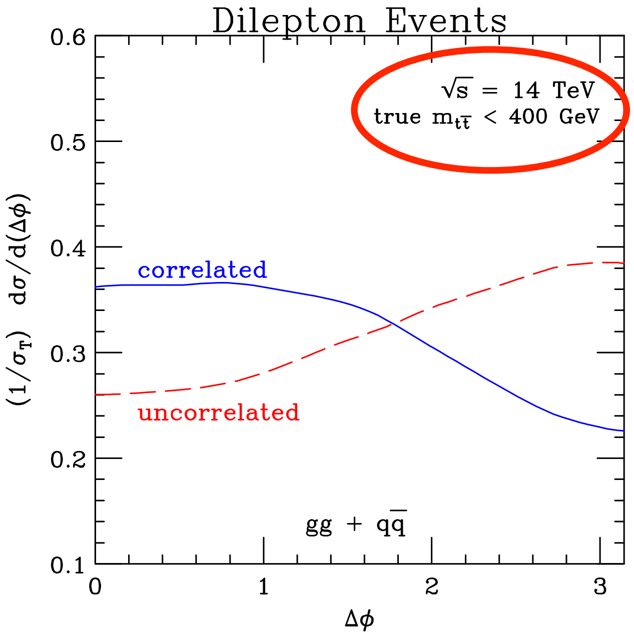
low $M_{(ttbar)}$

450 GeV

high $M_{(ttbar)}$

(JWH 2013)

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

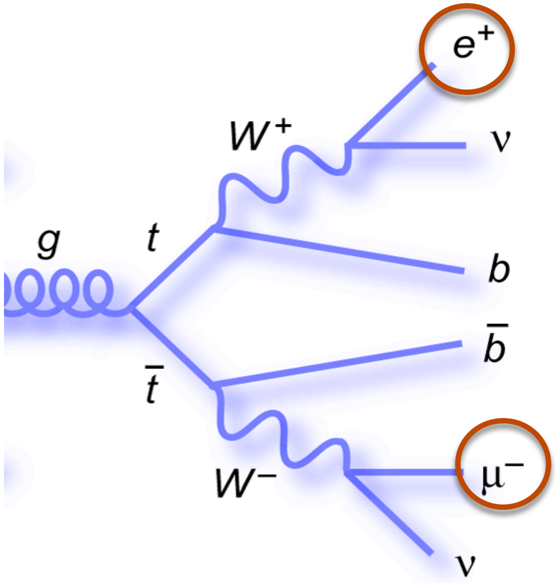


Mahlon and Parke
Phys. Rev. D 81, 074024

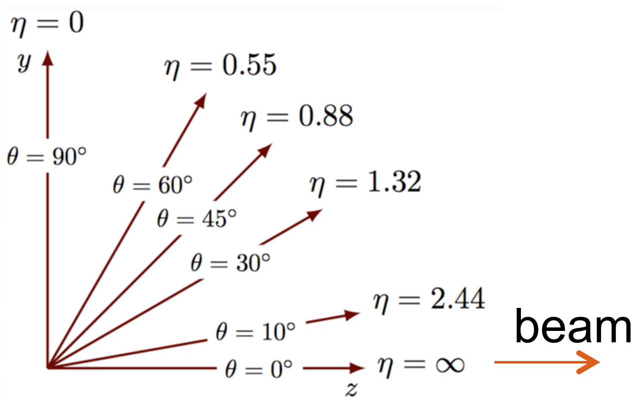
13 TeV analysis summary

Submitted to EPJC: arxiv:1903.07570

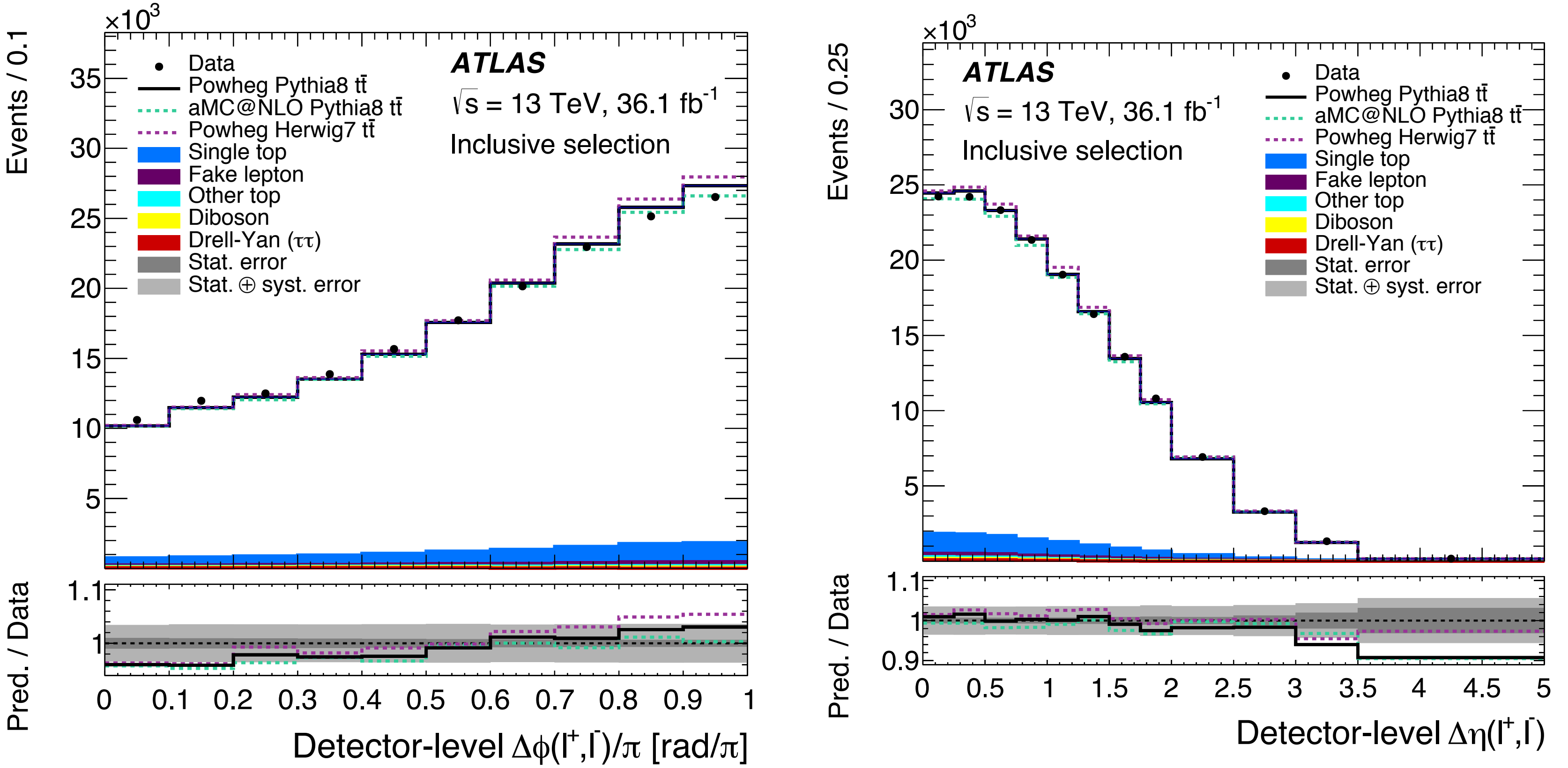
- 2015 + 2016 data (36 fb^{-1}) with a standard dilepton **eμ selection**:
  - Exactly 2 opposite-sign leptons (27, 25 GeV)
  - At least one b-jet; >= 2 jets pT > 25 GeV
  - No cuts on MET or on m(ll)
- Fiducial particle level:
  - Same kinematic cuts as above
  - “Dressed” leptons with radiated photons
  - Anti-k_T R=0.4 jets with “ghost-matching” for b-tagging
- Parton level, full phase space:
  - Tops defined after radiation, leptons before
  - eμ 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_{tt}:
  - Require tt event reconstruction
  - Use *Neutrino Weighting*

Event reconstruction for m_{tt} dependence

- Reconstruct dilepton tt 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: [171,174] GeV in 0.5 GeV steps
  - Smear jet p_T

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

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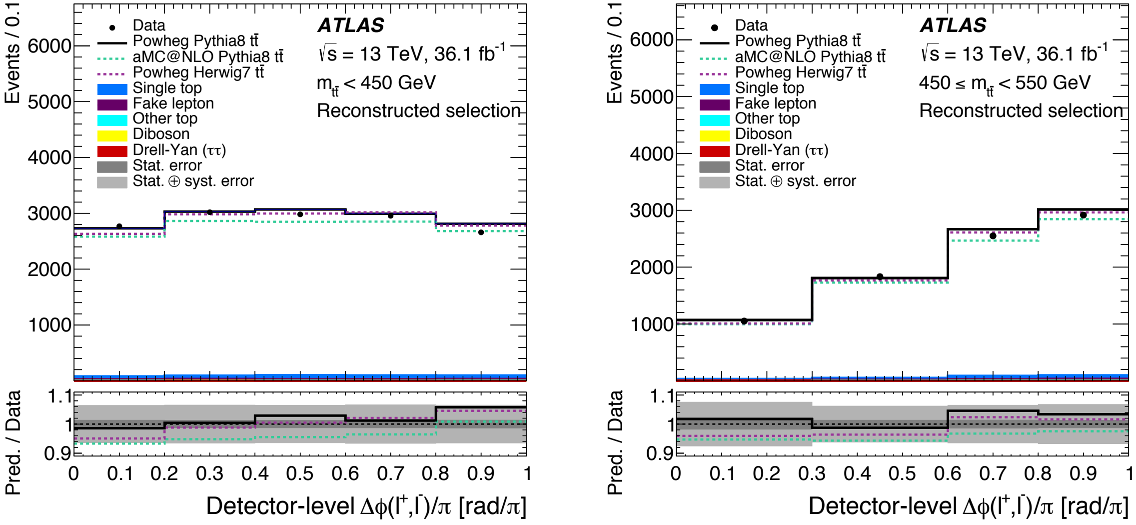
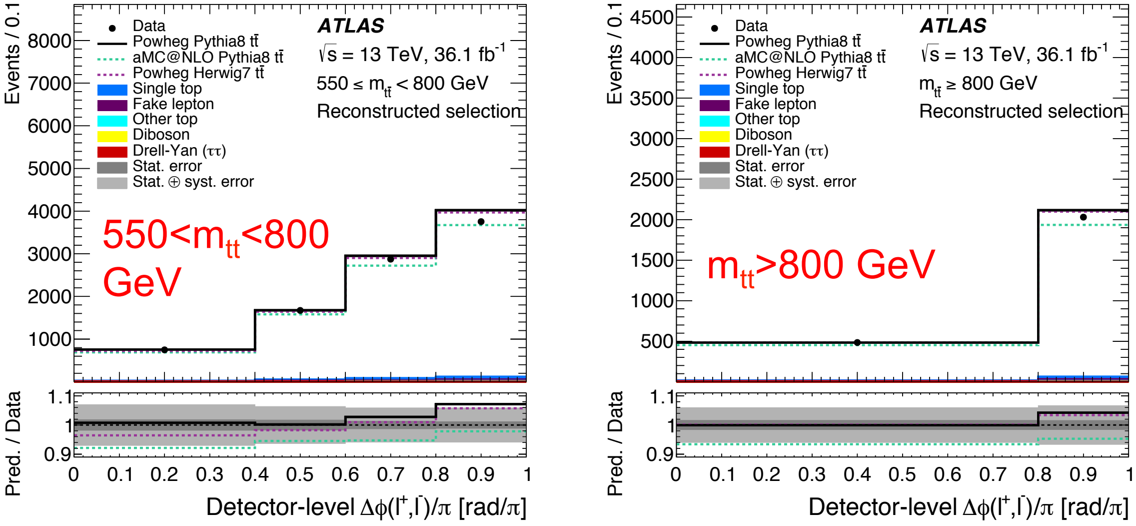
Measured distributions in 4 mass bins



m_{tt}<450 GeV   450<m_{tt}<550 GeV

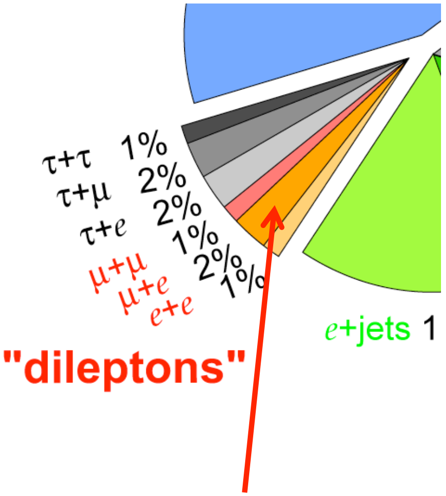


- Shape differences apparent
- Binning determined by statistical precision and resolution on m_{tt}, not $\Delta\phi$

Selected candidates

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

Recall:



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)

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

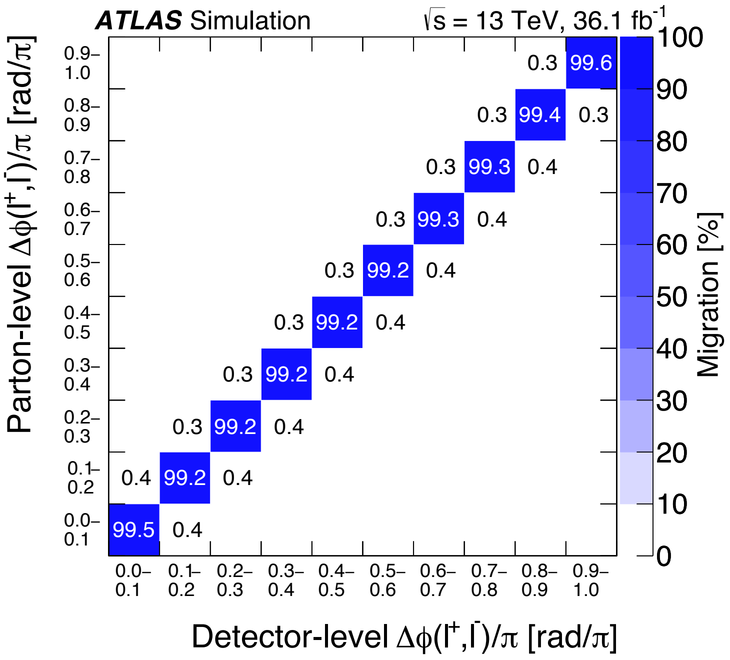
Unfolded data

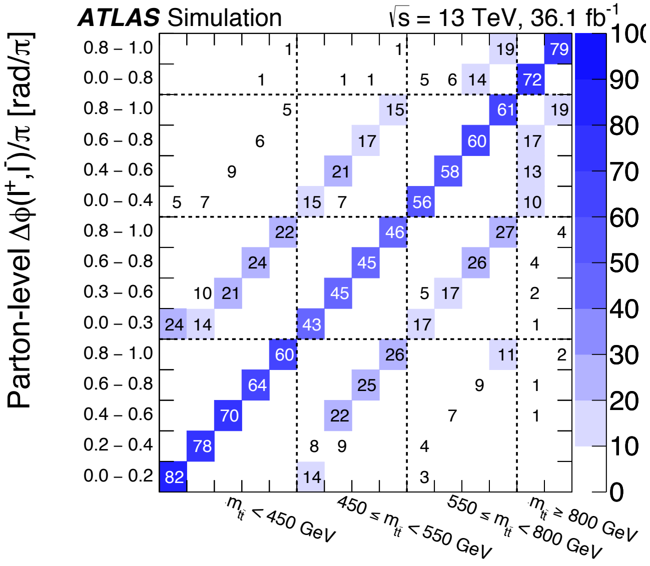
↓ Correct for fiducial phase-space acceptance

Fiducial data or full phase-space

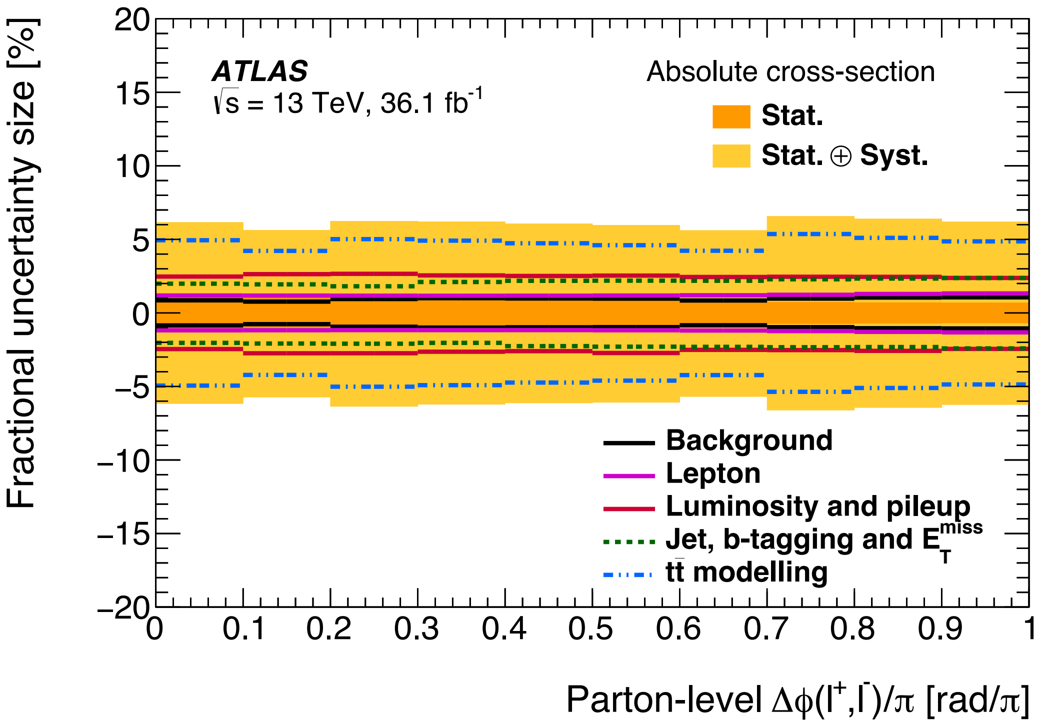
↓ Determine cross-section, absolute or normalised

Result





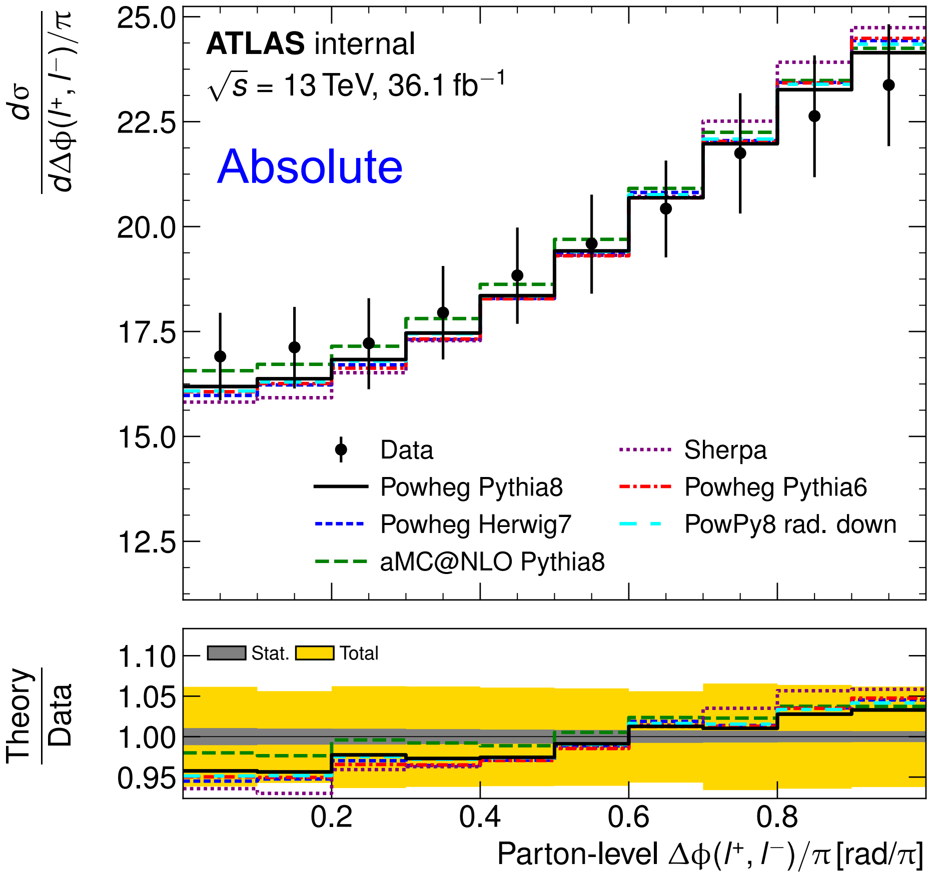
Systematic uncertainties

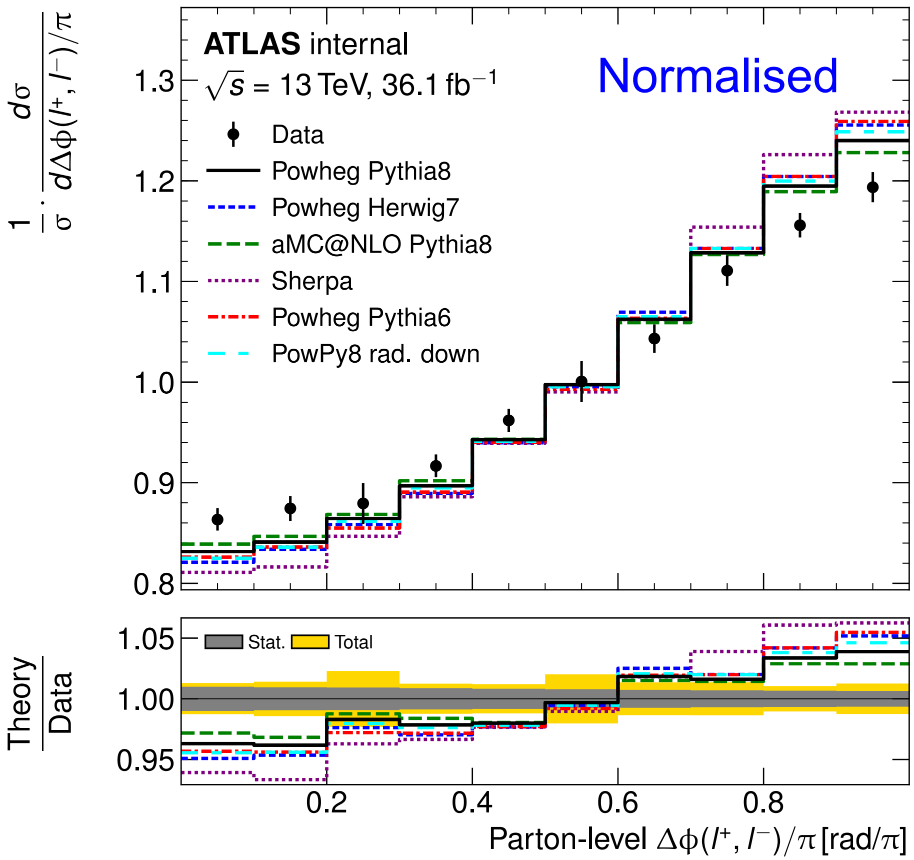


- **General method:**
  unfold shifted sample with nominal response matrix, compare to nominal sample

- Detector modelling
- Background and luminosity
- Signal modelling (dominant):
  - Parton shower: Pythia8 or Herwig7
  - NLO model: Powheg or aMC@NLO
  - Initial and final state radiation
  - PDF variation

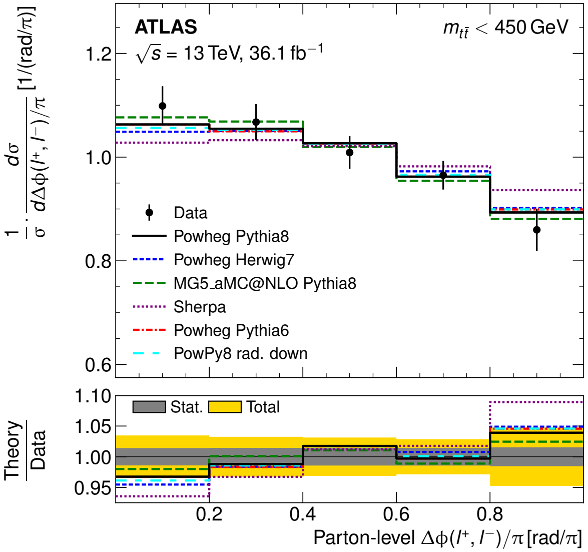
Results: Δϕ parton level

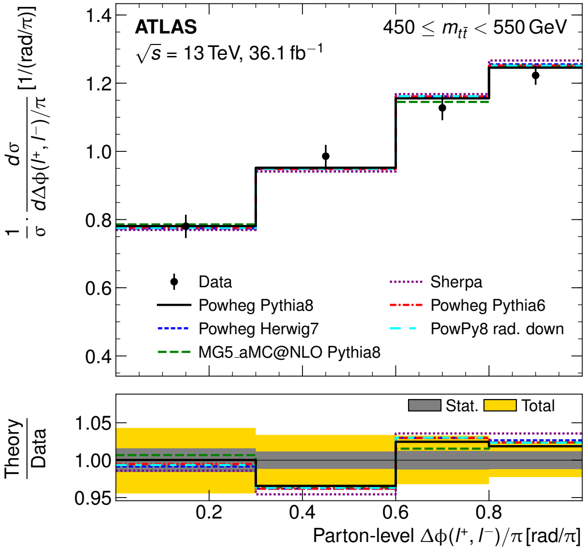


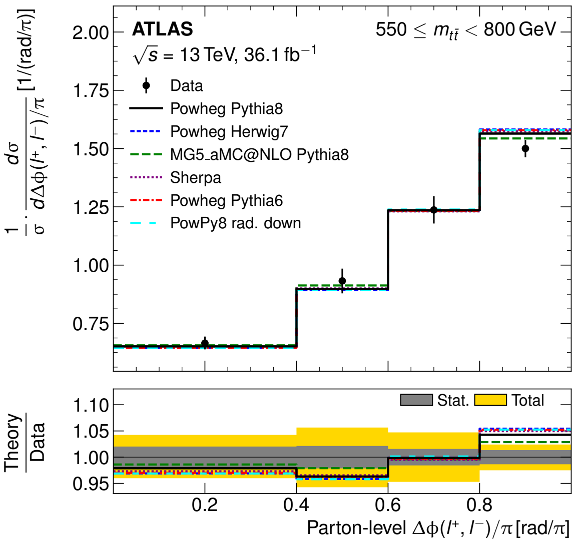


- Clear slope in the data relative to the MC predictions: none agree well
- Relative cross-sections shift due to acceptance effects when normalising, but shape remains the same
- Systematics are dominant in most bins

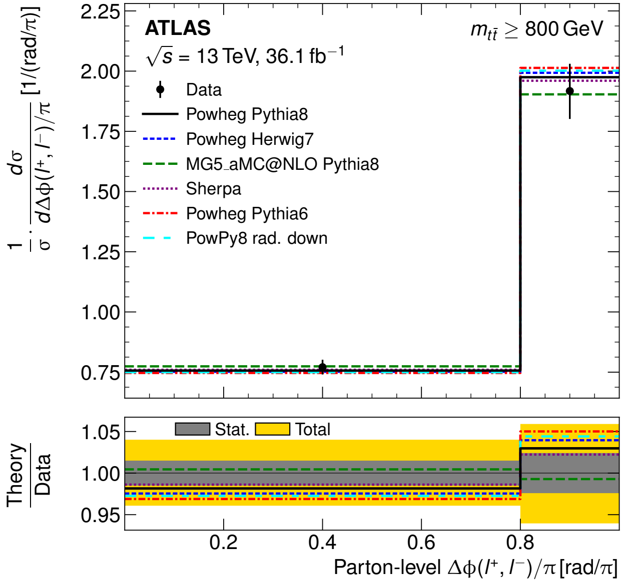
Unfolded distributions: double differential





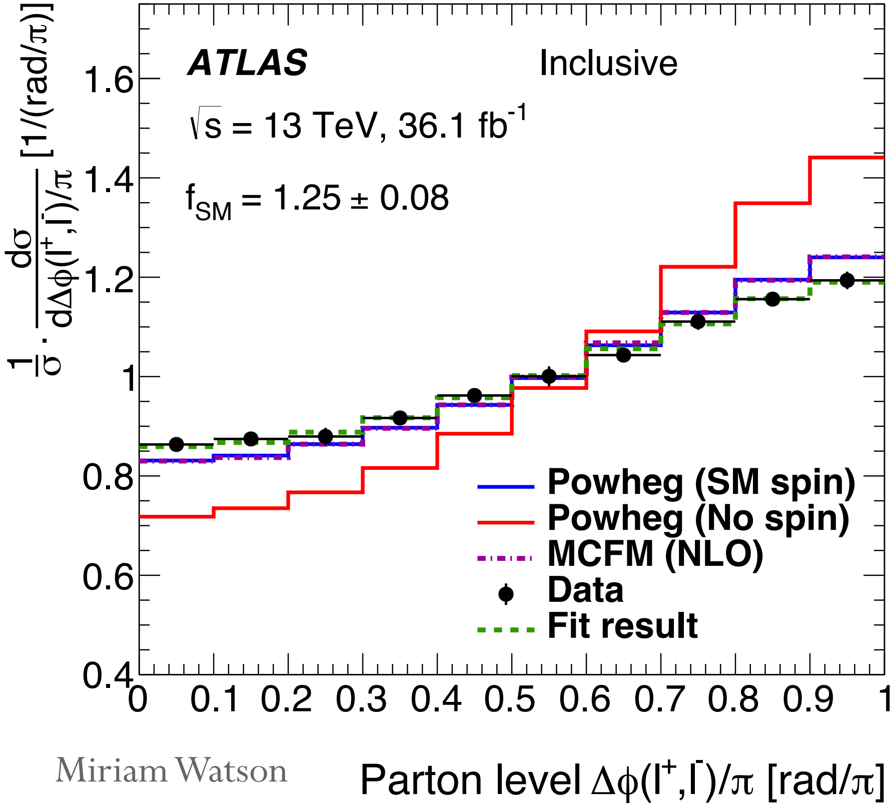


- The behaviour of the $\Delta\phi$ observable from low m_{tt} to high m_{tt} is clearly seen
- Uncertainties are larger here due to the tt reconstruction (jets and E^{T}_{miss} become important)



Results: extracting spin correlation

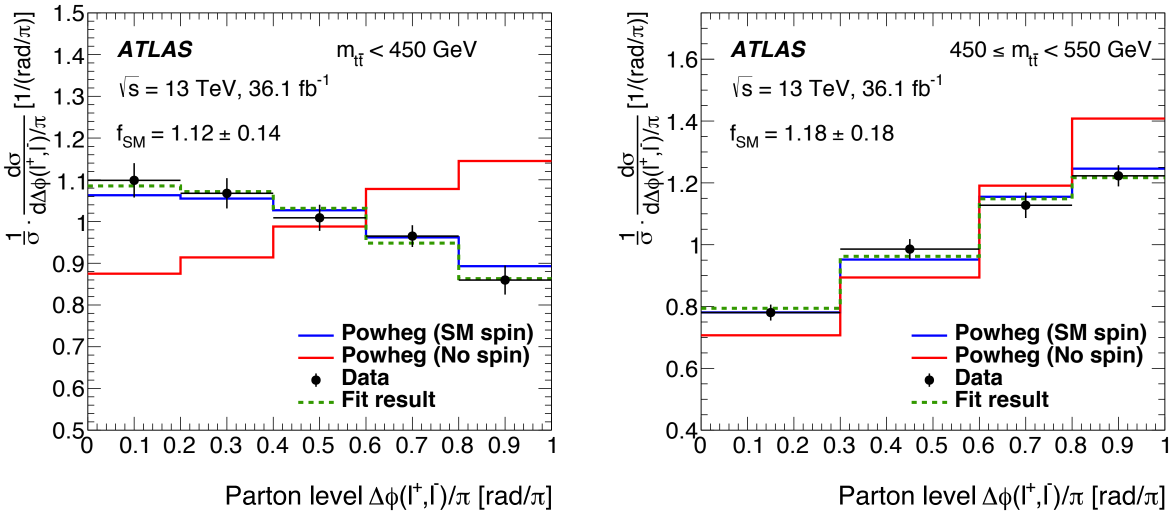
- Fraction of SM-like spin correlation (f_{SM}) is extracted using a binned maximum likelihood fit with two templates
- With-spin template: nominal MC (Poweg+Pythia8) with SM spin → $f_{SM} = 1$
- No-spin template: simulated with the same MC settings, but top quarks decayed using MadSpin with spin correlations between *t* and $\bar{t}$ disabled → $f_{SM} = 0$



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

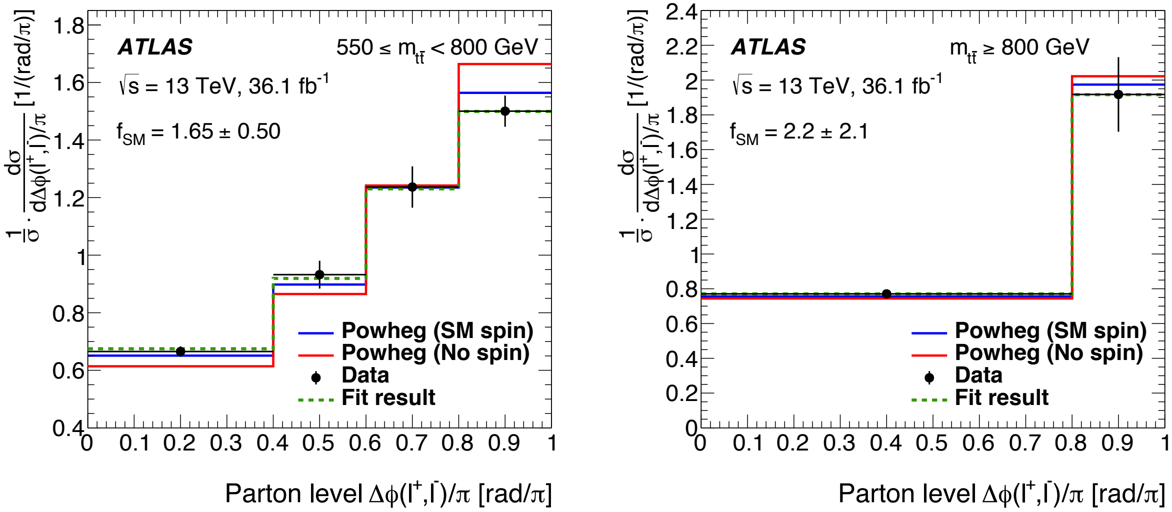
- Shallower slope in data is visible

Results: extracting spin correlation vs. m_{tt}



(a)

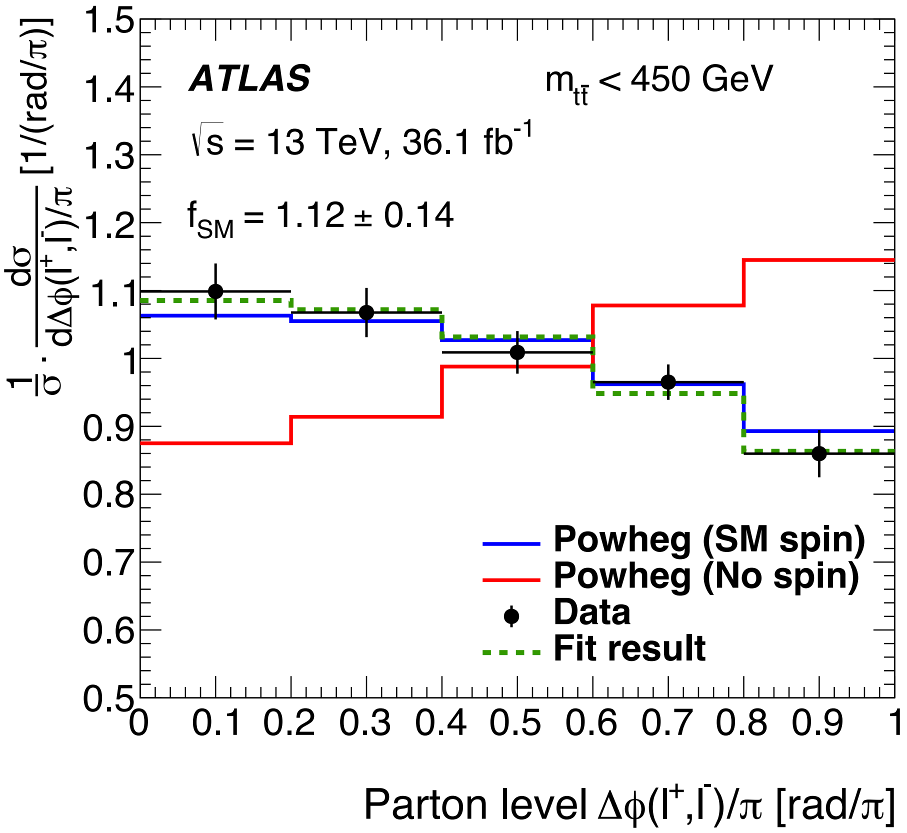
(b)

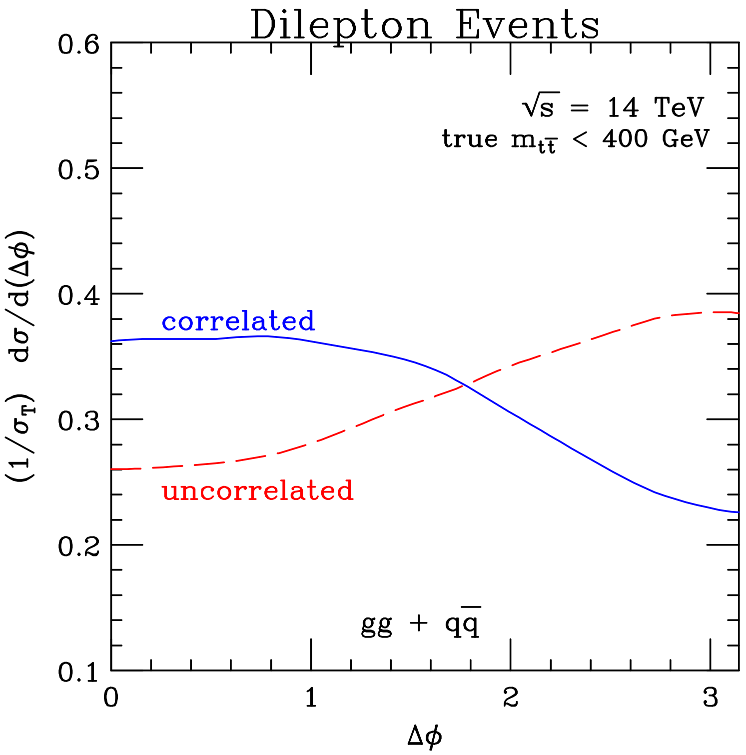


- Separation between spin and no-spin templates reduces with m_{tt}

Results: extracting spin correlation vs. m_{tt}

- MC parton-level distributions follow theoreretical predictions at low m_{tt}





Mahlon and Parke
Phys. Rev. D 81, 074024

Miriam Watson

Results: f_{SM} values

- The significance of the f_{SM}, relative to the SM template, is calculated using a CL_{s+b} method (effectively the same as counting the number of s.d. away from $f_{SM} = 1$)

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

Region	$f_{SM} \pm$ (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)

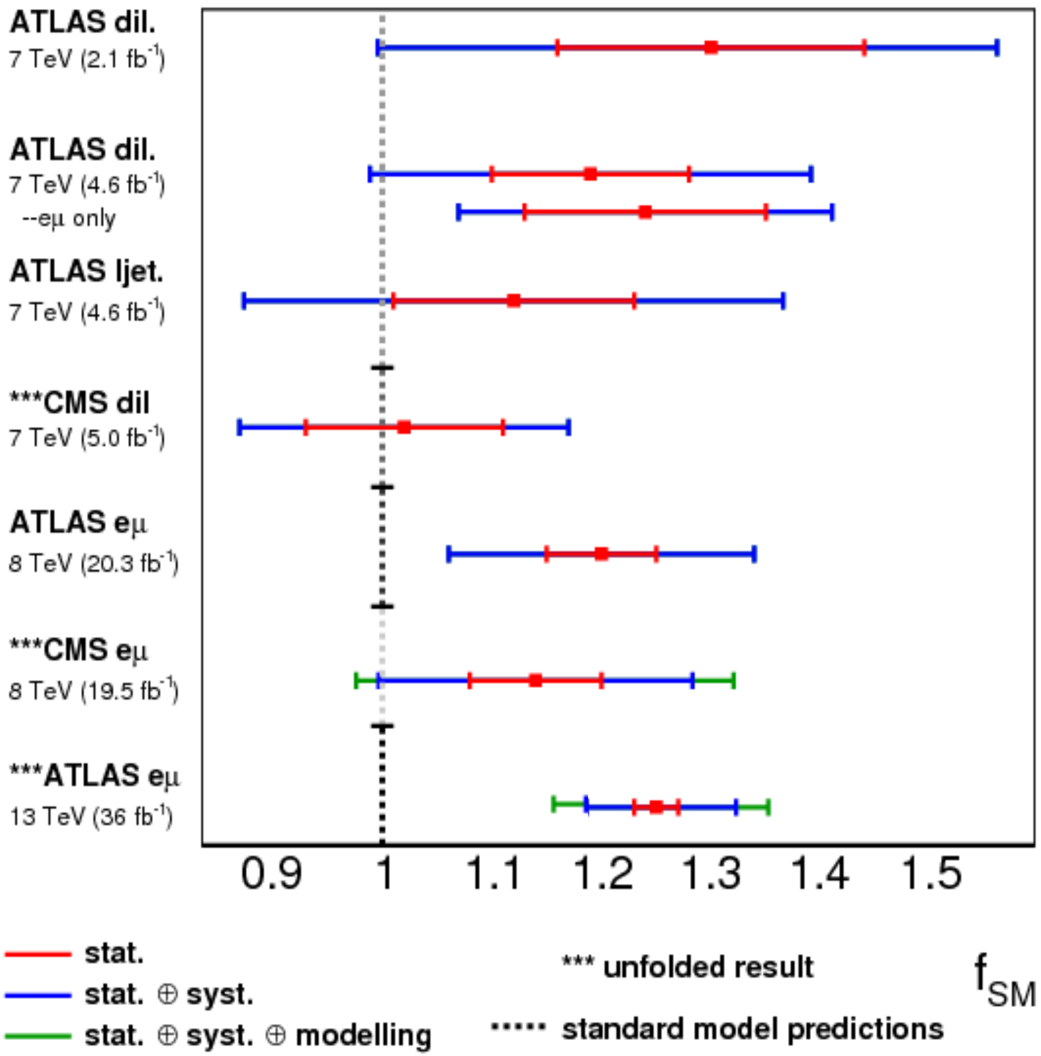
- Slight (but insignificant) increase in f_{SM} as a function of m_{tt}
- The inclusive f_{SM} deviates significantly from the SM prediction in NLO MC

Comparison of f_{SM} values

- When interpreted as spin correlation, shows ~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



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: initial-final state interference effects are neglected

Further checks

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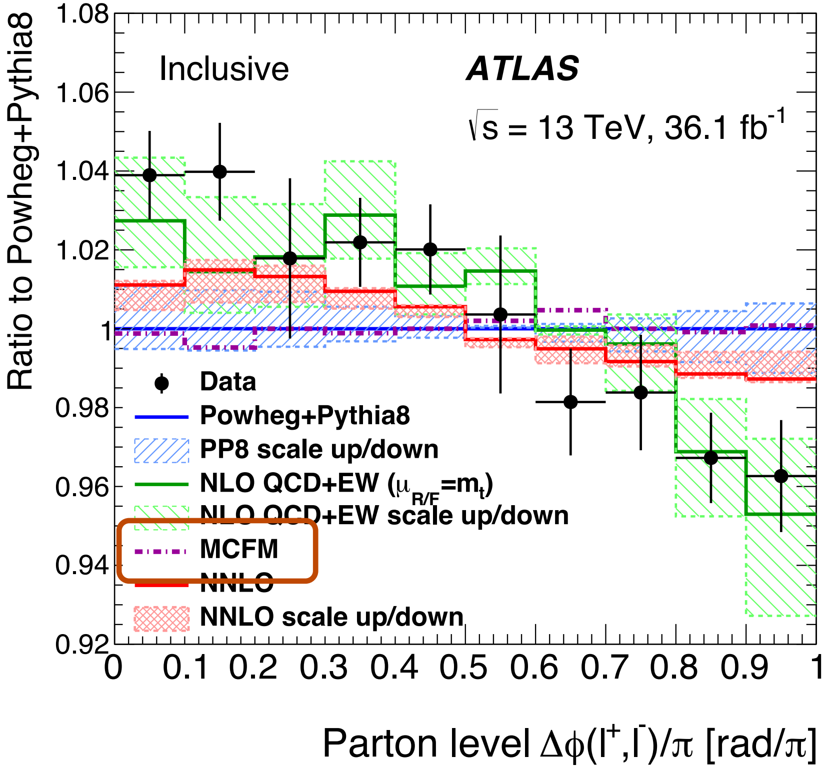
- **NLO effects in the decays of the top quarks**: compare the Δϕ distribution with MCFM (full NLO, including NLO decays) → very close to nominal template



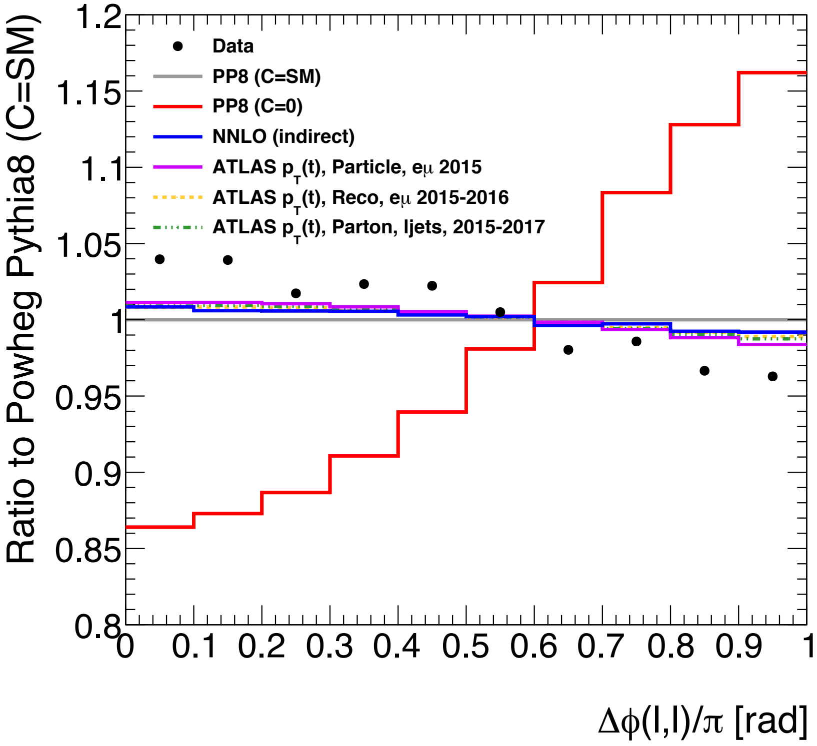
Further checks

- 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: initial-final state interference effects are neglected
- **NWA in the templates:** compare with Powheg-Box-Res bb4l for full *tt+tW* process without NWA → no significant differences

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: initial-final state interference effects are neglected

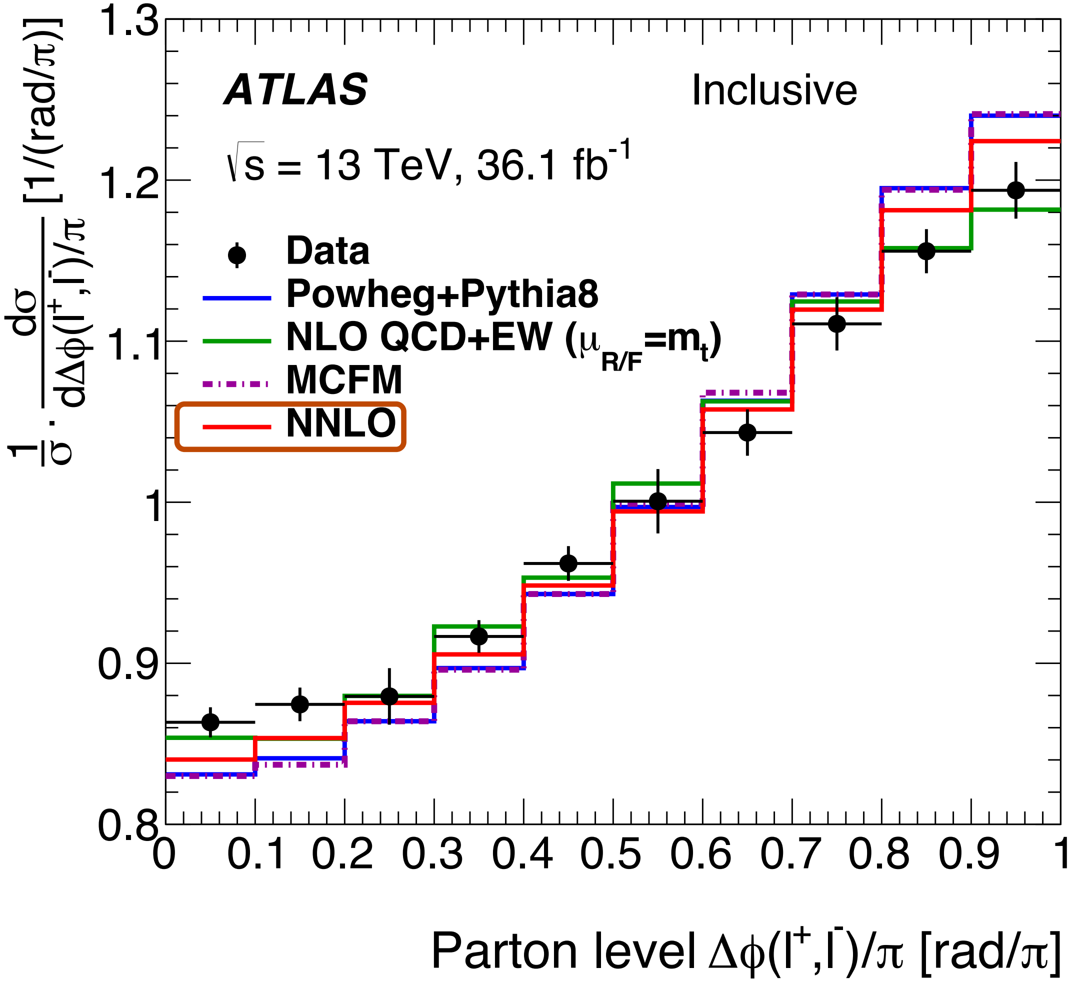
- **Effect of NNLO in production**: reweight the top p_T to match fixed-order NNLO predictions or unfolded data from several previous ATLAS measurements
- Deviations reduced slightly but consistent within scale uncertainties already considered



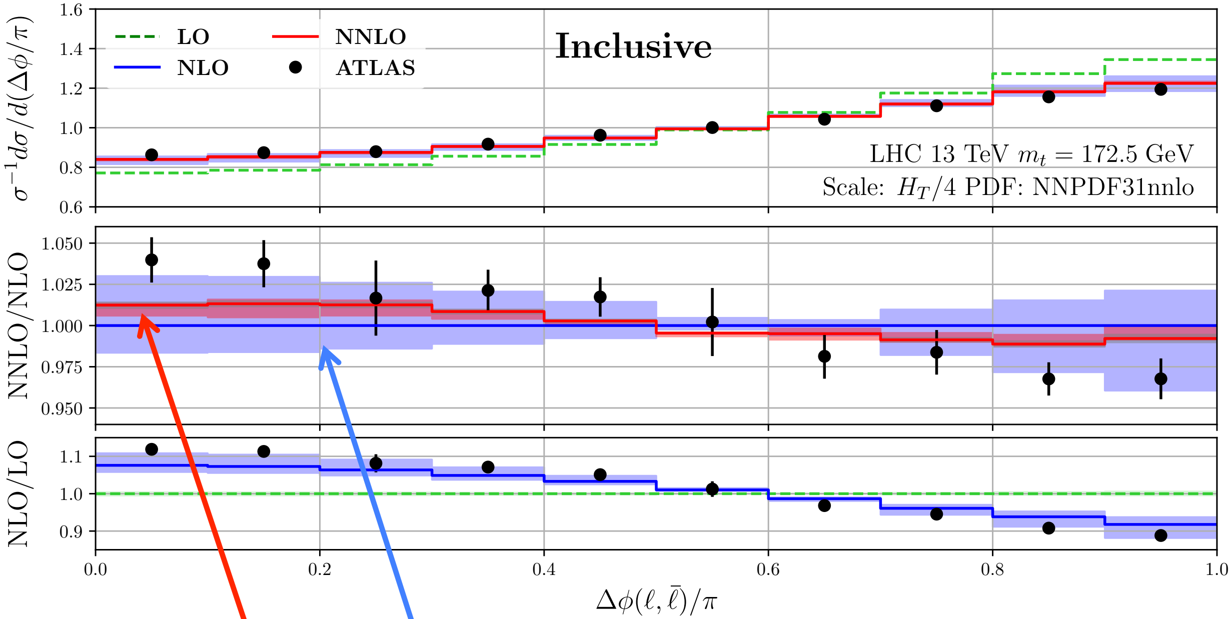
New theoretical predictions: NNLO

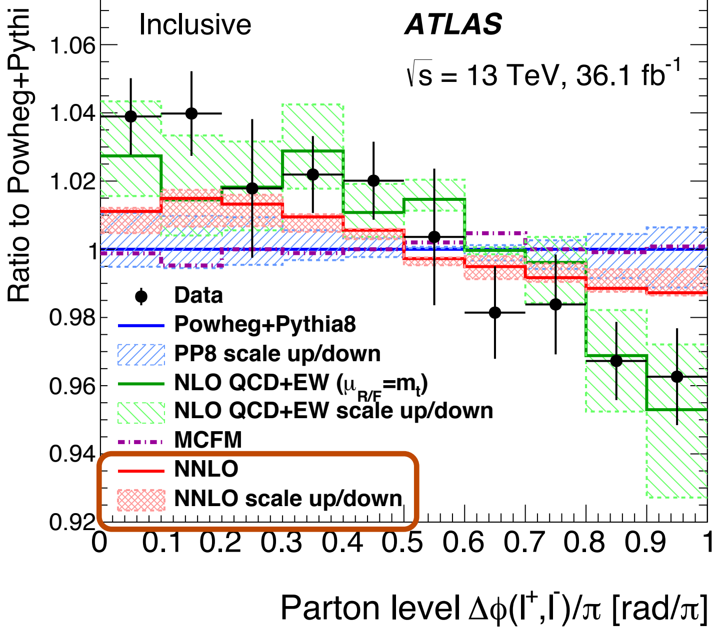
Behring et al. arXiv:1901.05407

- 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



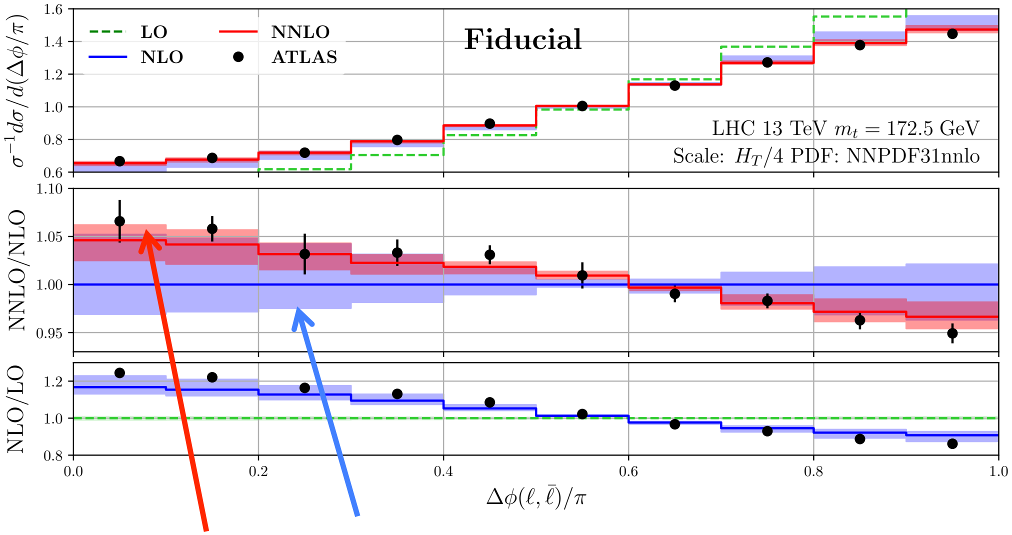
New theoretical predictions: NNLO inclusive



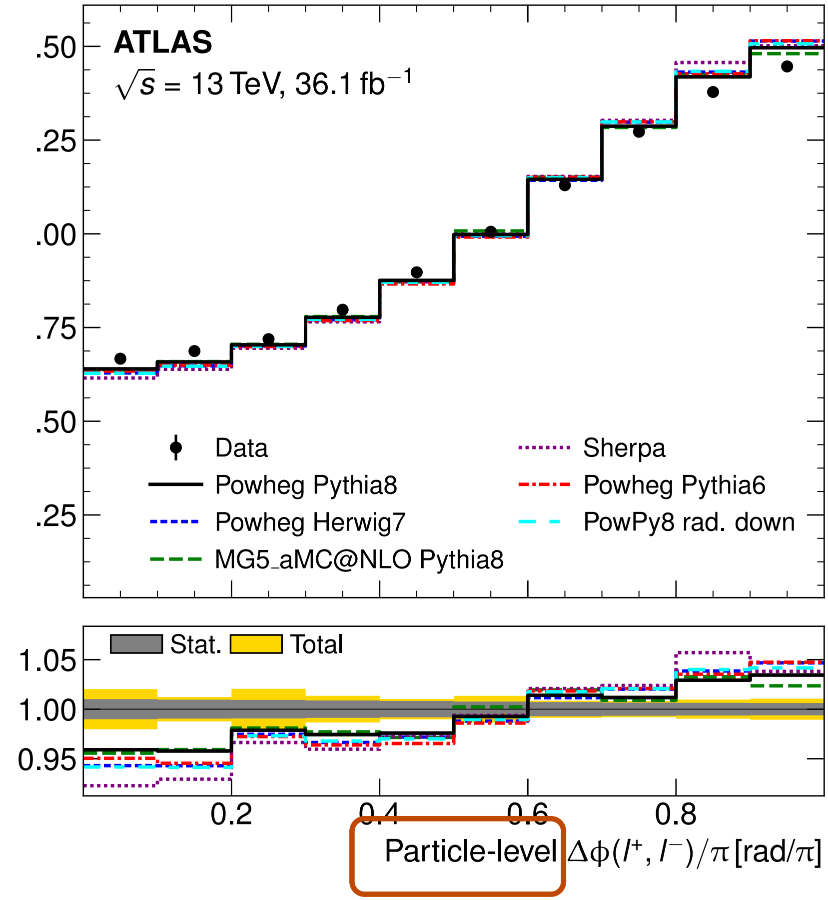


- Closer to parton-level unfolded data, but does not cover observed discrepancy
- Similar to our results with reweighting to top p_T for NNLO or data

New theoretical predictions: NNLO fiducial

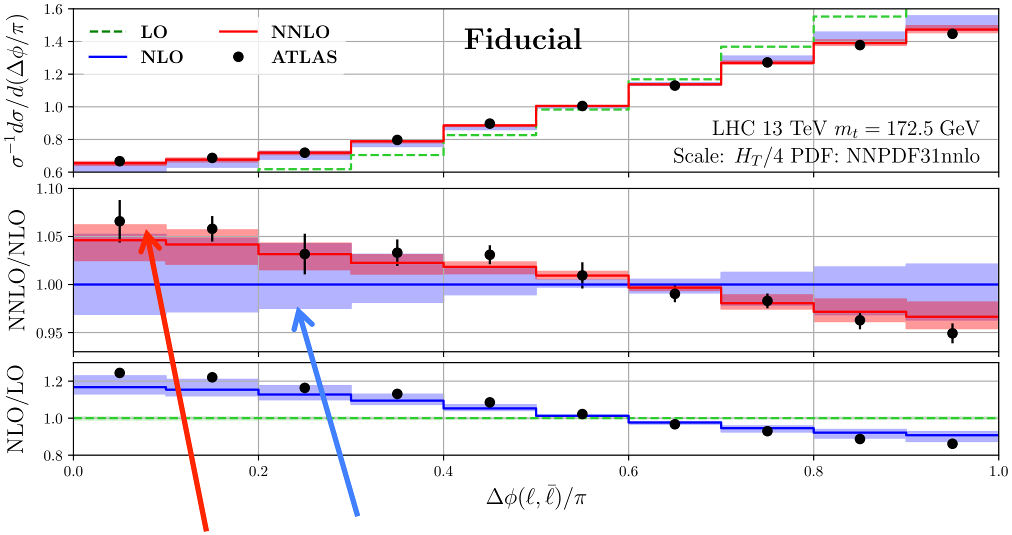


NNLO NLO



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

New theoretical predictions: NNLO fiducial



NNLO NLO

- **Author's conclusion:** There is a problem with the extrapolation of the ATLAS data to the full phase space with NLO/LO MC

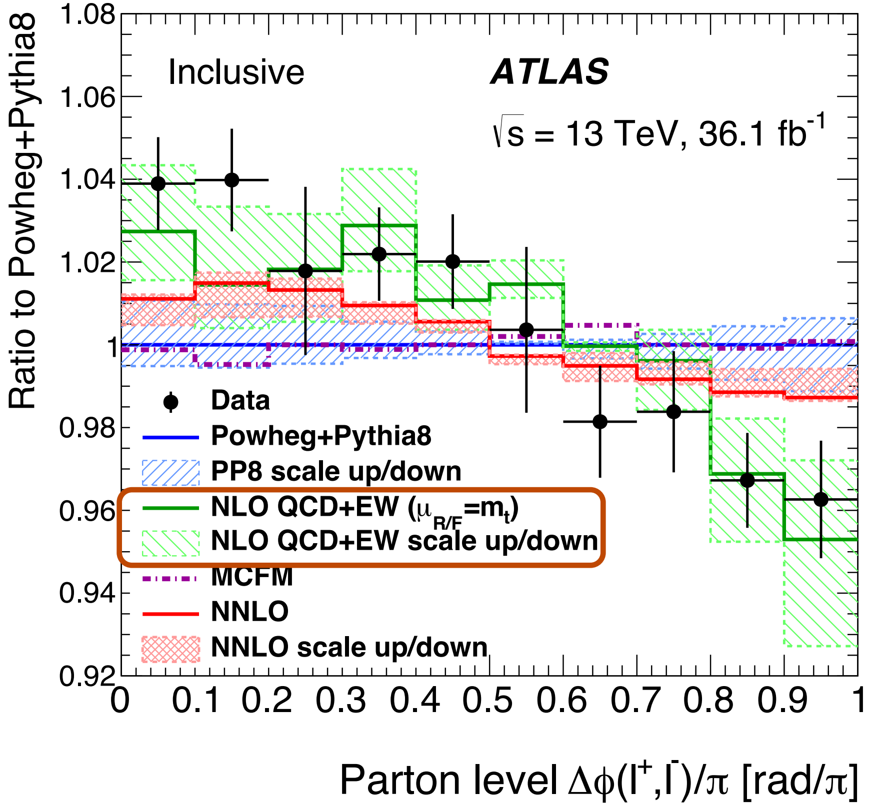
- **Comment:** Fiducial cuts are applied to the 'b-jets' (pT > 25 GeV, |η| < 2.5). These are unlikely to be the same for ATLAS particle level jets and fixed-order partons → could sculpt the shape

More theoretical predictions: NLO+weak effects

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

- **NLO+weak effects**: previous calculation now produced for our binning at 13 TeV
  - NLO QCD + weak corrections
  - Expanded as a ratio to fixed order
  - Less optimal fixed scale choice: $\mu_{R/F} = m_{top}$
  - Different PDF set CT10

- Better agreement with data, but large scale uncertainties
- Gives $f_{SM} = 1.03 \pm 0.13$ (scale)



Aside: renormalisation and factorisation scale choice

Czakon, Heymes, Mitov
JHEP 1704 (2017) 071

$$\mu_0 \sim m_t \,,$$ NLO+Weak

$$\mu_0 \sim m_T = \sqrt{m_t^2 + p_T^2} \,,$$ PP8

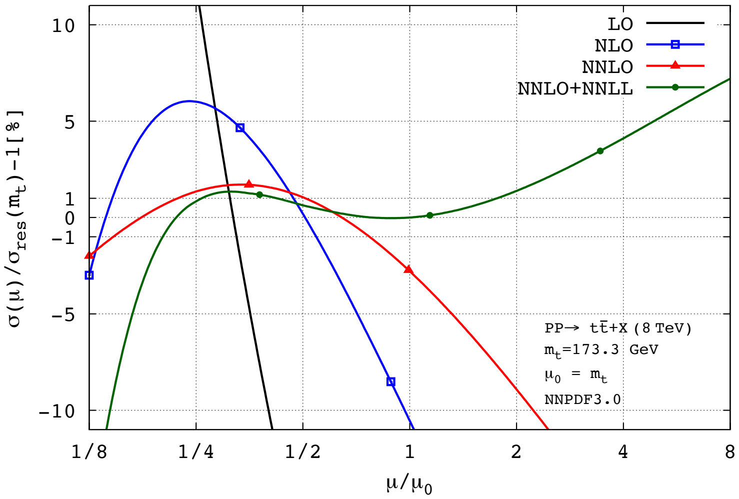
$$\mu_0 \sim H_T = \sqrt{m_t^2 + p_{T,t}^2} + \sqrt{m_t^2 + p_{T,\bar{t}}^2} \,,$$

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

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

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

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



$$\boxed{\mu_0 = \begin{cases} \dfrac{m_T}{2} & \text{for :} \quad p_{T,t},\ p_{T,\bar{t}} \text{ and } p_{T,t/\bar{t}}\,, \\[2ex] \dfrac{H_T}{4} & \text{for :} \quad \text{all other distributions} \end{cases}}$$

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

f_{SM} with alternative templates

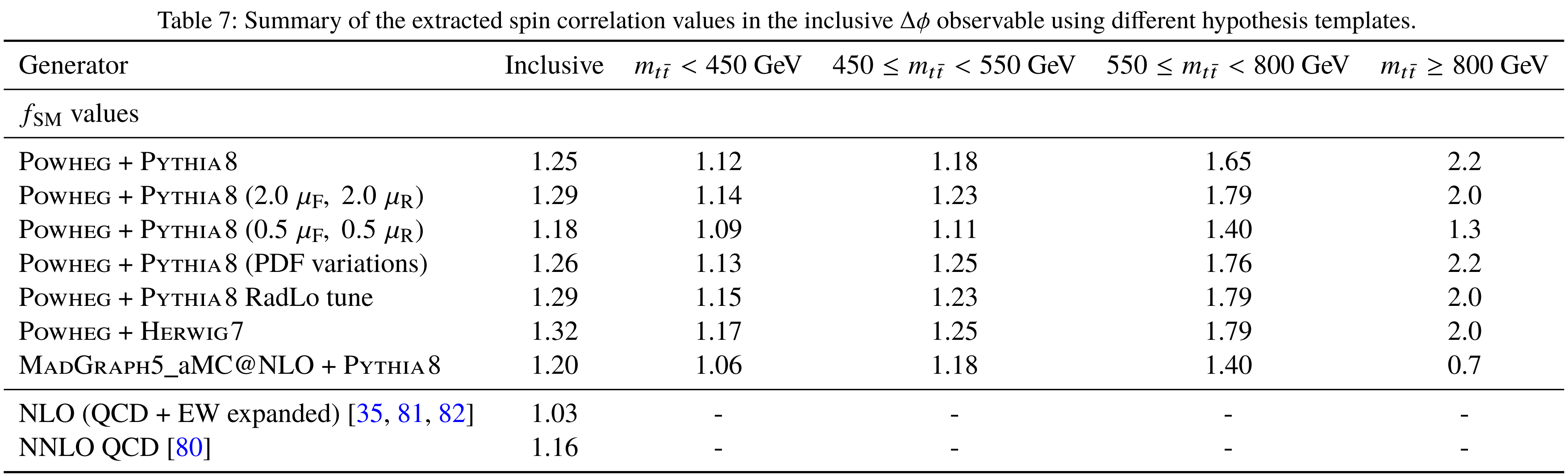
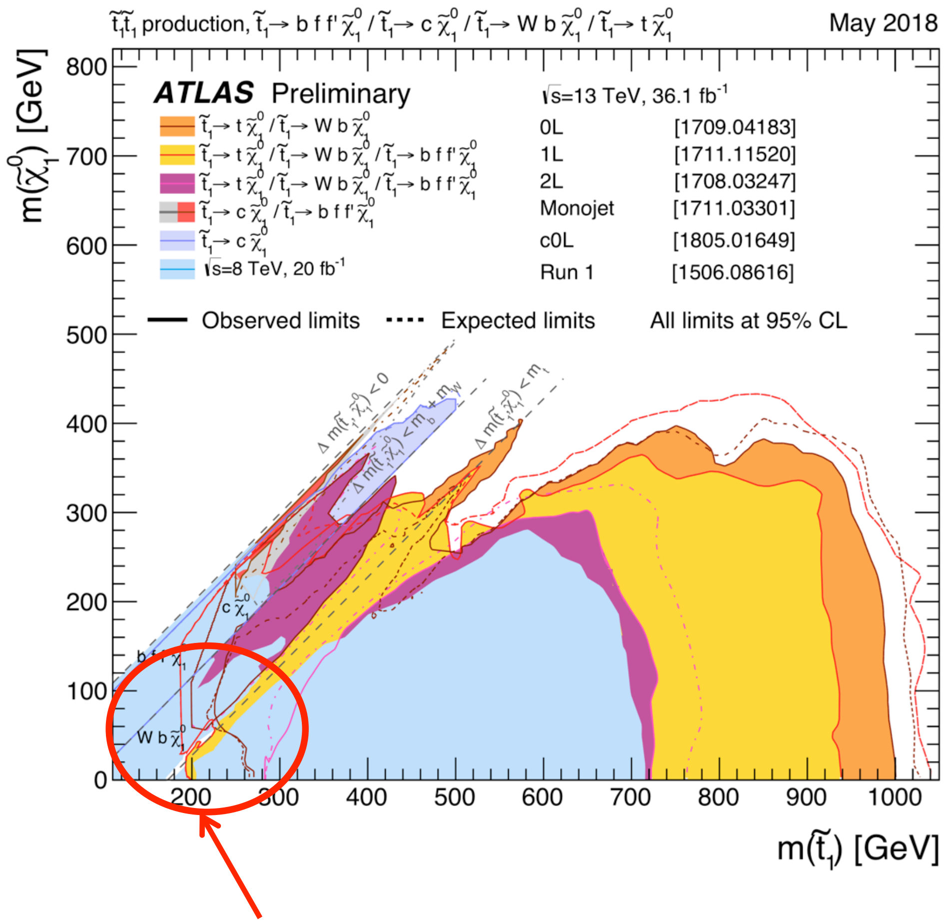


Table 7: Summary of the extracted spin correlation values in the inclusive $\Delta\phi$ observable using different hypothesis templates.

Generator	Inclusive	$m_{t\bar{t}} < 450$ GeV	$450 \leq m_{t\bar{t}} < 550$ GeV	$550 \leq m_{t\bar{t}} < 800$ GeV	$m_{t\bar{t}} \geq 800$ 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 sculpt 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 been kinematic effects and higher order corrections
  - Could also be new physics...

Supersymmetric top squark pair production

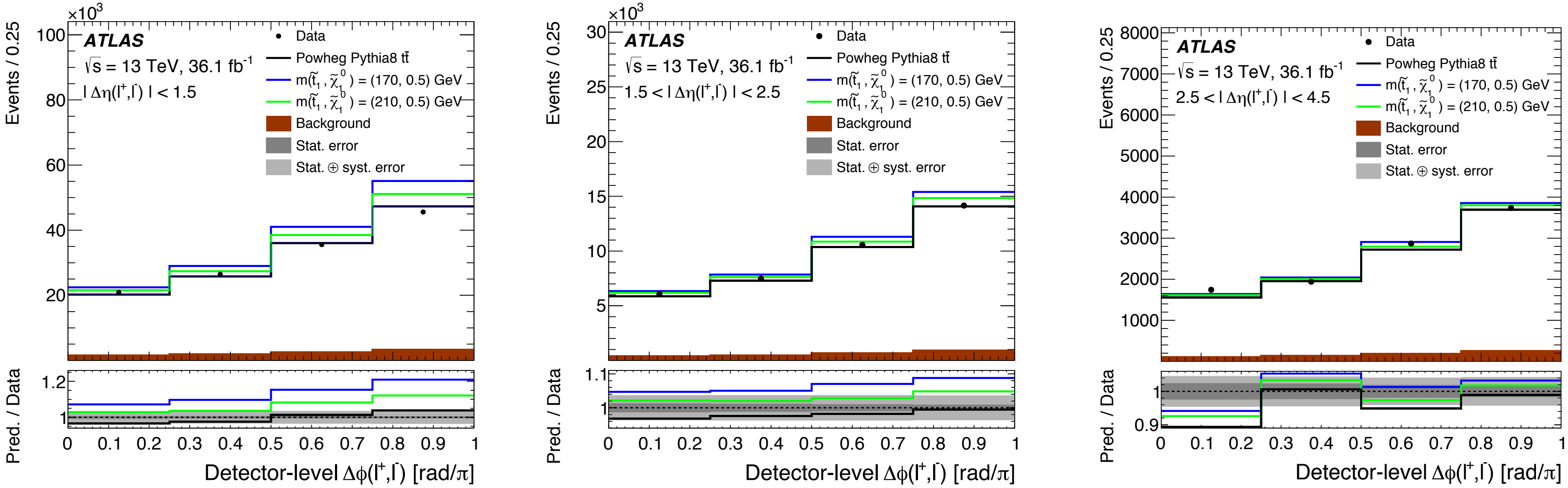


Exclusion contours as a function of

$m_{\tilde{\chi}_1^0}$ and $m_{\tilde{t}_1}$

Small region with $m_{\tilde{t}} \sim m_t$ difficult to access in direct searches

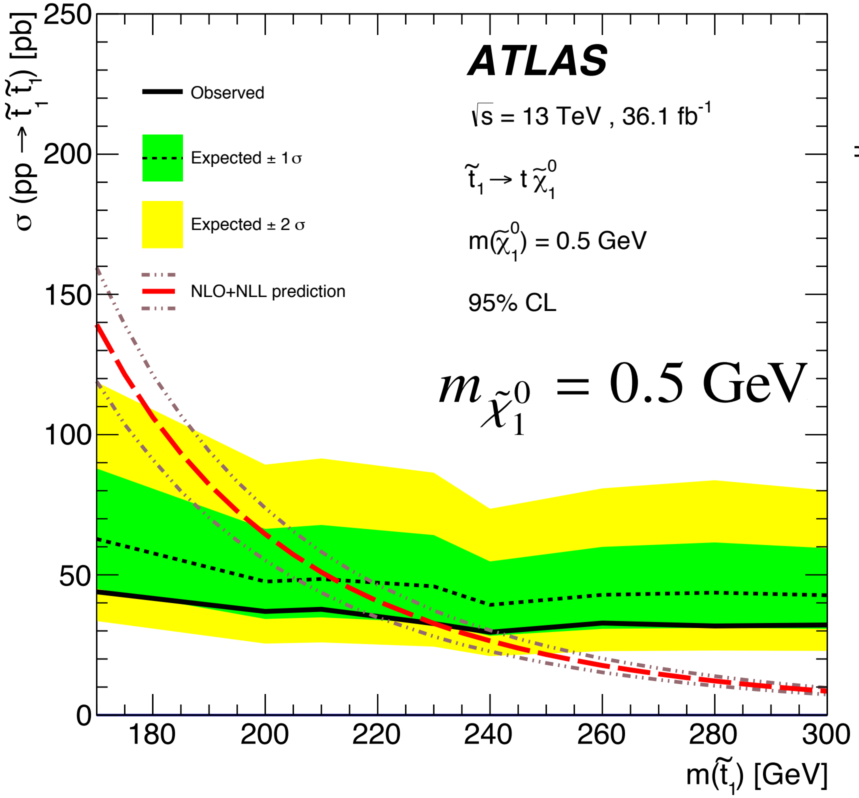
Supersymmetric top squark pair production

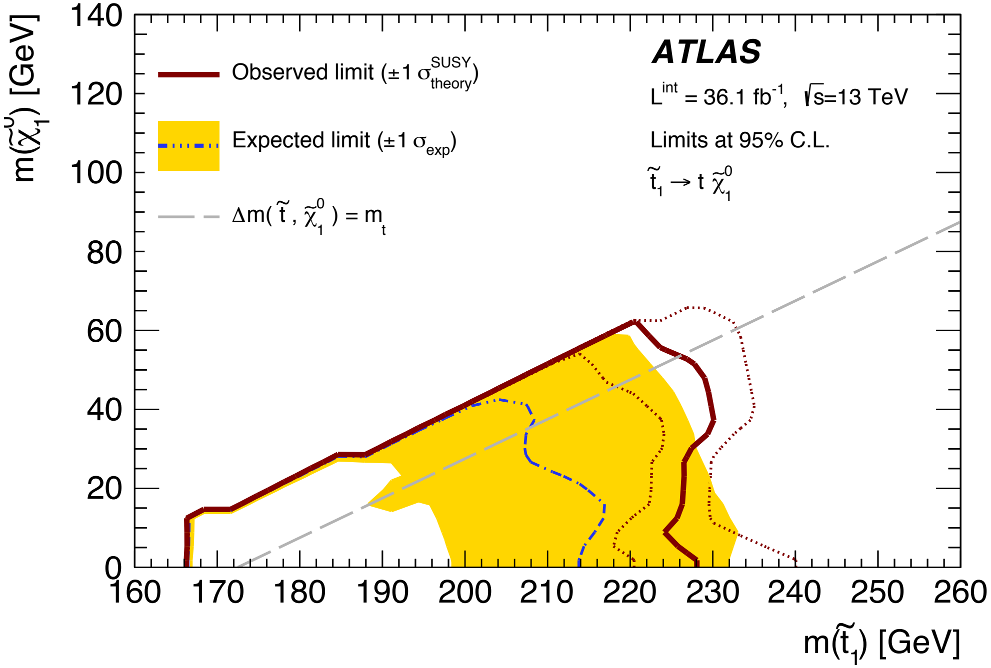


- Use double differential Δϕ in 3 bins of Δη to set limits on SUSY stop production
- More exclusion power comes from Δη than Δϕ
- Include additional theory uncertainty to cover data-MC difference observed in $t\bar{t}$ (based on NLO+Weak calculation)

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

Expected and observed cross-section limits





- Limit is still stronger than expected because the data look very unlike SUSY
- Closes off last hiding place for “stealth stops” with $m_{\tilde{t}} \sim m_t$

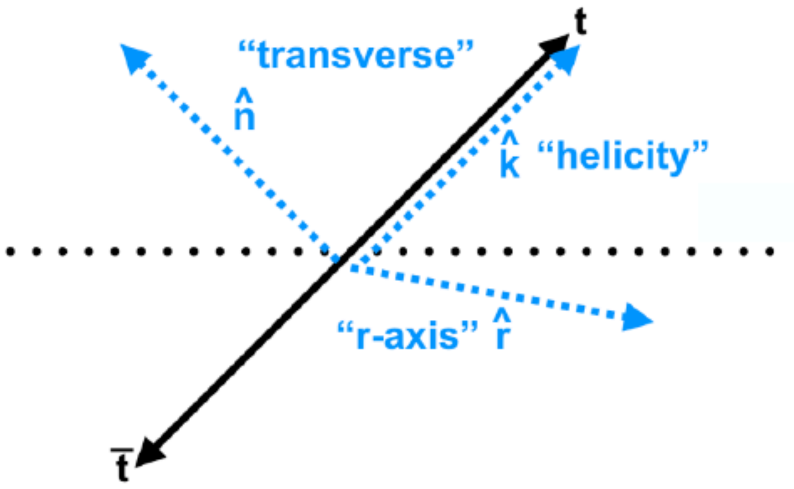
Miriam Watson

Direct spin correlation measurements

- 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).
- ↑ and ↓ 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.

Direct spin correlation measurements

- 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**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+ \, d\cos\theta^b_-} = \frac{1}{4}\left(1 + B^a_+ \cos\theta^a_+ + B^b_- \cos\theta^b_- - C(a,b)\cos\theta^a_+ \cos\theta^b_-\right)$$

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

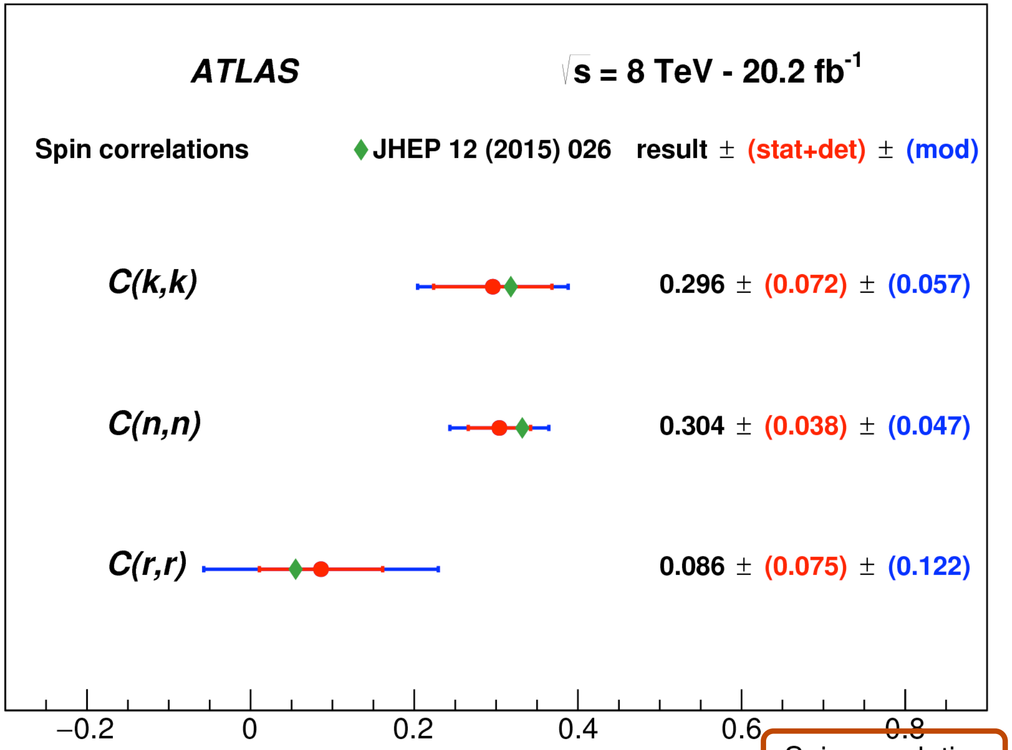
$$B_+ = 3 \cdot < cos(\theta_+) > \qquad C = -9 \cdot < cos(\theta_+) cos(\theta_-) >$$

- 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: JHEP 03 (2017) 113
- But these direct measurements require full $t\bar{t}$ reconstruction in dilepton events and therefore suffer from significant systematic uncertainties and resolution effects.

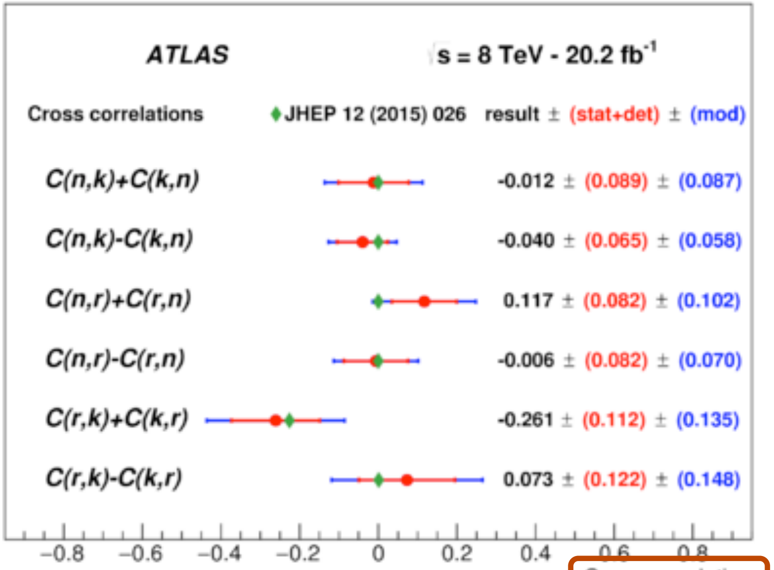
ATLAS spin observables at 8 TeV

JHEP 03 (2017) 113

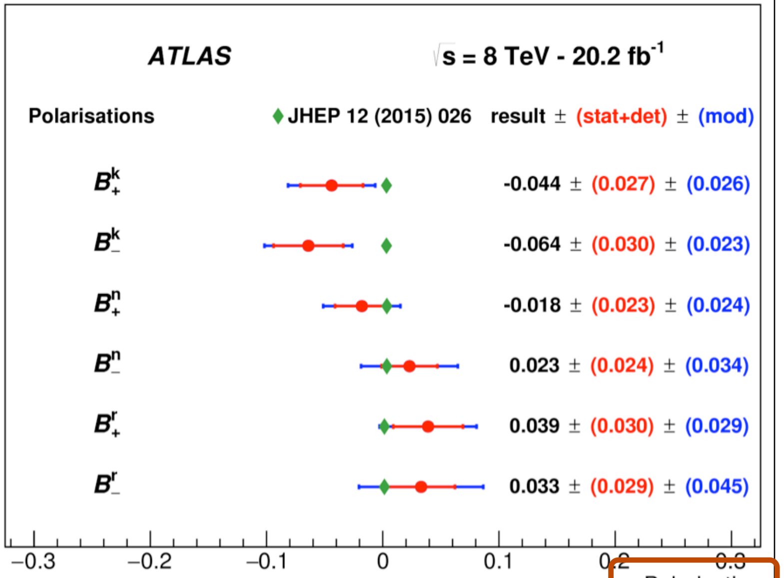
- 15 observables corrected to particle and parton level
- Compared to NLO predictions
- No significant deviation from the SM



Spin correlation



Cross correlation

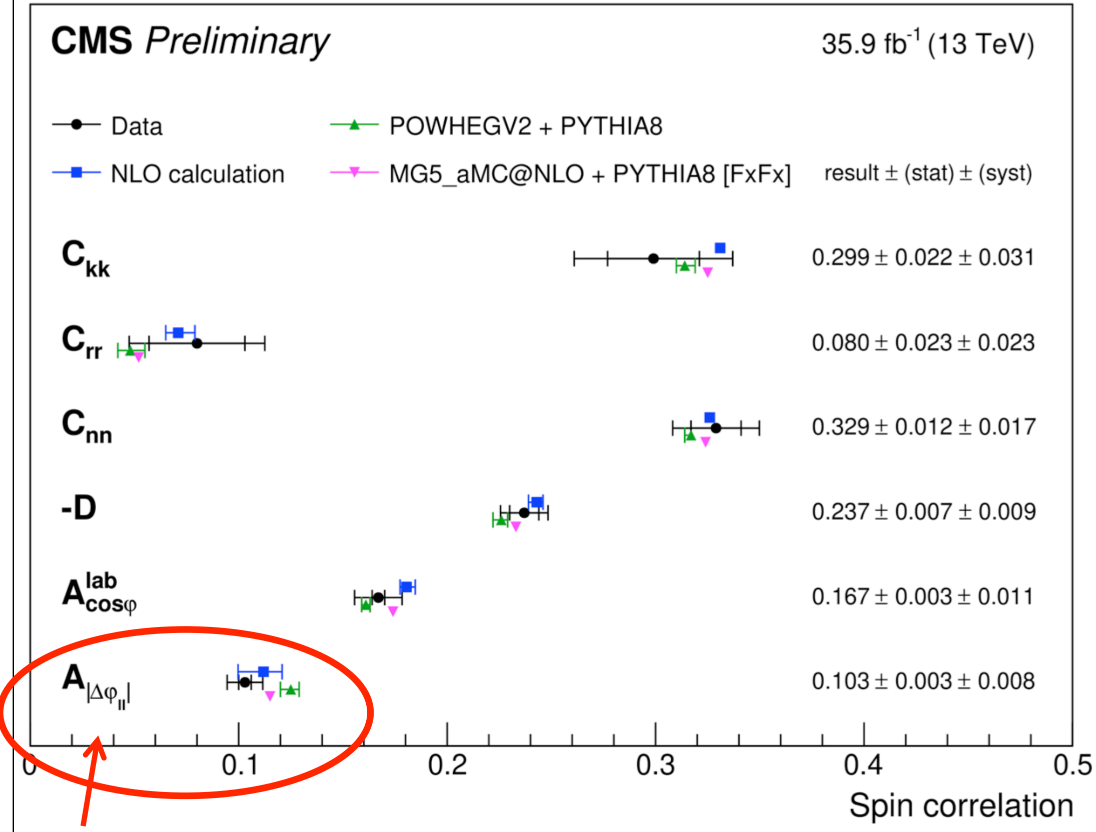


Polarisation

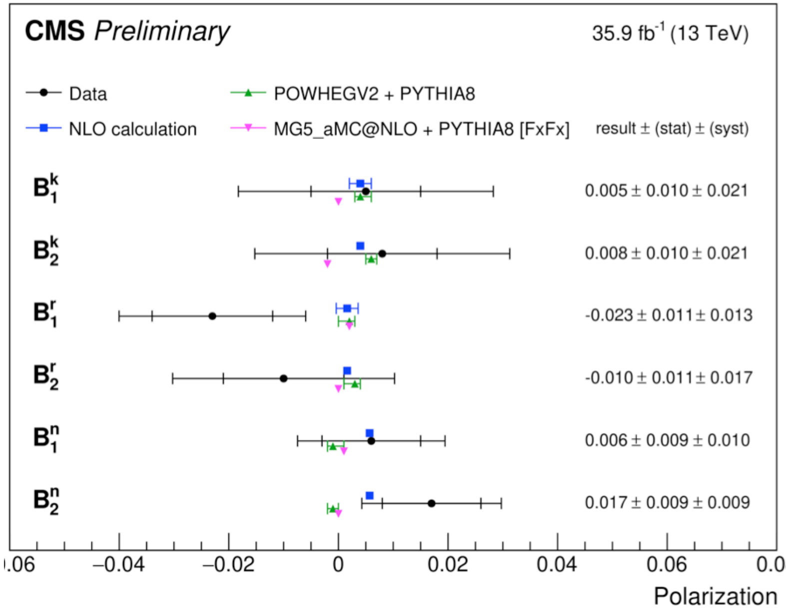
CMS spin/polarisation at 13 TeV

CMS-PAS-TOP-18-006

- Distributions corrected to parton level
- Compared to NLO QCD + weak corrections
- Improved regularised unfolding technique



N.b. lab frame



- All measurements consistent with the SM

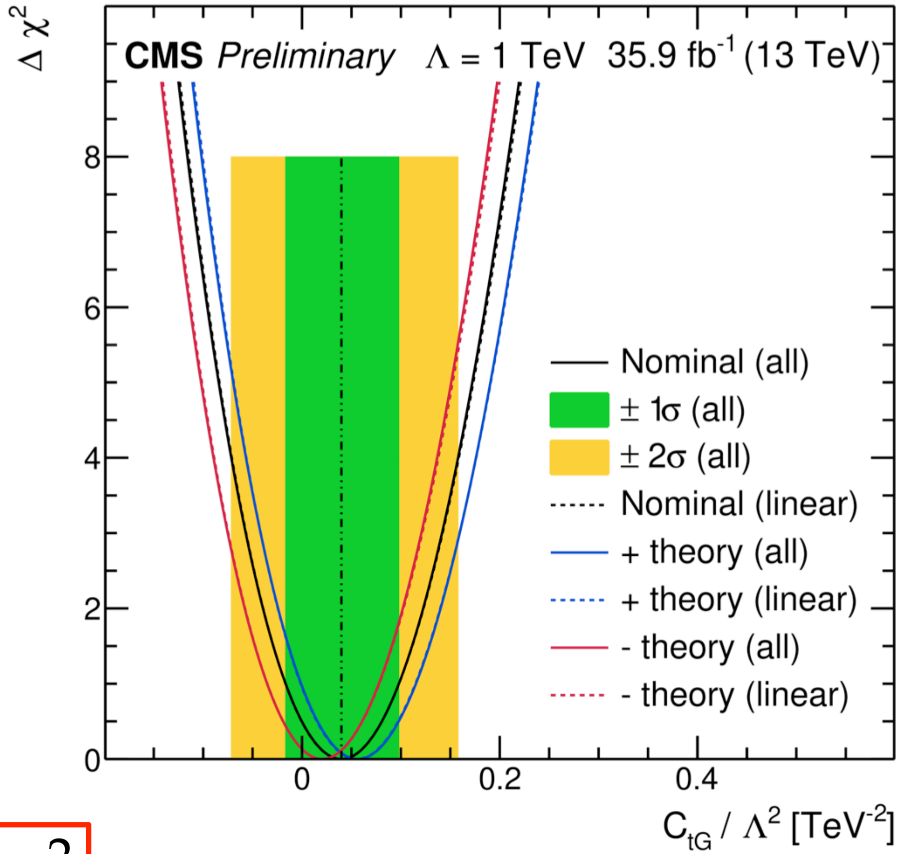
CMS spin/polarisation at 13 TeV

CMS-PAS-TOP-18-006

- Instead of SUSY contribution, use measurements to constrain the anomalous chromomagnetic dipole moment of the top quark

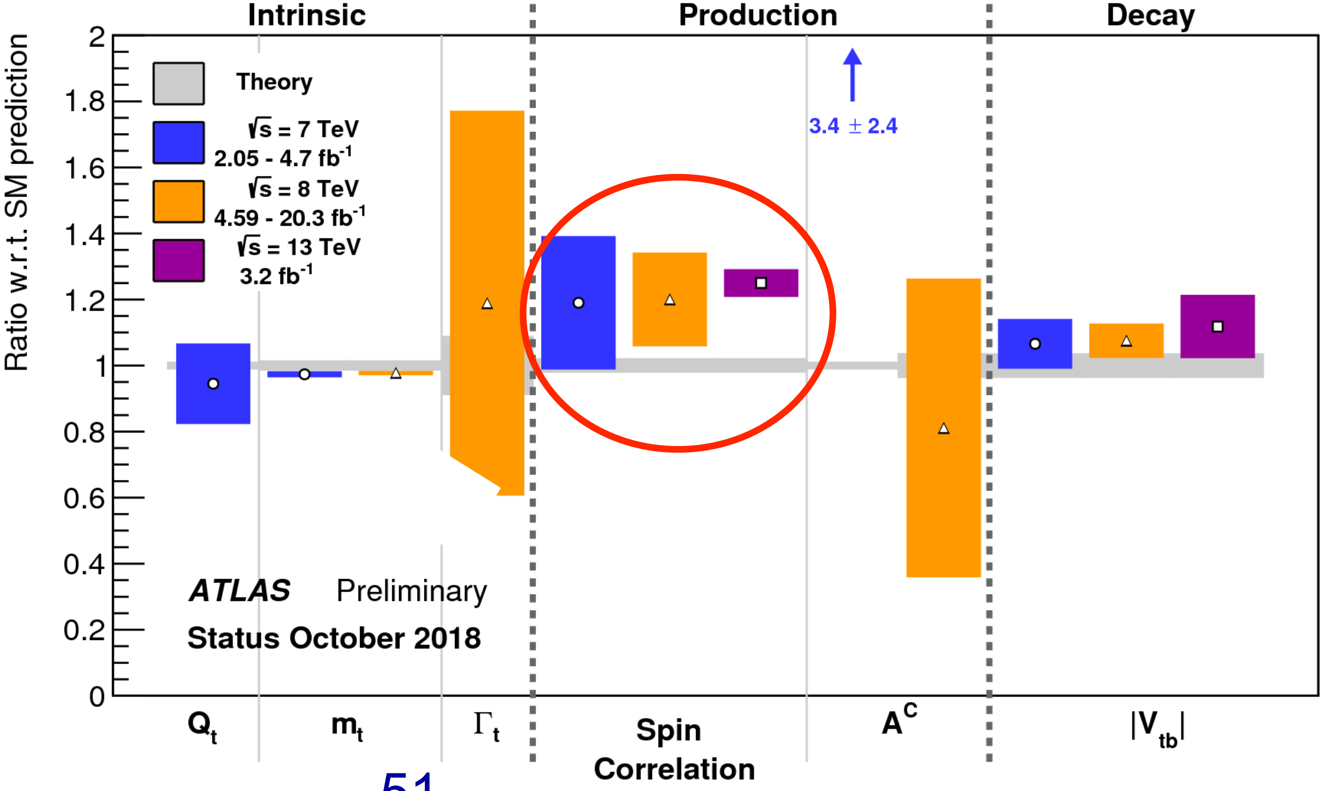
- Feature of many BSM models, e.g. two-Higgs-doublet models, supersymmetry, technicolor, top quark compositeness models

$$\boxed{-0.07 < C_{tG}/\Lambda^2 < 0.16\ \mathrm{TeV}^{-2}}$$



Summary

- Still more to do to understand tt 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!



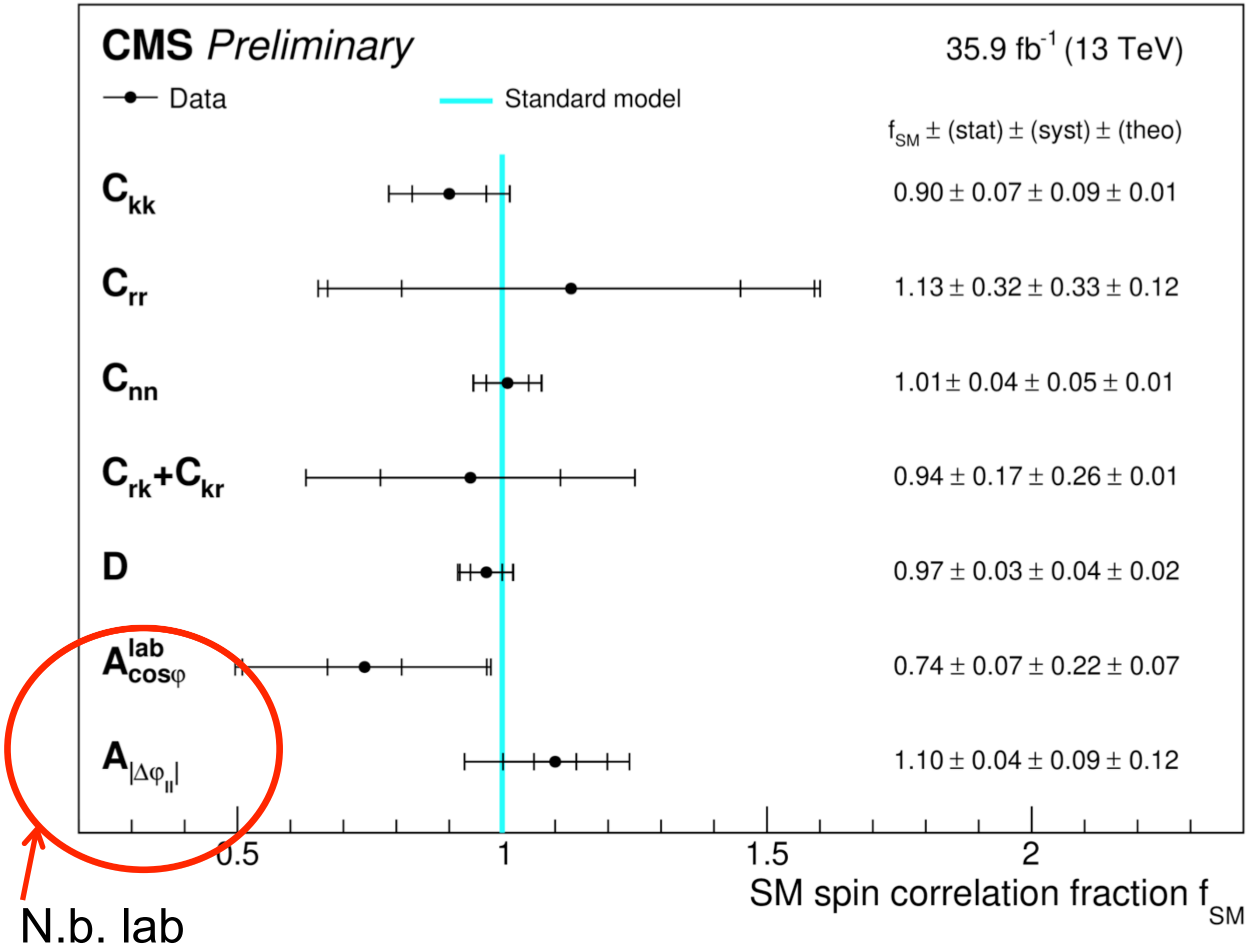
MC samples

- Dilepton signal (tt):
  - 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
  - ttW, ttZ, tWZ: aMC@NLO + Pythia8
  - tZ, ttWW, tttt: MadGraph + Pythia8
  - Fakes from MCTruthClassifier (l+jets tt, W+jets, single top, ttV, other), cross-checked with like-sign leptons

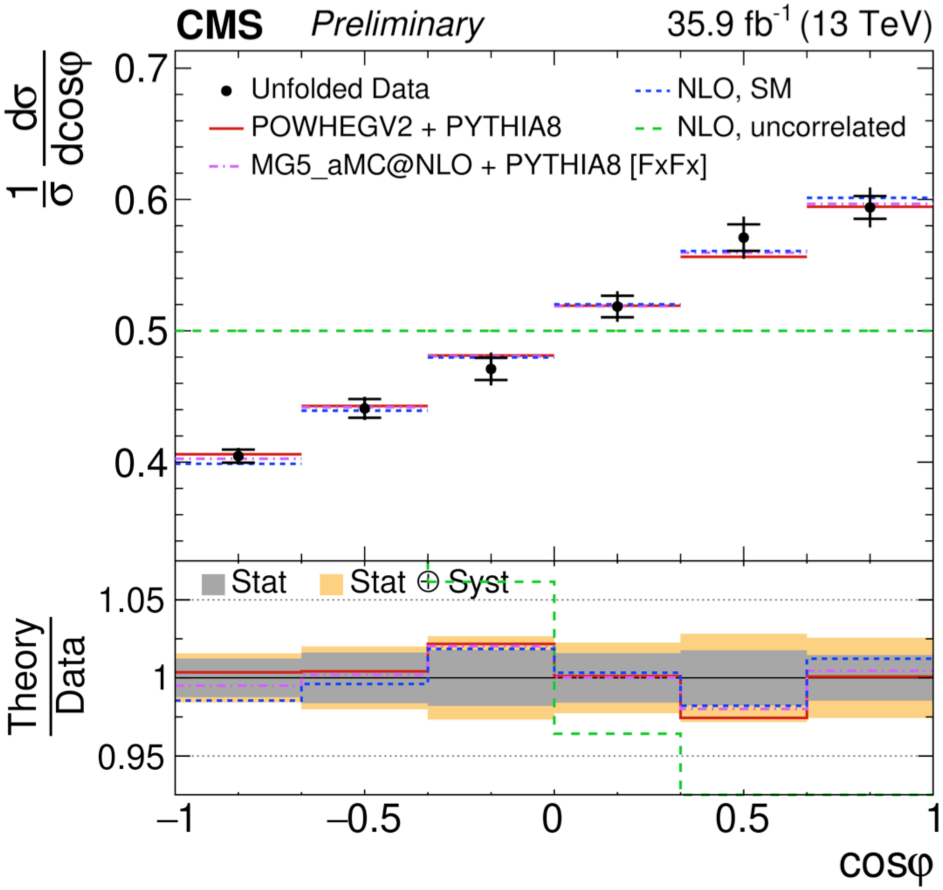
CMS f_{SM} values

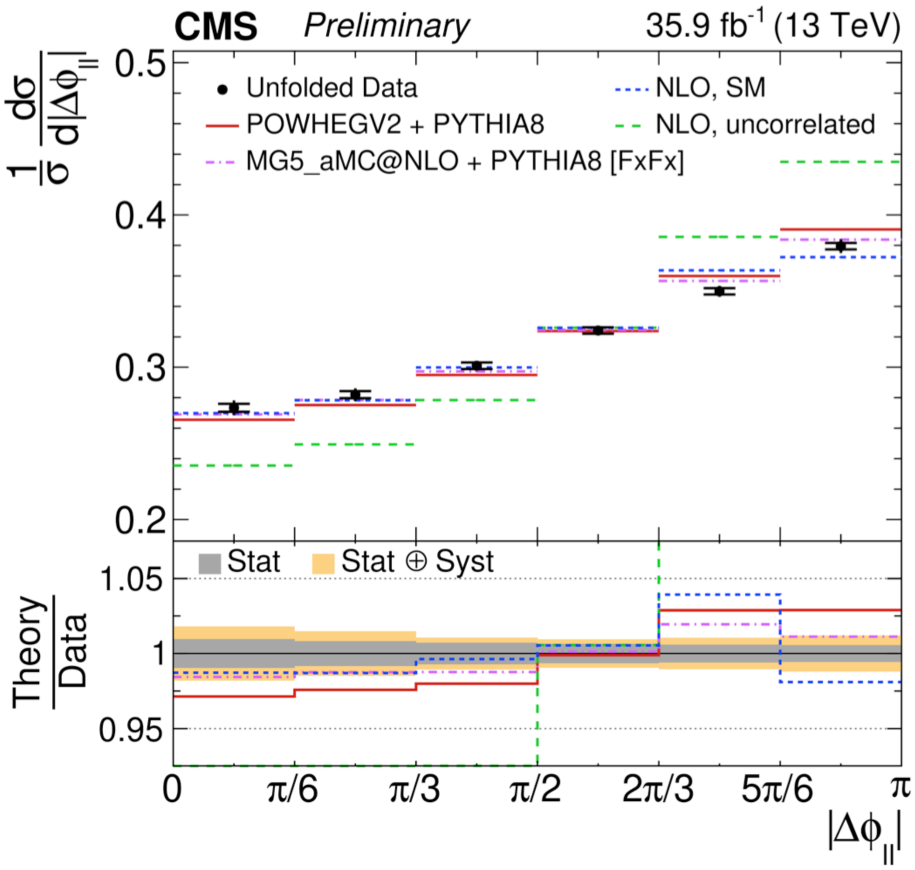
- Correlation term D from opening angle between leptons in parent top rest frames
- Most precise value of f_{SM}
- N.b. all f_{SM} values determined with Bernreuther-Si NLO QCD+weak predictions



N.b. lab frame

CMS distributions





ATLAS and NNLO Δη

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