

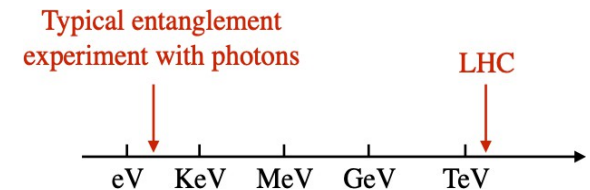


Top quark measurements at the LHC

30+ years of top quark physics!

Today's menu:

- Associated production
 - Vector bosons, fermions
- Top quark properties:
 - m_t
 - Top quarks as a Quantum Information Science Lab



Andy Jung

on behalf of the ATLAS and CMS collaborations

Xth QCD@LHC, Oxford, UK

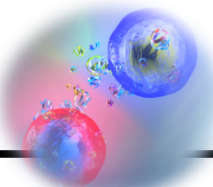
Oxford University, 28th Sep to 2nd Oct



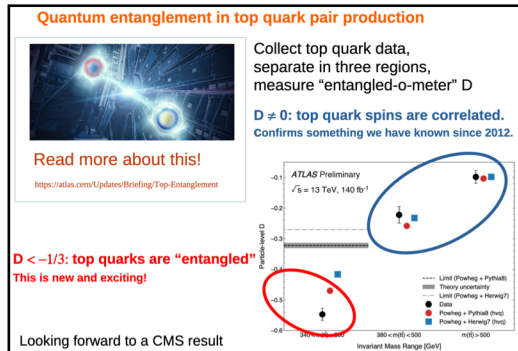
Sep 30, 2025



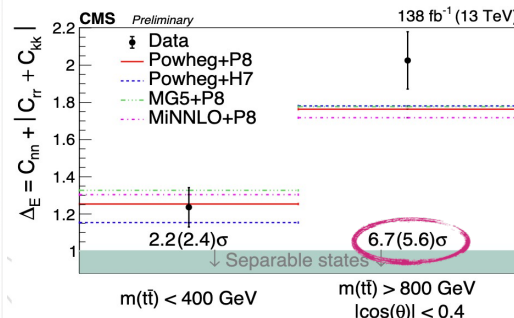
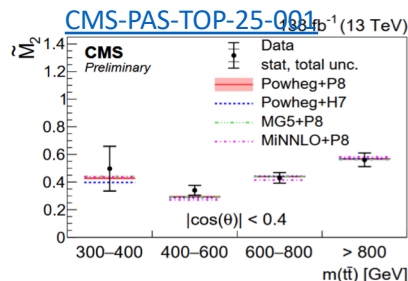
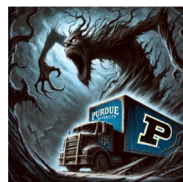
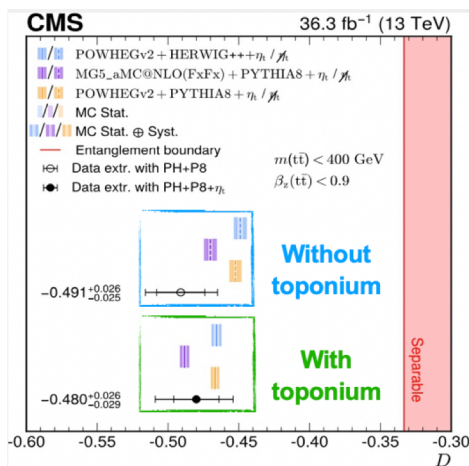
Exciting times...



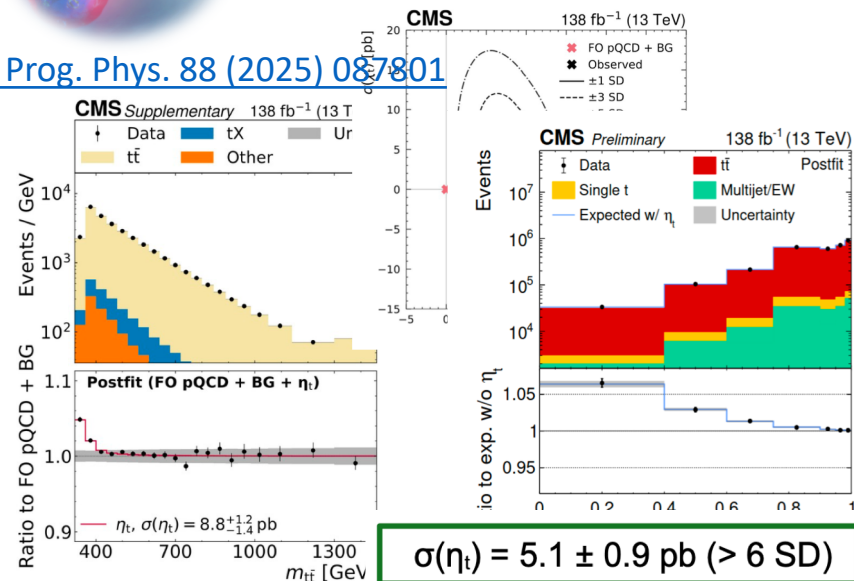
[Nature 633, 542–547 \(2024\)](#)



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

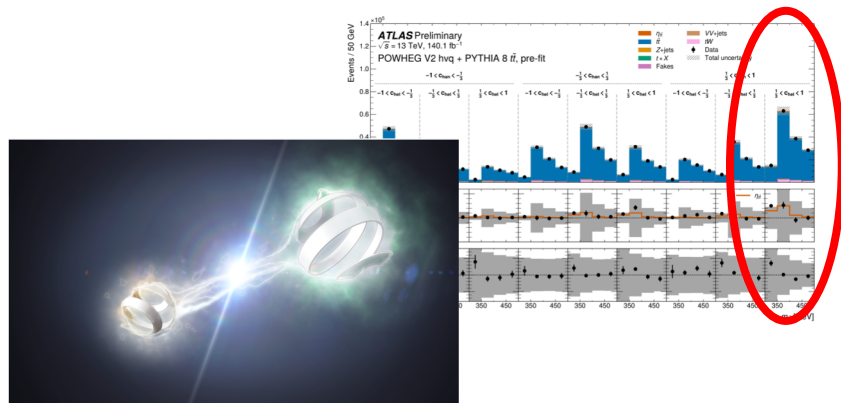


[Rep. Prog. Phys. 88 \(2025\) 087801](#)



[CERN-EP-2026-002 / TOPQ-2025-11](#)

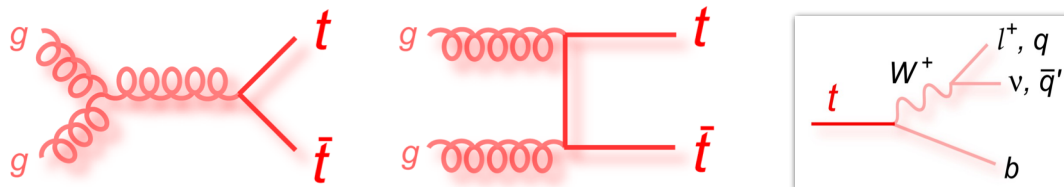
- “toponium” – lots of updates recently
- LHC as a quantum information lab
- More rare cross sections
- Rare processes



[Sept 17th 2026: Strong evidence for quantum entanglement between Z bosons found by ATLAS and CMS](#)

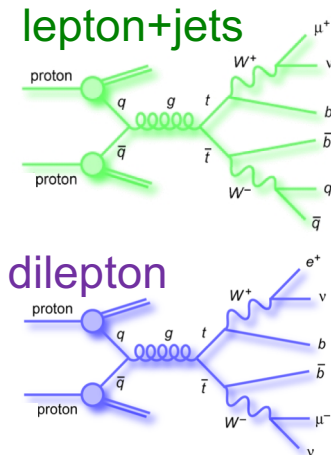
Standard Model – Top Quark Physics

Top quark production is dominated by QCD, decay is electroweak



Top quark is the heaviest fundamental particle discovered so far

→ $m_t = 172.52 \pm 0.33 \text{ GeV}$ [[PRL 132 \(2024\) 261902](#)]



Unique quark, not stable:

$$\frac{1}{m_t} < \frac{1}{\Gamma_t} < \frac{1}{\Lambda_{\text{QCD}}} < \frac{m_t}{\Lambda^2}$$

production 10^{-27} s lifetime 10^{-25} s hadronization 10^{-24} s spin-flip 10^{-21} s

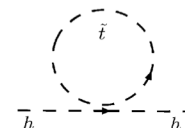
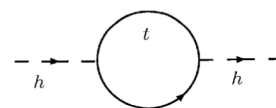
→ **Observe bare quark properties**

→ **Spin information preserved**

Large Yukawa coupling to Higgs boson

→ $\lambda_t \sim 1$ only m_t is a “natural mass”

Special role in EW symmetry breaking ?



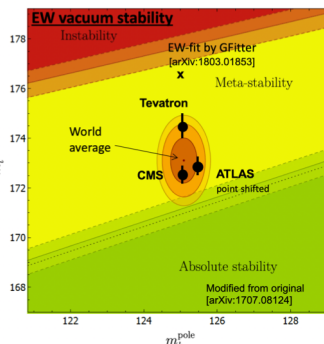
Higgs mass at ~ 125 GeV!

→ New physics in loops ?

→ BSM often has **top quark partners**

→ No fine-tuning if top quark partner

→ **New probes, e.g. based on quantum information science !?**



Top quark physics – m_t Highlights

30+ years of top quark physics!

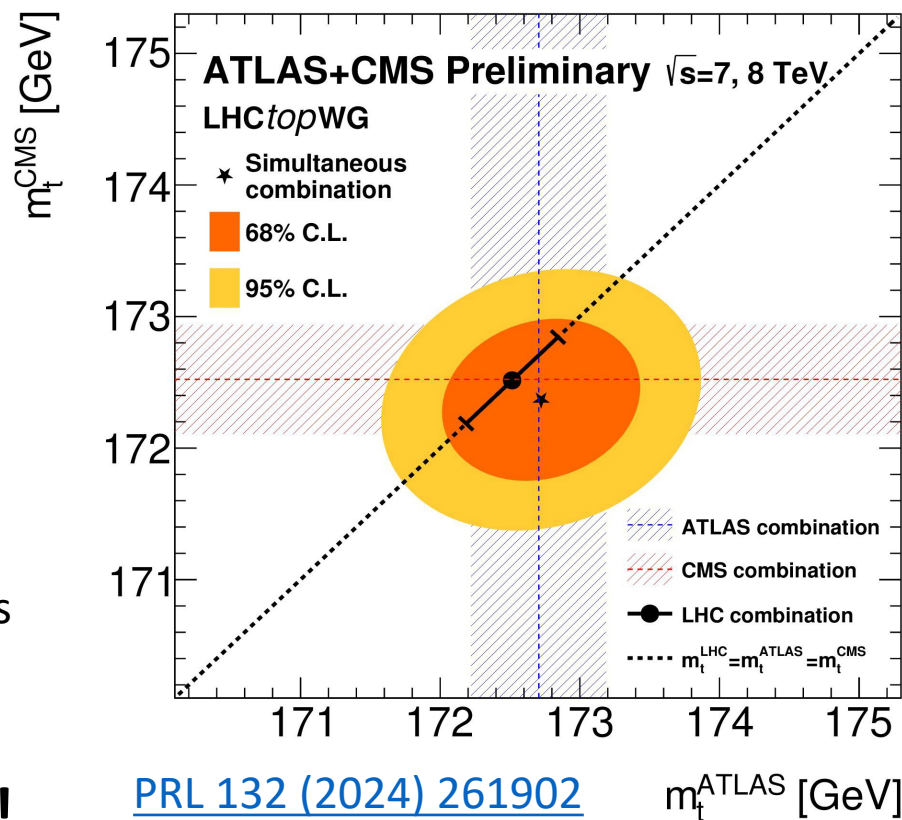
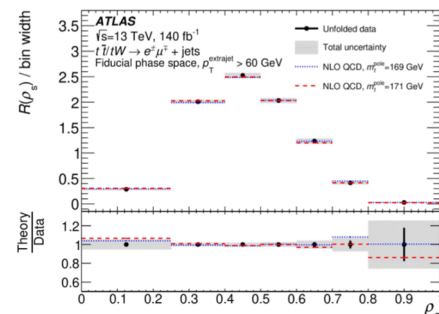
15 measurements at 7 and 8 TeV combined

- Best Linear Unbiased Estimate method
 - Correlation strengths of different systematic uncertainties between measurements evaluated
 - Combination stable against different assumptions
 - Jet energy scale, b-tagging and modelling largest uncertainties
- Good compatibility between the measurements
- Largest impact: CMS and ATLAS 8 TeV $l+jets$

Associated jet production

- Different systematic uncertainties

[JHEP 2026, 99 \(2026\)](#)



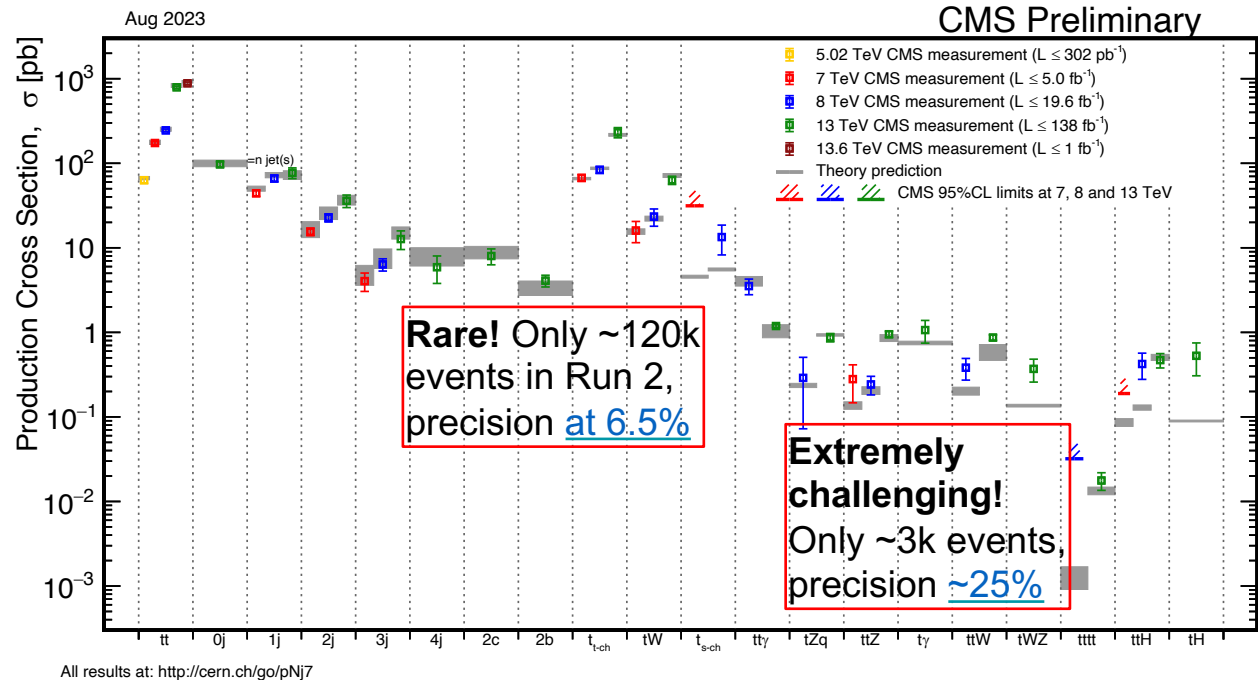
Most precise mass determination to date! relative precision < 0.2% !

[PRL 132 \(2024\) 261902](#)

Top quark physics: Current status...

Abundant production!
 $O(100M)$ events in Run 2
 Precision down to 1.8%

Abundant production at the LHC, $O(100M)$ $t\bar{t}$ pairs
 → **“Standard candle”**



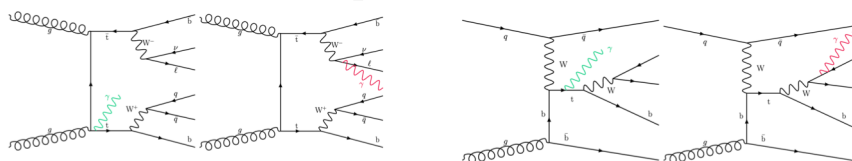
Top quark at QCD@LHC:

ATLAS results on associated top quark production (Top+X) and EFT interpretations	Oliver Rieger	Lucas Cremer
Seminar Room 7, St Anne's College	11:10 - 11:30	14:00 - 14:20
NNLO QCD corrections to $t\bar{t}W$ production at the LHC	Vsevolod Chestnov	Giovanni Limatola
Seminar Room 7, St Anne's College	11:30 - 11:50	14:20 - 14:40
State-of-the-art predictions for four-top production with invariant-mass threshold resummation.	Tommaso Saracco	Daniel Ernani Martins Neto et al.
Seminar Room 7, St Anne's College	11:50 - 12:10	
Top quark mass interpretation from simulation of top-flavoured mesons	Alexander Lind	Leon Mans
Seminar Room 7, St Anne's College	12:10 - 12:30	15:00 - 15:20
Matching flavour schemes via isolation of heavy-quark mass power corrections	Christian Biello	Vishakha Lingadahally
Seminar Room 7, St Anne's College	12:30 - 12:50	15:20 - 15:40
ATLAS results on top properties and threshold region	Tsuzuki Room, St Anne's College	
Top quark pair in the threshold at the LHC: NRQCD and key-uncertainties	Tsuzuki Room, St Anne's College	
ATLAS results on top quark cross section measurements and recent progress on modelling	Tsuzuki Room, St Anne's College	
Complete NLO corrections to off-shell $t\bar{t}$ production in the $t\bar{t}l\bar{l}$ decay channel	Tsuzuki Room, St Anne's College	
Top Quark Pair Production and Decay: The 1-Higgs-Singlet Model and Pseudoscalar Decay	Tsuzuki Room, St Anne's College	

Associated γ production (full Run 2)

Inclusive and differential fiducial cross sections for $t\gamma q$ and $t\bar{t}\gamma$ production

Phys. Rev. D 110 (2024) 096023



- Differential measurements performed vs kinematic observables at **particle level**, & vs $\Delta R(t, \gamma)$ and top-quark charge at **parton level**
- Larger Run-3 datasets will enable multidifferential studies and improved sensitivity to possible deviations from the SM.

$$\mu_{t\gamma q} = 1.141^{+0.082}_{-0.080} = 1.141^{+0.067}_{-0.066} (\text{syst})^{+0.047}_{-0.047} (\text{stat}),$$

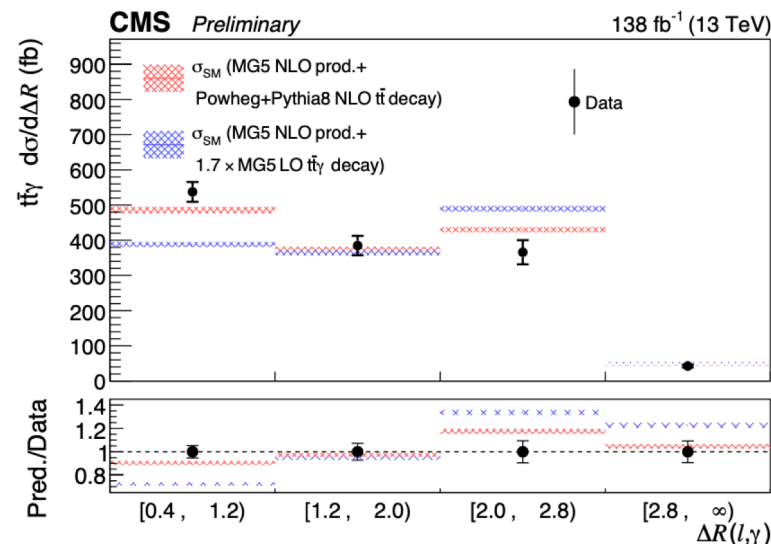
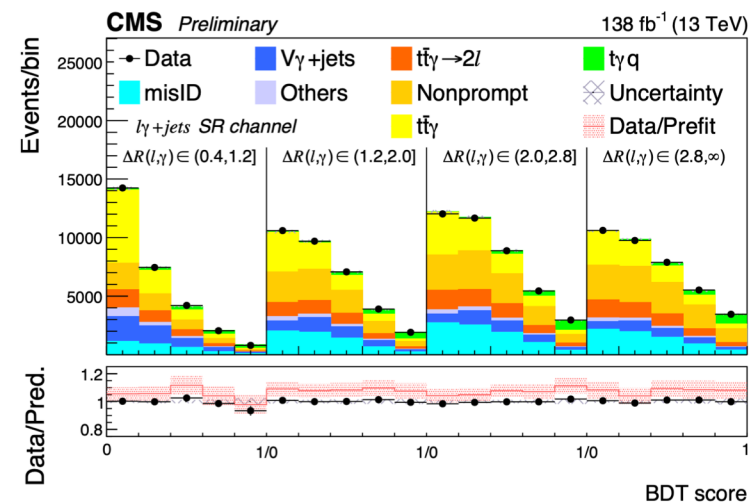
$$\mu_{t\bar{t}\gamma} = 1.055^{+0.059}_{-0.059} = 1.055^{+0.055}_{-0.055} (\text{syst})^{+0.021}_{-0.021} (\text{stat}),$$

$$\sigma_{\text{tot. } t\gamma q}^{\text{mea.}} = 237^{+17}_{-17} \text{ fb},$$

$$\sigma_{\text{tot. } t\bar{t}\gamma}^{\text{mea.}} = 1445^{+81}_{-81} \text{ fb}.$$

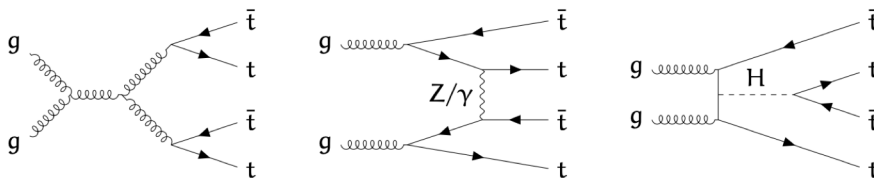
Good agreement with SM

- Dominated by MC stats, Theoretical prediction



$t\bar{t}+t\bar{t}$ cross section & VLL searches

- Measured $t\bar{t}+t\bar{t}$ production and search for vector-like lepton (VLL)

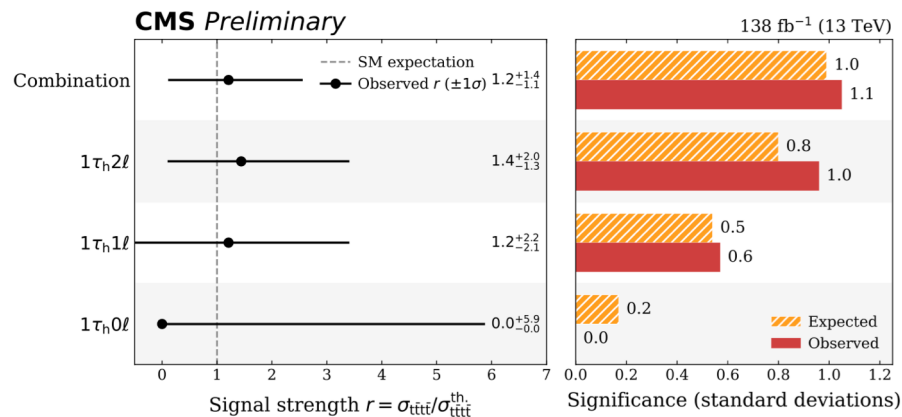
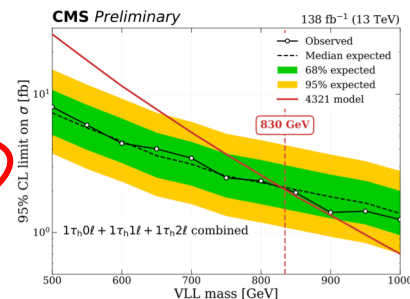
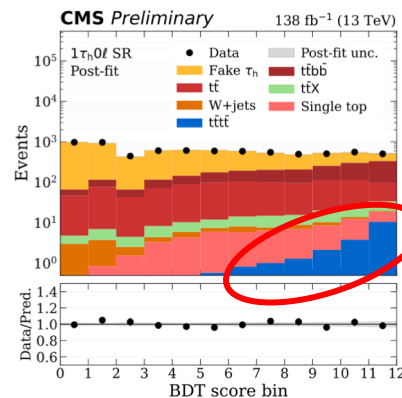
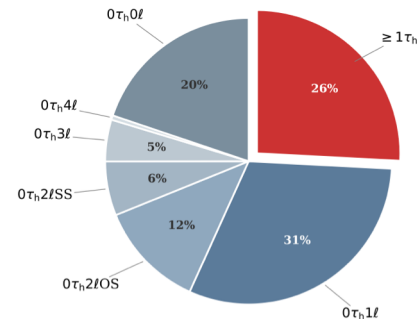


$$\sigma(t\bar{t}t\bar{t}) = 16_{-15}^{+18} \text{ fb}$$

SM prediction: $\sigma(t\bar{t}t\bar{t}) = 12.0_{-2.5}^{+2.2} \text{ fb}$
[NLO QCD+EW; JHEP 02 (2018) 031]

- Consistent with the SM prediction.
- No significant excess observed in the VLL search.
- First VLL-pair search in the 4321 model with light leptons, complementing previous all-hadronic searches.
- Consistent with the SM and does not confirm the earlier 2.8σ excess seen in the CMS all-hadronic channel result.

First exploration of τ -enriched final states

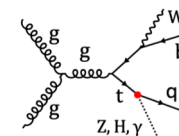
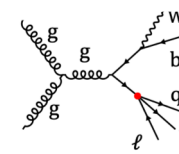
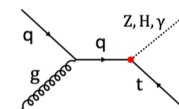
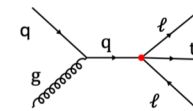


Rare processes (FCNC, ttt)



- First dedicated search for Standard Model three-top-quark (ttt) production at the LHC.

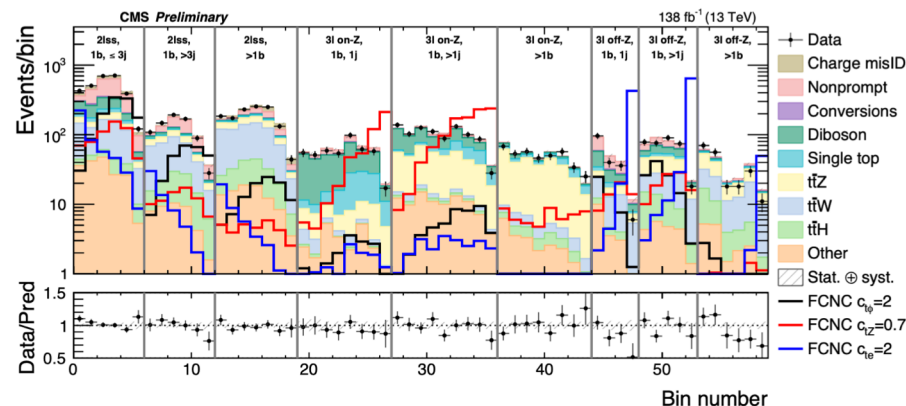
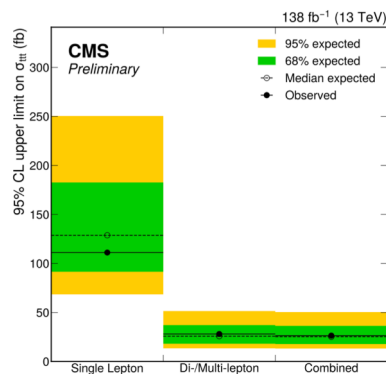
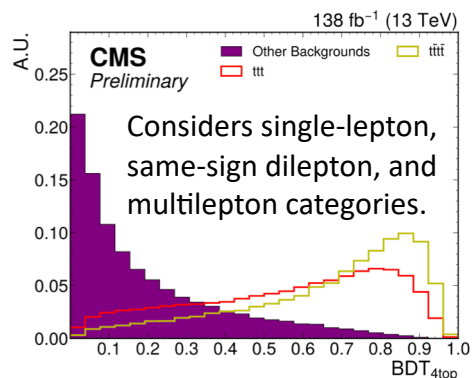
- FCNC targets same-sign dilepton and trilepton final states with exactly one b-tagged jet.



- ML-based bg estimation & optimized multivariate classifiers for sig/bg
- 95% CL upper limit of 25 fb on the ttt production cross section.

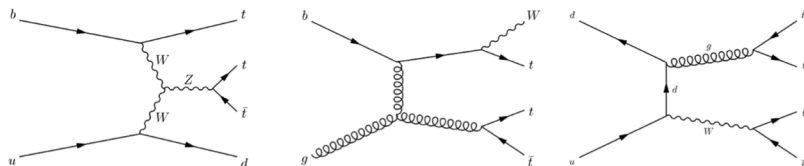
- Uses boosted decision trees (BDTs) to improve sig/bg & fit w max likelihood

- First simultaneous constraints on the complete set of relevant top-quark FCNC SMEFT operators, and on FCNC two-quark–two-lepton operators.



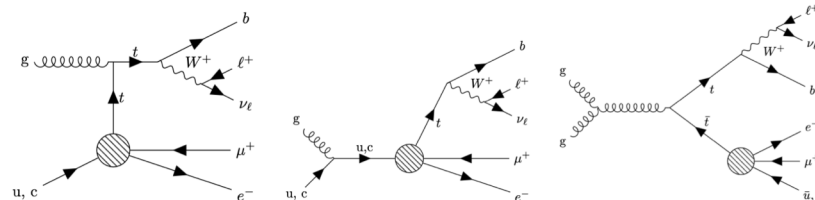
Rare processes (FCNC, ttt)

- CMS: First dedicated search for Standard Model three-top-quark (ttt) production at the LHC.

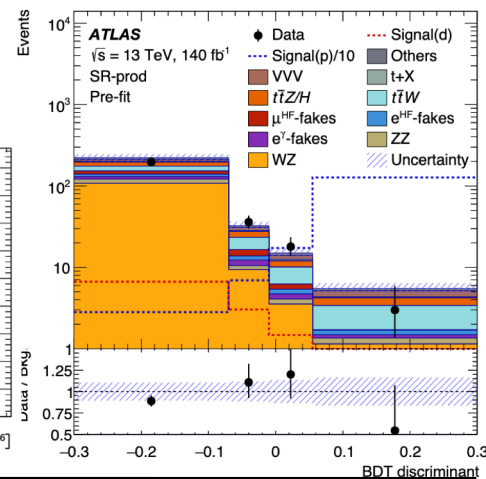
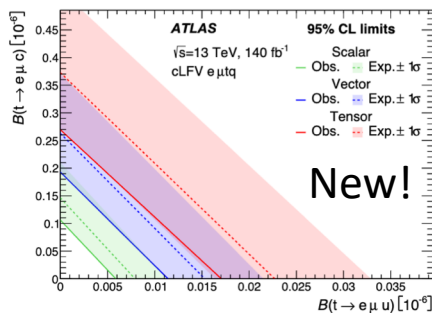
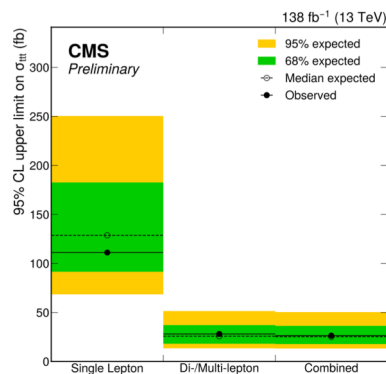
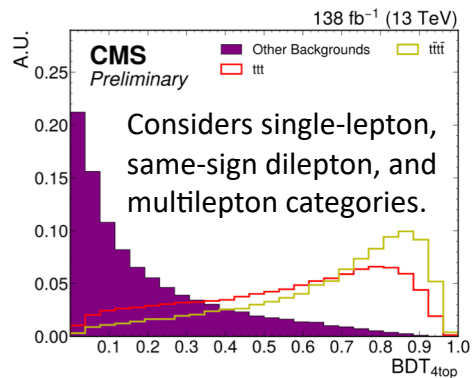


- ML-based bg estimation & optimized multivariate classifiers for sig/bg
- 95% CL upper limit of 25 fb on the ttt production cross section.

- ATLAS: Probes cLFV through both rare top decays, $t \rightarrow e\mu q$, and anomalous single-top production, $qg \rightarrow te\mu$ in a common trilepton final state.
- Uses separately optimized MV classifiers for the decay and production topologies
- Sensitivity driven mainly by the single-top production channel.

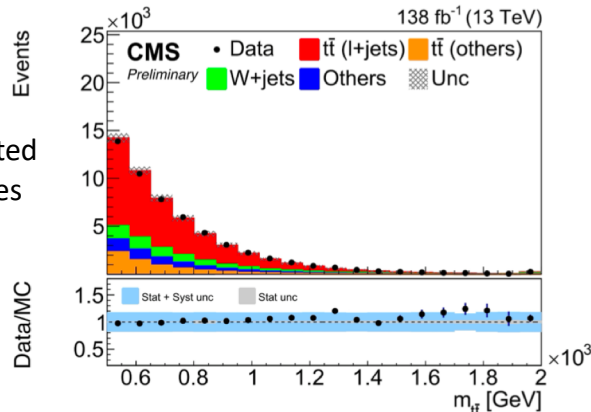
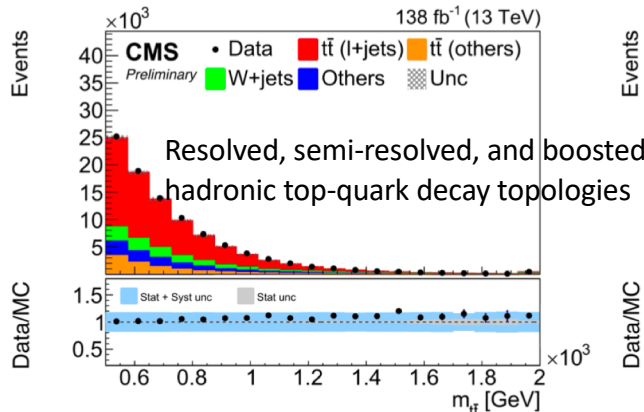
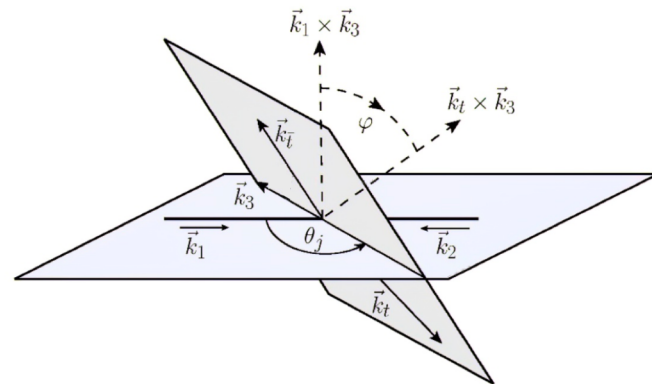


See talk by Oliver Rieger



Energy & Incline asymmetry

- 1st at CMS of the A_E in $t\bar{t}$ + jet production, and the 1st at LHC of A_I
- Sensitivity to asymmetries enhanced by using events where the extra jet is produced perpendicular to the top-quark
- Measurements are unfolded to the particle level using a likelihood-based procedure.



$$A_I \equiv \frac{\sigma^\varphi(y_{t\bar{t}j} > 0) - \sigma^\varphi(y_{t\bar{t}j} < 0)}{\sigma_{\text{tot}}}$$

$$A_E \equiv \frac{\sigma(\Delta E > 0) - \sigma(\Delta E < 0)}{\sigma_{\text{tot}}}$$

- A_E consistent with the SM within $\sim 2\sigma$
- Deviates from the zero-asymmetry hypothesis by 2.7σ
- A_I is consistent with SM

Source	Uncertainty A_E (%)	Uncertainty A_I (%)
Data statistical uncertainty	± 1.6	± 1.5
MC modeling	± 1.3	$-1.4, +1.3$
Size of MC samples	± 0.7	± 0.6
Theory	± 0.4	$-0.6, +0.9$
Jet energy corrections	± 0.3	$-0.2, +0.3$
Other experimental uncertainties	± 0.4	± 0.3
Total	± 2.3	± 2.3

Scenario	A_E (%)	A_I (%)
	$\frac{\pi}{4} \leq \theta_j^{\text{opt}} \leq \frac{3\pi}{5}$	$\frac{\pi}{4} \leq \theta_j^{\text{opt}} \leq \frac{3\pi}{5}$
Data	-6.3 ± 2.3	2.5 ± 2.3
SM (MG5_aMC@NLO+PYTHIA8)	-1.6 ± 0.3	-0.5 ± 0.5
SM (POWHEG+PYTHIA8)	-0.5 ± 0.3	-0.1 ± 0.1
SM (POWHEG+HERWIG7)	-0.1 ± 0.1	-0.4 ± 0.3

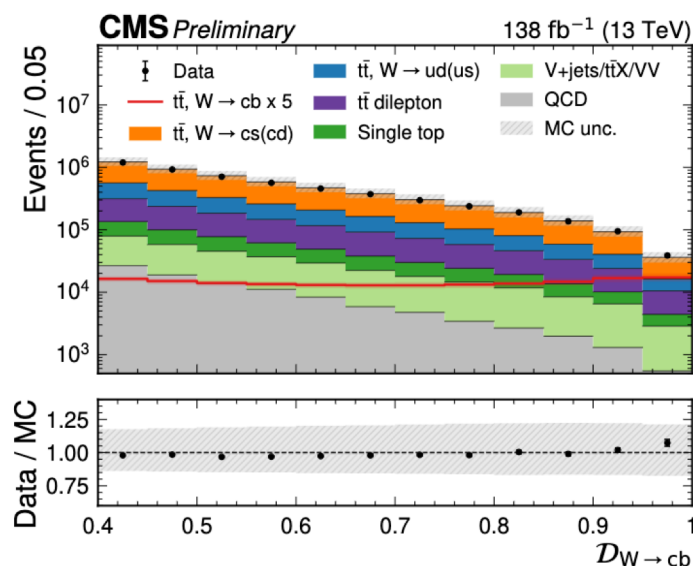
Utilize $W - cb$ to extract $|V_{cb}|$

See talk by X



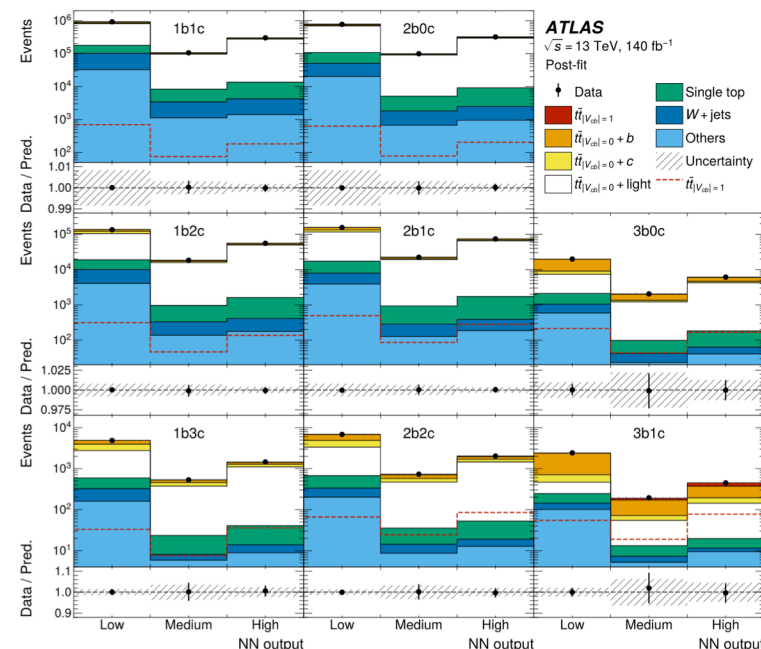
- CMS measurement of the CKM matrix element $|V_{cb}|$ using $t\bar{t}$ lepton+jets events.
- Extracts $|V_{cb}|$ from the hadronic $W \rightarrow cb$ decay in $t\bar{t}$ events.

$$|V_{cb}| = 4.59^{+0.44}_{-0.48} (stat)^{+0.64}_{-0.76} (syst) \times 10^{-2}$$
- Run 3 and future boosted-topologies: improve the precision & provide a complementary test of the “inclusive-exclusive” $|V_{cb}|$ discrepancy



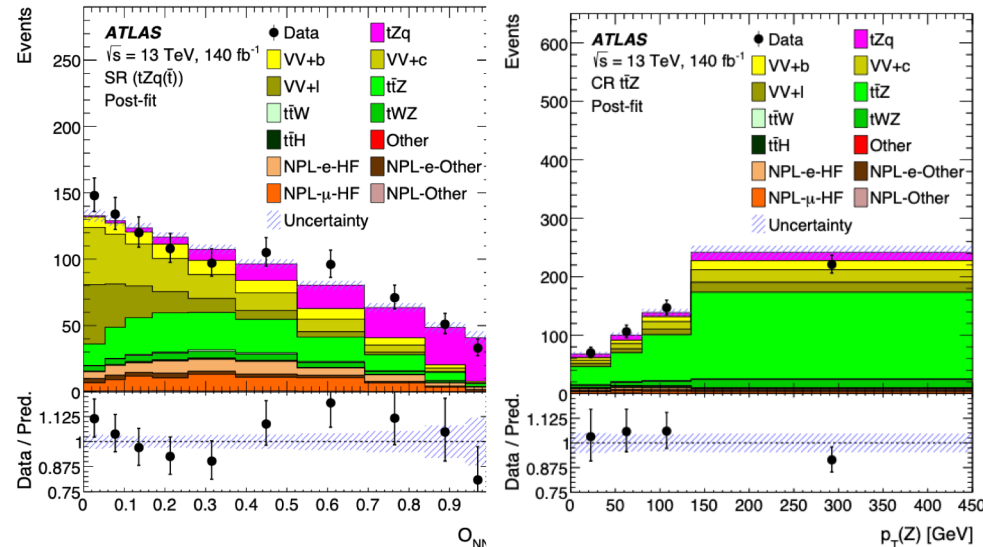
- ATLAS measurement of the CKM matrix element $|V_{cb}|$ at the weak/electroweak scale using single-lepton $t\bar{t}$ events with exactly four jets.
- Determines $|V_{cb}|$ from the ratio of $W \rightarrow cb$ to $W \rightarrow cq$ decays, where q is any down-type quark.

$$|V_{cb}| = 50^{+11}_{-14} \times 10^{-3}$$



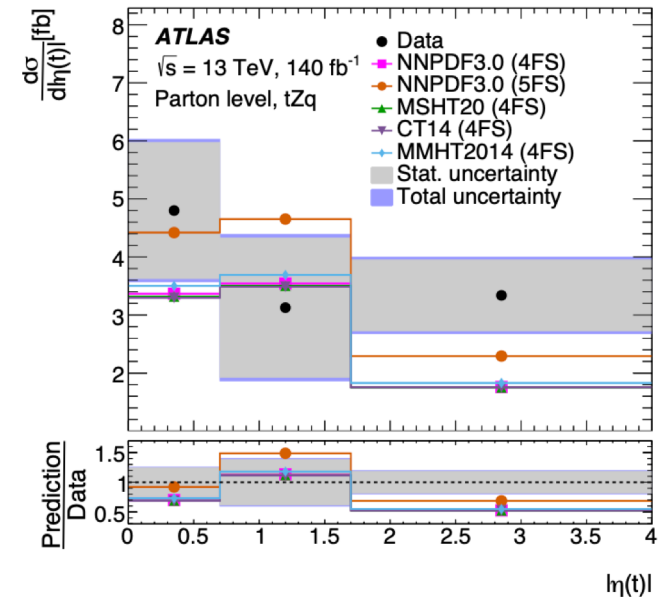
→ Dominant uncertainties come from $t\bar{t}$ + heavy-flavor modeling and flavor-tagging. But neither depend on nonperturbative B-hadron theory inputs. Higher precision needed to resolve...

- Events with 3 electrons or muons and 2–4 jets, including 1–2 b-tagged jets.
- Agrees with SM

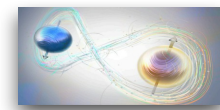


Phase space	Process	Measured [fb]	MC prediction [fb]
Particle level	$tZq(t)$	$3.09^{+0.35}_{-0.33}$ (stat.) $^{+0.14}_{-0.15}$ (syst.)	$3.45^{+0.29}_{-0.20}$
	$tZq(\bar{t})$	$2.21^{+0.33}_{-0.31}$ (stat.) $^{+0.15}_{-0.14}$ (syst.)	$1.96^{+0.16}_{-0.10}$
	tZq	$5.36^{+0.49}_{-0.47}$ (stat.) $^{+0.27}_{-0.28}$ (syst.)	$5.41^{+0.44}_{-0.28}$
Parton level	$tZq(t)$	$7.45^{+0.83}_{-0.76}$ (stat.) $^{+0.40}_{-0.39}$ (syst.)	$8.34^{+0.60}_{-0.23}$
	$tZq(\bar{t})$	$5.26^{+0.79}_{-0.71}$ (stat.) $^{+0.45}_{-0.43}$ (syst.)	$4.58^{+0.35}_{-0.13}$
	tZq	$12.60^{+1.15}_{-1.07}$ (stat.) $^{+0.65}_{-0.64}$ (syst.)	$12.92^{+0.92}_{-0.32}$

- **Extract spin asymmetry:**
 $A = 0.34 \pm 0.14 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$
 $A_{CMS} = 0.54 \pm 0.16 \text{ (stat.)} \pm 0.06 \text{ (syst.)}$



How to probe Entanglement

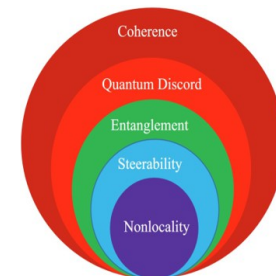
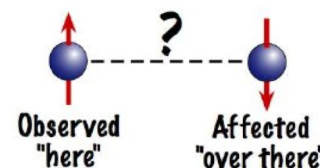


- **Qubit** = two-level quantum system $|0\rangle, |1\rangle \rightarrow$ most simple quantum system
- **Two qubits** $\rightarrow$ most simple example of quantum correlations
- **Entire hierarchy of quantum correlations**

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i \rightarrow \text{Non-separability of a bipartite quantum state} = \text{entanglement}$$

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

~ 0 ~ 0

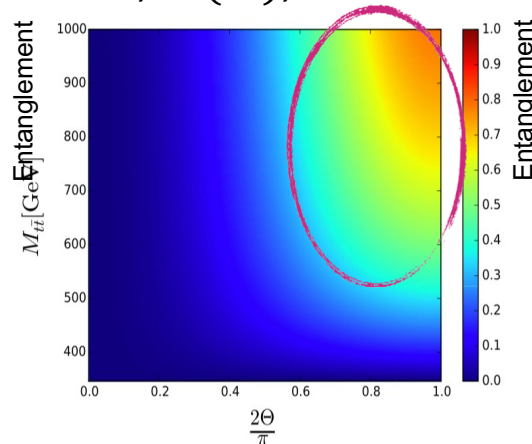
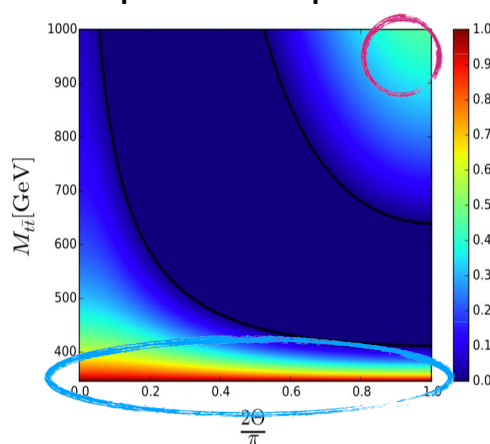


- Remarkably the $\text{tr}[C]$ can be probed from single differential distribution

$$\frac{1}{\sigma} \frac{d\sigma}{d\cos\varphi} = \frac{1}{2} (1 - D \cos\varphi) \quad D = -\frac{\text{tr}[C]}{3}$$

Experimental goal $\rightarrow$ measure D (entanglement proxy)

- Depends on production mode, $m(t\bar{t})$, and scattering angle (Θ)



SM predicts entangled states:

- $\rightarrow$ at the production threshold region in gg -fusion production
- $\rightarrow$ at the boosted region for central production of the system

Afik, De Nova, [Eur. Phys. J. Plus 136, 907](#)

Observation of Entanglement

1st measurement of entanglement of top quarks by ATLAS [Nature 633 \(2024\) 542](#)

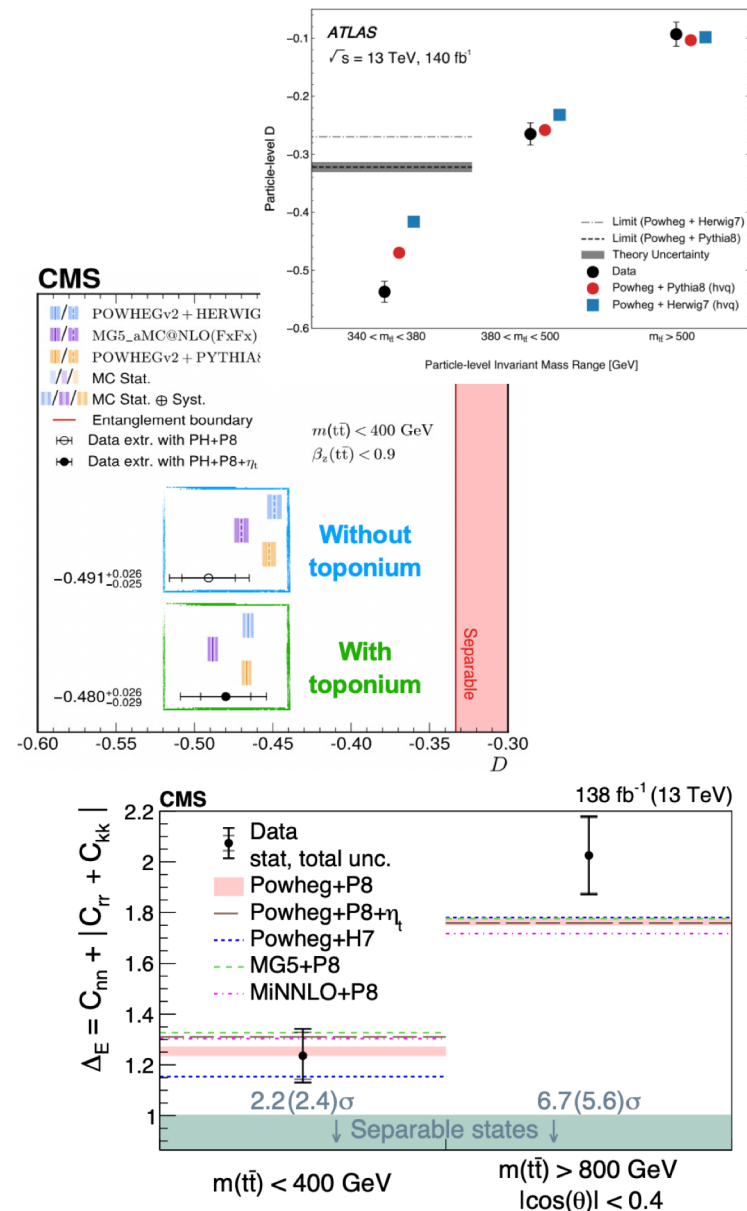
- A stronger entanglement is observed in data compared to nominal predictions at threshold
- Entering new realm: Quantum Information Science meets top's

CMS confirmed observation of top quarks being entangled at $t\bar{t}$ threshold

- 5 standard deviations, improved modeling at the threshold [RPP 87 \(2024\) 117801](#)
- ~ 1.5 tension with the expectation if toponium is not included
- Good agreement with SM significantly improved by including η_t

Observation of top quark entanglement in boosted region [PRD 110 \(2025\) 112016](#)

- Reasonable agreement with SM



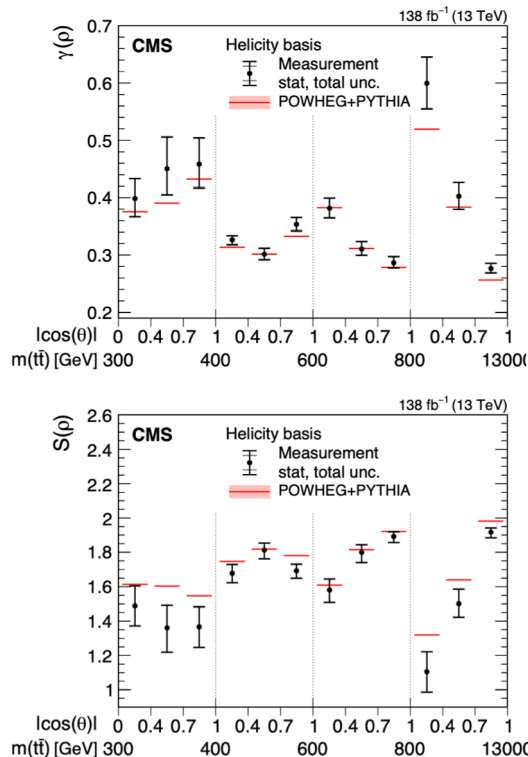
Top quarks as a Quantum Information Science Lab

- Exciting probes to SM
- On the heels of first measurements of entanglement in threshold by ATLAS, CMS and boosted by CMS
- Use l+jets full Run 2 data to measure quantum information science / QIS-observables in top quark pair production

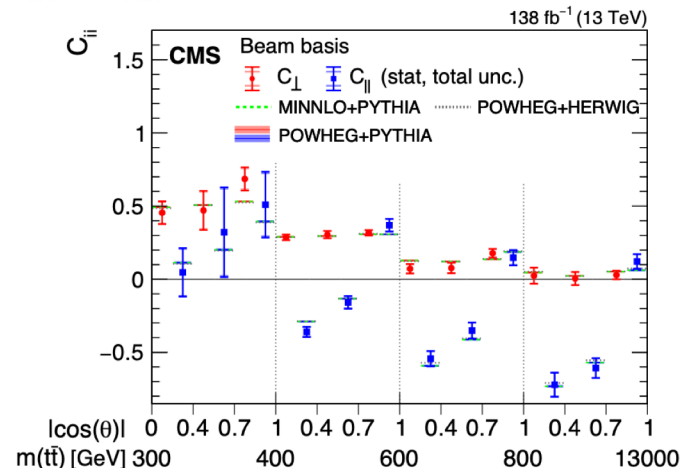
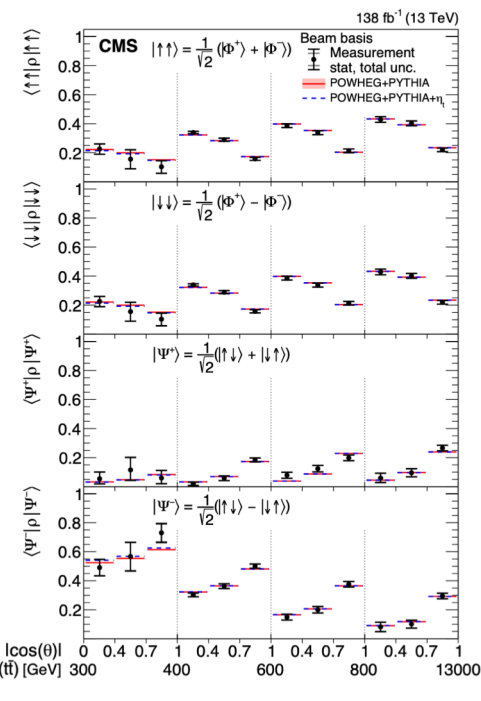
First measurements by CMS of:

- Decompose density matrix into Bell and spin states in helicity and beam basis
- Measurements of purity, von-Neumann entropy
- Entanglement in both basis
- In agreement with the SM
- Sizeable statistical uncertainty

See talk by X for more details



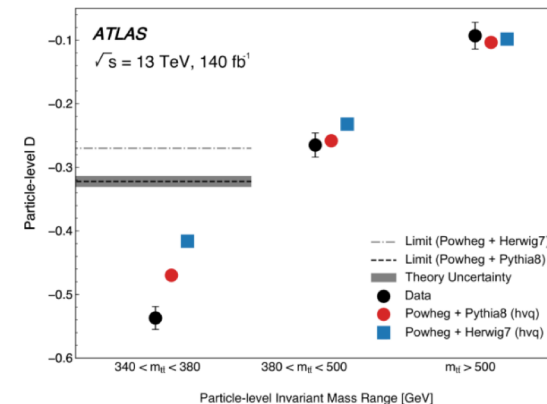
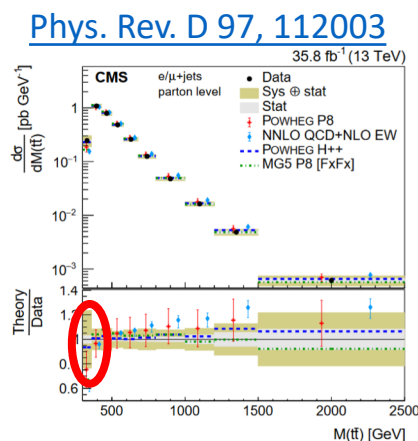
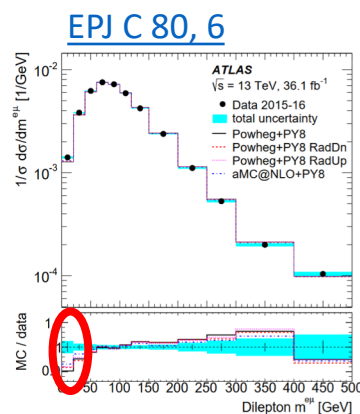
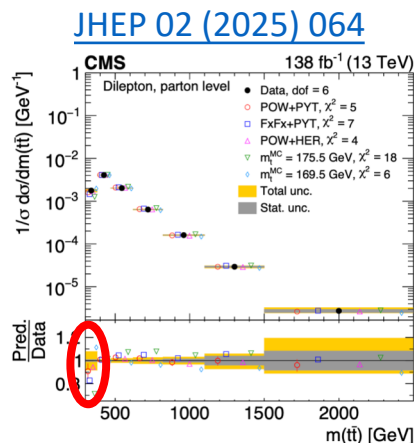
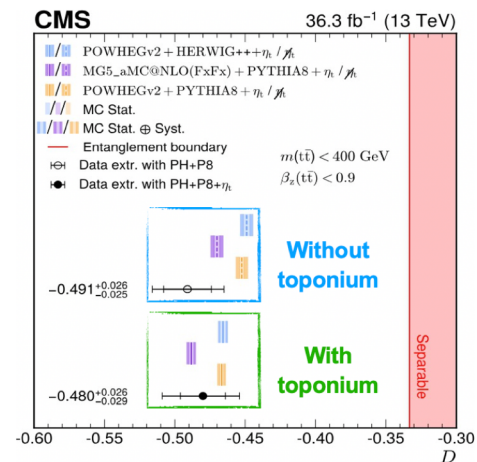
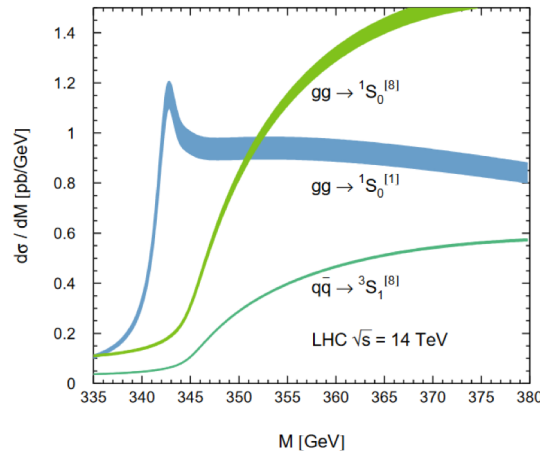
PRD 113 (2026) L051101



Intermediate summary

- Entanglement of top quark events established at LHC
- Level of observed entanglement cannot be explained by classical exchange of information between the two particles !

Can we say more on top quark bound state effects at threshold ?



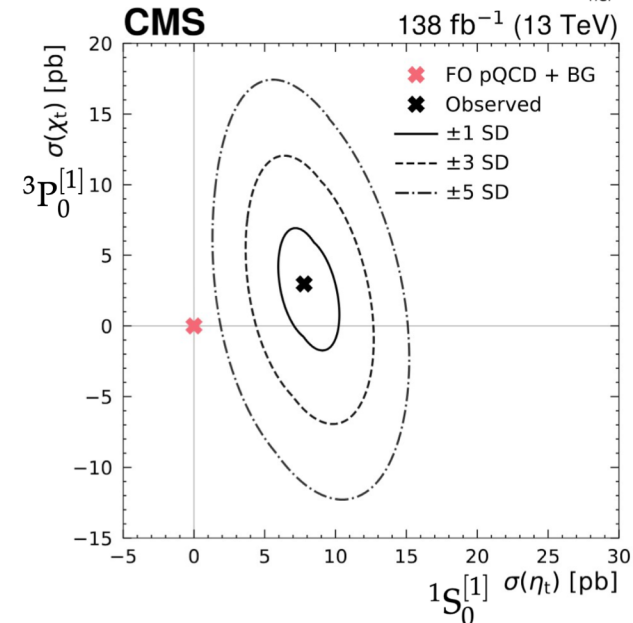
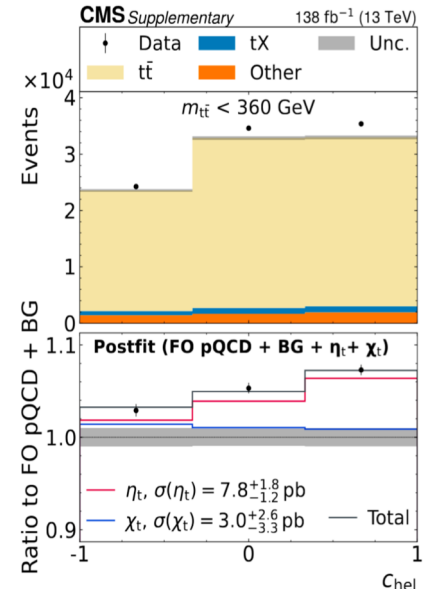
Quantify the excess at threshold

- Interpretation in terms of η_t [RPP 88 \(2025\) 087801](#)
- Extract cross section using the η_t color-singlet model
 - “cross section” = difference to perturbative prediction

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

→ See Talk by X

- Theory: $\sigma(\eta_t) = 6.43 \pm 0.90 \text{ pb}$ ([PRD 104 \(2021\) 034023](#))
([JHEP 09 \(2010\) 034](#))
- Differentiate between η_t (CP-odd) and χ_t (CP-even)
- Dominant systematic uncertainties:
 - bb4l: NLO, off-shell effects, interference tt and tW
 - PS FSR: α_s in final state radiation
 - top quark mass and Yukawa coupling
 - Herwig7 as alternative parton shower model
- Words of caution:
 - Cannot distinguish between η_t & pseudo-scalar Higgs
 - Missing e.g. color-octet states - these are expected to be small



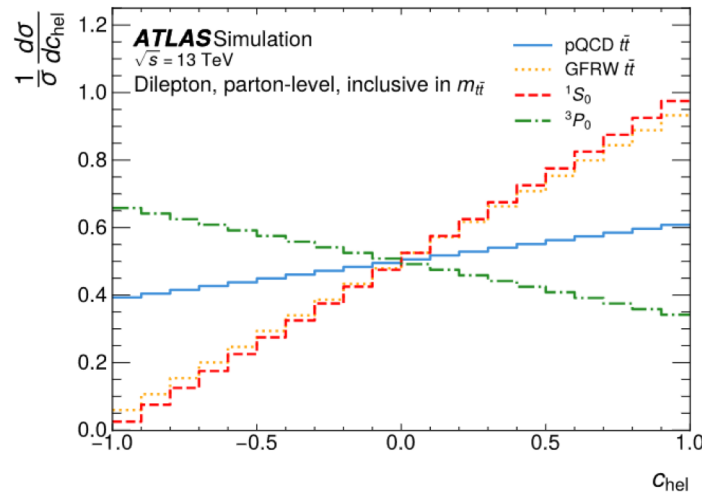
ATLAS result in dilepton threshold

- Confirmed by ATLAS
- Using dilepton events and spin-sensitive angular observables
- Baseline pQCD model without quasi-bound-state effects is disfavored at $>8\sigma$ (6σ) observed (exp.)
- Excess is compatible with color-singlet, spin-singlet S-wave $t\bar{t}$ quasi-bound state
- Threshold component:

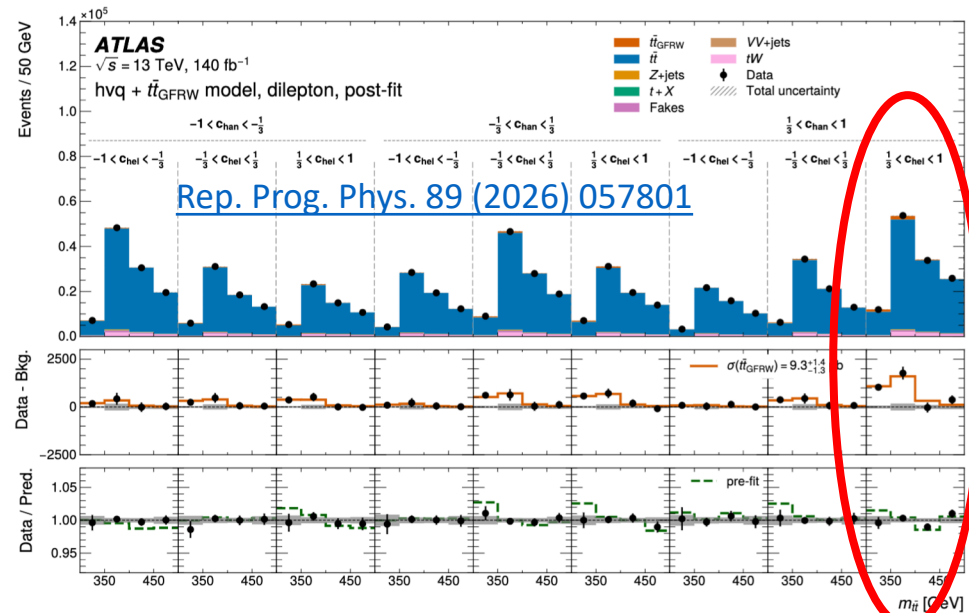
$$\sigma_{\text{threshold}} = 9.3_{-1.3}^{+1.4} \text{ pb}$$

- Improved NRQCD/off-shell modeling and pQCD–NRQCD matching are needed to fully characterize the excess.
- Dominated by GFRW & pQCD modeling (~ 7 and 5% , resp.)

[CERN Press-statement: "Elusive romance ..."](#)

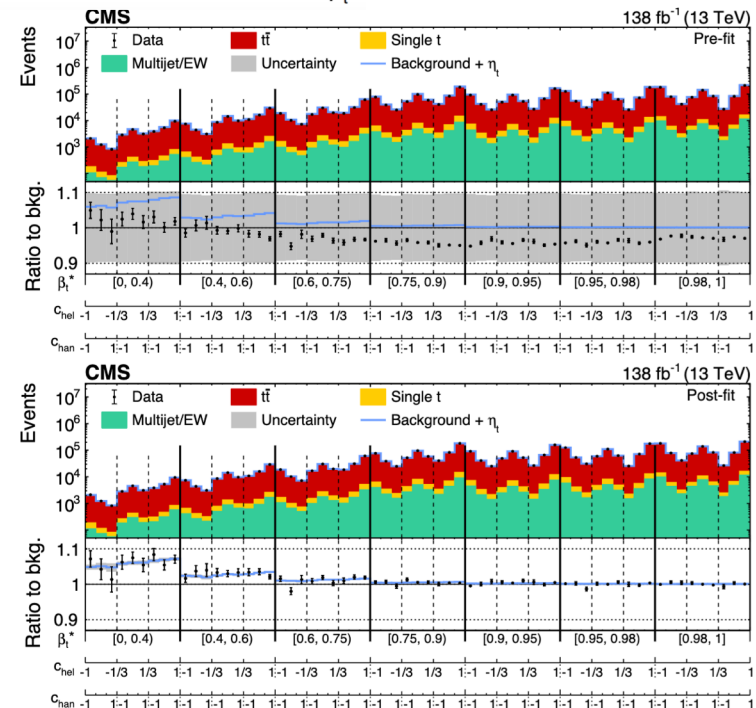
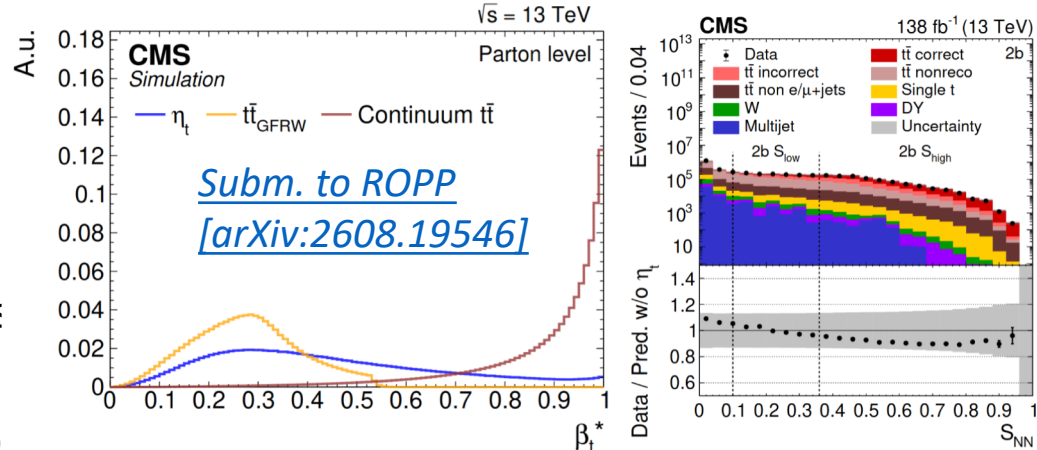


GFRW = Green's Function ReWeighting:
 NRQCD-inspired modeling of $t\bar{t}$ quasi-bound-state effects near threshold



CMS Observation in $l+jets$

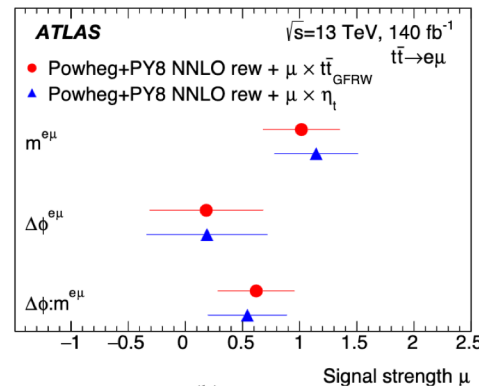
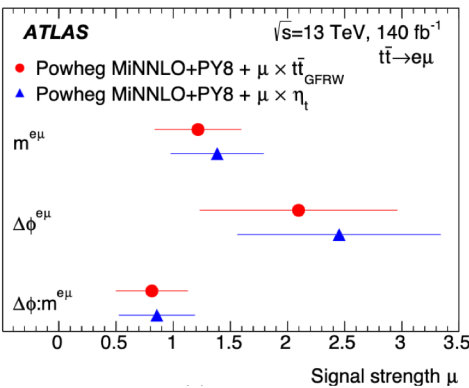
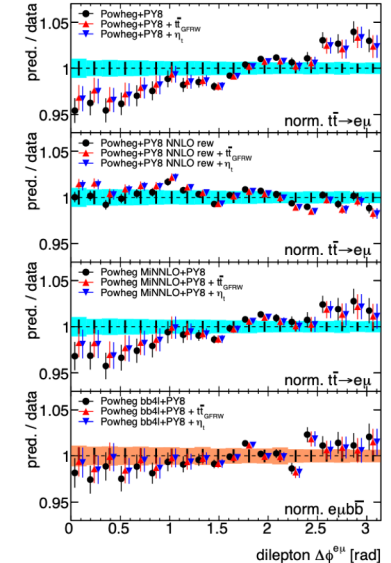
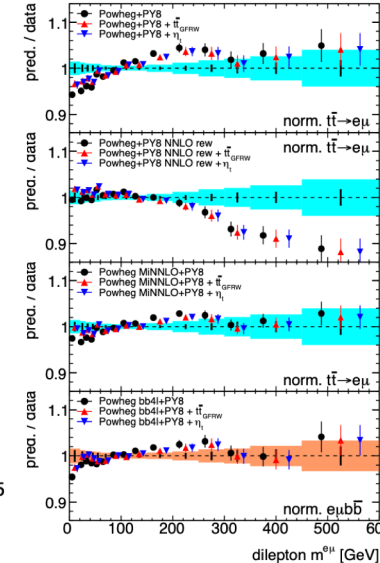
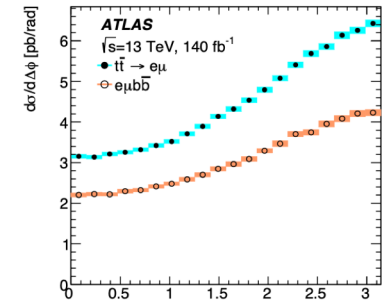
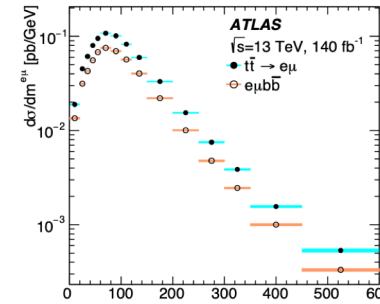
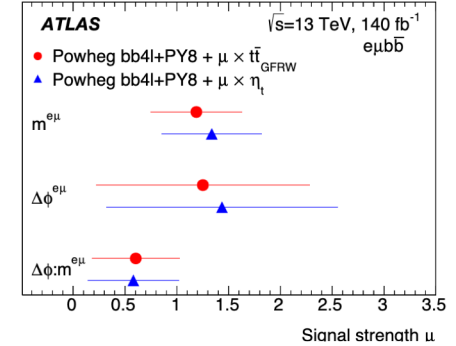
- First CMS search for this effect in the $e/\mu + jets$
- Uses two spin- and parity-sensitive observables together with β_t^* , which provides better sensitivity & robustness
- The background-only hypothesis is excluded with 6.1σ (obs) and 7.3σ (exp.
- Using a simplified pseudo-scalar color-singlet η_t model, the measured signal cross section is: $\sigma = 5.1 \pm 0.9 \text{ pb}$
 - Dominant uncertainties arise from modeling of continuum $t\bar{t}$ and η_t production.
 - For $m(t\bar{t}) < 350 \text{ GeV}$, both the η_t model and a Green's-function-based threshold model indicate an enhancement of about 3 pb.
 - Interpretation is still model-dependent, and improved theory is needed for a precise description of the $t\bar{t}$ threshold region.



β_t^* = top-quark velocity variable in the $t\bar{t}$ system

ATLAS reinterpretation of $\ell\bar{\ell}$ data

- Use differential distributions to test for $t\bar{t}$ quasi-bound-state effects
- Compares baseline pQCD predictions with models including color-singlet threshold contributions via NRQCD Green's functions or a pseudo-scalar η_t
- Including the threshold contribution describes data better
- Differential data shows 3σ evidence for a quasi-bound-state contribution
- Result is consistent with the dedicated ATLAS spin-angular threshold analysis



ML-based top quark reconstruction

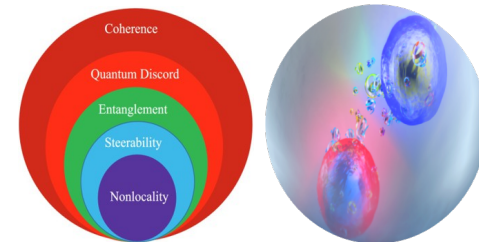
Double diff. xsec

Polarisation (0 in SM)

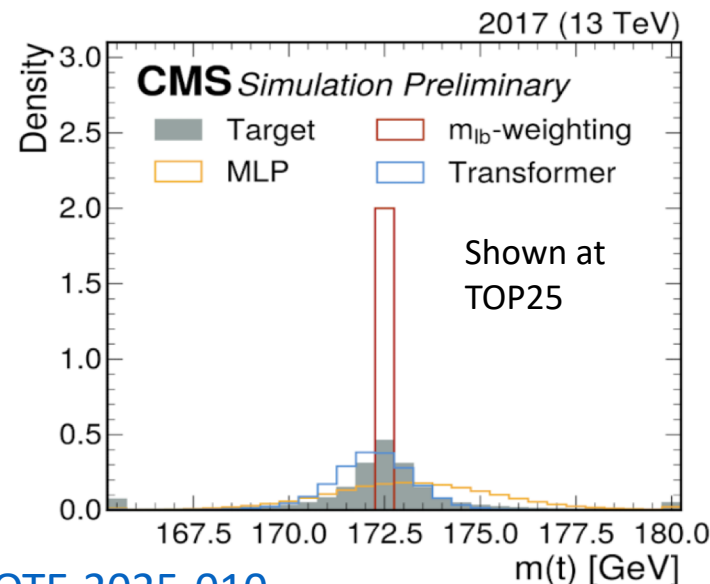
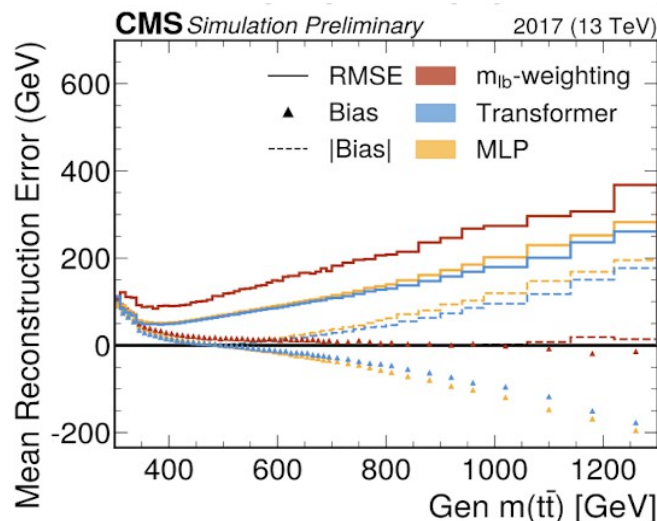
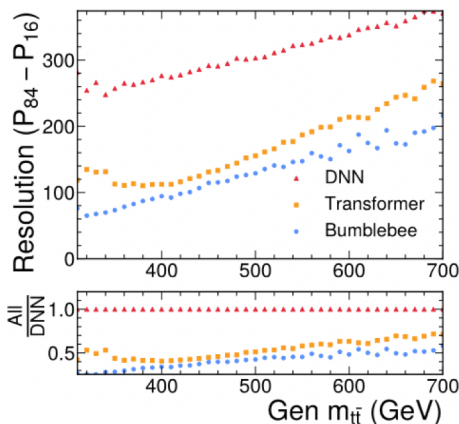
Spin Correlation

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4} (1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b) \cos\theta_+^a \cos\theta_-^b)$$

→ RMSE captures amount of bias and variance into singular value



LLM “bumblebee”:



[CMS-NOTE-2025-010](#)

- Transformer approximately 30% improvement vs *mlb* – method
- Reconstructs events for which 5% of time *mlb* - method fails
- Further studies to assess performance, e.g. angular distributions / QIS ob's)
- Exciting region for SM (aka η_t), EFT, and Quantum Correlations...

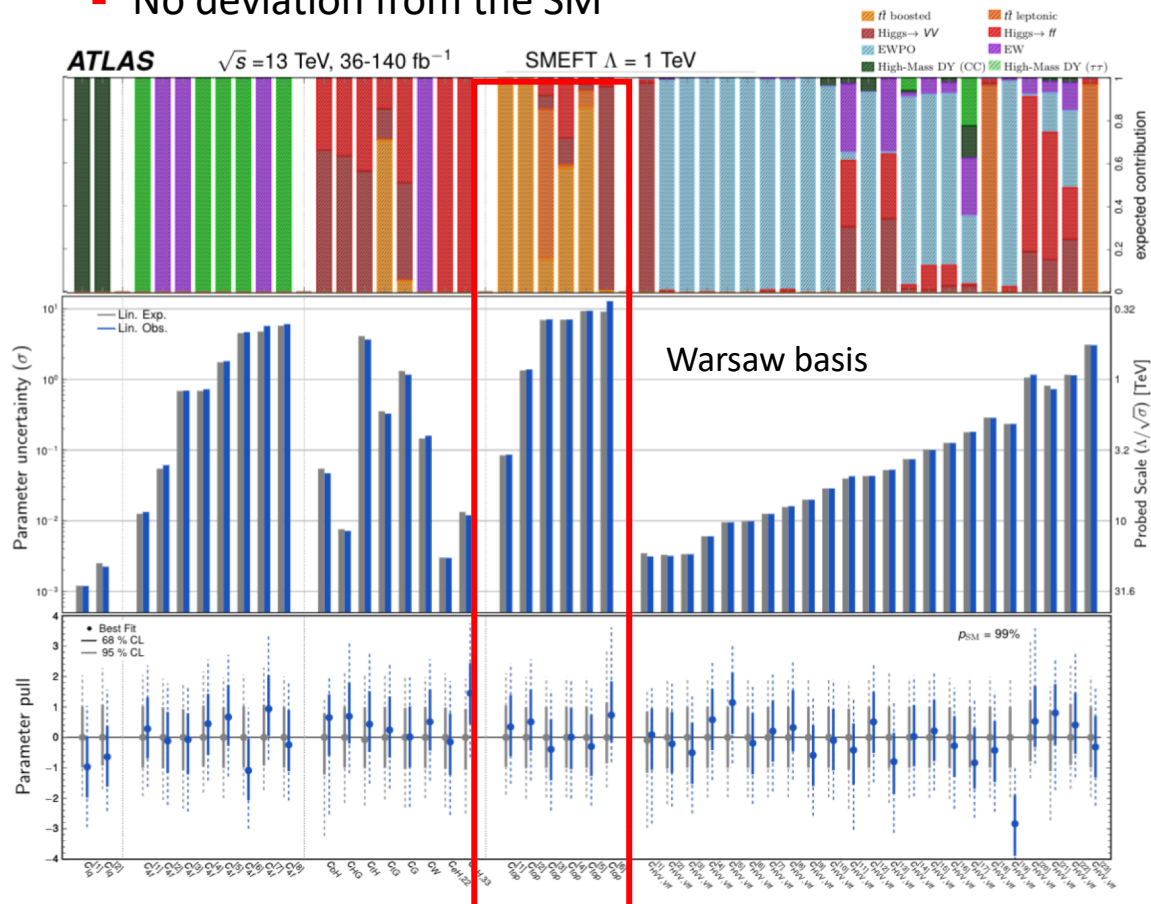
Global SMEFT interpretation (t, H, EW)

- The global fit simultaneously constrains 47 operators or linear combinations of operators.

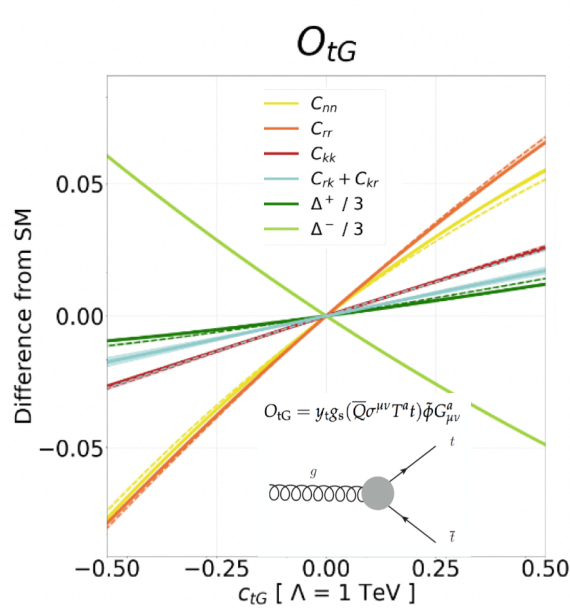
- Reports:

- linear SMEFT constraints including terms up to $1/\Lambda^2$ and also include quadratic $1/\Lambda^4$ contributions.
 - Finds that quadratic EFT terms can significantly modify the inferred constraints for a reference scale of $\Lambda = 1$ TeV.

- No significant deviation from the Standard Model is observed.
- Provides a broader framework in which top-quark measurements contribute to global constraints on possible BSM interactions.
- No deviation from the SM

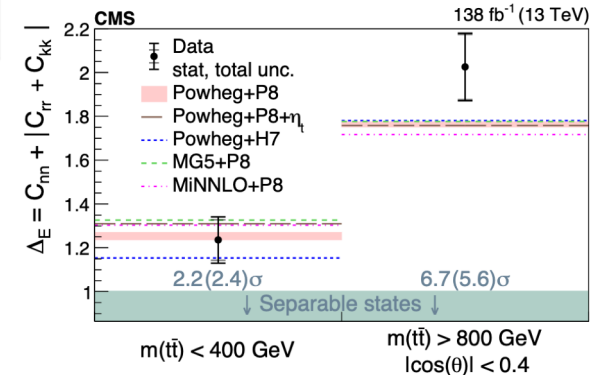
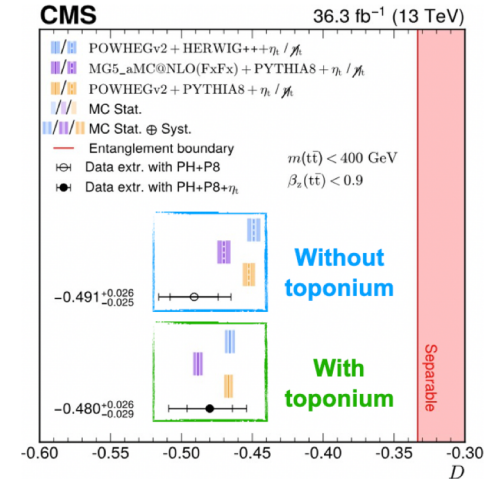
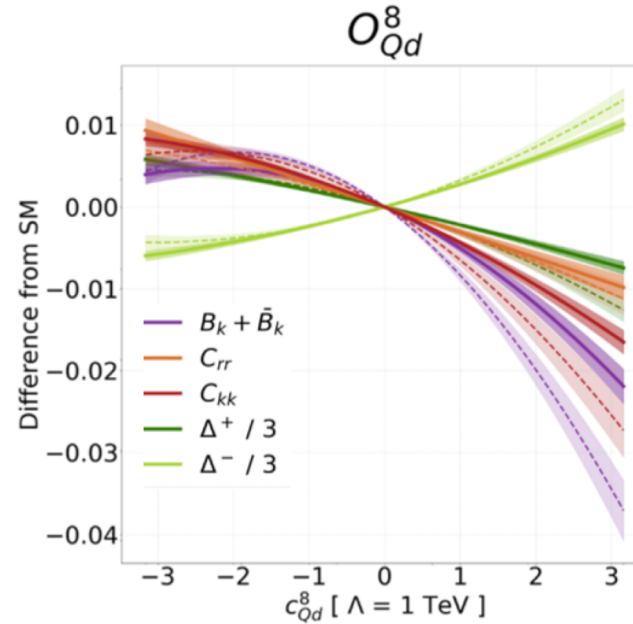


A new approach...new observables ?!



JHEP 01 (2023) 148 [2210.09330]

→ QIS observables anti-correlated / orthogonal to existing spin density / polarization observables!



- **Break flat directions by accessing quantum correlations**
→ unlock sensitivity to operators “invisible” in traditional analyses
- AI-based nuisance morphing in physics-aware bases
- Direct mapping: **observables** → **EFT parameters**
- **Not just for top quark sector but also for Higgs sector!**



Sept 17th 2026: Strong evidence for quantum entanglement between Z bosons found by ATLAS and CMS

Sufficient or looming limitations ?

Restricted EFT: $\mathcal{O}(50)$ Wilson coeff's in top quark sector

- Large HL-LHC datasets, many differential measurements
- But: information is not independent
→ strong correlations and flat directions

Why traditional observables fall short

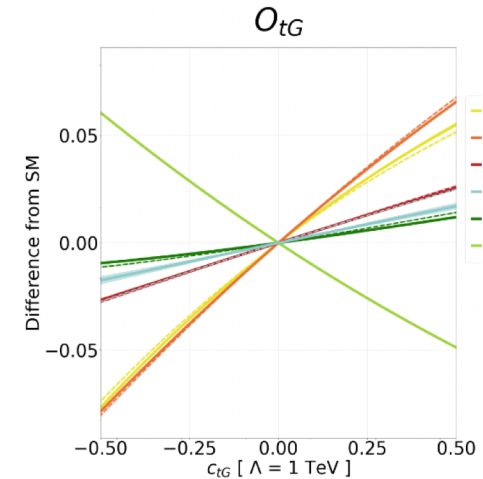
- Mostly 1D distributions / asymmetries
- Limited sensitivity to interference and correlations
- Different operators map onto degenerate combinations
- Information-limited system, not statistics-limited

e.g. utilize Quantum Steering Ellipsoid - reorganizes the spin-density matrix into an intuitive geometry

- Center $c \sim$ Single particle polarization
- Shape $Q \sim$ Spin-correlation anisotropy
- Semi-axis and angle $\sim$ Principal correlation direction
- Area and Volume $\sim$ Accessible conditional state space

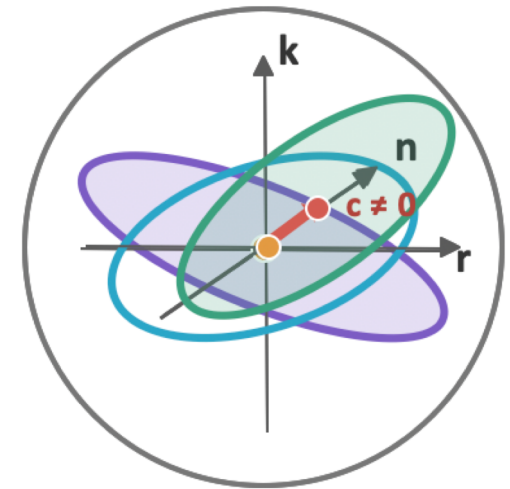
- Opportunity: go beyond classical observables & exploit full quantum structure of the event
- Powerful for top quark sector & Higgs sector

JHEP 01 (2023) 148 [2210.09330]

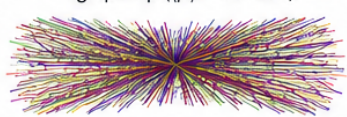
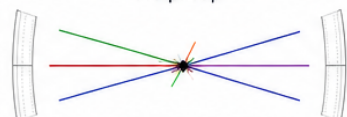
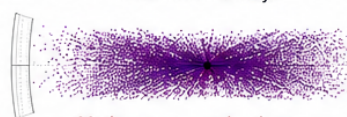
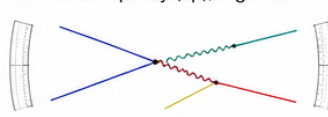
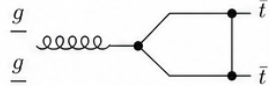
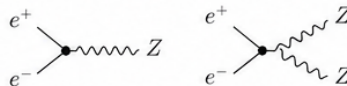
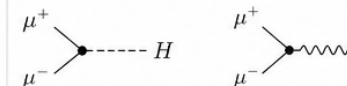
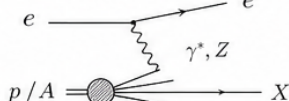


Subm. to PRX Quantum [arXiv:2608.30037]

Alvarez et al. (Jung group)



Represents all possible quantum states of a spin- $\frac{1}{2}$ particle or qubit A .

	 LHC (pp) 13–14 TeV	 FCC-ee (e^+e^-) 90 GeV – 365 GeV	 Muon Collider ($\mu^+\mu^-$) ~125 GeV – Multi-TeV	 EIC (e^-p / e^-A) 20 – 140 GeV
Initial state (quantum preparation)	Protons (composite) Mixed state (PDFs)  <i>Parton-level uncertainty → mixed initial state</i>	Electrons/positrons (elementary) Well-defined quantum state  <i>Clean, controlled initial state</i>	Muons/antimuons (elementary) Well-defined quantum state  <i>Clean initial state (leptonic)</i>	Electron (elementary) + proton/nucleus (composite) Controlled probe of partonic structure  <i>Well-defined lepton beam on hadronic target</i>
Environment & decoherence	Very busy hadronic environment High pileup ($\langle \mu \rangle \sim 50\text{--}200$)  <i>Strong decoherence, measurement noise</i>	Very clean environment No pileup  <i>Minimal decoherence</i>	Beam-induced background (BIB) from muon decays  <i>Moderate–strong decoherence (dominated by detector background)</i>	Medium-complexity environment Lower multiplicity (ep), higher in eA  <i>Reduced decoherence vs pp; clean probe</i>
Quantum observables accessible	- Entanglement (e.g. $t\bar{t}$, VV) - Spin correlations - Coarse-grained density matrices - Limited by PDFs & combinatorics	- Full density matrix (state tomography) - Precision entanglement measurements - CP phases via interference - Quantum coherence in rare decays	- Entanglement in heavy systems ($t\bar{t}$, VV, BSM) - Direct s-channel resonance quantum states - CP & coherence in Higgs (s-channel) - High-energy quantum interference	- Spin correlations in nucleon structure - TMDs, GPDs (quantum phase space) - Entanglement in partonic distributions - Access to confinement dynamics
Unique QIS strengths	 First discovery of quantum structure in high-energy collisions. Access to widest energy reach and new heavy states.	 Quantum tomography machine. Ultimate precision on quantum observables with minimal decoherence.	 Direct preparation of resonant quantum states (e.g. Higgs in s-channel). Quantum dynamics at multi-TeV energies.	 Tomography of QCD matter. Access to confinement and hadronization onset. Bridge between partonic and hadronic regimes.
Example processes	$pp \rightarrow t\bar{t}, WW, ZZ, H, \text{jets}$ (new physics searches) 	$e^+e^- \rightarrow Z, HZ, WW, t\bar{t}, \gamma\gamma$ (precision program) 	$\mu^+\mu^- \rightarrow H \text{ (s-channel)}, t\bar{t}, WW, ZZ, \mu^+\mu^- \rightarrow X$ (heavy resonances) 	$e p \rightarrow e' + X \text{ (DIS)}$ $e p \rightarrow e' + \text{jets}$ $e A \rightarrow e' + X$ 

Key takeaways:

- Colliders are complementary: 1st observations, precision studies, high control initial states
- QIS as an arch connecting colliders and to break “flat directions” in EFT space
- Powerful for top quark and Higgs sector at LHC! Rich and exciting at new colliders!

Big Questions & Challenges

■ Top quark physics at center of big questions...Precision era

- Plethora of cross section results
- Higgs potential

■ Associated production of vector bosons and fermions

- Powerful tests of SM and allows to leverage data for EFT approach

■ Observation of top quark pair entanglement by ATLAS & CMS

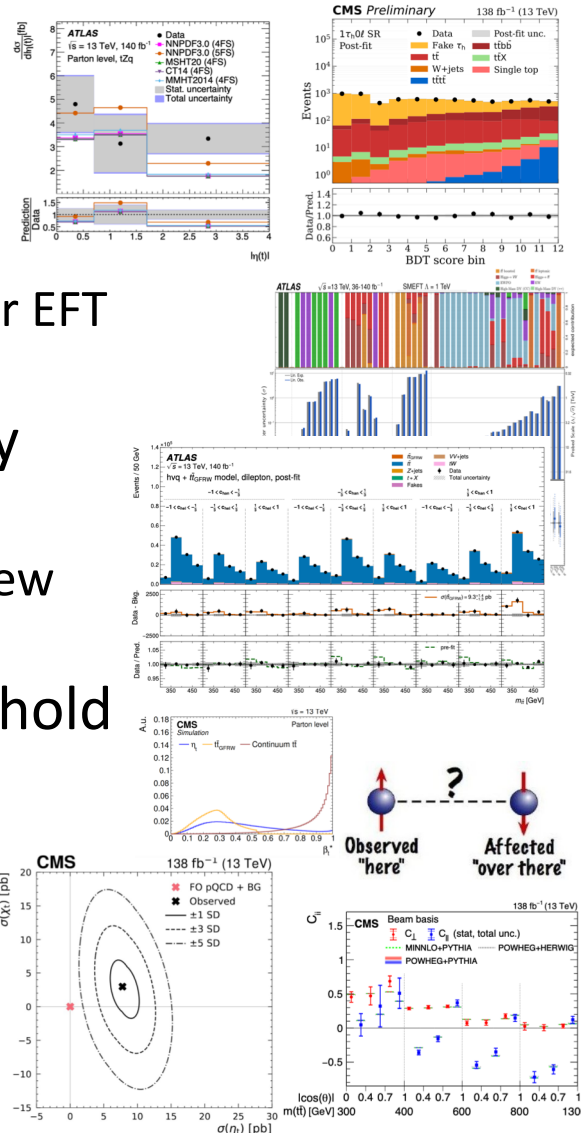
- Top quarks as Quantum Information Science Lab, new approaches!

■ Observation of a pseudo-scalar excess at threshold

- Quasi-bound states ?
- Full non-relativistic QCD calculation is needed!

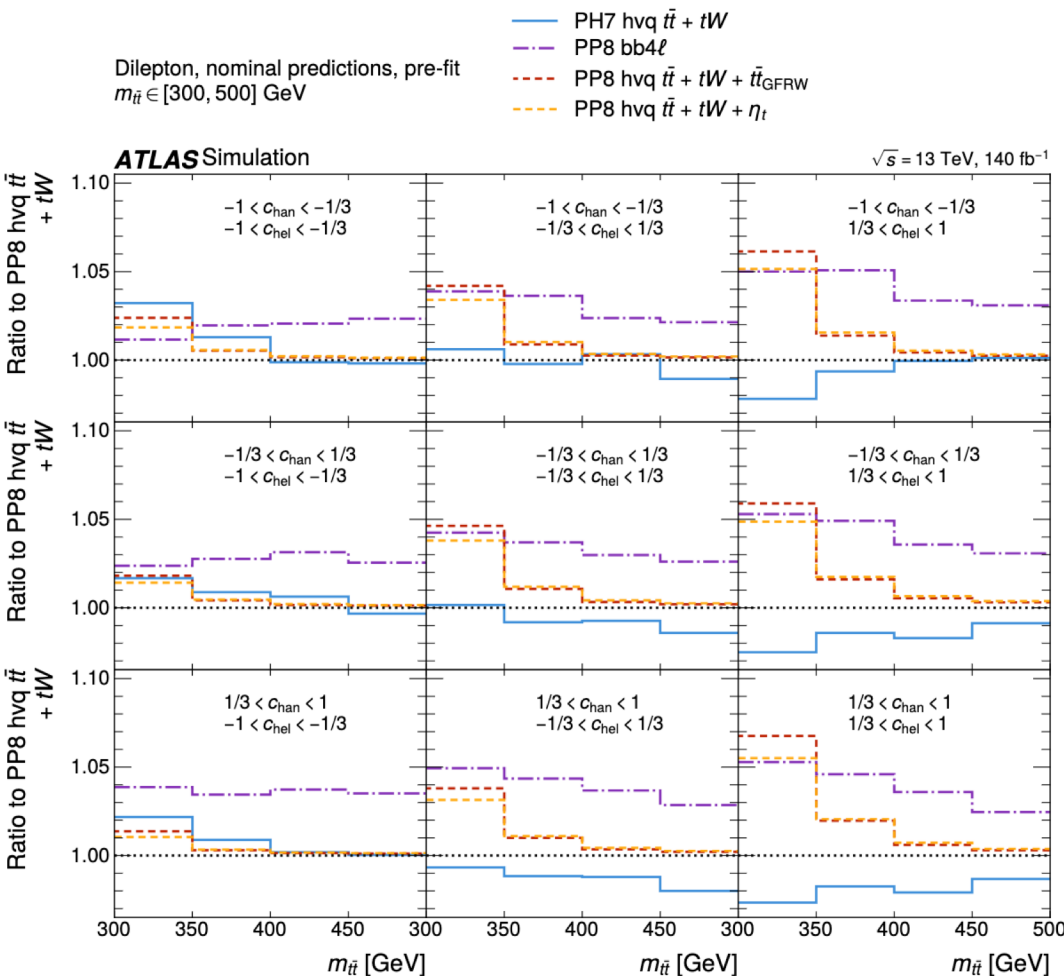
→ Top quark physics has a bright & exciting future – new probes, Quantum Information Science inspired

→ Vast amounts of top quarks to come



Backup

- Reinterpretation of published differential cross section data
- Evidence in the cross sections alone, compatible with other results



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%

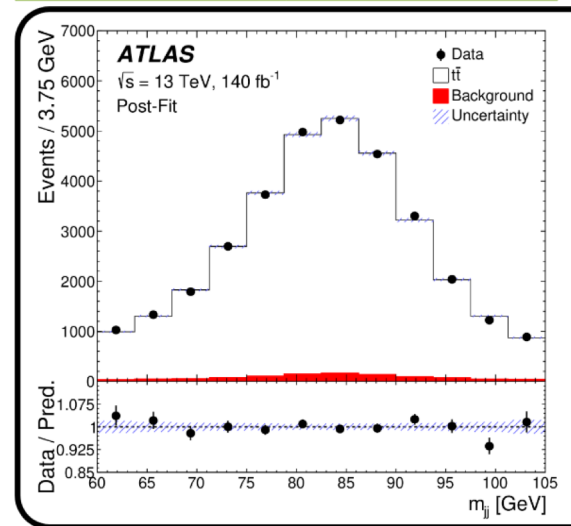
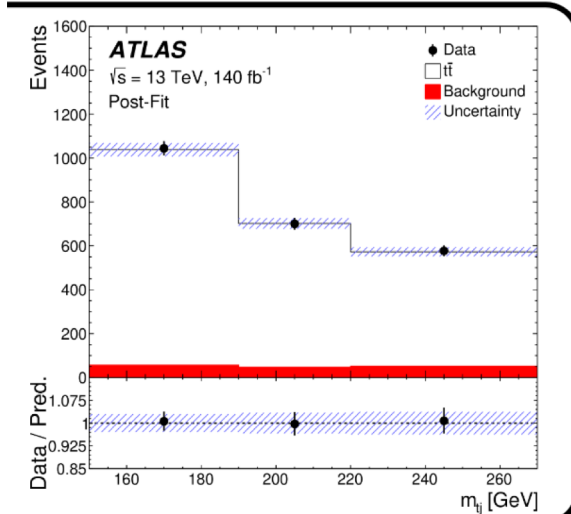
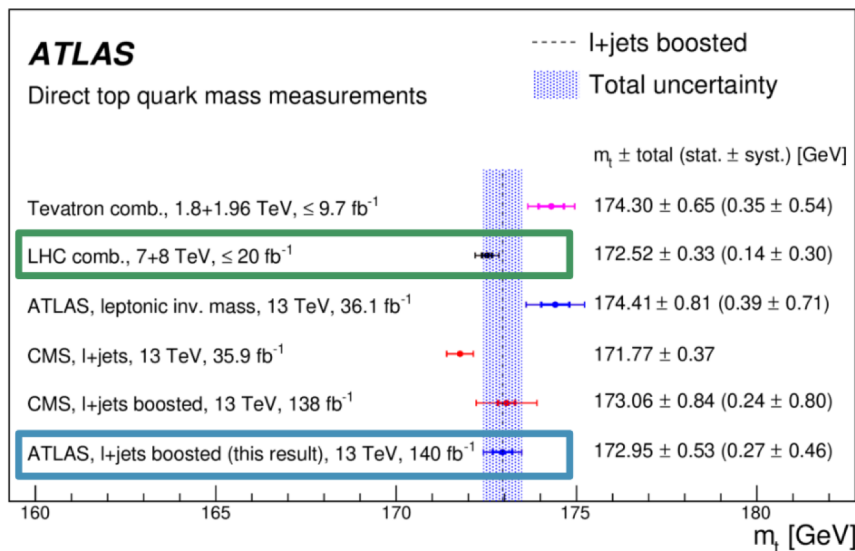
Top quark physics – m_t Highlights

30 years of top quark physics!

Profile likelihood fit setup fitting together with $m_{t\bar{t}}$ and m_{jj} – improves total uncertainty

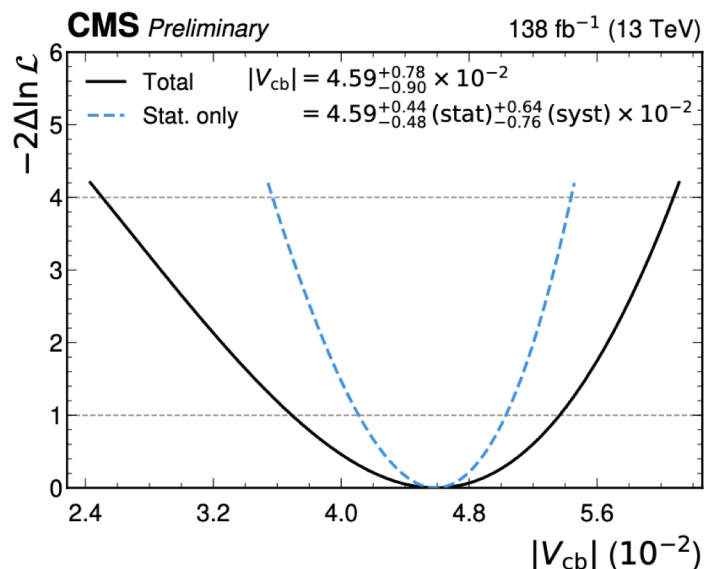
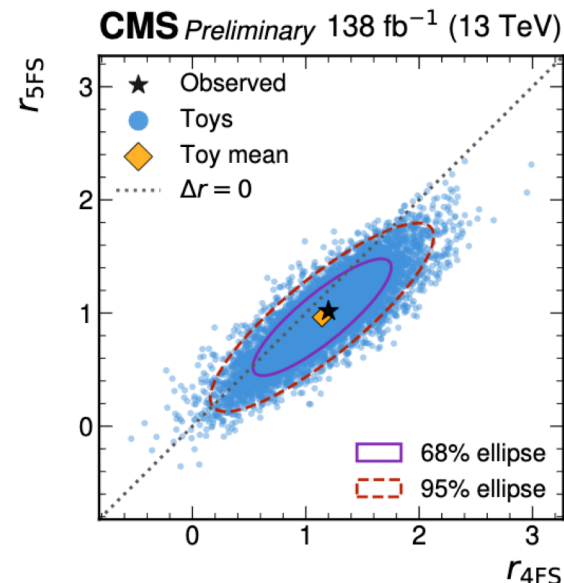
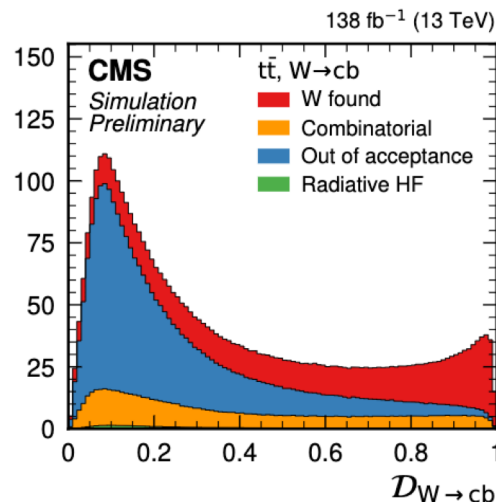
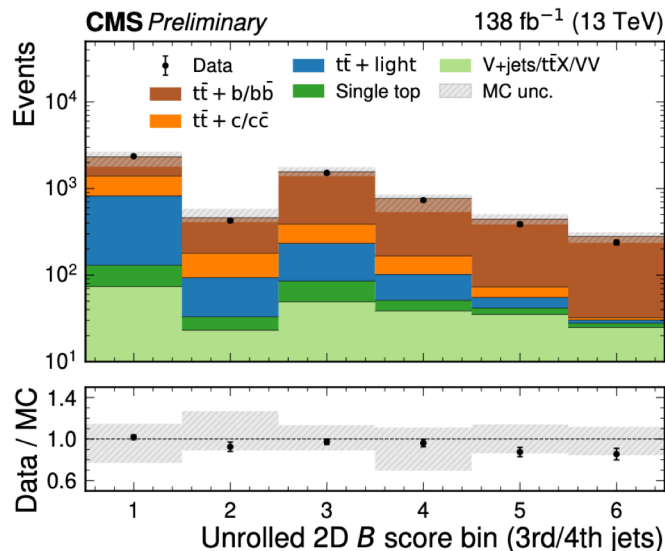
$$\overline{m}_J(m_t, \mu, \theta) = A + B \cdot (m_t - 172.5) + C \cdot (\mu - 1) + \sum_s \theta_s \Delta_s$$

- Systematic uncertainties significantly reduced in 3^d dimensional fit
 - JES: from 1.4 GeV to 0.26 GeV
 - ISR + FSR: from 0.82 GeV to 0.14 GeV
 - Recoil: from 0.36 GeV to 0.08 GeV



Most precise mass measurement from ATLAS to date [arxiv:2502.18216](https://arxiv.org/abs/2502.18216)

$|V_{cb}|$ extraction



Source	Uncertainty in r
Renormalization/factorization scales	+0.24/−0.23
Additional-b normalization/modeling	+0.14/−0.15
b tagging	+0.11/−0.10
Jet energy scale/resolution	+0.10/−0.08
Parton shower	+0.09/−0.06
Total (statistical and systematic)	+0.44/−0.42

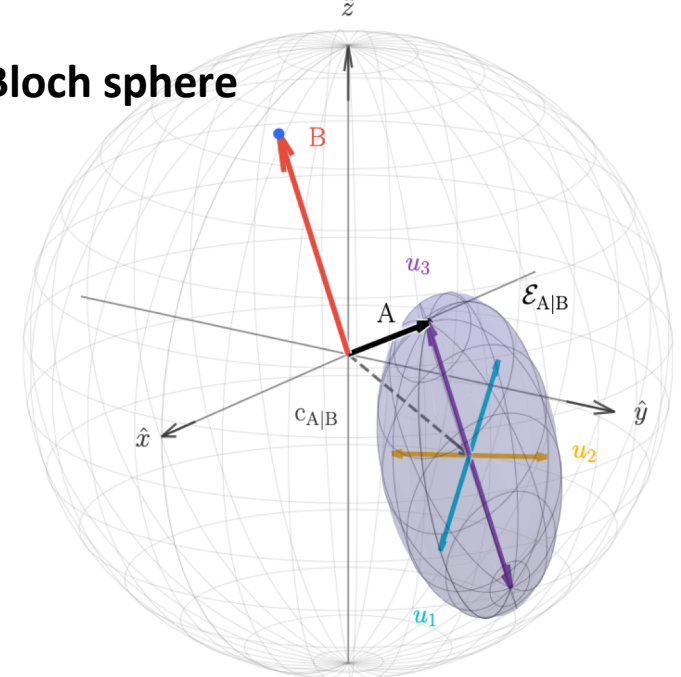
Quantum steering ellipsoids (QSE)

- **Conditional states:** For a correlated pair $A + B$, measuring B and selecting one outcome determines a “conditional” state of A .
- **Quantum steering:** Varying the measurement direction and outcome on B “steers” the conditional state of A .
- **Steering ellipsoid:** All accessible conditional states of A form an ellipsoid $E_{A|B}$ inside its Bloch sphere.
- **Geometric information:** Center $\vec{c}_{A|B}$ describes the displacement or polarization, while the semi-axes u_1, u_2, u_3 encode the strength and principal directions of the correlations.
- **Boundary and interior:** projective outcomes generate states on the ellipsoid’s surface; more general measurements can access its interior.

[Subm. to PRX Quantum \[arXiv:2608.30037\]](#)

Alvarez et al. (Jung group)

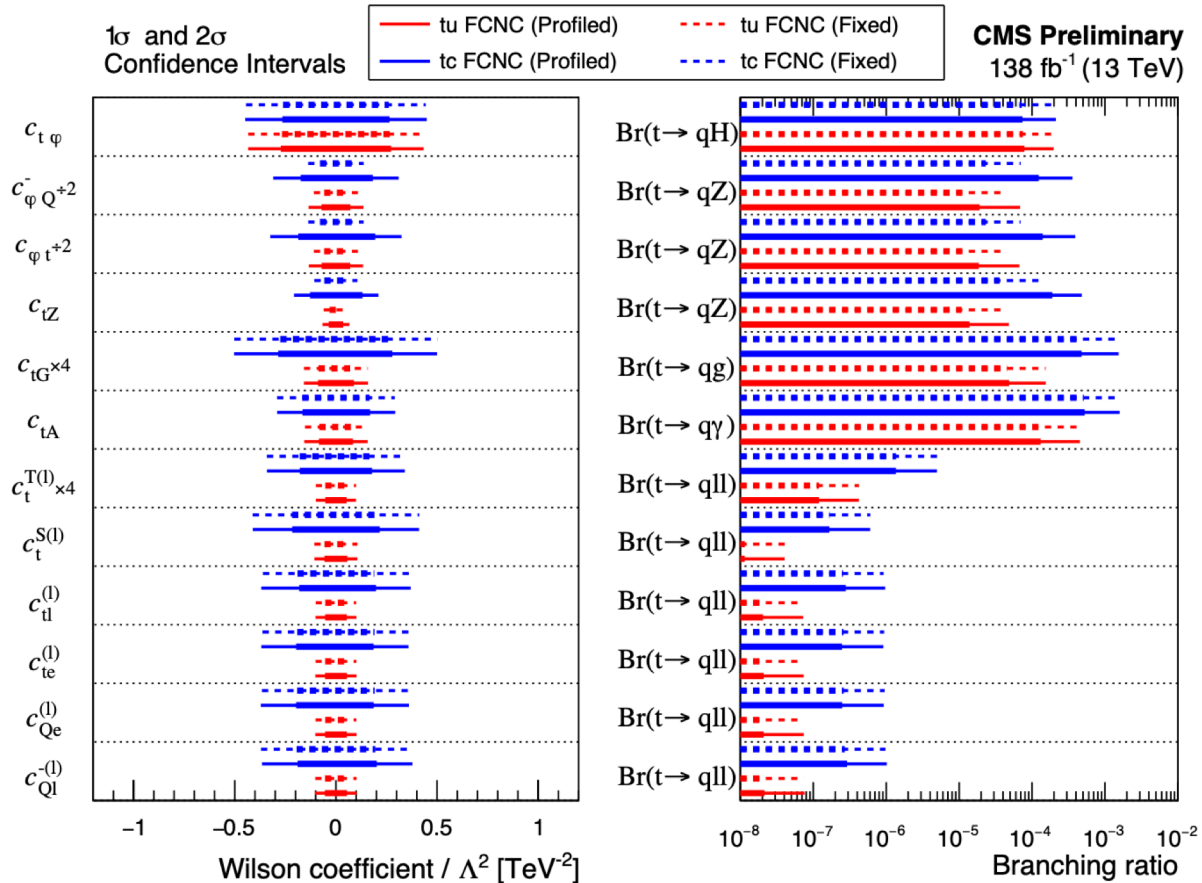
Bloch sphere



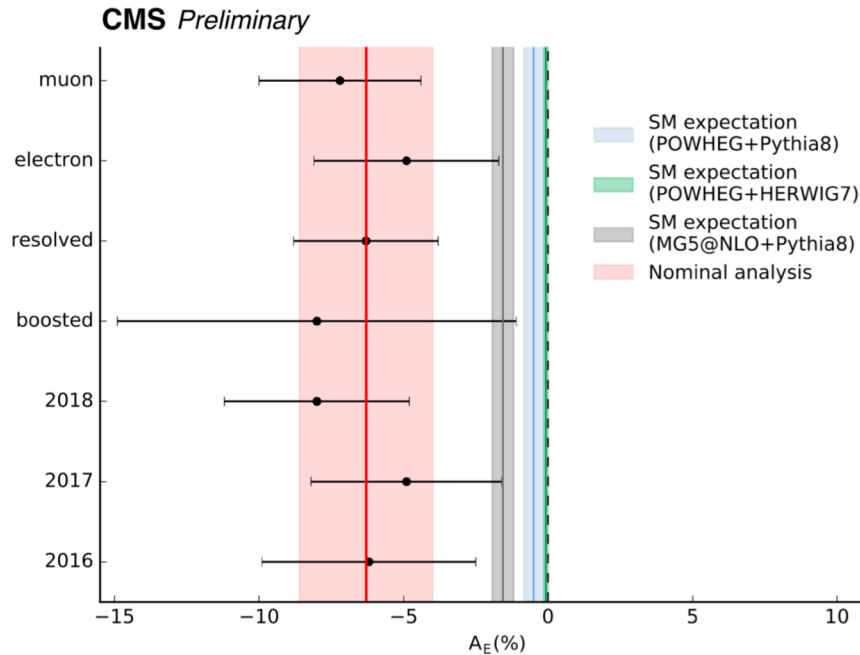
Represents all possible quantum states of a spin- $\frac{1}{2}$ particle or qubit A .

- The QSE reorganizes the spin-density matrix into an intuitive geometry
- **Steering does not enable faster-than-light communication:** without conditioning on the outcome measured for B , the local state of A remains unchanged.

FCNC EFT limits



Charge asymmetries



Process	Events		
$t\bar{t}$ (ℓ +jets)	88 800	$\pm$	3 600
$t\bar{t}$ (dileptonic)	12 500	$\pm$	580
$t\bar{t}$ (hadronic)	106	$\pm$	5
$t\bar{t}$ (out)	18 800	$\pm$	870
Single top quark	9 280	$\pm$	460
W+jets	9 250	$\pm$	690
Z+jets	770	$\pm$	65
QCD	1 010	$\pm$	140
Diboson	570	$\pm$	110
Total background	52 300	$\pm$	1 400
Total simulation	141 100	$\pm$	3 800
Data	137 100		

$$\chi^2 = \chi_{\text{lep}}^2 + \chi_{\text{had}}^2 = \left(\frac{m_{\text{lep}} - \bar{m}_{\text{lep}}}{\sigma_{\bar{m}_{\text{lep}}}} \right)^2 + \left(\frac{m_{\text{had}} - \bar{m}_{\text{had}}}{\sigma_{\bar{m}_{\text{had}}}} \right)^2$$

Entanglement in lepton+jets events

- Entanglement observed for first time in events with high $m(t\bar{t})$!

- highest sensitivity using full C

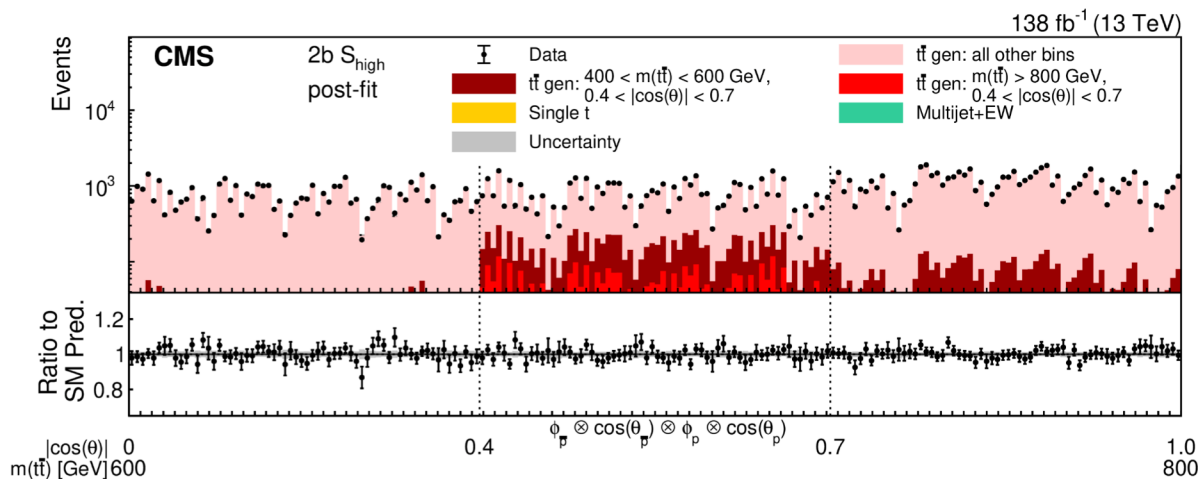
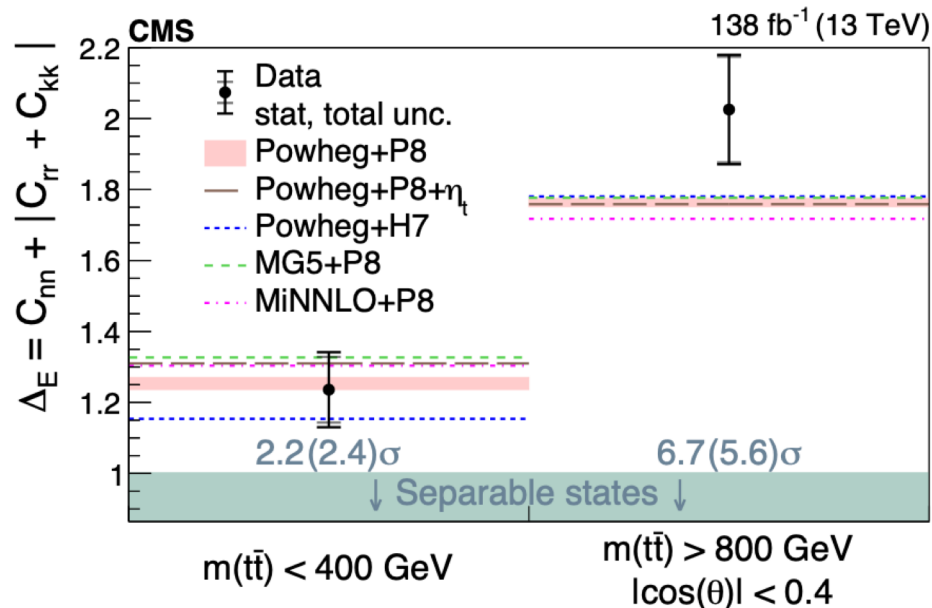
$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

$$C = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

- No sensitivity in low $m(t\bar{t})$ region

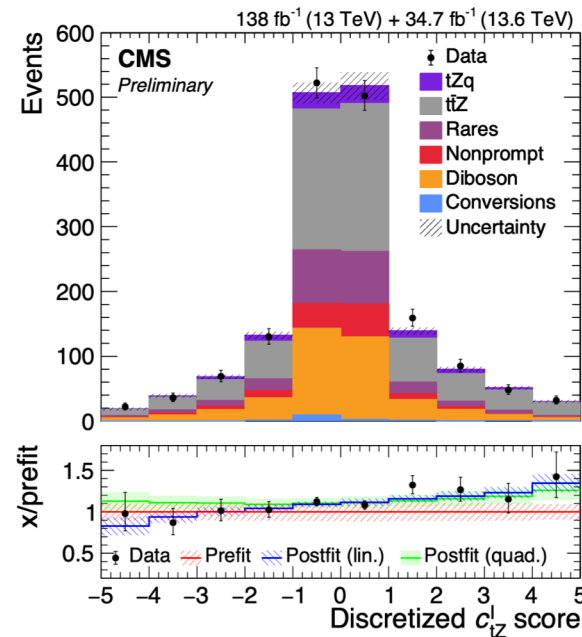
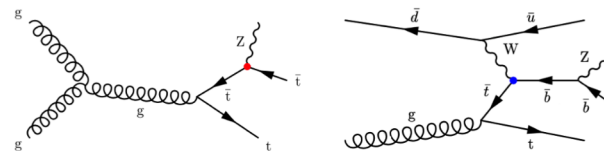
- Templates based on nominal generator
- Vary spin density matrix coefficients
- Fit templates to data based on a multidimensional distribution

[PRD 110 \(2025\) 112016](#)



Not enough CP violation to explain baryon asymmetry observed

- motivates searches for additional CP violation sources from new physics, NP can be parameterized by EFT
- CP-odd operators c_{tW}^l and c_{tZ}^l modify $t - V(Z, W)$ vertex
- SM-BSM interference proportional to $1/\Lambda^2$ (linear), gives rise to CP-odd contributions

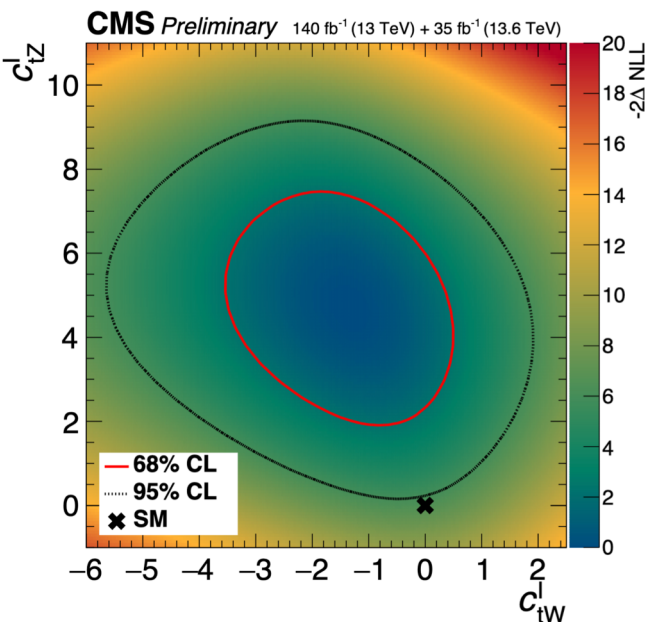


CP-odd observables using physics-informed ML

- [Phys. Rev. D 110 \(2024\) 096023](#)
- SM contribution CP-invariant
- pure BSM contribution CP-invariant (quadratic)
- SM-BSM interference CP-odd (linear)

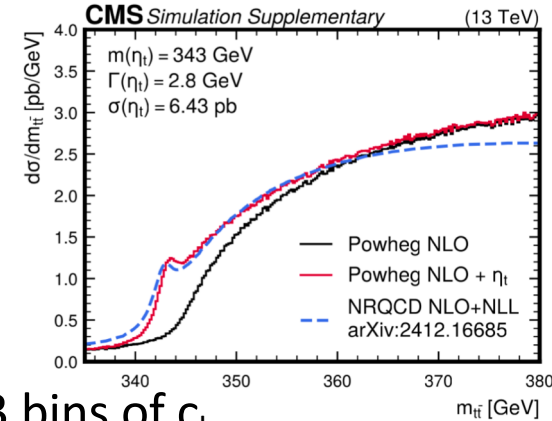
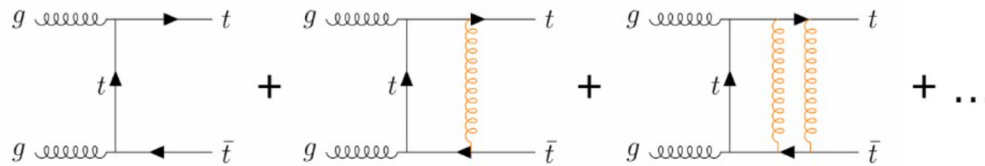
Good agreement with SM

- Pre-fit vs post-fit deviations: slight c_{tZ}^l asymmetry

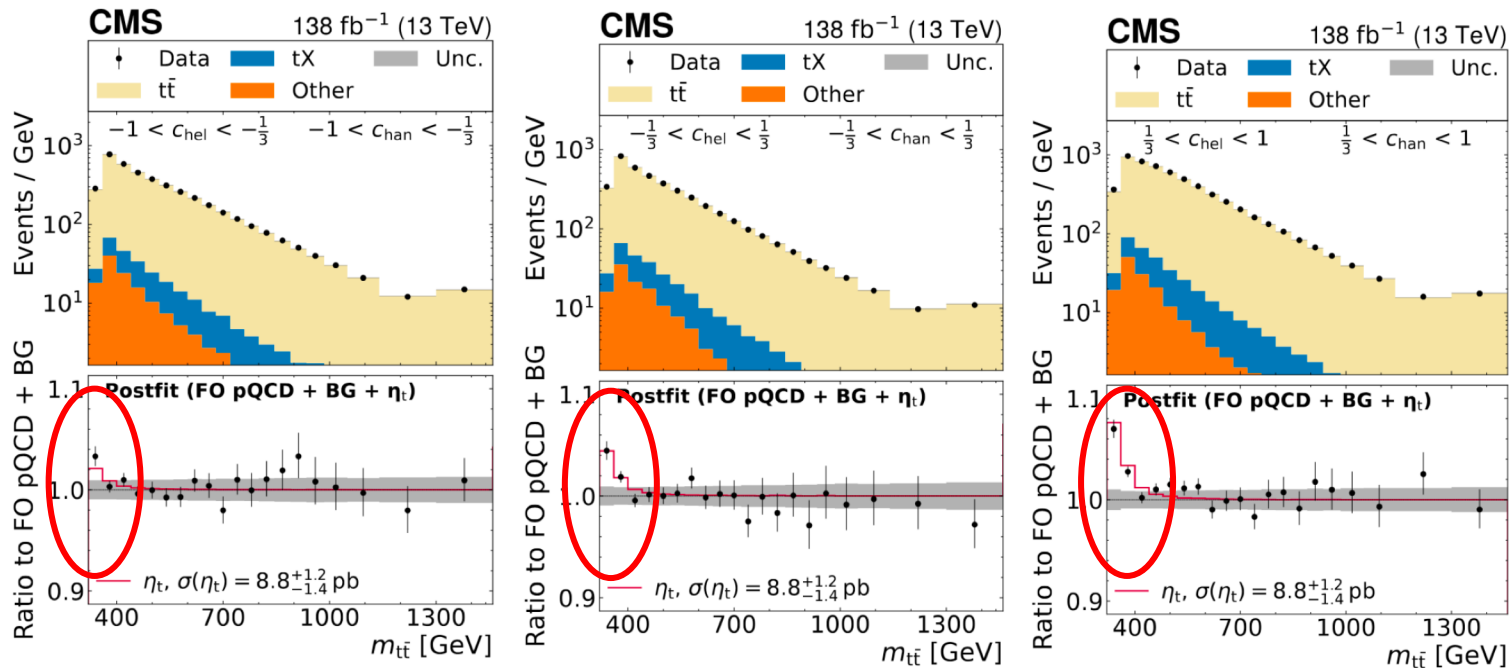


Quasi-bound states at threshold ?

- Shape differences between data and prediction observed in low $m(t\bar{t})$ bins!



- Profile-likelihood fit to 20 bins of $m(t\bar{t})$ x 3 bins of c_{hel} x 3 bins of c_{han}



→ Excess at low $m(t\bar{t})$ visible

[arXiv:2503.22382]

- Excess is located at low $m(t\bar{t})$, stronger for pseudo-scalar
→ could this be interpreted as $t\bar{t}$ quasi-bound state effects?
- Extract cross section using the η_t color-singlet model

- “cross section” = difference to perturbative prediction

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

- Agrees with NRQCD prediction: ([PRD 104 \(2021\) 034023](#))

$$\sigma(\eta_t) = 6.43 \pm 0.90 \text{ pb} \quad (\text{JHEP 09 (2010) 034})$$

■ Words of caution:

- This model is not a complete description of a $t\bar{t}$ bound state!
- Cannot distinguish between η_t & pseudo-scalar Higgs
- Missing e.g. color-octet states - these are expected to be small

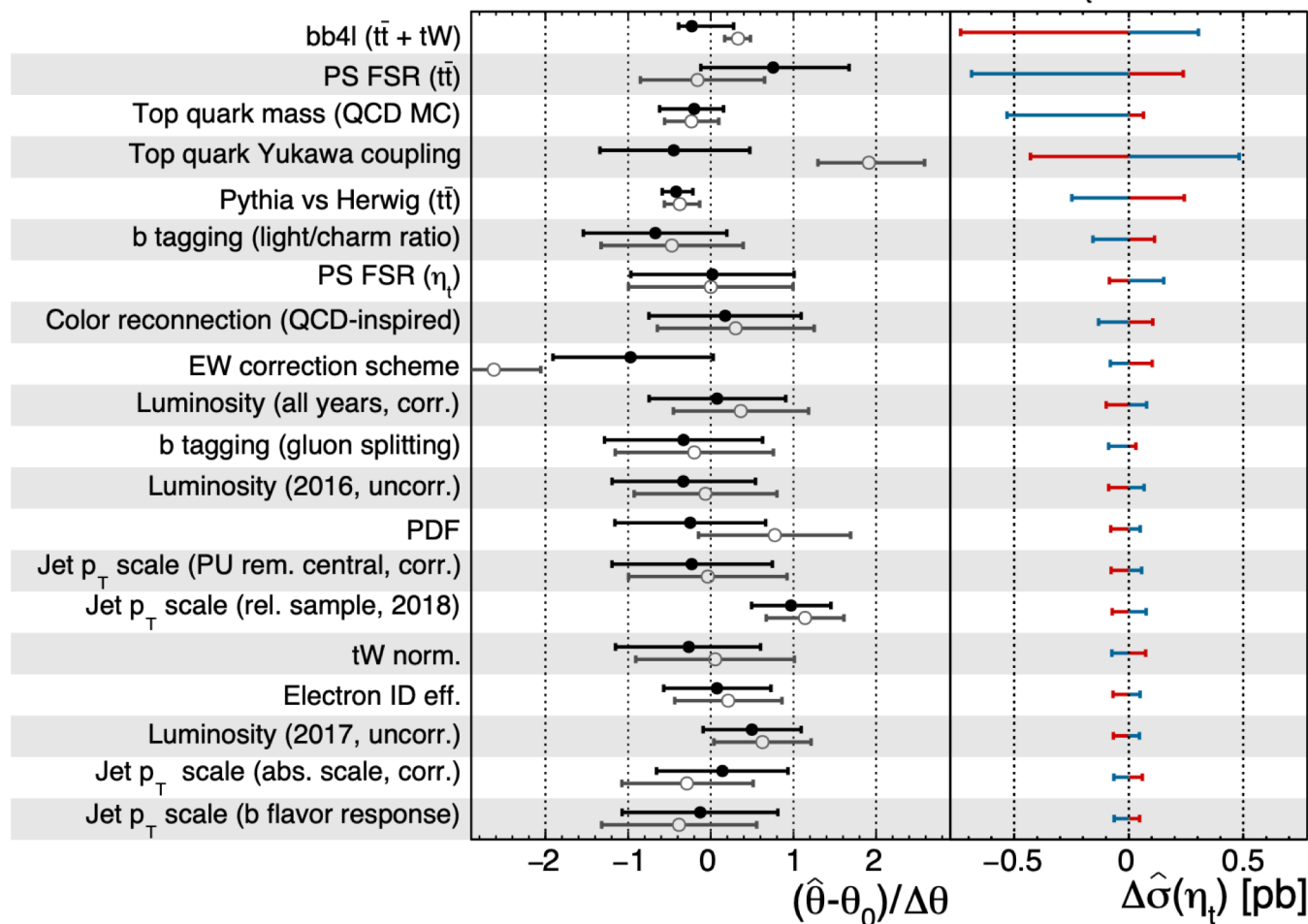
Nuisance parameters – impact plot



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)

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

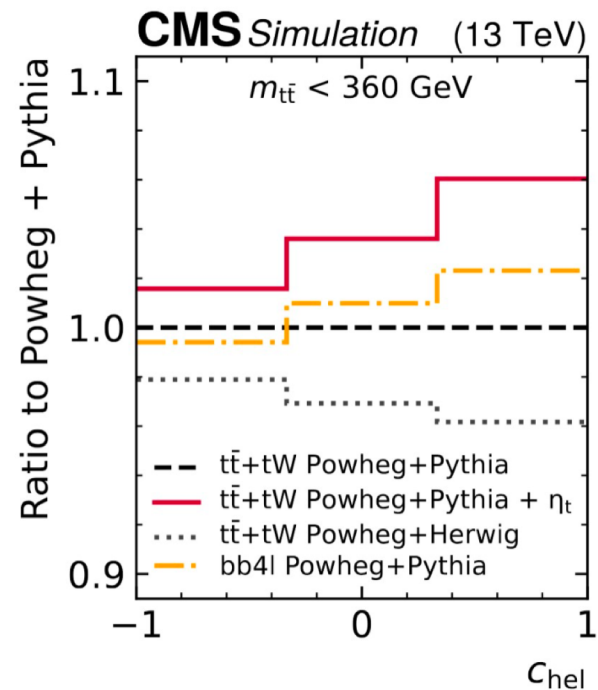
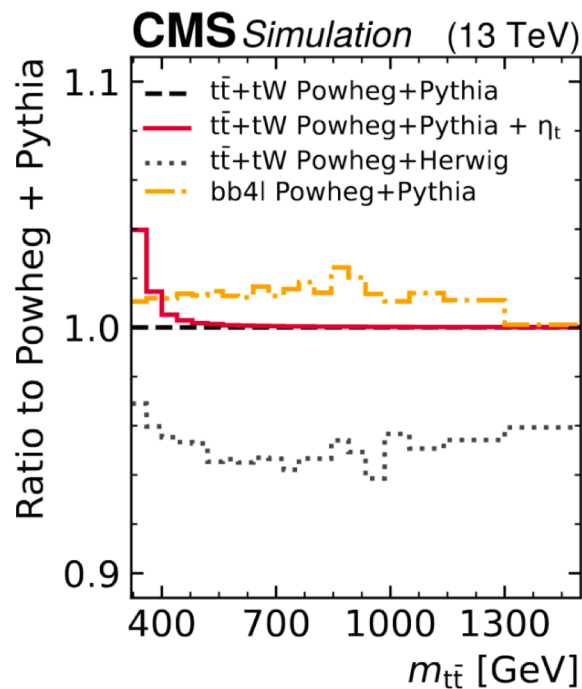


Alternative background models

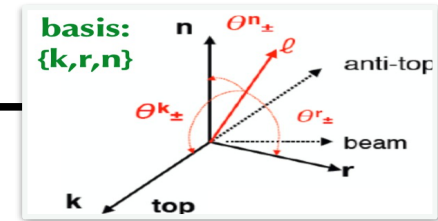


- Excess stable against changes of background model

FO pQCD generator setup	$\sigma(\eta_t)$ [pb]
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$



Top quark spin correlations



- Probed by angular distribution of decay products in helicity basis:

Double diff. xsec

Polarisation (0 in SM)

Spin Correlation

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4} (1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b) \cos\theta_+^a \cos\theta_-^b)$$

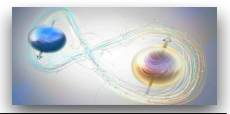
$$B^{+/-} = \begin{pmatrix} \times \\ \times \\ \times \end{pmatrix}$$

$$C = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

→ Spin dependence of $t\bar{t}$ production is **completely characterized by 15 coefficients** (but we have lost information better “correlations”)

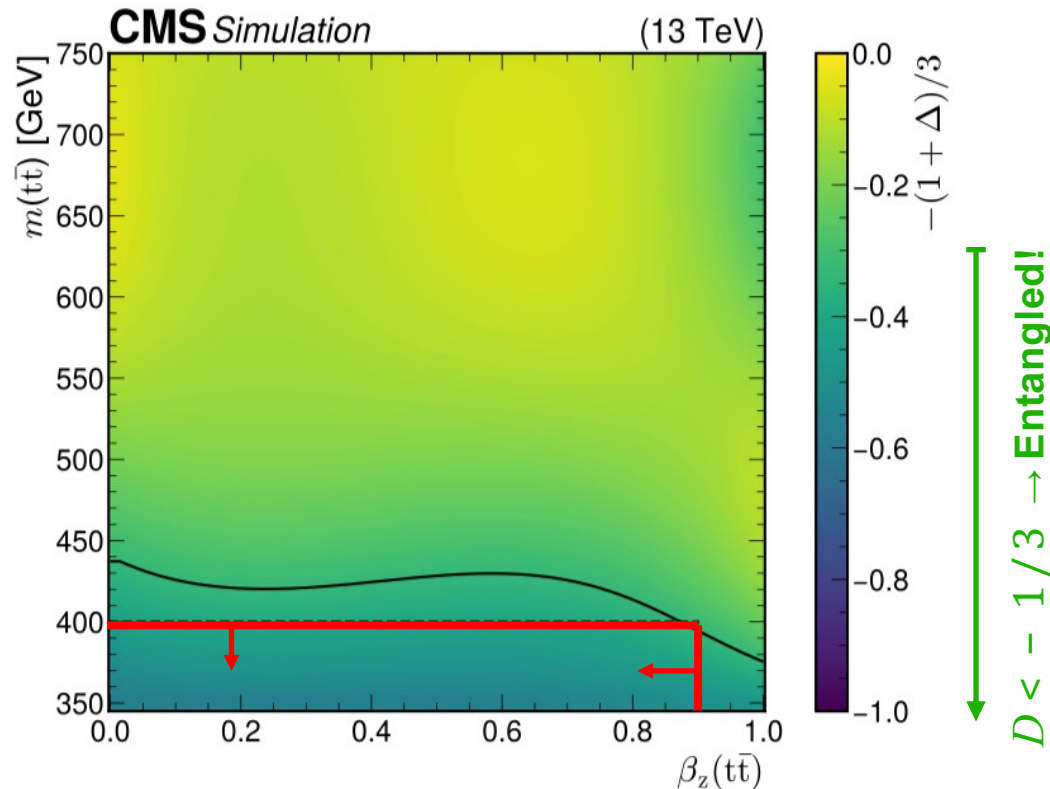
$$\frac{1}{\sigma} \frac{d\sigma}{dx} = \frac{1}{2} (1 + [\text{Coef.}] x) f(x)$$

Analysis in a nutshell...



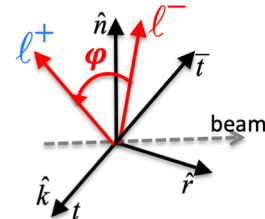
- The degree of entanglement is highly phase space-dependent
 $\rightarrow$ Scan of $m(t\bar{t})$ vs. $\cos(\Theta)$ vs β to determine most sensitive phase space while minimizing expected total uncertainties
- Focus on low-mass region ($345 < m(t\bar{t}) < 400$ GeV) to increase entanglement

Cut on velocity along the beam line of the $t\bar{t}$ system to increase $gg / q\bar{q}$ fraction:



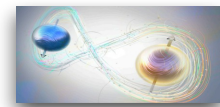
[arXiv:2205.00542](https://arxiv.org/abs/2205.00542) $\beta = \left| \frac{p_z^t + p_z^{\bar{t}}}{E_t + E_{\bar{t}}} \right| < 0.9$

- Measure helicity angle** $\cos \varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$
 - fully encapsulates spin correlations information for



- Perform a **profile maximum likelihood fit of the $\cos$ distribution** in the $m_{t\bar{t}} - \beta$ signal region

Observation of Entanglement



1st measurement of entanglement
of top quarks with CMS data

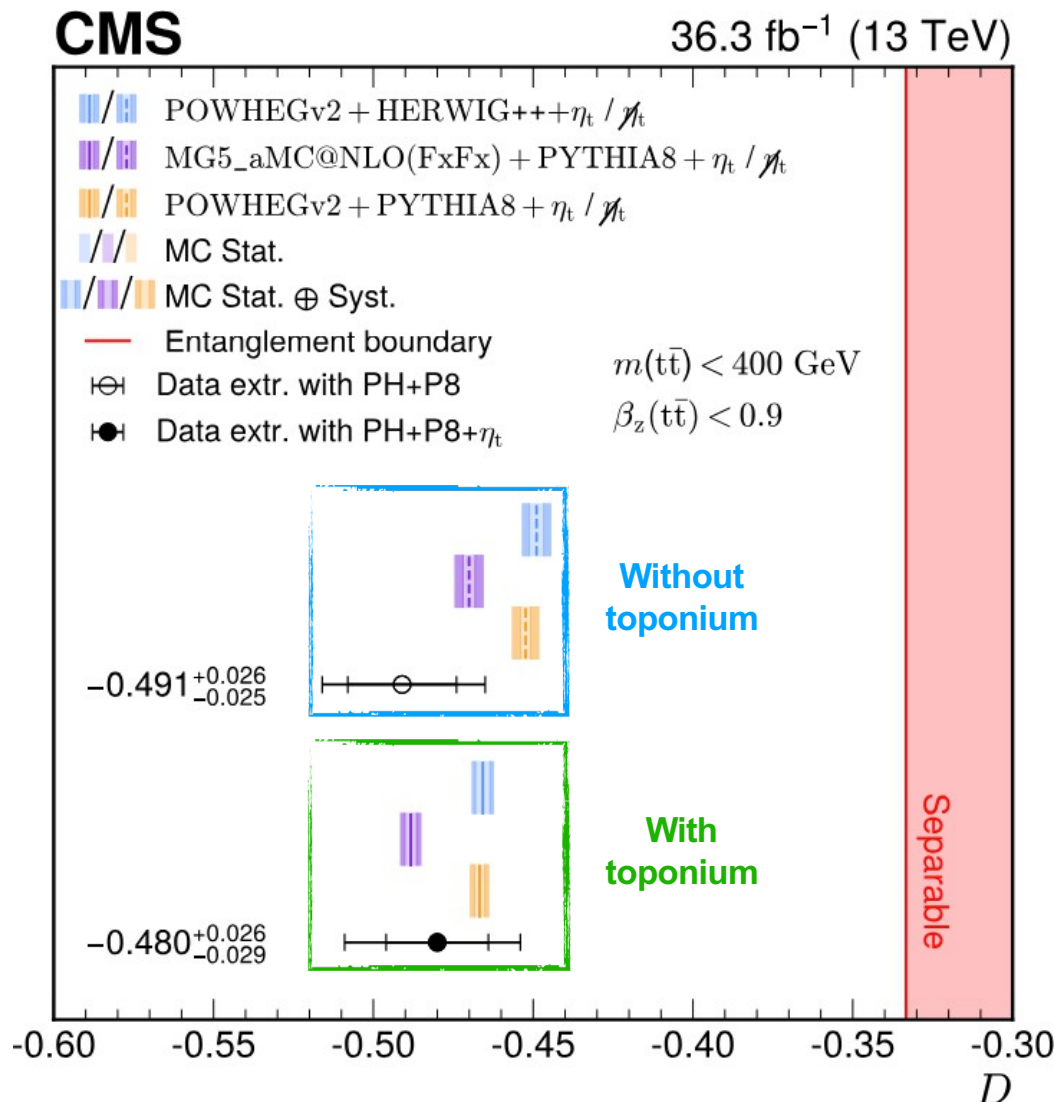
[Rep. Prog. Phys. 87 \(2024\) 117801](#)

- CERN press release:
[CERN Press release, Sept 2024:](#)
["LHC ... observe quantum entanglement..."](#)
- Also featured in "Symmetry"
["The Quantum Chase" – Symmetry, Nov 2024](#)

5 standard deviations
observation of top quarks
being entangled at $t\bar{t}$ threshold

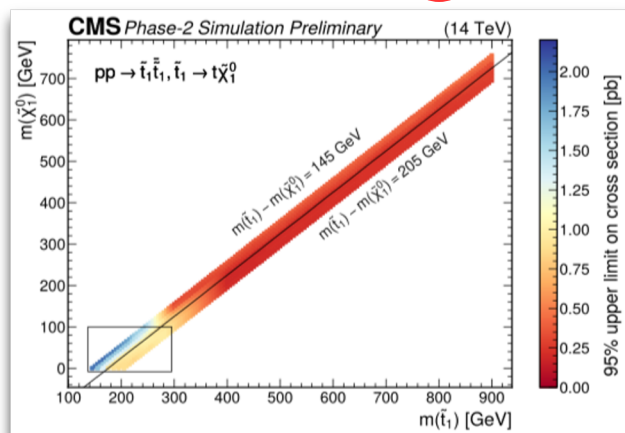
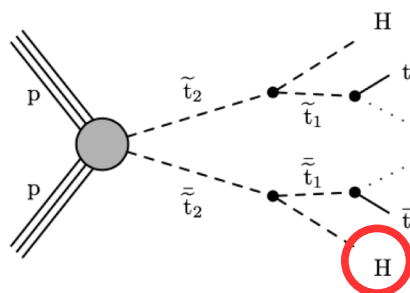
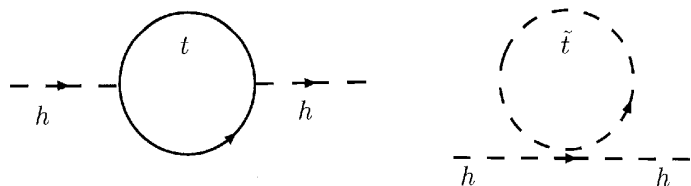
- ~ 1.5 tension with the expectation
if toponium is not included

Good agreement with SM
significantly improved by
including η_t

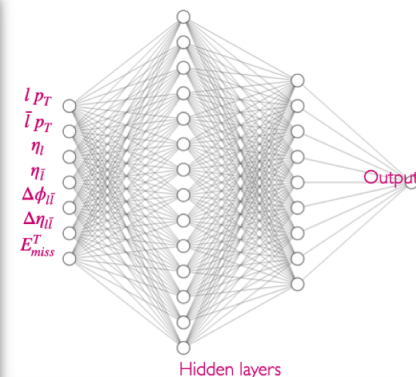
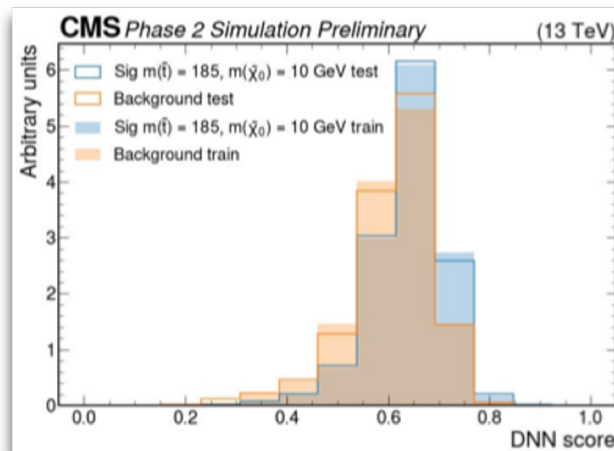


Prospects at the HL-LHC

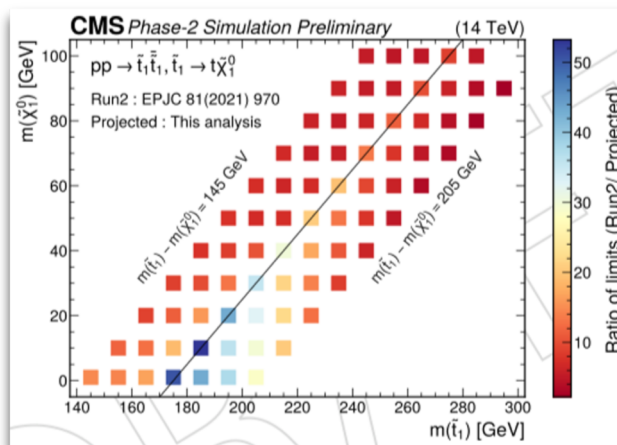
Reminder: Solve the hierarchy problem
→ need a top quark partner



Signal to bg separation at 185 GeV



Employ Machine learning to construct a more powerful discriminant based on top quark properties



Significantly better sensitivity

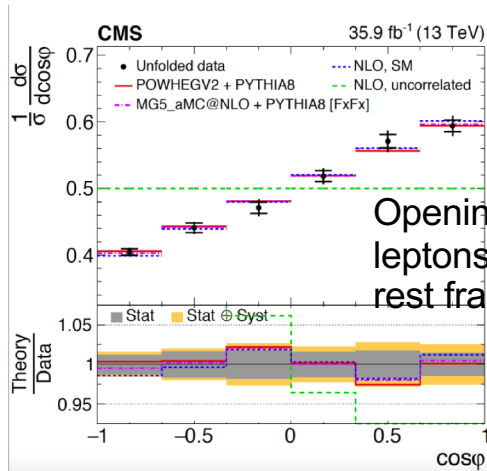
Prospects at the HL-LHC

Double diff. xsec

Polarisation (0 in SM)

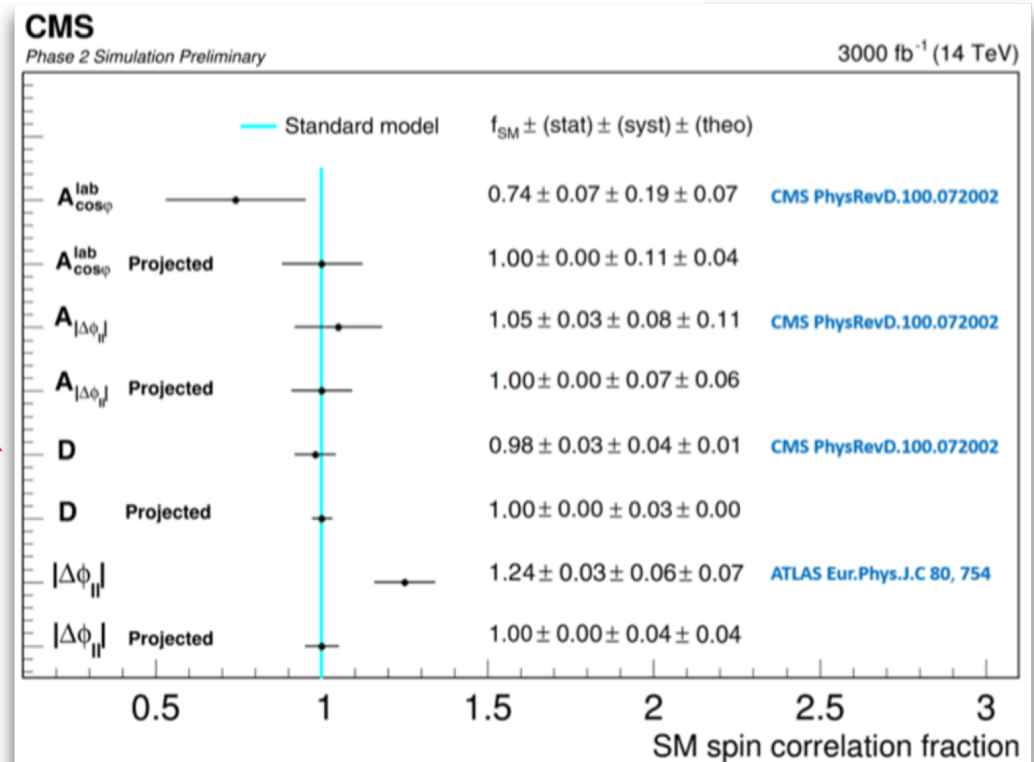
Spin Correlation

$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4} (1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b) \cos\theta_+^a \cos\theta_-^b)$$



$$f_{SM} = \frac{D_{measured} - D_{theory,uncorrelated}}{D_{theory,correlated} - D_{theory,uncorrelated}}$$

→ Expected precision:
 $\mathcal{O}(2 - 3)\%$



Contributed to Snowmass, [CMS-PAS-FTR-18-034](#)