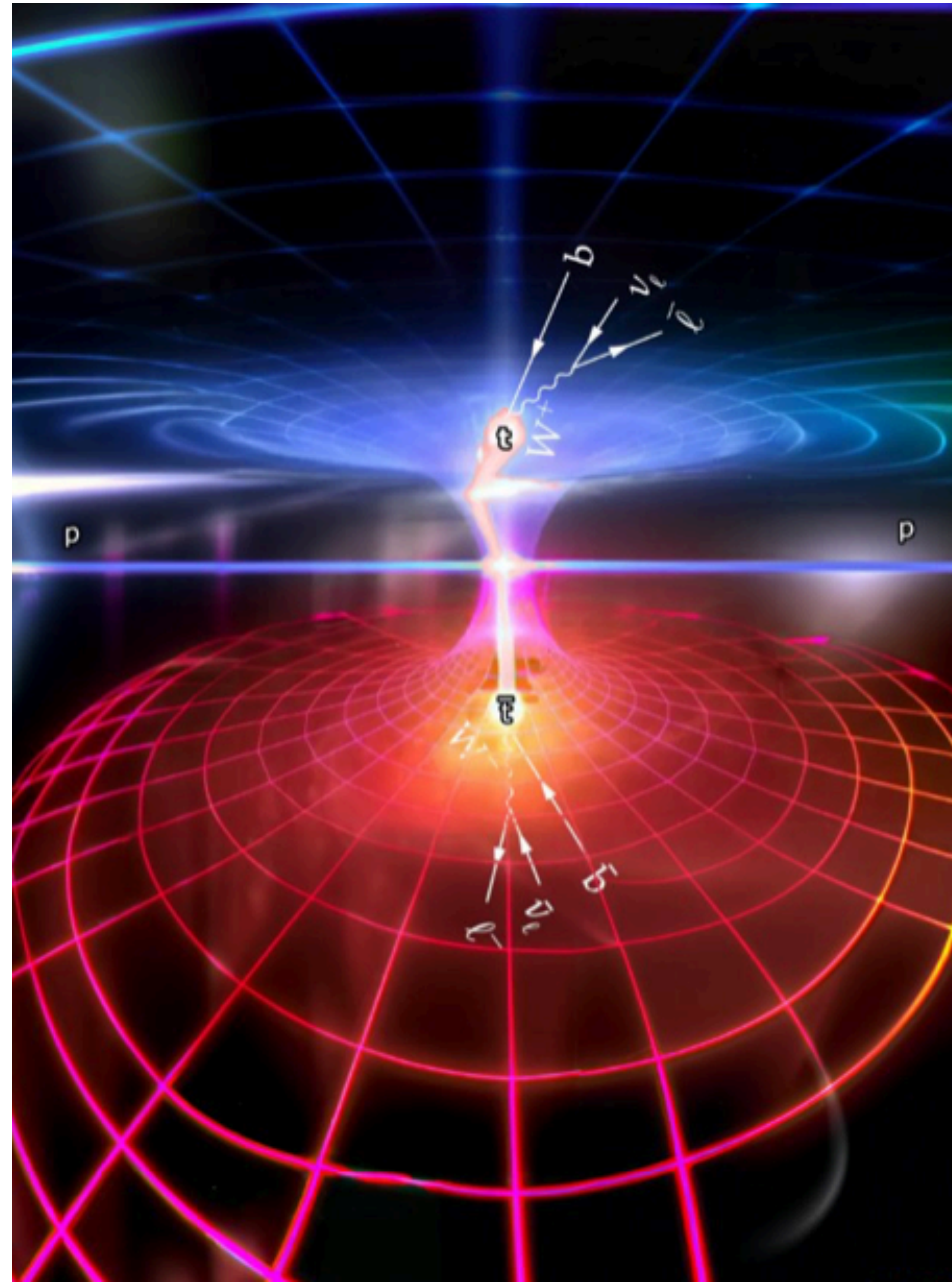
Probing entanglement in top quark production with the CMS detector

Giulia Negro

on behalf of the CMS Collaboration

LHC TOP WG meeting

26 April 2024



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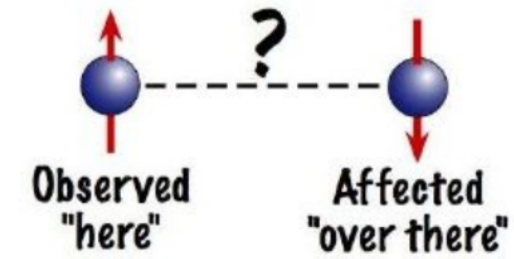
Entanglement at the LHC



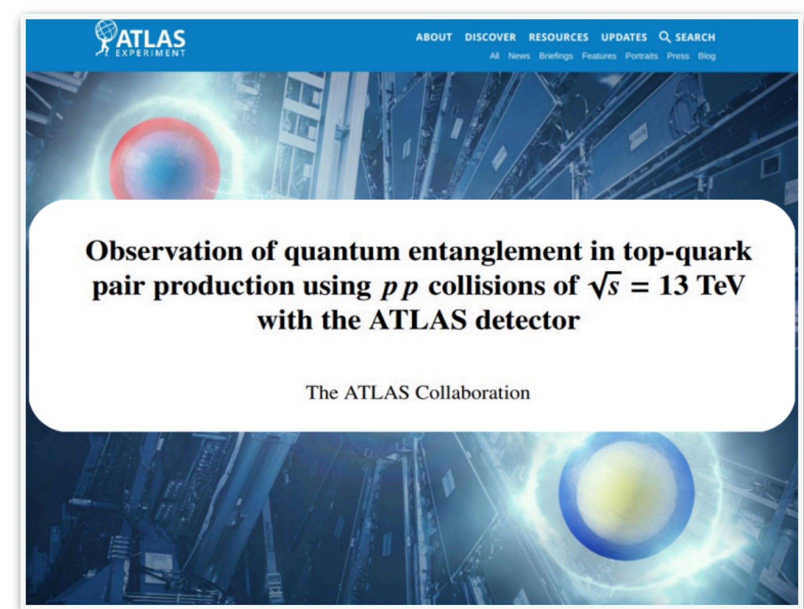
- **Fundamental predictions of Quantum Mechanics:**
  - entangled states cannot be described by independent superpositions
  - measuring particle spin in an entangled system immediately reveals the spin state of the second particle

- **A lot of measurements with electrons and photons already performed**

Nobel Prize in 2022 for
Aspect, Clauser, and Zeilinger

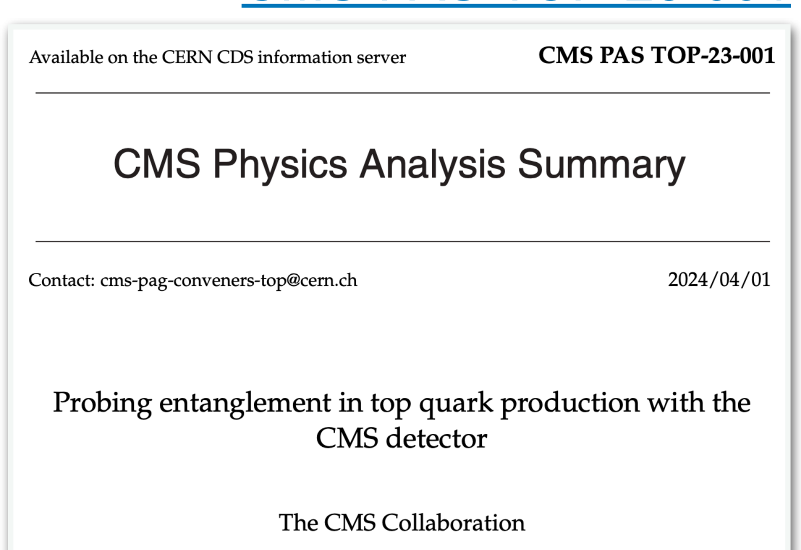
- **First observation of entanglement in $t\bar{t}$ by ATLAS at the end of last year**

arXiv:2311.07288



- **Now also with CMS!**

CMS-PAS-TOP-23-001



Available on the CERN CDS information server | **CMS PAS TOP-23-001**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch | 2024/04/01

Probing entanglement in top quark production with the CMS detector

The CMS Collaboration

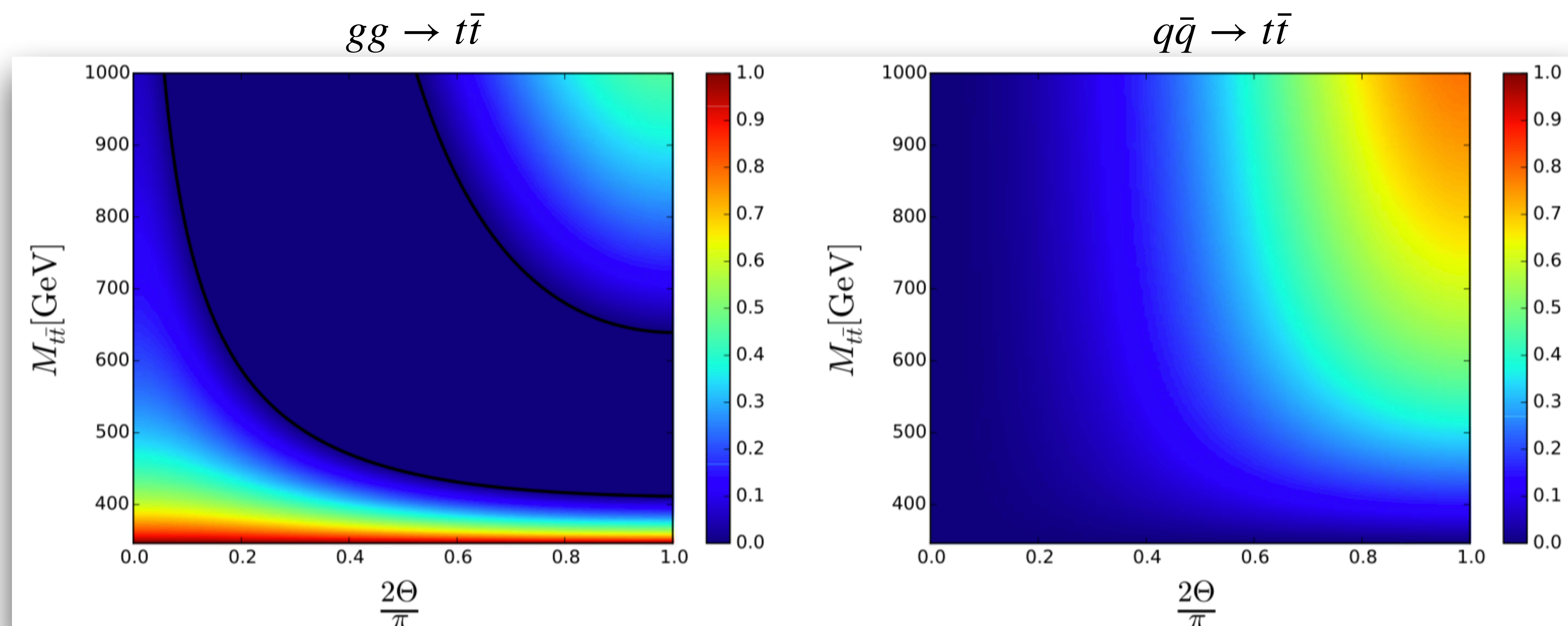
Entanglement of top quarks

- **Top quark = ideal candidate for spin measurements:**
  - **extremely short lifetime** allows measuring polarization and spin correlation in $t\bar{t}$ production
  - **spin information is preserved** in the angular distribution of its decay products

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

- **Entanglement present in top quark pairs can be measured using spin correlations variables**

- **Entanglement depends on production mode, $m_{t\bar{t}}$, scattering angle of the top quark (Θ)**



Afik, De Nova
Eur. Phys. J. Plus **136**, 907

How to probe entanglement

- **At the LHC, top quarks are produced in a mixed state**
  → can be represented as a density operator:

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

  - $B^{+/-}$ = 3-vectors characterizing degree of top quark/antiquark polarization
  - C = 3x3 matrix characterizing top quark and antiquark spin correlations

- **Peres-Horodecki criterion**:

  Peres, Phys. Rev. Lett. **77**, 1413
  Horodecki, Phys. Lett. A **232**, 5

  if a state is separable (i.e., non-entangled), the transpose with respect to a subspace of the density operator is positive definite
  → a state is non-separable (i.e., entangled) if this condition doesn't hold

→ top quarks are entangled in a certain phase space if at least one eigenvalue is < 0

How to probe entanglement

- **Peres-Horodecki criterion**:
  using simpler observables, a **sufficient condition to observe entanglement in top quarks is:**

$$\Delta = C_{33} + |C_{11} + C_{22}| - 1 > 0$$

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

- At low $m_{t\bar{t}}$, $C_{11} > 0$ and $C_{22} > 0$ $\rightarrow$ $\Delta + 1 = \mathrm{tr}[\mathrm{C}] > 1$

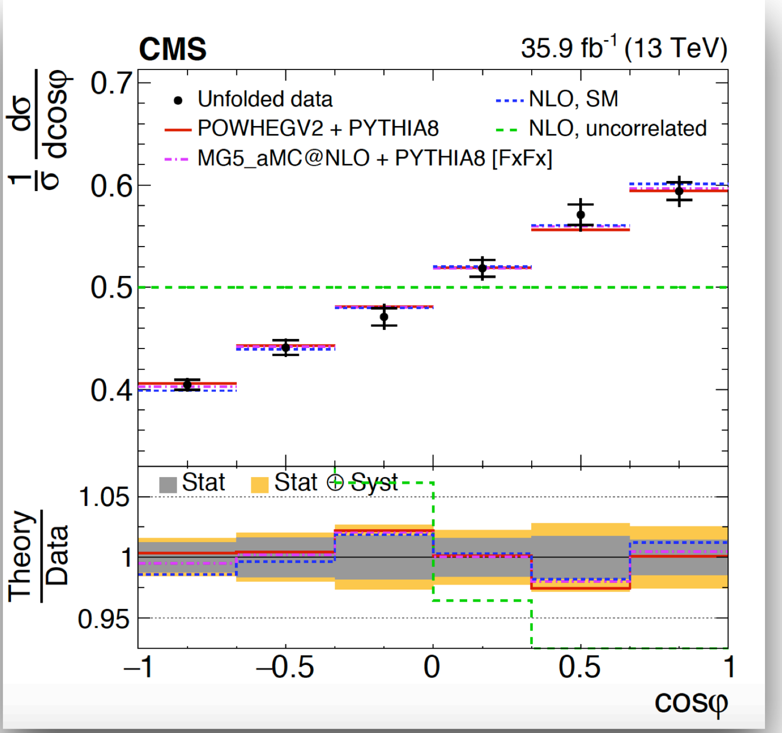
- tr[C] can be probed from a single-differential cross section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi) \qquad D = -\frac{\mathrm{tr}[C]}{3} \rightarrow D < -1/3$$

Sufficient condition for entanglement !

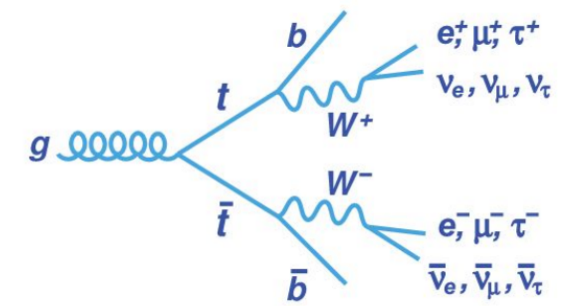
→ **measure D to access entanglement information in top quark events!**

- $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$ is the opening angle between leptons in parent top rest frame
  → **most sensitive and experimentally well measured observable**
  → **focus of entanglement measurement**



Phys. Rev. D 100 (2019) 072002

Analysis strategy



- **The degree of entanglement is highly phase space-dependent**
  - scan of $\cos\Theta$ vs $m_{t\bar{t}}$ 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**
  - threshold region dominated by gg
  - maximal sensitivity with high statistics

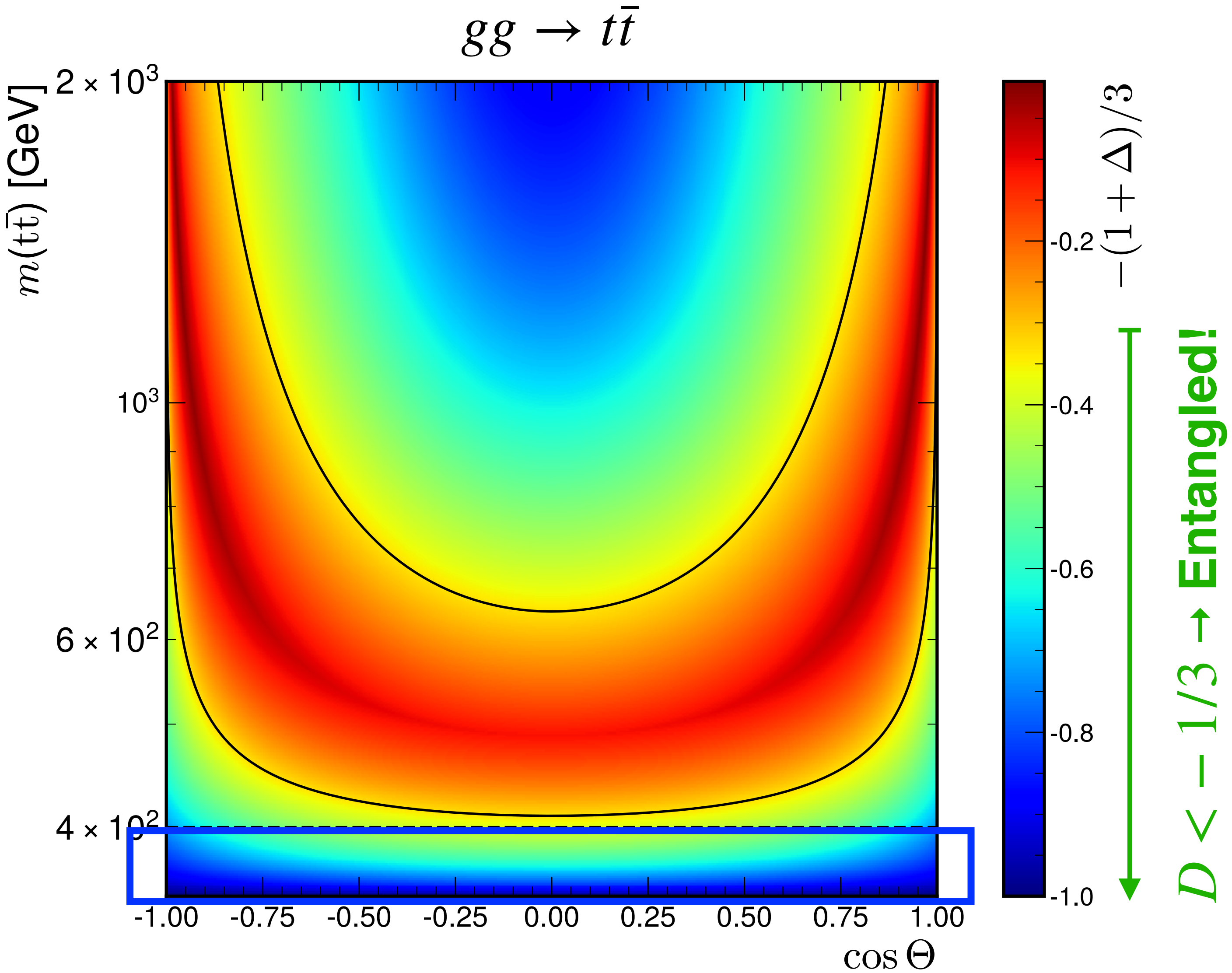
- **Cut on velocity along the beam line of the tt̄ system to increase $gg/q\bar{q}$ fraction:**

Aguilar-Saavedra, Casas arXiv:2205.00542

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

- **Use leptonic final states to measure the helicity angle $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$**
  - fully encapsulates the spin correlations information for gg fusion production at low mass

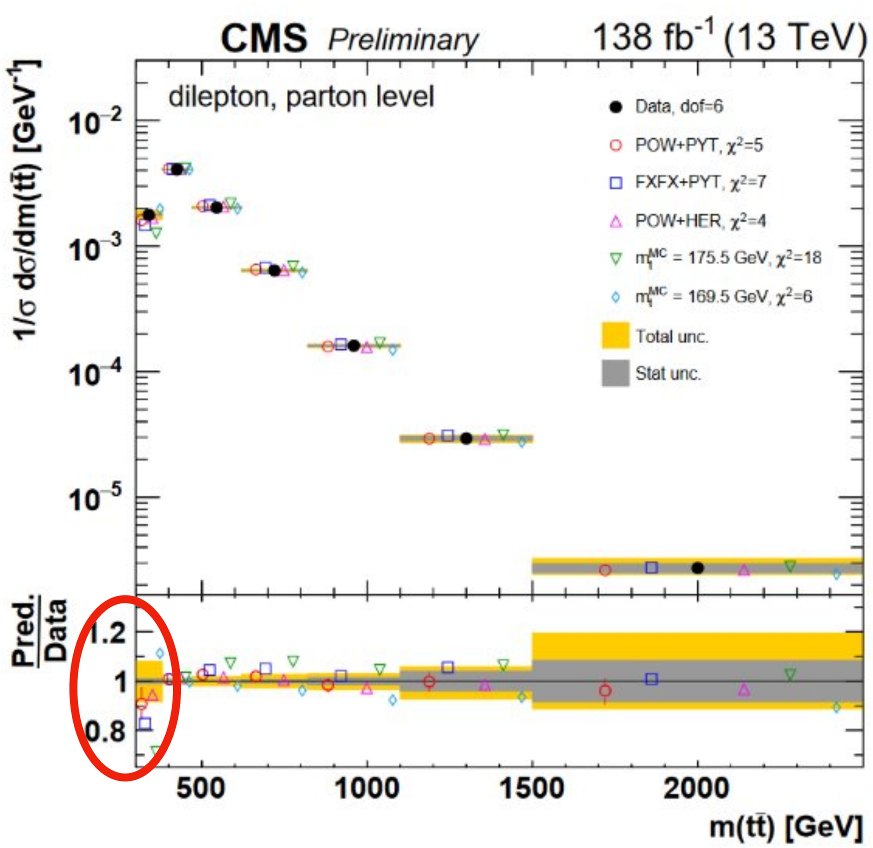
- **Perform a profile maximum likelihood fit of the $\cos\varphi$ distribution in the $m_{t\bar{t}}$ - β signal region**



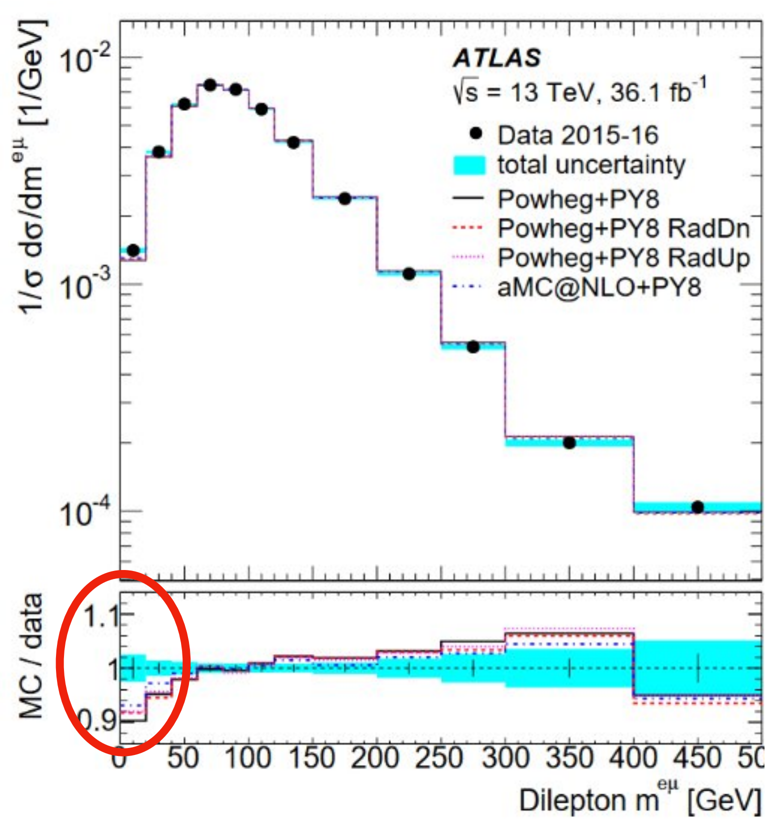
Threshold region

- **Mis-modeling at a level of ~10% seen for $m_{t\bar{t}}$ ~345 GeV ($m_{e\mu}$ < 50 GeV)**
- **Consistent between dilepton and lepton+jets analyses in both CMS and ATLAS**

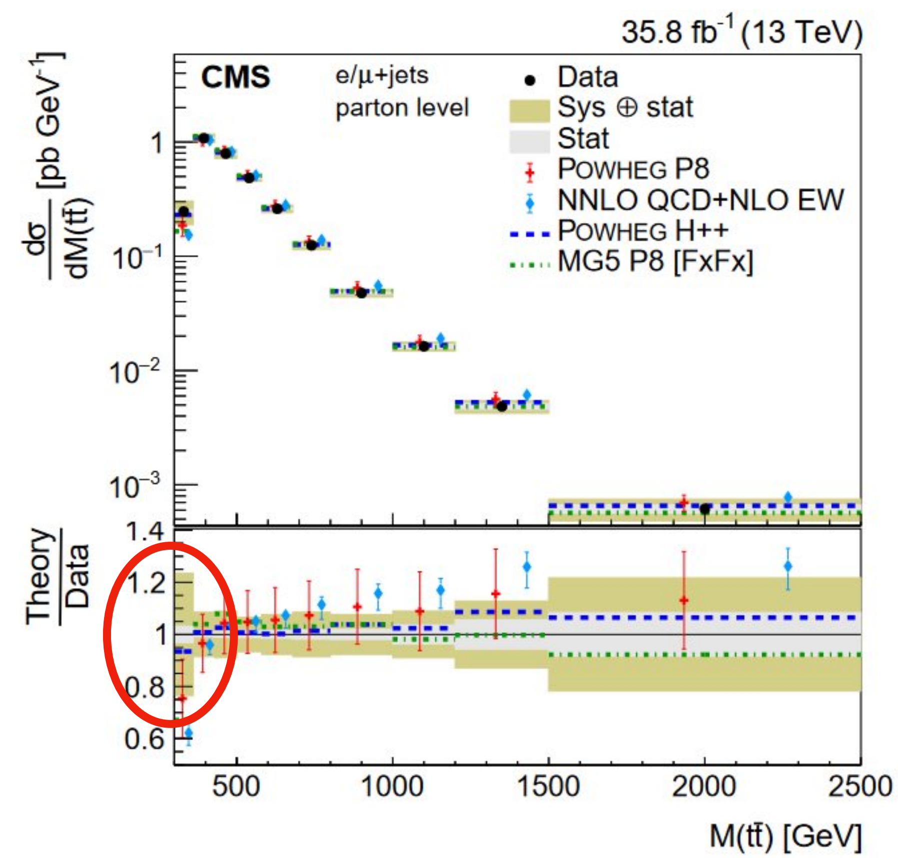
CMS-PAS-TOP-20-006



EPJ C 80, 6



Phys. Rev. D 97, 112003



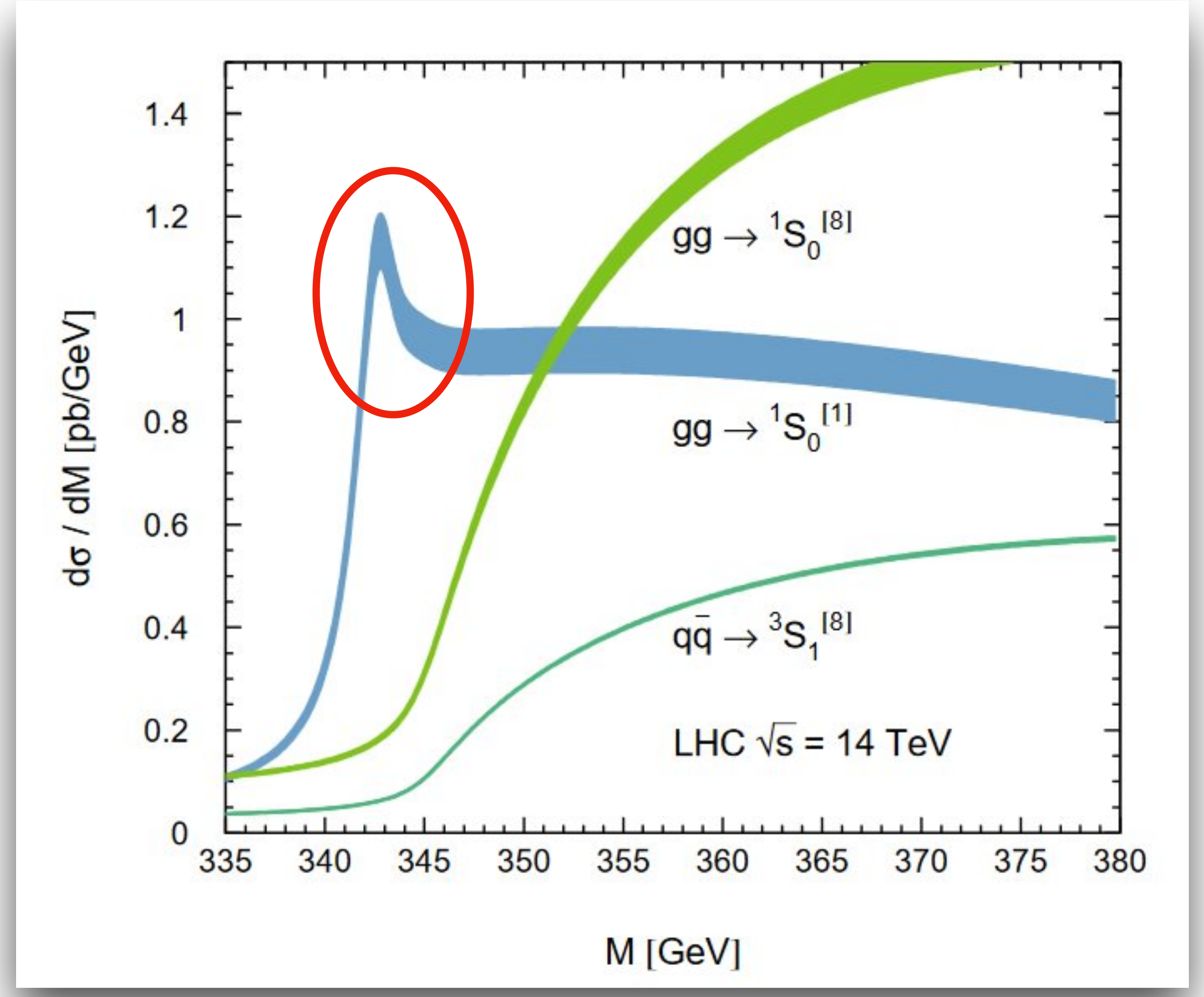
Threshold region

- **Mis-modeling at a level of ~10% seen for $m_{t\bar{t}}$ ~345 GeV ($m_{e\mu}$ < 50 GeV)**
- **Consistent between dilepton and lepton+jets analyses in both CMS and ATLAS**
- **NRQCD contributions close to threshold**
  - spin and color singlet state (η_t): maximally entangled ***toponium***
- **Excess seen could come from toponium ?**

→ **inclusion of toponium (η_t) contributions in our signal model**
using simplistic model based on
Phys Rev D 104 034023

Toponium = predicted top quark-antiquark quasi-bound state with a mass of 343 GeV and width of 7 GeV

JHEP 06, 158

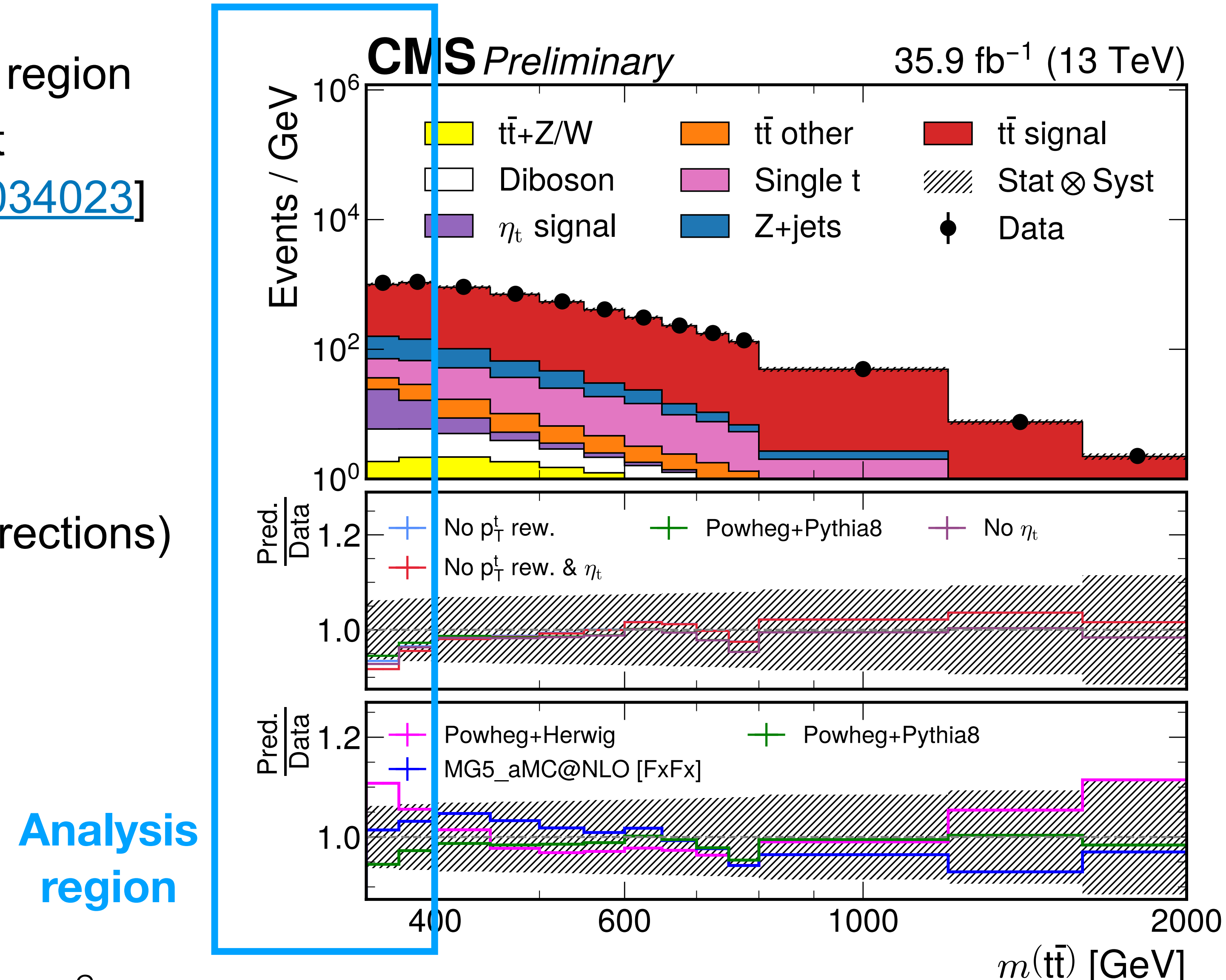


Dataset and signal model

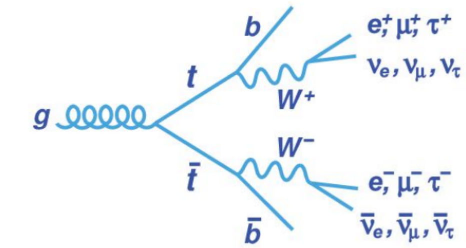
- **Current analysis = extension of 2016 top quark spin correlations analysis in dilepton events**
- **35.9 fb^{-1} of data @13 TeV collected in 2016**

Phys. Rev. D 100 (2019) 072002

- **Combined signal model: $t\bar{t}$ + toponium (η_t)**
  - PowhegBox+Pythia8 as nominal $t\bar{t}$ sample
  - PowhegBox+Herwig and MG5 aMC@NLO(+MadSpin) [FxFx] as alternatives $t\bar{t}$ samples
  - η_t improves data modeling in the threshold region
    - only spin-0 η_t accounted (colour singlet pseudoscalar state) [PRD 104 (2021) 034023]
    - toponium model generated with MG5 aMC@NLO(LO)+Pythia8 with $337 < m_{\eta_t} < 349$ GeV
- **Main background sources:**
  - Z+jets (MG5_aMC@NLO + data-driven corrections)
  - single top (Powheg MC)
  - diboson (Pythia8 MC)



Event selection



- **Current analysis = extension of 2016 top quark spin correlations analysis in dilepton events**
  - same strategy for event selection, kinematic reconstruction, and background estimation
  - **optimized sensitivity for entanglement measurement**

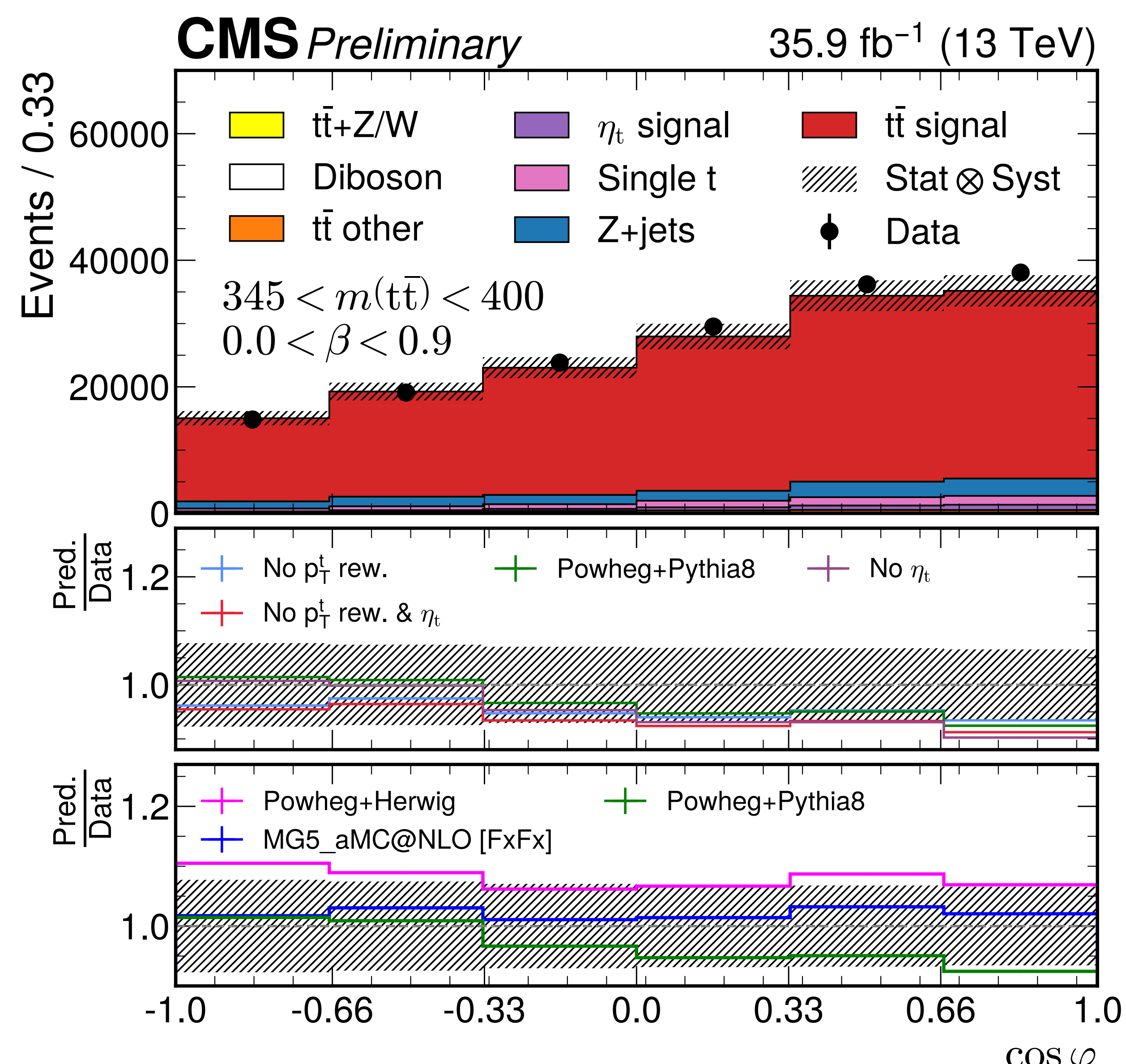
Phys. Rev. D 100 (2019) 072002

- **2 oppositely charged isolated leptons (ee, eμ and μμ)**
  - **including also leptons from tau decays** (different from 2016 analysis)
  - p_T > 25(20) GeV, for leading(trailing) lepton and $|\eta|$ < 2.4
  - veto events with more than two leptons
  - reject events with $m_{\ell\bar{\ell}}$ < 20 GeV
  - single lepton + dilepton triggers

- **≥ 2 jets (R=0.4), >=1 b jet**
  - p_T > 30 GeV and $|\eta|$ < 2.4
  - jet cleaning: ΔR(ℓ, jet) > 0.4

- **ee, μμ channels:**
  - E^T_{miss} > 40 GeV
  - Z veto: $|m_Z - m_{\ell\bar{\ell}}|$ > 15 GeV

- **Top quark reconstruction with $m_{\ell b}$ weighting method**
  - take solution with smallest $m_{t\bar{t}}$



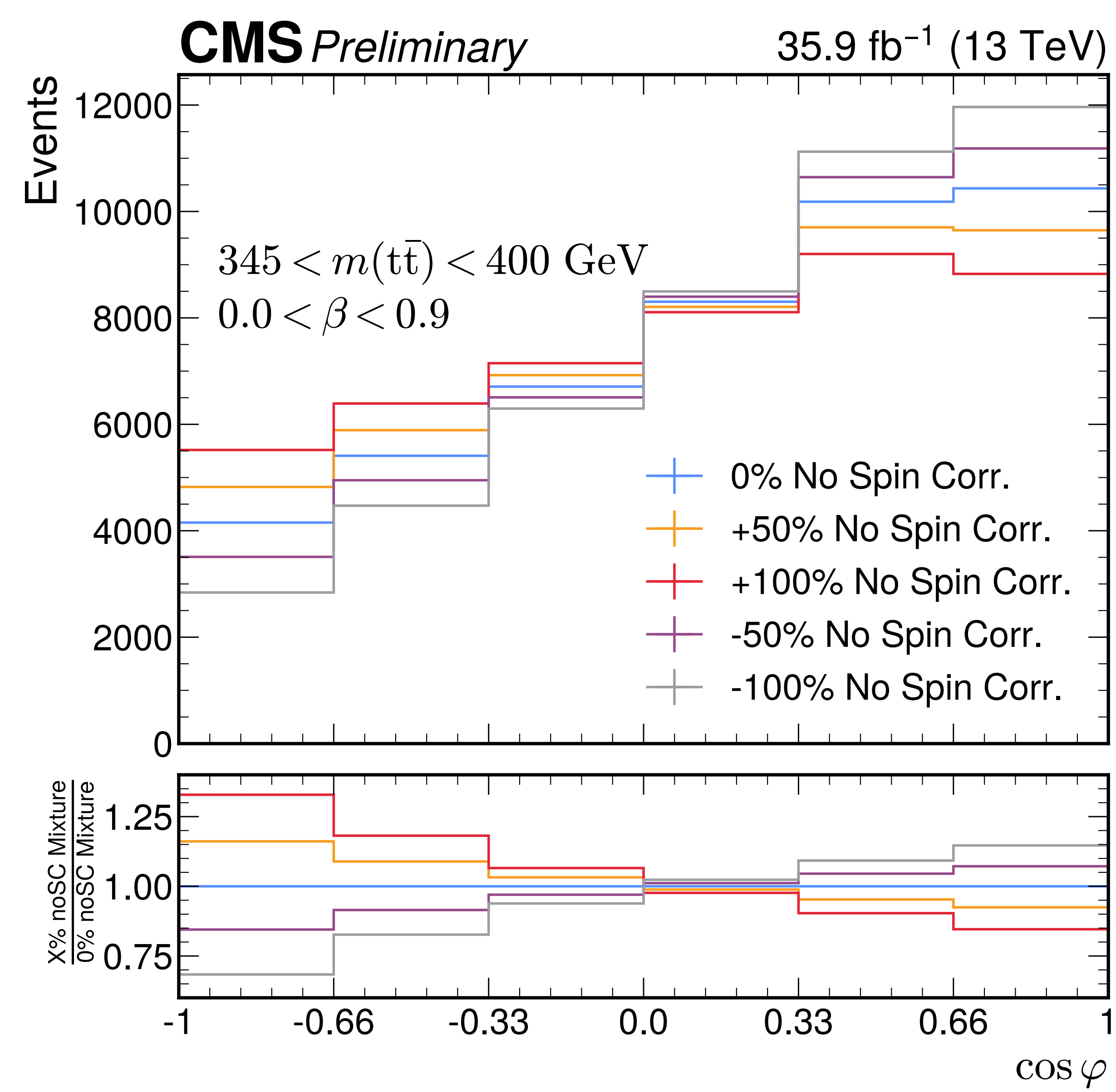
Extraction of entanglement proxy

- **The entanglement proxy D is extracted with a template fit**
  - all systematic effects included as nuisances

- **How can we create variations of D outside of SM?**
  1. generate top quark pairs with no spin correlations $\rightarrow D = 0$ (noSC samples)
  2. create new samples with mixtures of SM and noSC to obtain $D \in [D_{SM}, 0]$
  3. extend the fit for variations of $[-1, D_{SM}]$

- **Use mixtures 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

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



Mixed samples with and without spin correlations

Systematic uncertainties

- **Current analysis = extension of 2016 top quark spin correlations analysis in dilepton events**
  - same uncertainties considered + **additional ones for toponium**:
    - a flat uncertainty of 50% is applied on toponium
    - a binding energy uncertainty of ±0.5 GeV is considered

- **Breakdown of leading syst. unc. in the entanglement proxy D at the post-fit level**

- **Leading experimental uncertainties:**
  - Jet energy scale and resolution

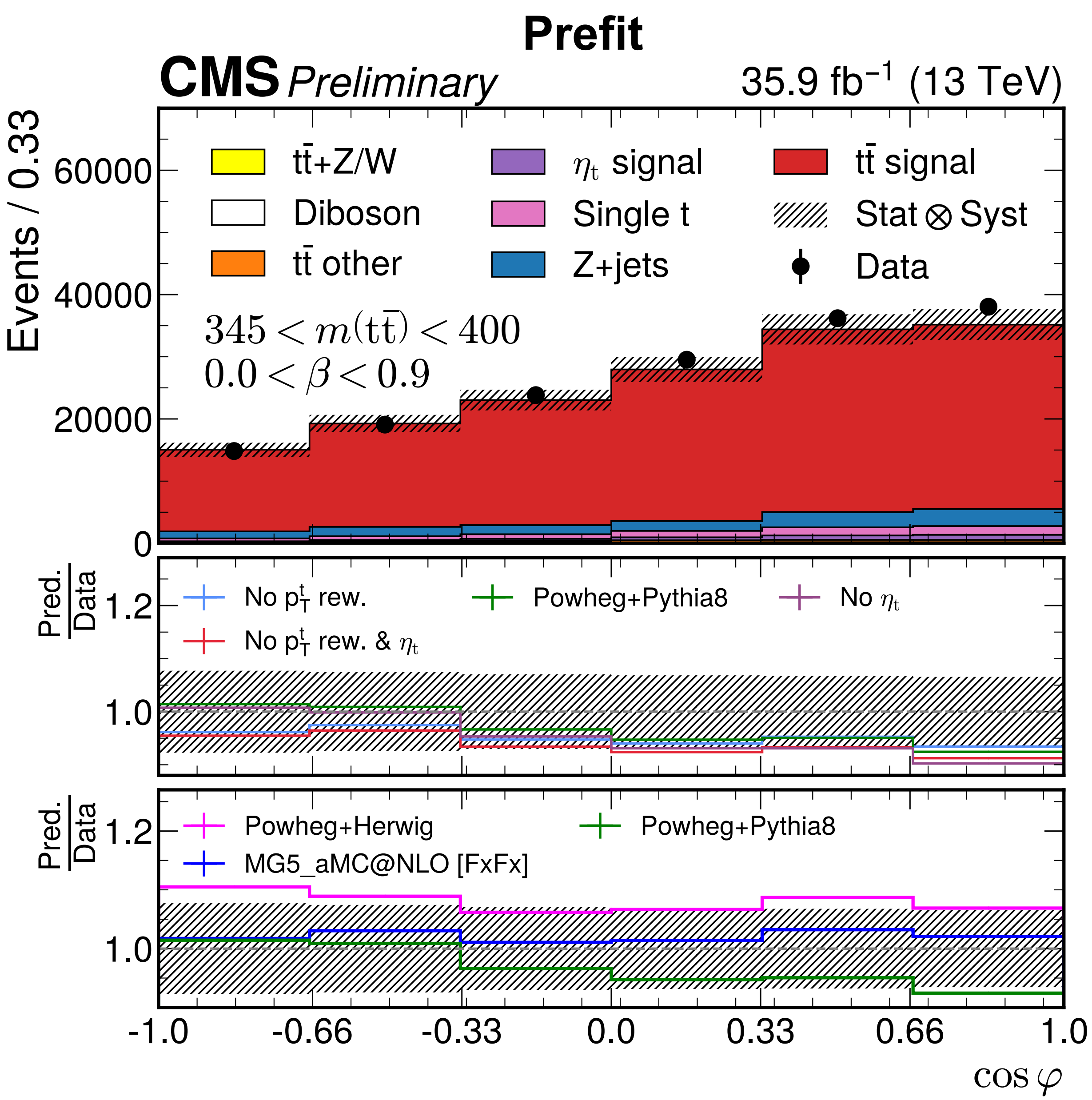
- **Leading theory-based uncertainties:**
  - Toponium normalization
  - Parton Shower

Source	**Uncertainty** D
JES	10.1%
Toponium normalization	10.1%
Parton Shower (ISR)	6.3%
Scale	1.8%
Parton Shower (FSR)	1.2%
JER	0.9%
Z+jets shape	0.8%
b quark fragmentation	0.4%
$t\bar{t}$ normalization	0.3%
PDF	0.3%

Results

- **Result of the binned profile likelihood fit of the $\cos\varphi$ distribution**
  - ~47500 signal candidates

- **Good agreement with SM predictions**



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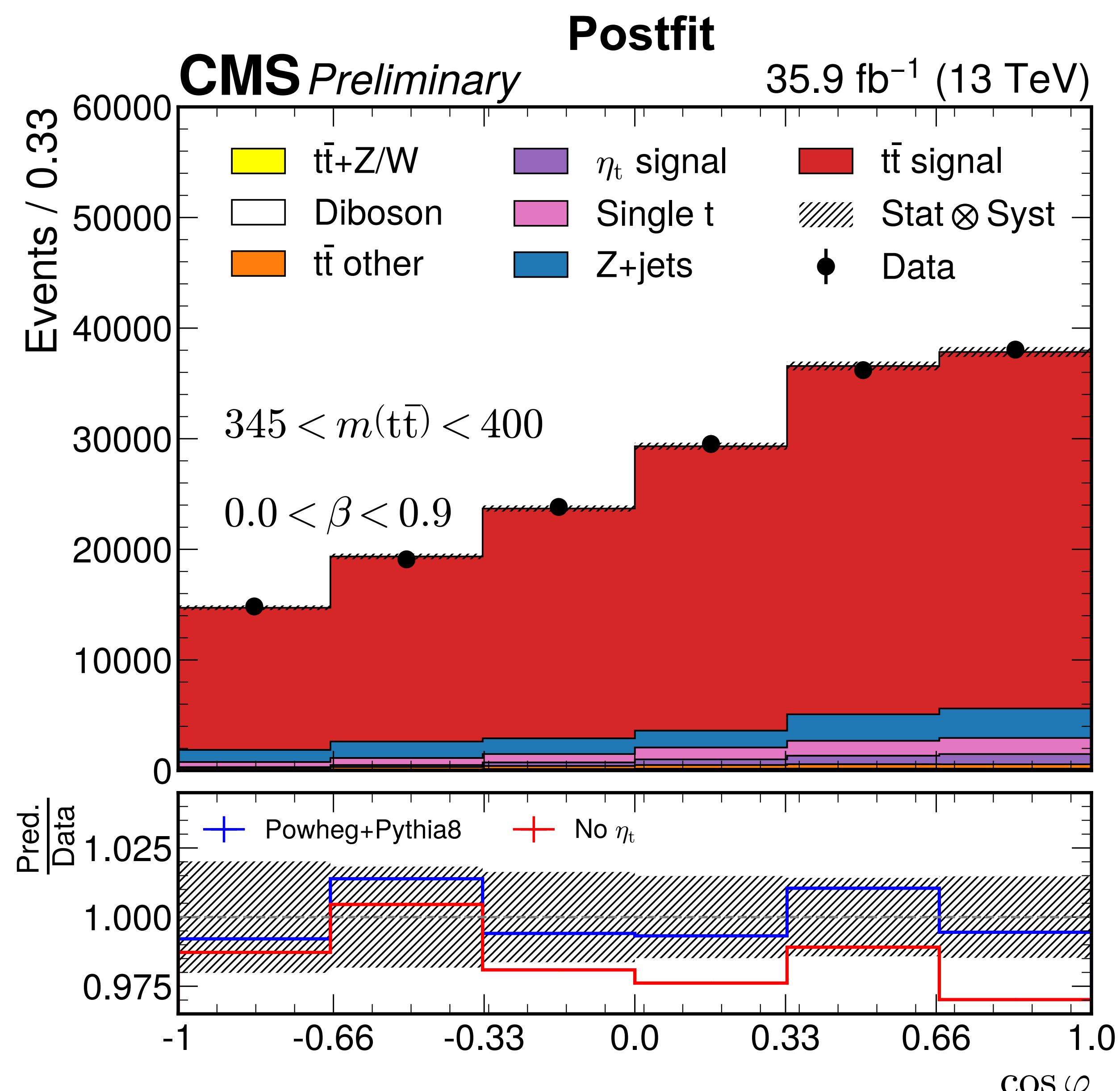


No η_t = η_t removed from signal without repeating the fit

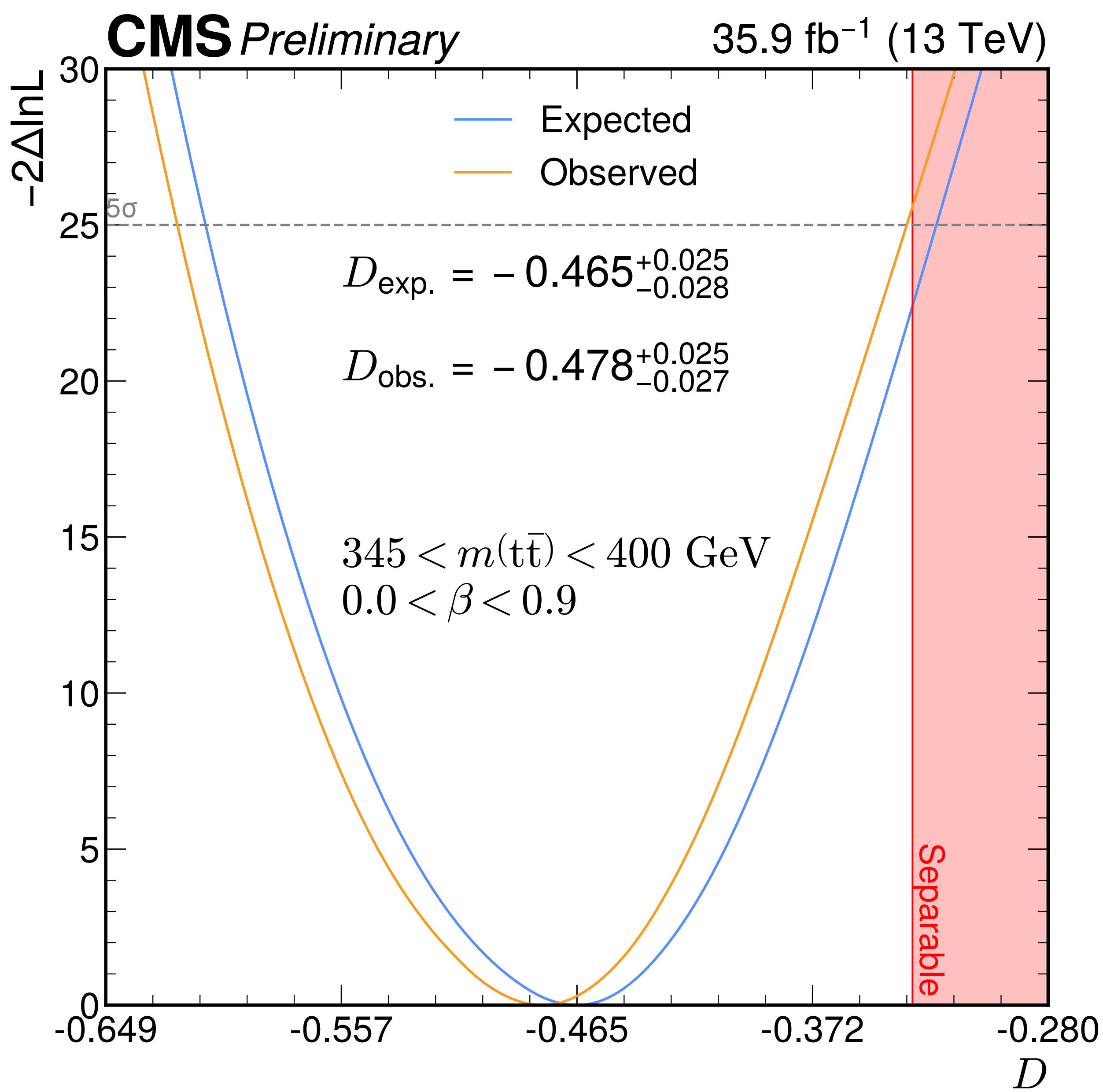
Results

- **Scan of the $-2\Delta lnL$ distribution yields D at parton level, accounting for all detector effects**

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

$$D_{exp} = -0.465^{+0.016}_{-0.017}(\text{stat})^{+0.019}_{-0.022}(\text{syst})$$

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



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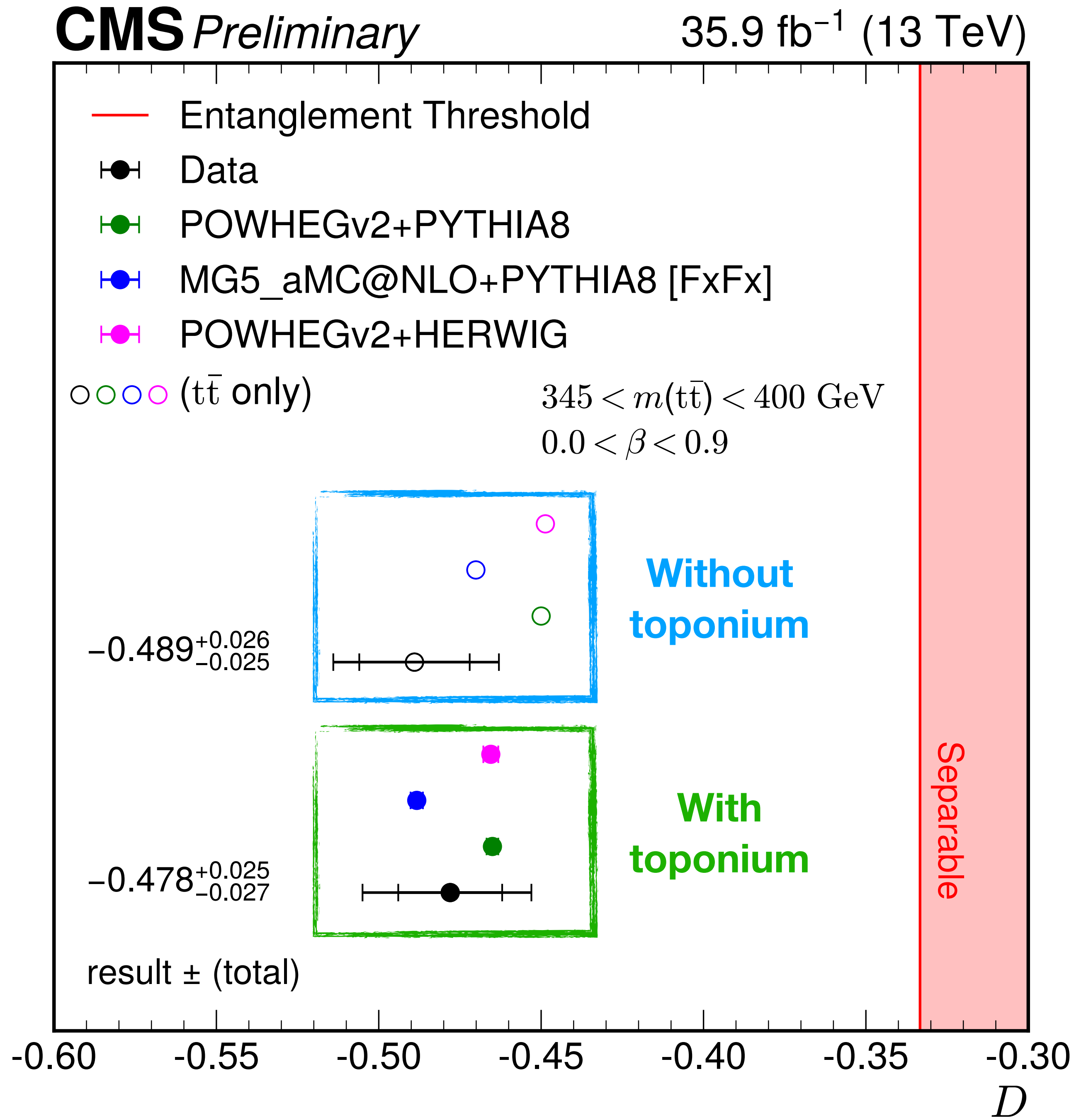
>5 standard deviations observation of top quarks being entangled at $t\bar{t}$ threshold !

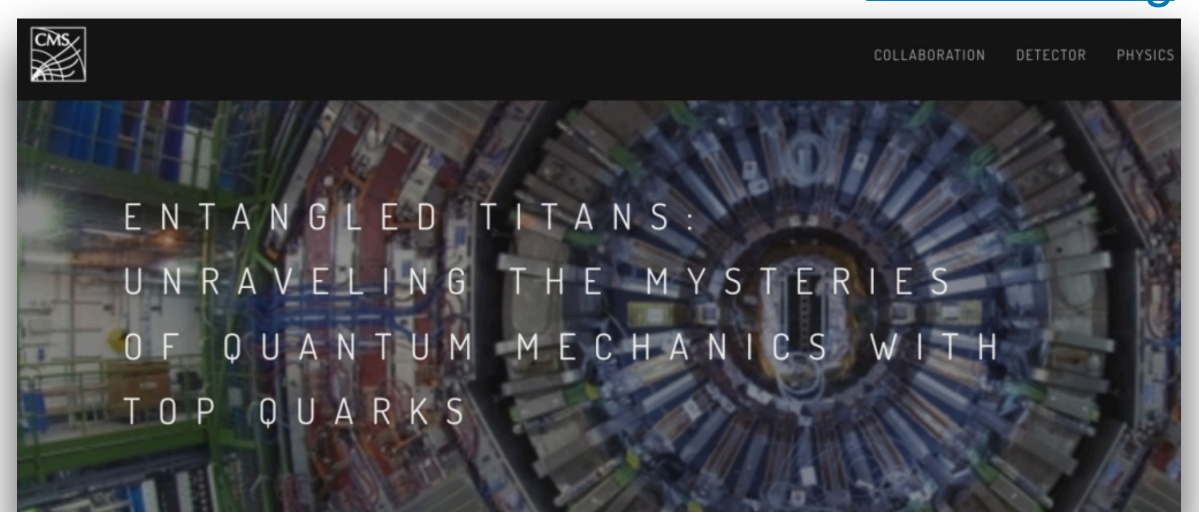
- **Good agreement with SM predictions**
  - **significantly improved with η_t inclusion**

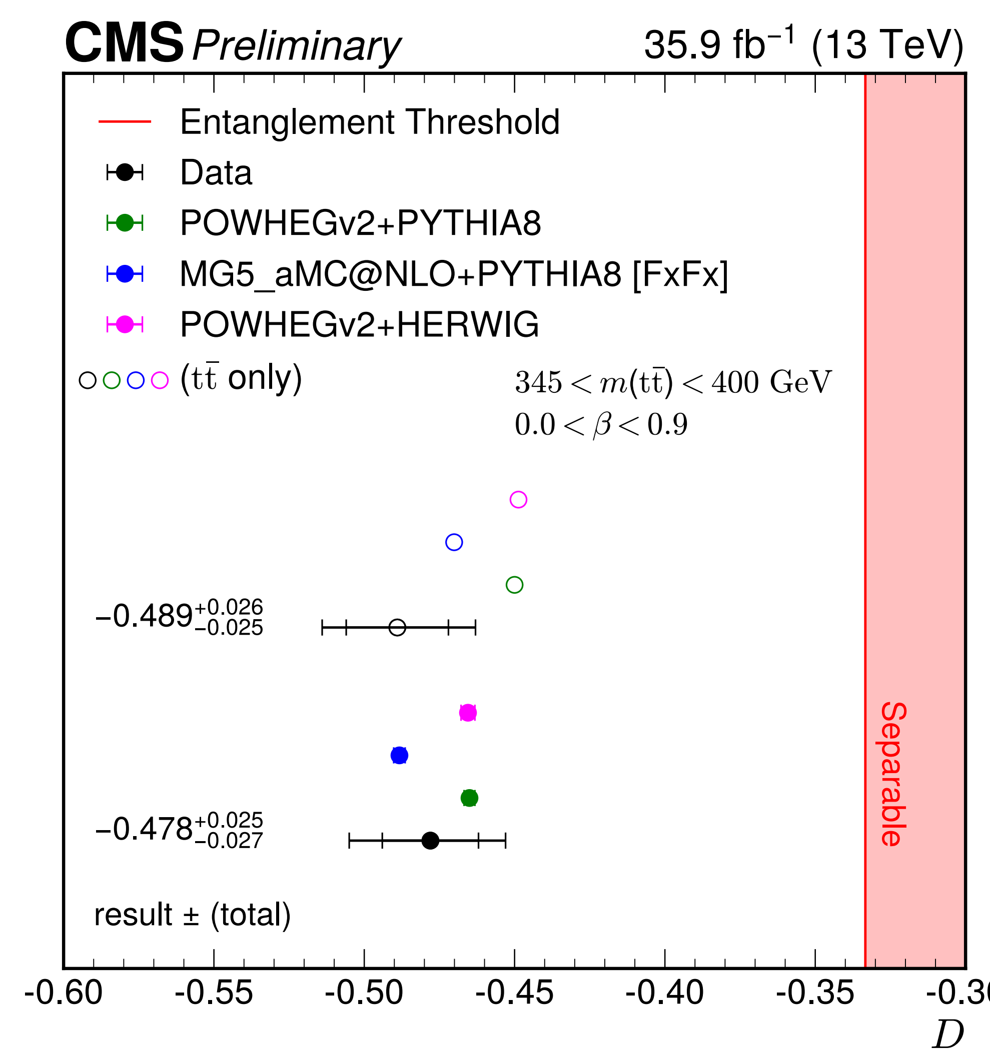


Conclusions

- **First observation of entanglement between top quarks with CMS data**
- **One of few quantum information studies in high energy physics**
- **Even in presence of a “toponium” bound state, we confirm the existence of entanglement in the $t\bar{t}$ system**
- **See next talk from Yoav for detailed comparison to ATLAS measurement**

CMS briefing





BACKUP