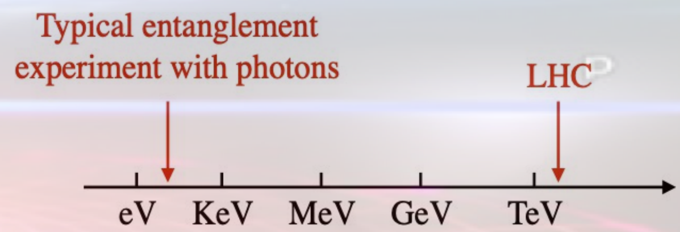
From Entangled Top Quarks to Detector Instrumentation

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



Today's menu:

- The basics…
- Entanglement: a "new" probe to top quark physics
- ML/AI tools to infer new physics
- Detector Mechanics/Instrumentation
- Conclusions

APS TV: From Detectors to Quantum Algorithms

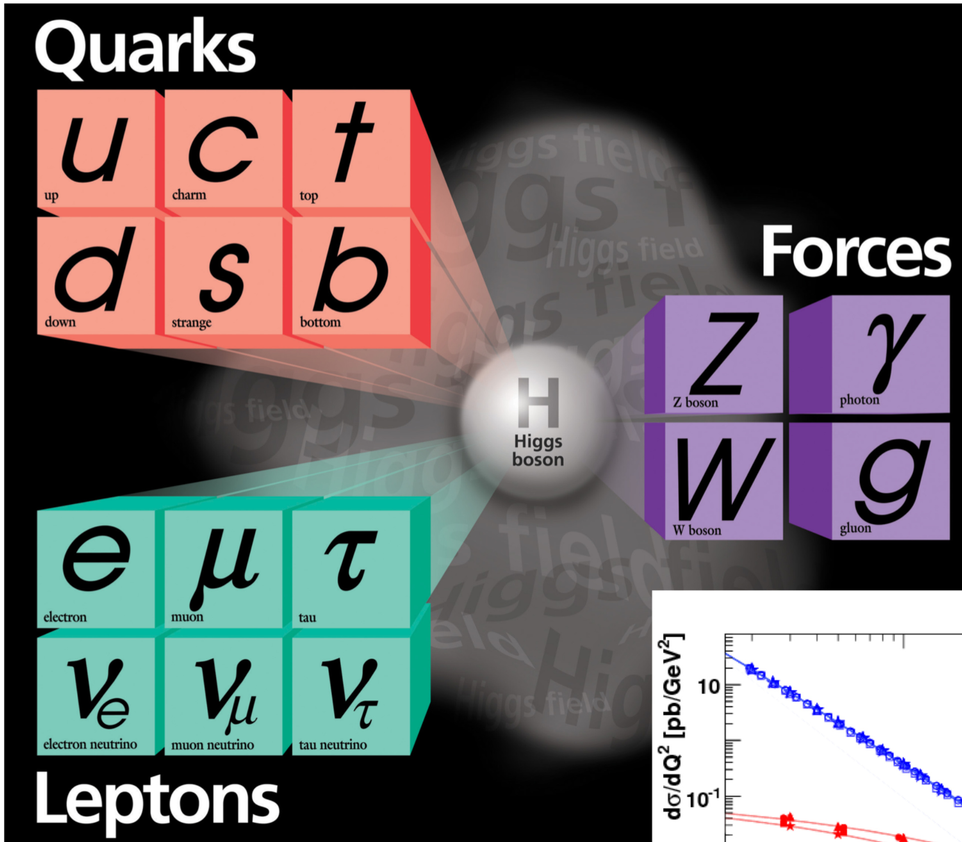
APS TV 2026: "From Detectors to Quantum Algorithms"

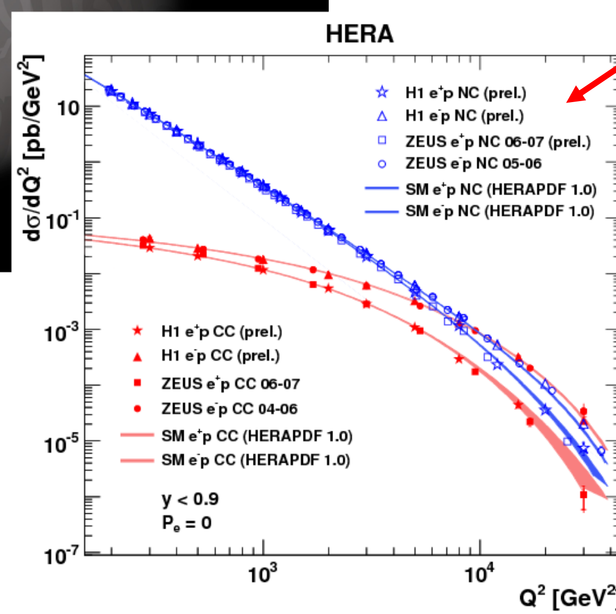
Andy Jung
Particle Physics Seminar
University of Oxford

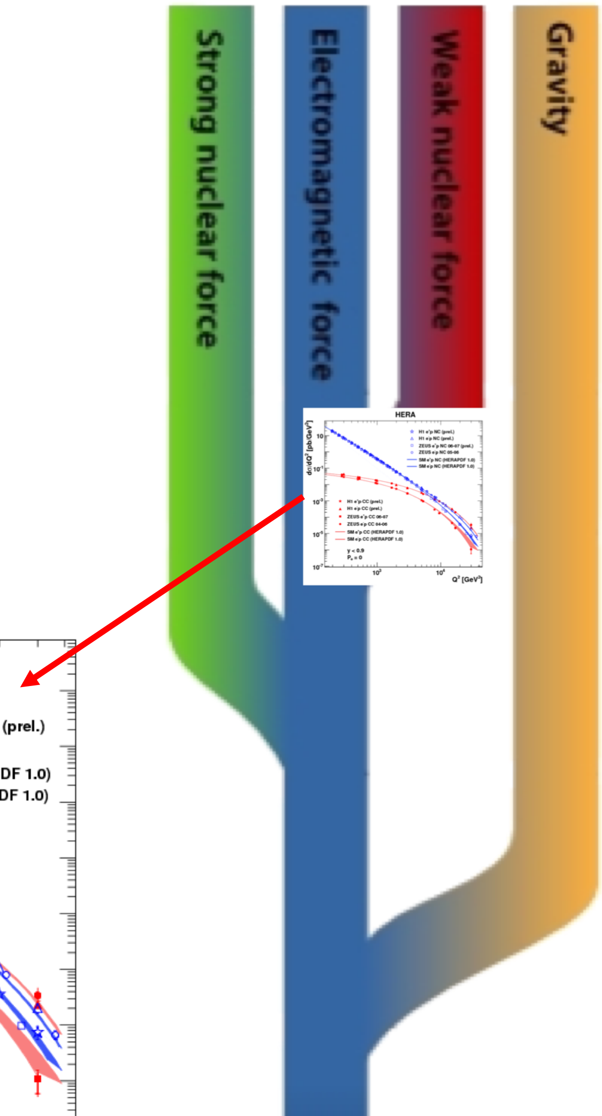
PURDUE UNIVERSITY

Apr 28th, 2026

Standard Model – Particle Physics

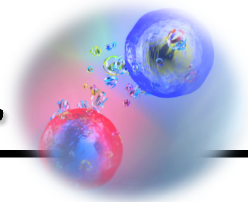




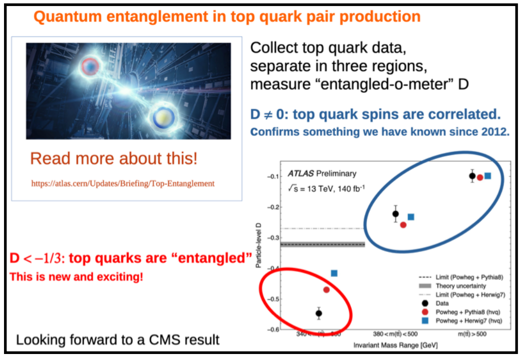


Quantum Observables for Collider Physics

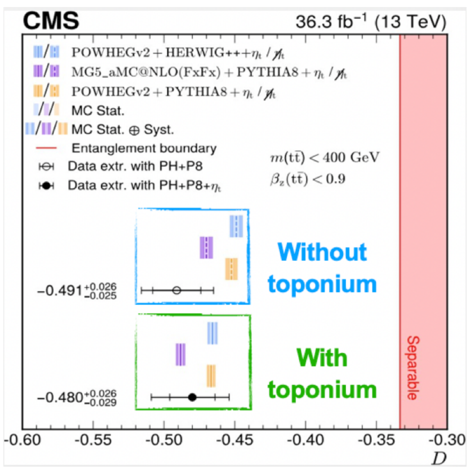
Exciting times…



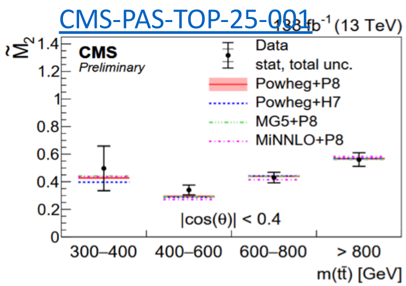
[Nature 633, 542–547 (2024)]

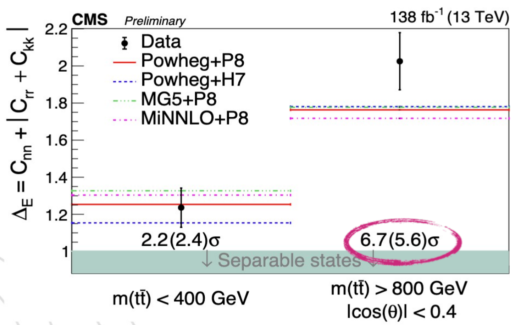


[Rep. Prog. Phys. 87 (2024) 117801]

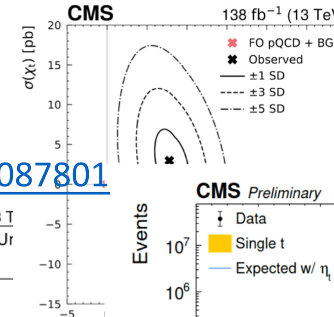


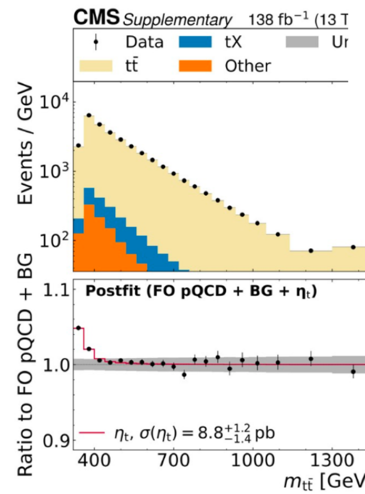
[CMS-PAS-TOP-25-001]

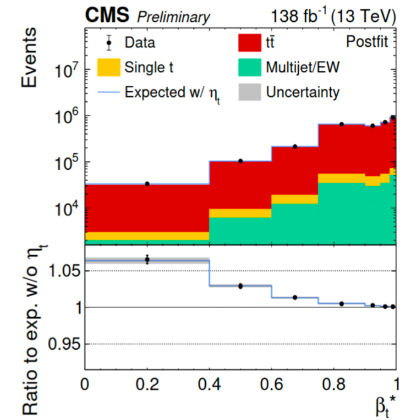




[Rep. Prog. Phys. 88 (2025) 087801]

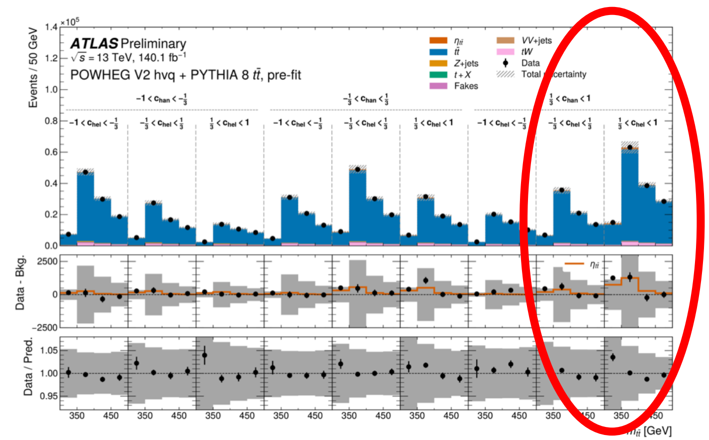






σ(ηt) = 5.1 ± 0.9 pb (> 6 SD)

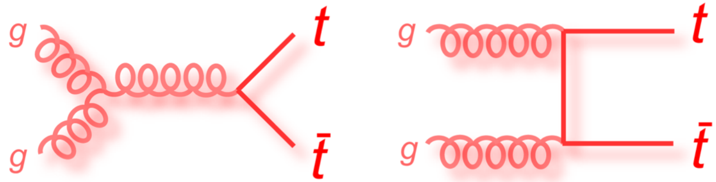
[CERN-EP-2026-002 / TOPQ-2025-11]

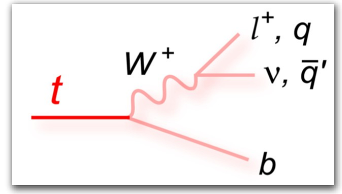


- Updates / News on Theory prediction
- Systematic uncertainties ?
- Need complete picture at LHC
  → stay tuned

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]

→ ***m_t* = 173.34 ± 0.76 GeV**

Unique quark, not stable: Caution!

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

→ **Observe bare quark properties**

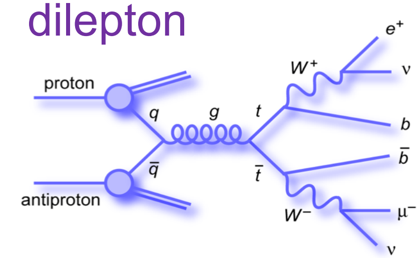
→ **Spin information preserved**

Large Yukawa coupling to Higgs boson

→ λ_t ~ 1 **only *m_t* is a "natural mass"**

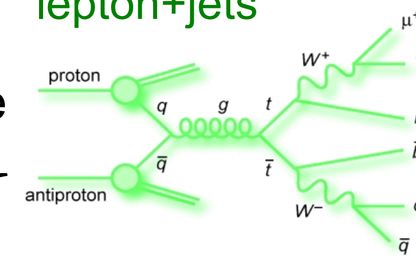
Special role in EW symmetry breaking ?

dilepton

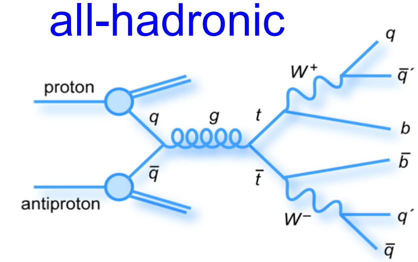


BR, bg increase

lepton+jets



all-hadronic

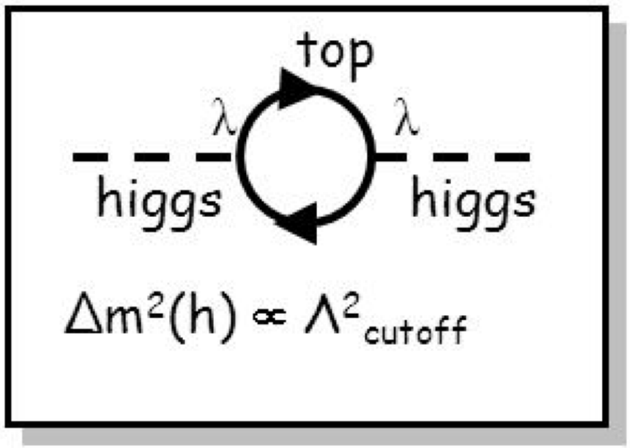


→ unique experimental signature

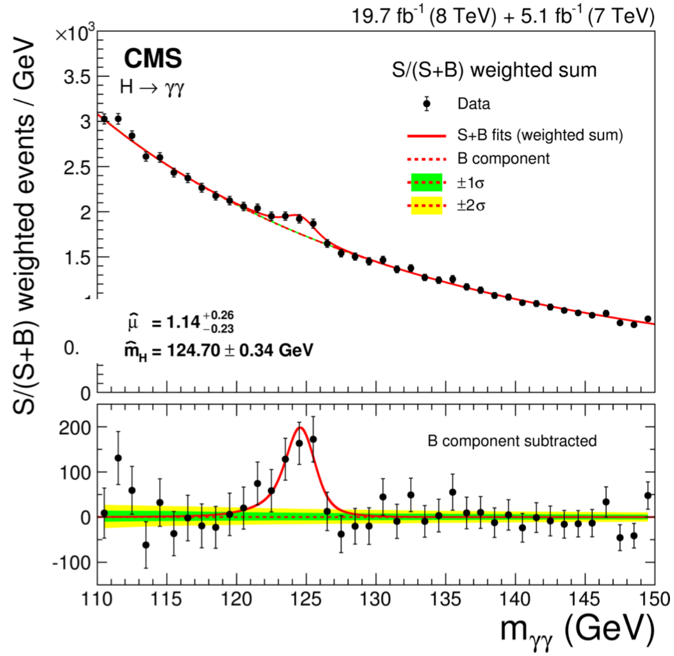
Top quark – Higgs boson interaction

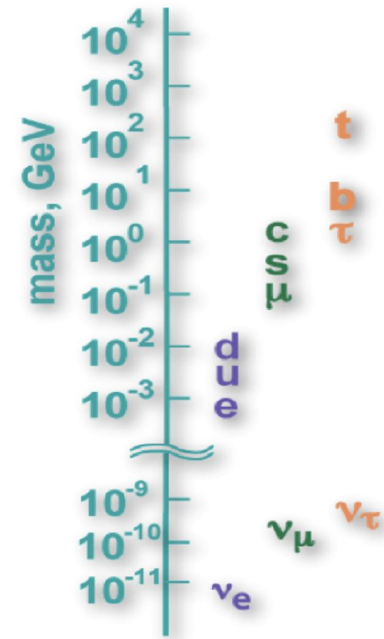
If we could calculate the Higgs mass:

→ Large corrections to the Higgs mass from top quark "loops"



Loops are dominated by top quarks

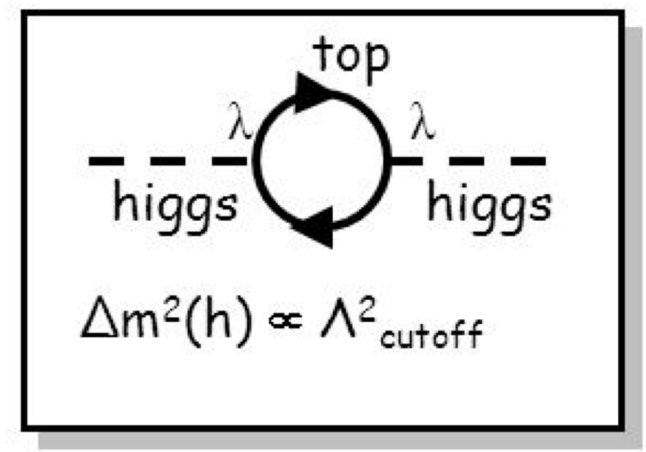




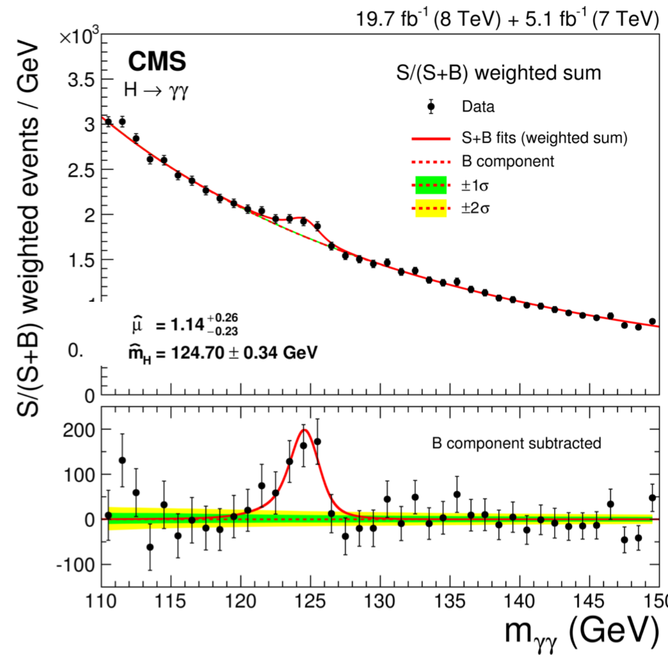
Natural Higgs mass close to Planck scale of 10^{19} GeV

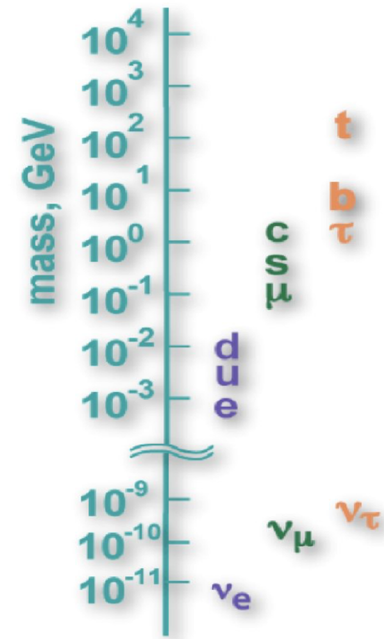
Top quark – Higgs boson interaction

→ Large corrections to the Higgs mass from top quark "loops"



Loops are dominated by top quarks

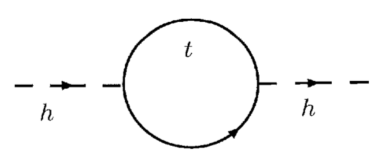


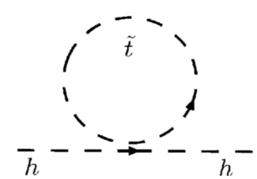


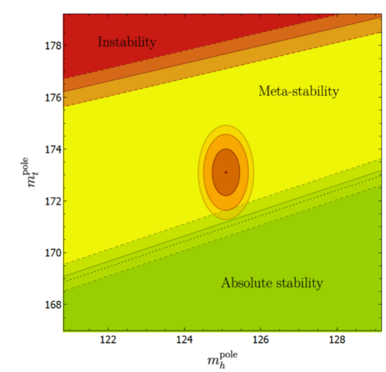
Natural Higgs mass close to Planck scale of 10^{19} GeV

Higgs mass at ~ 125 GeV

→ New physics in loops ?



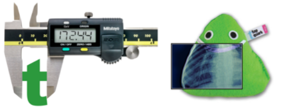




→ Many BSM extensions include a **top quark partner**

→ No fine-tuning if top quark partner exists

Top quark physics: Current status…

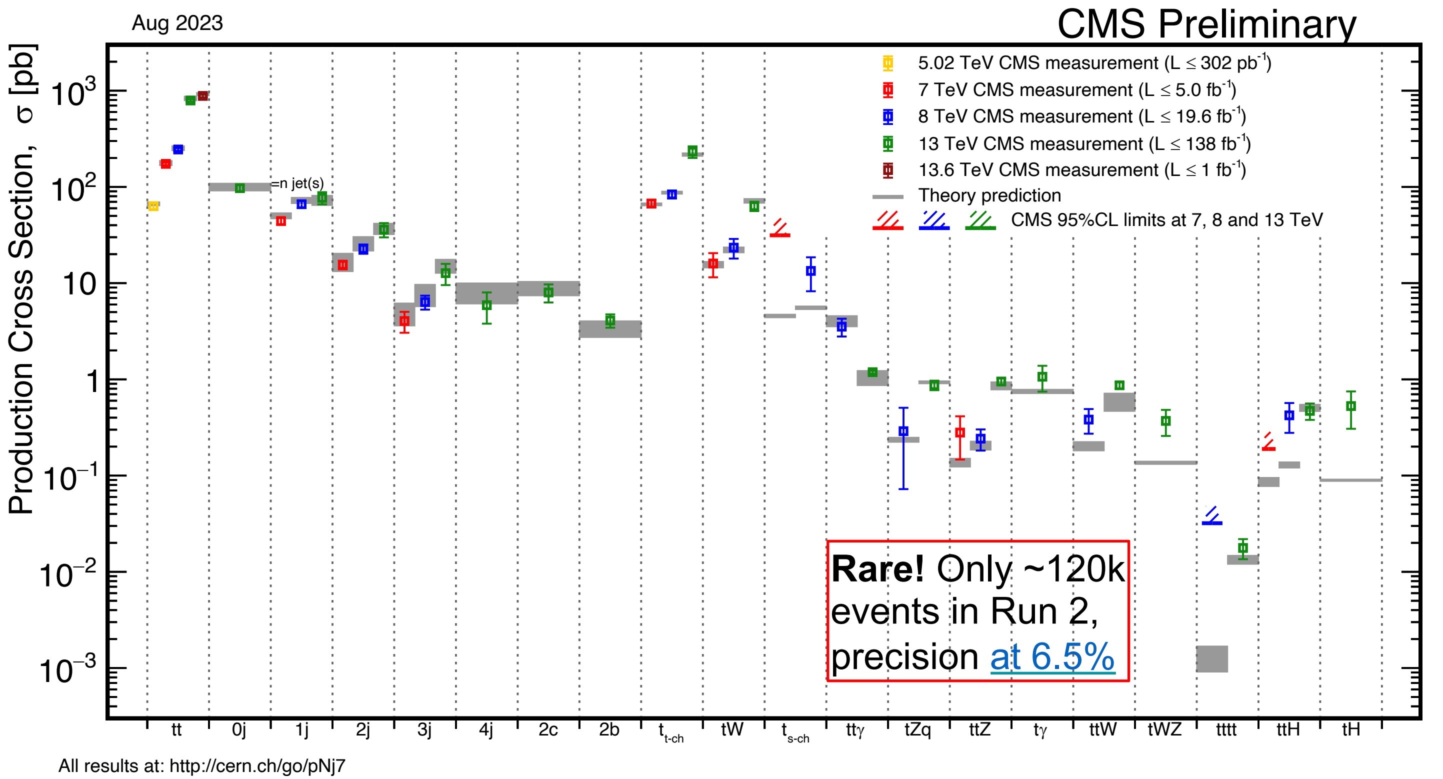


Abundant production!

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

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

→**"Standard candle"**



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

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

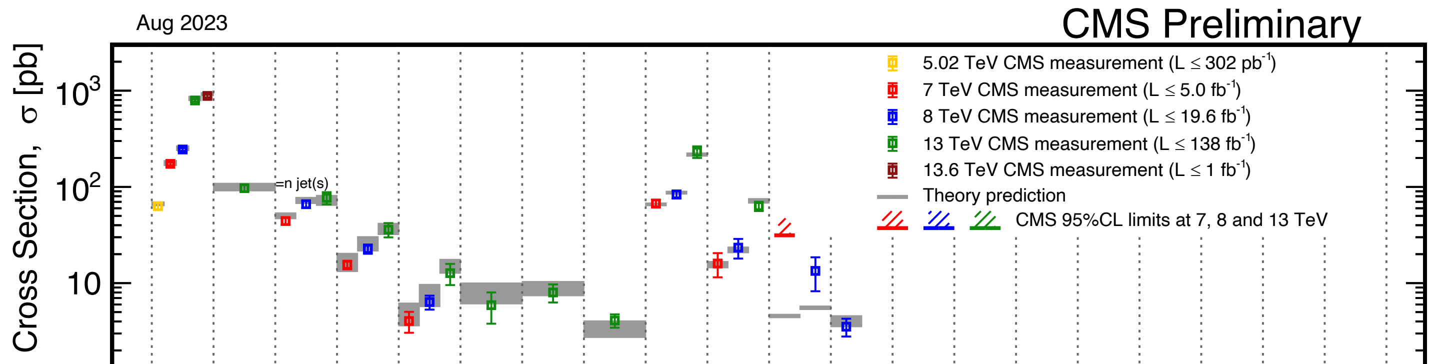
Top quark physics: Current status…

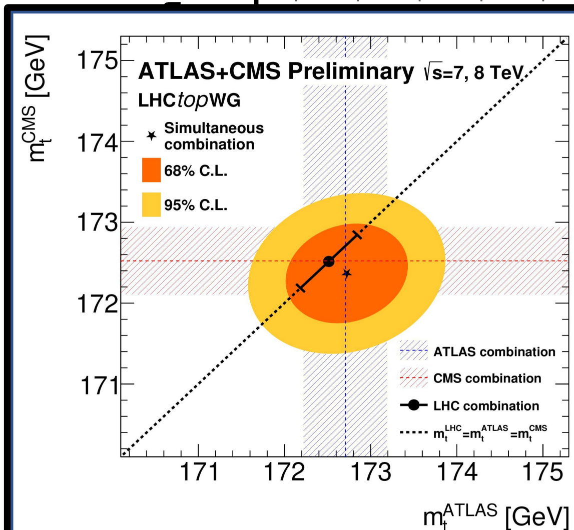
Abundant production!

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

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

→**"Standard candle"**





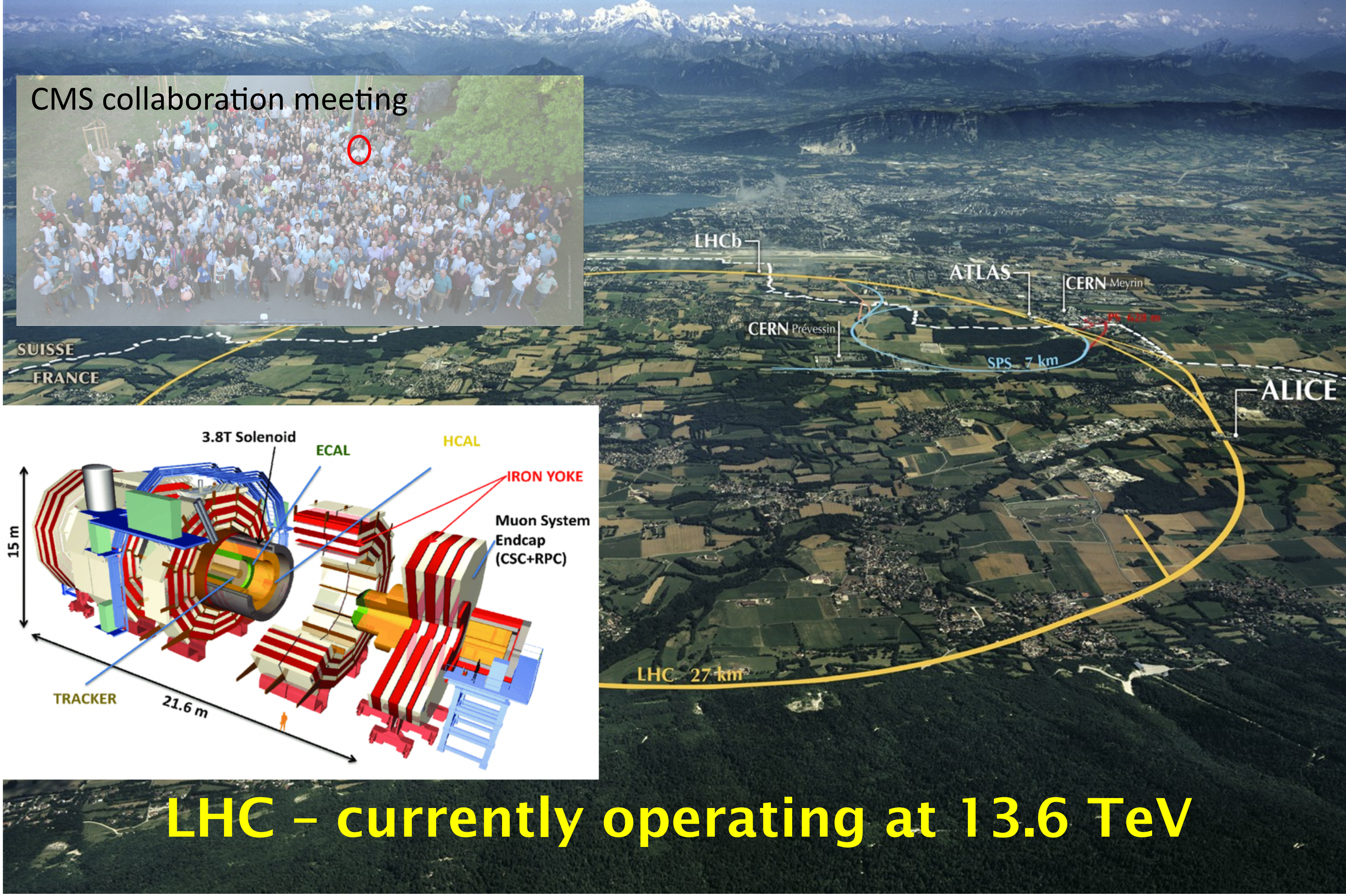
30 years of top quark physics!

Ever more precise measurements enabled by excellent collider and detector performance

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

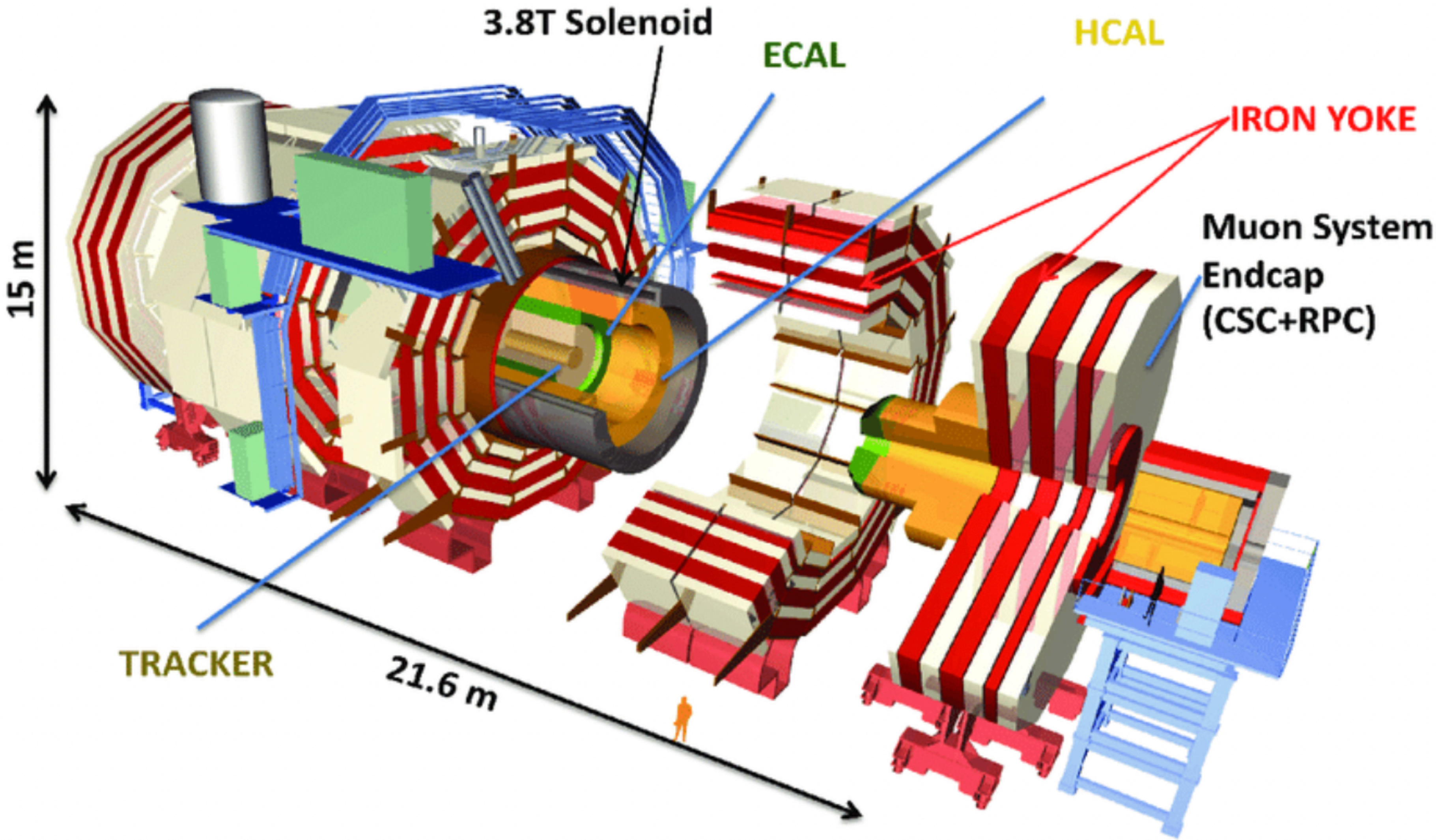
World's premier particle physics laboratory and particle accelerator

The Large Hadron Collider – LHC



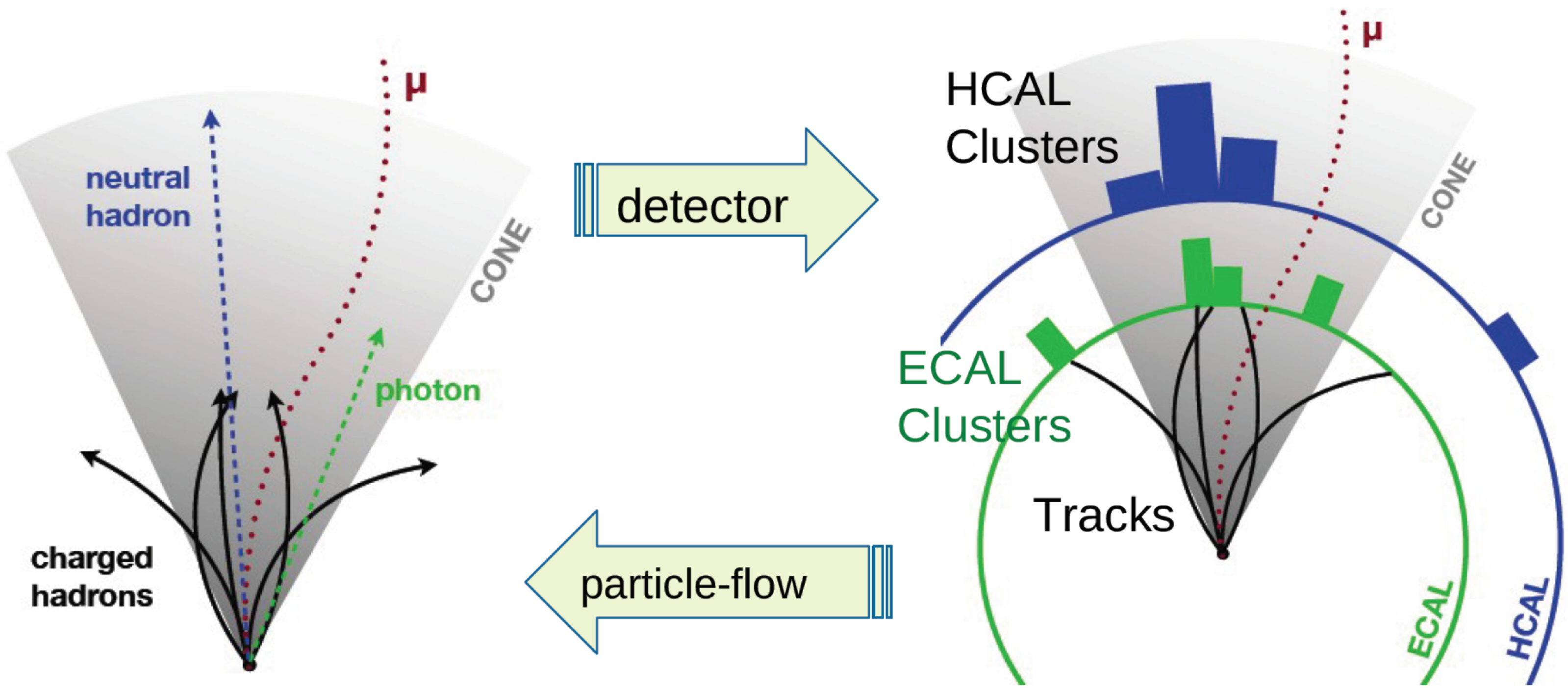
LHC – currently operating at 13.6 TeV

Compact Muon Solenoid / CMS



How to identify particles / objects ?

Combines detector information to ID particles CMS-JME-13001



<u>Isolated Leptons</u>

Dilepton resonances (Z, upsilon, J/psi)

<u>"b-tagging" of jets</u>

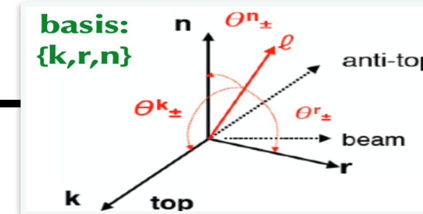
Several techniques, dominated by silicon tracker information

<u>Jets and missing E_T</u>

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**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+ \, d\cos\theta^b_-} = \frac{1}{4}\left(1 + B^a_+ \cos\theta^a_+ + B^b_- \cos\theta^b_- - C(a,b)\cos\theta^a_+ \cos\theta^b_-\right)$$

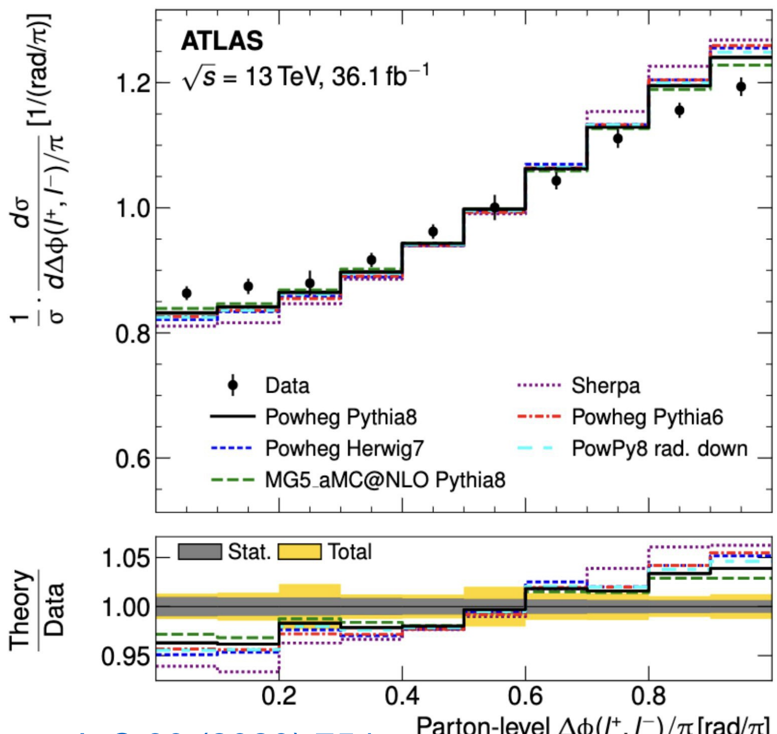
→ Spin dependence of $t\bar{t}$ production is **completely characterized by 15 coefficients** (but we have lost information better "correlations")

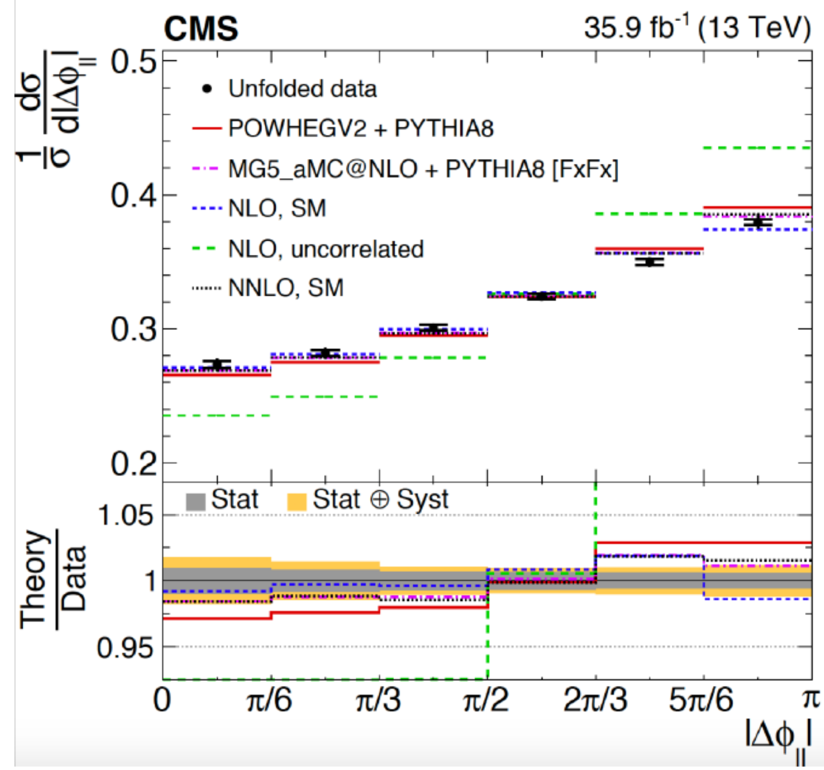
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 + [\text{Coef.}]\, x\right) f(x)$$

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…

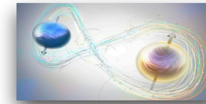




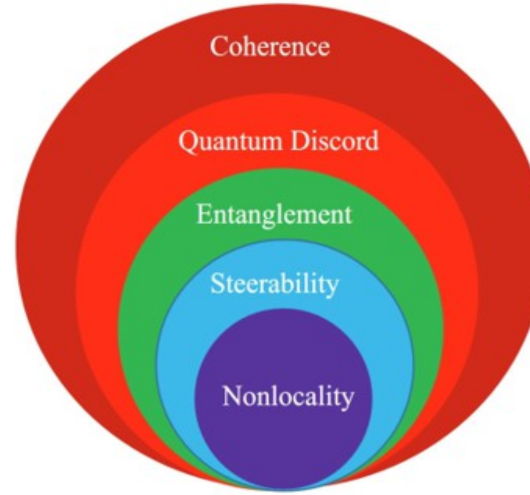
[Eur. Phys. J. C 80 (2020) 754]

← Opening angle between leptons in top parent rest frame

Entanglement in QM



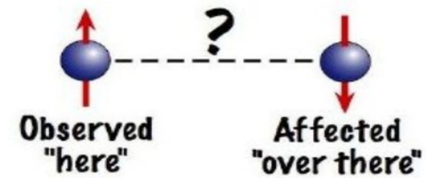
- **Qubit** = two-level quantum system $0\rangle$, $1\rangle$ → most simple quantum system
- **Two qubits** → most simple example of quantum correlations
- Entire hierarchy of quantum correlations



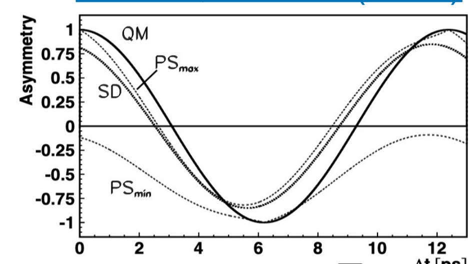
- **A quantum state of two subsystems A and B is separable when its density matrix:**

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

- **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)

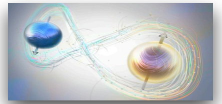


e+ e- → Υ(4s) → $B^0 \bar{B}^0$

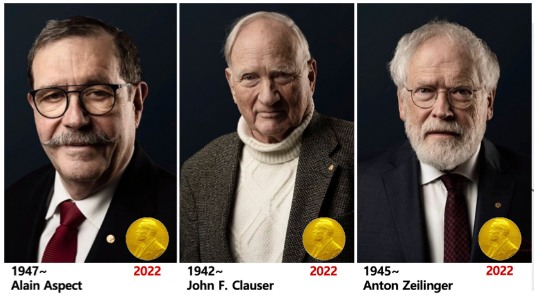
$$|\psi\rangle = \frac{1}{\sqrt{2}}\left[|B^0\rangle_1 \otimes |\overline{B}^0\rangle_2 - |\overline{B}^0\rangle_1 \otimes |B^0\rangle_2\right]$$

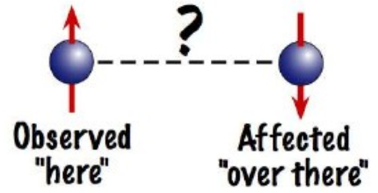
entangled state

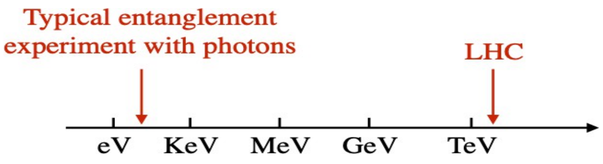
How to probe Entanglement



- 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 <u>not</u> separable!







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

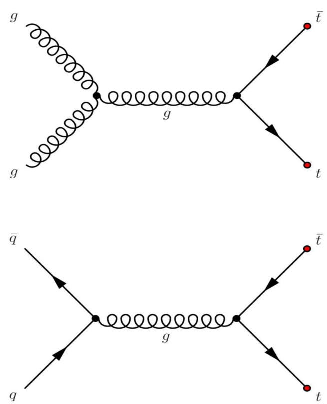
$$\rho = \frac{I_4 + \Sigma_i \left(B_i^+ \sigma^i \otimes I_2 + B_i^- I_2 \otimes \sigma^i \right) + \Sigma_{i,j} C_{ij} \sigma^i \otimes \sigma^j}{4}$$

~0 ~0

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

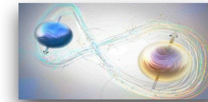
$$\frac{1}{\sigma}\frac{d\sigma}{dcos\varphi} = \frac{1}{2}(1 - D\ cos\varphi) \quad D = -\frac{tr[C]}{3}$$

How to produce a top quark



Experimental goal → measure D (entanglement proxy)

Entanglement of top quarks

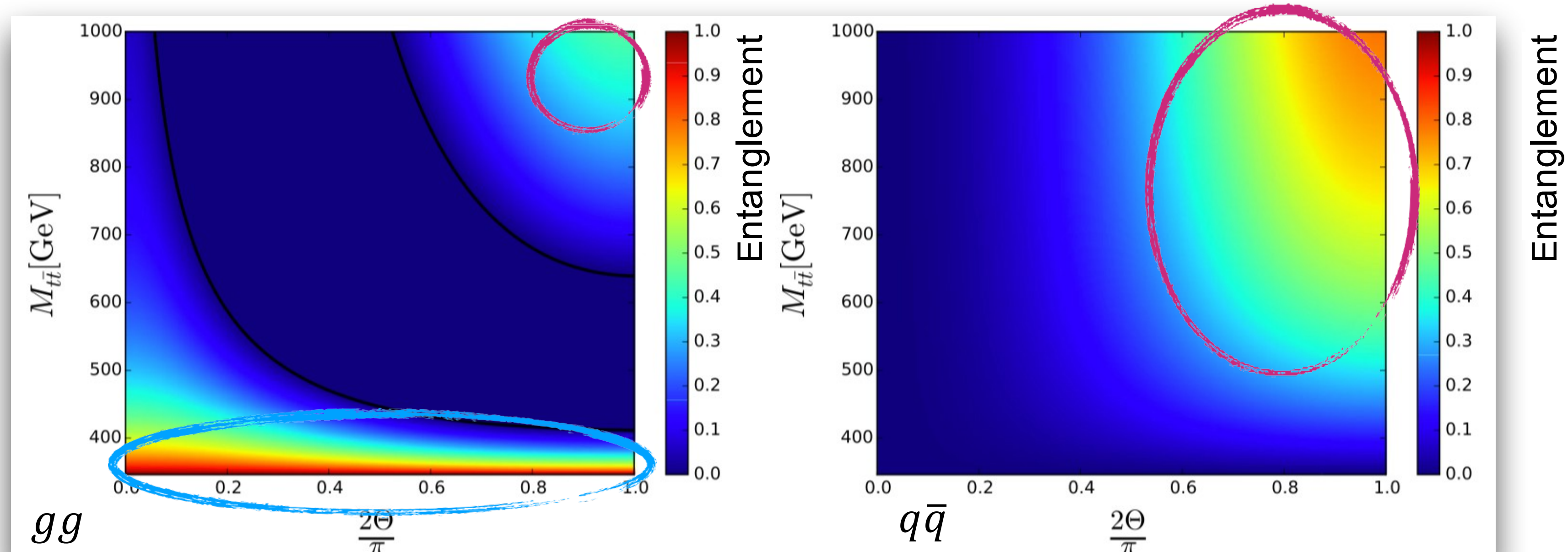


- Can be measured using spin correlations variables
- Depends on production mode, $m(t\bar{t})$, and scattering angle (Θ)

<u>SM predicts entangled states:</u>

→ at the production threshold region in gg-fusion production

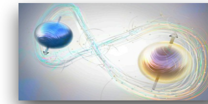
→ at the boosted region for central production of the system



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!

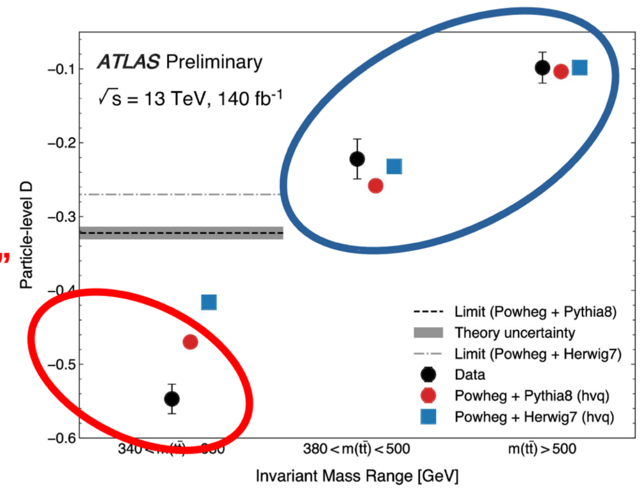
https://atlas.cern/Updates/Briefing/Top-Entanglement

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

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

[Nature 633, 542–547 (2024)]

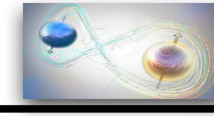
D < –1/3: top quarks are "entangled"
This is new and exciting!



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 me
high-energy colliders. We present here the general framework of the quantum state of a t
energy collider. We argue that, in general, the total quantum state that can be probed in a
rise to a mixed state. We compute the quantum state of a $t\bar{t}$ pair produced from the most
different regions of phase space. We show that any realistic hadronic production of a $t\bar{t}$ pa
experimentally relevant cases of proton-proton and proton-antiproton collisions, perform
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 me
form of violation of Bell's theorem, necessarily containing a number of loopholes.

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

[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. Th
discuss topics such as entanglement, Bell nonlocality or quantum tomography. Here, we provide the full picture of quantum correlations with top
discord and steering. We find that both phenomena are present at the LHC. In particular, quantum discord in a separable quantum state is expecte
statistical significance. Interestingly, due to the singular nature of the measurement process, quantum discord can be measured following its origi
ellipsoid can be experimentally reconstructed, both highly-demanding measurements in conventional se
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 - Phenomenolo
Cite as: arXiv:2209.03969 [quant-ph]
(or arXiv:2209.03969v1 [quant-ph] for this version)
https://doi.org/10.48550/arXiv.2209.03969

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

Entanglement and quantum tomography with top quarks at the LHC

Yoav Afik, Juan Ramón Muñoz de Nova

Entanglement is a central subject in quantum mechanics. Due to its genuine relativistic behavior and fundamental nature, high-energy colliders are attractive systems for the
experimental study of fundamental aspects of quantum mechanics. We propose the detection of entanglement between the spins of top-antitop-quark pairs at the LHC,
representing the first proposal of entanglement detection in a pair of quarks, and also the entanglement observation at the highest energy scale so far. We show that entanglement
can be observed by direct measurement of the angular separation between the leptons arising from the decay of the top-antitop pair. The detection can be achieved with high
top-antitop pair. This
nplements canonical
mation aspects.

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

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

thod is based on a Bloch parameterisation

[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 whic
ted experimentally from the directions of the charged lepton de
s of $H \to WW^*$ decays indicate that violation of a generalised
ental Bell tests could be performed at a variety of colliders and
cant violations could be observable even with datasets compara

. (12) (13) (23). Results and conclusions unchanged
Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex);
-ph]
[hep-ph] for this version)
50/arXiv.2106.01377
Journal reference: Physics Letters B 825 (2022) 136866
Related DOI: https://doi.org/10.1016/j.physletb.2021.136866

Journ
Relat

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 for exploring the fermionic Higgs portal at forthcoming hadron machines.

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

Quantum SMEFT tomography: top quark pair production at the LHC

Rafael Aoude, Eric Madge, Fabio Maltoni, Luca Mantani

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

Comments: 8 pages, 5 figures + appendix; v2: minor changes, published version
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex)

[Submitted on 28 Sep 2022]

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

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 $H \to WW \to \ell\nu\ell\nu$ 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

[Submitted on 27 Sep 2022]

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

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

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

Subjects: High
Cite as: arXiv:
(or ar
https:

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

Quantum tops at the LHC: from entanglement to Bell inequalities

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

We present the prospects of detecting quantum entanglement and the violation of Bell inequalities in $t\bar{t}$ events at the LHC. We introduce a unique set of observables suitable fo
measurements, and then perform the corresponding analyses using simulated events in the dilepton final state, reconstructing up to the unfolded level. We find that entanglem
can be established at better than 5σ 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 vio
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 EPJC
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

["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]

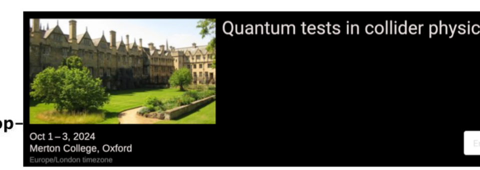
Constraining new physics in entangled two-qubit systems: top-quark, tau-lepton and photon pairs

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

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

$q\bar{q}$
the relevant
to a factor of



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

Testing Bell inequalities at the LHC with top-

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.

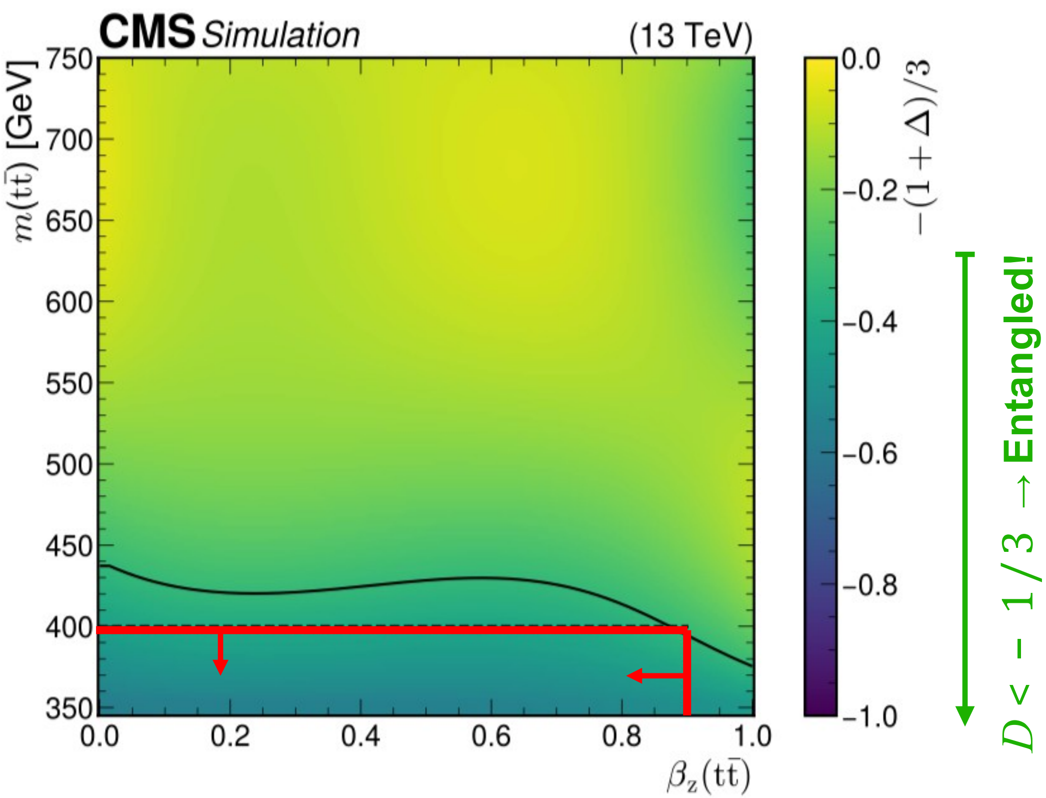
Comments: 4 pages, 1 figure
Subjects: High Energy Physics - Phenomenology (hep-ph); High Energy Physics - Experiment (hep-ex); Quantum Physics (quant-ph)
Cite as: arXiv:2102.11883 [hep-ph]
(or arXiv:2102.11883v2 [hep-ph] for this version)
https://doi.org/10.48550/arXiv.2102.11883
Journal reference: Phys.Rev.Lett.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

Analysis in a nutshell…

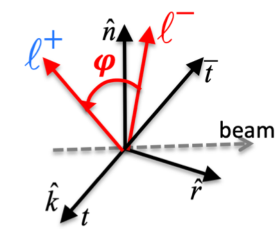
- The degree of entanglement is highly phase space-dependent
  → Scan of $m(t\bar{t})$ vs. $\cos(\Theta)$ vs β to determine most sensitive phase space while minimizing expected total uncertainties
- Focus on low-mass region ($345 < m(t\bar{t}) < 400$ GeV) to increase entanglement

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

arXiv:2205.00542 $\beta = \left|\frac{p_z^t + p_z^{\bar{t}}}{E^t + E^{\bar{t}}}\right| < 0.9$



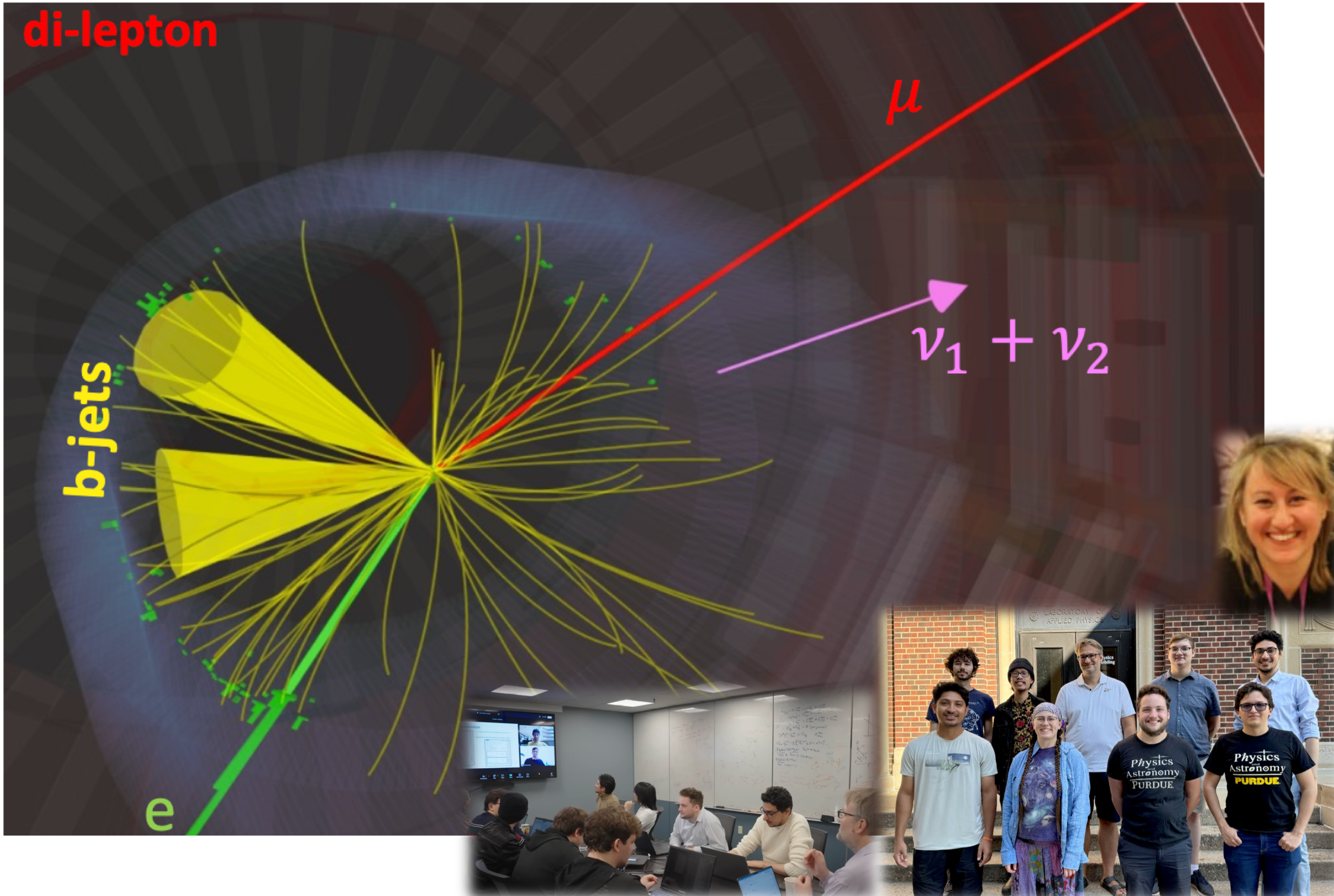
- Measure helicity angle $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$
  - fully encapsulates spin correlations information for



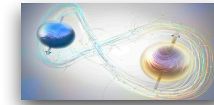
- Perform a **profile maximum likelihood fit of the cos distribution** in the $m_{t\bar{t}}$ - β signal region

Rep. Prog. Phys. 87 (2024) 117801

The data sample: Dilepton events



The data sample: Dilepton events

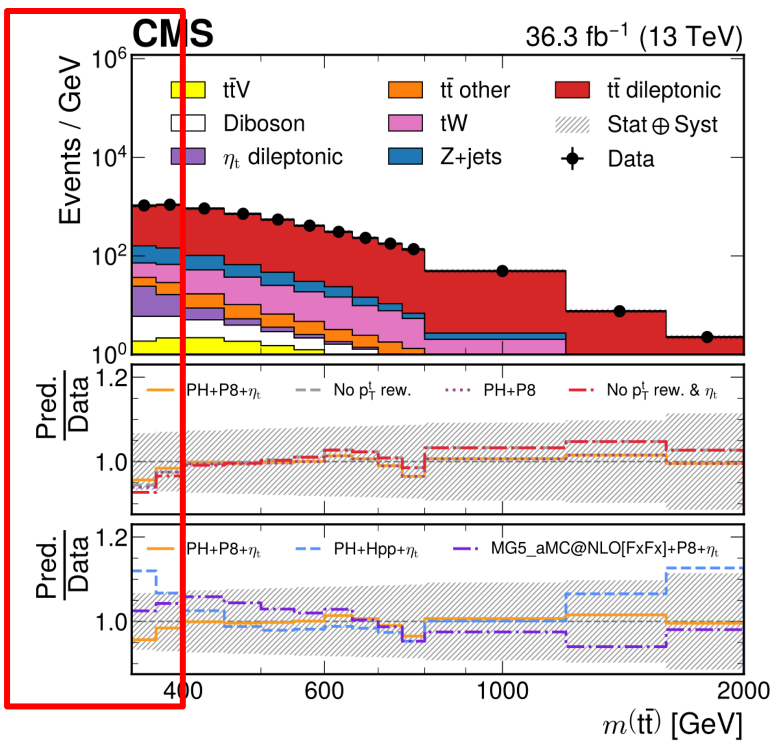


- Signal model: tt
  - Electroweak corrections applied
  - Using 35.9 fb^{-1} collected in 2016
- Main background sources: Z+jet (MG5 + data-driven corrections), single top (powheg MC), diboson (pythia8 MC)

Comput. Phys. Commun. 182 (2011) 10

PRL 127 (2021) 062001

Analysis region



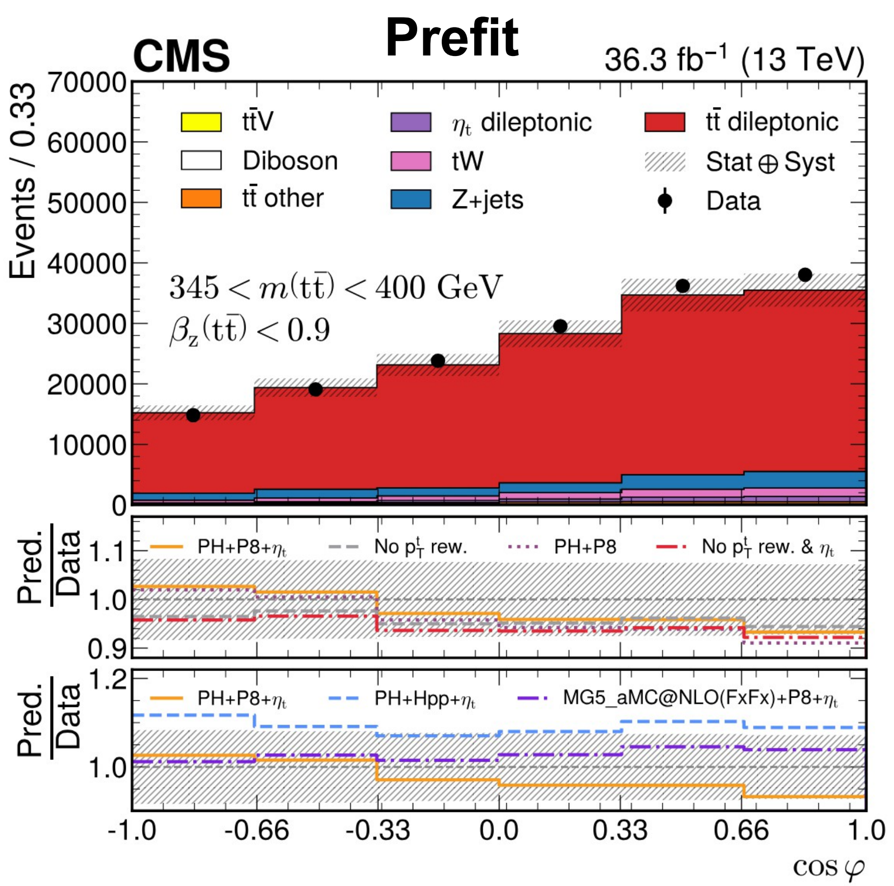
Leading experimental uncertainties
- Jet energy scale and resolution

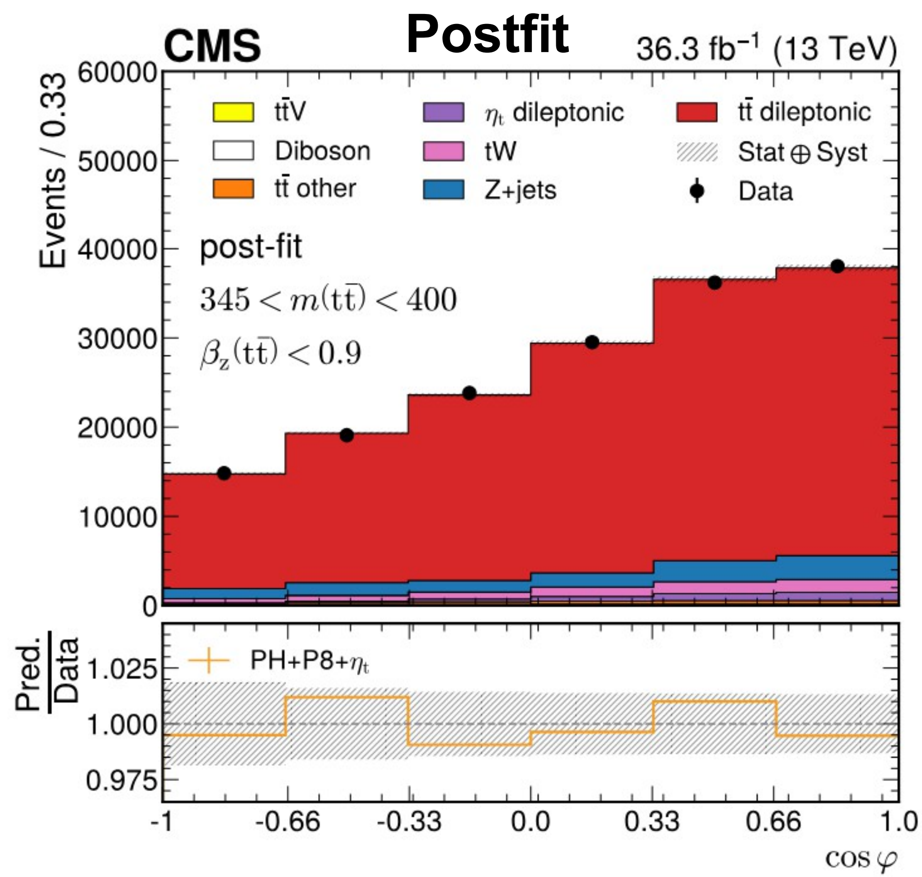
Leading theory-based uncertainties
- Toponium normalization
- Parton Shower

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%

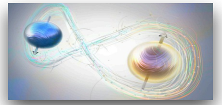
The data sample: Dilepton events

- 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 −2ΔlnL distribution at parton level, accounts for all detector effects

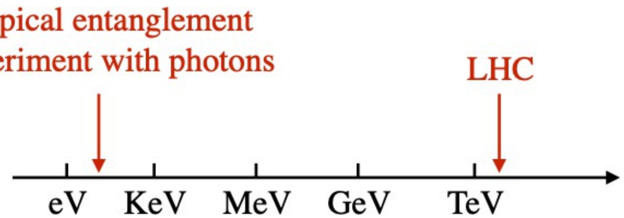
$$D_{obs} = -0.491^{+0.026}_{-0.025}(\text{tot})$$

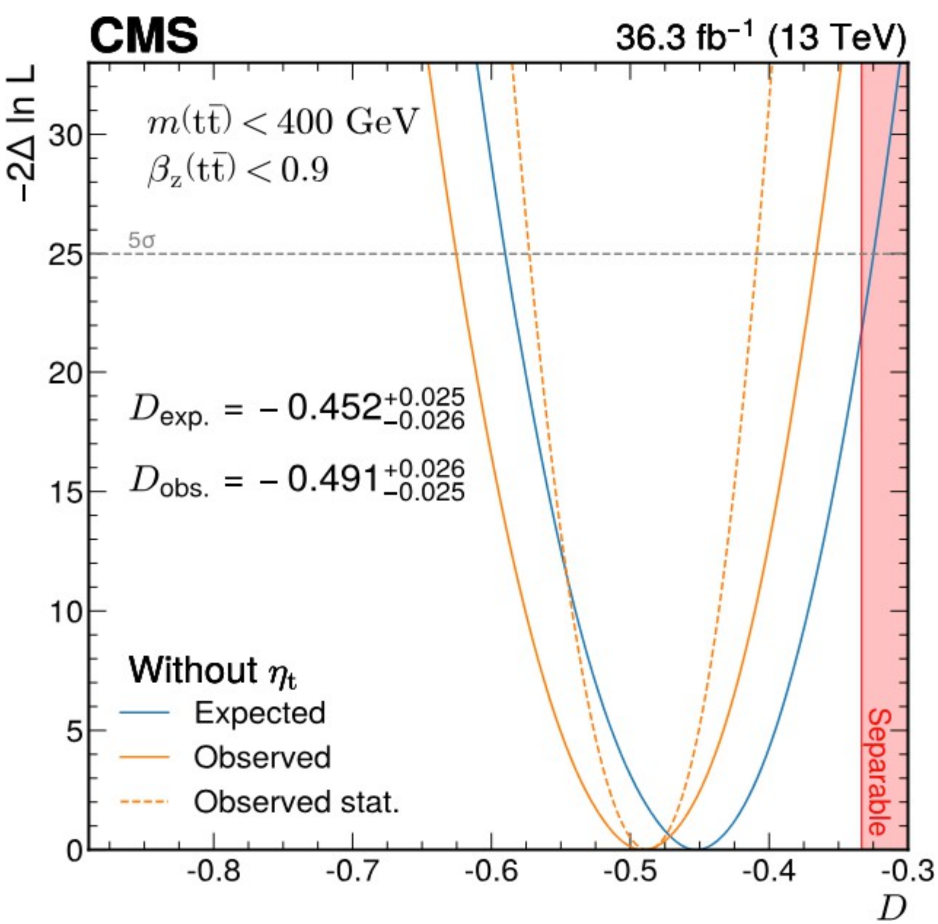
$$D_{exp} = -0.452^{+0.025}_{-0.026}(\text{tot})$$

- **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**



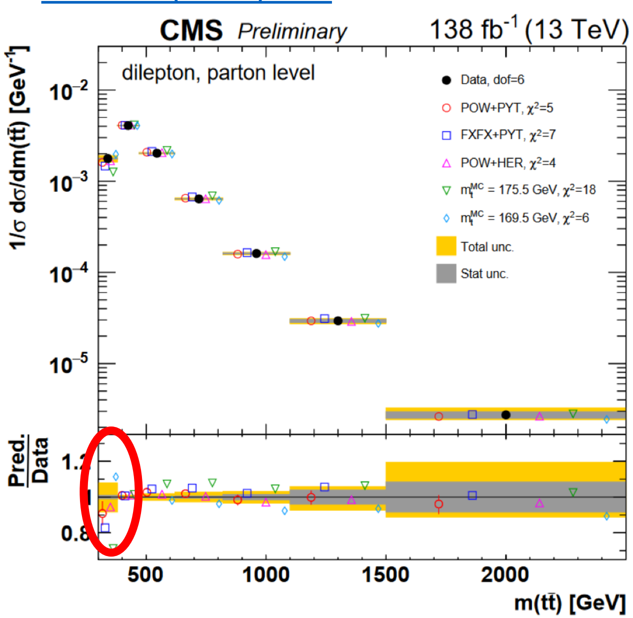


Threshold region of $t\bar{t}$ production

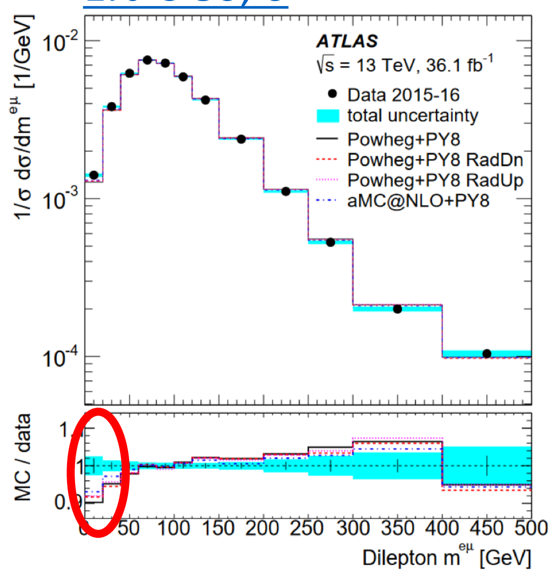
What can explain the (mild) excess ? Discovery of New physics ?

- Known “unknowns”
- Mismodeling seen for $m(t\bar{t}) = 345$ GeV since LHC Run 1
- Consistent between decay channel and ATLAS & CMS
- …even at different center-of-mass energies

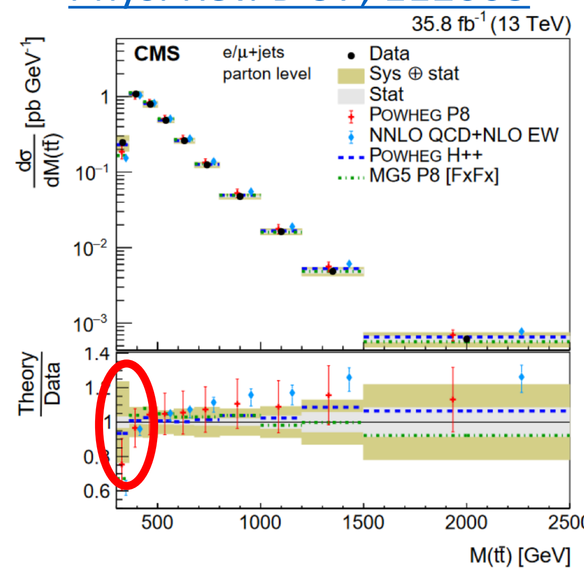
JHEP 02 (2025) 064



EPJ C 80, 6



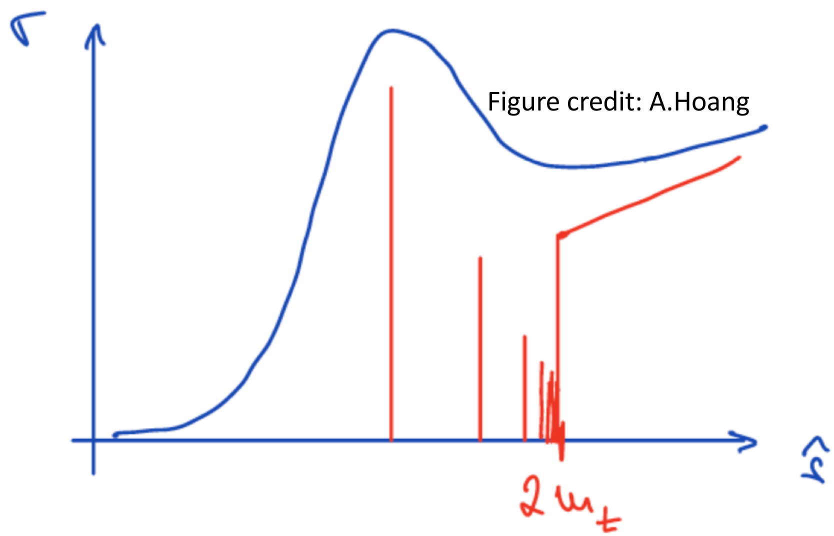
Phys. Rev. D 97, 112003

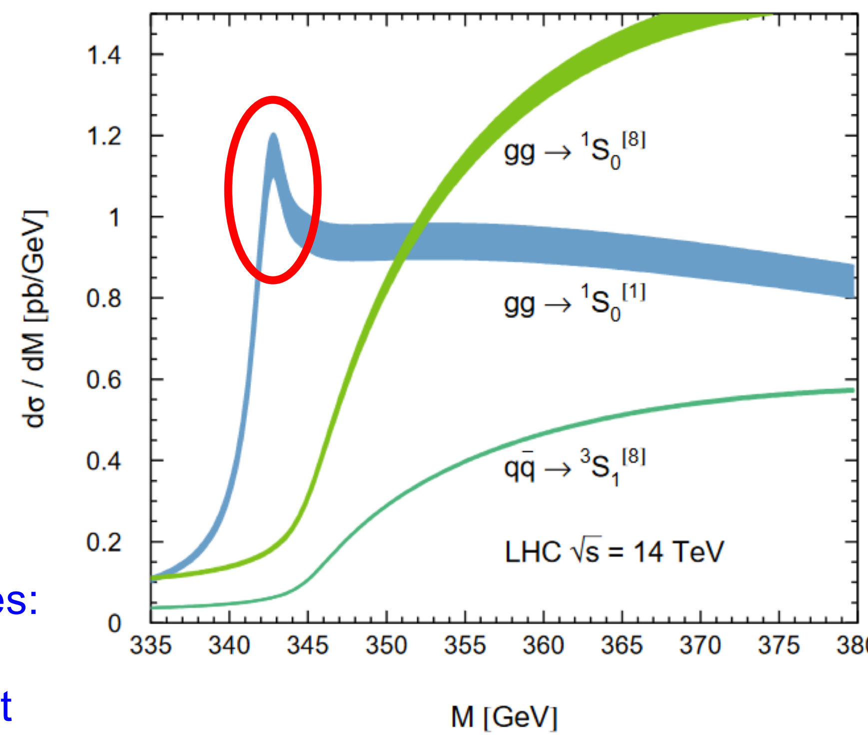


Toponium: top quark bound states

- New (hypothetical) exciting SM resonance
  - Spin and color singlet→ Maximal entanglement
- Excesses seen could be from toponium
- Signal model includes toponium contributions

EPJC **60**, 375
Kiyo, et. al

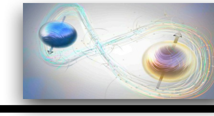




Ground state (n=1) S-wave bound state dominates:
- spin-singlet vs. spin-triplet (depending on production channel) color singlet vs color octett

→ Devise analysis that is "recognizing" $t\bar{t}$ bound state effects on entanglement…

Observation of Entanglement



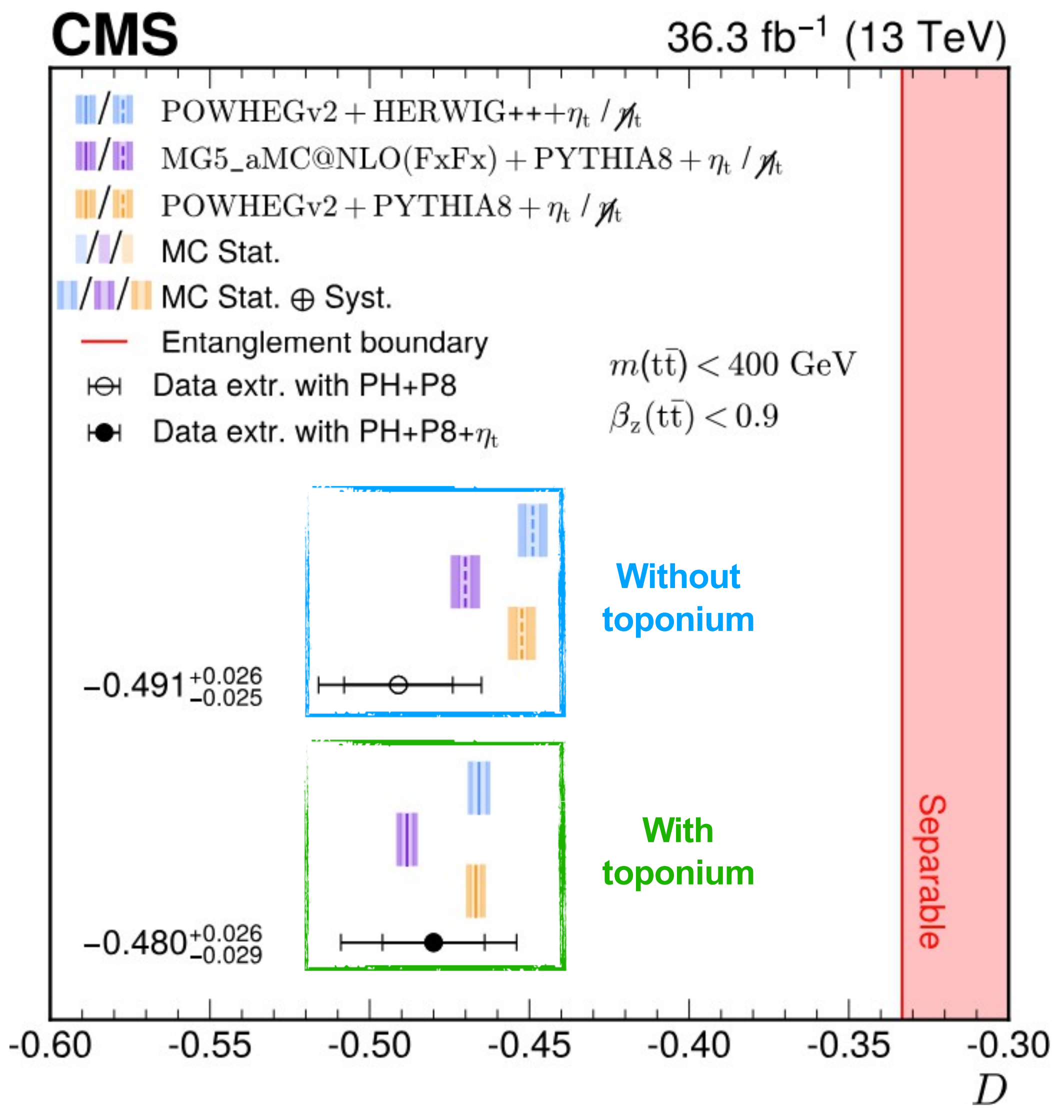
1st measurement of entanglement of top quarks with CMS data
[Rep. Prog. Phys. 87 (2024) 117801]

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

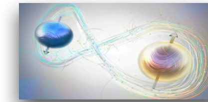
5 standard deviations observation of top quarks being entangled at $t\bar{t}$ threshold

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

Good agreement with SM significantly improved by including η_t



Celebration…yes!



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

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

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

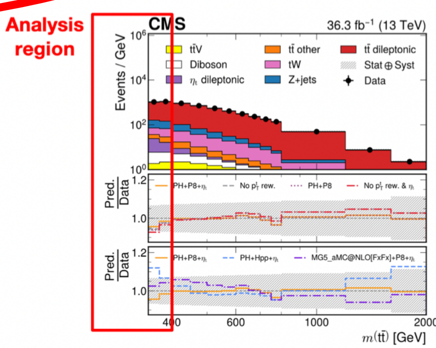
Photo via Getty Images, Hannah Foslien

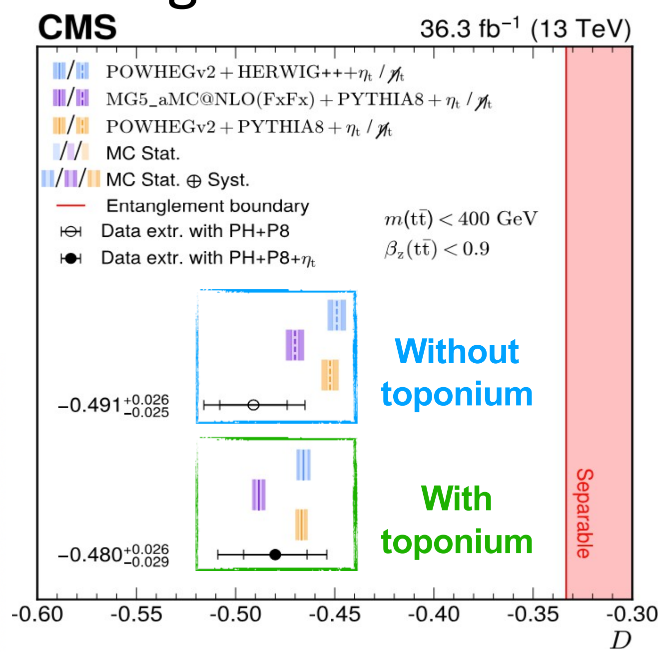
DRINK > NEWS > INDIANA SUNDAY ALCOHOL SALES

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…

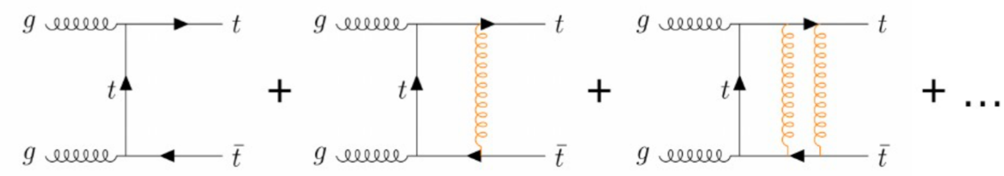
Can we say more on top quark bound state effects at threshold ?

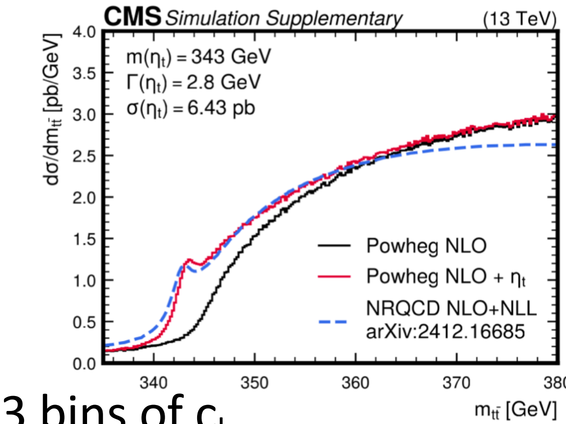




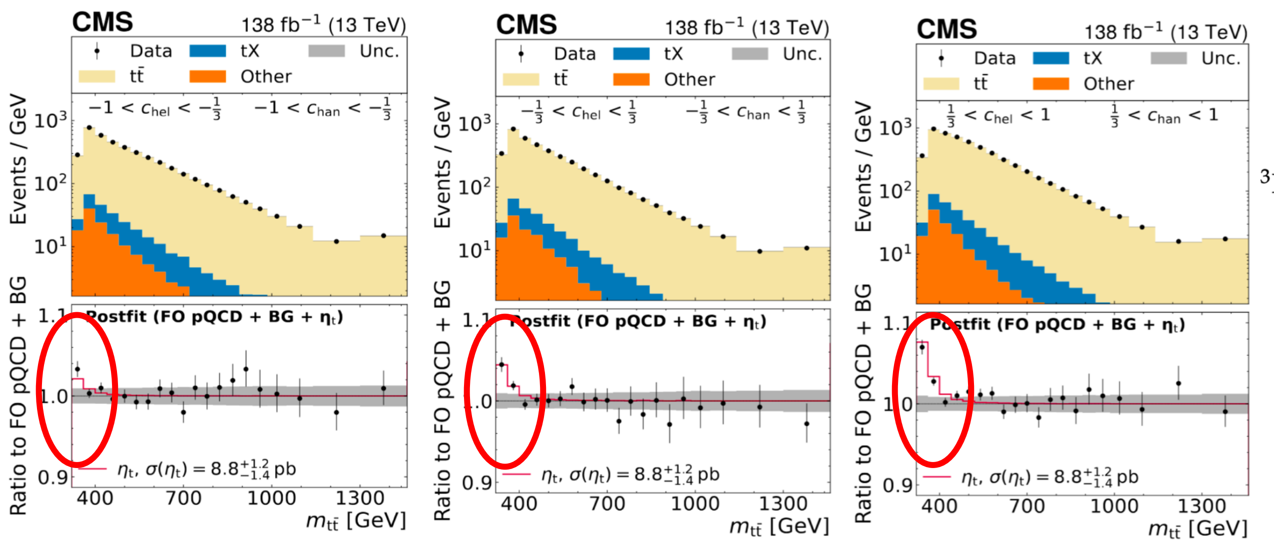
Quasi-bound states at threshold ?

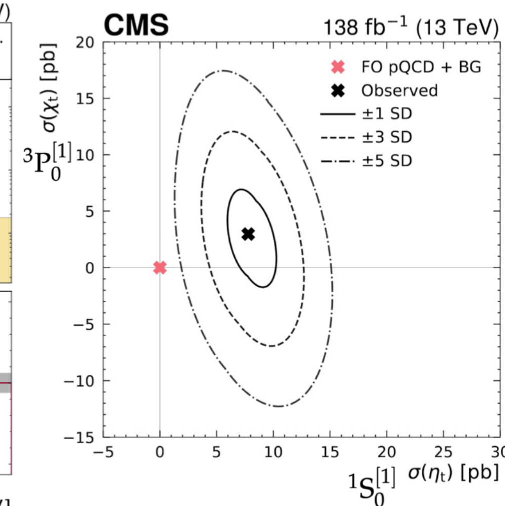
- Shape differences between data and prediction observed in low $m(t\bar{t})$ bins!





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





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

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

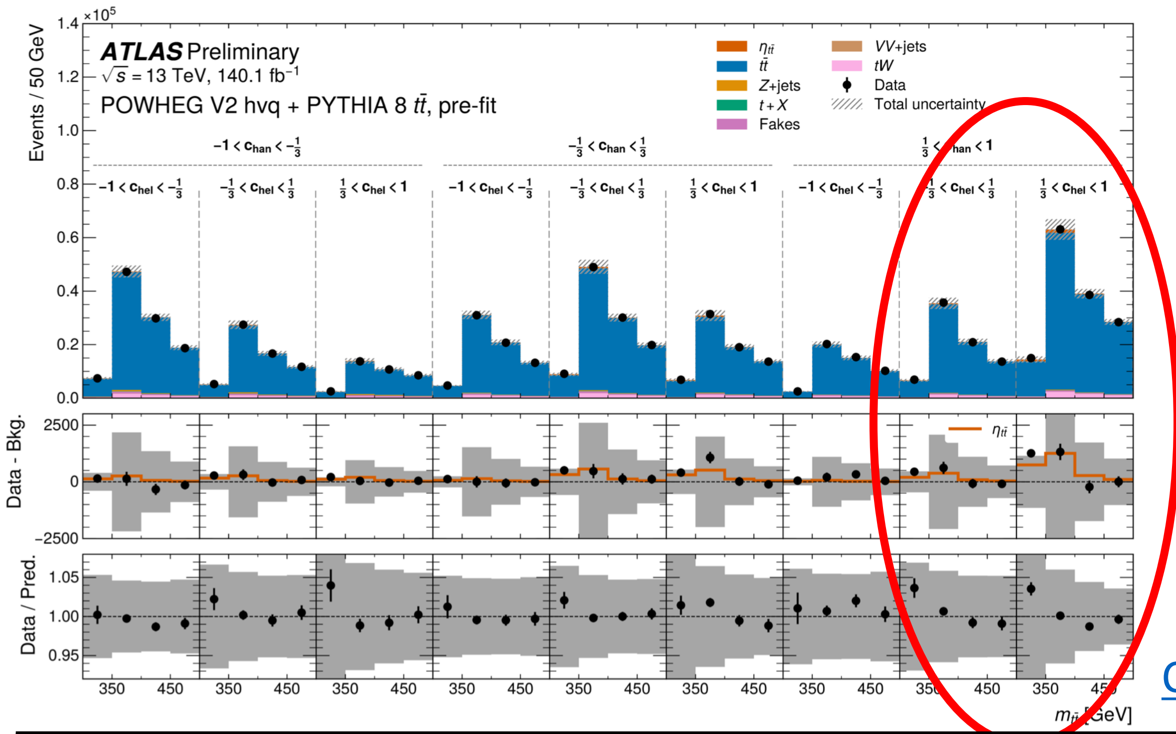
Press Statement

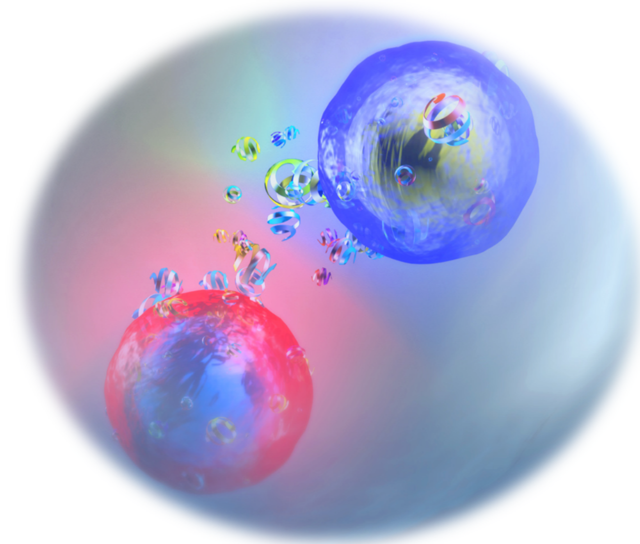
Tags:
EPS 2025,
top quark,
physics results

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

C Severi et al. arXiv:2110.10112v2

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

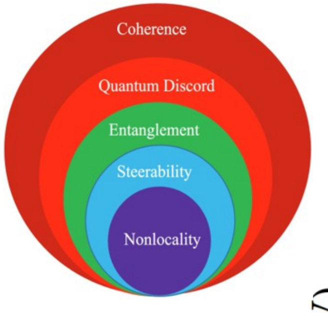
$$\left|\langle ab\rangle - \langle ab'\rangle + \langle a'b\rangle + \langle a'b'\rangle\right| \leq 2$$

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

$$|C(a_1,b_1) - C(a_1,b_2) + C(a_2,b_1) + C(a_2,b_2)| \leq 2$$

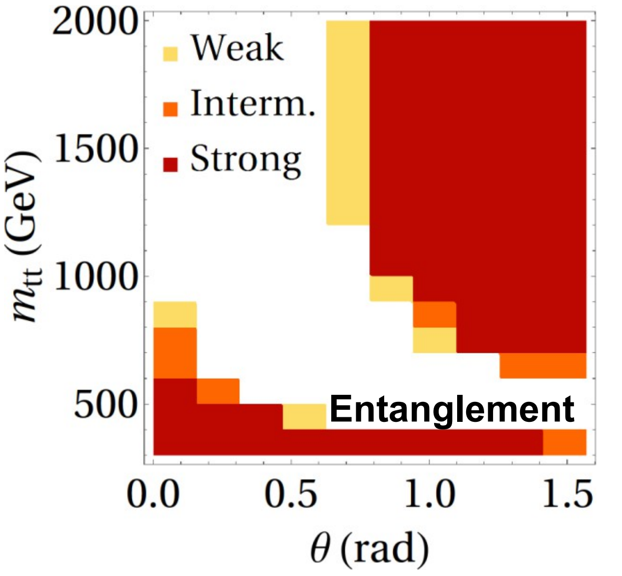
- or more simply as:

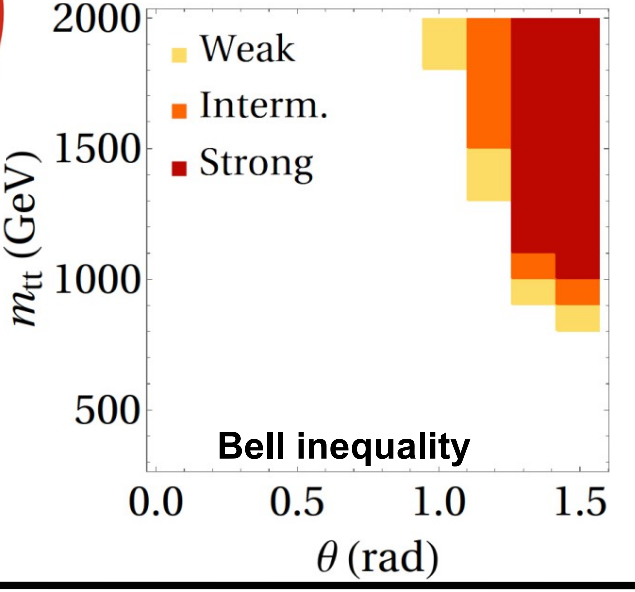
$$\sqrt{2}\,|-C_{rr} + C_{nn}| \leq 2$$



- **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**

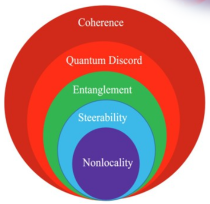




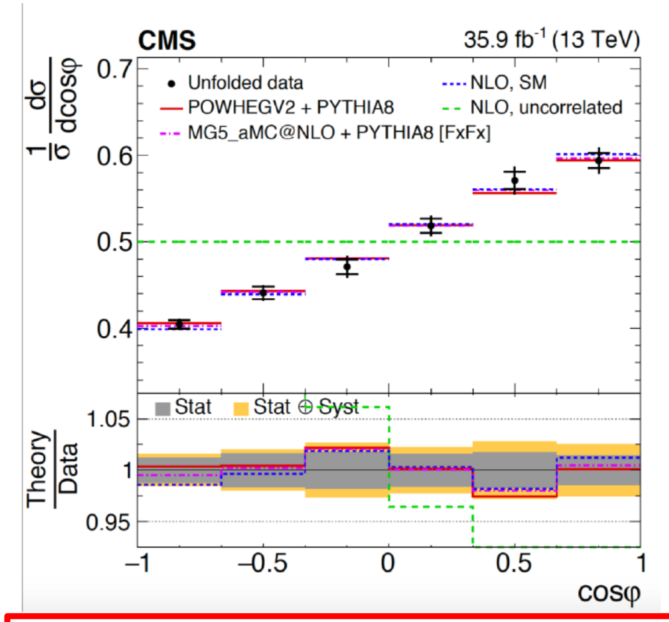
Precision measurements in top sector

Double diff. xsec **Polarisation (0 in SM)** **Spin Correlation**

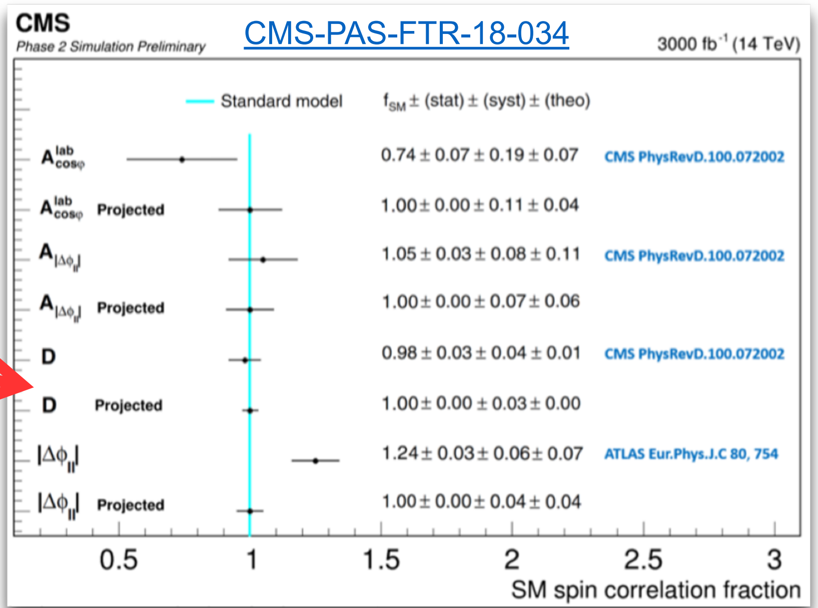
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+\, d\cos\theta^b_-} = \frac{1}{4}\left(1 + B^a_+\cos\theta^a_+ + B^b_-\cos\theta^b_- - C(a,b)\cos\theta^a_+\cos\theta^b_-\right)$$



- 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 → prospects at HL-LHC ?



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



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

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

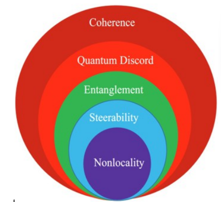
Contributed to Snowmass, CMS-PAS-FTR-18-034

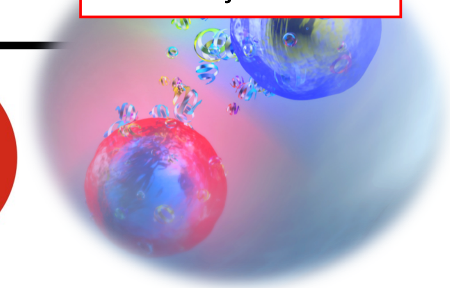
ML top Reconstruction

Quasi-bound state:
CMS ll + lj & ATLAS ll

Double diff. xsec — Polarisation (0 in SM) — Spin Correlation

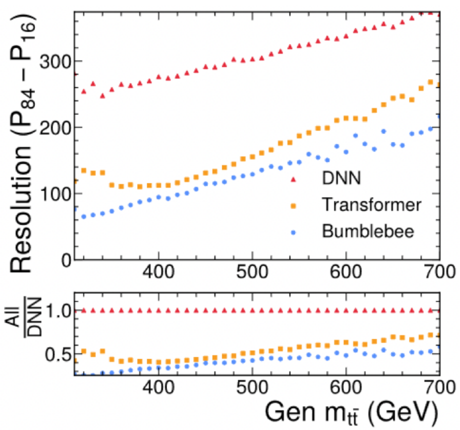
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_+^a\, d\cos\theta_-^b} = \frac{1}{4}(1 + B_+^a\cos\theta_+^a + B_-^b\cos\theta_-^b - C(a,b)\cos\theta_+^a\cos\theta_-^b)$$



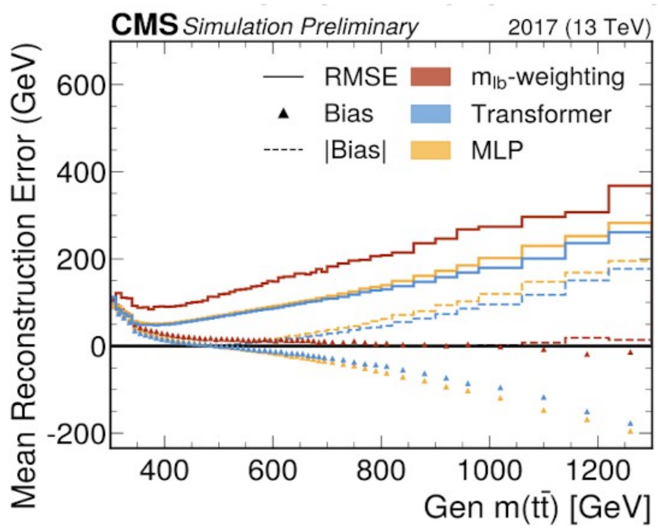


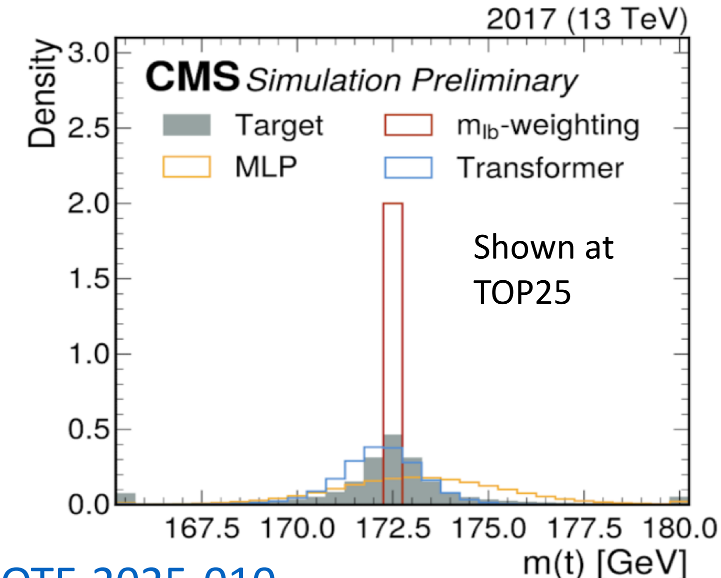
→ RMSE captures amount of bias and variance into singular value

LLM "bumblebee":



AJ Wildridge, …, A Jung, et al. NeurIPS (2024) [arXiv:2412.07867]





CMS-NOTE-2025-010

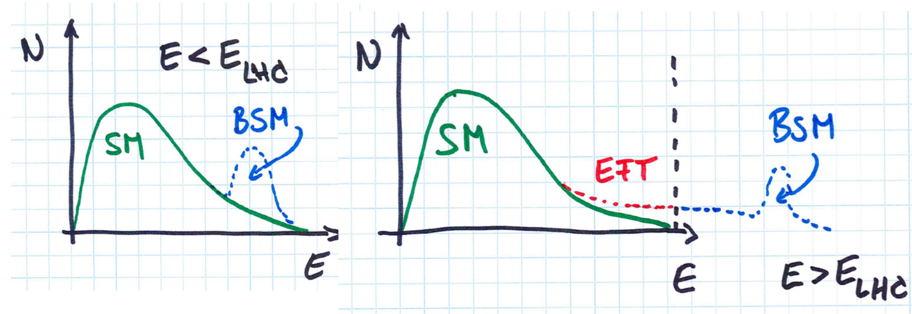
- Transformer approximately 30% improvement vs $m\ell b$ – method
- Reconstructs events for which 5% of time $m\ell b$ - method fails
- Further studies to assess performance, e.g. angular distributions / QIS ob's)
- Exciting region for SM (aka η_t), EFT, and Quantum Correlations…

DOE AI funded

Effective Field Theory to search for BSM

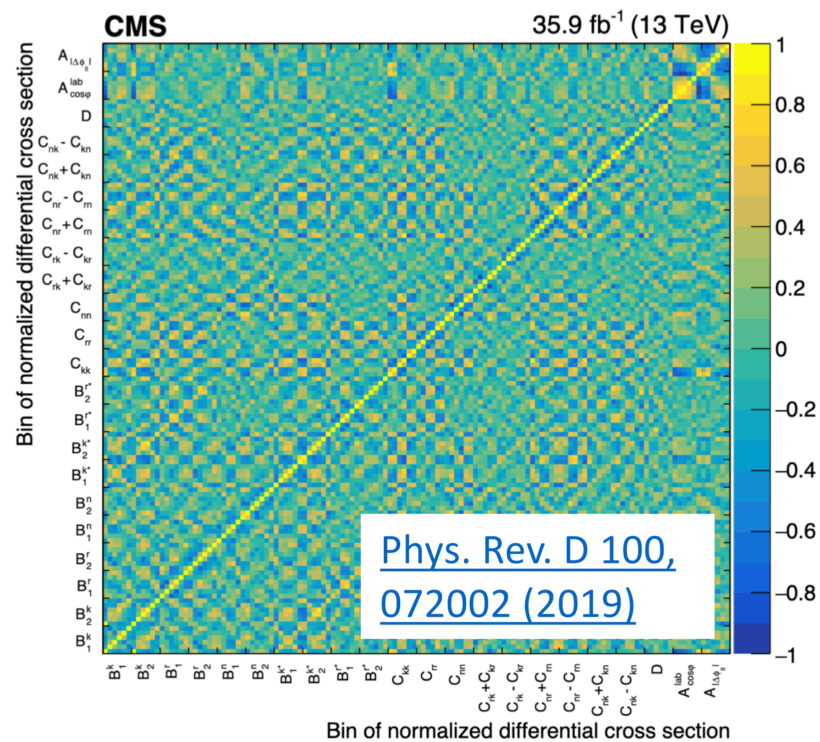
Effective Field Theory to the rescue

- Any BSM physics at $\Lambda \gg E$ leaves a model-independent imprint via higher-dim operators. No UV theory needed.
- 59 parameters/WC (Warsaw basis)
  - Multiple operators produce identical observables.
  - Individual measurements can't break degeneracies;
  - Global multi-observable fits are required.



$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)} \mathcal{O}_i^{(6)}}{\Lambda^2}$$

- Experiments need to provide and determine correlations of stat & all systs
- Full spin density matrix & polarization, 22 observables in 6-bins each (132x132)
- Full Run II in the works (~1000 x 1000)

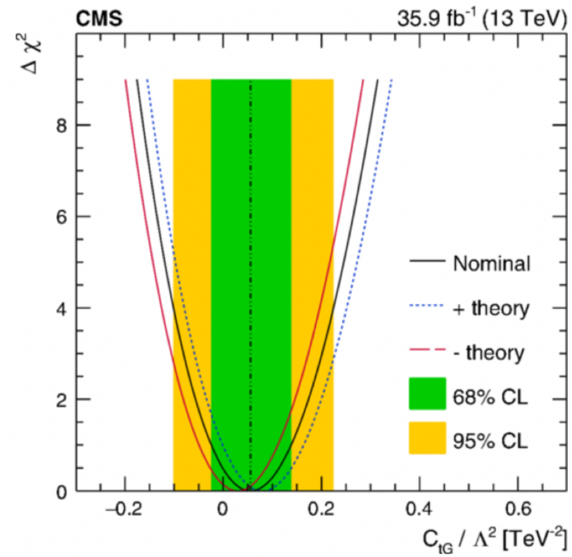


Phys. Rev. D 100, 072002 (2019)

Sufficient or can we expect limitations ?

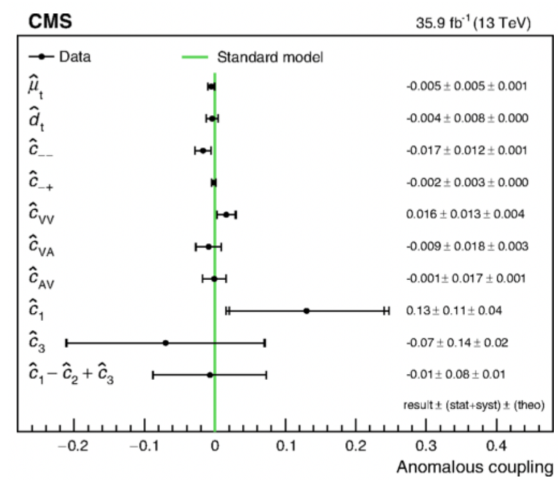
Even in restricted EFT: $\mathcal{O}(50)$ Wilson coeff's in top quark sector

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



Why traditional observables fall short

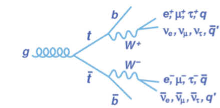
- Mostly 1D distributions / asymmetries
- Limited sensitivity to interference and correlations
- Different operators map onto degenerate combinations
- Information-limited system, not statistics-limited

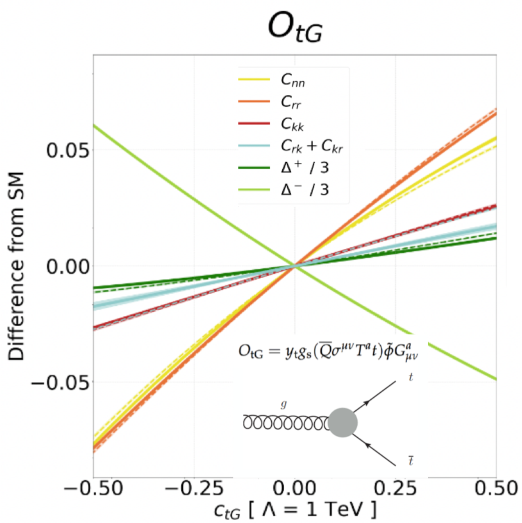


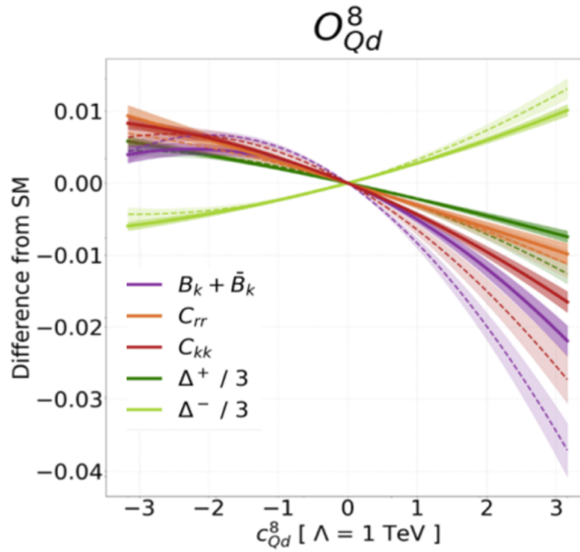
→ Opportunity: go beyond classical observables & exploit full quantum structure of the event
→ Powerful for top quark sector & Higgs sector

Phys. Rev. D 100, 072002 (2019)

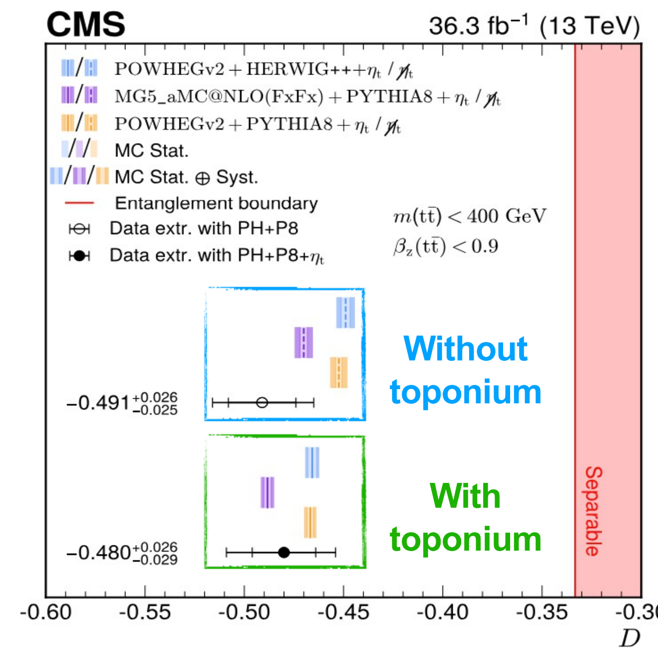
A "new" approach…







JHEP 01 (2023) 148 [2210.09330]



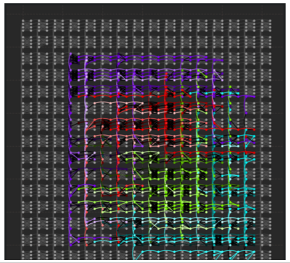
→ QIS observables anti-correlated / orthogonal to existing spin density / polarization obs!

- **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!**

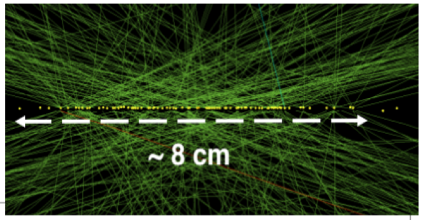
Prospects: QC & Machine Learning

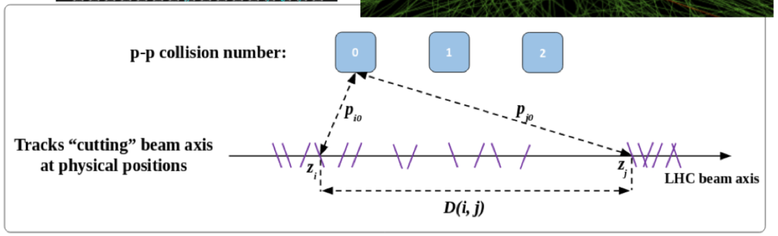
HL-LHC records enormously large sample of pp collisions, even larger sets of Monte Carlo are needed

→ AI/ML tools, e.g. toponium identification
→ Understand systematic uncertainties at permille level requires billions of events
→ Classification of signal vs background for top quarks



[arXiv:1903.08879]

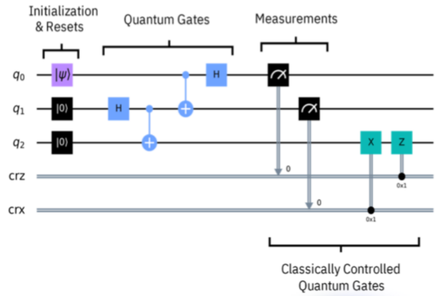




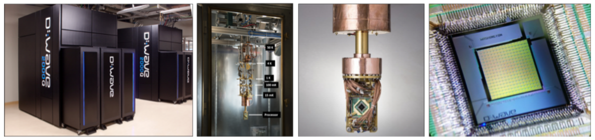
- Machine learning via Support Vector Machines
- Quantum Information Science for HEP
  - "Post-processing" to improve measurements
- Apply QML for supply-chain / economy
  - QML applied to real data shows 20-27% gains
  - Patent/s submitted & pending

QC potential:
- N qubits: 2^N
- 50 qubits → 10^{12} bits

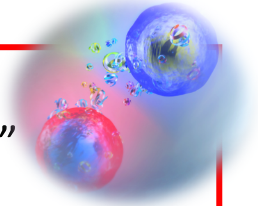
BUT error correction reduces usable # qubits



D-Wave

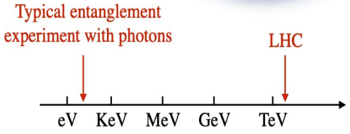


IBM Q



Cutting-edge computing for HEP

- Signal / Background ID classic ML: "toponium"
- Event reconstruction via QA
- ML on QC for real-world applications
- QIS Entanglement & HEP
- High interest by students & in-need for workforce

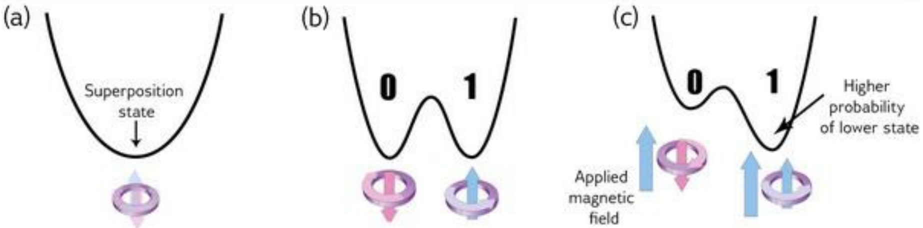


Quantum Computers

Purdue University | Purdue Quantum Science and Engineering Institute

Annealers

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



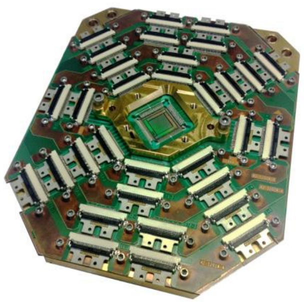
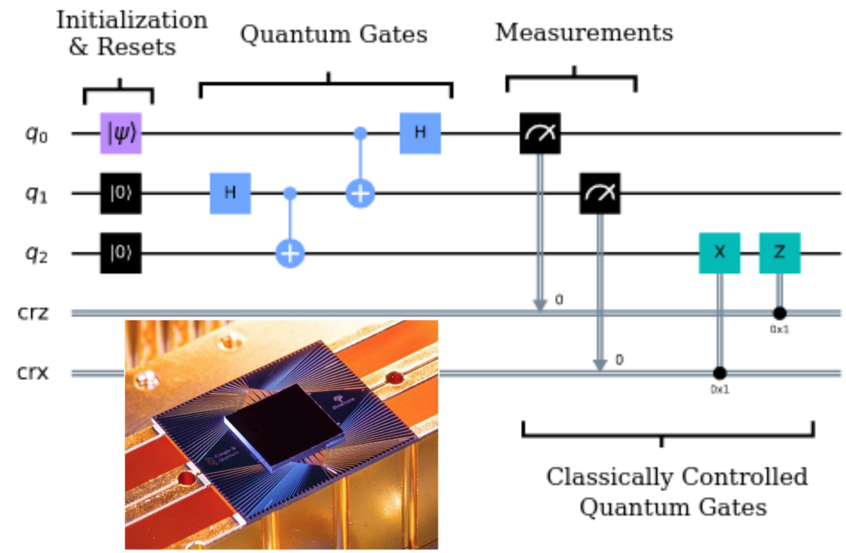


Image courtesy of: https://www.dwavesys.com/sites/default/files/14-1047A-A_Practical_Quantum_Computing_An_Update_0.pdf

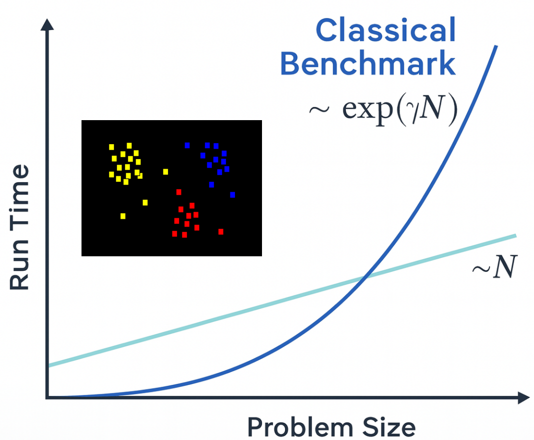
The Second Quantum Revolution, National Institute of Standards and Technology (NIST), 21.3.2018 (updated 5.4.2022)

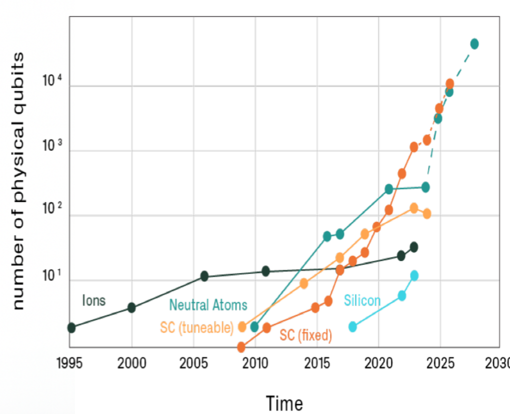
Circuits/Gates

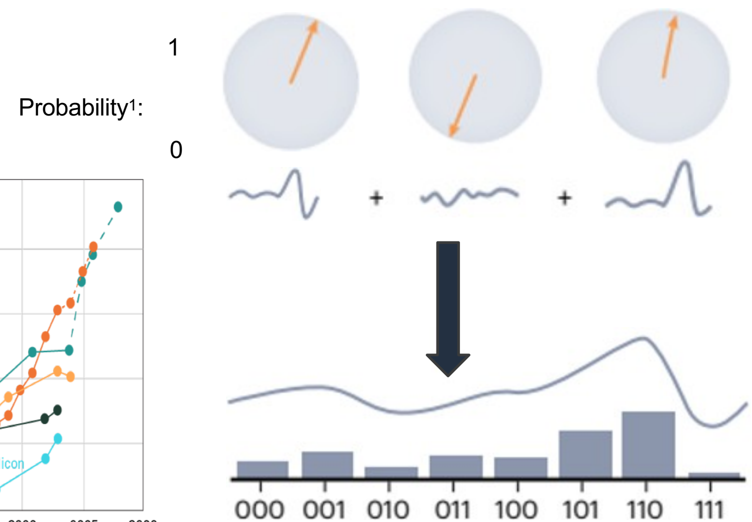
Image courtesy of: https://qiskit.org/textbook/ch-algorithms/defining-quantum-circuits.html



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



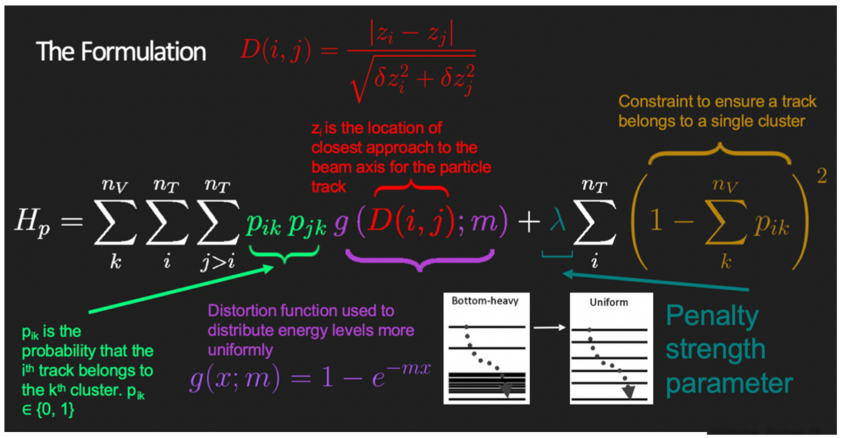


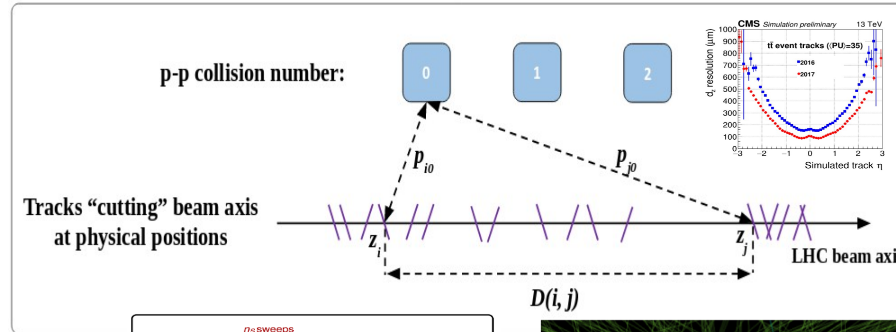


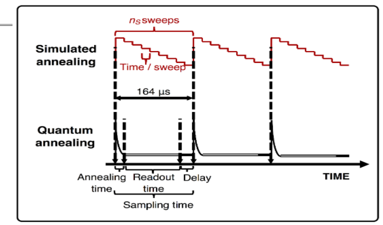
Quantum Computers – promise / dream ?

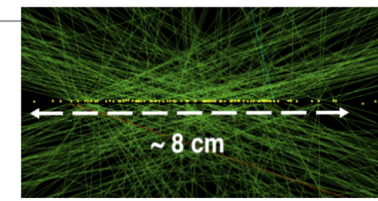
- Solve z-vertexing on a D-Wave annealer
- Centroid-based clustering is NP-hard
- System can be modeled as an **Ising model**

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

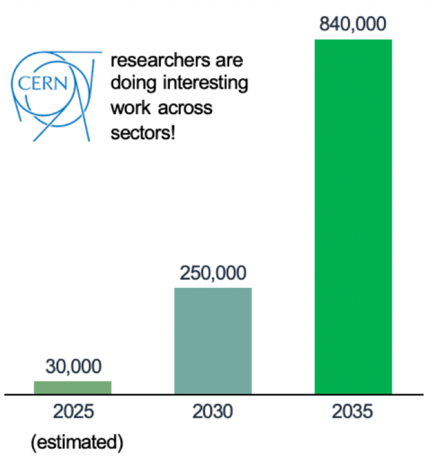




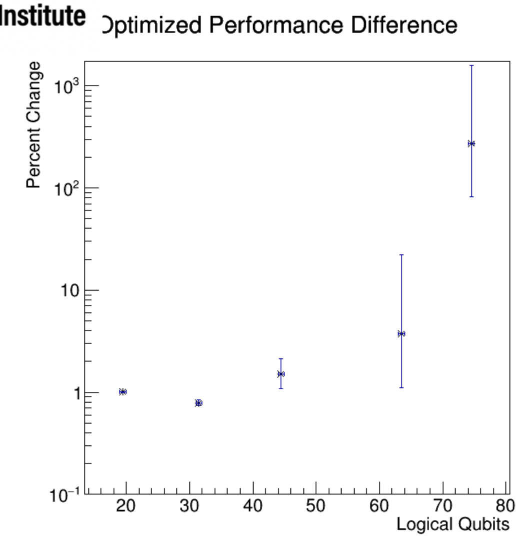


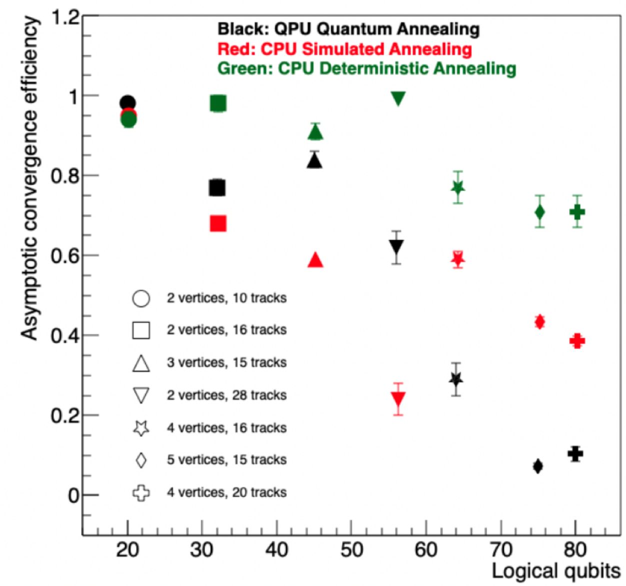


PURDUE UNIVERSITY | Purdue Quantum Science and Engineering Institute



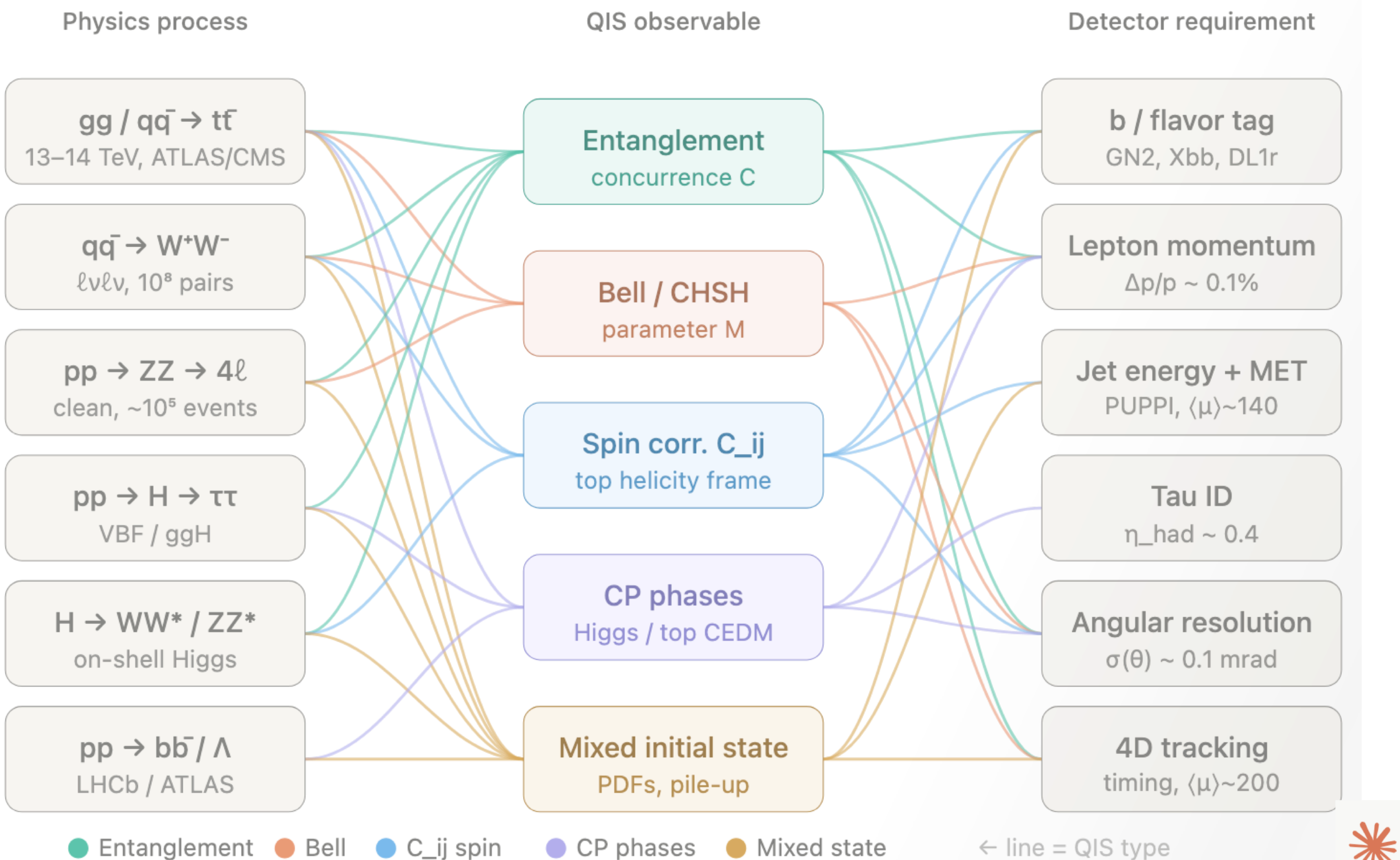
1. The Quantum Insider, September 2024.





Detector/Instrumentation: today's upgrade

Methods/Concepts & tools covering AI/ML to (optimistic) prospects of quantum, what about the detector requirements…

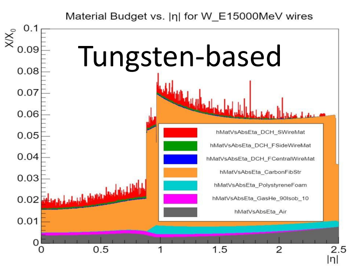


Detector Mechanics – why ?

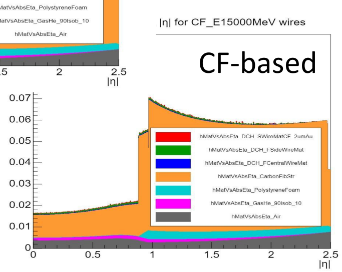
Carbon Fiber: Gold-standard and versatile material

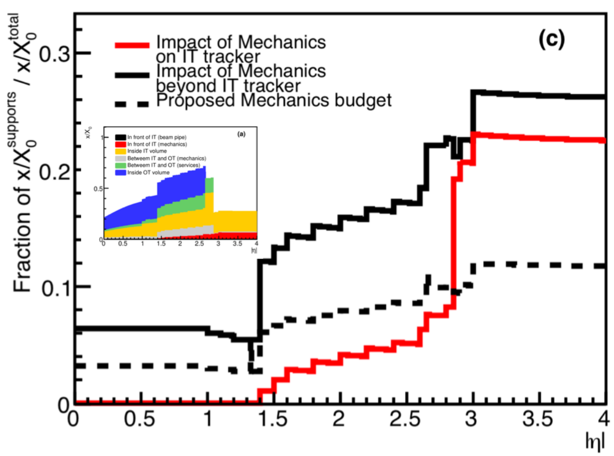
- Not just structural aspects, continuous carbon fibers mono-filaments can also be used for “drift chamber” wires and reduce mass
- Holistic approach for services, structures and cooling choices
- Applicable also to calorimetry, TOF, other systems

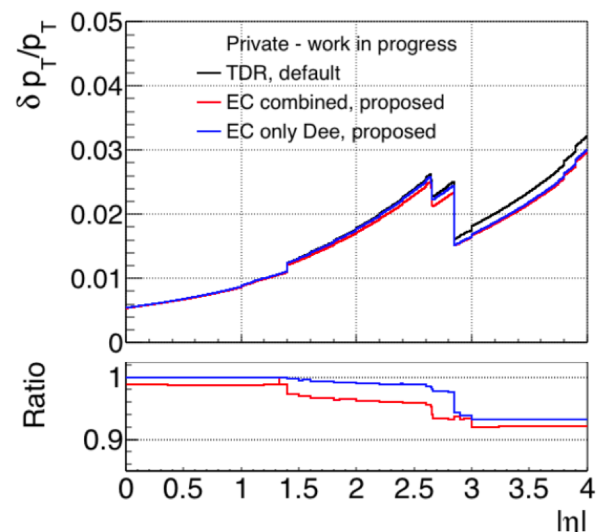
Are we harvesting all physics and performance out of great instruments to unravel mysteries of nature ?



DOE Blue-Sky R&D funded project







- Can improve b-ID efficiencies by ~2% per b-jet and high b-jet multiplicity ~10%
- Significant improvement by novel approach, b-ID relevant for top & Higgs physics

Pixel/Tracker support structures

- Composite Manufacturing & Simulation Center (CMSC) at Purdue, completed in summer 2016 Link: CMSC

  → Purdue Center of Excellence: Aeronautics, Chemical Eng, Materials Eng, Aviation Tech, Computer graphics, **and Physics**

  → A. Jung – Associated member of CMSC
    - Shared grants, "Center for Detector Mechanics"

- Professional composite experience:

  → Seven full-time technical staff, five post-doctoral researchers, twenty grad's

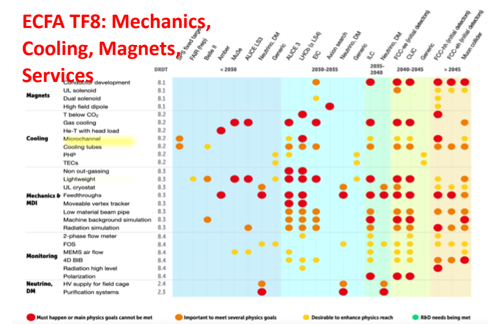
  → 35,000 sq. ft. of office and laboratory space
    - 2 large pressurized ovens, 1 larger oven with vacuum hook-ups
    - Larger ovens accessible with industry partners
    - Small & Large 3D printing (10 x 4 x 4) feet

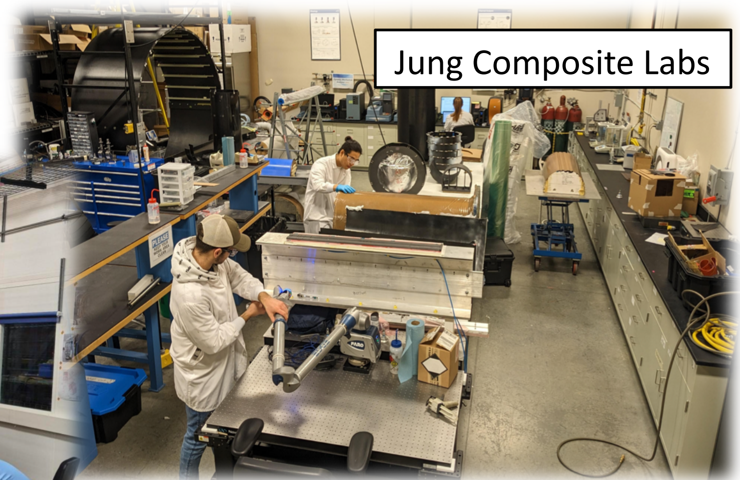
Jung Composite Labs

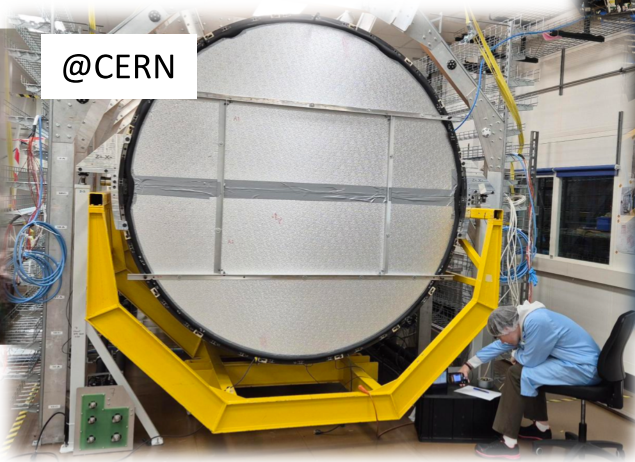
Critical need for detector R&D

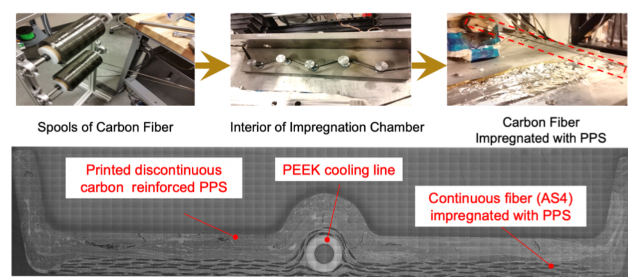
Composites Manufacturing & Simulation Center

- Detector “Mechanics” is a critical need, any future facility & detector concept depends on it!
  - **Chip packaging, thermal aspects, cooling, 3D integration and more …**
- Interdisciplinary R&D and manufacturing projects
  - CoE: Mechanical Engineering, Aero, Materials, …
- Things can go wrong … still exciting









More information can be found here (email: anjung@purdue.edu): https://www.physics.purdue.edu/jung

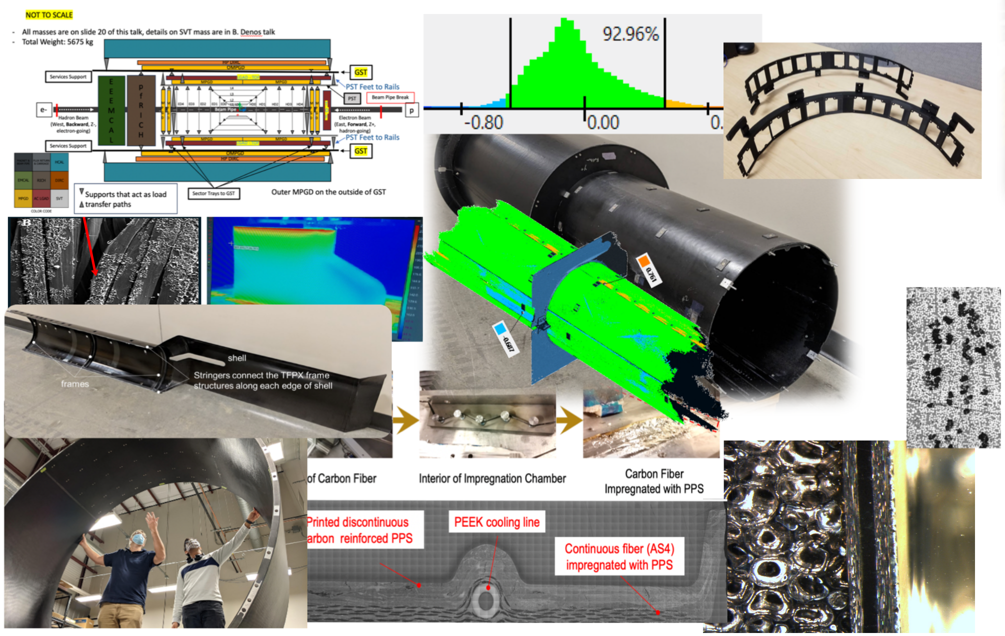
Detector Mechanics as a critical enabler

CMS (HL-LHC)
- Detector critical structures
- High radiation / thermal load
- High demand for adherence to tolerances, low deformation

EIC (ePIC)
- Global mechanics
- Subsystem integration
- Defining support interfaces

ATLAS, R&D & Future Colliders
- R&D, other Projects/scope
- Detector concepts (FCC)
- Scaling design principles

→ End-to-end design capabilities allow to optimize detector mechanics and are critical to success of detector concepts!
→ BUT need to focus on today's upgrades…



Future Mechanics and R&D:
1. "BlueSky Mechanics" for detectors at future Colliders (FCC, muon, LC, etc.) https://arxiv.org/abs/2203.14347
2. "CalVision" project for mechanics of dual readout calorimetry https://arxiv.org/abs/2203.04312
3. "Encyclopedia-like measurement campaign in internal CMS review, all TCs for HEP/NP

Impact of tracker mechanics…

Composites Manufacturing & Simulation Center

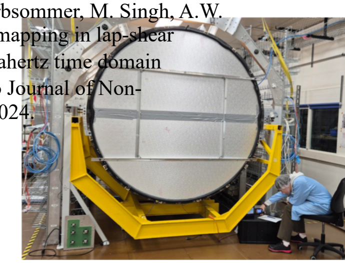
Tracker of the HL-LHC is a very significant fraction of the total CMS upgrade budget

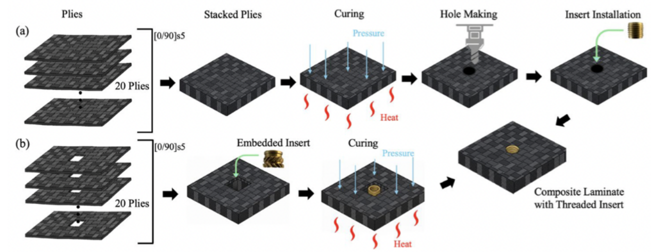
Support & Cooling is the constrain in which Tracker is operated, e.g. thermal runaway

Mechanics is sizeable fraction of the material budget

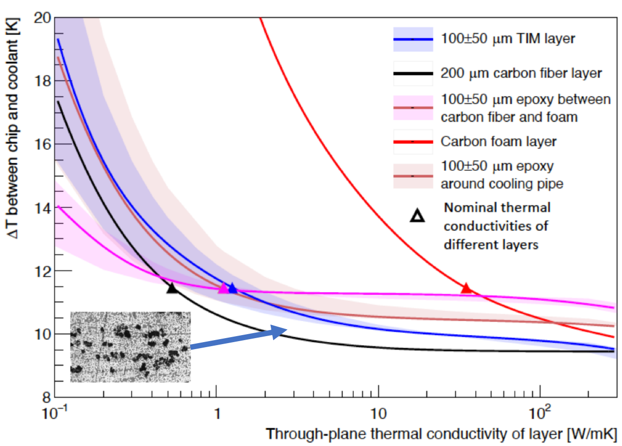
Curing and co-curing does not always go well, lots of chemistry, many stories…

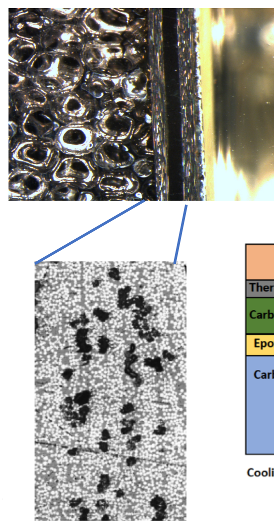
5.S. Karmarkar, M. Herbsommer, M. Singh, A.W. Jung, V. Tomar, Stress mapping in lap-shear adhesive joint using terahertz time domain spectroscopy., Subm. to Journal of Non-destructional Testing, 2024

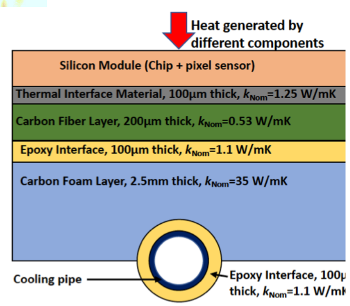


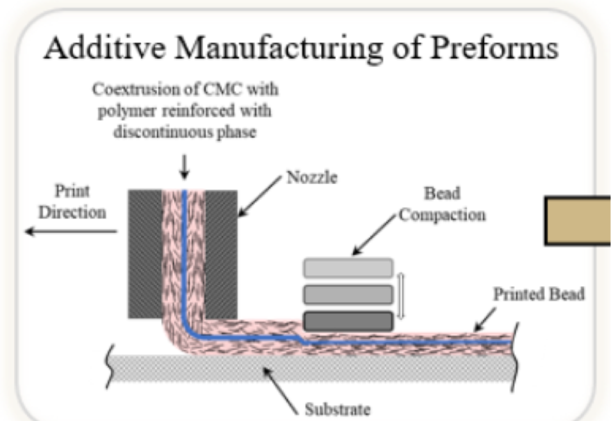


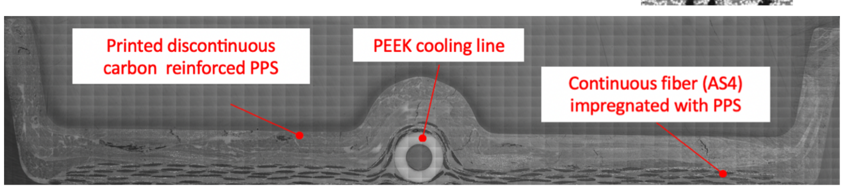
Appl Compos Mater 33, 88 (2026)
(joined between ME & Physics)



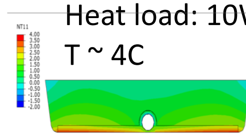








Heat load: 10W
T ~ 4C



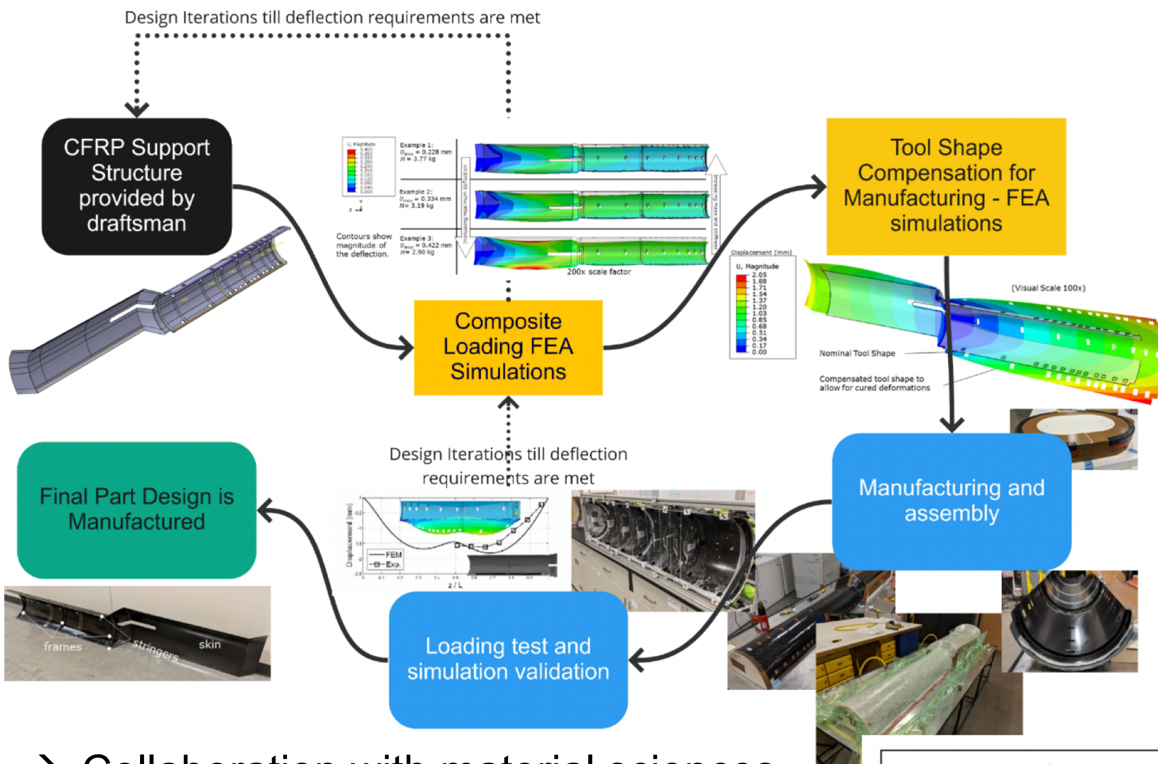
Composites Manufacturing & Simulation Center

Going into the future of mechanics

→ Scalable mechanics structures: multi-functional & mass optimized

→ It remains a **challenge** to design and manufacture large structures.

...with tolerances < 500 micron



Full cycle of Process & Performance simulation:

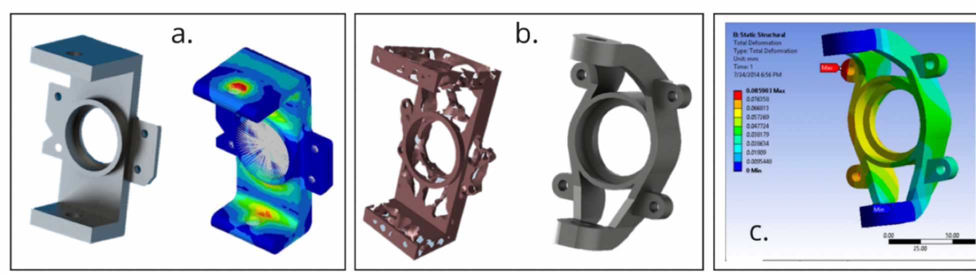
→ FEA, prototypes, iterative process.

→ Consistent approach to better controlled manufacturing process, eases assembly.

→ Especially true the larger the structures become, **integration is a "challenge"**

→ Collaboration with material sciences, companies for novel materials, and latest techniques.

→ Example: ML for optimization with HEP inputs, **excites future generation**



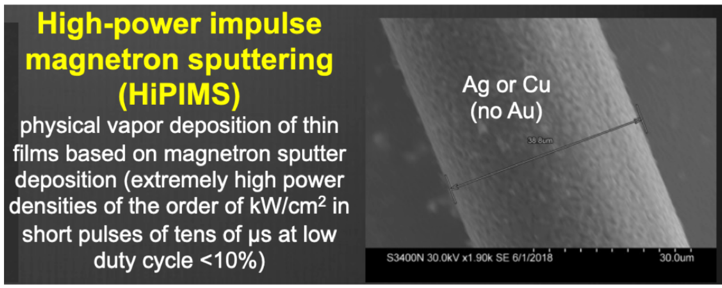
Critical need for “Mechanics” R&D

Composites Manufacturing & Simulation Center

DOE BlueSky R&D funded

Drift chamber, e.g. using “CF” wire chambers…

Dual readout calorimetry w carbon fiber supports…



→ This example: **factor 5 reduction** in material when moving from W+Al to C+Ag/Cu

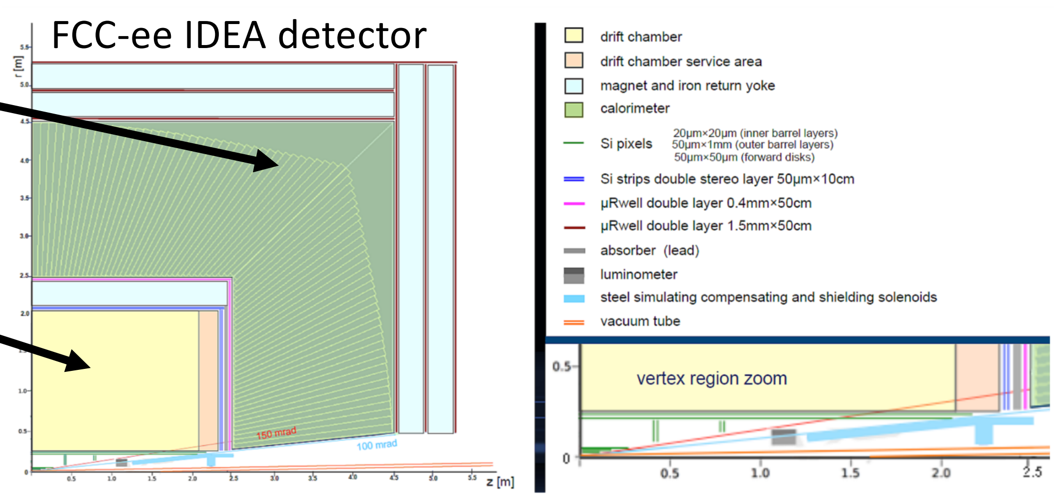


Figure 6: Cross section of the proposed layout for the IDEA detector concept.

NIM A Vol 855, 2017

→ **FCC IDEA: example of ”large detector”**
→ Detector mechanics/cooling play a significant role in a detector's performance
→ **Electron-Ion Collider & highly relevant also to small experiments**

Exchange of ideas & progress across existing collaborations:

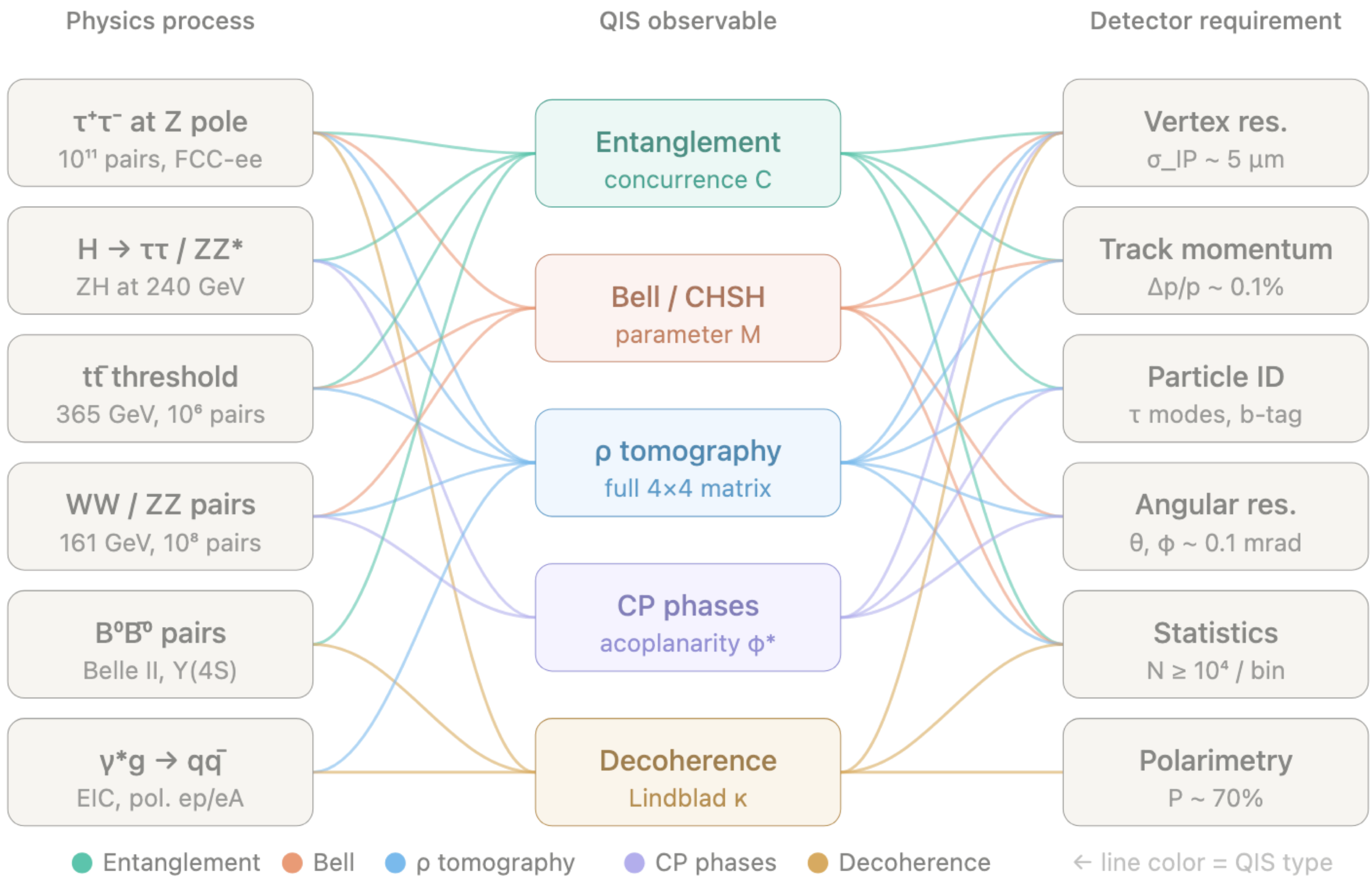
“CPAD RDC 10”: R&D Collaboration for “Detector Mechanics R&D” https://cpad-dpf.org

Bridges nuclear, high energy physics & space applications / satellites too – broad field!

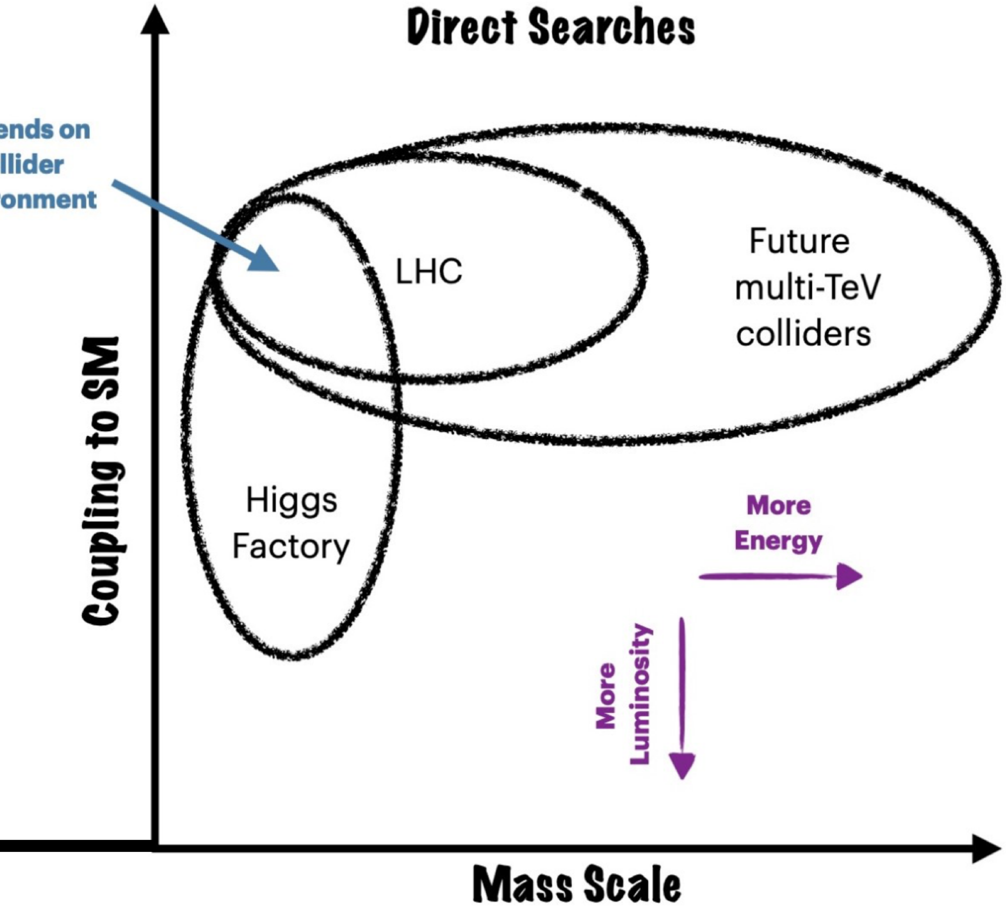
CERN DRD 8 Detector Mechanics collaboration

Detector/Instrumentation: tomorrow's prospects

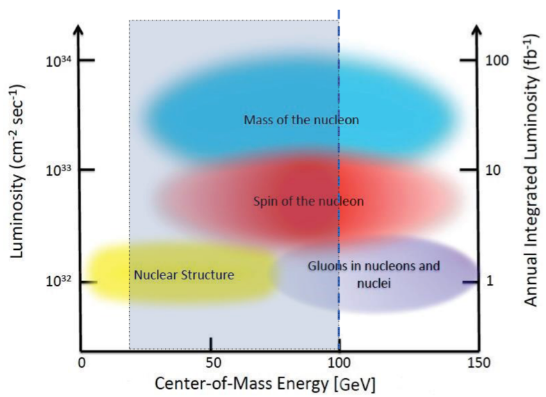
Methods/Concepts & tools covering AI/ML to (optimistic) prospects of quantum, what about the detector requirements…



Future collider landscape



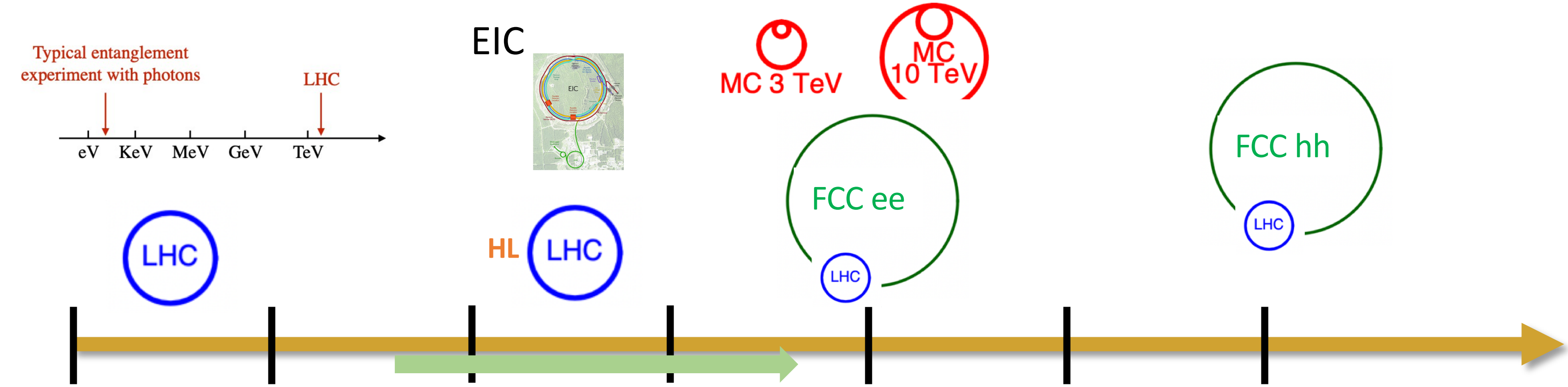
Electron-Ion collider



→ Successfully complete HL-LHC upgrades, but also

→ Essentially need to start R&D on detector (& accelerator) now-ish!

Exciting results – Going into Future

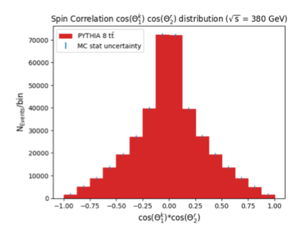


Differential Detector "Precision"

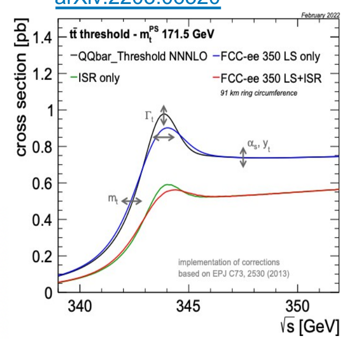
2030's

2050's

Time [yrs]



arXiv:2203.06520

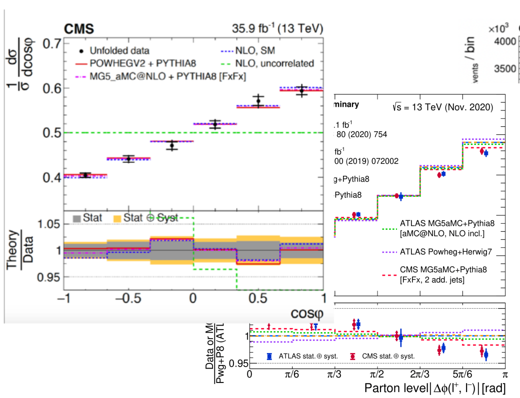


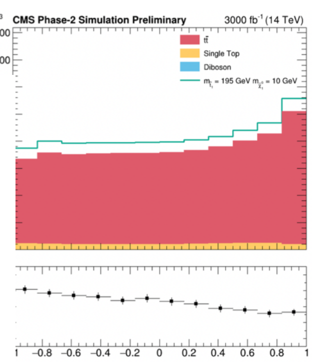
Future lepton colliders

- e+e- @Permille level
- **Prepare initial state**

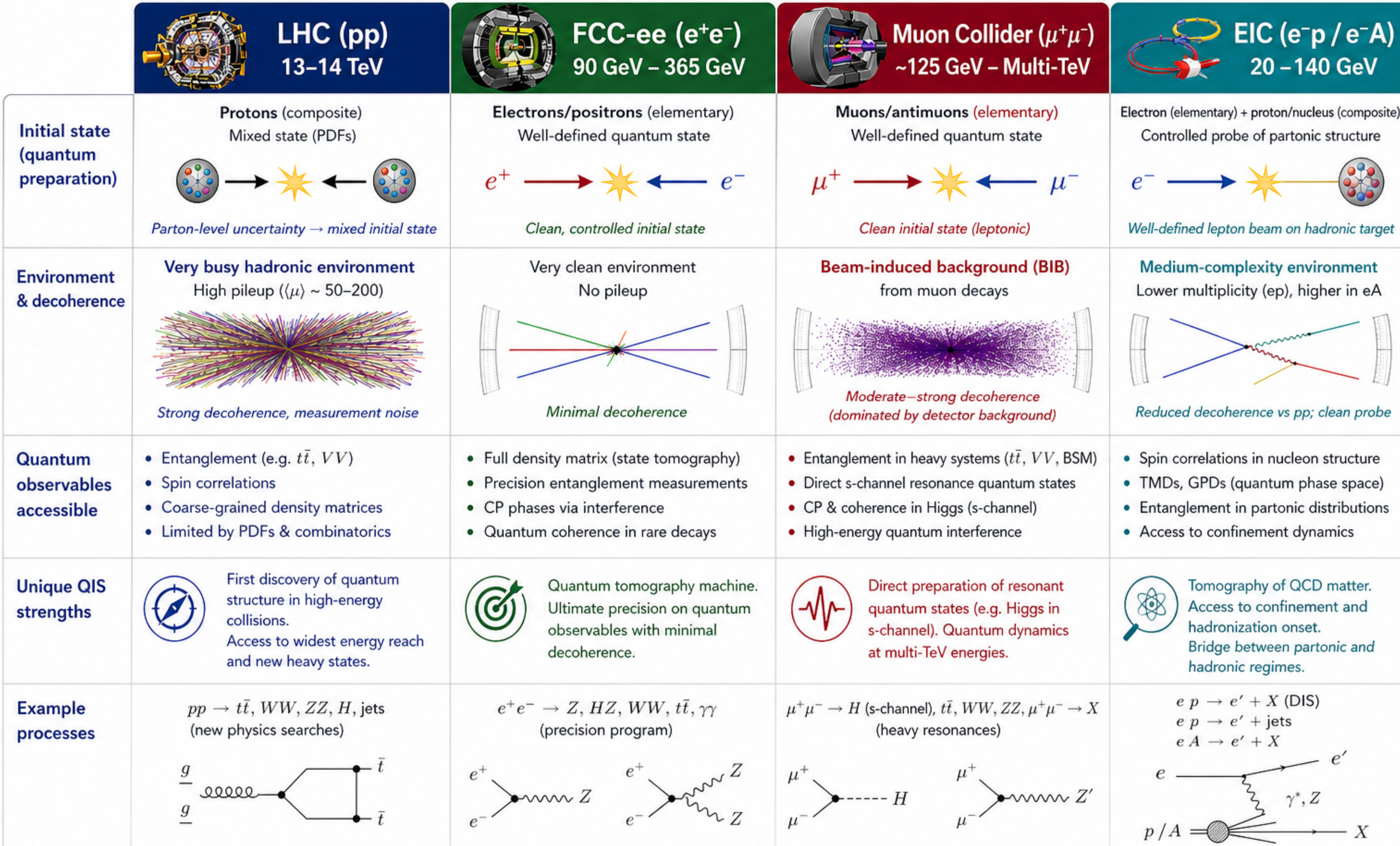
$\mathcal{O}(5-6)\%$

$\mathcal{O}(2-3)\%$





- **Top quark physics is exciting**
- **Bound states aka toponium**
- **Quantum Tomography – a rich exciting new field! Also @EIC!**

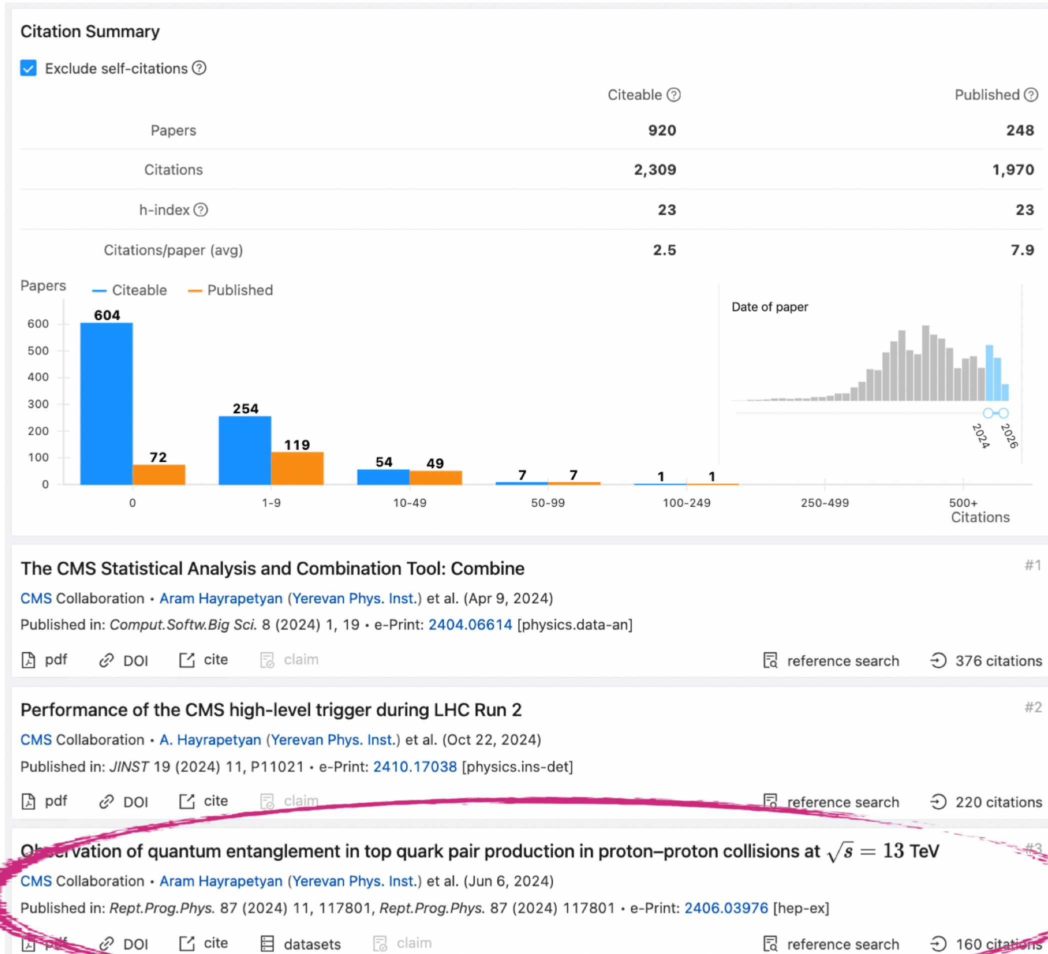


Key takeaways:

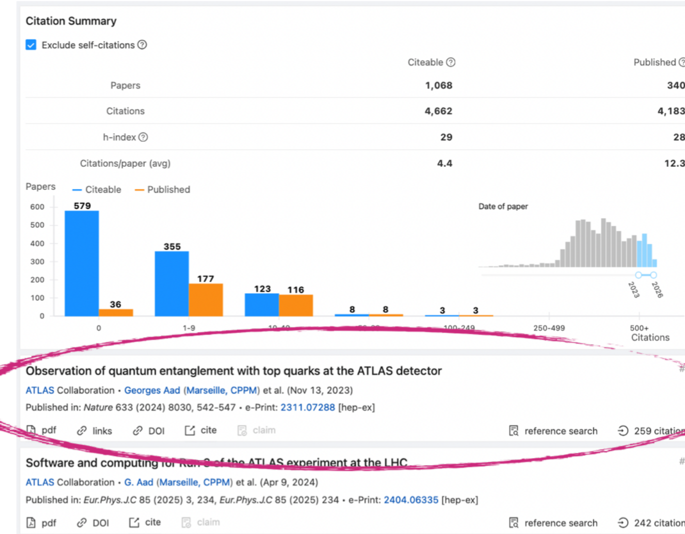
- **Colliders are complementary: 1st observations, precision studies, high control initial states**
- **QIS as an arch connecting colliders and to break "flat directions" in EFT space**
- **Powerful for top quark and Higgs sector at LHC!**

Exciting new results…

Not showing bound-state citations yet



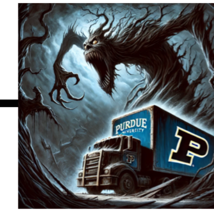
CMS: 3rd most cited paper since 2024…

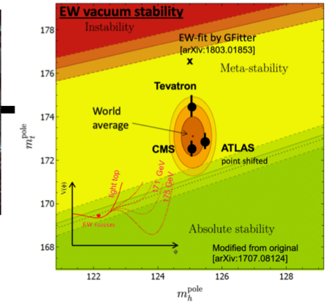


ATLAS: Most cited paper since 2023…

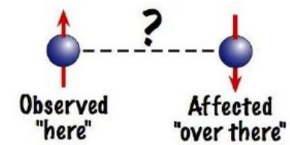
- **Quantum Tomography – a rich exciting new field!**
  … threshold scan at FCC-ee allows a deep-dive into $t\bar{t}$ ”structure” formation & QIS
- **Bright future ahead!**

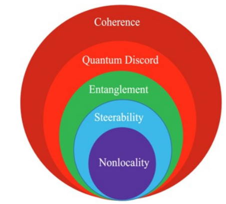
Big Questions & Challenges

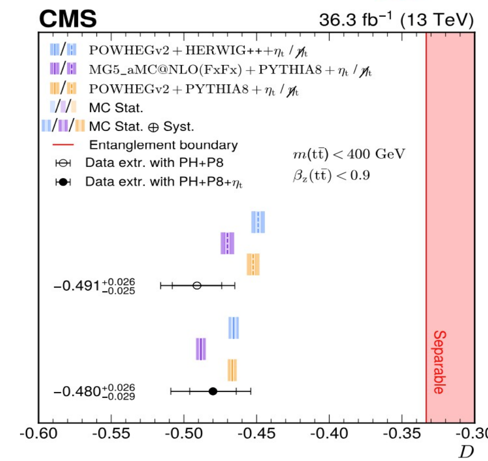




- HL-LHC Detector upgrades highest priority!
- ML/AI to leverage full wealth of data
- QIS observables for EFT to break "flat" directions for **top quark and Higgs sector**
- Top quark physics at center of big questions
  - Observation of top quark pair entanglement
  - Observation of an excess at threshold: pseudo-scalar resonance, caveats apply!
  - Quantum Entanglement & Tomography
    - **Exciting field of Quantum Information in HEP**







→ 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"

Backup

The Jung group

Composites Manufacturing & Simulation Center

Sushrut Karmarkar

Ben Denos

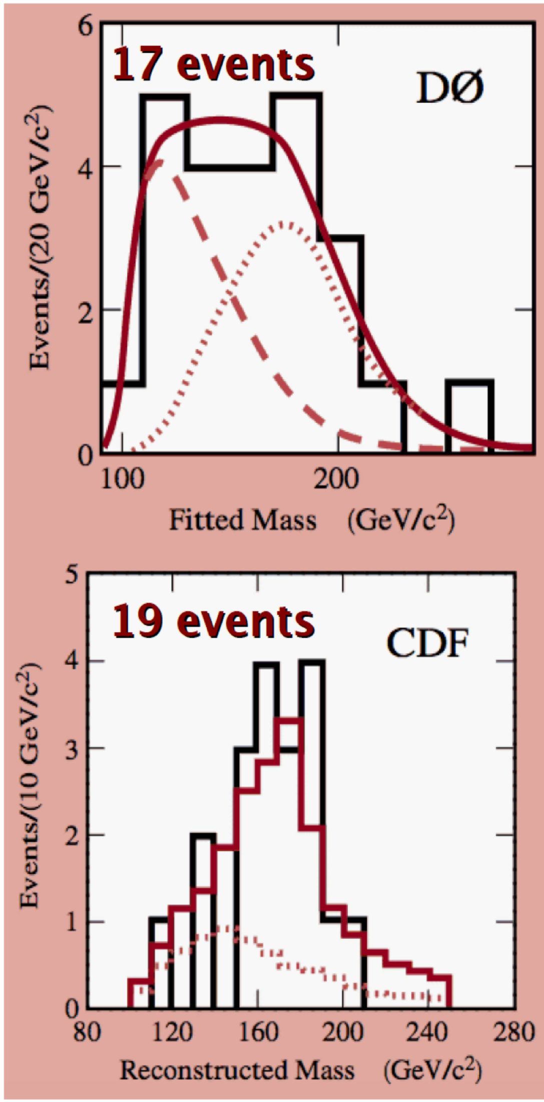
Giulia Negro

→ Purdue UG students
→ REU students and exchange students
→ Purdue – Dortmund + CERN exchange program, 31+5 participants since 2018

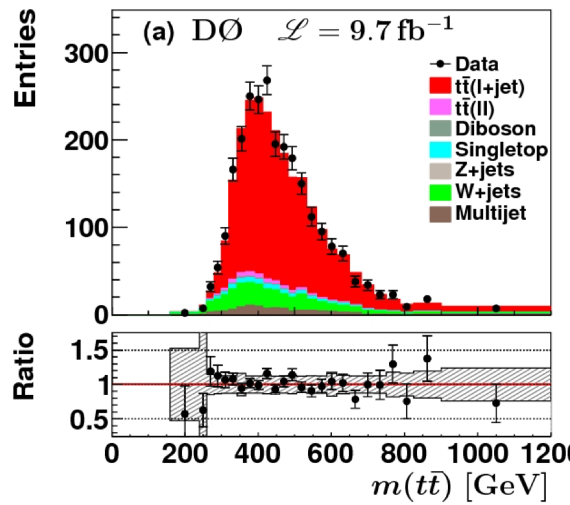
Missing: Noah Singer, Jacob Hartwick, Caden Glenn, Gino Daniels, …

Top quark physics: Origins...

Discovery at Tevatron: 1995

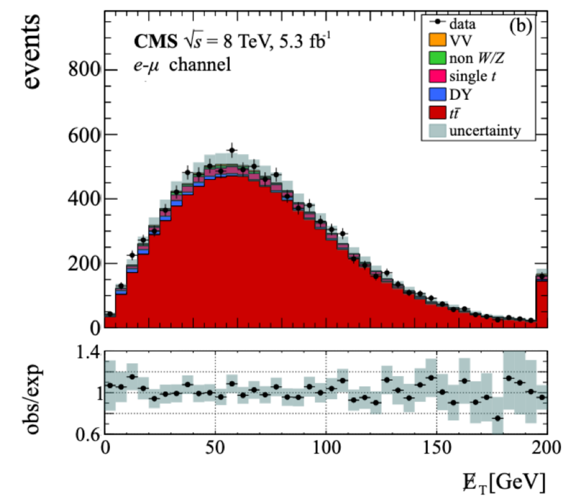


1000's events
(Tevatron Run II)



Establish top quark SM
1st differential measurements
Searches...

100,000's events
(LHC Run 1)



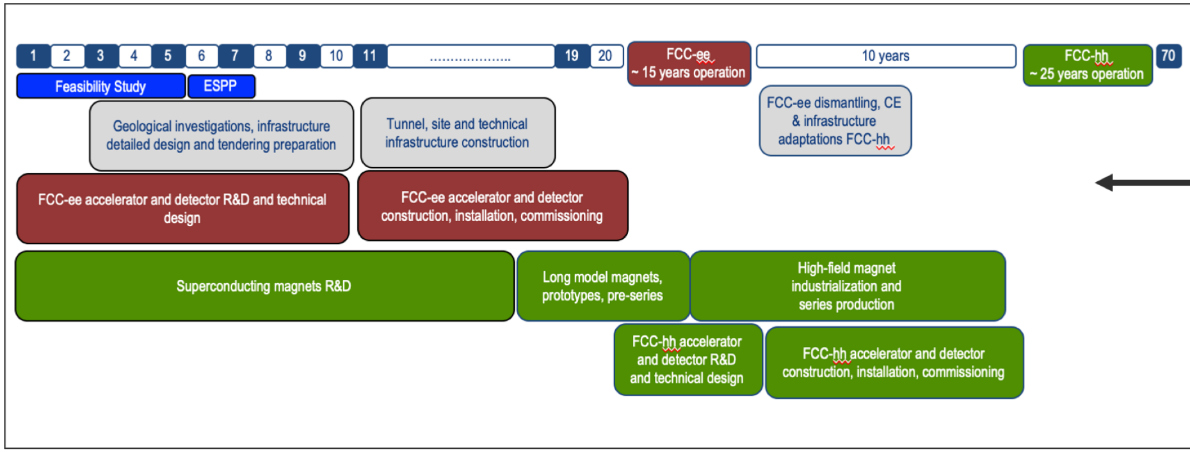
non-SM ?
Multi-differential precision measurements
Searches...

Quantum Observables for Collider Physics

…even further into the Future

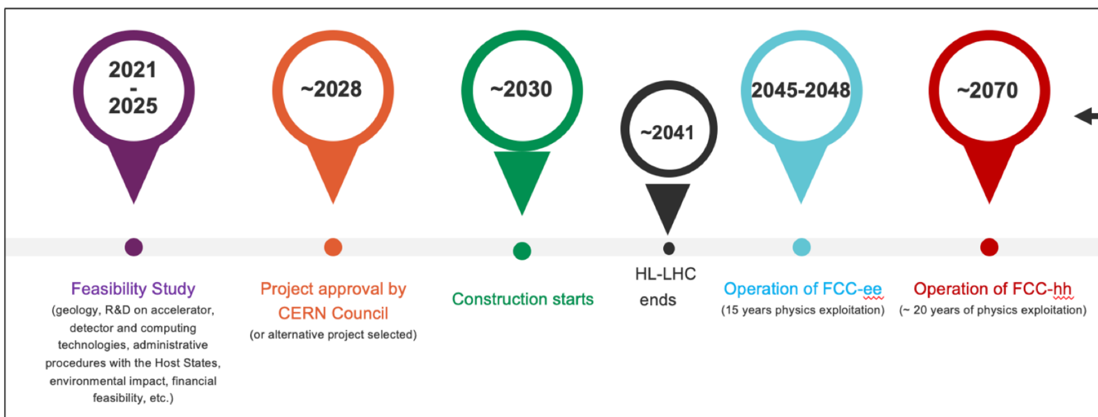
FUTURE CIRCULAR COLLIDER

FCC timeline



Note: FCC Conceptual Design Study started in 2014 leading to CDR in 2018

Technical schedule: FCC-ee could start operation **in 2040 or earlier**



Realistic schedule takes into account:
- ❑ CERN Council approval timeline
- ❑ past experience in building colliders at CERN
- ❑ that HL-LHC will run until ~ 2041

→ **ANY future collider at CERN cannot start physics operation before 2045-2048** (but construction will proceed in parallel to HL-LHC operation)

F. Gianotti

→ Essentially need to start R&D on detector (& accelerator) now-ish!

Enter a "new" probe...

Hidden variables! Pilot wave theory

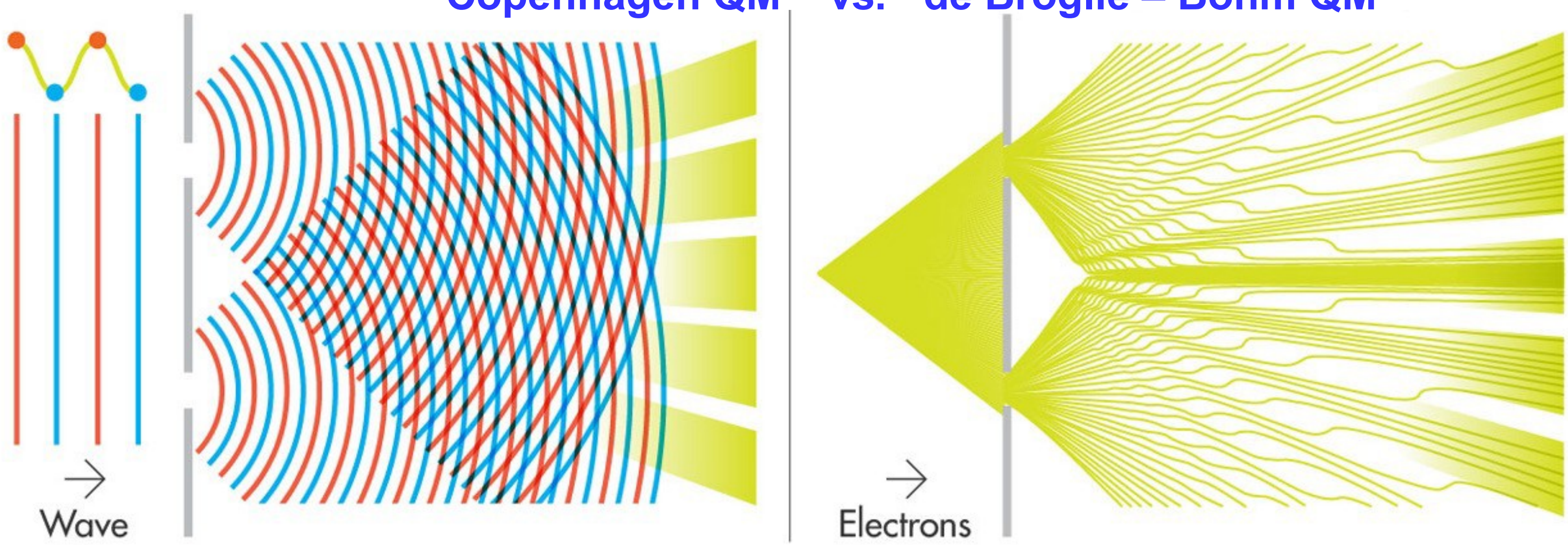
...to inner workings of top quark physics

$$\Delta x \cdot \Delta p \geq \hbar/2$$

- **Einstein:** Position and momentum can be measured simultaneously
- **Bohr:** Impossible due to disturbances in observation

5th Solvay Conference series

Copenhagen QM vs. de Broglie – Bohm QM



Schrödinger's cat

- **Einstein:** **Measure the time (Δt). Measure the mass (energy) difference (ΔE). Done!** $\Delta E \cdot \Delta t \geq \hbar / 2$
- **Bohr:** **If position changed, uncertainty in time arises, according to general relativity, …**

DIE NATURWISSENSCHAFTEN

23. Jahrgang — 29. November 1935 — Heft 48

Die gegenwärtige Situation in der Quantenmechanik.

Von E. SCHRÖDINGER, Oxford.

Inhaltsübersicht.

§ 1. Die Physik der Modelle.
§ 2. Die Statistik der Modellvariablen in der Quantenmechanik.
§ 3. Beispiele für Wahrscheinlichkeitsvoraussagen.
§ 4. Kann man der Theorie ideale Gesamtheiten unterlegen?
§ 5. Sind die Variablen wirklich verwaschen?
§ 6. Der bewußte Wechsel des erkenntnistheoretischen Standpunktes.
§ 7. Die ψ-Funktion als Katalog der Erwartung.
§ 8. Theorie des Messens, erster Teil.
§ 9. Die ψ-Funktion als Beschreibung des Zustandes.
§ 10. Theorie des Messens, zweiter Teil.
§ 11. Die Aufhebung der Verschränkung. Das Ergebnis abhängig vom Willen des Experimentators.
§ 12. Ein Beispiel.
§ 13. Fortsetzung des Beispiels: alle möglichen Messungen sind eindeutig verschränkt.
§ 14. Die Änderung der Verschränkung mit der Zeit. Bedenken gegen die Sonderstellung der Zeit.
§ 15. Naturprinzip oder Rechenkunstgriff?

§ 1. Die Physik der Modelle.

In der zweiten Hälfte des vorigen Jahrhunderts war aus den großen Erfolgen der kinetischen Gastheorie und der mechanischen Theorie der Wärme ein Ideal der exakten Naturbeschreibung hervorgewachsen, das als Krönung jahrhundertelangen Forschens und Erfüllung jahrtausendealter Gebilde, das sich mit der Zeit verändert, das verschiedene *Zustände* annehmen kann; und wenn ein Zustand durch die nötige Zahl von Bestimmungsstücken bekannt gemacht ist, so sind nicht nur alle anderen Stücke in diesem Augenblick mit gegeben (wie oben am Dreieck erläutert), sondern ganz ebenso alle Stücke, der genaue Zustand, zu jeder bestimmten späteren Zeit; ähnlich wie die Beschaffenheit eines Dreiecks an der Basis seine Beschaffenheit an der Spitze bestimmt. Es gehört mit zum inneren Gesetz des Gebildes, sich in bestimmter Weise zu verändern, das heißt, wenn es in einem bestimmten Anfangszustand sich selbst überlassen wird, eine bestimmte Folge von Zuständen kontinuierlich zu durchlaufen, deren jeden es zu ganz bestimmter Zeit erreicht. Das ist seine Natur, das ist die Hypothese, die man, wie ich oben sagte, auf Grund intuitiver Imagination setzt.

Natürlich ist man nicht so einfältig zu denken, daß solchermaßen zu erraten sei, wie es auf der Welt wirklich zugeht. Um anzudeuten, daß man das nicht denkt, nennt man den präzisen Denkbehelf, den man sich geschaffen hat, gern ein *Bild* oder ein *Modell*. Mit seiner nachsichtslosen Klarheit, die ohne Willkür nicht herbeizuführen ist, hat man es lediglich darauf abgesehen, daß eine ganz bestimmte Hypothese in ihren Folgen geprüft werden kann, ohne neuer Willkür Raum

'Der Alte würfelt nicht'

Physical reality must be local! - Podolsky

EPR Paradox

MAY 15, 1935 — PHYSICAL REVIEW — VOLUME 47

Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?

A. EINSTEIN, B. PODOLSKY AND N. ROSEN, *Institute for Advanced Study, Princeton, New Jersey*
(Received March 25, 1935)

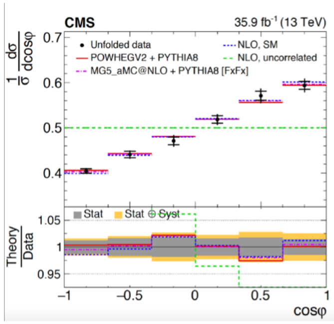
In a complete theory there is an element corresponding to each element of reality. A sufficient condition for the reality of a physical quantity is the possibility of predicting quantum mechanics is not complete or (2) these two quantities cannot have simultaneous reality. Consideration of the problem of making predictions concerning a system

6th Solvay Conference series

Prospects and Outlook

Double diff. xsec **Polarisation (0 in SM)** **Spin Correlation**

$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta^a_+ \, d\cos\theta^b_-} = \frac{1}{4}\left(1 + B^a_+\cos\theta^a_+ + B^b_-\cos\theta^b_- - C(a,b)\cos\theta^a_+\cos\theta^b_-\right)$$



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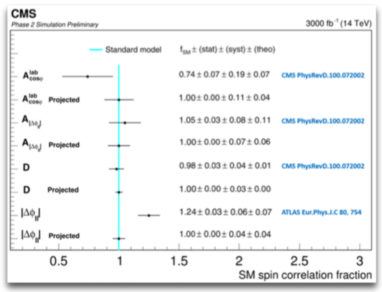
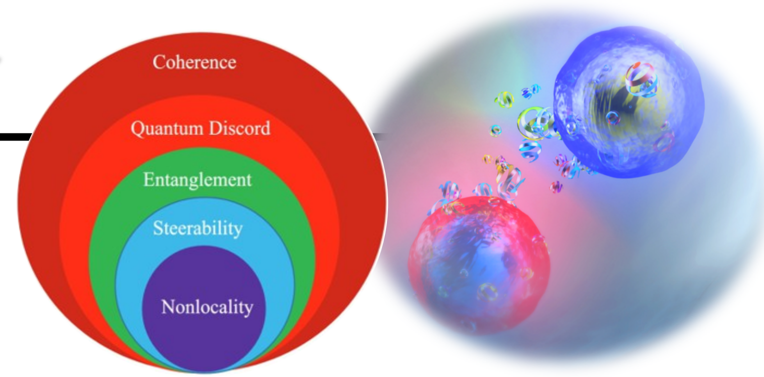
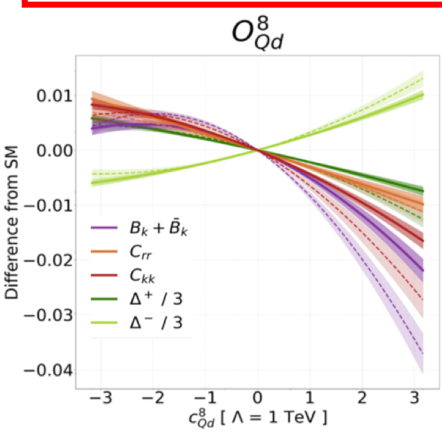


$$f_{SM} = \frac{D_{measured} - D_{theory,uncorrelated}}{D_{theory,correlated} - D_{theory,uncorrelated}}$$

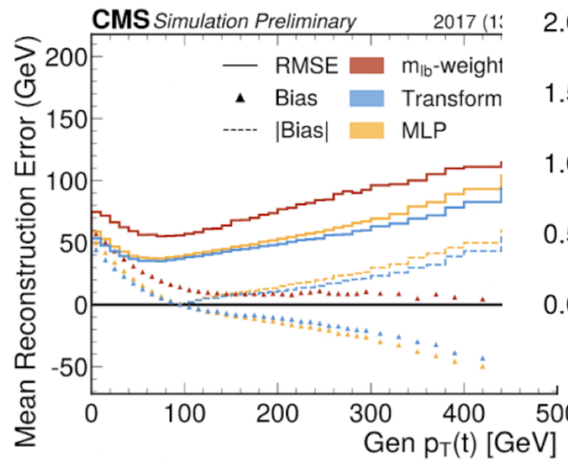
Opening angle between leptons in top parent rest frame

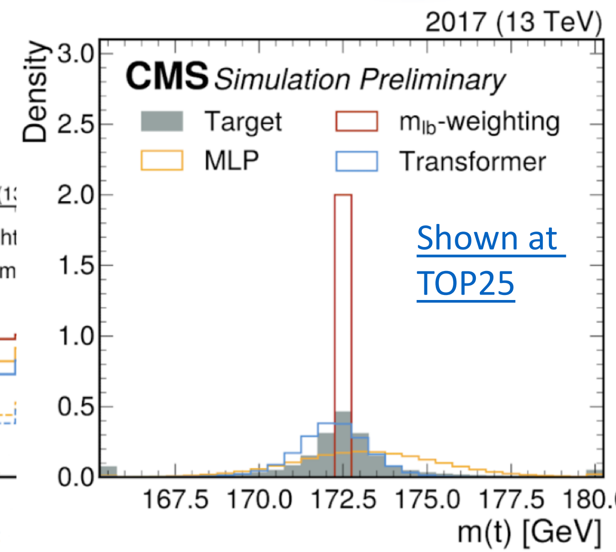
Expect: ~ 2 – 3% precision





JHEP 01 (2023) 148 [2210.09330]





Shown at TOP25

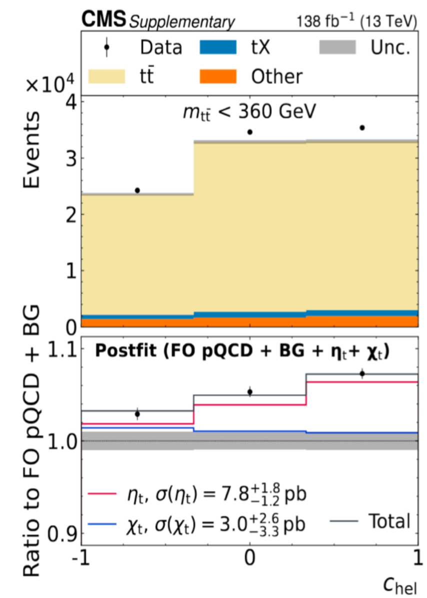
"Threshold" measurements impacted by top quark reco

- Transformer approximately 30% improvement vs $m\ell b$ – method
- Reconstructs events for which 5% of time $m\ell b$ - method fails
- Exciting region for SM (aka η_t), EFT, and Quantum Correlations…
- **Break flat directions in EFT with QIS-based observables**

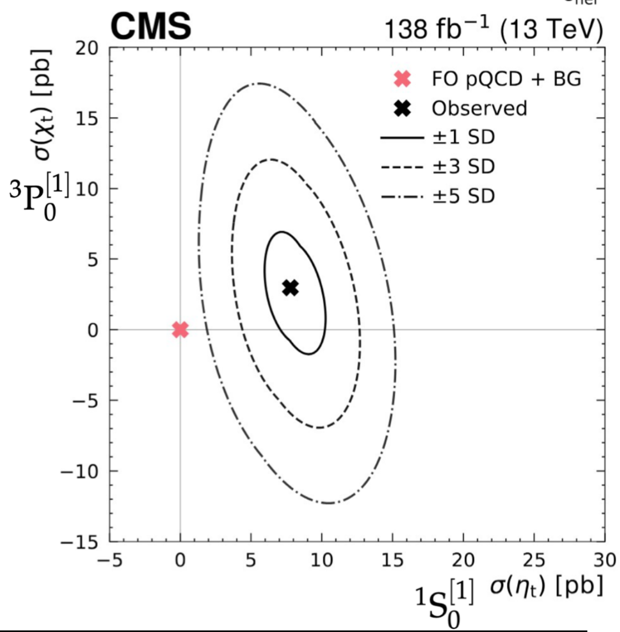
Quantify the excess at threshold

- Interpretation in terms of η_t ROPP 88 (2025) 087801
- Extract cross section using the η_t color-singlet model
  - "cross section" = difference to perturbative prediction

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



- Theory: $\sigma(\eta_t) = 6.43 \pm 0.90$ pb (PRD 104 (2021) 034023) (JHEP 09 (2010) 034)



- Differentiate between η_t (CP-odd) and χ_t (CP-even)
- Dominant systematic uncertainties:
  - bb4l: NLO, off-shell effects, interference tt and tW
  - PS FSR: α_S in final state radiation
  - top quark mass and Yukawa coupling
  - Herwig7 as alternative parton shower model
- Words of caution:
  - Cannot distinguish between η_t & pseudo-scalar Higgs
  - Missing e.g. color-octet states - these are expected to be small

Quantum Computers

Annealers

- **5436 qubits (Advantage_system1.1)**
- **Non-universal****
- **plings between qubits**

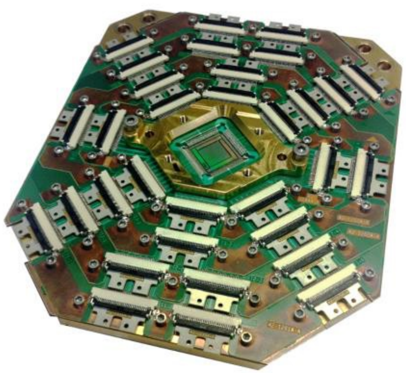
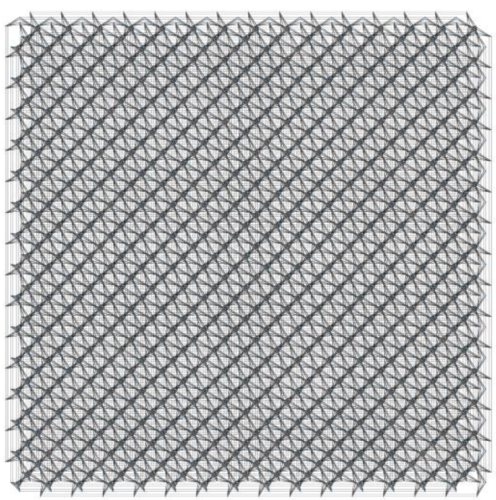
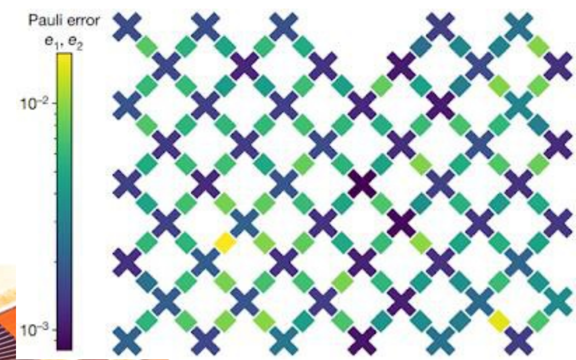


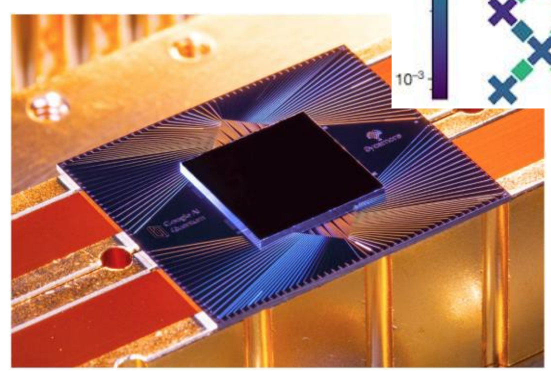
Image courtesy of: https://www.dwavesys.com/sites/default/files/14-1047A-A_Practical_Quantum_Computing_An_Update_0.pdf



Circuits/Gates

- **53 qubits***
- **Universal**
- **86 couplings between qubits**

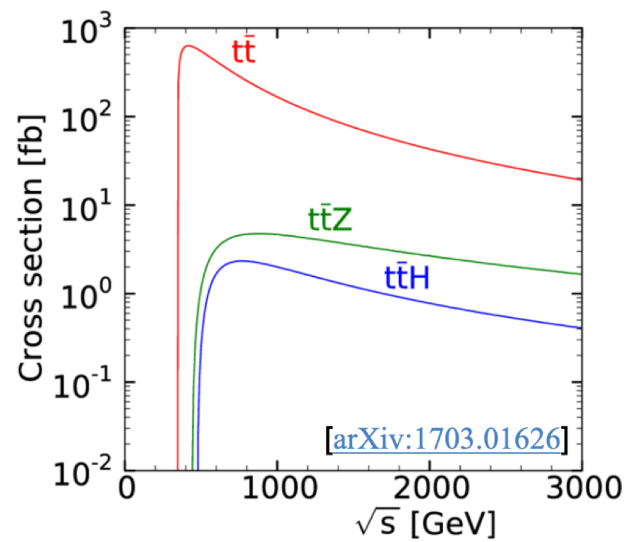




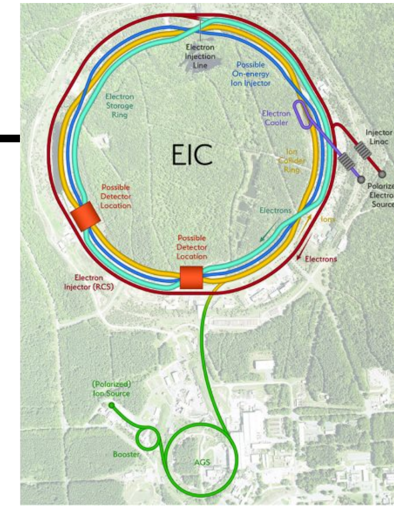
FCC ee – Prospects

- To achieve these precisions on top quark mass and coupling it needs about 40/fb per mass scan point. [arXiv:2503.18713]
  - Precisions below require about 10 mass points
  - Total luminosity at threshold around 400/fb
  - Around 20k events all inclusive per mass point
- Some options accumulate ~2.65/ab of luminosity at the threshold! This is 4 years of data taking.

Observable	present value	±	uncertainty	FCC-ee **Stat.**	FCC-ee Syst.	Comment and leading uncertainty
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10.0**	6.0	From $t\bar{t}$ threshold scan QCD uncert. dominate
y_{top}		±	10%	**1.5 %**	1.5 %	From $\sqrt{s} = 365$ GeV run QCD uncert. dominate
g_{ttZ} (L-R)		±	10-30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run



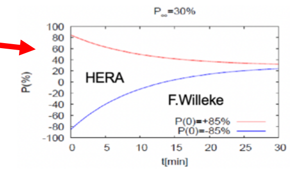
Other opportunities: EIC



→ Will be the 2nd ep/Ion collider after 1st HERA ep collider @DESY

→ Probes of Entanglement ? Polarization @HERA

→Yes! This session…



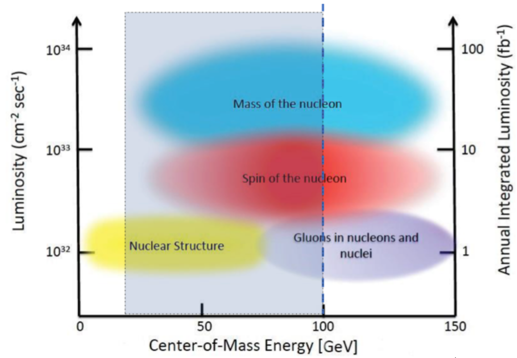
The Electron-Ion Collider User Group *(EICUG)* consists of more than **1200 physicists** from over [250 laboratories and universities from around the world]

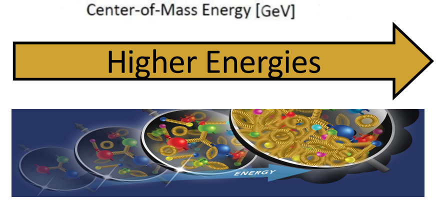
2.4 miles long accelerator

Project Design Goals

- High Luminosity: L= $10^{33} – 10^{34}$ cm^{-2}sec^{-1}, 10 – 100 fb-1/year
- Highly Polarized Beams: 70%
- Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
- Large Ion Species Range: protons – Uranium
- Accommodate a Second Interaction Region (IR) with a 2nd detector

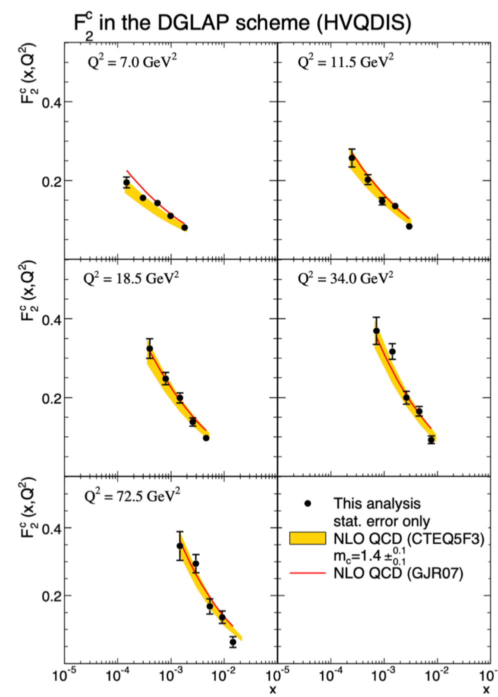
Physics goals: Understand origin of mass & spin of the nucleon structure / proton





EIC QIS:

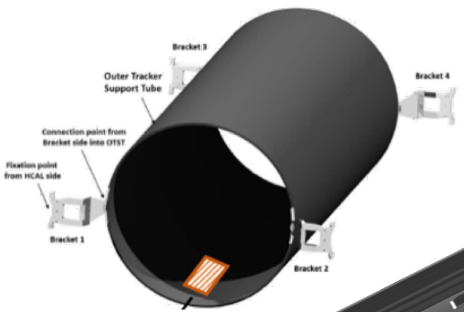
- High-x dominated by charm
- Systematic's ?!
- Intrinsic charm

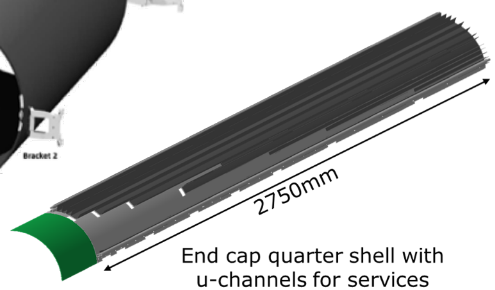


https://inis.iaea.org/records/xq8kk-2qa52

What's possible today… *(biased view/selection)*

Advanced Mechanics & Composites activities at Purdue





Large Support Structures – light-weight but rigid

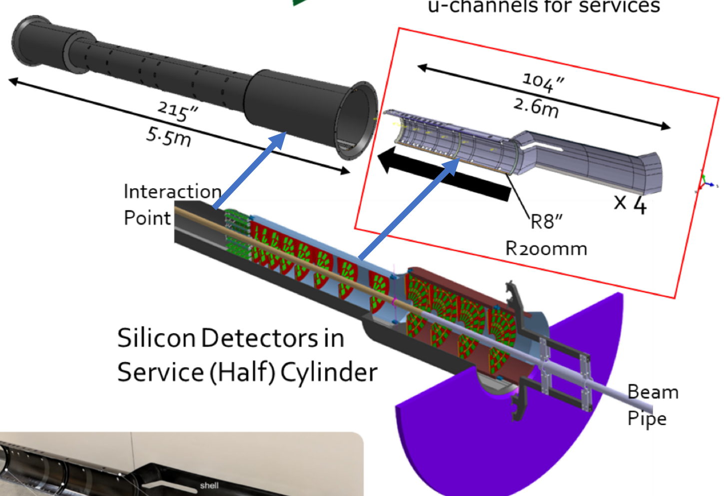
1. BTL Tracker Support Tube (CMS)
2. Inner Tracker Support Tube (CMS)
3. Inner Tracker Service Cylinder (CMS)
4. End Cap Quarter-Shells (ATLAS)

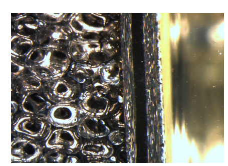
Small Structures – extremely flat and thin

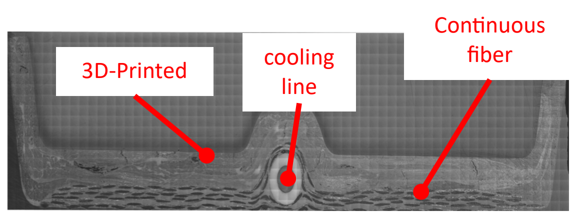
1. Pixel Dees Support Structure (CMS)
2. High-TC flat sheets for silicon modules (CMS)

Irradiation campaigns:

- In collaboration with US TFPX institutes (Cornell, Rice, others)







Future Mechanics and R&D:

1. "BlueSky Mechanics" for detectors at future Colliders (FCC, muon, LC, etc.) https://arxiv.org/abs/2203.14347
2. "CalVision" project for mechanics of dual readout calorimetry https://arxiv.org/abs/2203.04312

Lots of opportunities ahead…

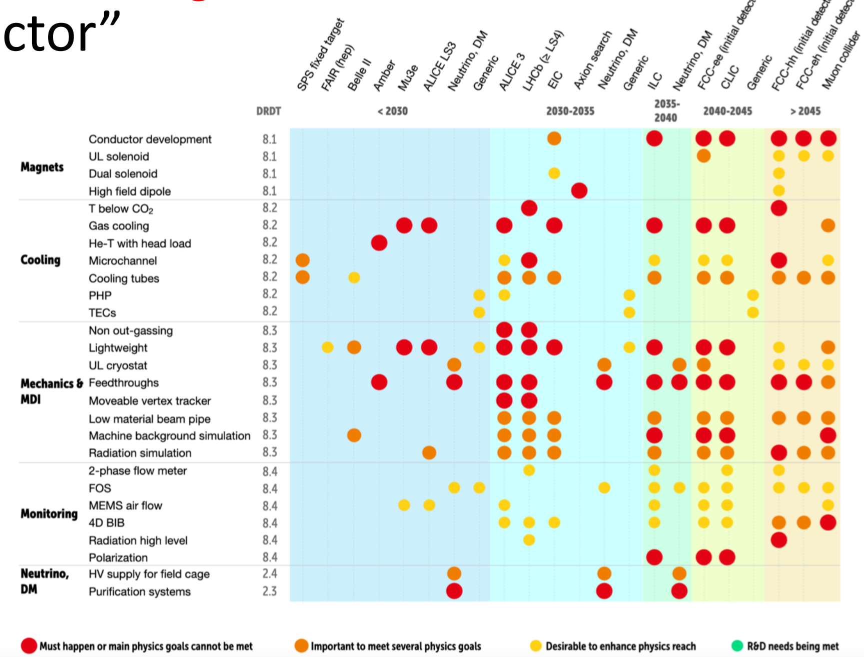
- ECFA (European Committee for Future Accelerators) matrix of experiment/detector" mapped to technologies / R&D (DRD)
- ECFA Detector R&D roadmap: https://cds.cern.ch/record/2784893

R&D collaborations

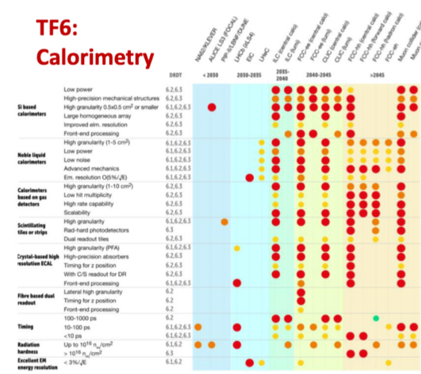
- US CPAD RDC's
- Europe CERN DRD's

→ Just few examples, Get involved!

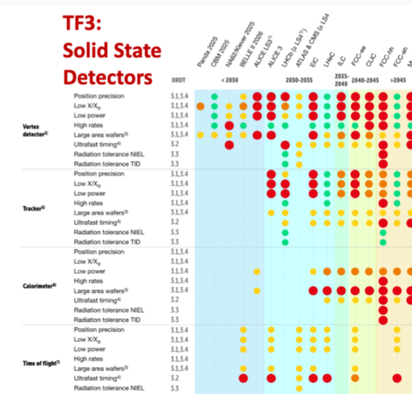
TF8: Mechanics, Cooling, Magnets, Services



TF6: Calorimetry



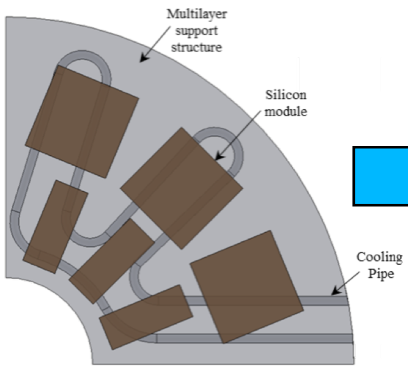
TF3: Solid State Detectors

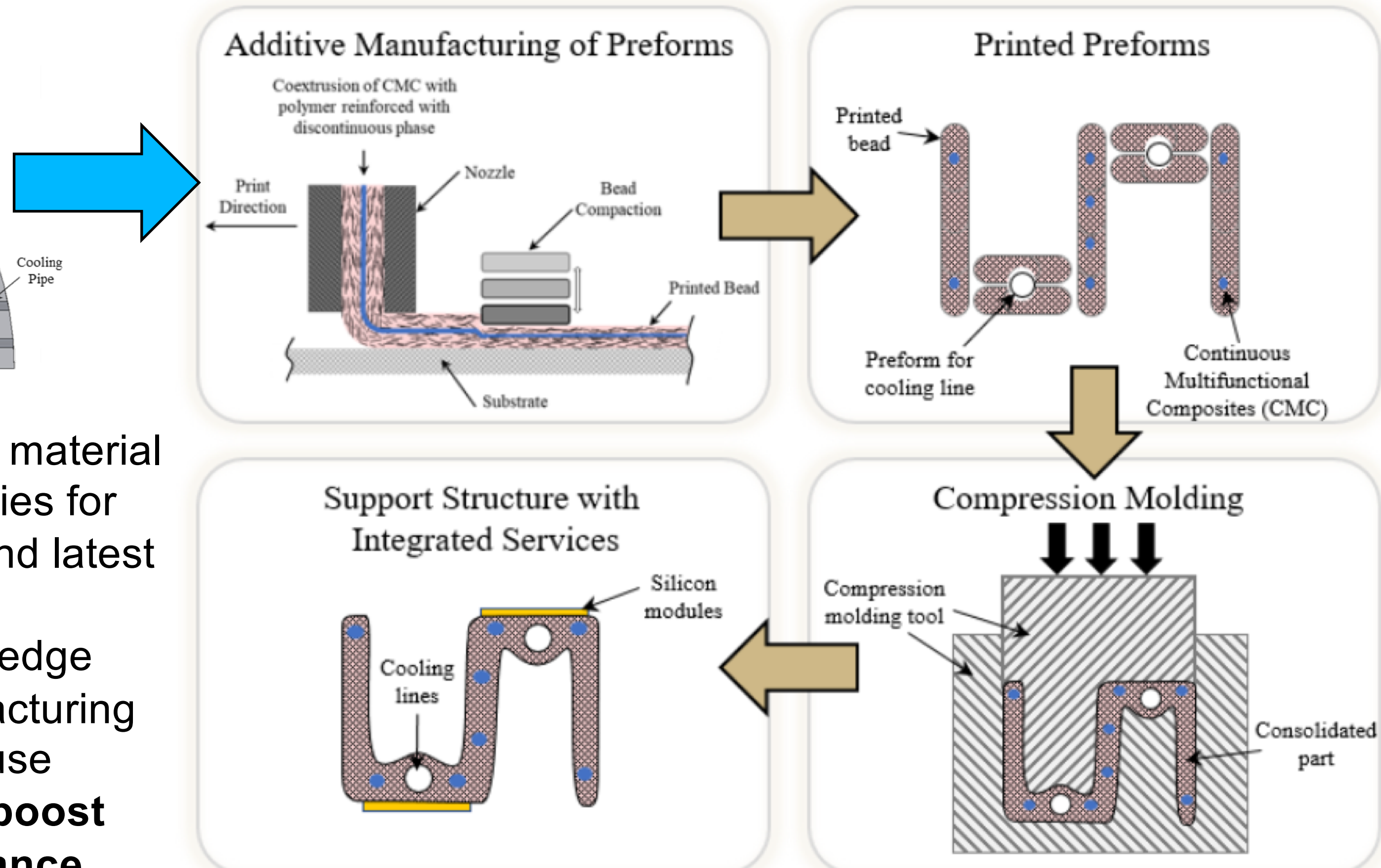


Going into the future of mechanics

Identified by DOE BRN effort & CPAD

- Scaling of low-mass detector system towards irreducible support structures with integrated services. Includes: integrated services, power management, cooling, data flow, and multiplexing.

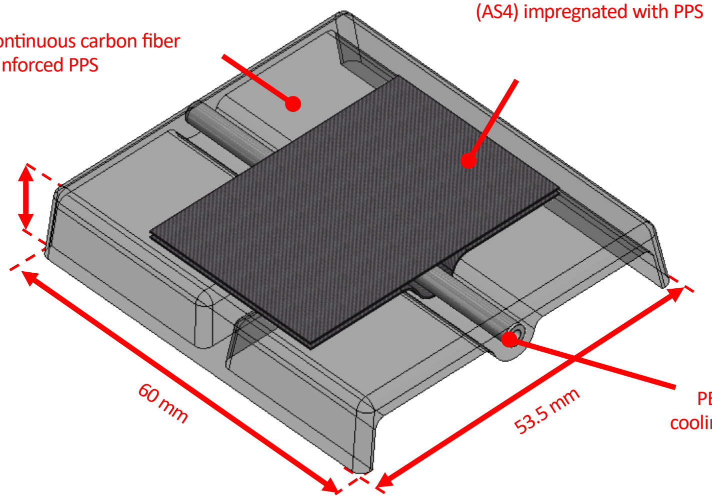


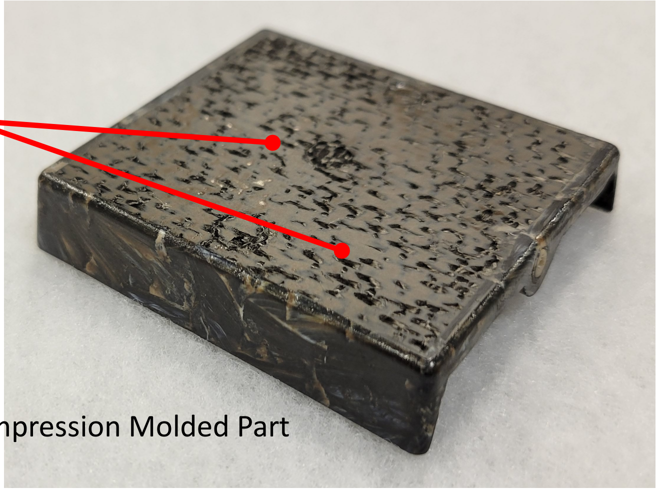


→ Collaboration with material sciences, companies for novel materials, and latest techniques.
→ Example: Cutting-edge composite manufacturing techniques, in-house
→ **Reduce mass & boost thermal performance**

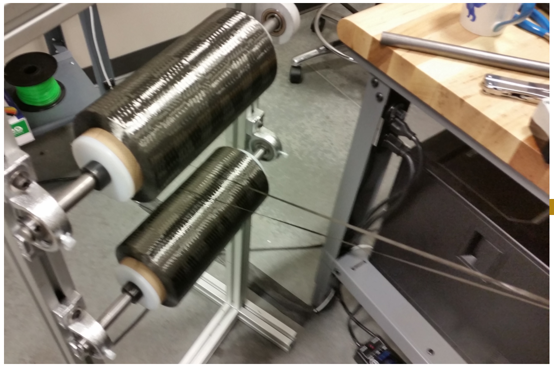
Going into the future of mechanics

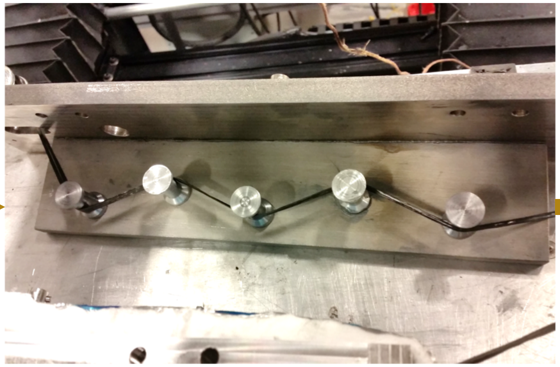
First prototypes look promising…

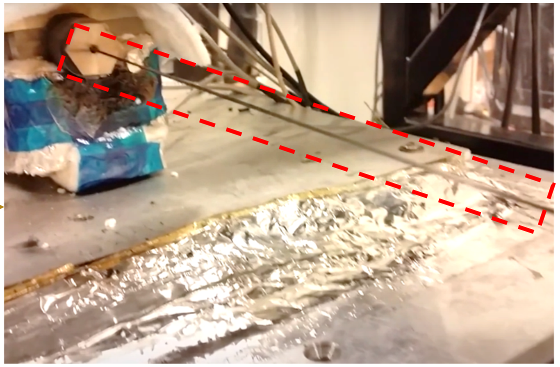




Compression Molded Part

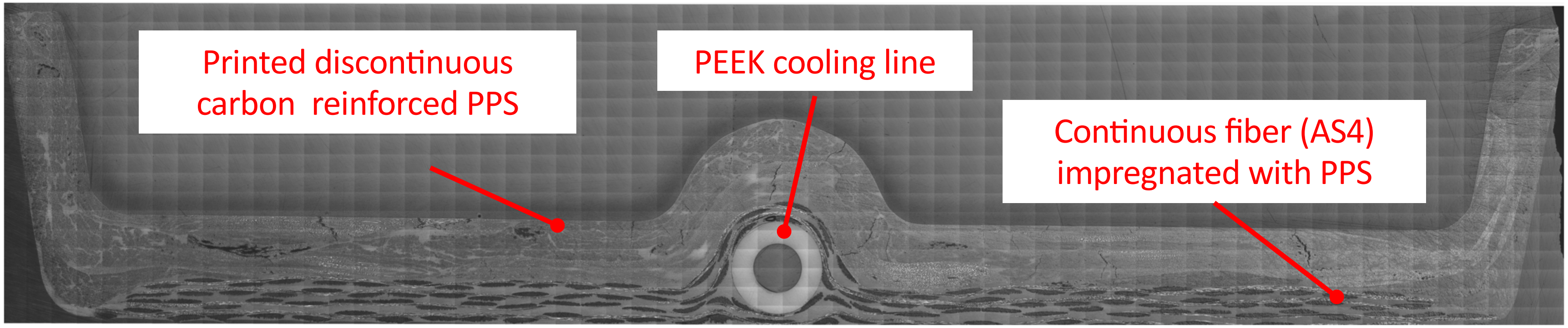

Spools of Carbon Fiber


Interior of Impregnation Chamber


Carbon Fiber Impregnated with PPS

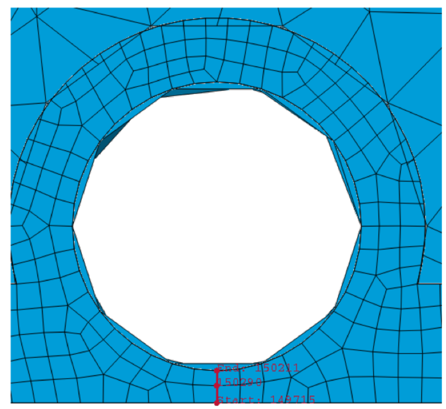
Going into the future of mechanics

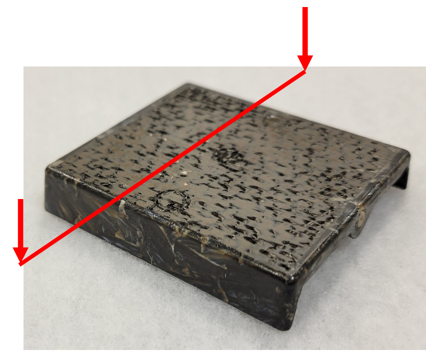
Cross-sectional micrograph of first prototypes

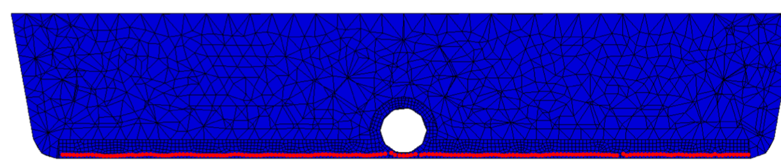


Detailed FEA studies:

- Similar conditions as for CMS HL-HLC FEAs
- For now: Modeled as an N2 turbulent flow at –20 Celsius with a constant volumetric flow
- Different scenarios for thermal transfer coefficient
- Compare results along continuous fibers and between “pipe” and surface







Thermal performance improved compared to state-of-the-art

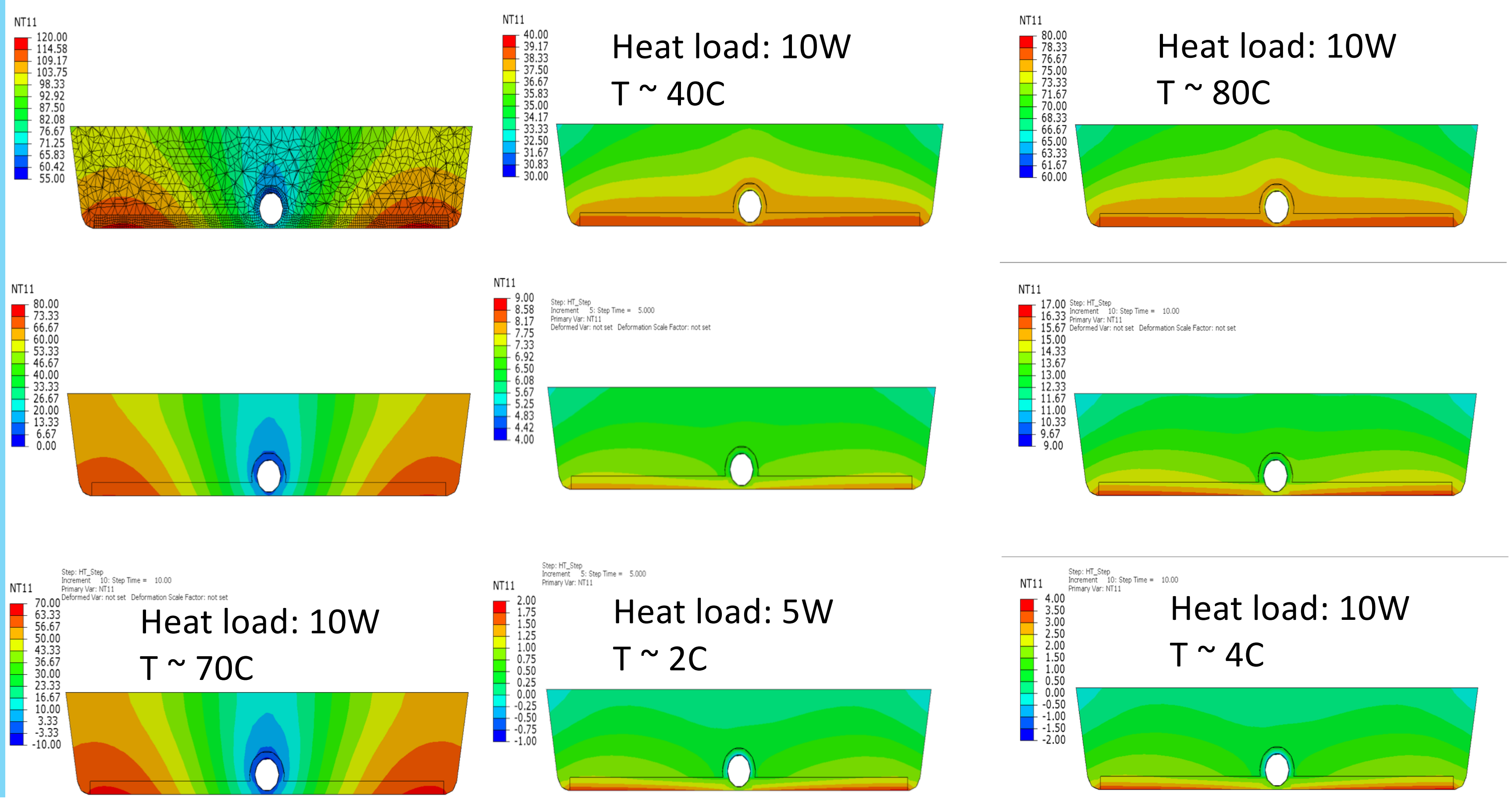
Already at a lower mass and can be further reduced…

h (W/m^2K) | K = 5 (W/mK) | K = 800 (W/mK) | K = 800 (W/mK)

136

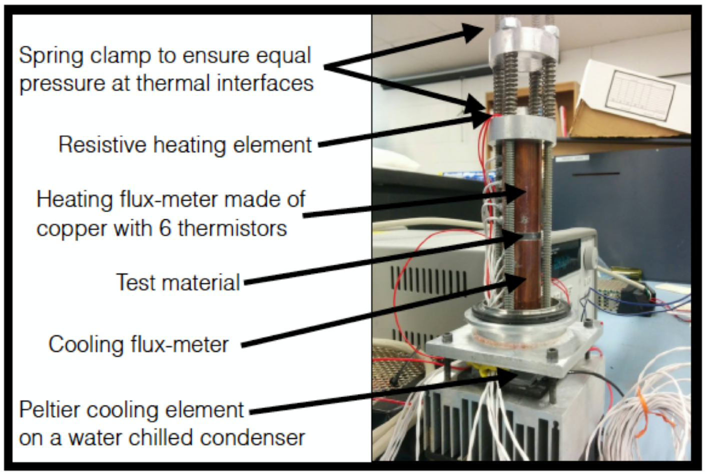
495

847

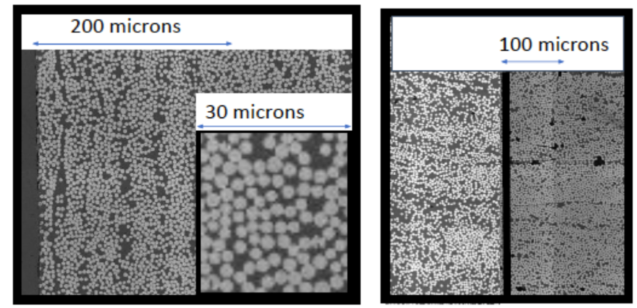


Thermal conductivities

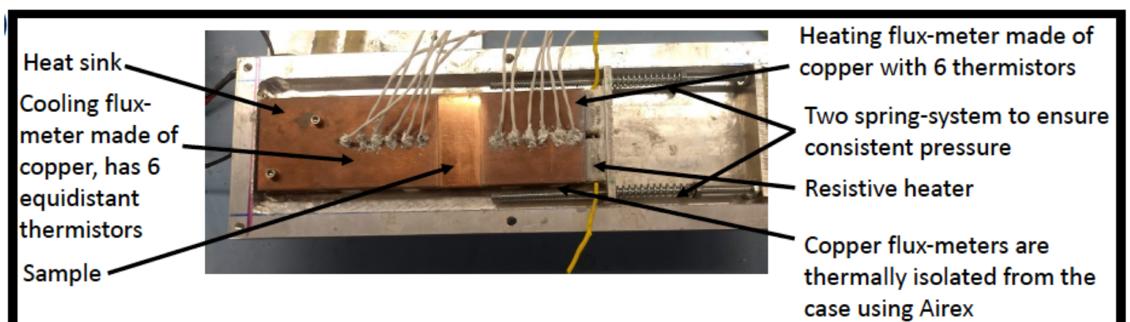
→ UG student driven activities, low-cost but precise
→ High pressure curing to boost TC, factor 2 improvement
→ Additional fillers to boost TC while maintaining mechanical strength
→ Method & Results to be submitted to JINST soon…



→ High pressure samples increase volume fraction to 72%
→ Microscopies to measure volume fractions



Sample/ Direction of measurement	Thermal conductivity (k) [W/mK]	Interface thermal resistance of Flux-meter-TIM-Sample (R_{int}) [Km^2/W]	Reduced χ^2 of the linear fit	Expected value of k [W/mK]
K13C2U+EX1515 carbon fiber composite (Unidirectional)				
x-axis	(320 ± 28)	$(1.8 \pm 0.4) \cdot 10^{-5}$	0.83	318 [3]
y-axis	(6.0 ± 2.6)	$(3.8 \pm 2.8) \cdot 10^{-4}$	0.17	0.53 [3]
z-axis	(1.09 ± 0.15)	$(-6.0 \pm 17.0) \cdot 10^{-5}$	0.05	0.53 [3]
z-axis (20 bar)	(2.21 ± 0.31)	$(3.0 \pm 7.0) \cdot 10^{-5}$	0.09	1.2 [3]
K13D2U+EX1515 carbon fiber composite (Unidirectional)				
x-axis	(376 ± 31)	$(1.7 \pm 0.3) \cdot 10^{-5}$	0.65	410 [3]
y-axis	(7.5 ± 4.4)	$(3.9 \pm 3.5) \cdot 10^{-4}$	0.01	0.53 [3]
z-axis	(1.44 ± 0.24)	$(1.4 \pm 1.4) \cdot 10^{-4}$	0.44	0.53 [3]
z-axis (20 bar)	(2.79 ± 0.46)	$(2.0 \pm 9.0) \cdot 10^{-5}$	0.43	1.2 [3]
Other materials				
IM7 8552 (x-axis)	(8.0 ± 2.3)	$(1.2 \pm 0.8) \cdot 10^{-4}$	0.85	5.50 [20]
Celstran© PPS-CF50-01 (z-axis)	(0.34 ± 0.08)	$(-2.2 \pm 4.6) \cdot 10^{-4}$	1.09	0.39 [21]

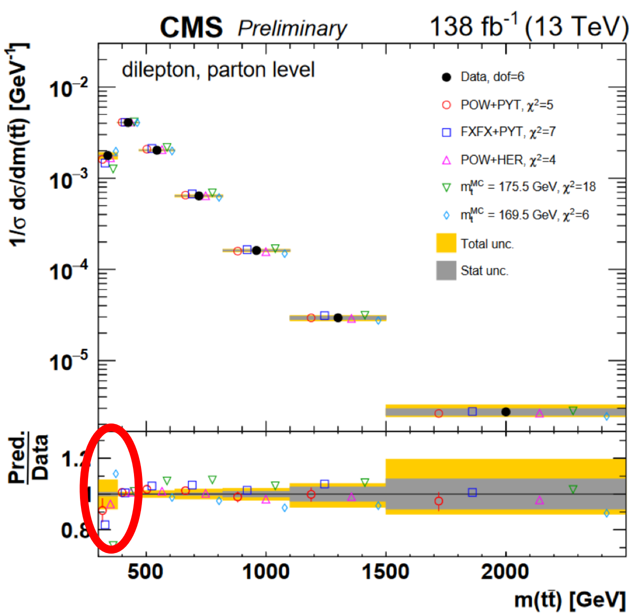


Threshold region of $t\bar{t}$ production

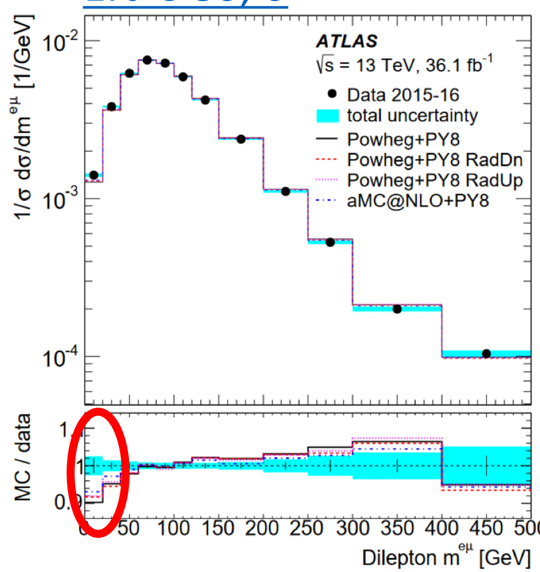
Reminder:

- Mismodeling seen for $m(t\bar{t}) = 345$ GeV since LHC Run 1
- Consistent between decay channel and ATLAS & CMS
- …even at different center-of-mass energies

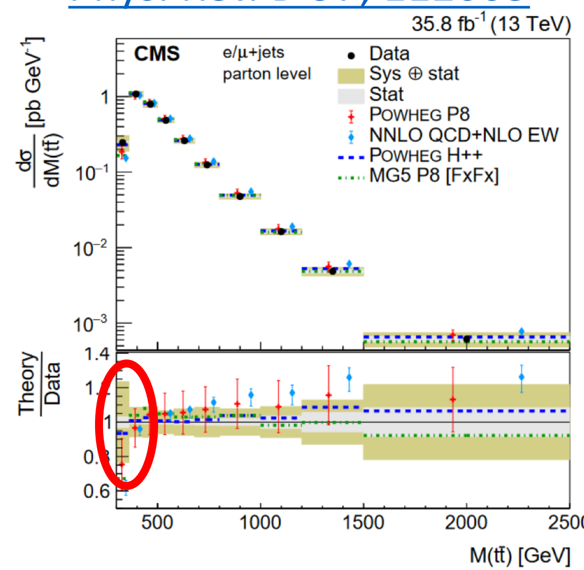
CMS-PAS-TOP-20-006



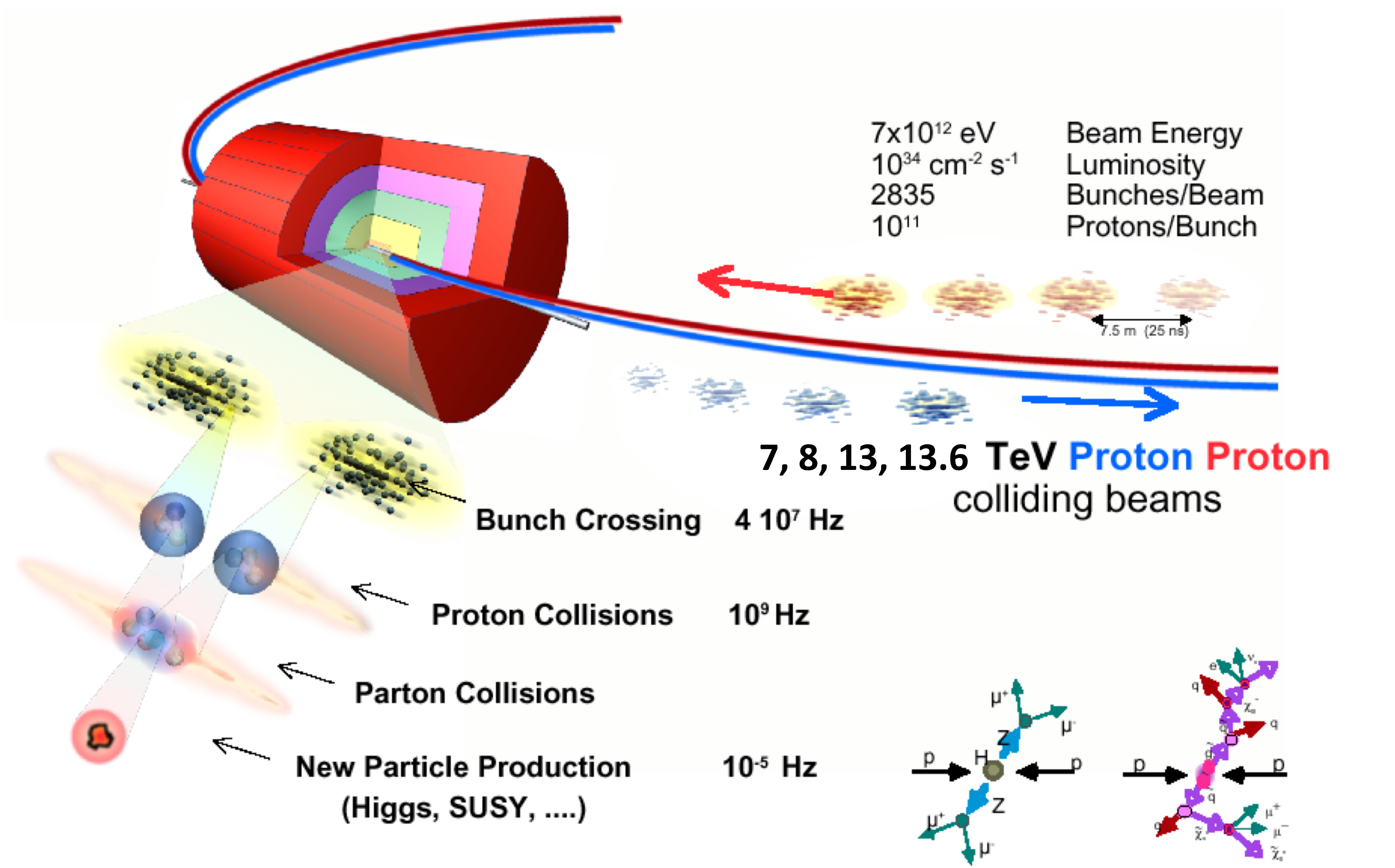
EPJ C 80, 6



Phys. Rev. D 97, 112003



LHC: Colliding protons



Selection of 1 event in 10,000,000,000,000

The CMS collaboration

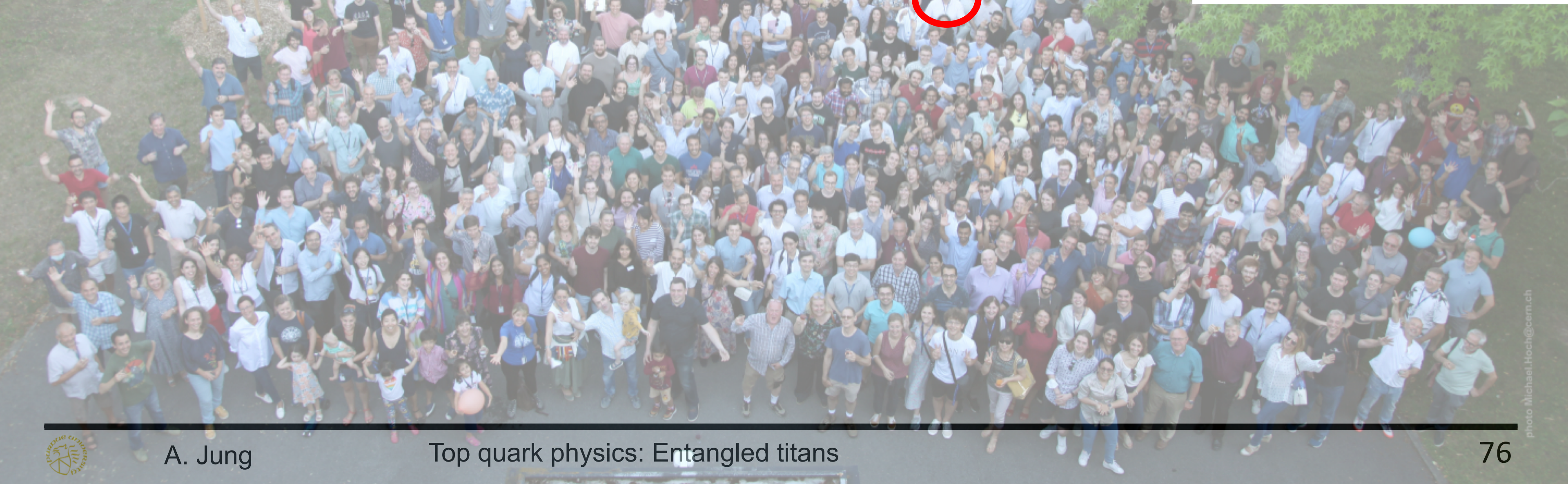
The CMS collaboration has around:

5507
ACTIVE PEOPLE
(PHYSICISTS, ENGINEERS, TECHNICAL, ADMINISTRATIVE, STUDENTS, ETC.)

3394	1102	282	247	57
PHYSICISTS (1228 STUDENTS)	ENGINEERS	TECHNICIANS	INSTITUTES	COUNTRIES & REGIONS

- It takes a “small” village to operate and run the CMS detector…
- Gigantic electronic “camera”

June 2022
CMS collaboration week

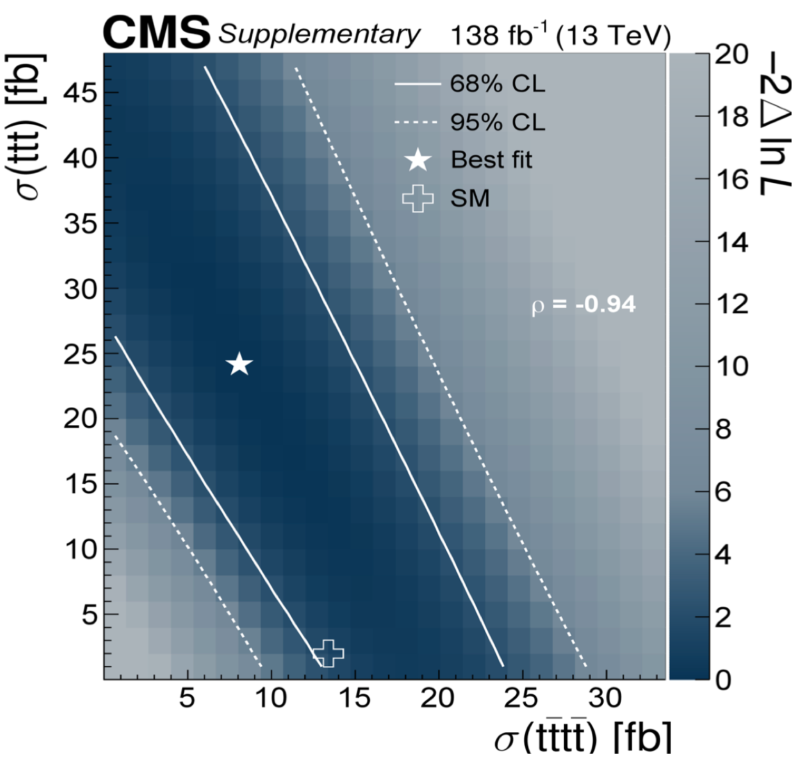


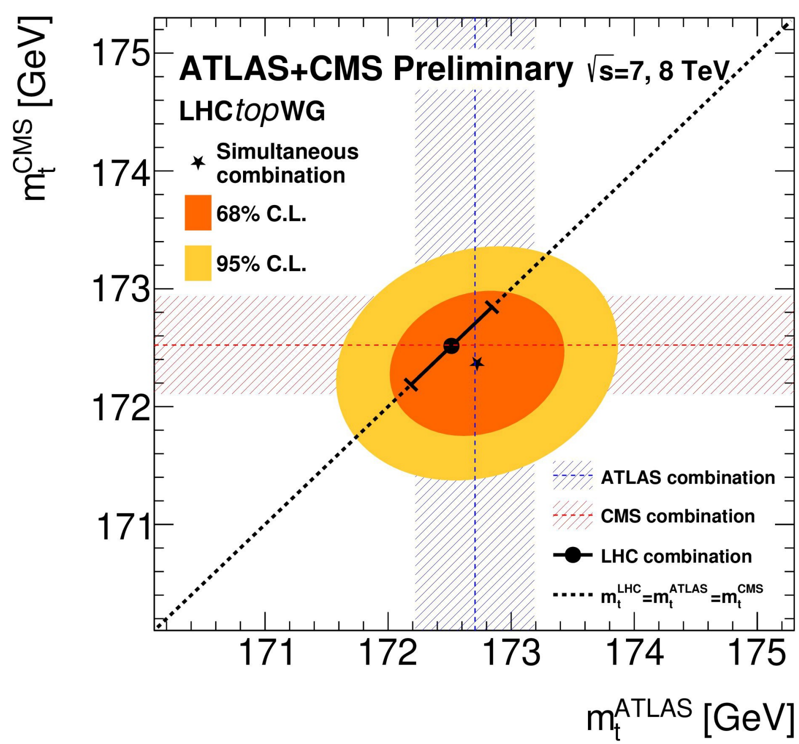
Top quark physics – Highlights

30 years of top quark physics!

- Ever more precise measurements enabled by excellent collider and detector performance

Benefit from all areas of Combined Performance:
- jets & missing energy
- flavour tagging
- lepton ID & isolation
- luminosity
- …





Purdue University ? West Lafayette, IN

- About 200km south of Chicago
- Endless corn fields, magnificent Lake Michigan
- Tornados & Winter storms

Purdue University:

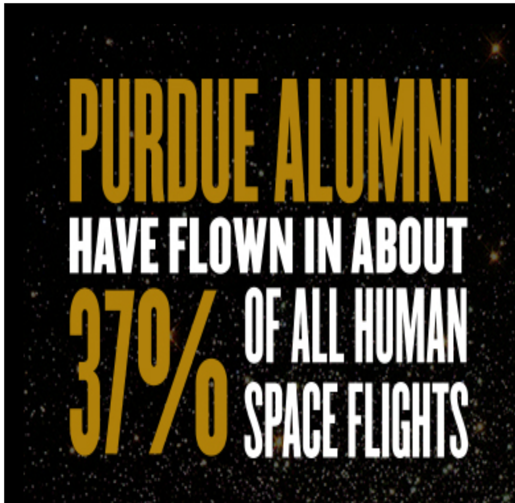
- 52,500 students on campus
  - > 100,000 in the Purdue system
- Public University, considered new “Ivy league”, in the top 10 in US
  - [Ranks 88th in Natural Sciences]
  - # 1 Destination for International Students in STEM Discipline
  - Patents/yr: #4 in US / #7 globally
- Physics saw largest growth during Manhattan project

Trivia:

- Mascot “Purdue Pete” & “Boilermakers”
- 2nd busiest airport in Indiana (training)

Purdue – Cradle of the Astronauts

- Video of the 50th anniversary of the Apollo missions https://youtu.be/c8SN92zF2Gw
  - Purdue astronauts have made 61 space flights and spent the equivalent of 741 days in space
- Honoring Sully ("Miracle on the Hudson"), Purdue alumni https://youtu.be/ngYo-y9SAOM



On July 20, 1969, Purdue alumnus Neil Armstrong took his famous "small step" into history to set foot on the moon. And in 1972, Eugene Cerman, another Purdue alumnus, became the most recent person to step on the lunar surface.

Threshold region of $t\bar{t}$ production

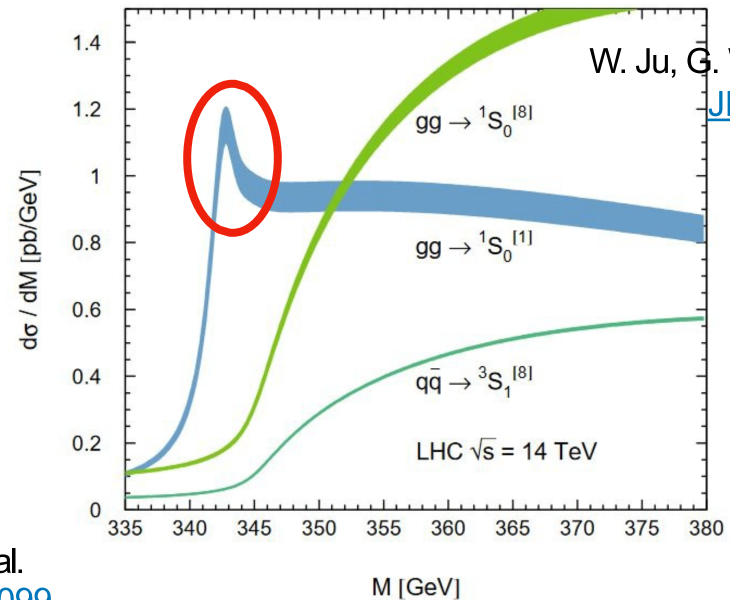
- **NRQCD contributions close to threshold**
  - **toponium:** predicted top quark-antiquark quasi-bound state with a mass of 343 GeV and a width of 7 GeV

- **Excess seen could come from toponium ?**

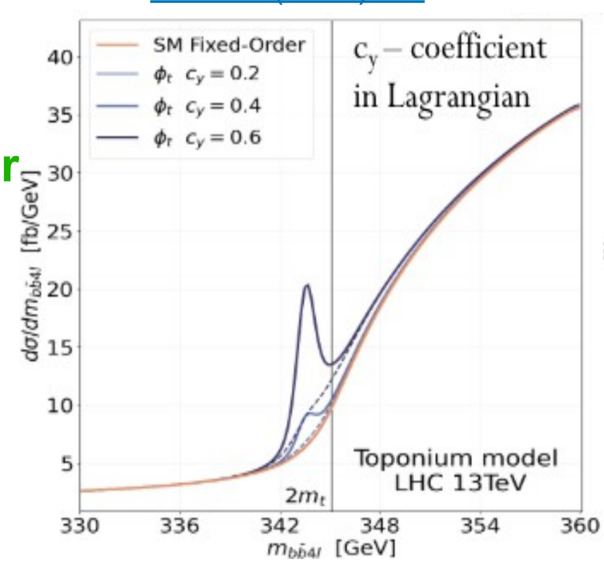
- It affects the invariant mass distribution and the spin correlations at threshold

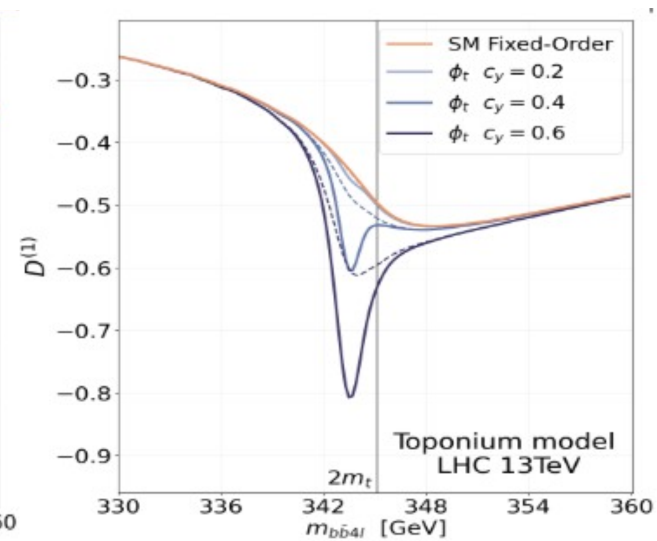
→ **inclusion of toponium (η_t) contributions in our signal model**

W. Ju, G. Wang, et al.
JHEP 06, 158



F. Maltoni et al.
JHEP03(2024)099

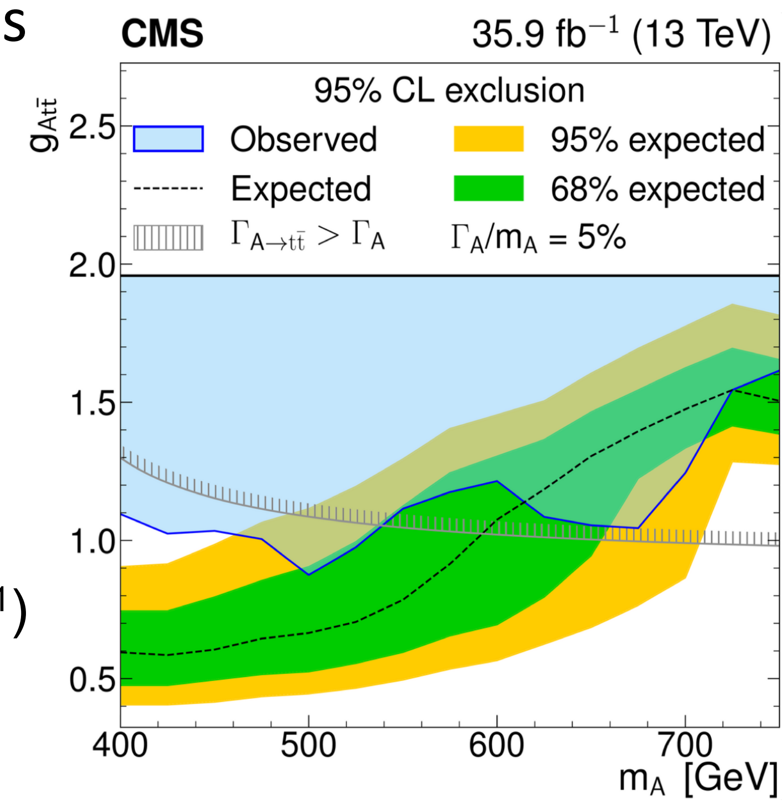




Earlier results: BSM searches

- Many models predict extended Higgs sectors, e.g. 2HDM, MSSM…
  - new scalar or pseudo-scalar states
  - If couplings are Yukawa-like: strongest coupling to top quark
  - If $M > 2m_t$: decay to $t\bar{t}$ is dominant
- <u>Strong motivation:</u>
  - Search for new spin-0 (pseudo)scalars in $t\bar{t}$ final states; Run 2 dataset (138 fb^{-1})
  - Utilize differential information
    - Make use of invariant $t\bar{t}$ mass, angular and spin correlation observables

JHEP 04 (2020) 171

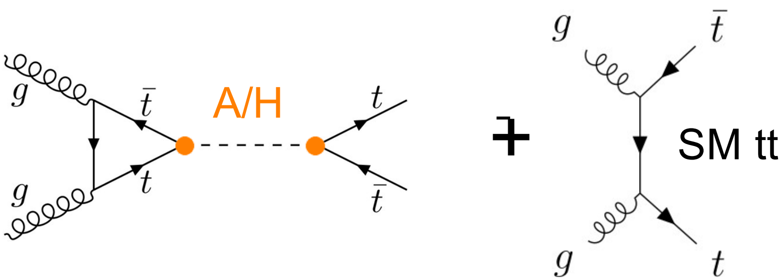


Signal modeling

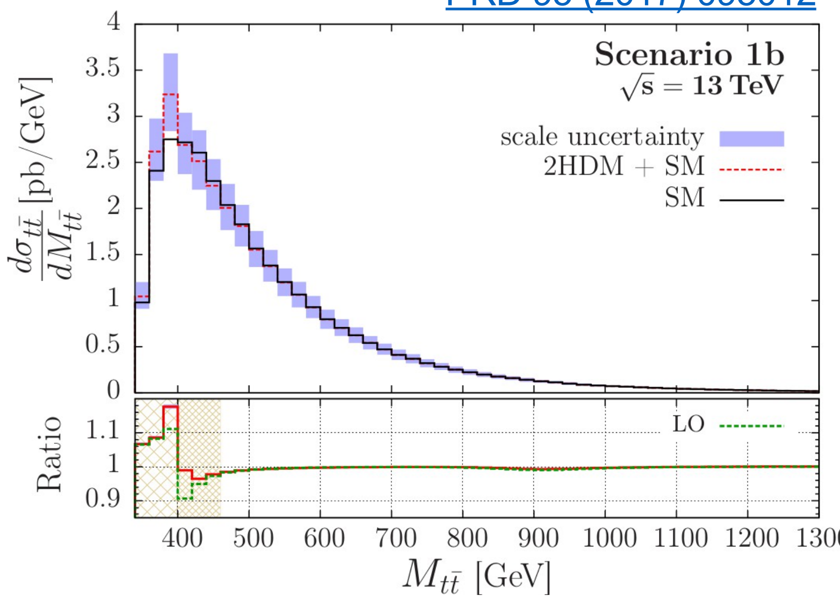
- Generic heavy pseudo-scalar (A) or scalar (H) coupling solely to top quarks
  - Production in gluon fusion via top quark loop
  - Same final state as SM $t\bar{t}$ → interference
  - → peak-dip structure in $m(t\bar{t})$

$$\mathcal{L}_A^{\text{int}} = i g_{\text{At}\bar{\text{t}}} \frac{m_\text{t}}{v} \bar{\text{t}}\gamma_5 \text{t} A$$

$$\mathcal{L}_H^{\text{int}} = -g_{\text{Ht}\bar{\text{t}}} \frac{m_\text{t}}{v} \bar{\text{t}}\text{t} H$$



PRD 95 (2017) 095012



- Free parameters: masses, widths, coupling modifiers g_A and g_H
- Use NNLO QCD K-factors for normalization

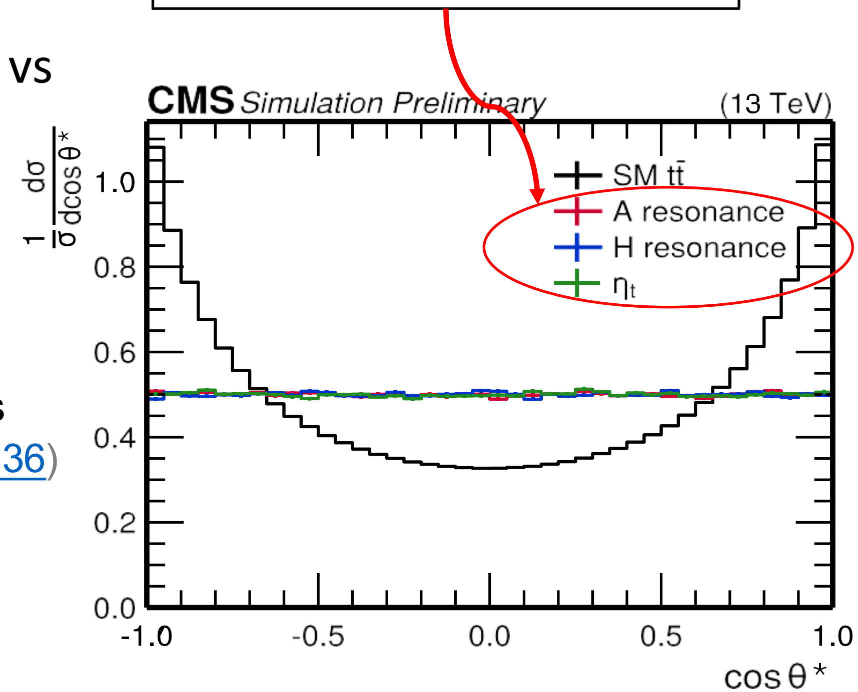
Search/Analysis strategy

- Require exactly one lepton (e/μ), 3 or more jets and 2 or more b tags
  - Split into 4 categories: e vs μ and 3 jets vs 4+ jets
  - Reconstruct $t\bar{t}$ system with NeutrinoSolver algorithm:

    → Assign b jets by maximum likelihood

    → Energy corr. factor applied for 3 jet events (lost or merged jets) (NIM A 788 (2015) 128-136)

New particles all "degenerate" in this variable



<u>2D binning in $m(t\bar{t}) \times |cos(\theta^*)|$</u>

θ*: scattering angle of leptonic top quark

SM $t\bar{t}$: peaks at large angles

A/H signal: isotropic → flat distribution

- Reminder: Top decays before hadronization → transfer spin information to decay products
  - Add spin correlation variables to the "mix
  - But …

Search/Analysis strategy

- Add spin correlation variables to the "mix"

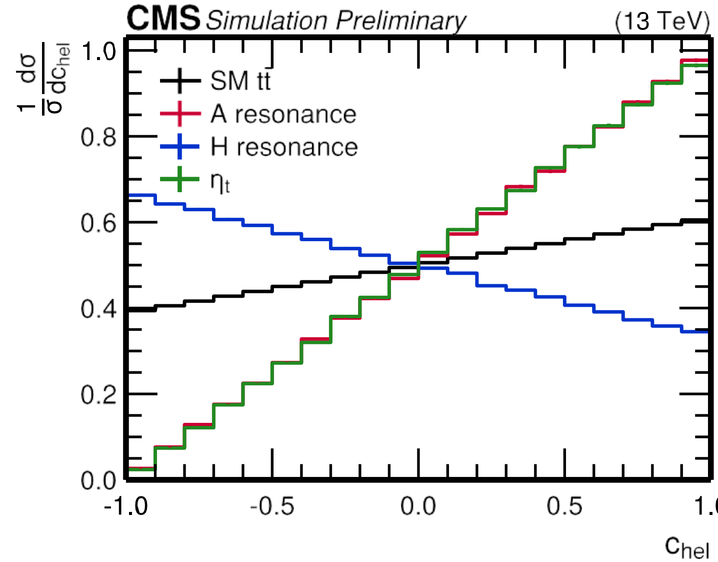
Variable #1: c_{hel}

Boost leptons into rest frames of their parent tops

→ Scalar product between directions of flight

→ Straight line with slope sensitive to tt spin state ("D")
Maximal for $^1S_0$ (from A / η_t) – separates from SM

→ This is also referred to as $cos(\varphi)$

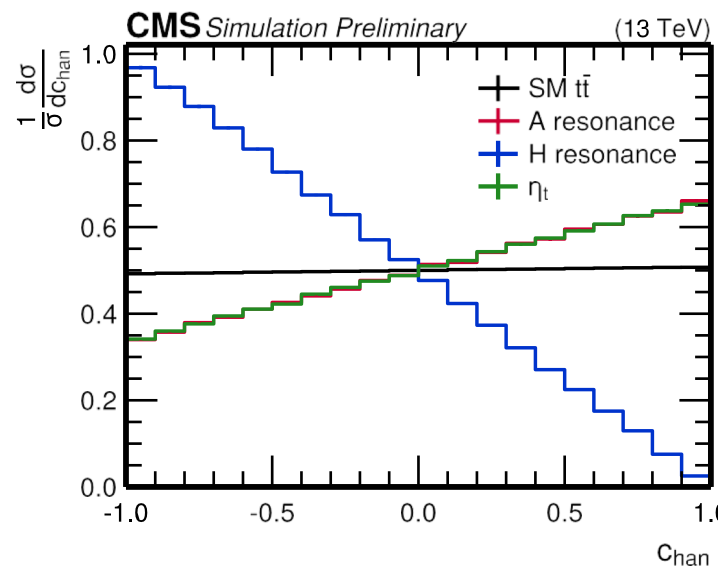


Variable #2: c_{han}

→ Similar as c_{hel}, separating scalars from SM

→ Maximally negative slope for $^3P_0$ state (from H)

→ Construct similarly from lepton momenta, with sign flip for component parallel to top momentum

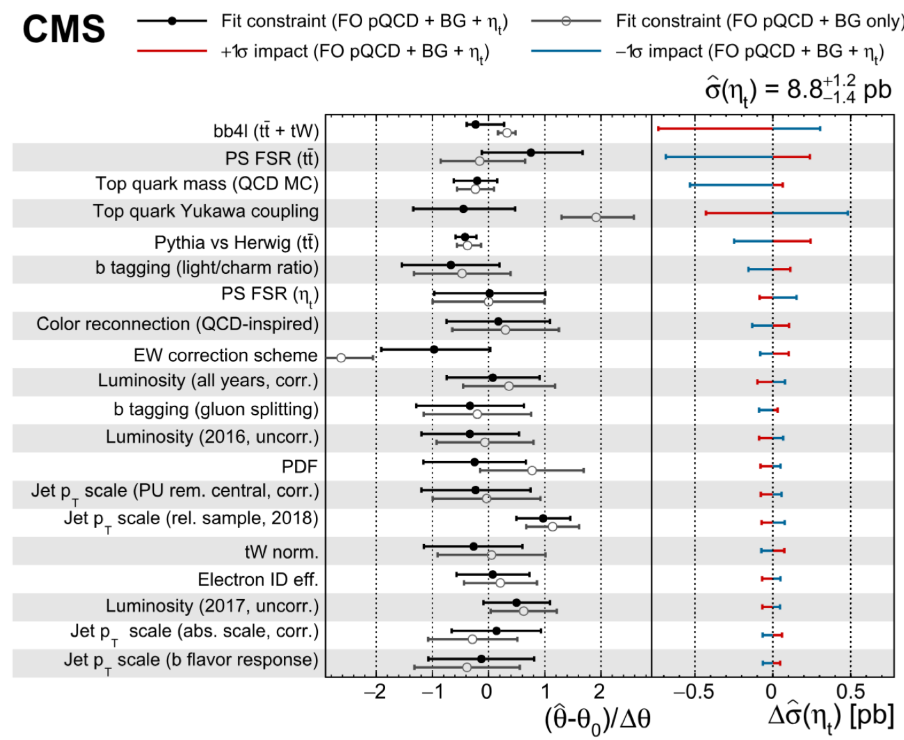


- 3 search variables in dilepton:

$$m(t\bar{t}) \times c_{\text{hel}} \times c_{\text{han}}$$

Uncertainties & other extractions (η_t)

- Impact distribution for leading systematic uncertainties
  - Signal model (bb4l)
  - Parton showers
  - Top quark mass
  - Yukawa coupling
  - Pythia vs Herwig & b-tag

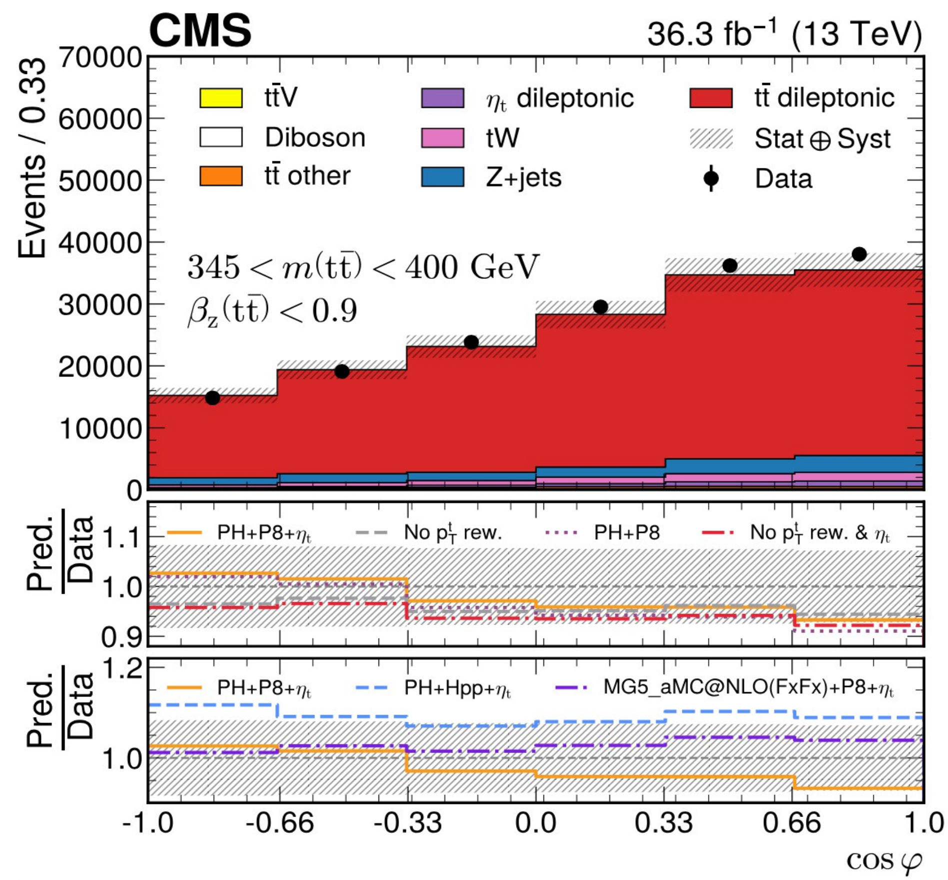


- Different setups to extract signal
  - Robust & within uncertainties

FO pQCD generator setup	$\sigma(\eta_t)$ (pb)
POWHEG v2 hvq + PYTHIA	8.7 ± 1.1
POWHEG v2 hvq + HERWIG	8.6 ± 1.1
MADGRAPH5_aMC@NLO FxFx + PYTHIA	9.8 ± 1.3
POWHEG vRES bb4l + PYTHIA	6.6 ± 1.4
Nominal result	$8.8^{+1.2}_{-1.4}$

Combined signal model

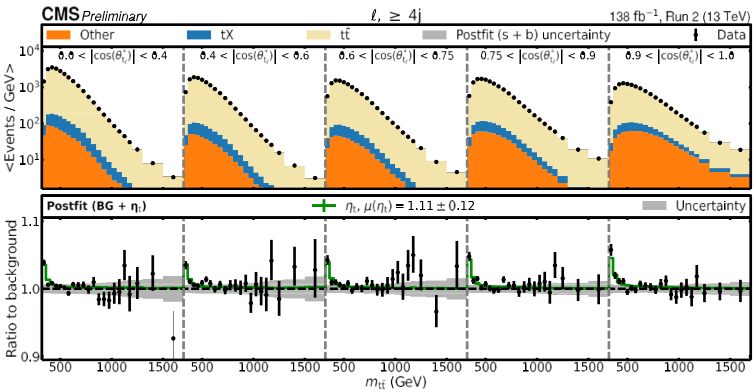
- **Combined signal model: $t\bar{t}$ + toponium (η_t)**
  - PowhegBox+Pythia8 (NLO) as **nominal $t\bar{t}$ sample**
  - **toponium model** generated with MG5 aMC@NLO(LO) + P8
    - B. Fuks et al. [Phys Rev D 104 034023]()
    - $337 < m_{\eta_t} < 349$ GeV
    - only pseudoscalar colour singlet and spin-0 η_t state accounted for
    - η_t improves data modeling in the threshold region

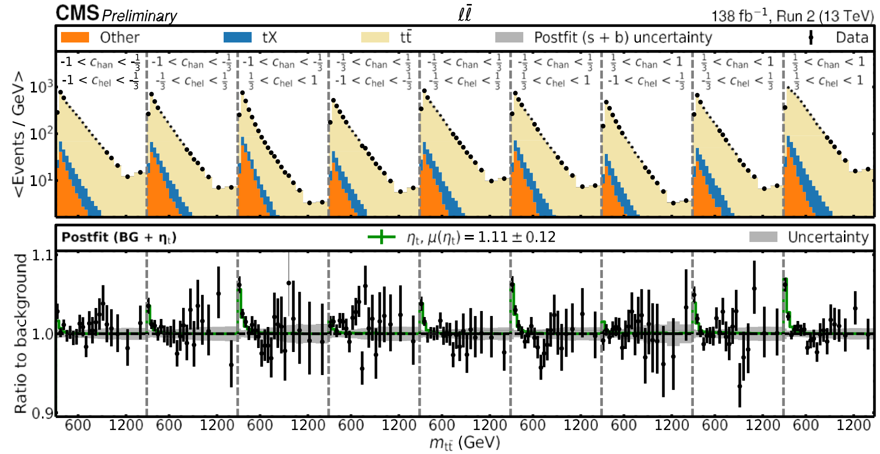


Including bound state effects

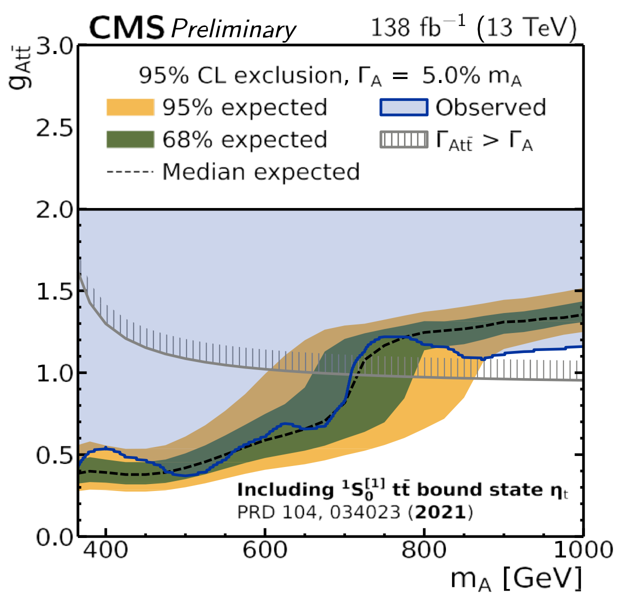
[CMS-PAS-HIG-22-013]

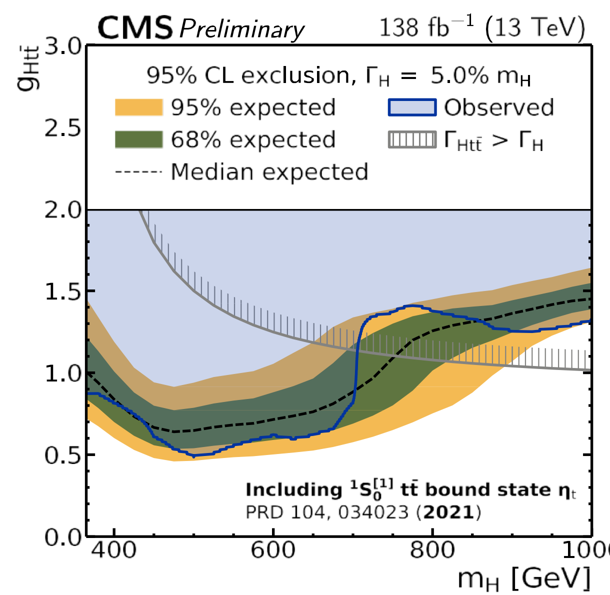
- Excess no longer present





- Most stringent limits set to date





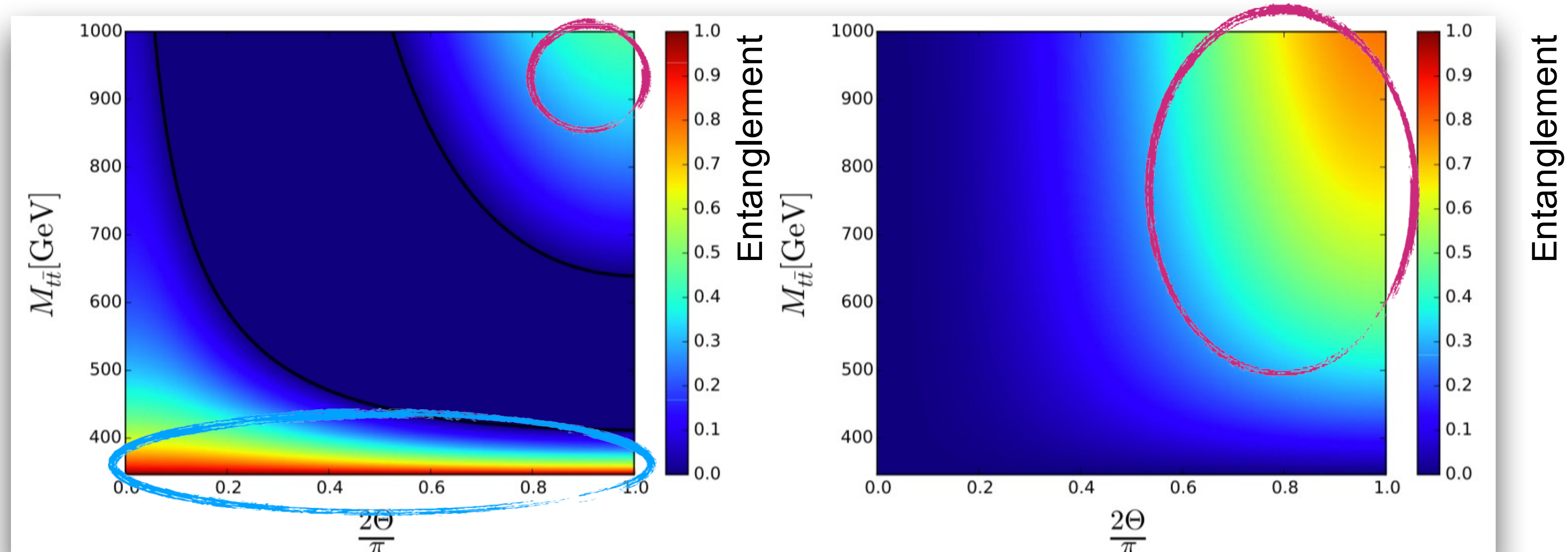
Entanglement of top quarks

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

<u>SM predicts entangled states:</u>

→ at the production threshold region in gg-fusion production

→ at the boosted region for central production of the system



Afik, De Nova

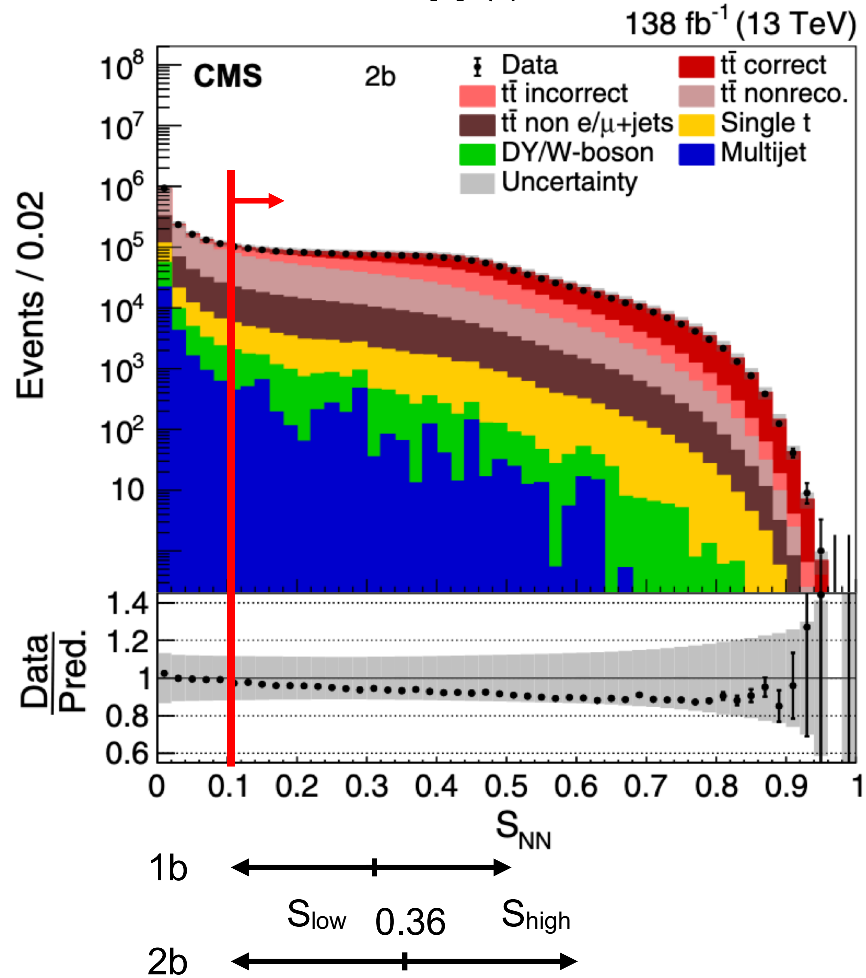
Eur. Phys. J. Plus **136**, 907

Measurement strategy l+jets

- Evaluation of **full correlation matrix C and polarization vectors P + measurement of** $\Delta_E, \widetilde{D}$
  - inclusive + differential measurements in bins of $m(t\bar{t}), |cos(\theta)|$, and $p_T(t)$

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

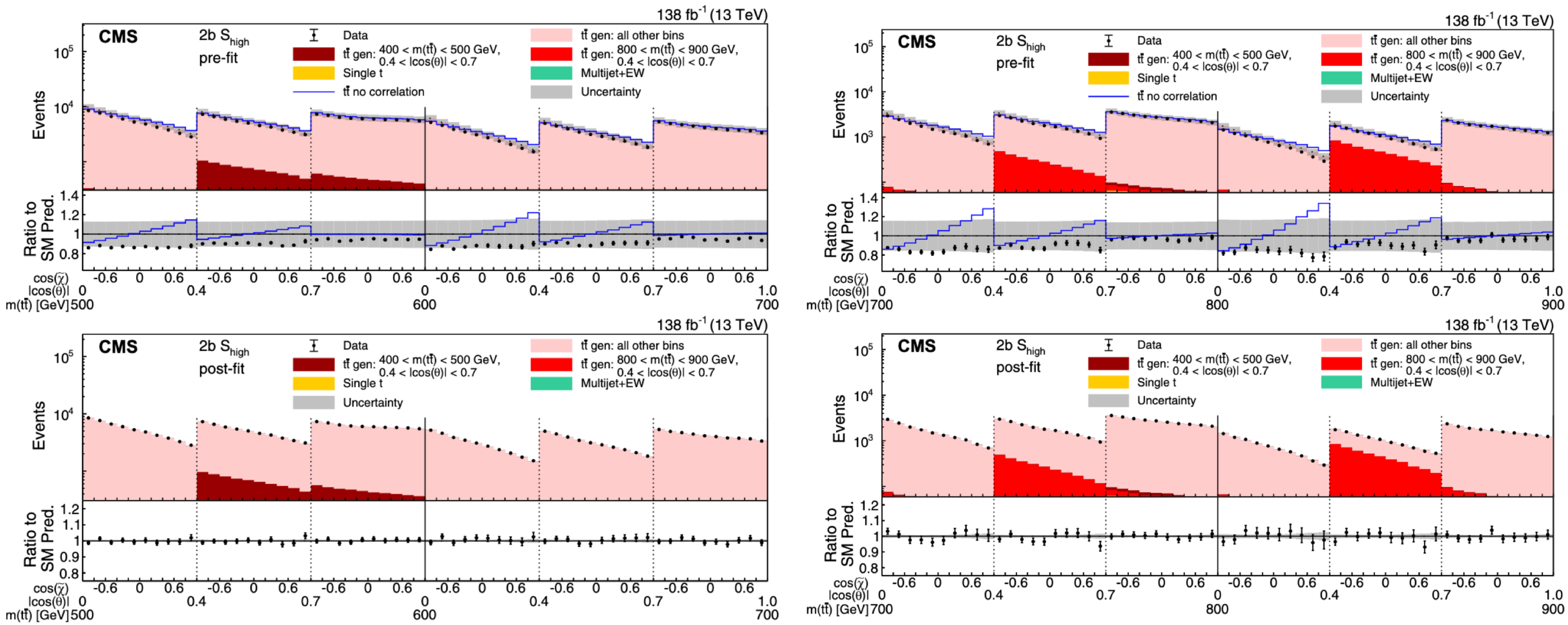
- **Artificial NN** used to reconstruct the $t\bar{t}$ system in each event
- Main background sources (larger vs $\ell\ell$ channel):
  - single top quark
  - DY+jets
  - W+jets
  - QCD multijet production
- Reduce bg by mass window cuts in top and W mass
- **Remove events with NN score** S_{NN} **< 0.1**
  - Dominated by not correctly reco'ed events
  - Large contribution of background processes
- Events divided into **categories based on lepton flavor, number of b-tags, and NN score**



Maximum likelihood fit strategy

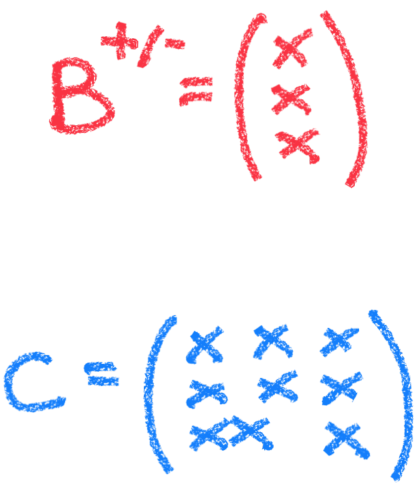
- **Maximum likelihood fit** combining information of the 4 categories: (2b, 1b) x (S_{high}, S_{low})
- $\cos\chi$ distribution is fit to the **reconstruction-level templates** in each ($m(t\bar{t})$, $|cos(\theta)|$) bin

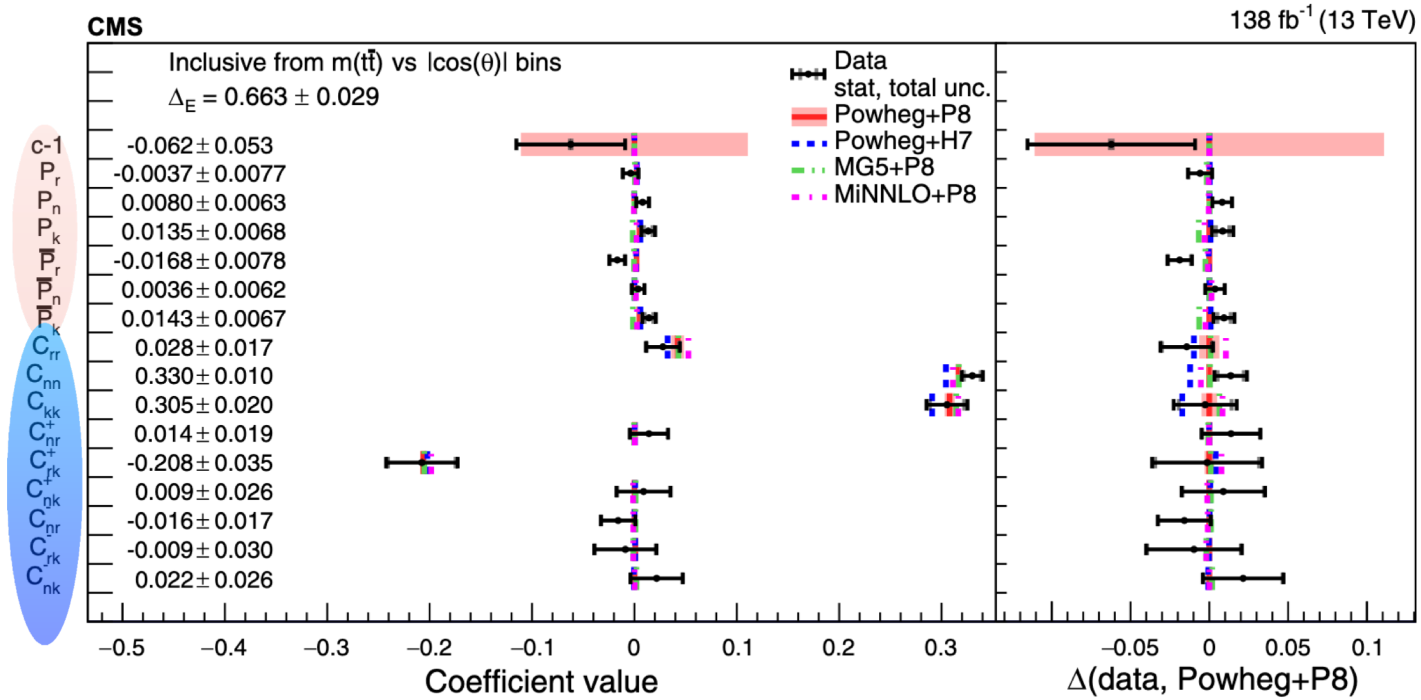
PRD 110 (2025) 112016



Full spin correlation density (l+jets)

- Full measurement of P and C performed inclusively and differentially in bins of $m(t\bar{t}) \times |cos(\theta)|$ or $p_T(t/\bar{t}) \times |cos(\theta)|$
- Inclusive results shown here: [PRD 110 (2025) 112016]





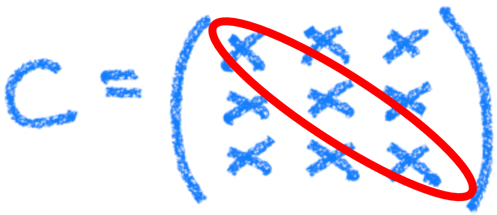
Good agreement with SM prediction
(and with existing spin density results)

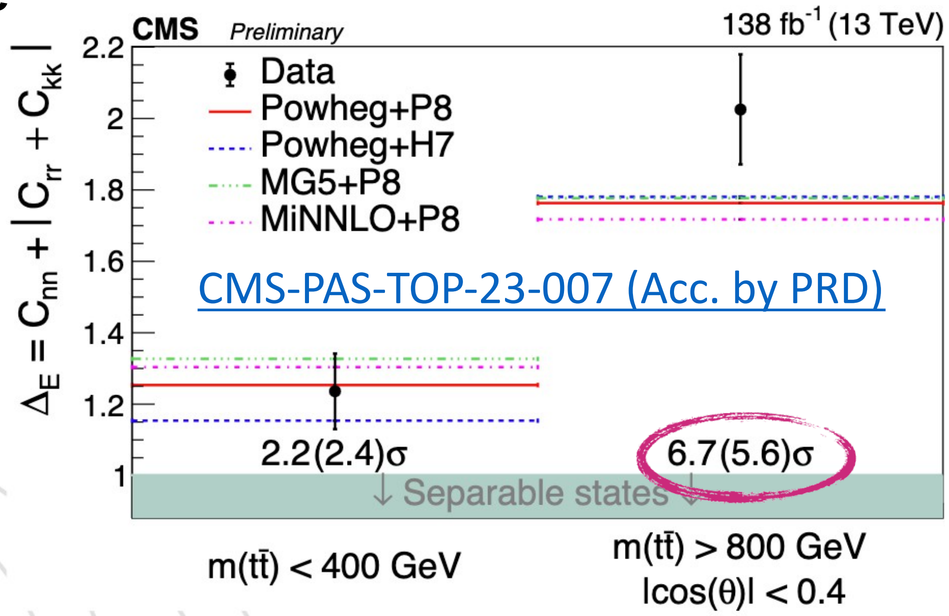
Inclusive from $m(t\bar{t}) \times |cos(\theta)|$

Entanglement in lepton+jets events

- **Entanglement observed for first time in events with high $m(t\bar{t})$!**
  - highest sensitivity using full C

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





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

Entanglement in lepton+jets events

- **Entanglement observed for first time in events with high $m(t\bar{t})$!**
  - highest sensitivity using full C

- **Fraction of events with space-like separation increases with $m(t\bar{t})$**

- What is the maximum value of Δ_E that can still be explained by non-quantum communication ($v \leq c$) ?
  - time-like separated events: ΔE max = 3 (C_{ii} = 1)
  - space-like separated events: ΔE sep = 1

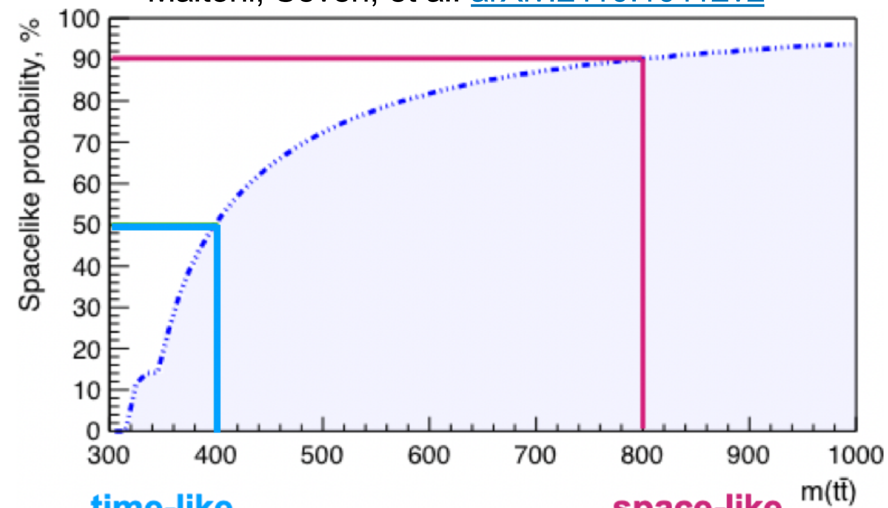
- The **boundary of critical entanglement** ($\Delta_{E\ critical}$) is defined for a given fraction f of space-like separated events as:

$$\Delta_{\mathrm{E\,crit}} = f\Delta_{\mathrm{E\ sep}} + (1-f)\Delta_{\mathrm{E\ max}}$$

Observed Δ_E exceeds $\Delta_{E\,\mathrm{crit}}$ by > 5 SD

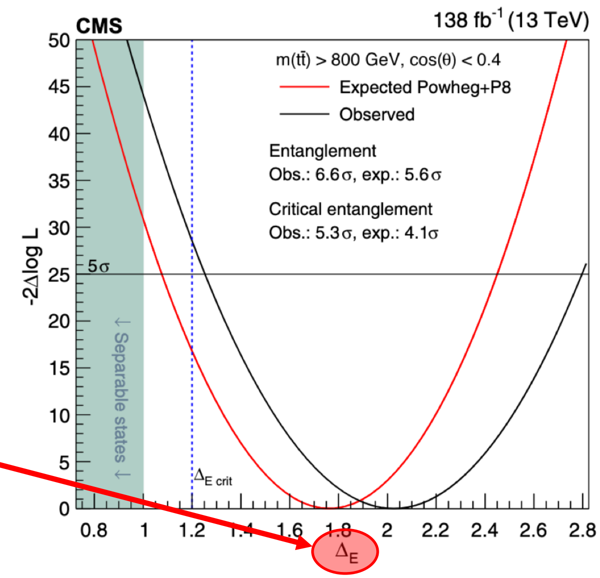
→ **level of observed entanglement cannot be explained by classical exchange of information between the two particles !**

Maltoni, Severi, et al. arXiv:2110.10112v2

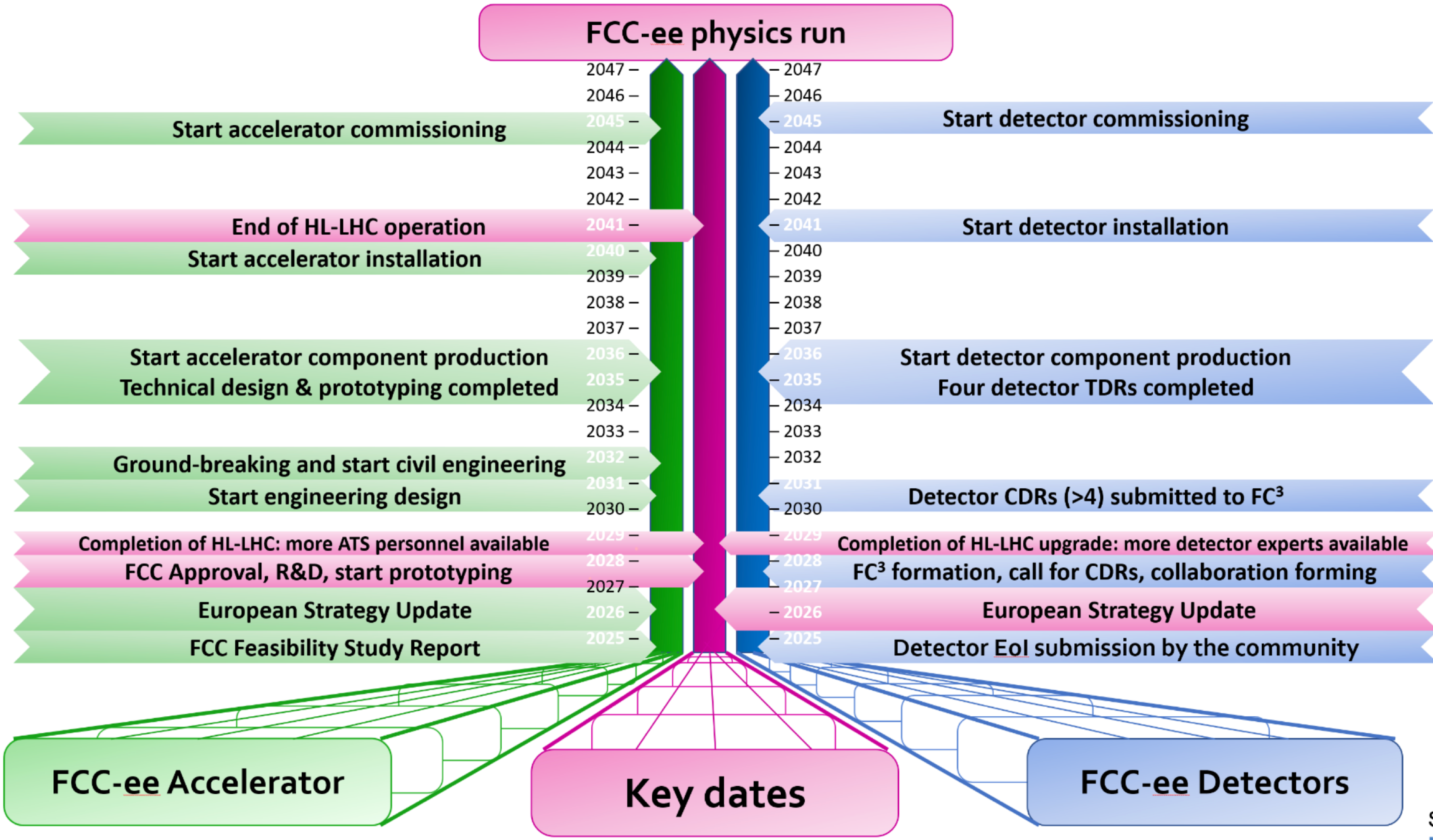


time-like separated

space-like separated



FCC ee – an example timeline



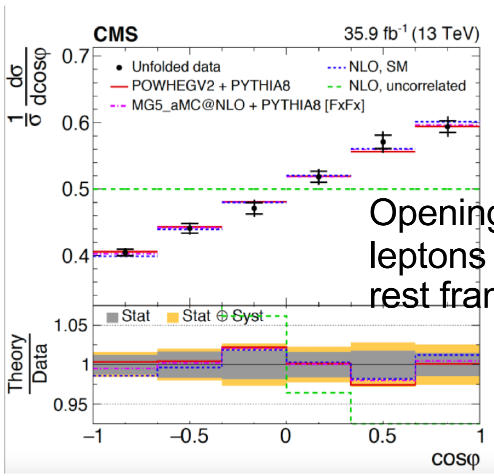
Slide from
Michael Benedikt

→ Essentially need to start R&D on detector (& accelerator) now-ish!

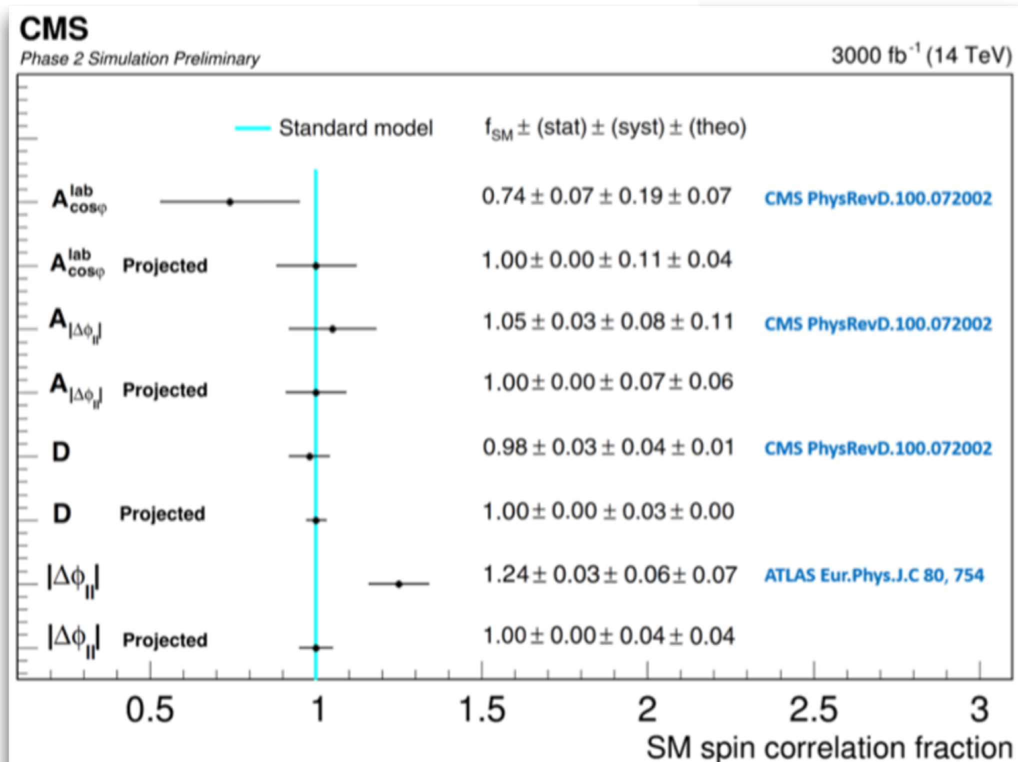
Prospects at the HL-LHC

Double diff. xsec **Polarisation (0 in SM)** **Spin Correlation**

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



Opening angle between leptons in top parent rest frame

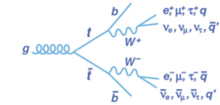


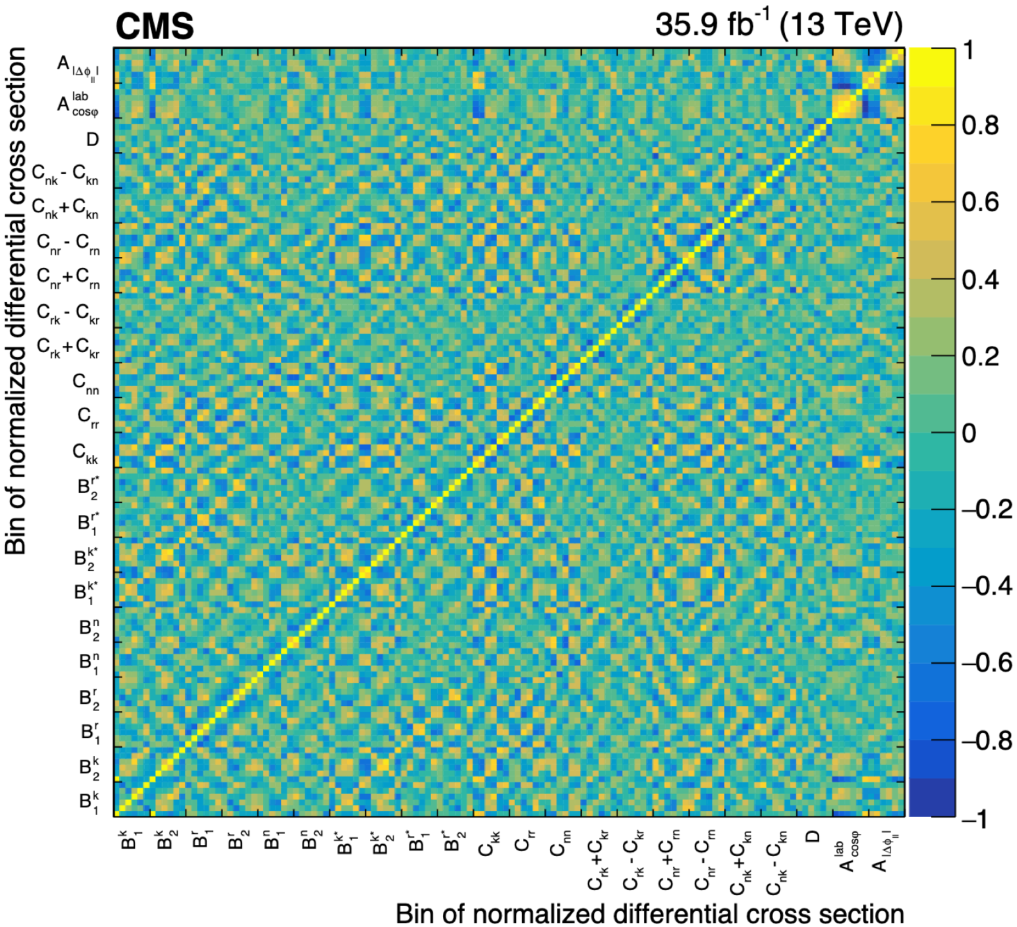
$$f_{SM} = \frac{D_{measured} - D_{theory,uncorrelated}}{D_{theory,correlated} - D_{theory,uncorrelated}}$$

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

Contributed to Snowmass, CMS-PAS-FTR-18-034

Side track: What to measure…



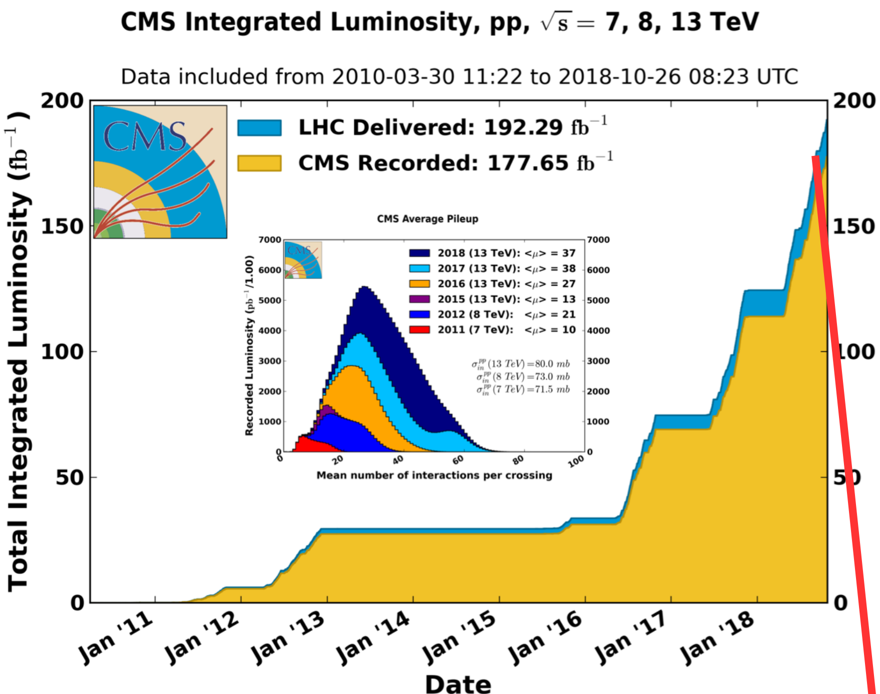


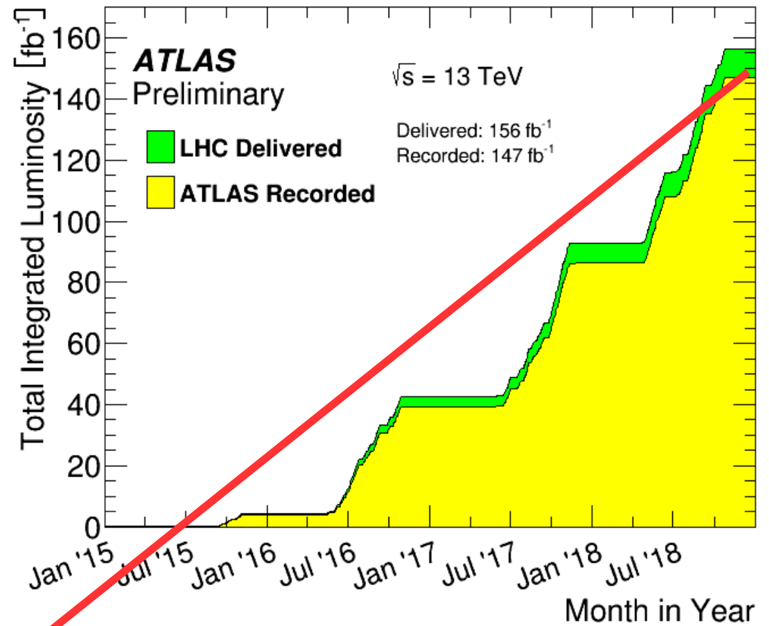
[Phys. Rev. D 100, 072002 (2019)](https://doi.org/10.1103/PhysRevD.100.072002)

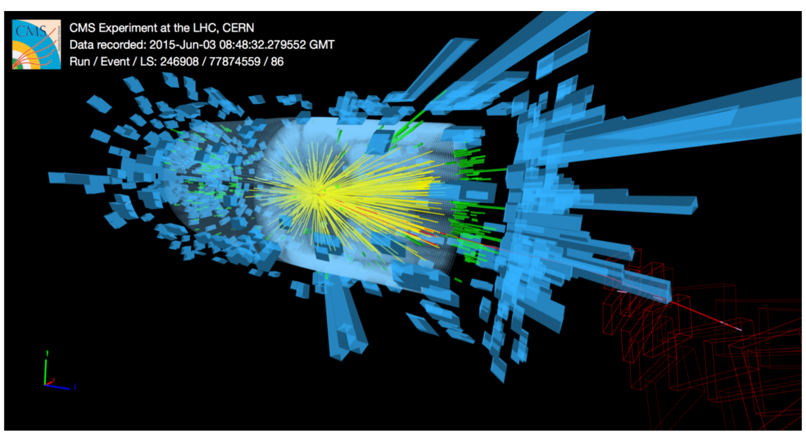
Observable	Coefficient	Coefficient function
$\cos\theta_1^k$	B_1^k	b_k^+
$\cos\theta_2^k$	B_2^k	b_k^-
$\cos\theta_1^r$	B_1^r	b_r^+
$\cos\theta_2^r$	B_2^r	b_r^-
$\cos\theta_1^n$	B_1^n	b_n^+
$\cos\theta_2^n$	B_2^n	b_n^-
$\cos\theta_1^k\cos\theta_2^k$	C_{kk}	c_{kk}
$\cos\theta_1^r\cos\theta_2^r$	C_{rr}	c_{rr}
$\cos\theta_1^n\cos\theta_2^n$	C_{nn}	c_{nn}
$\cos\theta_1^r\cos\theta_2^k + \cos\theta_1^k\cos\theta_2^r$	$C_{rk}+C_{kr}$	c_{rk}
$\cos\theta_1^r\cos\theta_2^k - \cos\theta_1^k\cos\theta_2^r$	$C_{rk}-C_{kr}$	c_n
$\cos\theta_1^n\cos\theta_2^r + \cos\theta_1^r\cos\theta_2^n$	$C_{nr}+C_{rn}$	c_{nr}
$\cos\theta_1^n\cos\theta_2^r - \cos\theta_1^r\cos\theta_2^n$	$C_{nr}-C_{rn}$	c_k
$\cos\theta_1^n\cos\theta_2^k + \cos\theta_1^k\cos\theta_2^n$	$C_{nk}+C_{kn}$	c_{kn}
$\cos\theta_1^n\cos\theta_2^k - \cos\theta_1^k\cos\theta_2^n$	$C_{nk}-C_{kn}$	$-c_r$
$\cos\varphi$	D	$-(c_{kk}+c_{rr}+c_{nn})/3$
$\cos\varphi_{\mathrm{lab}}$	$A^{\mathrm{lab}}_{\cos\varphi}$	—
$\lvert\Delta\phi_{\ell\ell}\rvert$	$A_{\lvert\Delta\phi_{\ell\ell}\rvert}$	—
$\lvert\Delta\eta_{\ell\ell}\rvert$	$\lvert\Delta\eta_{\ell\ell}\rvert$	—

Correlation are non-trivial and only experiments can determine!

Top quark physics: Current status…







<u>Full Run II provides about</u>

~ 120 million tt pairs

~ 30 million single top

~ 120k ttZ, tZ

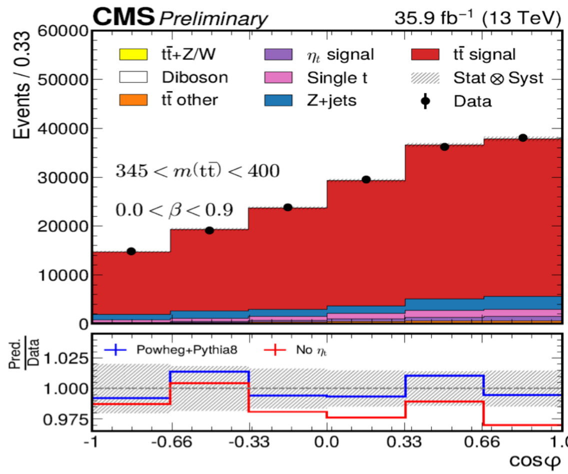
~ 30k ttH

Access entanglement information

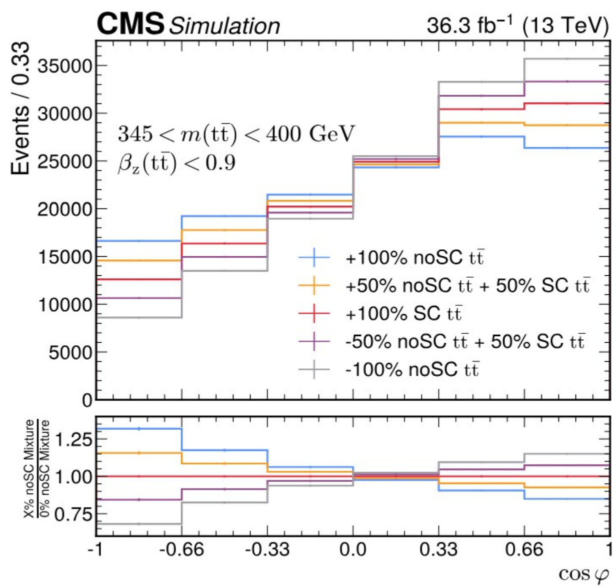
- **The entanglement proxy *D* is extracted with a template fit**
  - Systematic effects included as nuisances
- **How to create variations of *D* outside of SM ?**
  1. Generate top pairs with no spin correlation (noSC, D = 0)
  2. Created new samples with mixture of SM and noSC to obtain $D \in [D_{SM}, 0]$
  3. Extend the fit for variations of $[-1, D_{SM}]$
- Use samples of SC and noSC to change fraction of tt with aligned vs opposite spins
  - Any value of D between -1 and 1 can be reached

$$D \sim \frac{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)-\sigma(\uparrow\downarrow)-\sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)+\sigma(\uparrow\downarrow)+\sigma(\downarrow\uparrow)}$$

Post-fit cos φ distribution

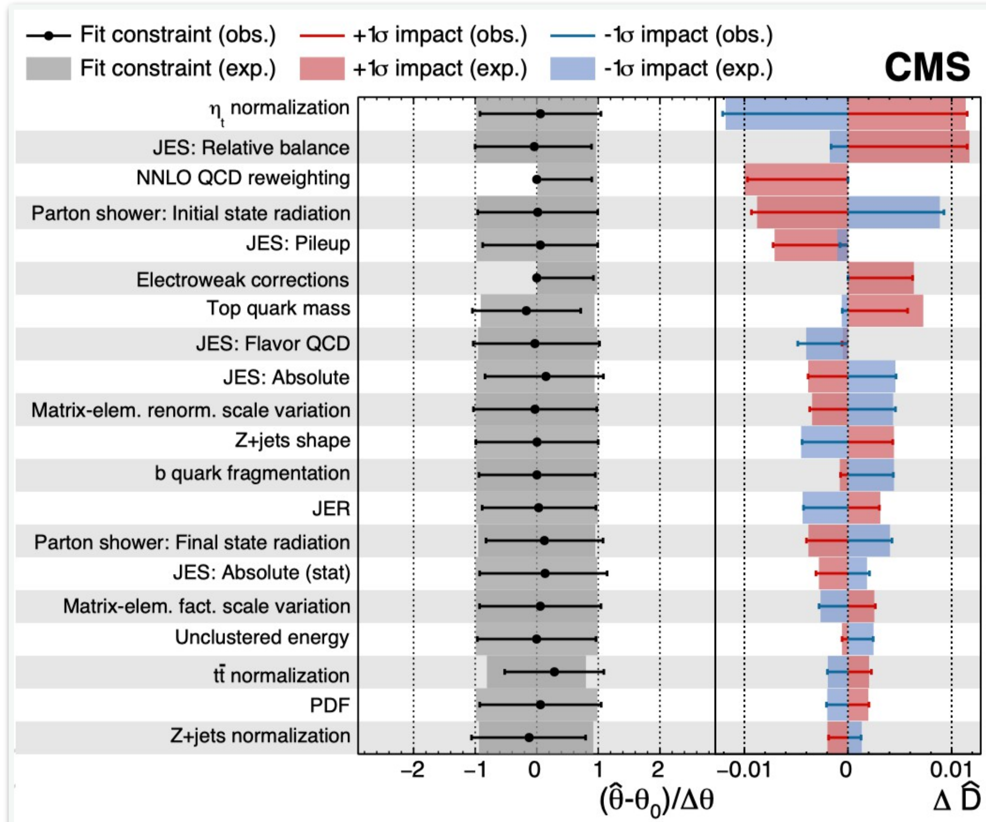


Mixture templates



Entanglement – dilepton uncertainties

- **Same uncertainties considered in 2016 spin corr analysis + additional ones for toponium:**
  - a *flat uncertainty of 50%* is applied on toponium xsec due to missing octet contributions
  - a *binding energy uncertainty of ±0.5 GeV* is considered
- **Leading theory-based uncertainties:**
  - Toponium normalization
  - NNLO QCD reweighing
  - Parton Shower
- **Leading experimental uncertainties:**
  - Jet energy scale



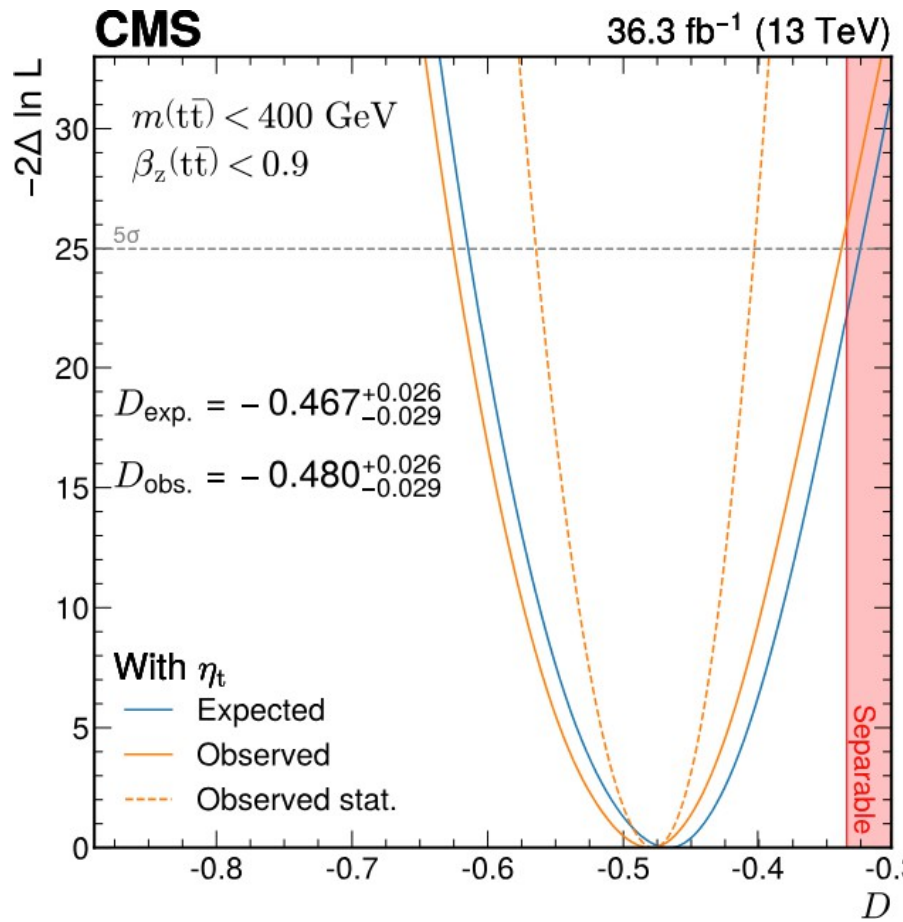
Including pseudo-scalar state

- Scan of the −2ΔlnL distribution yields accounting for all detector effects at parton level

$$D_{obs} = -0.480^{+0.016}_{-0.017}(\text{stat})^{+0.020}_{-0.023}(\text{syst})$$

$$D_{exp} = -0.467^{+0.016}_{-0.017}(\text{stat})^{+0.021}_{-0.024}(\text{syst})$$

- Significance is 5.1 SD (obs)
  - Expected is 4.7 SD
- Reduced significance but still observe entanglement!



Entanglement prospects

- Studied extensively theoreticaly.
- Measured by the D0, CDF, ATLAS and CMS collaborations.
- No link between spin-correlations and quantum entanglement so far.
- Spin-Correlations *not* Quantum Entanglement!
- However, Quantum Entanglement ⊂ Spin-Correlations.

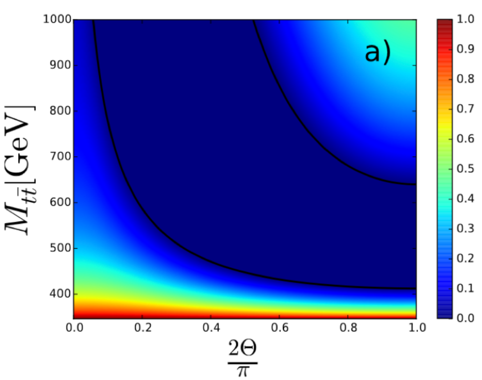
Many ref's, latest one:

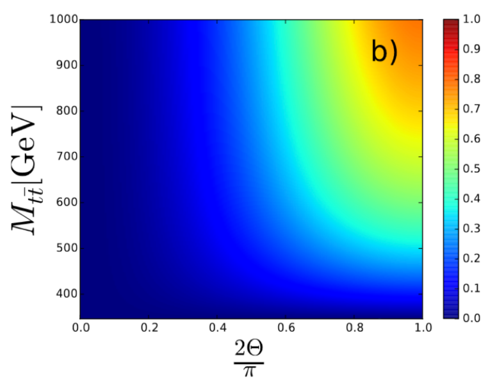
- Y. Afik & J. de Nova

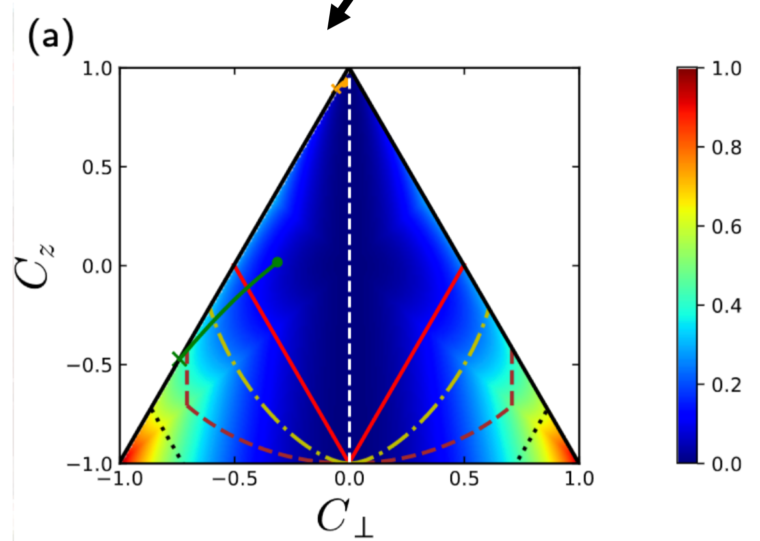
Phys. Rev. Lett. 130, 221801 (2023)

New probes:

Discord & Steering



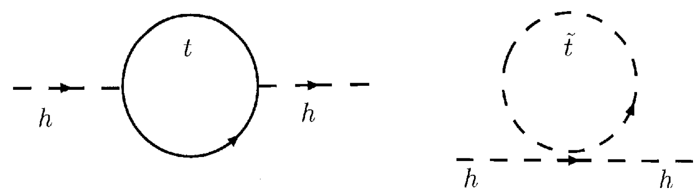


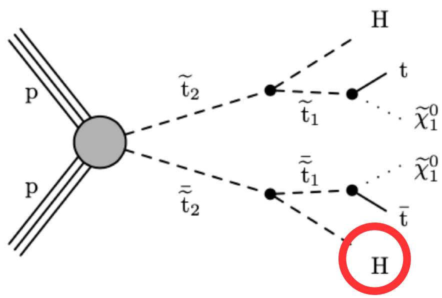


Prospects at the HL-LHC

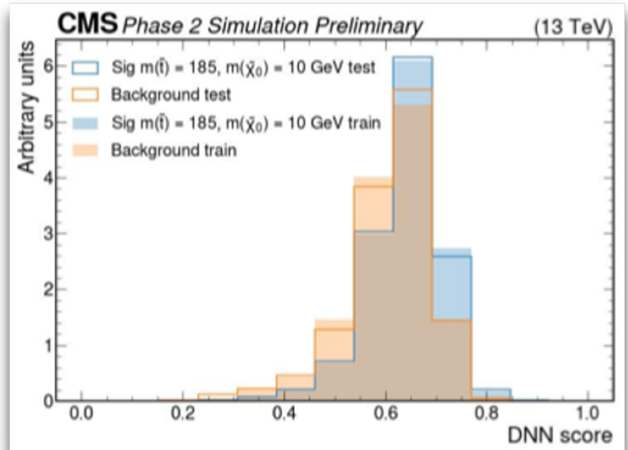
CMS-PAS-FTR-18-034, 2022

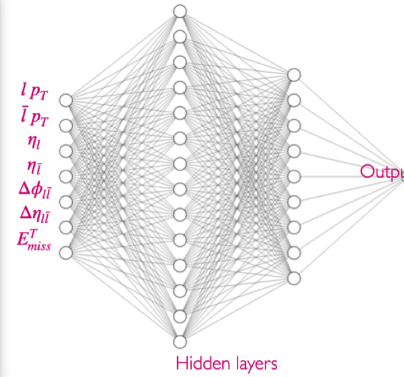
Reminder: Solve the hierarchy problem
→ need a top quark partner



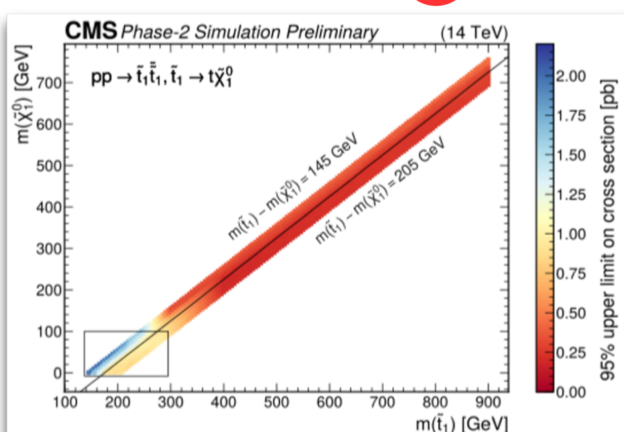


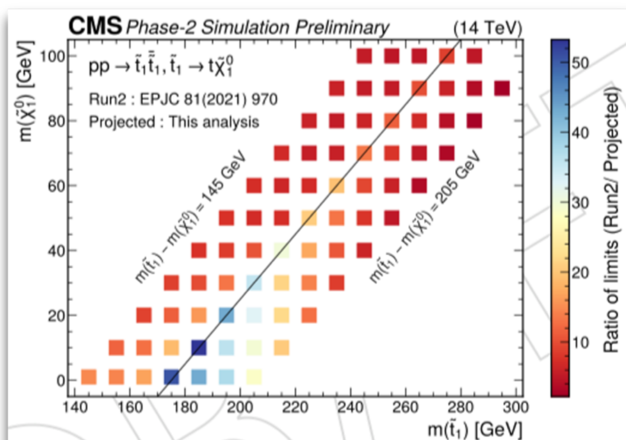
Signal to bg separation at 185 GeV





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





Significantly better sensitivity

FCC ee – Prospects

- Ultimate precision for top quark properties: mass, width, and Yukawa coupling
- Can use measurement of cross section shape around threshold to extract m_t, Γ_t, y_t and α_s
- $m_t \otimes \Gamma_t$ simultaneous fit expected δ_{stat}: $\pm$17 MeV (m_t), $\pm$45 MeV (Γ_t)
- δ_{syst} dominated by theory, e.g. m_t ~ 45 MeV!
- Current top mass average (LHC + Tevatron): 172.69$\pm$0.3 GeV
- **Entanglement prospects: Prepare initial state!**
- **HERA demonstrated polarization is possible but challenging and time-dependent!**
- **EIC will have improved methods…**