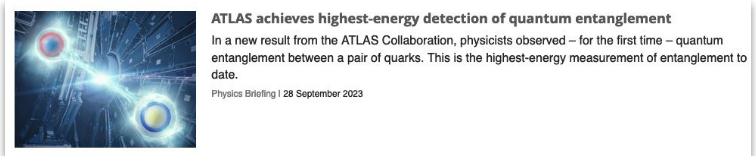
Quantum tops
at the LHC

University of Geneva – DPNC Seminar, 08/10/2025

Baptiste Ravina (CERN)

Outline of the seminar

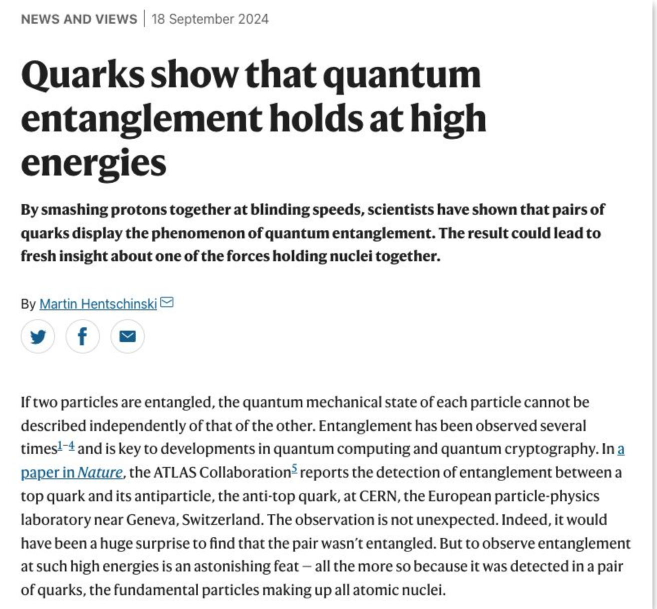
- $t\bar{t}$ production from the point of view of Quantum Information Theory
- Observation of **quantum entanglement** by ATLAS and CMS
- Observation of **toponium** formation?



ATLAS achieves highest-energy detection of quantum entanglement

In a new result from the ATLAS Collaboration, physicists observed – for the first time – quantum entanglement between a pair of quarks. This is the highest-energy measurement of entanglement to date.

Physics Briefing | 28 September 2023



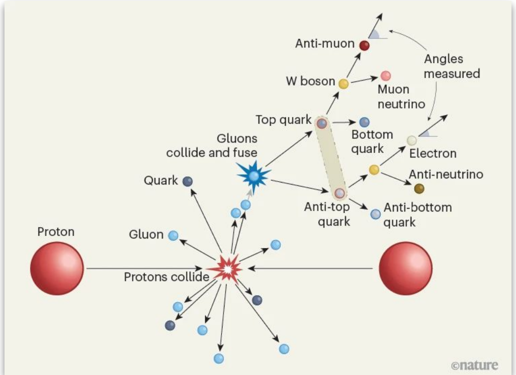
NEWS AND VIEWS | 18 September 2024

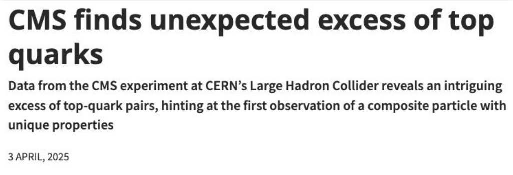
Quarks show that quantum entanglement holds at high energies

By smashing protons together at blinding speeds, scientists have shown that pairs of quarks display the phenomenon of quantum entanglement. The result could lead to fresh insight about one of the forces holding nuclei together.

By Martin Hentschinski

If two particles are entangled, the quantum mechanical state of each particle cannot be described independently of that of the other. Entanglement has been observed several times[1–4] and is key to developments in quantum computing and quantum cryptography. In a paper in *Nature*, the ATLAS Collaboration[5] reports the detection of entanglement between a top quark and its antiparticle, the anti-top quark, at CERN, the European particle-physics laboratory near Geneva, Switzerland. The observation is not unexpected. Indeed, it would have been a huge surprise to find that the pair wasn't entangled. But to observe entanglement at such high energies is an astonishing feat – all the more so because it was detected in a pair of quarks, the fundamental particles making up all atomic nuclei.

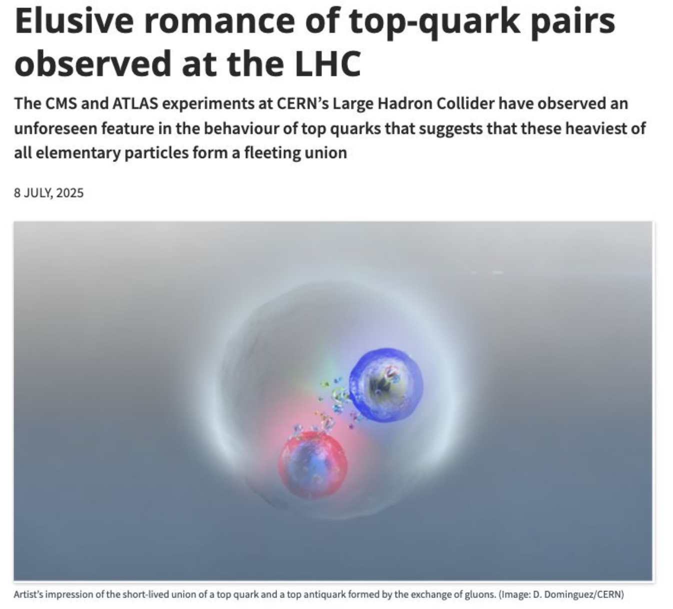




CMS finds unexpected excess of top quarks

Data from the CMS experiment at CERN's Large Hadron Collider reveals an intriguing excess of top-quark pairs, hinting at the first observation of a composite particle with unique properties

3 APRIL, 2025



Elusive romance of top-quark pairs observed at the LHC

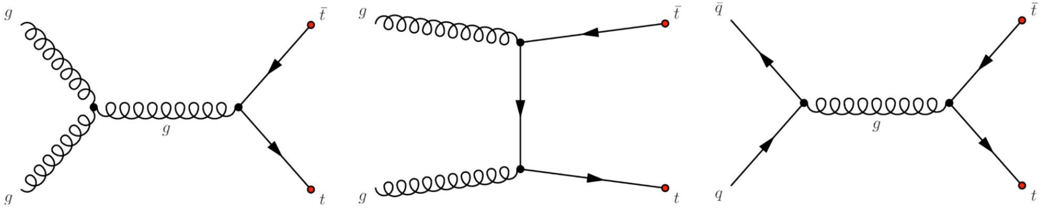
The CMS and ATLAS experiments at CERN's Large Hadron Collider have observed an unforeseen feature in the behaviour of top quarks that suggests that these heaviest of all elementary particles form a fleeting union

8 JULY, 2025

Artist's impression of the short-lived union of a top quark and a top antiquark formed by the exchange of gluons. (Image: D. Dominguez/CERN)

Starting with top quark physics…

Fundamentals of top quark physics



- Most massive fundamental particle in the SM

→ its Mass / Yukawa is a free parameter: need to measure it

- Mean lifetime ~5x10^{-25}s << 1/Λ$_{QCD}$ ~10^{-23}s

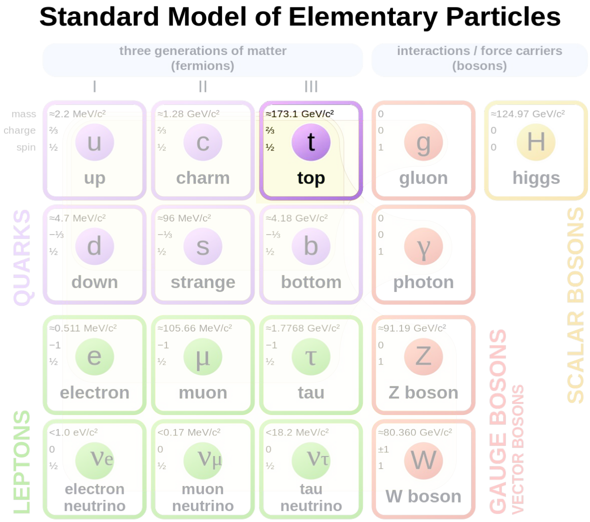
→ the only “bare quark”

- BR(t→Wb) ~ 100%

→ unique experimental signature

- Abundant production at the LHC, O(100M) pairs

→ **“standard candle”**, very useful for calibrations



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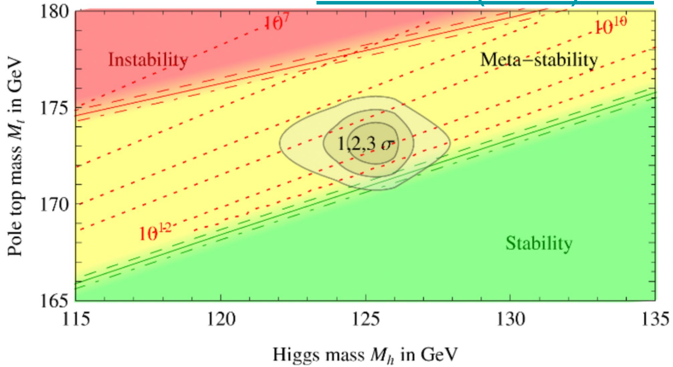
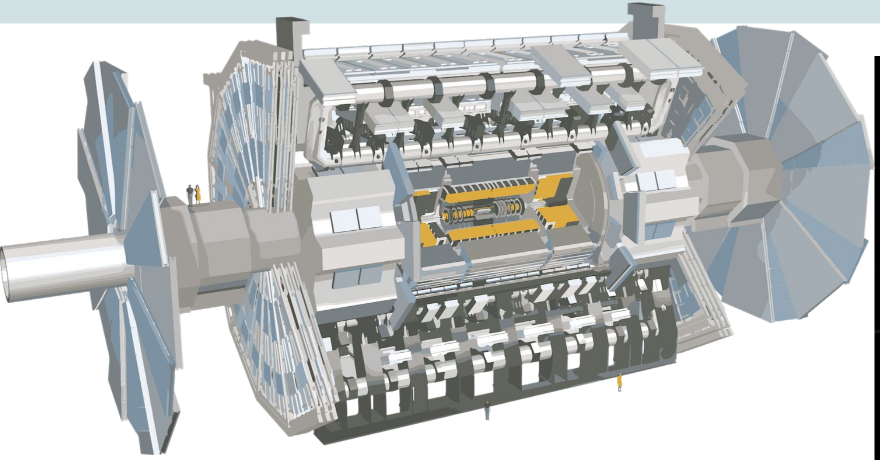
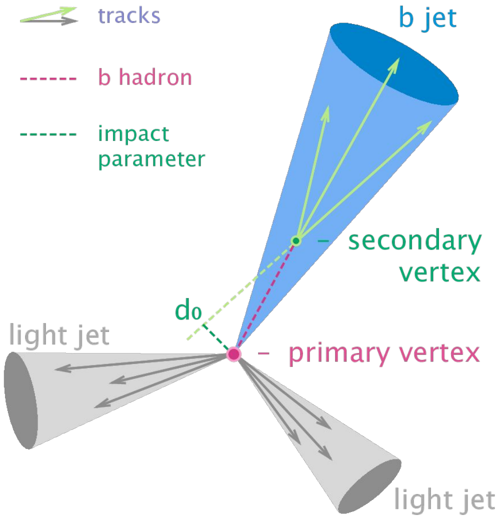
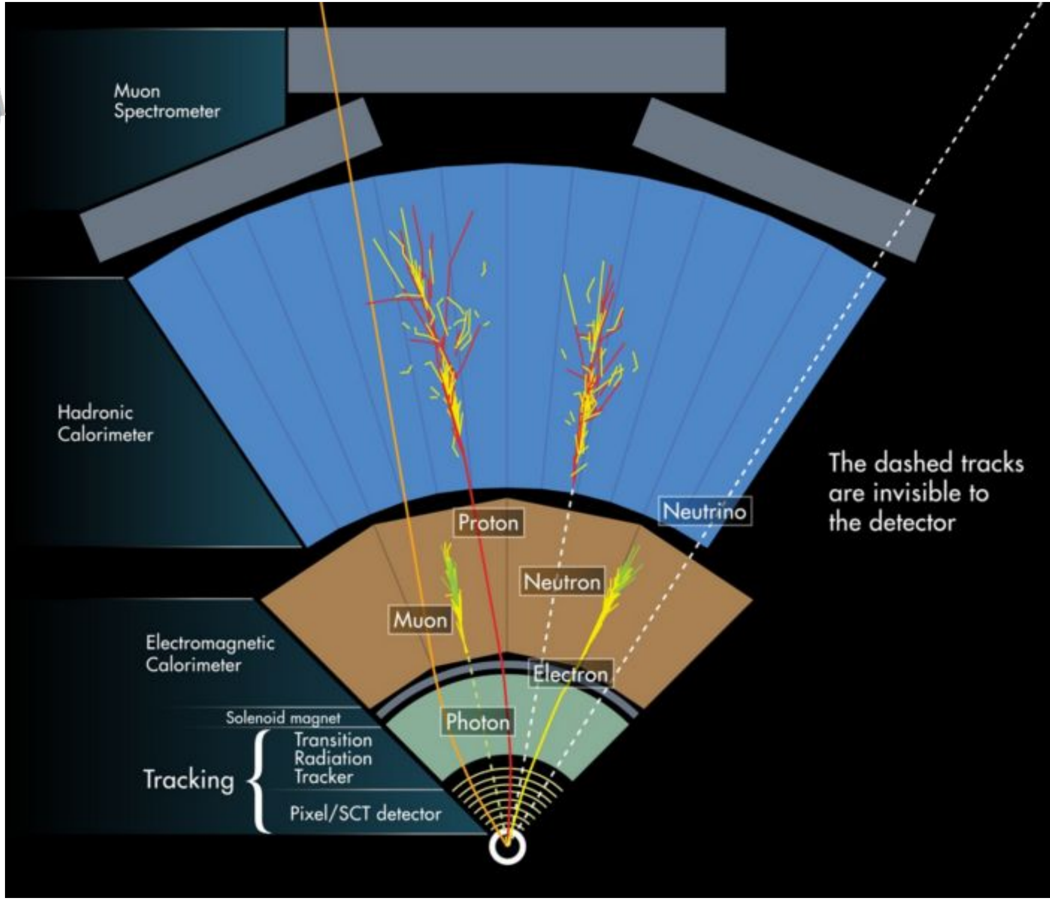


Particle identification at ATLAS in one slide







The dashed tracks are invisible to the detector

A long way to the top…

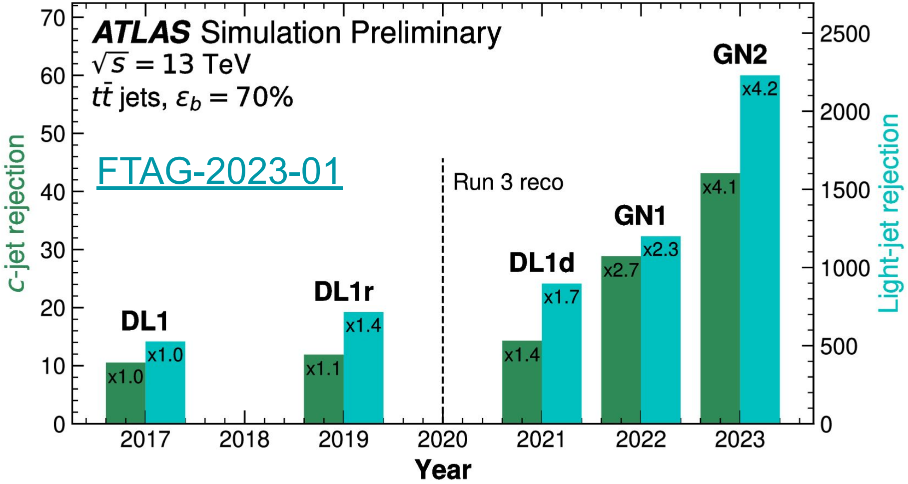
👉 CMS results
👉 ATLAS results

30 years of top quark physics!

Ever more precise measurements enabled by excellent collider and detector performance

Benefit from all areas of Combined Performance:

- jets & missing energy
- flavour tagging
- lepton ID & isolation
- luminosity
- …



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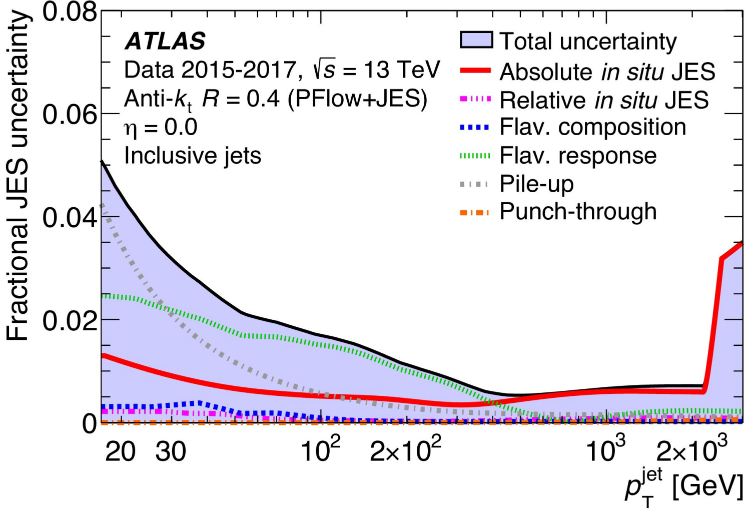
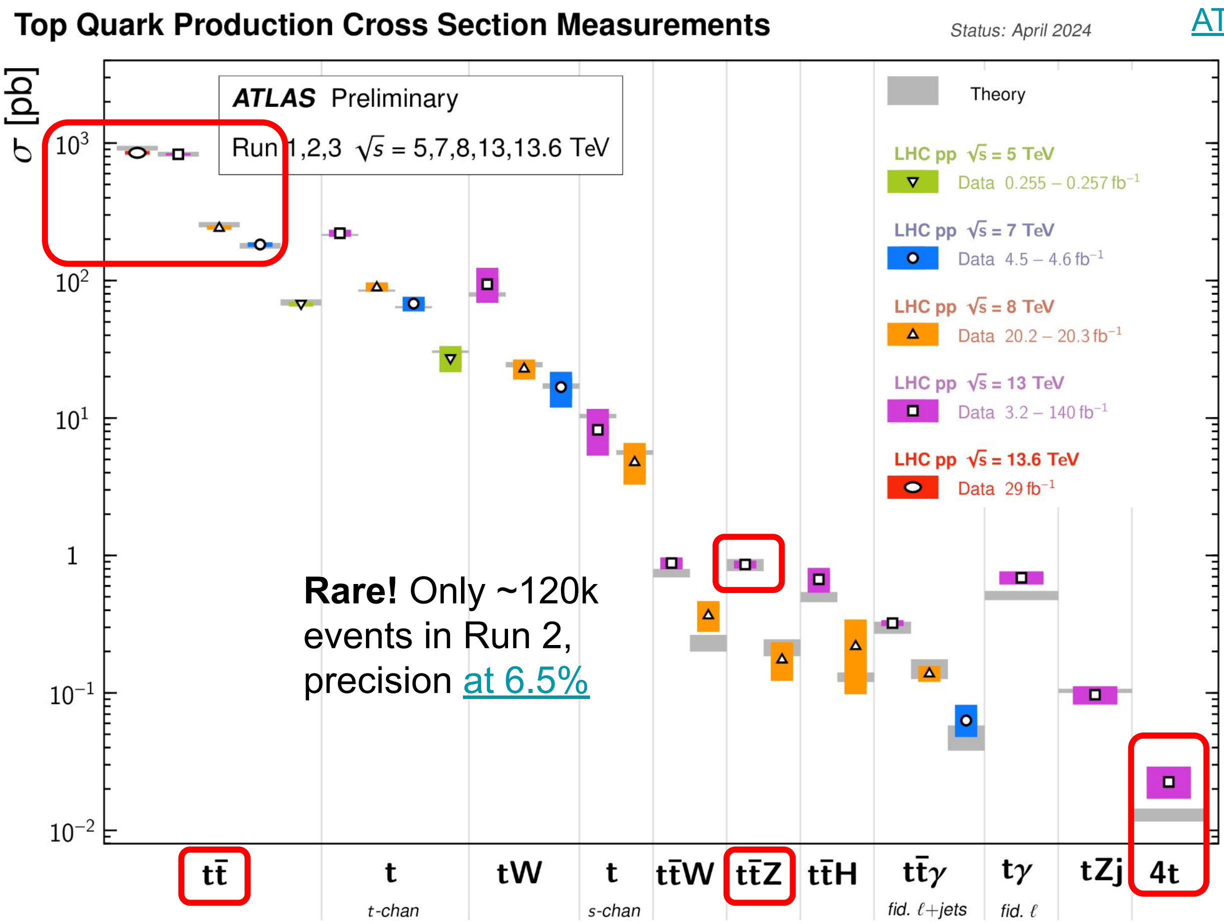
Eur. Phys. J. C 81 (2021) 689



The range of top quark physics

Abundant production!

O(100M) events in Run 2
Precision down to 1.3%


Top Quark Production Cross Section Measurements
Status: April 2024

ATL-PHYS-PUB-2024-006

Rare! Only ~120k events in Run 2, precision at 6.5%

Extremely challenging! Only ~3k events, precision ~25%

Prelude: top quark spin correlations

The top quark has a mean lifetime ~5x10^{-25}s << $1/\Lambda_{QCD}$ ~10^{-23}s

→ **spin information is correlated and transferred** to decay products

BR(t→Wb)~100% + weak interaction is maximally parity-violating

→ **correlations are observable!**

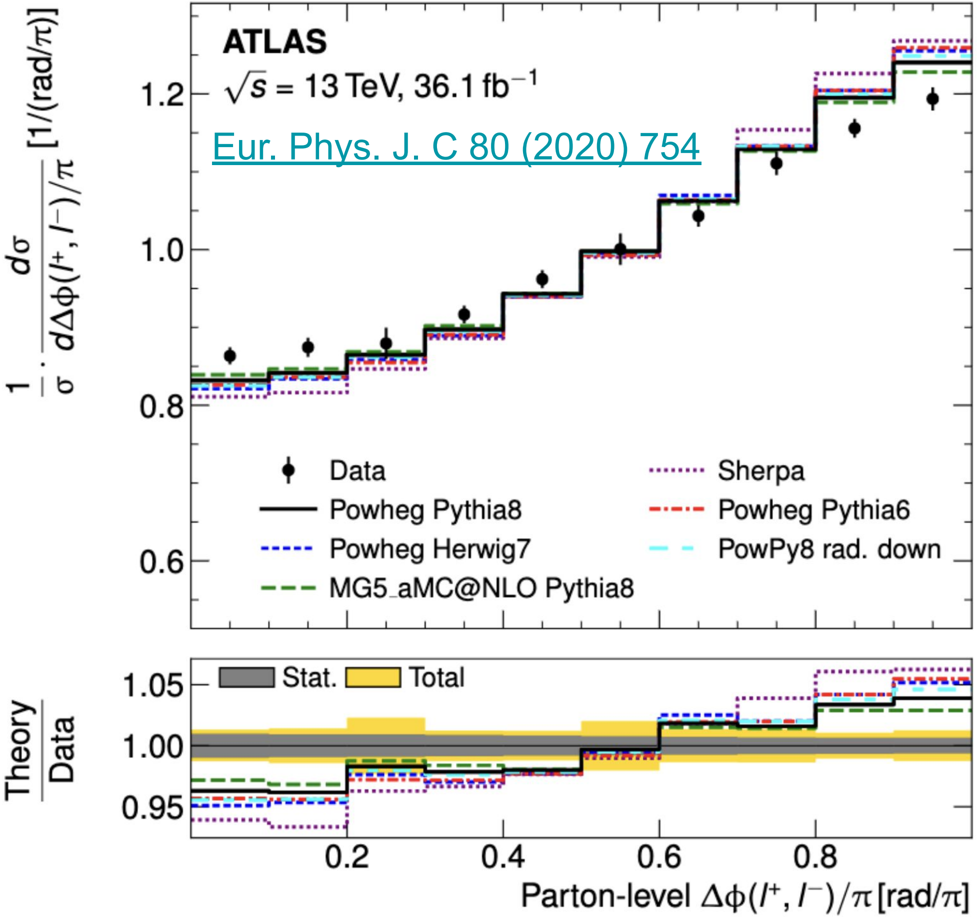
$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

top polarisations (3+3) ✚ spin correlations (3x3)

= full spin density matrix (15 elements)

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

State-of-the-art in 2020…



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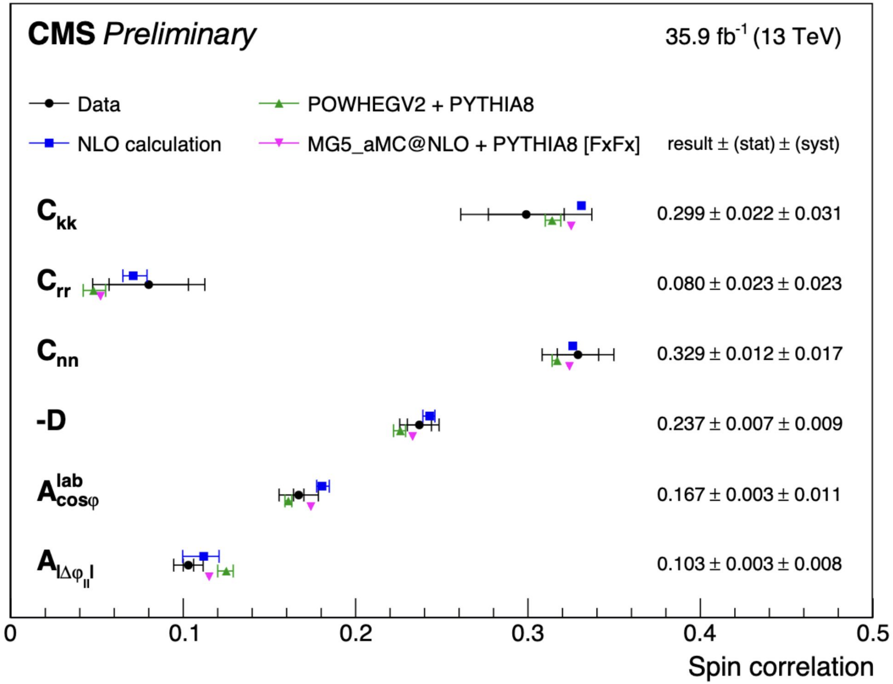
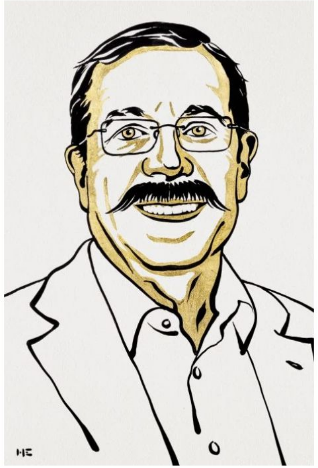
Spin correlations in $t\bar{t}$ are well-established



Phys. Rev. D 100 (2019) 072002

As you may have heard...



Ill. Niklas Elmehed © Nobel Prize Outreach

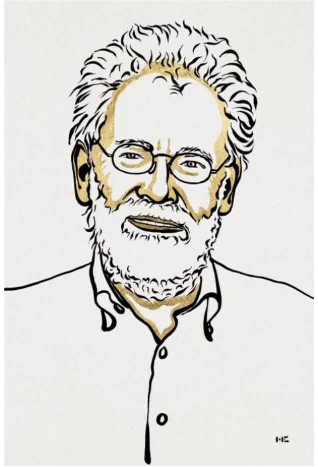
Alain Aspect

Prize share: 1/3

Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

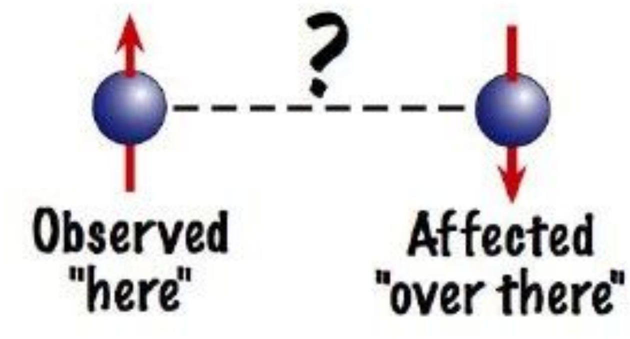


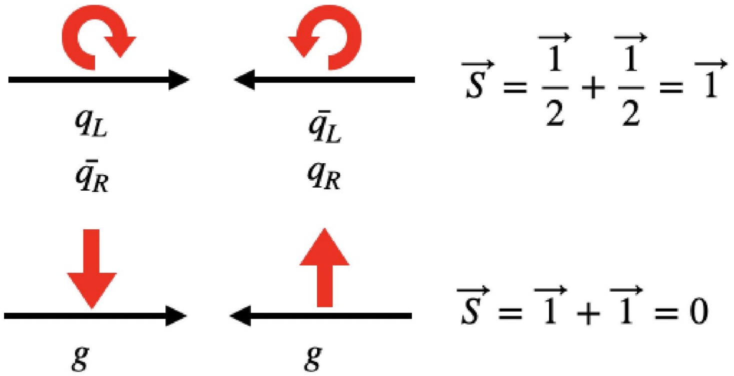
Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science"





$$\vec{S} = \vec{\frac{1}{2}} + \vec{\frac{1}{2}} = \vec{1}$$

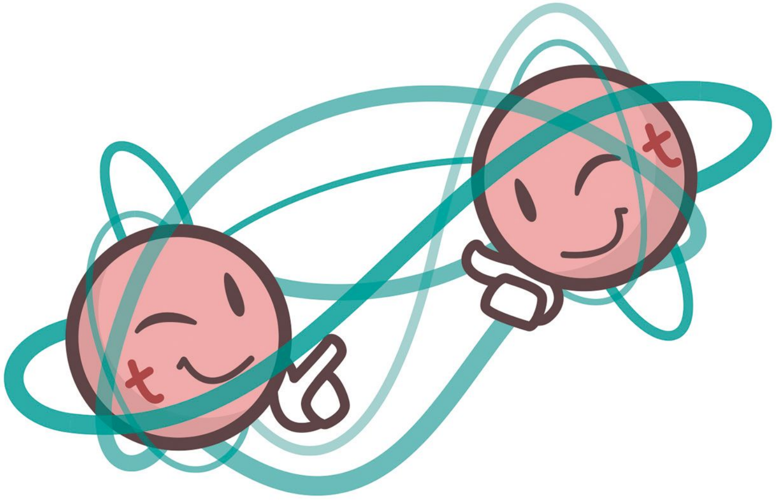
$$\vec{S} = \vec{1} + \vec{1} = 0$$

gg→tt̄: spin-singlet state at threshold
(Landau-Yang suppression of spin-triplet)

The change in paradigm

EPJC (2021) 136:907

(March 2020)
first analysis of top quark pair production
from the quantum information point of view:
“**bipartite qubit system**”



Eur. Phys. J. Plus (2021) 136:907
https://doi.org/10.1140/epjp/s13360-021-01902-1

THE EUROPEAN PHYSICAL JOURNAL PLUS

Regular Article

Entanglement and quantum tomography with top quarks at the LHC

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Abstract Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top–antitop–quark pairs at the LHC, representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top–antitop pair. The detection can be achieved with high statistical significance, using the current data recorded during Run 2 at the LHC. In addition, we develop a simple protocol for the quantum tomography of the top–antitop pair. This experimental technique reconstructs the quantum state of the system, providing a new experimental tool to test theoretical predictions. Our work explicitly implements canonical experimental techniques in quantum information in a two-qubit high-energy system, paving the way to use high-energy colliders to also study quantum information aspects.

Criteria for quantum entanglement

EPJC (2021) 136:907

A **separable state** is of the form $\rho = \sum_n p_n \rho_n^a \otimes \rho_n^b, \ \sum_n p_n = 1, \ p_n \geq 0$

An **entangled state** is one that is non-separable. [classical ⇔ separable, but quantum ⇎ non-separable]

$$\rho = \frac{I_4 + \sum_i \left(\cancelto{0}{B_i^+} \sigma^i \otimes I_2 + \cancelto{0}{B_i^-} I_2 \otimes \sigma^i\right) + \sum_{i,j} \boxed{C_{ij}} \sigma^i \otimes \sigma^j}{4}$$

1. Well-known QI result $\operatorname{Tr}\left[\mathbb{C}\right] < -1$ *Peres-Horodecki criterion for quantum entanglement*

2. Well-known HEP result $\frac{1}{\sigma} \frac{\mathrm{d}\sigma}{\mathrm{d}\cos\varphi} = \frac{1}{2}\left(1 - D\cos\varphi\right)$ *a simple angular observable*

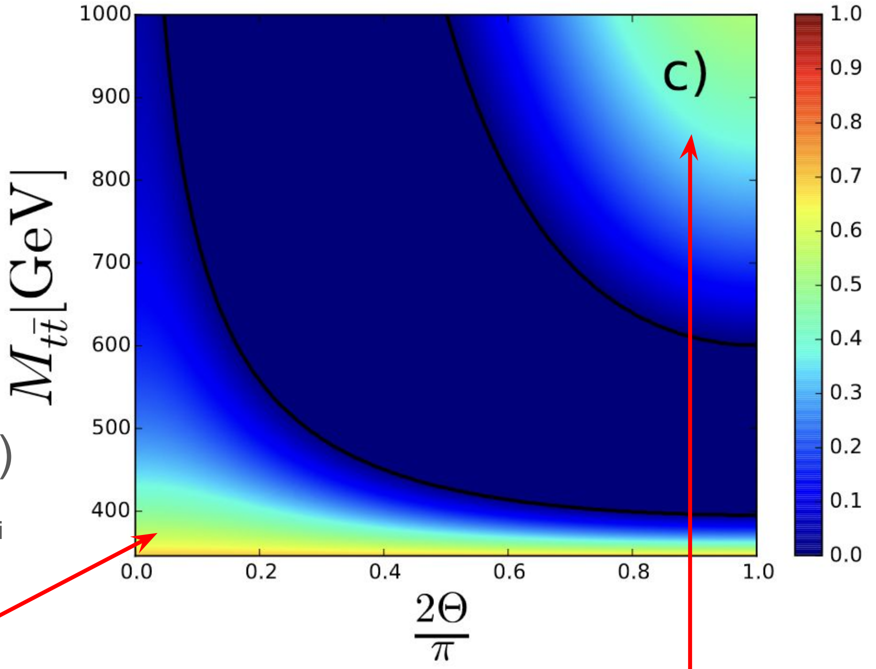
∴ 3. LHC as a QI lab $D = \frac{\operatorname{Tr}\left[\mathbb{C}\right]}{3} \Rightarrow D < -\frac{1}{3}$ *a quantum entanglement marker!*

Spin configurations and phase-space

The 4 Bell states form a maximally entangled basis:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(\,|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\,\big),$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(\,|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\,\big).$$

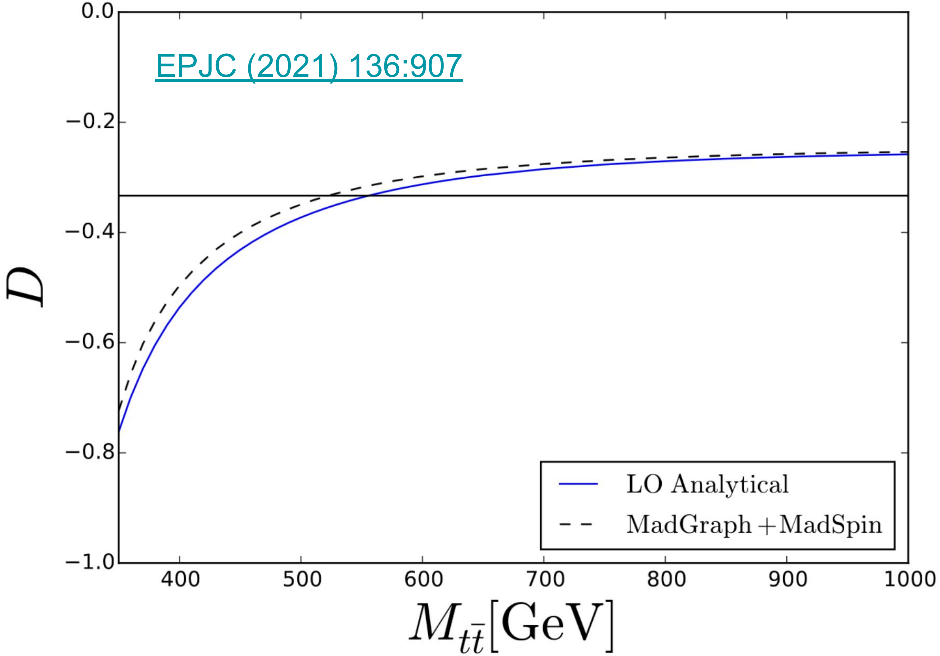


- At low M($t\bar{t}$): pseudo-scalar state Ψ^-
  - this is also what toponium looks like!
- At high M($t\bar{t}$): triplet vector-state ($\Phi^+ \pm \Phi^-, \Psi^+$)
  - we get a sign-flip in the spin correlation matrix C_{ii}
  - D is no longer an optimal observable!
  - introduce D_3 which corrects for the sign-flip

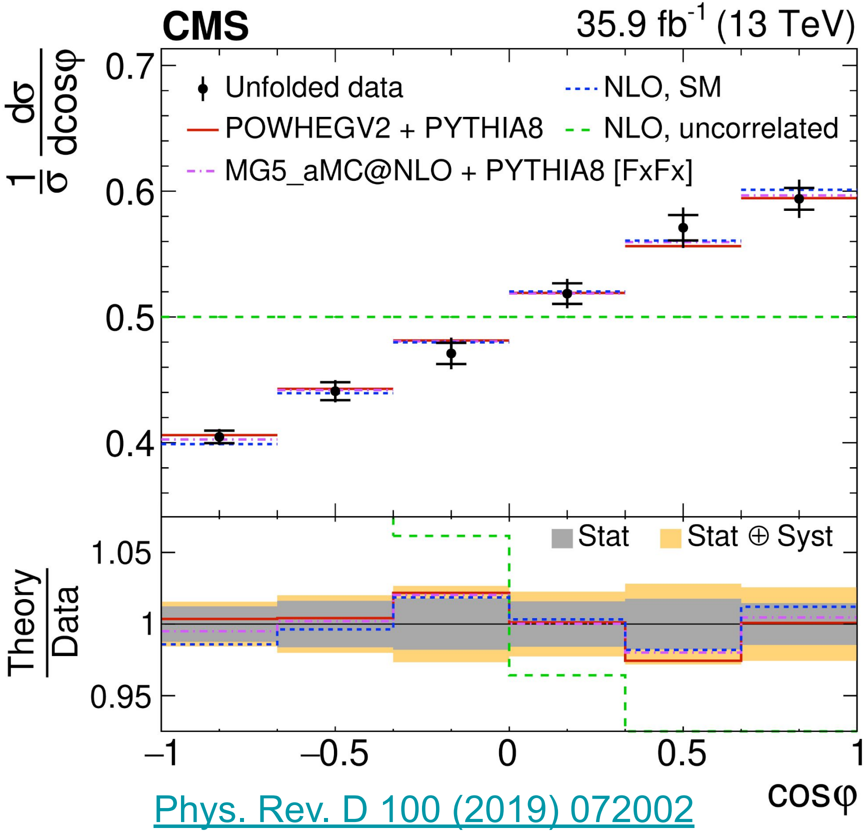
$$C_{kk} + C_{rr} + C_{nn} \equiv 3D$$

$$C_{kk} + C_{rr} - C_{nn} \equiv 3D_3$$

So... had CMS observed quantum entanglement in 2019 ?



EPJC (2021) 136:907



Phys. Rev. D 100 (2019) 072002

CMS measured $D = -0.237 \pm 0.011 > -\frac{1}{3}$

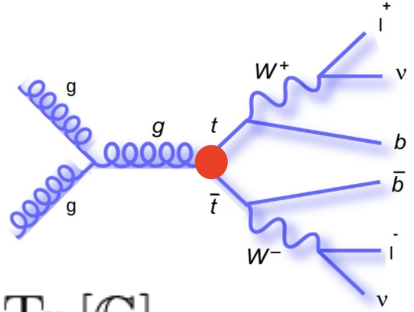
inclusively → need to go differential in $M(t\bar{t})$

Observation of quantum entanglement

Quantum entanglement in dilepton $t\bar{t}$

Nature 633 (2024) 542

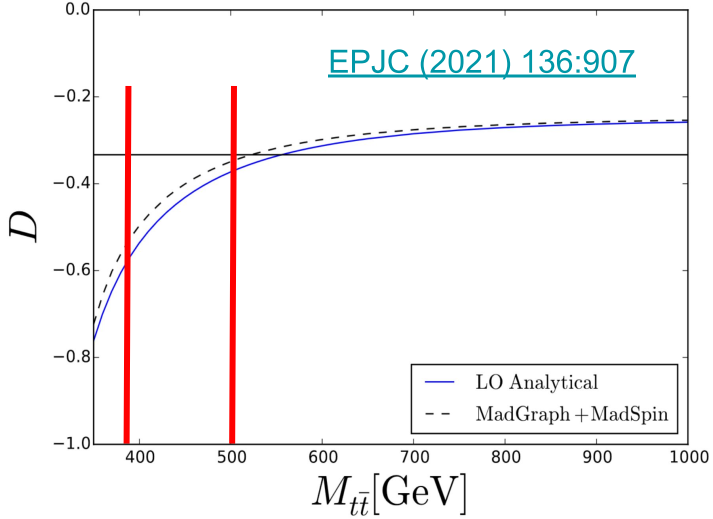
Dilepton eμ final state is very clean (90% purity) and at the end of Run 2 we have about a million events after preselection.



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

Then partition events into three selections:

- **340<M$_{tt}$<380: entanglement signal region**
- 380<M$_{tt}$<500: validation region
  (dilution from mis-reconstruction)
- **500<M$_{tt}$: no-entanglement** validation region


EPJC (2021) 136:907

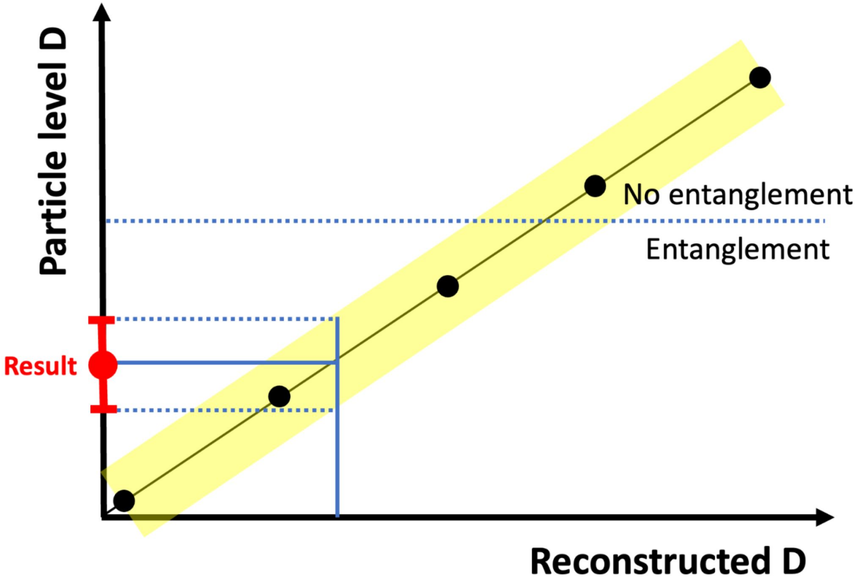
The mass cuts are crucial!

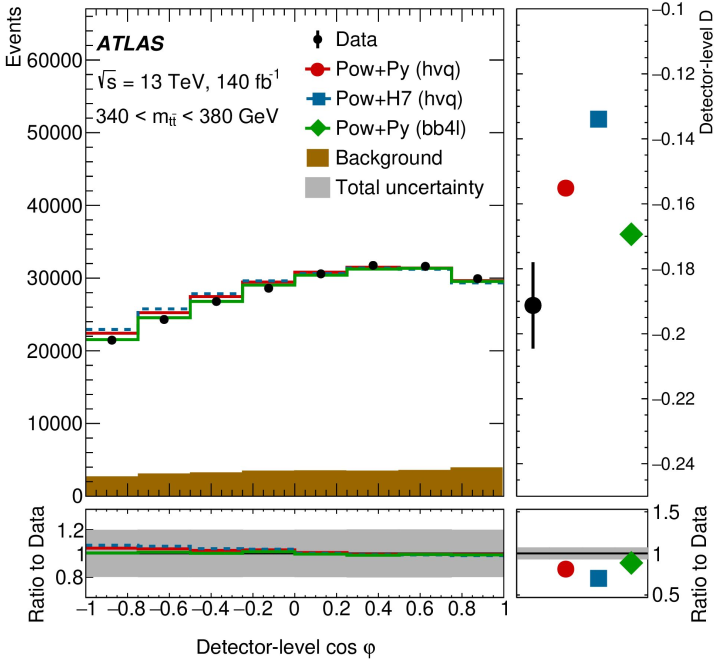
Analysis procedure

"Calibration curve" method: use the nominal MC to map the detector-level D value (average of distribution) to the fiducial particle-level D.

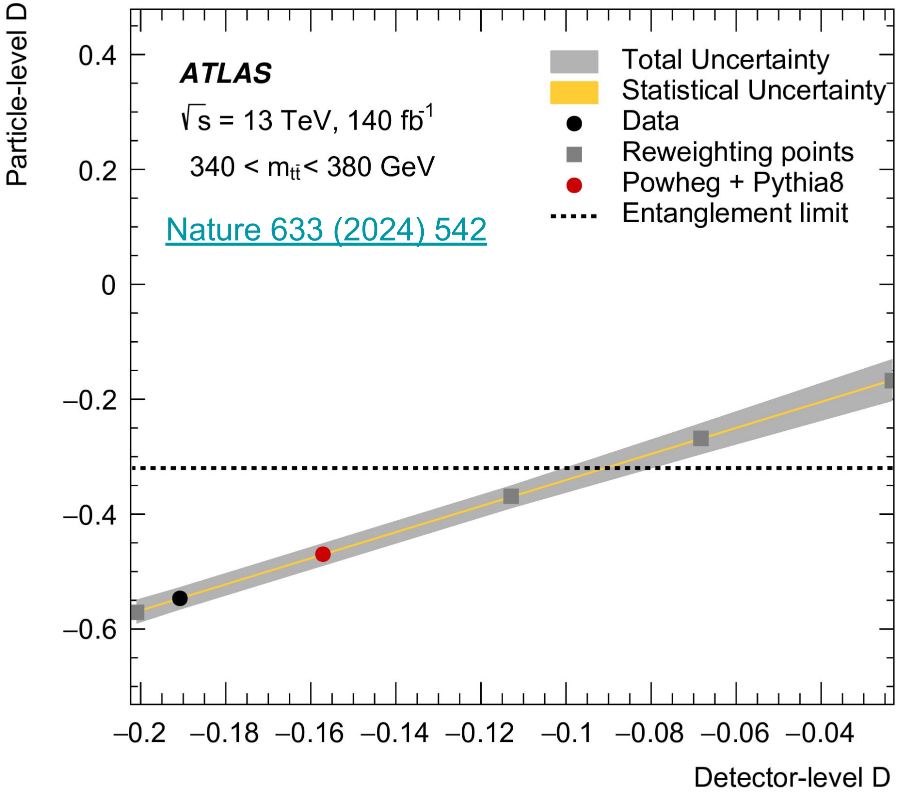
Systematics are propagated with their own curves, quadratic envelope.

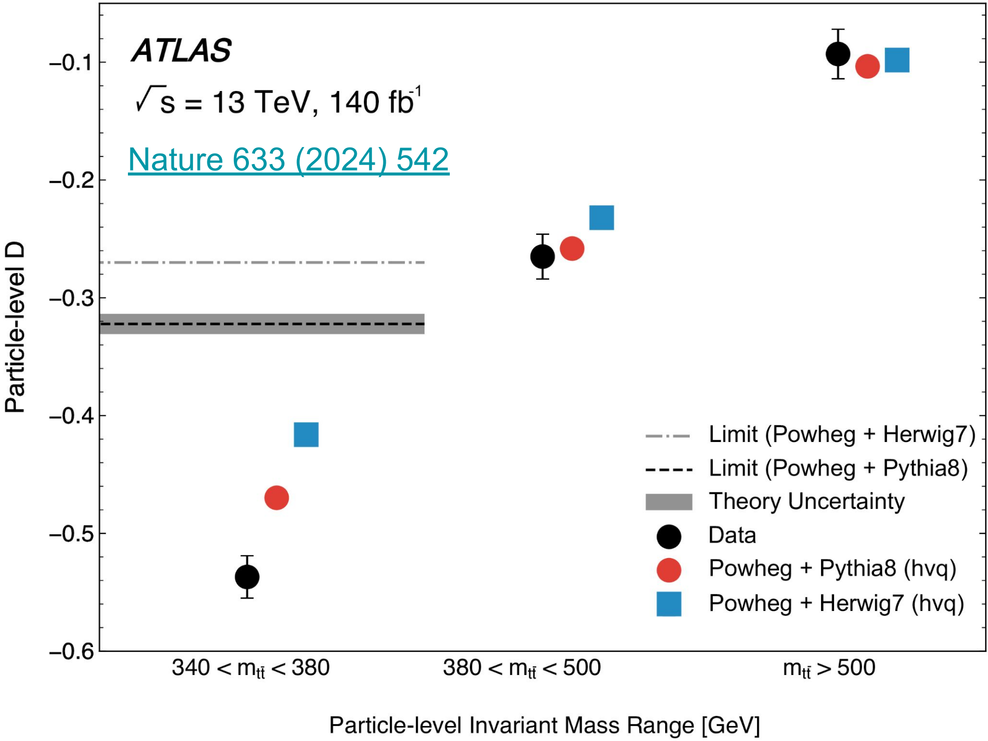
→ Build the curve by sampling different D values.





Observation of quantum entanglement in dilepton $t\bar{t}$





non-relativistic QCD effects close to threshold, not included in MC generators → would only affect predictions, not calibration

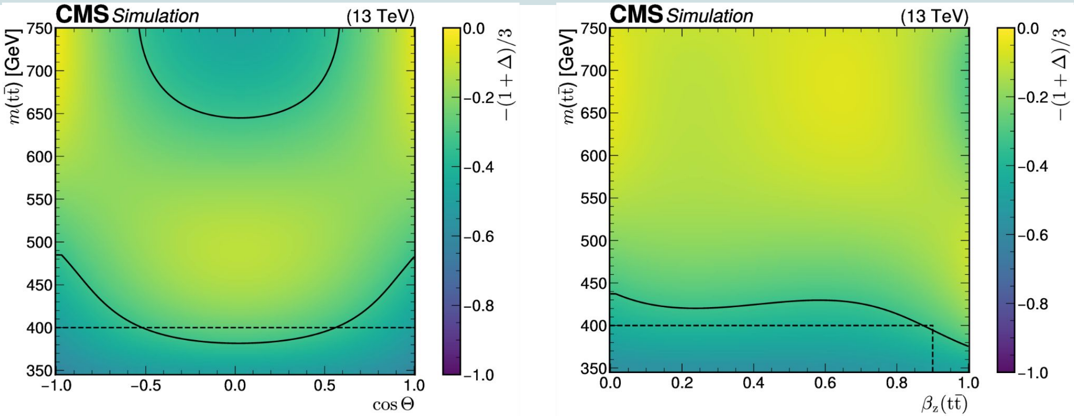
expected: D = -0.470 ± 0.002 (stat.) ± 0.017 (syst.)

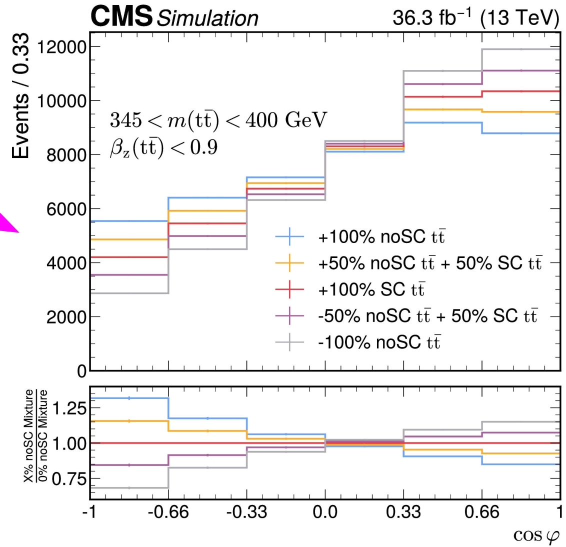
D = -0.537 ± 0.002 (stat.) ± 0.019 (syst.)

Different analysis strategy for CMS

Rep. Prog. Phys. 87 (2024) 117801

- Signal region: **345-400 GeV window in M(tt̄)**
- Cut on tt̄ velocity (β<0.9) to enrich sample in gg→tt̄
- Consider ee+μμ+eμ events, but only 2016 data
- Mix spin-on and spin-off samples to get different predictions for D
- Profile-likelihood fit at detector-level
- **Toponium**: spin-0 colour-singlet pseudo-scalar modelled in MadGraph+Pythia 8
  - $M(\eta_t)$ = 343 GeV (337-349 GeV)
  - $\Gamma(\eta_t)$ = 7 GeV
  - $\sigma(\eta_t)$ = 6.43 pb





Another observation of quantum entanglement

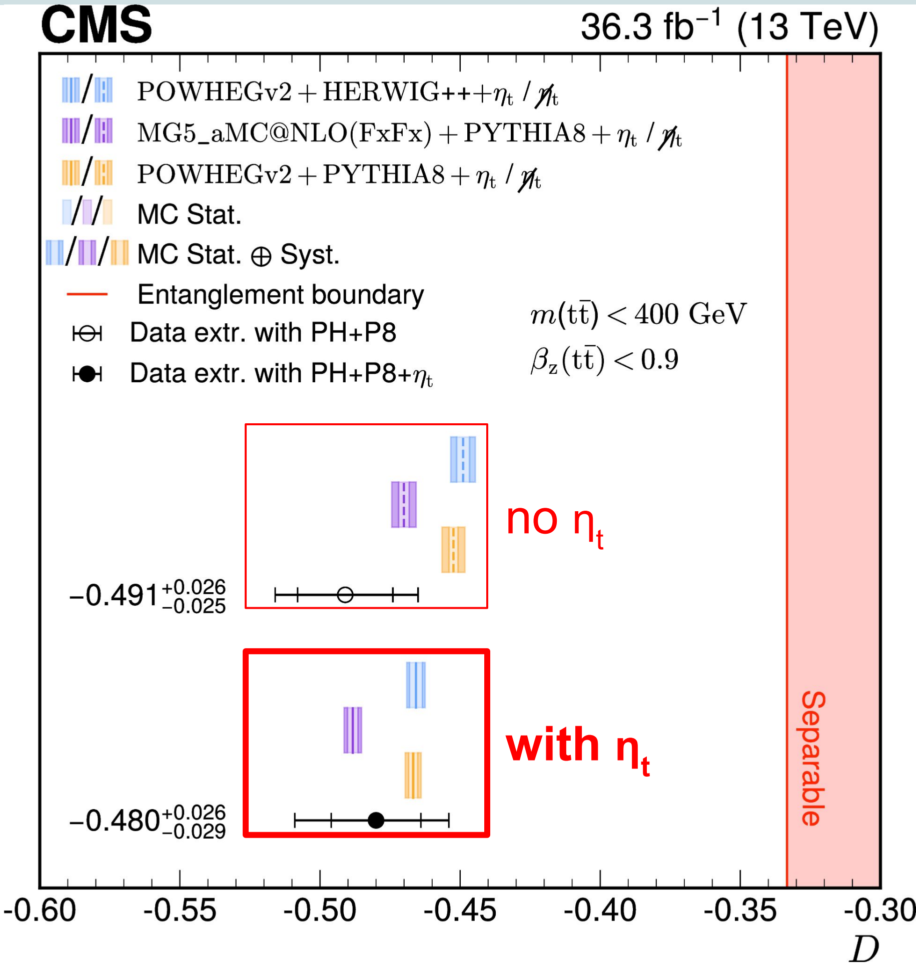
Rep. Prog. Phys. 87 (2024) 117801

5.1σ observed (4.7σ expected)

Toponium 50% normalisation uncertainty
+ vary binding energy ±0.5 GeV

D = -0.480 ± 0.017 (stat.) ± 0.023 (syst.)

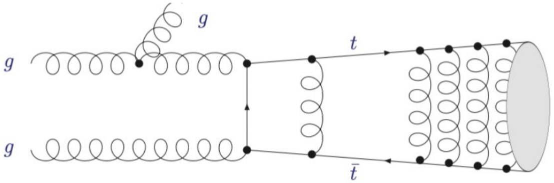
Source	Uncertainty *D*
JES	10.1%
Toponium normalization	10.1%
Parton Shower (ISR)	6.3%
Scale	1.8%
Parton Shower (FSR)	1.2%
JER	0.9%
Z+jets shape	0.8%
b quark fragmentation	0.4%
$t\bar{t}$ normalization	0.3%
PDF	0.3%

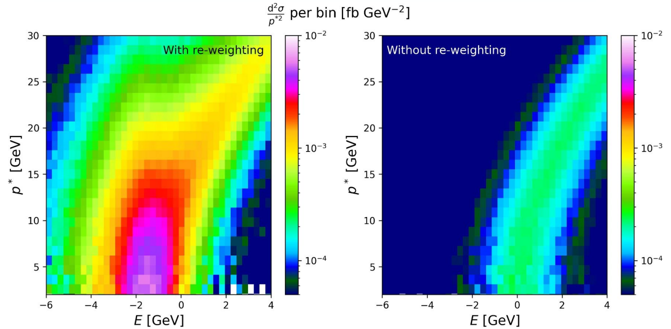


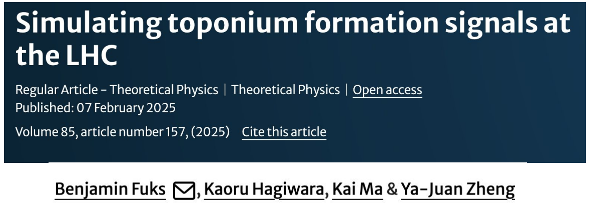
Toponium: bound to be discovered?

What is toponium?

- Standard Model predicts a **quasi-bound** **state below the tt̄ threshold**
  - “*toponia*” were not expected to be visible at the LHC! → dedicated threshold scan at FCC-ee
  - Coulomb potential with gluon and soft-gluon emissions between the tops ~ $(\alpha_S/\beta)^n$
  - can be computed in potential non-relativistic QCD (**NR-QCD**) at next-to-leading power in β
- It behaves dominantly like a pseudoscalar [important for spin correlations!] but crucially is NOT an s-channel resonance [no destructive interference terms!]







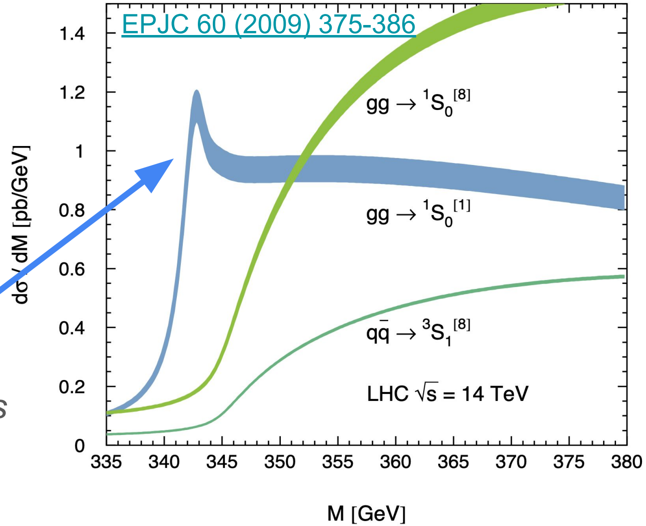
Simulating toponium formation signals at the LHC

Regular Article – Theoretical Physics | Theoretical Physics | Open access
Published: 07 February 2025
Volume 85, article number 157, (2025) Cite this article

Benjamin Fuks ✉, Kaoru Hagiwara, Kai Ma & Ya-Juan Zheng

$$|\mathcal{M}|^2 \quad \to \quad |\mathcal{M}|^2 \left| \frac{\widetilde{G}(E;p^*)}{\widetilde{G}_0(E;p^*)} \right|^2$$

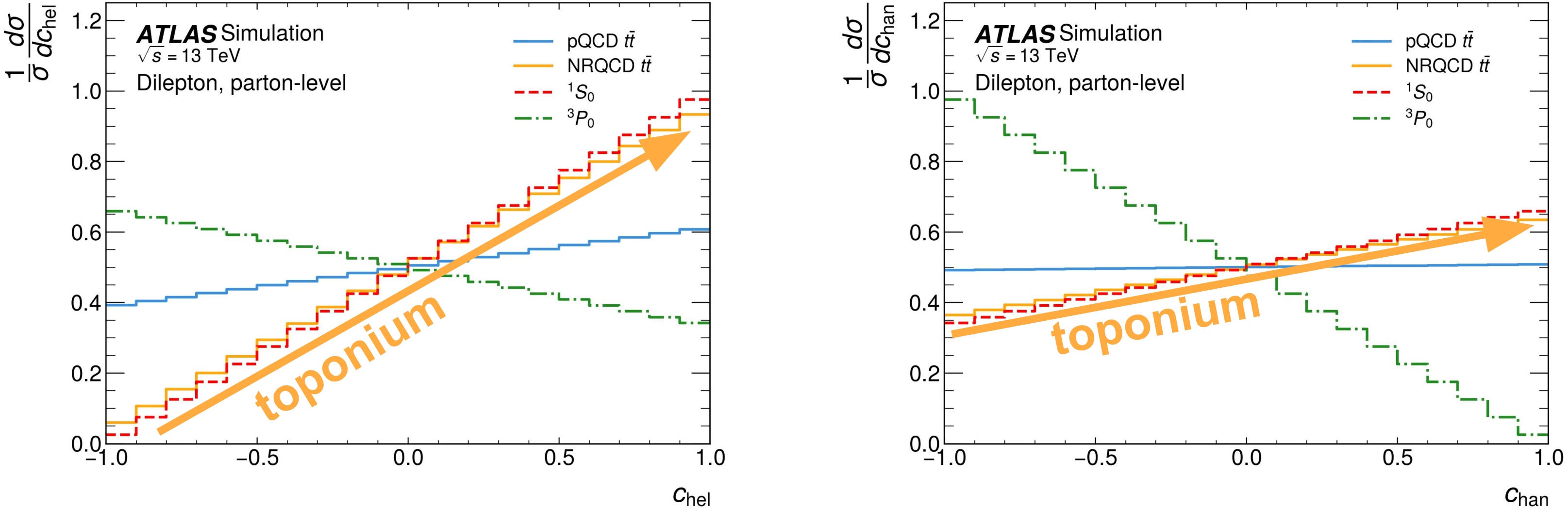
modelling full S-wave contributions



Analysis strategy

- Exploit the **di-leptonic final state**: very pure tt̄ selection, clean measurement of high-fidelity spin analysers, but requires difficult top reconstruction

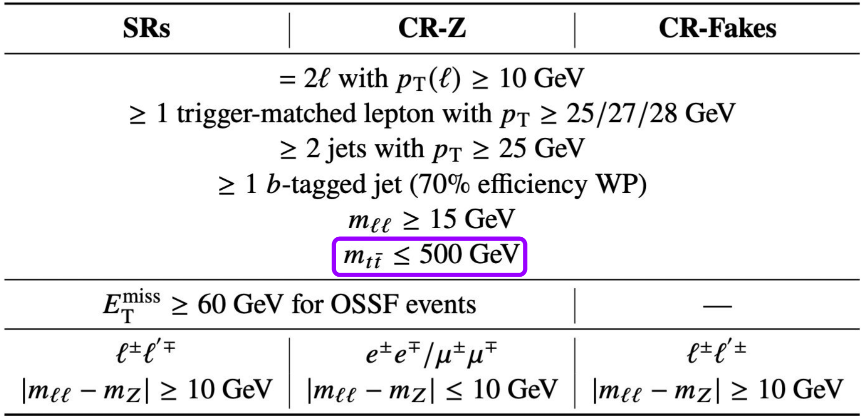
- Reconstruct the tops and **use spin-sensitive observables**
  - **c_{hel}**: angle between the leptons' directions of flight in their parent top quark's rest frame → *maximally sensitive to $^1S_0$* [this is same distribution we used for quantum entanglement, "D"]
  - **c_{han}**: same as c_{hel}, but with sign flip along the top direction → *maximally sensitive to $^3P_0$*



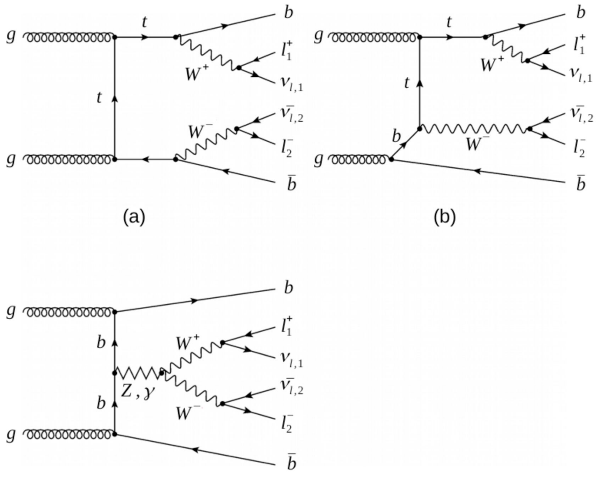
Analysis strategy

ATLAS-CONF-2025-008

- Suppress reducible backgrounds, and use either **state-of-the-art MC modelling** or **data-driven techniques** for the remaining contributions
  - in ee/μμ selections, can reject low-m_{ll} events and cut away the Z peak
  - Drell-Yan and fake lepton backgrounds can be obtained from data
  - **interference of tW and tt̄ at NLO QCD** treated with **Diagram Removal (DR)** or **Diagram Subtraction (DS)** approaches, or with **dedicated 2→6 simulation (bb4l)**
- Perform a **profile-likelihood fit at detector-level**
  - using the 3 sensitive observables $m_{t\bar{t}}$, c_{hel}, and c_{han}



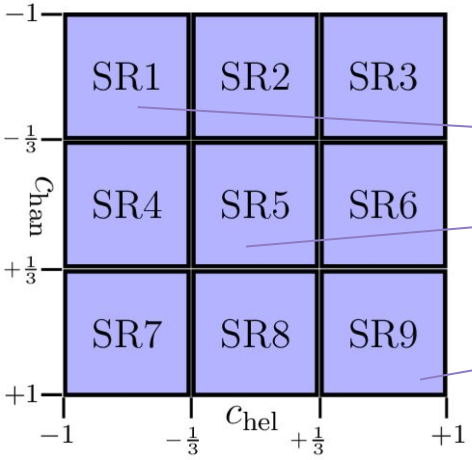
SRs	**CR-Z**	**CR-Fakes**
$= 2\ell$ with $p_T(\ell) \geq 10$ GeV ≥ 1 trigger-matched lepton with $p_T \geq 25/27/28$ GeV ≥ 2 jets with $p_T \geq 25$ GeV ≥ 1 b-tagged jet (70% efficiency WP) $m_{\ell\ell} \geq 15$ GeV $\boxed{m_{t\bar{t}} \leq 500\ \text{GeV}}$		
$E_T^{\text{miss}} \geq 60$ GeV for OSSF events		—
$\ell^\pm \ell'^\mp$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV	$e^\pm e^\mp / \mu^\pm \mu^\mp$ $\lvert m_{\ell\ell} - m_Z \rvert \leq 10$ GeV	$\ell^\pm \ell'^\pm$ $\lvert m_{\ell\ell} - m_Z \rvert \geq 10$ GeV

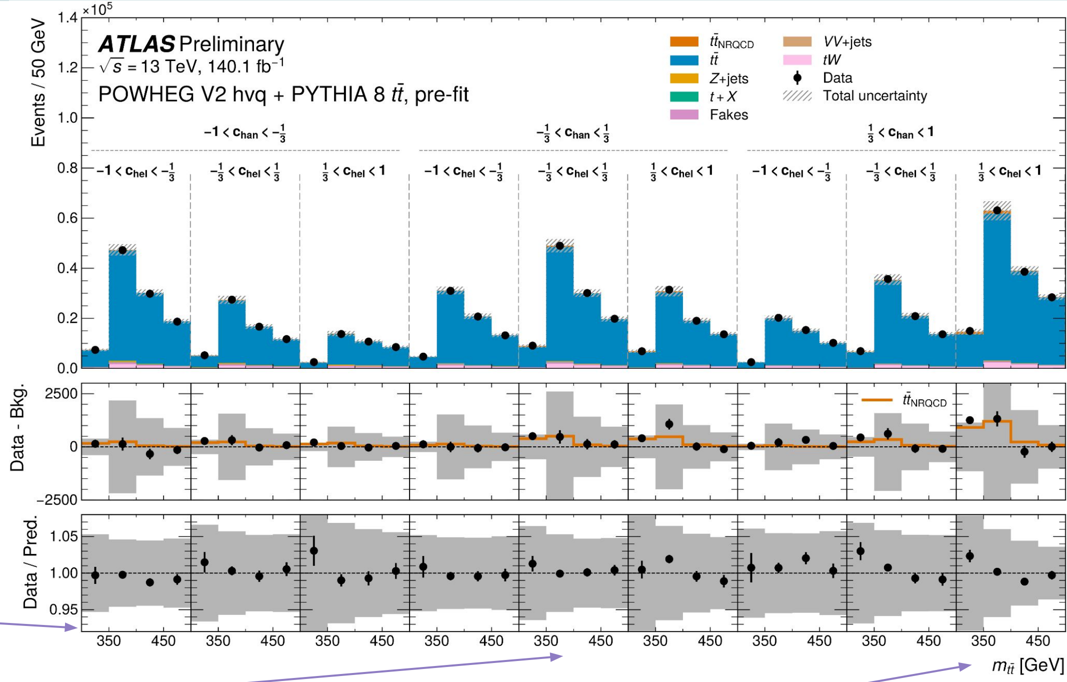


Doubly-, singly-, and non-resonant bbllvv final states

Signal regions

- Split the event selection according to the reconstructed values of c_{hel} and c_{han}
    - 9 SRs with different S/B ratios
    - idea from the original CMS BSM A/H→tt̄ search: enhance sensitivity to A and H bosons in different bins

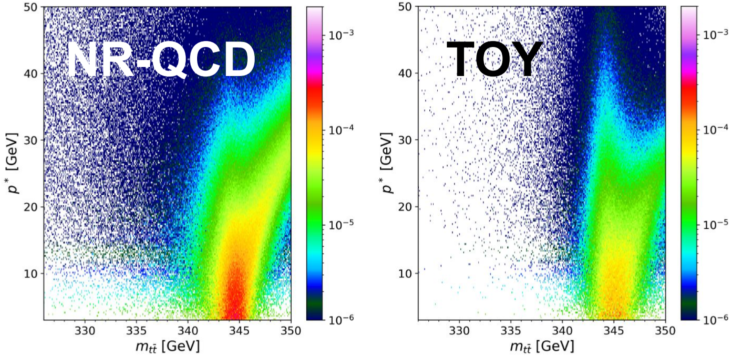




Modelling of the signal toponium process

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

- **ATLAS setup** according to B. Fuks et al. in Eur. Phys. J. C 85 (2025) 157
  - **directly inspired by NR-QCD**: Green’s function reweighting + PS matching
  - apply 2D mass/momentum cut to retain validity of NR-QCD calculations
  - claims to accurately represent the LO S-wave colour-singlet contributions
  - MC cross section: 5.60 pb → scaled to theory estimate of 6.43 pb, which includes also P-waves and colour-octet contributions
- **CMS setup** according to F. Maltoni et al. in JHEP 03 (2024) 099
  - generate gg→η→WbWb in MG at LO, use M(η)=343 GeV, Γ(η)=2.8 GeV + tune the couplings to reproduce 1-dimensional NR-QCD results in $m_{t\bar{t}}$
  - no Green’s function reweighting, no mass cuts → differences in top kinematics
  - this model is also tested by ATLAS

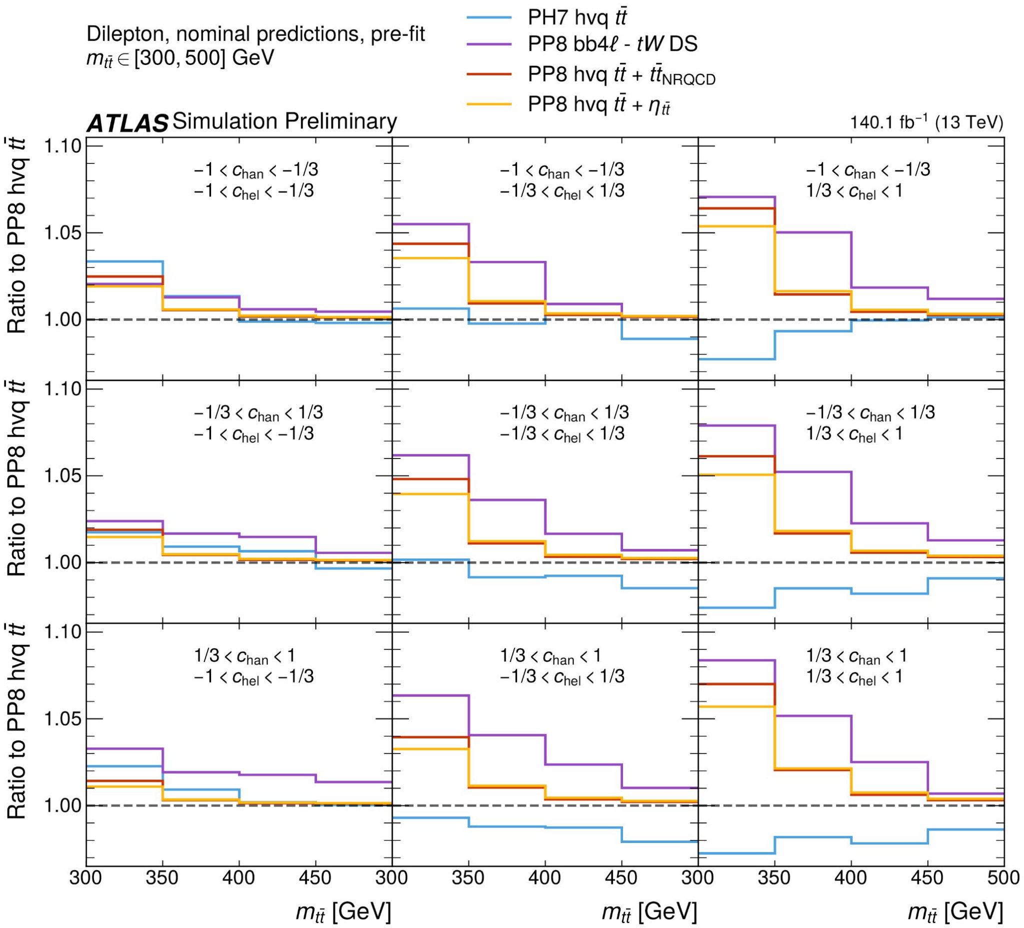


Modelling of the background tt̄ process

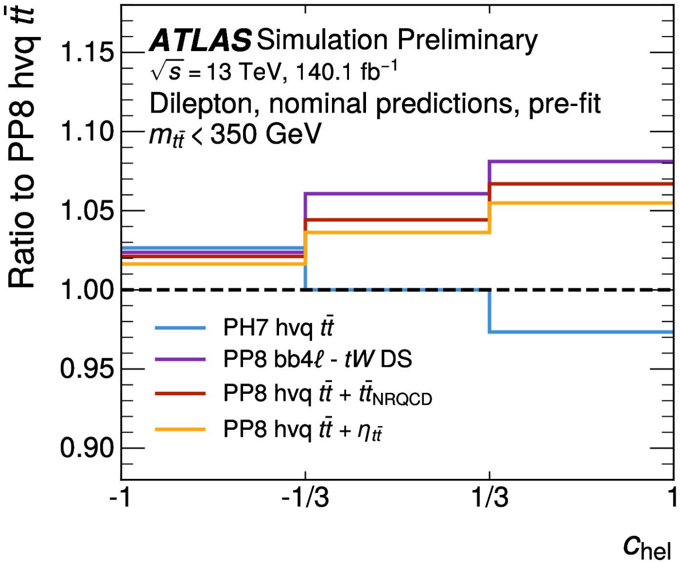
- **Powheg+Pythia8 hvq tt̄** (NLO production, LO decay): **nominal setup**
  - well-understood by both ATLAS and CMS, entire set of systematics built around it, standard tt̄ sample for Run 2 analyses
  - needs dedicated NNLO QCD and NLO EW reweighting
- **Powheg+Pythia8 bb4l** (NLO 2⟶6 production): **alternative setup**
  - decay is NLO-accurate and off-shell effects are accounted for properly
  - ***open questions:*** dedicated tuning? different Powheg settings from hvq? how to reweight to NNLO? how to normalise inclusively? [DPA NNLO calculation only very recently became available!]
- **MadGraph5_aMC@NLO FxFx** (NLO+1,2j production, LO decay): **CMS only**
  - better description of events with higher jet multiplicities
- Kinematic **reweighting to higher order predictions**
  - NNLO QCD with MATRIX, NLO EW with HATHOR
  - 2D reweighting in (cosθ*, $m_{tt̄}$) with associated uncertainties
  - extensive validation → can reproduce fixed-order predictions, as well as MiNNLOps

Key differences in MC predictions

ATLAS-CONF-2025-008

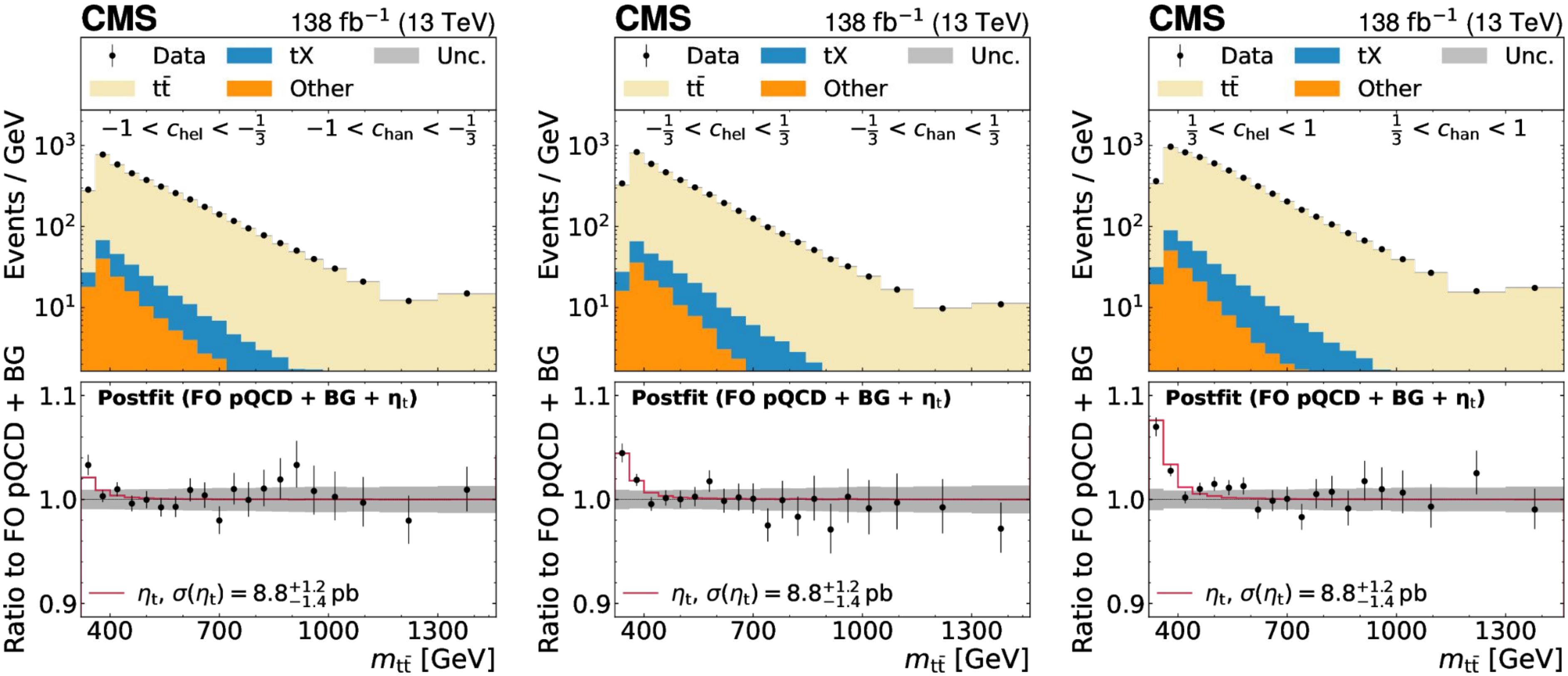


- Slight differences in **toponium** predictions for the first bin of $m_{t\bar{t}}$
- **Herwig** similarly observed to have lower acceptance and opposite slope in c_{hel}
- **bb4l** behaves even more “like toponium” → *due to the differences in higher-order reweighting*



Main results of the ATLAS & CMS analyses

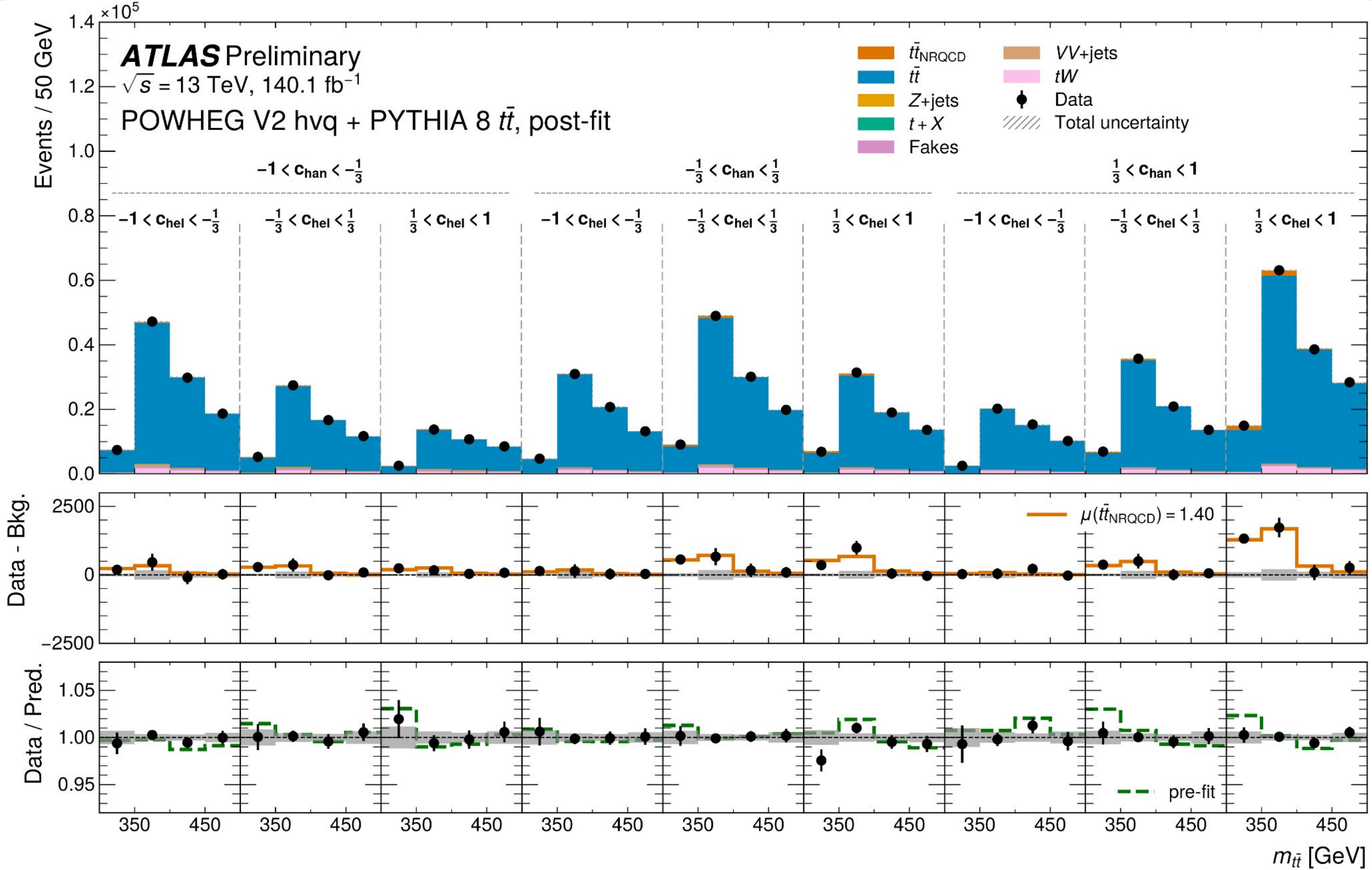
RoPP, 88 (2025) 087801



*Clear **excess near threshold**, behaving like **pseudo-scalar toponium***

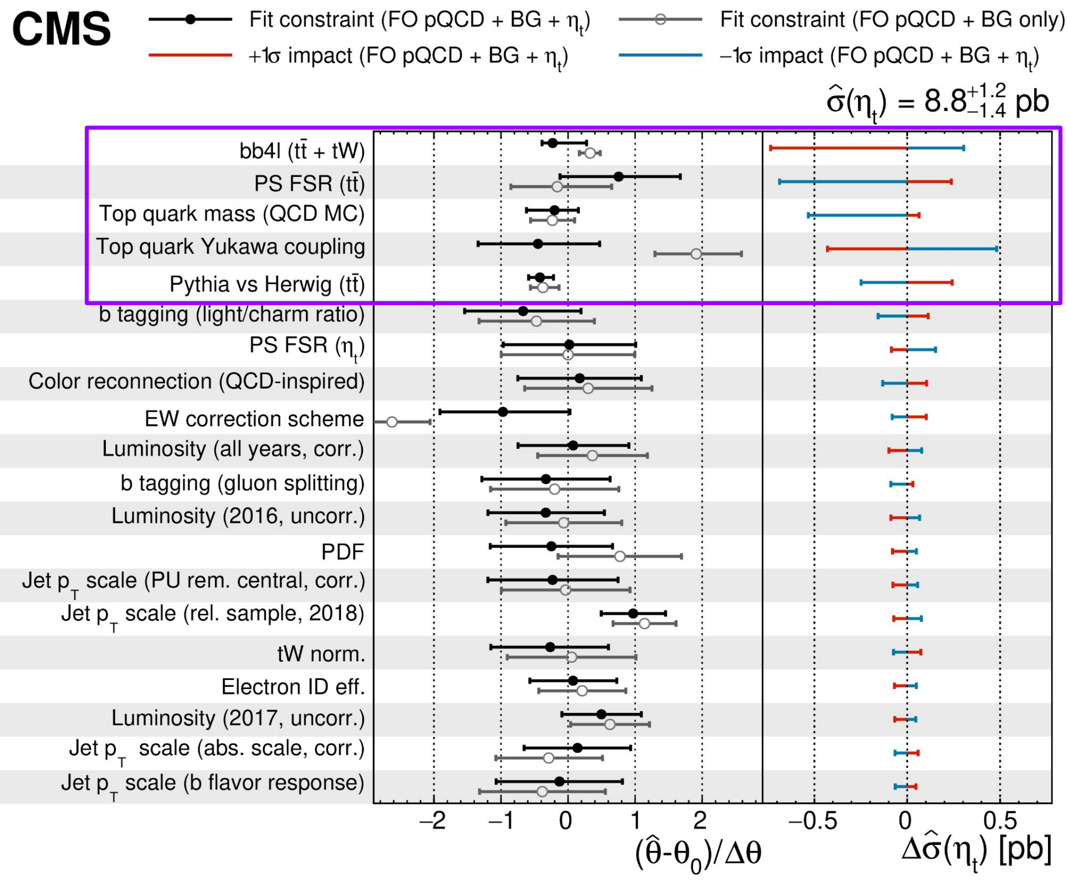
Main results of the ATLAS & CMS analyses

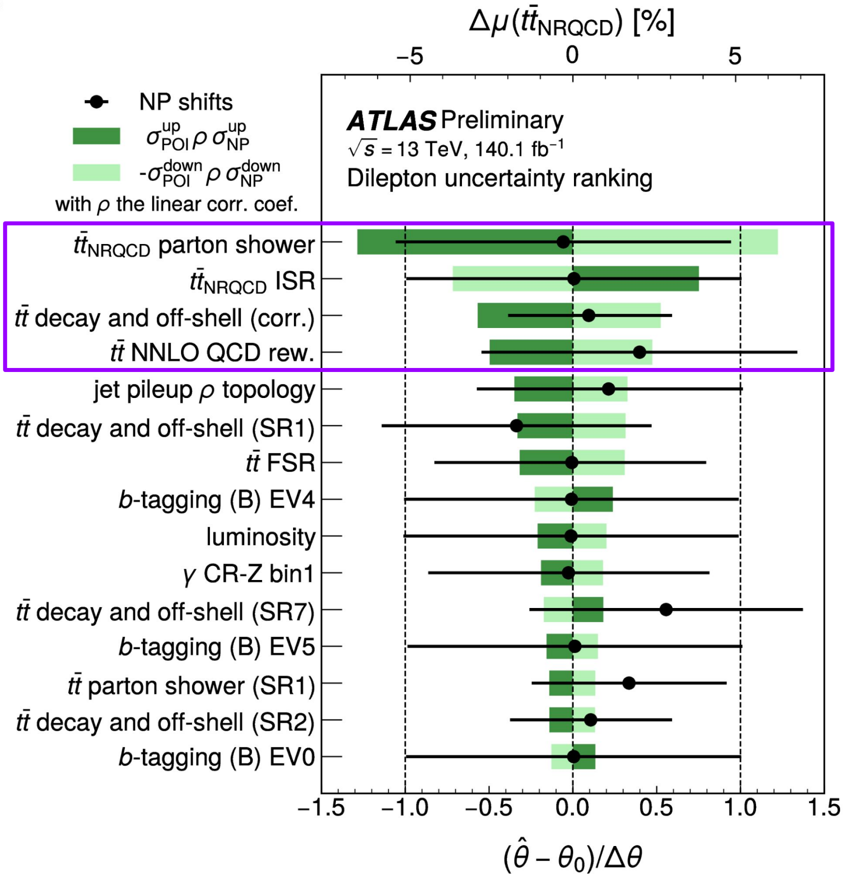
ATLAS-CONF-2025-008



Impact of systematic uncertainties

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

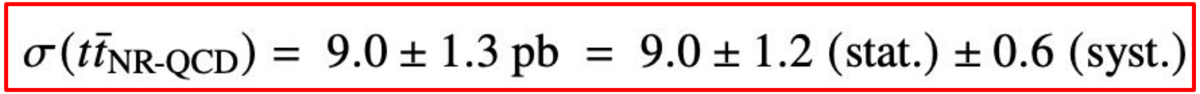




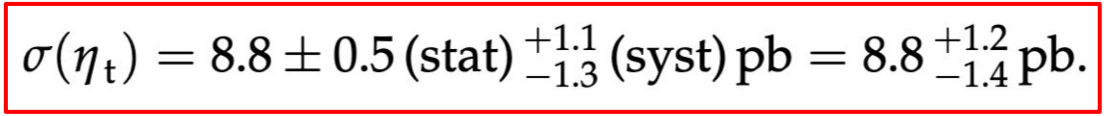
Main results of the ATLAS & CMS analyses

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

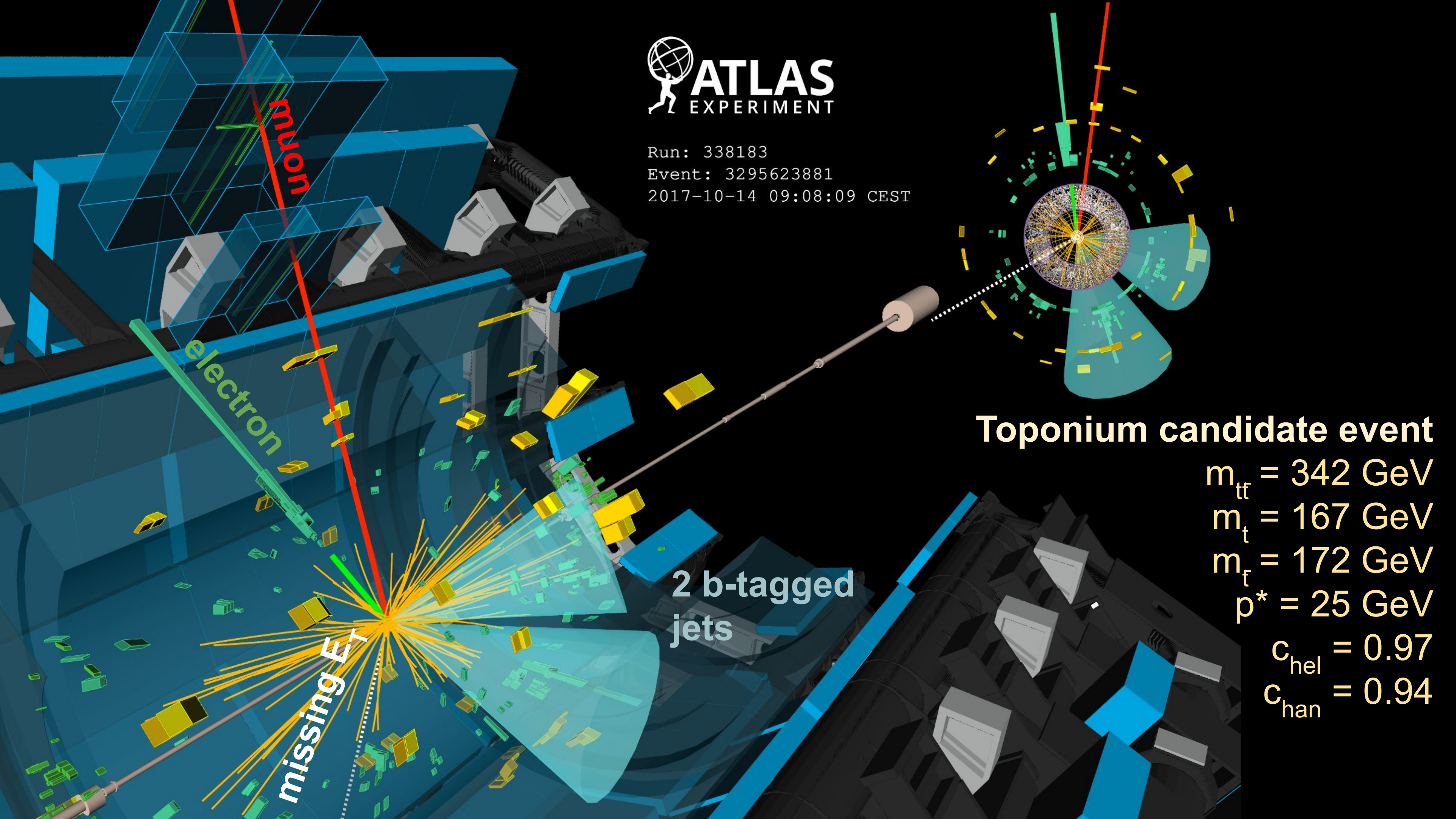
- The predicted NRQCD toponium cross section is 6.4pb
- **ATLAS:** 7.7σ obs. (5.7σ exp.), with a GoF of 0.93 [7x10^{-5} for background-only hypothesis]
- **CMS:** >5σ obs.
- **Measured cross sections are compatible with each other and with the NRQCD prediction**, although roughly (40 ± 20)% larger
    - ***Do recall that two different signal models are used!***
- Large impact of tt̄ modelling systematics on both results



$$\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3\ \text{pb} = 9.0 \pm 1.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})$$



$$\sigma(\eta_{\mathrm{t}}) = 8.8 \pm 0.5\,(\mathrm{stat})\,^{+1.1}_{-1.3}\,(\mathrm{syst})\,\mathrm{pb} = 8.8\,^{+1.2}_{-1.4}\,\mathrm{pb}.$$



Toponium candidate event

$m_{t\bar{t}}$ = 342 GeV

m_t = 167 GeV

$m_{\bar{t}}$ = 172 GeV

p^* = 25 GeV

c_{hel} = 0.97

c_{han} = 0.94

The landscape of quantum information at the LHC

SIGNIFICANT interest from the THEORY community

[Submitted on 10 Mar 2022 (v1), last revised 20 Sep 2022 (this version, v2)]

Quantum information with top quarks in QCD

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks represent unique high-energy systems since their spin correlations can be high-energy colliders. We present here the general framework of the quantum state of energy collider. We argue that, in general, the total quantum state that can be probed i rise to a mixed state. We compute the quantum state of a $t\bar{t}$ pair produced from the m different regions of phase space. We show that any realistic hadronic production of a $t\bar{t}$ experimentally relevant cases of proton-proton and proton-antiproton collisions, perfo energy of the collisions. We provide experimental observables for entanglement and C single observable, which in the case of entanglement represents the violation of a Cauc pair proposed in the literature to more general quantum states, and for any production form of violation of Bell's theorem, necessarily containing a number of loopholes.

Comments: 36 pages, 10 figures, 1 table. Accepted version of the manuscript
Subjects: Quantum Physics (quant-ph); High Energy Physics - Phenomenology (hep-ph); High
Cite as: arXiv:2203.05582 [quant-ph]
(or arXiv:2203.05582v2 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2203.05582
Journal reference: Quantum 6, 820 (2022)
Related DOI: https://doi.org/10.22331/q-2022-09-29-820

[Submitted on 8 Sep 2022]

Quantum discord and steering in top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks have been recently shown to be a promising system to study quantum information problems at the hi discuss topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture o discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a se statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord ca ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional setups. In c discord and steering can provide witnesses of new physics beyond the Standard Model.

Comments: 6 pages, 3 figures
Subjects: Quantum Physics (quant-ph); High Energy Physics - Experiment (hep-ex); High Energy Physics - Phenomenology (hep-p
Cite as: arXiv:2209.03969 [quant-ph]
(or arXiv:2209.03969v1 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2209.03969

[Submitted on 4 Mar 2020 (v1), last revised 6 Sep 2021 (this version, v3)]

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top-antitop-quark pairs at the LHC, representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with high statistical significance, using the current data recorded during Run 2 at the LHC. In addition, we develop a simple protocol for the quantum tomography of the top-antitop pair. This experimental te experimental te

Comments: 15
Subjects: Qu
Cite as: ar
(or
htt
Journal reference: Eu
Related DOI: htt

[Submitted on 28 Sep 2022 (v1), last revised 11 Oct 2022 (this version, v2)]

Quantum state tomography, entanglement detection and Bell violation prospects in weak decays of massive particles

Rachel Ashby-Pickering, Alan J. Barr, Agnieszka Wierzchucka

A rather general method for determining the spin density matrix of a multi-particle system from angular decay data is presented. The method is based on a Bloch parameterisation of the d-dimensional generalised Gell-Mann representation of ρ and exploits the associated Wigner- and Weyl-transforms on the sphere. Each parameter of a (possibly multipartite) spin density matrix can can b non-projective decays are des Monte Carlo simulations of pp $H \to ZZ^*$. Measurements are

Comments: v2: additional references
Subjects: Quantum Physics (quan

[Submitted on 10 Mar 2022 (v1), last revised 30 Aug 2022 (this version, v2)]

Quantum SMEFT tomography: top quark pair production at the LHC

Rafael Aoude, Eric Madge, Fabio Maltoni, Luca Mantani

Quantum information observables, such as entanglement measures, provide a powerful way to characterize the properties of quantum states. We propose to use them structure of fundamental interactions and to search for new physics at high energy. Inspired by recent proposals to measure entanglement of top quark pairs produced we examine how higher-dimensional operators in the framework of the SMEFT modify the Standard Model expectations. We explore two regions of interest in the phas the Standard Model produces maximally entangled states: at threshold and in the high-energy limit. We unveil a non-trivial pattern of effects, which depend on the init partons, $q\bar{q}$ or gg, on whether only linear or up to quadratic SMEFT contributions are included, and on the phase space region. In general, we find that higher-dimensi lower the entanglement predicted in the Standard Model.

[Submitted on 2 Jun 2021 (v1), last revised 26 Jul 2022 (this version, v4)]

Testing Bell inequalities in Higgs boson decays

Alan Barr

Higgs boson decays produce of the $W^{\pm}$ pair may be recon determined. Numerical simul near-maximally violated. Exp controlled then statistically s

Comments: Sign corrections t
Subjects: High Energy Phy
Cite as: arXiv:2106.01377
(or arXiv:2106.01
https://doi.org/1
Journal reference: Physics Letters B
Related DOI: https://doi.org/1

[Submitted on 28 Sep 2022]

Laboratory-frame tests of quantum entanglement in $H \to WW$

J. A. Aguilar-Saavedra

Quantum entanglement between frame observables that only invol be used to observe the quantum dimensional) angular distribution

Comments: LaTeX 6 pages
Subjects: High Energy Physics -
Report number: IFT-UAM/CSIC-22-119
Cite as: arXiv:2209.14033 [hep-
(or arXiv:2209.14033v1
https://doi.org/10.4855

[Submitted on 27 Sep 2022]

Testing entanglement and Bell inequalities in $H \to ZZ$

J. A. Aguilar-Saavedra, A. Bernal, J. A. Casas, J. M. Moreno

We discuss quantum entanglement and violation of Bell inequalities in the $H \to ZZ$ decay, in particular when the two Z-bosons decay into light leptons. Although such pr implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally-entangled" system, which makes it very promising to check these phenomena at high energy. In this paper we devise a novel framework to extract from $H \to ZZ$ data all significant information related to this goal, in particular spin correl observables. In this context we derive sufficient and necessary conditions for entanglement in terms of only two parameters. Likewise, we obtain a sufficient and improved for the violation of Bell-type inequalities. The numerical analysis shows that with a luminosity of $L = 300\text{fb}^{-1}$ entanglement can be probed at $> 3\sigma$ level. For $L = 3\text{ab}^{-1}$ (H entanglement can be probed beyond the 5σ level, while the sensitivity to a violation of the Bell inequalities is at the 4.5σ level

heory (hep-th); Quantum Physics (quant-ph)

[Submitted on 1 May 2022 (v1), last revised 1 Aug 2022 (this version, v2)]

Improved tests of entanglement and Bell inequalities with LHC tops

J. A. Aguilar-Saavedra, J. A. Casas

We discuss quantum entanglement in top pair production at the LHC. Near the $t\bar{t}$ threshold, entanglement observa subprocesses, which is achieved by a simple cut on the velocity of the $t\bar{t}$ system in the laboratory frame. Furtherm combinations of $t\bar{t}$ spin correlation coefficients involved in the measurement of entanglement and Bell inequalities 7 for Bell inequalities near threshold

[Submitted on 19 Oct 2021 (v1), last revised 25 Mar 2022 (this version, v2)]

Quantum tops at the LHC: from entanglement to Bell inequalities

Claudio Severi, Cristian Degli Esposti Boschi, Fabio Maltoni, Maximiliano Sioli

We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable fo measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglem only very high-p_T events are sensitive to a vio different unfolding methods and independent he high luminosity LHC run.

[Submitted on 24 Aug 2022]

Constraining new physics in entangled two-qubit systems: top-quark, tau-lepton and photon pairs

Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli

The measurement of quantum entanglement can provide a new and most sensitive probe to physics beyond the Standard Model. We use the concurrence of the top-quark pairs spin states produced at colliders to constrain the magnetic dipole term in the coupling between top quark and gluons, that of τ-lepton pairs spin states to bound contact interactions an that of τ-lepton pairs or two photons spin states from the decay of the Higgs boson to try distinguishing between CP-even and odd couplings. These four examples show the power of the new approach as well as its limitations. We show that differences in the entanglement in the top-quark and τ-lepton pairs production cross sections can provide constraints better than those previously estimated from total cross sections or classical correlations. Instead, the final states in the decays of the Higgs boson remain maximally entangled even in the presence of CP-odd couplings and cannot be used to set bounds on new physics. We discuss the violation of Bell inequalities featured in all four processes and find that the decays of the Higgs boson into τ-lepton pairs or two photons constitute the best instances to observe such violations.

Comments: 31 pages, 16 Figures
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2208.11723 [hep-ph]
(or arXiv:2208.11723v1 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2208.11723

[Submitted on 23 Feb 2021 (v1), last revised 27 Oct 2021 (this version, v2)]

Testing Bell inequalities at the LHC with top-quark pairs

M. Fabbrichesi, R. Floreanini, G. Panizzo

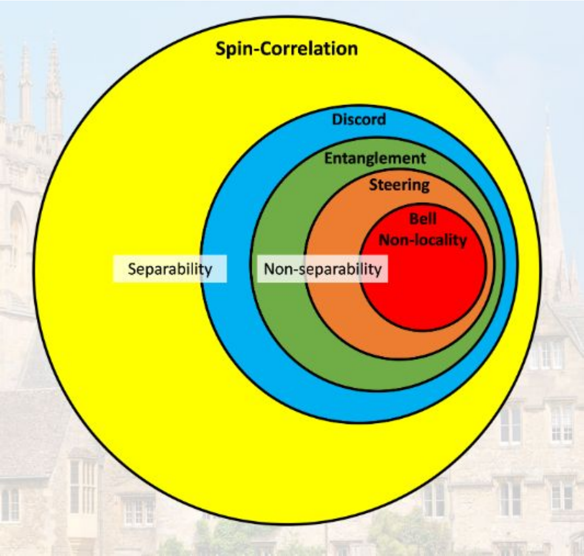
Entanglement between the spins of top-quark pairs produced at a collider can be used to test a (generalized) Bell inequality at energies never explored so far. We show how the measurement of a single observable can provide a test of the violation of the Bell inequality at the 98% CL with the data already collected at the Large Hadron Collider and at the 99.99% CL with the higher luminosity of the next run.

Comments: 4 pages, 1 figure
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 [hep-ph]
(or arXiv:2102.11883v2 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2102.11883
Journal reference: Phys.Rev.Lett. 127 (2021) 16, 161801
Related DOI: https://doi.org/10.1103/PhysRevLett.127.161801

Quantum tops beyond entanglement

Further phenomenology towards additional quantum information theory concepts in term of tt̄ production at the LHC:

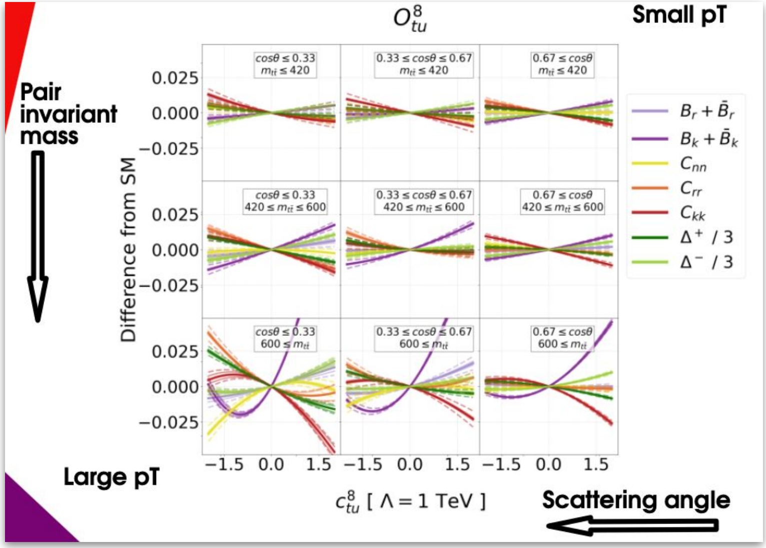
- **Quantum Discord** measures the departure of the information entropy from classical theory
- **Quantum Steering** measures the non-local effect of one measurement on the outcome of the other
- both are usually very hard to measure, given the need to repeat experiments over large samples of spin directions → the LHC gives us millions of randomly sampled directions “for free”!
- both are **asymmetric** quantities → new tests of CP violation in the strong sector!



In general, want to perform quantum tomography = reconstruct the full spin density matrix

Quantum entanglement in the SMEFT

- The 15 components of the tt̄ spin density matrix can constrain SMEFT operators affecting top production
    - entanglement and Bell observables are also sensitive
    - in the dilepton channel, all O(1/Λ^2) effects in the top decay cancel out (to less than permille level)
    - best predictions are currently at NLO QCD with approximate-NLO spin effects: this is not something we can match with our MC, **better to unfold the data**
- 4-quark operators need NLO calculations
    - projections of CMS-like analysis to full Run 2+3 give competitive constraints wrt. to current **full global fits to top LHC data**



negligible EFT in top decays!

$$\alpha_\ell = 1 - \frac{c^2_{uW,33} v^4}{\Lambda^4} \frac{4(2m_t^6 + 3m_t^4 m_W^2 - 6m_t^2 m_W^4 + m_W^6 + 12 m_t^4 m_W^2 \log m_W/m_t)}{(m_W^2 - m_t^2)^2 (m_t^2 + 2m_W^2)}$$

The CMS lepton+jets SDM measurement

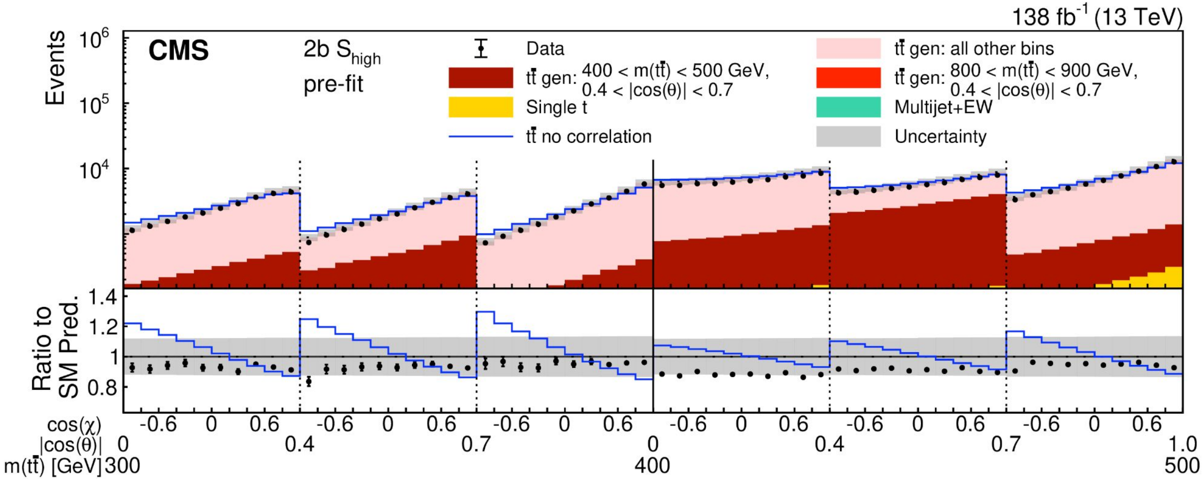
Phys. Rev. D 110 (2024) 112016

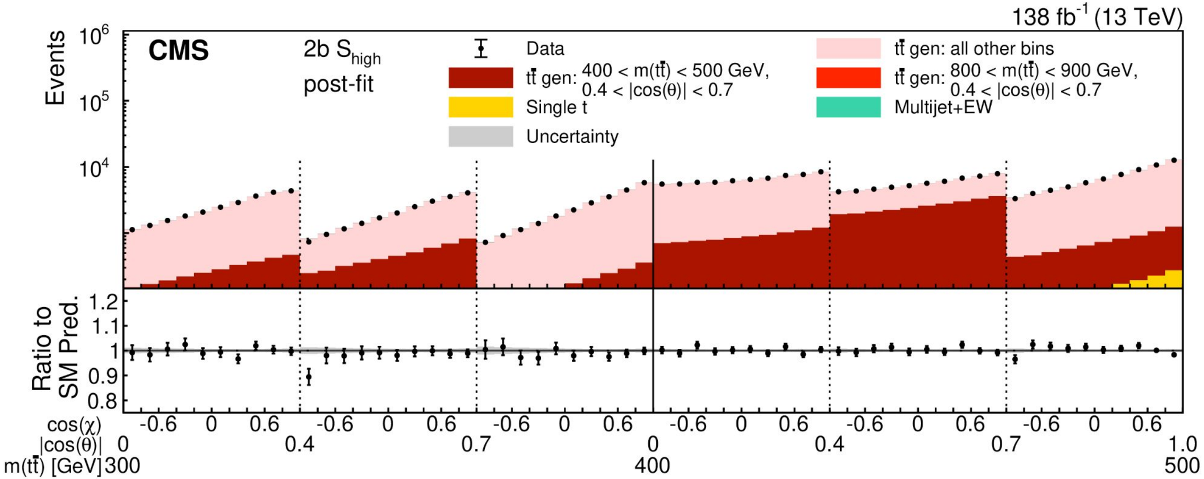
Detector-level template fit ⇒ **simultaneous extraction** of all polarisation and spin correlation coefficients!

Binned in top/$t\bar{t}$ kinematics: $m(t\bar{t})$, $p_T(t)$, $|\cos(\Theta)|$

Similar strategy used to **extract D and D_3** in top/$t\bar{t}$ kinematic bins

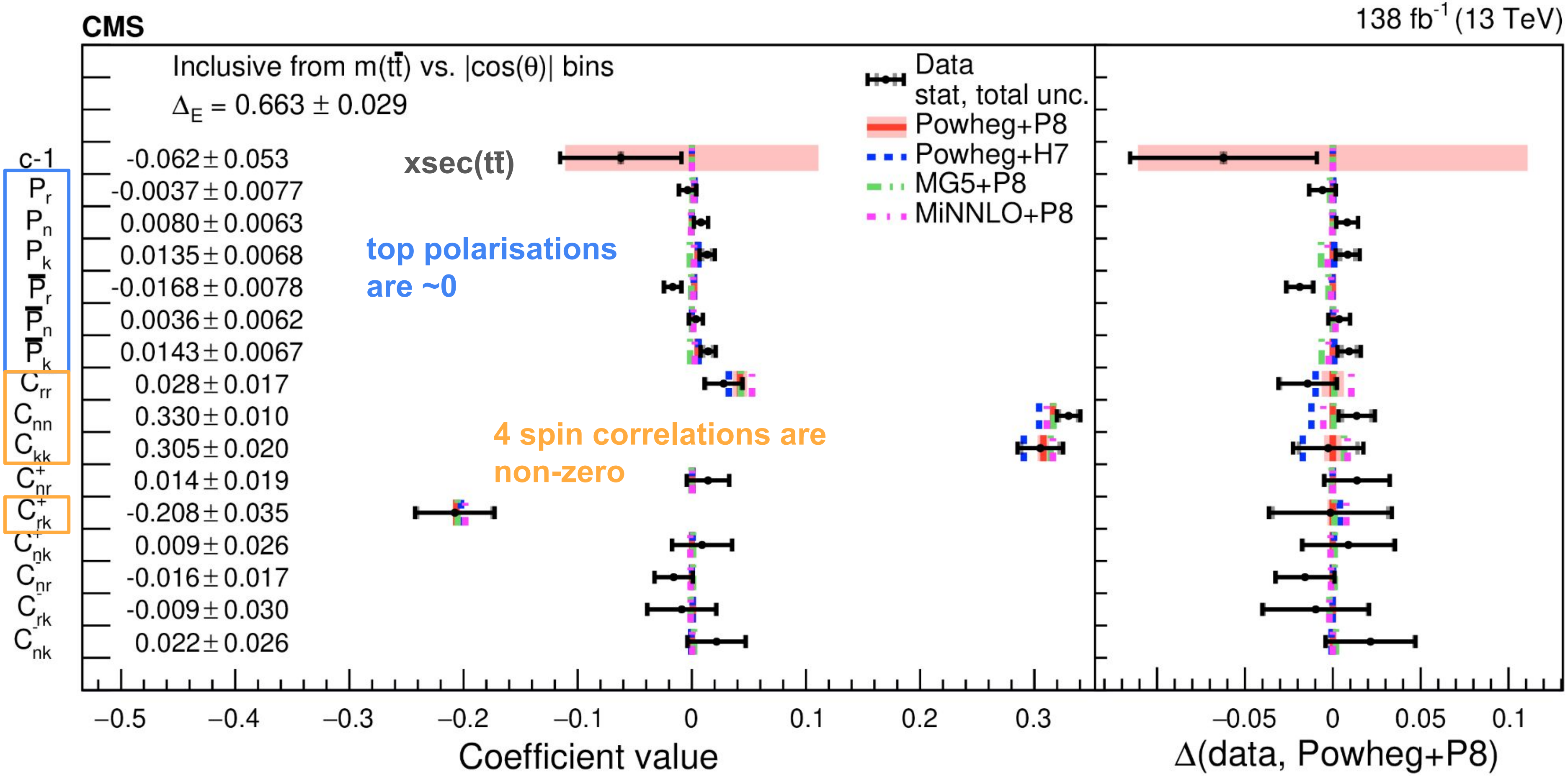
⇒ probe entanglement at low and high energies!





The CMS lepton+jets SDM measurement

Phys. Rev. D 110 (2024) 112016



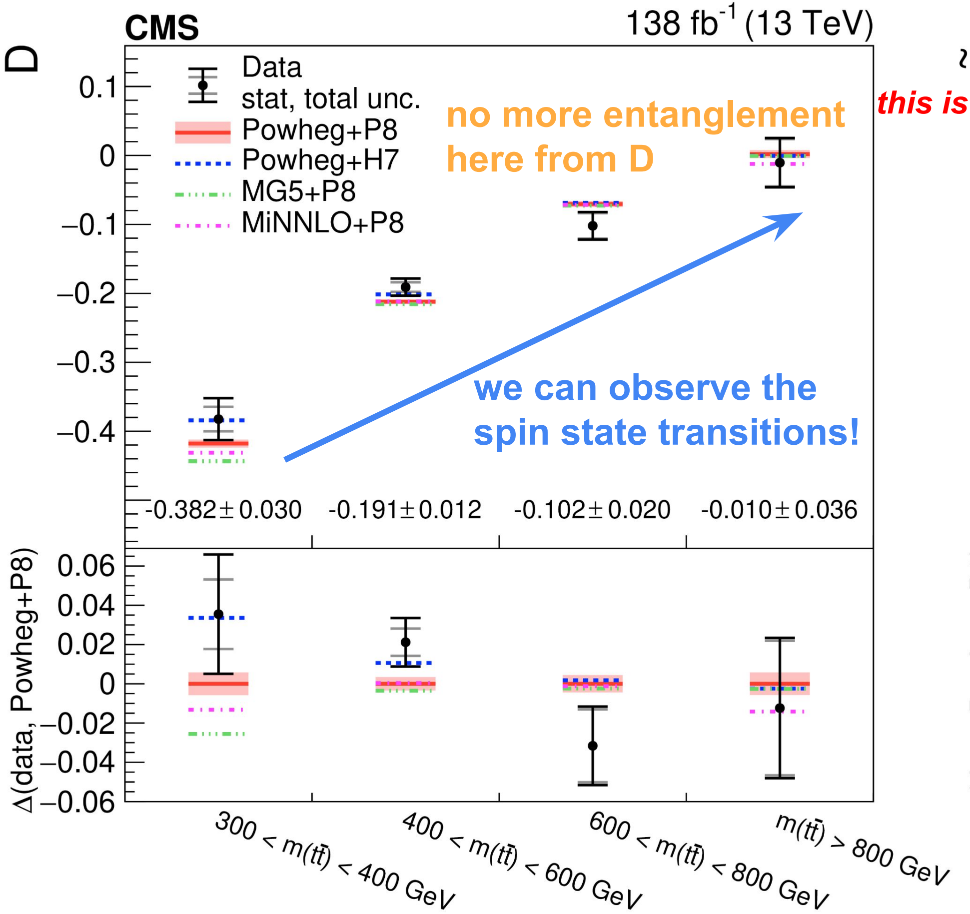
xsec(tt̄)

top polarisations are ~0

4 spin correlations are non-zero

The CMS lepton+jets SDM measurement

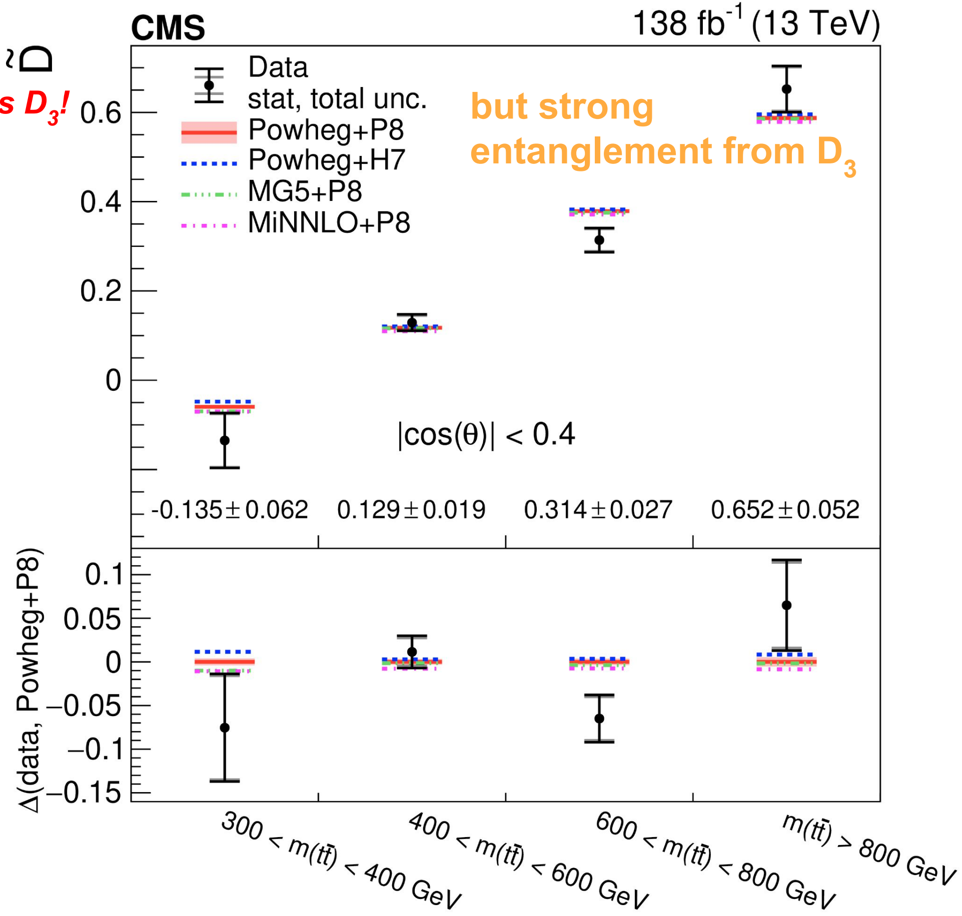
Phys. Rev. D 110 (2024) 112016



no more entanglement here from D

we can observe the spin state transitions!

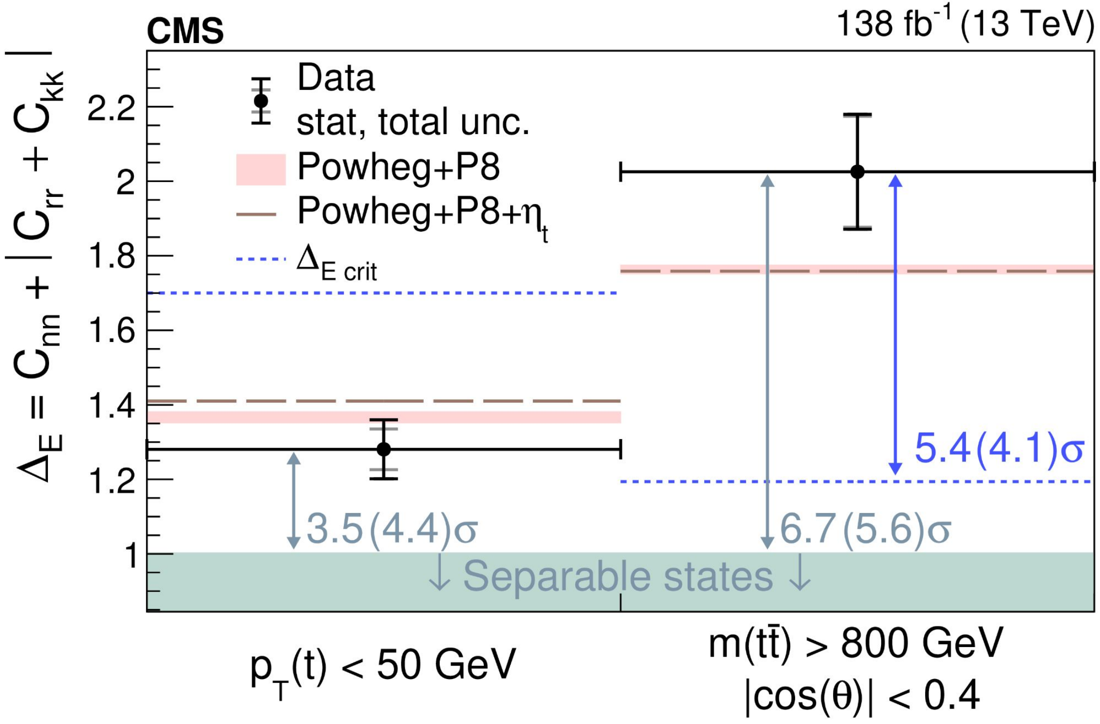
this is D_3!



but strong entanglement from D_3

The CMS lepton+jets SDM measurement

Phys. Rev. D 110 (2024) 112016



Entanglement seen in the high-energy regime!

But not sensitive enough near threshold…

Blue line: **critical threshold for classical communication**

Imagine the $t\bar{t}$ system is purely classical and is actively conspiring against us…

→ **time-like events** (that can communicate) will look maximally entangled

→ **space-like events** (that can't communicate) will look like they are at the limit of separability

→ this is the "worst case scenario" we could observe classically

The question is then: is our sample of space-like enriched $t\bar{t}$ events above that limit?

This is not a proper Bell test!

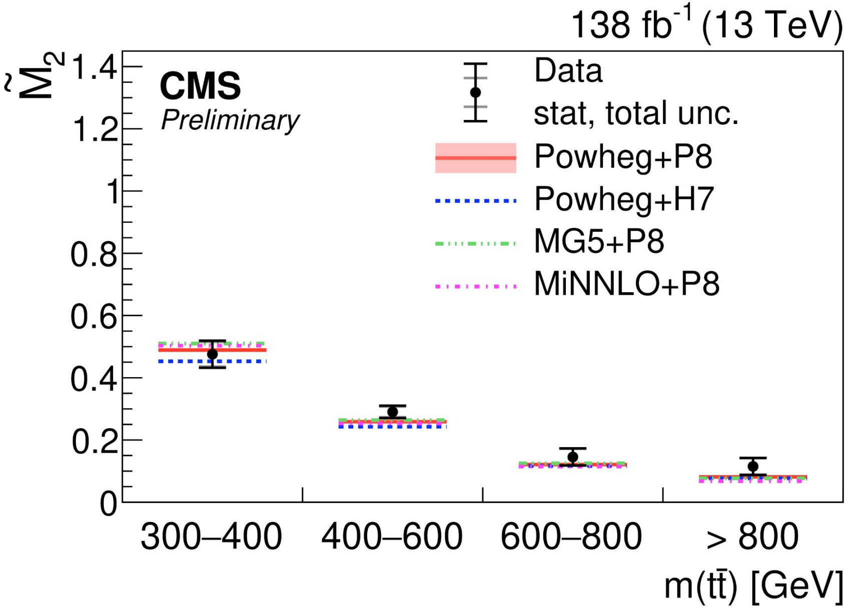
See arXiv:2407.15223

The magic of quantum states

CMS-PAS-TOP-25-001
C. White & M. White, PRD 110 (2024) 116016

Gottesman-Knill theorem: “for every quantum computer containing stabiliser states, there is a classical computer that is just as efficient”

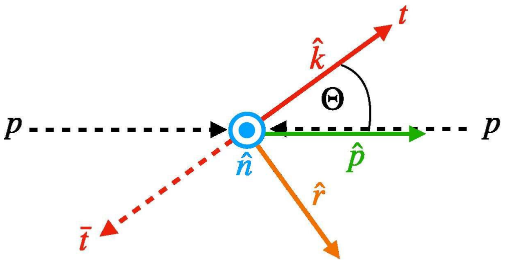
- some entangled states are stabilisers (but not all)
- “magic” states are not! (M_2>0)
- **magic ⇔ quantum advantage**

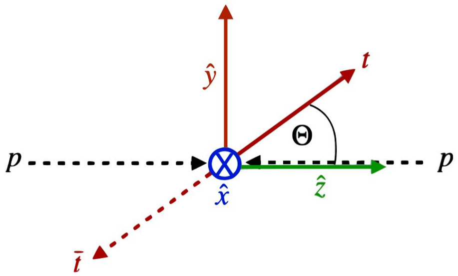


$$\tilde{M}_2 = -\log_2 \left(\frac{1 + \sum_{i\in n,k,r}[(P_i^4 + \bar{P}_i^4)] + \sum_{i,j\in n,k,r} C_{ij}^4}{1 + \sum_{i\in n,k,r}[(P_i^2 + \bar{P}_i^2)] + \sum_{i,j\in n,k,r} C_{ij}^2} \right)$$

Quantum Discord at the LHC

Y. Afik & JRMdN (2023)
T. Han & M. Low & N. McGinnis & S. Su (2024)



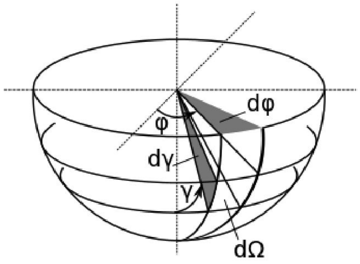


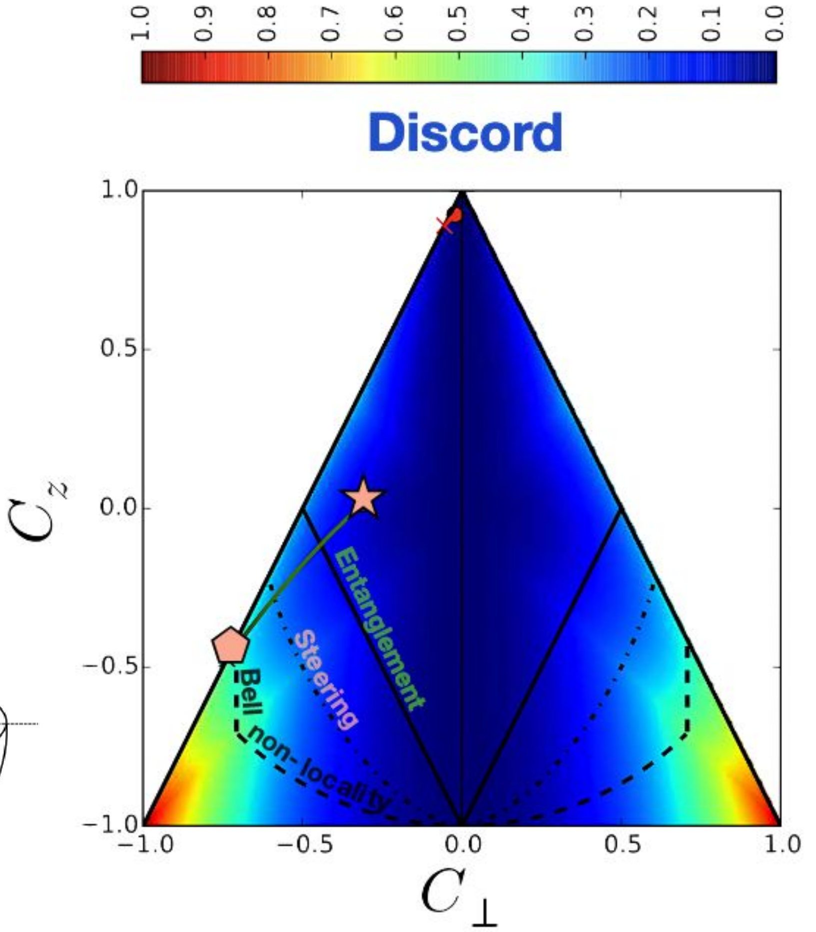
Discord quantifies the “degree of quantumness” of the system, but is **extremely challenging to measure!**

$$\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{n}} p_{\hat{n}} S(\rho_{\hat{n}}) + p_{-\hat{n}} S(\rho_{-\hat{n}})$$

A quick recipe…

1. Measure the density matrices inclusively
2. Partition the phase-space based on anti-top kinematics
3. Measure the top kinematics
4. Compute D_A above
5. Repeat with the other particle





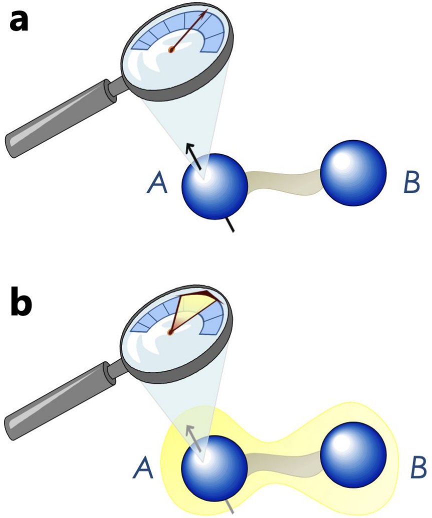
Local Quantum Uncertainty

D. Girolami et al. (2013)

Alternative [with clearer interpretability?] based on **quantum uncertainty under local measurements:** even when a system is *not entangled*, a local measurement on one part can disturb the global state *if there are* quantum correlations.

Wigner-Yanase skew information: $\mathcal{I}(\rho, K_A \otimes \mathbb{I}_B) = -\frac{1}{2}\mathrm{Tr}([\sqrt{\rho}, K_A \otimes \mathbb{I}_B]^2)$

quantifies the non-commutativity between state ρ and observable K
→ the part that is not just “classical ignorance” [=quantum-certain]



Therefore if the **minimal value of I** achievable on a single local measurement is **non-zero**, we are dealing with a **discordant state**

$$\boxed{\mathcal{U}(\rho) \equiv \min_{K_A} \mathcal{I}(\rho, K_A \otimes \mathbb{I}_B)}$$

the Local Quantum Uncertainty (LQU)

Conclusions

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

- **Quantum Information Theory meets High Energy Physics**
→ exciting new prospects at the LHC and beyond!
  - Both ATLAS and CMS have **observed quantum entanglement**, for the first time with quarks and at the highest energies so far
- **Extremely challenging measurements**
  - need large statistics, precise models of the threshold region, pQCD and NRQCD calculations, full system reconstruction, understanding of NLO EW and NNLO QCD corrections to production, NLO and off-shell effects in decay…
- Proof-of-concept application of these new tools: ATLAS and CMS **observe a significant excess** seemingly compatible with **toponium formation**
  - unexpected discovery of “new SM physics” → ***LHC as a precision machine***

$$\boxed{\sigma(t\bar{t}_{\text{NR-QCD}}) = 9.0 \pm 1.3\ \text{pb} = 9.0 \pm 1.2\ (\text{stat.}) \pm 0.6\ (\text{syst.})}$$

$$\boxed{\sigma(\eta_{\text{t}}) = 8.8 \pm 0.5\,(\text{stat})\,^{+1.1}_{-1.3}\,(\text{syst})\,\text{pb} = 8.8\,^{+1.2}_{-1.4}\,\text{pb}.}$$

Backup

General bipartite qubit system

$$\rho = \frac{1}{4}\left(\mathbb{1}\otimes\mathbb{1} + \sum_i \left(B_i^+ \sigma_i \otimes \mathbb{1} + B_i^- \mathbb{1}\otimes\sigma_i\right) + \sum_{ij} C_{ij}\sigma_i\otimes\sigma_j\right)$$

$$\rho = \frac{1}{4}\begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} - i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} - C_{22} - i(C_{12} + C_{21}) \\ B_1^- + C_{31} + i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} + C_{22} + i(C_{12} - C_{21}) & B_1^+ - C_{13} - i(B_2^+ - C_{23}) \\ B_1^+ + C_{13} + i(B_2^+ + C_{23}) & C_{11} + C_{22} - i(C_{12} - C_{21}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} - i(B_2^- - C_{32}) \\ C_{11} - C_{22} + i(C_{12} + C_{21}) & B_1^+ - C_{13} + i(B_2^+ - C_{23}) & B_1^- - C_{31} + i(B_2^- - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

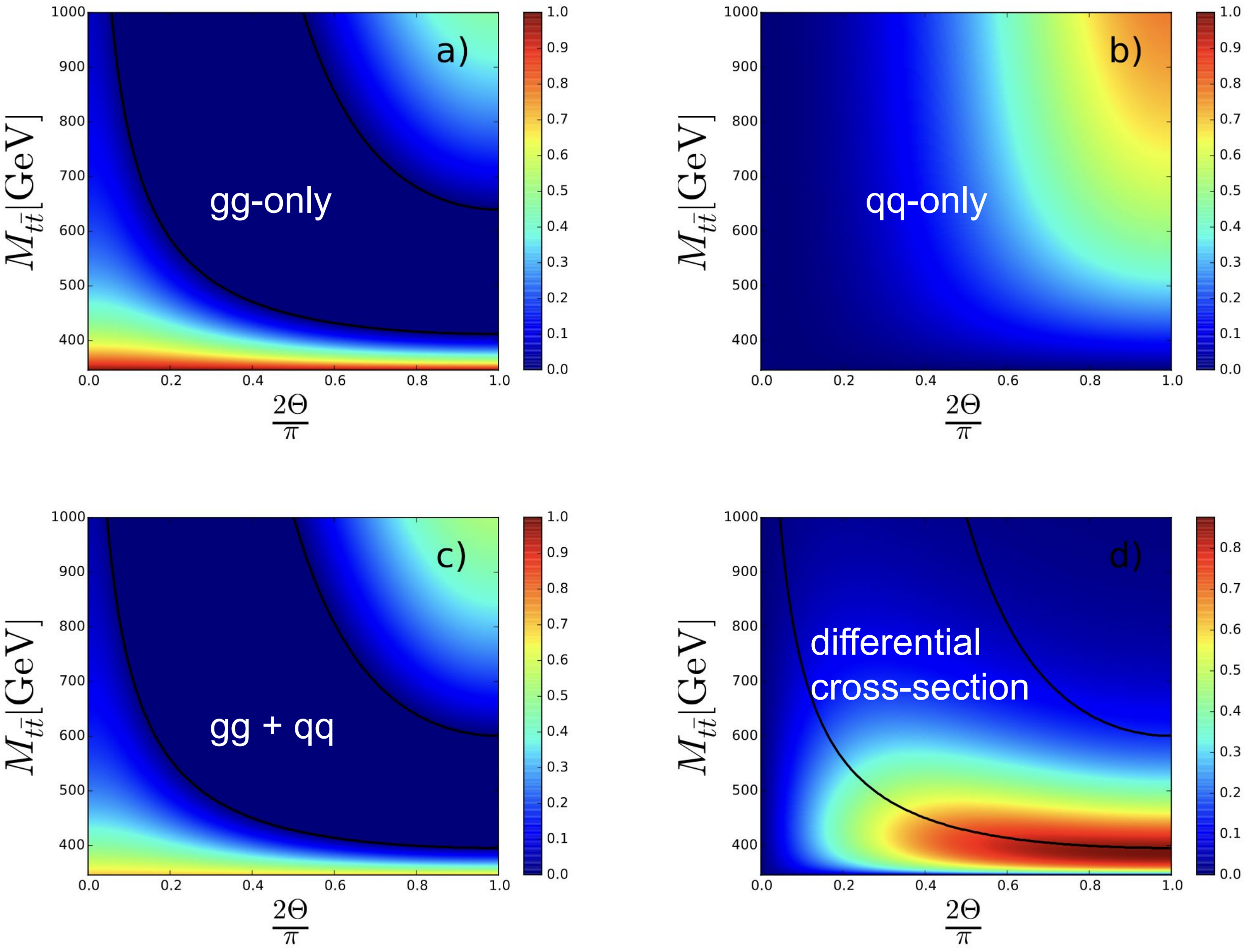
$$\rho^{T_2} = \frac{1}{4}\begin{bmatrix} 1+B_3^+ + B_3^- + C_{33} & B_1^- + C_{31} + i(B_2^- + C_{32}) & B_1^+ + C_{13} - i(B_2^+ + C_{23}) & C_{11} + C_{22} + i(C_{12} - C_{21}) \\ B_1^- + C_{31} - i(B_2^- + C_{32}) & 1 + B_3^+ - B_3^- - C_{33} & C_{11} - C_{22} - i(C_{12} + C_{21}) & B_1^+ - C_{13} - i(B_2^+ - C_{23}) \\ B_1^+ + C_{13} + i(B_2^+ + C_{23}) & C_{11} - C_{22} + i(C_{12} + C_{21}) & 1 - B_3^+ + B_3^- - C_{33} & B_1^- - C_{31} + i(B_2^- - C_{32}) \\ C_{11} + C_{22} - i(C_{12} - C_{21}) & B_1^+ - C_{13} + i(B_2^+ - C_{23}) & B_1^- - C_{31} - i(B_2^- - C_{32}) & 1 - B_3^+ - B_3^- + C_{33} \end{bmatrix}$$

Peres-Horodecki: if ρ^{T2} has at least one negative eigenvalue, the state is entangled

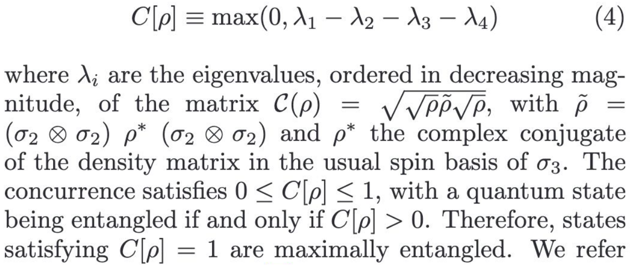
$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_1\Omega_2} = \frac{1}{4\pi^2}\left(1 + \alpha_1\,\mathbf{B}_1\cdot\hat{\ell}_1 + \alpha_2\,\mathbf{B}_2\cdot\hat{\ell}_2 + \alpha_1\alpha_2\,\hat{\ell}_1\cdot\mathbb{C}\cdot\hat{\ell}_2\right)$$

Production phase-space

EPJC (2021) 136:907



z-axis: concurrence C[ρ]



$$C[\rho] \equiv \max(0, \lambda_1 - \lambda_2 - \lambda_3 - \lambda_4) \qquad (4)$$

where λ_i are the eigenvalues, ordered in decreasing magnitude, of the matrix $\mathcal{C}(\rho) = \sqrt{\sqrt{\rho}\tilde{\rho}\sqrt{\rho}}$, with $\tilde{\rho} = (\sigma_2 \otimes \sigma_2)\ \rho^*\ (\sigma_2 \otimes \sigma_2)$ and ρ^* the complex conjugate of the density matrix in the usual spin basis of σ_3. The concurrence satisfies $0 \leq C[\rho] \leq 1$, with a quantum state being entangled if and only if $C[\rho] > 0$. Therefore, states satisfying $C[\rho] = 1$ are maximally entangled. We refer

C[ρ] > 0 ⇔ entanglement

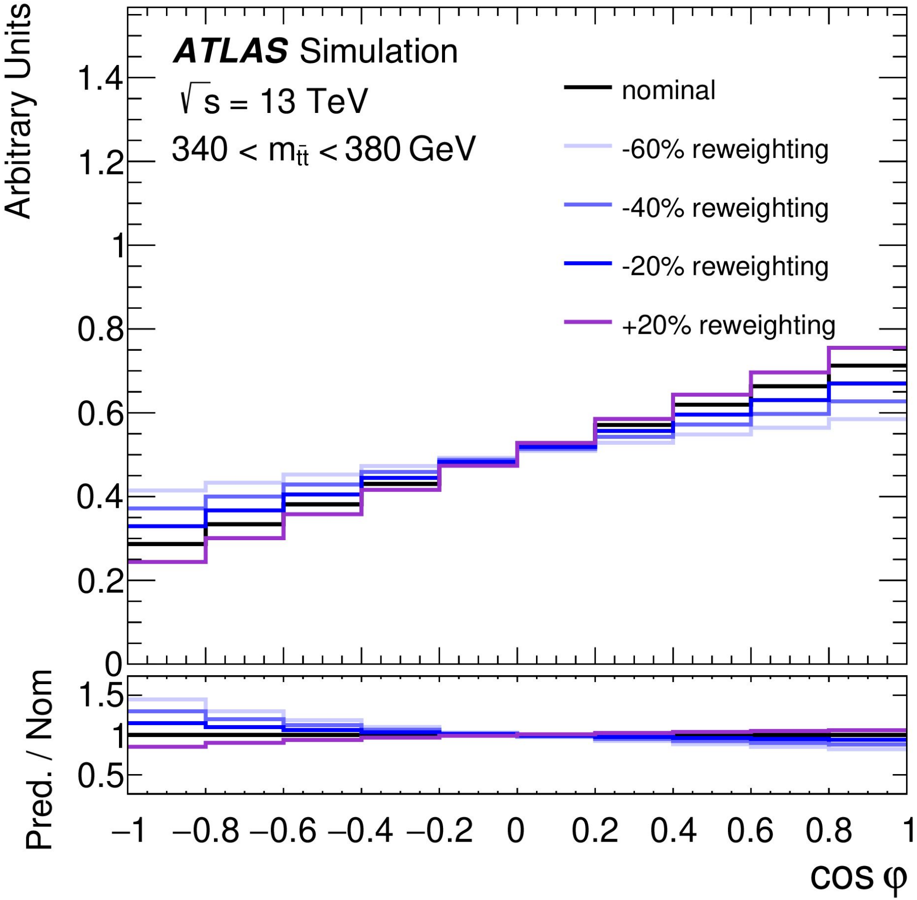
The reweighting method

- We have no handle on the “amount of entanglement” in the generators, but we know exact functional forms at parton-level → can reweight D
- Fit a 3rd order polynomial to extract the dependence on M(tt̄)

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

- Then reweight each event as

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



A closer look at uncertainties

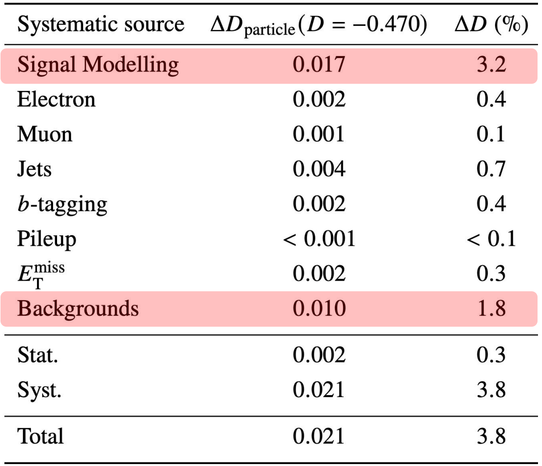
Nature 633 (2024) 542

“Backgrounds”: mostly $Z\rightarrow\tau\tau$, which leads to a flat cos(φ) distribution

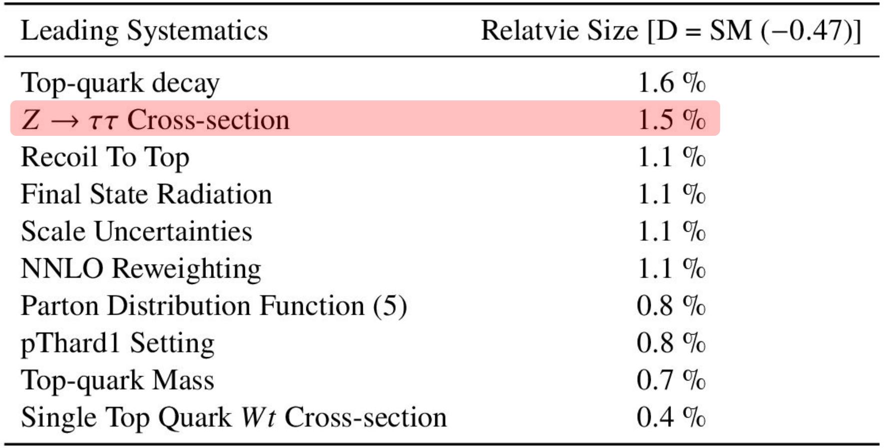
(spin information from taus is lost)

Calibrating to fiducial particle-level reduces the parton shower uncertainty (Pythia vs Herwig) : full details in the paper.

Signal modelling: by far the largest contribution



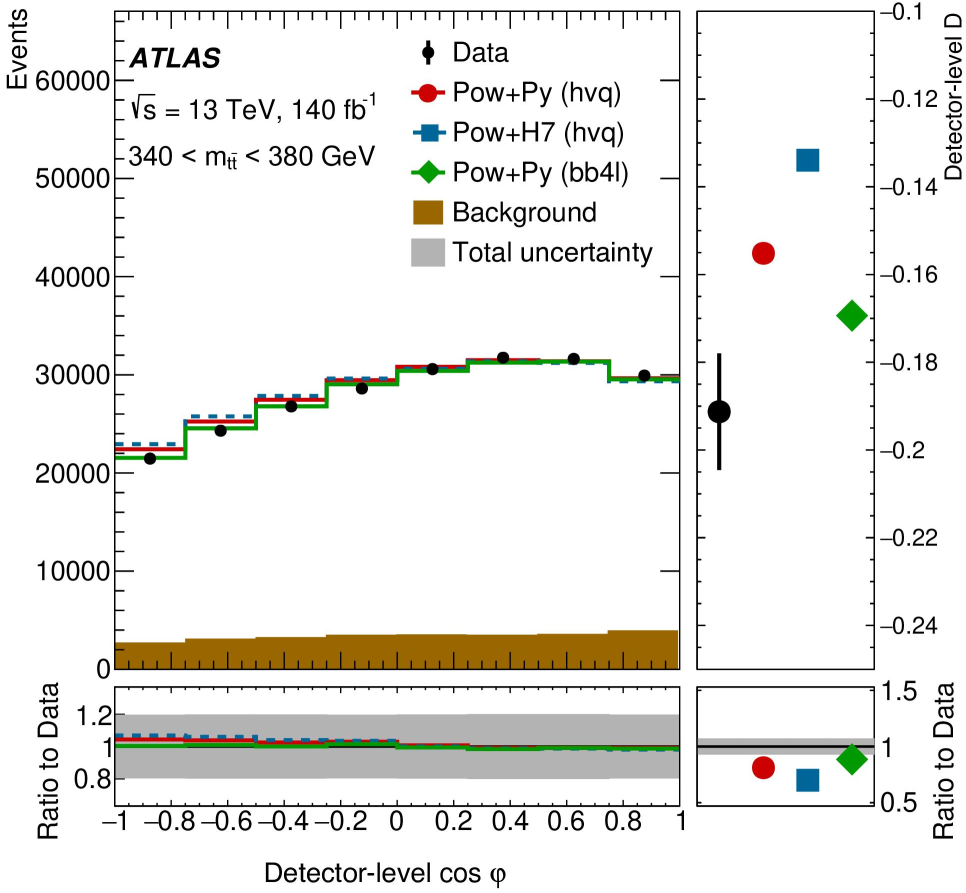
Systematic source	$\Delta D_{\text{particle}}\,(D=-0.470)$	ΔD (%)
Signal Modelling	0.017	3.2
Electron	0.002	0.4
Muon	0.001	0.1
Jets	0.004	0.7
b-tagging	0.002	0.4
Pileup	< 0.001	< 0.1
$E_{\text{T}}^{\text{miss}}$	0.002	0.3
Backgrounds	0.010	1.8
Stat.	0.002	0.3
Syst.	0.021	3.8
Total	0.021	3.8



Leading Systematics	Relatvie Size [D = SM (−0.47)]
Top-quark decay	1.6 %
$Z\rightarrow\tau\tau$ Cross-section	1.5 %
Recoil To Top	1.1 %
Final State Radiation	1.1 %
Scale Uncertainties	1.1 %
NNLO Reweighting	1.1 %
Parton Distribution Function (5)	0.8 %
pThard1 Setting	0.8 %
Top-quark Mass	0.7 %
Single Top Quark Wt Cross-section	0.4 %

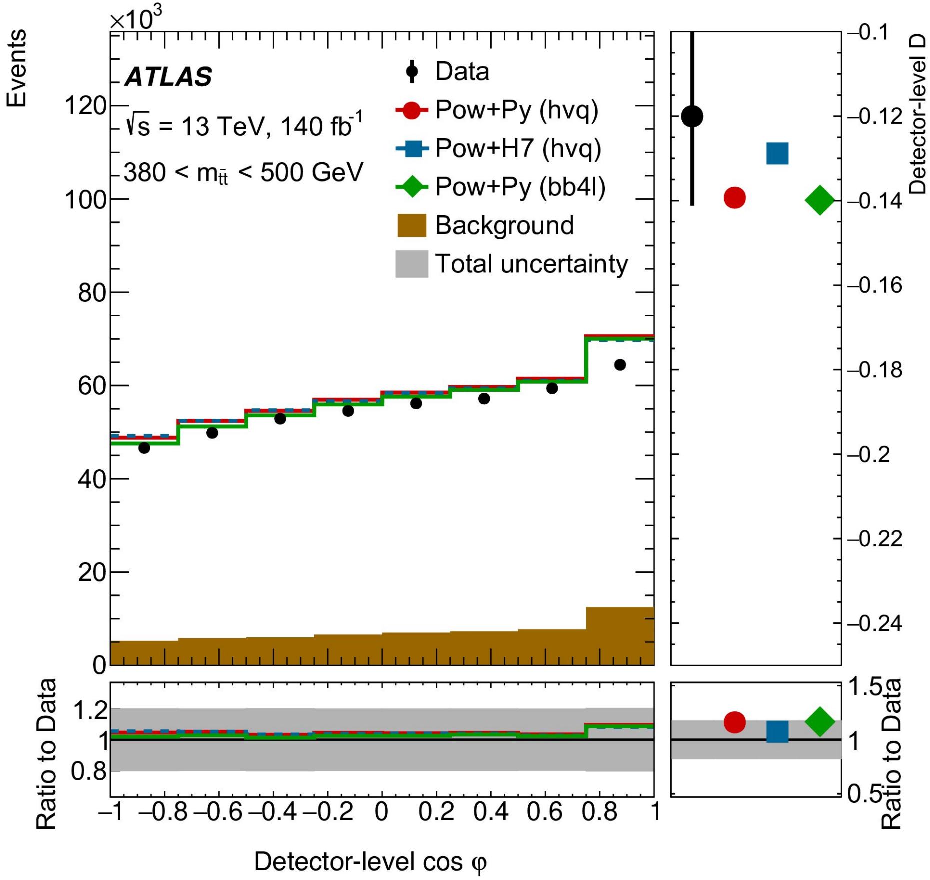
Data / MC in the signal region

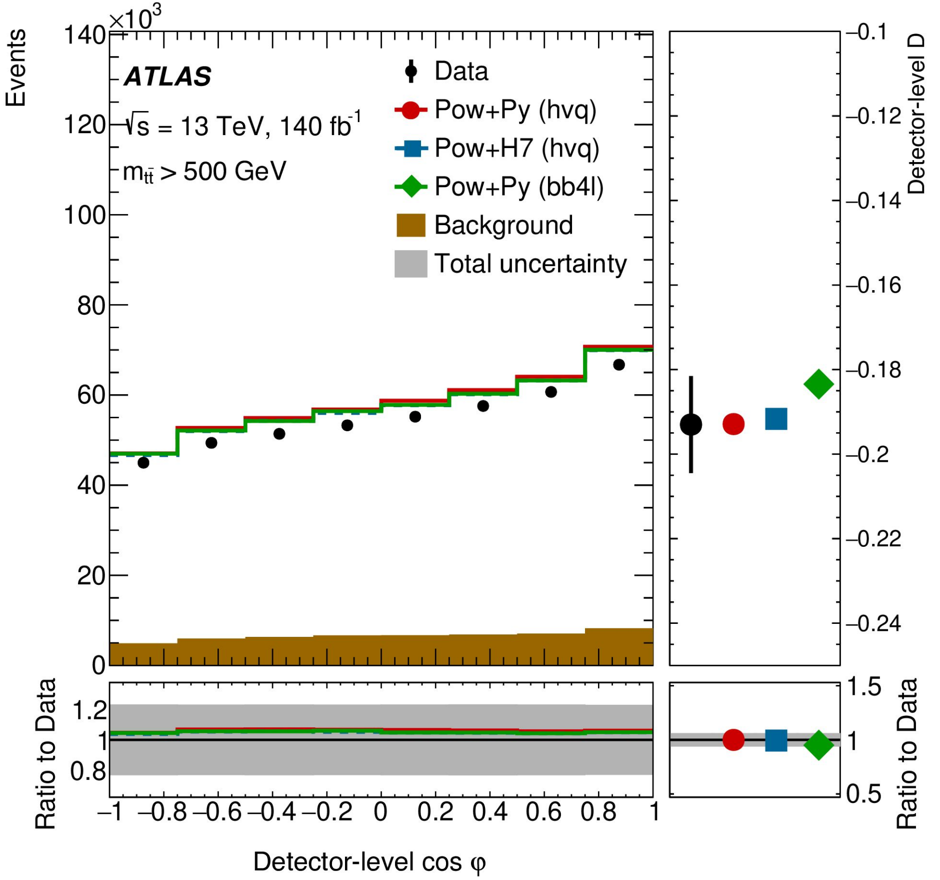
Nature 633 (2024) 542



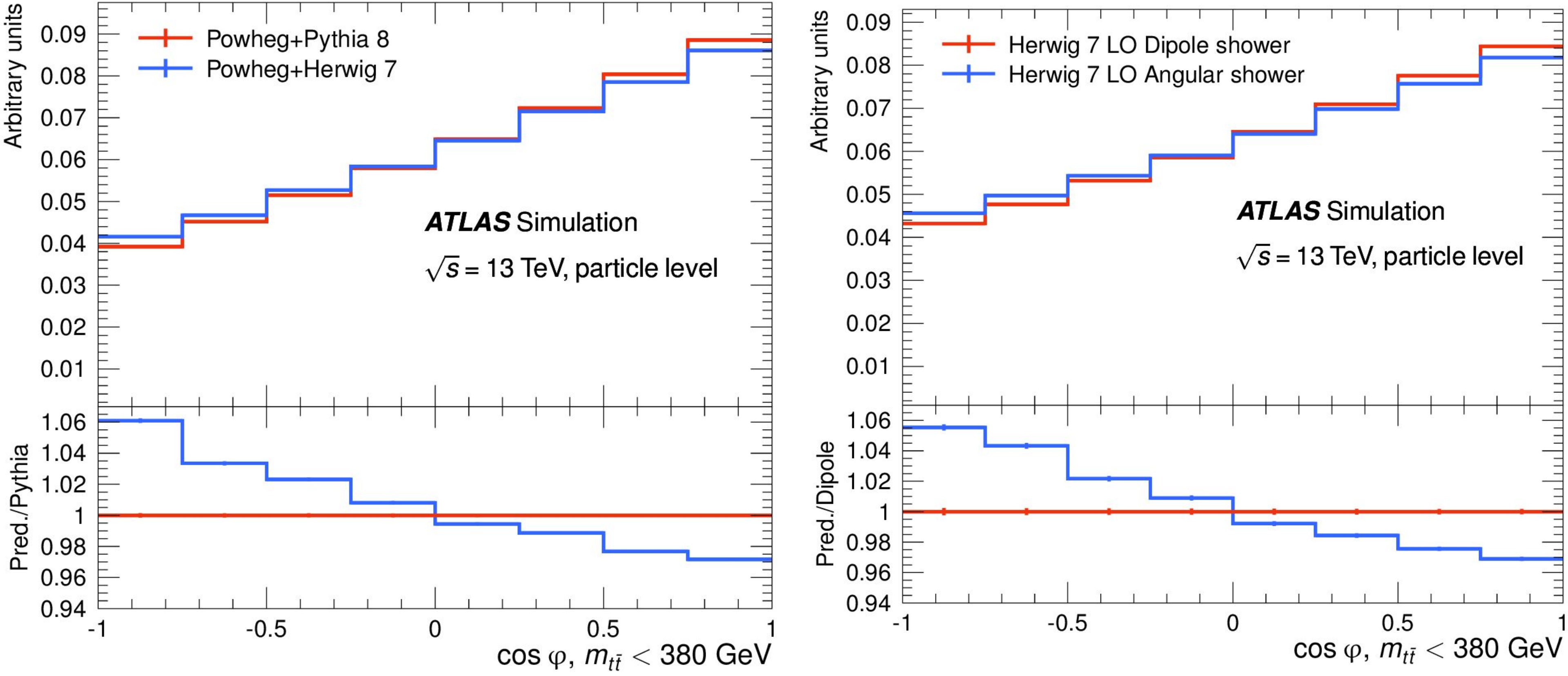
Data / MC outside the signal region

Nature 633 (2024) 542





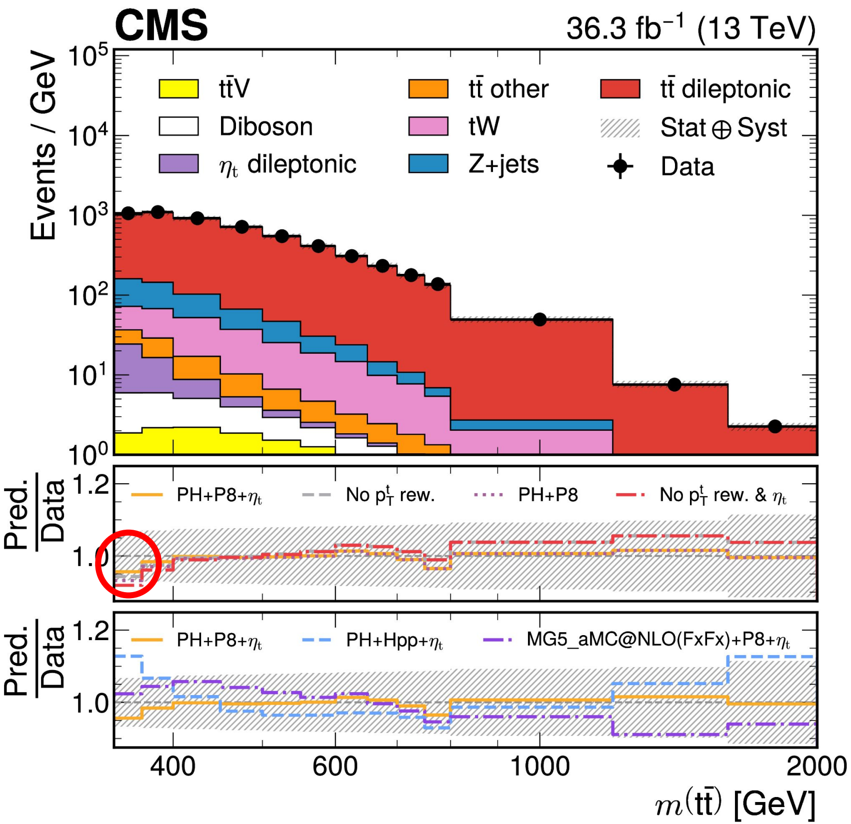
Investigations of parton shower effects



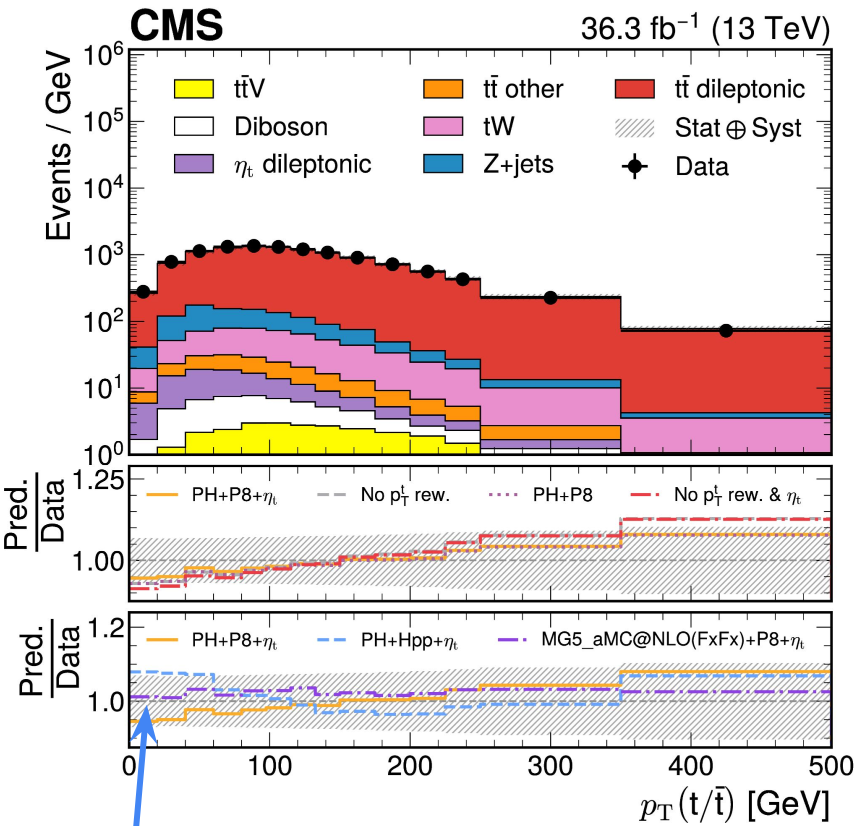
Differences appear in the parton→particle level transition,
and seem to largely match the Dipole vs Angular ordering schemes

Modelling in the inclusive phase-space

Rep. Prog. Phys. 87 (2024) 117801



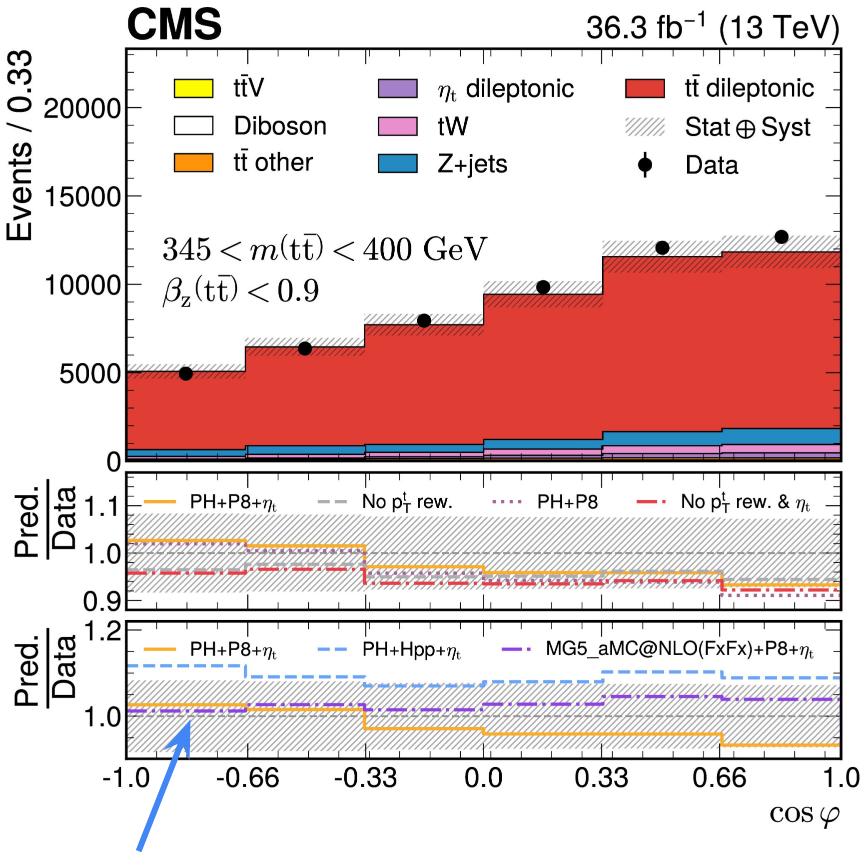
Toponium improves modelling



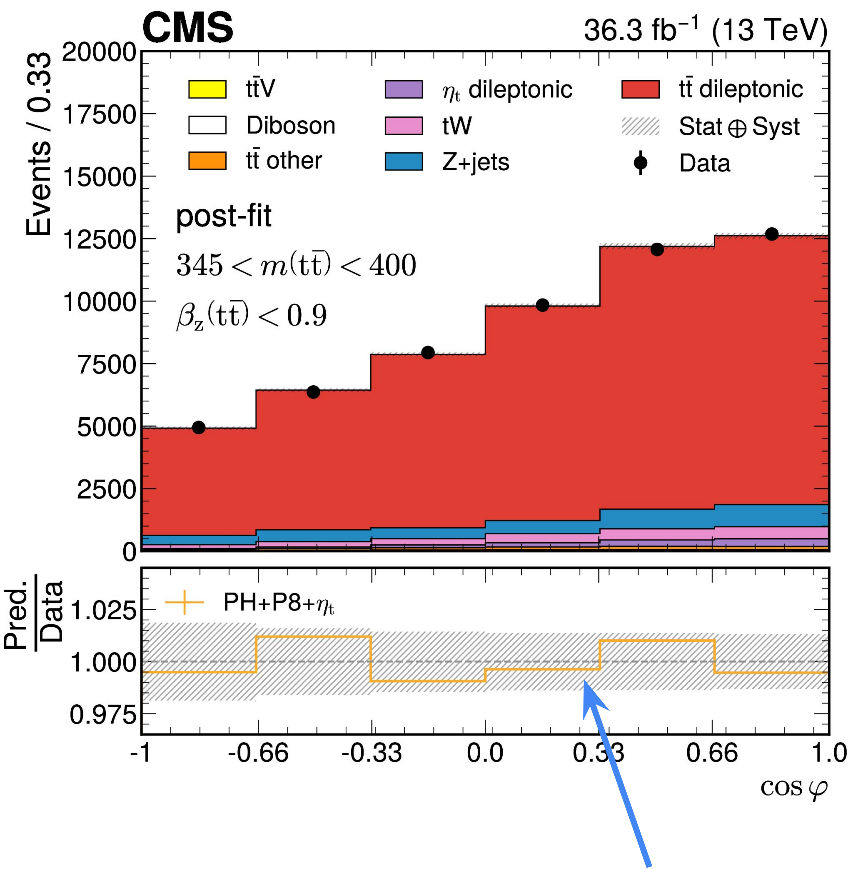
***FxFx**: better for p_T than $M(t\bar{t})$*

Modelling at threshold

[Rep. Prog. Phys. 87 (2024) 117801](#)



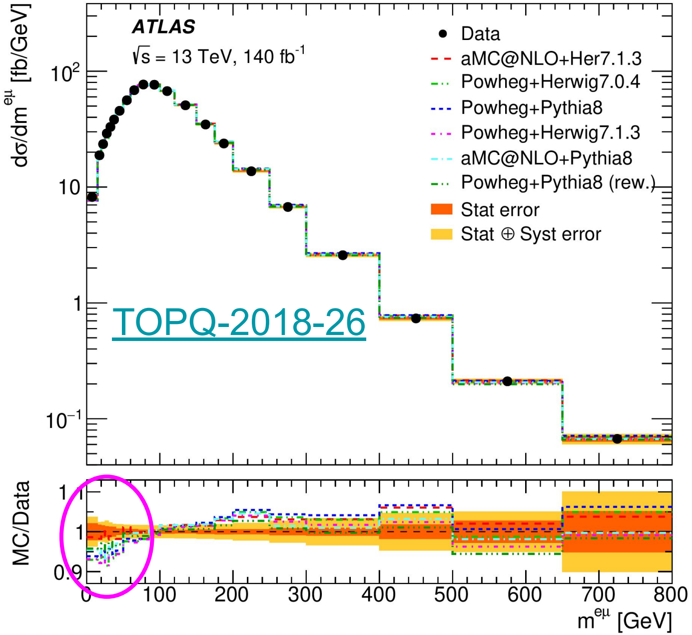
***FxFx** gives best modelling at threshold*

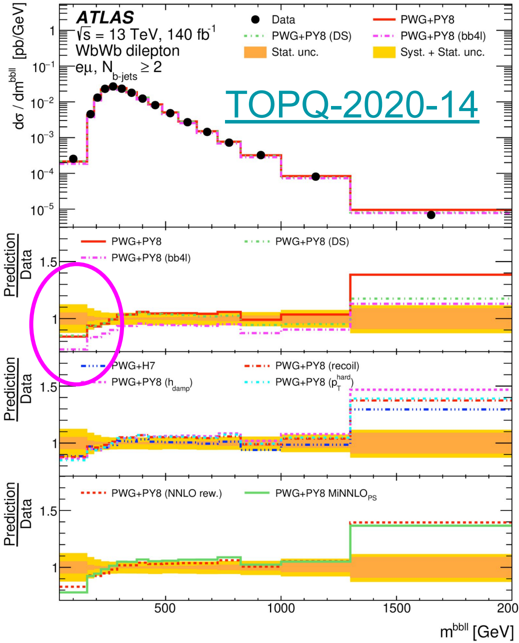


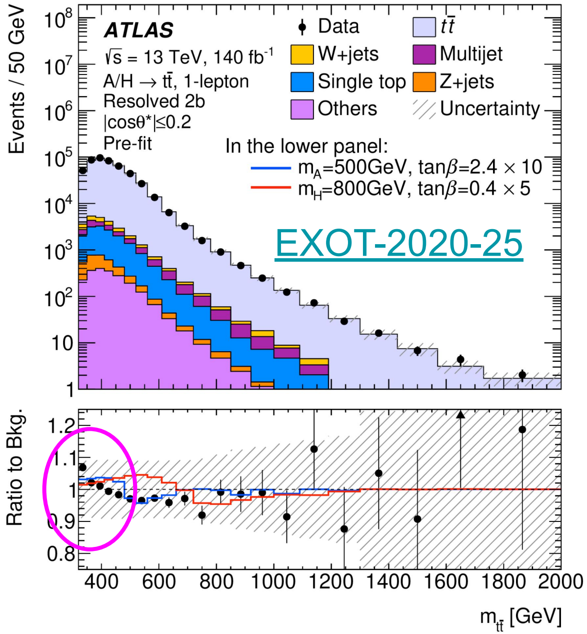
*Post-fit clearly prefers **toponium***

Previous hints: differential cross sections & BSM searches

- Slight excess in data near production threshold
    - the inclusive toponium cross section is roughly 0.6% that of inclusive tt̄ at 13 TeV
    - we don't have the resolution to see it directly in $m_{t\bar{t}}$
    - **need to use spin-sensitive observables** to leverage the pseudoscalar component







Event selection

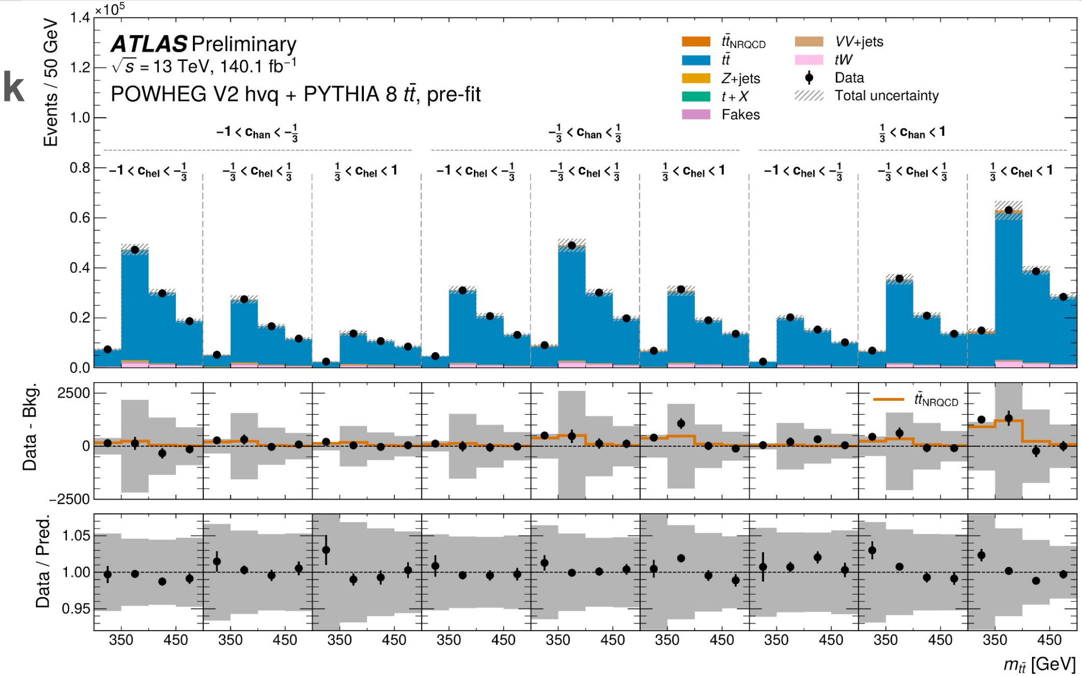
ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

Selection requirement	**ATLAS**	**CMS**
Leptons	Exactly 2 $p_T \geq 25/27/28, 10$ GeV	Exactly 2 $p_T \geq 25, 20$ GeV
Jets	At least 2 $p_T \geq 25$ GeV	At least 2 $p_T \geq 30$ GeV
b-tagged jets	At least 1 (70% efficiency)	At least 1 (77% efficiency)
Range of reconstructed $m_{t\bar{t}}$	300 to 500 GeV *no overflow above!*	300 to ~1400 GeV *with overflow above*
Only for OSSF ee/μμ		
Dilepton invariant mass	$m_{ll} \geq 15$ GeV $\lvert m_{ll}-m_Z \rvert \geq 10$ GeV	$m_{ll} \geq 20$ GeV $\lvert m_{ll}-m_Z \rvert \geq 15$ GeV
Missing ET	MET ≥ 60 GeV	MET ≥ 40 GeV

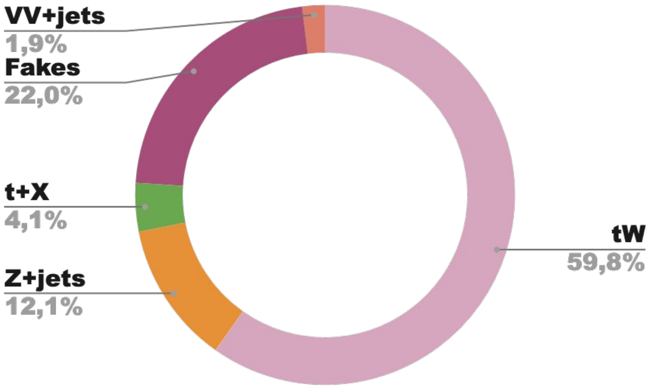
Background estimation

ATLAS-CONF-2025-008

- Expect **~700k tt̄ events** and **~40k additional background events**
    - ○ *for only about ~7k signal events!*
- tW is mostly irreducible, taken from MC with detailed set of systematic uncertainties
- t+X and diboson are negligible

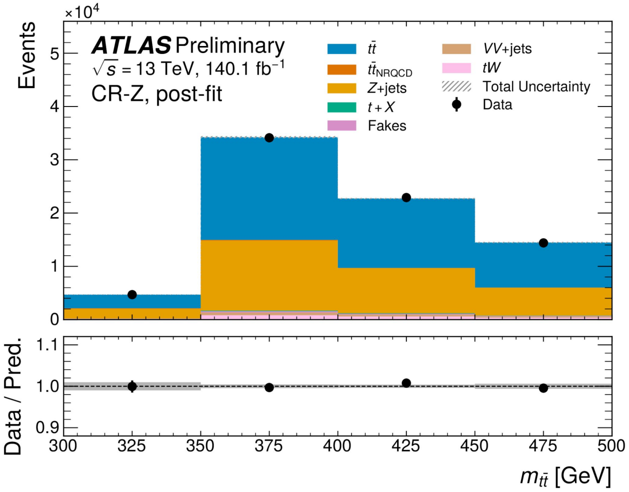


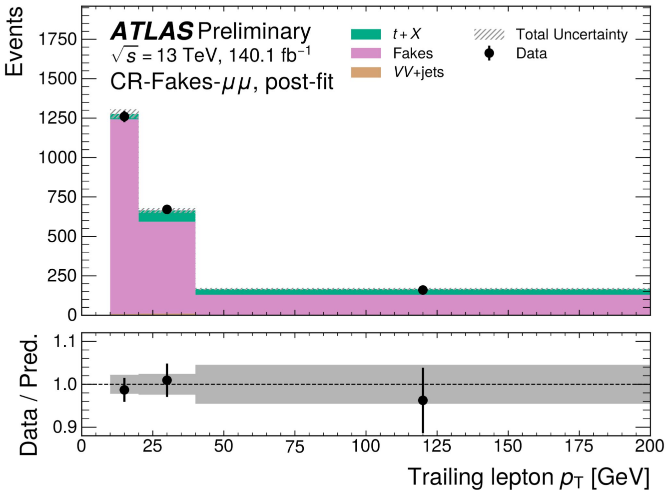
- **CMS:** model contribution of fake leptons directly from MC, use data to normalise Z+jets events
- **ATLAS:** normalise both fake and Z+HF to data, but closer to the SR kinematic space



Background normalisation

- Define a **CR-Z** equivalent to the SR, but inverting the Z-mass cut
  - extract the normalisation of Z+b-jets (1 NF), the leading component in the SR
  - still a large contribution of pQCD tt̄ in the CR-Z, but no toponium due to high m_{ll} requirement!
- Define **CR-Fakes-ee/μμ/eμ** equivalent to the SR, but with same-sign leptons
  - extract the normalisation of electron and muon fakes from HF decays, and electron fakes from photon conversions (3 NFs)
  - sub-leading lepton p_T provides good enough separation power between types of fakes





Statistical analysis

- Perform a **binned detector-level profile-likelihood fit** in the 9 SRs
    - ATLAS also includes the CR-Z and 3 CR-Fakes directly in the likelihood, CMS propagates the normalisation factors for Z+jets from an auxiliary measurement
    - **20 bins of $m_{t\bar{t}}$ per SR for CMS**, only **4 bins per SR for ATLAS**
- Different assumptions can be tested
    - background-only fit
    - **ATLAS:** check the two different toponium signal models, check also bb4l instead of $t\bar{t}$+tW
    - **CMS:** check pseudo-scalar only vs pseudo-scalar + scalar, check also alternative generators
- **Strong constraints of some $t\bar{t}$ modelling uncertainties are observed** – and indeed expected from previous measurements
    - due to different descriptions of both the $m_{t\bar{t}}$ distribution and spin-sensitive observables in different MC generators [mostly Herwig and bb4l]
    - ATLAS applies a “partial decorrelation by region” approach to these problematic uncertainties
        - split the nuisance parameter into 1 fully correlated part (retaining 50% of the effect) and N uncorrelated parts (another 50%) in each region [here N=9+4=13]
        - many other approaches were also tested, no effect on the central values, but constraints can be relaxed and goodness-of-fit (GoF) improved

Systematic uncertainties

ATLAS-CONF-2025-008
RoPP, 88 (2025) 087801

Type	**ATLAS**	**CMS**
Experimental	electrons, muons, jets, b-tagging, MET, pileup, luminosity	
Minor backgrounds	normalisation unc. only	normalisation unc. μ_R/μ_F and ISR/FSR for Drell-Yan
Fake background	normalised in data shape variations	shape variations only
tW background	aNNLO normalisation with 4% unc. parton shower [Herwig 7.2], matching [pThard, hdamp], interference scheme [DR/DS], top mass [±0.5 GeV]	aNNLO normalisation with 15% unc. μ_R/μ_F and ISR/FSR
Signal toponium modelling	μ_R/μ_F, PDF + α_S PS [Herwig 7.2] and ISR/FSR obtained from particle-level reweighting	μ_F [μ_R irrelevant because of contact interaction] top mass [±1 GeV], corr. with pQCD $t\bar{t}$ ISR/FSR PDF found to be negligible

Systematic uncertainties: $t\bar{t}$ modelling

ATLAS-CONF-2025-008
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Type	**ATLAS**	**CMS**
Scales & PDF	— PDF + α_S [PDF4LHC15]	μ_R/μ_F [NLO QCD] PDF + α_S [NNPDF3.1], with PCA
Higher-order reweighting	NNLO QCD: scales NLO EW: additive vs multiplicative schemes [top Yukawa variation tested, irrelevant]	— NLO EW: additive vs multiplicative schemes, and ±11% variation of top Yukawa
Top quark mass	±0.5 GeV	±1 GeV
Top quark decay and off-shell effects	compare hvq+tW DS and bb4l [bb4l is reweighted independently to HO]	compare hvq+tW DR and bb4l [bb4l is reweighted like hvq to HO]
Parton shower and hadronisation	Powheg+Herwig 7.2	Powheg+Herwig 7.2
ME/PS matching (Powheg)	hdamp = $1.5m_t \rightarrow 2m_t$ pThard = $0 \rightarrow 1$	hdamp = $1.58m_t$ $+0.66m_t$ $-0.59m_t$ —

Systematic uncertainties: $t\bar{t}$ modelling

ATLAS-CONF-2025-008
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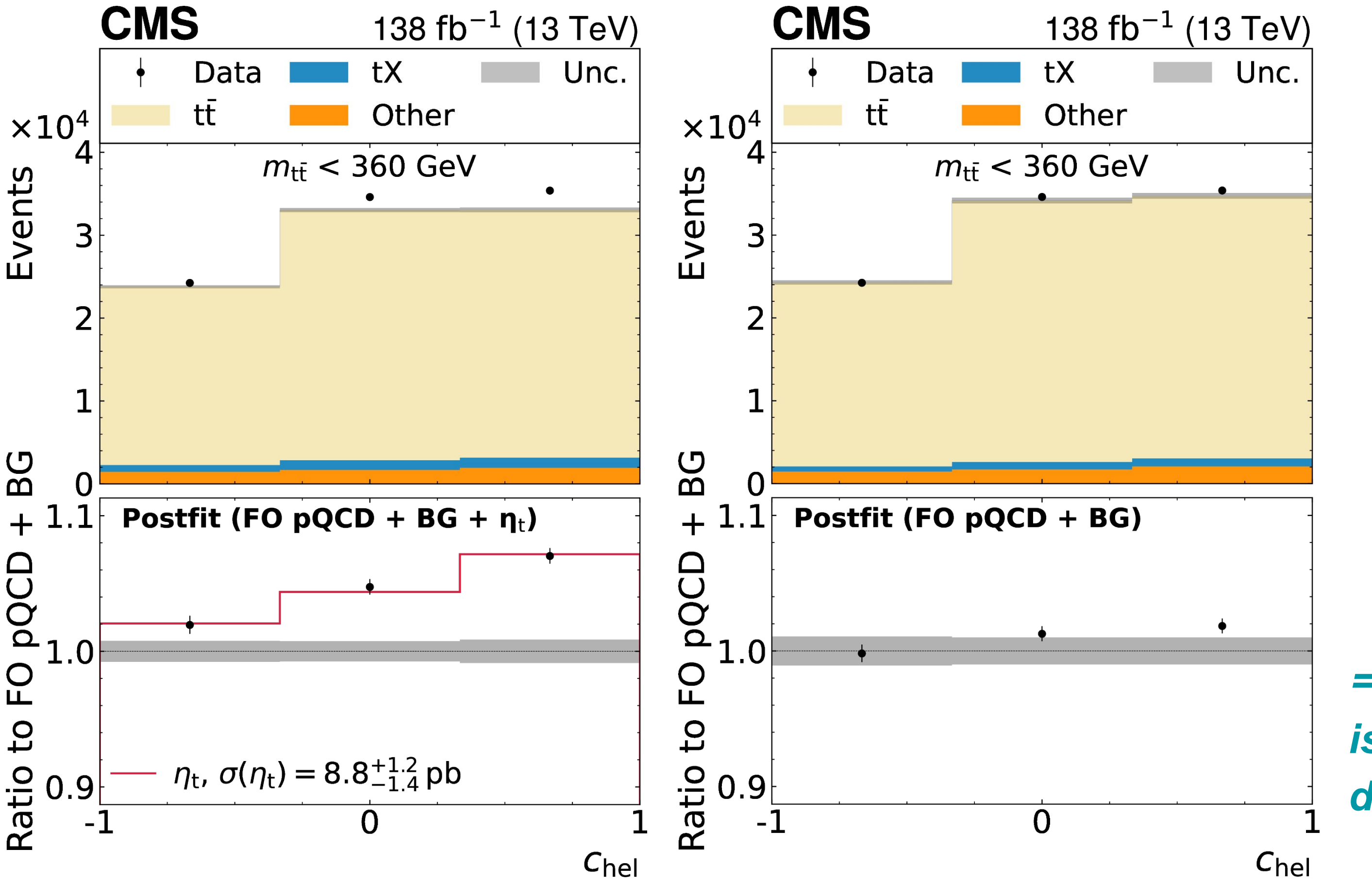
Type	**ATLAS**	**CMS**
Initial state radiation (Pythia) Final state radiation (Pythia)	Var3c variation of the A14 tune (α_S) μ_R variation in the PS	μ_R variation in the PS μ_R variation in the PS
Recoil scheme (Pythia)	recoil-to-colour → recoil-to-top	—
Colour reconnection (Pythia)	maximum of CR1 [QCD-based] and CR2 [gluon-move] compared to CR0 [MPI-based] [CR2-based unc. found negligible]	CR1 and CR 2 compared to CR0, and CR0 + EarlyResonanceDecay compared to CR0 [CR2-based unc. found negligible]
Underlying event (Pythia)	Var1 variation of the A14 tune	variations of the CP5 tune

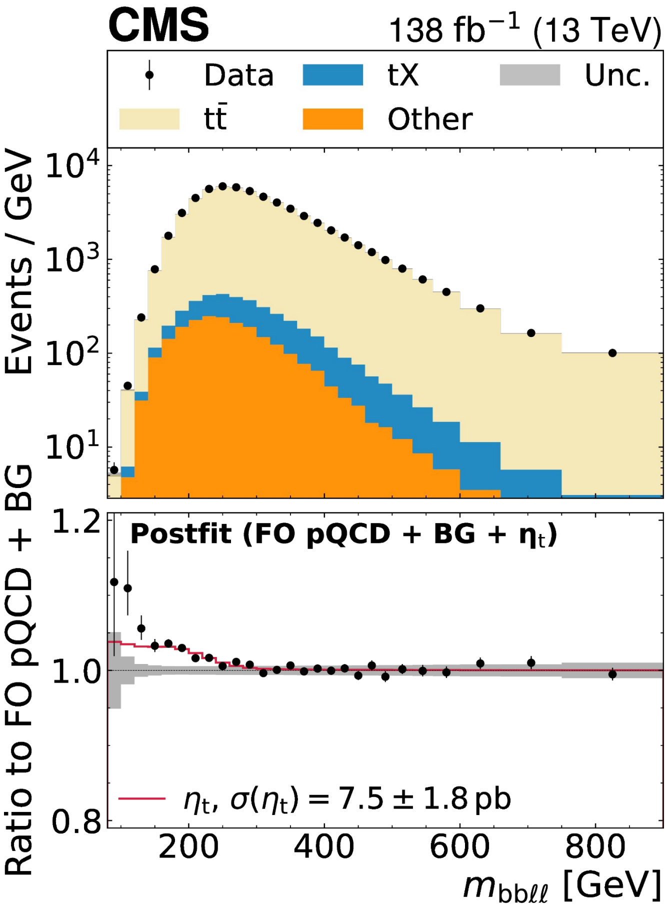
Further checks: background-only fits

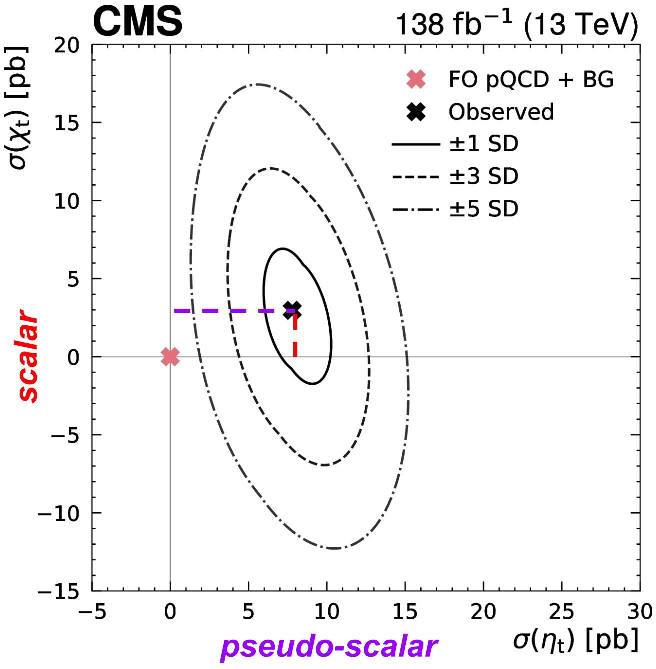


- **Residual slope clearly visible** in the fit **without any toponium** template
- **Large unphysical pulls** of many uncertainties
- **Significantly degraded GoF** for ATLAS

⇒ toponium-like signal is needed to explain the data!

Further checks: alternative templates





- **Fit to m_{bbll}** instead of $m_{t\bar{t}}$ is less precise but still returns compatible cross section
- Fit to both **scalar** and **pseudo-scalar** components prefers the pseudo-scalar hypothesis to >5σ

Further checks: alternative models

- Various combinations of toponium and pQCD $t\bar{t}$ models have been checked by **ATLAS** and **CMS**
- The extracted toponium cross sections (in pb) are reported below

Models	Powheg hvq + Pythia 8	Powheg hvq + Herwig 7	aMC@NLO FxFx + Pythia 8	Powheg bb4l + Pythia 8
NRQCD [Fuks et al.]	**9.0 ± 1.3**	—	—	**4.2 ± 1.0**
η_t [Maltoni et al.]	**8.8 ± 1.3** **13.4 ± 1.9**	**8.6 ± 1.1**	**9.8 ± 1.3**	**6.6 ± 1.4**

- All models point to an excess **compatible with toponium formation**, with two caveats
  - ATLAS sees slightly different results between the two toponium models, likely due to the differences in top kinematics affecting the reconstruction → **~2σ tension with CMS if both use the same model**
  - **the results obtained with bb4l are weaker**: still need to study and validate this model [tuning?], but kinematic reweighting to higher-order already identified as a current limitation → *follow-up ATLAS paper to adopt new recommendations from theorists*

Normalisation of bb4l: HO tt̄ + HO tW vs DPA NNLO

From the recent paper by Jonas Lindert et al.: arXiv:2507.11410

The ***DPA NNLO cross section*** *for bb4l dilepton is:*

10278 ± 55 (MC/extrapolation) ± 152 (NWA) fb = **10278 ± 162 fb**

The branching ratio they use is **BR(W→lv)=10.8598%**

Therefore the inclusive cross section is: **871.5 ± 13.7 pb**

The HO tt̄ cross section is: 833.9 ± 30 (scales) ± 21 (PDF) ± 23 (m_{top}) pb

The HO tW cross section is: 79.3 ± 1.9 (scales) ± 2.2 (PDF) ± 1.2 (m_{top}) pb

The total HO cross section is: 913.2 ± 30 (scales) ± 21 (PDF) ± 23 (m_{top}) pb = **913.2 ± 43.4 pb**

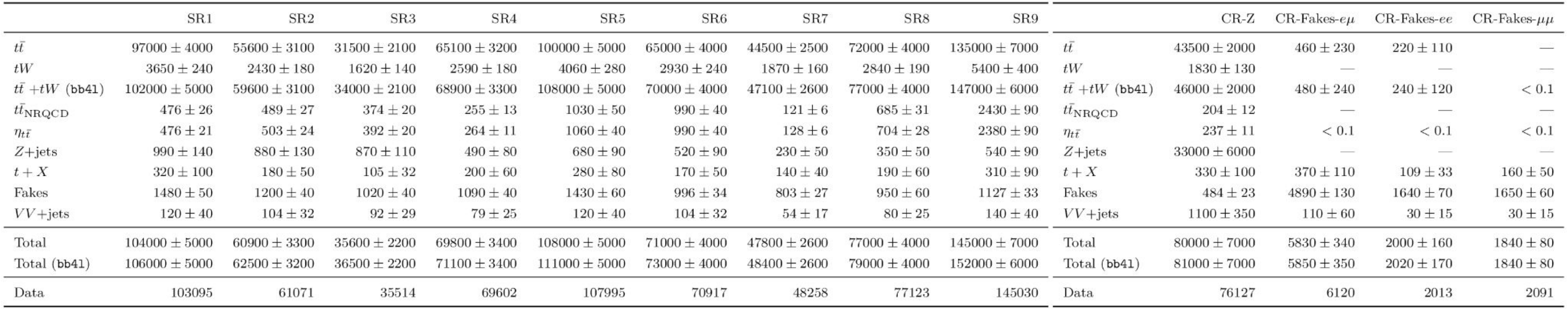
Therefore the ***ratio DPA/sum(HO)*** *is*: **0.954 ± 0.048** [assuming no correlation]

or: **0.954 ± 0.030** [assuming full correlation]

Quote from Jonas Lindert: “proper comparison would require careful alignment of all input parameters”

Background estimation (ATLAS)

ATLAS-CONF-2025-008



	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9
$t\bar{t}$	97000 ± 4000	55600 ± 3100	31500 ± 2100	65100 ± 3200	100000 ± 5000	65000 ± 4000	44500 ± 2500	72000 ± 4000	135000 ± 7000
tW	3650 ± 240	2430 ± 180	1620 ± 140	2590 ± 180	4060 ± 280	2930 ± 240	1870 ± 160	2840 ± 190	5400 ± 400
$t\bar{t}$ $+tW$ (`bb4l`)	102000 ± 5000	59600 ± 3100	34000 ± 2100	68900 ± 3300	108000 ± 5000	70000 ± 4000	47100 ± 2600	77000 ± 4000	147000 ± 6000
$t\bar{t}_{\mathrm{NRQCD}}$	476 ± 26	489 ± 27	374 ± 20	255 ± 13	1030 ± 50	990 ± 40	121 ± 6	685 ± 31	2430 ± 90
$\eta_{t\bar{t}}$	476 ± 21	503 ± 24	392 ± 20	264 ± 11	1060 ± 40	990 ± 40	128 ± 6	704 ± 28	2380 ± 90
Z+jets	990 ± 140	880 ± 130	870 ± 110	490 ± 80	680 ± 90	520 ± 90	230 ± 50	350 ± 50	540 ± 90
$t + X$	320 ± 100	180 ± 50	105 ± 32	200 ± 60	280 ± 80	170 ± 50	140 ± 40	190 ± 60	310 ± 90
Fakes	1480 ± 50	1200 ± 40	1020 ± 40	1090 ± 40	1430 ± 60	996 ± 34	803 ± 27	950 ± 60	1127 ± 33
VV+jets	120 ± 40	104 ± 32	92 ± 29	79 ± 25	120 ± 40	104 ± 32	54 ± 17	80 ± 25	140 ± 40
Total	104000 ± 5000	60900 ± 3300	35600 ± 2200	69800 ± 3400	108000 ± 5000	71000 ± 4000	47800 ± 2600	77000 ± 4000	145000 ± 7000
Total (`bb4l`)	106000 ± 5000	62500 ± 3200	36500 ± 2200	71100 ± 3400	111000 ± 5000	73000 ± 4000	48400 ± 2600	79000 ± 4000	152000 ± 6000
Data	103095	61071	35514	69602	107995	70917	48258	77123	145030

	CR-Z	CR-Fakes-$e\mu$	CR-Fakes-ee	CR-Fakes-$\mu\mu$
$t\bar{t}$	43500 ± 2000	460 ± 230	220 ± 110	—
tW	1830 ± 130	—	—	—
$t\bar{t}$ $+tW$ (`bb4l`)	46000 ± 2000	480 ± 240	240 ± 120	< 0.1
$t\bar{t}_{\mathrm{NRQCD}}$	204 ± 12	—	—	—
$\eta_{t\bar{t}}$	237 ± 11	< 0.1	< 0.1	< 0.1
Z+jets	33000 ± 6000	—	—	—
$t + X$	330 ± 100	370 ± 110	109 ± 33	160 ± 50
Fakes	484 ± 23	4890 ± 130	1640 ± 70	1650 ± 60
VV+jets	1100 ± 350	110 ± 60	30 ± 15	30 ± 15
Total	80000 ± 7000	5830 ± 340	2000 ± 160	1840 ± 80
Total (`bb4l`)	81000 ± 7000	5850 ± 350	2020 ± 170	1840 ± 80
Data	76127	6120	2013	2091

Largest background: single-top tW production (4%) → detailed systematic model

Smaller backgrounds: Z+jets (0.8%) and fake leptons (1.5%) → decent pre-fit description from MC templates, normalisation to data in CRs.

Uncertainty breakdown (ATLAS)

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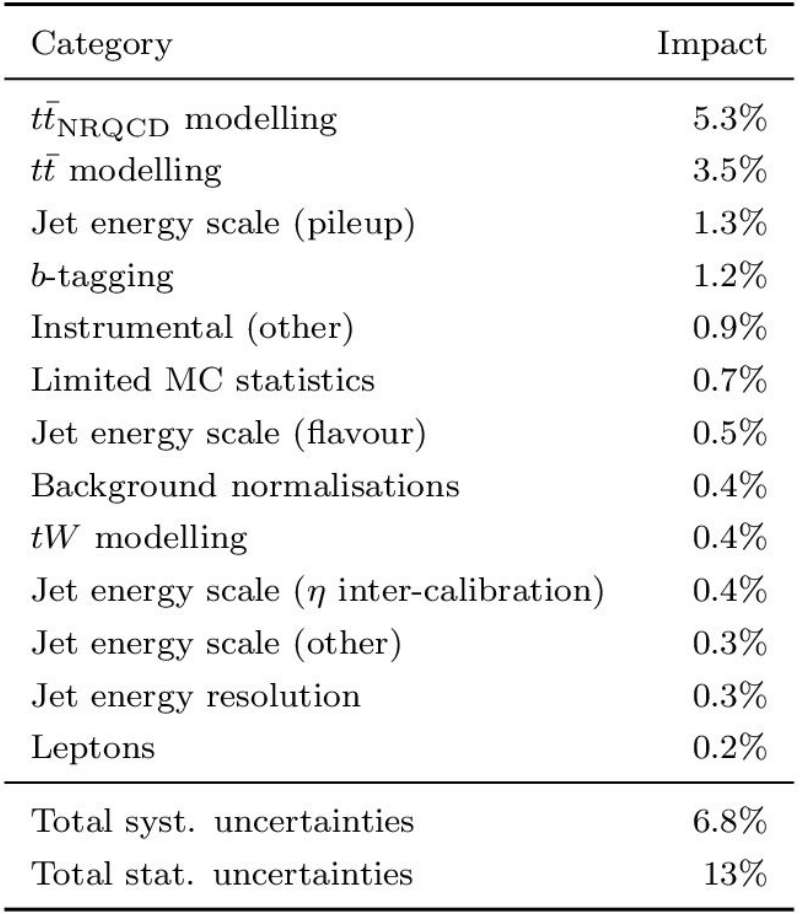

Category	Impact
$t\bar{t}_{\text{NRQCD}}$ modelling	5.3%
$t\bar{t}$ modelling	3.5%
Jet energy scale (pileup)	1.3%
b-tagging	1.2%
Instrumental (other)	0.9%
Limited MC statistics	0.7%
Jet energy scale (flavour)	0.5%
Background normalisations	0.4%
tW modelling	0.4%
Jet energy scale (η inter-calibration)	0.4%
Jet energy scale (other)	0.3%
Jet energy resolution	0.3%
Leptons	0.2%
Total syst. uncertainties	6.8%
Total stat. uncertainties	13%

bb4l settings (ATLAS)

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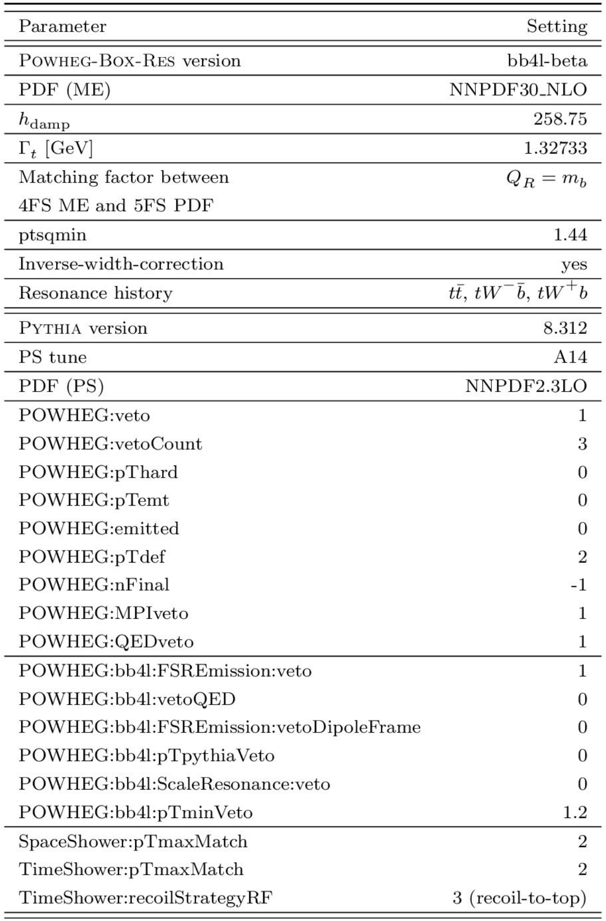
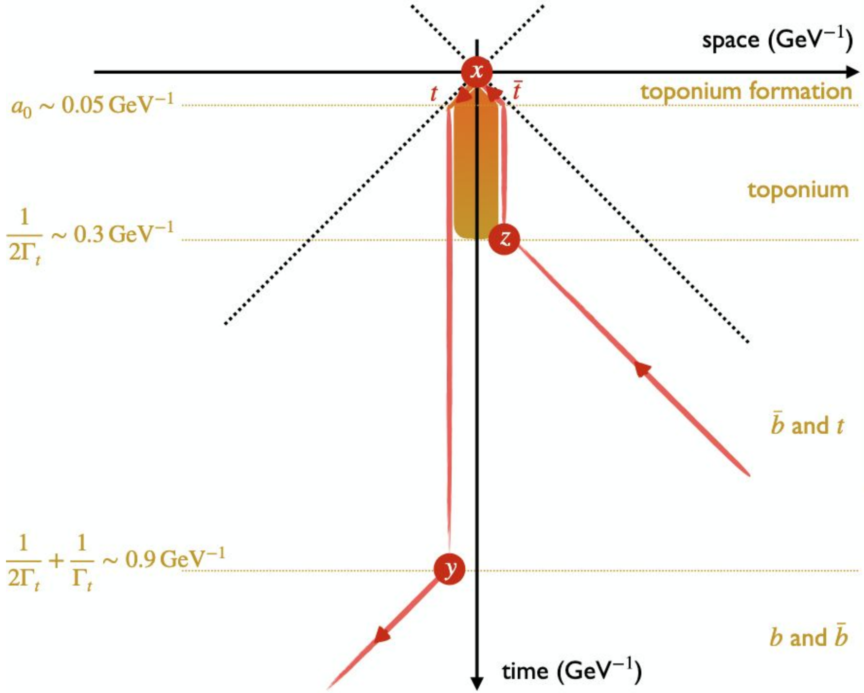


Parameter	Setting
Powheg-Box-Res version	bb4l-beta
PDF (ME)	NNPDF30_NLO
h_{damp}	258.75
Γ_t [GeV]	1.32733
Matching factor between 4FS ME and 5FS PDF	$Q_R = m_b$
ptsqmin	1.44
Inverse-width-correction	yes
Resonance history	$t\bar{t}$, $tW^-\bar{b}$, tW^+b
Pythia version	8.312
PS tune	A14
PDF (PS)	NNPDF2.3LO
POWHEG:veto	1
POWHEG:vetoCount	3
POWHEG:pThard	0
POWHEG:pTemt	0
POWHEG:emitted	0
POWHEG:pTdef	2
POWHEG:nFinal	-1
POWHEG:MPIveto	1
POWHEG:QEDveto	1
POWHEG:bb4l:FSREmission:veto	1
POWHEG:bb4l:vetoQED	0
POWHEG:bb4l:FSREmission:vetoDipoleFrame	0
POWHEG:bb4l:pTpythiaVeto	0
POWHEG:bb4l:ScaleResonance:veto	0
POWHEG:bb4l:pTminVeto	1.2
SpaceShower:pTmaxMatch	2
TimeShower:pTmaxMatch	2
TimeShower:recoilStrategyRF	3 (recoil-to-top)

Timeline of toponium formation

Benjamin Fuks



In analogy with hydrogen atom:

- bound states are characterised by $v \approx \alpha_s$, momenta of order $p \approx m\alpha_s$, the atom size of order $1/(m\alpha_s)$, and energies of order $m\alpha_s^2$
- The time it takes for a top with velocity α_s to cover a distance of order $2\pi/(m\alpha_s)$ is $2\pi/(m\alpha_s^2) \approx$ 3,6 GeV^{-1}
- The toponium lifetime is $\approx 1/(2\boldsymbol{\Gamma}_{top}) \approx$ 0.3 GeV^{-1}

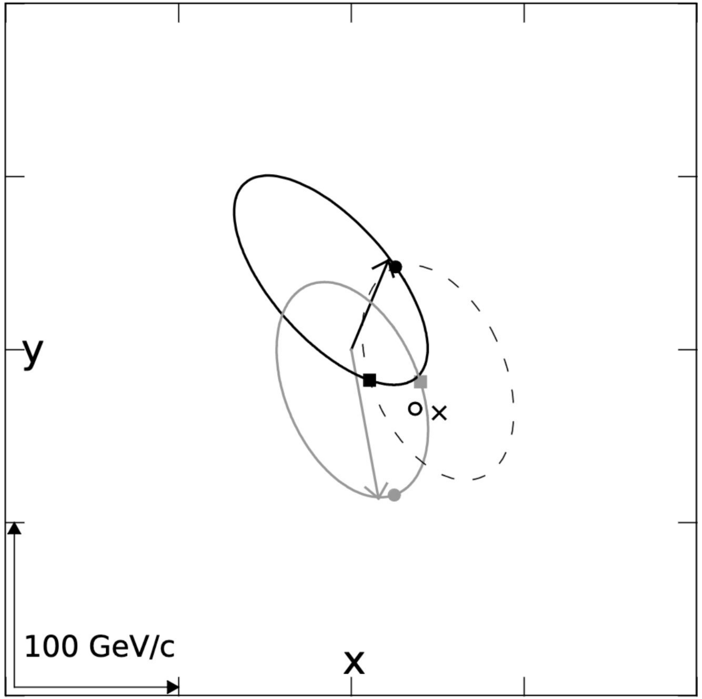
↪A state that decays *before* it can form a well-defined wavefunction (i.e. before one orbit) is usually **not considered a true bound state**, but rather just a correlated state or a near-threshold resonance.

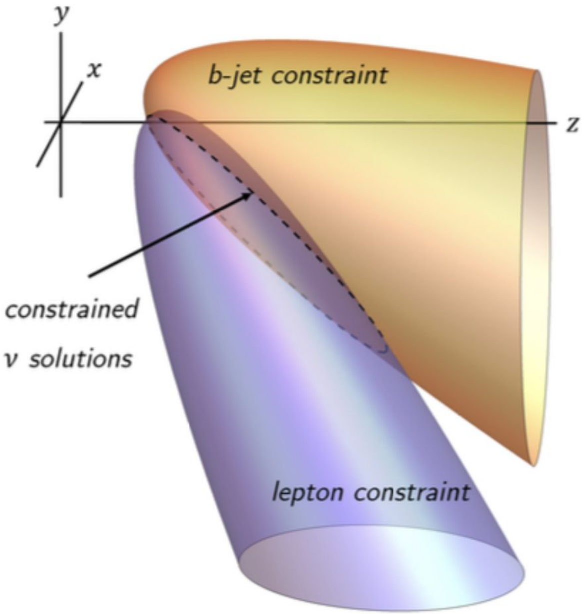
The Ellipses method

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

Assume: everything is on-shell AND neutrinos are the source of the missing E_T

→ neutrino momenta are **geometrically** constrained to an ellipse





The Neutrino Weighting method

Phys. Rev. Lett. 80 (1998) 2063

- Dates back to D0 (1997), they measured $m_{top} = 172.0 \pm 7.5$ GeV
- LHC Run 1 combination (2023) measured $m_{top} = 172.52 \pm 0.33$ GeV
- **Don't assume** that the missing E_T comes from the neutrinos
    - instead **scan (η_1,η_2)** and for each pair extract (p_{x1},p_{y1}) and (p_{x2},p_{y2}) from the mass constraints
    - then compare to missing E_T and extract a weight

$$w = \exp\left(\frac{-\Delta E_x^2}{2\sigma_x^2}\right) \cdot \exp\left(\frac{-\Delta E_y^2}{2\sigma_y^2}\right)$$

- Still have to check the b-jet assignments, possible dependence on m_{top}, smearing in case there are no solutions, …

  → **very CPU-expensive!**

Improved tests of entanglement with tops

- A new **general marker** of quantum entanglement has been proposed
    - in the **threshold** region, exactly what is being done now (D=Tr[C]/3)
    - in the **boosted** region, would need slightly different angular distribution
    - at threshold, additional cut on the tt̄ velocity β can reduce the qq contamination
    - both approaches can increase the statistical sensitivity by ~20%
- Similarly, we can **simplify tests** of Bell's inequality violation
    - sufficient to know the 3 spin correlation coefficients, but better done in the beam basis
    - alternatively, could measure a simple asymmetry

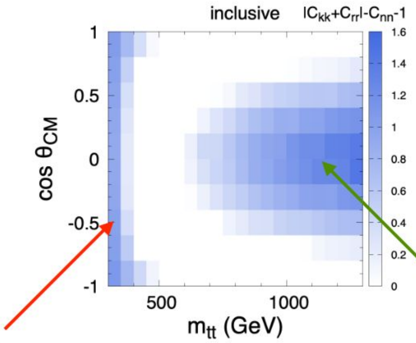
$$E \equiv |C_{kk} + C_{rr}| - C_{nn} - 1 > 0$$

spin correlations

	Threshold $\not\beta$	Threshold β	Boosted
Individual	0.021 ± 0.053	0.119 ± 0.074	0.218 ± 0.141
Direct	0.027 ± 0.035	0.121 ± 0.045	0.208 ± 0.125

asymmetry

cut on β



Threshold region,

$E = -(C_{kk} + C_{rr} + C_{nn}) - 1 > 0$

Boosted region,

$E = C_{kk} + C_{rr} - C_{nn} - 1 > 0$

Quantum Discord

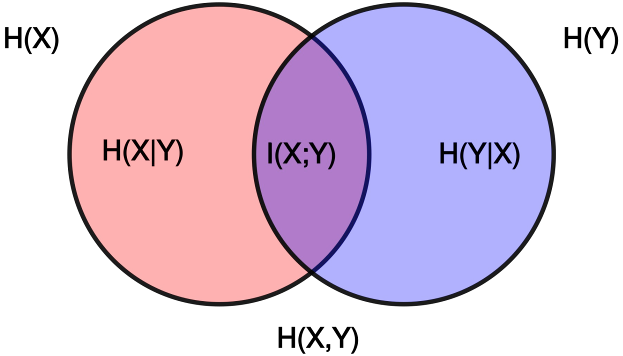
Y. Afik & JRMdN (2023)
T. Han & M. Low & N. McGinnis & S. Su (2024)

Captures the ***non-classicality of correlations*** by measuring differences in the **total mutual information** [Shannon entropy H → von Neumann entropy S]

$$I(X;Y) = H(X) + H(Y) - H(X,Y)$$

$$J(X;Y) = H(X) - H(X|Y)$$

$$I(X;Y) \stackrel{?}{=} J(X;Y)$$ [classically they are the same]



Discord → $\mathcal{D}_A = S(\rho_B) - S(\rho) + \min_{\hat{\mathbf{n}}} p_{\hat{\mathbf{n}}} S(\rho_{\hat{\mathbf{n}}}) + p_{-\hat{\mathbf{n}}} S(\rho_{-\hat{\mathbf{n}}})$

- In general: **$0 \leq D_A \leq 1$** and **D_A != D_B**
- **Experimentally very challenging!** Requires a ***minimisation*** over projective measurements.
- **Analytical results exist** for special classes of states (e.g. Bell-diagonal states, T states)

$$S(\rho) = -\mathrm{Tr}\rho \log_2 \rho \qquad \rho_{\hat{\mathbf{n}}} = \frac{1 + \mathbf{B}^{+}_{\hat{\mathbf{n}}} \cdot \sigma}{2}, \ \mathbf{B}^{+}_{\hat{\mathbf{n}}} = \frac{\mathbf{B}^{+} + \mathbf{C} \cdot \hat{\mathbf{n}}}{1 + \hat{\mathbf{n}} \cdot \mathbf{B}^{-}}, \ p_{\hat{\mathbf{n}}} = \frac{1 + \hat{\mathbf{n}} \cdot \mathbf{B}^{-}}{2}$$

Closed-form formulae when A is a qubit

T. Han & M. Low & N. McGinnis & S. Su (2024)

$$\mathcal{D}_A = S(\rho_B) - S(\rho) + \boxed{\min_{\hat{\mathbf{n}}}} p_{\hat{\mathbf{n}}} S(\rho_{\hat{\mathbf{n}}}) + p_{-\hat{\mathbf{n}}} S(\rho_{-\hat{\mathbf{n}}})$$

$$\mathcal{U}(\rho) \equiv \boxed{\min_{K_A}} \mathcal{I}(\rho, K_A \otimes \mathbb{I}_B)$$

Our **alternative measure of discord** suffers from the **same issue**: we need to perform a **minimisation** over possible measurements…

- Discord: get around this **only for X-states** [this is the case for tt̄ at LO in QCD]
- **LQU: closed-form formula valid for generic 2 x d systems!** [qubit-qudit]

Pick non-degenerate observables K_A on the qubit A such that $K_A = \vec{n} \cdot \vec{\sigma}, \ |\vec{n}| = 1$

Then compute the eigenvalues (w_1,w_2,w_3) of the matrix

$$\left(\mathcal{W}\right)_{ij} \equiv \mathrm{Tr}\left\{\sqrt{\rho}\left(\sigma_{Ai} \otimes \mathbb{I}_2\right)\sqrt{\rho}\left(\sigma_{Aj} \otimes \mathbb{I}_2\right)\right\}$$

The LQU simplifies to $\boxed{\mathcal{U}\left(\rho\right) = 1 - \max\left(\omega_1, \omega_2, \omega_3\right)}$

[we only need the SDM!]