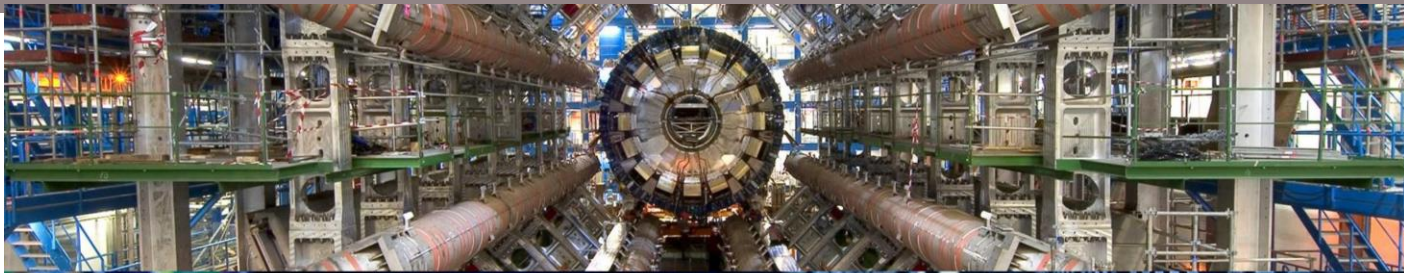


Highlights from LHC



R. Demina

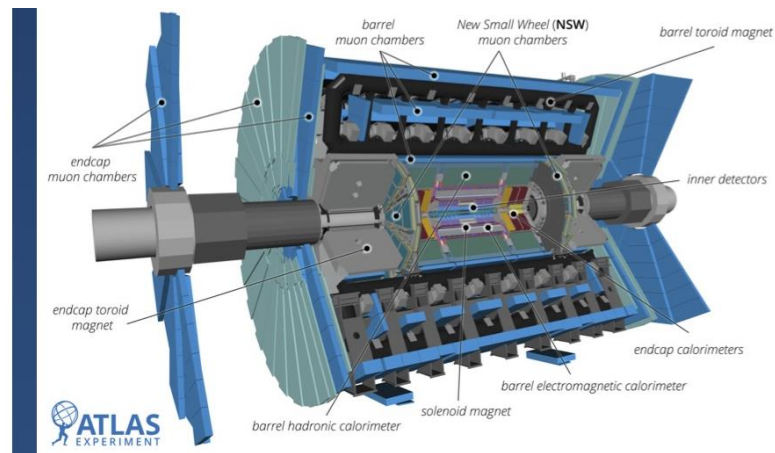
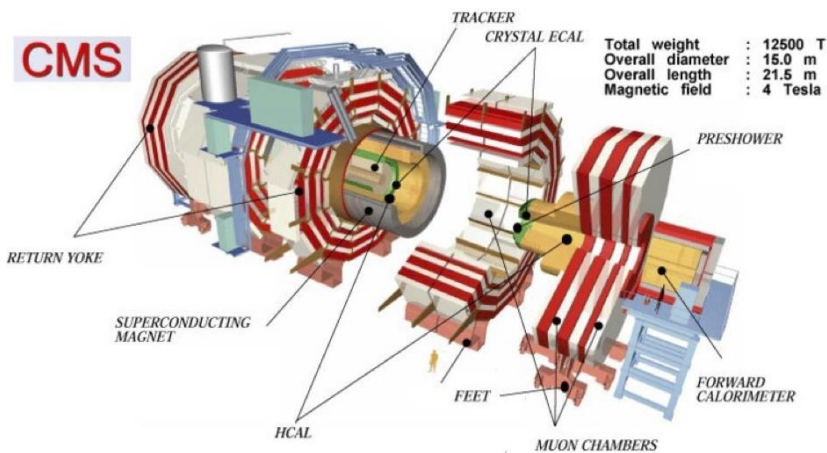
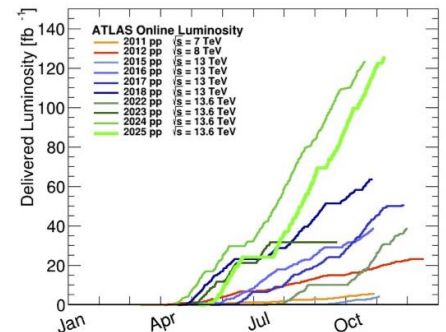
University of Rochester

05/12/2026



Performance → new strategies

- With energy increase the search concentrates on new (rare) signatures
 - E- μ channel for top quark discovery at the Tevatron
 - ZZ → 4l for Higgs boson discovery at LHC
 - 3-lepton golden channel for SUSY
- With increase luminosity shift to kinematic characteristics
 - Bump-hunting
 - Tails of distributions
- Further increase – angular correlations – **physics of spin**



Outline

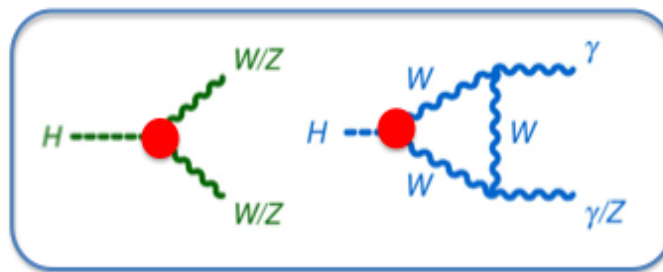
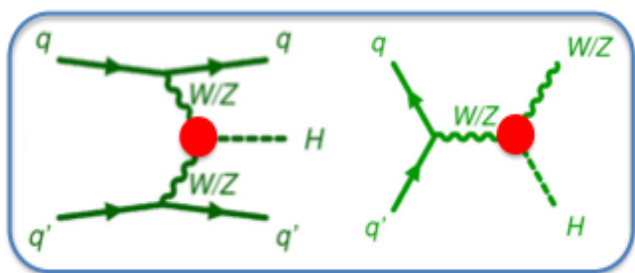
- CP and polarization of Higgs boson
 - Atlas: VBF production, $H \rightarrow \gamma\gamma$ decay
 - CMS: $H \rightarrow \tau\tau$
 - CMS: $H \rightarrow Z^*Z \rightarrow 4l$
- Entanglement in Higgs decay
 - CMS and Atlas: $H \rightarrow Z^*Z \rightarrow 4l$
- Entanglement and quantum observables in top-antitop system
 - Atlas and CMS – dilepton channel
 - CMS – lepton+jets channel
- “Toponium” – quasi-bound state production
 - Atlas and CMS – dilepton channel
 - CMS – lepton+jets channel
- Conclusions

Higgs boson properties

CP and polarization of Higgs boson

- Current experimental sensitivity still allows for possible CP-violating contributions
- VBF Higgs production with $H \rightarrow \gamma\gamma$ decay, using 164 fb^{-1} of Run3 data

• **HVV couplings** can be probed via **VBF/VH production** and **HVV decays**



• Using the Standard Model Effective Field Theory (**SMEFT**) formalism to parameterize the HVV interactions

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\lambda^{D-4}} O_i^{(D)}$$

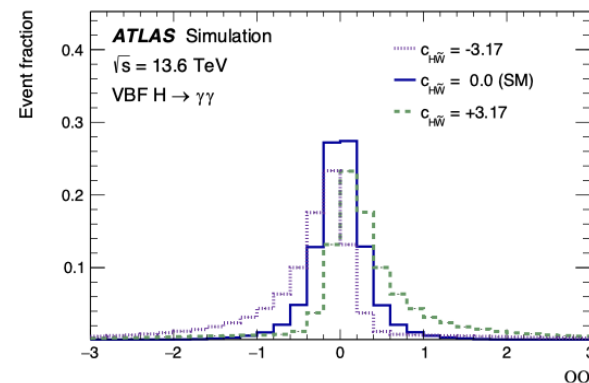
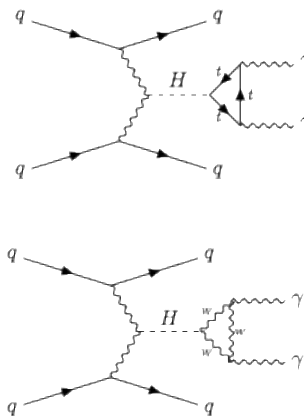
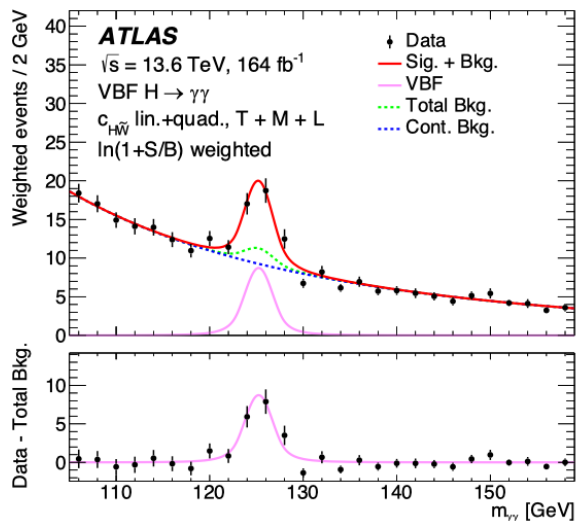
c_i : Wilson coefficients
 O_i : SMEFT CP-odd dim-6 operators

Cross-section decomposition:

$$O_n = O_n^{\text{SM}} \left(1 + \underbrace{\sum_i A_{ni} c_i}_{\text{Linear (CP-odd)}} + \underbrace{\sum_i B_{ni} c_i^2}_{\text{Quadratic (CP-even)}} + \underbrace{\sum_{i<j} C_{nij} c_i c_j}_{\text{Cross-term (CP-even)}} \right),$$

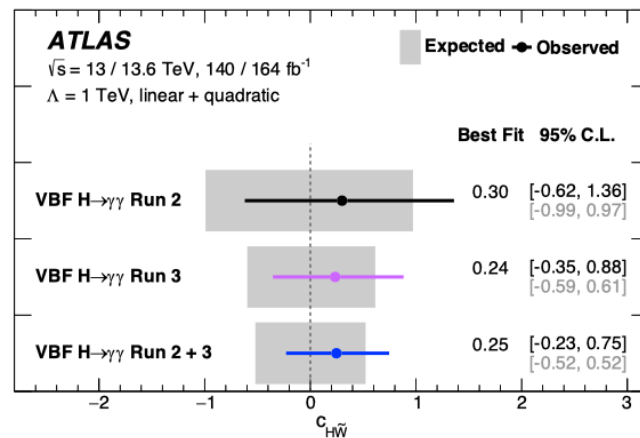
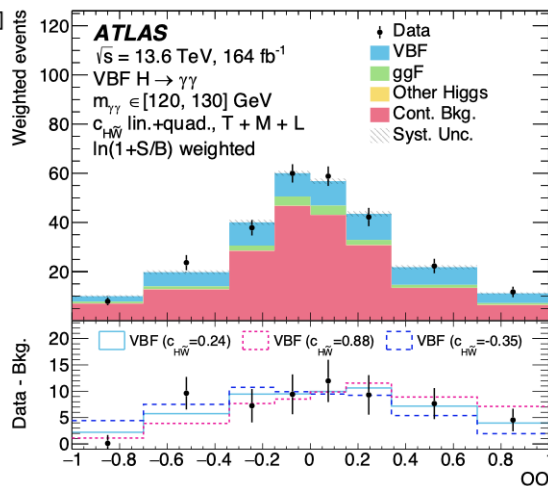
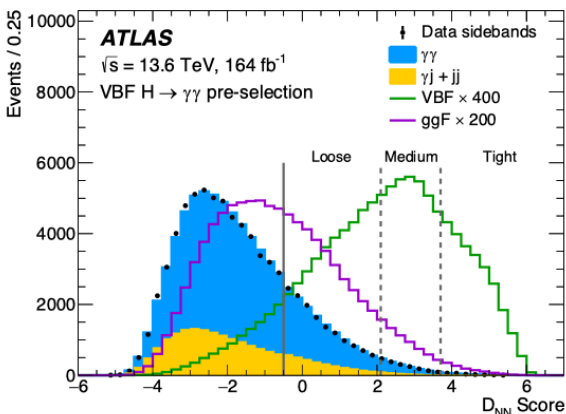
Operator	Structure	Coupling
Warsaw Basis		
$O_{\Phi\tilde{W}}$	$\Phi^\dagger \Phi \tilde{W}_{\mu\nu}^I W^{\mu\nu I}$	$c_{H\tilde{W}}$
$O_{\Phi\tilde{W}B}$	$\Phi^\dagger \tau^I \Phi \tilde{W}_{\mu\nu}^I B^{\mu\nu}$	$c_{H\tilde{W}B}$
$O_{\Phi\tilde{B}}$	$\Phi^\dagger \Phi \tilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\tilde{B}}$

CP and polarization of Higgs boson



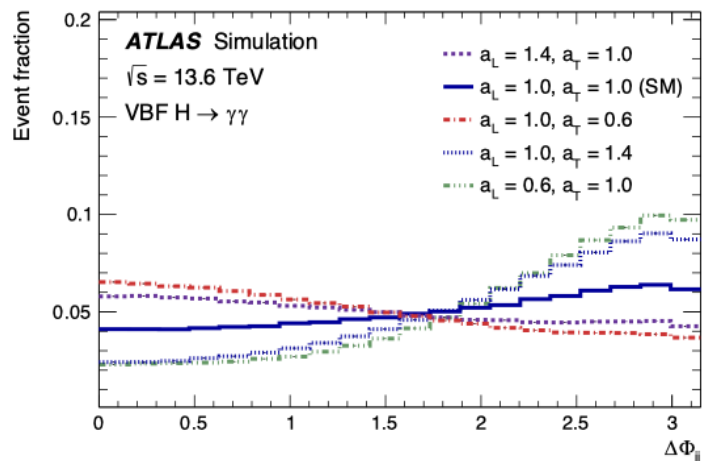
CP: SMEFT Warsaw basis

$$OO = 2\text{Re}(M_{SM}^* M_{BSM}) / |M_{SM}|^2$$



CP and polarization of Higgs boson

- Sensitive to polarization – $\Delta\phi$ between VBF jets

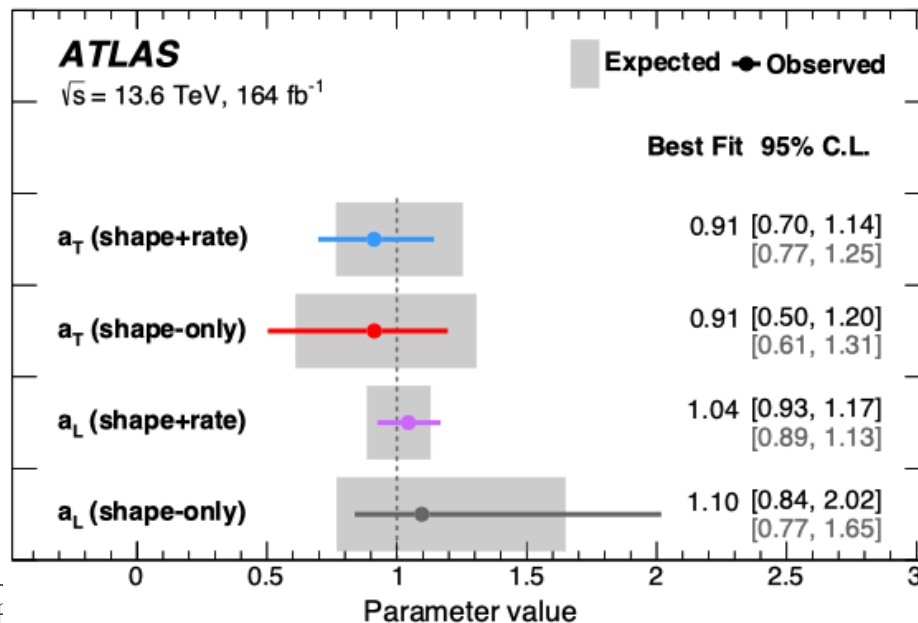
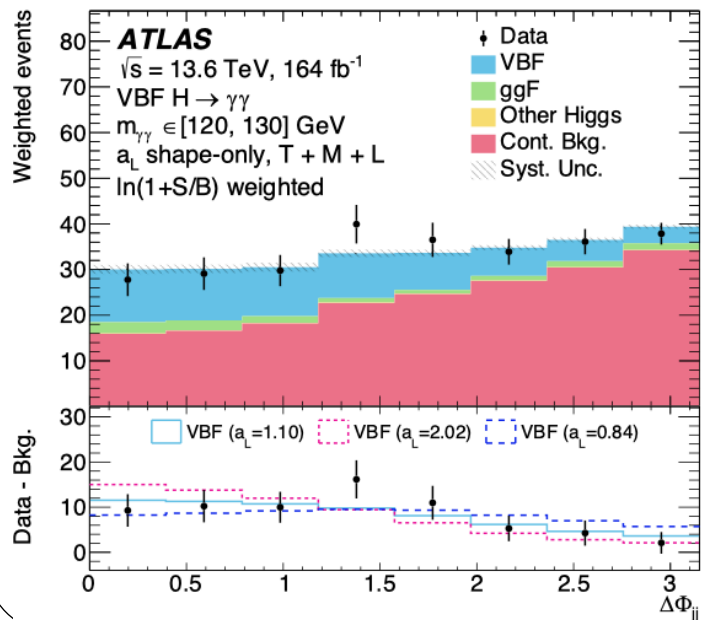


Polarization:

$$\alpha_L = g(HV_L V_L) / g(HVV)$$

$$\alpha_T = g(HV_T V_T) / g(HVV)$$

In the SM: $\alpha_L = \alpha_T = 1$,
 anomalous couplings predicted by BSM models,
 e.g., **composite Higgs**

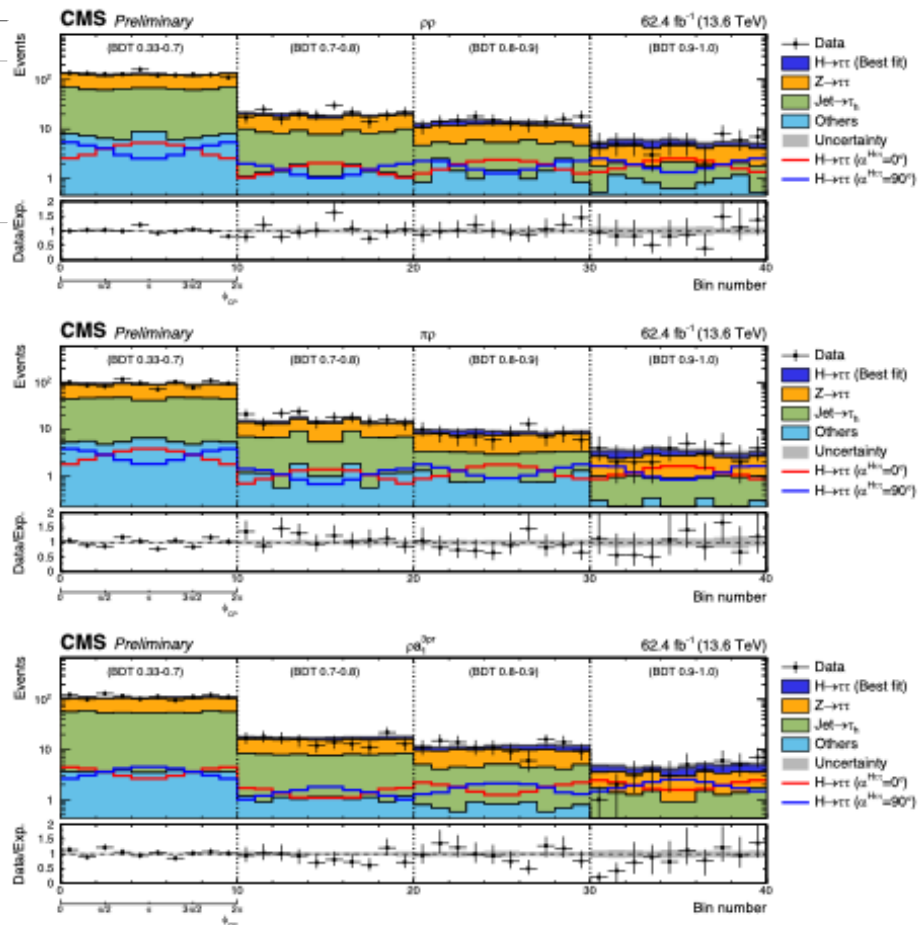
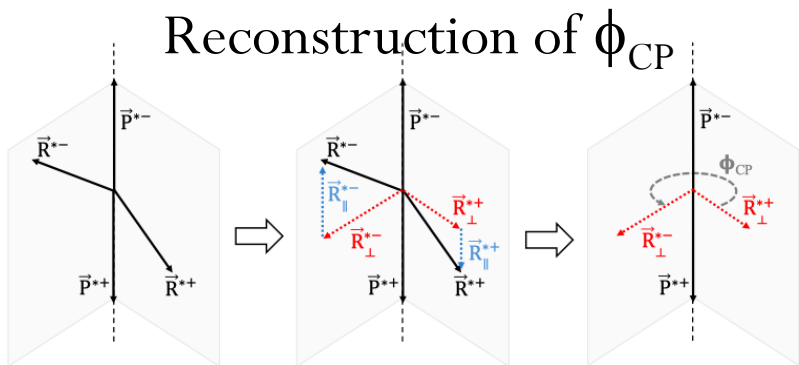


CP structure of Higgs- τ Yukawa coupling

- Use $\tau \rightarrow e, \mu, \text{ or } \pi, \rho, a^{1pr}, a^{3pr}$ decays, with P – the charged decay product momentum, R – their Impact parameter vector from PV

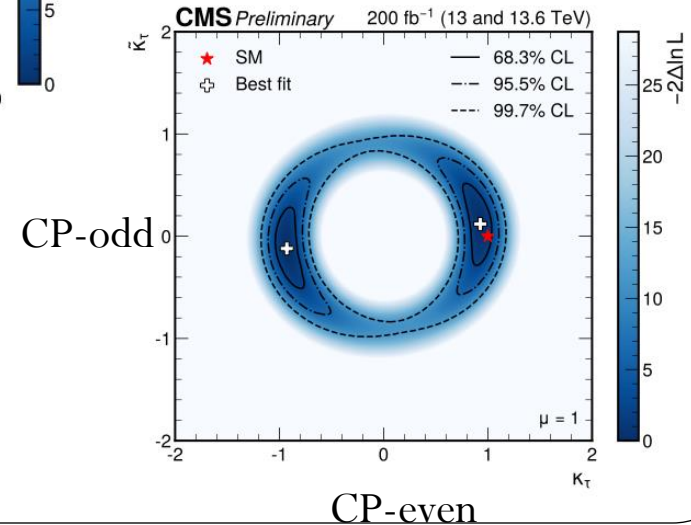
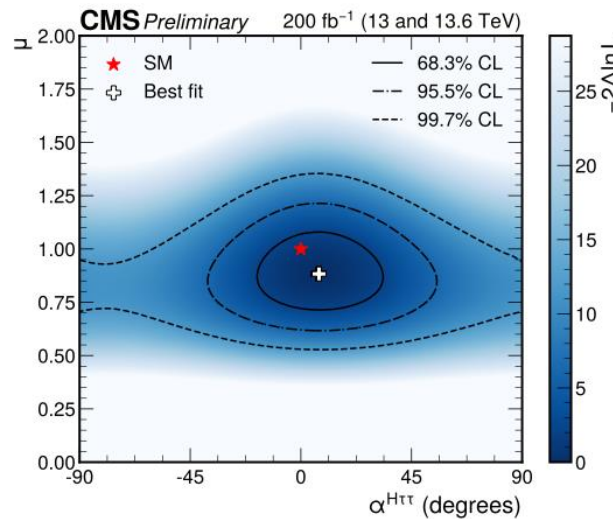
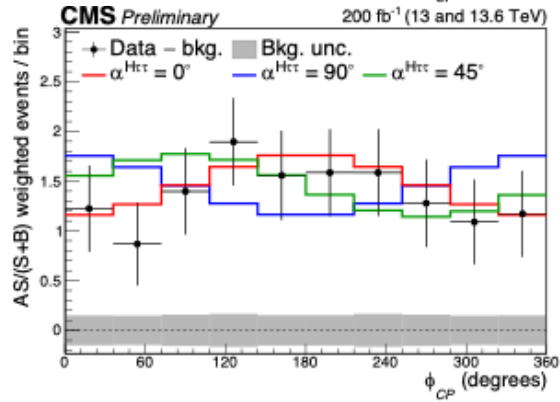
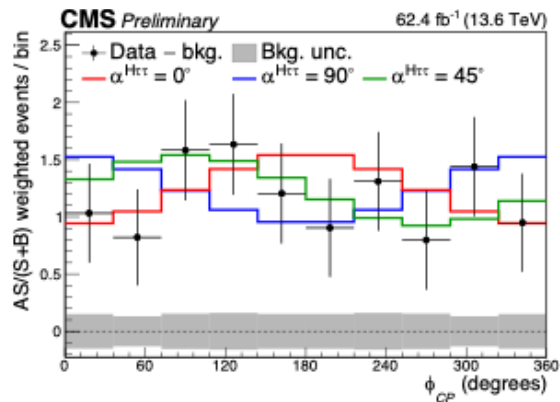
Mode	$e^\pm \nu$	$\mu^\pm \nu$	$h^\pm \nu$	$h^\pm \pi^0 \nu$	$h^\pm \pi^0 \pi^0 \nu$	$h^\pm h^\mp h^\pm \nu$
Type	τ_e	τ_μ	τ_h	τ_h	τ_h	τ_h
$\mathcal{B}(\%)$	17.8	17.4	11.5	25.9	9.5	9.8
Resonance	—	—	—	$\rho(770)$	$a_1(1260)$	$a_1(1260)$
Symbol	e	μ	π	ρ	a_1^{1pr}	a_1^{3pr}

Reconstruction of ϕ_{CP}



CP structure of Higgs- τ Yukawa coupling

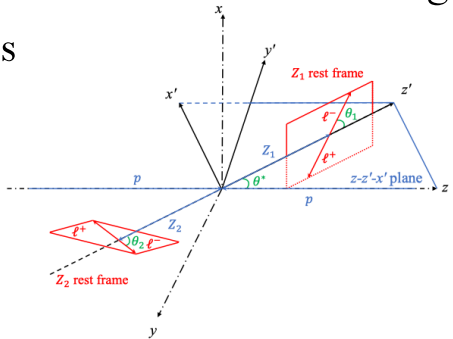
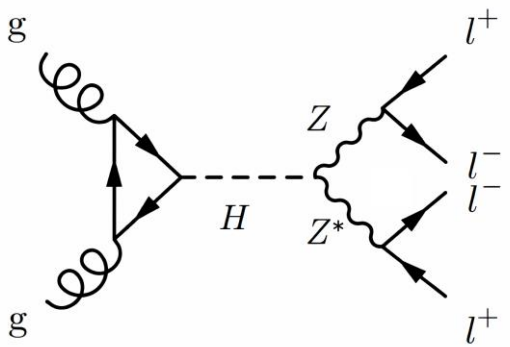
- Use $H \rightarrow \tau\tau$ channel to constrain the effective CP mixing angle $\alpha^{H\tau\tau}$, of the admixture of scalar and pseudoscalar couplings
- $\alpha^{H\tau\tau} = 7 \pm 16^\circ$, SM expected value of $0 \pm 14^\circ$.



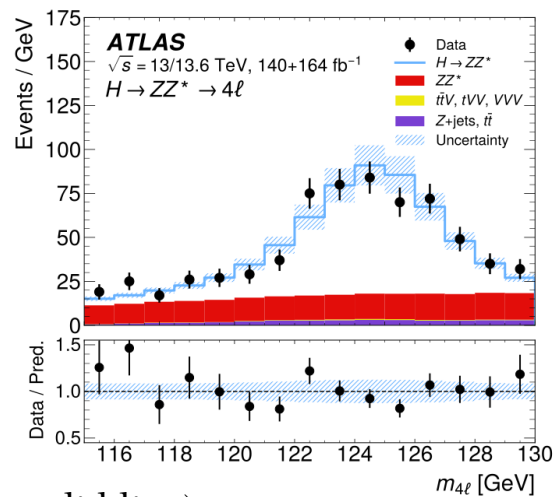
Spin correlations in $H \rightarrow ZZ \rightarrow 4l$ (Atlas)

The golden channel of Higgs discovery continues to deliver stunning results

Very clean channel, rich angular correlations



Negative leptons – spin analyzers



$S=1$ Z bosons – 2 qutrit system \rightarrow

$9 \times 9 = 81$ spin correlation coefficients;

Only 9 are non-zero ($s(H)=0$)

6 off-diagonal are related to two

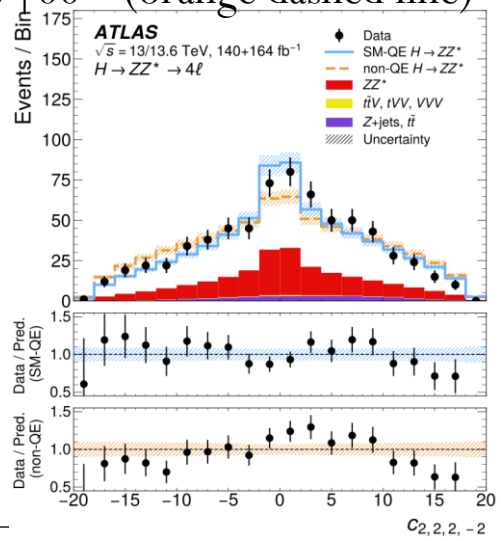
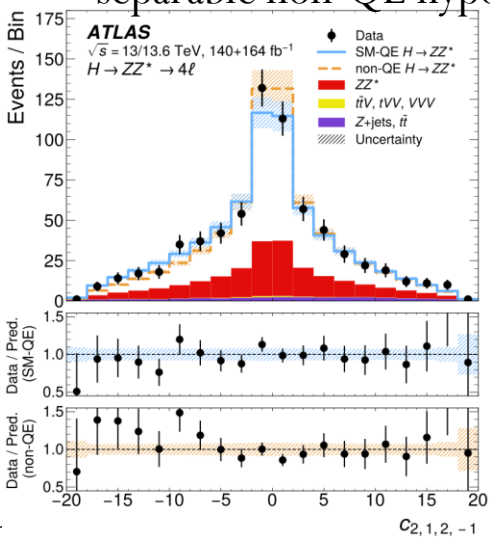
parameters:

$C_{212,-1}$ and $C_{222,-2}$, estimated on event-by-event basis from angles of the spin analyzers

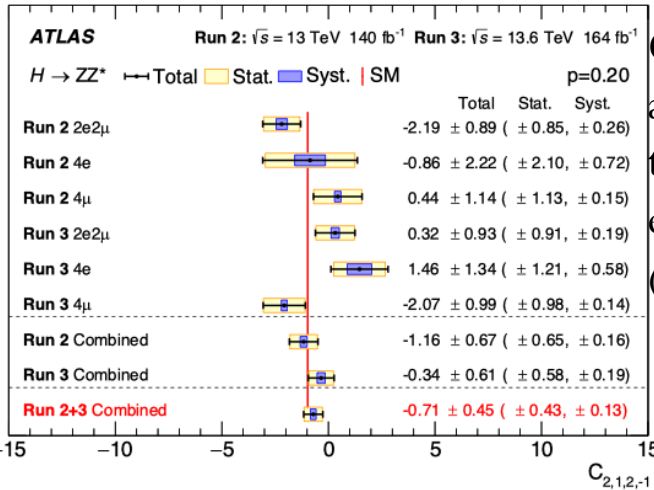
System is entangled if at least one is non-zero.

entangled hypothesis (blue solid line)

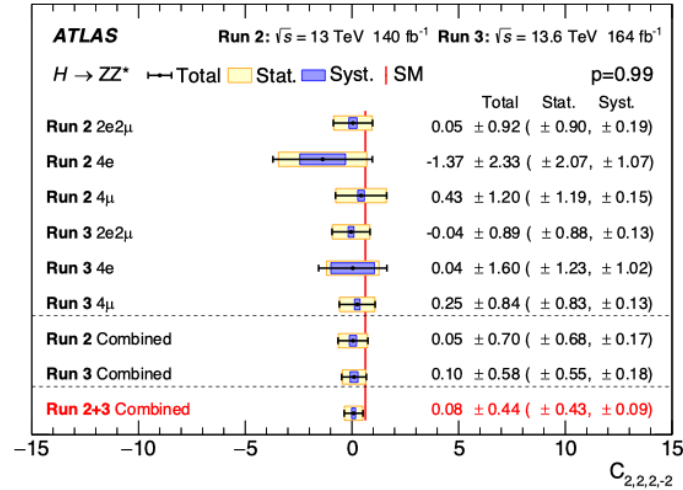
separable non-QE hypothesis $|00\rangle$ (orange dashed line)



Entanglement in $H \rightarrow ZZ \rightarrow 4l$ (Atlas)



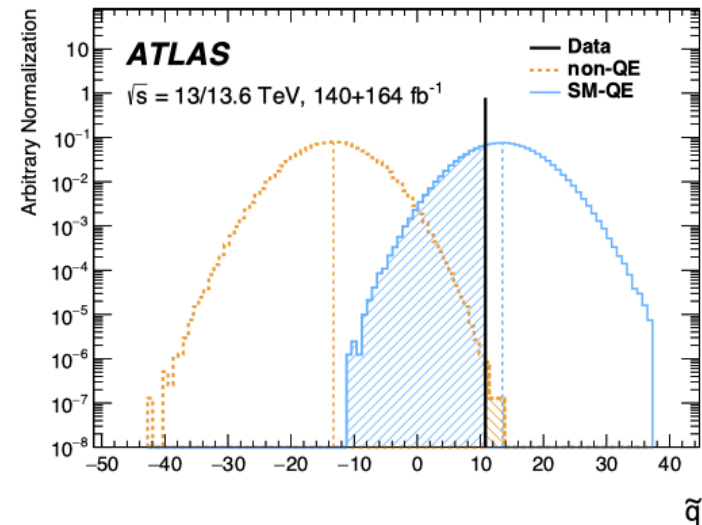
Combined results on C_{212-1} and C_{222-2} are consistent with the SM prediction, but do not exclude separable scenario (both=0)



An alternative approach: Use full angular distributions to construct the test statistic q for the entangled (blue solid line) and non-entangled (orange dashed line) hypotheses.

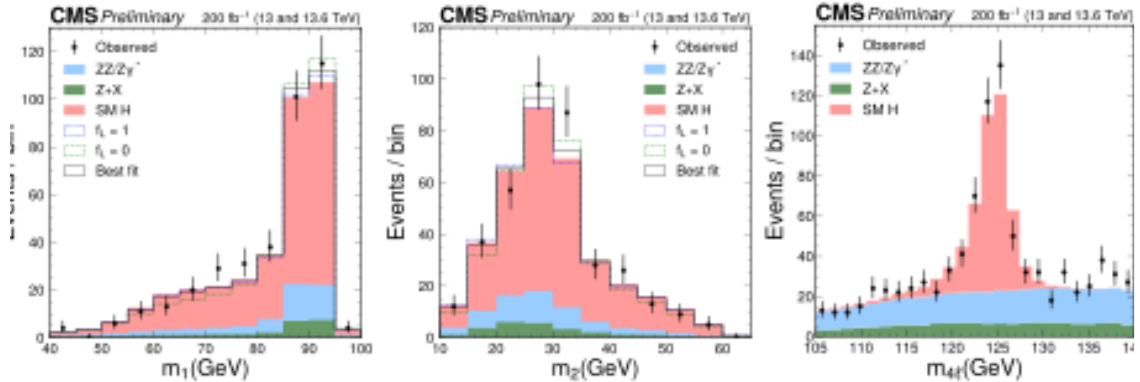
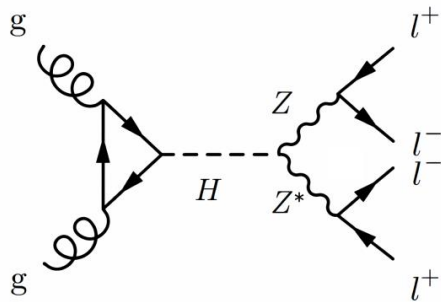
Distributions for 10 millions of pseudo-experiments.

Data (solid black line) disfavor the separable-state hypothesis at a significance of 4.7 (expected 4.9) standard deviations



CP structure of Higgs

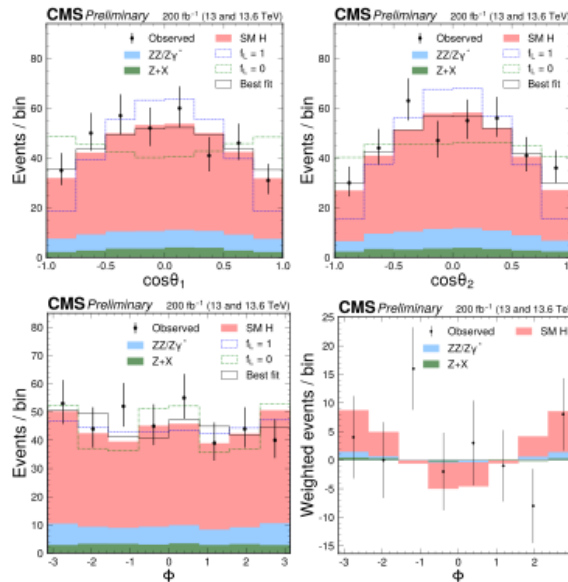
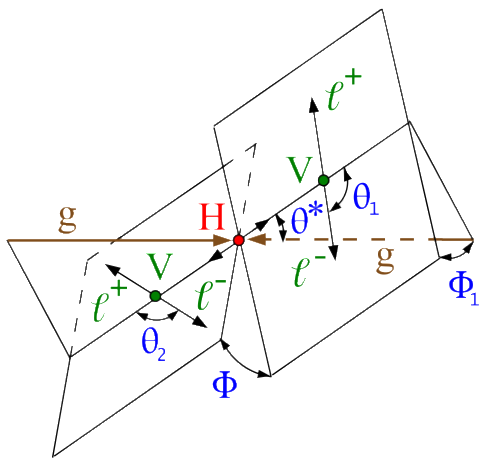
- CMS: $H \rightarrow Z^* Z \rightarrow 4l$



Hypothesis testing:

Purely longitudinal polarization $f_L=1$ (dashed blue)

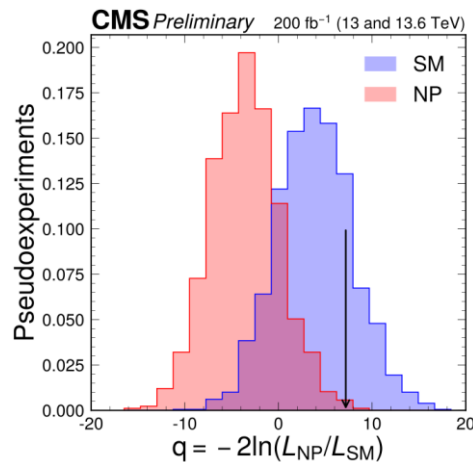
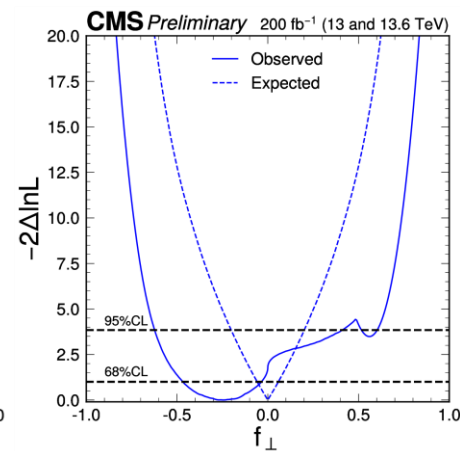
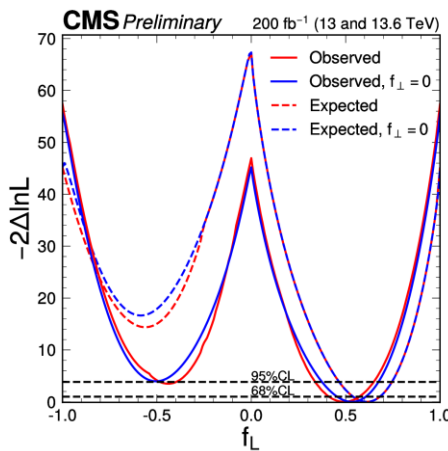
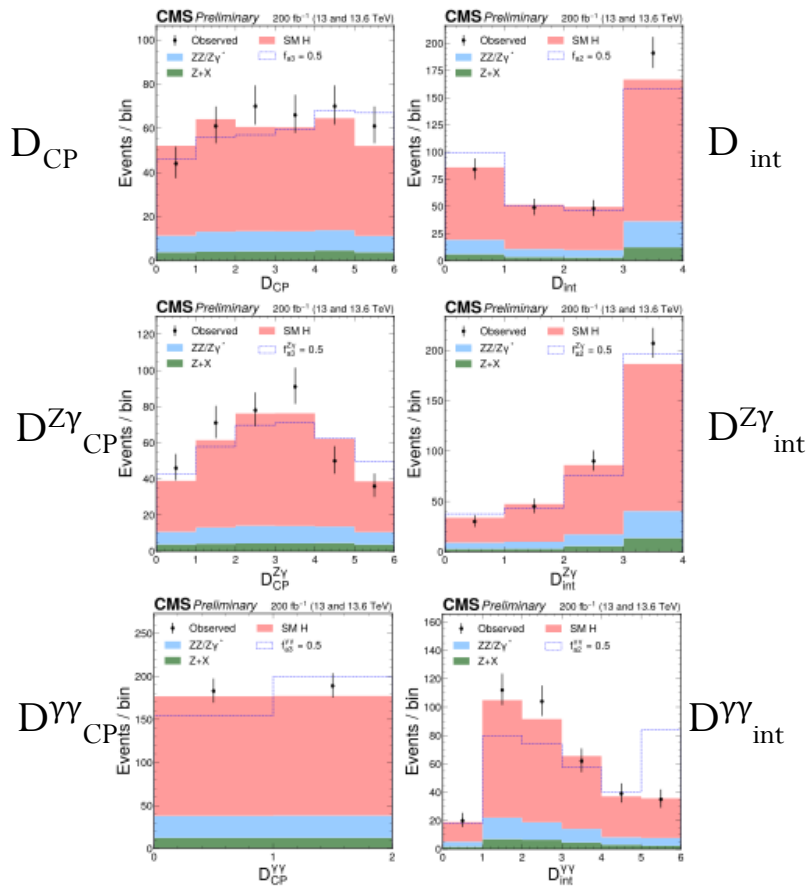
Purely transverse polarization $f_L=0$ (dot-dashed green)



weight = sign of $(\cos\theta_1 \cdot \cos\theta_2)$

CP structure of Higgs and entanglement of Z bosons

Dashed blue line - $f_{\Lambda 1} = 0.5$



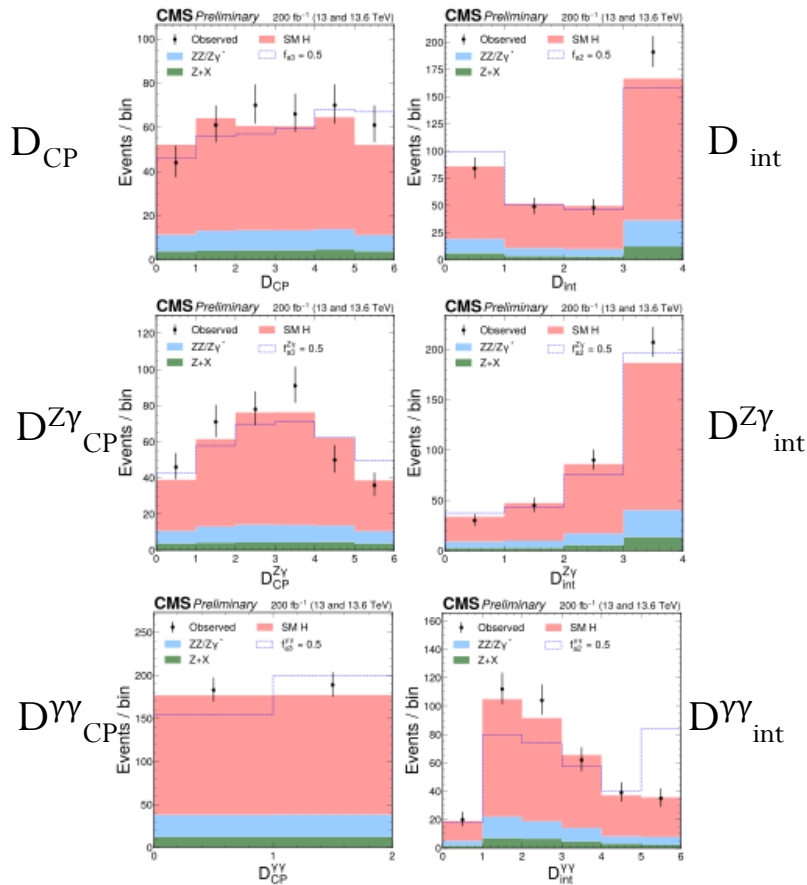
Bonus: The model with no permutation of leptons is excluded at 2.7σ level – muons are identical particles!

The fully longitudinal (f_L) and fully transverse (f_T) Z boson polarizations are excluded at $>6\sigma$.

➔ **entangled state of qutrits** (assuming Quantum Mechanics and CP conservation) conditions exist for measuring violation of the **Bell-type inequality in the $H \rightarrow ZZ$ decays** (assuming large coherence of the transverse and longitudinal amplitudes)

EFT analysis of HVV couplings

Dashed blue line - $f_{\Lambda 1} = 0.5$



\vec{f}	Scenario	Observed		Expected	
		68% CL	95% CL	68% CL	95% CL
f_{a3}	float all	$0.16^{+0.15}_{-0.11}$	[0.01, 0.46]	$0.00^{+0.14}_{-0.15}$	[-0.47, 0.46]
	fix others	$0.18^{+0.16}_{-0.12}$	[0.01, 0.50]	$0.00^{+0.06}_{-0.06}$	[-0.23, 0.22]
$f_{a3}^{Z\gamma}$	float all	$0.00^{+0.08}_{-0.08}$	[-0.25, 0.23]	$0.00^{+0.31}_{-0.30}$	[-0.49, 0.51]
	fix others	$0.00^{+0.06}_{-0.11}$	[-0.27, 0.20]	$0.00^{+0.22}_{-0.22}$	[-0.40, 0.40]
$f_{a3}^{\gamma\gamma}$	float all	$0.03^{+0.08}_{-0.05}$	[-0.11, 0.20]	$0.00^{+0.05}_{-0.05}$	[-0.15, 0.17]
	fix others	$0.01^{+0.07}_{-0.03}$	[-0.09, 0.16]	$0.00^{+0.03}_{-0.03}$	[-0.09, 0.10]
f_{a2}	float all	$0.17^{+0.25}_{-0.15}$	[-0.03, 0.63]	$0.00^{+0.53}_{-0.08}$	[-0.23, 0.83]
	fix others	$0.33^{+0.25}_{-0.24}$	[0.00, 0.77]	$0.00^{+0.14}_{-0.05}$	[-0.15, 0.79]
$f_{a2}^{Z\gamma}$	float all	$0.00^{+0.05}_{-0.06}$	[-0.18, 0.19]	$0.00^{+0.33}_{-0.34}$	[-0.54, 0.57]
	fix others	$0.02^{+0.10}_{-0.03}$	[-0.09, 0.26]	$0.00^{+0.18}_{-0.16}$	[-0.39, 0.41]
$f_{a2}^{\gamma\gamma}$	float all	$0.00^{+0.02}_{-0.07}$	[-0.19, 0.08]	$0.00^{+0.03}_{-0.08}$	[-0.22, 0.11]
	fix others	$-0.01^{+0.01}_{-0.05}$	[-0.13, 0.03]	$0.00^{+0.02}_{-0.02}$	[-0.08, 0.07]
$f_{\Lambda 1}$	float all	$0.06^{+0.19}_{-0.05}$	[-0.13, 0.42]	$0.00^{+0.22}_{-0.34}$	[-0.60, 0.47]
	fix others	$0.09^{+0.13}_{-0.08}$	[-0.04, 0.35]	$0.00^{+0.10}_{-0.11}$	[-0.41, 0.31]

Observed and expected constraints on fractional contribution in the EFT framework. A simultaneous measurement of eight Higgs boson couplings to electroweak vector bosons is carried out within the frameworks of anomalous couplings and effective field theory.

Top quark-antiquark pair at LHC

Spin correlation in top-antitop system

Polarization, P and **spin correlation matrix, C** determines the angular distribution of the decay products in the helicity basis as in [[1212.4888](#)]

$$\frac{d\sigma}{d\Omega d\bar{\Omega}} = \sigma_{norm} (1 + \kappa \vec{P} \cdot \vec{\Omega} + \bar{\kappa} \vec{\bar{P}} \cdot \vec{\bar{\Omega}} - \kappa \bar{\kappa} \vec{\Omega} \cdot \mathbf{C} \cdot \vec{\bar{\Omega}})$$

κ - spin analyzing power of top/antitop decay products – max for charged leptons and d-type quarks (d or s)

$\vec{\Omega}$ – unit vector in the direction of the decay product

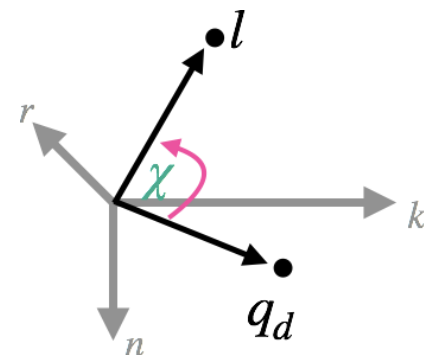
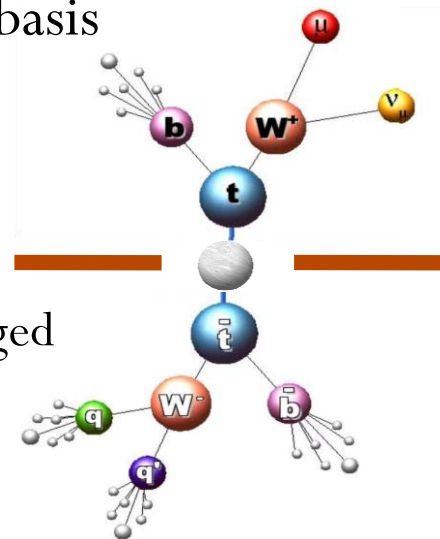
$2 \times 3(\mathbf{P}) + 3 \times 3(\mathbf{C}) = \mathbf{15 coefficients } Q_m$

There is a shortcut: use χ – opening angle between the two decay products in rotated tt frame (a.k.a helicity angle)

$$\frac{dS}{d \cos C} = A(1 + Dk\bar{K} \cos C)$$

and $\tilde{\chi}$, where the sign of n-component in one of the decay products is inverted:

$$\frac{d\sigma}{d \cos \tilde{\chi}} = A(1 + \tilde{D}\kappa\bar{\kappa} \cos \tilde{\chi})$$



Spin correlation and entanglement in $t\bar{t}$ system

Top quark has $s=1/2$, it is a **qubit** \rightarrow Top-antitop quark pair is a two-qubit system

The system is considered **separable** if its density matrix can be factored into individual states

$$r = \hat{a}_n p_n r_n^t r_n^{\bar{t}}$$

Otherwise, it is considered **entangled** \rightarrow **Peres-Horodecki criterion**

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

There are four pure maximally entangled (Bell) states:

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

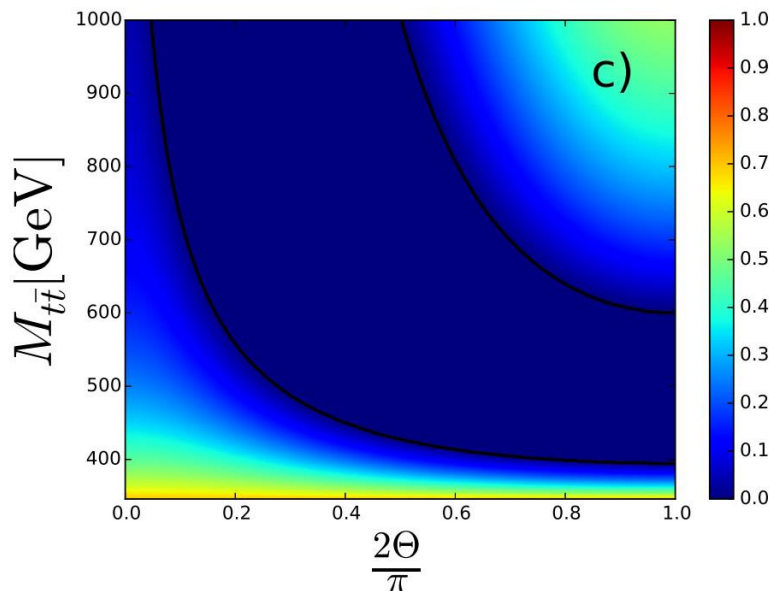
$$|\Psi^\pm\rangle = \frac{1}{\sqrt{2}} (|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle).$$

at low $M_{t\bar{t}}$ singlet
pseudoscalar state Ψ^-
Peres-Horodecki criterion

$$D_E = \text{Tr}(C) = -3D > 1$$

$$D < -\frac{1}{3}$$

A. Peres, Phys. Rev. Lett. 77, 1413 (1996)
P. Horodecki, Physics Letters A 232 (1997)



Top angle with the beam axis

at high $M_{t\bar{t}}$ triplet vector state
($\Phi^+ - \Phi^-$, Ψ^+ , $\Phi^+ + \Phi^-$)
Peres-Horodecki criterion

$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

$$\tilde{D} > \frac{1}{3}$$

Plot from Afik, De Nova
EPJP136(2021)9,907
hep-ph:2003.02280

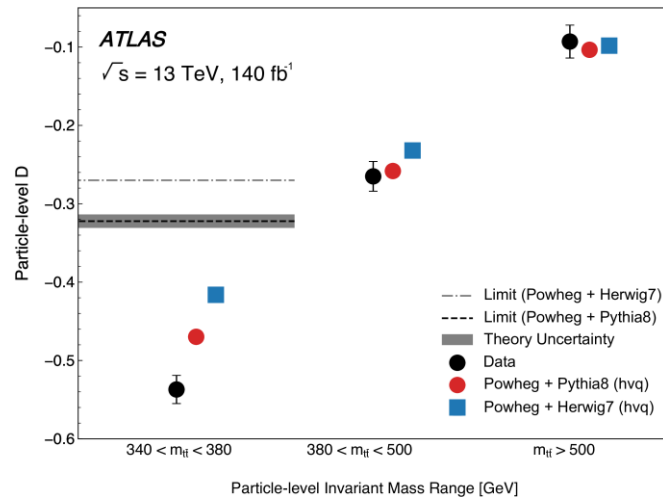


Dilepton channel

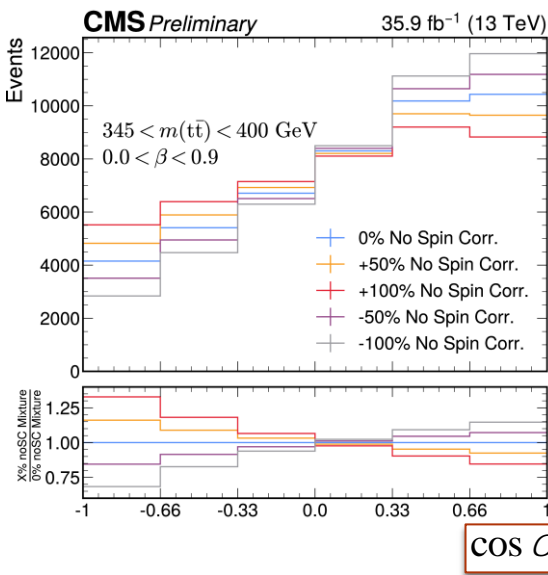
Advantages of dilepton channel: clean, have 2 charged leptons(max spin analyzing power)

To extract D we measure the distribution in the sensitive variable – $\cos \chi$ \square fit for the slope

The $t\bar{t}$ entanglement is observed (expected) at the $5.0(4.7)\sigma$ level for $345 < M_{t\bar{t}} < 400$ GeV, $\beta < 0.9$

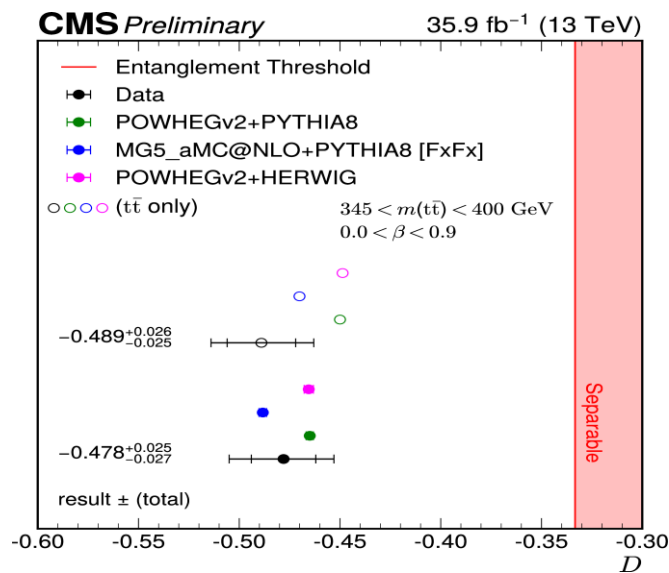


Nature **633**, 542–547 (2024)



$$\frac{dS}{d \cos C} = A(1 + D K \bar{K} \cos C)$$

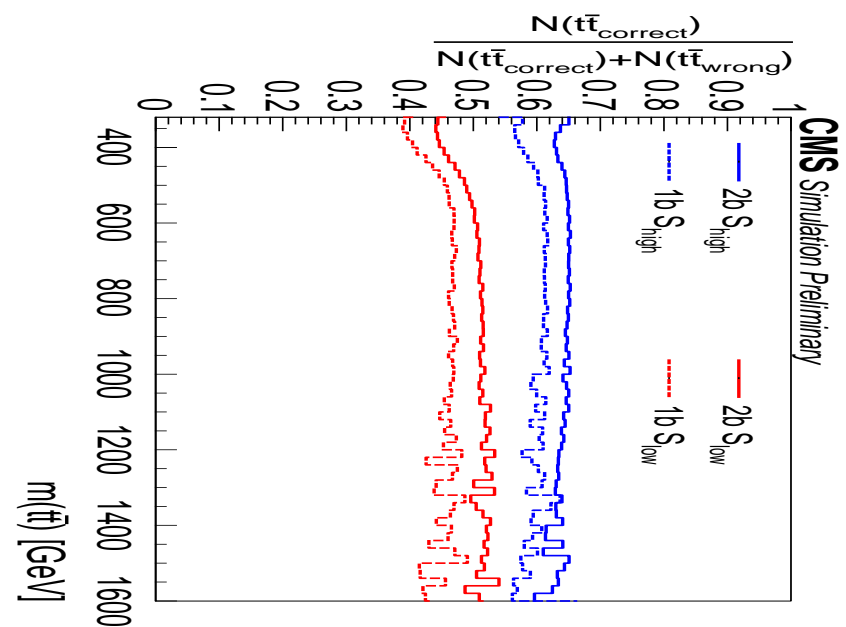
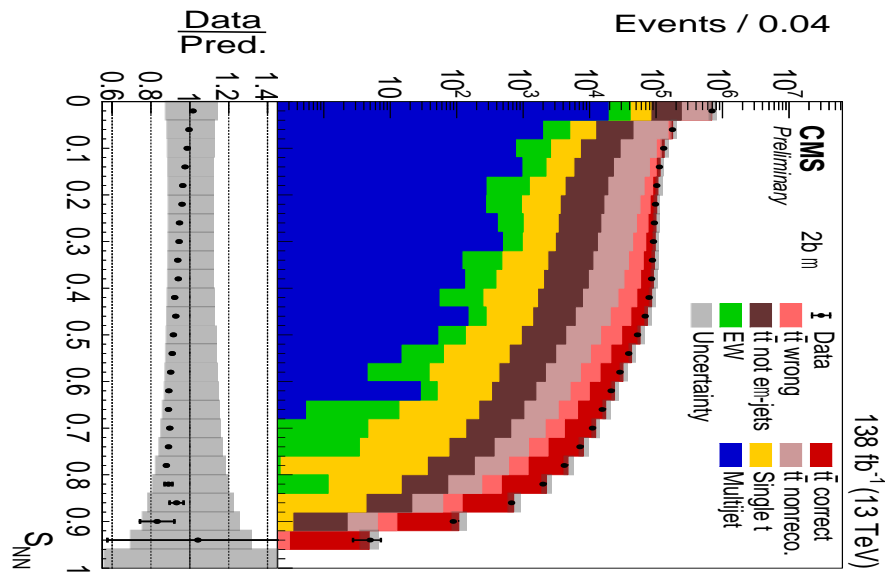
ROPP 87 (2024) 117801



L+jets channel

- We pursue both strategies – evaluation of the full correlation matrix C and polarization vectors P as well as D and $D\sim$ measurements
- The measurements are done inclusively and differentially in bins of $M_{t\bar{t}}$, $\cos\theta$ and top quark p_T
- Event reconstruction (jet-parton assignment) is performed using NN
- Lepton+jets have higher statistics and better $M_{t\bar{t}}$ resolution, but
- **Major challenge – identify d -type jets from W boson decay**
- Divide events into categories based on lepton flavor, number of b-tags, and NN score

Fraction of $t\bar{t}$ events with correctly assigned jets to partons including d -type quark



Extraction of spin correlation

We observe the distribution over top quark decay products:

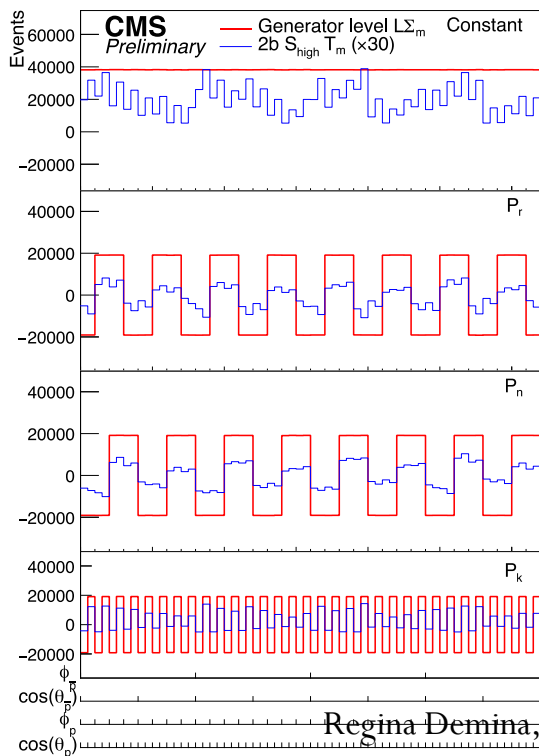
$$\frac{d\sigma}{d\Omega d\bar{\Omega}} = \sigma_{norm} (1 + \kappa \vec{P} \cdot \vec{\Omega} + \bar{\kappa} \vec{P} \cdot \vec{\bar{\Omega}} - \kappa \bar{\kappa} \vec{\Omega} \cdot C \cdot \vec{\bar{\Omega}})$$

Full measurement of the vectors \vec{P} and matrix C is performed using templates defined based on the functions of angles of top and antitop decay products

$$S_m = \left\{ k \sin q_p \cos f_p, \dots - k \bar{k} \cos q_p \cos q_{\bar{p}} \right\}$$

The total cross section is a linear combination of these templates with coefficients Q_m components of \vec{P} and C

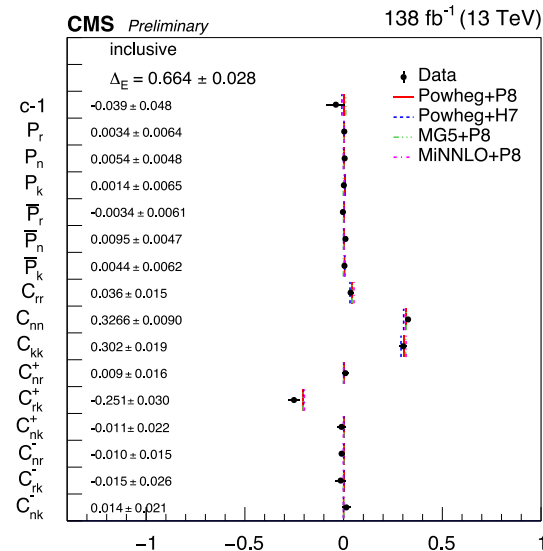
$$S_{tot} = S_0 + \sum_{m=1}^{15} Q_m S_m$$



Σ_m Theoretically predicted distributions in angles of decay products

T_m Reconstruction level distributions, which take into the account selection criteria, efficiency and resolution of the detector.

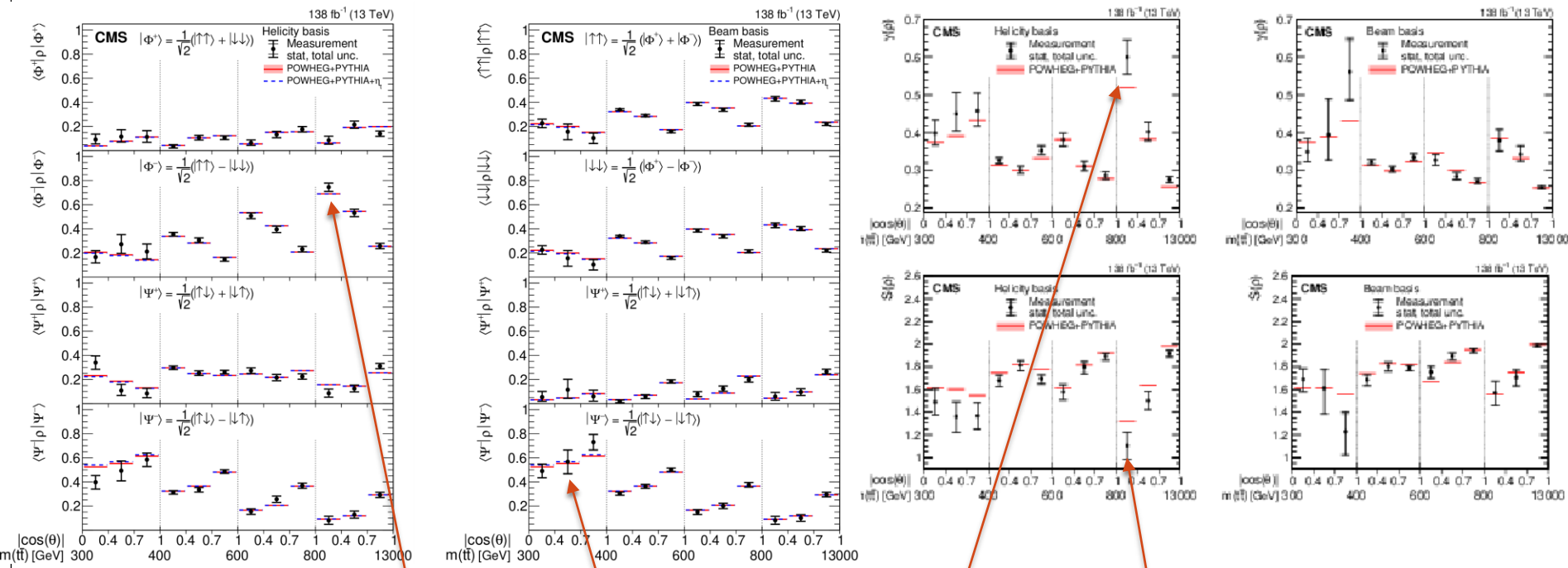
Data distribution is fit the sum of T_m with free coefficients – P_i and C_{ij} \longrightarrow



[PRD 110 \(2024\) 112016](#)

Decomposition into eigenstates

- Based on the measured polarizations and full spin correlation matrix we can construct the probability density matrix and decompose it into its eigenstates, evaluate properties like **purity** and **von Neumann entropy** Phys. Rev. D 113, L051101 – DOI: <https://doi.org/10.1103/hkgw-dztk>



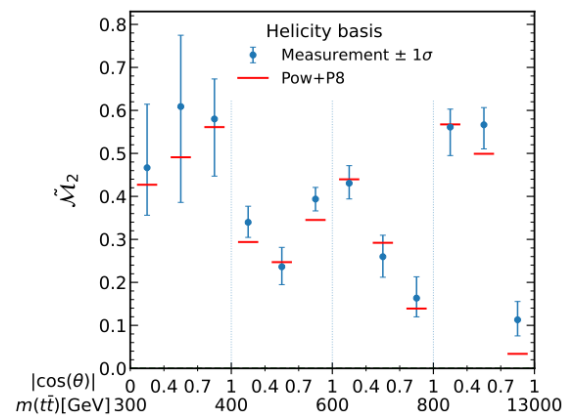
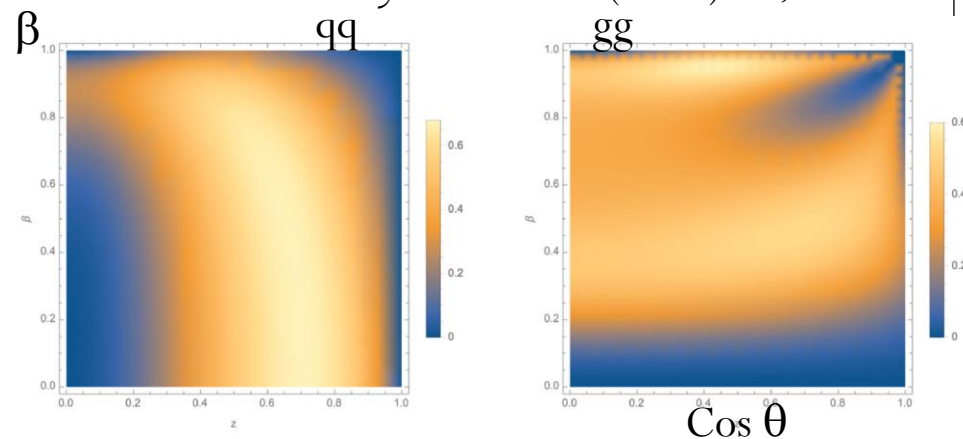
At the threshold – mostly pseudoscalar

At high Mtt – mostly vector, highest purity and lowest entropy

Quantum magic

Phys.Rev.D 110 (2024) 11, 116016

- Knowing the full spin correlation matrix allows to evaluate many quantum information properties of the system
- Quantum computers are expected to vastly outperform classical computers.
- Naïvely, this is due to quantum *superposition* and *entanglement*.
- However, this not quite true.
- To see why, we need the concept of a *stabiliser state*
- *Gottesman-Knill theorem*: For every quantum computer containing stabiliser states only, there is a classical computer that is just as efficient!
- Need **quantum magic** - *Stabilizer Rényi Entropies*



[2602.15115](#)



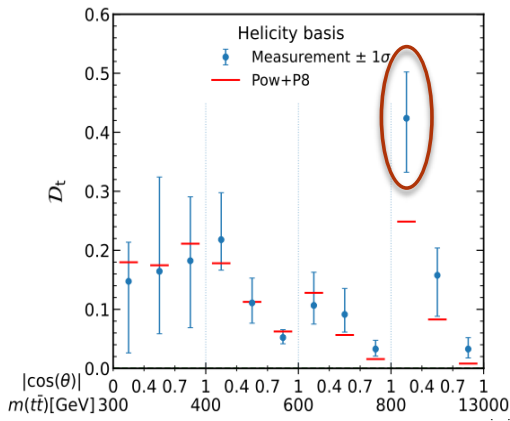
Magic – story got picked up by Quanta Magazine

More QIS from $t\bar{t}$

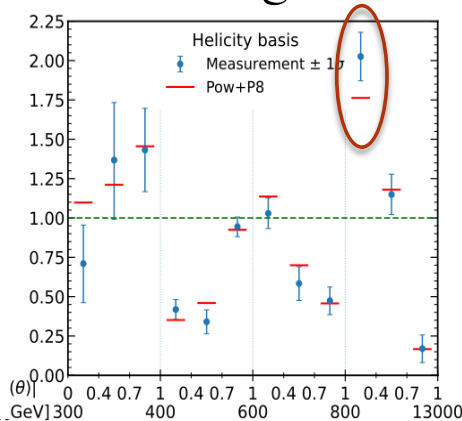
2602.15115

- Discord – a measure of correlation beyond classical mutual information
- Entanglement = non-separability
- Steerability – ability to influence (or steer) the result of the measurement on the “Bob” (top antiquark) part of the system by observing “Alice” (top)
- Bell inequality violation marker – if > 1 BIV can be observed in this region of phase space

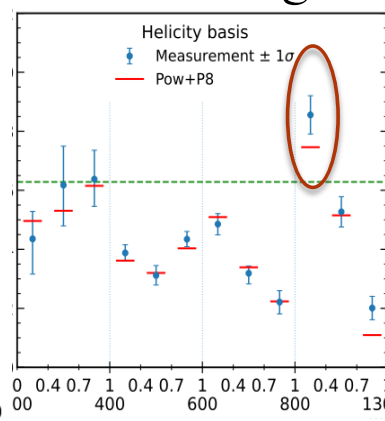
Discord



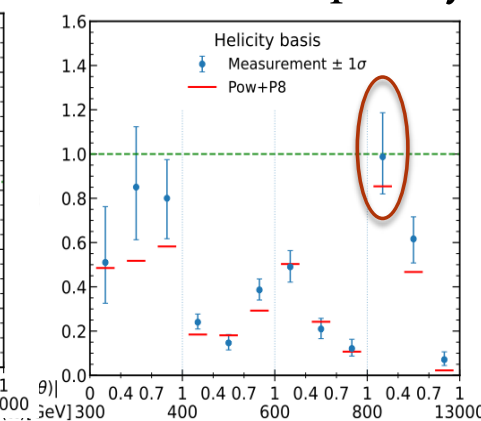
Entanglement



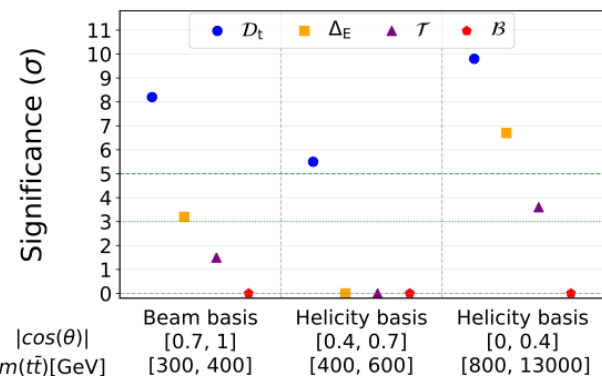
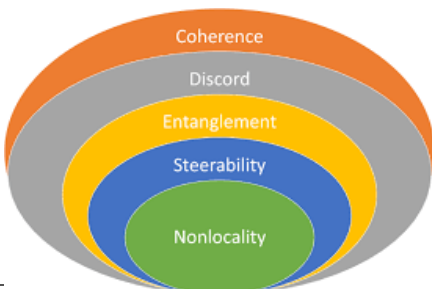
Steering



Bell inequality



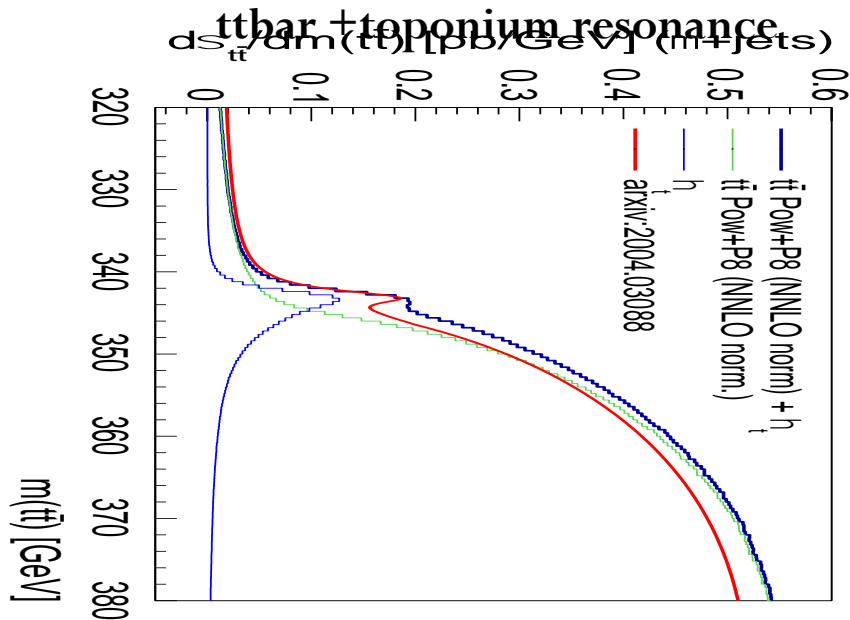
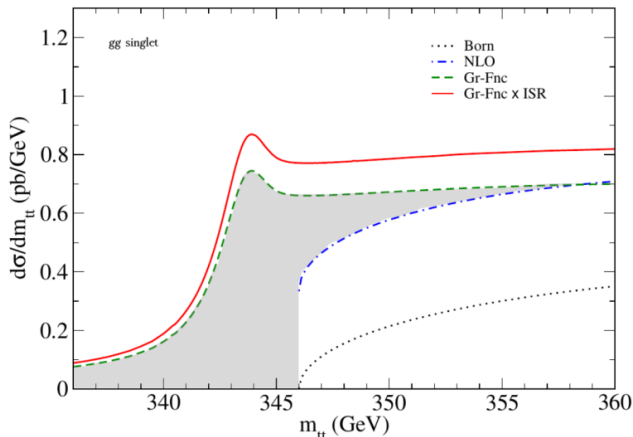
Observed steering with $>3\sigma$ significance



Toponium predictions

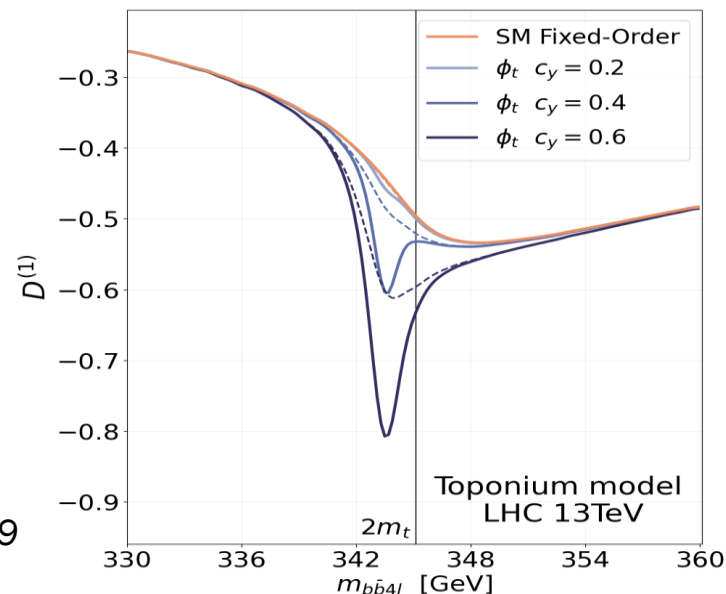
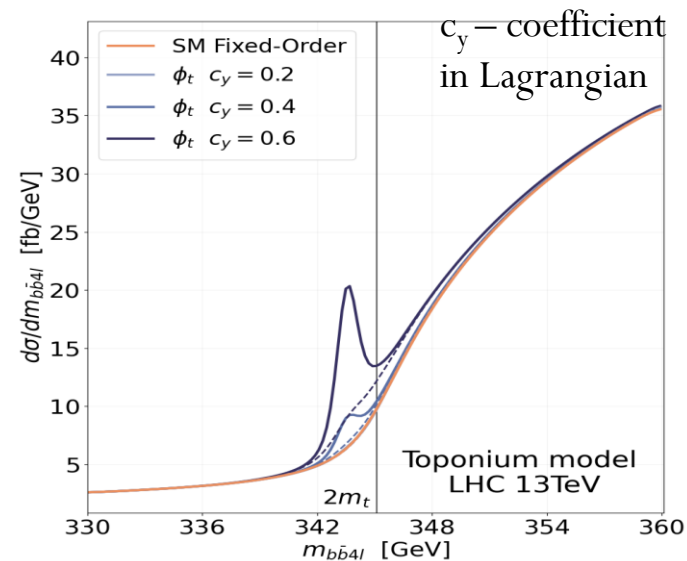
- Top quark is very short-lived $O(10^{-25}s) < \text{hadronization time } O(10^{-24}s)$
- It is not expected to form bound states, but, in quantum mechanics what is not forbidden is allowed
- A small contribution from the $t\bar{t}$ bound state (pseudoscalar color singlet)
- [Z. Phys. C 48 (1990) 613] hypothesized before top quark discovery
- Expected just below the production threshold K. Hagiwara et al. PLB 666 (2008) 71
- More recent works: B. Fuks et al *Phys.Rev.D* 104 (2021) 3, 034023 – Green function reweighting, Wan-Li Ju et al. [2004.03088] use NR-QCD
- Small and narrow color-singlet pseudoscalar resonance with a mass of 343 GeV and a width of $2\Gamma_t$, $\sigma=7$ pb.

For 14 TeV: total effect 336–346 GeV is about 6.5 pb [K. Hagiwara et al. PLB 666 (2008) 71] with gg singlet Green-function about 4.2 pb (grey area)



Toponium and entanglement

- Toponium (pseudo-scalar color singlet predicted by non-relativistic QCD)
 - $M(\text{toponium}) \sim 344 \text{ GeV}$, $\sigma \sim 6.5 \text{ pb}$
 - Sumino, Fujii, Hagiwara, Murayama & Ng (PRD '93)
 - Jezabek, Kuhn & Teubner (Z.Phys.C '92)
 - B. Fuks et al. (PRD 104 (2021) 034023)
 - Toponium affects both the invariant mass distribution and entanglement at the threshold, but
 - **Full spin correlations provide better sensitivity, than one compound property – entanglement**

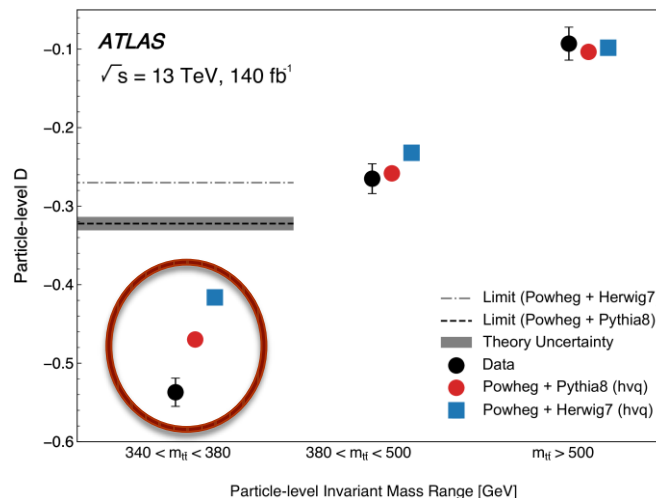
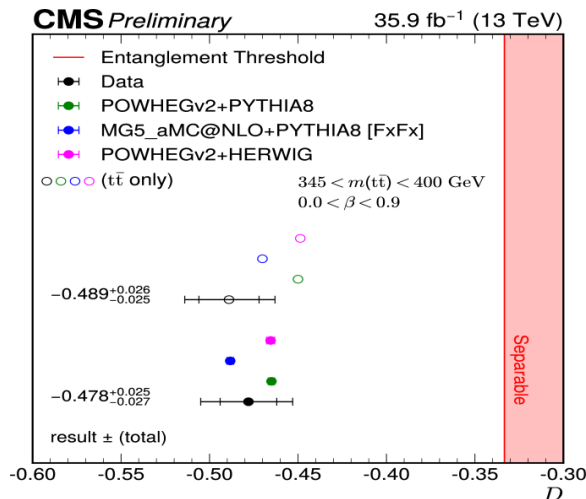


F. Maltoni et al. JHEP03(2024)099

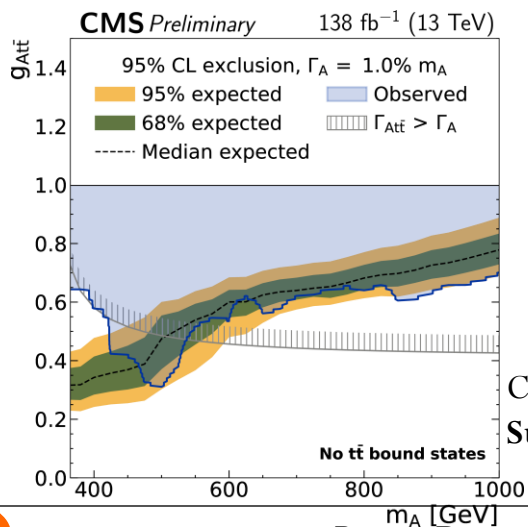
Nature's hints

w/out Toponium

w/ Toponium

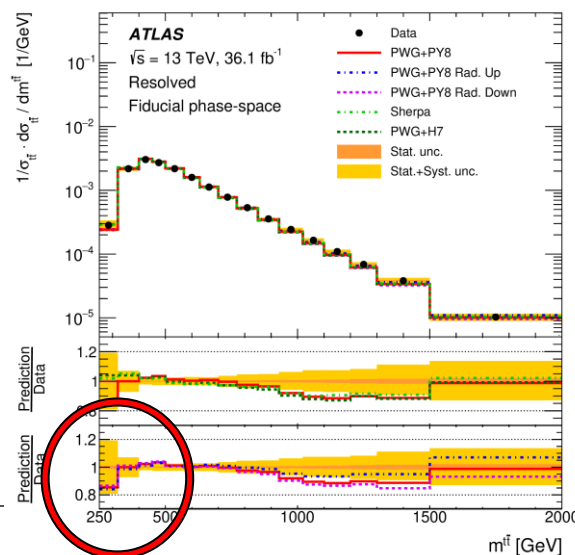


$\sim 1.5\sigma$ tension with the expectation if toponium is not included – one of many hints (differential cross section, weakened limits in $A/H \rightarrow t\bar{t}$)



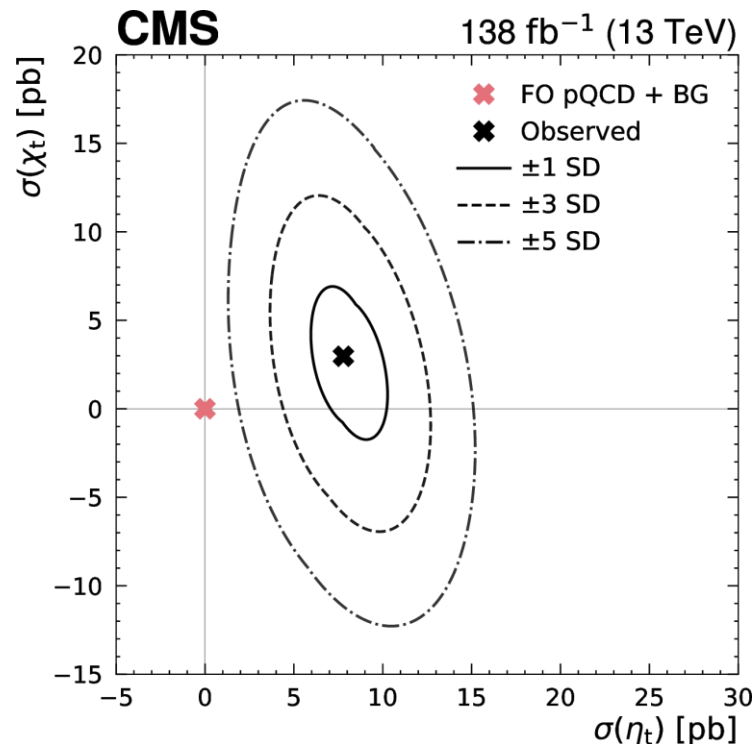
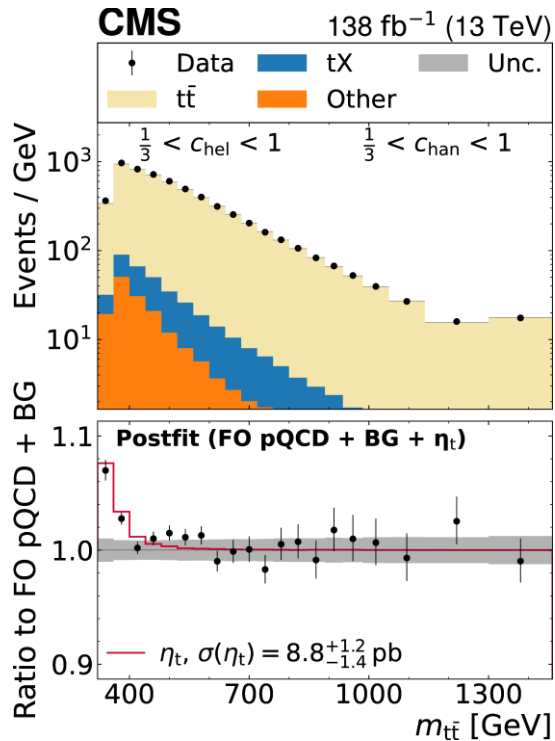
CMS-PAS-HIG-22-013
Submitted to ROPP

Eur. Phys. J. C 79 (2019) 1028



Dilepton channel - CMS

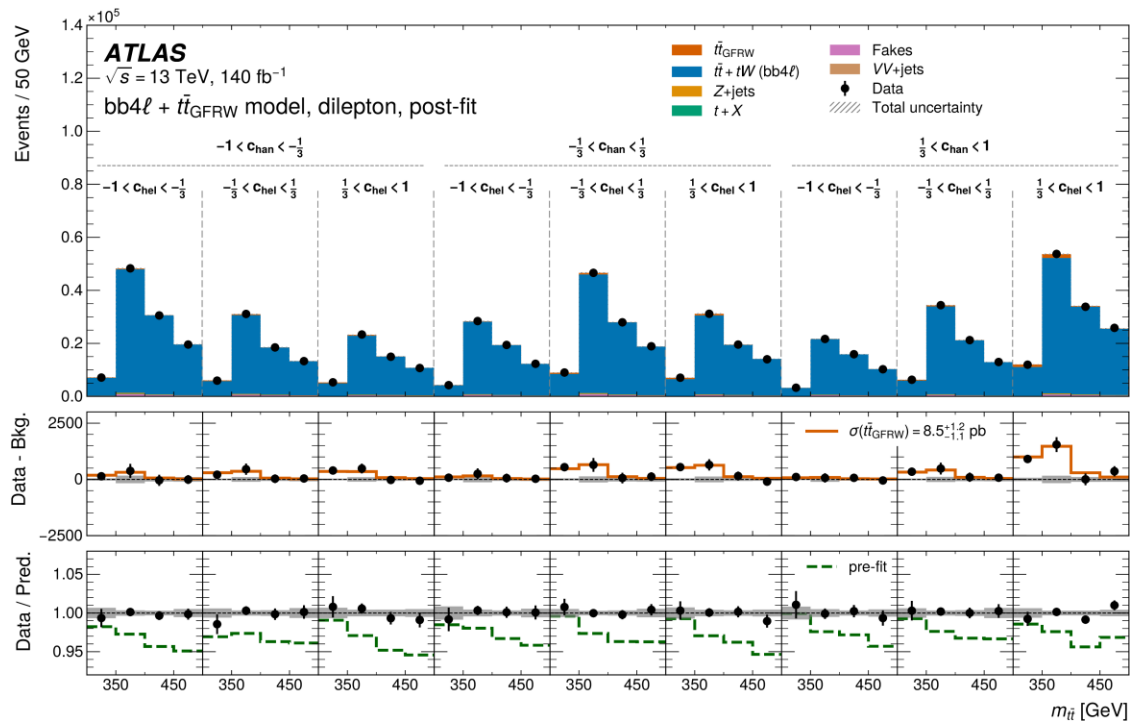
- Dilepton channel: [*Rep. Prog. Phys.*, 88 \(2025\) 087801](#) A significant excess is observed near the $t\bar{t}$ threshold compared to the non-resonant production (pQCD), consistent with the production of a **color-singlet pseudoscalar quasi-bound toponium state**, predicted by NRQCD.
- $\sigma = 8.8 +1.2 -1.4$ pb.



Dilepton channel – Atlas

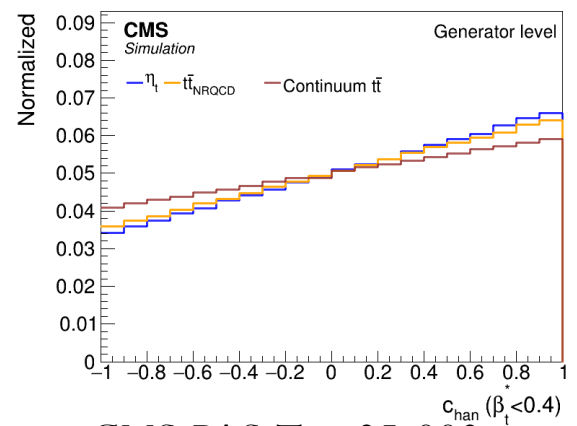
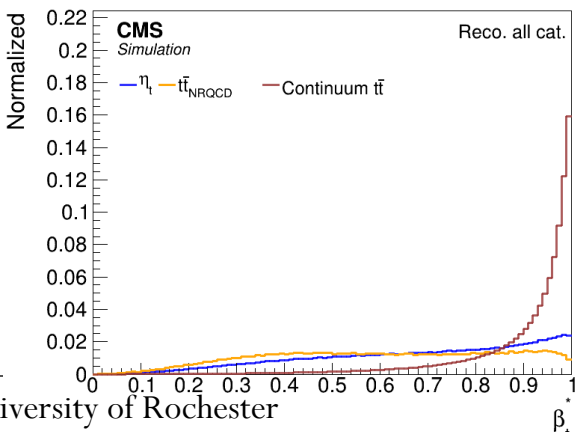
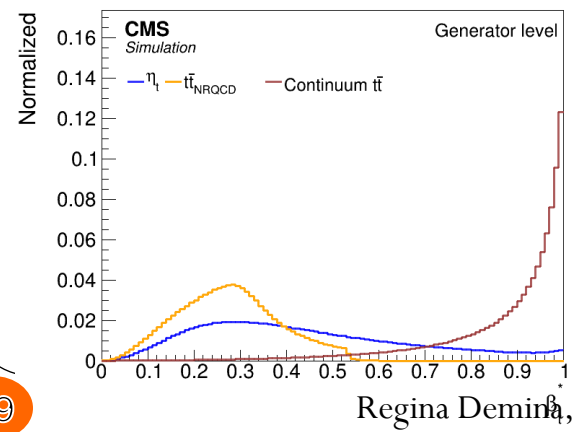
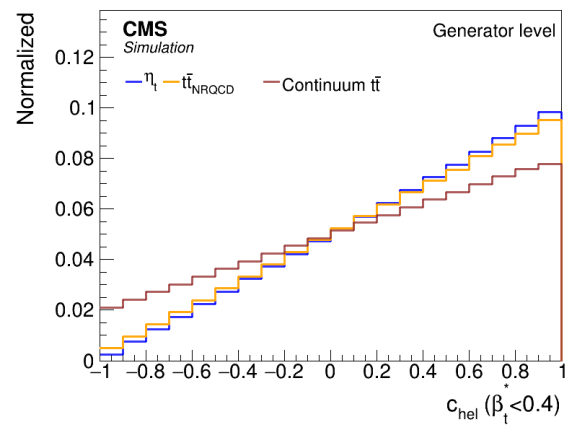
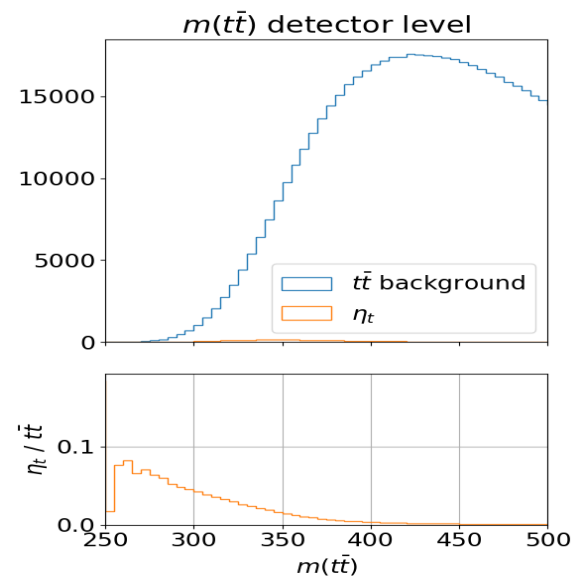
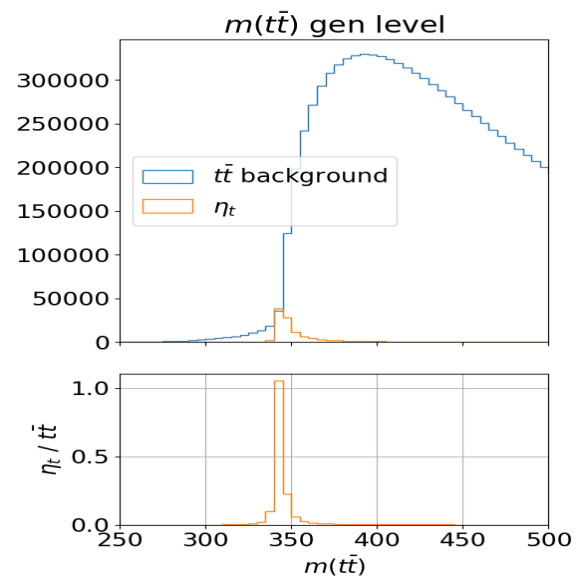
This excess is consistent with the formation of colour-singlet and spin-singlet quasi-bound states, as predicted by non-relativistic QCD, and corresponds to an observed cross-section of $9.3^{+1.4}_{-1.3}$ pb.

[arXiv:2601.11780](https://arxiv.org/abs/2601.11780)



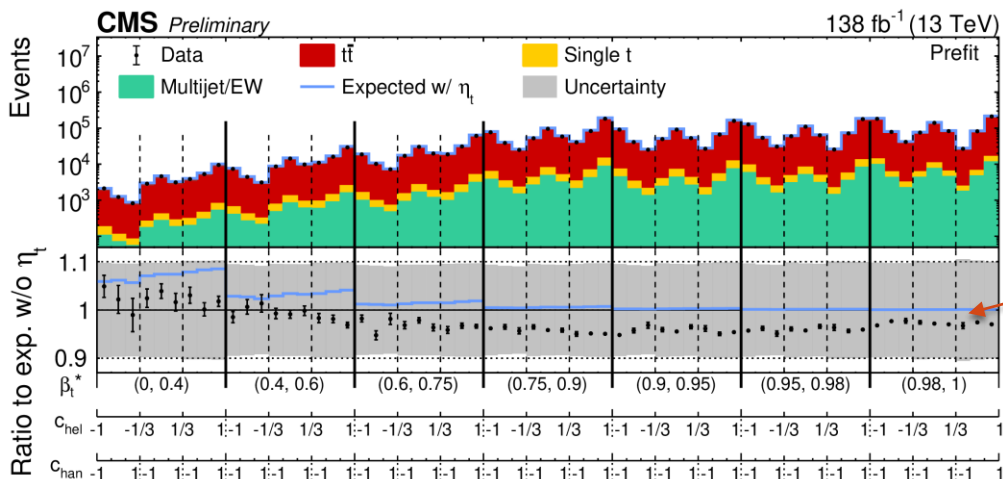
CMS: lepton+jets channel

- $M_{t\bar{t}}$, the $t\bar{t}$ invariant mass $\rightarrow \beta^*$, the velocity of the top relative to antitop
- Several systematic uncertainties (m_t , JES, JER) are minimized, if not cancelled

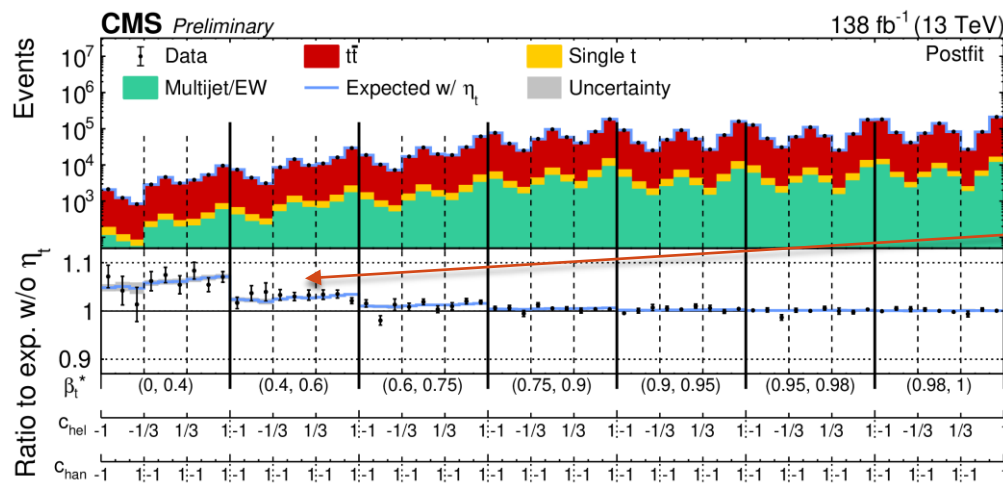


Pseudo scalar excess in lepton+jets

- Pre and post-fit “rolled out” distributions in β^* , c_{hel} , c_{han}



For the baseline use theoretical top pair production $\sigma_{NNLO} = 832^{+40}_{-46}$ pb
 Measured in l+jets $\sigma_{CMS} = 791^{+-25}$ pb



Excess of events over the continuum tt production is observed with low β^* (~ 2 first large bins)

$$\sigma_{obs}(\eta_t) = 5.14^{+0.85}_{-0.87} \text{ pb}$$

Consistent with predicted

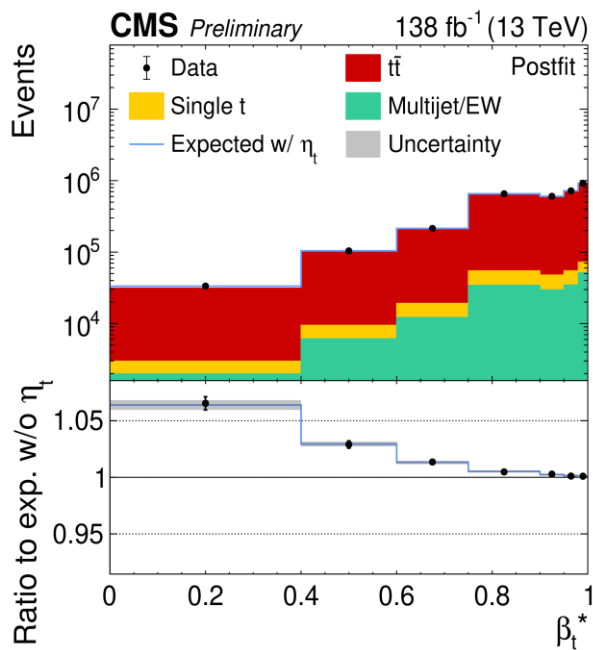
$$\sigma_{exp}(\eta_t) = 6.43 \text{ pb}$$

[2102.11281, 2401.08751]

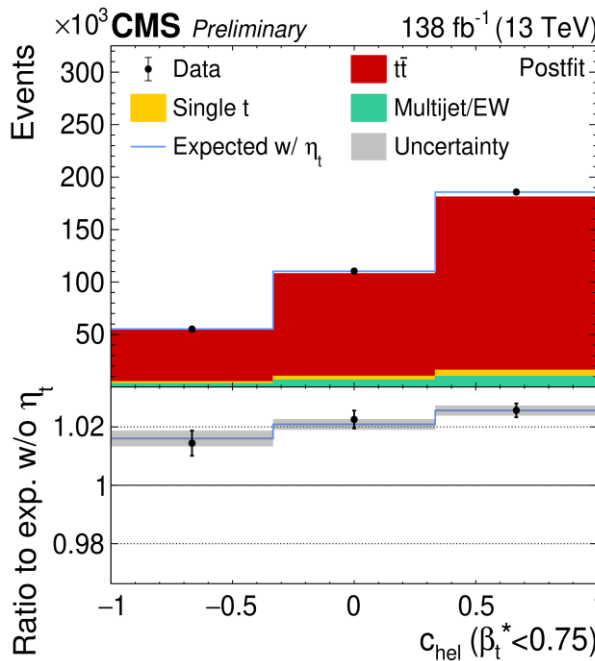
Significance 6.07

Pseudoscalar excess in lepton+jets

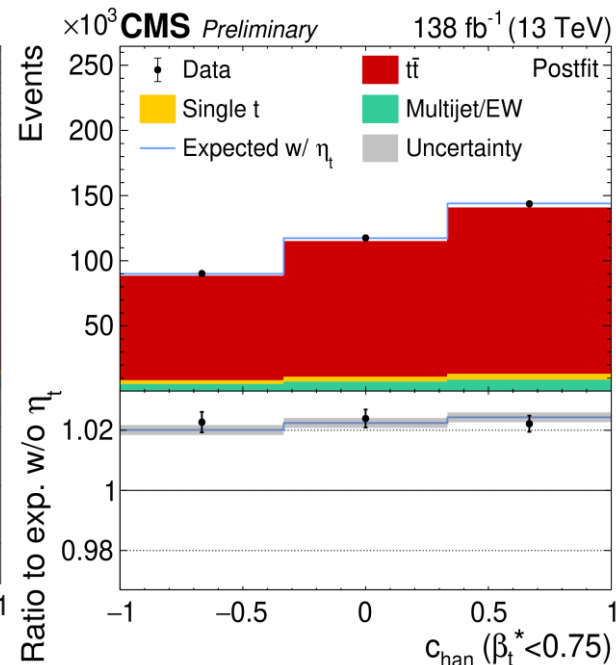
- Distributions in β^* , c_{hel} , c_{chan}
 - integrated over other variables
 - Not used to the fit, just an illustration
- Agreement with the pseudoscalar nature of excess



Excess of events at low β^*



Angular distributions consistent with pseudoscalar



Have we discovered toponium?

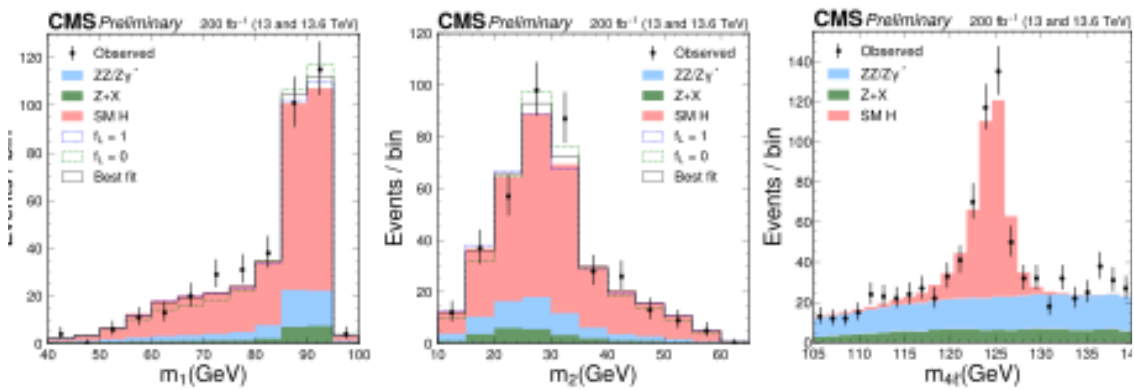
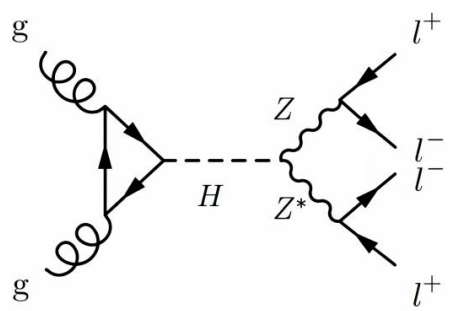
- Toponium – a pseudoscalar $t\bar{t}$ bound state, a.k.a η_t is predicted by non-relativistic QCD with a mass of **343 GeV** – It would be nice to discover η_t
- In 2002, a team of Russian and American scientists created the first ever atom of oganesson (Og), which is the heaviest chemical element ever recorded to date. This nucleus, which consists of 118 protons and 161 neutrons, has a mass number of **279**
- If confirmed toponium would be the heaviest particle ever observed
- The existing evidence is tantalizing
- Entanglement and spin correlations played an important role in this observation
- More studies are needed to confirm the nature of the excess

Conclusion

- Excellent performance of LHC accelerator complex and Atlas and CMS detectors produced high quality, high statistics data, and enabled exploration of subtle new signatures and phenomena
- Probe CP structure of Higgs boson
- Establish quantum entanglement in the system of Z bosons and top-antitop quark pairs
- Quantum tomography opens new possibilities to study new effects (e.g. toponium) and explore the foundations of quantum mechanics in systems of unstable relativistic particles

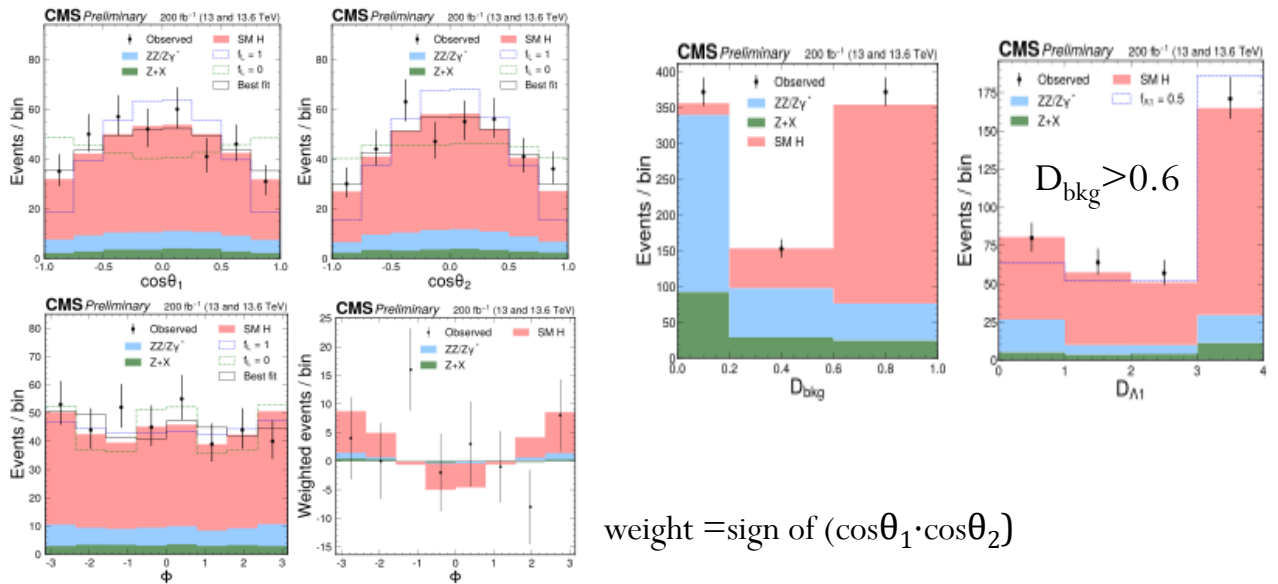
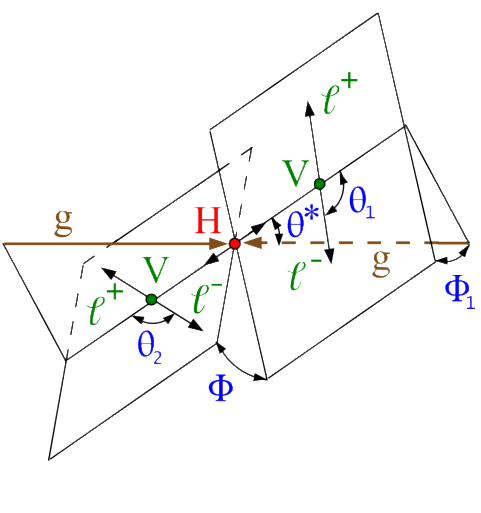
CP structure of Higgs

• CMS: $H \rightarrow Z^* Z \rightarrow 4l$



Purely longitudinal polarization $f_L=1$ (dashed blue)

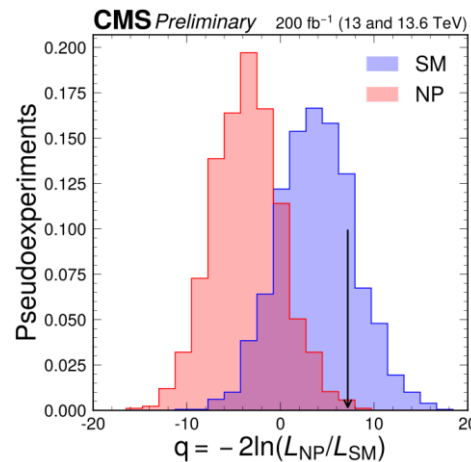
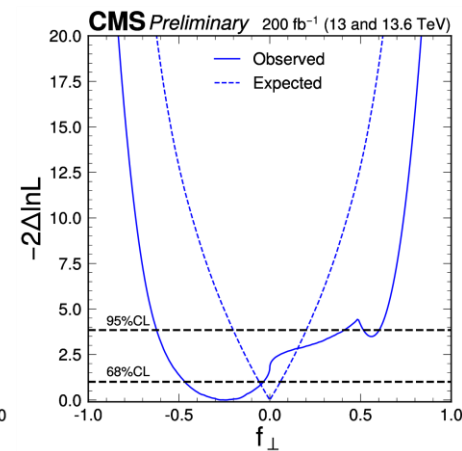
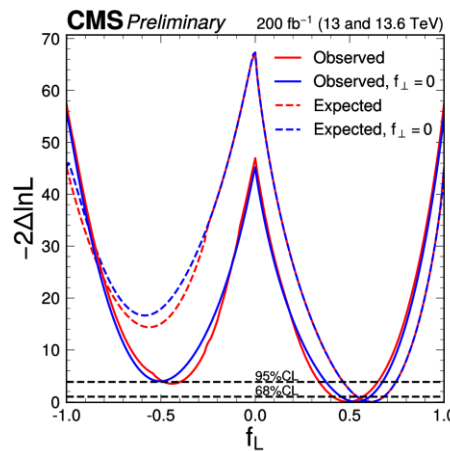
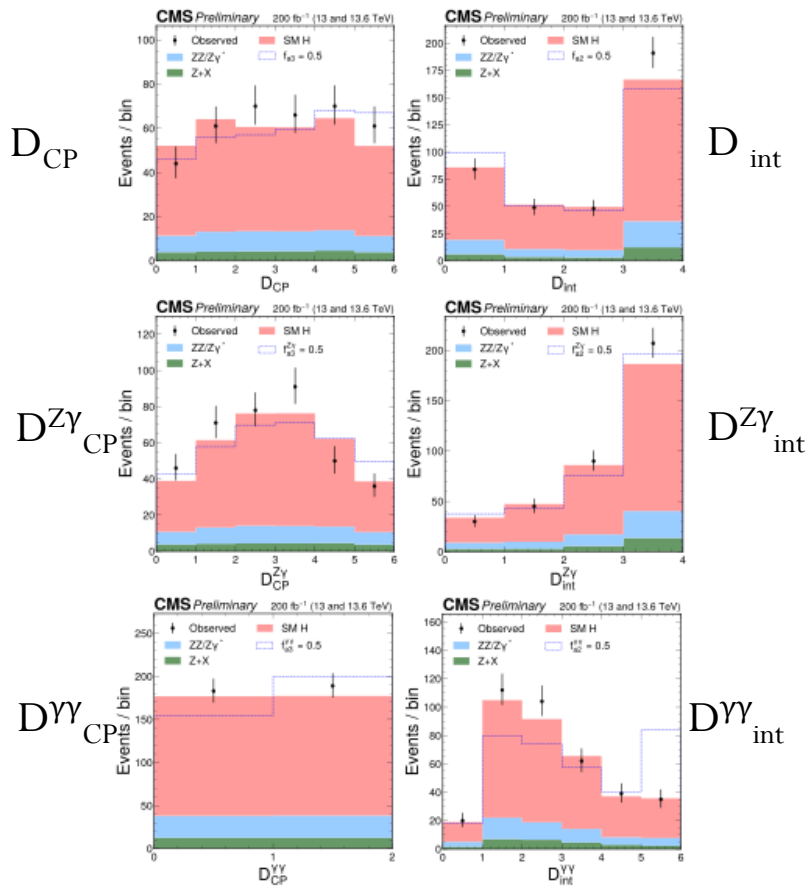
Purely transverse polarization $f_L=0$ (dot-dashed green)



weight = sign of $(\cos\theta_1 \cdot \cos\theta_2)$

CP structure of Higgs and entanglement of Z bosons

Dashed blue line - $f_{\Lambda 1} = 0.5$



Bonus: The model with no permutation of leptons is excluded – muons are identical particles!

The fully longitudinal (f_L) and fully transverse (f_T) Z boson polarizations are excluded at $>6\sigma$.

➔ **entangled state of qutrits** (assuming Quantum Mechanics and CP conservation)
 conditions exist for measuring violation of the **Bell-type inequality in the $H \rightarrow ZZ$ decays**
 (assuming large coherence of the transverse and longitudinal amplitudes)