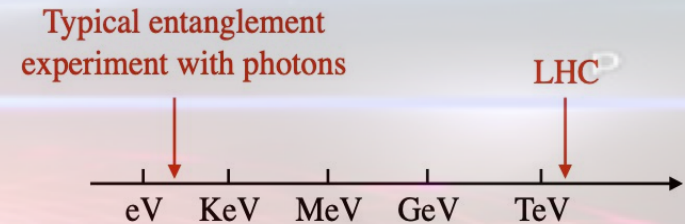


QIS Frontiers: Entangled Top Quarks to Quantum Computing

A brief introduction to the Quantum Life of the Top Quark: Spin, Entanglement, and quasi-bound states

Today's menu:

- The basics: Particle Physics
- Entanglement: a “new” probe to top quark physics
- Quantum Probes & ML/AI tools for HEP
- Quantum Computing + bonus: PQSEI
- Outlook & Conclusions



[APS TV: From Detectors to Quantum Algorithms](#)

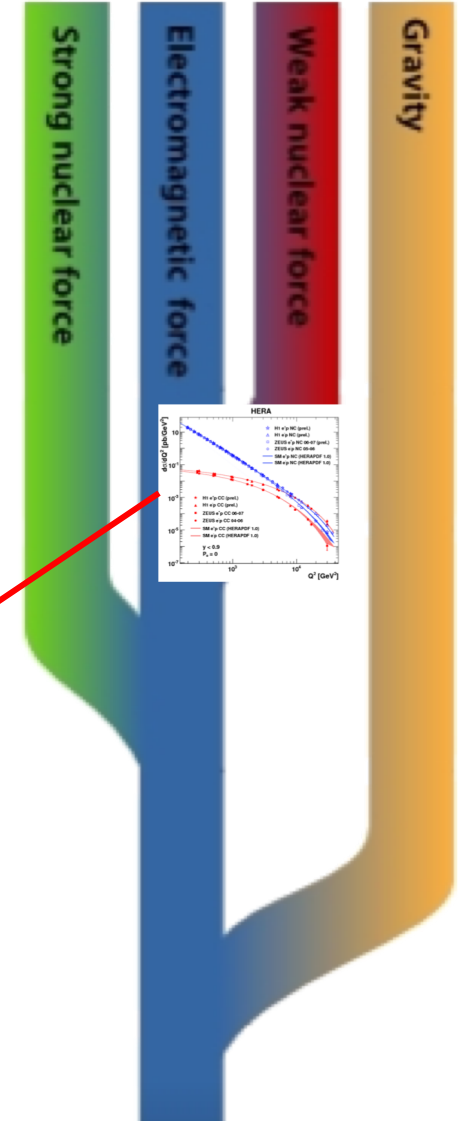
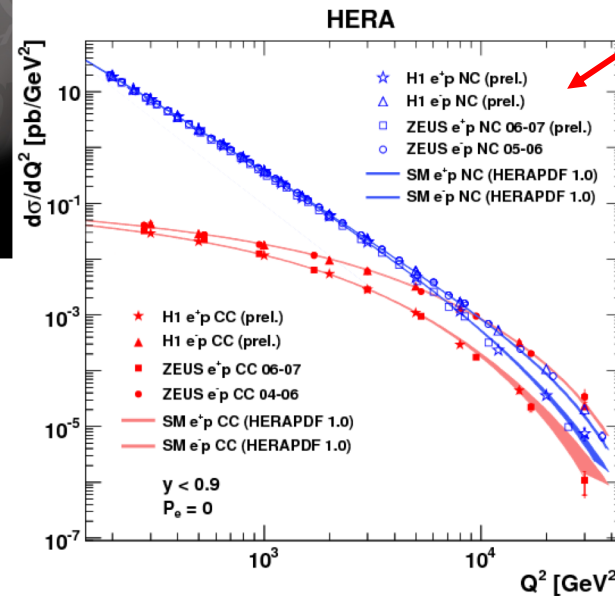
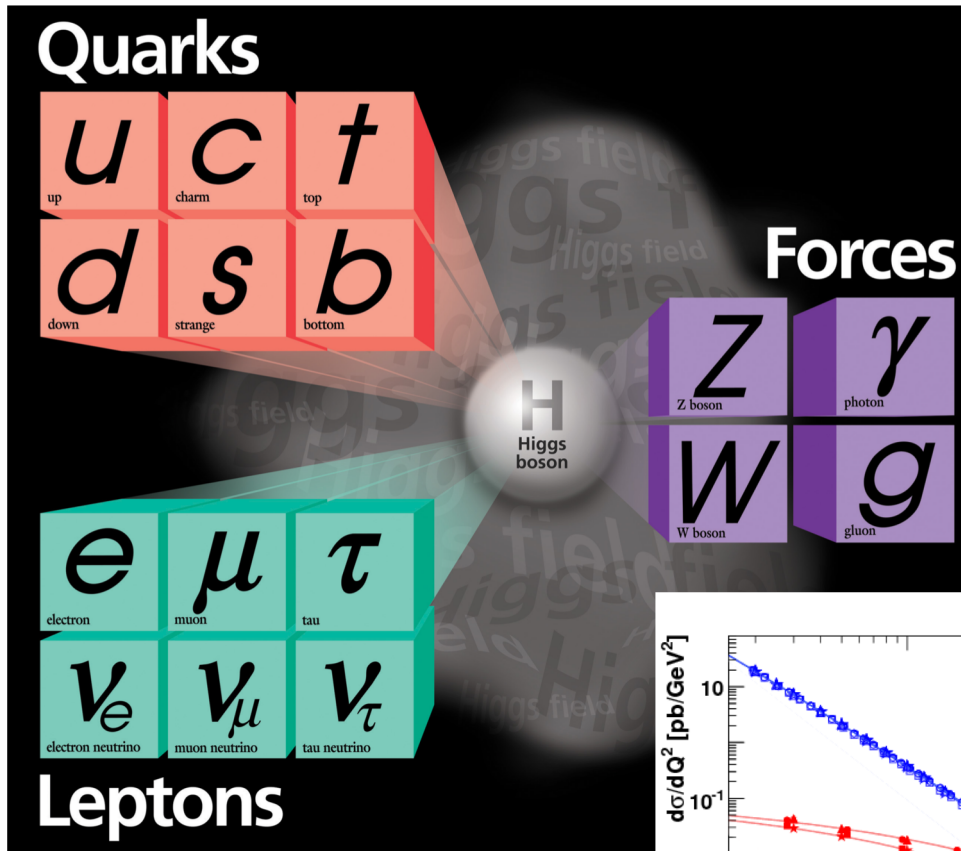
APS TV 2026:
“From
Detectors to
Quantum
Algorithms”



Andy Jung

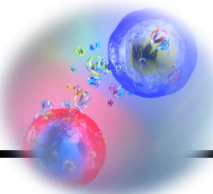
54th SLAC Summer Institute
Quantum Probes for a Quantum Universe

Standard Model – Particle Physics

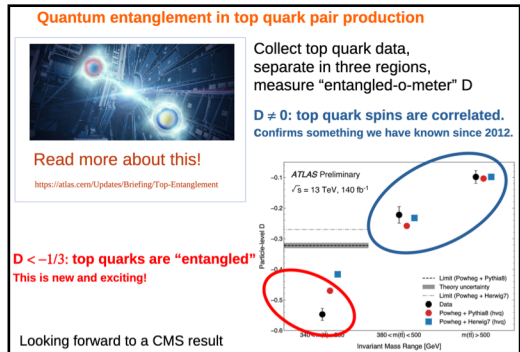




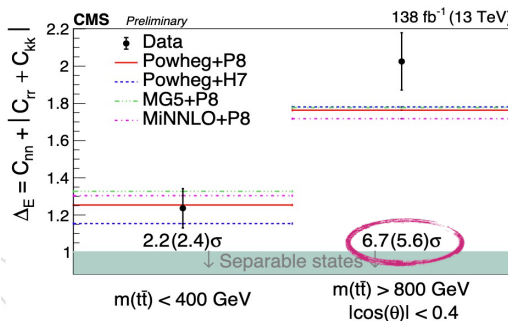
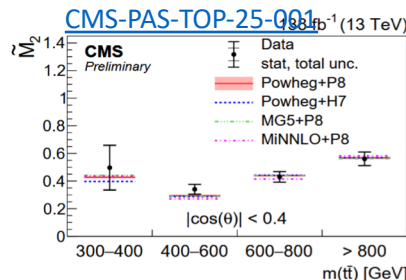
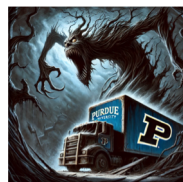
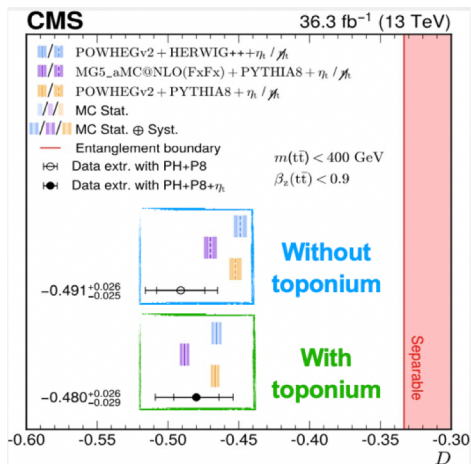
Exciting times...



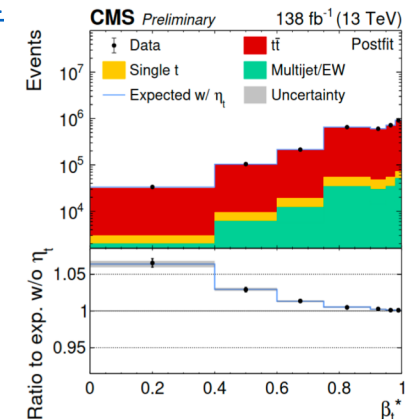
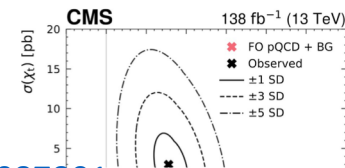
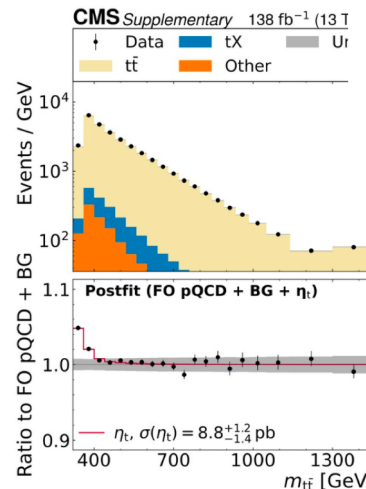
[Nature 633, 542–547 \(2024\)](#)



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

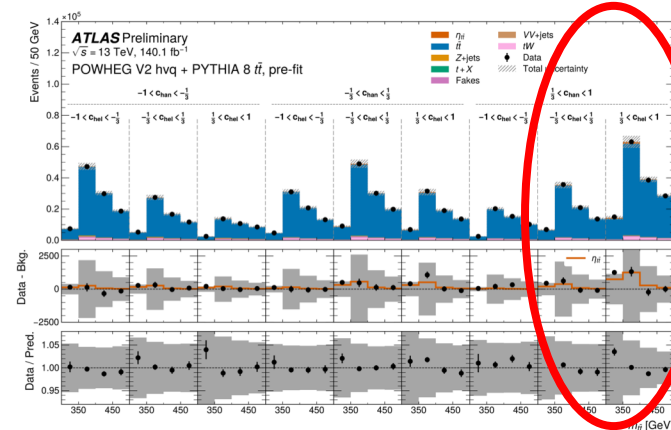


[Rep. Prog. Phys. 88 \(2025\) 087801](#)



$$\sigma(\eta_t) = 5.1 \pm 0.9 \text{ pb } (> 6 \text{ SD})$$

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

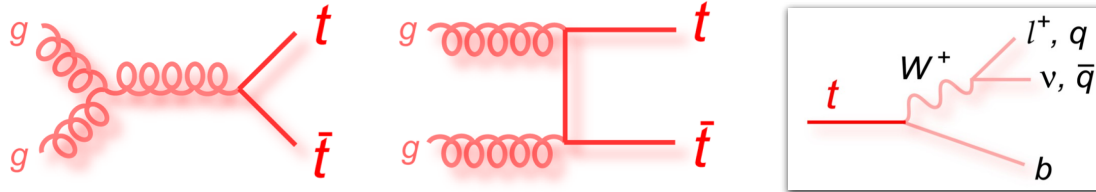


- Updates / News on Theory prediction
 - Systematic uncertainties ?
 - Need complete picture at LHC
- stay tuned

Standard Model – Top Quark Physics



- Production of top quarks is dominated by QCD, decay is electroweak



- Top quark is the heaviest fundamental particle discovered so far [\[arxiv:1403.4427\]](https://arxiv.org/abs/1403.4427)

$$\rightarrow m_t = 173.34 \pm 0.76 \text{ GeV}$$

- Unique quark, not stable:

Caution!

$$\underbrace{\frac{1}{m_t}}_{\text{production } 10^{-27} \text{ s}} < \underbrace{\frac{1}{\Gamma_t}}_{\text{lifetime } 10^{-25} \text{ s}} < \underbrace{\frac{1}{\Lambda_{\text{QCD}}}}_{\text{hadronization } 10^{-24} \text{ s}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\text{spin-flip } 10^{-21} \text{ s}}$$

→ **Observe bare quark properties**

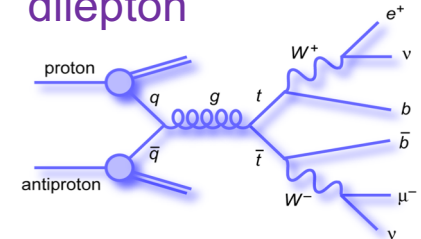
→ **Spin information preserved**

- Large Yukawa coupling to Higgs boson
→ $\lambda_t \sim 1$ **only m_t is a “natural mass”**
- Special role in EW symmetry breaking ?

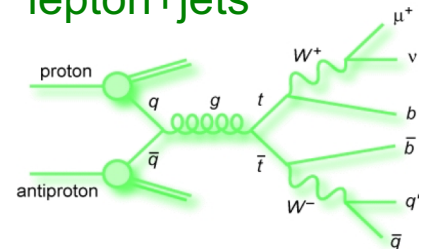
BR, bg increase



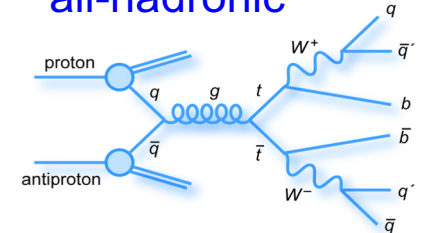
dilepton



lepton+jets



all-hadronic



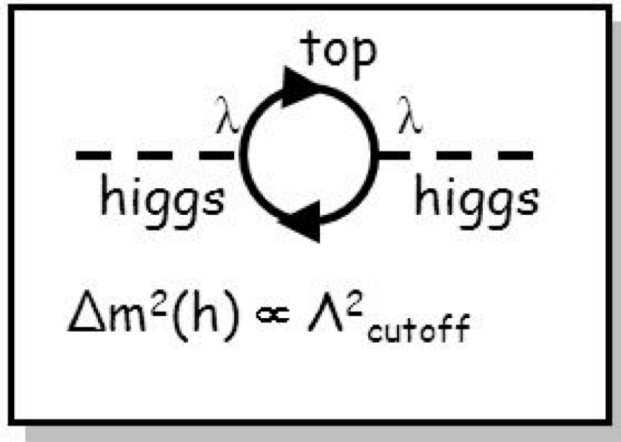
→ **unique experimental signature**

Top quark – Higgs boson interaction



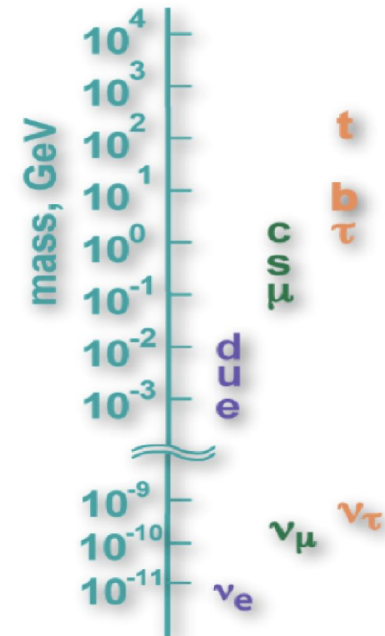
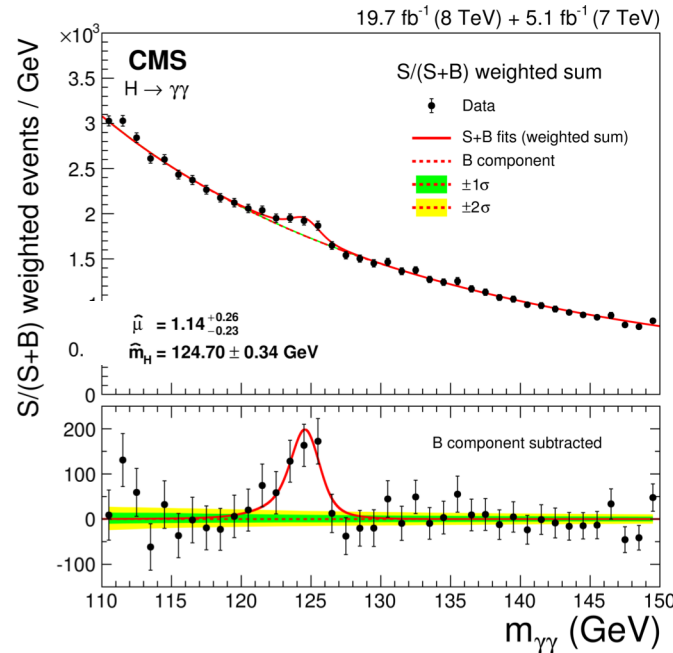
If we could calculate the Higgs mass:

→ Large corrections to the Higgs mass from top quark “loops”



Loops are dominated by top quarks

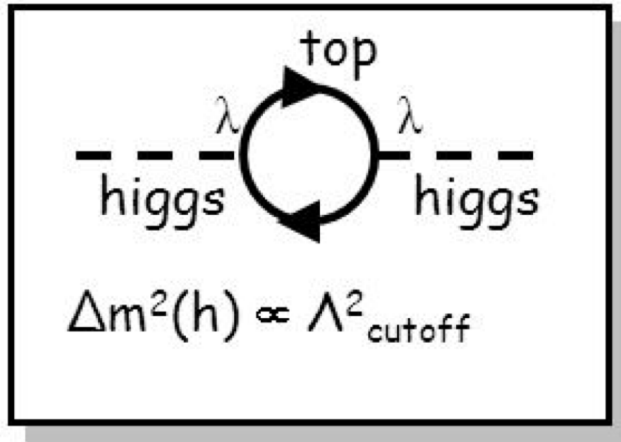
Natural Higgs mass close to
Planck scale of 10^{19} GeV



Top quark – Higgs boson interaction



→ Large corrections to the Higgs mass from top quark “loops”



Loops are dominated by top quarks

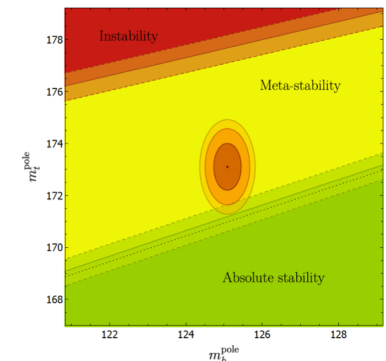
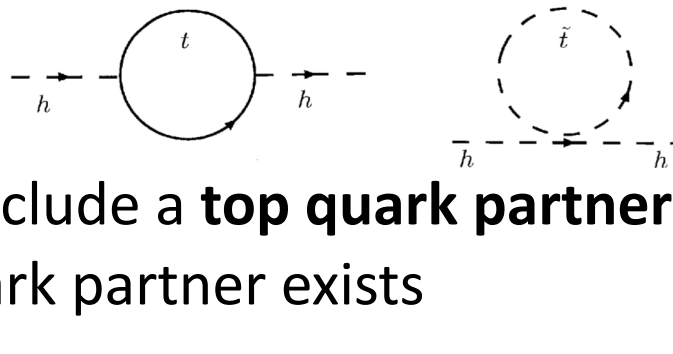
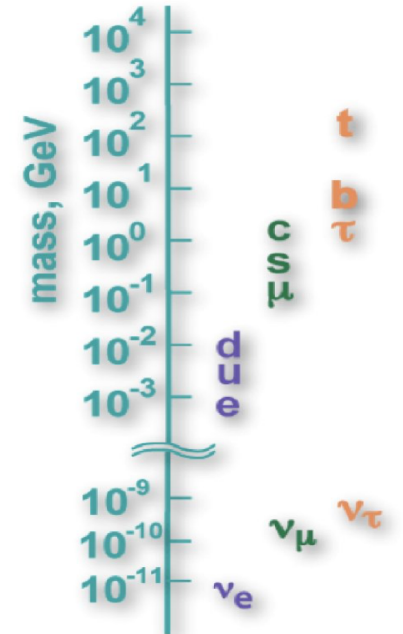
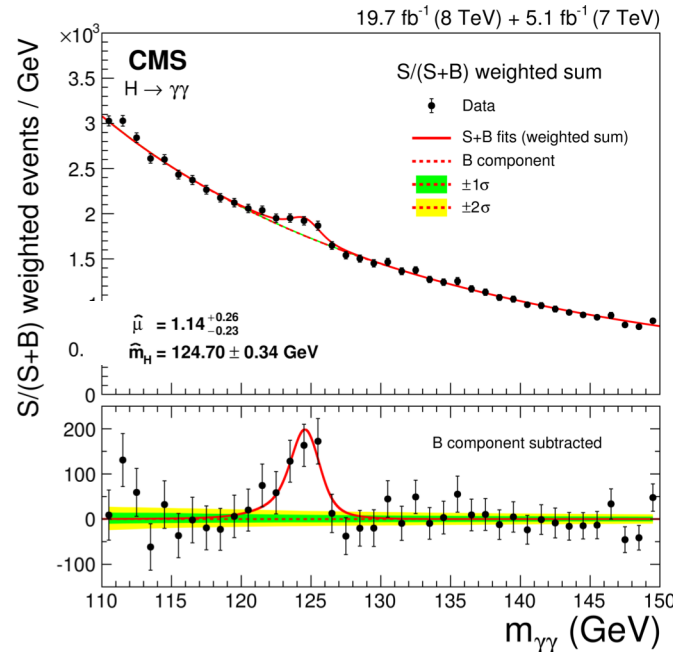
Natural Higgs mass close to Planck scale of 10^{19} GeV

Higgs mass at ~ 125 GeV

→ New physics in loops ?

→ Many BSM extensions include a **top quark partner**

→ No fine-tuning if top quark partner exists



Top quark physics: Current status...

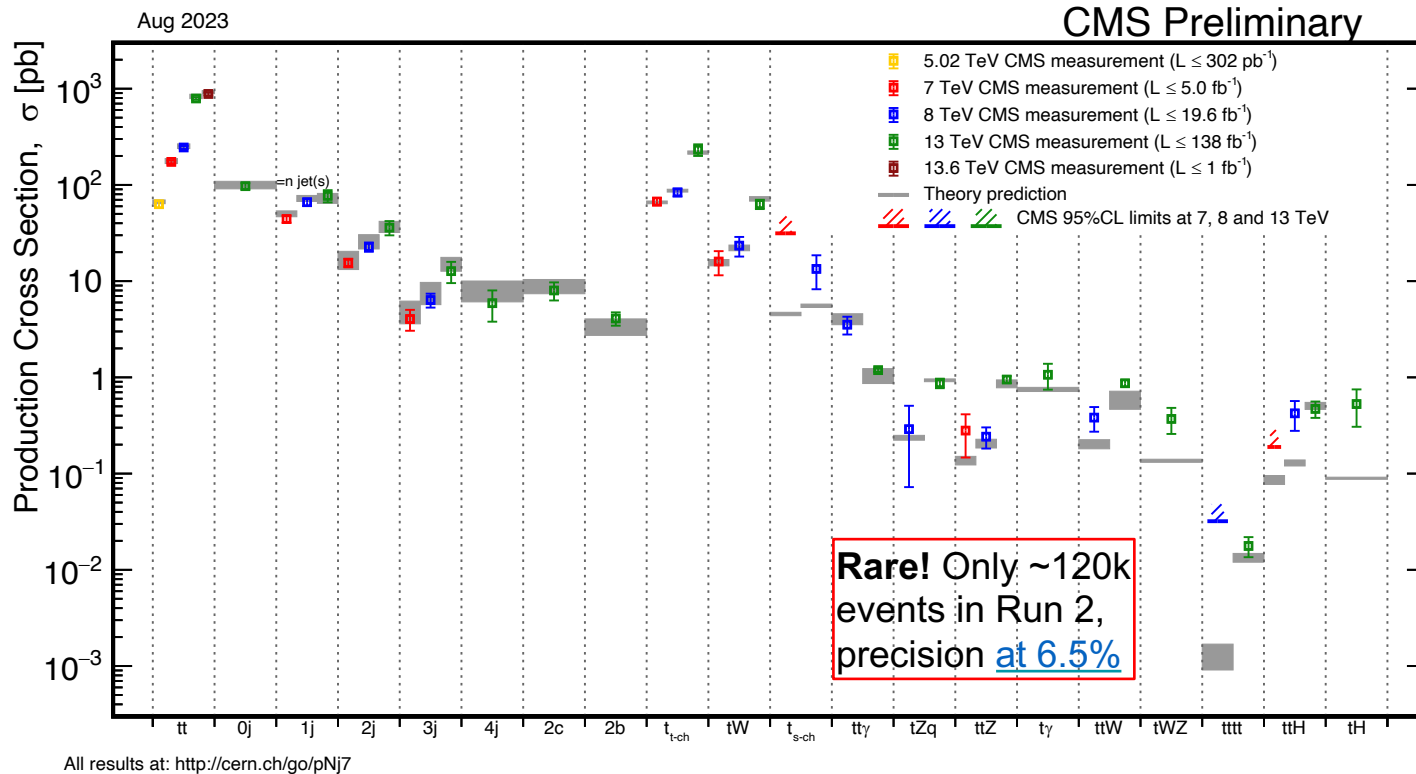


Abundant production!

O(100M) events in Run 2
Precision down to 1.8%

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

→ "Standard candle"



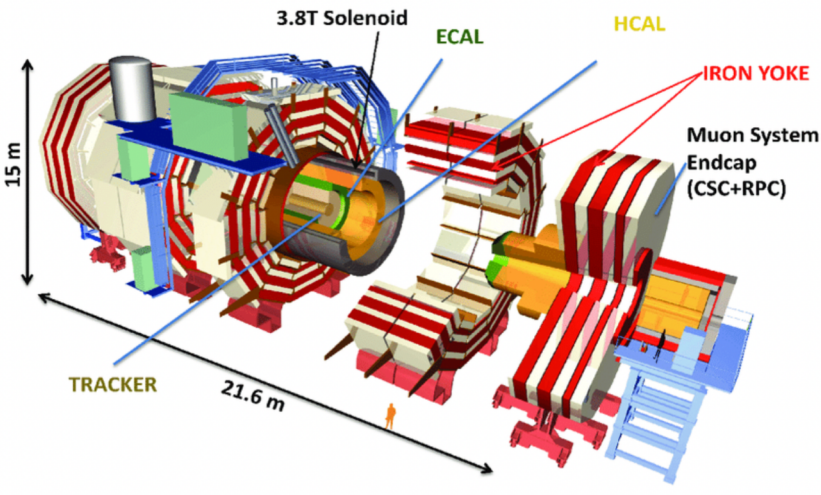
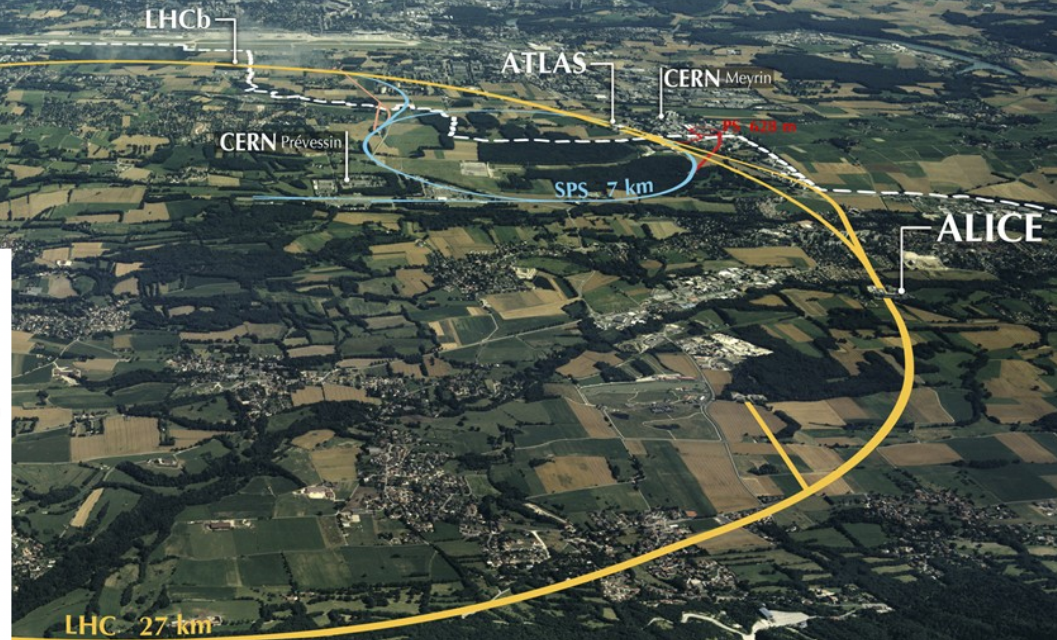
Extremely challenging!
Only ~3k events,
precision ~25%

World's premier particle physics laboratory and particle accelerator The Large Hadron Collider – LHC

CMS collaboration meeting

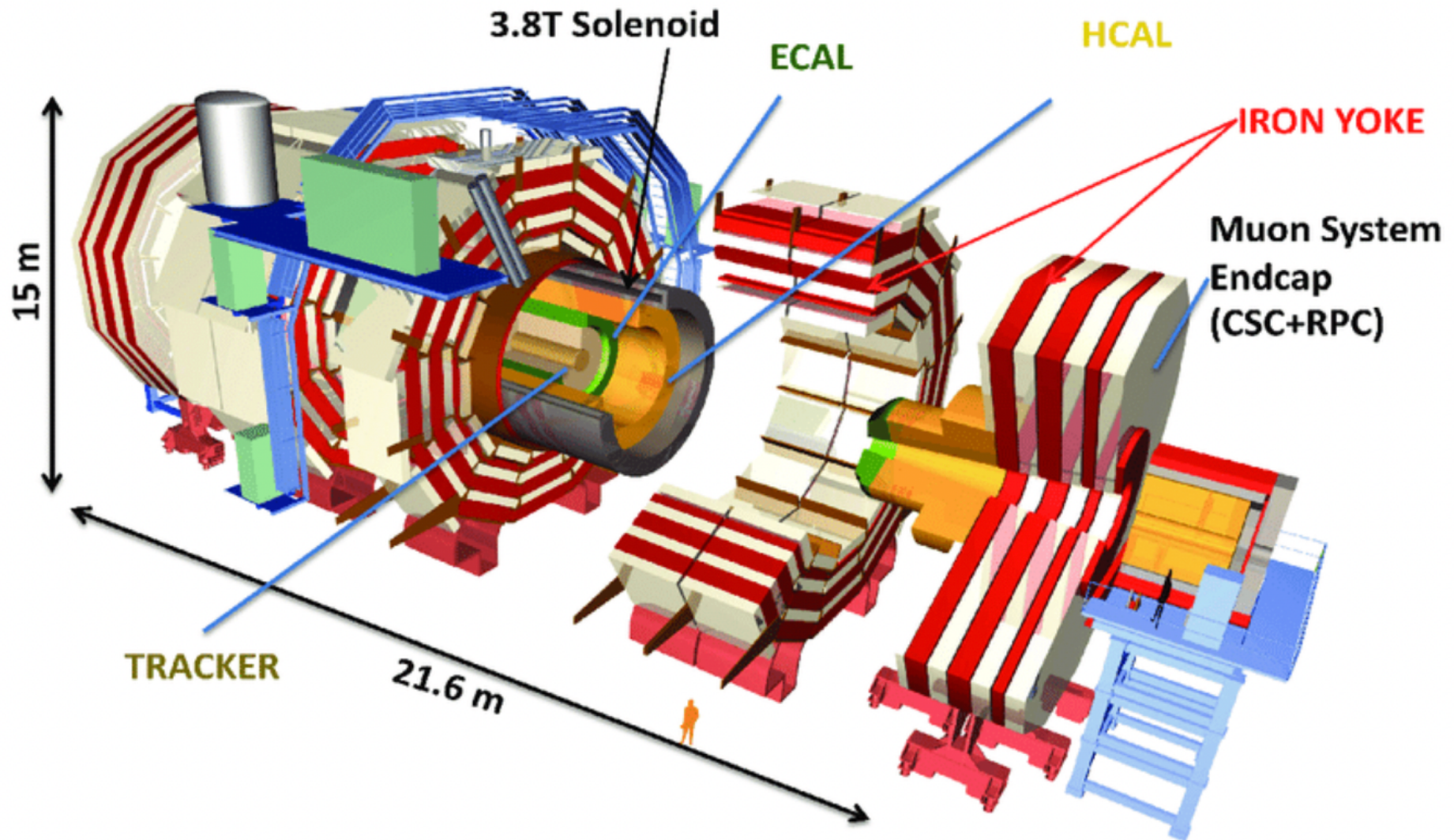


SUISSE
FRANCE



LHC – currently operating at 13.6 TeV

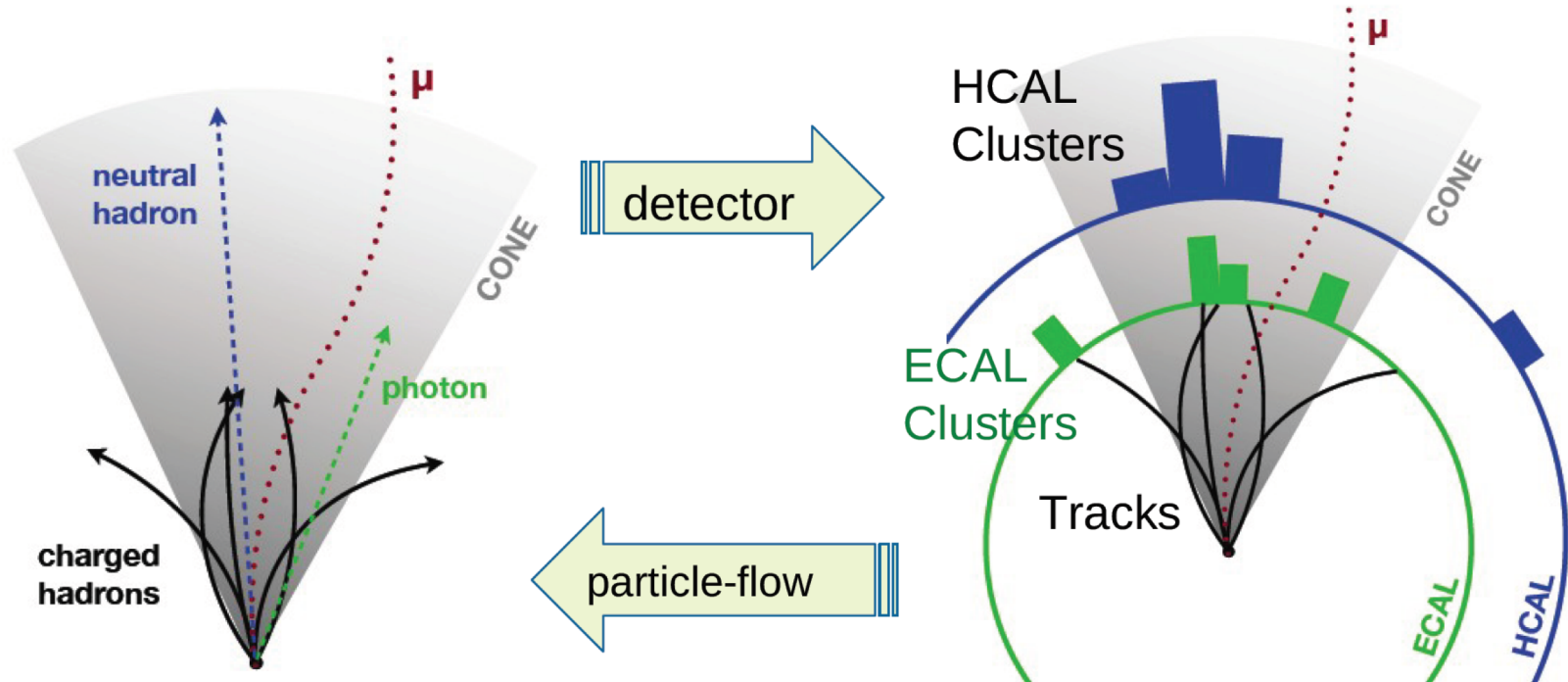
Compact Muon Solenoid / CMS



How to identify particles / objects ?

Combines detector information to ID particles

[CMS-JME-13001](#)



Isolated Leptons

Dilepton resonances (Z, upsilon, J/psi)

“b-tagging” of jets

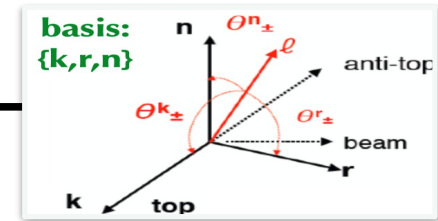
Several techniques, dominated by silicon tracker information

Jets and missing E_T

Gamma & Z-jet balance

Pile-up subtraction

Top quark spin correlations



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

Double diff. xsec

Polarisation (0 in SM)

Spin Correlation

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

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

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

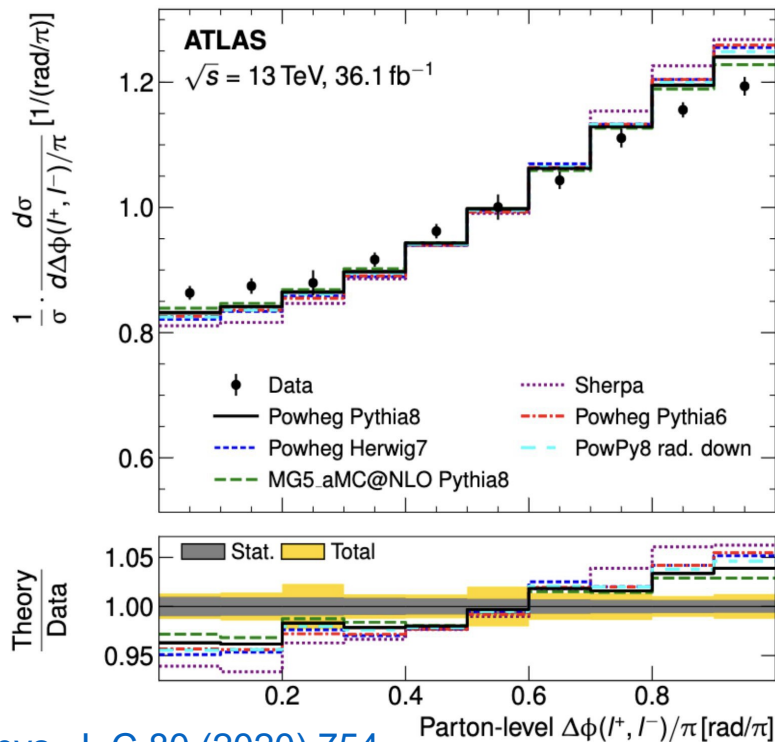
→ Spin dependence of $t\bar{t}$ production is **completely characterized by 15 coefficients** (but we have lost information better “correlations”)

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

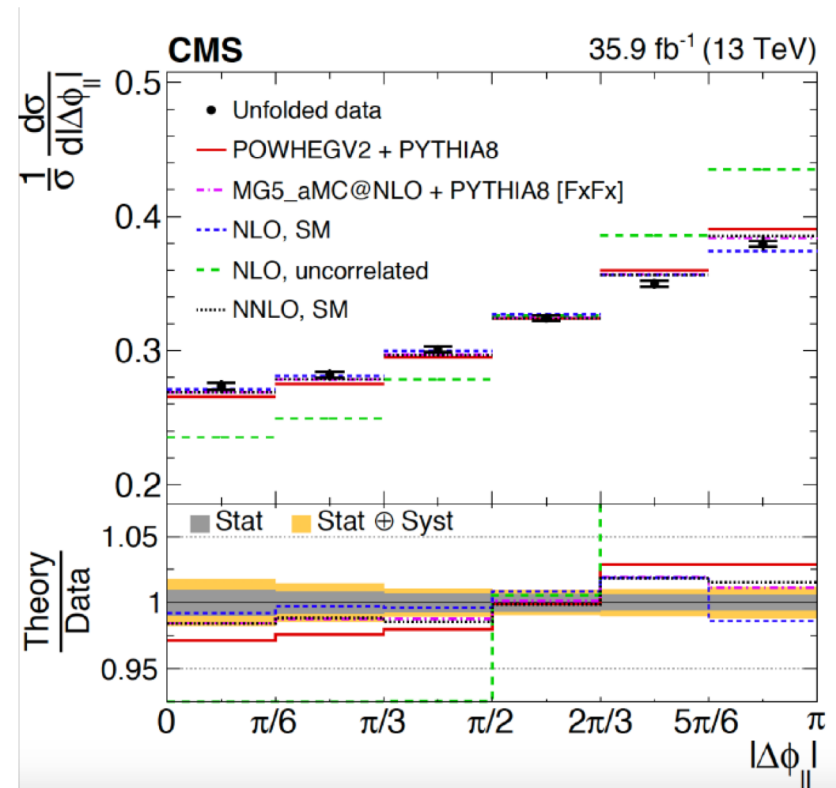
State of the art < 2023

Measurements of angular correlations since Tevatron

- Has seen excitement and deviations in the past, aka forward-backward asymmetry at Tevatron
- Latest debated result prior to 2023: spin correlations...

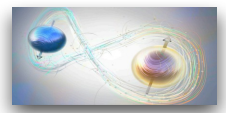


[Eur. Phys. J. C 80 \(2020\) 754](#)



← Opening angle between leptons
in top parent rest frame

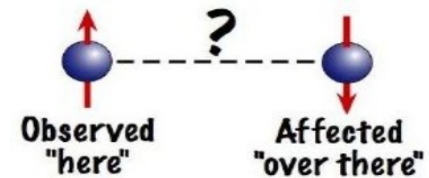
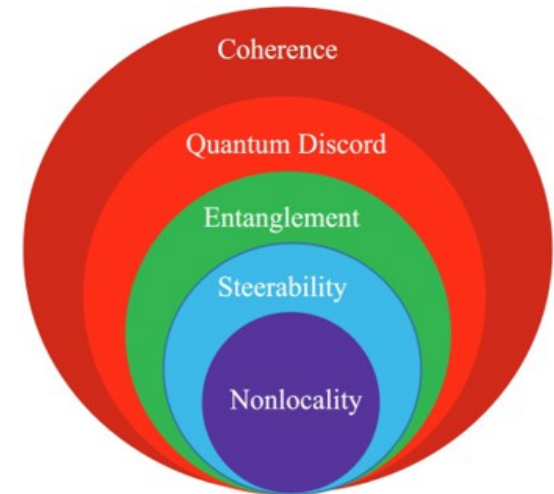
Entanglement in QM



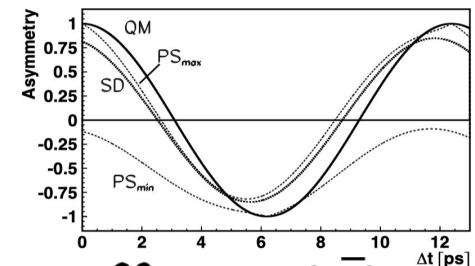
- **Qubit** = two-level quantum system $|0\rangle, |1\rangle \rightarrow$ most simple quantum system
- **Two qubits** $\rightarrow$ most simple example of quantum correlations
- Entire hierarchy of quantum correlations
- A quantum state of two subsystems A and B is separable when its density matrix:

$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$

- **Non-separability of a bipartite quantum state = entanglement**
 - entangled states cannot be described by independent superpositions
 - measuring particle spin in an entangled system immediately reveals the spin state of the second particle



[PRL 99, 131802 \(2007\)](#)

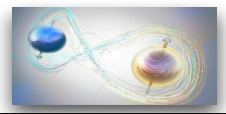


$$e^+ e^- \rightarrow \Upsilon(4s) \rightarrow B^0 \bar{B}^0$$

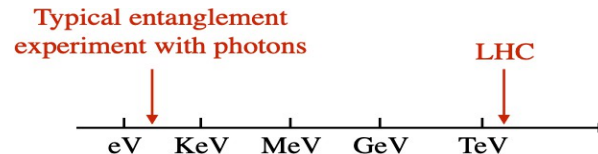
$$|\psi\rangle = \frac{1}{\sqrt{2}} [|B^0\rangle_1 \otimes |\bar{B}^0\rangle_2 - |\bar{B}^0\rangle_1 \otimes |B^0\rangle_2]$$

entangled state

How to probe Entanglement



- Fundamental predictions of QM:
 - Entangled states cannot be described by independent superpositions: measuring particle spin in an entangled system immediately reveals the spin state of the second particle
 - Nobel Prize in 2022 for Aspect, Clauser in Zeilinger
- What does it mean to be entangled: if not separable!



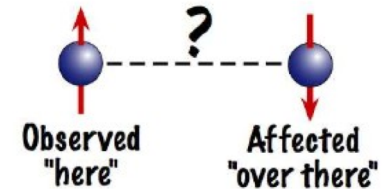
- At the LHC top quarks are produced in a mixed state and thus can be represented as a (complex) density operator

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

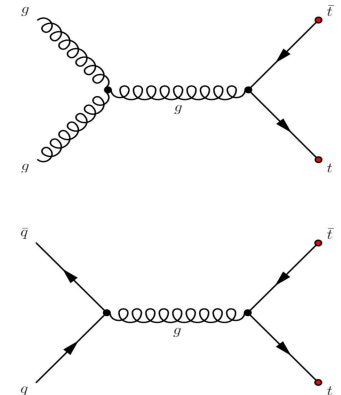
~0 ~0

- Remarkably, $\text{tr}[C]$ can be probed from a single differential cross section

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

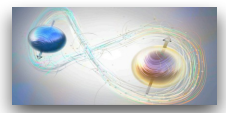


How to produce a top quark



Experimental goal →
measure D
(entanglement proxy)

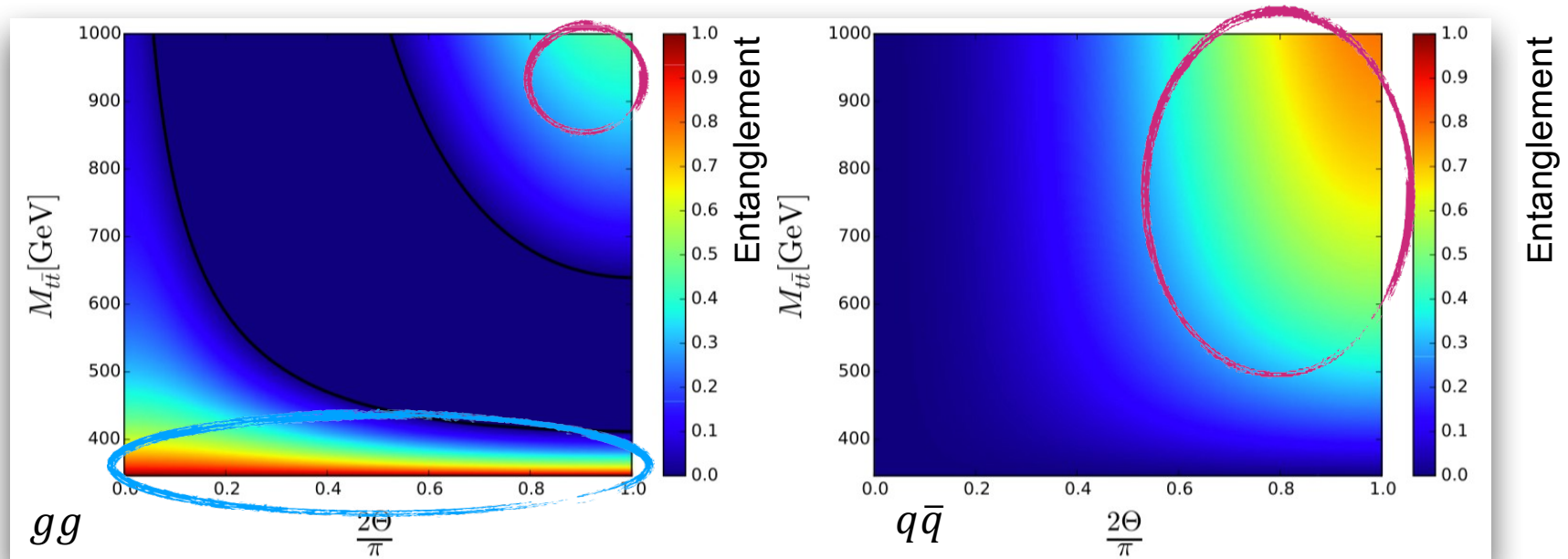
Entanglement of top quarks



- Can be measured using spin correlations variables
- Depends on production mode, $m(t\bar{t})$, and scattering angle (Θ)

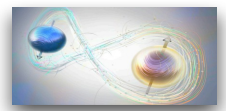
SM predicts entangled states:

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



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

1st Observation of Entanglement



Quite a race...ATLAS was faster!

["The Quantum Chase" – Symmetry, Nov 2024](#)



Quantum entanglement in top quark pair production

Slide by
M. Vos



Read more about this!

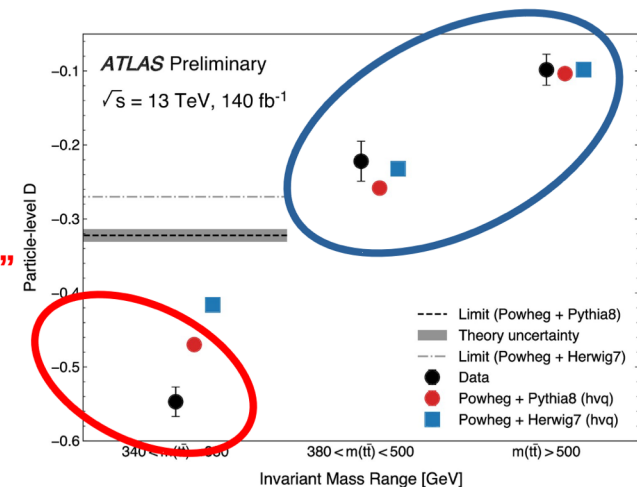
<https://atlas.cern/Updates/Briefing/Top-Entanglement>

[Nature 633, 542–547 \(2024\)](#)

$D < -1/3$: top quarks are “entangled”
This is new and exciting!

Collect top quark data,
separate in three regions,
measure “entangled-o-meter” D

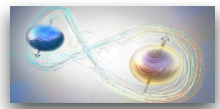
$D \neq 0$: top quark spins are correlated.
Confirms something we have known since 2012.



Looking forward to a CMS result

More than 3 sigma away from Standard Model
→ Signs of new physics ?
→ Exciting times ... all eyes on CMS

Excitement from theory community



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

Quantum information with top quarks in QCD

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks represent unique high-energy systems since their spin correlations can be high-energy colliders. We present here the general framework of the quantum state of a top quark pair produced in a $t\bar{t}$ pair produced from the most different regions of phase space. We show that any realistic hadronic production of a $t\bar{t}$ pair experimentally relevant cases of proton-proton and proton-antiproton collisions, the perfect energy of the collisions. We provide experimental observables for entanglement and CHSH single observable, which in the case of entanglement represents the violation of a Cauchy pair proposed in the literature to more general quantum states, and for any production mechanism of violation of Bell's theorem, necessarily containing a number of loopholes.

Comments: 36 pages, 10 figures, 1 table. Accepted version of the manuscript
Subjects: Quantum Physics (quant-ph); High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:2203.05582 [quant-ph]
(or arXiv:2203.05582v2 [quant-ph] for this version)
<https://doi.org/10.48550/arXiv.2203.05582>

Quantum collider probes of the fermionic Higgs portal

U. Haisch, M. Ruhdorfer, K. Schmid, A. Weiler

We explore the sensitivity of future hadron colliders to constrain the fermionic Higgs portal, with a focus on scenarios where the new fermions cannot be directly observed in exotic Higgs decays. This portal emerges in various models including twin-Higgs scenarios and dark matter models, posing significant challenges for collider tests. Working in an effective field theory (EFT), we determine the reach of the high-luminosity option of the Large Hadron Collider (HL-LHC), the high-energy upgrade of the LHC (HE-LHC) and a proposed Future Circular Collider (FCC) in probing the fermionic Higgs portal through off-shell and double-Higgs production. Notably, we find that quantum-enhanced indirect probes offer a better sensitivity than other direct Higgs measurements. We argue that this finding is valid in a wide class of ultraviolet realisations of the EFT. Our study presents a roadmap of a multifaceted search strategy for exploring the fermionic Higgs portal at forthcoming hadron machines.

Journal reference: Physics Letters B 825 (2022) 136866
Related DOI: <https://doi.org/10.1016/j.physletb.2021.136866>

"The Quantum Chase" – Symmetry, Nov 2024

LHC experiments at CERN observe quantum entanglement at the highest energy yet

The results open up a new perspective on the complex world of quantum physics



CERN Press release, Sept 2024: "LHC ... observe quantum entanglement..."

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

Improved tests of entanglement and Bell inequalities with LHC tops

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

[Submitted on 24 Aug 2022]

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

Marco Fabbrichesi, Roberto Floreanini, Emidio Gabrielli

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

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

[Submitted on 8 Sep 2022]

Quantum discord and steering in top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Top quarks have been recently shown to be a promising system to study quantum information problems at the highest-energy scale available. This discusses topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture of quantum correlations with top quark discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a separable quantum state is expected statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord can be measured following its original ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional quantum discord and steering can provide witnesses of new physics beyond the Standard Model.

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

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

Testing Bell inequalities in Higgs boson decays

of W bosons in a maximally entangled state, the spins of which are measured experimentally from the directions of the charged lepton decay products of $H \rightarrow WW^*$ decays indicate that violation of a generalised entangled Bell tests could be performed at a variety of colliders and that violations could be observable even with datasets comparable to those of the LHC.

Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); High Energy Physics - Theory (hep-th)

[Submitted on 28 Sep 2022]

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

J. A. Aguilar-Saavedra

Quantum entanglement between the two W bosons resulting from the decay of a Higgs boson may be investigated in the dilepton channel $H \rightarrow WW \rightarrow \ell\ell\nu\bar{\nu}$ using laboratory-frame observables that only involve the charged leptons $\ell = e, \mu$. The dilepton invariant mass distribution, already measured by the ATLAS and CMS Collaborations at the LHC, can be used to test Bell inequalities.

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

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

We discuss quantum entanglement and violation of Bell inequalities in the $H \rightarrow ZZ$ decay, in particular when the two Z -bosons decay into light leptons. Although such a violation implies an important suppression of the statistics, this is traded by clean signals from a "quasi maximally-entangled" system, which makes it very promising to check these phenomena.

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

Quantum tops at the LHC: from entanglement to Bell inequalities

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

We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable for measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglement can be established at better than 5 σ both at threshold as well as at high p_T already in the LHC Run 2 dataset. On the other hand, only very high- p_T events are sensitive to a violation of Bell inequalities, making it significantly harder to observe experimentally. By employing a sensitive and robust observable, two different unfolding methods and independent statistical approaches, we conclude that, at variance with previous estimates, testing Bell inequalities will be challenging even in the high luminosity LHC run.

Comments: Accepted for publication in EPJ C
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2110.10112 [hep-ph]
(or arXiv:2110.10112v2 [hep-ph] for this version)
<https://doi.org/10.48550/arXiv.2110.10112>
Related DOI: <https://doi.org/10.1140/epjc/s10052-022-10245-9>

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

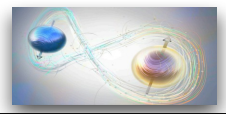
Testing Bell inequalities at the LHC with top-quarks

M. Fabbrichesi, R. Floreanini, G. Panizzo

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

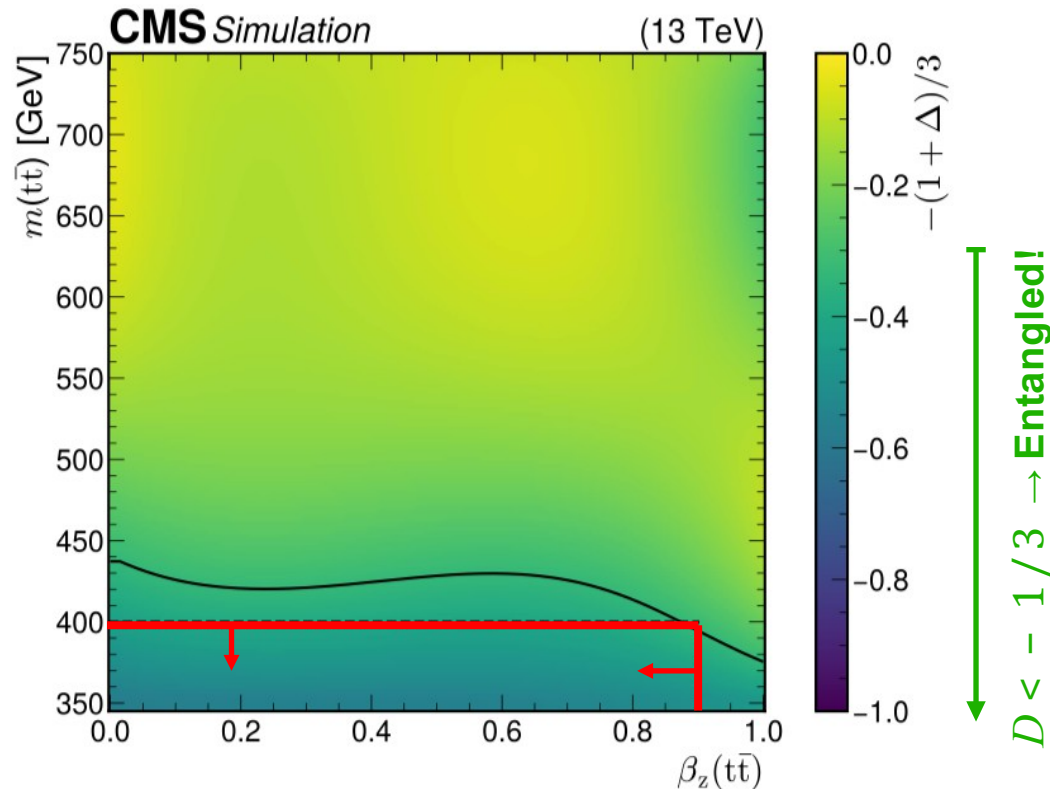
Comments: 4 pages, 1 figure
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 [hep-ph]
(or arXiv:2102.11883v2 [hep-ph] for this version)
<https://doi.org/10.48550/arXiv.2102.11883>
Journal reference: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

Analysis in a nutshell...



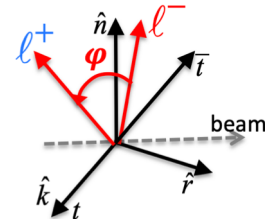
- The degree of entanglement is highly phase space-dependent
 → Scan of $m(t\bar{t})$ vs. $\cos(\Theta)$ vs β to determine most sensitive phase space while minimizing expected total uncertainties
- Focus on low-mass region ($345 < m(t\bar{t}) < 400$ GeV) to increase entanglement

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) $\beta = \left| \frac{p_z^t + p_z^{\bar{t}}}{E_t + E_{\bar{t}}} \right| < 0.9$

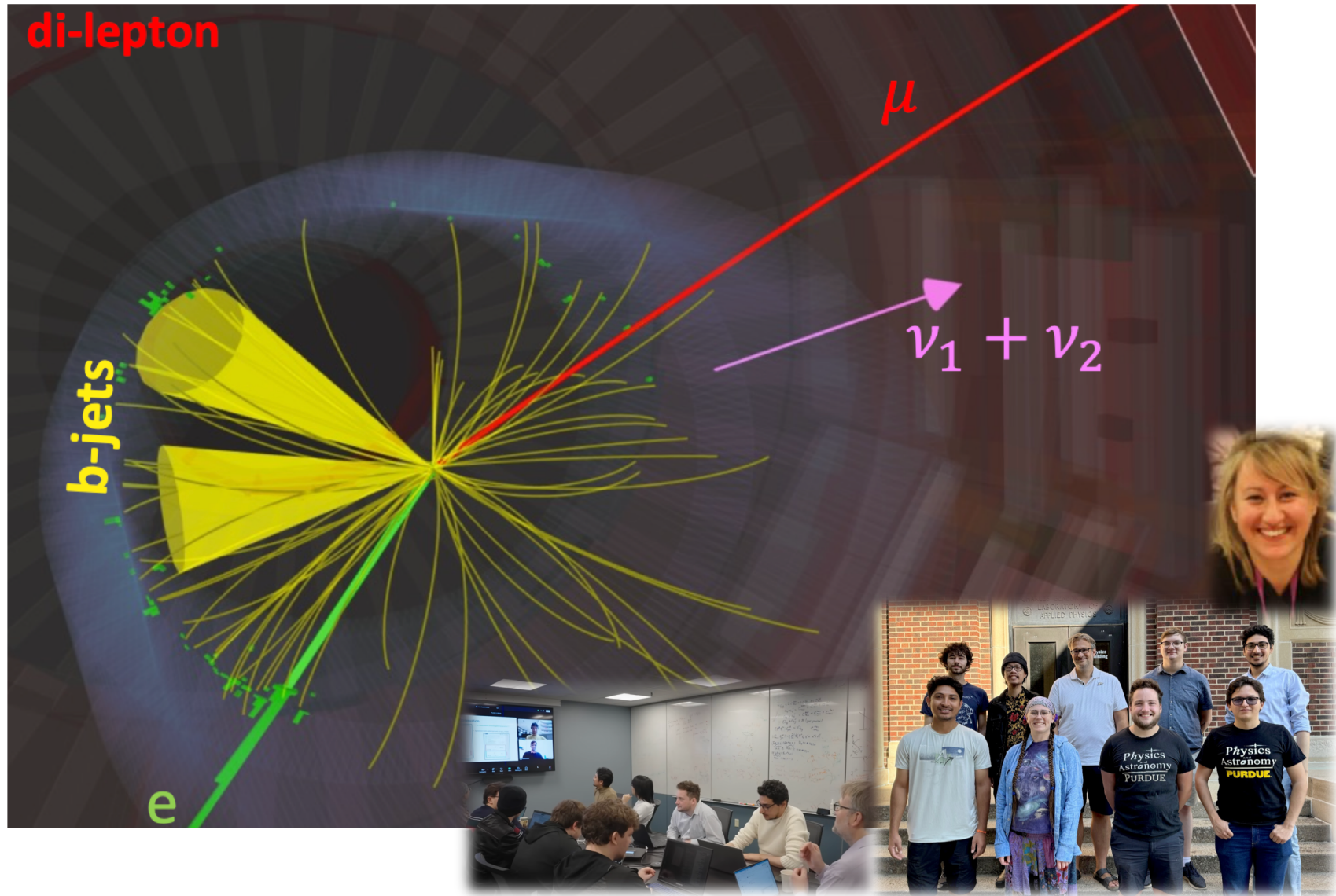
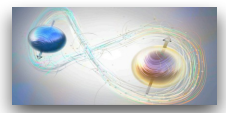
- Measure helicity angle** $\cos \varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$
 - fully encapsulates spin correlations information for



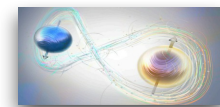
- Perform a **profile maximum likelihood fit of the cos distribution** in the $m_{t\bar{t}} - \beta$ signal region

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

The data sample: Dilepton events



The data sample: Dilepton events

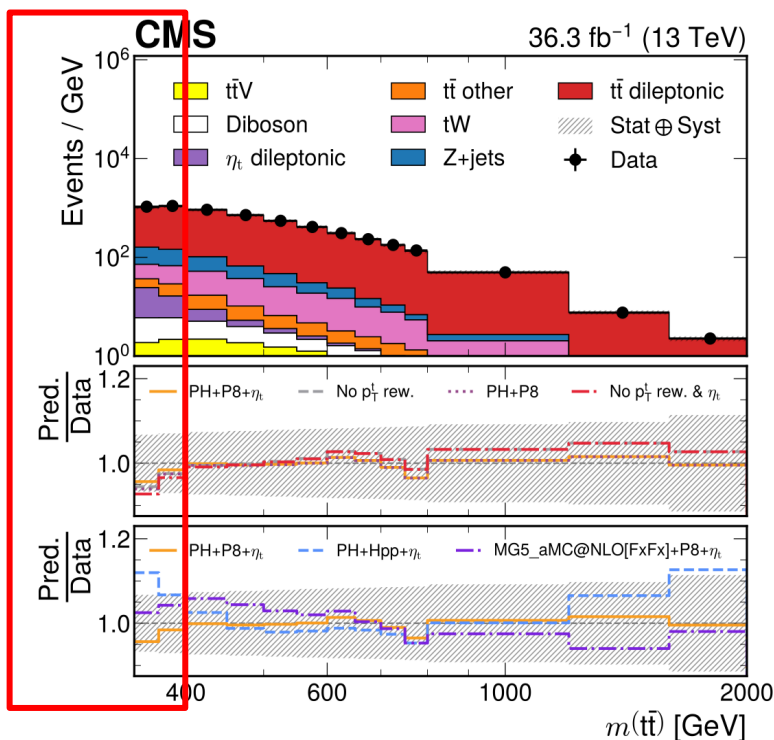


- Signal model: $t\bar{t}$
 - Electroweak corrections applied
 - Using 35.9 fb^{-1} collected in 2016
- Main background sources: Z+jet (MG5 + data-driven corrections), single top (powheg MC), diboson (pythia8 MC)

[Comput. Phys. Commun. 182 \(2011\) 10](#)

[PRL 127 \(2021\) 062001](#)

**Analysis
region**



Leading experimental uncertainties

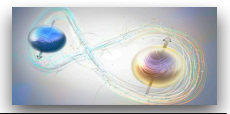
- Jet energy scale and resolution

Leading theory-based uncertainties

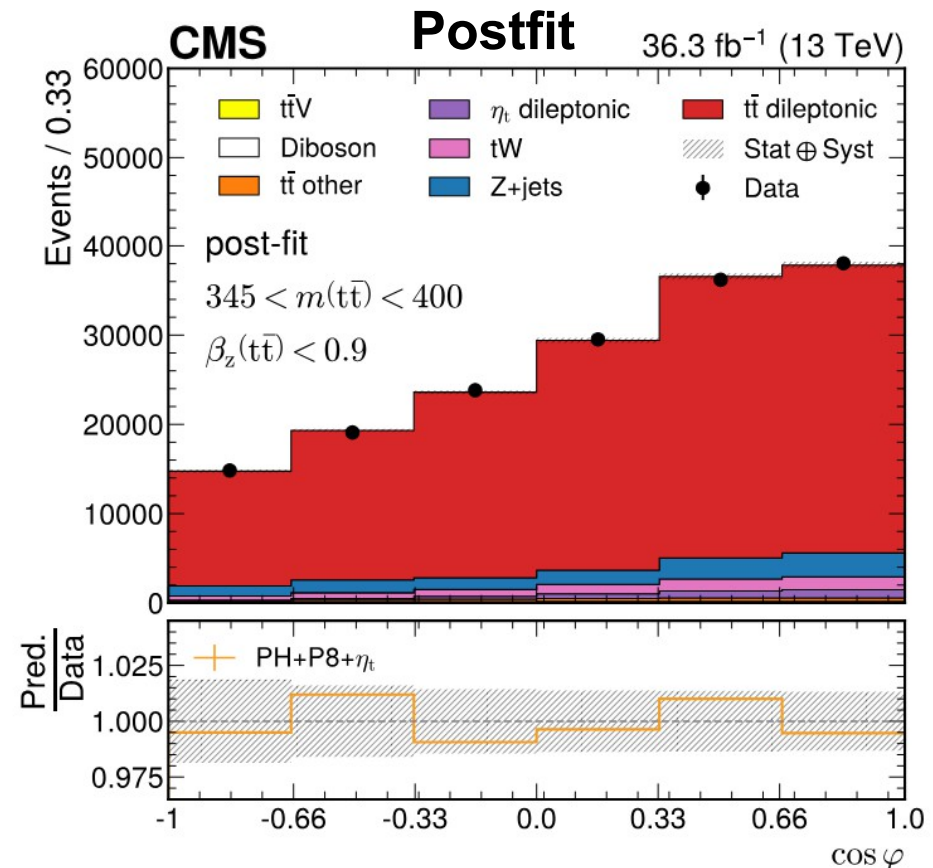
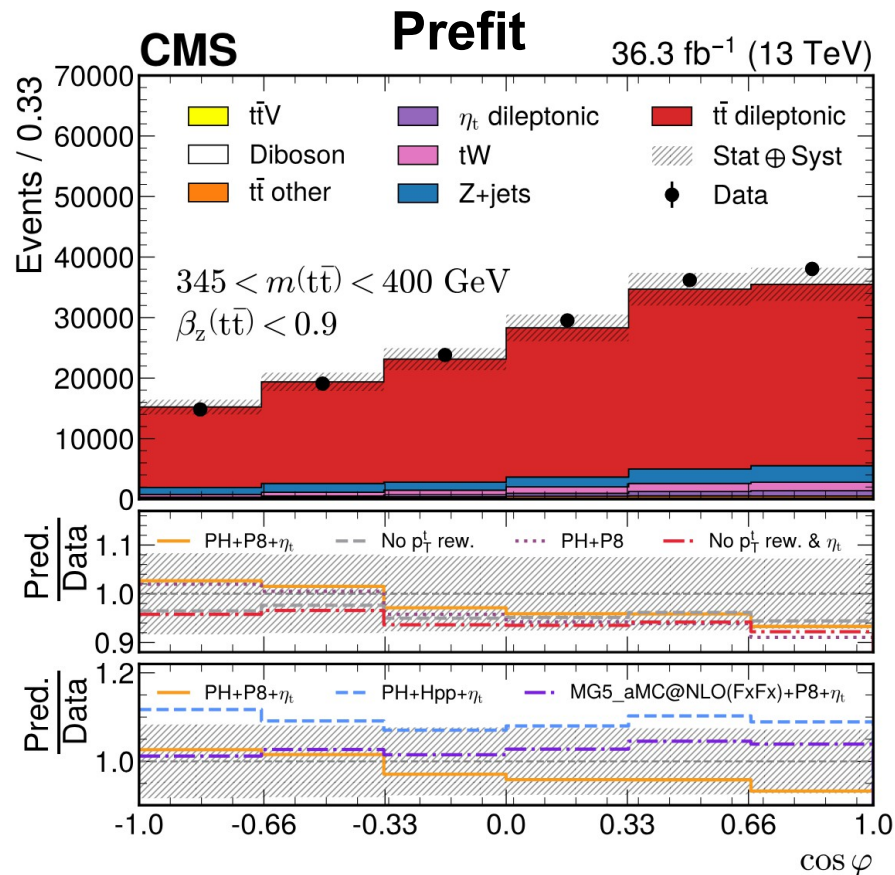
- Toponium normalization
- Parton Shower

Source	Uncertainty
	$D_{345 < m_{t\bar{t}} < 400}$
Toponium normalization	9.79%
JES	9.68%
Parton Shower (ISR)	6.81%
Scale	1.68%
Parton Shower (FSR)	1.00%
JER	0.76%
Z+jets shape	0.67%
Top quark p_T	0.23%
PDF	0.16%
Color reconnection	0.11%

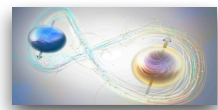
The data sample: Dilepton events



- Result of the binned profile likelihood fit of the $\cos(\varphi)$ *vs* $m(t\bar{t})$
- Good agreement with SM predictions



CMS Observation of Entanglement



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

→ Scan of the $-2\Delta\ln L$ distribution at parton level, accounts for all detector effects

$$D_{obs} = -0.491^{+0.026}_{-0.025}(\text{tot})$$

$$D_{exp} = -0.452^{+0.025}_{-0.026}(\text{tot})$$

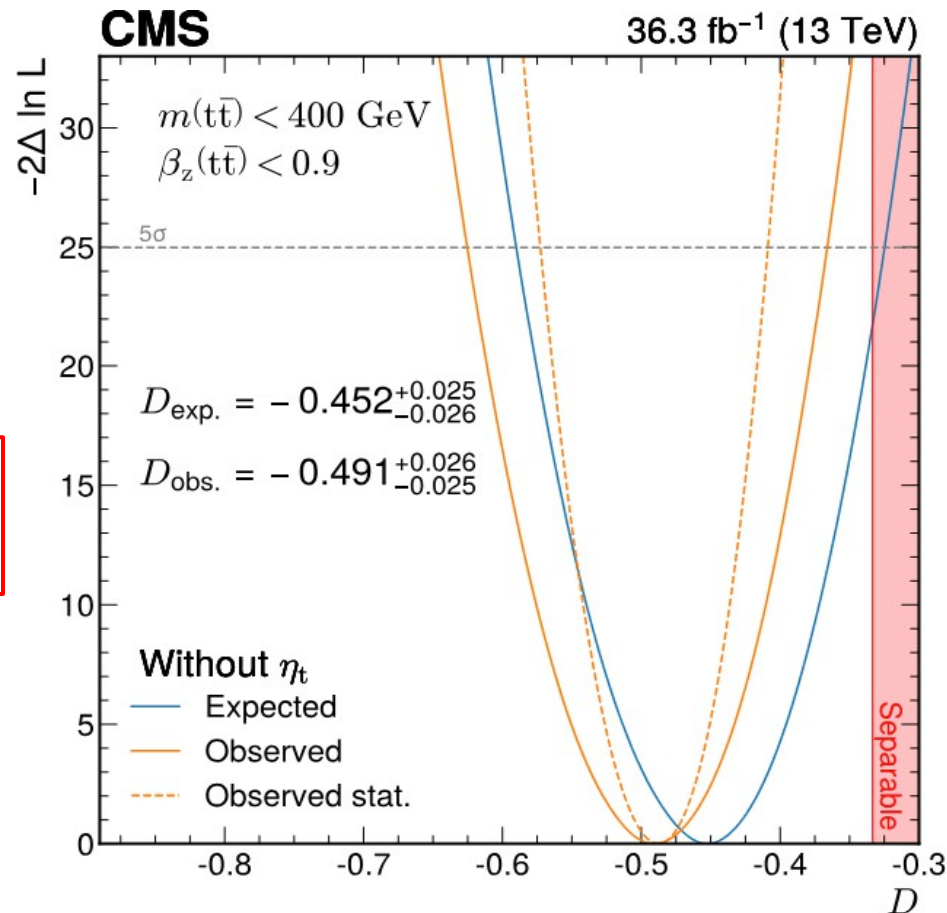
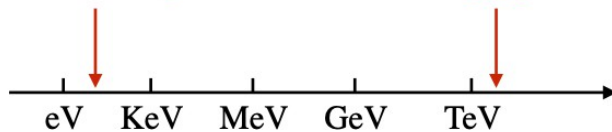
- **Significance: 6.3 SD obs and (4.7 SD exp.)**

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

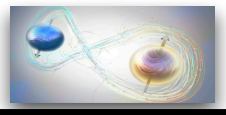
- **New & exciting field at the LHC**

Typical entanglement experiment with photons

LHC



Celebration...yes!



- ...and since 2018, we can buy alcohol on a Sunday
- Prohibition only ended in Indiana 70 years later...BUT...

Indiana Looks to Finally End Prohibition-Era Restriction on Sunday Alcohol Sales

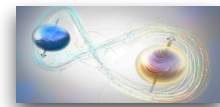
By Jim Vorel | January 12, 2018 | 10:53am

Photo via Getty Images, Hannah Foslien

[DRINK](#) > [NEWS](#) > [INDIANA SUNDAY ALCOHOL SALES](#)



Observation of Entanglement



1st measurement of entanglement
of top quarks with CMS data

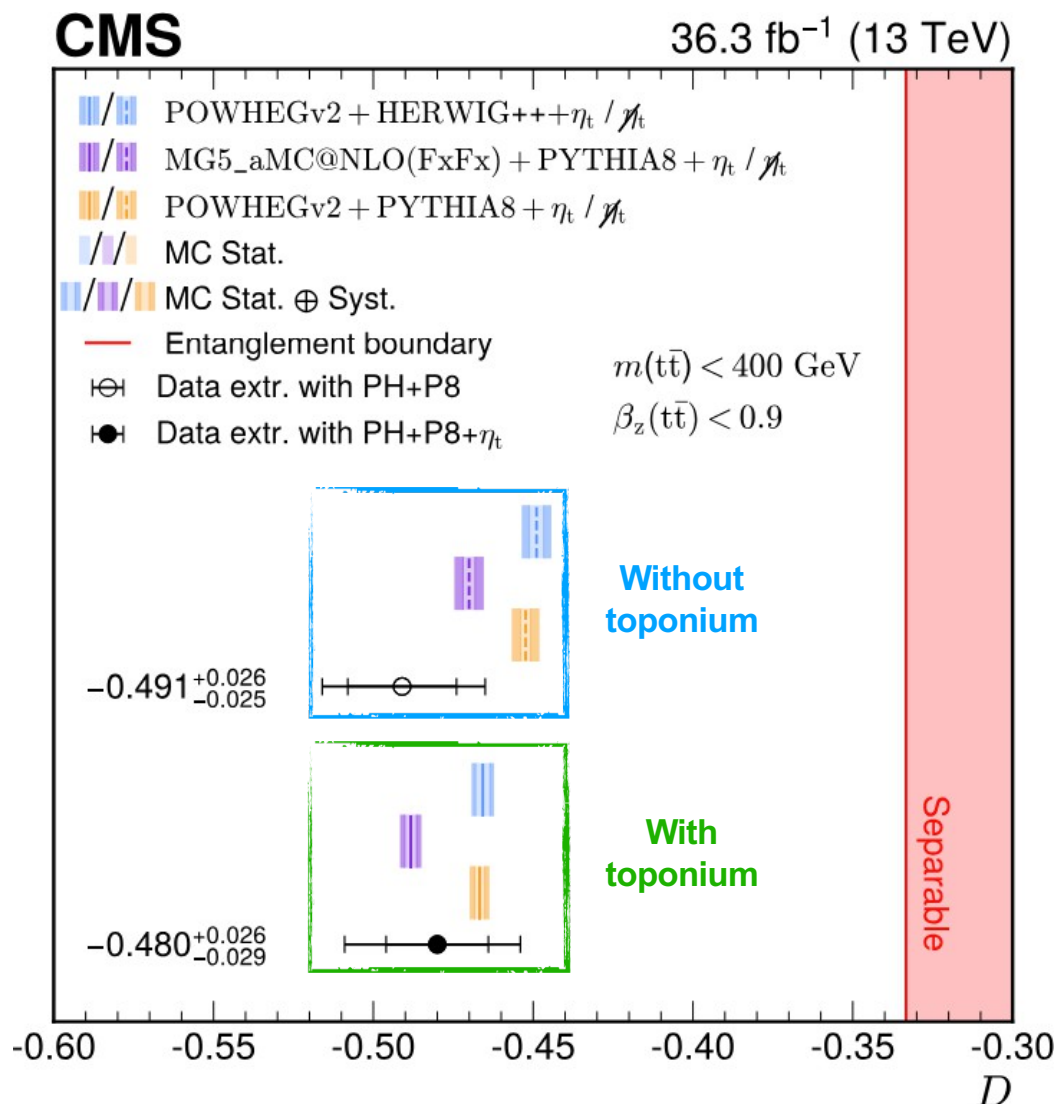
[Rep. Prog. Phys. 87 \(2024\) 117801](#)

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

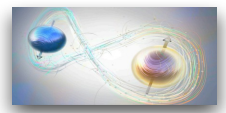
5 standard deviations
observation of top quarks
being entangled at $t\bar{t}$ threshold

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

Good agreement with SM
significantly improved by
including η_t



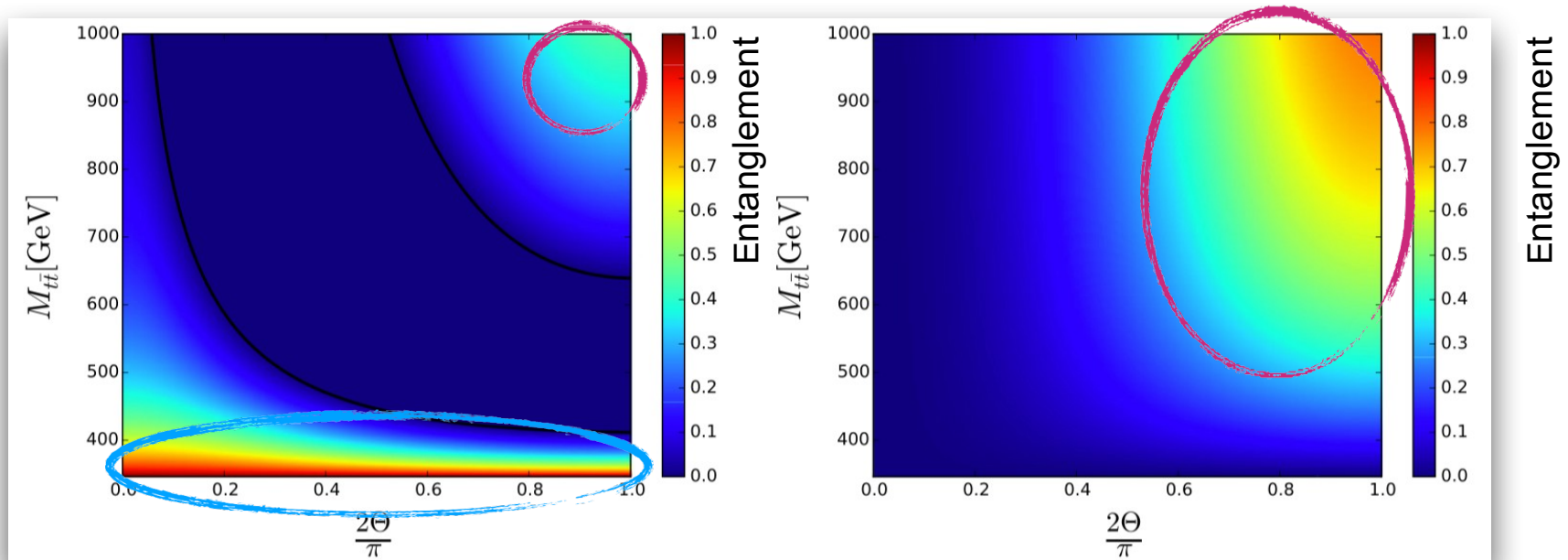
Entanglement of top quarks



- **Other decay channels: l+jets – only brief overview**
- Can be measured using spin correlations variables
- Depends on production mode, $m(t\bar{t})$, and scattering angle (Θ)

SM predicts entangled states:

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



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

Entanglement in lepton+jets events

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

- highest sensitivity using full C

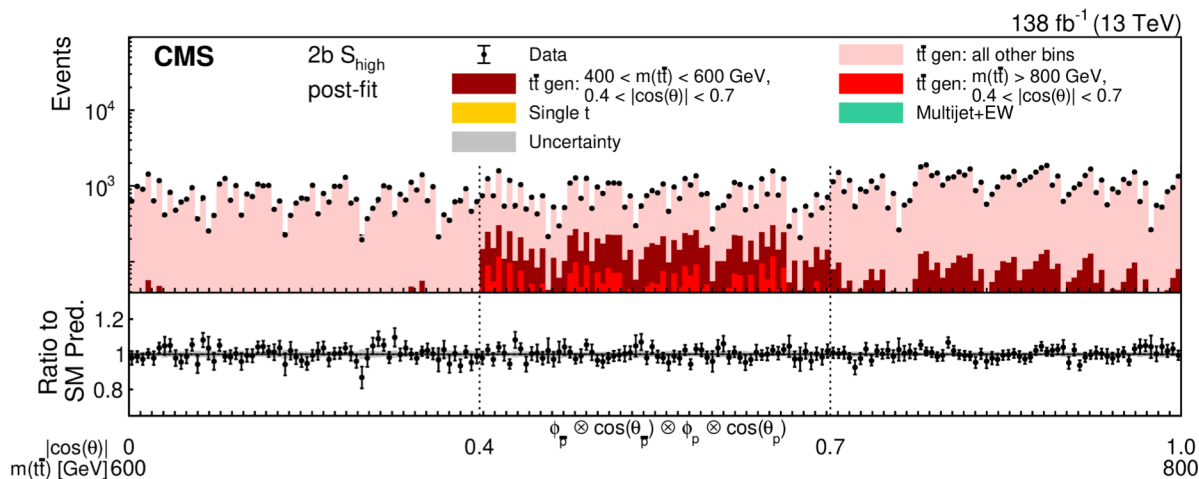
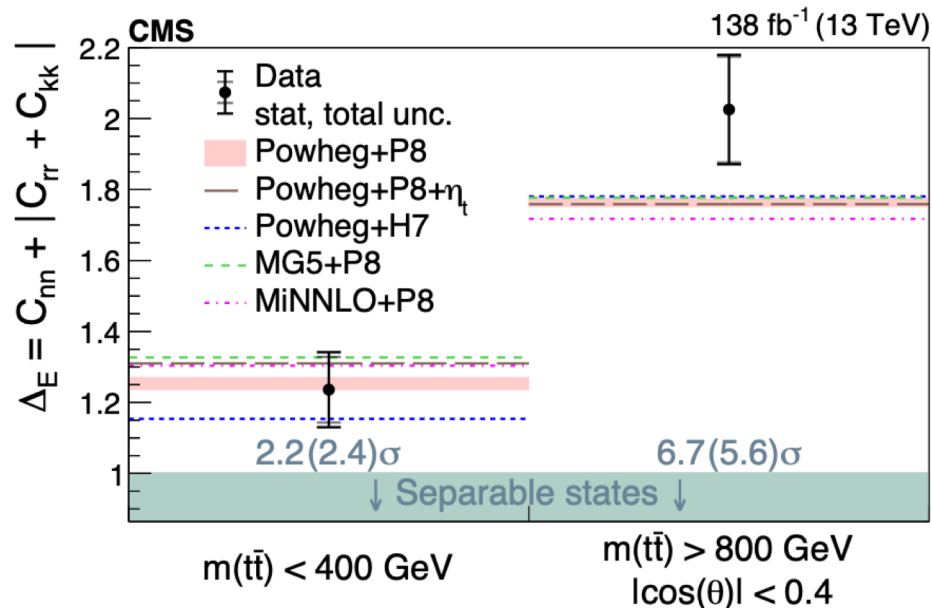
$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

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

- 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](#)

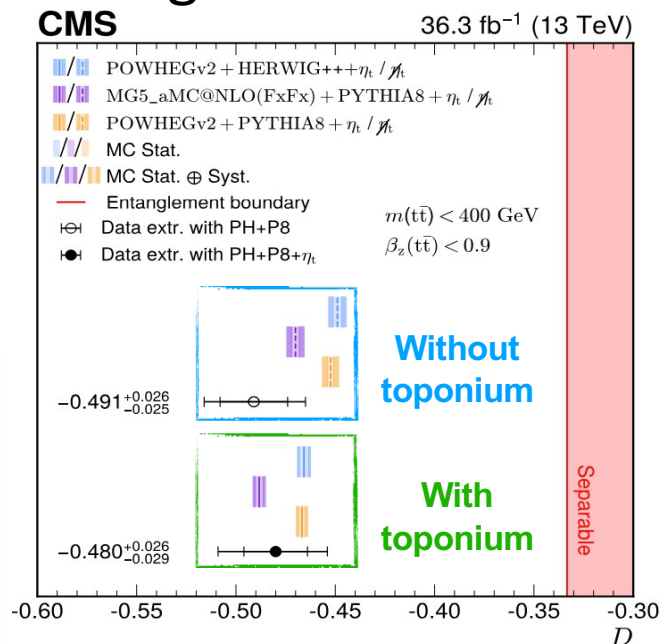
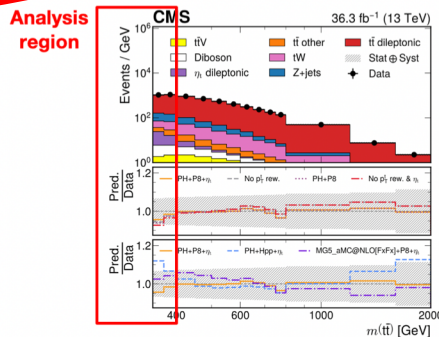


Intermediate summary



- Entanglement of top quark events observed at LHC by ATLAS, confirmed by CMS
 - Extended to high mass: [PRD 110 \(2025\) 112016](#)
- Level of observed entanglement cannot be explained by classical exchange of information between the two particles !
- Let's get back to the CMS Observation of Entanglement...

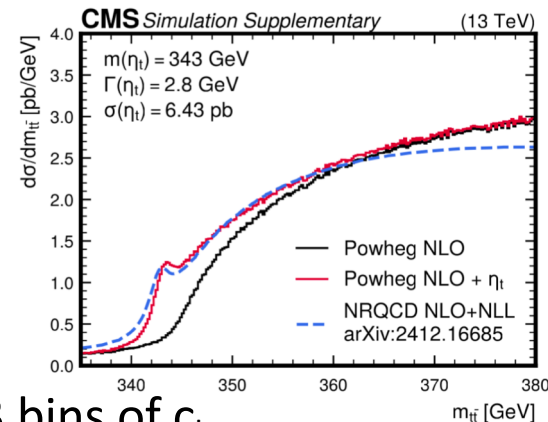
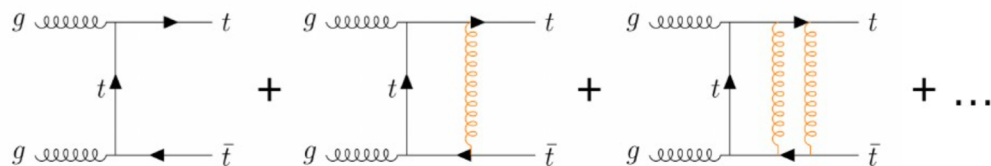
Can we say more on top quark bound state effects at threshold ?



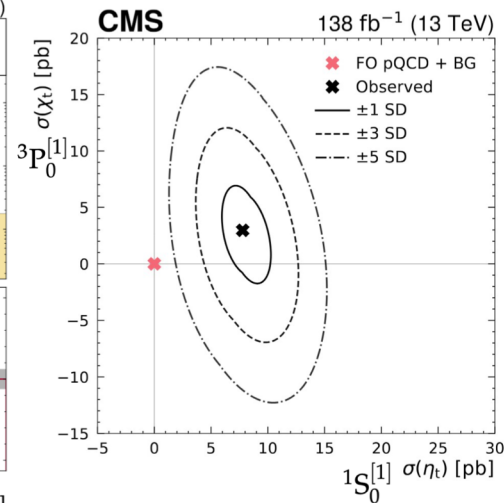
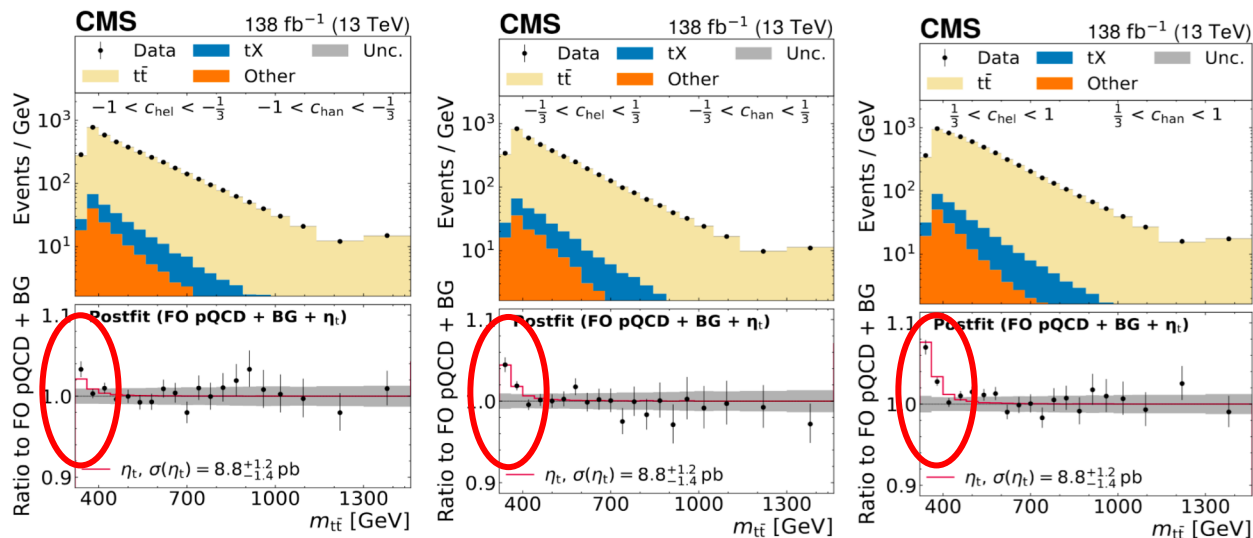


Quasi-bound states at threshold ?

- 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_{chan}



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

[ROPP 88 \(2025\) 087801](#)

- Words of caution:

- Cannot distinguish between η_t & pseudo-scalar Higgs
- Missing e.g. color-octet states - these are expected to be

Confirmation by ATLAS...

- Confirmed by ATLAS at EPS conference...a significance of 7.7 SD
- Exciting times and a lot of debate around theory and experimental aspects

CERN Press-statement: "Elusive romance ..."

[Updates](#) > [Press Statement](#) > Elusive romance of top-quark pairs observed at the LHC

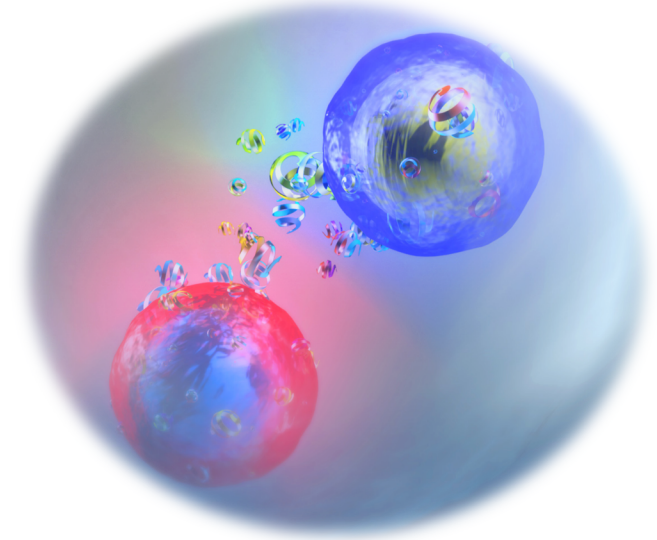
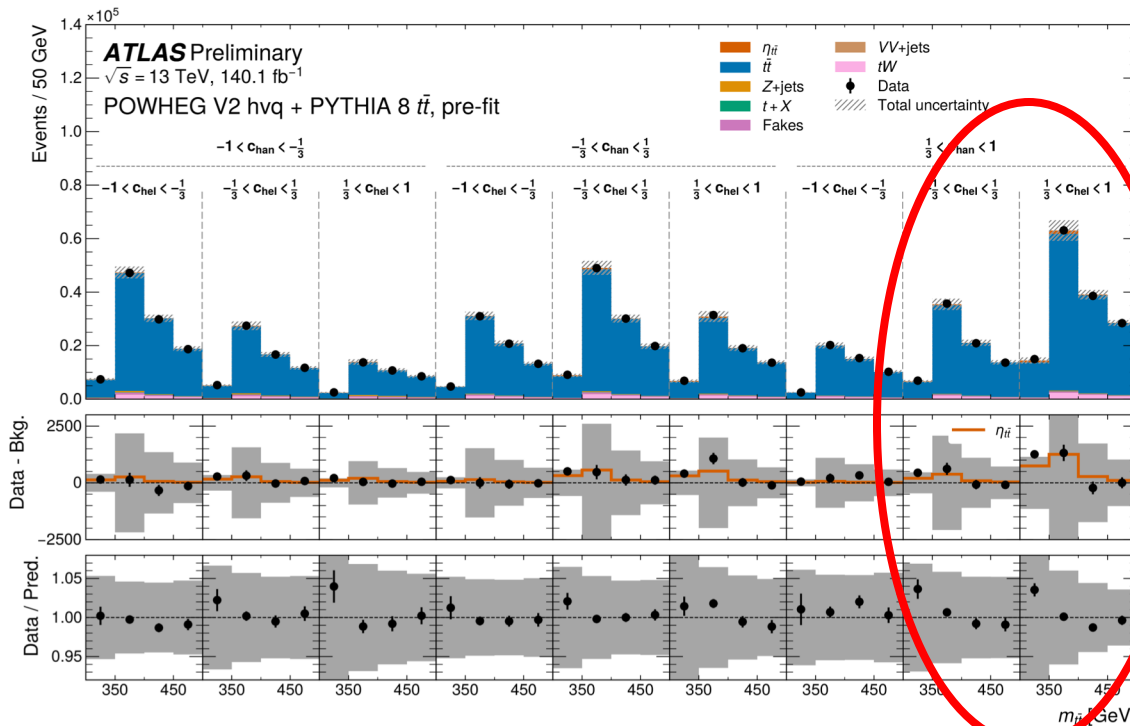
Press Statement

Tags:
EPS 2025,
top quark,
physics results

Elusive romance of top-quark pairs observed at the LHC

8 July 2025 | By CERN

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.



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

Bell inequality

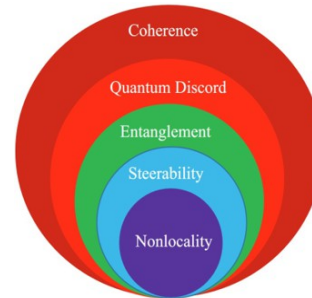
- BI is expressed by **Clauser, Horne, Simony, Holt (CHSH) inequality** = measurements a, a' and b, b' on subsystems A and B must classically satisfy:

$$|\langle ab \rangle - \langle ab' \rangle + \langle a'b \rangle + \langle a'b' \rangle| \leq 2$$

- For $\bar{t}$ system it can be written in terms of C matrix as

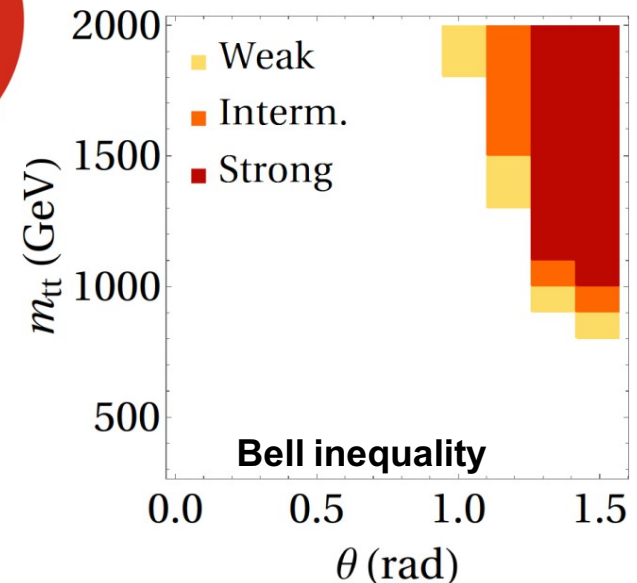
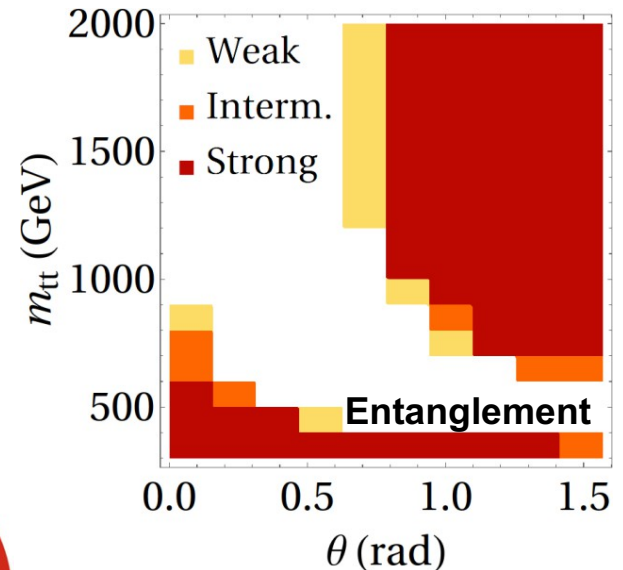
$$|C(a_1, b_1) - C(a_1, b_2) + C(a_2, b_1) + C(a_2, b_2)| \leq 2$$
- or more simply as:

$$\sqrt{2} | -C_{rr} + C_{nn} | \leq 2$$

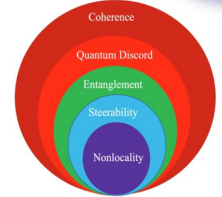
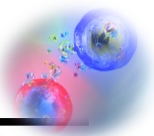


- **Entanglement is a necessary but not sufficient condition for Bell inequality violation**
- **BI is expected to happen at even higher $m_{t\bar{t}}$**
 - more statistics is needed to measure it

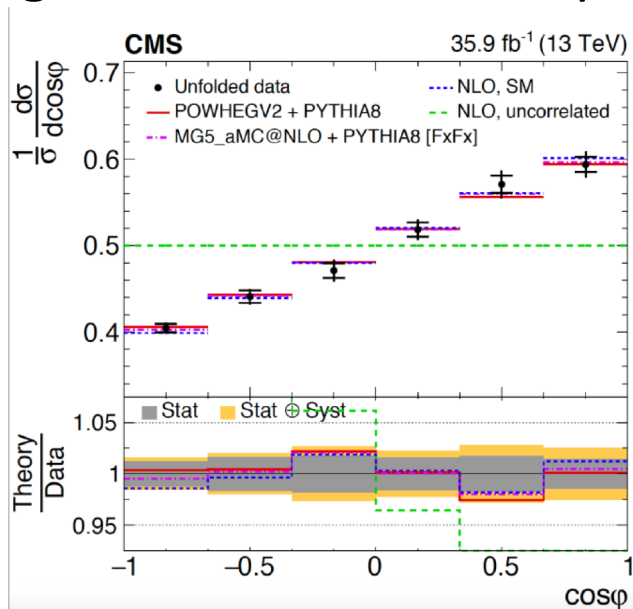
C Severi et al. [arXiv:2110.10112v2](https://arxiv.org/abs/2110.10112v2)



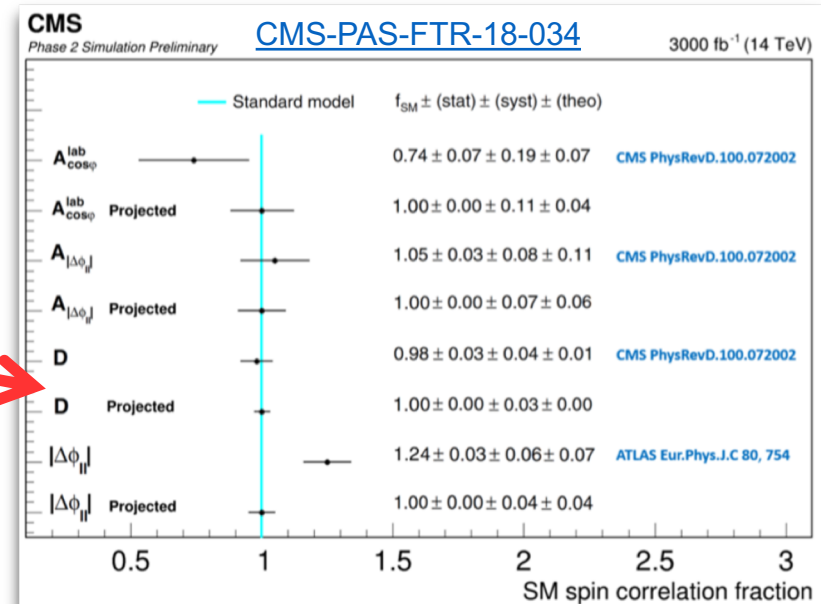
Precision measurements in top sector



- Allows to access quantum correlations in top quark production and unravel quasi-bound state puzzle: NRQCD vs weakly bound $t\bar{t}$ ground-level state $\rightarrow$ prospects at HL-LHC ?
- Allows to access quantum correlations in top quark production and unravel quasi-bound state puzzle: NRQCD vs weakly bound $t\bar{t}$ ground-level state $\rightarrow$ prospects at HL-LHC ?



Accessible via opening angle between l 's in top parent rest frame



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

Contributed to Snowmass, [CMS-PAS-FTR-18-034](https://arxiv.org/abs/1803.08481)

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

ML top Reconstruction

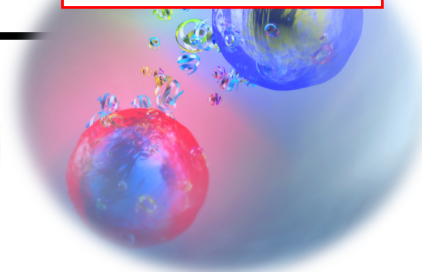
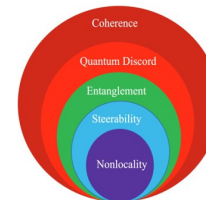
Quasi-bound state:
CMS II + l_j & ATLAS II

Double diff. xsec

Polarisation (0 in SM)

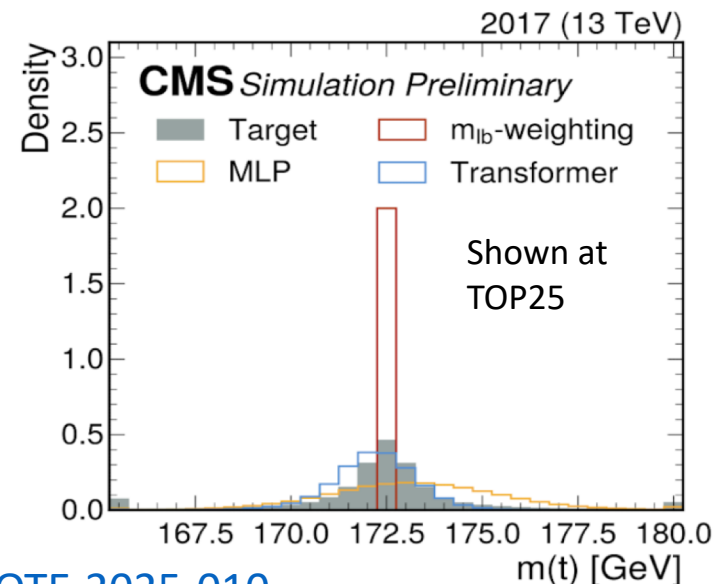
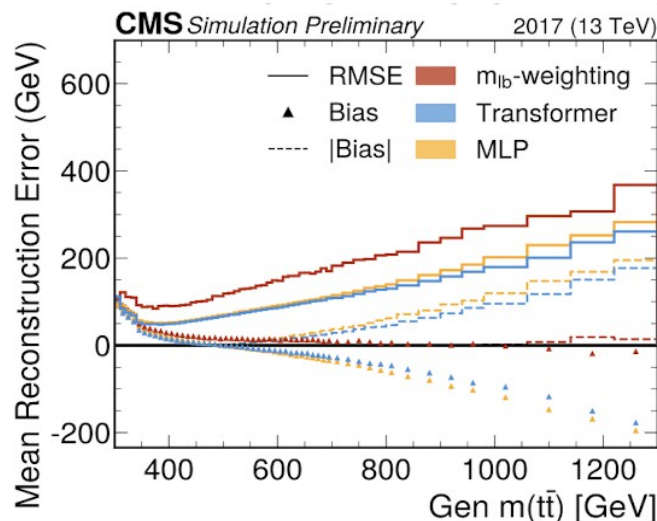
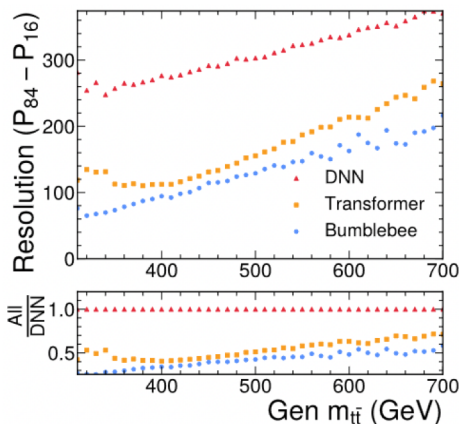
Spin Correlation

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



→ RMSE captures amount of bias and variance into singular value

LLM “bumblebee”:

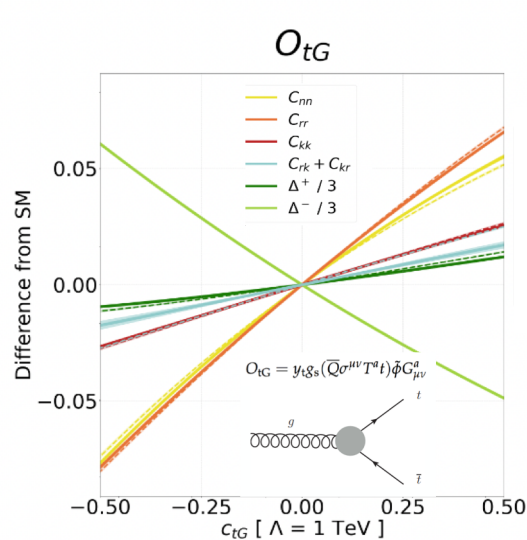
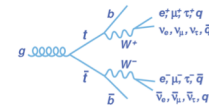


[CMS-NOTE-2025-010](#)

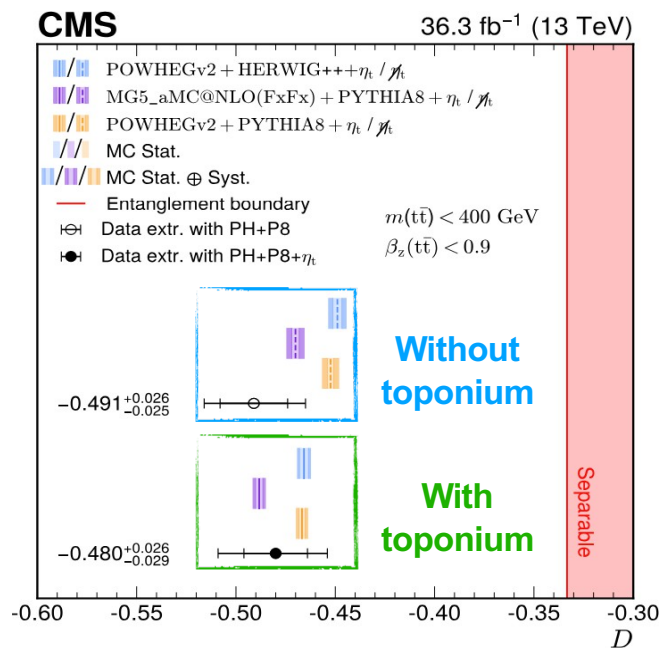
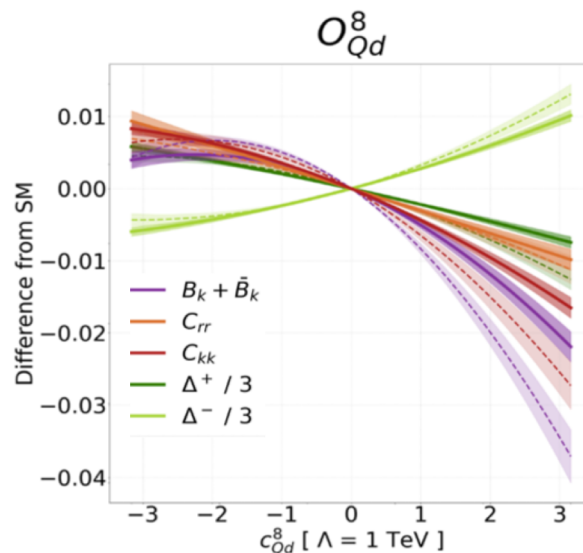
- Transformer approximately 30% improvement vs *mlb* – method
- Reconstructs events for which 5% of time *mlb* - method fails
- Further studies to assess performance, e.g. angular distributions / QIS ob's)
- Exciting region for SM (aka η_t), EFT, and Quantum Correlations...

DOE AI funded

A “new” approach...



JHEP 01 (2023) 148 [2210.09330]



- QIS observables anti-correlated / orthogonal to existing spin density / polarization obs!
- Stay tuned: exciting new submission by Jung group soon on arxiv!

- **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!**

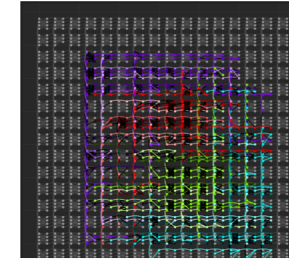
QC & Machine Learning



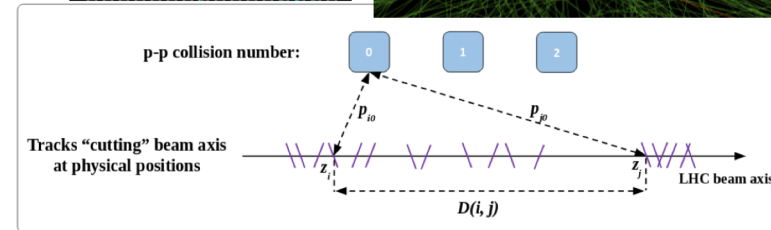
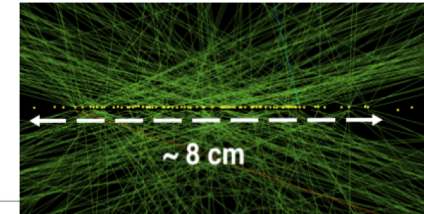
HL-LHC records enormously large sample of pp collisions, even larger sets of Monte Carlo are needed

- AI/ML tools, e.g. toponium identification
- Understand systematic uncertainties at permille level requires billions of events

- “Dream”: Event reconstruction via QC
- Machine learning via Support Vector Machines
- Quantum Information Science for HEP
- **Apply QML for DoD supply-chain / economy**
 - STTR phase I, II now in III
 - QML applied to real data showed 20-27% gains
 - Patent submitted & pending



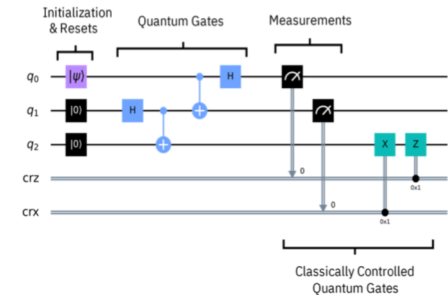
[arXiv:1903.08879]



QC potential:

- N qubits: 2^N
- 50 qubits $\rightarrow 10^{12}$ bits

BUT error correction reduces usable # qubits

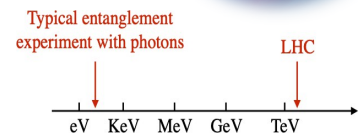


D-Wave
IBM Q



Cutting-edge computing for HEP

- Signal / Background ID via ML: “toponium”
- Event reconstruction via QA
- ML on QC for real-world applications
- Exciting: top quark entanglement
- High interest by students & in-need for workforce



Annealers

Image courtesy of: https://docs.dwavesys.com/docs/latest/c_gs_2.html

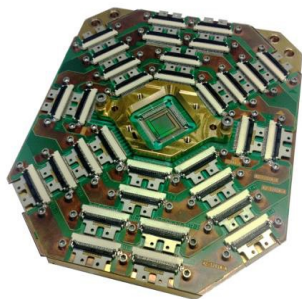
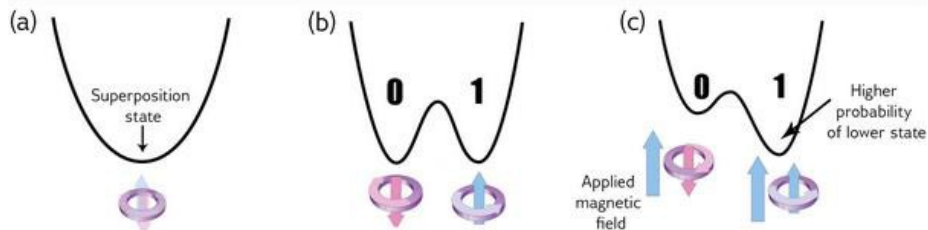
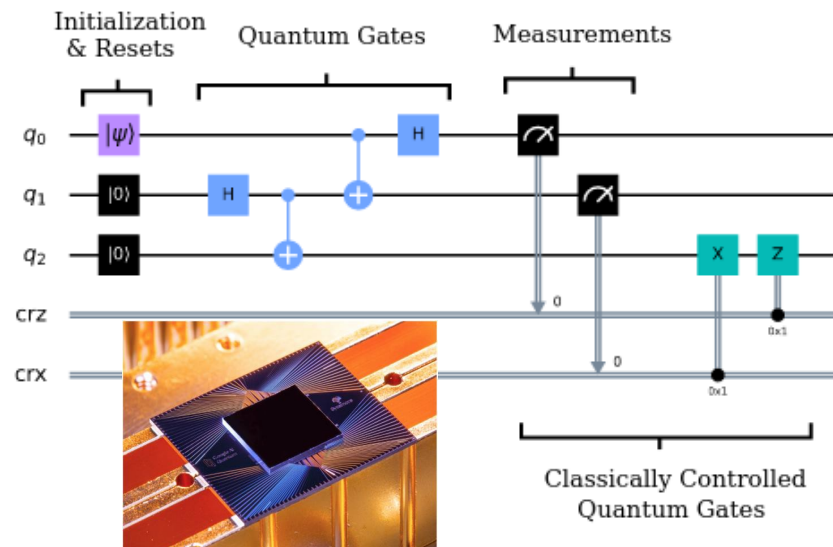


Image courtesy of:
https://www.dwavesys.com/sites/default/files/14-1047A-A_Practical_Quantum_Computing_An_Update_0.pdf

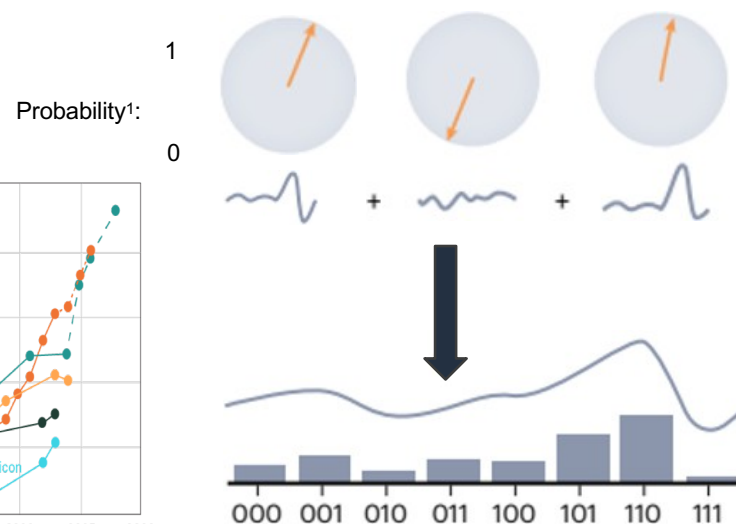
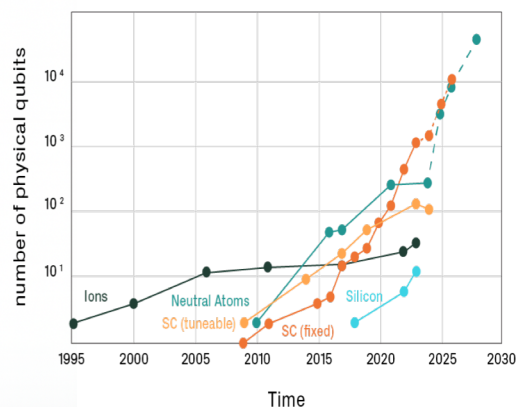
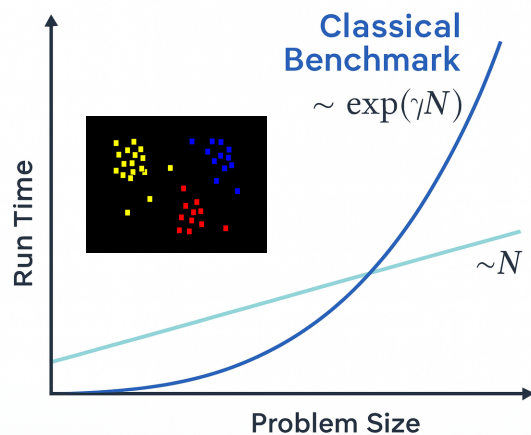
The Second Quantum Revolution, National Institute of Standards and Technology (NIST), 21.3.2018 (updated 5.4.2022)

Circuits/Gates

Image courtesy of: <https://qiskit.org/textbook/ch-algorithms/defining-quantum-circuits.html>



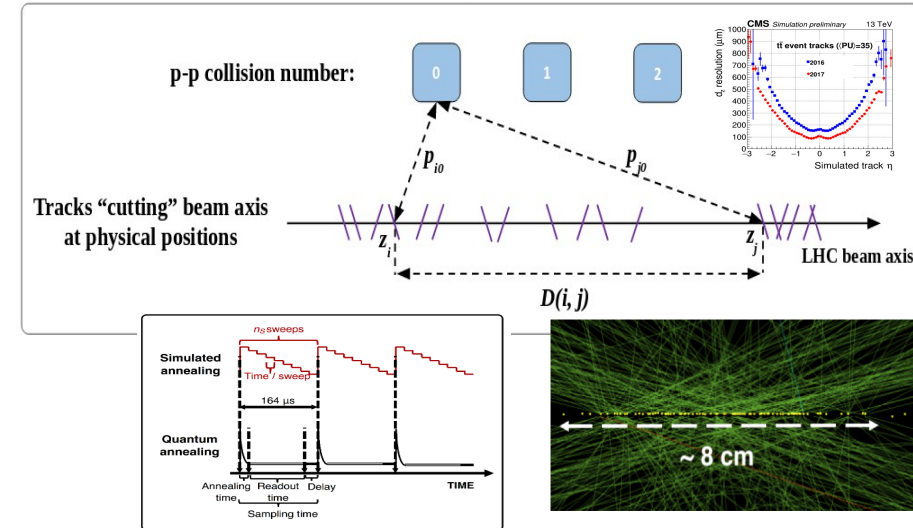
1. Combinatorial optimization problems
2. Fast to check, hard to solve (classically)



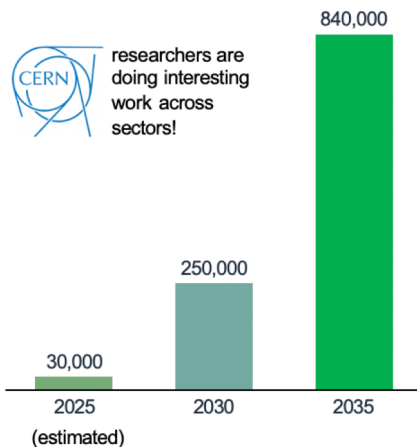
Quantum Computers – promise / dream ?

- Solve z-vertexing on a D-Wave annealer
- Centroid-based clustering is NP-hard
- System can be modeled as an **Ising model**

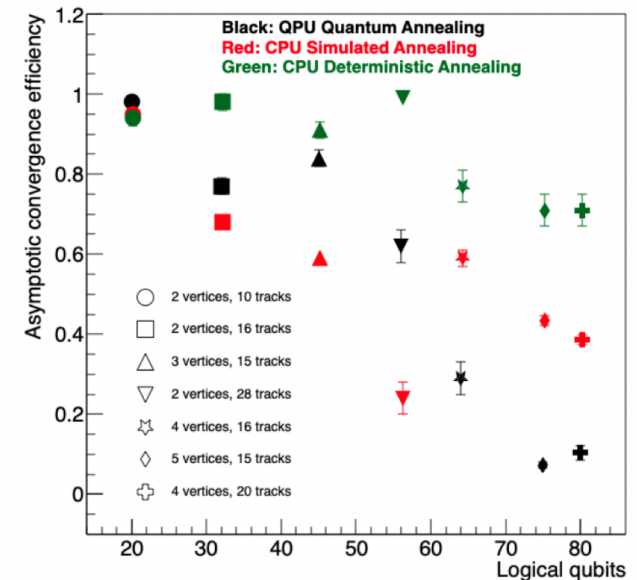
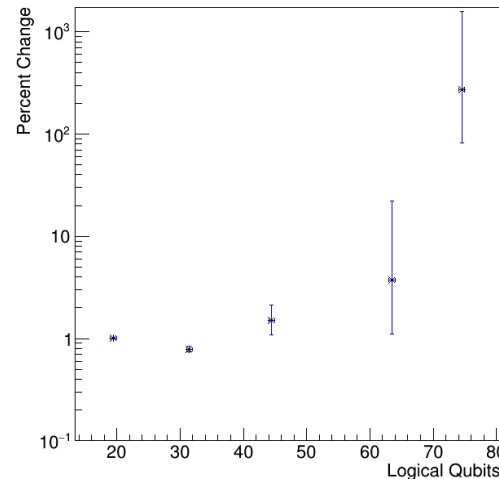
[Das, Wildridge, Jung \(2023\) \[arXiv:1903.08879 - v4\]](#)



Estimated total quantum job growth²



Optimized Performance Difference



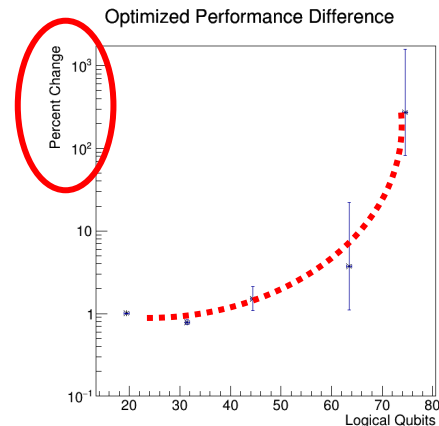
Quantum Computing: Improvements



- CPU is tied to similar performance as QPU
 - 100% convergence if allowed enough time
- Excellent convergence for “small” problems
- 1D clustering → not a 3D event reconstruction
- New physics detection by qbit arrays

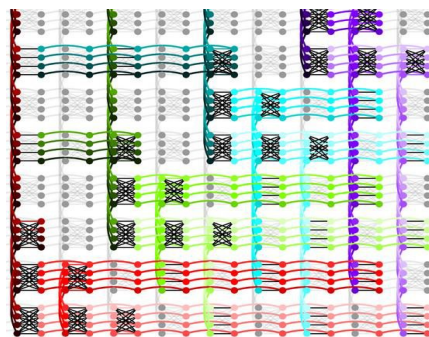
Significant impact on QPU performance

- Supported by Seed grants
- - Phase III direct contract with **QRS** AirForce to optimize

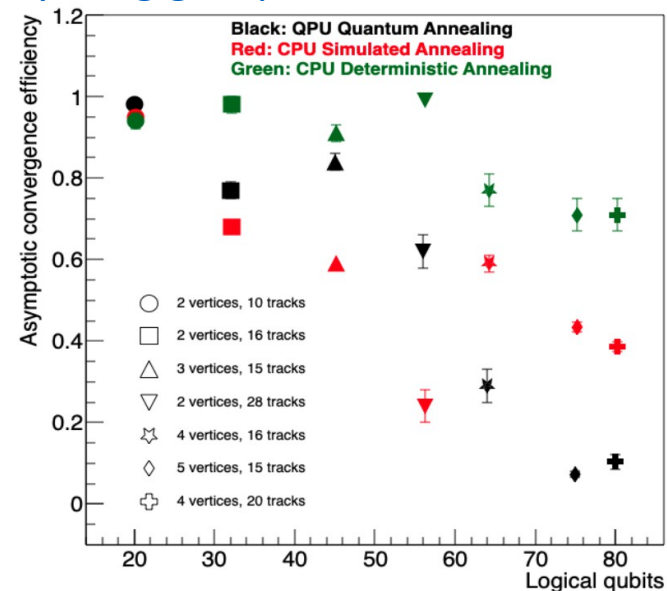


ce

4 Vertices, 16 tracks



By Jung group [arXiv:1903.08879]



Optimized results for a variety of event complexities

Huge improvement at large logical q-bits!
Preparing for (re)-submission!

- QPU has an advantage for certain data types & complexities
- Even with no QPU tuning applied: Performance comparable to modern CPU...
- Factors of 100x improvement possible!

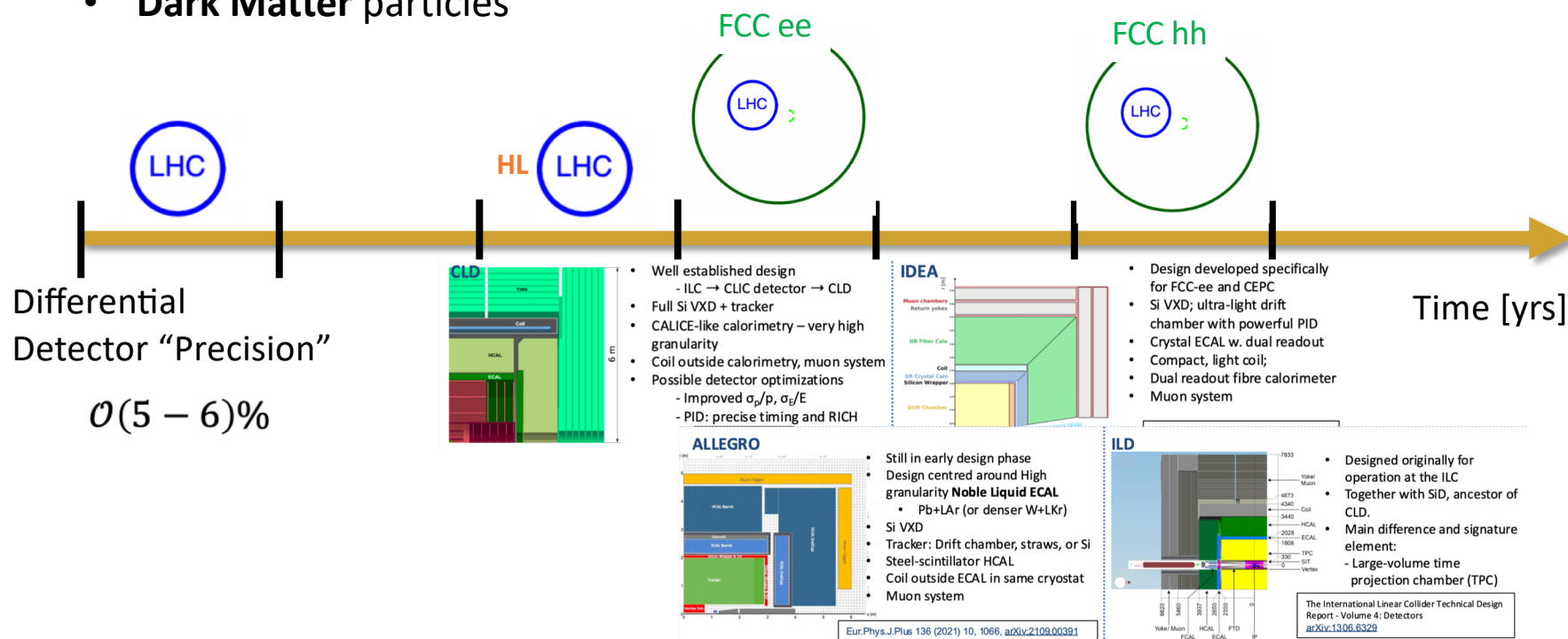
Future colliders (FCC like)

Quantum Information Science for Particle Physics going into the (far) future

- Harvest ML/AI but also Quantum Computing

Applications to HEP:

- Support Vector Machine to separate complex data set, use qSVM
- Development of Machine Learning algorithms
 - Tracking of “disturbance” in a fully entangled QC, new physics
 - **Dark Matter** particles



FCC – *ee*: basics

5×10^{12} Z bosons

- ▶ Unprecedented $\tau^+\tau^-$ statistics at Z pole $\rightarrow$ full quantum tomography

10^6 Higgs bosons

- ▶ ZH production at 240 GeV $\rightarrow$ $H \rightarrow ZZ^*$, WW^* , $\tau\tau$ entanglement channels

10^6 top-quark pairs

- ▶ $t\bar{t}$ above threshold $\rightarrow$ entanglement & Bell tests in quark sector

Known ν s to ppm

- ▶ Resonant depolarization calibration $\rightarrow$ exact density matrix normalization

Zero pileup

- ▶ Perfect kinematic reconstruction — no hadronic contamination

parameter	Z	WW	H (ZH)	$t\bar{t}$
beam energy [GeV]	45.6	80	120	182.5
synchrotron radiation/beam [MW]	50	50	50	50
beam current [mA]	1294	135	26.8	5.1
number bunches / beam	11200	1852	300	64
total RF voltage 400/800 MHz [GV]	0.08 / 0	1.0 / 0	2.09 / 0	2.1 / 9.2
luminosity / IP [$10^{34} \text{ cm}^{-2}\text{s}^{-1}$]	145	20	7.5	1.4
total integrated luminosity / IP / year [$\text{ab}^{-1} / \text{yr}$]	17	2.4	0.9	0.17
beam lifetime [min]	21	13	9	10

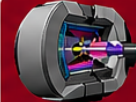
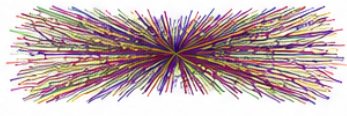
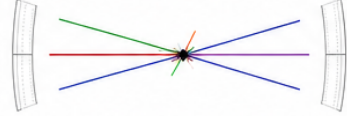
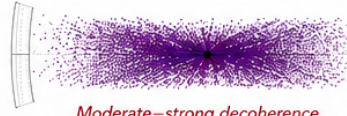
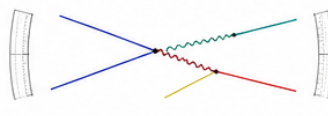
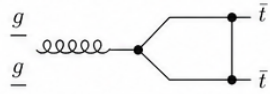
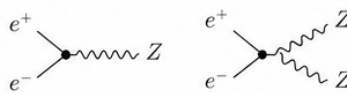
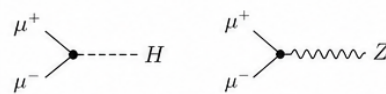
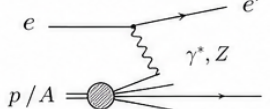
4 years
 6×10^{12} Z
LEP $\times 10^5$

2 years
 $> 10^8$ WW
LEP $\times 10^4$

3 years
 $> 2 \times 10^6$ H

5 years
 2×10^6 $t\bar{t}$ pairs

- Better control of parametric uncertainties (α_S , m_t , m_H)
- Higher order calculations
- Experimental systematic uncertainties
 - Understand **correlations among bins** in distributions
 - See earlier slides...

	 LHC (pp) 13–14 TeV	 FCC-ee (e⁺e⁻) 90 GeV – 365 GeV	 Muon Collider (μ⁺μ⁻) ~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!**

AI generated Table

Lots of opportunities ahead...

- ECFA (European Committee for Future Accelerators) matrix of experiment/detector” mapped to technologies / R&D (DRD)

- ECFA Detector R&D roadmap:

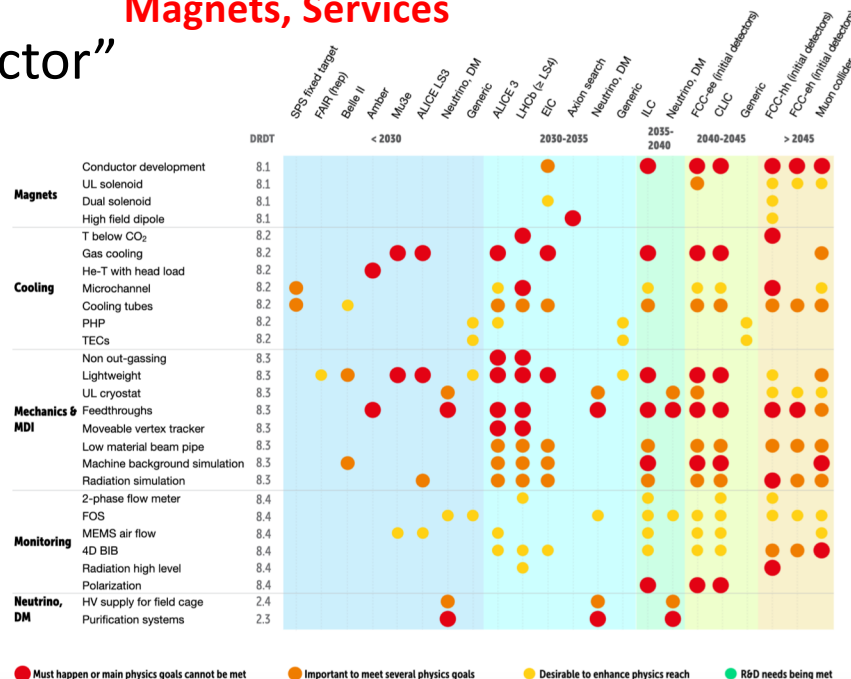
<https://cds.cern.ch/record/2784893>

R&D collaborations

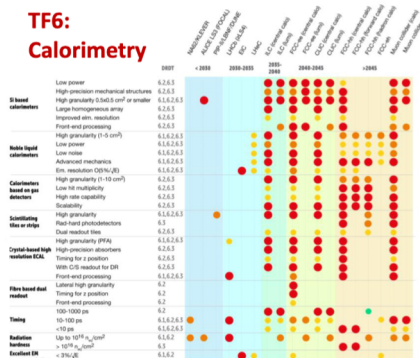
- [US CPAD RDC's](#)
- [Europe CERN DRD's](#)

→ Just few examples,
Get involved!

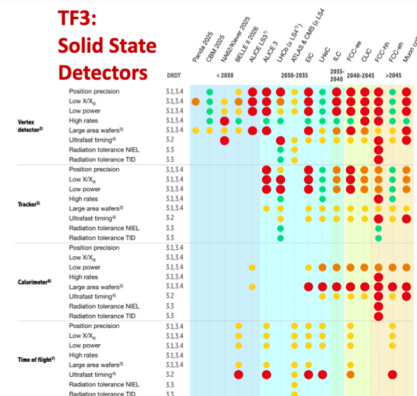
TF8: Mechanics, Cooling, Magnets, Services



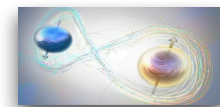
TF6: Calorimetry



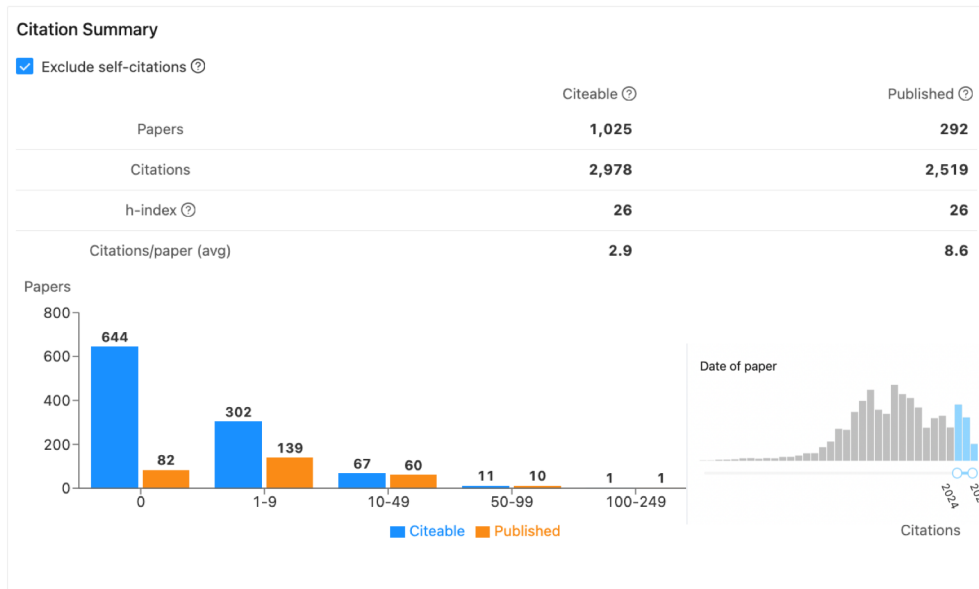
TF3: Solid State Detectors



Exciting new results...



Not showing bound-state citations yet

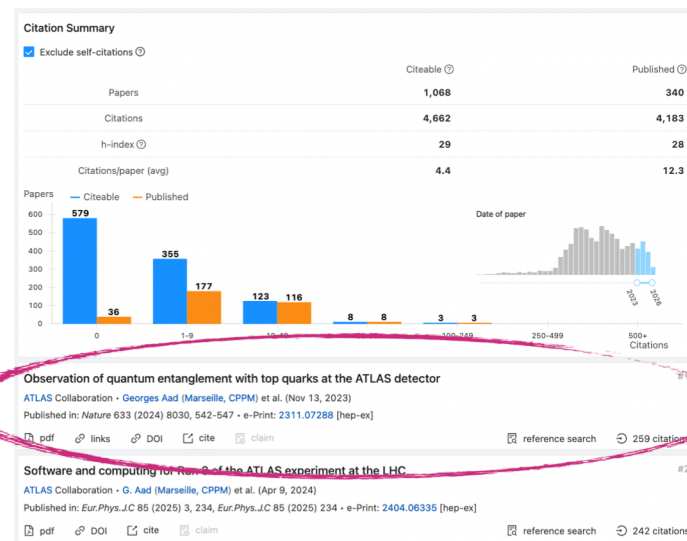


The CMS Statistical Analysis and Combination Tool: Combine #1
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Apr 9, 2024)
Published in: *Comput.Softw.Big Sci.* 8 (2024) 1, 19 • e-Print: [2404.06614](#) [physics.data-an]
pdf DOI cite reference search 460 citations

Performance of the CMS high-level trigger during LHC Run 2 #2
CMS Collaboration • A. Hayrapetyan (Yerevan Phys. Inst.) et al. (Oct 22, 2024)
Published in: *JINST* 19 (2024) 11, P11021 • e-Print: [2410.17038](#) [physics.ins-det]
pdf DOI cite reference search 310 citations

Observation of quantum entanglement in top quark pair production in proton–proton collisions at $\sqrt{s} = 13$ TeV #3
CMS Collaboration • Aram Hayrapetyan (Yerevan Phys. Inst.) et al. (Jun 6, 2024)
Published in: *Rept.Prog.Phys.* 87 (2024) 11, 117801 • e-Print: [2406.03976](#) [hep-ex]
pdf DOI cite datasets reference search 208 citations

CMS: 3rd most cited paper since 2024...



ATLAS: Most cited paper since 2023...

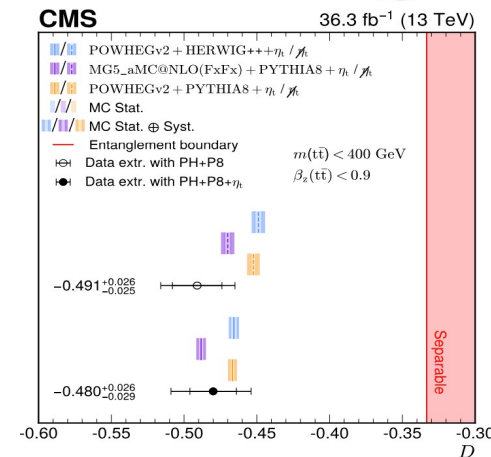
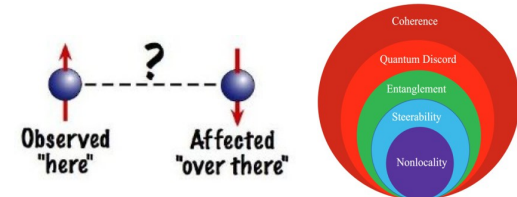
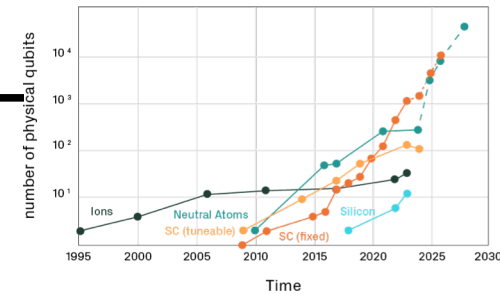
- **Quantum Tomography – a rich exciting new field!**
... threshold scan at FCC-ee allows a deep-dive into $t\bar{t}$ "structure" formation & QIS
- **Bright future ahead!**

Big Questions & Challenges

- QIS observables for EFT to break “flat” directions for **top quark and Higgs sector**
- Top quark physics at center of big questions
 - Observation of entanglement & a pseudo-scalar resonance, caveats apply!
 - **Exciting field of Quantum Information in HEP**
- Quantum Observables for Collider Physics
 - Early May 2027 @Northwestern U
- QML has applications today demonstrating the power of QC’s in “niche applications”!

→ Designing detectors that preserve quantum information, performing measurements that expose it, and developing inference tools capable of interpreting it.

Collider experiments become laboratories for quantum information science.



[APS TV: From Detectors to Quantum Algorithms](#)

APS TV 2026:
“From
Detectors to
Quantum
Algorithms”



Bonus: PQSEI – Quantum Informatics



Andreas Jung

Professor of Physics and Astronomy

Research Interests

High Energy Physics, quantum AI/ML, Algorithms

Research Impact

The current research of Dr Jung and his group focuses on quantum informatics with applications of quantum machine learning to solve real-life problems in supply chain and others, as well as R&D for highly integrated electric circuits to track charged particles in high energy collisions including quantum sensing with novel applications for particle physics. One of the specialties of the Jung group is to leverage AI and ML applications to analyze vast data sets at the Large Hadron Collider with respect to top quark quantum tomography.

Contact Info

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anjung@purdue.edu

Phone

(765) 494-5399

Research Area

QUANTUM DEVICES →

QUANTUM INFORMATICS →

QUANTUM SIMULATION →



The Jung group

APS TV 2026:
“From
Detectors to
Quantum
Algorithms”





Purdue Quantum Science
and Engineering Institute

QUANTUM

Purdue Quantum Science and Engineering Institute (PQSEI): The hub for quantum activities at Purdue

(Pronounced P-Q-say)

**Quantum science and engineering
is a priority at Purdue**

- Quantum is pillar of Purdue Computes, a strategic initiative that drives Purdue's forward-looking planning and investment.
- Prof. Manfra announced as Chief Quantum Officer in early 2026.

~70 affiliated faculty

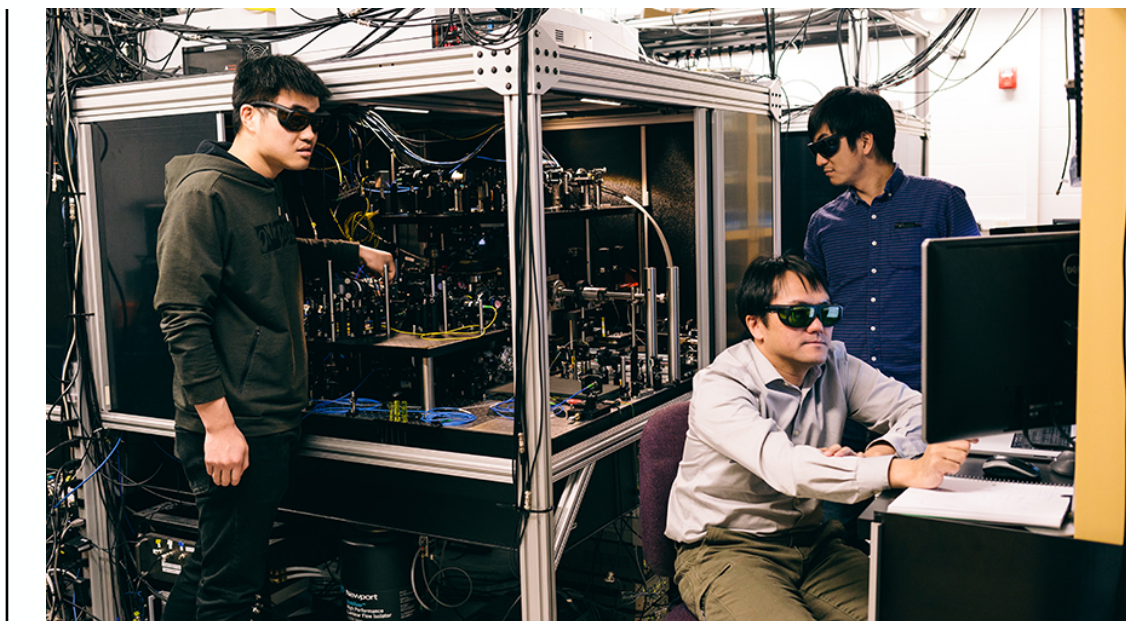
- Primarily from College of Science and College of Engineering

Wide-ranging fields of study:

- Physics and Astronomy
- Electrical and Computer Engineering
- Chemistry
- Computer Science
- Mathematics
- Materials Engineering
- Industrial Engineering
- Nuclear Engineering
- Chemical Engineering

A deeper look at research areas *Key research strengths*

- Atomic molecular and optical physics
- Solid-state qubit fabrication and measurement
- Quantum photonics
- Topological quantum materials
- Quantum chemistry
- Quantum simulation
- Quantum algorithms and optimization





Intentional cross-disciplinary collaboration

Scientists and engineers working together to solve real world issues

Our strength is our intentional cross-disciplinary collaboration between the **SCIENTISTS** who discover quantum phenomena and **ENGINEERS** who develop quantum technologies.

Birck Nanotechnology Center – \$70M upgrade completed in 2025

State-of-the-art facilities foster innovation

- Three-level structure consists of a full sub-fab, the cleanroom level, and an air-handling level above the cleanroom
- 25,000 sq. ft. of bay-chase cleanroom, with 20% of the bays operating at ISO 3 (Class 1), 50% operating at ISO 4 (Class 10), and the remaining 15% operating at ISO 5 (Class 100)
- Capabilities include nano- and microscale lithography, wet- and dry-etching, physical vapor deposition, three-tube banks of process furnaces, ultra-pure water system, and pharmaceutical-grade bio cleanroom.
- Facility also provides 33,000 sq. ft. of specialized laboratories and offices for 45 resident faculty.



Major PQSEI Initiatives

Building cross-sector partnerships and bolstering Midwest/Indiana quantum ecosystem

▪ Chicago Quantum Exchange (CQE)

- Advances the science and engineering of quantum information, trains the quantum workforce, and drives the quantum economy
- Partnership with U. Chicago, Illinois, Northwestern, Wisconsin, Argonne, and Fermilab.



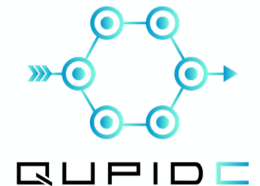
▪ Midwest Quantum Collaboratory (MQC)

- Partnership with UM, MSU, OSU, UIC, IU, NU, and WashU to build collaborations across sectors

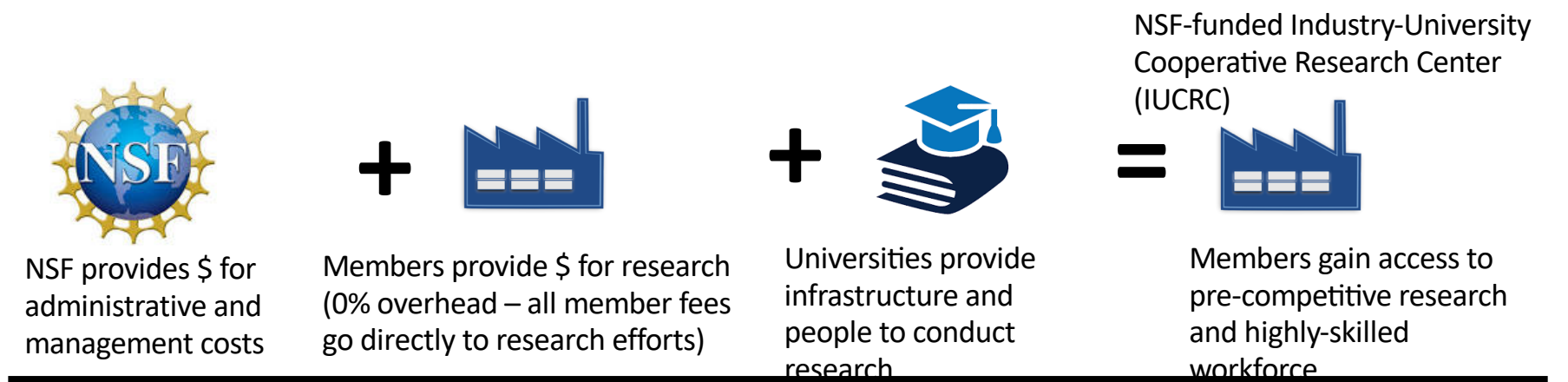


▪ Quantum Photonic Integrated Design Center (QuPIDC)

- DOE Energy Frontier Research Center (~\$14M, 4-year award); Libai Huang (Chemistry) is PI
- Goal: To discover, design, and realize robust many-body entangled photon and matter states



Center for Quantum Technologies (CQT)



PI & Director
Prof. Tongcang Li
tcli@purdue.edu

Industry Liaison
Officer/Exec. Dir.:
Dr. David Stewart
davidstewart@purdue.edu

Benefits for Industry/Government Members:

- All research projects are selected by members
- Access to talent (students and faculty)
- Leverage of research dollars (minimum 17:1 leverage on ~\$55K member fee)
- Network opportunities with other CQT members
- Royalty-free, non-exclusive license to center IP
- R&D risk mitigation – sharing risks with peers

CQT Members:

- AFRL
- AWS
- Cummins
- D-Wave
- Eli Lilly

- Entanglement, Inc.
- L3Harris
- Quantum Computing Inc.
- Toyota

Year 4 Projects Underway

Microsoft Quantum West Lafayette

Industrial-Academic partnership to develop full-stack utility-scale quantum computer

Roadmap to fault tolerant quantum computation using topological qubit arrays

- ~ 10 MSFT employees working on-site
- Dedicated laboratory space, including growth facilities, space in the Birck cleanroom, and characterization laboratories
- Integral contributions to recent Microsoft Quantum progress
- Long-term investment by Microsoft spanning 15 years

Microsoft Quantum[†]
(Dated: July 22, 2025)

We describe a concrete device roadmap towards a fault-tolerant quantum computing architecture based on noise-resilient, topologically protected Majorana-based qubits. Our roadmap encompasses four generations of devices: a single-qubit device that enables a measurement-based qubit benchmarking protocol; a two-qubit device that uses measurement-based braiding to perform single-qubit Clifford operations; an eight-qubit device that can be used to show an improvement of a two-qubit operation when performed on logical qubits rather than directly on physical qubits; and a topological qubit array supporting lattice surgery demonstrations on two logical qubits. Devices that enable this path require a superconductor-semiconductor heterostructure that supports a topological phase, quantum dots and coupling between those quantum dots that can create the appropriate loops for interferometric measurements, and a microwave readout system that can perform fast, low-error single-shot measurements. We describe the key design components of these qubit devices, along with the associated protocols for demonstrations of single-qubit benchmarking, Clifford gate execution, quantum error detection, and quantum error correction, which differ greatly from those in more conventional qubits. Finally, we comment on implications and advantages of this architecture for utility-scale quantum computation.

20 Second Parity Lifetime in an InAs–Pb Tetron Device

Microsoft Quantum[†]
(Dated: June 4, 2026)

A central promise of topological quantum computing is that increasing the excitation gap improves device performance significantly. Here, we experimentally validate this principle in an InAs–Pb tetron device via interferometric single-shot parity measurements. By replacing aluminum with the higher-gap superconductor lead in our superconductor-semiconductor hybrid devices, we have improved the robustness of our topological phase. In addition, to enable fast and precise bring-up at scale, we have developed an rf measurement technique that resolves low-energy wire-end states and directly measures their energy splitting with μeV precision. We employ this technique to bring up a device in a multi-tetron array and perform parity measurements of one of the tetron's hybrid nanowires (NWs). By controllably switching the wire parity, we observe $h/2e$ -periodic bimodal shifts in the quantum capacitance of a quantum dot coupled to the hybrid nanowire in an interference loop. Further time-resolved measurements reveal a characteristic parity switching time of ~ 20 s with some instances reaching minute-scale. Such extremely long parity lifetimes are orders of magnitude longer than typical qubit operation times, which are on the order of μs . Finally, we discuss potential implications for the fidelity of Pauli measurements.

Workforce Development



- Comprehensive Quantum Degrees Program
 - Spanning academic levels from undergraduate to graduate to working professionals
 - Combining both science and engineering fields
 - Breadth of disciplines with opportunities in quantum computing, sensing, and communications
 - Industry guidance and involvement
- Quantum Micromasters Program (online through edX)
- Contributing to Quantum Economic Development Consortium (QED-C) Workforce Committee



Backup
