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Observation of quantum entanglement in top-quark pair production with the ATLAS detector

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On behalf of the ATLAS Collaboration

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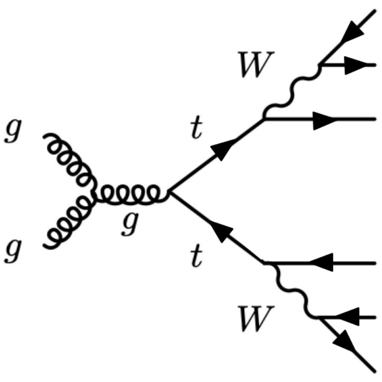
ATLAS
EXPERIMENT

Top Quark

- Produced in huge numbers at the LHC, mainly by gluon-gluon fusion
- Heaviest Standard Model particle, with very short lifetime $\approx 5 \times 10^{-25} s$
- Therefore decays (t→Wb) before it can hadronise ($\approx 10^{-23} s$) or undergo spin decorrelation ($\approx 10^{-21} s$), meaning we can effectively study bare quarks



Entanglement

- 2022 Nobel Prize for Physics awarded for entanglement measurement
- If two particles are entangled, we cannot descibe their states independently
- In the context of a 2 qubit system, (eg 2 spin-1/2 top quarks!!!), can describe the spin density matrix as:

  $$\rho = \frac{1}{4}[I_4 + \sum_i (B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j]$$

  where C_{ij} is the spin correlation matrix
- 15 parameters in total, but sufficient entanglement criteria is Tr[C]< -1
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- Only recently have we begun to study entanglement in the LHC's high-energy regime

Entanglement

- Considering top decays going to 2 leptons
- Since they decay before hadronisation and spin decorrelation, and because of weak decay's maximum parity violation, spin information of tops is passed onto leptons
- Looking at the leptons in their parents' rest frame, can use a more simple variable:

$$D = \frac{\mathbf{Tr}[C]}{3} = -3 < cos\phi >$$

$$\frac{1}{\sigma}\frac{d\sigma}{cos\phi} = \frac{1}{2}(1 - Dcos\phi)$$

- And now using the Peres-Horodecki criterion, we need:

$$D < -\frac{1}{3}$$

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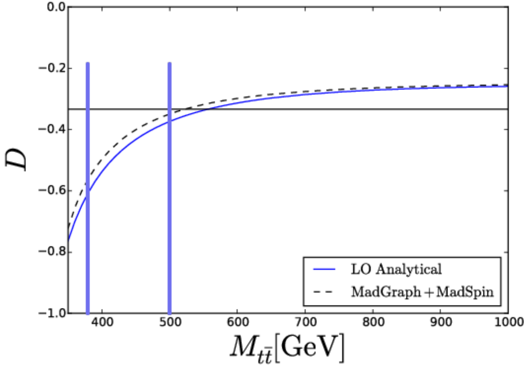
Analysis Regions

- Near threshold, majority of pairs produced in spin singlet state, enabling measurement of entanglement
- At higher M_{tt} effect is diluted
- Split events into three:
  - $340 < M_{tt} < 380$ GeV - signal region
  - $380 < M_{tt} < 500$ GeV - validation region
  - $M_{tt} > 500$ GeV - validation region



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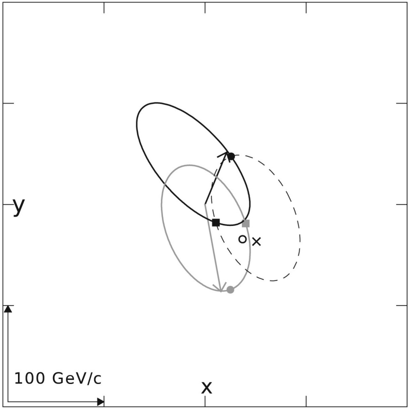
Top Reconstruction

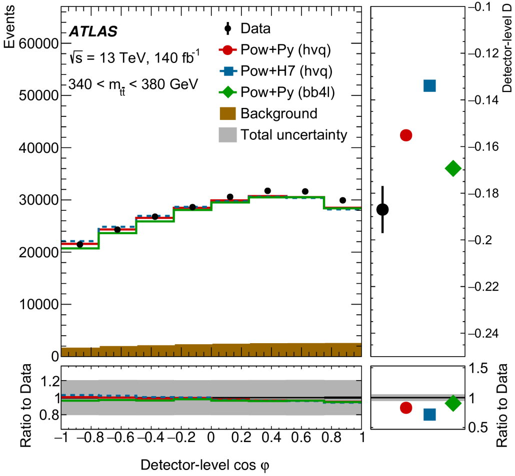
- Small M_{tt} window for signal region → we need good reconstruction of $t\bar{t}$ system
- Neutrinos particularly difficult
- Three methods used:
    - 85% Ellipse method (right) - analytical method finding overlap of two sets of possible p_T^ν values
    - 5% Neutrino weighting
    - 10% Only use leptons + jets



Nucl.Instrum.Meth.A 736 (2014) 169-178

Analysis Strategy

- 140fb^{-1} of 13TeV data used
- Key selections:
    - $1e$ & 1μ with opposite charges, $p_T > 25 - 28\,GeV$
    - Single lepton triggers
    - ≥ 2 jets
    - ≥ 1 b-tagged jet (85% efficiency)
- Backgrounds:
    - tW
    - tt + X (X=H,W,Z).
    - VV (V=W,Z)
    - $Z \rightarrow \tau\tau$
    - Fakes
- All regions have $t\bar{t}$ purity $\approx$ 90% and good data/MC agreement



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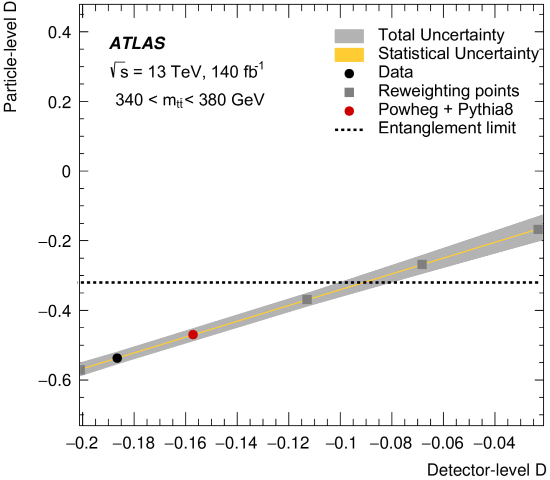
Calibration Curve

- Use 'calibration curve' to translate from detector level to particle level D value
- Performed in each M_{tt} region using MC samples with expected background contribution subtracted
- Different points created using reweighted samples, assuming different values of D, then interpolating between these.



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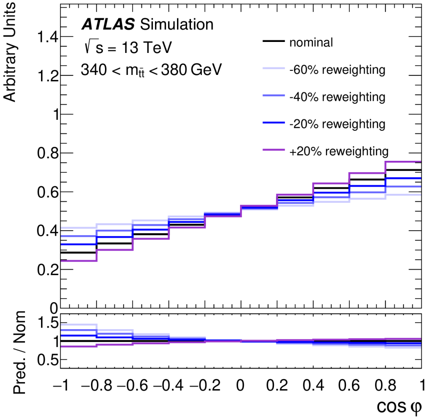
Reweighting

- Can't rewrite quantum physics in MC directly
  - so need to reweight events appropriately
- At parton level, model $D(M_{tt})$ as polynomial (so we can preserve linearity of $cos\phi$)
- Then reweight event by $cos\phi$ using:

$$w = \frac{1 - D(M_{tt}) \cdot \chi \cdot cos\phi}{1 - D(M_{tt}) \cdot cos\phi}$$

where χ controls the degree of reweighting



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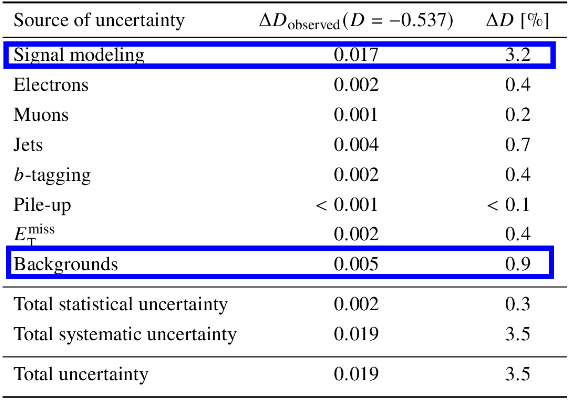
Systematic uncertainties

- Systematic uncertainties propagated using this method too, each having a separate calibration curve
- Signal modelling by far dominant source, in large part by changing the M_{tt} line shape
- Largest background effect from $Z \rightarrow \tau\tau$, due to its particularly flat $cos\phi$ distribution



Source of uncertainty	$\Delta D_{\text{observed}}(D = -0.537)$	ΔD [%]
Signal modeling	0.017	3.2
Electrons	0.002	0.4
Muons	0.001	0.2
Jets	0.004	0.7
b-tagging	0.002	0.4
Pile-up	< 0.001	< 0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.002	0.4
Backgrounds	0.005	0.9
Total statistical uncertainty	0.002	0.3
Total systematic uncertainty	0.019	3.5
Total uncertainty	0.019	3.5

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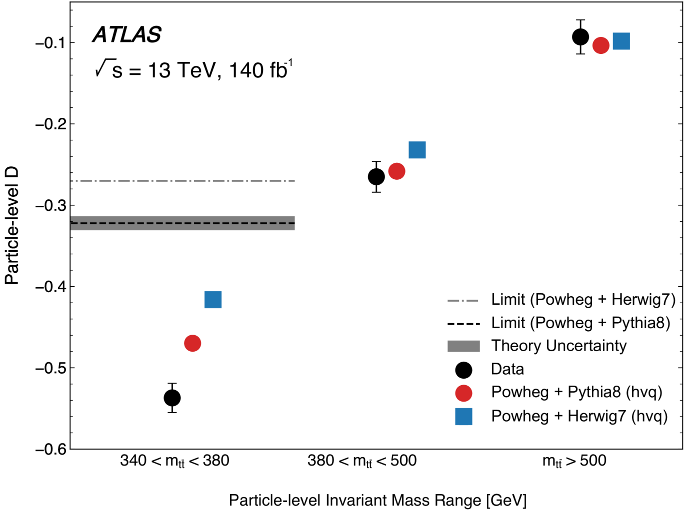
Results

$D = -0.537 \pm 0.002$ (stat.) ± 0.019 (syst.)

Entanglement observed at $> 5\sigma$!



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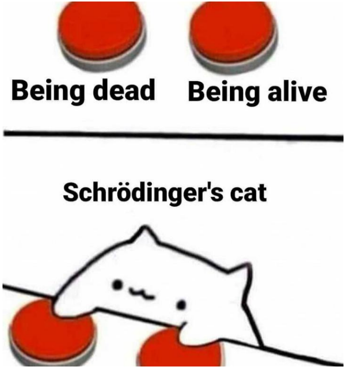
Conclusions

- Highest energy entanglement measurement yet performed
- Quantum information at the LHC is a relatively new and promising field
- Highlights importance of accurate top modelling (eg. potential to include 'toponium' effects)



Backup

Modelling Breakdown

Systematic uncertainty source	Relative size (for SM D value)
Top-quark decay	1.6%
Parton distribution function	1.2%
Recoil scheme	1.1%
Final-state radiation	1.1%
Scale uncertainties	1.1%
NNLO QCD + NLO EW reweighting	1.1%
pThard setting	0.8%
Top-quark mass	0.7%
Initial-state radiation	0.2%
Parton shower and hadronization	0.2%
h_{damp} setting	0.1%

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Event Yields

Process	Inclusive	340 – 380 GeV	380 – 500 GeV	> 500 GeV
$t\bar{t}$	1030000 ± 40000	202000 ± 8000	408000 ± 16000	417000 ± 17000
tW	59800 ± 1100	10330 ± 200	23800 ± 500	25700 ± 500
Z+jets	9100 ± 800	2470 ± 240	4000 ± 400	2620 ± 250
$WW/WZ/ZZ$	5950 ± 330	850 ± 50	2130 ± 120	2960 ± 170
$t\bar{t}X$	2959 ± 6	437.7 ± 2.1	1080.1 ± 3.4	1441 ± 4
fakes	29000 ± 5000	6000 ± 1100	11700 ± 2100	11700 ± 2100
Expectation	1140000 ± 40000	220000 ± 8100	450000 ± 16000	460000 ± 17000
Data	1105403	225056	441196	439151
data/MC	0.97 ± 0.03	1.02 ± 0.04	0.98 ± 0.03	0.95 ± 0.04

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