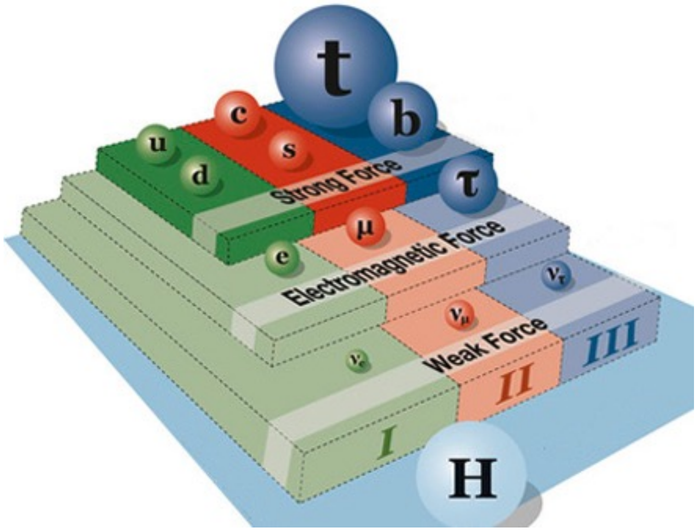
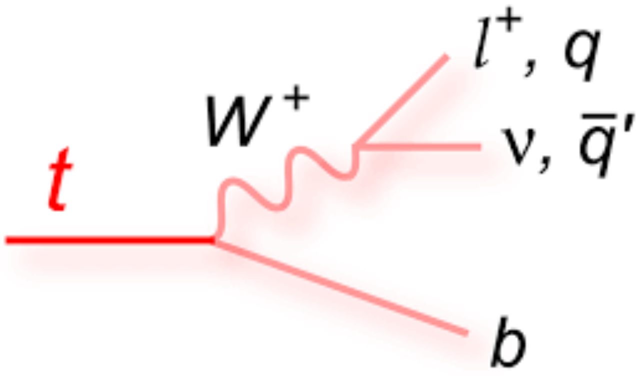
ATLAS results on quantum entanglement

Vasiliki A. Mitsou on behalf of the ATLAS Collaboration

Top quark

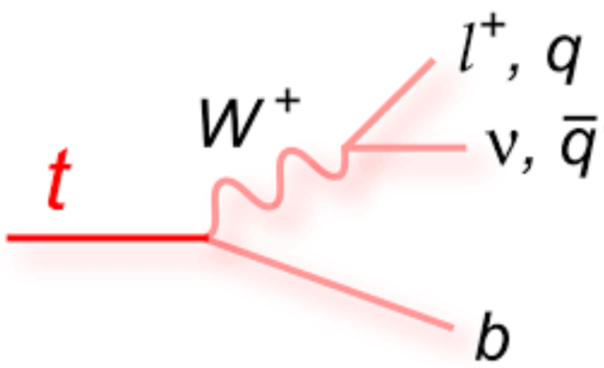
- Top quark is the heaviest fundamental particle at ~173 GeV
- Decays promptly almost exclusively to an on-shell *W* boson and a *b* quark
  - *W* may decay leptonically, to a charged lepton, *ℓ*, and a neutrino, *ν*
  - *W* may decay hadronically, to pair of lighter quarks





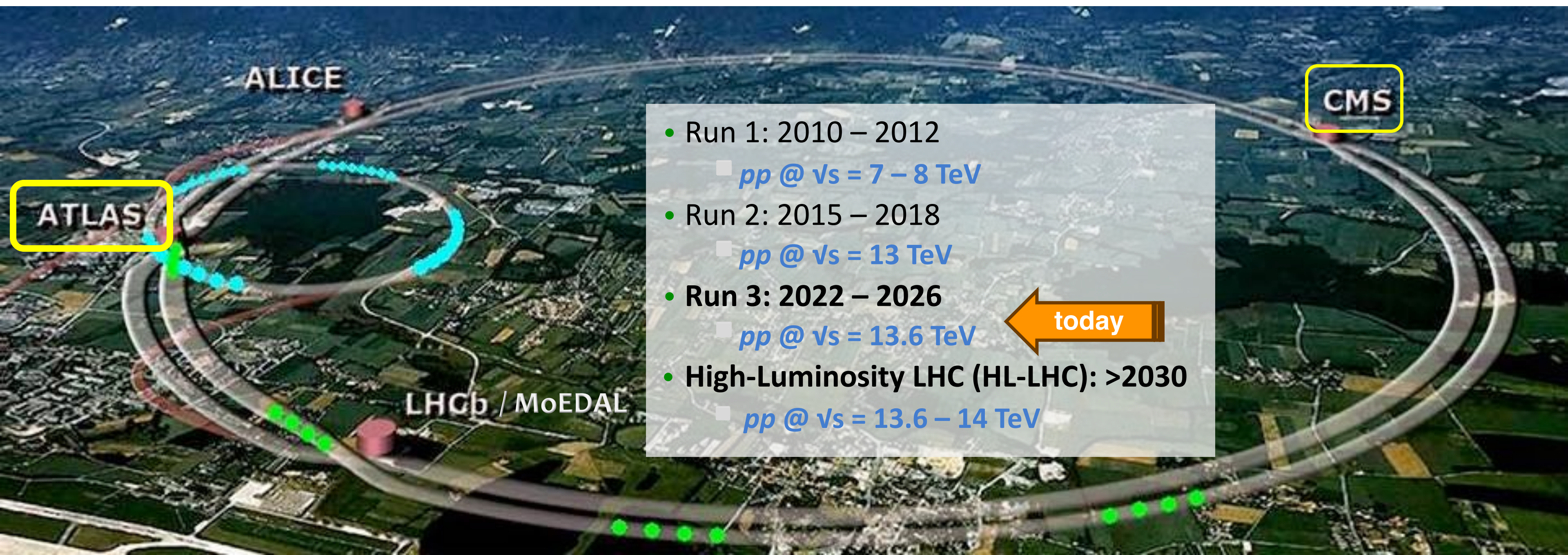
Top-quark spin

- Top has very short lifetime: 5×10^{-25} s
- Decays *before* hadronisation ($\sim 10^{-23}$ s)
  - its spin not hidden by strong interactions
- Decays *before* undergoes spin decorrelation ($\sim 10^{-21}$ s)
  - maintains quantum coherence
- Spin information transferred directly to its decay products
  - allows access to quantum properties via final-state particles
- We can effectively study bare quarks!



LHC – Large Hadron Collider

- The most powerful collider in the world!
- Collisions of protons and/or heavy ions
- Top-quarks abundantly produced → **top-quark factory**
  - studied in **ATLAS** and CMS experiments



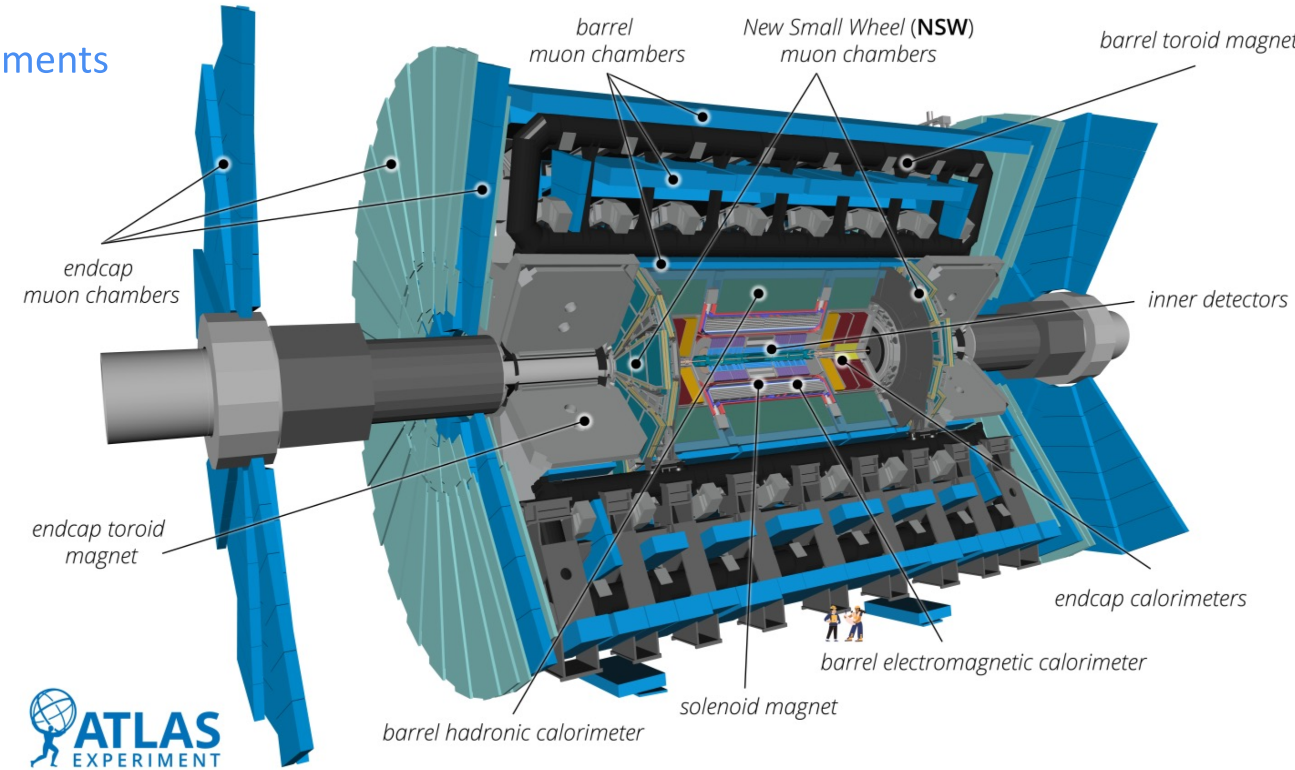
- Run 1: 2010 – 2012
  - ***pp* @ √s = 7 – 8 TeV**
- Run 2: 2015 – 2018
  - ***pp* @ √s = 13 TeV**
- **Run 3: 2022 – 2026**
  - ***pp* @ √s = 13.6 TeV**
- **High-Luminosity LHC (HL-LHC): >2030**
  - ***pp* @ √s = 13.6 – 14 TeV**

ATLAS detector

In 2012, discovered **Higgs boson** together with CMS

- Large, symmetric, almost hermetic experiment at LHC
- Multi-purpose
  - Standard Model measurements
  - searches for New Physics
- Direct detection of
  - photons
  - hadronised quarks & gluons *(jets)*
  - tau leptons
  - electrons
  - muons

identified and their position/momentum measured with high precision



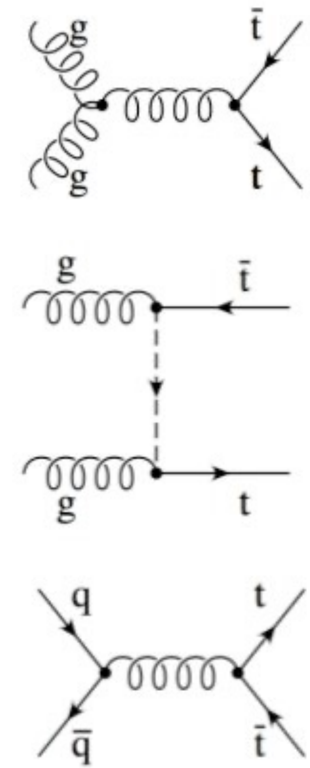
Top-antitop pair production

- At the LHC, top-quarks are produced copiously in pairs via strong interaction
  - also electroweak production, but heavily suppressed
- Spin quantum state of $t\bar{t}$ pair described by spin density matrix

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

$t, \bar{t}$ intrinsic polarisation

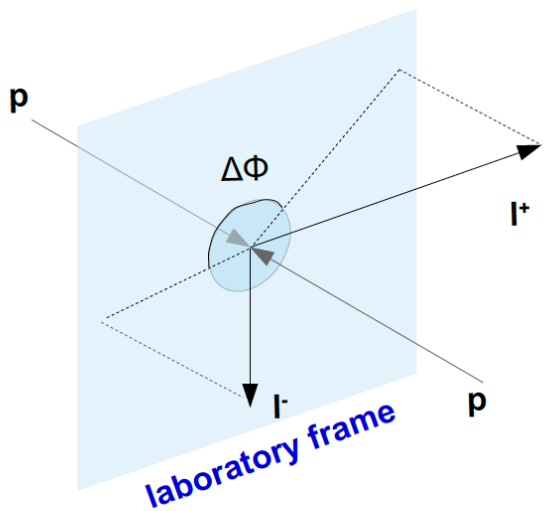
spin correlation matrix

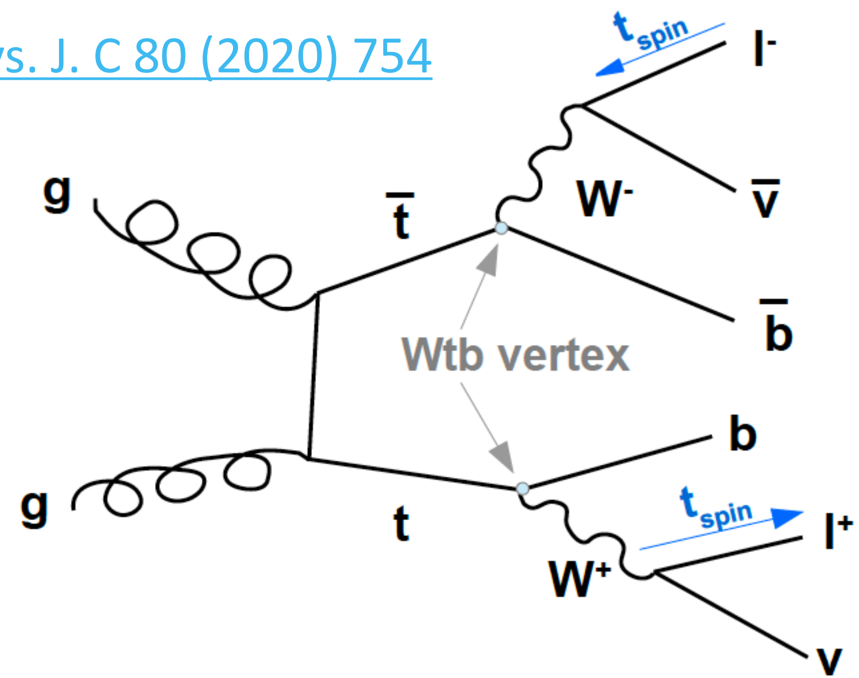


- Top-quarks strongly produced not polarised in any particular direction → $B^{\pm}_{ij} \simeq 0$
  - parity conservation and time invariance
- However, spins of top- and antitop-quarks are correlated in Standard Model → $C_{ij} \neq 0$

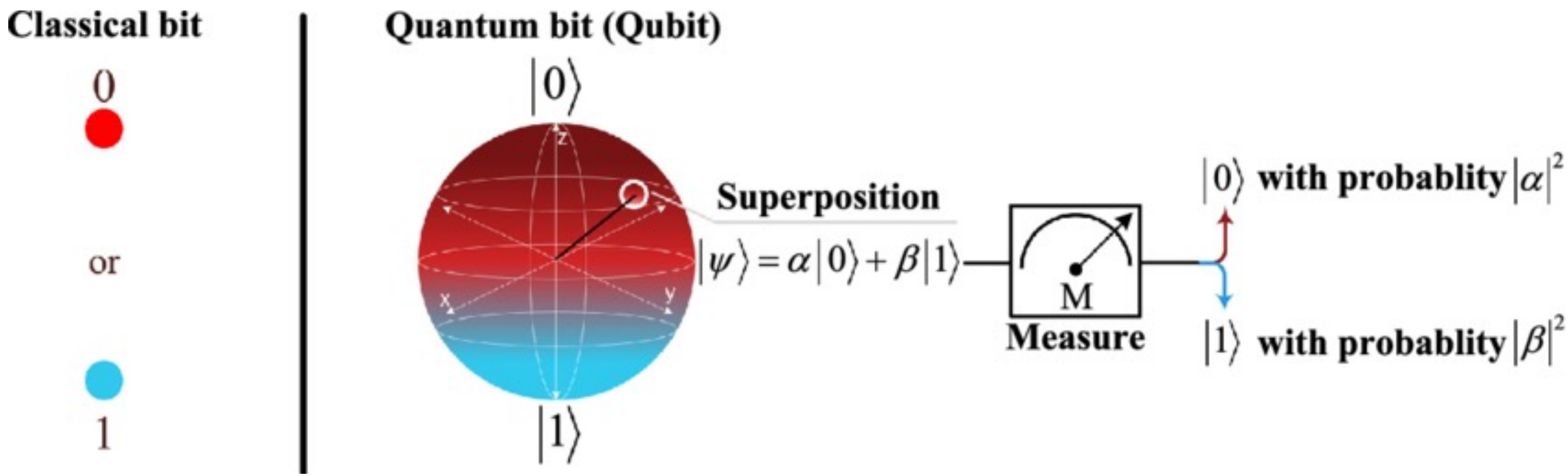
Top-quark spin correlations in $t\bar{t}$ production

- Observable $\Delta\Phi(\ell^+, \ell^-)$: absolute azimuthal opening angle between the two charged leptons measured in laboratory frame in plane transverse to beam line
- Measured in ATLAS, see e.g. [Eur. Phys. J. C 80 (2020) 754]



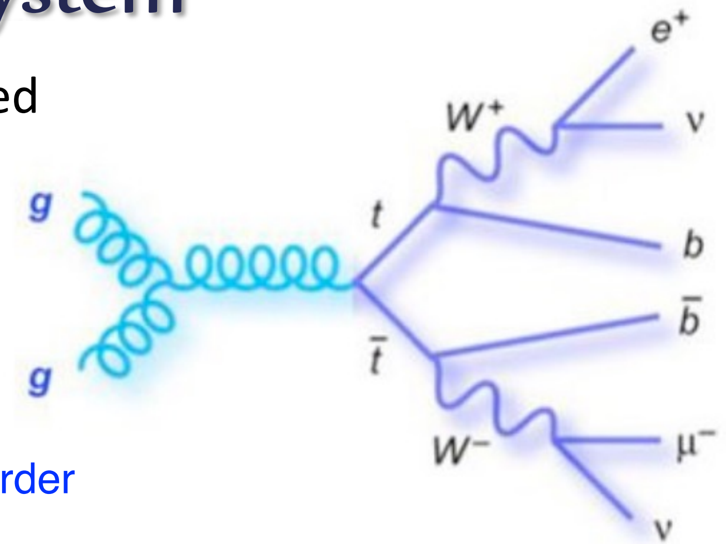


Top-quarks as qubits



Spin quantum number of a fermion (±½) → simplest example of a qubit

Top-antitop pair as two-qubit system



- Spin info in **measured leptons** very closely related to **parent quarks** since electroweak charged current is *maximally* parity violating
- Spin density matrix $\rho \rightarrow$ angular differential cross-section for dilepton decay

QCD *P*-even: zero polarisations at leading order

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1 \cancelto{0}{\mathbf{B}_1} \cdot \hat{\ell}_1 + \alpha_2 \cancelto{0}{\mathbf{B}_2} \cdot \hat{\ell}_2 + \alpha_1\alpha_2 \hat{\ell}_1 \cdot \mathbb{C} \cdot \hat{\ell}_2\right)$$

$\alpha_1 = \alpha_2 = 1$ (maximal) for leptons

$\ell^{\pm}$: direction of ℓ^+ (ℓ^-) in its parent t ($\bar{t}$) rest frame

- Differential cross-section → C measurement → spin quantum state reconstruction

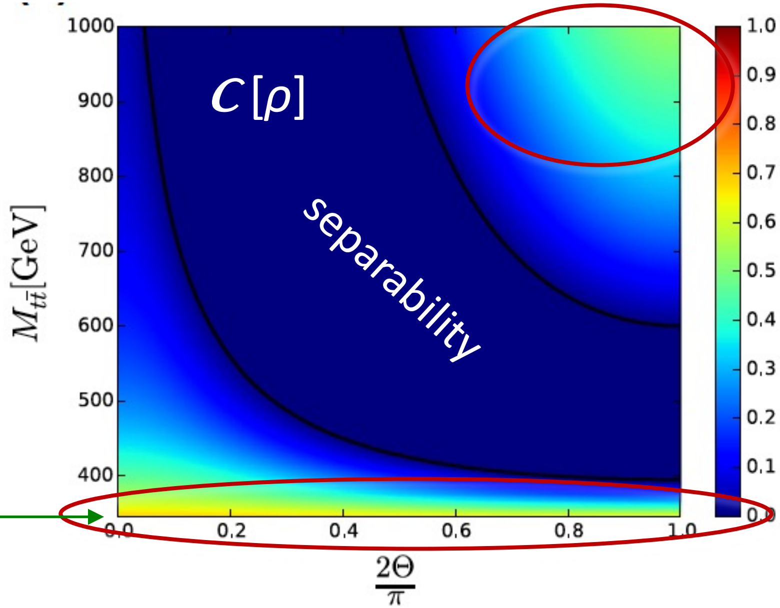
Quantum entanglement conditions

- Quantitative measure of entanglement: **concurrence** $C[\rho]$ of spin density matrix ρ:

  less entangled ⟵ $0 \leq C[\rho] \leq 1$ ⟶ *maximally entangled*

- At hadron colliders, initial state is not controlled (no pure state) → mixed state gg, $q\bar{q}$
  - different expressions for entanglement criterion for gg and $q\bar{q}$

$t\bar{t}$ production (gg, $q\bar{q}$) at $\sqrt{s}$ = 13 TeV pp collisions



spin-triplet pure state maximally entangled

$t\bar{t}$ production threshold: invariant mass ≈ twice top mass ≈ 350 GeV

gg spin polarisation allows to align in different directions (spin-singlet state; 80% of $t\bar{t}$ production)

Afik & Muñoz de Nova, Eur. Phys. J. Plus 136 (2021) 907

Top-antitop pair as “bipartite qubit system”

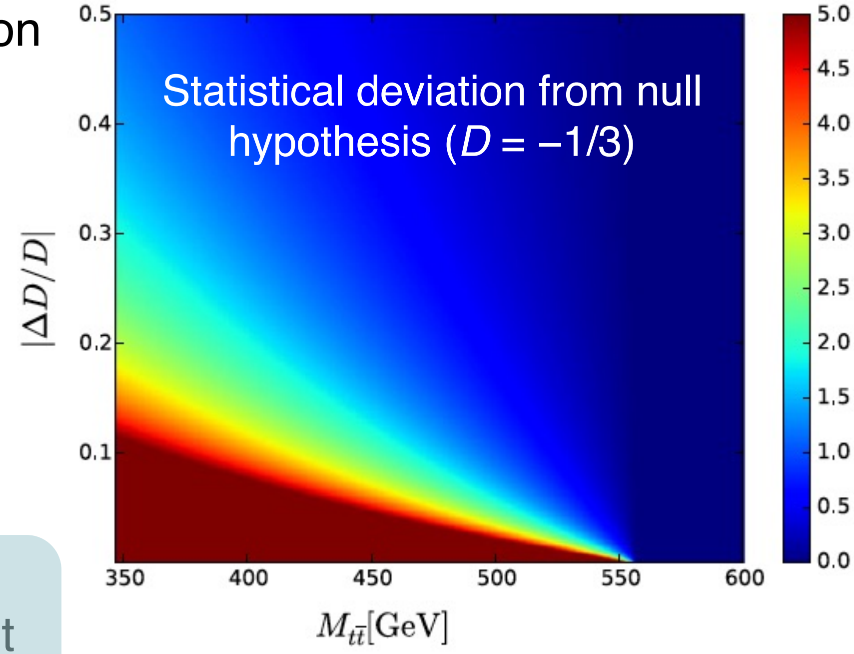
$$\mathrm{Tr}\left[\mathbb{C}\right] < -1$$ Peres-Horodecki criterion

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}\left(1 - D\cos\varphi\right)$$

φ: angle between lepton directions in rest frames of parent (anti)top-quark

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

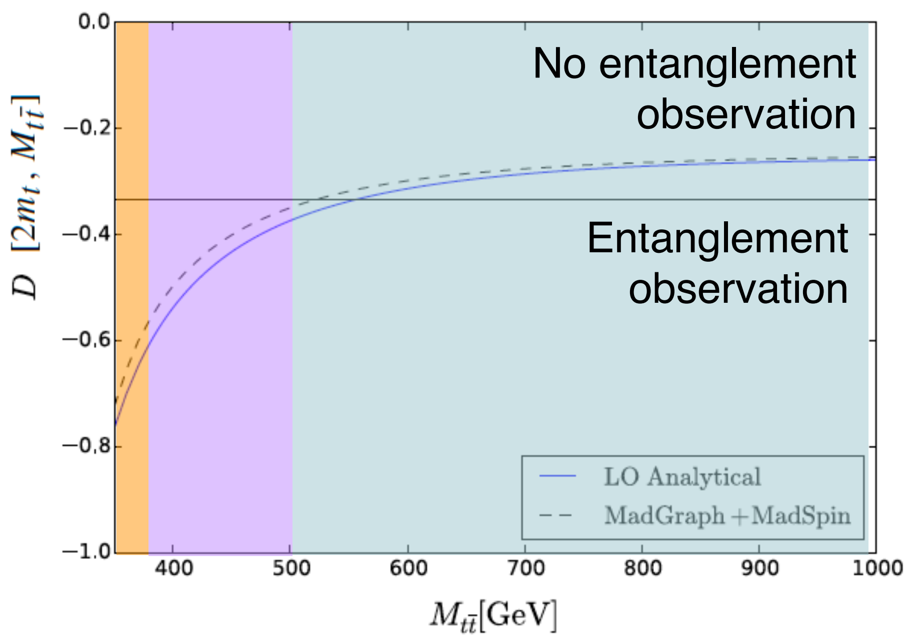
$$D = \frac{\mathrm{Tr}\left[\mathbb{C}\right]}{3} \Rightarrow D < -\frac{1}{3}$$ quantum entanglement marker!



Afik & Muñoz de Nova, [Eur. Phys. J. Plus 136 (2021) 907]

Entanglement measurement phase space

- $t\bar{t}$ entanglement observation depends on $t\bar{t}$ system energy
- Focusing on production threshold ($m_{t\bar{t}} \approx 350$ GeV)
- Dividing into three mass regions:
  - signal region ($340 < m_{t\bar{t}} < 380$ GeV) close to mass threshold
  - two validation regions expecting little or no entanglement
    - $380 < m_{t\bar{t}} < 500$ GeV
    - $m_{t\bar{t}} > 500$ GeV



ATLAS, Nature 633 (2024) 542

Afik & Muñoz de Nova, Eur. Phys. J. Plus 136 (2021) 907

Event selection & backgrounds

- Single-lepton triggers
- Opposite-sign 1 electron & 1 muon: p_T > 25–28 GeV
- ≥ 2 jets with p_T > 25 GeV; ≥ 1 *b*-tagged jet (85% efficiency)

ATLAS, Nature 633 (2024) 542

- ~90% purity of $t\bar{t}$ signal
- Dominant backgrounds: single top (~60%), fakes (~30%)
- SM processes estimated by simulation
- Fakes partly evaluated by data-driven techniques

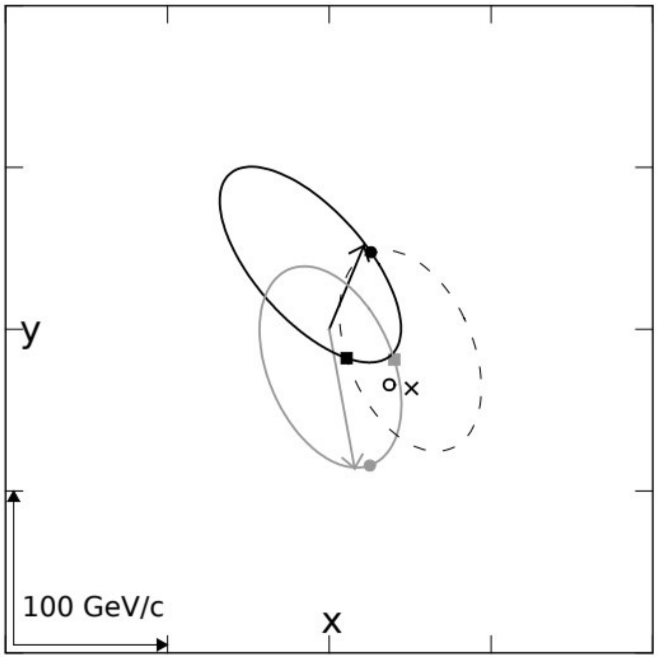
Run 2
$\sqrt{s}$ = 13 TeV
140 fb^{-1}

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

Top-quark reconstruction

- Reconstruction of top momenta complicated due to two neutrinos
- Several methods developed, reconstructing ν momenta from missing traverse momentum (MET), using m_t and m_W as constraints

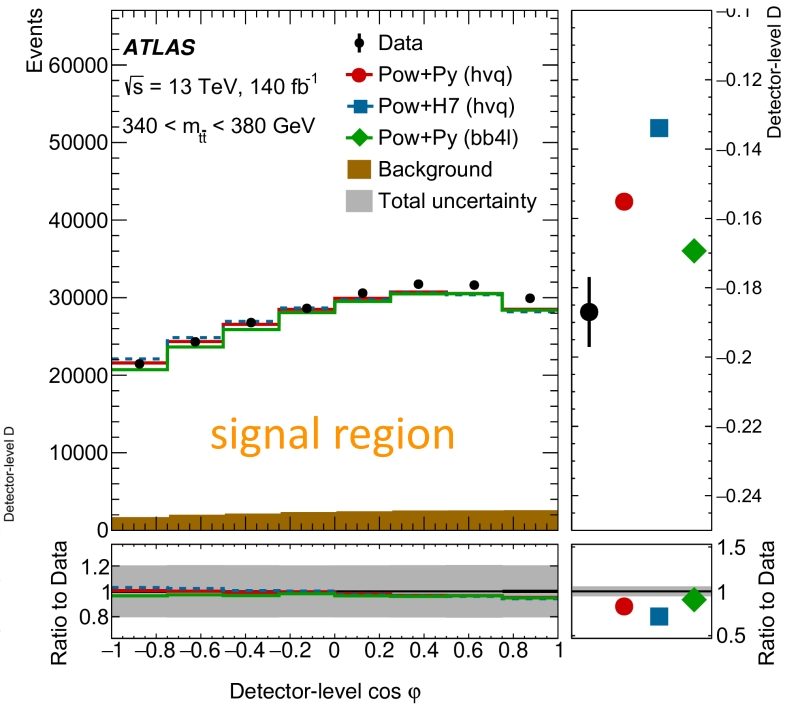
1. Main: ***Ellipse*** method (85% efficiency)
   - analytically calculate two ellipses for p_T^ν and find intersections
2. If Ellipse fails → ***Neutrino weighting*** method (5%)
   - scans η^ν, $\eta^{\bar{\nu}}$ phase-space
   - solutions weighted based on compatibility between p_T^ν and MET
3. If both methods fail: **simple pairing** of leptons with closest *b*-jets (10%)
   - use highest-p_T jet if only 1 *b*-tagged jet

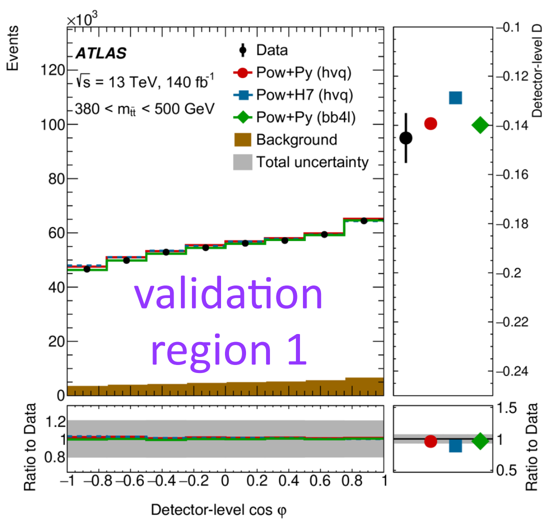


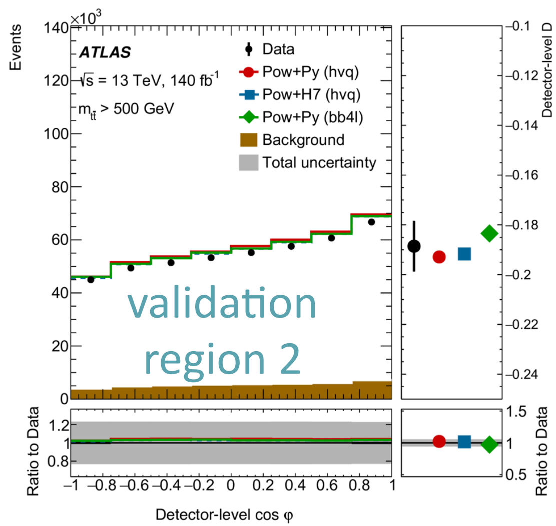
Betchart, Demina, Harel, Nucl.Instrum.Meth.A 736 (2014) 169-178

Detector-level measurement

- Measure cosφ after boosting leptons into their parent top's rest frame
- Compare with different Monte Carlo predictions
- Calculate $D = -3\ \langle \cos\varphi \rangle$







ATLAS, [Nature 633 (2024) 542]

Calibration curve

- Detector effects induce shape distortions to distributions
  - detector response (resolution, noise)
  - reconstruction of top quarks and their decay products
  - event selection
- Measured (reconstructed) data corrected to truth (particle) level
  - particle-level cuts similar to reconstruction-level
- Calibration curves created for signal and validation regions by reweighting simulation based on truth *D* value

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Reweighing cosφ distribution

- Degree of entanglement inherent in particle generators → cannot be changed
- Fit a 3rd order polynomial to extract $D_\Omega(m_{t\bar{t}})$ dependence on $m_{t\bar{t}}$ at parton level

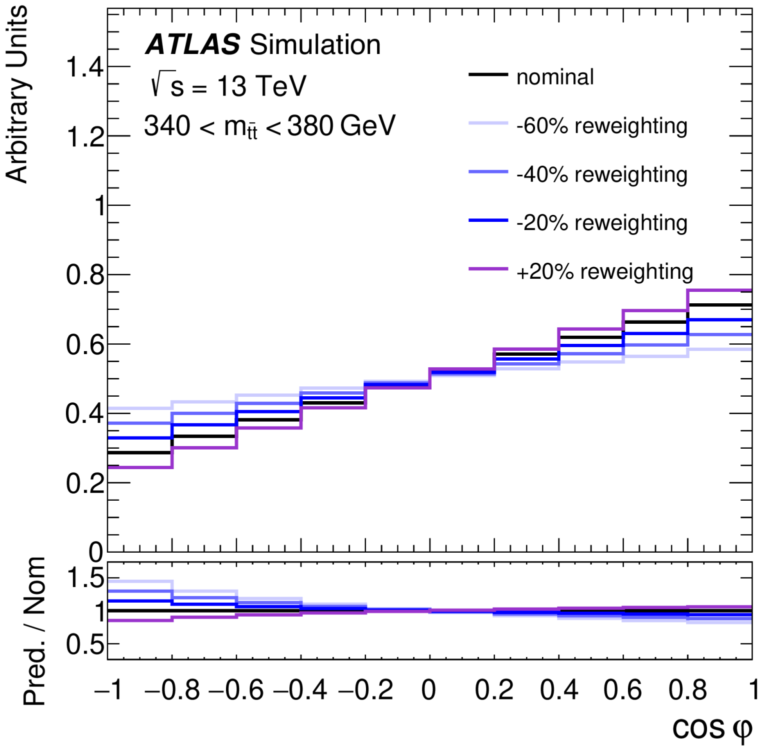
$$D_\Omega(m_{t\bar{t}}) = x_0 + x_1 \cdot m_{t\bar{t}}^{-1} + x_2 \cdot m_{t\bar{t}}^{-2} + x_3 \cdot m_{t\bar{t}}^{-3}$$

- Each event reweighted at parton level to modify D, taking into account $m_{t\bar{t}}$ to preserve linearity of cosφ distribution

$$w = \frac{1 - D_\Omega(m_{t\bar{t}}) \cdot \mathcal{X} \cdot \cos\varphi}{1 - D_\Omega(m_{t\bar{t}}) \cdot \cos\varphi}$$

$$\mathcal{X} = 0.4, 0.6, 0.8, 1.2$$

- Modified parton-level D propagated to particle- and detector level → calibration curves



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- Uncertainty due to signal/background modelling & object reconstruction

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Systematic uncertainties

- Each source of systematic uncertainty results in a different calibration curve

1. Signal modelling → dominant
    - main component: t decay (1.6%)
2. Background modelling: $Z \to \tau\tau$ dominant (0.8%)
    - leads to a flat cosφ distribution
    - spin information from τ is lost
3. Object reconstruction

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%

Source of uncertainty	$\Delta D_{\text{observed}} (D = -0.537)$	ΔD [%]	$\Delta D_{\text{expected}} (D = -0.470)$	ΔD [%]
Signal modeling	0.017	3.2	0.015	3.2
Electrons	0.002	0.4	0.002	0.4
Muons	0.001	0.2	0.001	0.1
Jets	0.004	0.7	0.004	0.8
b-tagging	0.002	0.4	0.002	0.4
Pile-up	< 0.001	< 0.1	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.4	0.002	0.4
Backgrounds	0.005	0.9	0.005	1.1
Total statistical uncertainty	0.002	0.3	0.002	0.4
Total systematic uncertainty	0.019	3.5	0.017	3.6
Total uncertainty	0.019	3.5	0.017	3.6

ATLAS EXPERIMENT

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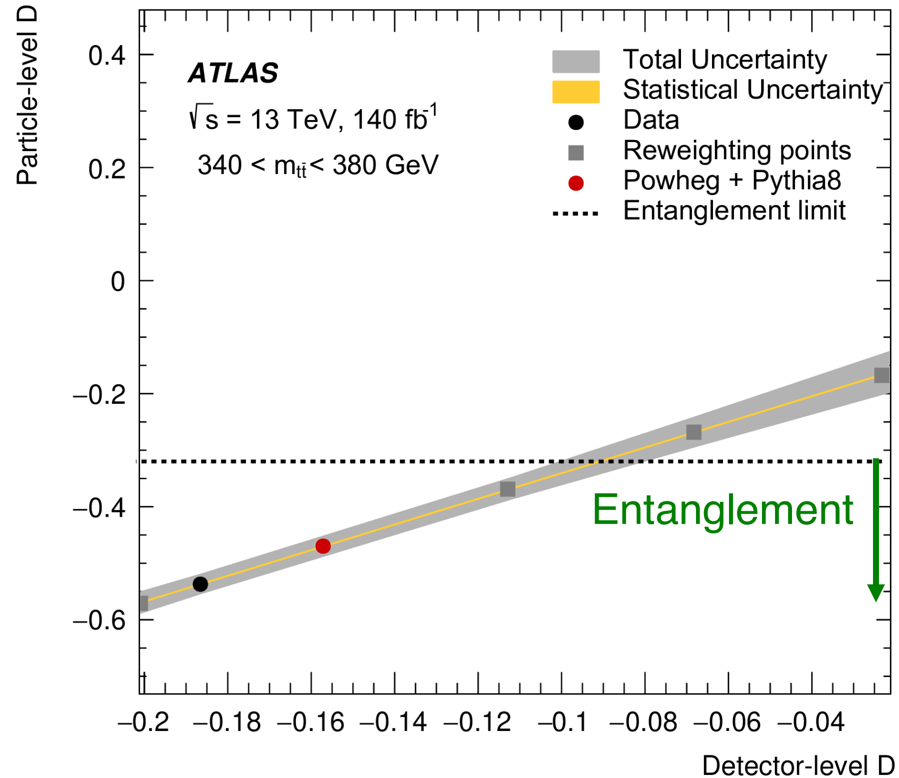

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D in validation regions

- Measured D in validation regions
  - $380 < m_{t\bar{t}} < 500$ GeV

$$D = -0.265 \pm 0.001\,(\text{stat.}) \pm 0.019\,(\text{syst.})$$

  - $m_{t\bar{t}} > 500$ GeV

$$D = -0.093 \pm 0.001\,(\text{stat.}) \pm 0.021\,(\text{syst.})$$

- Good agreement with theoretical predictions

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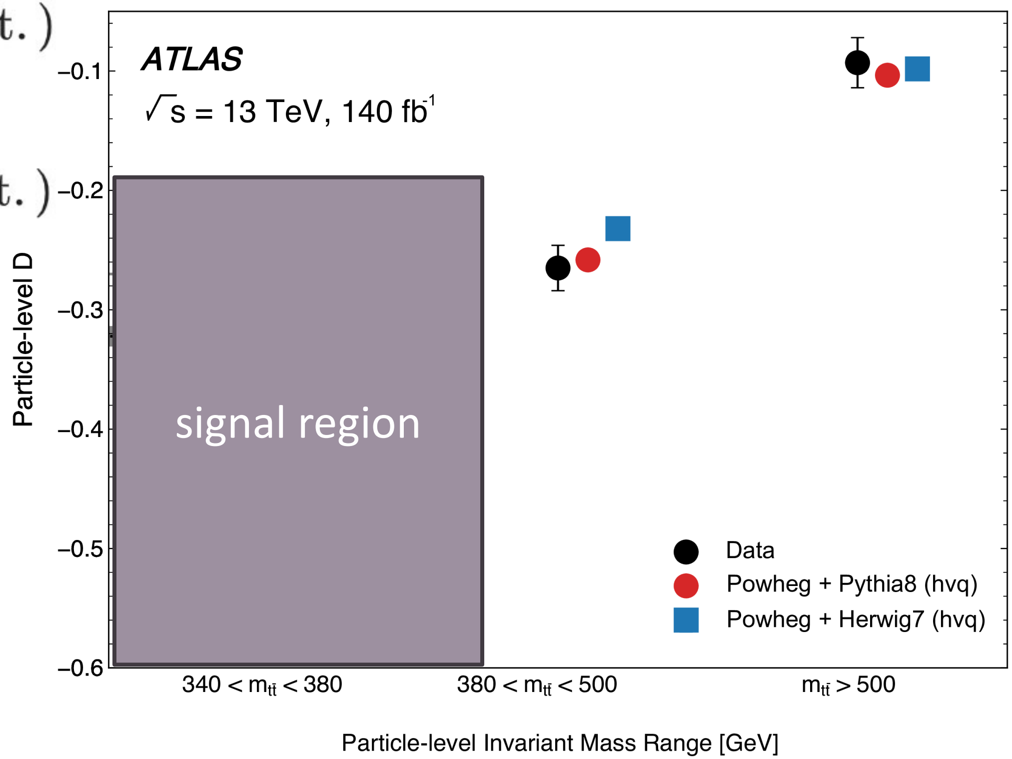

D marker: parton- to particle-level

- Parton-level entanglement limit *D* < −1/3 folded to particle level
- Another calibration curve constructed to relate *D* value of parton- to corresponding particle-level
- Systematic uncertainties related to $t\bar{t}$ production modelling and decay process considered

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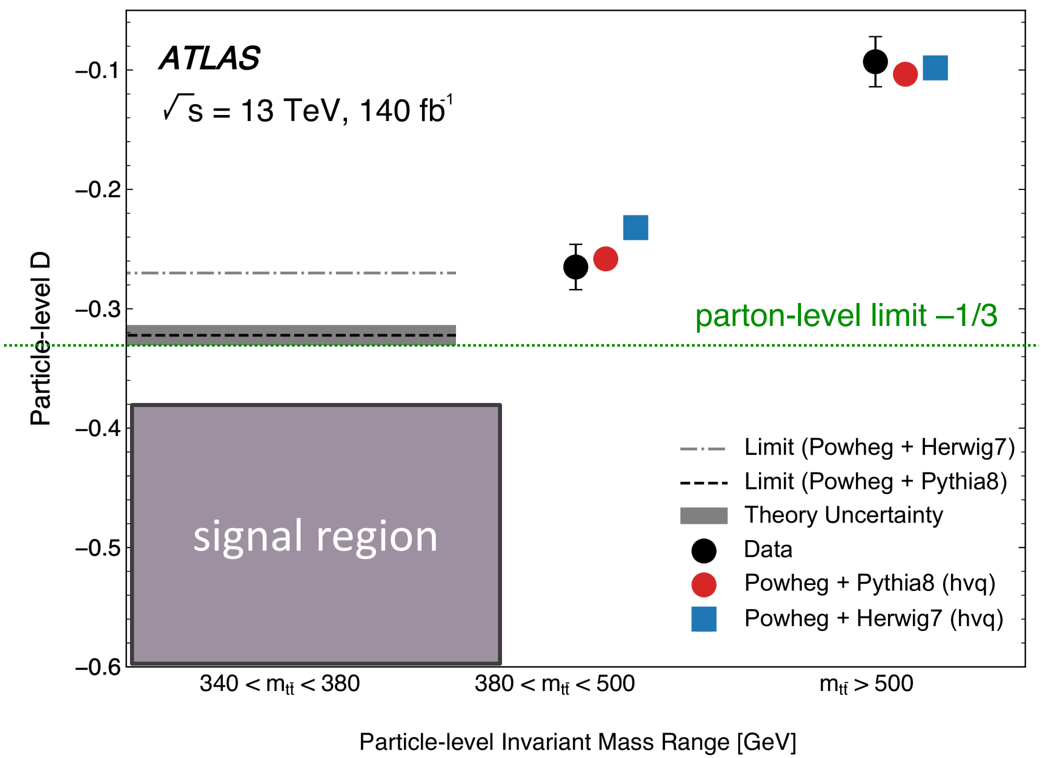

Parton shower and hadronisation effects

- Large difference between Powheg+Pythia 8 and Powheg+Herwig 7 in signal region
  - difference at particle and reconstruction level, while similar at parton level
- Two main differences in models:
  - hadronisation model (Lund-string vs. cluster model)
  - shower ordering (p_T-ordered vs. angular-ordered parton shower) ☚ main cause of differences

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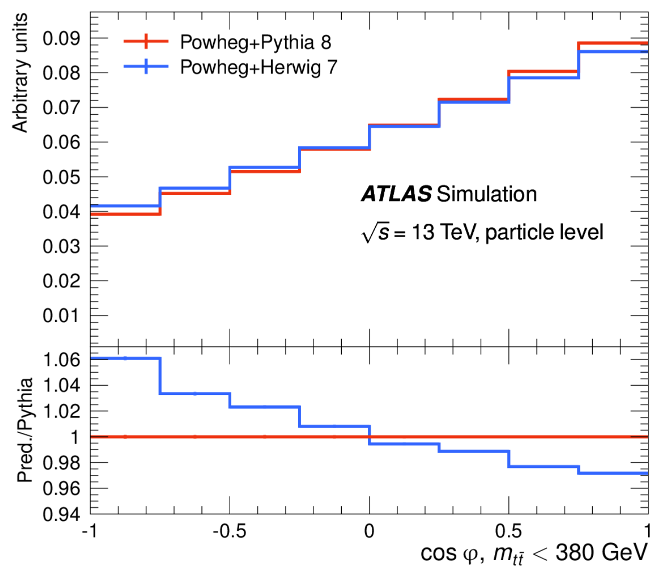
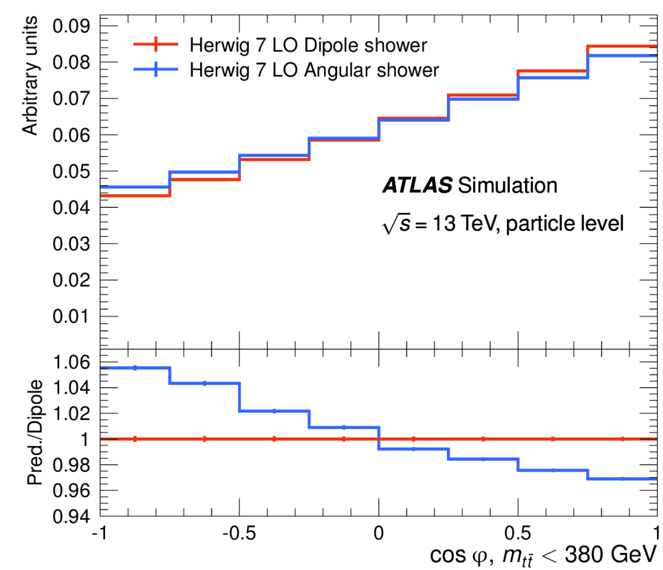
Future higher-precision quantum information measurements would benefit from improved understanding of parton shower mechanisms





D in signal region

- Measured *D* in signal region

$$D = -0.537 \pm 0.002\,(\mathrm{stat.}) \pm 0.019\,(\mathrm{syst.})$$

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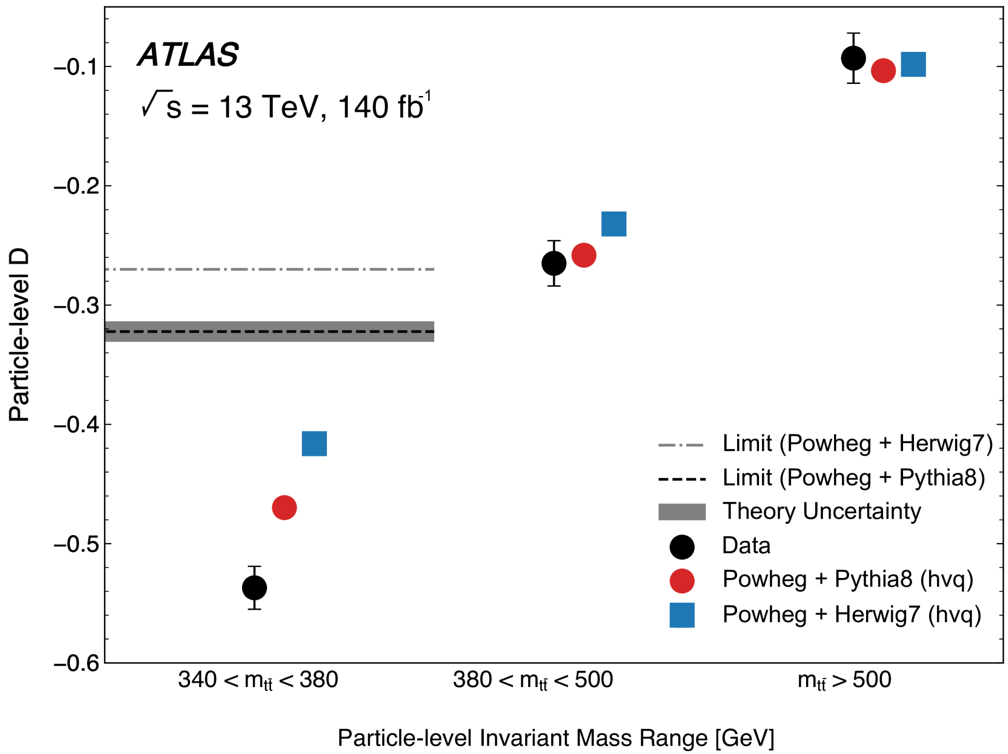
- Measured value significantly ($\gg 5\sigma$) below entanglement limit (–0.322 ± 0.009 for Powheg+Pythia 8)

- **First observation of quantum entanglement**



Outlook

☞ ATLAS Briefing
☞ CERN Courier

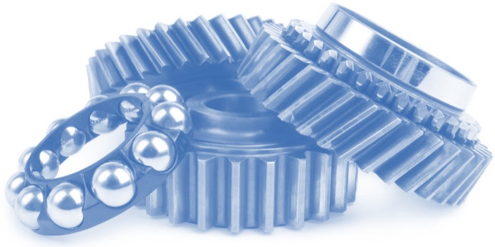
- Entanglement has been observed in a wide spectrum of physical systems
- ATLAS performed first observation of quantum entanglement between a pair of ‘bare’ quarks!
- Simple but robust measurement that already highlights the importance of precise top quark modelling near pair production threshold
- Paves the way for future experimental tests of quantum entanglement, decoherence, and quantum information transfer at LHC

ATLAS EXPERIMENT

Image: Daniel Dominguez/CERN

Thank you for your attention!

Spares



$t\bar{t}$ spin correlation measurements (I)

- Measured $\Delta\Phi(\ell^+,\ell^-)$ differential cross-section compared to NLO Monte Carlo generators and fixed-order calculations at parton level
- Level of correlation assessed by quantifying it in relation to amount of correlation expected in SM, f_{SM}

Run-2
2015-2016
$\sqrt{s}$ = 13 TeV

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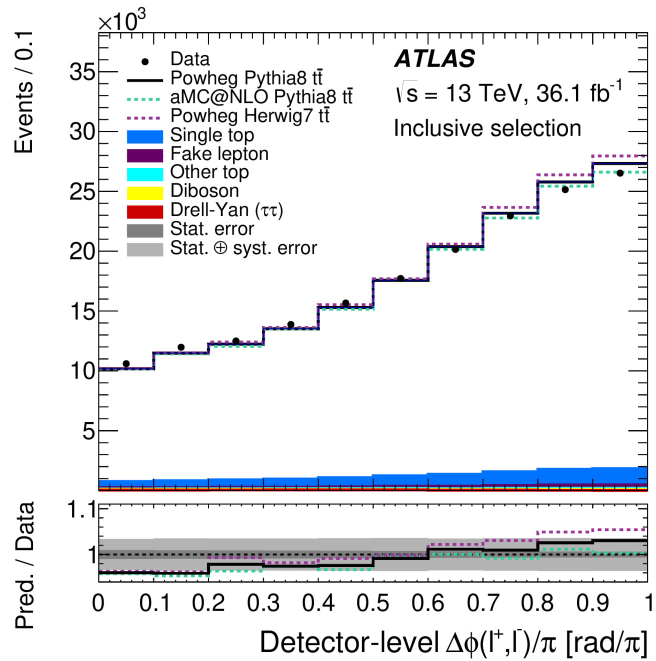
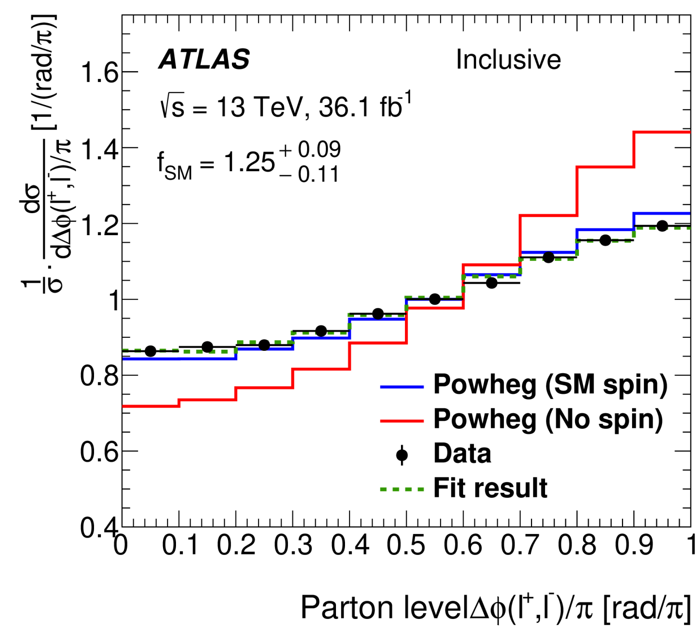
Event selection:

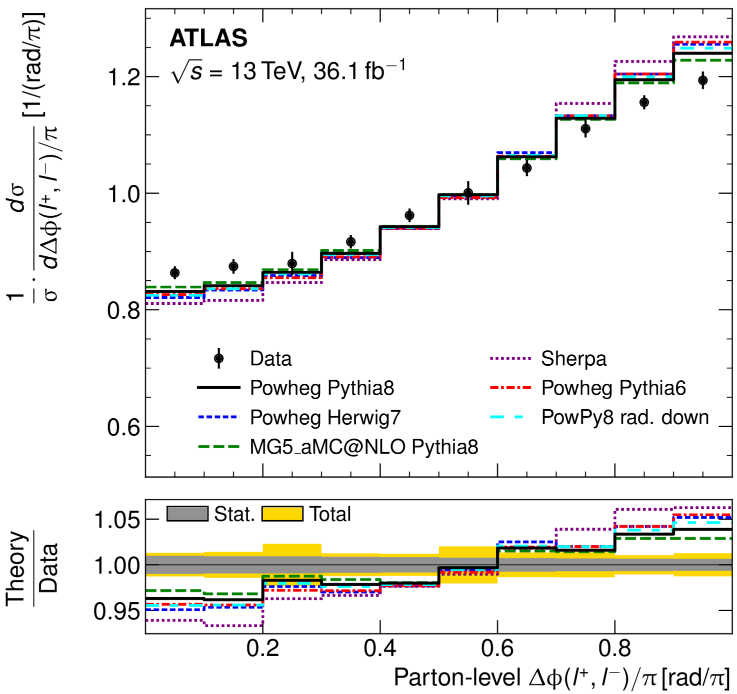
- 1 electron
- 1 muon
- 2 jets (≥ 1 *b*-tagged)





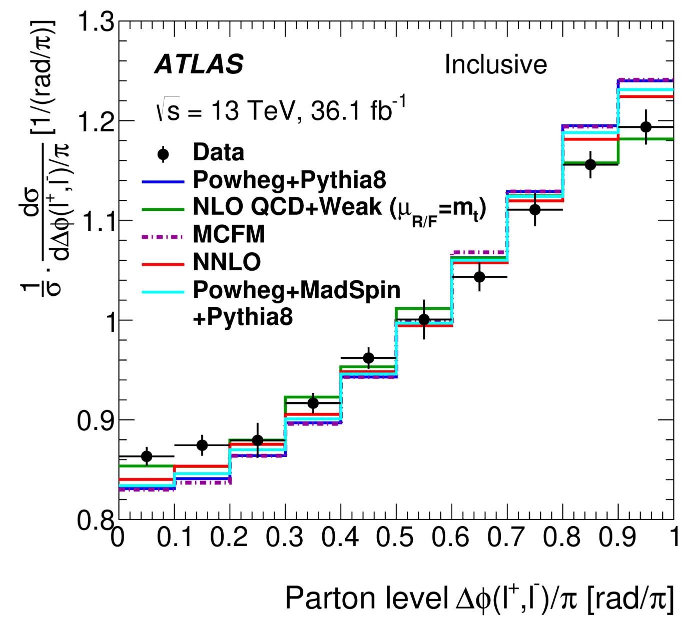
$t\bar{t}$ spin correlation measurements (II)

- Observed spin-correlation degree higher than predicted by generators
- Results compatible with CMS analysis



Significance strongly varies with theory precision

- fixed-order NNLO predictions closer to data but still not fully agree
- d ata agrees well with alternative differential prediction at NLO in QCD+weak



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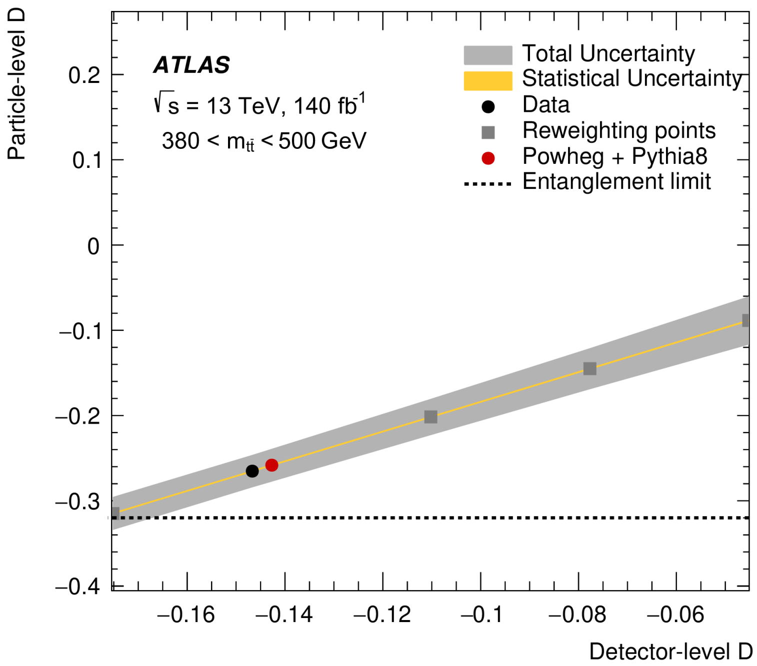
ATLAS
√s = 13 TeV, 140 fb-1
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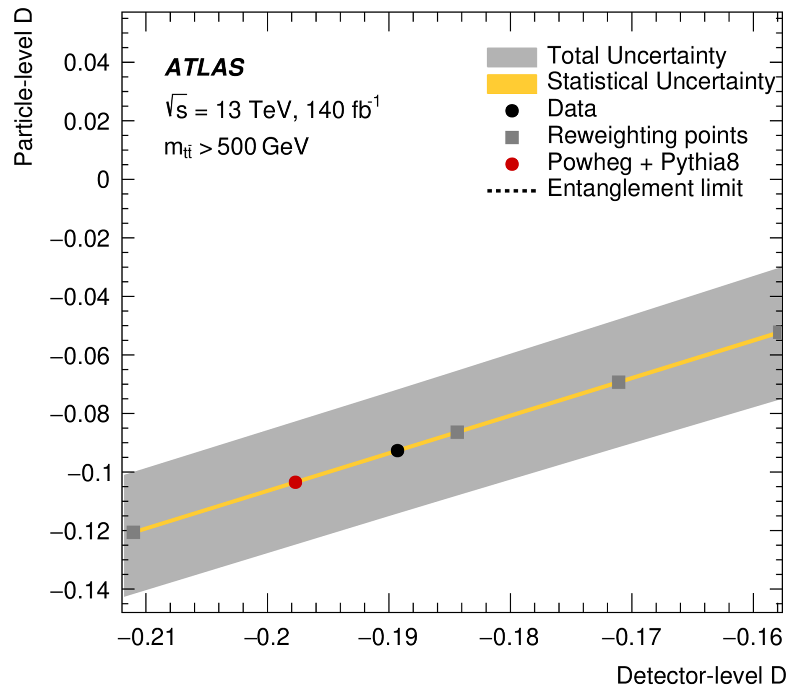
Total Uncertainty
Statistical Uncertainty
Data
Reweighting points
Powheg + Pythia8
Entanglement limit
Particle-level D
Detector-level D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