Top quark entanglement at the ATLAS detector

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Entanglement

The quantum state of one entangled particle cannot be described independently of another

→ Measurement of one seems to affect the other

Quantify entanglement of two particles using the trace of spin correlation matrix:

$$D = \frac{\mathrm{Tr}\left[\mathbb{C}\right]}{3} \Rightarrow D < -\frac{1}{3}$$

Entanglement at the LHC

Entanglement has been measured in a wide variety of situations, but only recently tested at the high energy scales available with the LHC

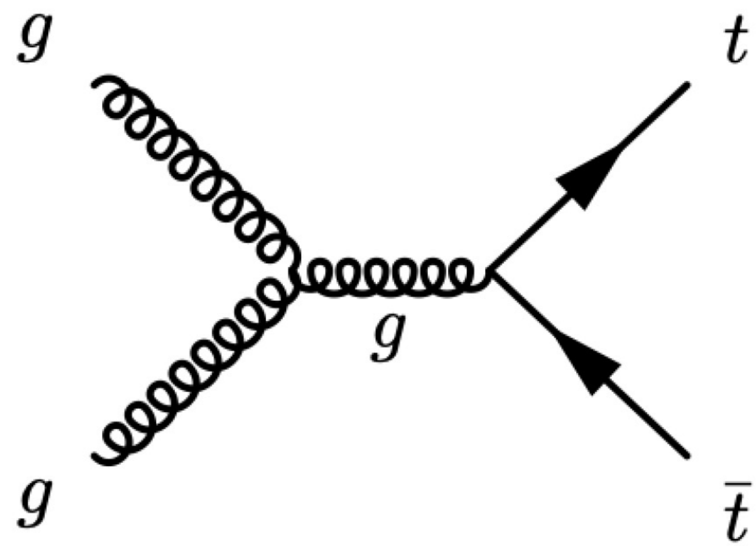
First observation of quantum entanglement between a pair of 'bare' quarks!

The top

The top is the heaviest fundamental particle at 173 GeV

Top-antitop pairs produced primarily by gluon-gluon fusion at the LHC

Each spin ½ top is a qubit → $t\bar{t}$ is a two qubit system

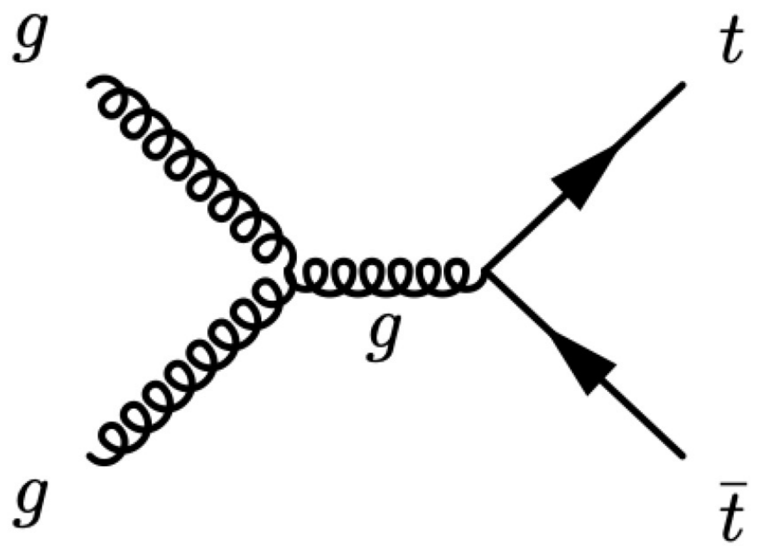


The top

Each spin ½ top is a qubit → $t\bar{t}$ is a two qubit system

For an entangled system spin density matrix ρ is inseparable

Applying Peres–Horodecki criterion gives $D < -\frac{1}{3}$ entanglement threshold



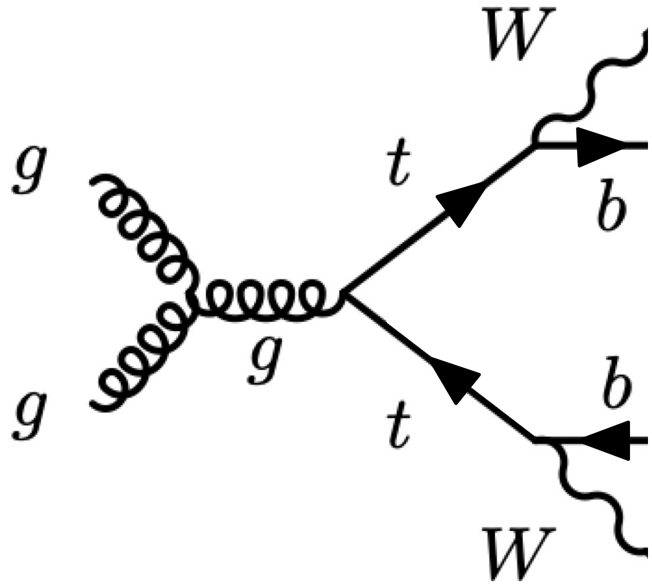
$$\rho = \frac{1}{4}[I_4 + \sum_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i\right) + \sum_{i,j} C_{ij} \sigma^i \otimes \sigma^j]$$

The top

Very short lifetime O(10^{-24}) s

→ top decays before it can hadronise (O(10^{-23}) s), and before spin decorrelation (O(10^{-21}) s)

Can study behavior as bare quark, and spin correlation from entanglement



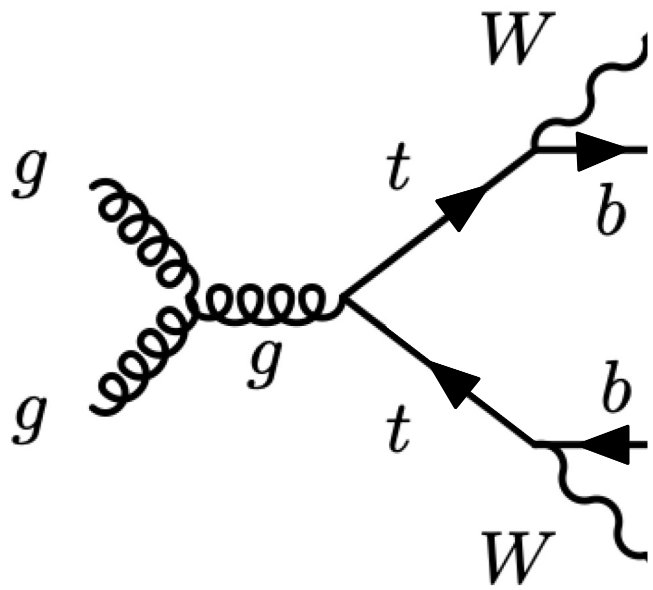
Decays overwhelmingly to W+b

$t\bar{t}$ entanglement

Decay before spin decorrelation → spin info transferred to decay products

Can use measurements of $t\bar{t}$ final state products to probe entanglement

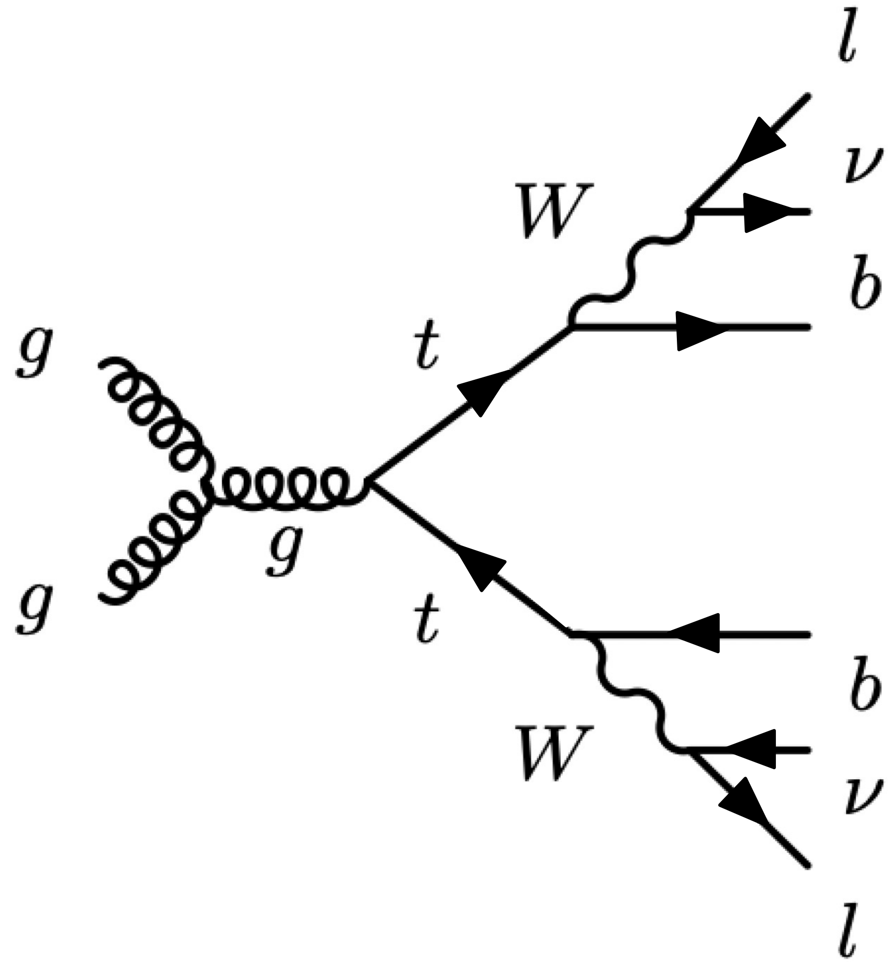
Quantum tomography: reconstruction of a quantum state by measuring of a set of identical quantum states.



$t\bar{t}$ entanglement

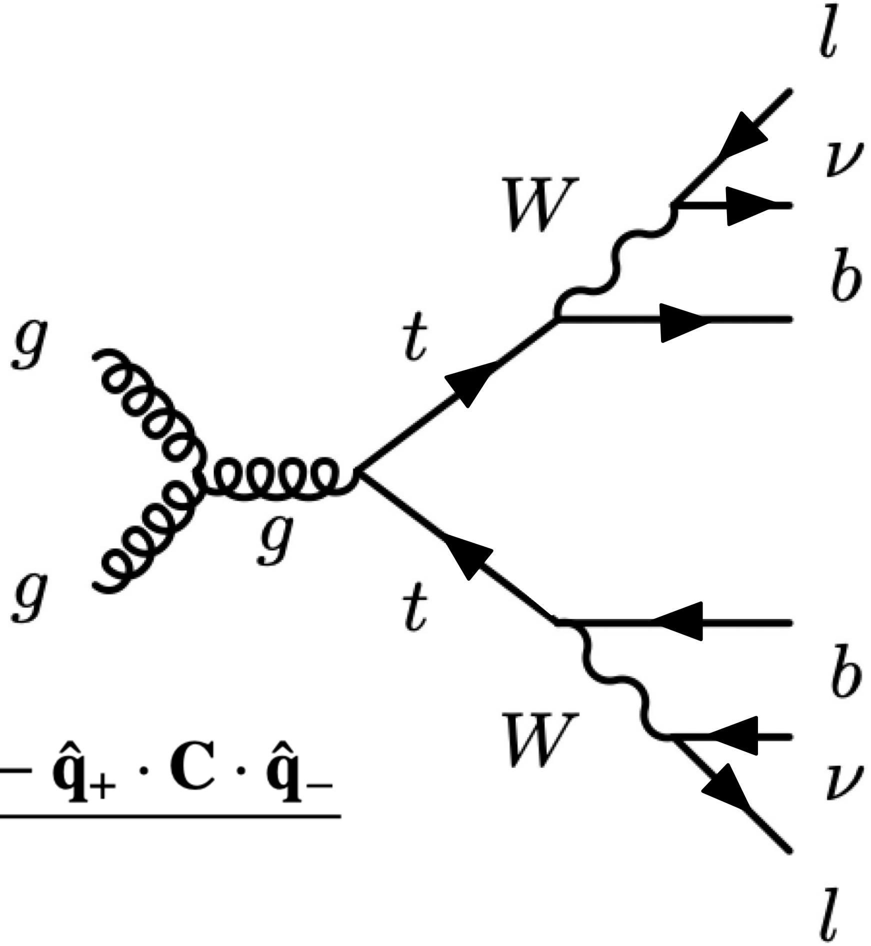
Considering fully leptonic $t\bar{t}$ decays – can measure with higher precision than hadronic decay modes

Require one electron and one muon



$t\bar{t}$ entanglement

Spin info in leptons very closely related to the parent quarks since electroweak charged current is maximally parity violating

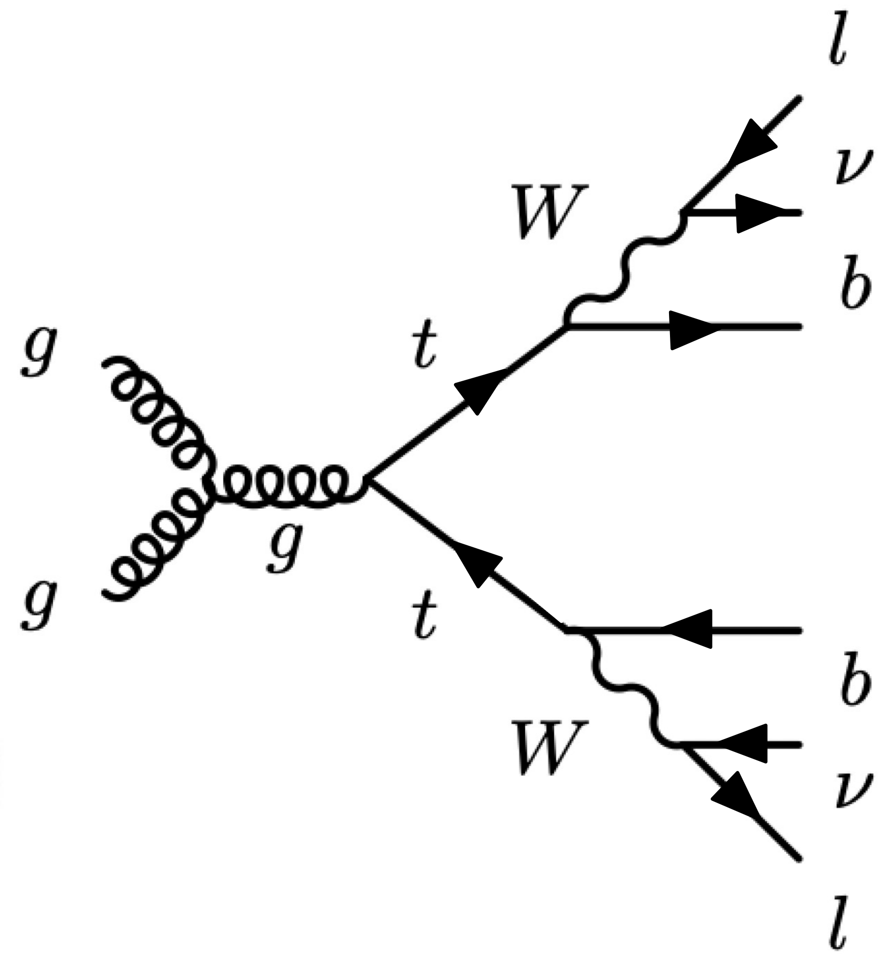


$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1 + \mathbf{B}^+ \cdot \hat{\mathbf{q}}_+ - \mathbf{B}^- \cdot \hat{\mathbf{q}}_- - \hat{\mathbf{q}}_+ \cdot \mathbf{C} \cdot \hat{\mathbf{q}}_-}{(4\pi)^2}$$

$t\bar{t}$ entanglement

Can extract spin correlation from the average angle between the leptons in the parent quarks' rest frames to find

$$D = -3 \cdot \langle \cos \varphi \rangle$$



$t\bar{t}$ entanglement

$t\bar{t}$ entanglement is dependent on energy of the $t\bar{t}$ system

At production threshold (invariant mass ≈ twice top mass) 80% of $t\bar{t}$ is produced from a spin-0 singlet state

→ maximally entangled!

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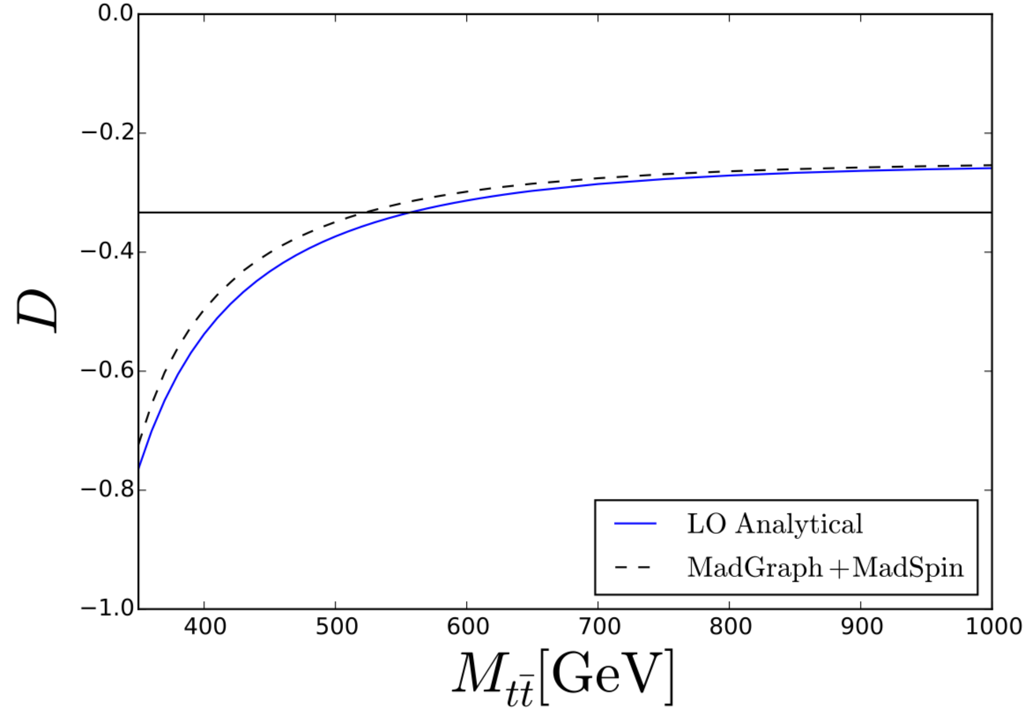
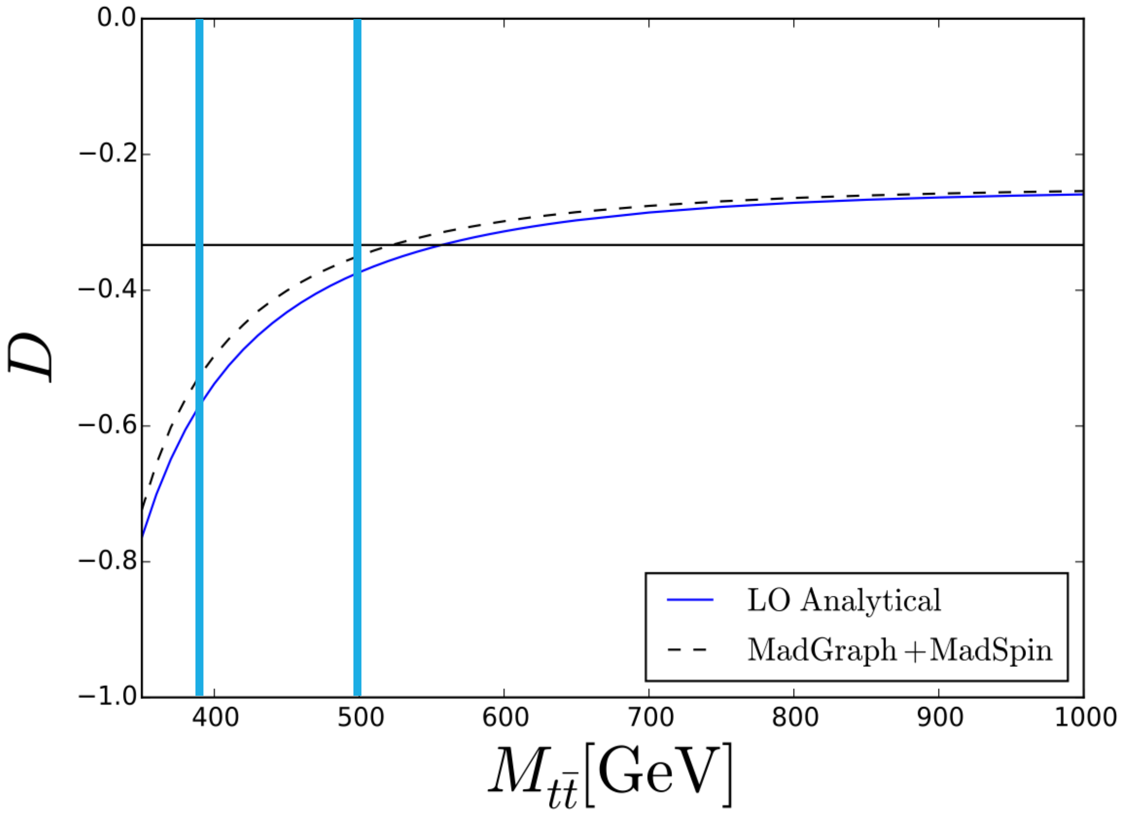


Region definitions

Dividing into three mass regions:

Signal region ($340 < m_{t\bar{t}} < 380$) close to mass threshold

Two validation regions ($380 < m_{t\bar{t}} < 500$, $m_{t\bar{t}} > 500$) expecting little or no entanglement



Region definitions

140 fb^{-1} of √13 TeV data collected by ATLAS using single lepton triggers. Selection requires:

- Opposite sign electron and muon pair, with p_T > 25 GeV
- Two+ jets with p_T > 25 GeV, at least one b-tagged

Each region with $t\bar{t}$ purity ≈ 90%, close data/MC

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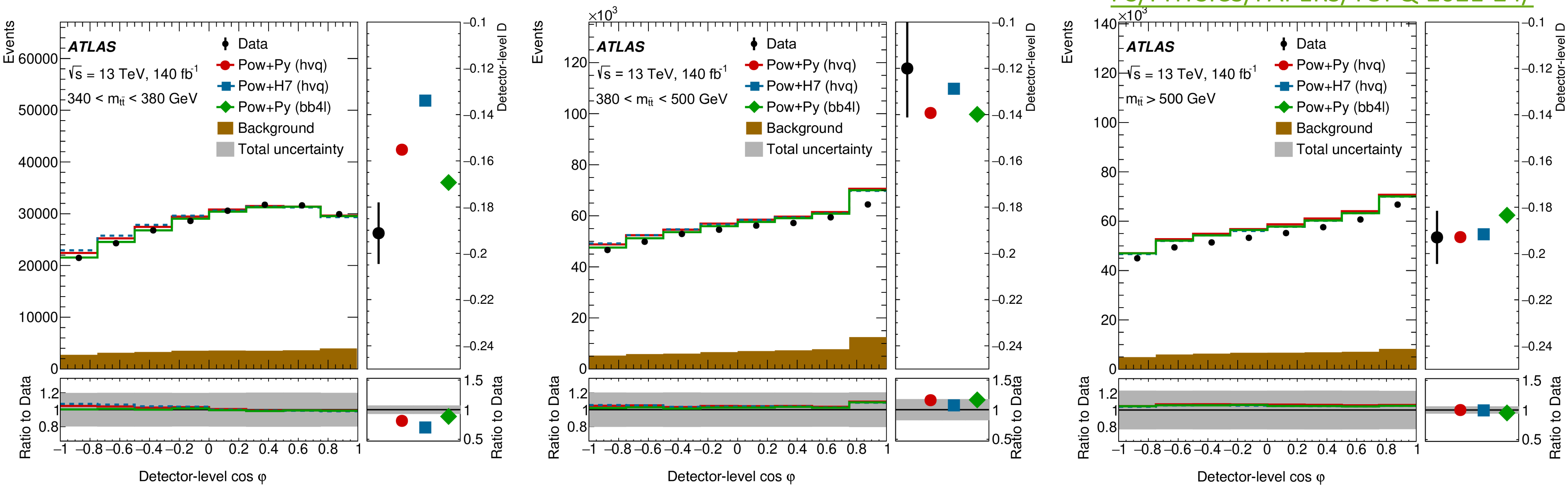
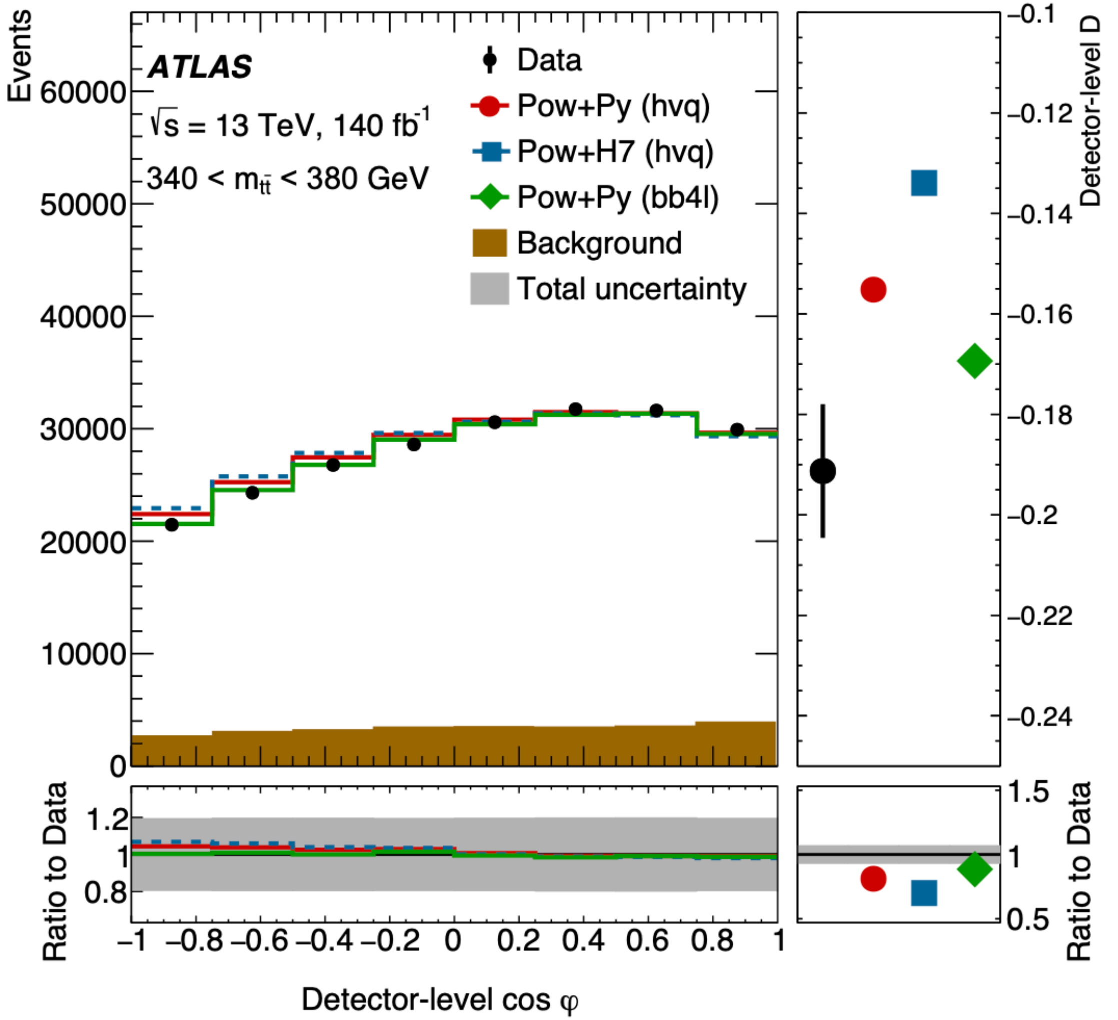


Measurement

Background subtracted measurement of cos φ between leptons in top quarks' rest frames

Distribution is distorted by detector response, selection, and reconstruction → correct with calibration curve



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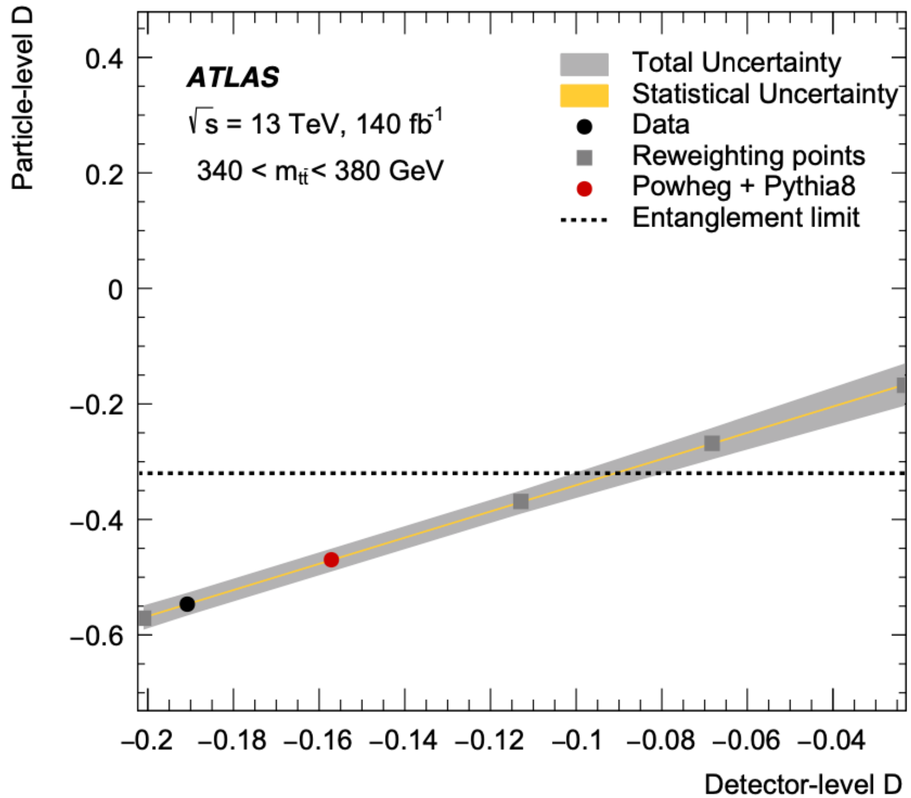
Calibration

A calibration curve is built for each region using MC samples generated with alternative values of D and interpolating

Particle-level D can be read off for any value of detector-level D



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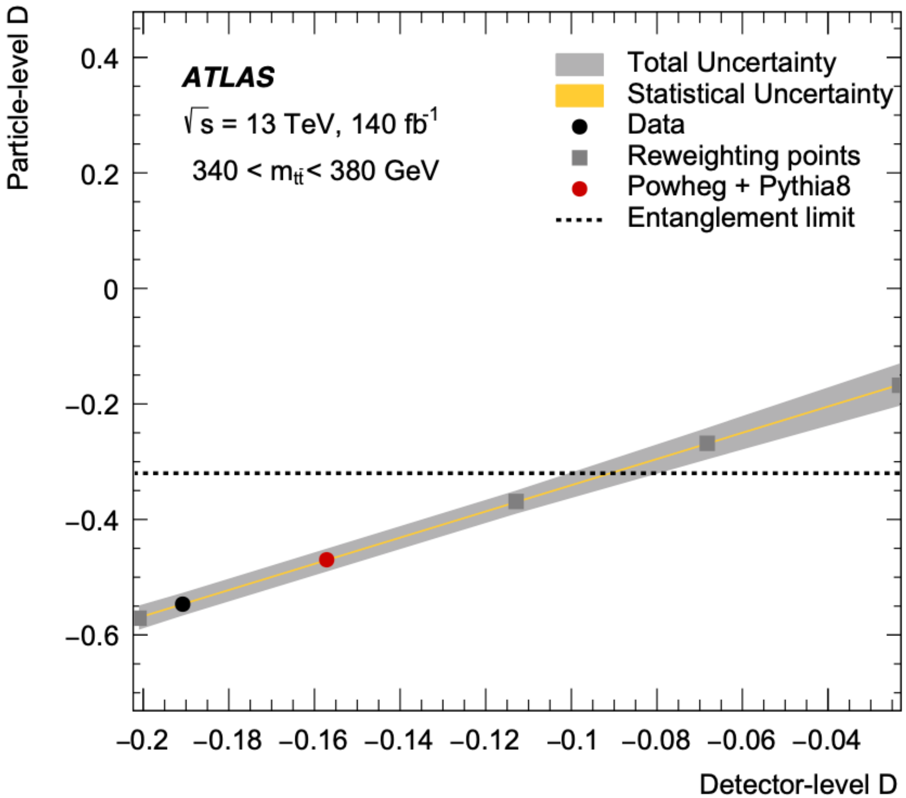
Calibration

Also used to estimate systematic variations - $t\bar{t}$ modelling, background modelling, and detector effects

New curve for each → differences from nominal results taken as systematic uncertainties on data



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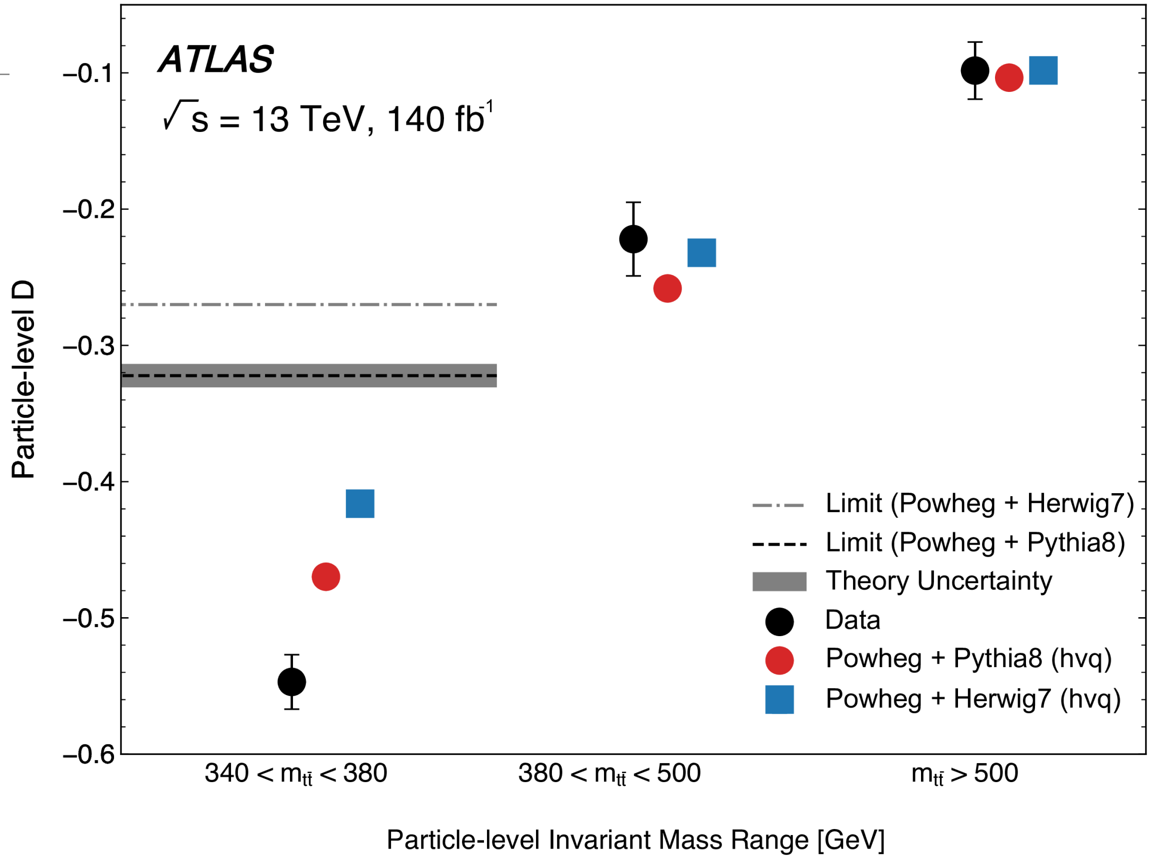
Results

D = -0.5487 ± 0.002 (stat.) ± 0.021 (syst.)

→ entanglement observed > 5σ!



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Conclusion

Entanglement observed between top-antitop quark pairs at > 5σ

First observation of entanglement between bare quarks, and highest energy per particle observation

Thanks :)

Region definitions

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	38000	±	4000	9300	±	400	19000	±	4000	9730	±	270
$WW/WZ/ZZ$	9140	±	340	1320	±	50	3280	±	120	4540	±	170
$t\bar{t}X$	2959	±	6	437.7	±	2.1	1080.1	±	3.4	1441	±	4
fakes	17700	±	8900	3600	±	1900	7100	±	3800	7000	±	3700
Expectation	1150000	±	40000	227000	±	8000	462000	±	17000	466000	±	17000
Data	1105403			225056			441196			439151		
data/MC	0.96	±	0.03	0.99	±	0.04	0.95	±	0.04	0.94	±	0.04

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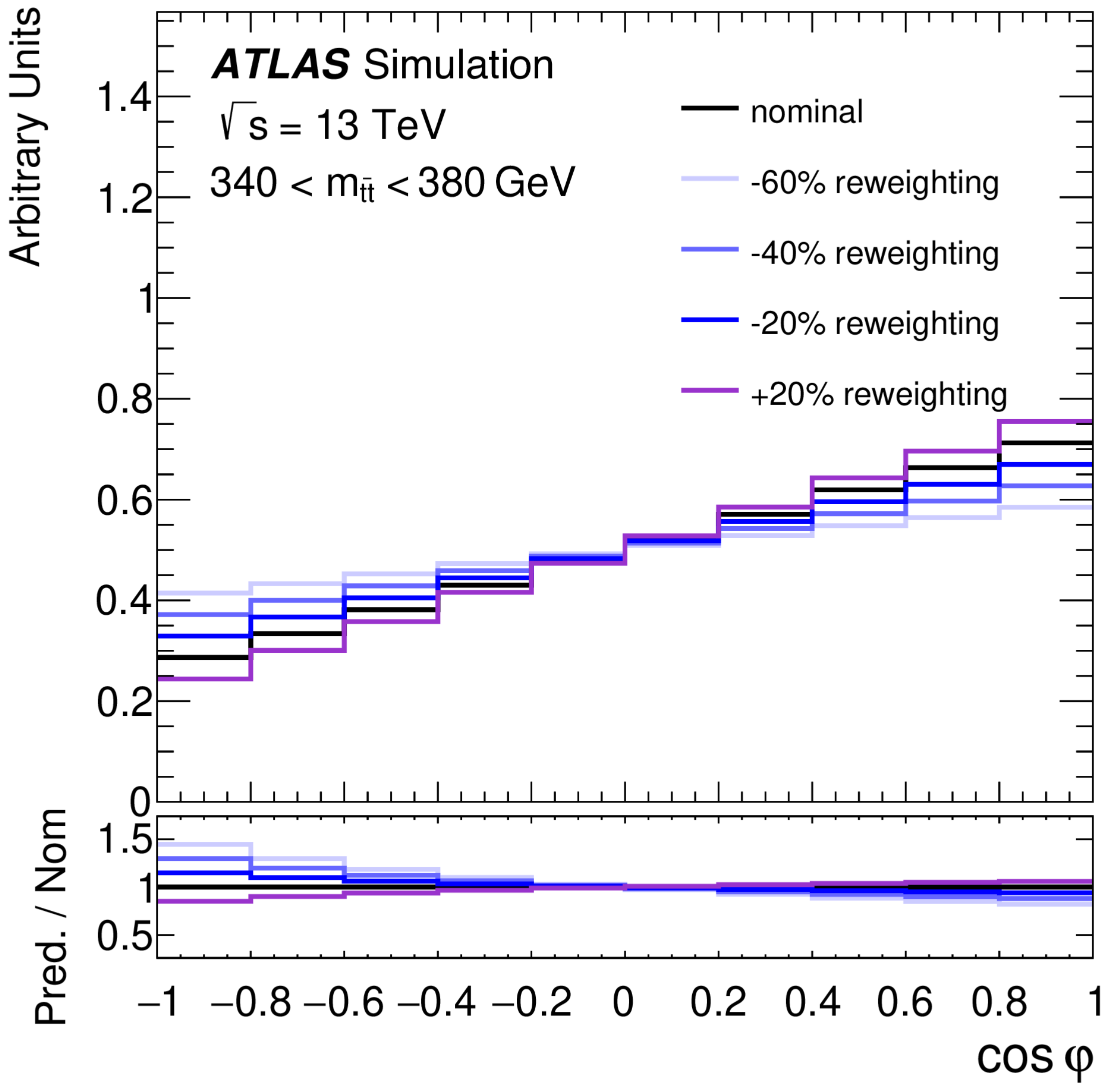
D reweighting

Degree of entanglement is in MC event generator calculations

Instead reweight event-by-event based on D at parton level



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MC comparison

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