

Quantum tops at the LHC

Universität Bern – AEC Seminar, 25/03/2025
Baptiste Ravina (CERN)



- tt 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

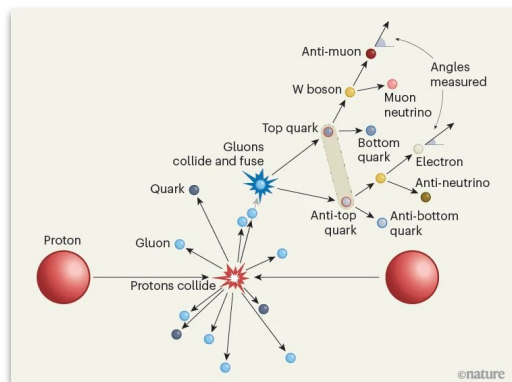
Quarks show that quantum entanglement holds at high energies

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 times¹⁻⁴ and is key to developments in quantum computing and quantum cryptography. In a [paper in Nature](#), the ATLAS Collaboration⁵ 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

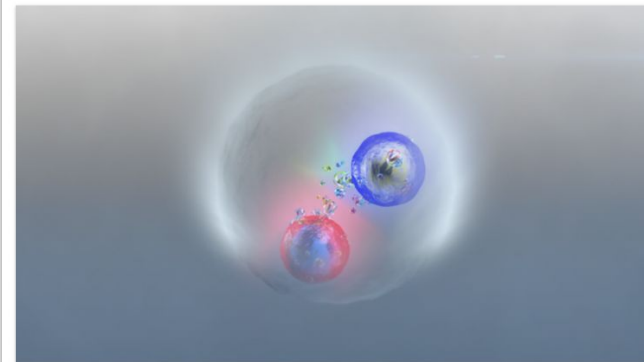
Data from the CMS experiment at CERN's Large Hadron Collider reveals an intriguing excess of top-quark pairs, hinting at the first observation of a composite particle with unique properties

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

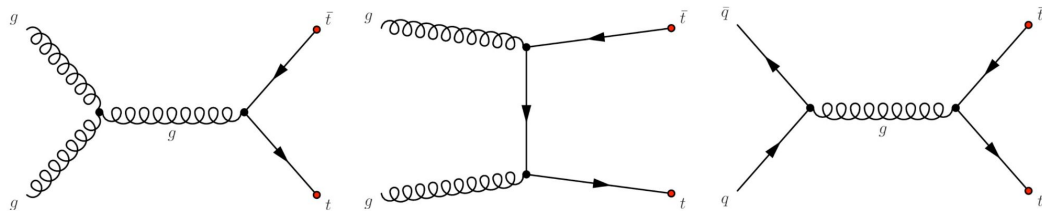
8 JULY, 2025



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

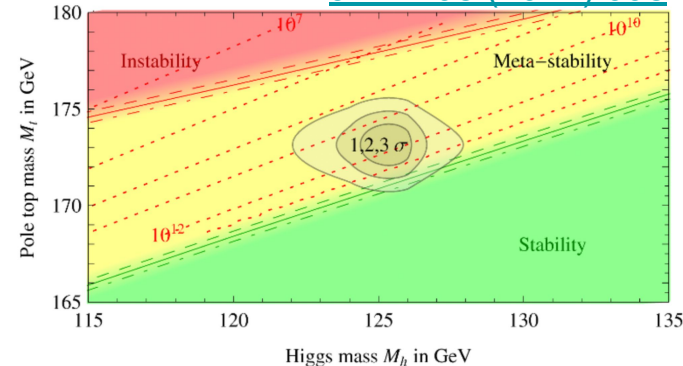


- **Most massive** fundamental particle in the SM
- its Mass / Yukawa is a free parameter: need to measure it
- Mean lifetime $\sim 5 \times 10^{-25} \text{s} \ll 1/\Lambda_{\text{QCD}} \sim 10^{-23} \text{s}$
- the only “bare quark”
- $\text{BR}(t \rightarrow Wb) \sim 100\%$
- **unique experimental signature**
- Abundant production at the LHC, $O(100\text{M})$ pairs
- **“standard candle”**, very useful for calibrations

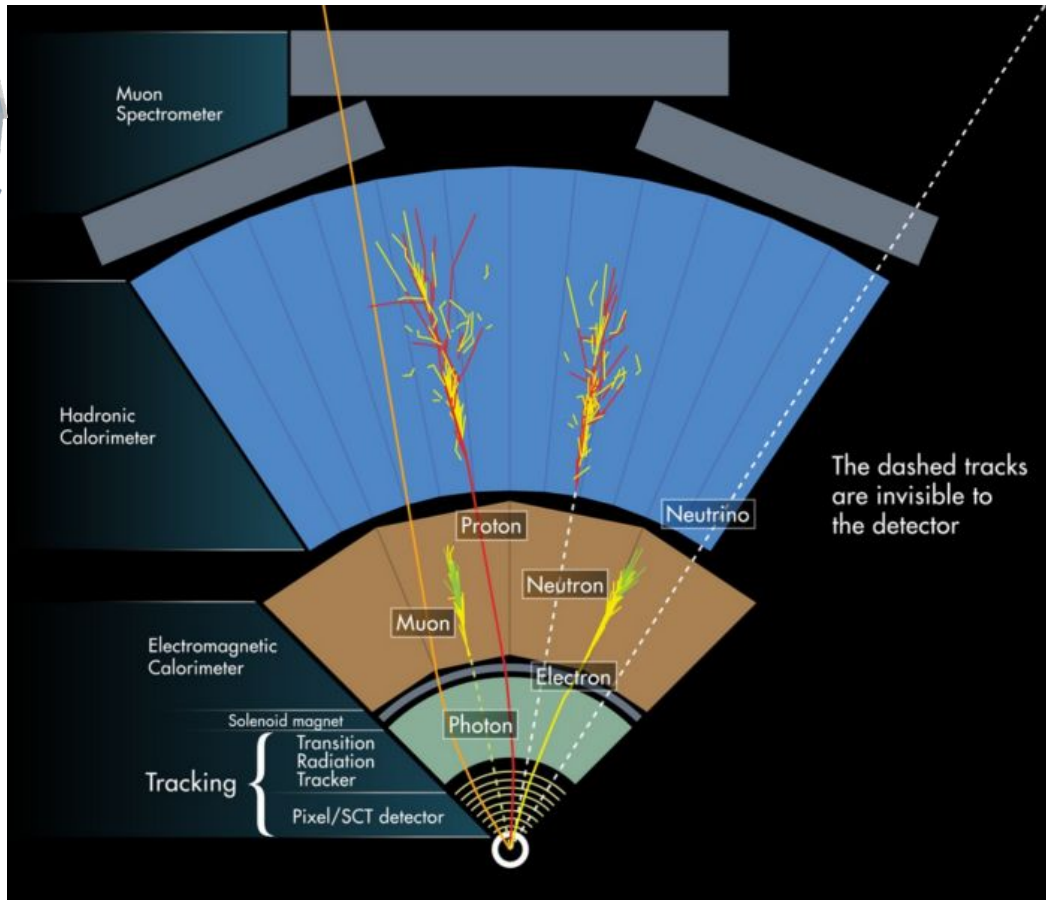
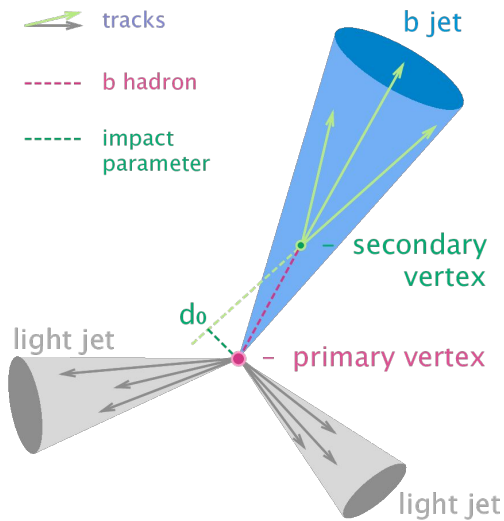
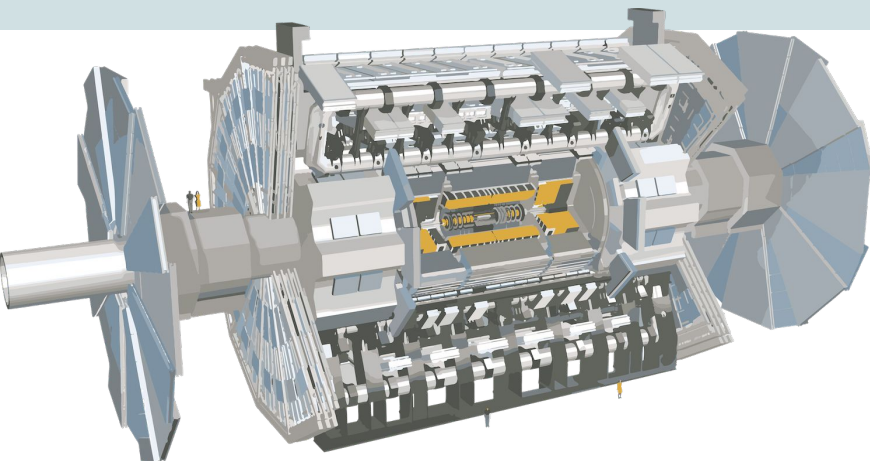
Standard Model of Elementary Particles

three generations of matter (fermions)			interactions / force carriers (bosons)	
I	II	III		
mass charge spin 1/2 2/3 1/2	$\approx 2.2 \text{ MeV}/c^2$ u up	$\approx 1.28 \text{ GeV}/c^2$ c charm	$\approx 173.1 \text{ GeV}/c^2$ t top	0 0 0 1 1
			g gluon	$\approx 124.97 \text{ GeV}/c^2$ H higgs
QUARKS	$\approx 4.7 \text{ MeV}/c^2$ d down	$\approx 96 \text{ MeV}/c^2$ s strange	$\approx 4.18 \text{ GeV}/c^2$ b bottom	0 0 0 1 1
			γ photon	SCALAR BOSONS
	$\approx 0.511 \text{ MeV}/c^2$ e electron	$\approx 105.66 \text{ MeV}/c^2$ μ muon	$\approx 1.7768 \text{ GeV}/c^2$ τ tau	0 0 0 1 1
			Z Z boson	GAUGE BOSONS
LEPTONS	$< 1.0 \text{ eV}/c^2$ ν_e electron neutrino	$< 0.17 \text{ MeV}/c^2$ ν_μ muon neutrino	$< 18.2 \text{ MeV}/c^2$ ν_τ tau neutrino	0 ±1 ±1 1 1
			W W boson	VECTOR BOSONS

JHEP 08 (2012) 098



Particle identification at ATLAS in one slide

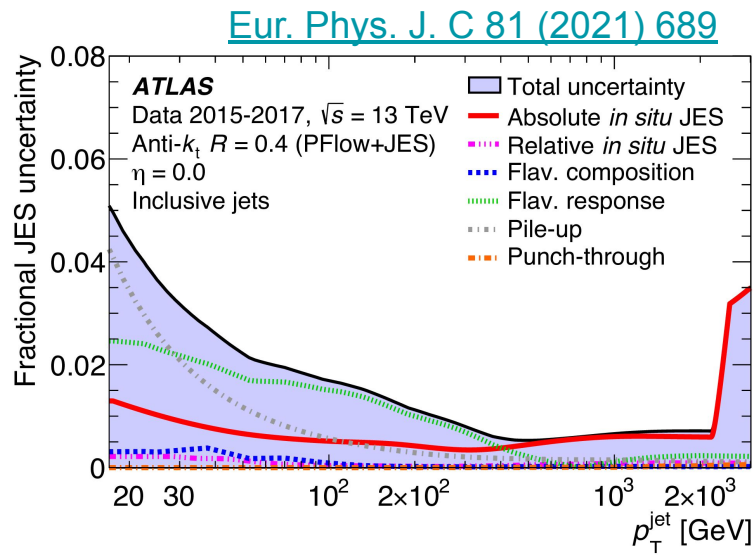
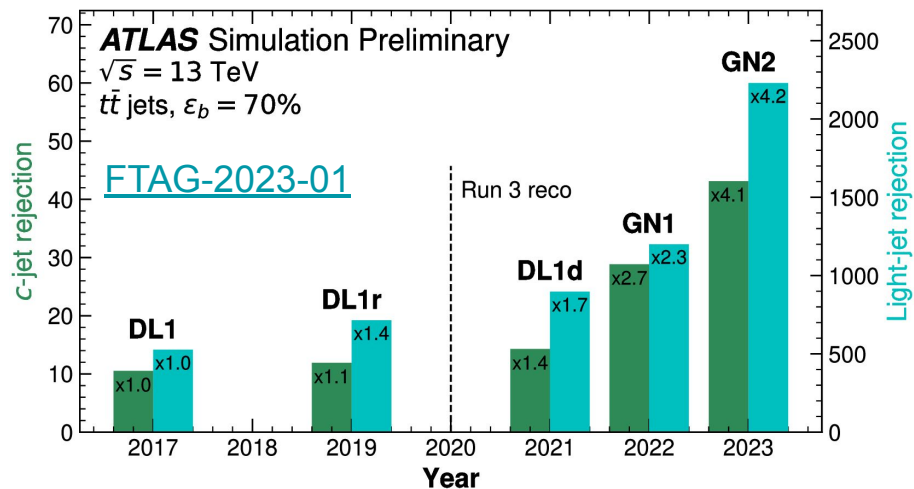


30 years of top quark physics!

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](#)
- ...



The range of top quark physics

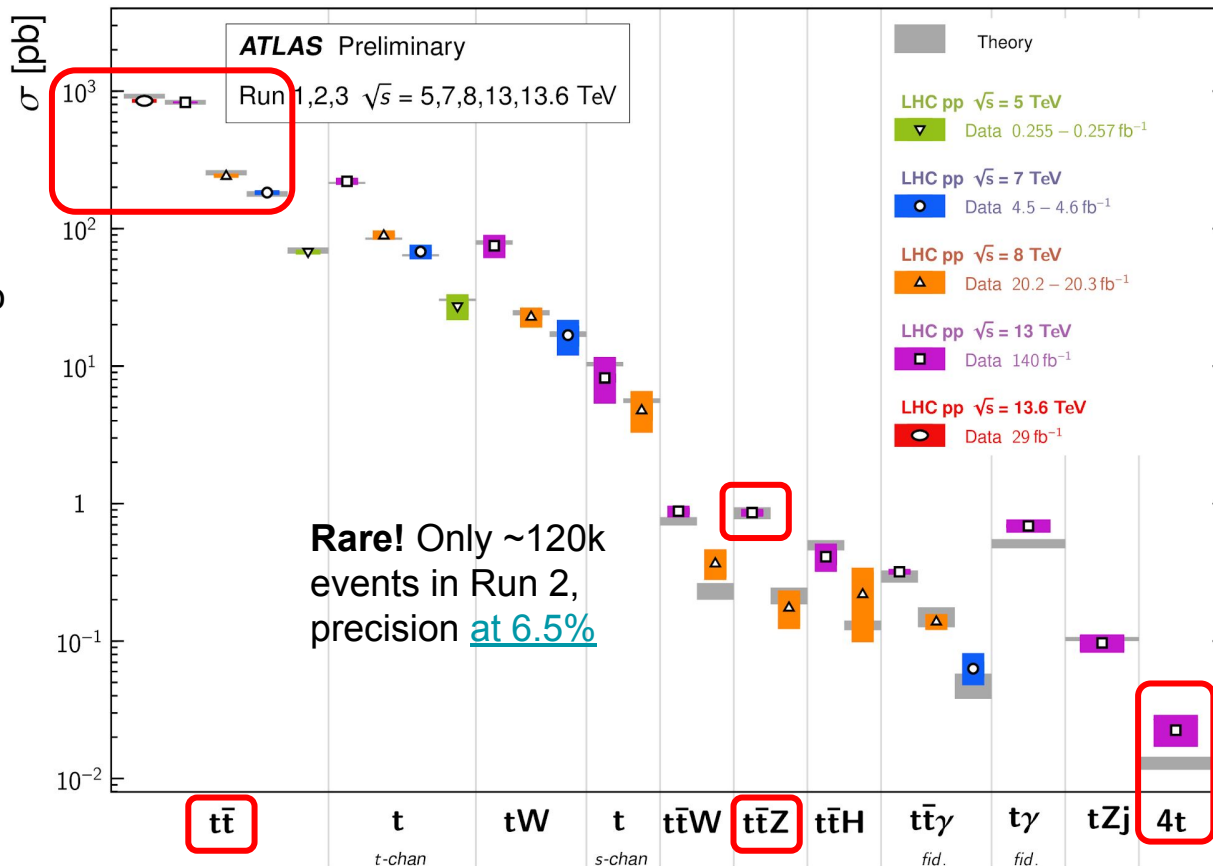
Top Quark Production Cross Section Measurements

Status: May 2025

[ATL-PHYS-PUB-2025-024](#)

Abundant production!

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



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 $\sim 5 \times 10^{-25} \text{s} \ll 1/\Lambda_{\text{QCD}} \sim 10^{-23} \text{s}$

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

$\text{BR}(t \rightarrow Wb) \sim 100\%$ + weak interaction is maximally parity-violating

→ correlations are **observable!**

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

top polarisations (3+3)

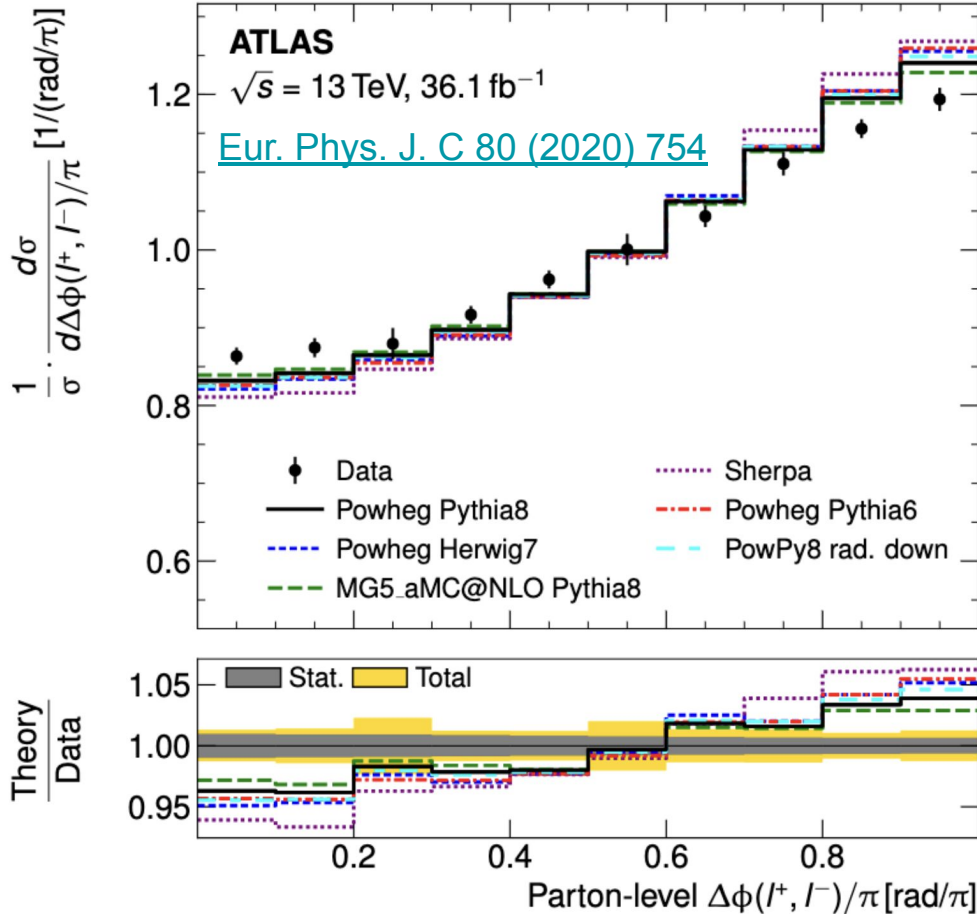


spin correlations (3x3)

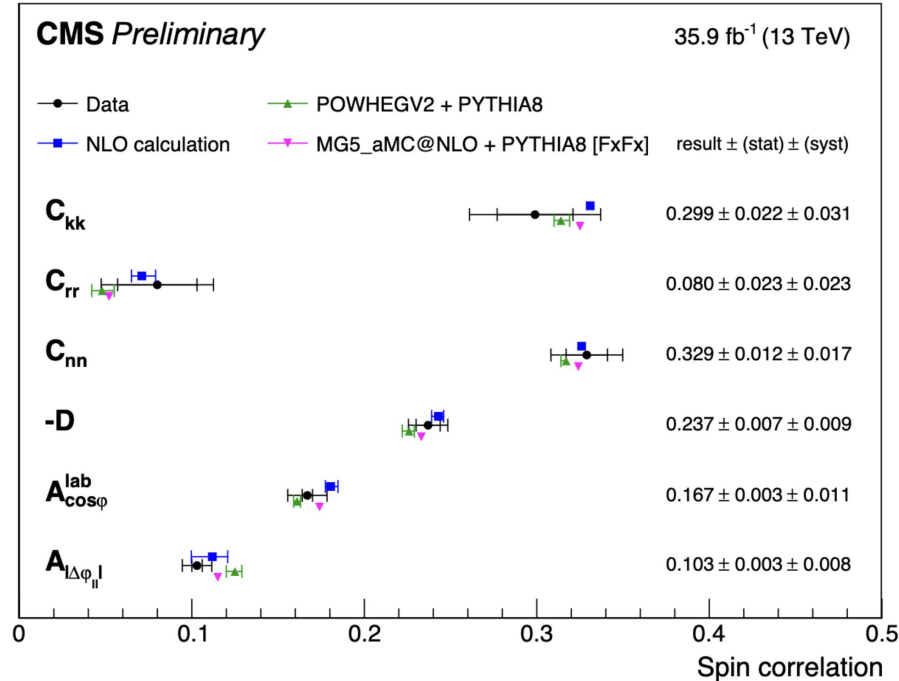
$\alpha_1 = \alpha_2 = 1$ (maximal) for leptons

= full spin density matrix (15 elements)

State-of-the-art in 2020...



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

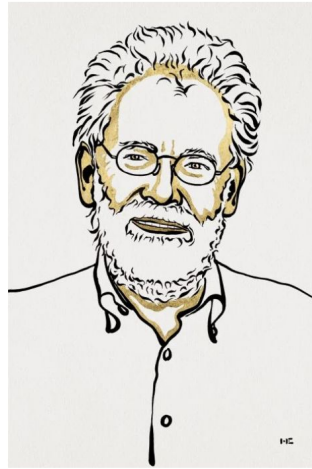
Prize share: 1/3



Ill. Niklas Elmehed © Nobel Prize Outreach

John F. Clauser

Prize share: 1/3

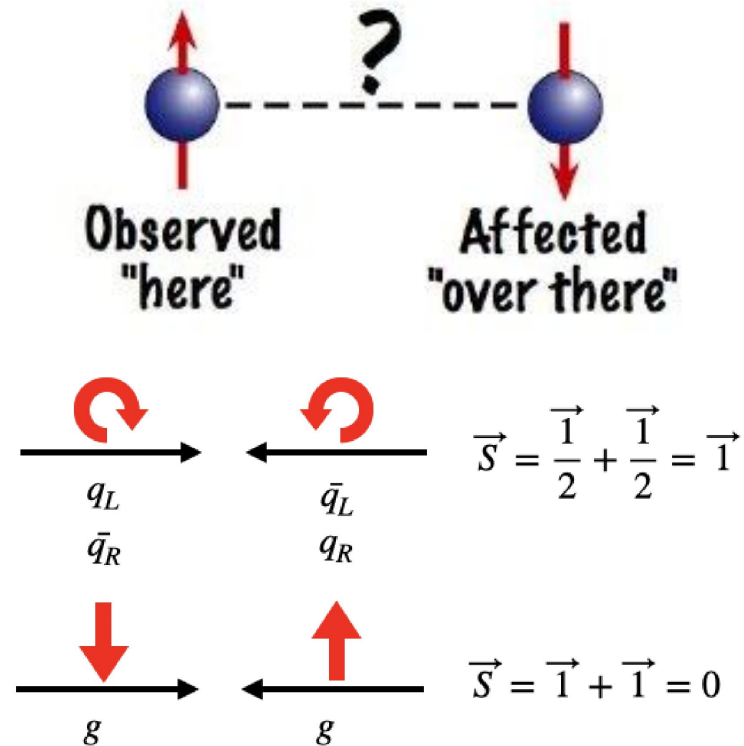


Ill. Niklas Elmehed © Nobel Prize Outreach

Anton Zeilinger

Prize share: 1/3

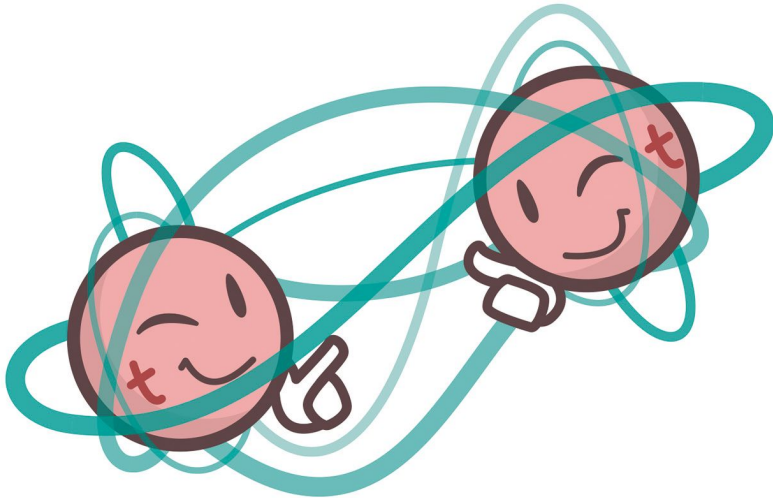
The Nobel Prize in Physics 2022 was awarded jointly to Alain Aspect, John F. Clauser and Anton Zeilinger "for experiments with **entangled photons**, establishing the **violation of Bell inequalities** and pioneering **quantum information science**"



$gg \rightarrow t\bar{t}$: spin-singlet state at threshold
(Landau-Yang suppression of spin-triplet)

(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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Received: 7 June 2021 / Accepted: 25 August 2021

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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.

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 \Rightarrow separable, but quantum $\not\Rightarrow$ non-separable]

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

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

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

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

The 4 Bell states form a maximally entangled basis:

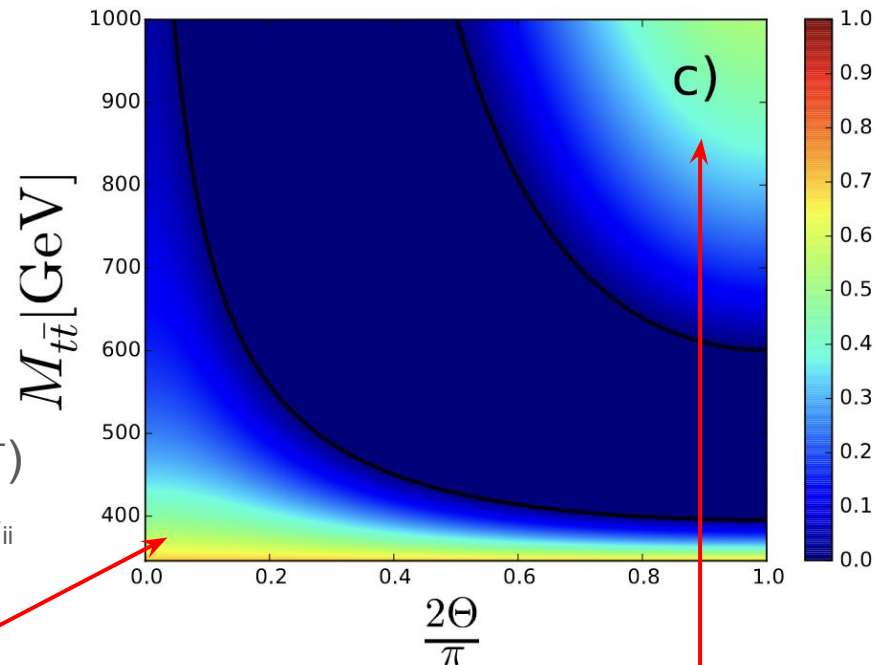
$$|\Phi^\pm\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle),$$

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

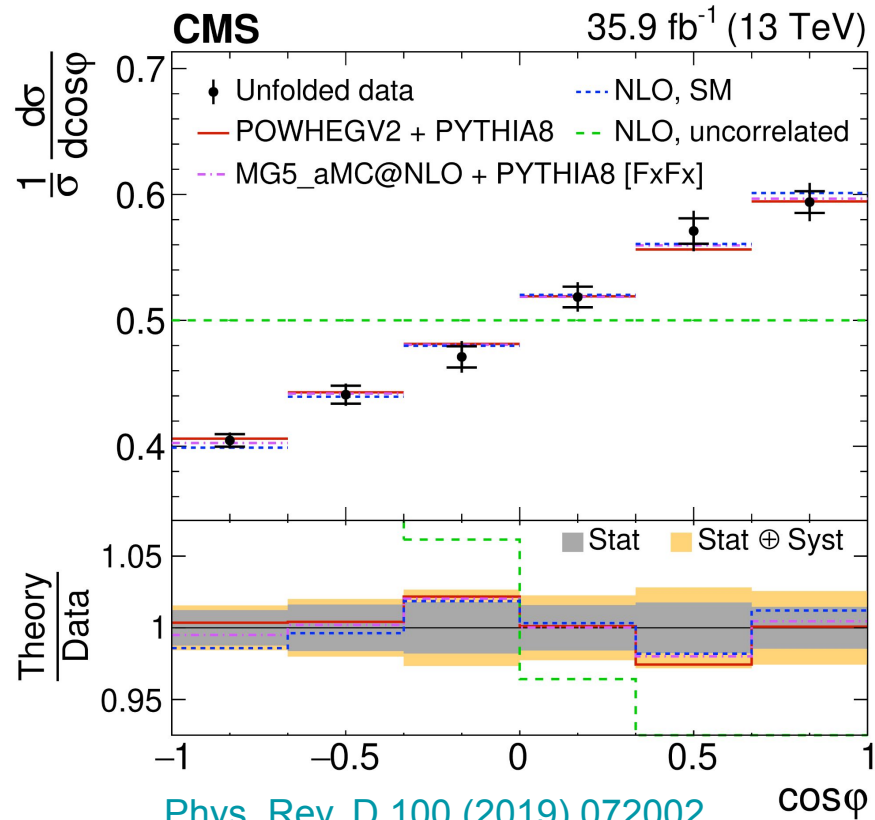
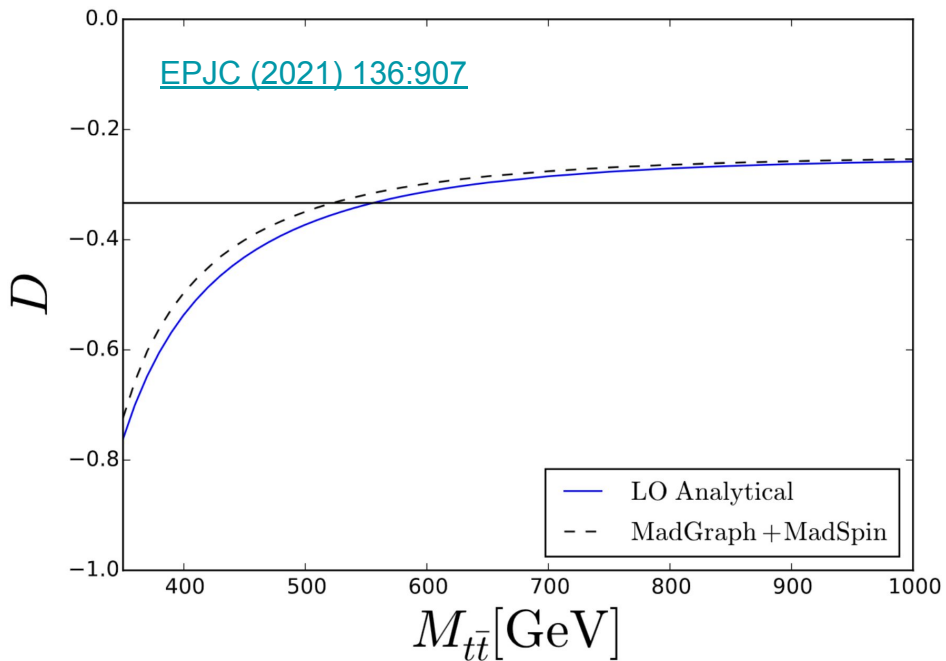
- At low $M(t\bar{t})$: pseudo-scalar state ψ^0
 - this is also what toponium looks like!
- At high $M(t\bar{t})$: triplet vector-state ($\Phi^+ \pm \Phi^-, \Psi^+$)
 - we get a sign-flip in the spin correlation matrix C_{ij}
 - D is no longer an optimal observable!
 - introduce D_3 which corrects for 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 ?



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

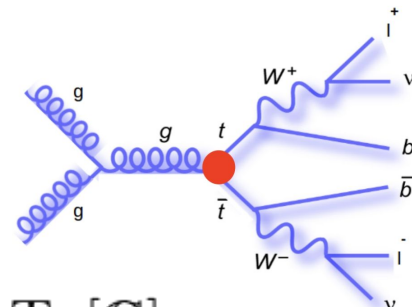
Quantum entanglement in dilepton $t\bar{t}$

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

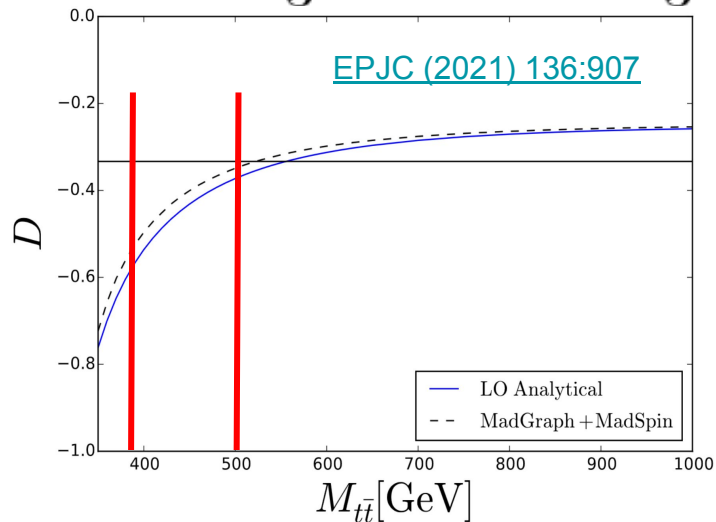
Then partition events into three selections:

- $340 < M_{t\bar{t}} < 380$: **entanglement signal region**
- $380 < M_{t\bar{t}} < 500$: validation region
(dilution from mis-reconstruction)
- $500 < M_{t\bar{t}}$: **no-entanglement** validation region

The mass cuts are crucial!



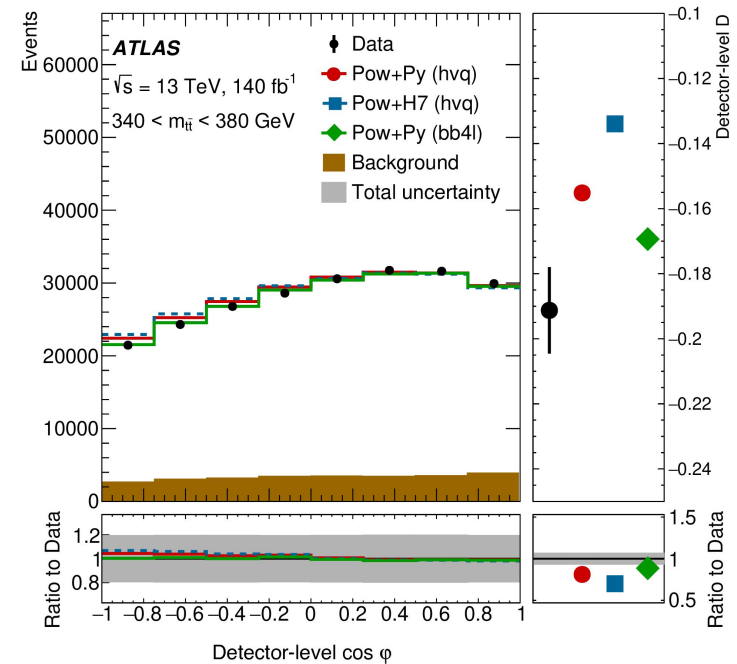
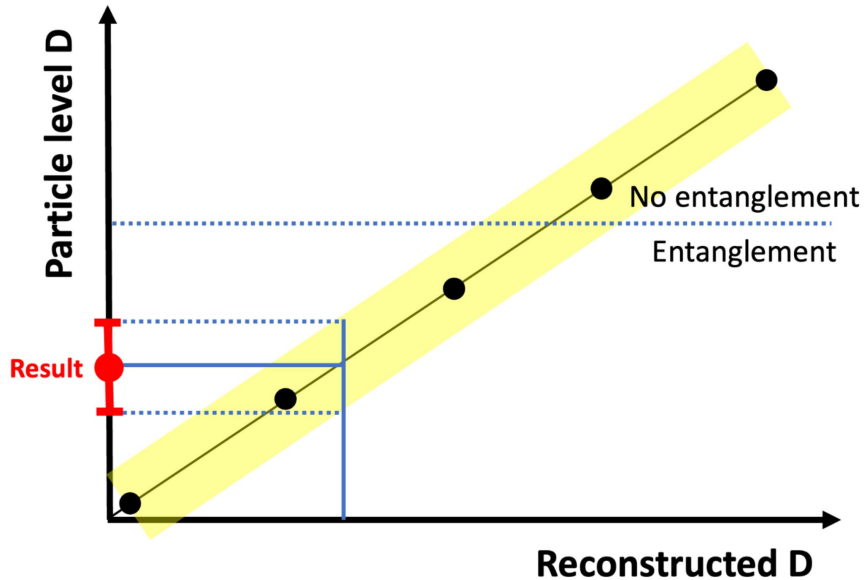
$$D = \frac{\text{Tr} [C]}{3} \Rightarrow D < -\frac{1}{3}$$



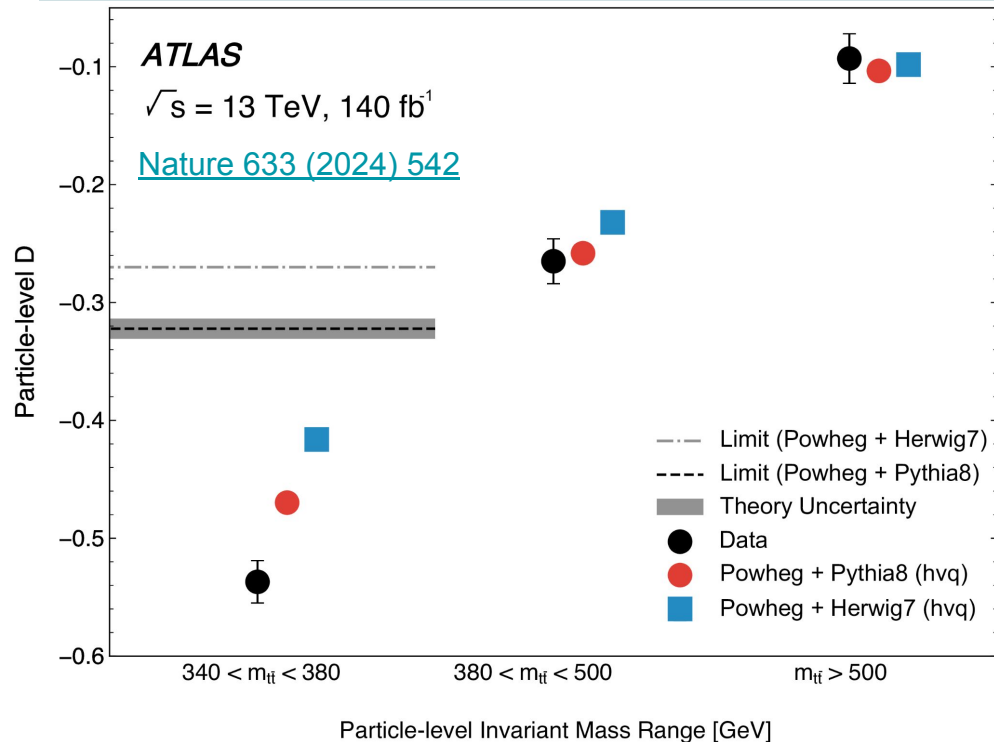
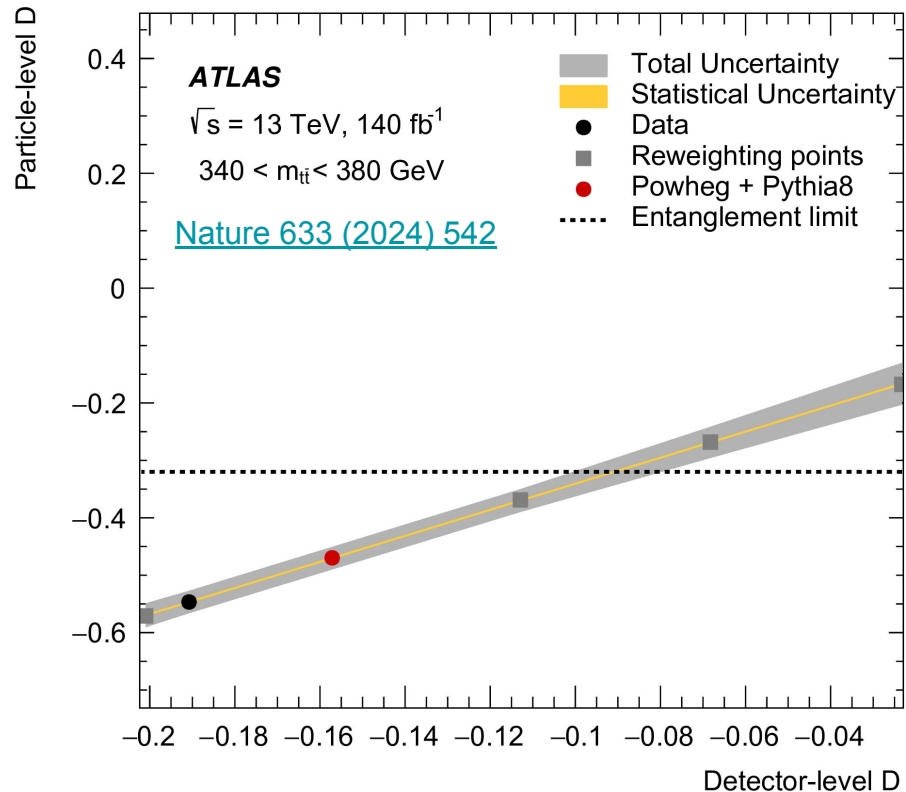
“**Calibration curve**” method: use the nominal MC to map the detector-level D value (average of distribution) to the fiducial particle-level D.

Systematics are propagated with their own curves, quadratic envelope.

→ Build the curve by sampling different D values.



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

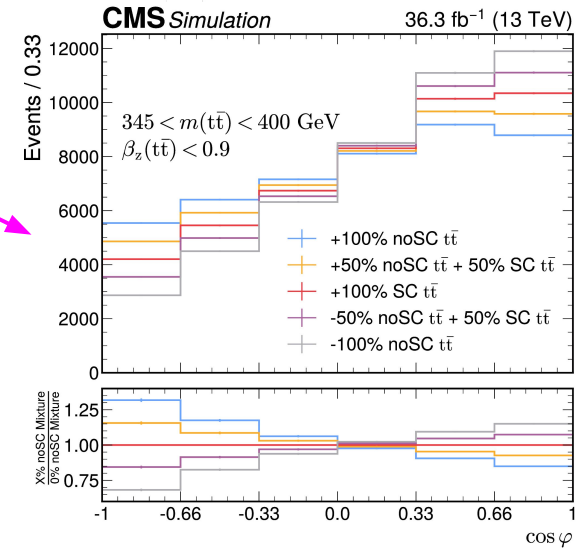
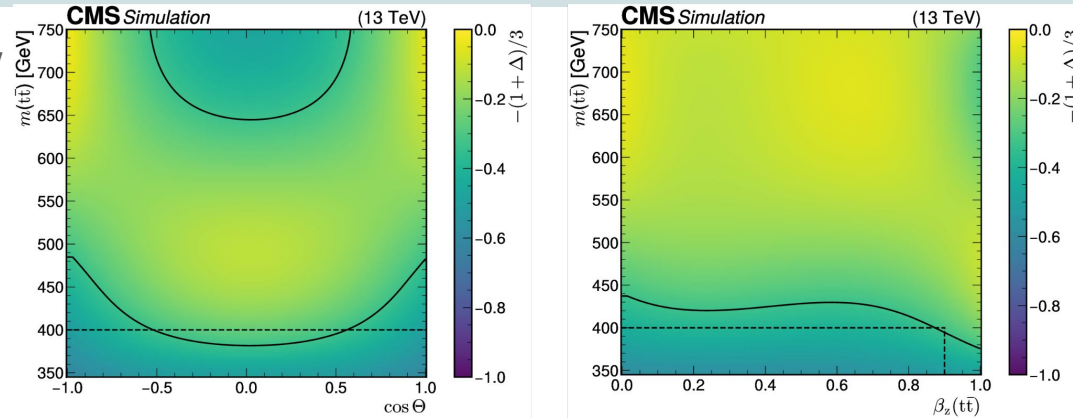


non-relativistic QCD effects close to threshold, not included in MC generators → would only affect predictions, not calibration

expected: $D = -0.470 \pm 0.002 \text{ (stat.)} \pm 0.017 \text{ (syst.)}$

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

- Signal region: **345-400 GeV window in $M(t\bar{t})$**
- Cut on $t\bar{t}$ velocity ($\beta < 0.9$) to enrich sample in $gg \rightarrow t\bar{t}$
- Consider $ee + \mu\mu + e\mu$ 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
 - $M(\eta_t) = 343 \text{ GeV}$ (337-349 GeV)
 - $\Gamma(\eta_t) = 7 \text{ GeV}$
 - $\sigma(\eta_t) = 6.43 \text{ pb}$



Another **observation** of quantum entanglement

5.1 σ observed (4.7 σ expected)

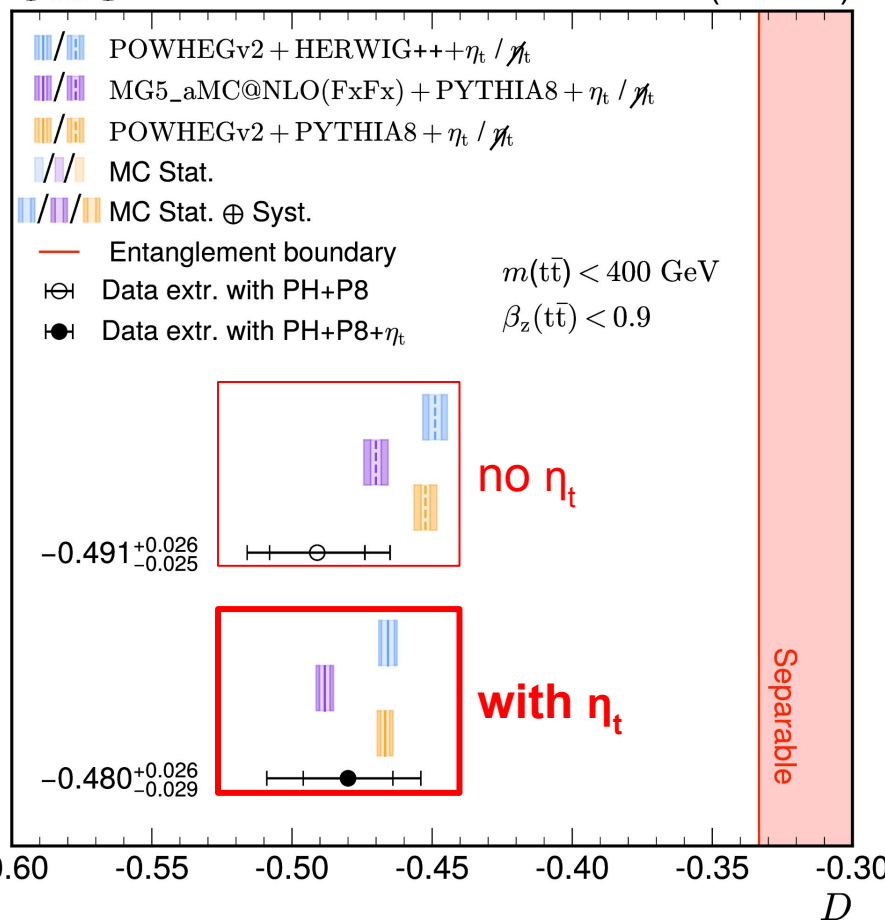
Toponium 50% normalisation uncertainty
+ vary binding energy ± 0.5 GeV

$$D = -0.480 \pm 0.017 \text{ (stat.)} \pm 0.023 \text{ (syst.)}$$

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%

CMS

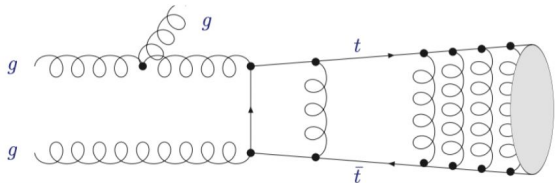
36.3 fb⁻¹ (13 TeV)



Toponium: bound to be discovered?

What is toponium?

- Standard Model predicts a **quasi-bound state below the $t\bar{t}$ 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 $\sim (\alpha_s/\beta)^n$
 - 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!]



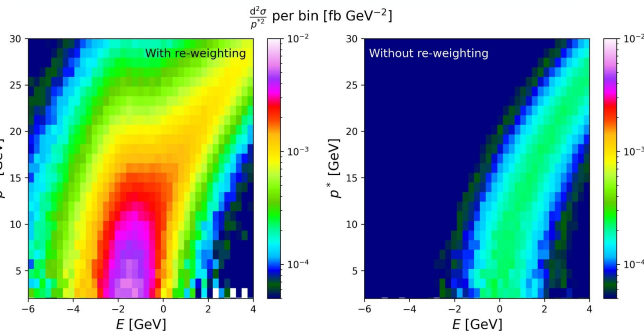
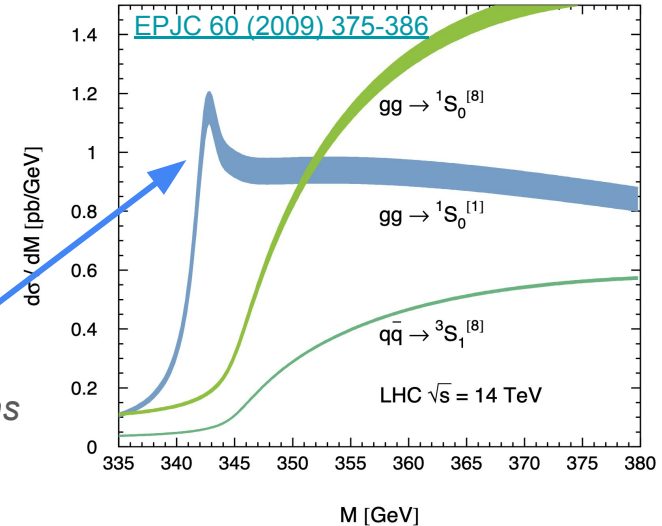
Simulating toponium formation signals at the LHC

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

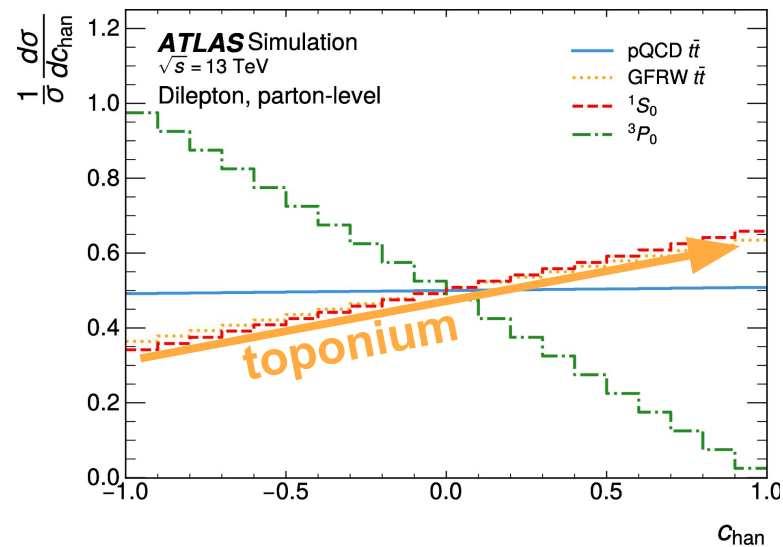
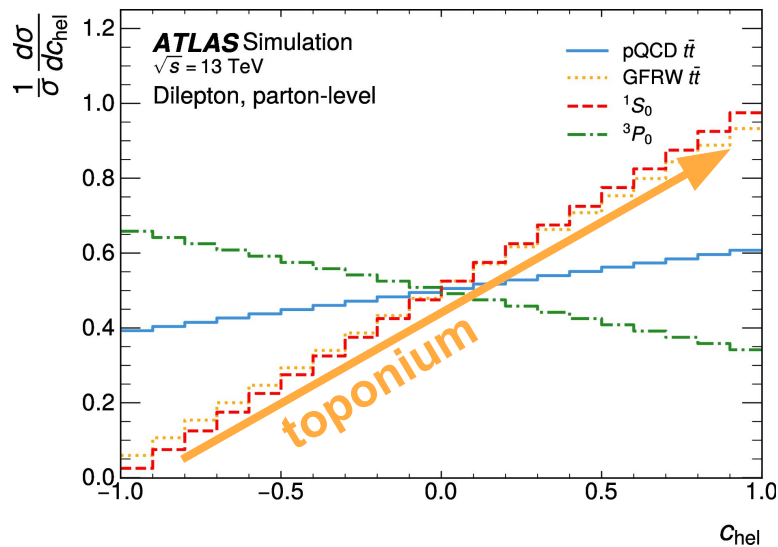
Benjamin Fuks ✉, Kaoru Hagiwara, Kai Ma & Ya-Juan Zheng

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

modelling full S-wave contributions



- Exploit the **di-leptonic final state**: very **pure $t\bar{t}$ 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*

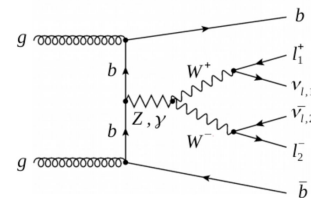
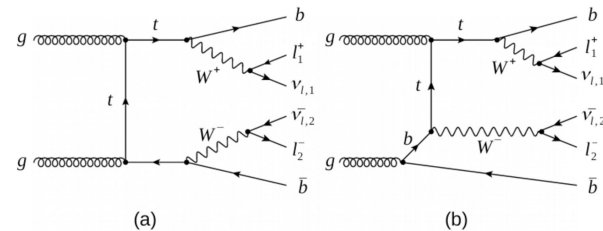


- Suppress reducible backgrounds, and use either **state-of-the-art MC modelling** or **data-driven techniques** for the remaining contributions
 - in $ee/\mu\mu$ selections, can reject low- m_{ll} events and cut away the Z peak
 - Drell-Yan and fake lepton backgrounds can be obtained from data
 - **interference of tW and $t\bar{t}$ 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**

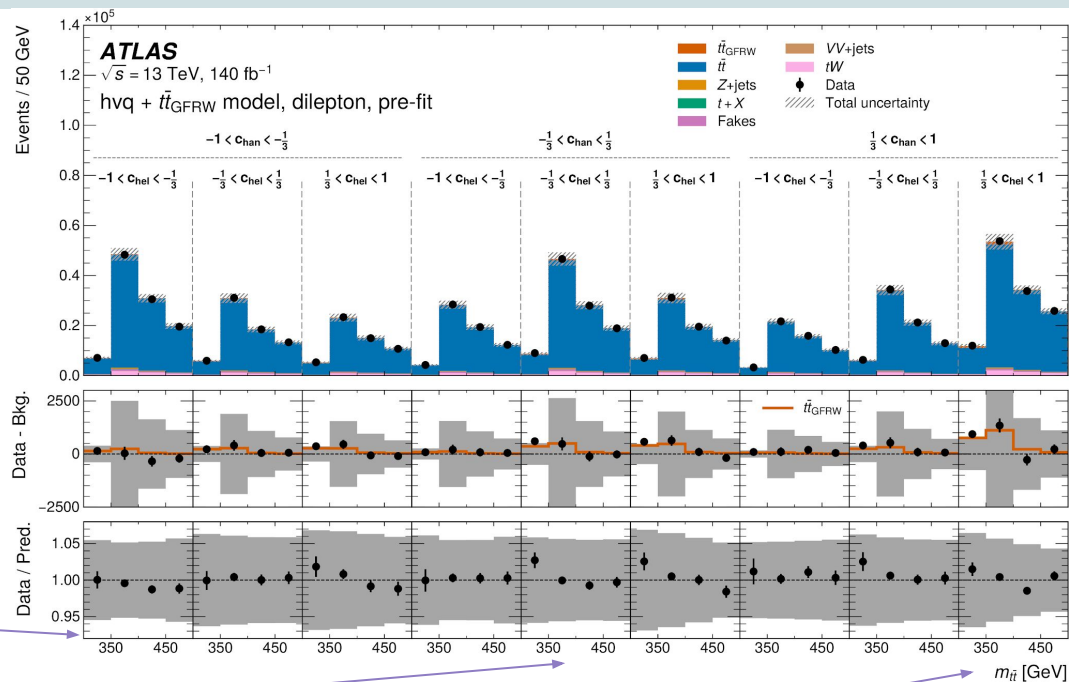
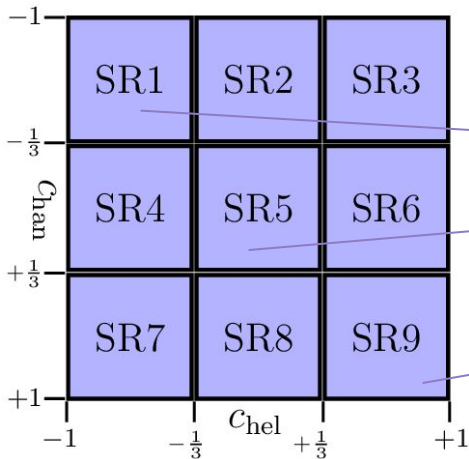
- using the 3 sensitive observables $m_{t\bar{t}}$, c_{hel} , and c_{han}

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 $m_{t\bar{t}} \leq 500$ GeV	
$E_T^{miss} \geq 60$ GeV for OSSF events		—
$\ell^\pm \ell'^\mp$	$e^\pm e^\mp / \mu^\pm \mu^\mp$	$\ell^\pm \ell'^\pm$
$ m_{\ell\ell} - m_Z \geq 10$ GeV	$ m_{\ell\ell} - m_Z \leq 10$ GeV	$ m_{\ell\ell} - m_Z \geq 10$ GeV

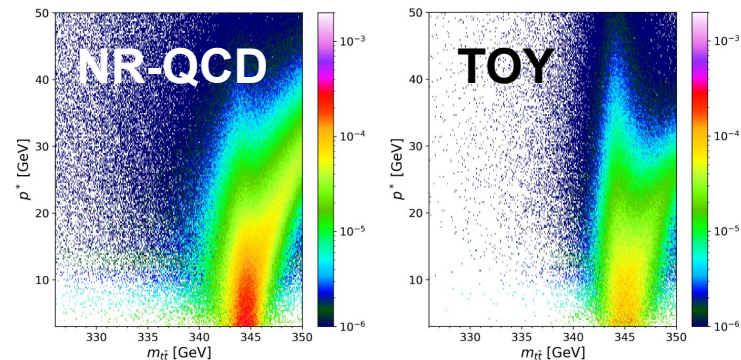


Doubly-, singly-, and non-resonant $b\bar{b}ll\nu\nu$ final states

- 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 \$\rightarrow\$ \$t\bar{t}\$ search](#): enhance sensitivity to A and H bosons in different bins



- **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 \rightarrow 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 $gg \rightarrow \eta \rightarrow WbWb$ in MG at LO, use $M(\eta)=343$ GeV, $\Gamma(\eta)=2.8$ GeV + tune the couplings to reproduce 1-dimensional NR-QCD results in $m_{t\bar{t}}$
 - **no Green's function reweighting, no mass cuts** \rightarrow differences in top kinematics
 - this model is also tested by ATLAS

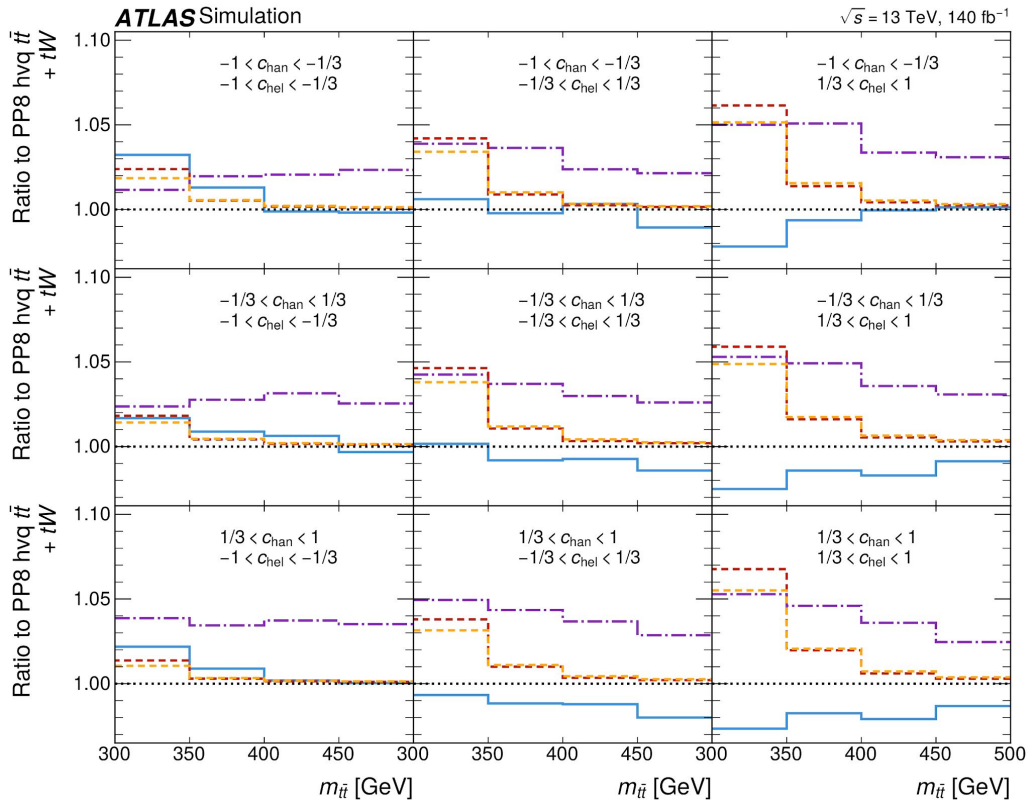


- **Powheg+Pythia8 hvq $t\bar{t}$** (NLO production, LO decay): **nominal setup**
 - well-understood by both ATLAS and CMS, entire set of systematics built around it, standard $t\bar{t}$ sample for Run 2 analyses
 - needs dedicated NNLO QCD and NLO EW reweighting
- **Powheg+Pythia8 bb4l** (NLO $2\rightarrow 6$ 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 $(\cos\theta^*, m_{t\bar{t}})$ with associated uncertainties
 - extensive validation \rightarrow can reproduce fixed-order predictions, as well as MiNNLOps

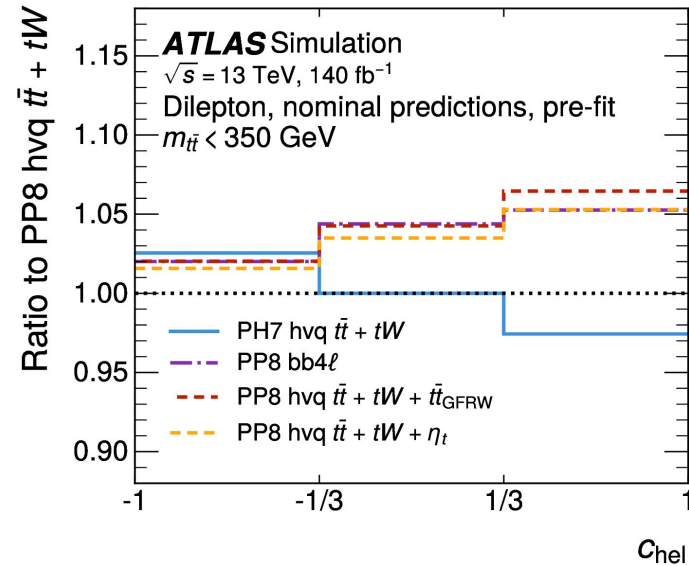
Key differences in MC predictions

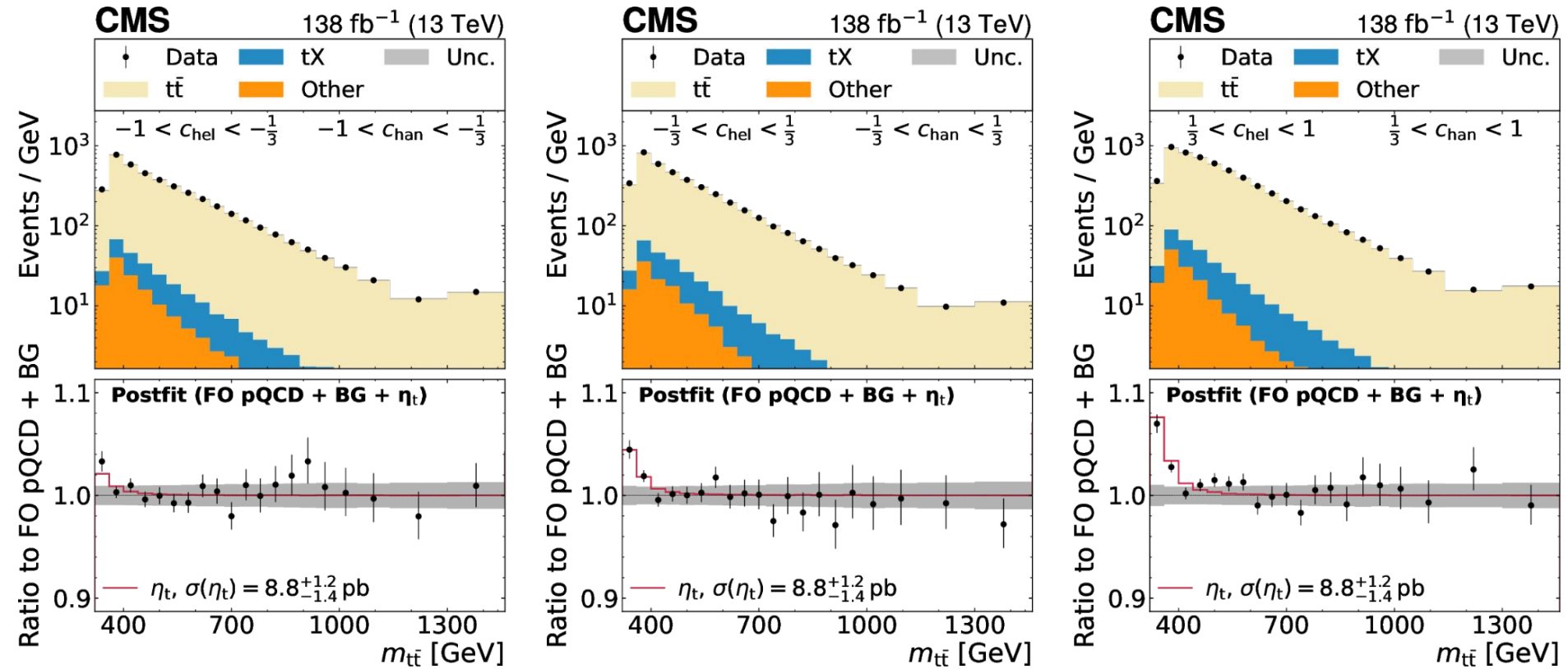
Dilepton, nominal predictions, pre-fit
 $m_{\bar{t}t} \in [300, 500]$ GeV

- PH7 hvq $\bar{t}t + tW$
- PP8 bb4 ℓ
- - - PP8 hvq $\bar{t}t + tW + \bar{t}t_{\text{GFRW}}$
- - - PP8 hvq $\bar{t}t + tW + \eta_t$

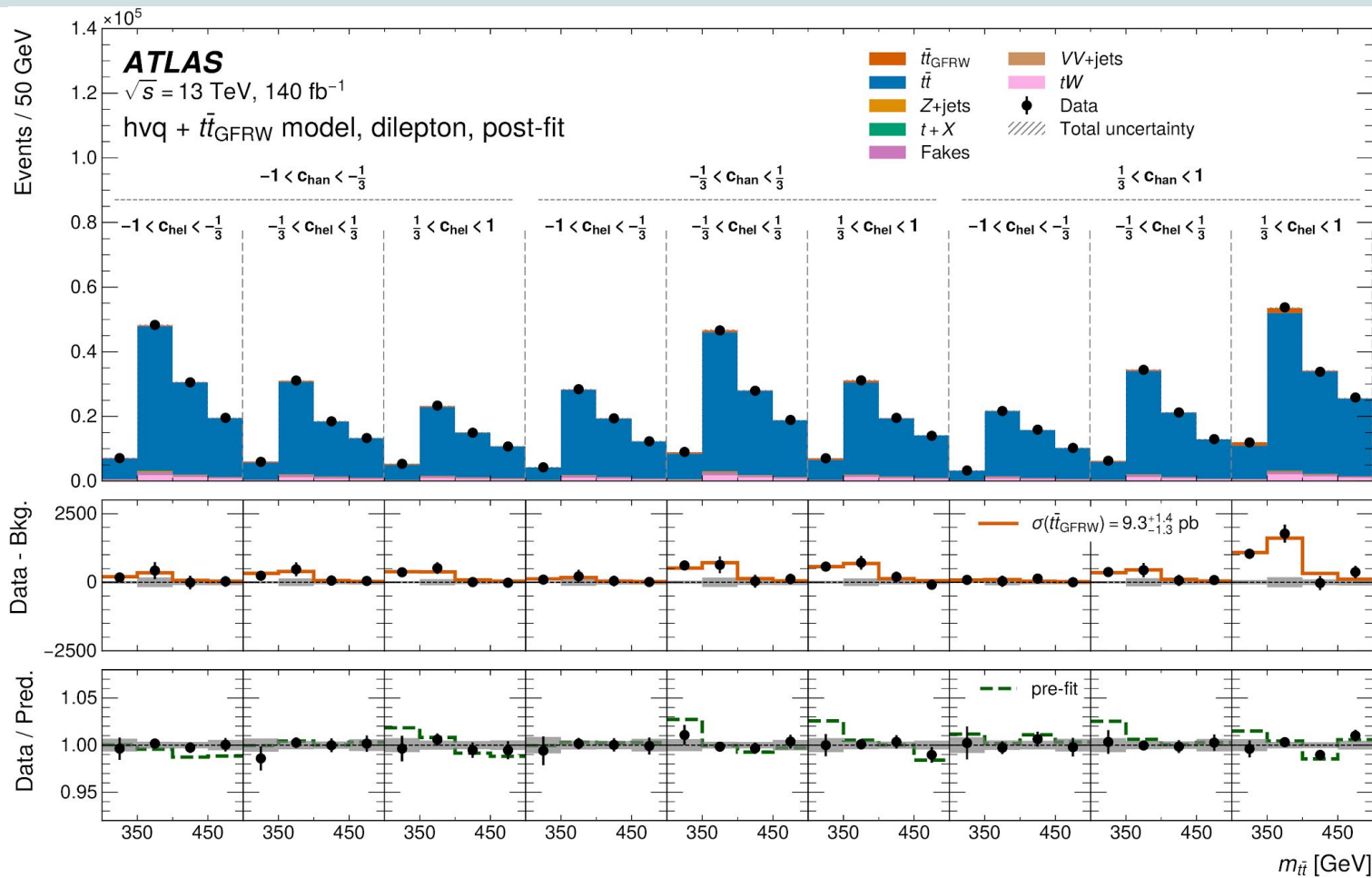


- Slight differences in **toponium predictions** for the first bin of $m_{\bar{t}t}$
- **Herwig** similarly observed to have lower acceptance and opposite slope in c_{hel}
- **bb4l** seems to behave “like toponium”
 → *but full 3D distribution allows to distinguish between them*





Clear excess near threshold, behaving like pseudo-scalar toponium

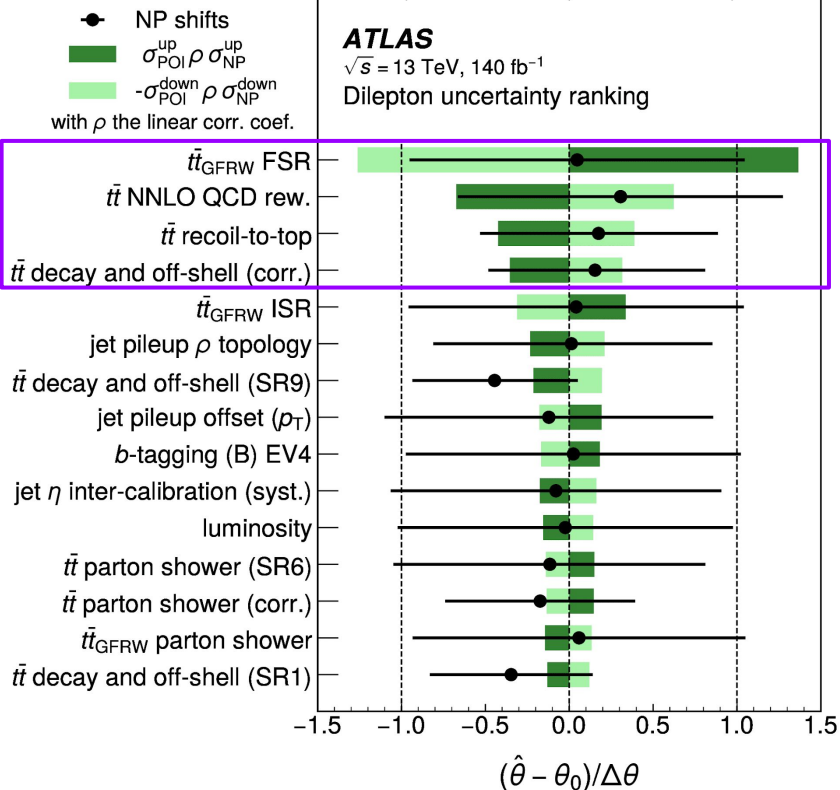
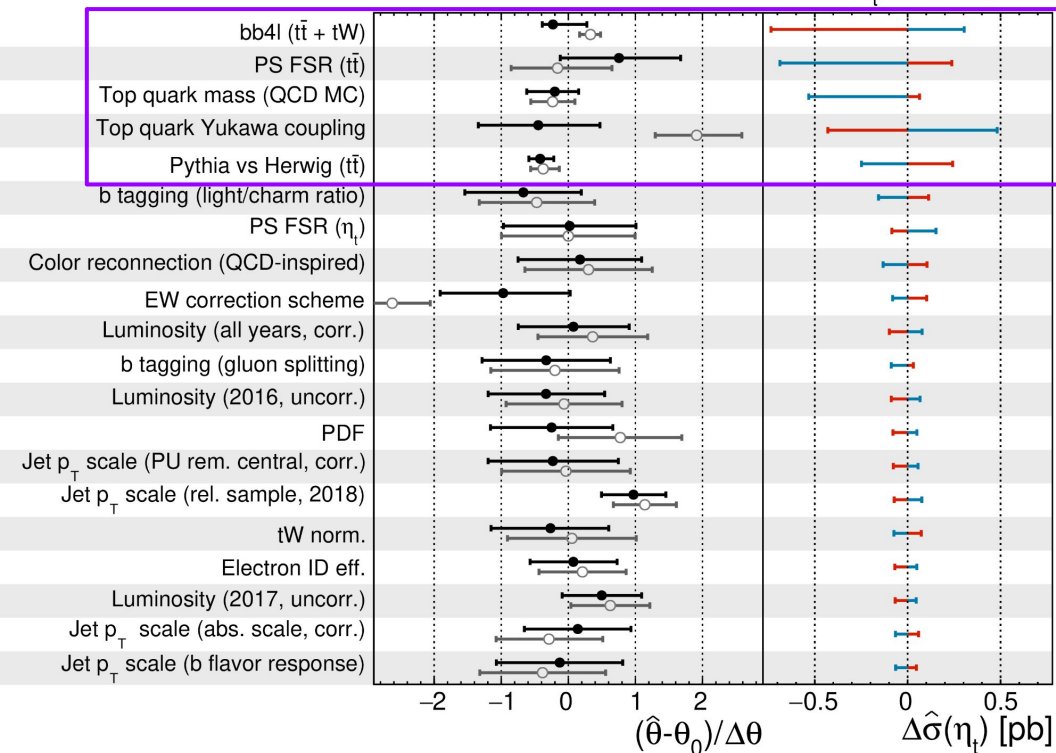


Impact of systematic uncertainties

CMS

- Fit constraint (FO pQCD + BG + η_t)
- Fit constraint (FO pQCD + BG only)
- +1 σ impact (FO pQCD + BG + η_t)
- -1 σ impact (FO pQCD + BG + η_t)

$$\hat{\sigma}(\eta_t) = 8.8_{-1.4}^{+1.2} \text{ pb}$$



- The predicted NRQCD toponium cross section is 6.4pb
- **ATLAS:** $>8\sigma$ obs. (6σ exp.), with a GoF of 0.98 [$<10^{-5}$ for background-only hypothesis]
- **CMS:** $>5\sigma$ obs.
- **Measured cross sections are compatible with each other and with the NRQCD prediction**, although roughly $(45 \pm 20)\%$ larger
 - *Do recall that two different signal models are used!*
- Large impact of $t\bar{t}$ modelling systematics on both results

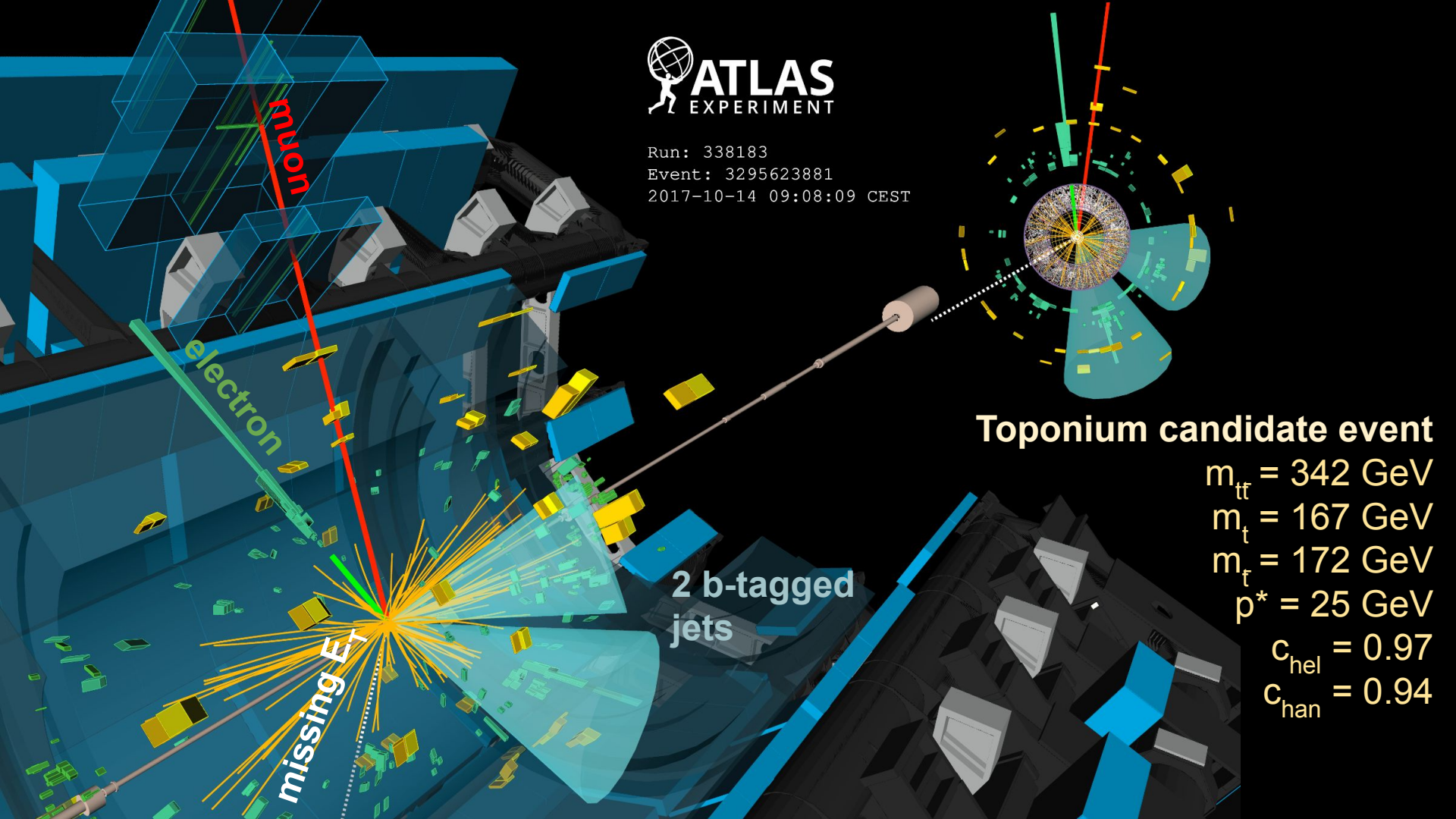


$$\sigma(t\bar{t}_{\text{GFRW}}) = 9.3_{-1.3}^{+1.4} \text{ pb} = 9.3_{-1.0}^{+1.1} \text{ (stat.)} \pm 0.8 \text{ (syst.) pb}$$



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

Run: 338183
Event: 3295623881
2017-10-14 09:08:09 CEST



Toponium candidate event

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

$m_t = 167 \text{ GeV}$

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

$p^* = 25 \text{ GeV}$

$C_{\text{hel}} = 0.97$

$C_{\text{han}} = 0.94$

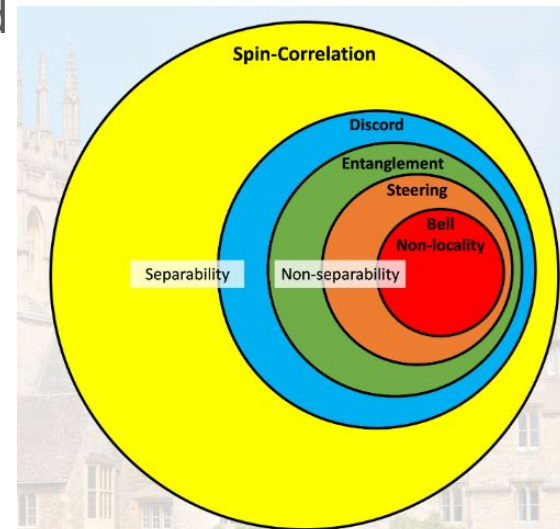
The **landscape** of quantum information **at the LHC**

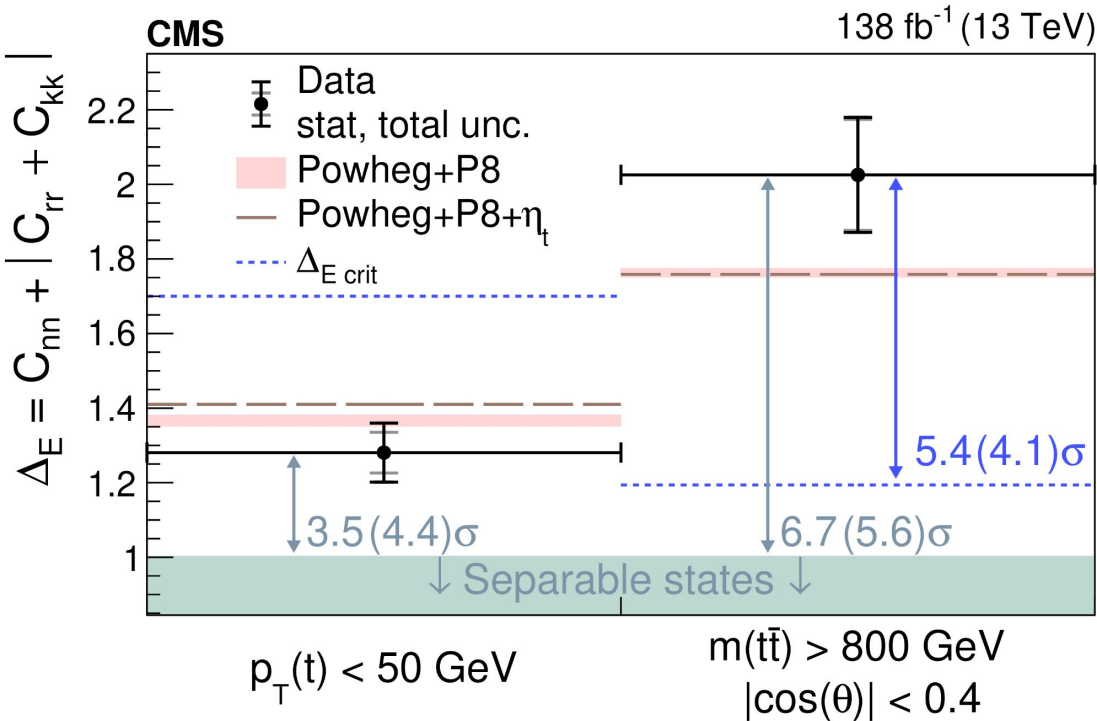
Quantum tops [beyond entanglement](#)

Further phenomenology towards additional [quantum information theory](#) concepts in term of [tf 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





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](https://arxiv.org/abs/2407.15223)

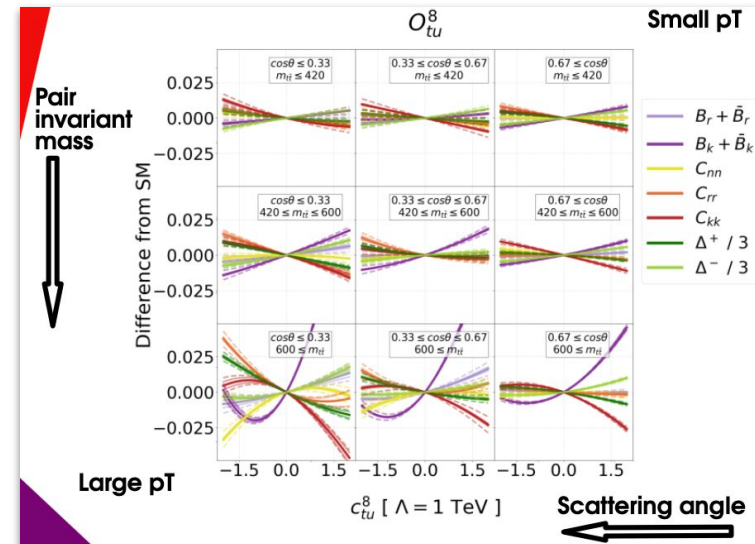
Entanglement seen in the high-energy regime!

But not sensitive enough near threshold...

- The 15 components of the $t\bar{t}$ spin density matrix can constrain SMEFT operators affecting top production
 - entanglement and Bell observables are also sensitive
 - in the dilepton channel, **all $O(1/\Lambda^2)$ 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!

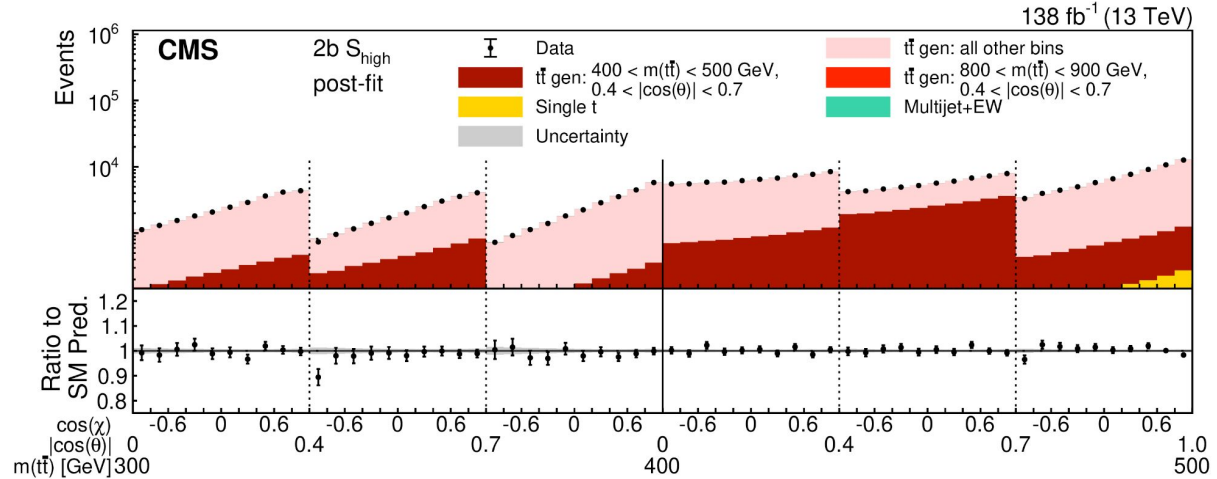
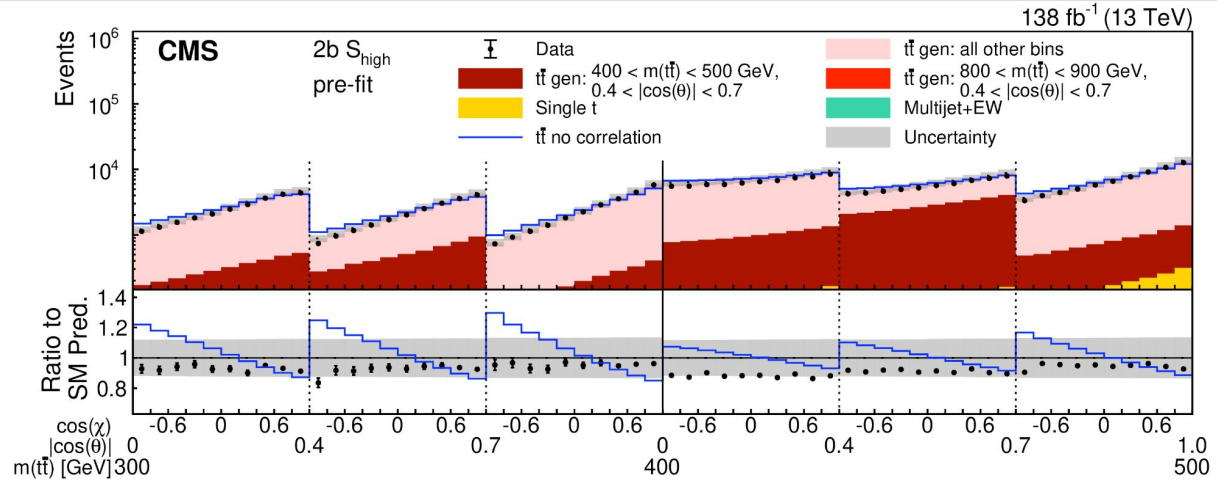
$$\alpha_\ell = 1 - \frac{c_{uW,33}^2 v^4}{\Lambda^4} \frac{4(2m_t^6 + 3m_t^4 m_W^2 - 6m_t^2 m_W^4 + m_W^6 + 12m_t^4 m_W^2 \log m_W/m_t)}{(m_W^2 - m_t^2)^2 (m_t^2 + 2m_W^2)}$$



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!



138 fb⁻¹ (13 TeV)

CMS

Inclusive from $m(t\bar{t})$ vs. $|\cos(\theta)|$ bins

$$\Delta_E = 0.663 \pm 0.029$$

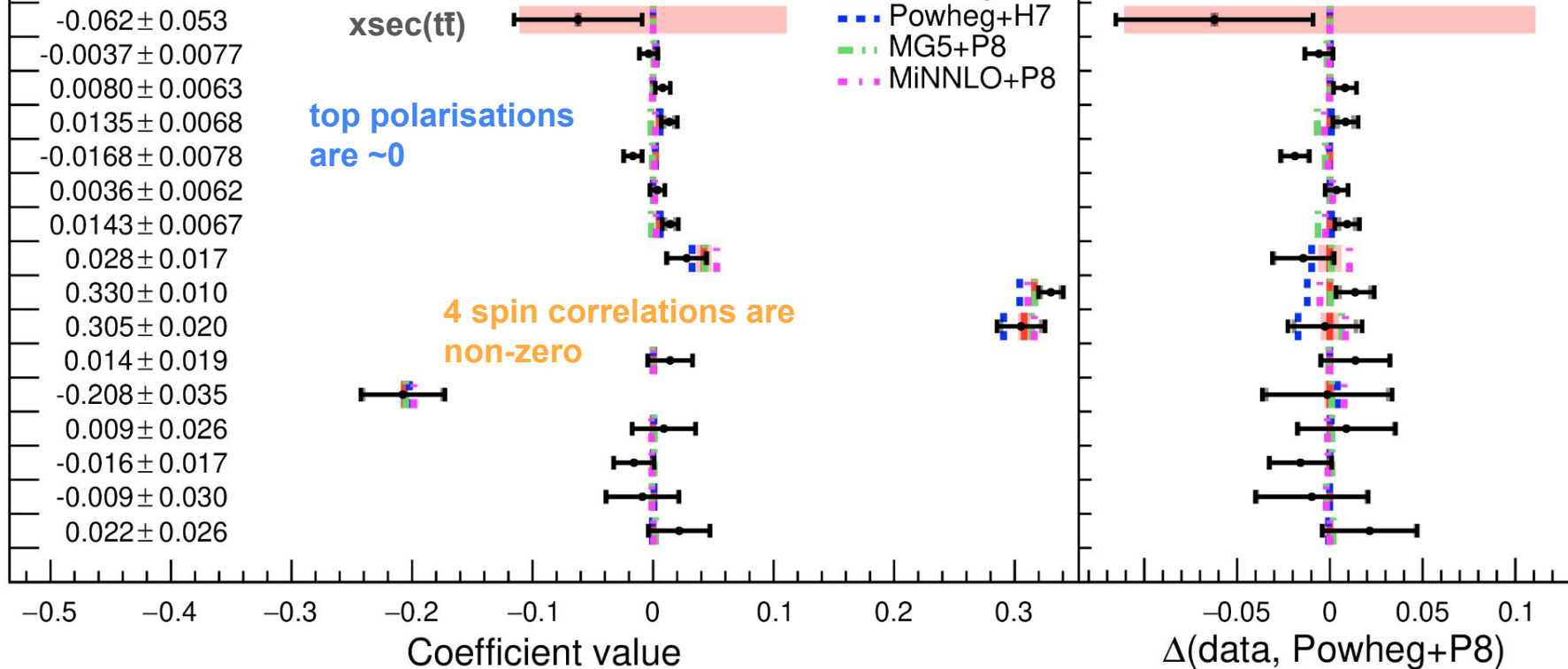
$x_{\text{sec}}(t\bar{t})$

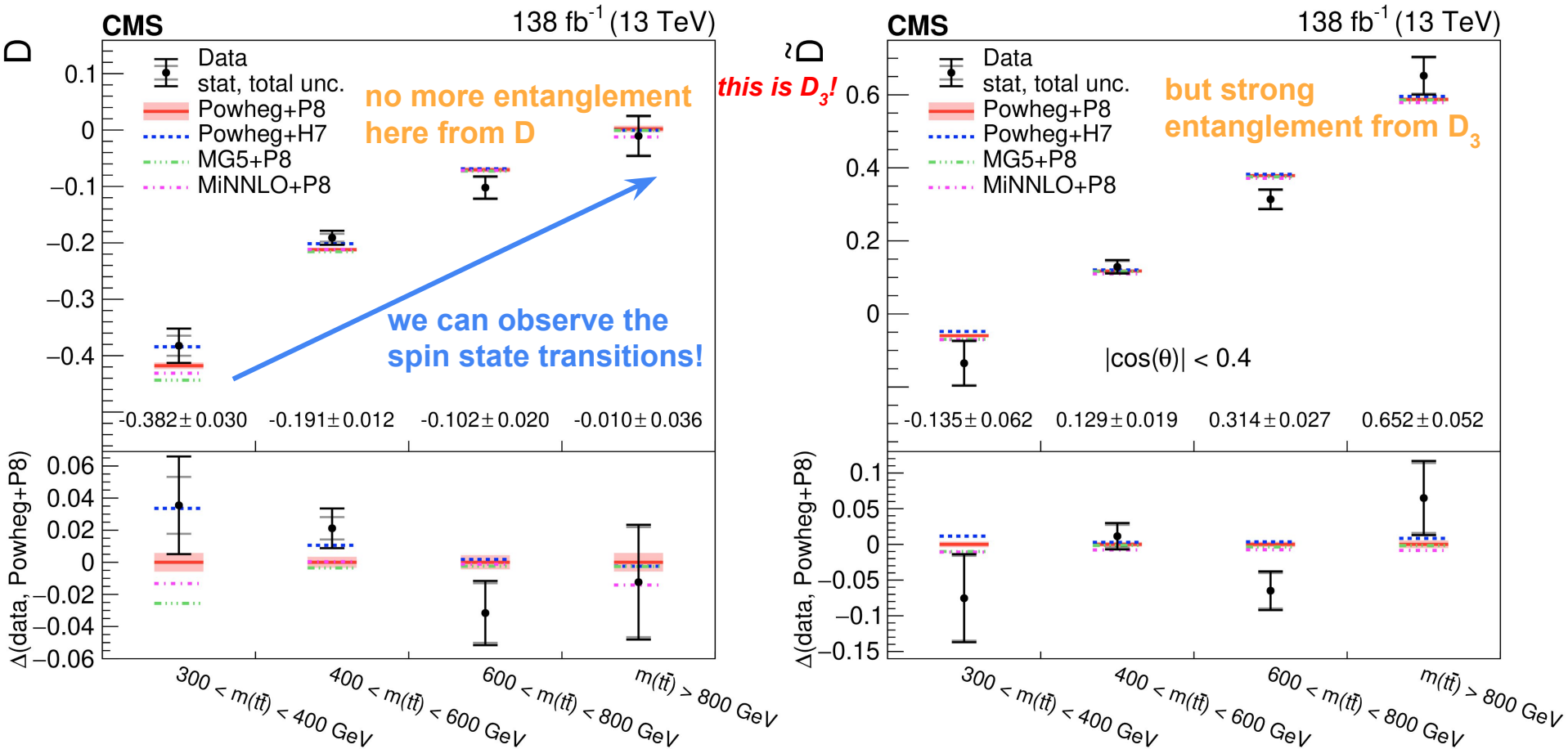
top polarisations
are ~ 0

4 spin correlations
are non-zero

Data
 stat, total unc.
 Powheg+P8
 Powheg+H7
 MG5+P8
 MiNNLO+P8

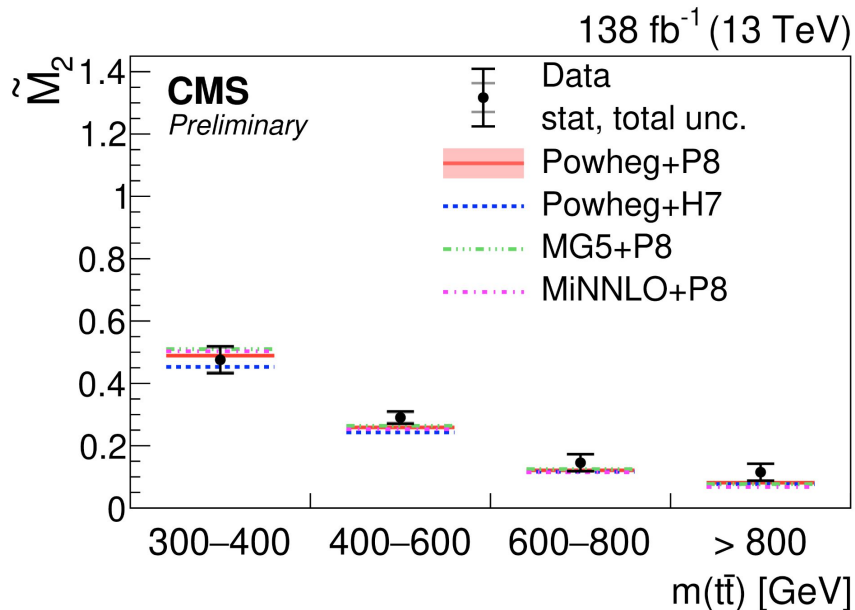
c_{-1}
 P_r
 P_n
 P_k
 \bar{P}_r
 \bar{P}_n
 \bar{P}_k
 C_{rr}^-
 C_{nn}^-
 C_{kk}^-
 C_{nr}^+
 C_{rk}^+
 C_{nk}^-
 C_{nr}^-
 C_{rk}^-
 C_{nk}^+





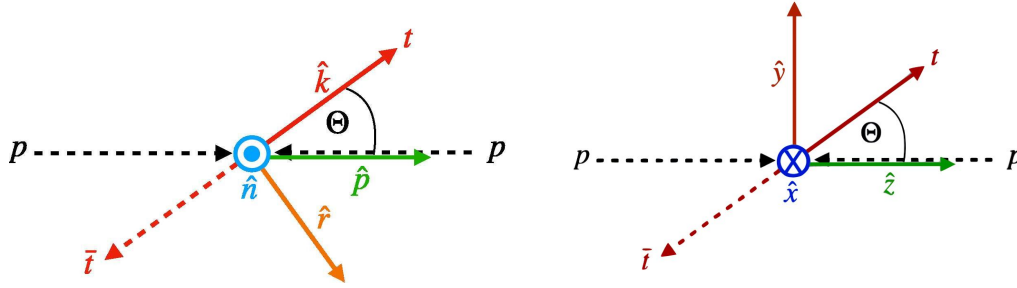
Gottesman-Knill theorem: “for every quantum computer containing stabiliser states, there is a classical computer that is just as efficient”

- some entangled states are stabilisers (but not all)
- “magic” states are not! ($M_2 > 0$)
- **magic \Leftrightarrow 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

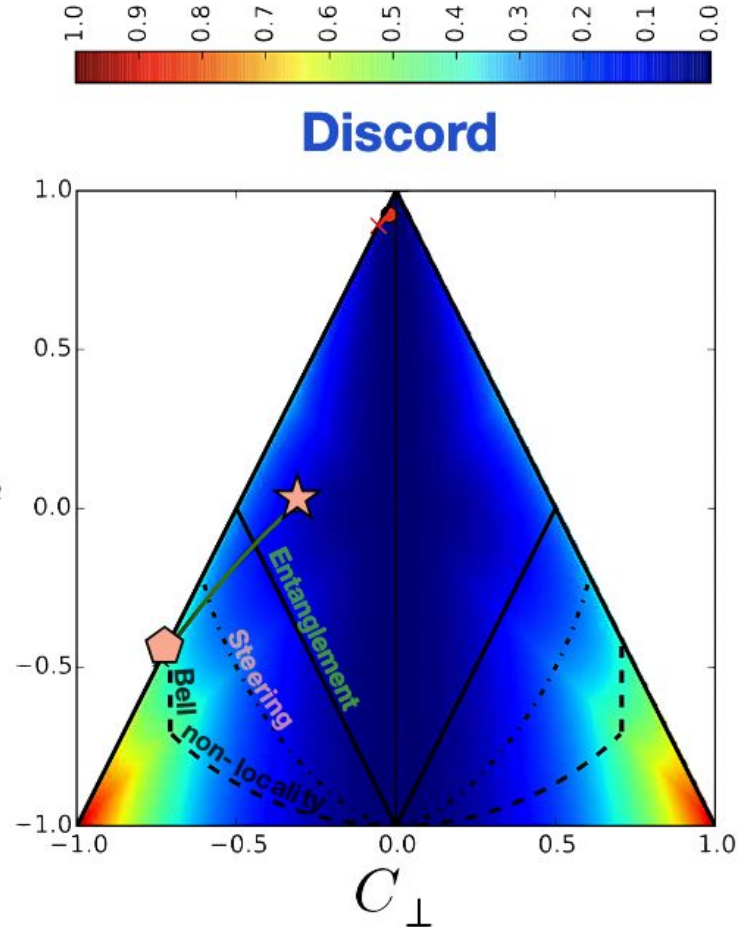
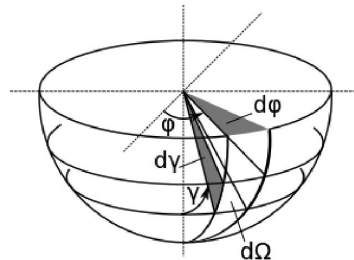


Discord quantifies the “degree of quantumness” of the system, but is **extremely challenging to measure!**

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

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 \mathcal{D}_A above
5. Repeat with the other particle



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.

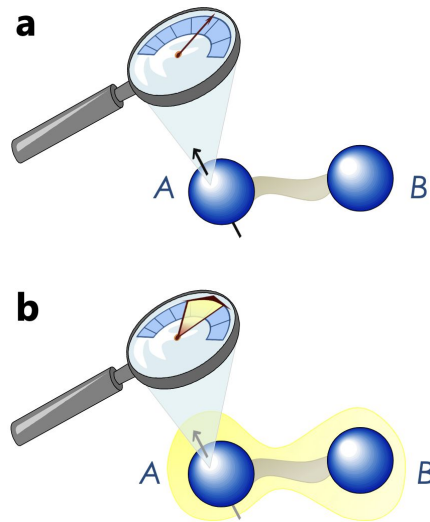
Wigner-Yanase skew information: $\mathcal{I}(\rho, K_A \otimes \mathbb{I}_B) = -\frac{1}{2} \text{Tr}([\sqrt{\rho}, K_A \otimes \mathbb{I}_B]^2)$

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

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

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

the Local Quantum Uncertainty (LQU)



- **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*



$$\sigma(t\bar{t}_{\text{GFRW}}) = 9.3_{-1.3}^{+1.4} \text{ pb} = 9.3_{-1.0}^{+1.1} (\text{stat.}) \pm 0.8 (\text{syst.}) \text{ pb}$$



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

Backup

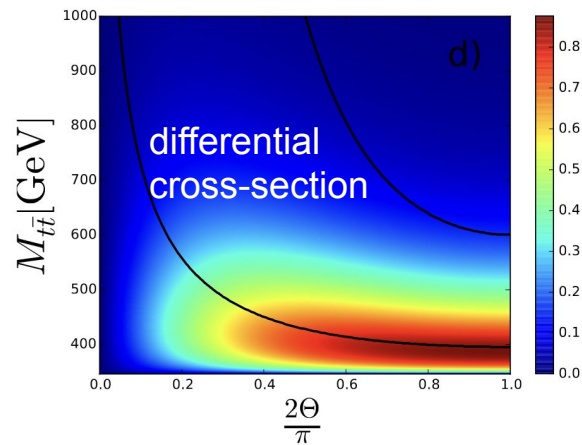
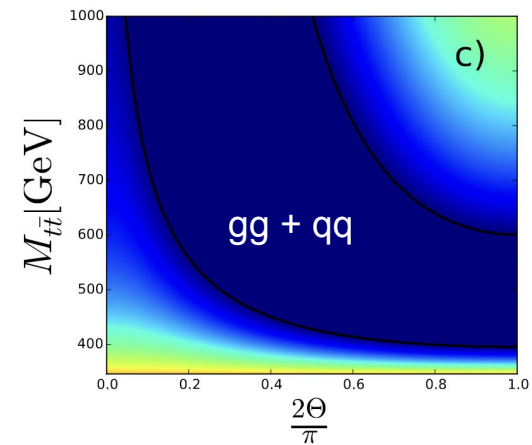
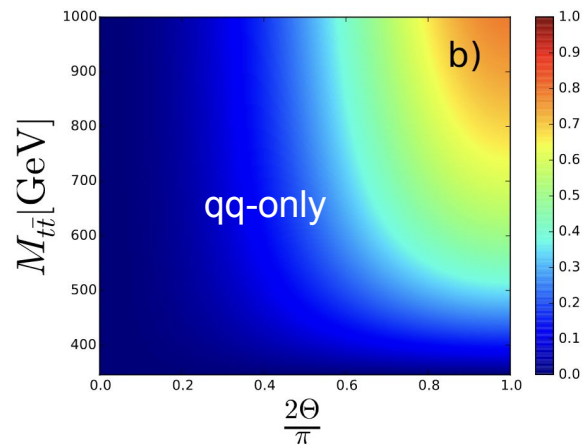
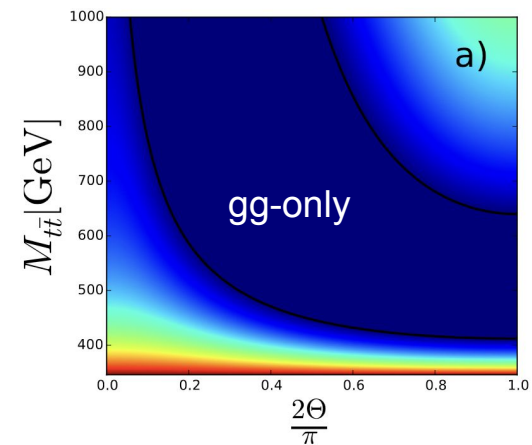
$$\rho = \frac{1}{4} \left(\mathbb{1} \otimes \mathbb{1} + \sum_i (B_i^+ \sigma_i \otimes \mathbb{1} + B_i^- \mathbb{1} \otimes \sigma_i) + \sum_{ij} C_{ij} \sigma_i \otimes \sigma_j \right)$$

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

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

Peres-Horodecki: if ρ^{T_2} has at least one negative eigenvalue, the state is entangled

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



z-axis: concurrence $C[\rho]$

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

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

$C[\rho] > 0 \Leftrightarrow$ entanglement

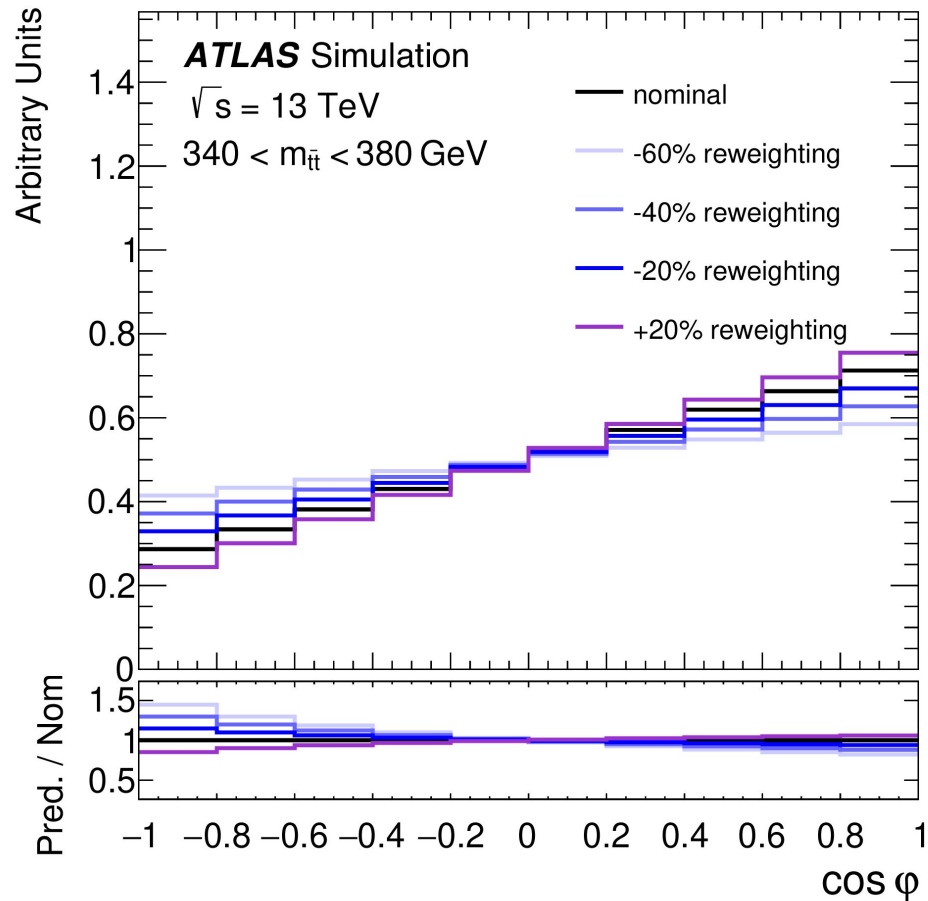
The reweighting method

- 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 $M(t\bar{t})$

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

- 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

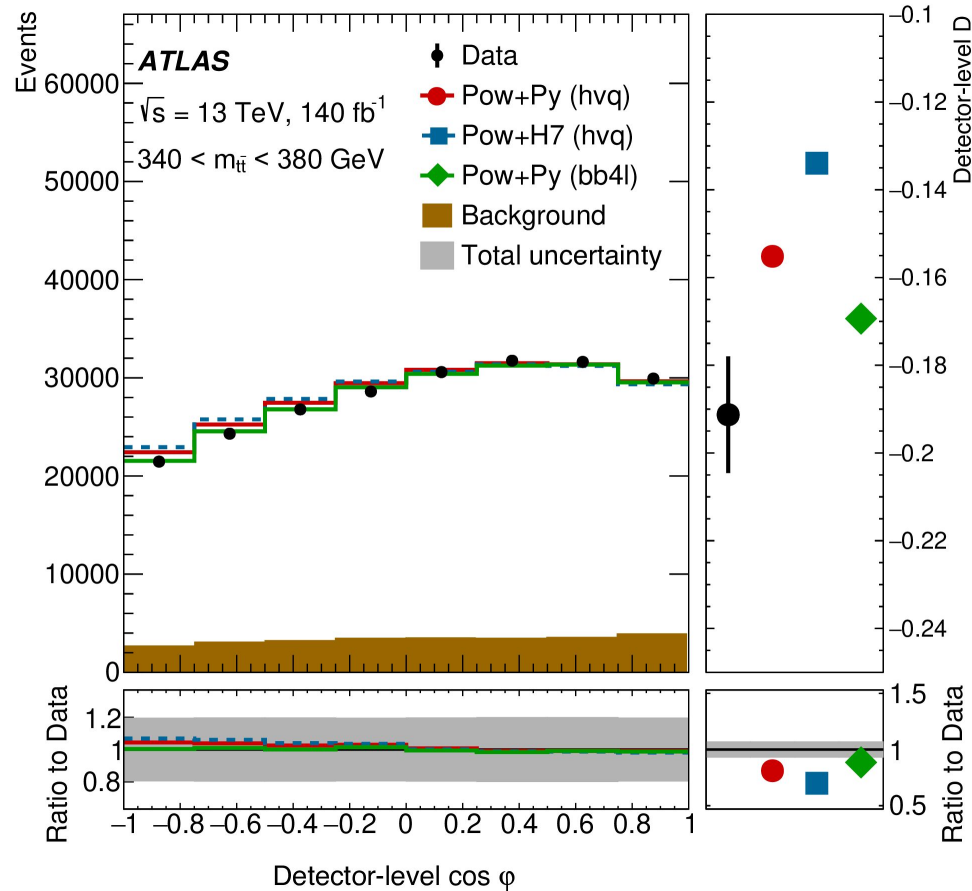
“Backgrounds”: mostly $Z \rightarrow \tau\tau$, which leads to a flat $\cos(\varphi)$ distribution (spin information from taus is lost)

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

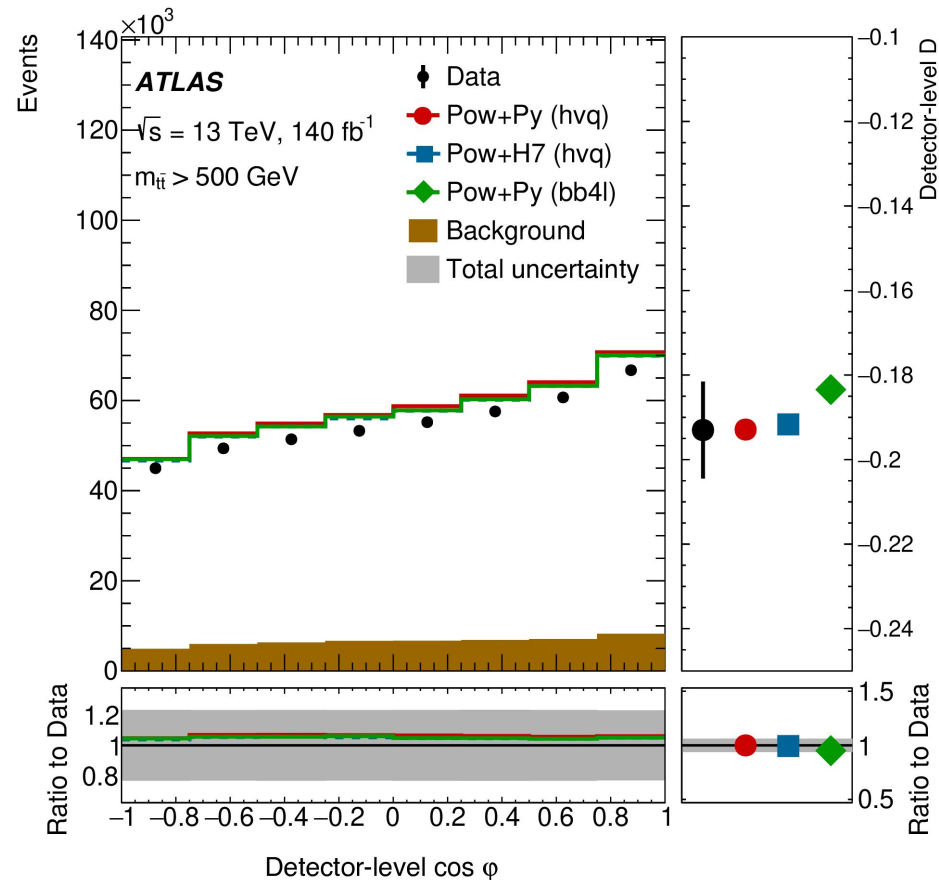
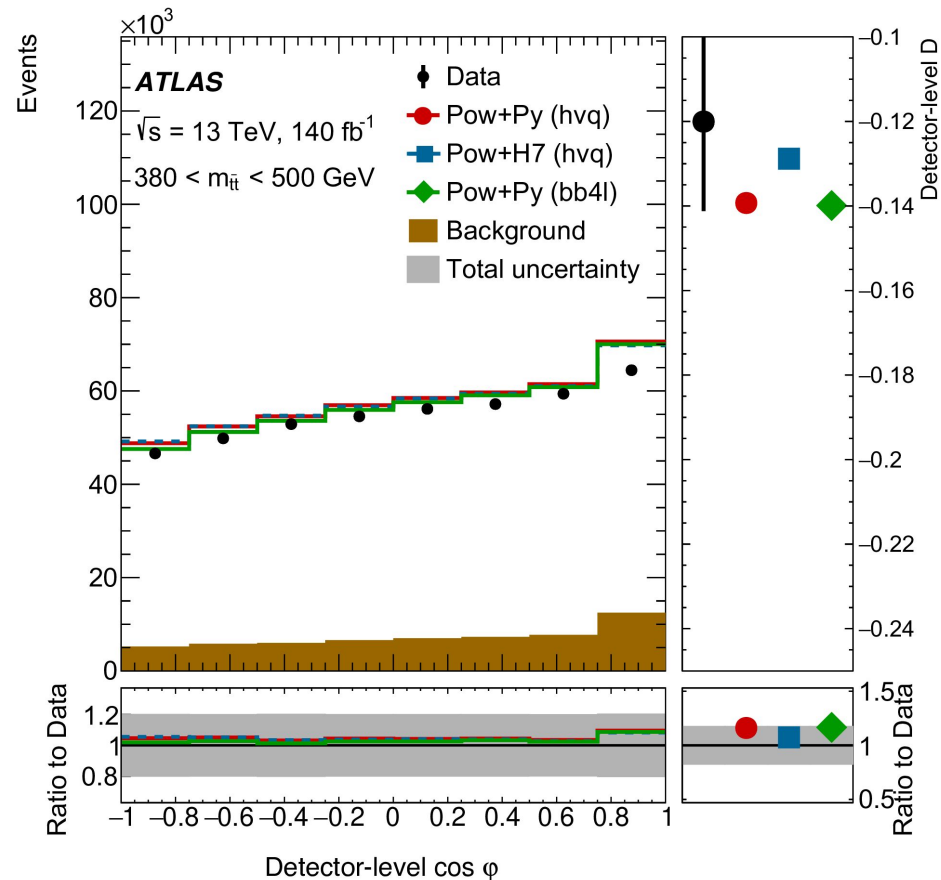
Signal modelling: by far the largest contribution

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_T^{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

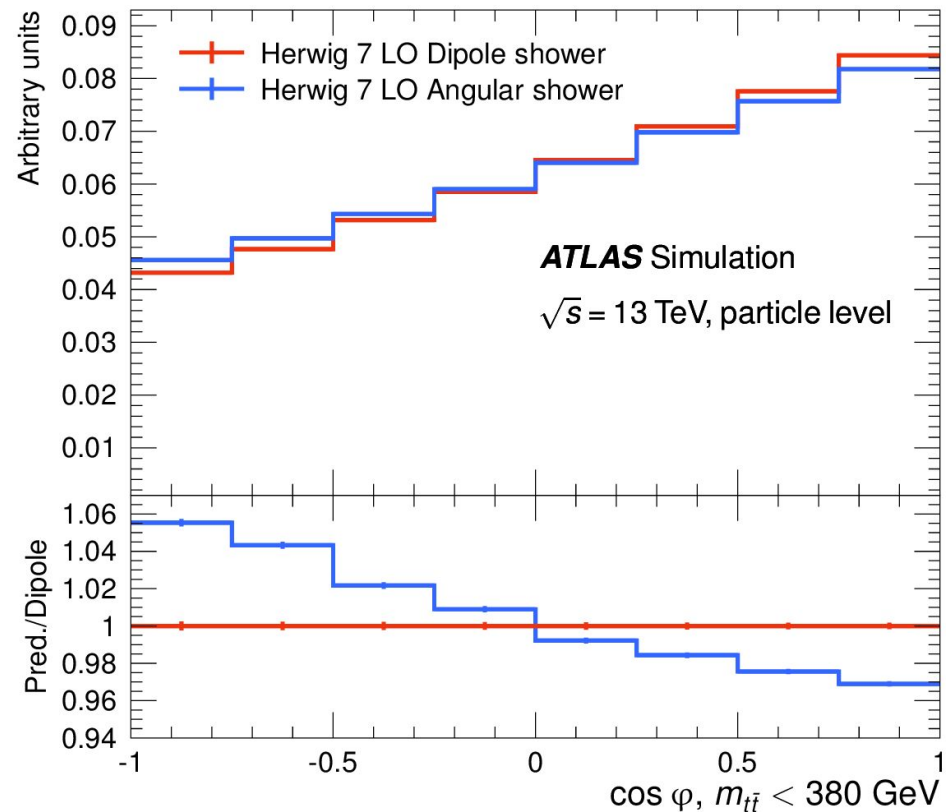
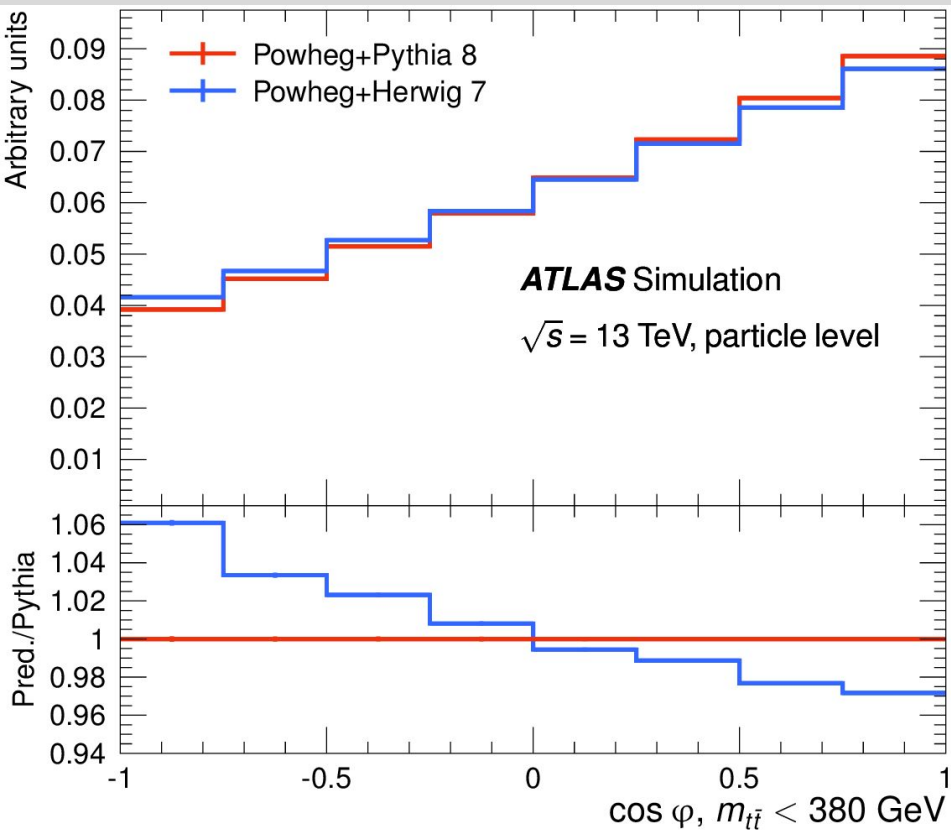
Leading Systematics	Relative Size [D = SM (-0.47)]
Top-quark decay	1.6 %
$Z \rightarrow \tau\tau$ Cross-section	1.5 %
Recoil To Top	1.1 %
Final State Radiation	1.1 %
Scale Uncertainties	1.1 %
NNLO Reweighting	1.1 %
Parton Distribution Function (5)	0.8 %
pThard1 Setting	0.8 %
Top-quark Mass	0.7 %
Single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



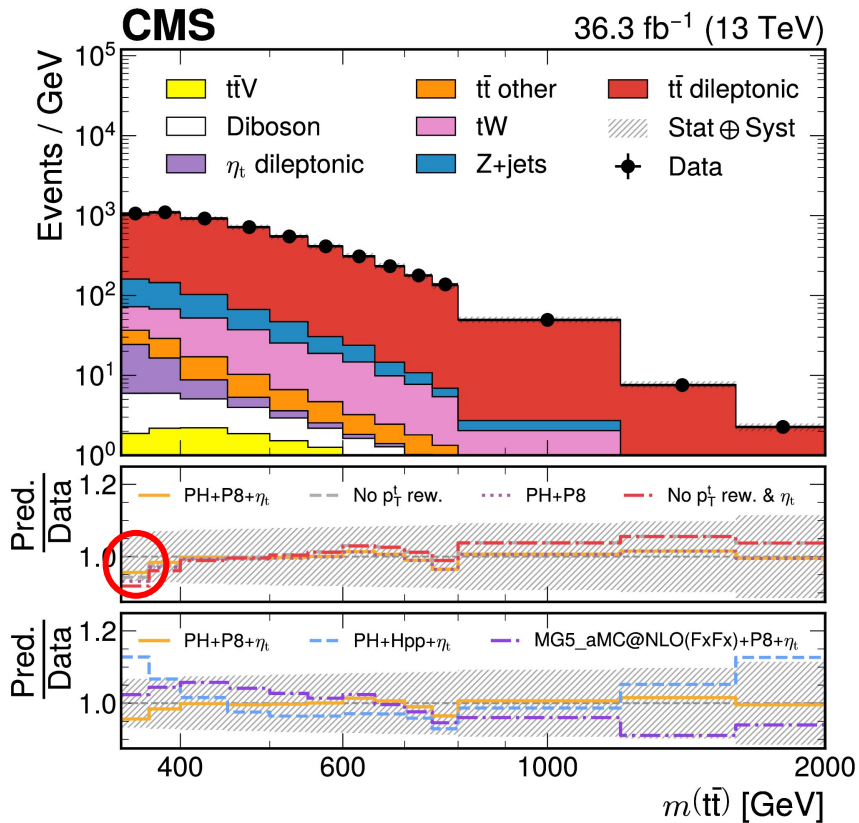
Data / MC outside the signal region



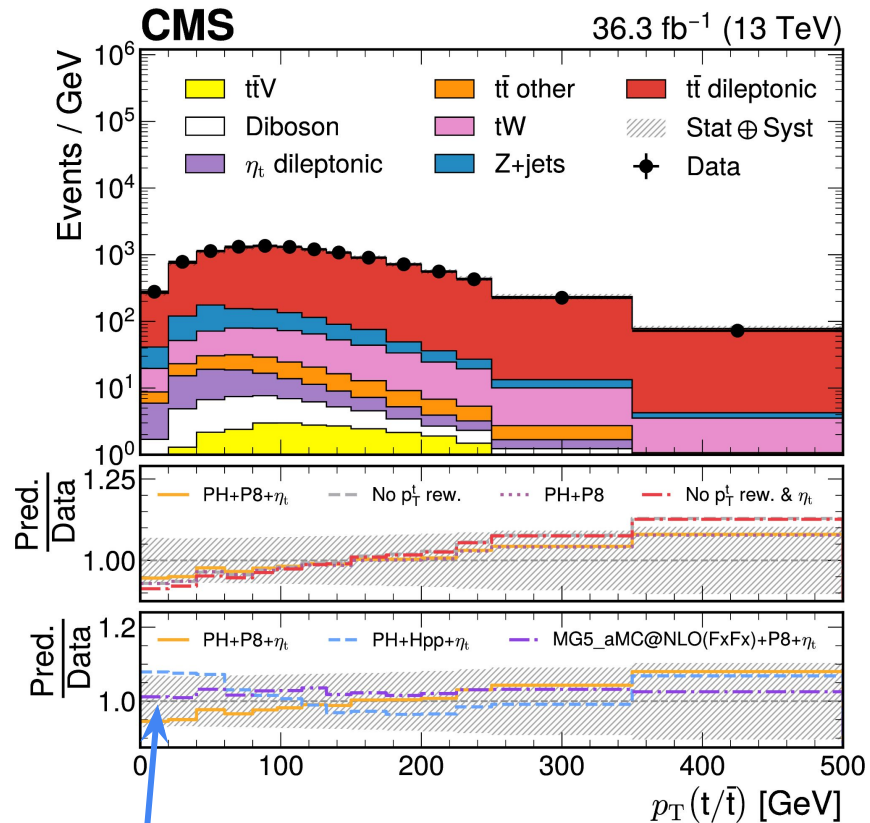
Investigations of parton shower effects



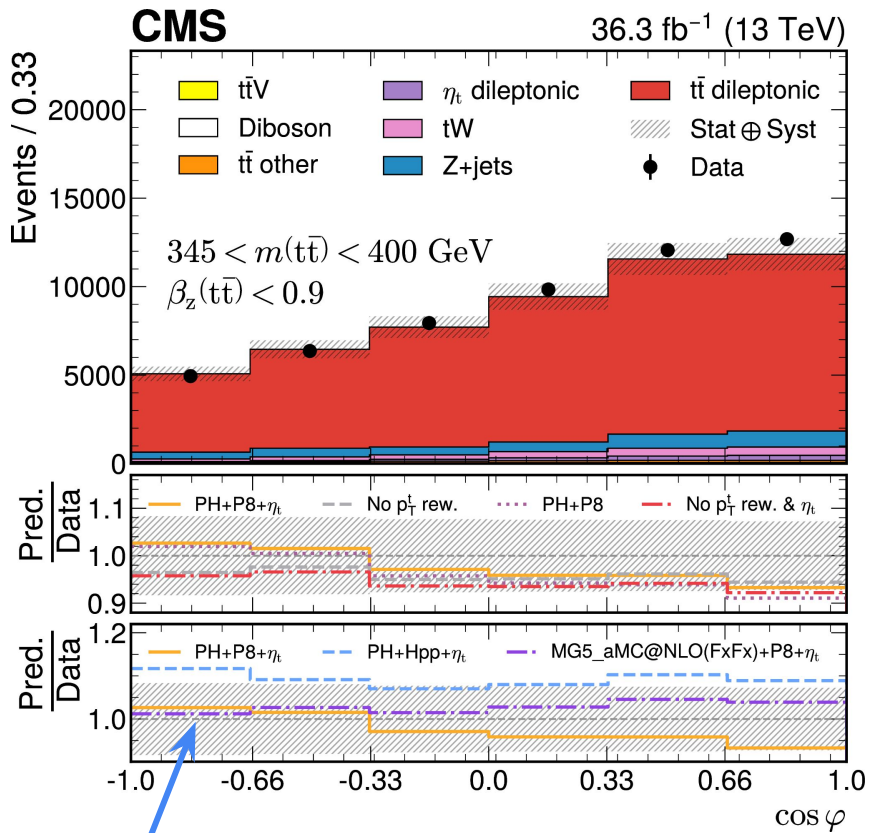
Differences appear in the parton \rightarrow particle level transition,
and seem to largely match the Dipole vs Angular ordering schemes



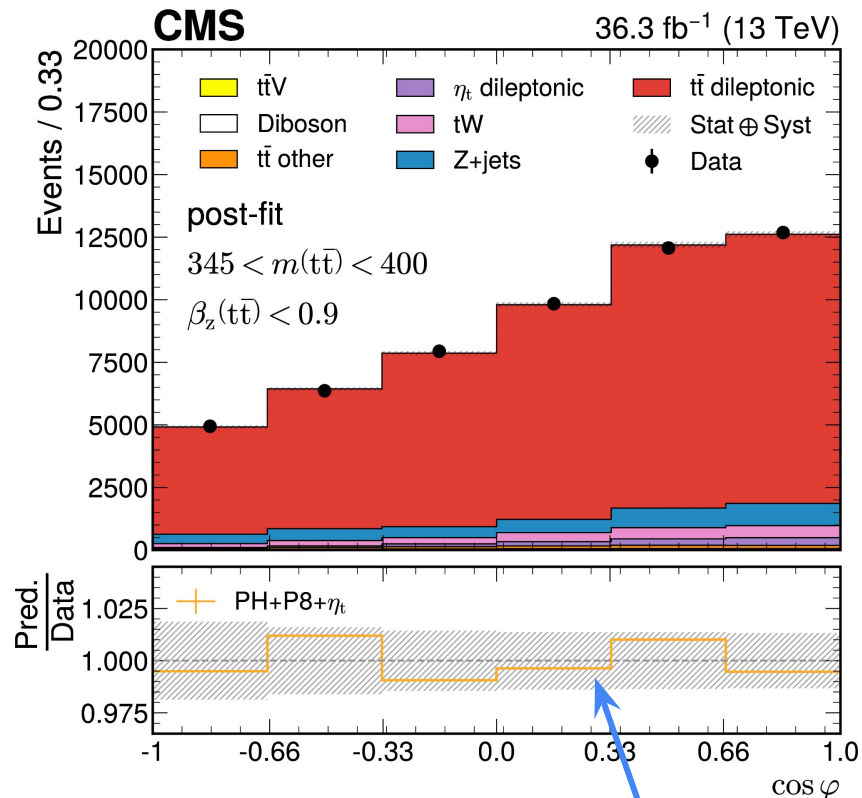
Toponium improves modelling



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

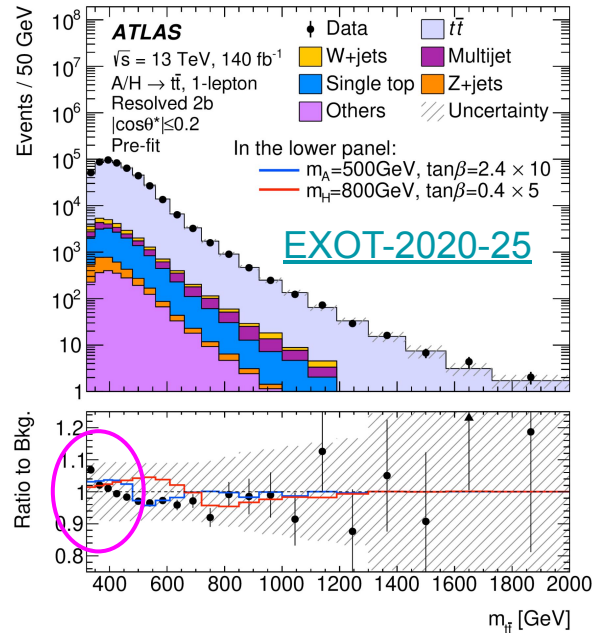
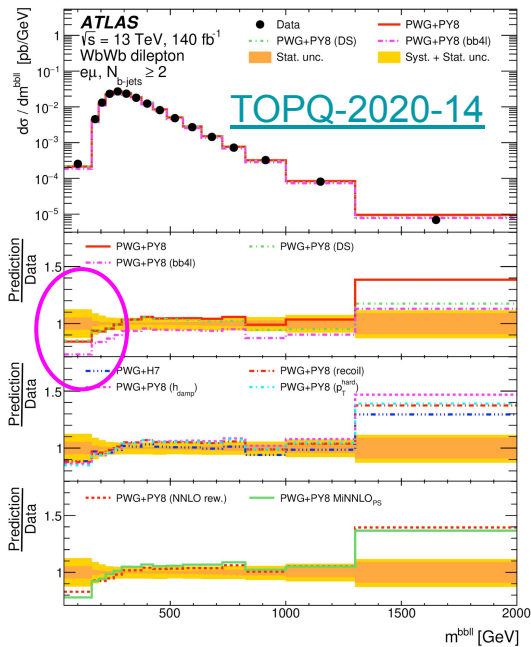
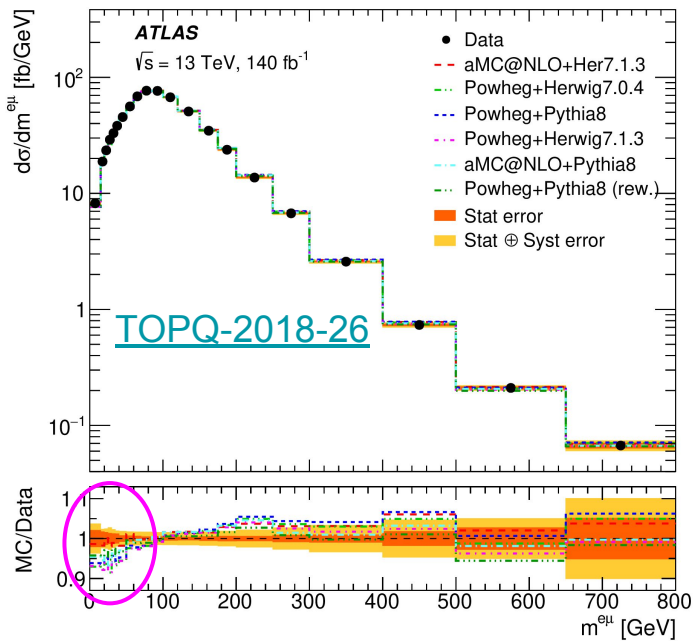


FxFx gives best modelling at threshold



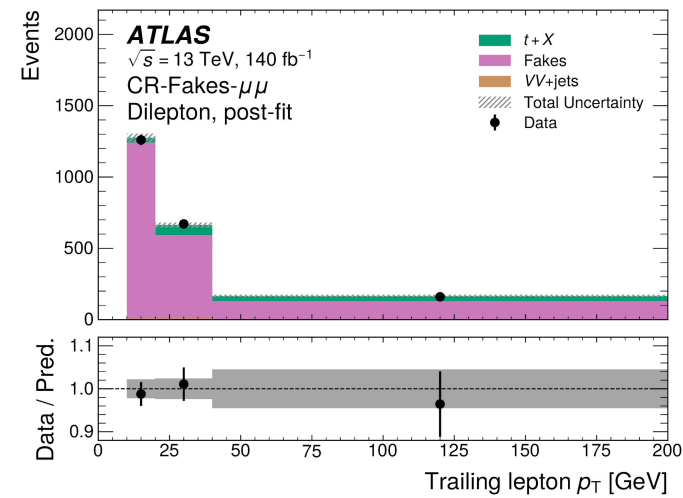
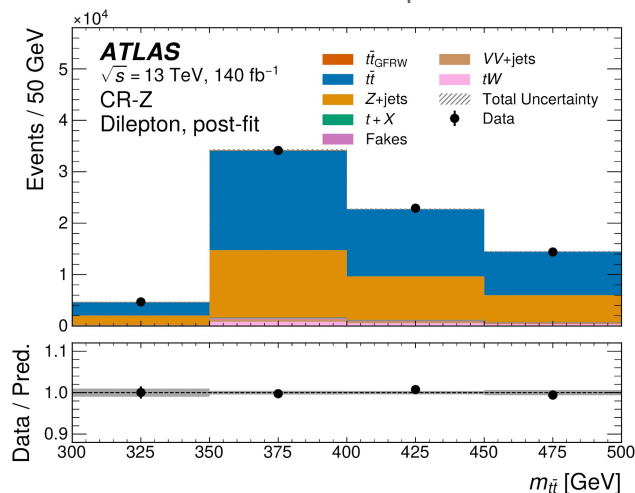
Post-fit clearly prefers *toponium*

- **Slight excess** in data near production threshold
 - the inclusive toponium cross section is roughly 0.6% that of inclusive $t\bar{t}$ 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



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_{tt}	300 to 500 GeV <i>no overflow above!</i>	300 to ~1400 GeV <i>with overflow above</i>
Only for OSSF ee/$\mu\mu$		
Dilepton invariant mass	$m_{ll} \geq 15$ GeV $ m_{ll} - m_Z \geq 10$ GeV	$m_{ll} \geq 20$ GeV $ m_{ll} - m_Z \geq 15$ GeV
Missing ET	MET ≥ 60 GeV	MET ≥ 40 GeV

- 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 $t\bar{t}$ in the CR-Z, but no toponium due to high m_{ll} requirement!
- Define **CR-Fakes- $ee/\mu\mu/e\mu$** 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



- 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_{tt} 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 $\text{tt}+\text{tW}$
 - **CMS:** check pseudo-scalar only vs pseudo-scalar + scalar, check also alternative generators
- **Strong constraints of some tt modelling uncertainties are observed** – and indeed expected from previous measurements
 - due to different descriptions of both the m_{tt} 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

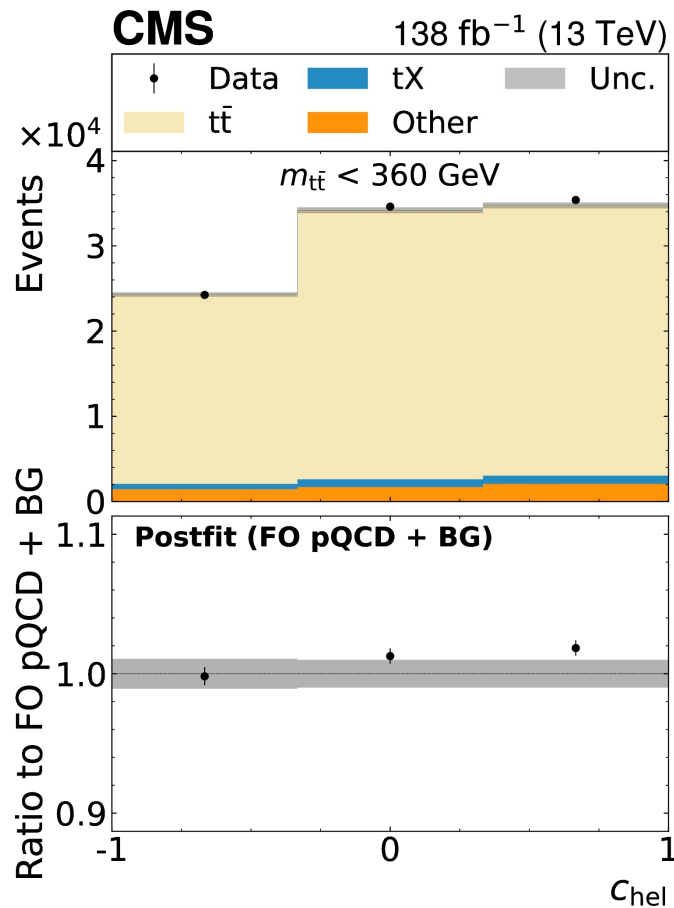
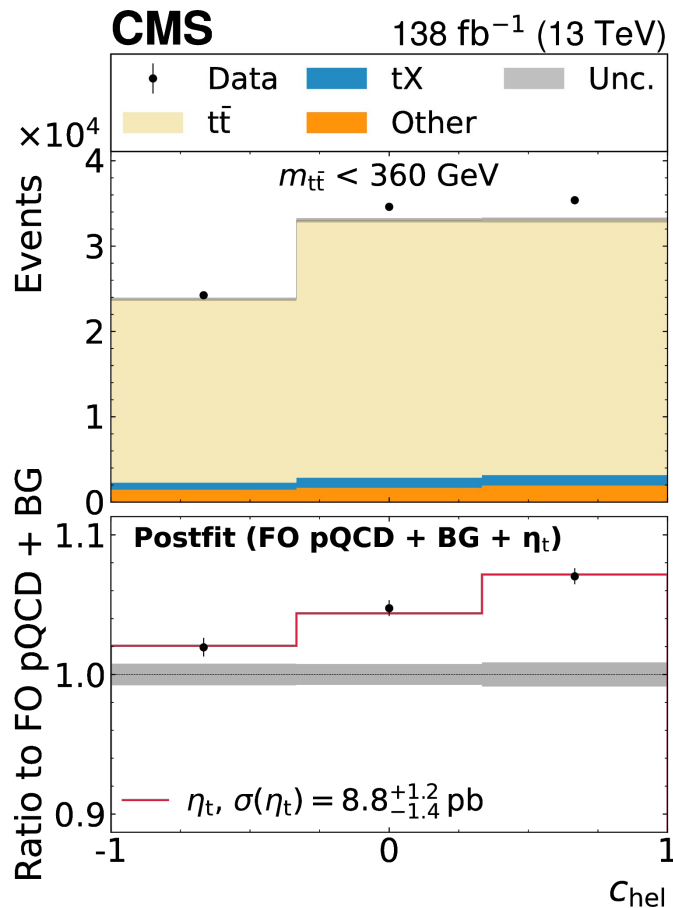
Type	ATLAS	CMS
Experimental	electrons, muons, jets, b-tagging, MET, pileup, luminosity	
Minor backgrounds	normalisation unc. only	normalisation unc. μ_R/μ_F and ISR/FSR for Drell-Yan
Fake background	normalised in data shape variations	shape variations only
tW background	aNNLO normalisation with 4% unc. 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	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

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 $\pm 11\%$ 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 [no reweighting in the comparison]	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 = $1.58m_t + 0.66m_t - 0.59m_t$ —

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 \rightarrow 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

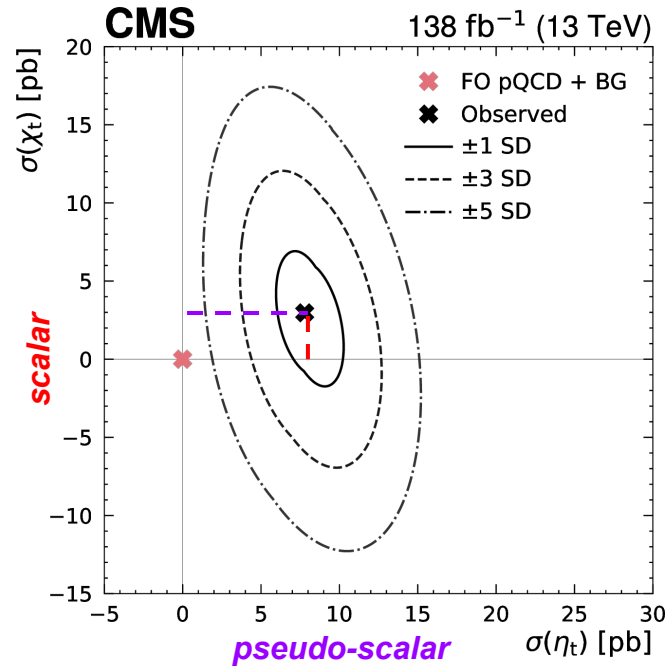
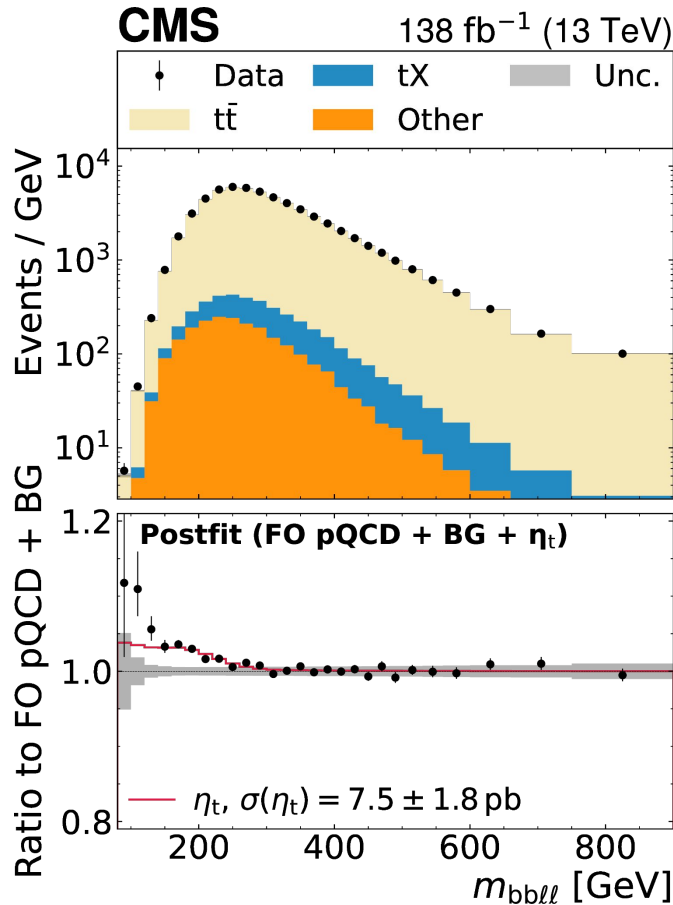
Further checks: background-only fits



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

\Rightarrow toponium-like signal is needed to explain the data!

Further checks: alternative templates



- Fit to $m_{bbl l}$ 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 $>5\sigma$**

- 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
GFRW [Fuks et al.]	9.3 ± 1.3	—	—	8.5 ± 1.1
η_t [Maltoni et al.]	8.8 ± 1.3 13.1 ± 1.8	8.6 ± 1.1	9.8 ± 1.3	6.6 ± 1.4

- All models point to an excess **compatible with toponium formation**, with **one caveat**
 - ATLAS sees slightly different results between the two toponium models, likely due to the differences in top kinematics affecting the reconstruction \rightarrow **$\sim 2\sigma$ tension with CMS if both use the same model**

Normalisation of bb4l: HO $t\bar{t}$ + HO tW vs DPA NNLO

From the recent paper by Jonas Lindert et al.: [arXiv:2507.11410](https://arxiv.org/abs/2507.11410)

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

$$10278 \pm 55 \text{ (MC/extrapolation)} \pm 152 \text{ (NWA)} \text{ fb} = \mathbf{10278 \pm 162 \text{ fb}}$$

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

Therefore the inclusive cross section is: **871.5 \pm 13.7 pb**

The HO $t\bar{t}$ 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 \pm 43.4 pb**

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

or: **0.954 \pm 0.030** [assuming full correlation]

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

	SR1	SR2	SR3	SR4	SR5	SR6	SR7	SR8	SR9		CR-Z	CR-Fakes- $e\mu$	CR-Fakes- ee	CR-Fakes- $\mu\mu$
$t\bar{t}$	97000 ± 4000	55600 ± 3100	31500 ± 2100	65100 ± 3200	100000 ± 5000	65000 ± 4000	44500 ± 2500	72000 ± 4000	135000 ± 7000	$t\bar{t}$	43500 ± 2000	460 ± 230	220 ± 110	—
tW	3650 ± 240	2430 ± 180	1620 ± 140	2590 ± 180	4060 ± 280	2930 ± 240	1870 ± 160	2840 ± 190	5400 ± 400	tW	1830 ± 130	—	—	—
$t\bar{t} + tW$ (bb41)	102000 ± 5000	59600 ± 3100	34000 ± 2100	68900 ± 3300	108000 ± 5000	70000 ± 4000	47100 ± 2600	77000 ± 4000	147000 ± 6000	$t\bar{t} + tW$ (bb41)	46000 ± 2000	480 ± 240	240 ± 120	< 0.1
$t\bar{t}_{\text{NRQCD}}$	476 ± 26	489 ± 27	374 ± 20	255 ± 13	1030 ± 50	990 ± 40	121 ± 6	685 ± 31	2430 ± 90	$t\bar{t}_{\text{NRQCD}}$	204 ± 12	—	—	—
$\eta t\bar{t}$	476 ± 21	503 ± 24	392 ± 20	264 ± 11	1060 ± 40	990 ± 40	128 ± 6	704 ± 28	2380 ± 90	$\eta t\bar{t}$	237 ± 11	< 0.1	< 0.1	< 0.1
Z+jets	990 ± 140	880 ± 130	870 ± 110	490 ± 80	680 ± 90	520 ± 90	230 ± 50	350 ± 50	540 ± 90	Z+jets	33000 ± 6000	—	—	—
$t + X$	320 ± 100	180 ± 50	105 ± 32	200 ± 60	280 ± 80	170 ± 50	140 ± 40	190 ± 60	310 ± 90	$t + X$	330 ± 100	370 ± 110	109 ± 33	160 ± 50
Fakes	1480 ± 50	1200 ± 40	1020 ± 40	1090 ± 40	1430 ± 60	996 ± 34	803 ± 27	950 ± 60	1127 ± 33	Fakes	484 ± 23	4890 ± 130	1640 ± 70	1650 ± 60
VV+jets	120 ± 40	104 ± 32	92 ± 29	79 ± 25	120 ± 40	104 ± 32	54 ± 17	80 ± 25	140 ± 40	VV+jets	1100 ± 350	110 ± 60	30 ± 15	30 ± 15
Total	104000 ± 5000	60900 ± 3300	35600 ± 2200	69800 ± 3400	108000 ± 5000	71000 ± 4000	47800 ± 2600	77000 ± 4000	145000 ± 7000	Total	80000 ± 7000	5830 ± 340	2000 ± 160	1840 ± 80
Total (bb41)	106000 ± 5000	62500 ± 3200	36500 ± 2200	71100 ± 3400	111000 ± 5000	73000 ± 4000	48400 ± 2600	79000 ± 4000	152000 ± 6000	Total (bb41)	81000 ± 7000	5850 ± 350	2020 ± 170	1840 ± 80
Data	103095	61071	35514	69602	107995	70917	48258	77123	145030	Data	76127	6120	2013	2091

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

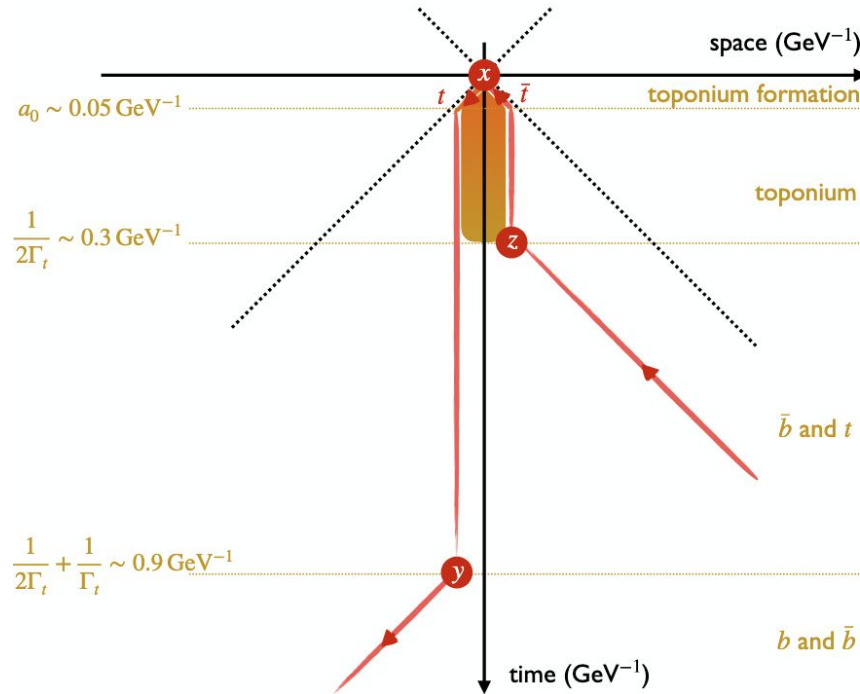
Smaller backgrounds: Z+jets (0.8%) and fake leptons (1.5%) → decent pre-fit description from MC templates, normalisation to data in CRs.

Uncertainty breakdown (ATLAS)

Category	Impact
$t\bar{t}_{\text{GFRW}}$ modelling	6.9%
pQCD $t\bar{t}$ modelling	4.7%
JES pile-up	1.5%
b -tagging	1.3%
Instrumental (other)	0.9%
JES η inter-calibration	0.9%
Jet energy scale (JES)	0.6%
Background normalisations	0.6%
Leptons	0.6%
JES flavour	0.6%
tW modelling	0.5%
Limited MC statistics	0.3%
Jet energy resolution (JER)	0.2%
Total syst. uncertainties	8.8%
Total stat. uncertainties	11%

Timeline of toponium formation

Benjamin Fuks

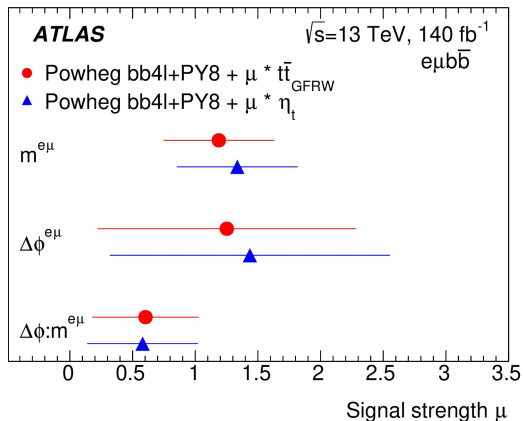
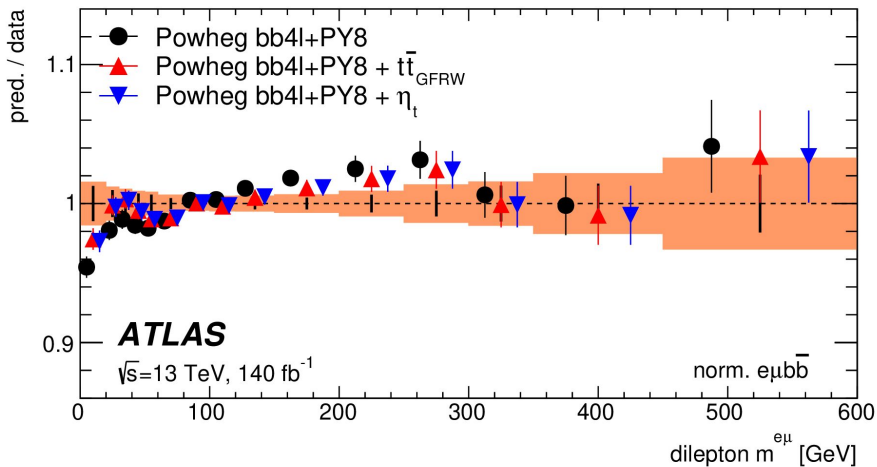


In analogy with hydrogen atom:

- ▶ 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 $2\pi/(m\alpha_s^2) \approx 3,6 \text{ GeV}^{-1}$
- ▶ The toponium lifetime is $\approx 1/(2\Gamma_{\text{top}}) \approx 0.3 \text{ GeV}^{-1}$

↪ 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.

Evidence of toponium formation from $t\bar{t} \rightarrow e\mu + b\bar{b}$

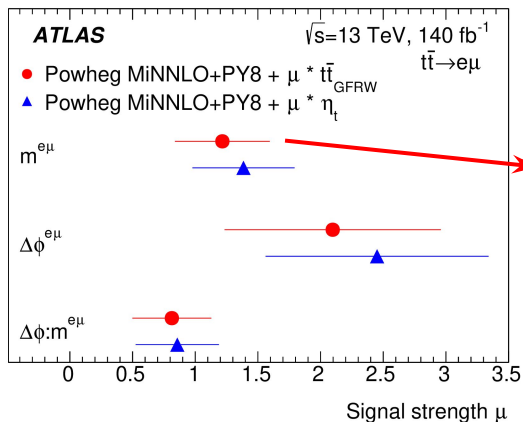
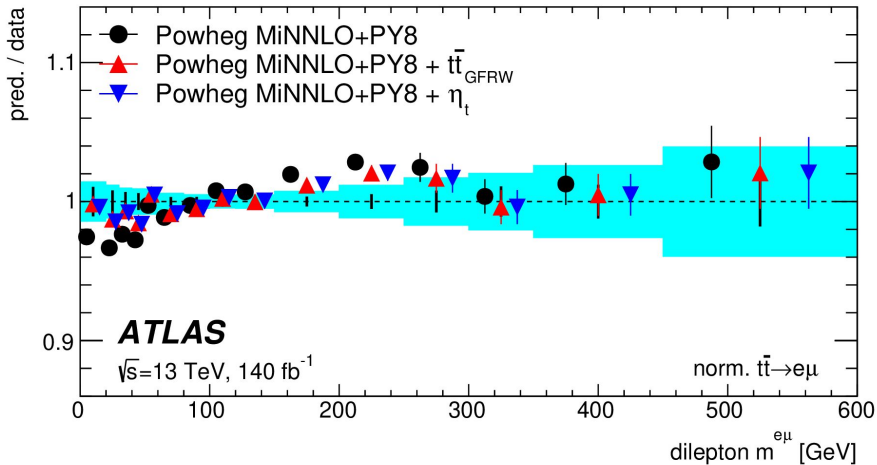


- Adding either model of the toponium signal **improves the description of the data at threshold**

- Fitting **MiNNLOps + GFRW- $t\bar{t}$** yields **evidence for toponium formation:**

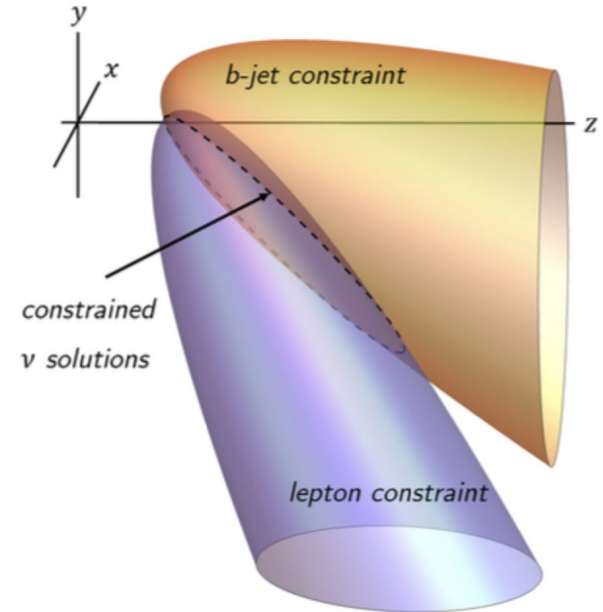
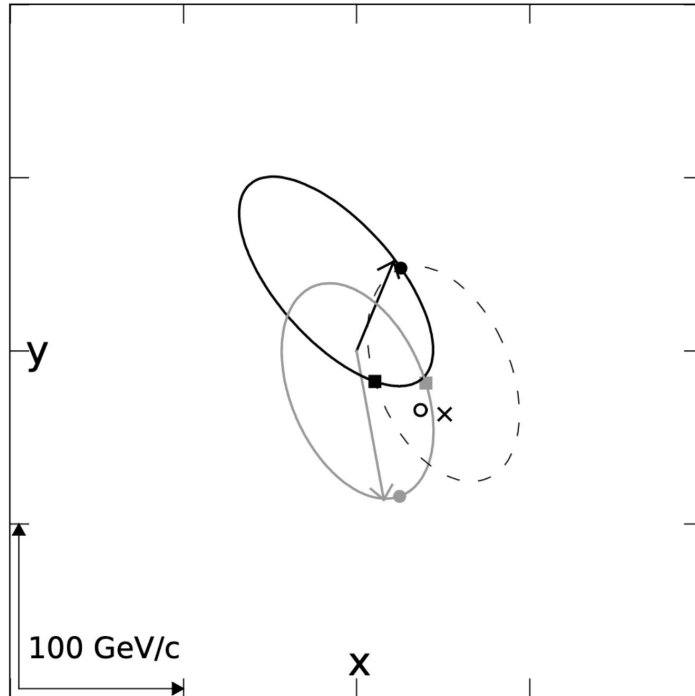
$$\mu = 1.22 \pm 0.38$$

$$\sigma(tt_{\text{GFRW}}) = 7.8 \pm 2.4 \text{ pb}$$



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

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



- Dates back to [D0](#) (1997), they measured $m_{\text{top}} = 172.0 \pm 7.5$ GeV
- [LHC Run 1 combination](#) (2023) measured $m_{\text{top}} = 172.52 \pm 0.33$ 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!**

- A new **general marker** of quantum entanglement has been proposed
 - in the **threshold** region, **exactly what is being done now** ($D = \text{Tr}[C]/3$)
 - in the **boosted** region, would need **slightly different** angular distribution
 - at threshold, additional cut on the $t\bar{t}$ velocity β can reduce the $q\bar{q}$ contamination
 - both approaches can increase the statistical sensitivity by $\sim 20\%$
- 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

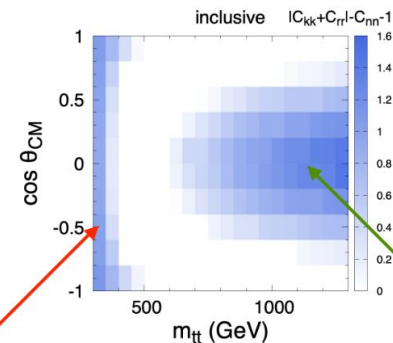
spin correlations

	Threshold β	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

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



Threshold region,

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

Boosted region,

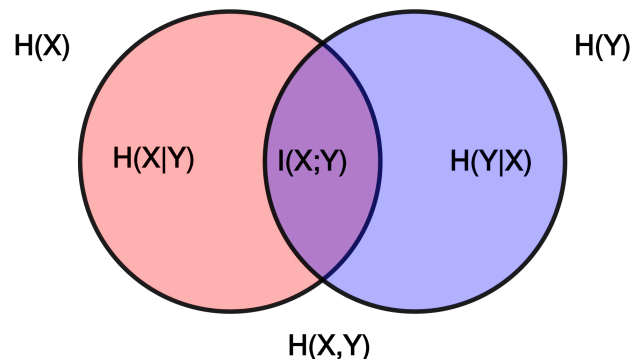
$$E = C_{kk} + C_{rr} - C_{nn} - 1 > 0$$

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

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

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

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



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

- In general: $0 \leq \mathcal{D}_A \leq 1$ and $\mathcal{D}_A \neq \mathcal{D}_B$
- **Experimentally very challenging!** Requires a *minimisation* over projective measurements.
- **Analytical results exist** for special classes of states (e.g. Bell-diagonal states, T states)

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

Closed-form formulae when A is a qubit

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

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

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 $\mathfrak{t}\mathfrak{t}$ 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 $(\omega_1, \omega_2, \omega_3)$ of the matrix

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

The LQU simplifies to

$$\mathcal{U}(\rho) = 1 - \max(\omega_1, \omega_2, \omega_3)$$

[we only need the SDM!]