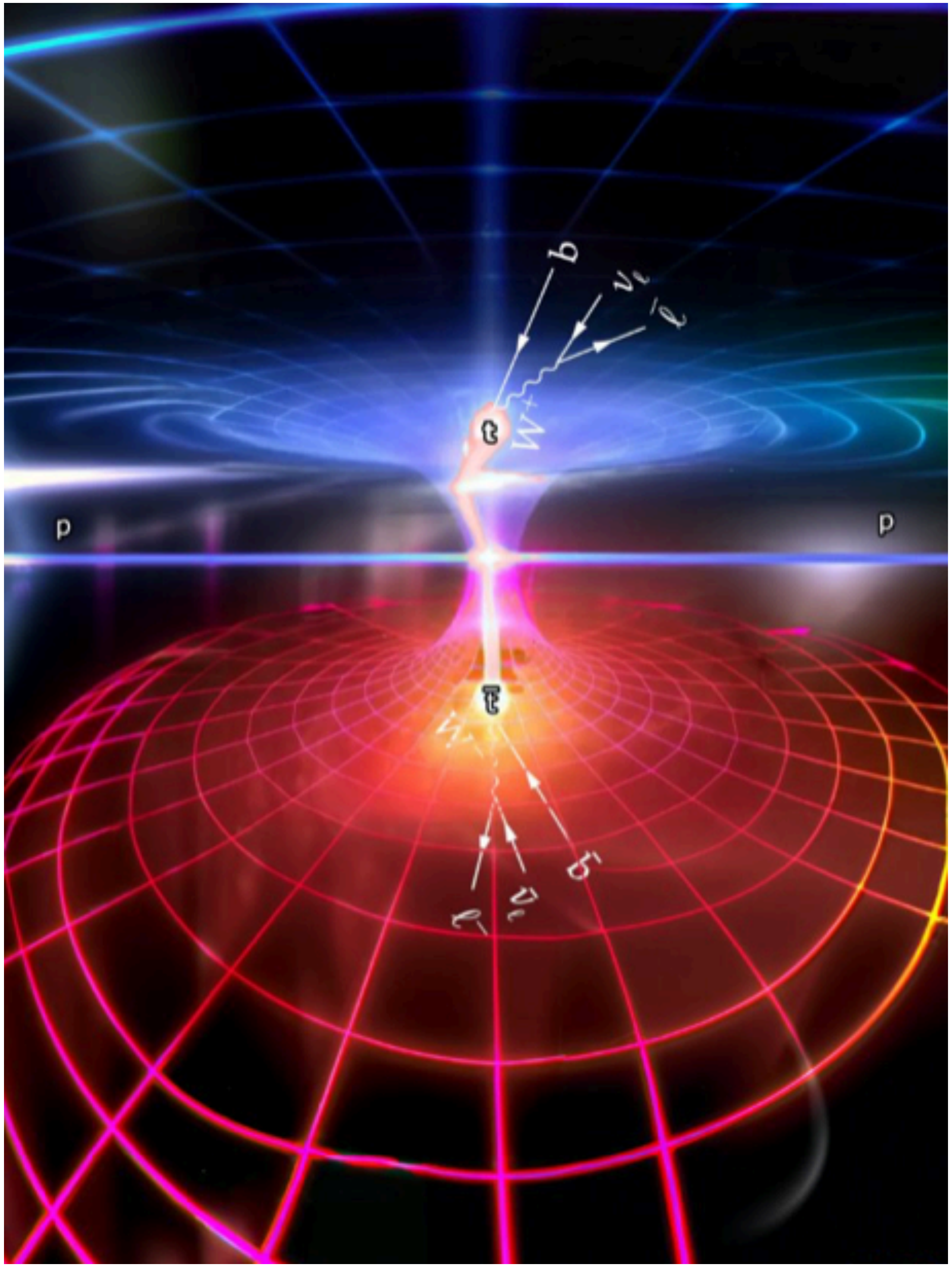
Probing entanglement in top quark production with the CMS detector

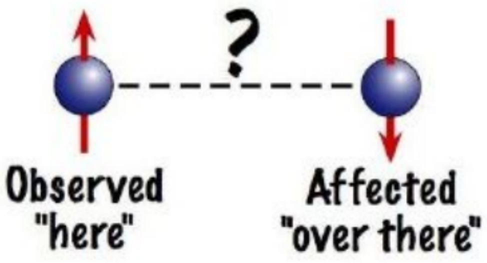
Giulia Negro
on behalf of the CMS Collaboration

Standard Model at the LHC 2024
10 May 2024



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

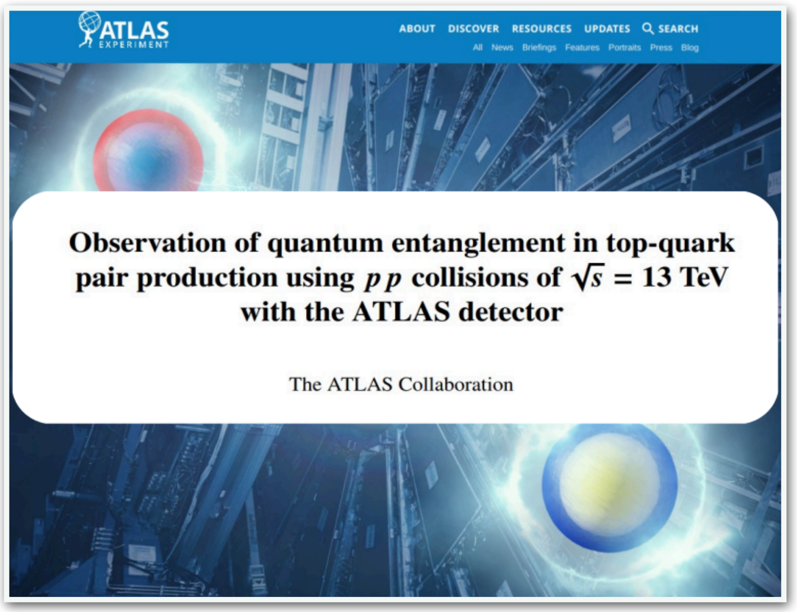


- **A lot of measurements with electrons and photons already performed**

Nobel Prize in 2022 for
Aspect, Clauser, and Zeilinger

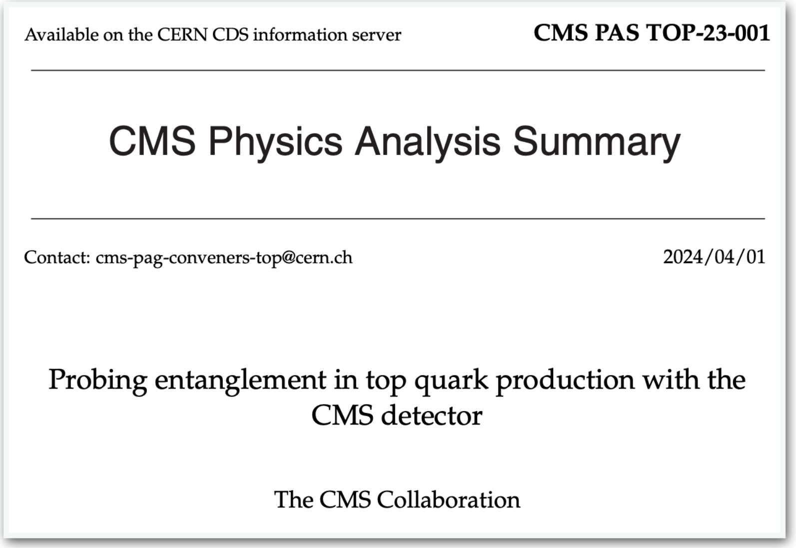
- **First observation of entanglement in $t\bar{t}$ by ATLAS at the end of last year**

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

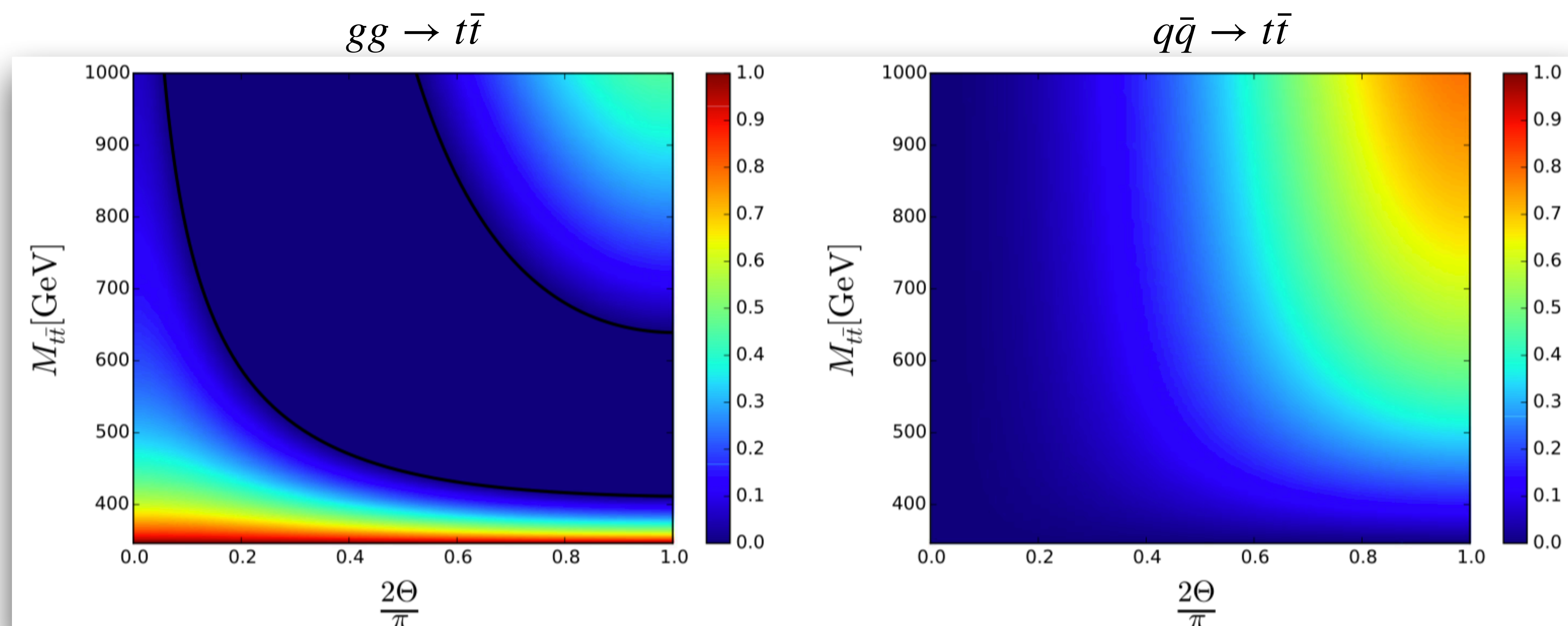
Entanglement of top quarks

- **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

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

- **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**:

  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

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

→ 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 $C_{22} > 0$ $\rightarrow$ $\Delta + 1 = \mathrm{tr}[C] > 1$

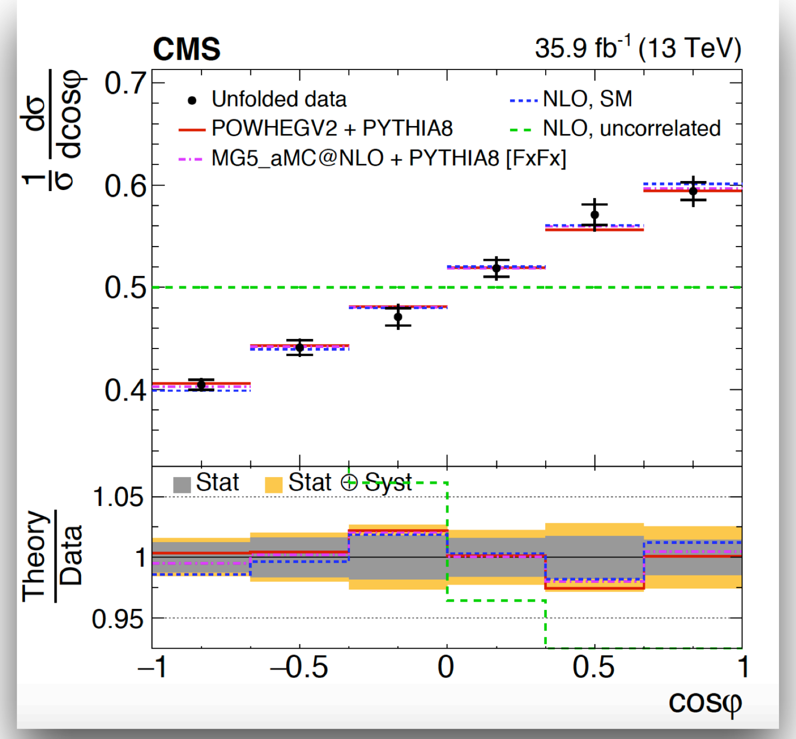
- tr[C] can be probed from a single-differential cross section:

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

Sufficient condition for entanglement !

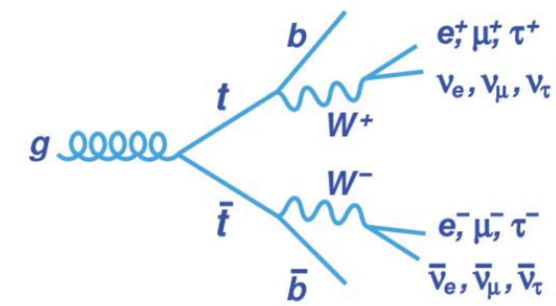
→ **measure D to access entanglement information in top quark events!**

- $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$ 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

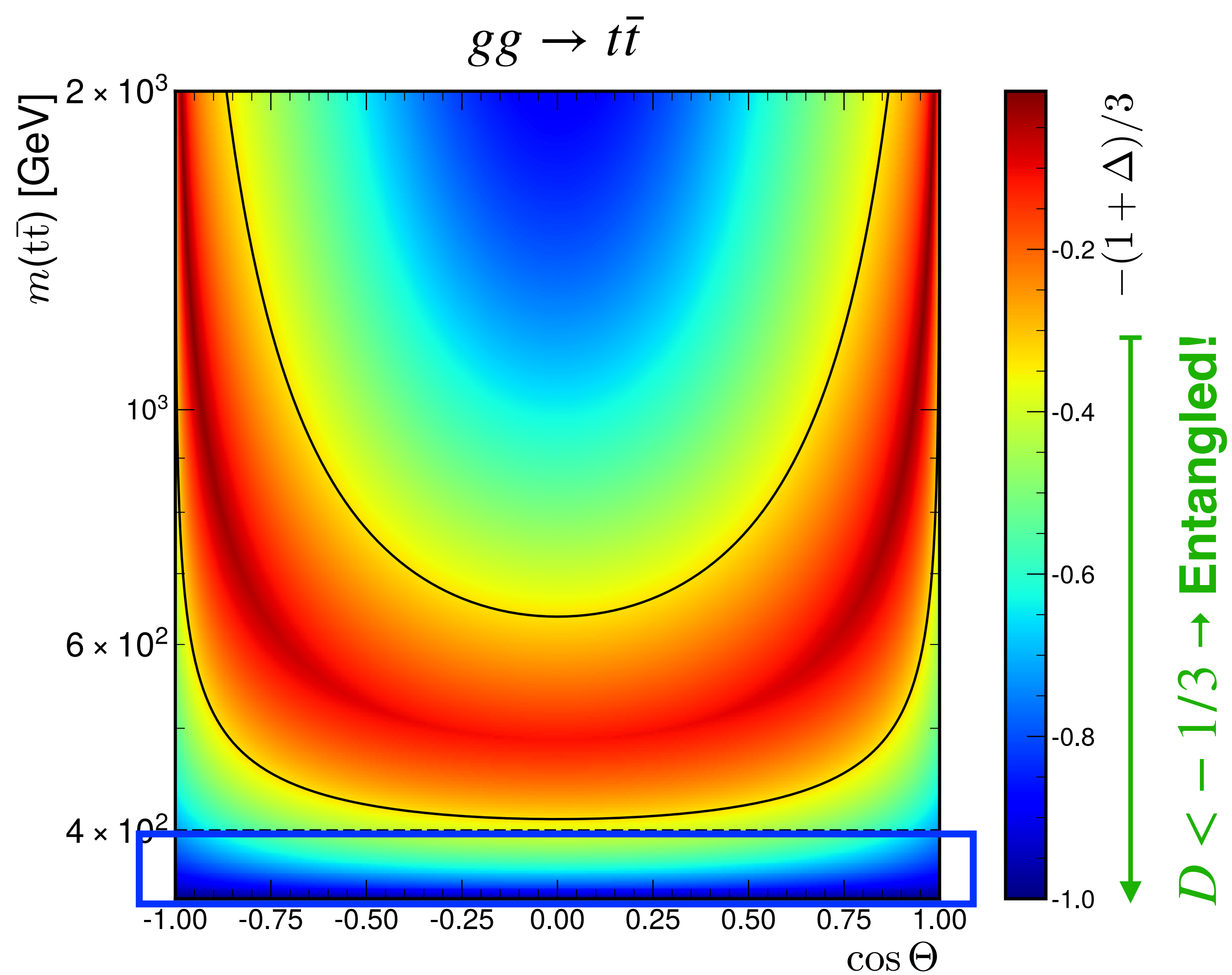


- **The degree of entanglement is highly phase space-dependent**
  - scan of $\cos\Theta$ vs $m_{t\bar{t}}$ to determine most sensitive phase space while minimizing expected total uncertainties
- **Focus on low-mass region ($345 < m_{t\bar{t}} < 400$ GeV) to increase entanglement**
  - threshold region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

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

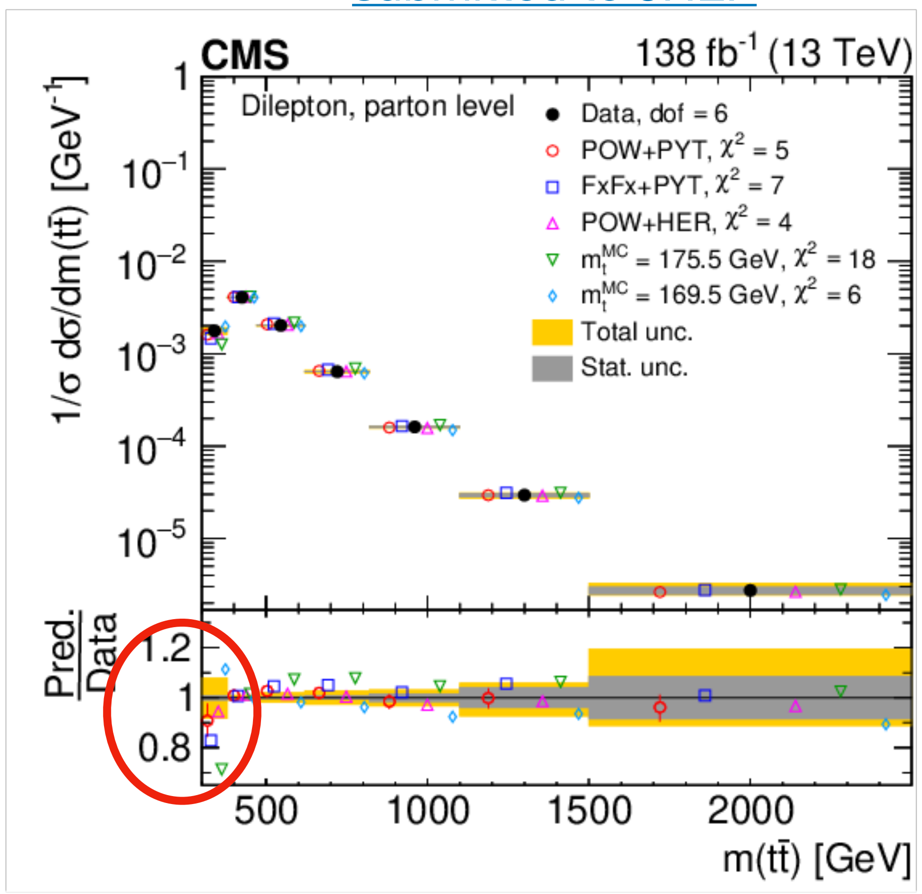
- **Use leptonic final states to measure the helicity angle $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$**
  - fully encapsulates the spin correlations information for gg fusion production at low mass
- **Perform a profile maximum likelihood fit of the $\cos\varphi$ distribution in the $m_{t\bar{t}}$ - β signal region**



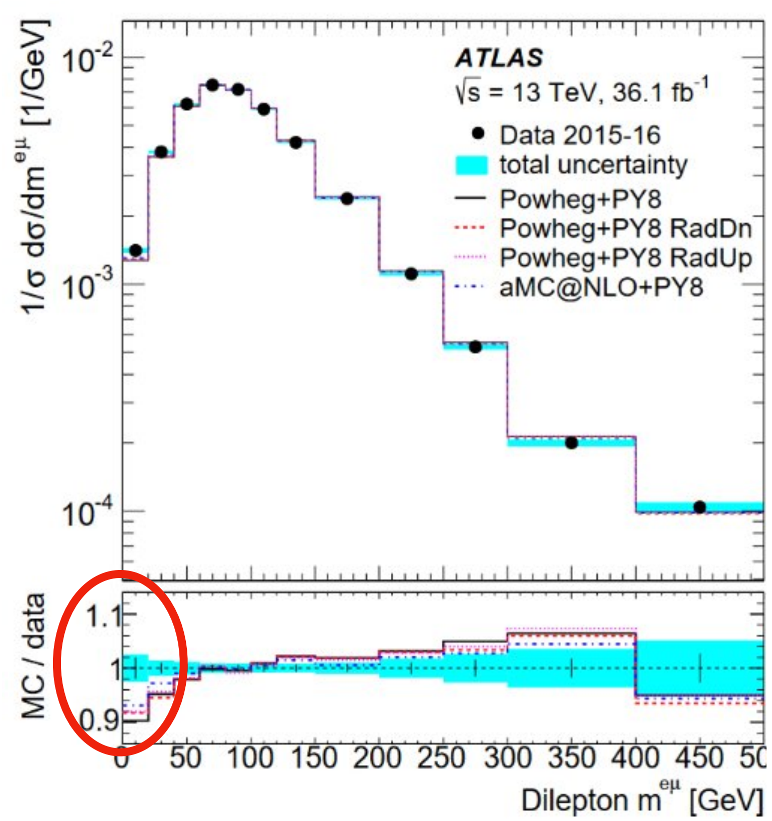
Threshold region

- **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**

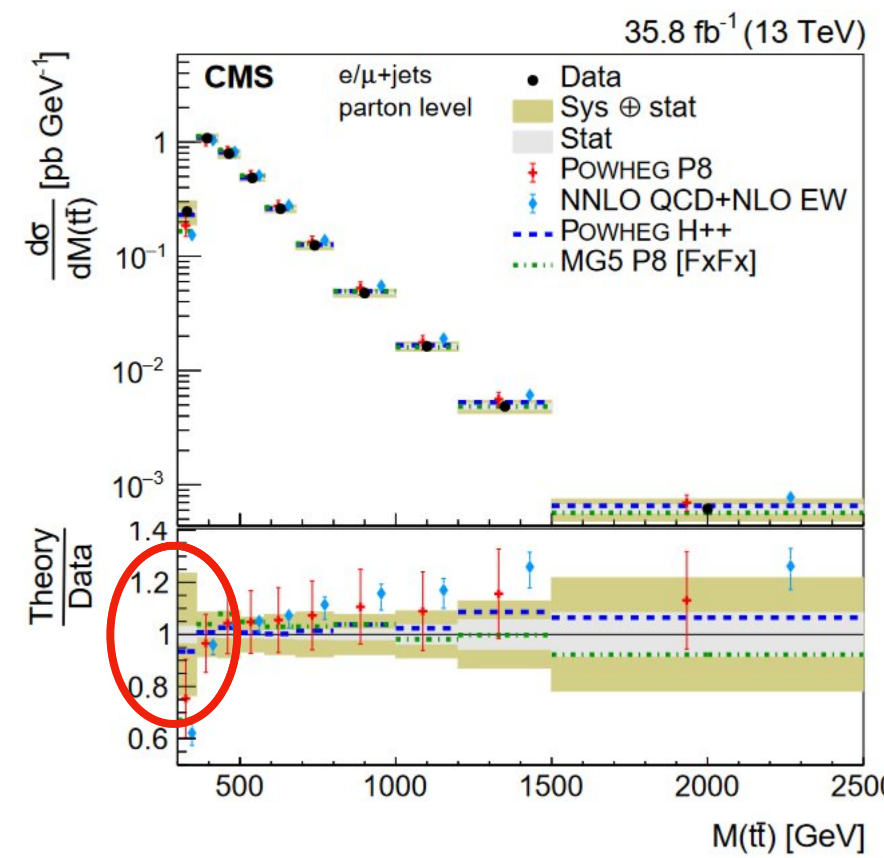
arXiv:2402.08486, submitted to JHEP



EPJ C 80, 6



Phys. Rev. D 97, 112003



Threshold region

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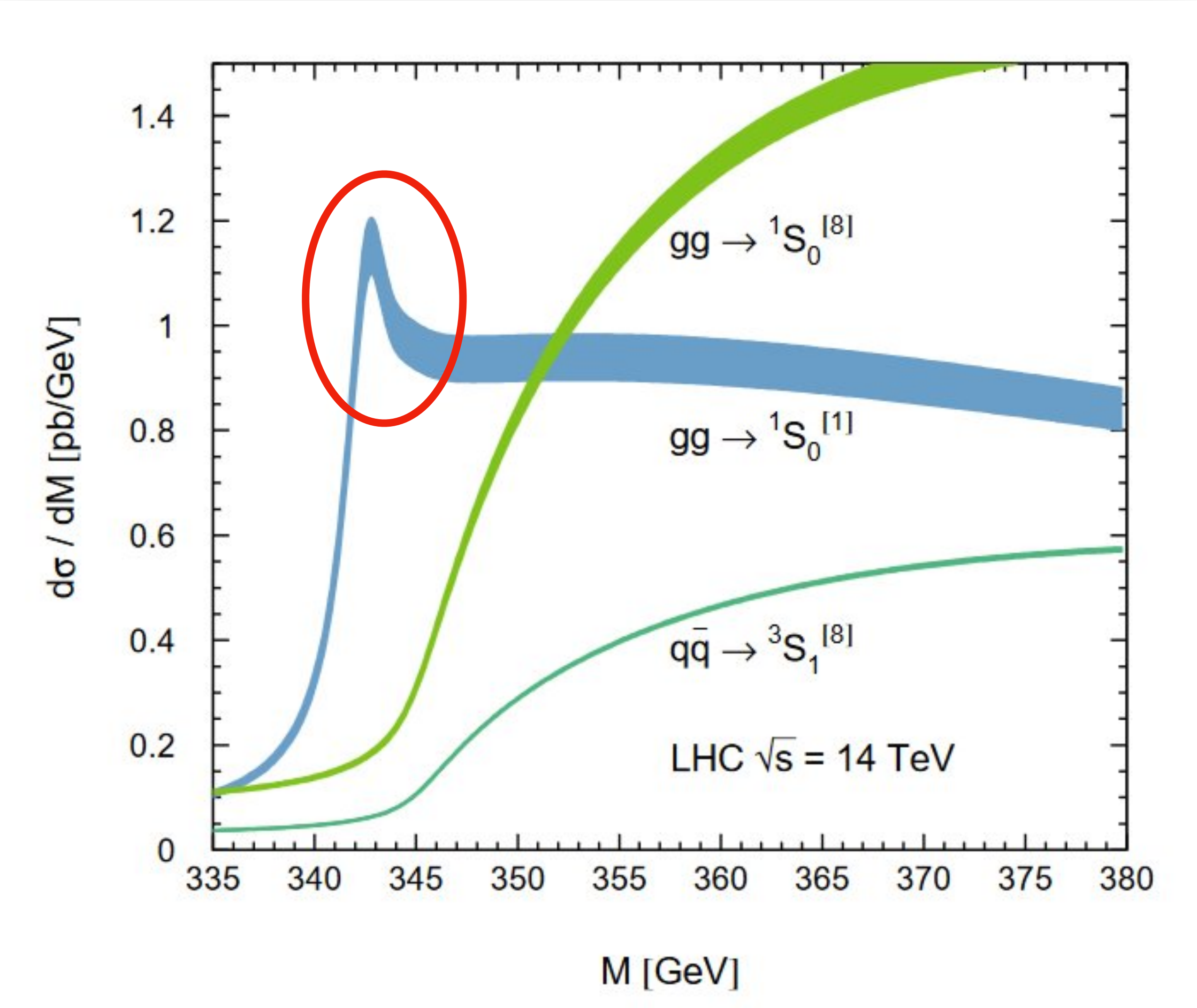
- **Consistent between dilepton and lepton+jets analyses in both CMS and ATLAS**
- **NRQCD contributions close to threshold**
  - spin and color singlet state (η_t): maximally entangled ***toponium***
- **Excess seen could come from toponium ?**

→ **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

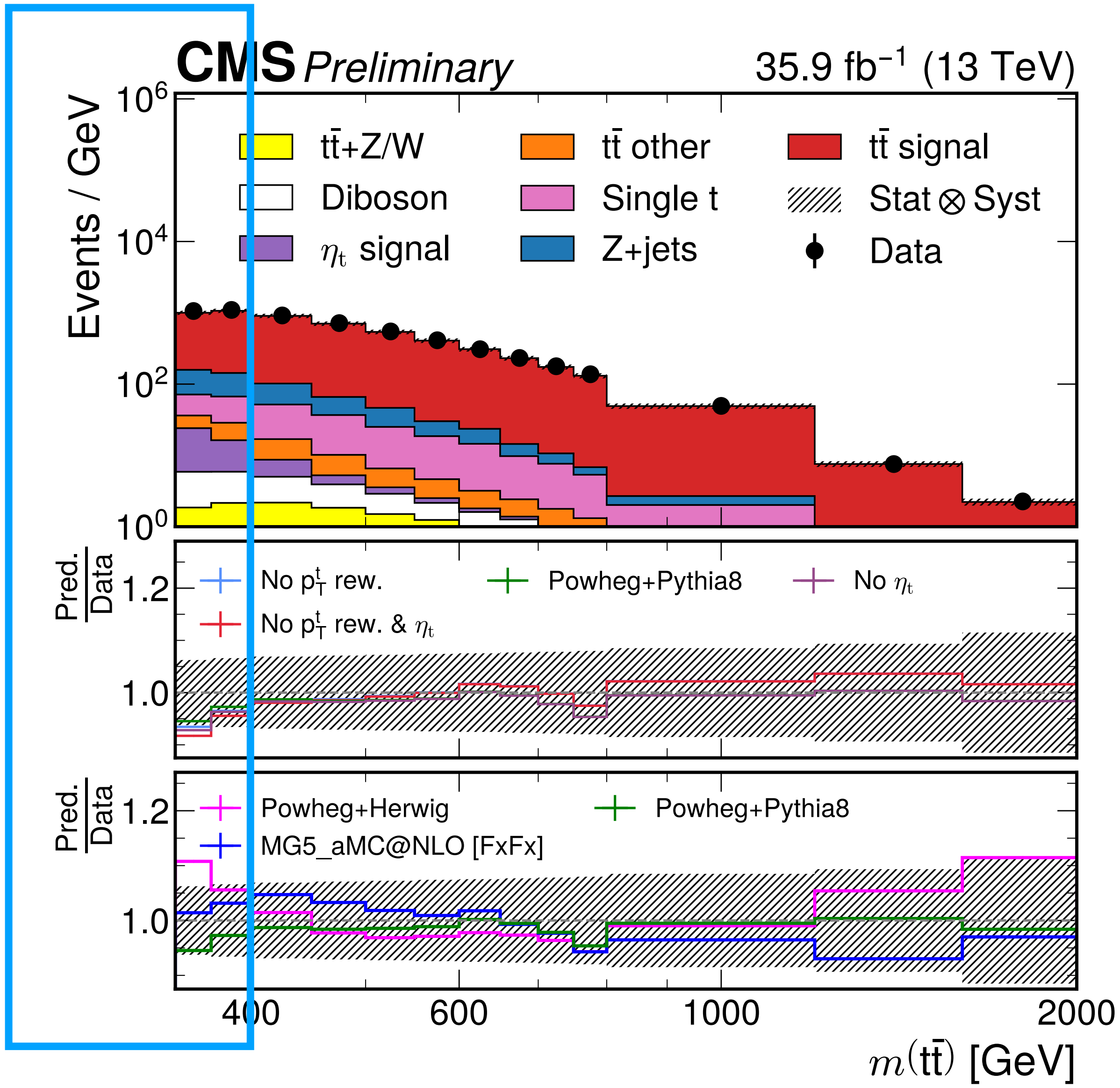


Dataset and signal model

- **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

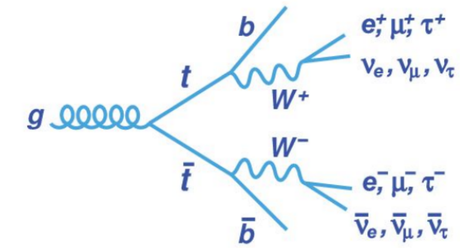
- **Combined signal model: $t\bar{t}$ + toponium (η_t)**
  - PowhegBox+Pythia8 as nominal $t\bar{t}$ sample
  - PowhegBox+Herwig and MG5 aMC@NLO(+MadSpin) [FxFx] as alternative $t\bar{t}$ samples
  - η_t improves data modeling in the threshold region
    - only spin-0 η_t accounted (colour singlet pseudoscalar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



Analysis region

- **Main background sources:**
  - Z+jets (MG5_aMC@NLO + data-driven corrections)
  - single top (Powheg MC)
  - diboson (Pythia8 MC)

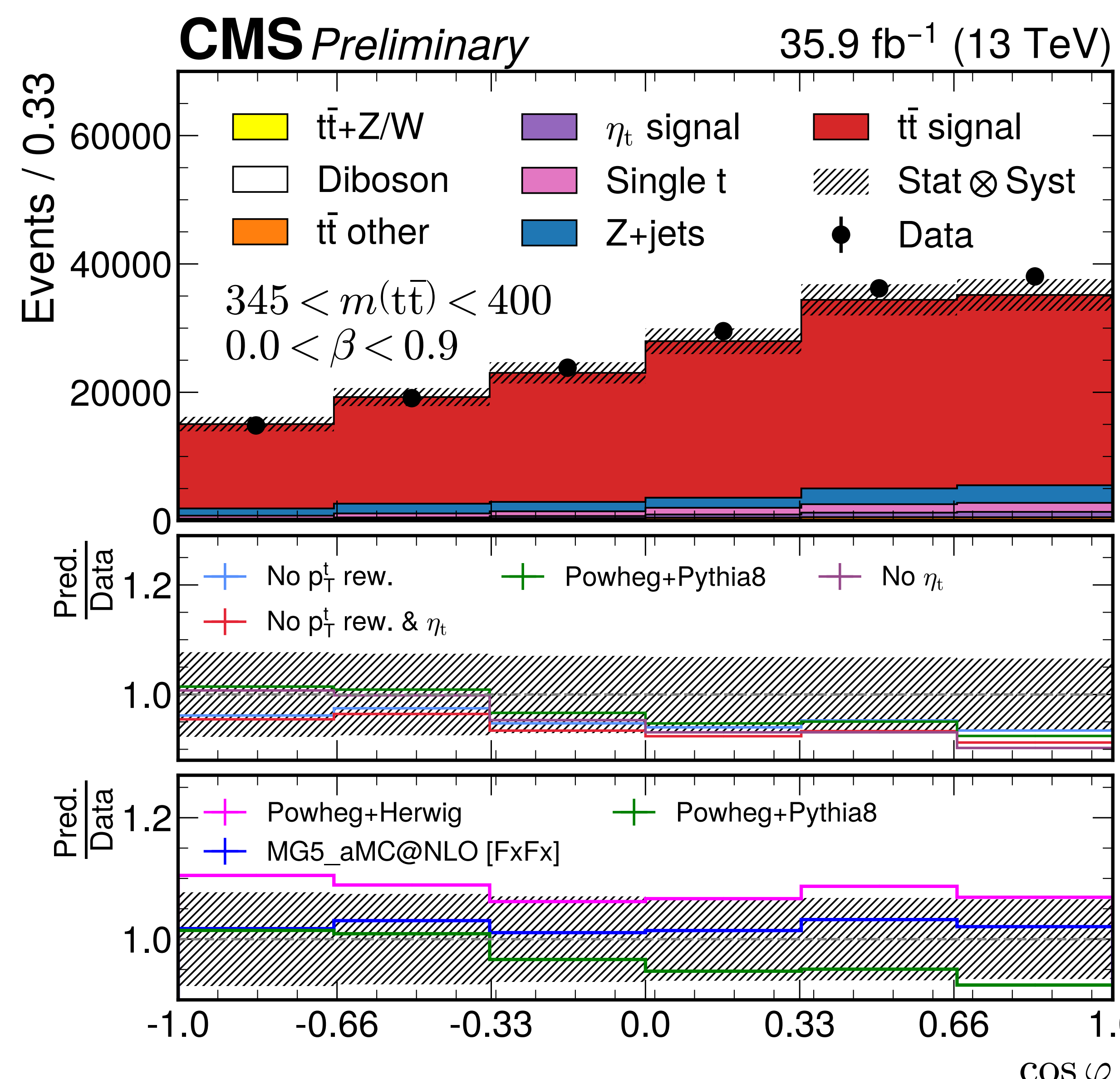
Event selection



- **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_{miss}^{T} > 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 $m_{t\bar{t}}$



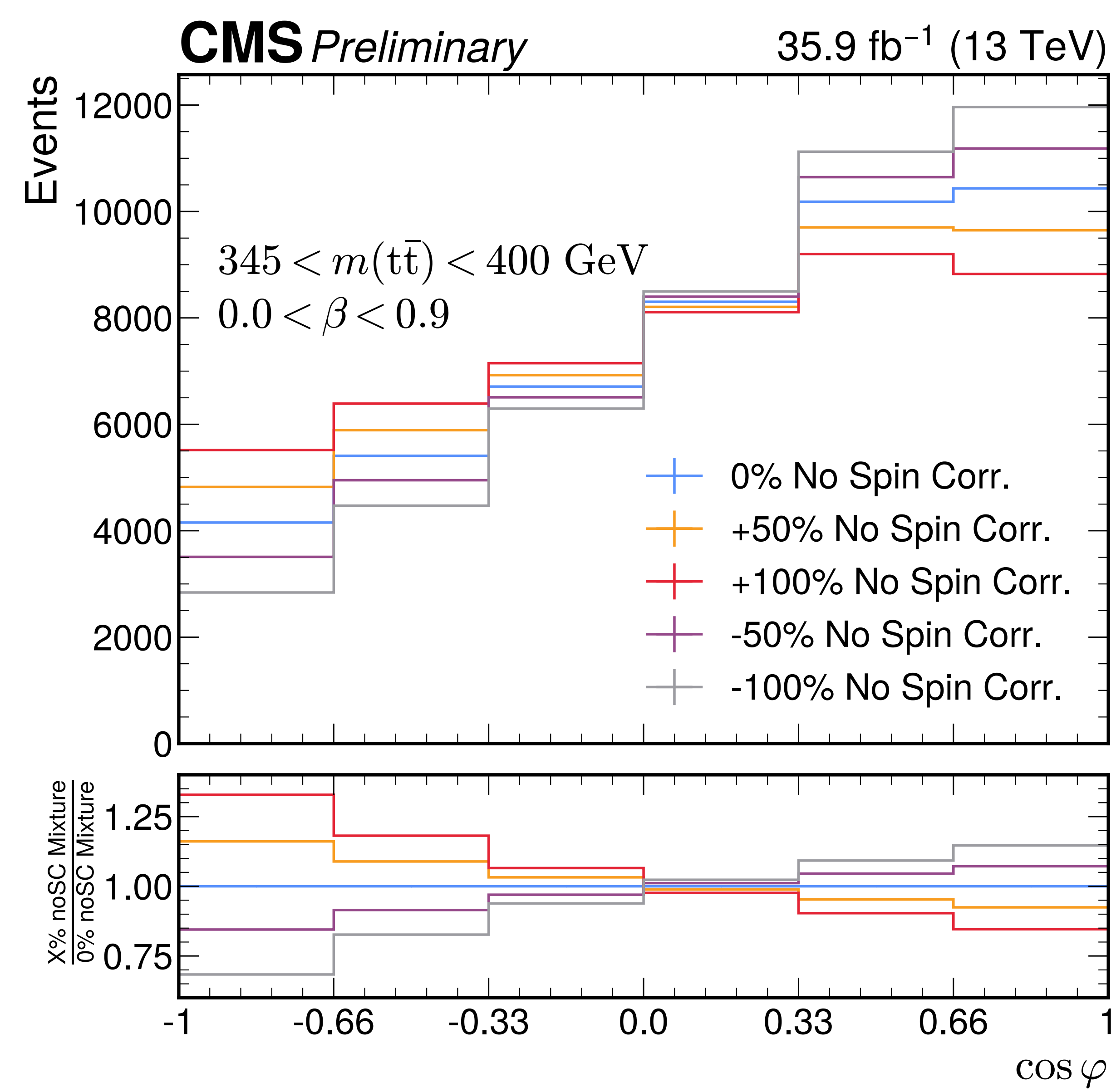
Extraction of entanglement proxy

- **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

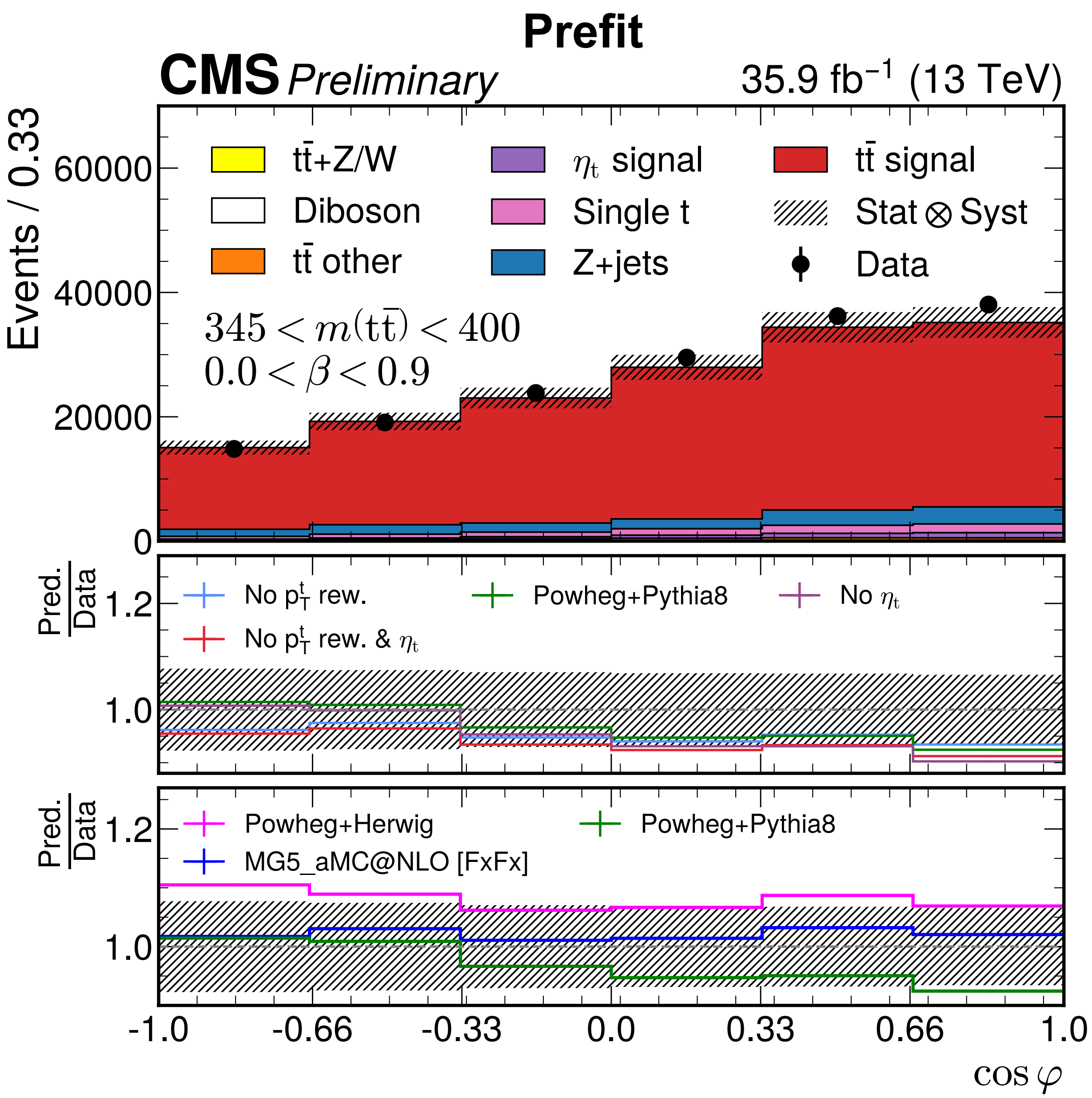
- **Leading theory-based uncertainties:**
  - Toponium normalization
  - Parton Shower

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%

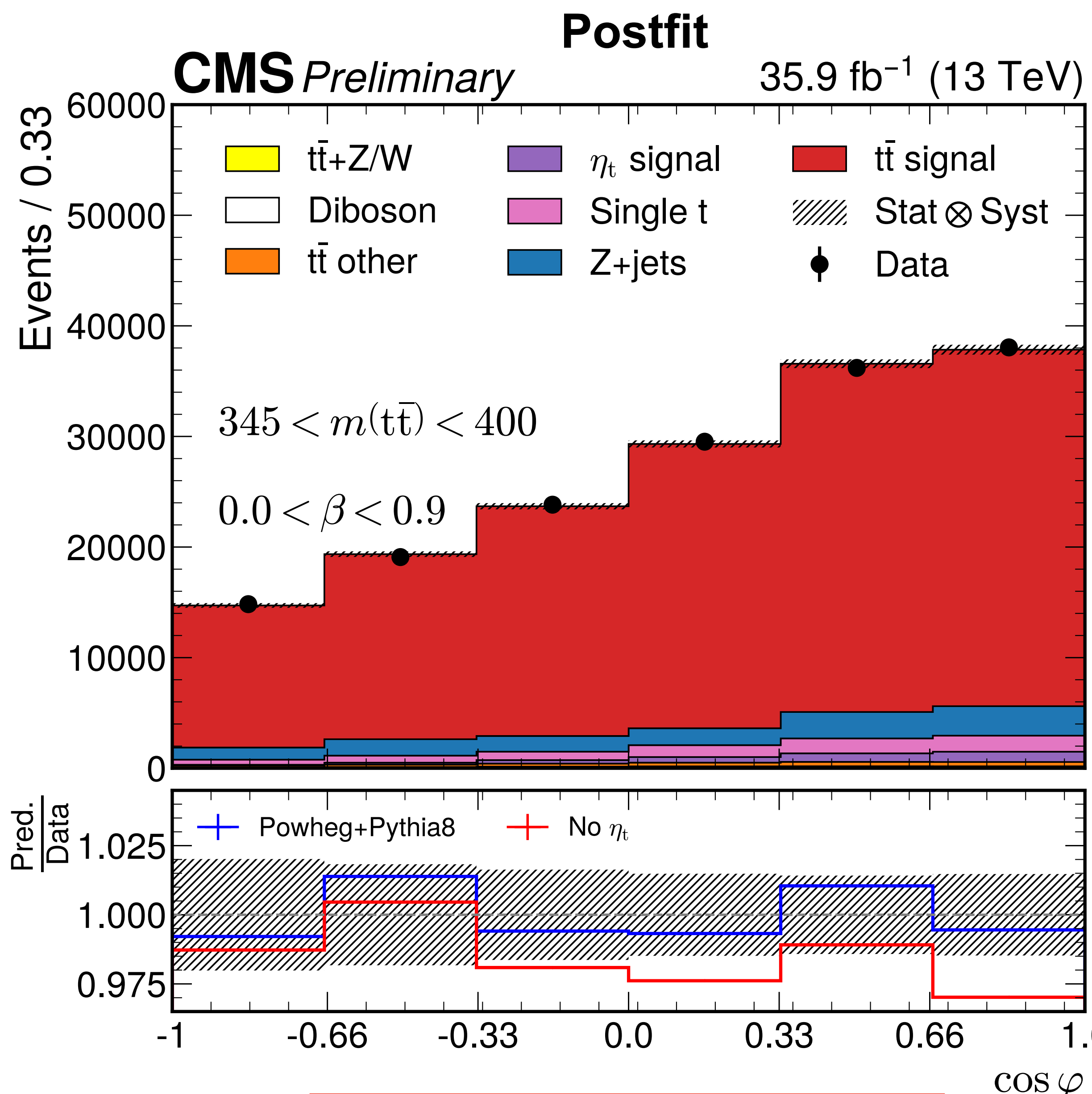
Results

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

- **Good agreement with SM predictions**



→



No η_t = η_t removed from signal without repeating the fit

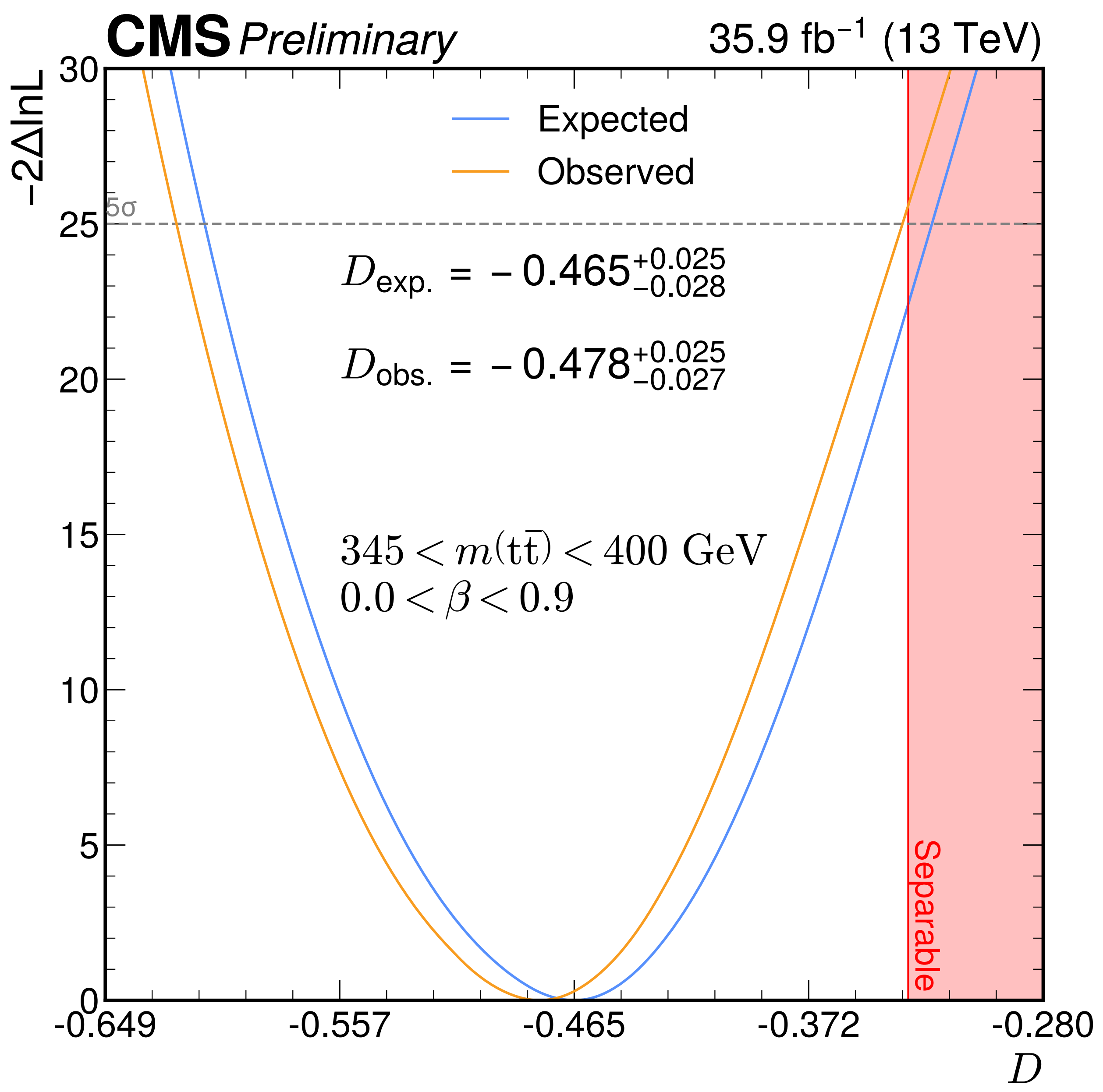
Results

- **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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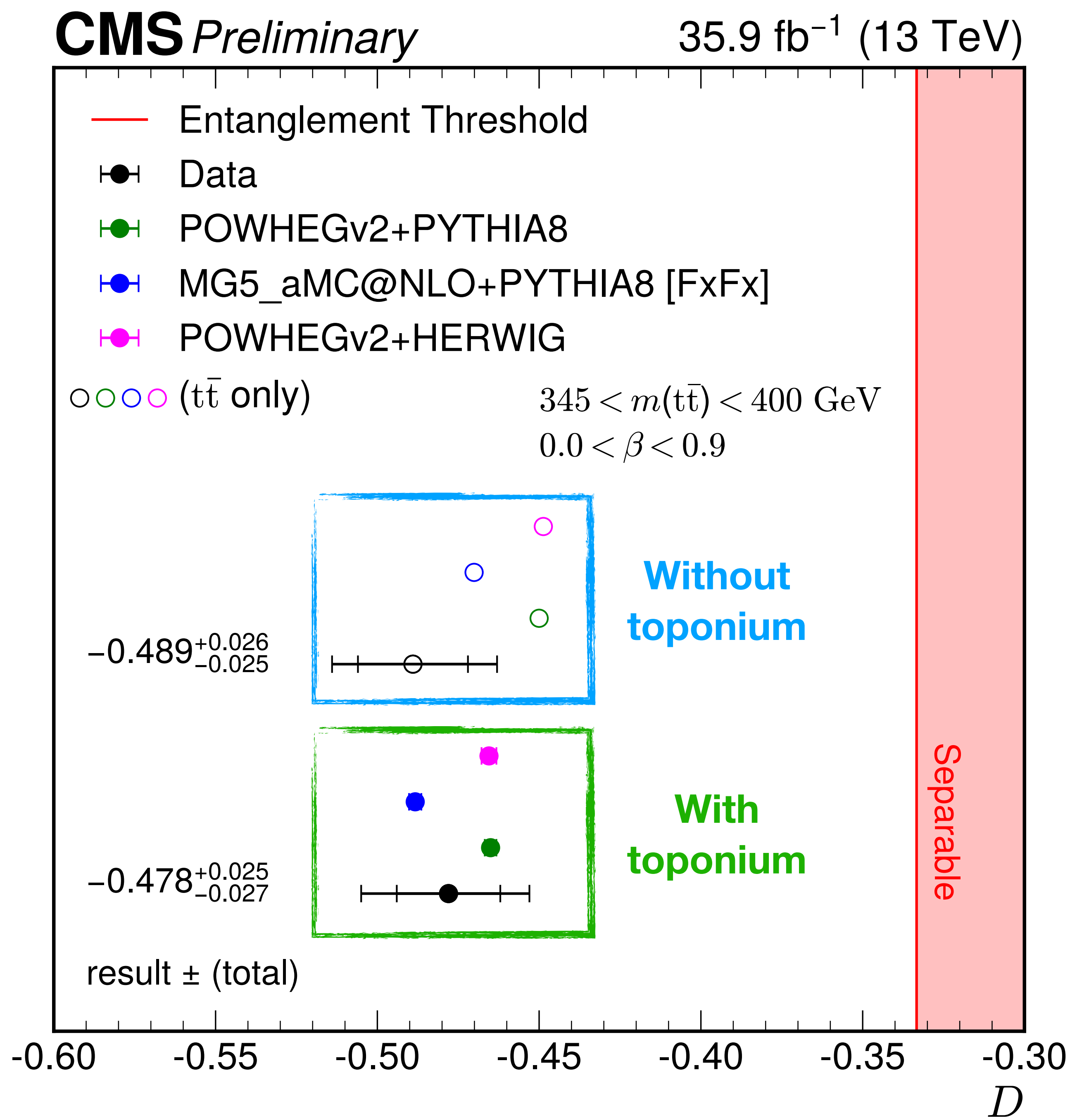
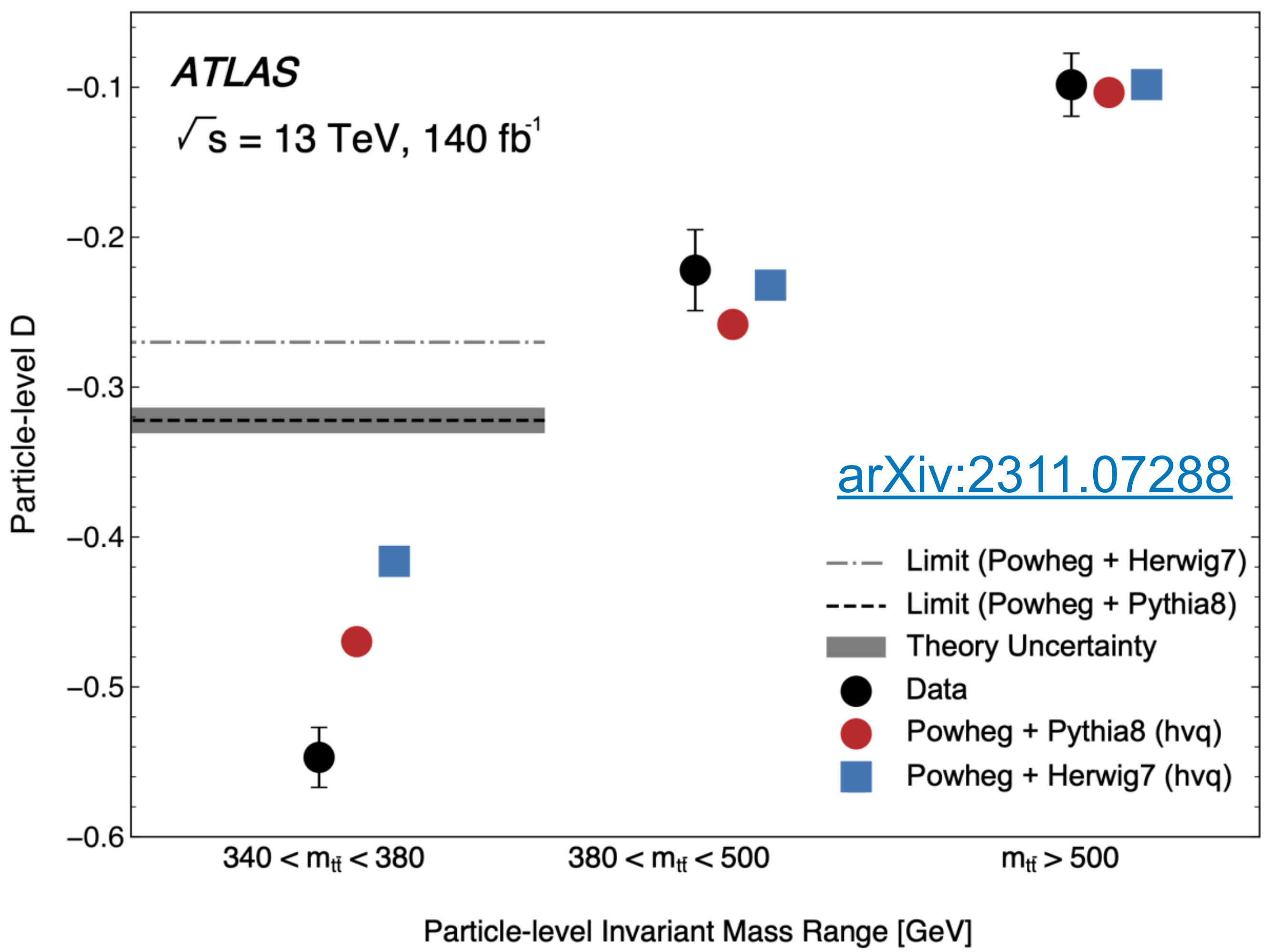
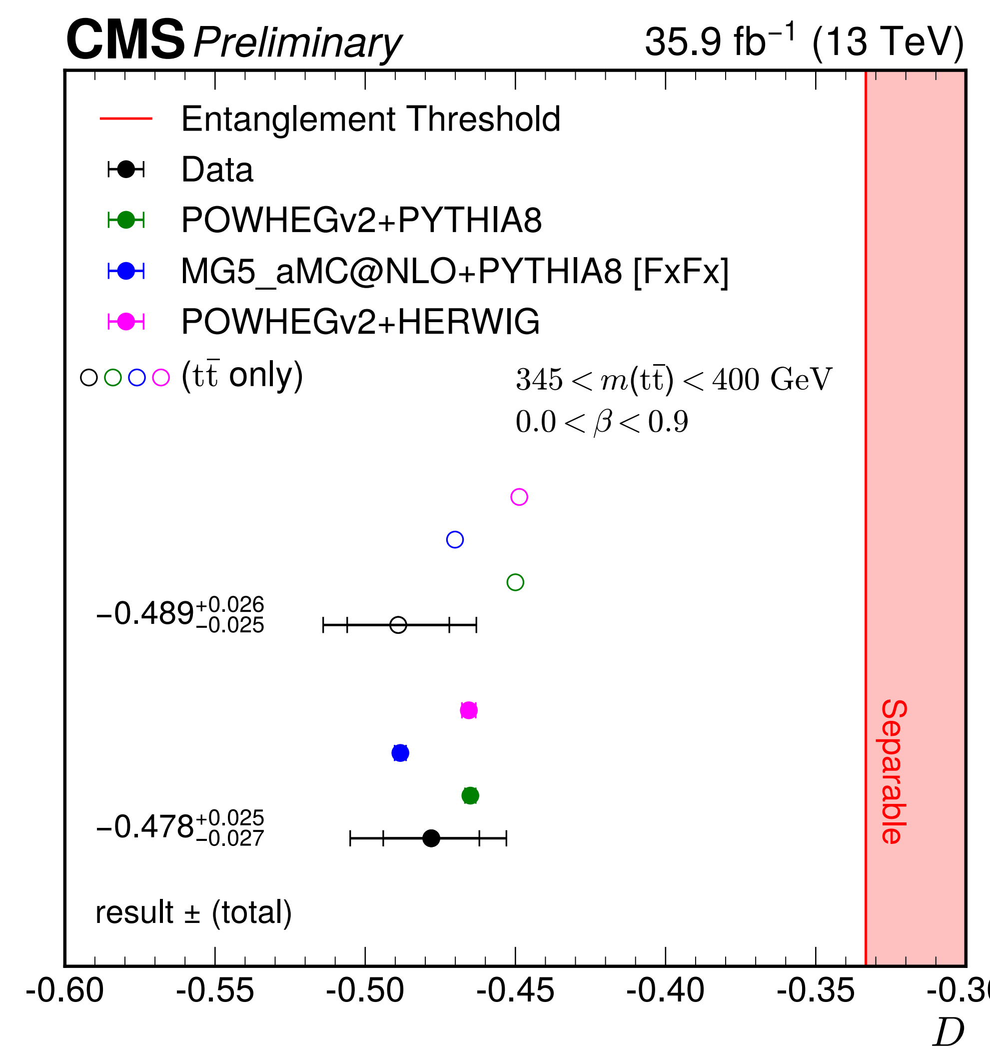


- **Good agreement with SM predictions**
  - **significantly improved with η_t inclusion**

Comparison with ATLAS

- **Entanglement in top quark observed by both ATLAS and CMS with >5 standard deviations!**
- No clear preference for a specific MC prediction
- **Both analyses are dominated by systematic uncertainty**
- Total (stat.) uncertainty is an order of magnitude larger in the CMS analysis
- Total (syst.) uncertainty is similar between ATLAS & CMS, but different systematics are considered





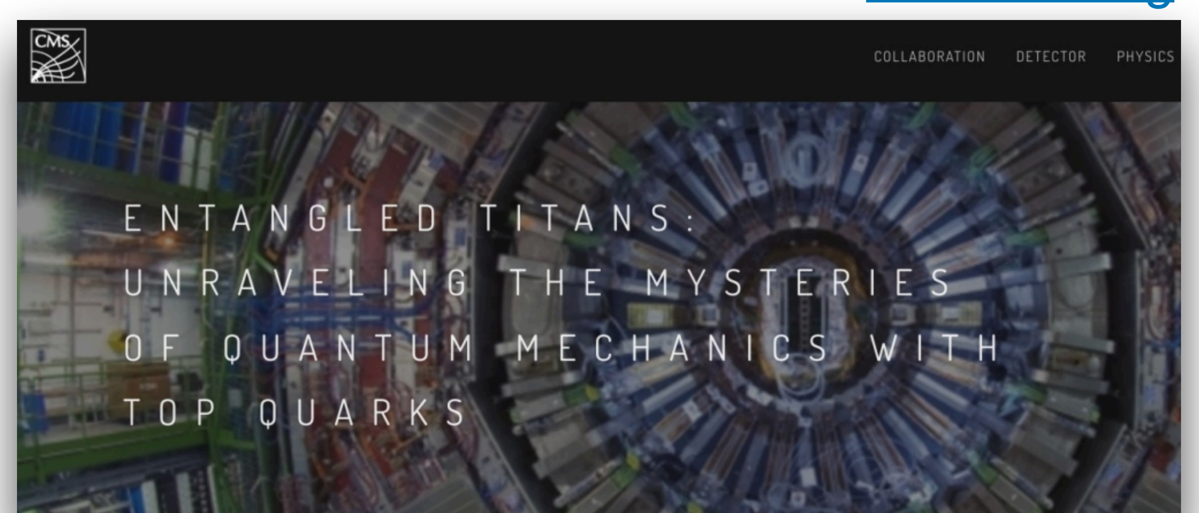
ATLAS: limit of D = −1/3 is folded from parton to **particle-level**

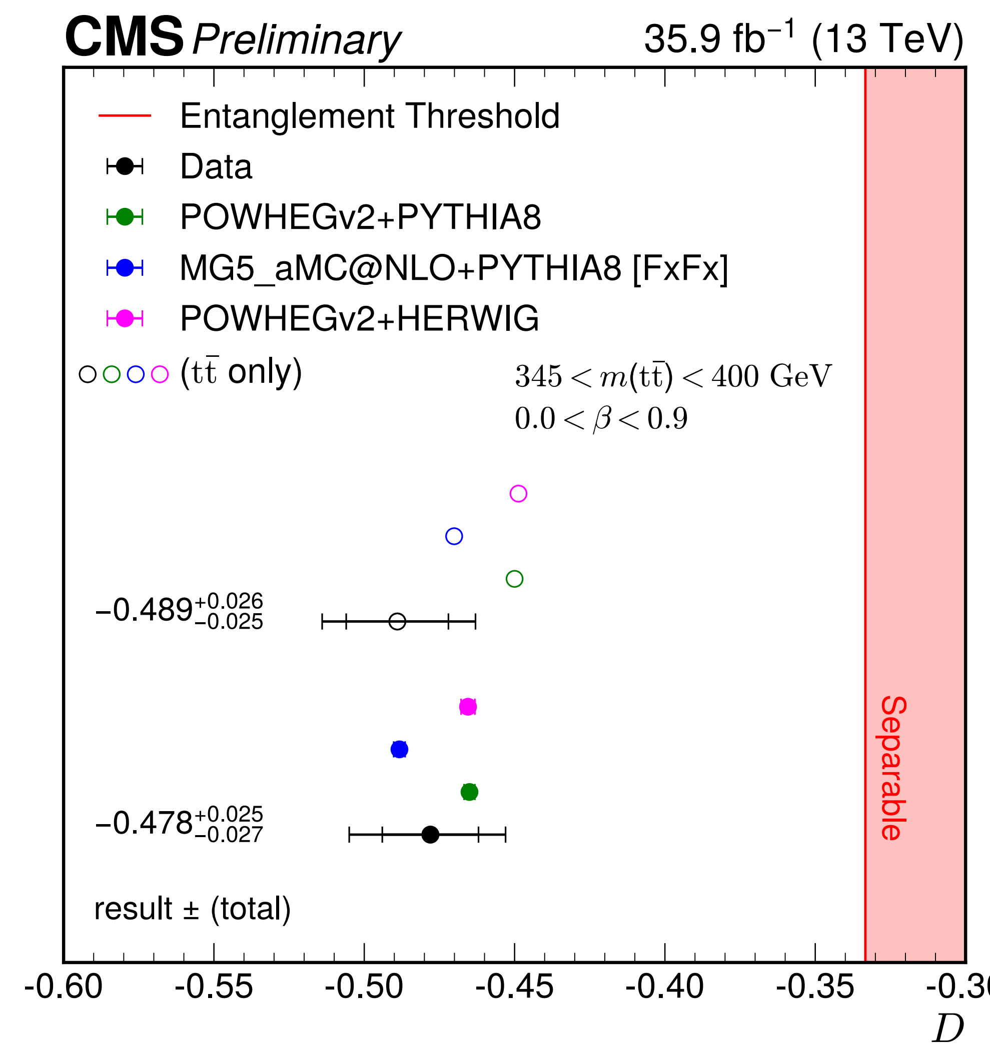
CMS: limit of D = −1/3 is shown at **parton-level**

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 with > 5 standard deviations**
- **A better modeling next to the production threshold is required → theory community is working on improving the prediction of mainstream generators for precision measurements**

CMS briefing





BACKUP

Top quark reconstruction

- Use algebraic method to solve for neutrino 3-vectors
- Results in quartic equation for neutrino momenta
- Pick solution with lowest $m_{t\bar{t}}$
- Repeat process 100x for leptons and b jets smeared within resolution
- Weight solutions by the $m_{\ell b}$ distribution

$$0 = \sum_{i=0}^{4} c_i(m_t, p_{\ell^+}, p_{\ell^-}, p_b, p_{\bar{b}})\, p_x(\bar{\nu})^i$$

$$\begin{aligned} \not{E}_x &= p_{\nu_x} + p_{\bar{\nu}_x} \\ \not{E}_y &= p_{\nu_y} + p_{\bar{\nu}_y} \end{aligned}$$

$$\begin{aligned} m_{W^+}^2 &= (E_{\ell^+} + E_\nu)^2 - (p_{\ell_x^+} + p_{\nu_x})^2, \\ &\quad -(p_{\ell_y^+} + p_{\nu_y})^2 - (p_{\ell_z^+} + p_{\nu_z})^2, \\ m_{W^-}^2 &= (E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\ell_x^-} + p_{\bar{\nu}_x})^2, \\ &\quad -(p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\ell_z^-} + p_{\bar{\nu}_z})^2, \\ m_t^2 &= (E_b + E_{\ell^+} + E_\nu)^2 - (p_{b_x} + p_{\ell_x^+} + p_{\nu_x})^2, \\ &\quad -(p_{b_y} + p_{\ell_y^+} + p_{\nu_y})^2 - (p_{b_z} + p_{\ell_z^+} + p_{\nu_z})^2, \\ m_{\bar{t}}^2 &= (E_{\bar{b}} + E_{\ell^-} + E_{\bar{\nu}})^2 - (p_{\bar{b}_x} + p_{\ell_x^-} + p_{\bar{\nu}_x})^2, \\ &\quad -(p_{\bar{b}_y} + p_{\ell_y^-} + p_{\bar{\nu}_y})^2 - (p_{\bar{b}_z} + p_{\ell_z^-} + p_{\bar{\nu}_z})^2. \end{aligned}$$

Mixtures of SC and noSC

- In order to have templates implementing an alternative value of the entanglement proxy D, we employ the noSC sample and “mix” it in steps ranging from −100% to 100% with the combined signal model SM template
- The negative mixtures are created mirroring the corresponding positive mixtures around the 0% noSC mixture, i.e., the nominal combined signal model

- Any particular mixture of combined SC and noSC signal corresponds to a certain value of D at the parton level by means of calculating a 2-bin asymmetry:

$$A_D = (N(\cos\varphi > 0) - N(\cos\varphi < 0))/(N(\cos\varphi > 0) + N(\cos\varphi < 0))$$

yields D as $-2 \cdot A_D$, with N always being the sum of $\mathrm{t\bar{t}}$ and η_t.