

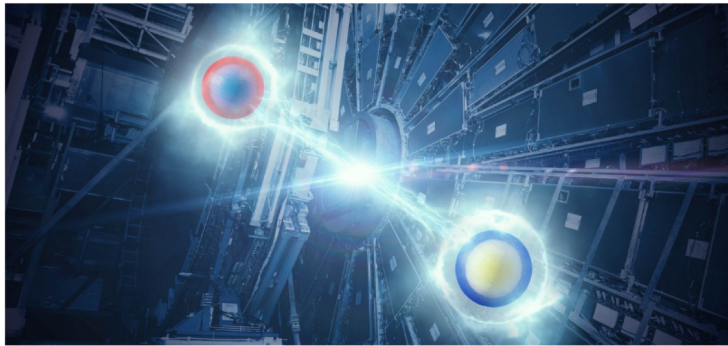
Observation of top quark pair entanglement

- Current status
- Phase Space & Strategy
- Entangled top quarks
- Prospects
- Conclusion

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DPF-Pheno 2024: Division of Particle and Fields meeting
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Quantum entanglement in top quark pair production



Read more about this!

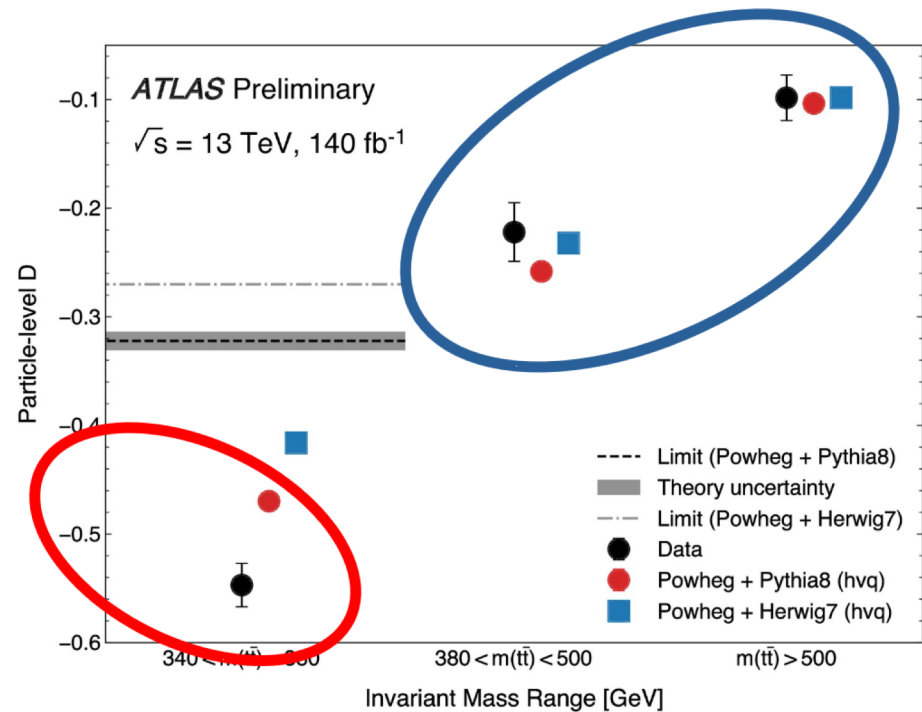
<https://atlas.cern/Updates/Briefing/Top-Entanglement>

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

- Updates / News on Theory prediction
- Systematic uncertainties ?
- Need complete picture at LHC
→ **CMS answer is out!**

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

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



Q: Tell me about the quantum entanglement of top quarks

A: It's important to note that the behavior of particles on the quantum level is not always intuitive, and while **entanglement is a fascinating and well-studied phenomenon**, its application and relevance depend on the specific characteristics of the particles involved.

At the current state of knowledge up to my last training cut-off in January 2022, discussions of quantum entanglement with top quarks were **not a common topic in the scientific literature**.

If there have been significant developments or new insights in this area beyond 2022, I recommend checking more recent sources for the latest information.

Q: Tell me about the quantum entanglement of top quarks

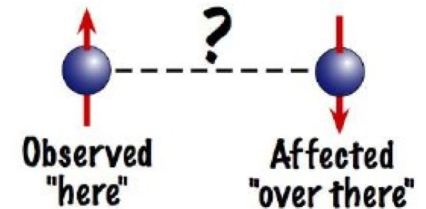
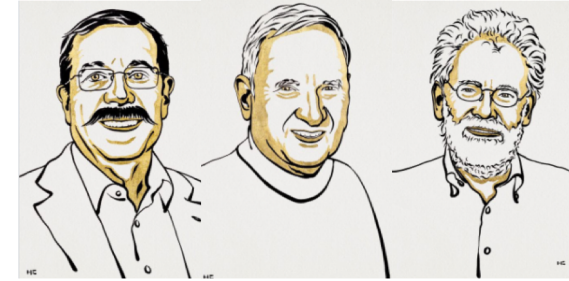
A: Quantum entanglement is a physical phenomenon that occurs when pairs or groups of particles are generated, interact, or share spatial proximity in a way such that the quantum state of each particle cannot be described independently of the state of the others, even when the particles are separated by a large distance.

In the context of top quarks, quantum entanglement can occur during particle collisions, such as those produced in a particle accelerator (e.g., the Large Hadron Collider). Top quarks are produced in pairs through the strong force and, due to their incredibly short lifetime, they decay almost instantly after their production.

During their production, certain properties (like spin) of the two top quarks can become entangled. ...

How to probe entanglement

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



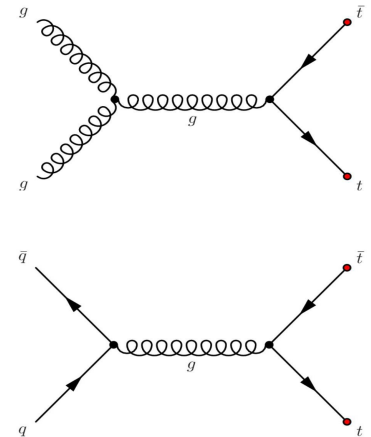
- At the LHC top quarks are produced in a mixed state and thus can be represented as a (complex) density operator

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

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

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

How to produce a top quark

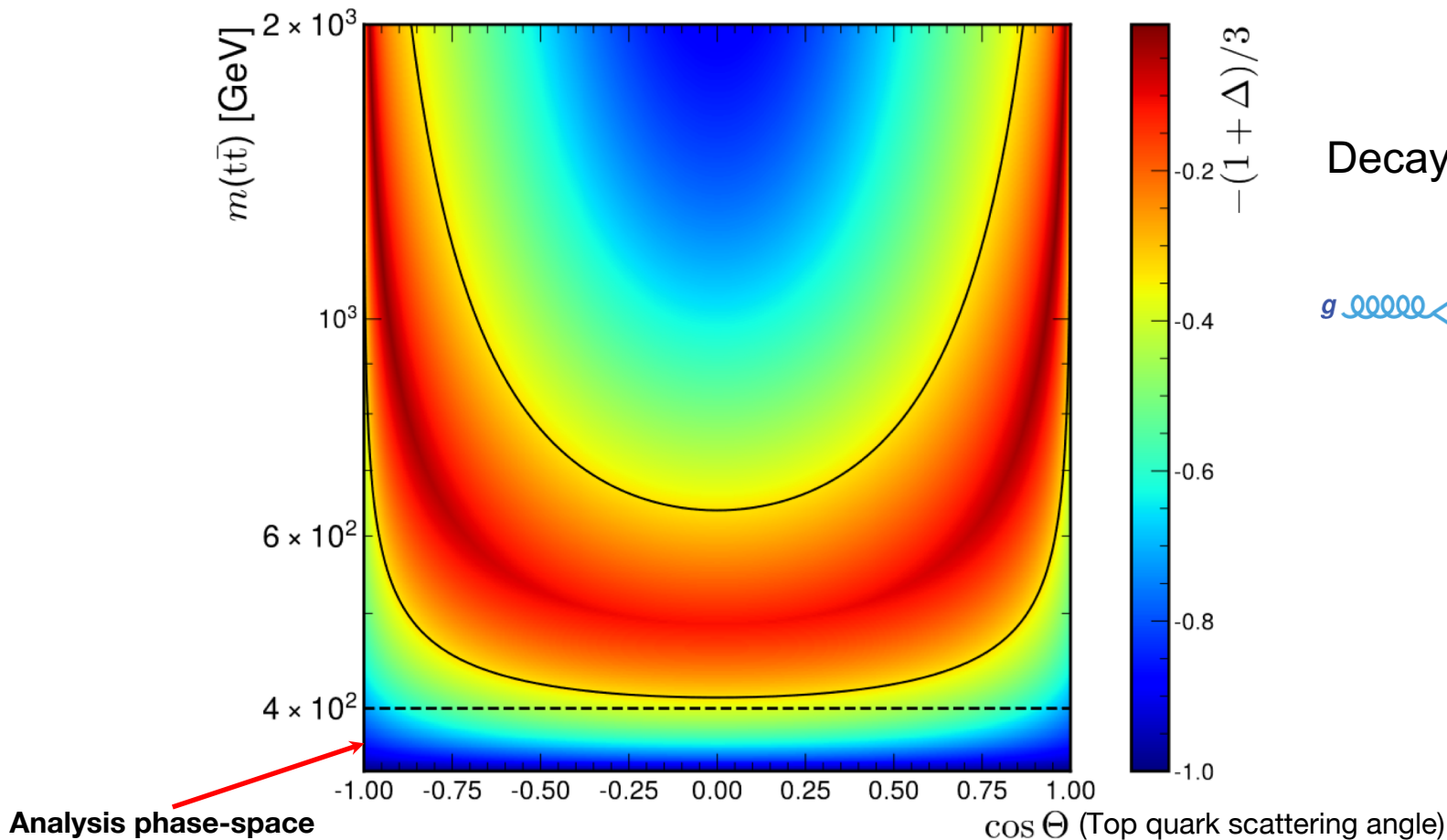


Experimental goal →
measure D
(entanglement proxy)

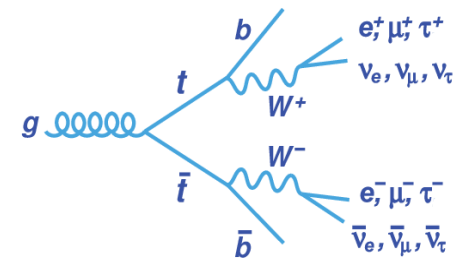
Phase space of Entanglement

- $D < -\frac{1}{3} \rightarrow$ Entangled!
- Focus on low mass phase space $m(t\bar{t}) < 400$ GeV
 - Most statistics
 - Sensitive with only 2016 data
- Apply additional $\beta_z(t\bar{t}) < 0.9$ cut to enhance $\frac{gg}{q\bar{q}}$ fraction

[J.A. Aguilar-Saavedra & J. A. Casas EPJC 82, 666](#)



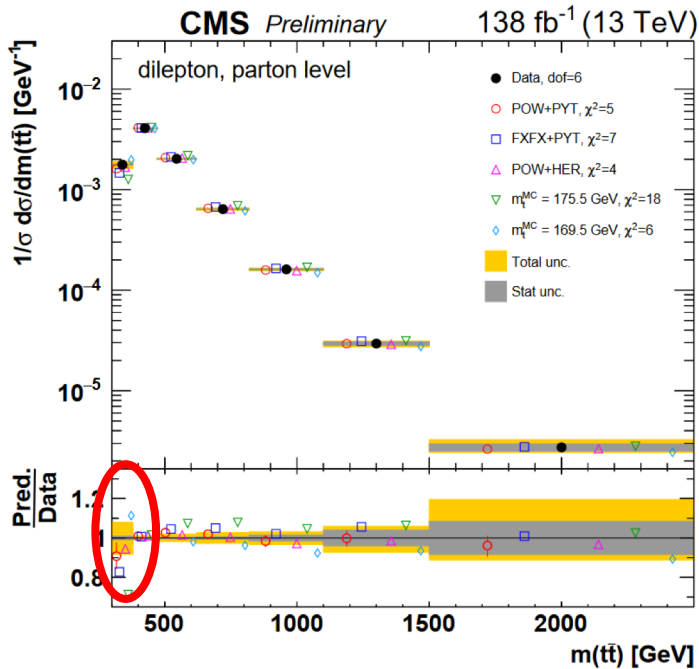
Decay channel:



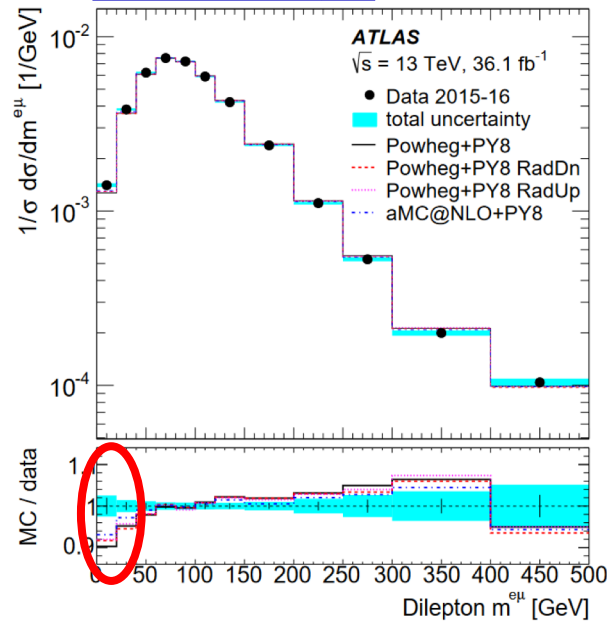
Top quark threshold region

- Known “unknowns” ...
- Mismodeling seen for $m_{t\bar{t}} \approx 345$ GeV
- Consistent between dilepton & lepton+jets and CMS & ATLAS
- Even at different center-of-mass energies

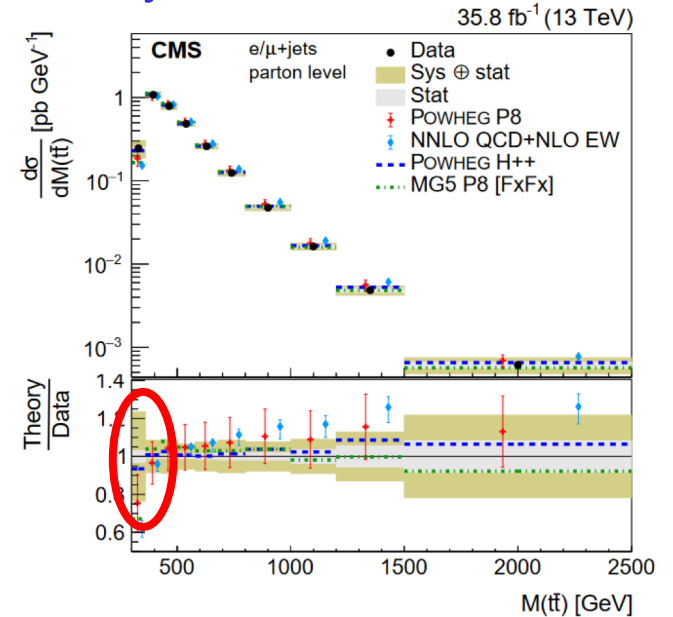
CMS-PAS-TOP-20-006



EPJ C 80, 6



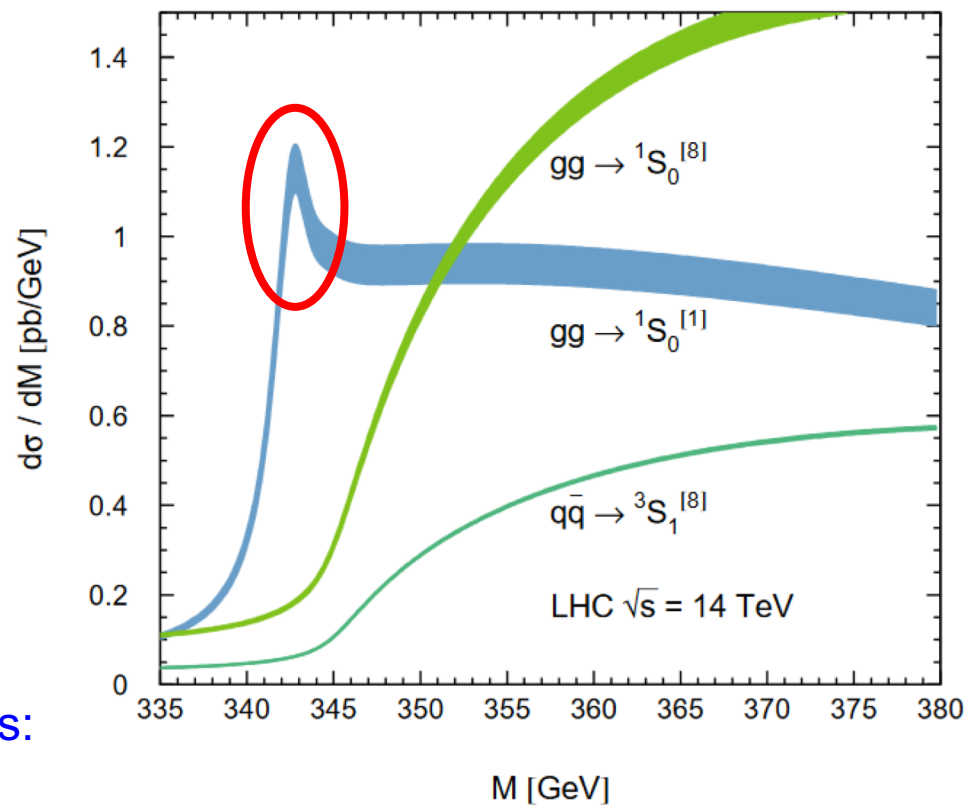
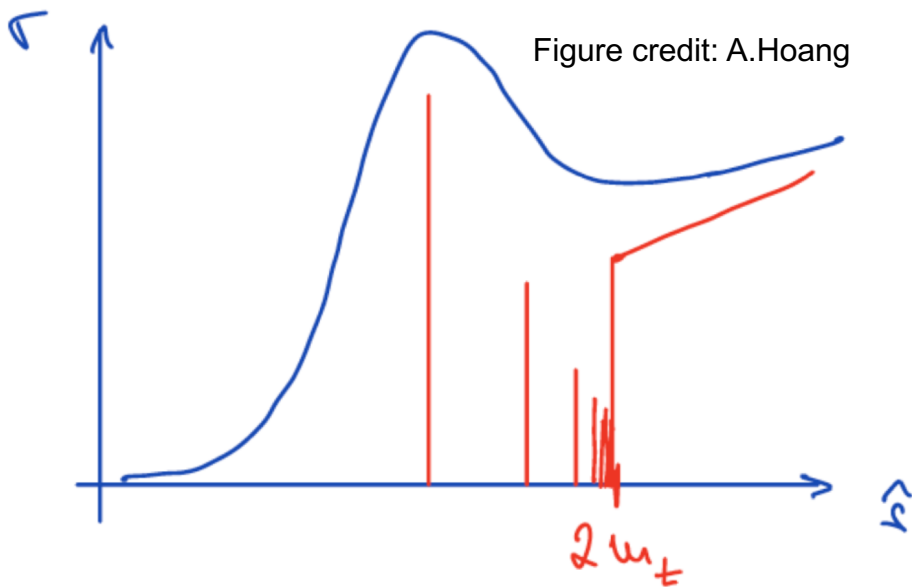
Phys. Rev. D 97, 112003



Toponium – top quark bound states

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

[EPJC 60, 375](#)
[Kiyo, et. al](#)



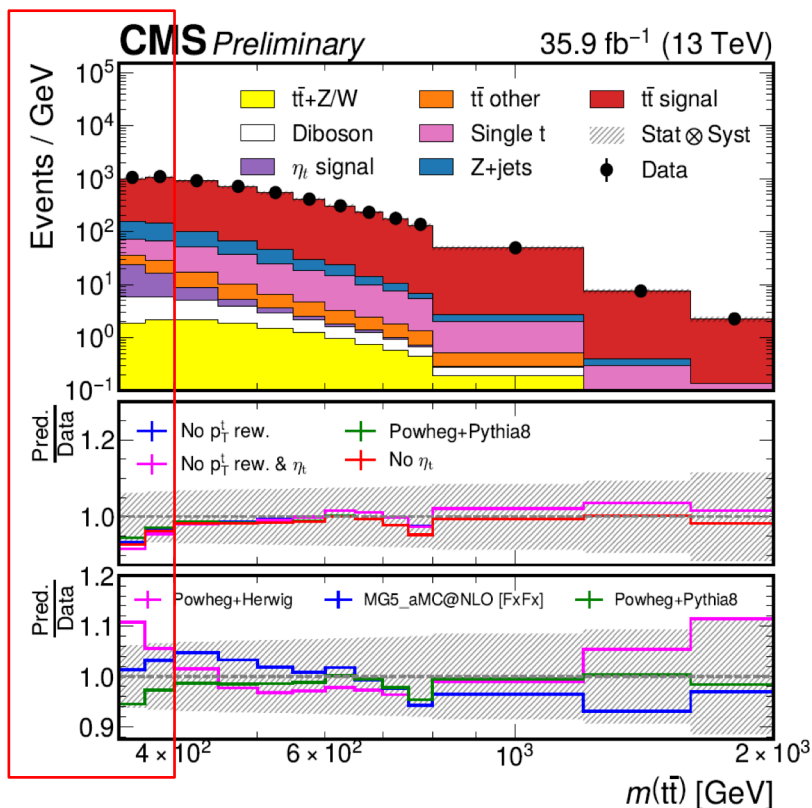
Ground state (n=1) S-wave bound state dominates:

- spin-singlet vs. spin-triplet (depending on production channel) color singlet vs color octett

Signal modeling & Uncertainties

- Combined signal model: $t\bar{t}$ + toponium (η_t)
 - Only spin-0 η_t accounted for
 - η_t improves data modeling in the threshold region
 - 47 500 signal candidates in 35.9 fb^{-1} collected in 2016
- Main background sources: Z+jet (MG5 + data-driven corrections), single top (powheg MC), diboson (pythia8 MC)

Analysis region



Leading experimental uncertainties

- Jet energy scale and resolution

Leading theory-based uncertainties

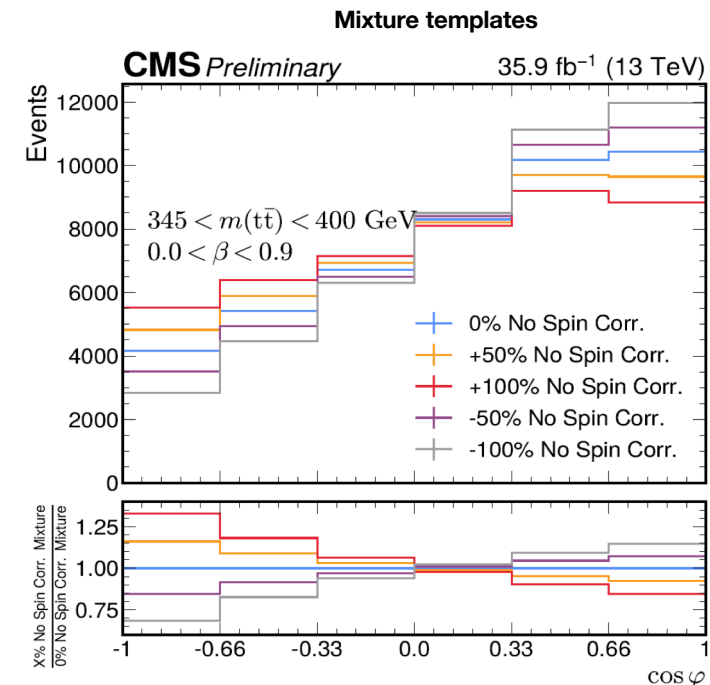
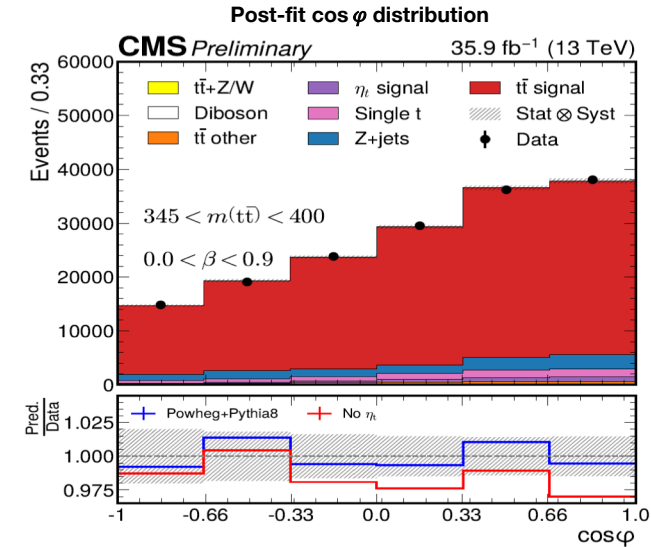
- Toponium normalization
- Parton Shower

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%

Observation of Entanglement

- 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 $t\bar{t}$ with aligned vs opposite spins
 - Any value of D between -1 and 1 can be reached

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



X% No Spin Corr. Mixture
0% No Spin Corr. Mixture

Observation of Entanglement

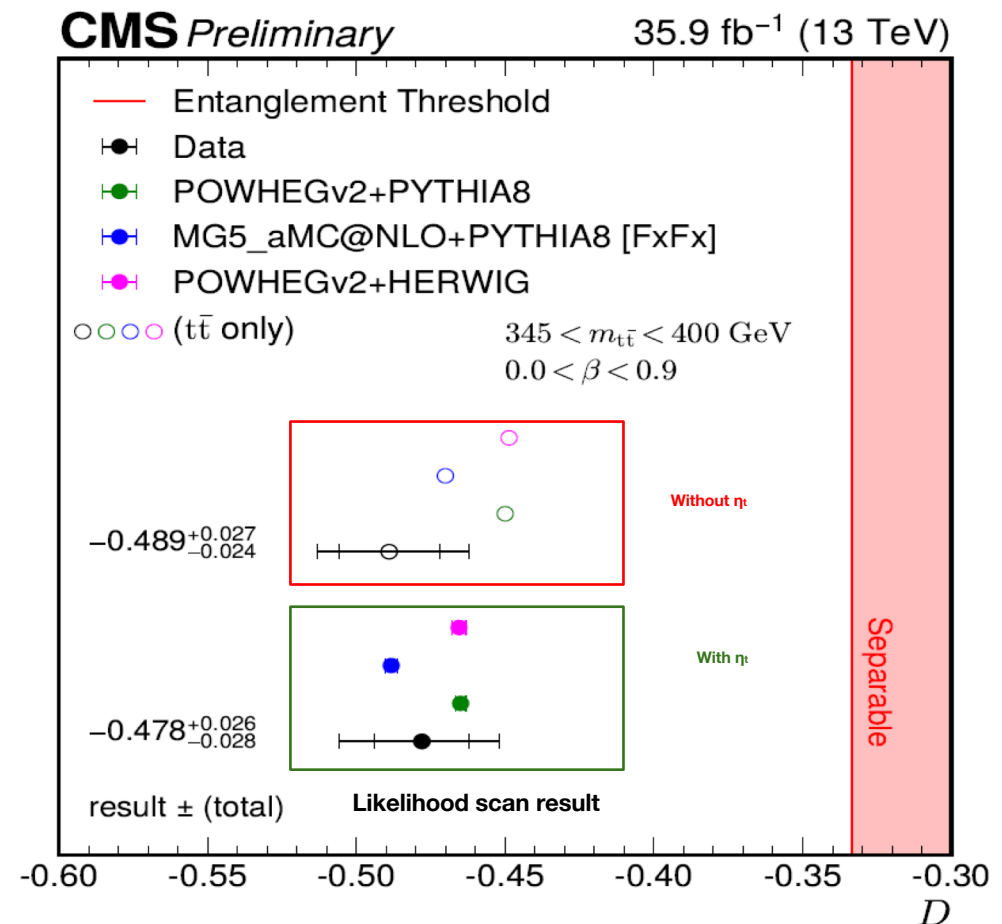
- Fit yields D at parton level, accounting for all detector effects
- **5 standard deviations observation** of top quarks being entangled at $t\bar{t}$ threshold
- Good agreement with SM
 - significantly improved by including η_t

$$D_{obs} = -0.478 \pm 0.017 (stat) \quad {}^{+0.018}_{-0.021} (syst)$$

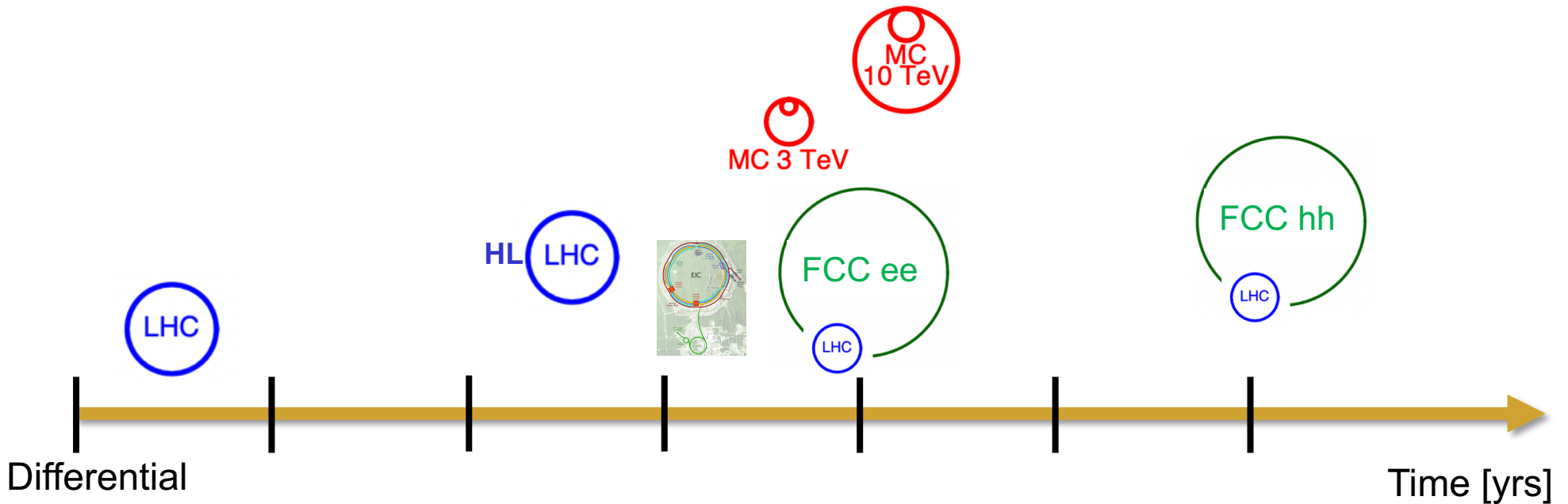
$$D_{exp} = -0.465 \pm 0.017 (stat) \quad {}^{+0.019}_{-0.022} (syst)$$

First measurement of entanglement of top quarks with CMS data

[Check the PAS for more information](#)



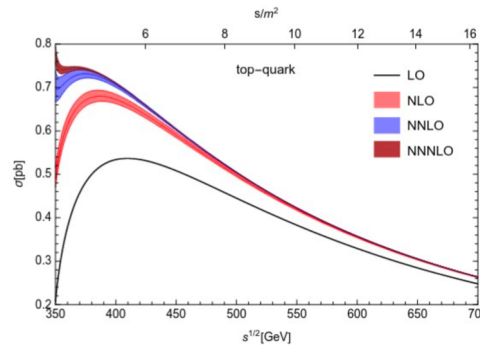
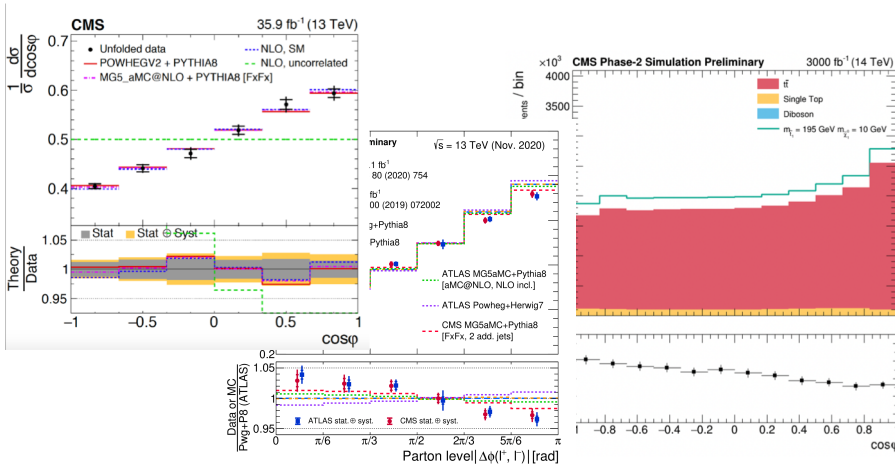
Quantum Tomography @Future colliders



Differential
Detector “Precision”

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

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



e+e- @Per mille level

- A rich exciting new field!
- Bright future ahead - join the fun

Conclusions & Outlook

- ATLAS measurement of entanglement in top quark events shows deviations to the SM
- CMS: Top quark pair entanglement is in agreement with SM
 - Improved description & modeling when including toponium
- Quantum Entanglement & Tomography (at high energy colliders)
 - **New and exciting field of Quantum Information in HEP**
 - New approach to test and challenge the SM
- Exciting community study completed and P5 vision is out!
- Future e+e- collider machines: careful preparation of initial state, other probes of entanglement
 - Promising scenarios of entanglement probes

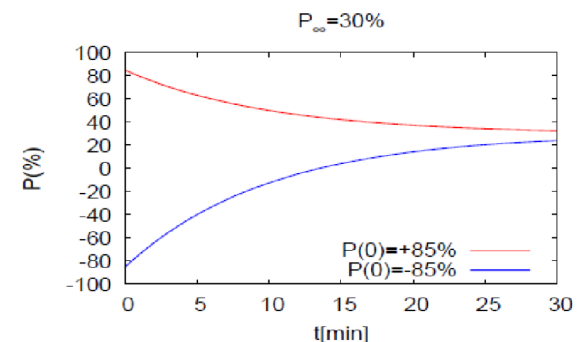
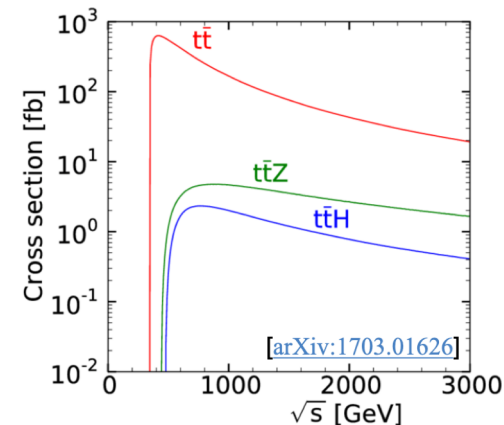
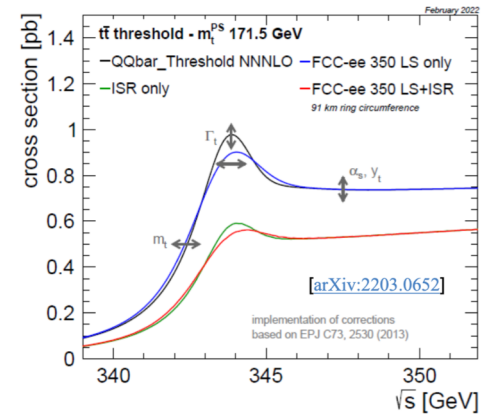
Stay tuned for new results on top quark entanglement!



Backup

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} : ± 17 MeV (m_t), ± 45 MeV (Γ_t)
- δ_{syst} dominated by theory, e.g. $m_t \sim 45$ MeV!
- Current top mass average (LHC + Tevatron): 172.69 ± 0.3 GeV
- **Entanglement prospects: Prepare initial state!**
- **HERA demonstrated polarization is possible but challenging and time-dependent!**
- **EIC will have improved methods...**



- If a state is separable \rightarrow Unit trace, Hermitian, Eigenvalues ≥ 0
- Therefore, a state is **entangled** if the above conditions **don't** hold for the partial transpose of the spin density matrix, ρ
- A sufficient condition for **entanglement** using Peres-Horodecki Criterion:

$$\Delta = C_{33} + |C_{11} + C_{22}| - 1 > 0 \quad [\textit{Eur. Phys. J. Plus 136, 907}]$$

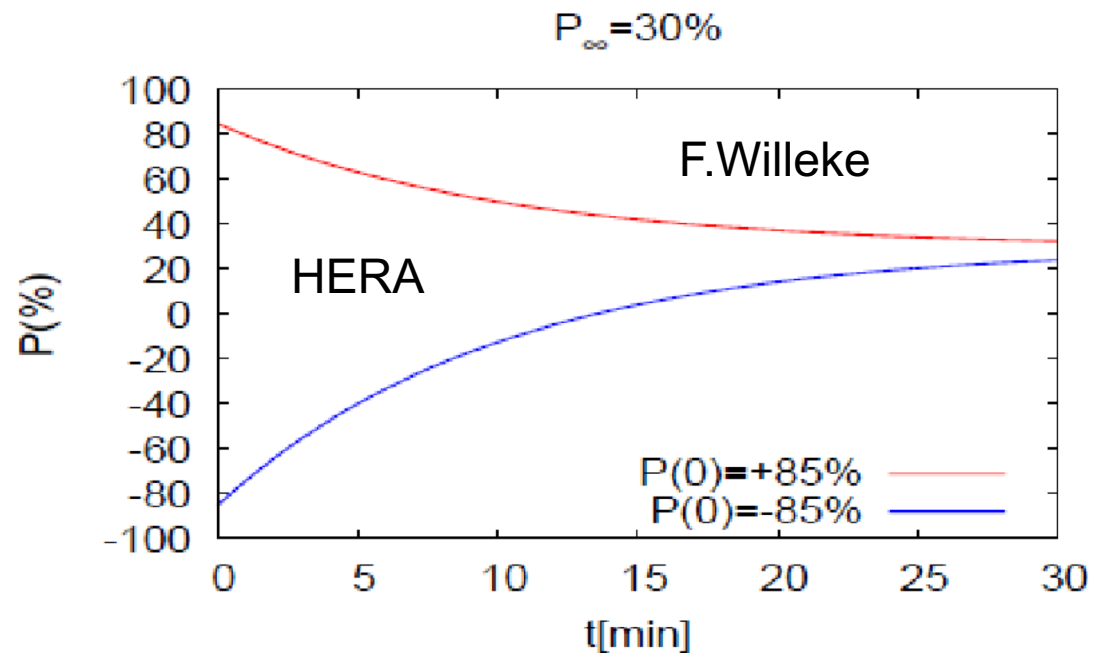
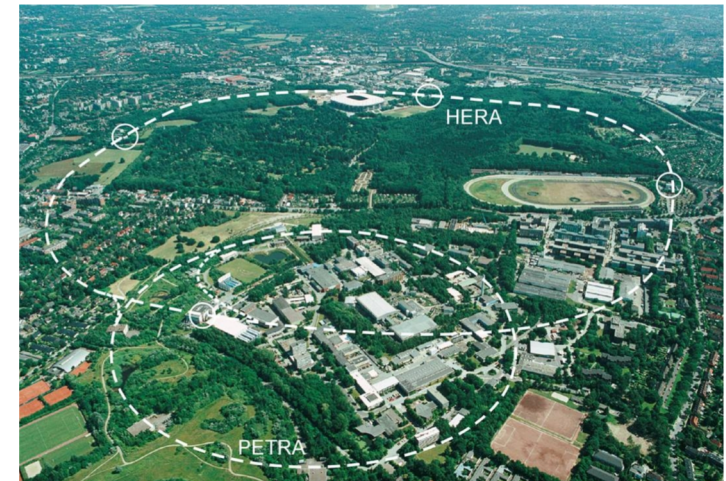
- At low $m_{t\bar{t}}$, $C_{11} > 0$ & $C_{22} > 0 \rightarrow \Delta + 1 = \textit{tr}[C] > 1$
- Remarkably, $\textit{tr}[C]$ can be probed from a single differential cross section

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

- This yields $-3D > 1$ as a sufficient condition for **entanglement**
- **Measure D to access entanglement information!**

Initial State: Polarization of e-beam

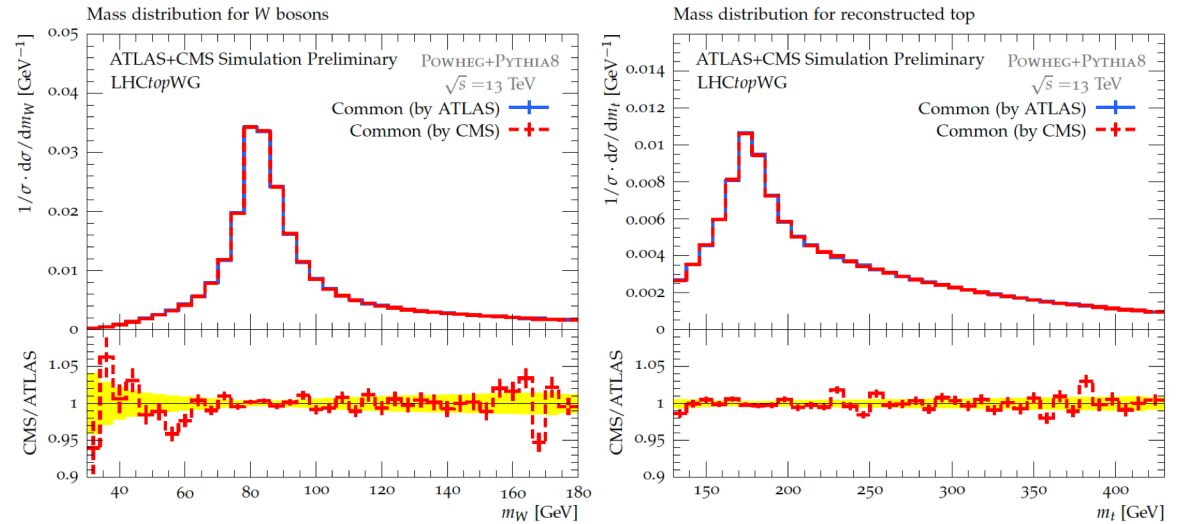
- **HERA demonstrated polarization is possible but challenging and time-dependent!**
- **EIC will have improved methods...but**
- Need high polarization for hadrons and electrons of $> 70\%$
- Need both polarization directions present in the same fill to suppress systematics
- Spin need to be longitudinal in the IP
- Electron spin need to be vertical in the arcs
- **Systematic uncertainties for entanglement proxies ?**



Hard Groundwork

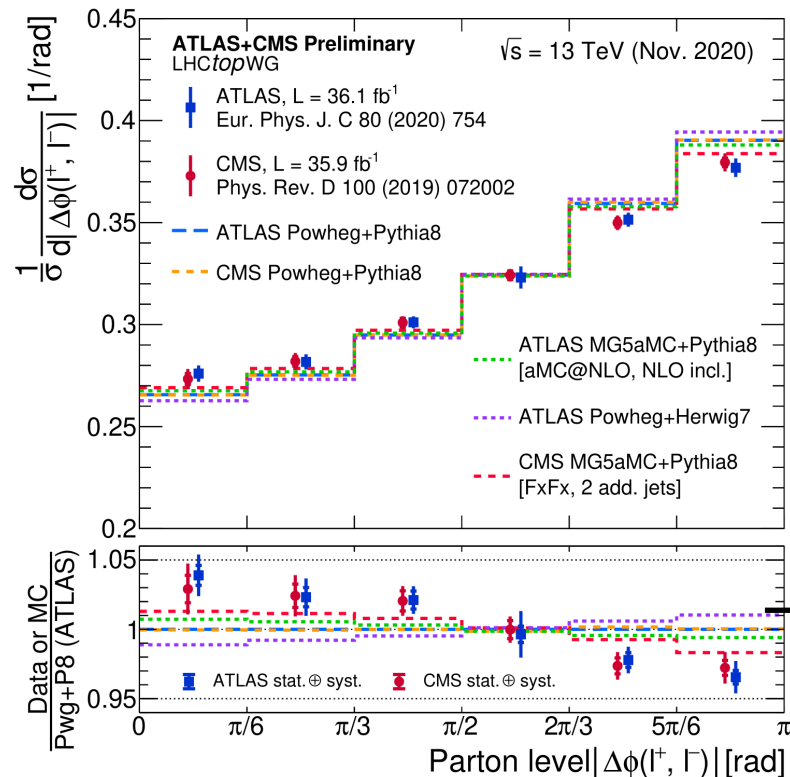
- Complex issue of different setups in ATLAS & CMS

- LHCtopWG effort from both sides: joined ATLAS + CMS effort
- Enormous amount of person power also in understanding of systematic uncertainties across both experiments



- Facilitate future combinations, studies on systematic uncertainties, etc.
- Vital and critical for success of Run 3 (and beyond)
- Many details, please check:

[\[LHCtopWG: Common samples\]](#)



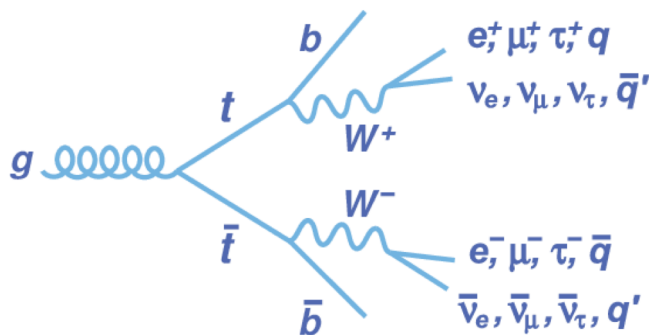
Towards common MC settings in ATLAS & CMS:
ATL-PHYS-PUB-2021-016 & CMS NOTE-2021/005

Double diff. xsec

Polarisation (0 in SM)

Spin Correlation

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



- Using conservation of 4-momentum (with the mass of the top and W boson assumed)
- The measured b and l momenta together help constrain the neutrino momentum to an ellipse.
- For the double neutrino case, an additional MET constraint is imposed.

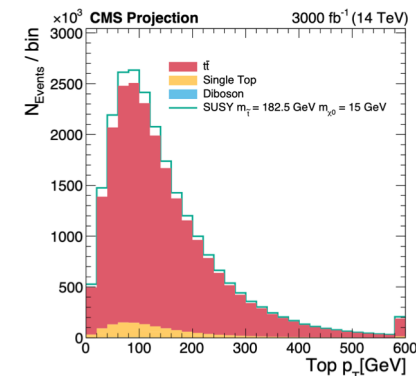
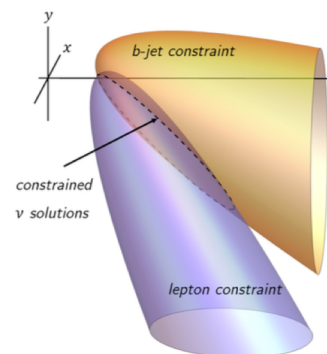
Cut	SUSY	$t\bar{t}$	Single Top	Diboson
2 leptons	3180752	46942286	6291825	875681
$\epsilon_{tot}, \epsilon_{cut}$	14 %, 14 %	14 %, 14 %	2 %, 2 %	9 %, 9 %
2 jets	2230452	34109607	3035953	123486
$\epsilon_{tot}, \epsilon_{cut}$	10 %, 70 %	10 %, 73 %	1 %, 48 %	1 %, 14 %
MET	1867103	27796121	2462018	112145
$\epsilon_{tot}, \epsilon_{cut}$	8 %, 84 %	8 %, 81 %	1 %, 81 %	1 %, 91 %
b-tag	1812201	27133968	2204553	49470
$\epsilon_{tot}, \epsilon_{cut}$	8 %, 97 %	8 %, 98 %	1 %, 90 %	1 %, 44 %

Table 3: Summary of flat systematic uncertainties.

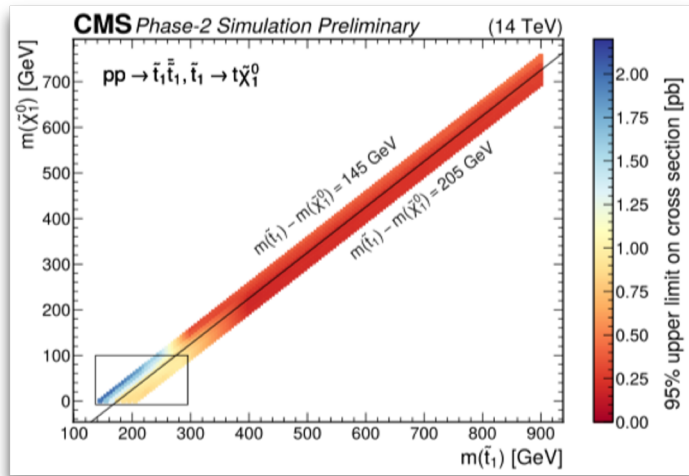
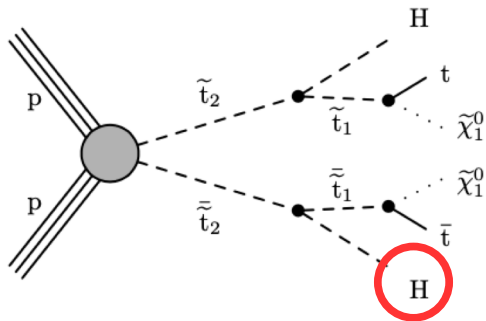
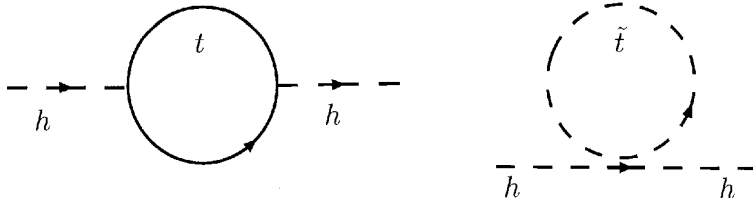
Systematic Uncertainty	Yellow Report Recommendation
Muon ID	0.5 %
Electron ID	1 %
Luminosity	1 %
b-tagging	1 %
Pile Up	2 %
Theoretical	50 % of current 14 TeV cross-sections

Table 4: Summary of shape-based systematic uncertainties.

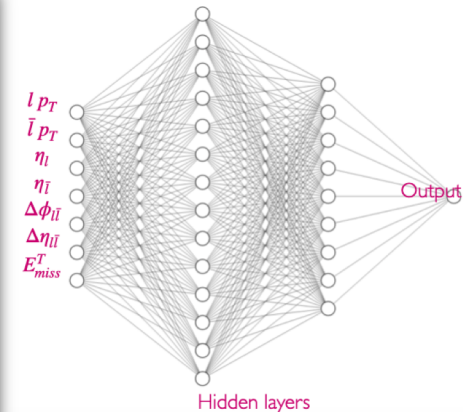
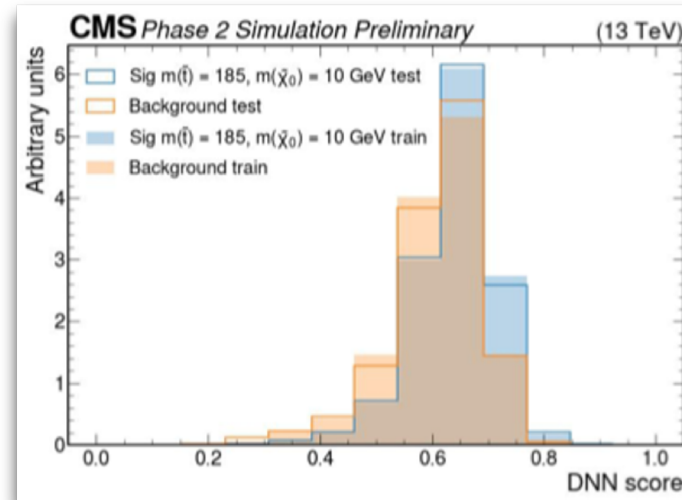
Systematic Uncertainty	Yellow Report Recommendation
PDF	M_x based look-up table
top p_T	33% of Run2
Jet Energy Scale	from shape
Jet Energy Resolution	from shape
Renormalization and Factorization Scale	50 % of Run2



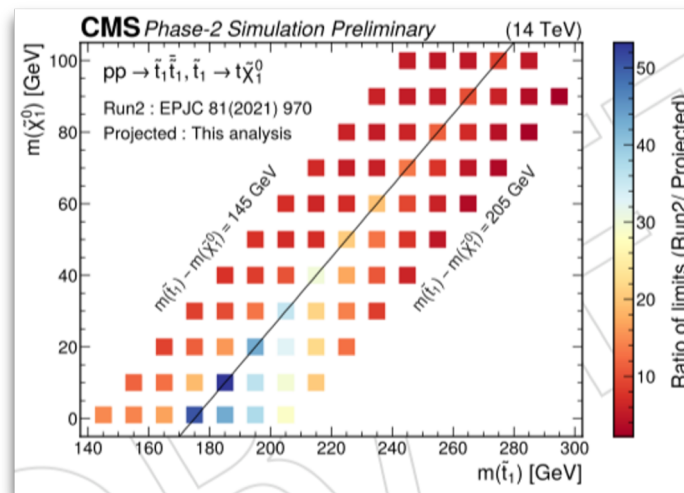
Reminder: Solve the hierarchy problem
 → need a top quark partner



Signal to bg separation at 185 GeV



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



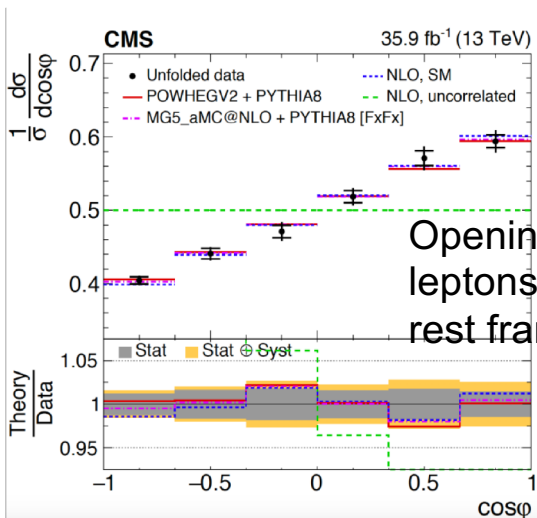
Significantly better sensitivity

Double diff. xsec

Polarisation (0 in SM)

Spin Correlation

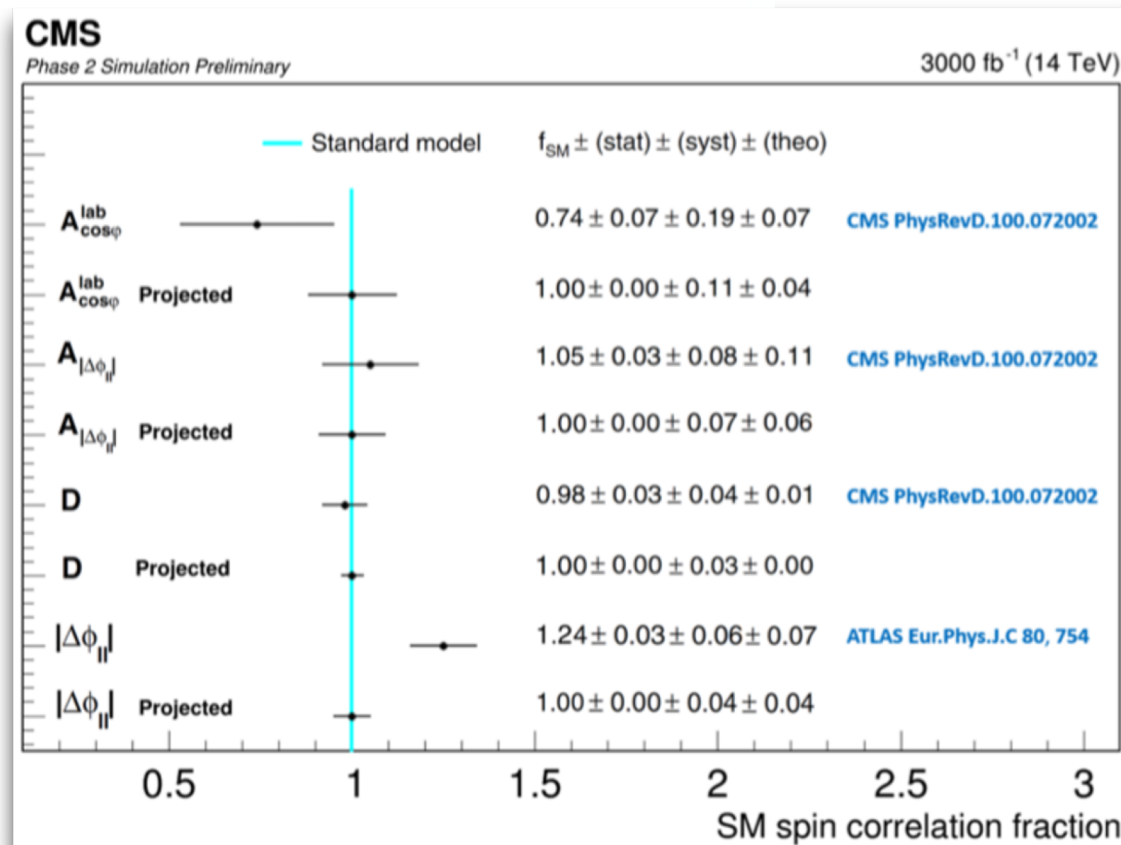
$$\frac{1}{\sigma} \frac{d^2\sigma}{d\cos\theta_+^a d\cos\theta_-^b} = \frac{1}{4} (1 + B_+^a \cos\theta_+^a + B_-^b \cos\theta_-^b - C(a,b) \cos\theta_+^a \cos\theta_-^b)$$



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:
O(2 - 3)%



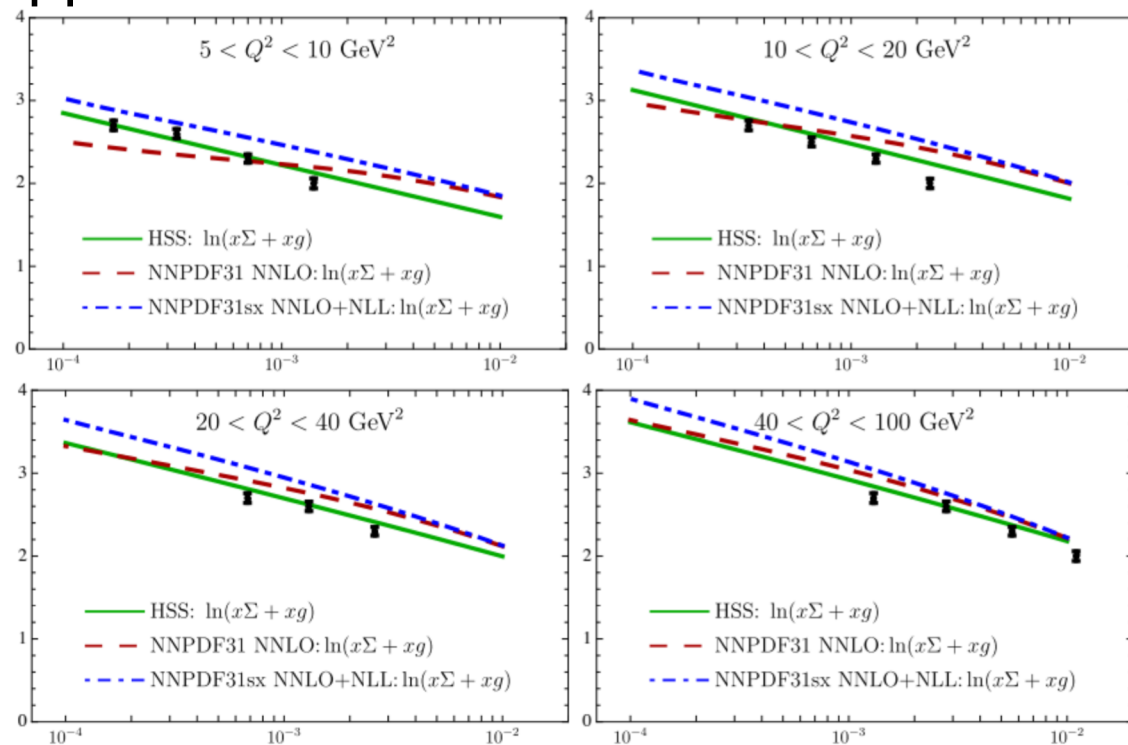
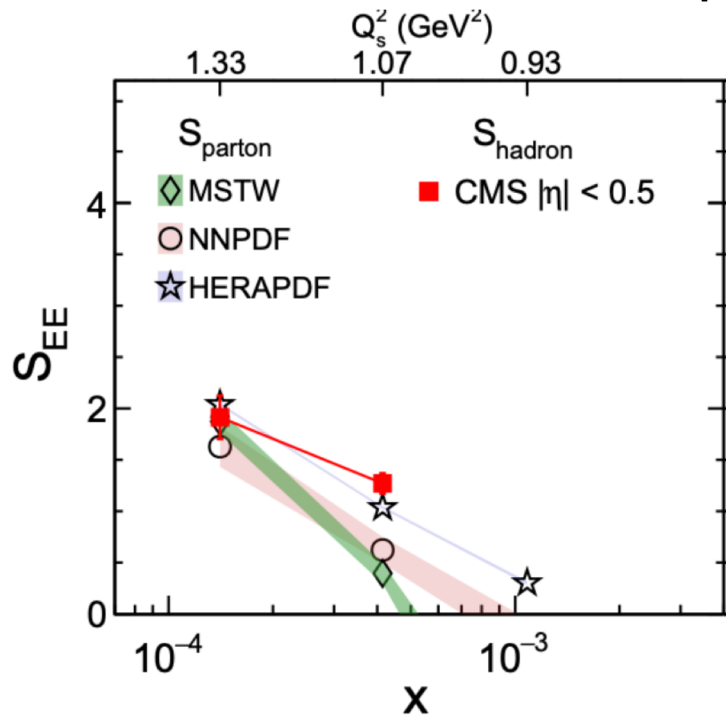
Contributed to Snowmass, CMS-PAS-FTR-18-034

Ep/ion: Entanglement Entropy

- Entanglement entropy based on number of charged particles
- Idea: “regions” of proton by means of Bjorken x
- Always very hard to model accurately
- Factorization ansatz ? ep vs pp

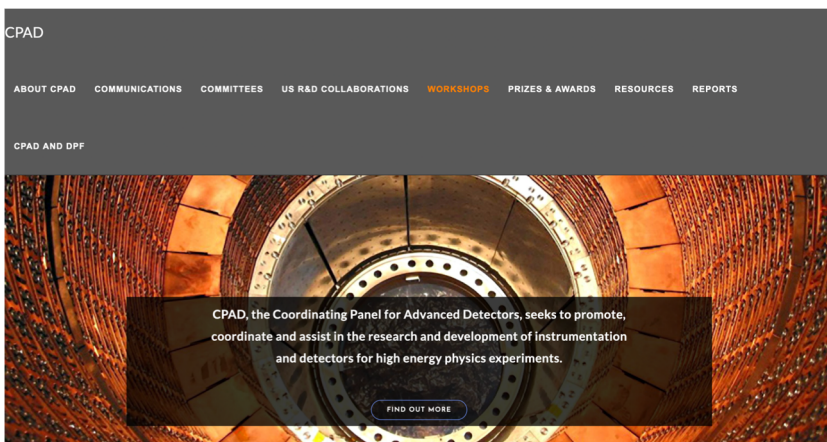
$$S = -\text{tr} \rho \ln \rho = - \sum_n p_n \ln p_n$$

$$S = \ln[xG(x)]$$



CPAD: Detector R&D in the US

- **Coordinated Panel for Advanced Detectors** <https://cpad-dpf.org>



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RDC#	TOPIC
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6	Gaseous Detectors
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9	Calorimetry
10	Detector Mechanics
11	Fast Timing