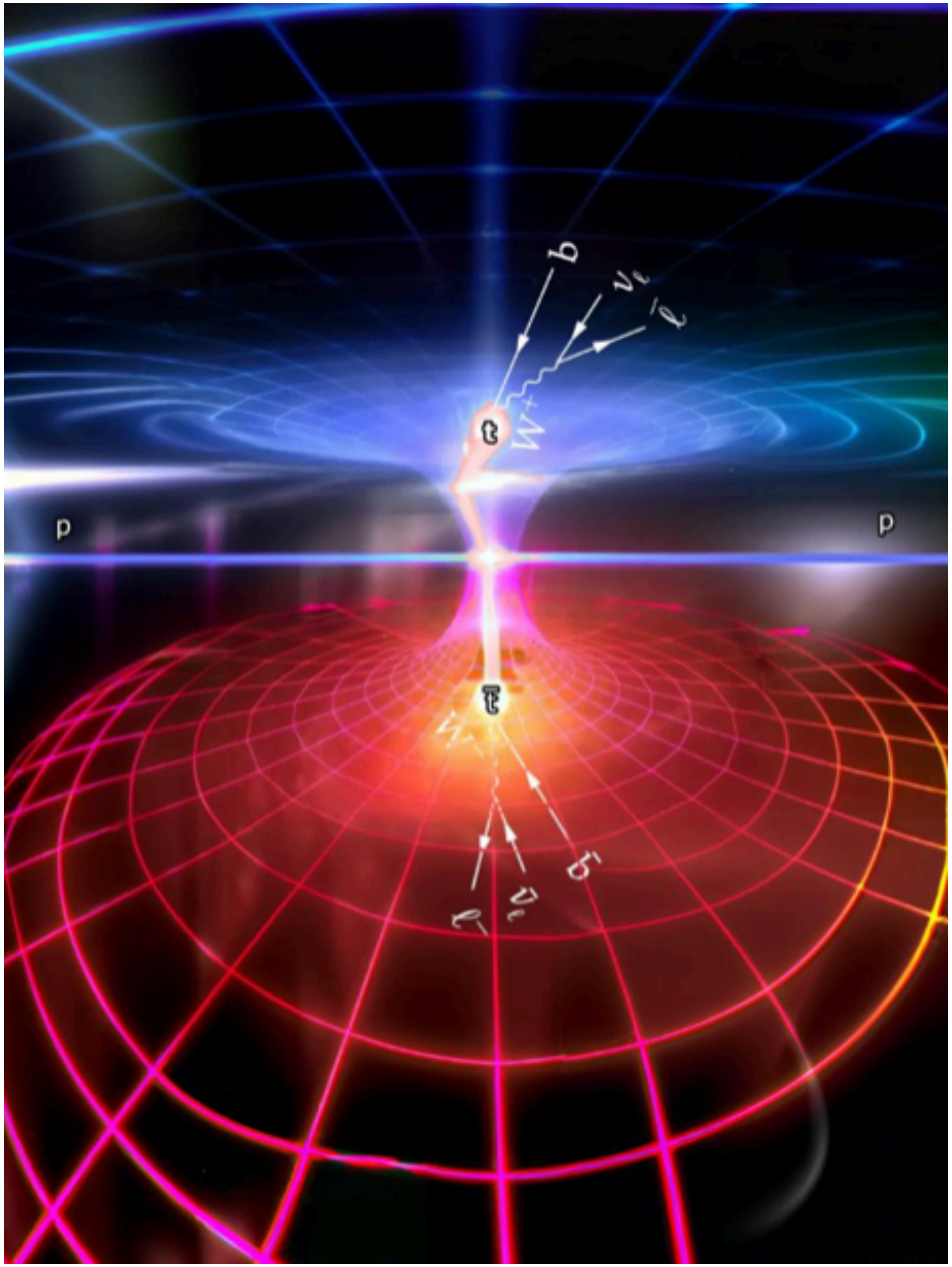
# Study of entanglement in space-like and time-like separated top quark pairs at CMS

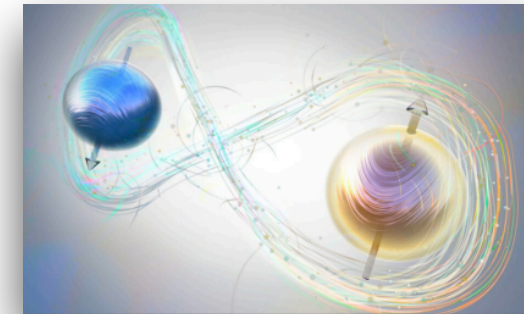
**Giulia Negro**
on behalf of the CMS Collaboration

**CERN EP seminar**
*25 June 2024*

PURDUE UNIVERSITY



# Entanglement in QM

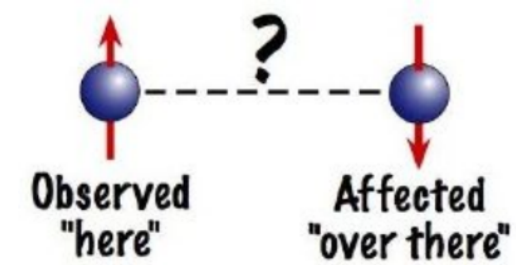


- **Qubit** = two-level quantum system $|0\rangle, |1\rangle \rightarrow$ most simple quantum system

- **Two qubits** $\rightarrow$ most simple example of quantum correlations

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

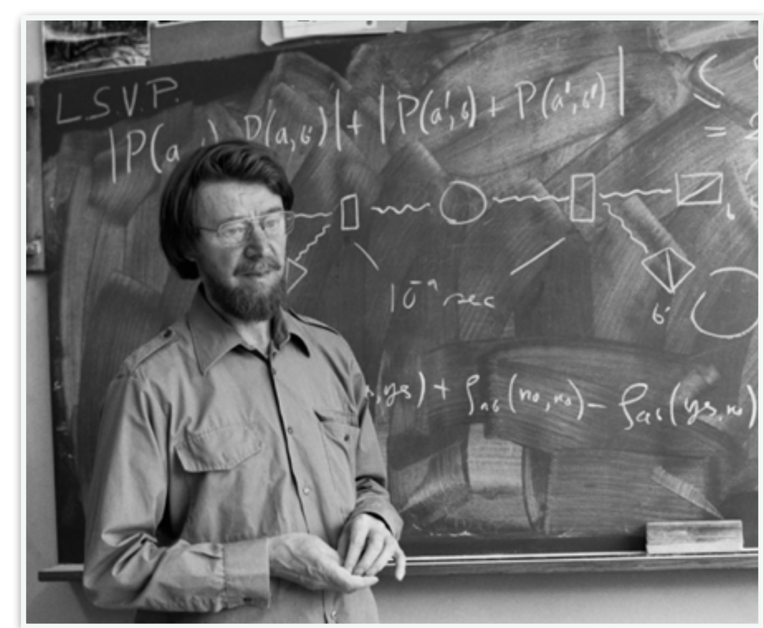
$$\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$$




- **Non-separability of a 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 even when casually separated

- "Spooky Action at a Distance": in 1935 **Einstein, Podolsky and Rosen suggested that QM was incomplete** (hidden variables)

- In 1964, John **Bell** introduced his famous **inequality**, suggesting an experimental test that could disproof EPR



# Entanglement in HEP

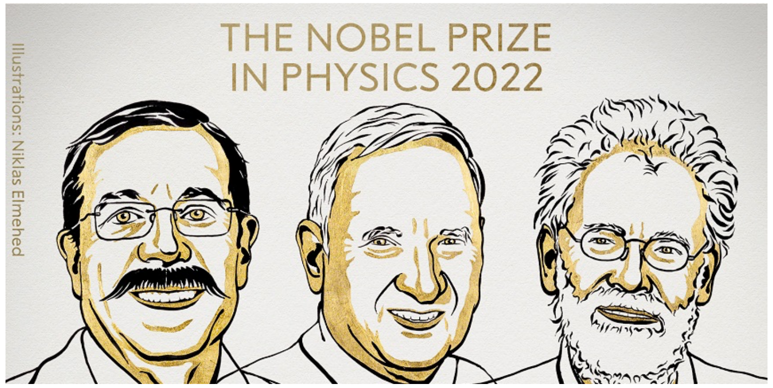
- **Several experimental tests carried out since 1972**
  - mostly with electrons and photons at low energy
- **Interest to repeat these tests with massive systems at high energy**
- **Measurements with K and B meson pairs** performed by CPLEAR, KLOE, BABAR, and Belle:
  - **e+e- entanglement at Belle** measured using time-dependent flavor asymmetry

**e+ e- → ϒ(4s) → $B^0$ $\bar{B}^0$**

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

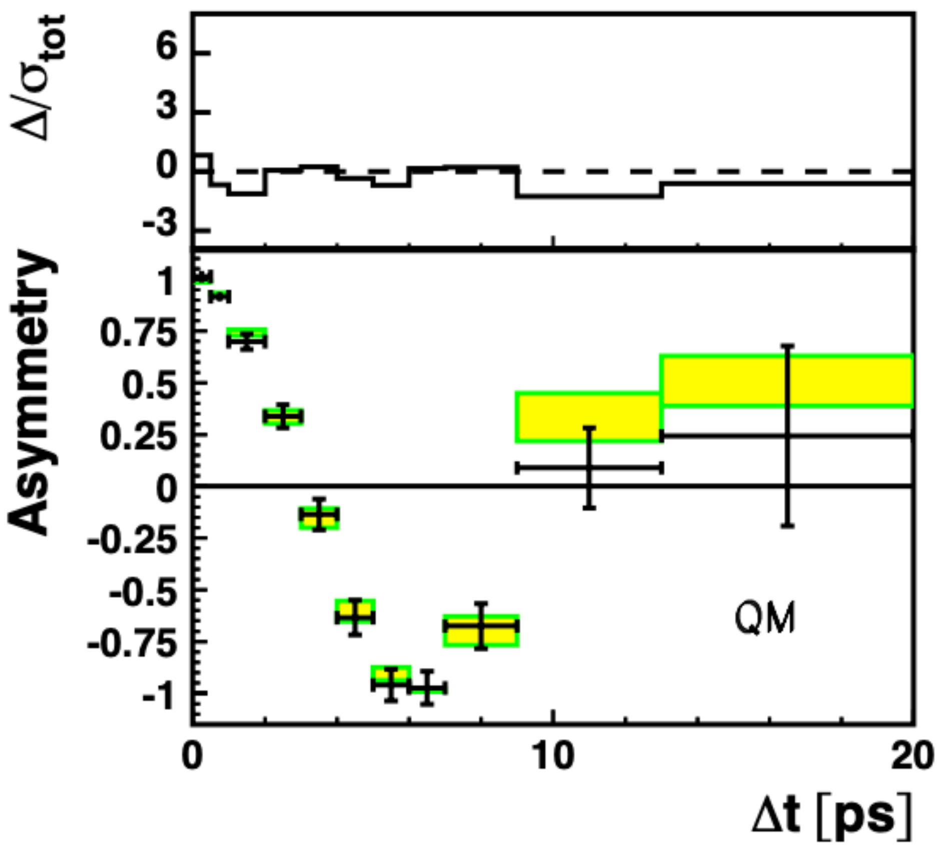
entangled state

**→ data described by quantum mechanics**



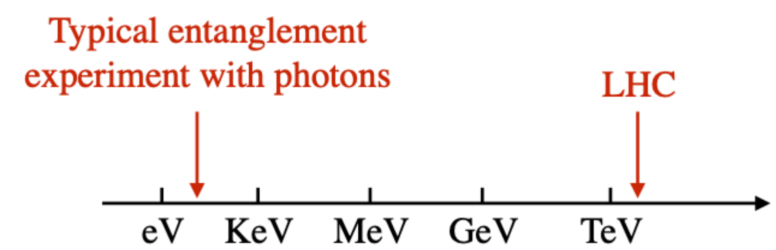
Aspect, Clauser, and Zeilinger

PRL 99, 131802 (2007)

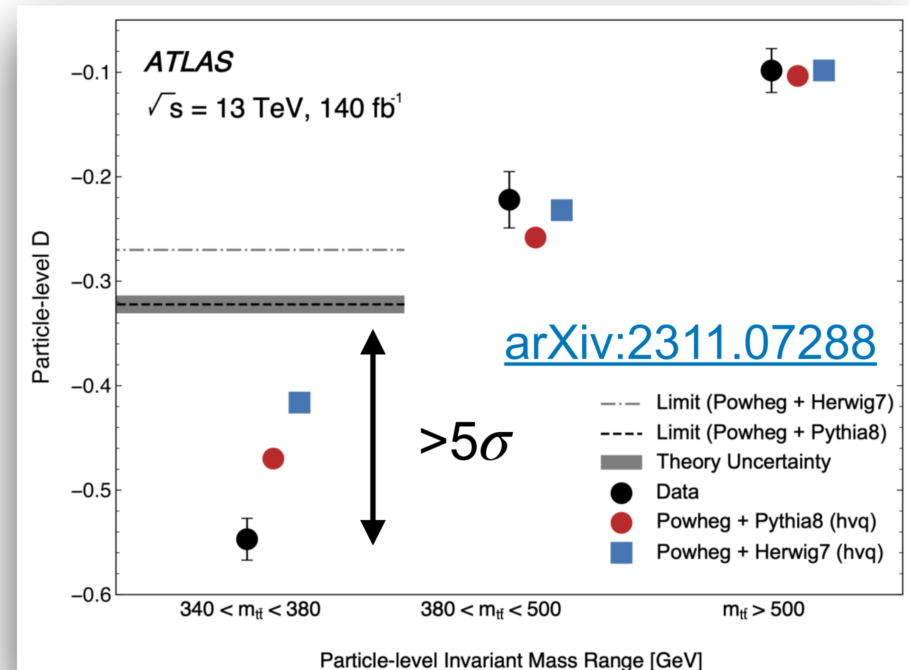


# Entanglement at the LHC

- LHC can provide a unique environment to study entanglement and violation of Bell's inequalities
  - **simplest qubits at LHC = $t\bar{t}$ pair**



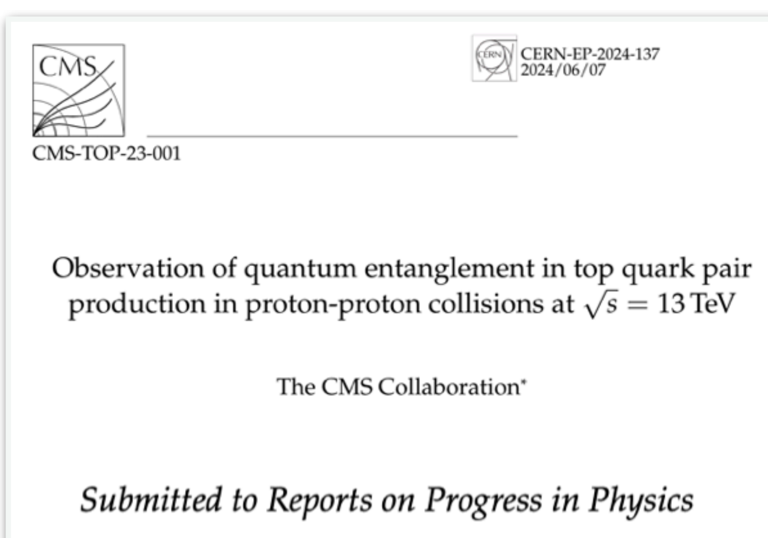

- **First observation of entanglement in $t\bar{t}$ by ATLAS** at the end of last year




- **First observation by CMS** a few months ago in dilepton events

- Recently **first observation in lepton+jets events by CMS - first time with casually separated top quarks at high $m_{t\bar{t}}$ !**

[arXiv:2406.03976](arXiv:2406.03976)



CMS-TOP-23-001

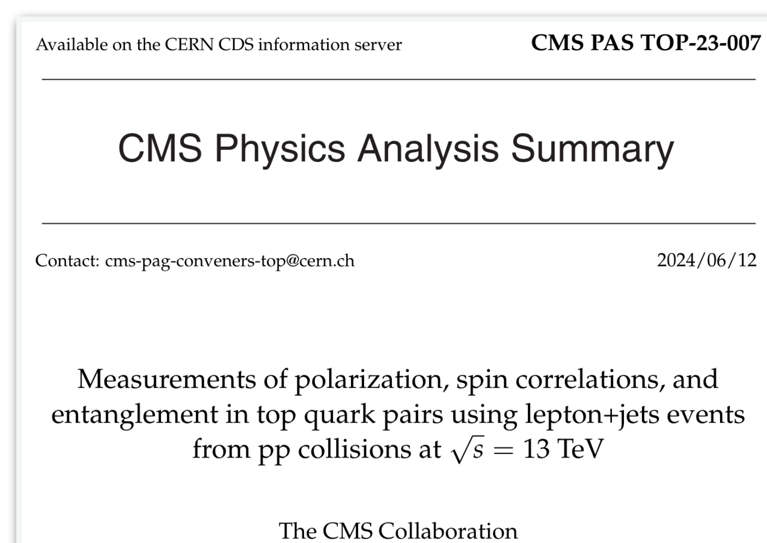
CERN-EP-2024-137
2024/06/07

Observation of quantum entanglement in top quark pair production in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*

*Submitted to Reports on Progress in Physics*

[CMS-PAS-TOP-23-007](CMS-PAS-TOP-23-007)



Available on the CERN CDS information server

CMS PAS TOP-23-007

CMS Physics Analysis Summary

Contact: cms-pag-conveners-top@cern.ch

2024/06/12

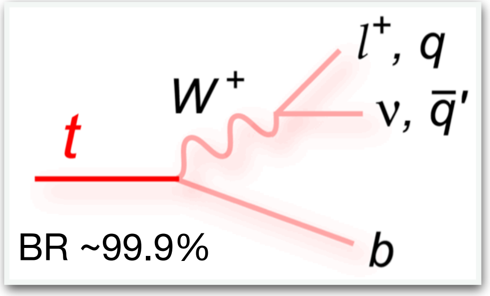
Measurements of polarization, spin correlations, and entanglement in top quark pairs using lepton+jets events from pp collisions at $\sqrt{s} = 13$ TeV

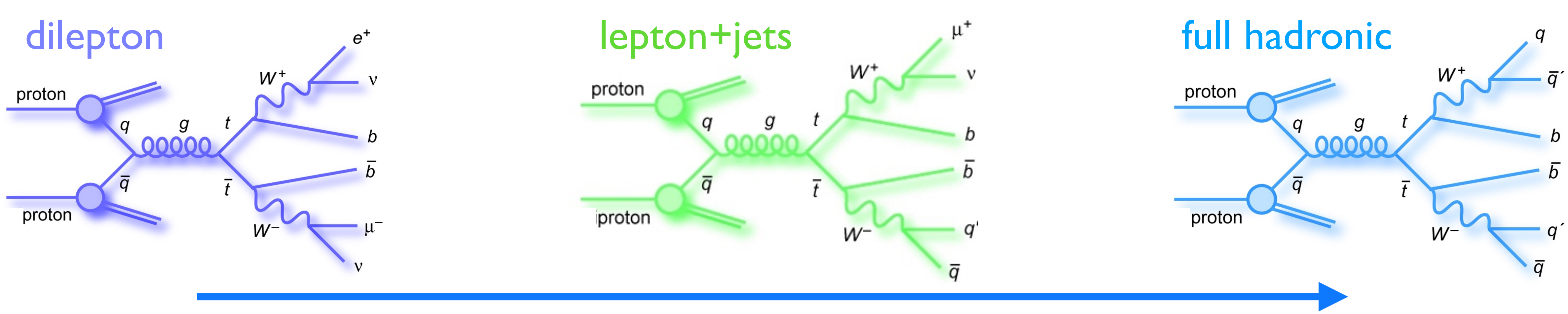
The CMS Collaboration

# Why Top Quarks ?

- **Ideal candidate for spin measurements:**
  - **extremely short lifetime** allows measuring polarization and spin correlation in $t\bar{t}$ production
  - **spin information preserved** in the angular distribution of its decay products
  - spin information ~100% transmitted to charged leptons and down type quarks
- Top spin information accessed “best” in leptonic decays of W

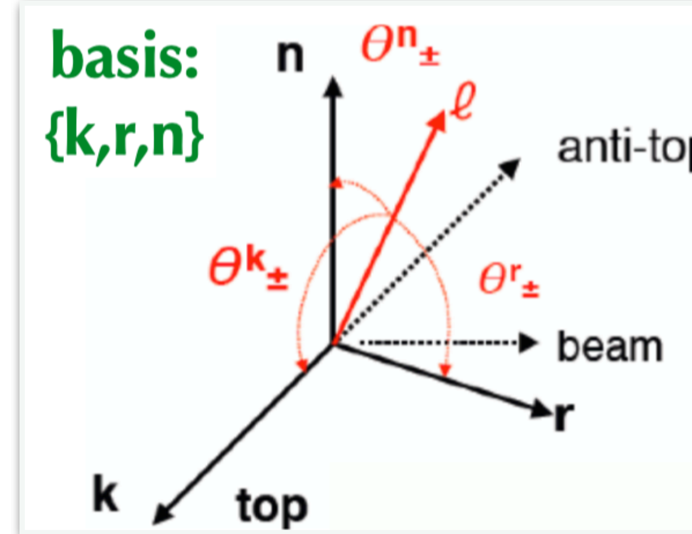
$$\underbrace{\frac{1}{m_t}}_{\substack{\text{production} \\ 10^{-27}\ \text{s}}} < \underbrace{\frac{1}{\Gamma_t}}_{\substack{\text{lifetime} \\ 10^{-25}\ \text{s}}} < \underbrace{\frac{1}{\Lambda_{QCD}}}_{\substack{\text{hadronization} \\ 10^{-24}\ \text{s}}} < \underbrace{\frac{m_t}{\Lambda^2}}_{\substack{\text{spin-flip}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




**BR increases..** **but background too!**

# Spin correlations




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

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega_+ d\Omega_-} = \frac{1}{(4\pi)^2}\left(1 + \mathbf{B}^+ \cdot \hat{\ell}^+ + \mathbf{B}^- \cdot \hat{\ell}^- - \hat{\ell}^+ \cdot \mathbb{C} \cdot \hat{\ell}^-\right)$$

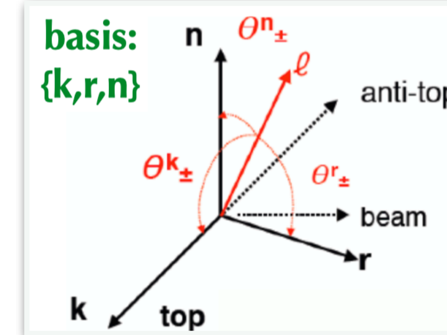
polarization — spin correlations


- Spin dependence of $t\bar{t}$ production **completely characterized by 15 coefficients**
  - can be probed individually by measuring 1D angular distributions

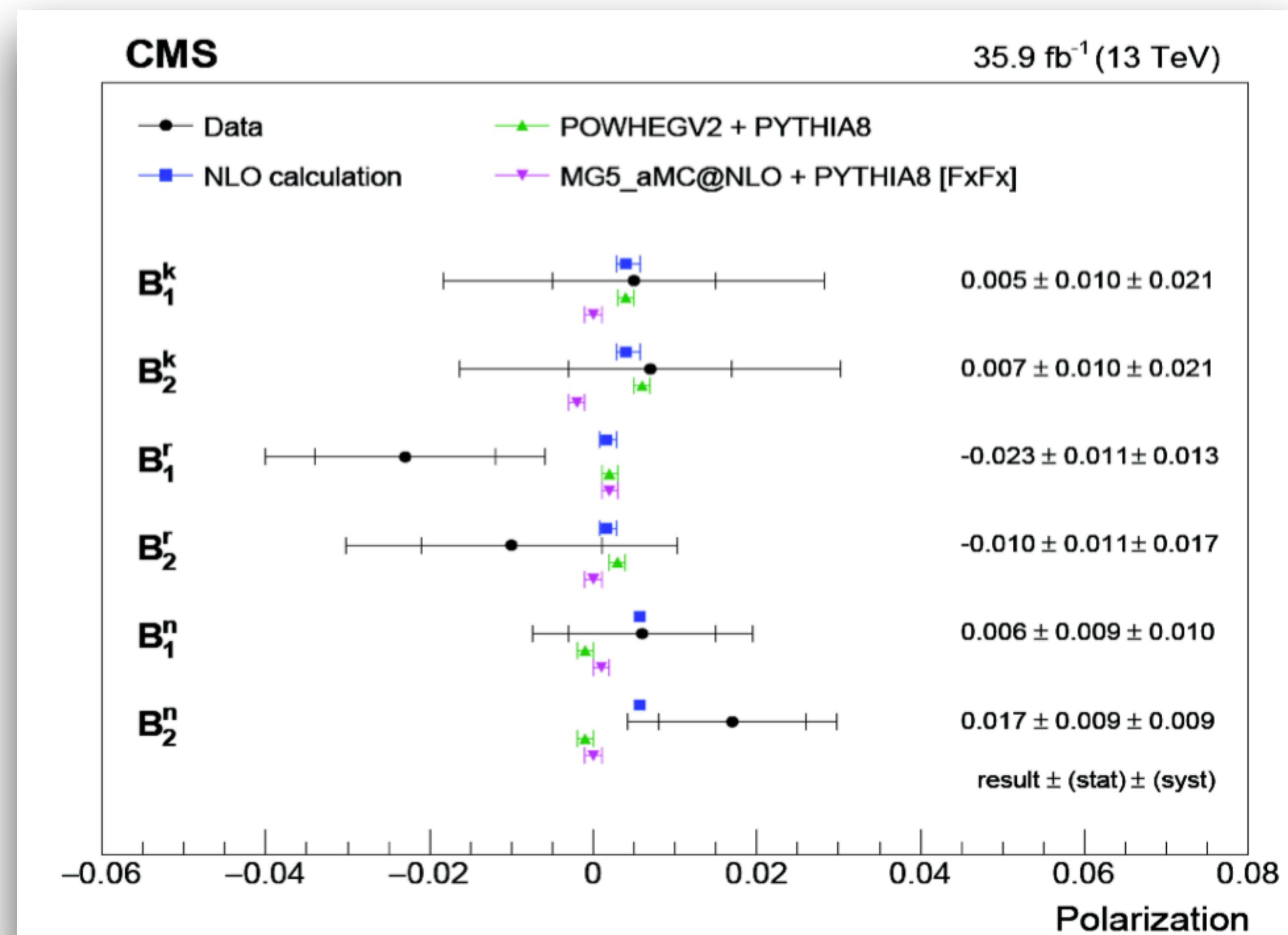
$$\frac{1}{\sigma}\frac{d\sigma}{dx} = \frac{1}{2}\left(1 + [\mathbf{Coef.}]\, x\right) f(x)$$

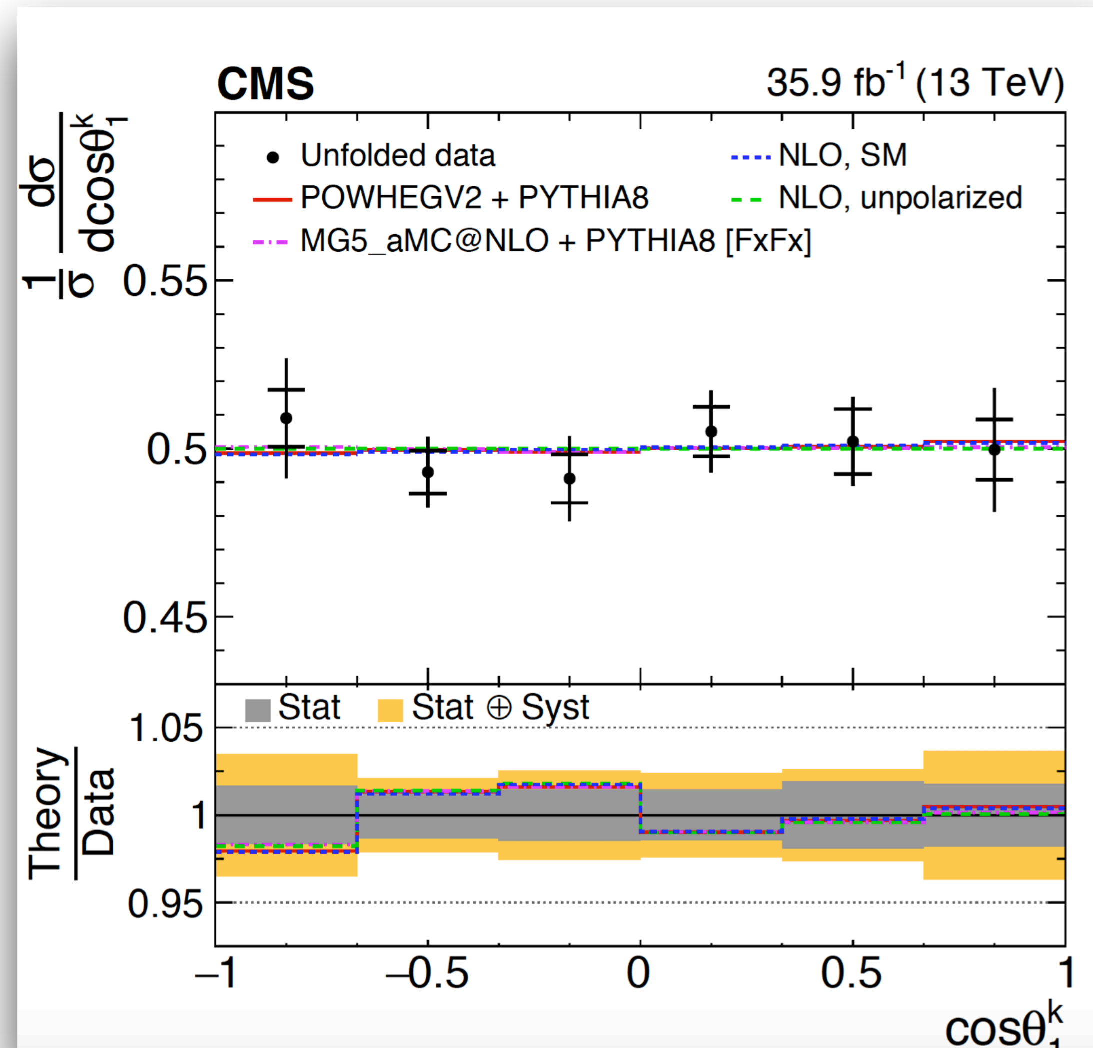
| Observable | Coefficient | Coefficient function |
|---|---|---|
| $\cos\theta_1^k$ | $B_1^k$ | $b_k^+$ |
| $\cos\theta_2^k$ | $B_2^k$ | $b_k^-$ |
| $\cos\theta_1^r$ | $B_1^r$ | $b_r^+$ |
| $\cos\theta_2^r$ | $B_2^r$ | $b_r^-$ |
| $\cos\theta_1^n$ | $B_1^n$ | $b_n^+$ |
| $\cos\theta_2^n$ | $B_2^n$ |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

# Top spin measurements




- In SM, $t\bar{t}$ production ~ unpolarized
  - $$\frac{1}{\sigma}\frac{d\sigma}{dcos\theta^i_{1/2}} = \frac{1}{2}(1 + B^i_{1/2} cos\theta^i_{1/2})$$
    for polarization coefficients
    → not sensitive to entanglement




PRD 100 (2019) 072002

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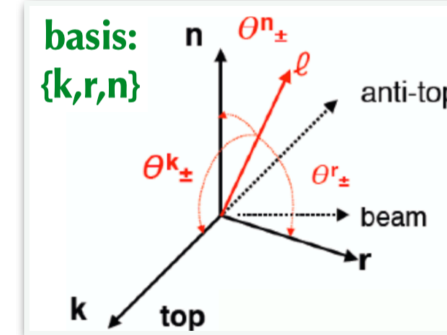
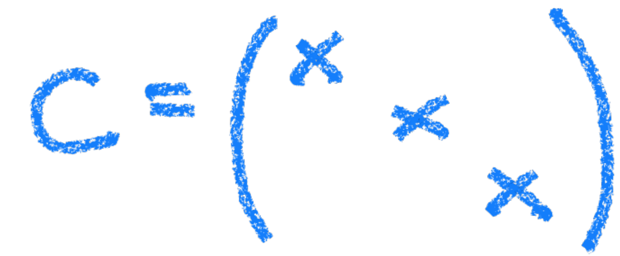
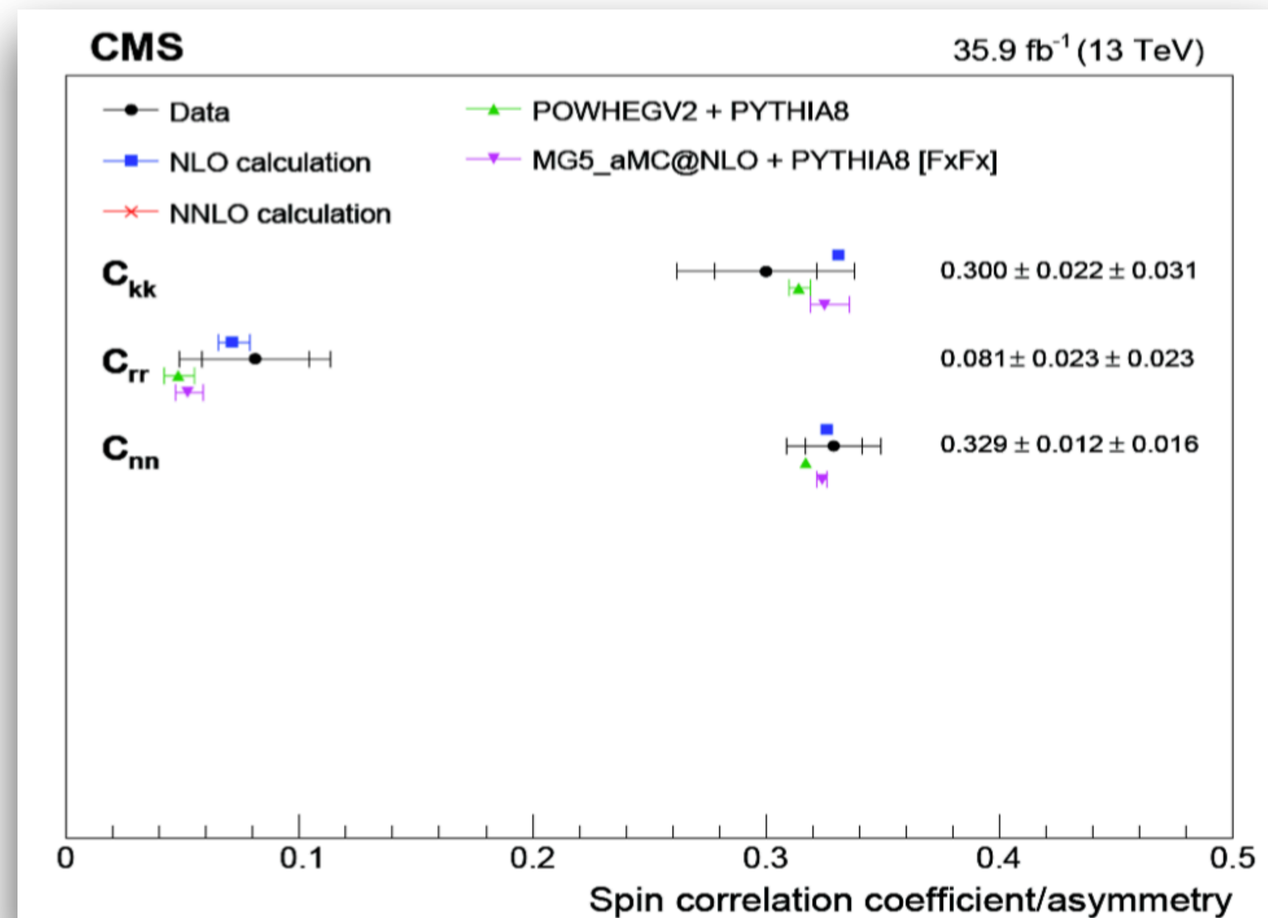
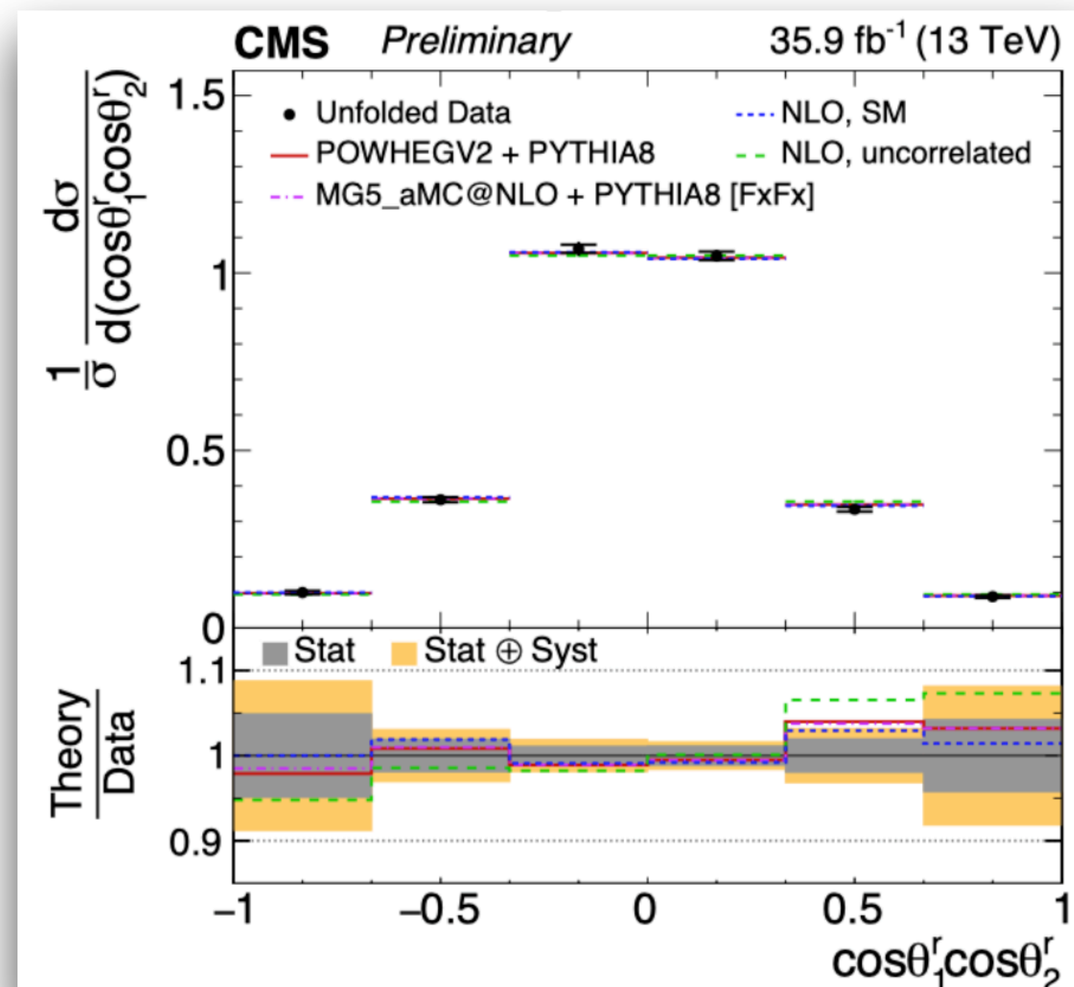



- In SM, $t\bar{t}$ production ~ unpolarized
  but top spins strongly correlated with antitop spins → rich structure of spin correlations

- $$\frac{1}{\sigma}\frac{d\sigma}{d(cos\theta_1^i cos\theta_2^i)} = \frac{1}{2}[1 - C_{ii}(cos\theta_1^i cos\theta_2^i)]\ln\frac{1}{|cos\theta_1^i cos\theta_2^i|}$$
  for diagonal spin correlations coefficients



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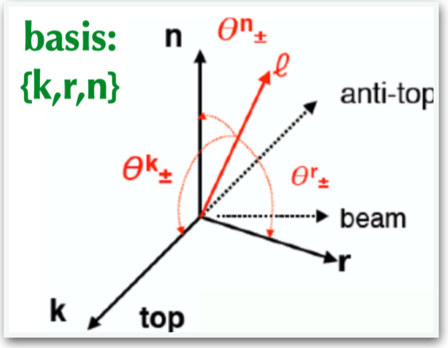


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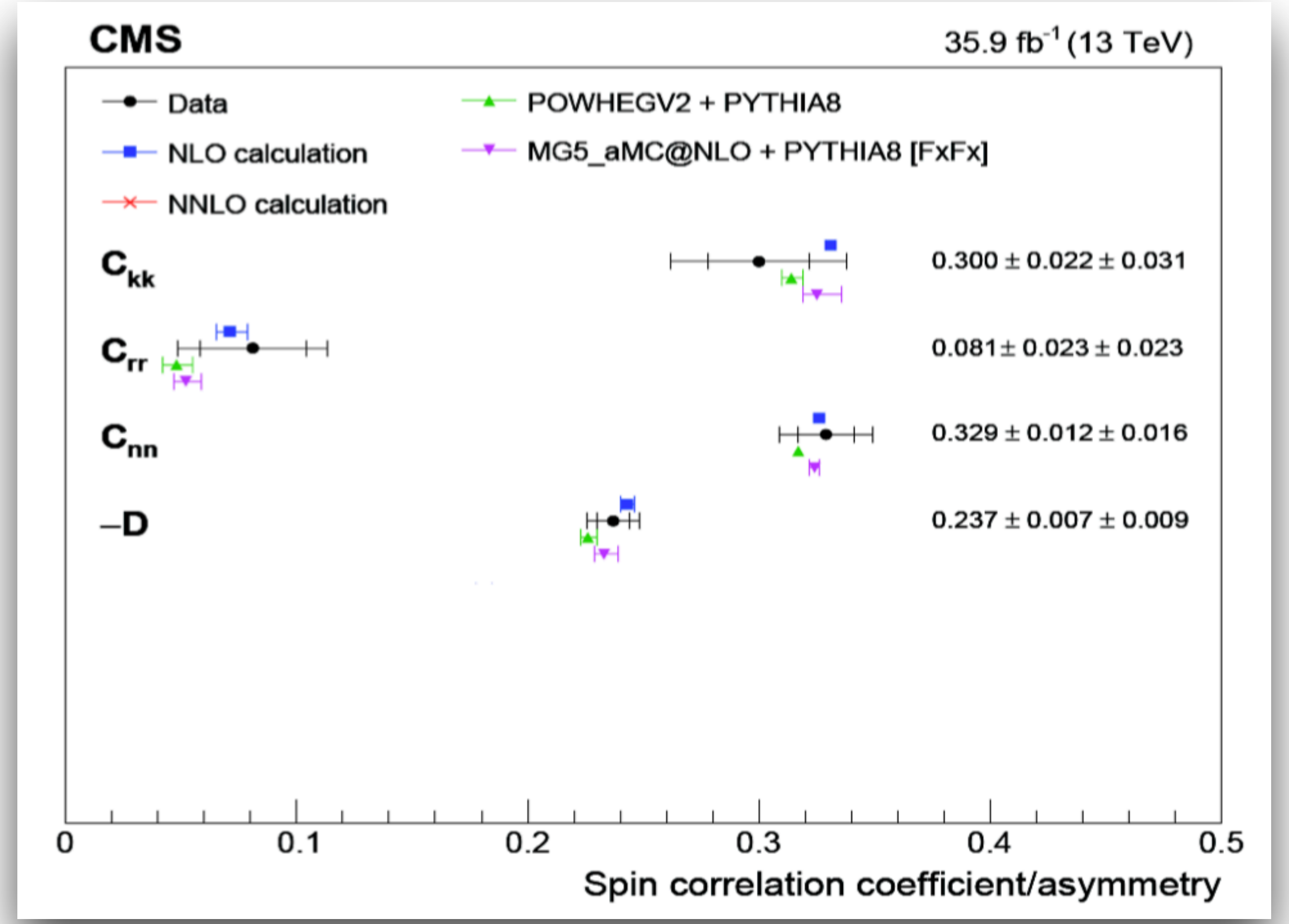
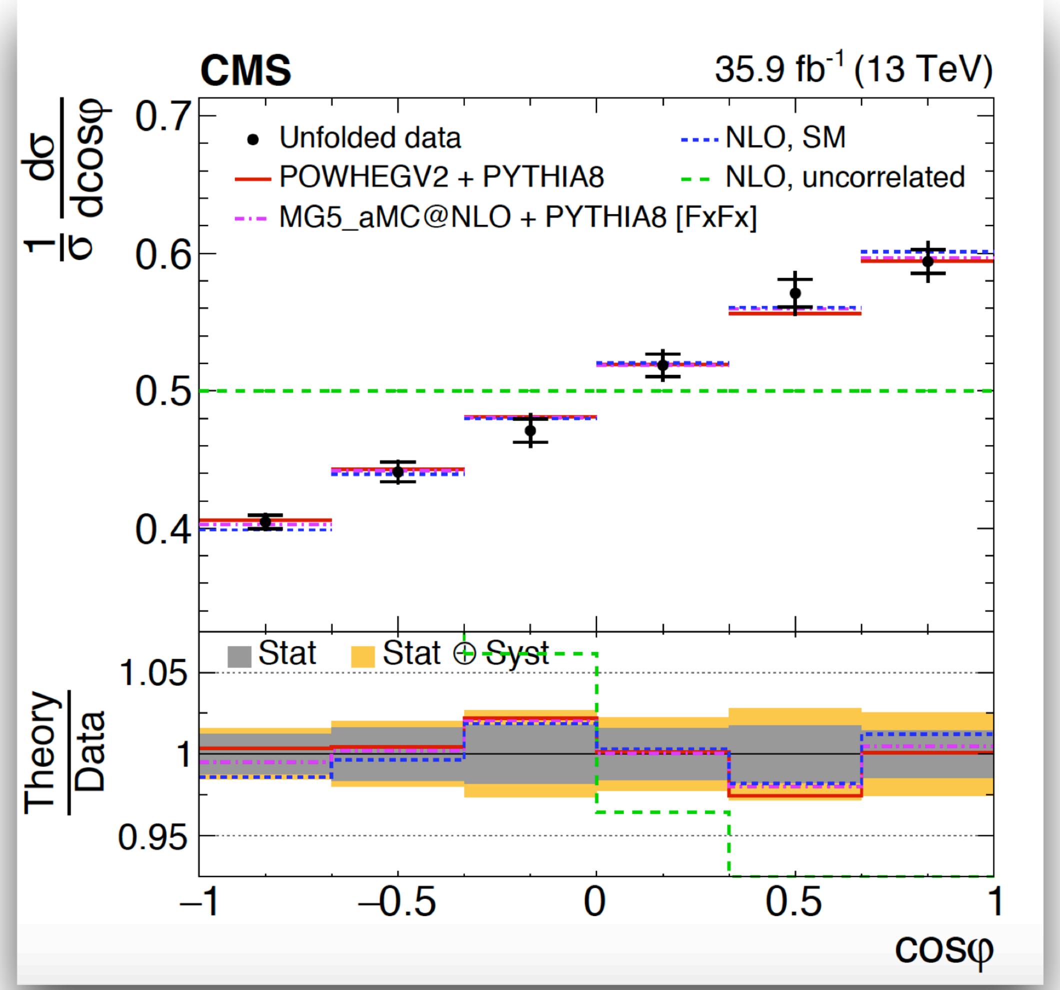
- $$\frac{1}{\sigma}\frac{d\sigma}{dcos\varphi} = \frac{1}{2}(1 - Dcos\varphi) \text{ for}$$

  $$D = -\frac{Tr[C]}{3} = -\frac{C_{kk} + C_{rr} + C_{nn}}{3}$$

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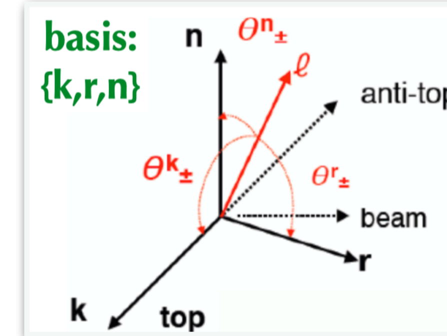


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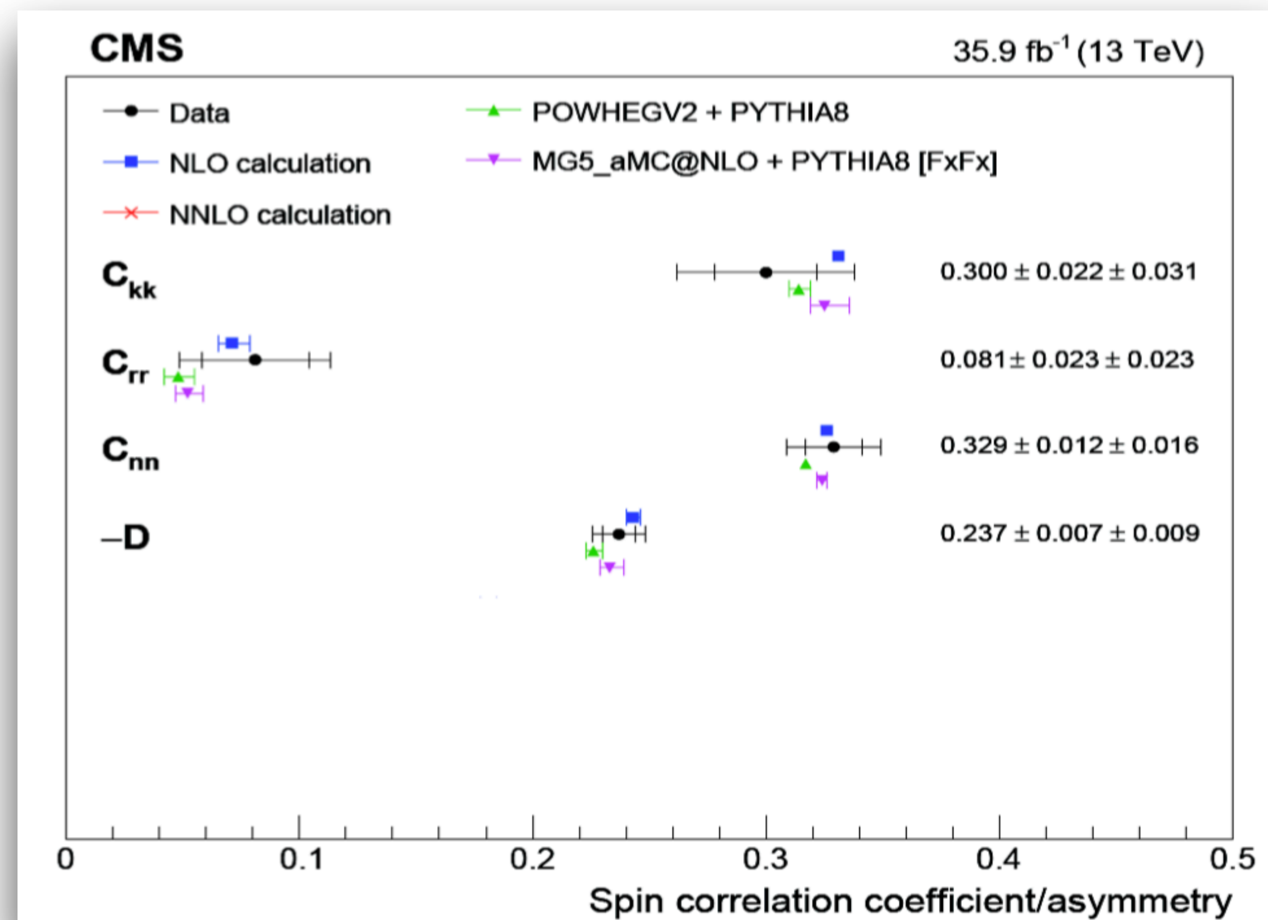
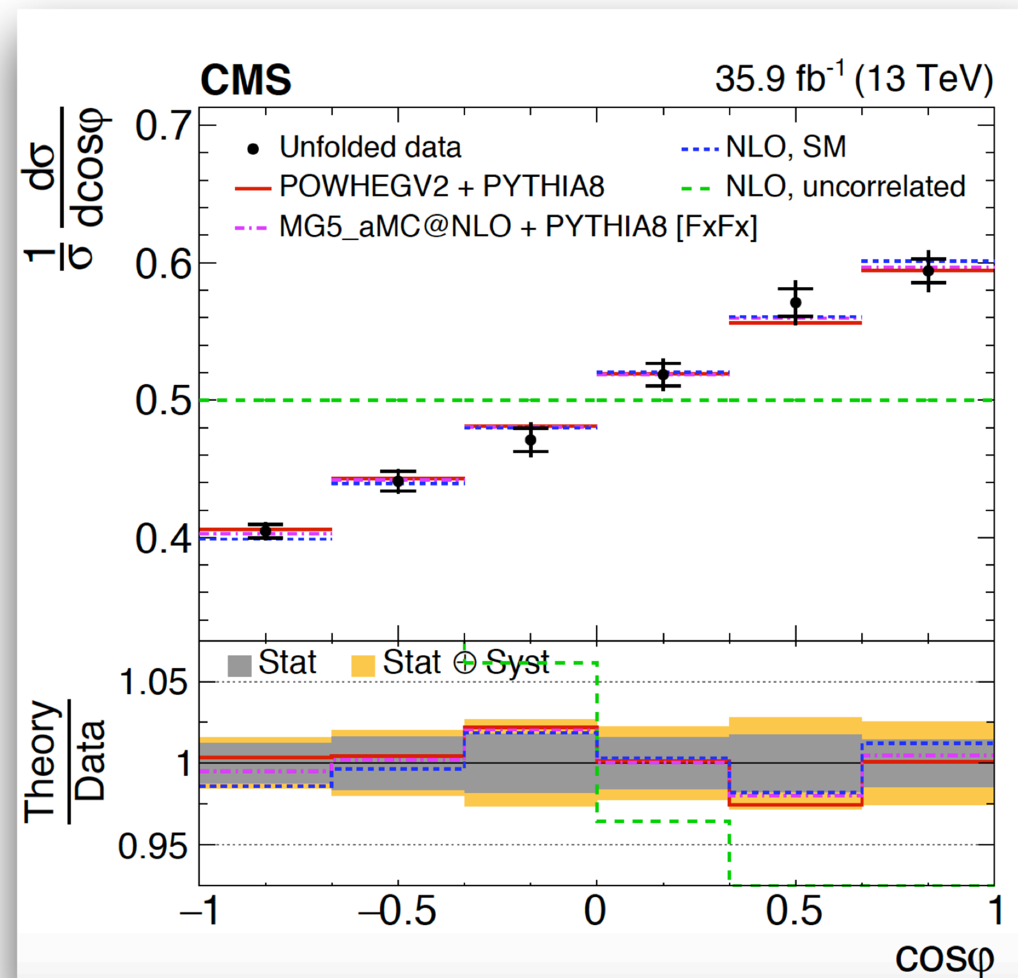
  $$D = -\frac{Tr[C]}{3} = -\frac{C_{kk} + C_{rr} + C_{nn}}{3}$$

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

- most precise observable
- maximal sensitivity to degree of alignment of top quark spins
  → focus of entanglement measurement

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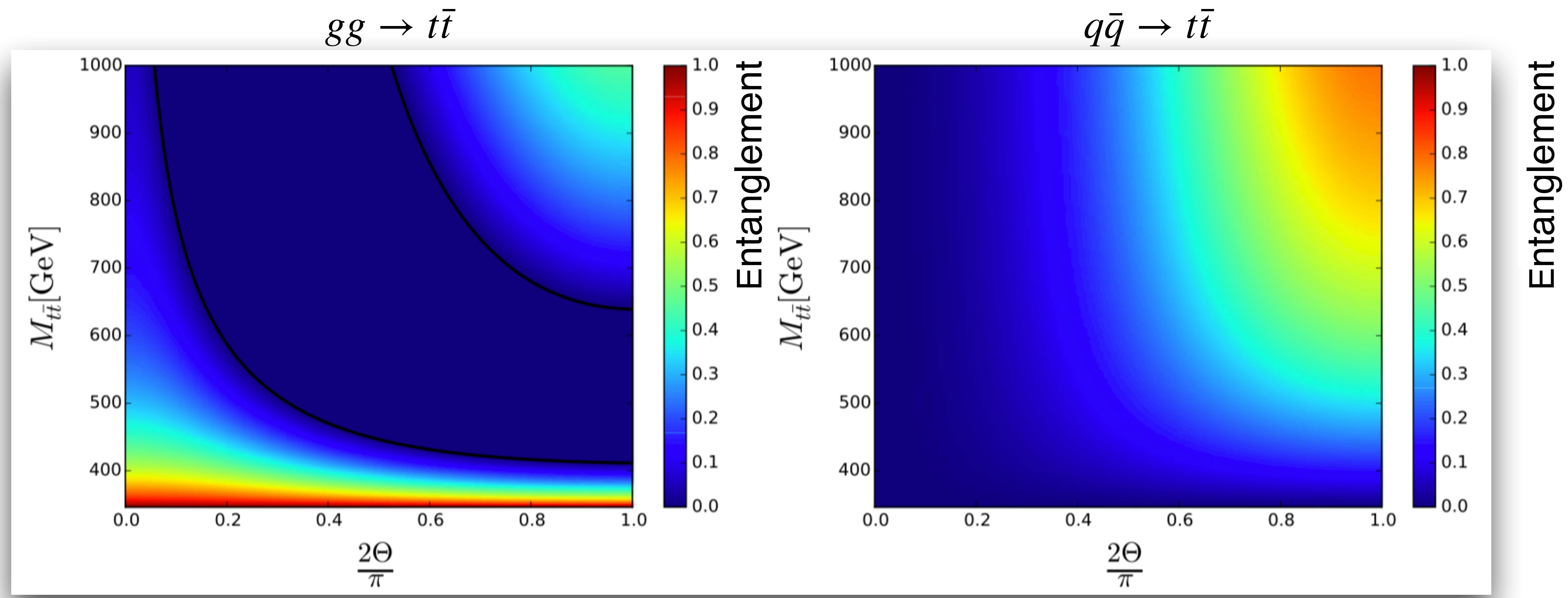
# Entanglement of top quarks

- Can be measured using **spin correlations variables**
- Depends on production mode, $m_{t\bar{t}}$, scattering angle of the top quark ($\Theta$)

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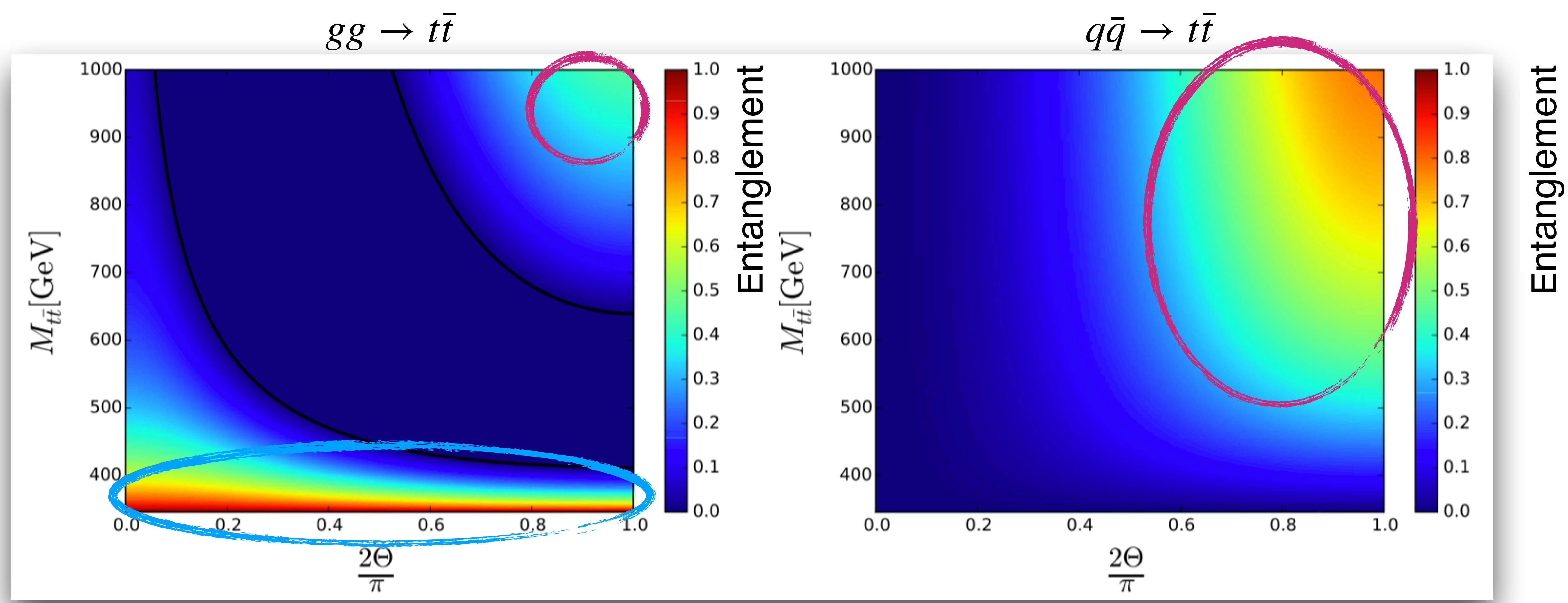
- **SM predicts entangled states:**
  - **at the production threshold region in gg fusion production**
  - **at the boosted region for central production of the $t\bar{t}$ system**

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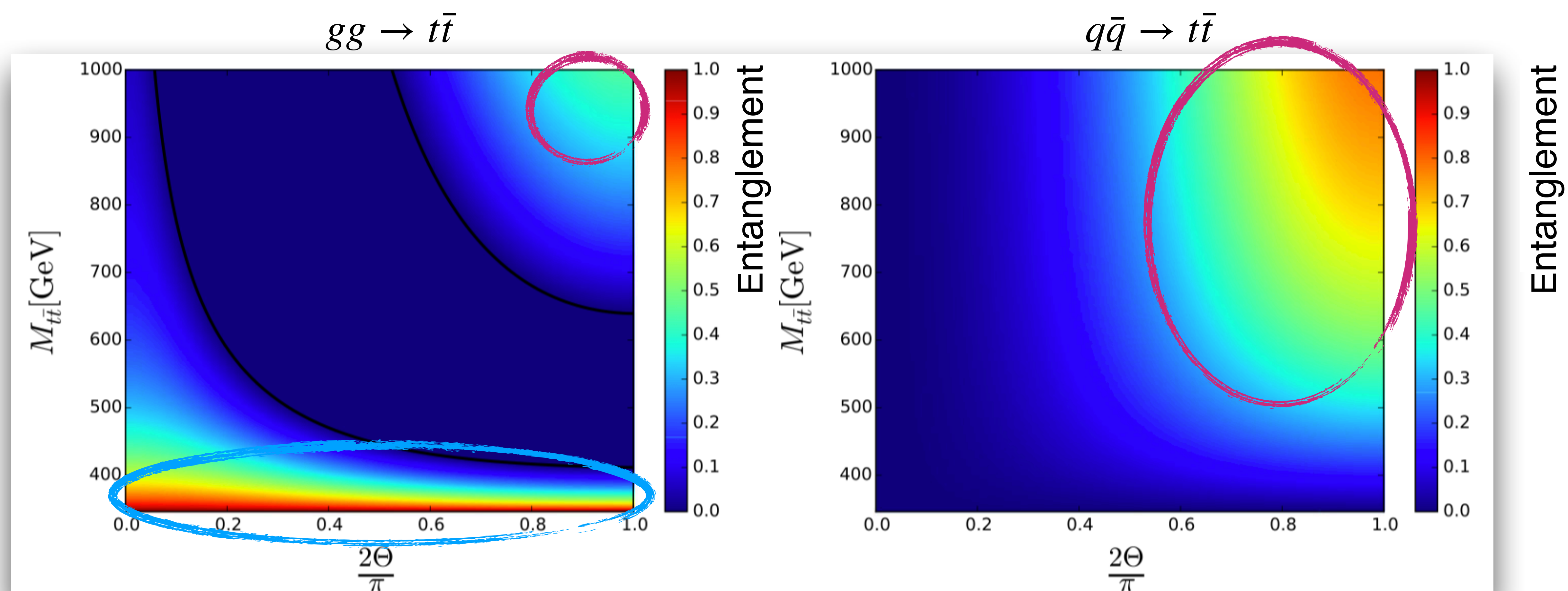
**high relative velocity of top quarks $\rightarrow$ space-like separated** events




**low relative velocity of top quarks $\rightarrow$ time-like separated** events

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# How to probe entanglement

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

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

$$B^{+/-} = \begin{pmatrix} x \\ x \\ x \end{pmatrix} \qquad C = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

- **Peres-Horodecki criterion**:
  if a system is separable, $\rho = \sum_i p_i \rho_A^i \otimes \rho_B^i$

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

  the transpose with respect to a subspace of $\rho$ is a non-negative operator

$$\rho^{T2} = \sum_i p_i \rho_A^i \otimes (\rho_B^i)^T$$

  → system is entangled if at least 1 eigenvalue is negative

- **For $t\bar{t}$ system, spin density matrix is separable if all eigenvalues are positive**

  → **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**:

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

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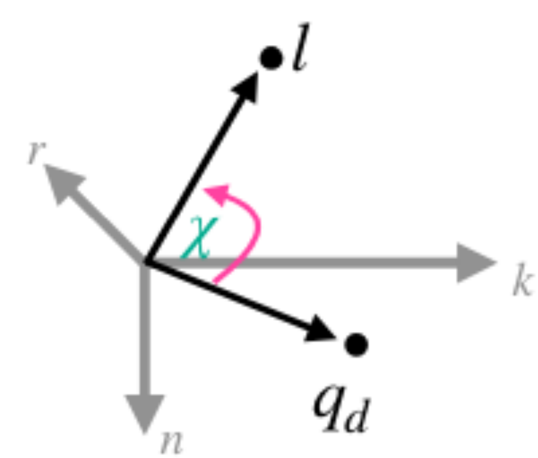
- **Two approaches:**
  - Use **full angular information of two decay products** to measure full matrix $C$ and then construct $\Delta_E$
  - Use **$\chi$ and $\tilde{\chi}$ distributions** to measure $D$ and $\tilde{D}$
    - potentially improved sensitivity since we can use simpler 1D angular distributions

$$\frac{d\sigma}{d\cos\chi} = A(1 + D\cos\chi)$$

$$\frac{d\sigma}{d\cos\tilde{\chi}} = A(1 + \tilde{D}\cos\tilde{\chi})$$

$\chi$ = opening angle between the 2 decay products

$\tilde{\chi} = \chi$ with inverted sign of n-component in one of the decay products



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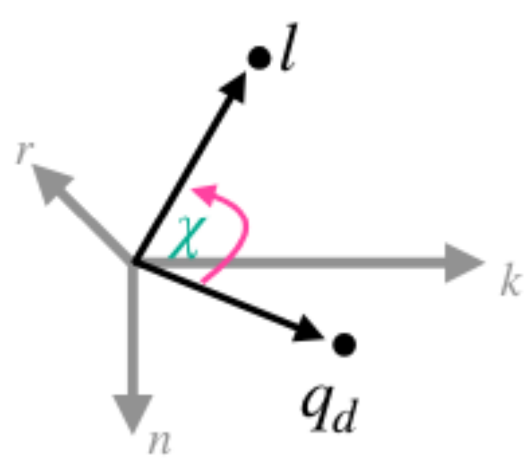
$$\frac{d\sigma}{d\cos\chi} = A(1 + D\cos\chi) \qquad \rightarrow \frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi)$$ in dilepton events

$$\frac{d\sigma}{d\cos\tilde{\chi}} = A(1 + \tilde{D}\cos\tilde{\chi})$$

$\chi$ = opening angle between the 2 decay products




$\tilde{\chi} = \chi$ with inverted sign of n-component in one of the decay products

# How to probe entanglement

- Four maximally entangled states: $$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\right)$$ $$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right)$$

$$gg \to t\bar{t}$$

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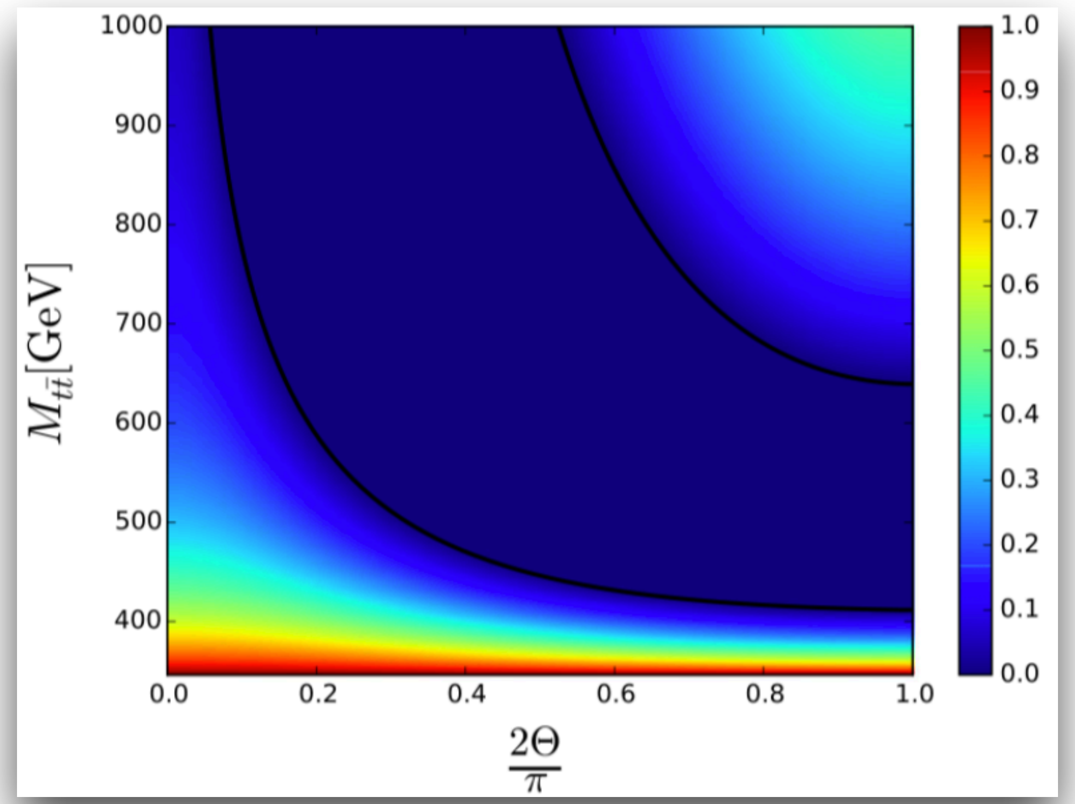


$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

**Sufficient condition for entanglement**

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$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right)$$

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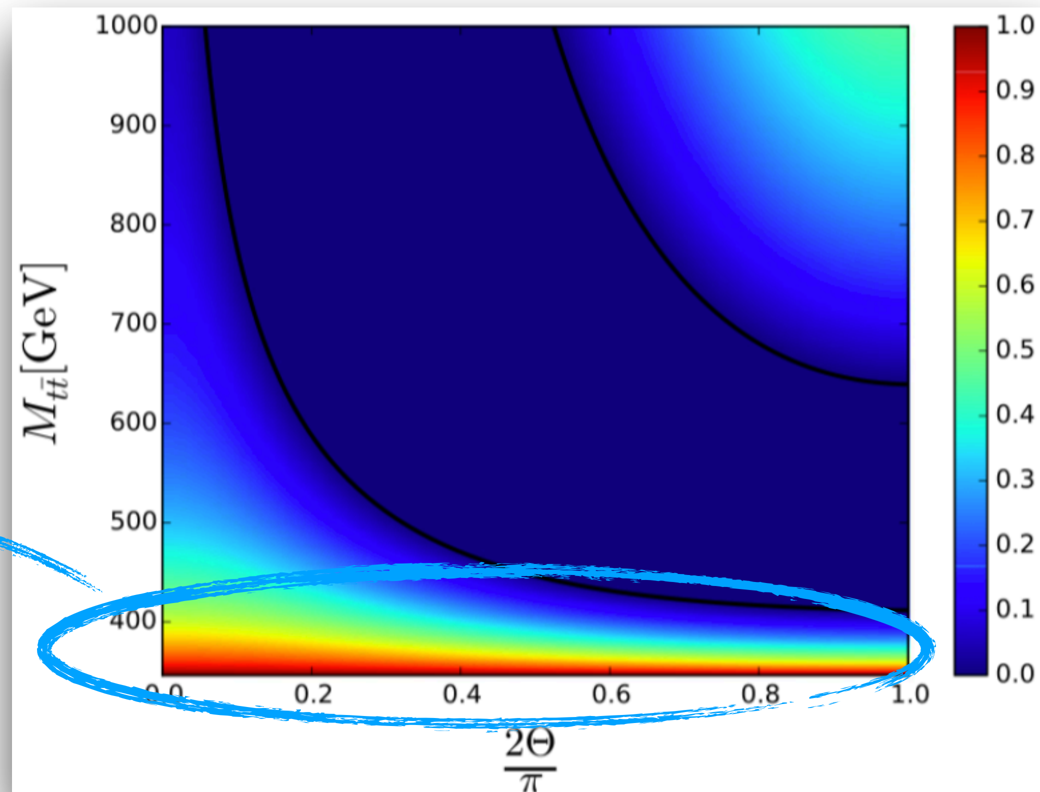


- Spin-singlet pseudoscalar state $\Psi^{-}$

- At low $m_{t\bar{t}}$ : $C_{rr} > 0$ and $C_{kk} > 0$

$$\Delta_E = C_{nn} + C_{rr} + C_{kk} = Tr[C] = -3D > 1$$

$$D = -\frac{\text{tr}[C]}{3} \quad \to \quad D < -1/3$$

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

**Sufficient condition for entanglement**

# How to probe entanglement

- Four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\right)$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right)$$

$gg \to t\bar{t}$

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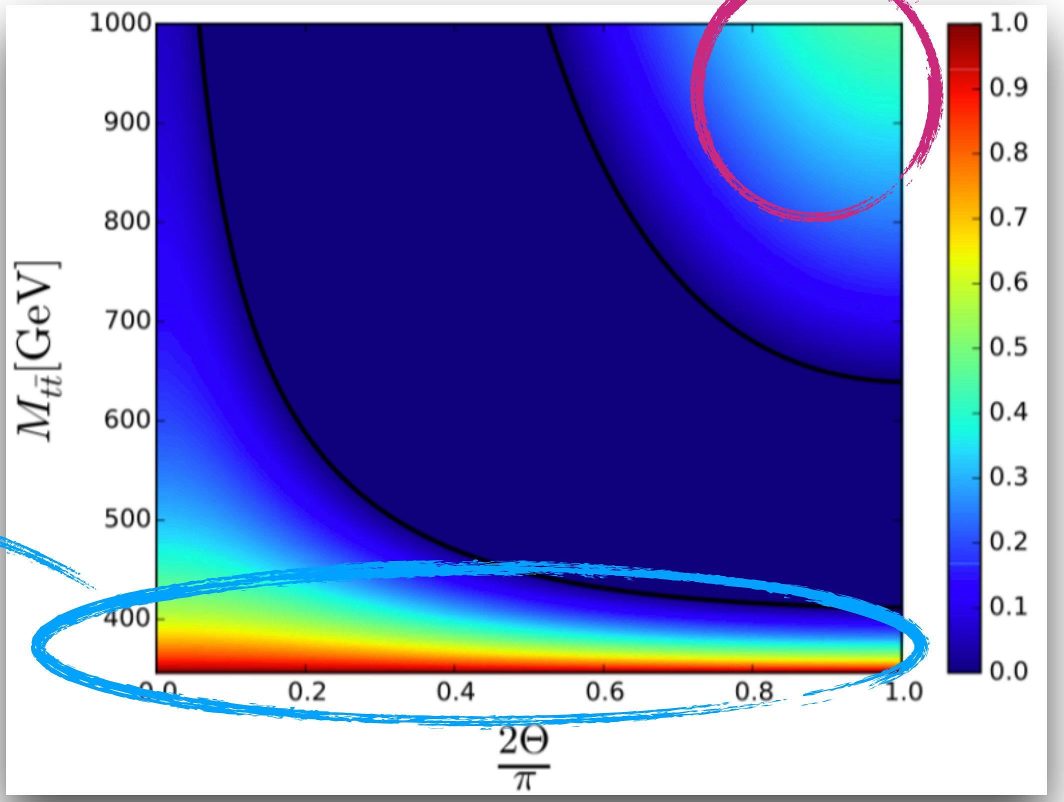


- Spin-triplet vector state ($\Phi^+ - \Phi^-$, $\Psi^+$, $\Phi^+ + \Phi^-$)
- At high $m_{t\bar{t}}$ and low $|\cos\Theta|$: $C_{kk} < 0$ and $C_{rr} < 0$

$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

$$\to \ \tilde{D} > 1/3$$

- Spin-singlet pseudoscalar state $\Psi^-$
- At low $m_{t\bar{t}}$: $C_{rr} > 0$ and $C_{kk} > 0$

$$\Delta_E = C_{nn} + C_{rr} + C_{kk} = Tr[C] = -3D > 1$$

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**Sufficient condition for entanglement**

# How to probe entanglement

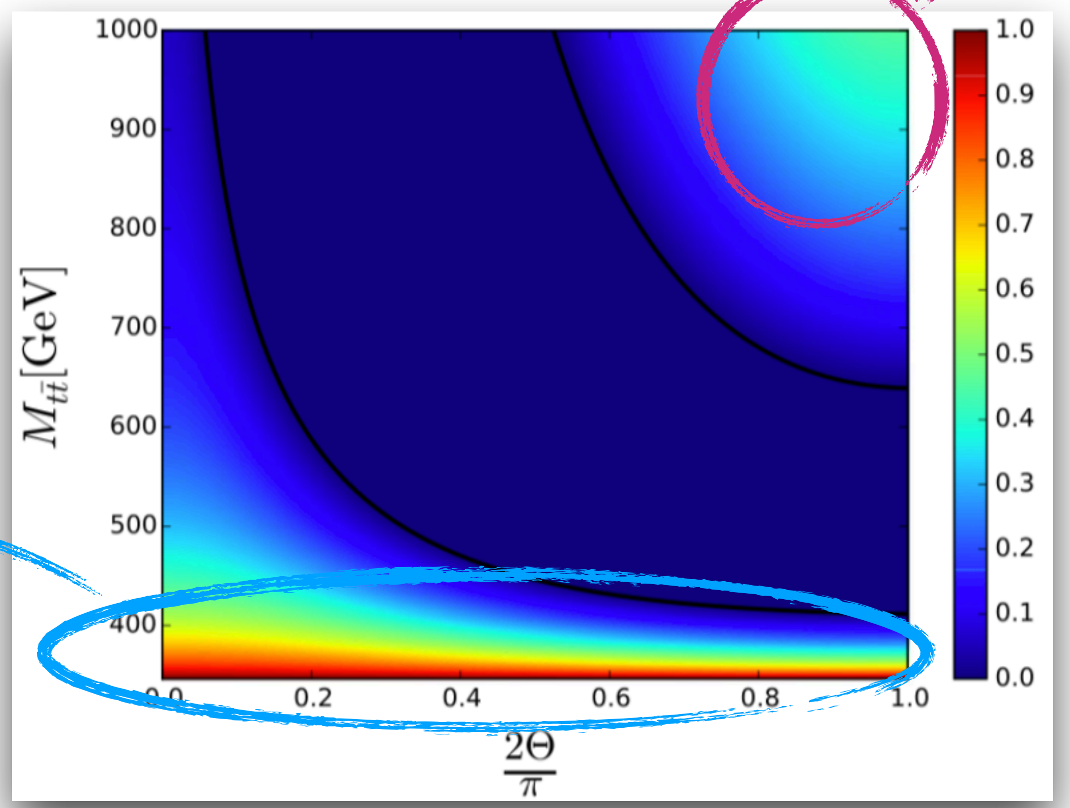
- Four maximally entangled states:

$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\uparrow\rangle \pm |\downarrow\downarrow\rangle\right)$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right)$$

$gg \to t\bar{t}$

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




- Spin-triplet vector state $(\Phi^+ - \Phi^-, \Psi^+, \Phi^+ + \Phi^-)$
- At high $m_{t\bar{t}}$ and low $|\cos\Theta|$: $C_{kk} < 0$ and $C_{rr} < 0$

$$\Delta_E = C_{nn} - C_{rr} - C_{kk} = 3\tilde{D} > 1$$

$$\to \tilde{D} > 1/3$$

- Spin-singlet pseudoscalar state $\Psi^-$
- At low $m_{t\bar{t}}$: $C_{rr} > 0$ and $C_{kk} > 0$

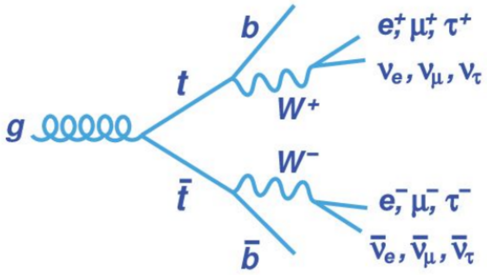
$$\Delta_E = C_{nn} + C_{rr} + C_{kk} = Tr[C] = -3D > 1$$

$$D = -\frac{\text{tr}[C]}{3} \quad \to D < -1/3$$

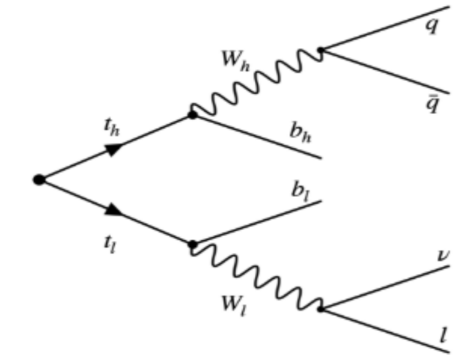
$$\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$$

**Sufficient condition for entanglement**

**→ measure $D$, $\tilde{D}$ to access entanglement information in top quark events!**




# Dilepton vs lepton+jets




## Dilepton

[arXiv:2406.03976](arXiv:2406.03976)
submitted to ROPP

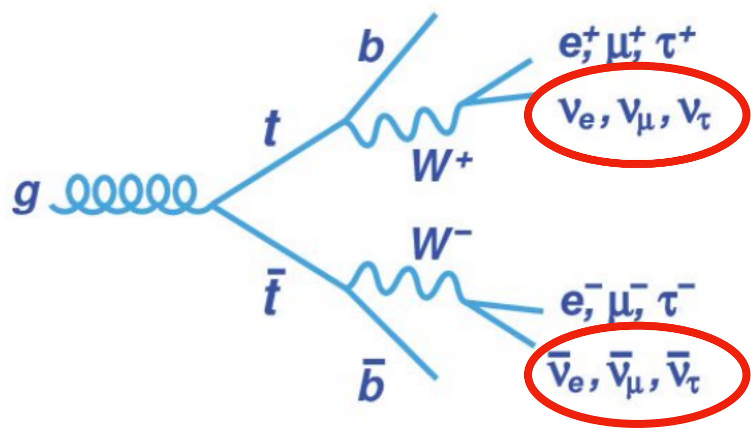
- **36.3 fb$^{-1}$ of 2016 data @13 TeV**
  - based on PRD 100 (2019) 072002
- Lower branching ratio
- top spin info 100 % transmitted to charged leptons → easy to identify
- Lower $p_T$ cuts for leading/subleading lepton (25/20 GeV) → higher efficiency at the threshold
- Worse $m_{t\bar{t}}$ resolution → not ideal for differential measurement
- Best for threshold region
  - high entanglement
  - mostly **time-like separated events**

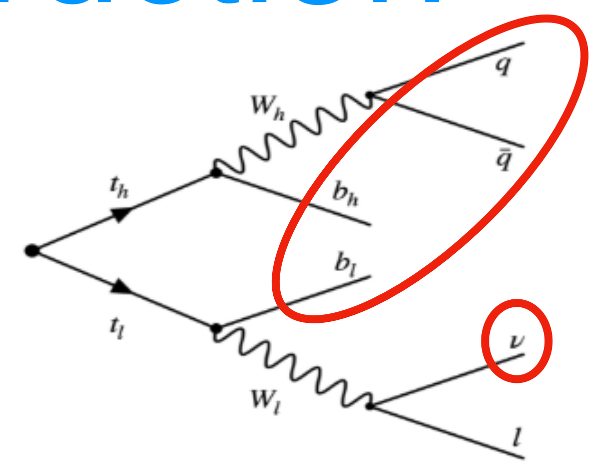
## Lepton + jets

CMS-PAS-TOP-23-007

- **138 fb$^{-1}$ of data @13 TeV** collected in **full Run 2**
- Higher branching ratio
- top spin info ~100 % transmitted to down-type quarks → hard to identify
- Higher $p_T$ cut for single lepton (30 GeV) and for 4 jets (30 GeV) → lower efficiency at the threshold but OK for high $m_{t\bar{t}}$
- Better $m_{t\bar{t}}$ resolution → good for differential measurement
- Advantage for high $m_{t\bar{t}}$
  - high entanglement
  - mostly **space-like separated events**

# Dilepton vs lepton+jets top quark reconstruction



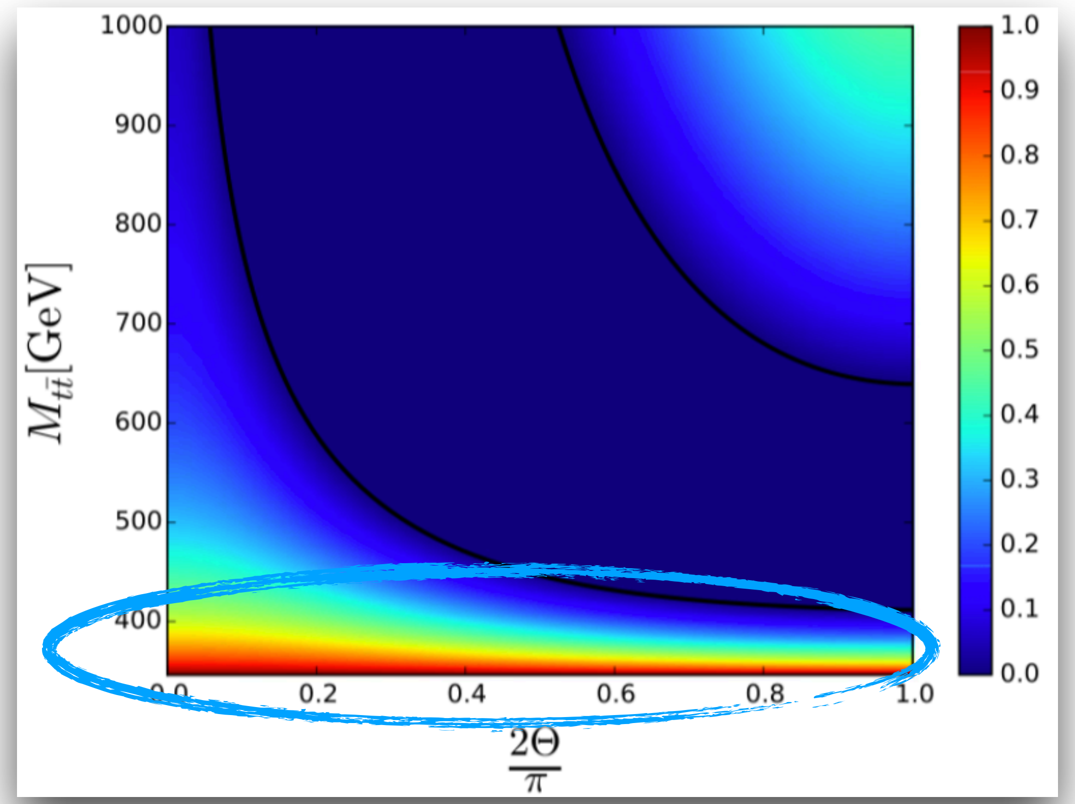

- **$m_{\ell b}$ weighting method**
  - use algebraic method to solve for neutrino 3-vectors
  - pick solution with smallest $m_{t\bar{t}}$
  - pair lepton and jet according to expected $m_{\ell b}$

- **Artificial NN**
  - goal = correctly identify detector-level objects and up/down jet assignment
  - NN trained on permutations
- For each event:
  - provide all possible permutations of objects as input to NN
  - use permutation resulting in the highest NN score
  - calculate neutrino momentum with W boson mass constraint

$$(p_\nu + p_l)^2 = m_W^2$$

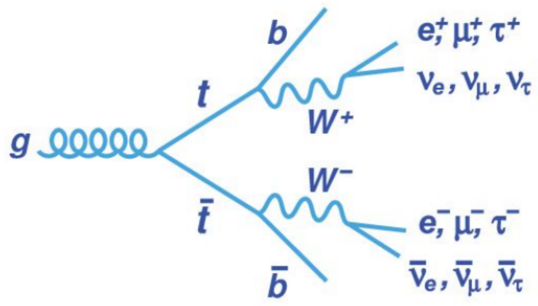
# Dilepton analysis

$gg \to t\bar{t}$

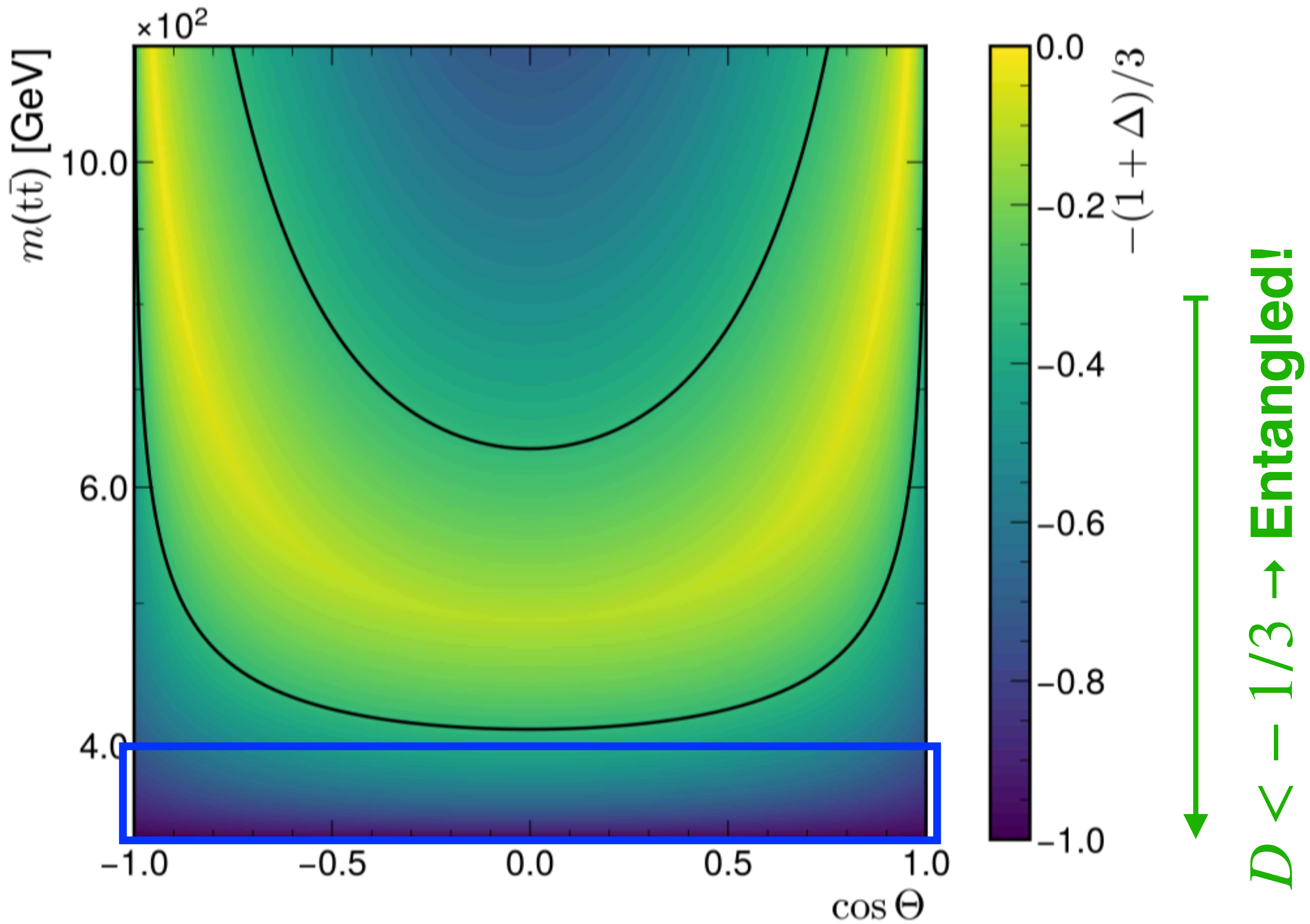


# Dilepton analysis: strategy

- **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**



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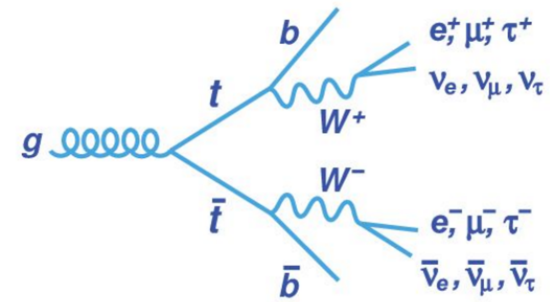


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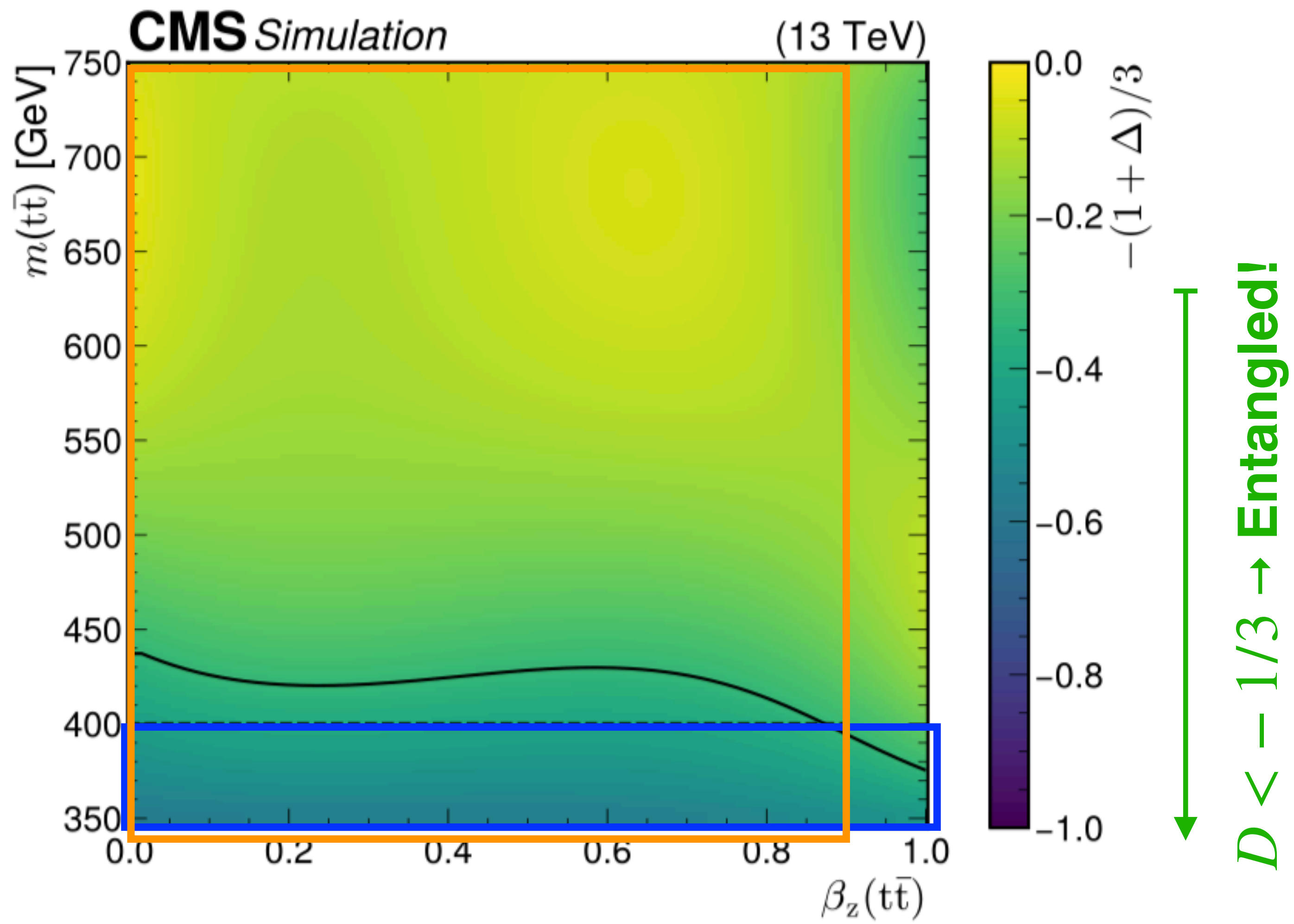
- **Cut on velocity along the beam line of the tt̄ system to increase $gg/q\bar{q}$ fraction:**

Aguilar-Saavedra, Casas
arXiv:2205.00542

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



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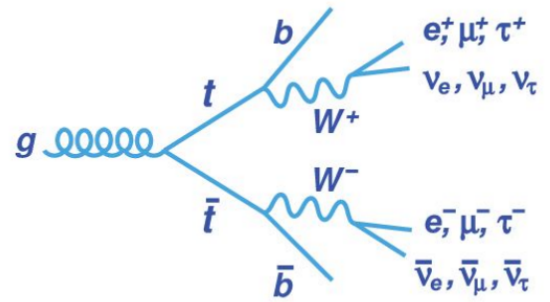


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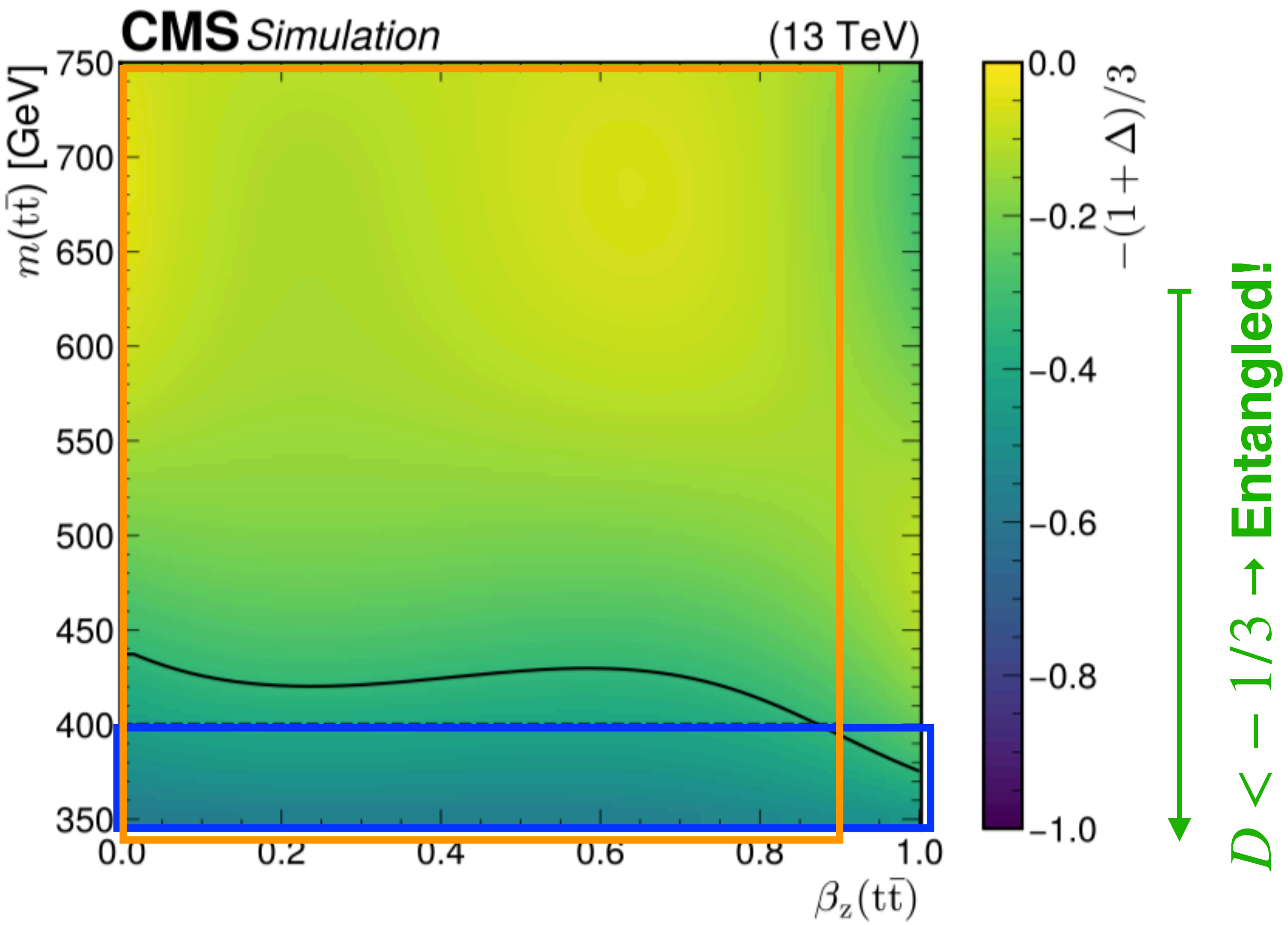
Aguilar-Saavedra, Casas [arXiv:2205.00542](arXiv:2205.00542)

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

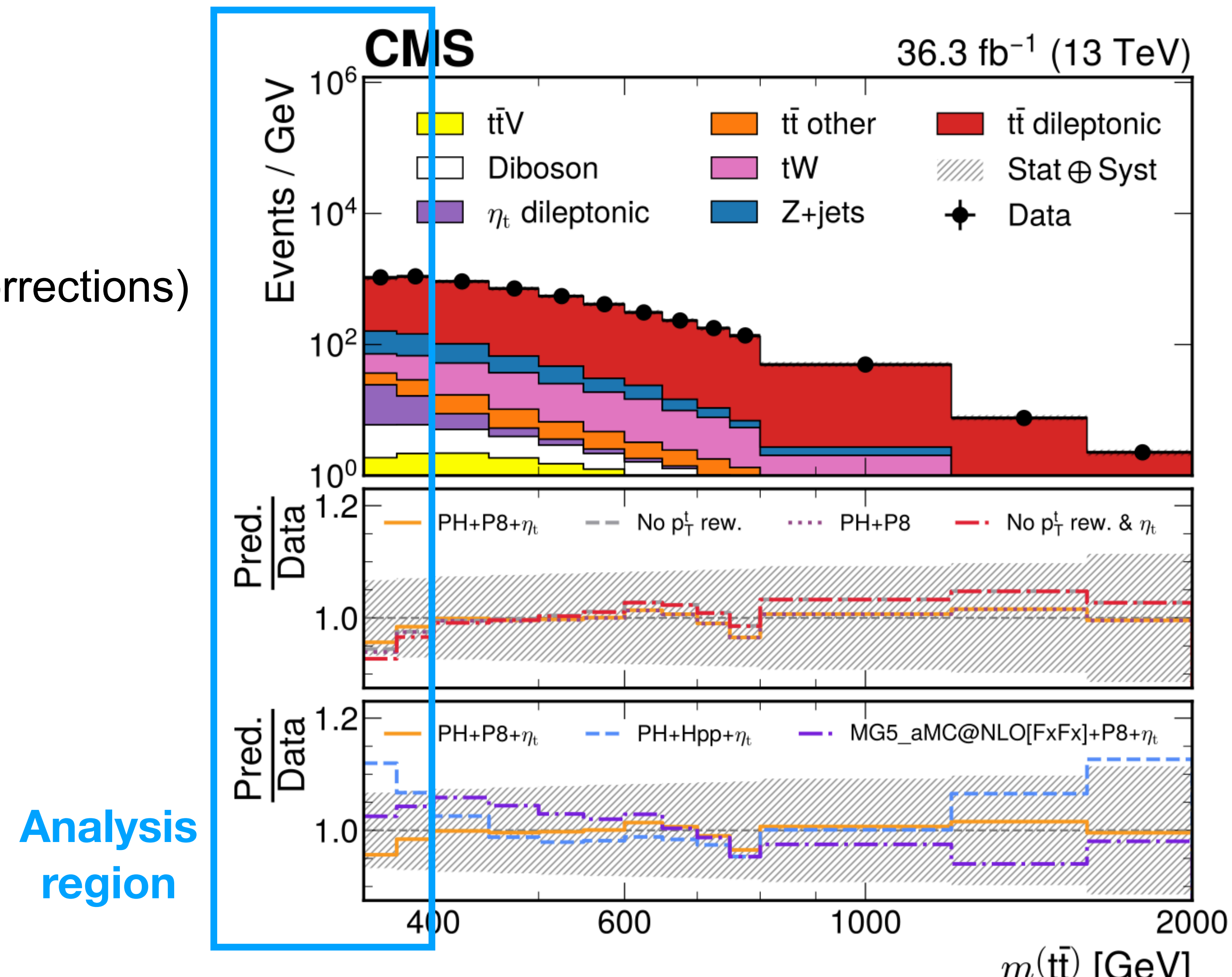
- **Measure helicity angle $\cos\varphi = \hat{\ell}_1 \cdot \hat{\ell}_2$**
  - fully encapsulates spin correlations information for $gg$

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



# Signal model

- PowhegBox+Pythia8 (NLO) as **nominal $t\bar{t}$ sample**
  - inclusion of **EWK corrections at NLO** with HATHOR [Comput. Phys. Commun. 182 (2011) 10]
  - **reweighting to NNLO QCD calculations** [PRL 127 (2021) 062001]
    - $p_T$ reweighting to match the top quark $p_T$ spectrum from a fixed order ME calculation at NNLO
- **Main background sources:**
  - Z+jets (MG5_aMC@NLO + data-driven corrections)
  - single top (Powheg MC)
  - diboson (Pythia8 MC)

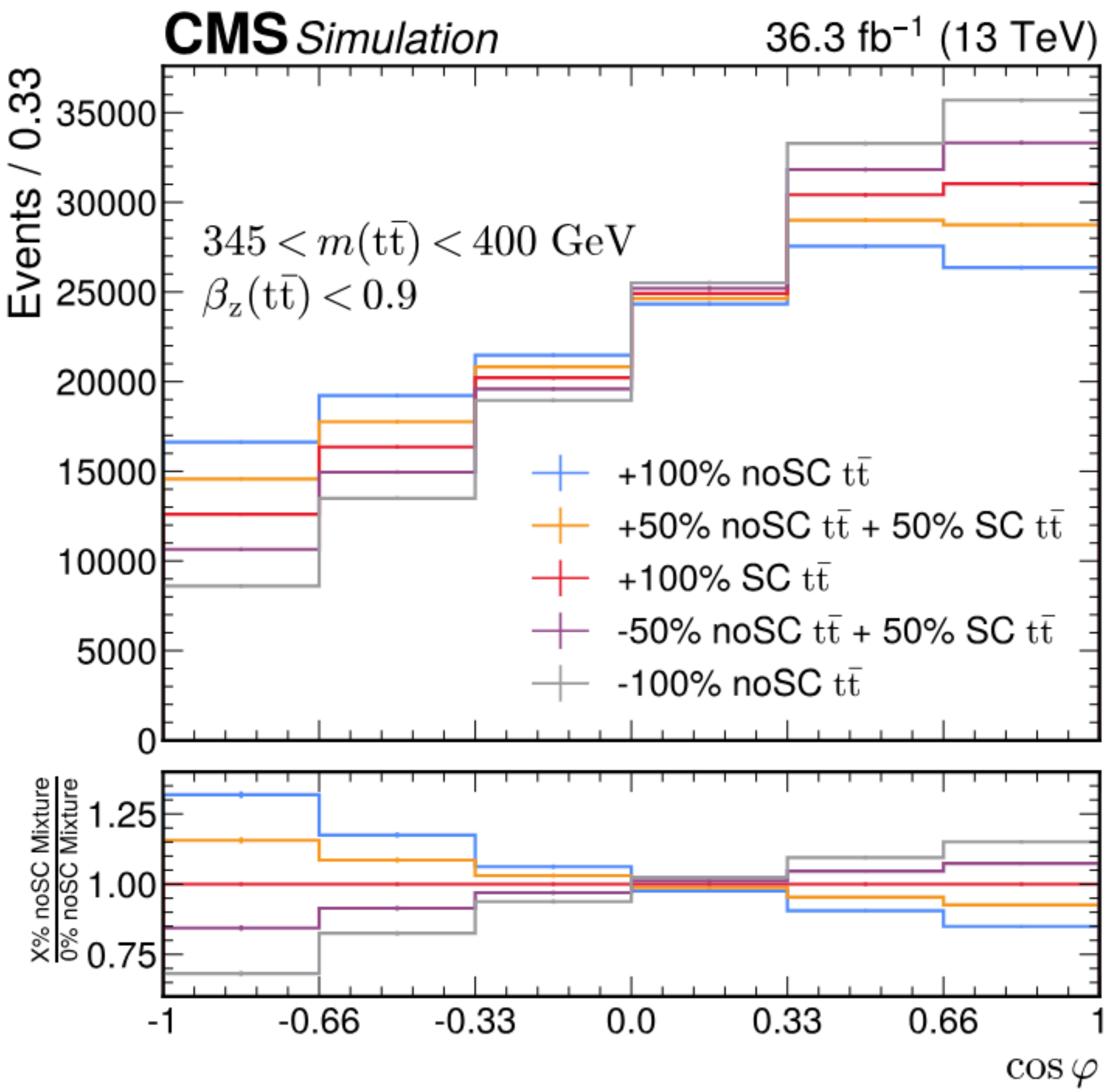


# Extraction of entanglement proxy

- **The entanglement proxy $D$ is extracted with a template fit**
  - all systematic effects included as nuisance parameters
- **Variations of $D$ outside of SM needed to model variation of entanglement**
- **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**

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

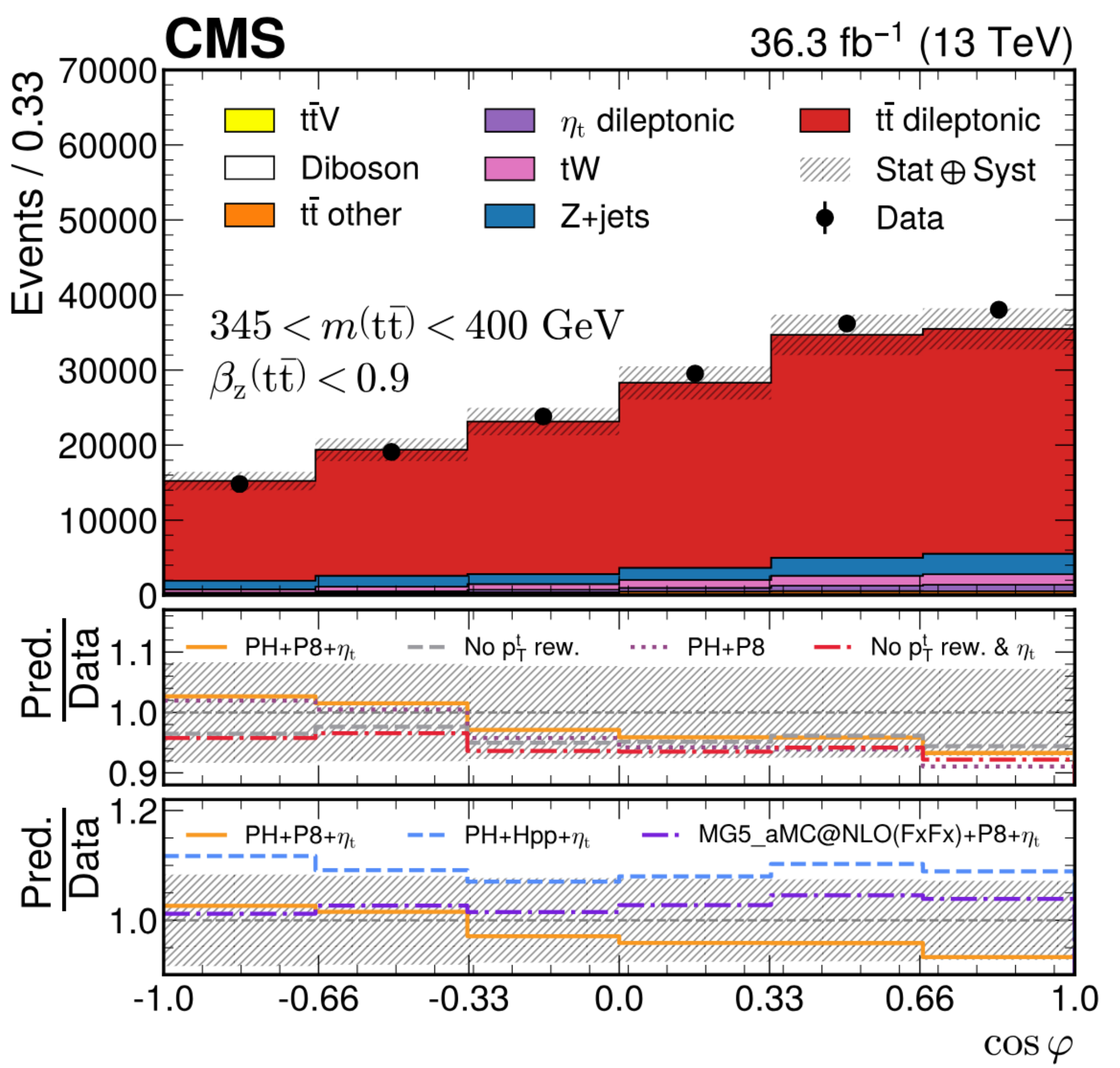
**Mixed samples with (SC) and without (noSC) spin correlations**



# Dilepton results

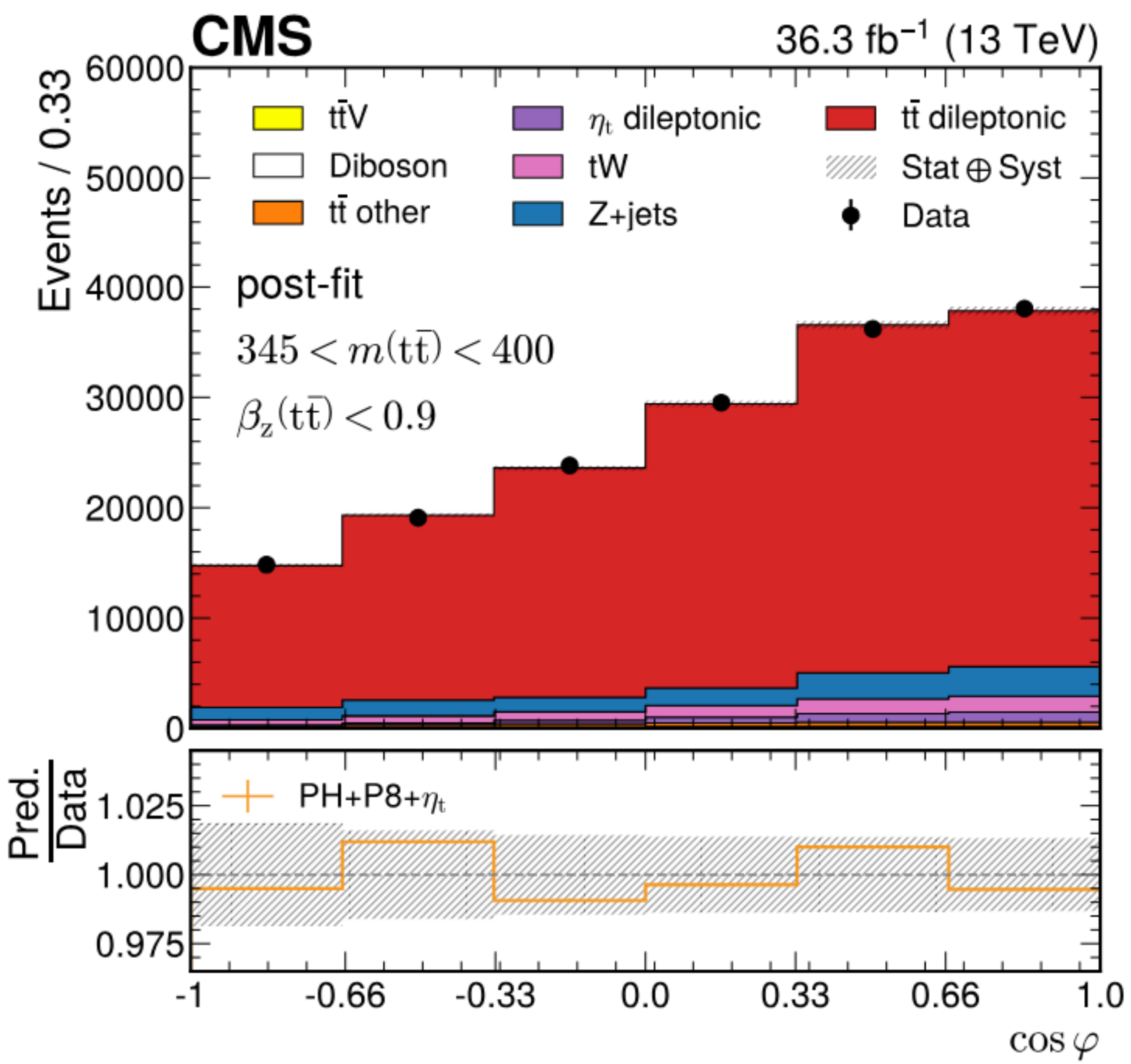
- **Result of the binned profile likelihood fit of the $\cos\varphi$ distribution**
  - ~47500 signal candidates
- **Good agreement with SM predictions**

**Prefit**




→

**Postfit**



# Dilepton results

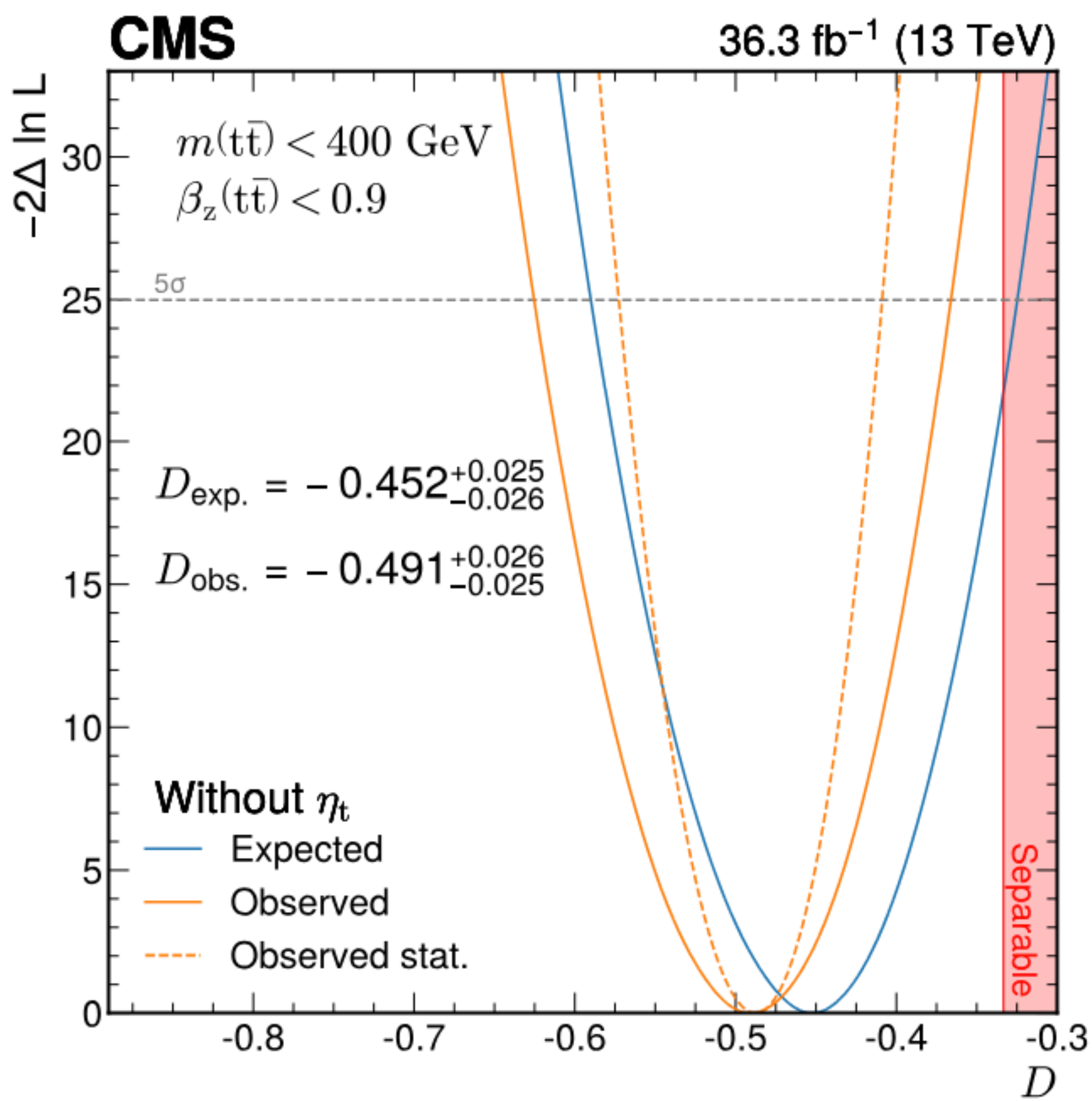
- **Scan of the $-2\Delta lnL$ distribution yields $D$ at parton level, accounting for all detector effects**

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

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

- **Significance: 6.3$\sigma$ obs. (4.7$\sigma$ exp.)**

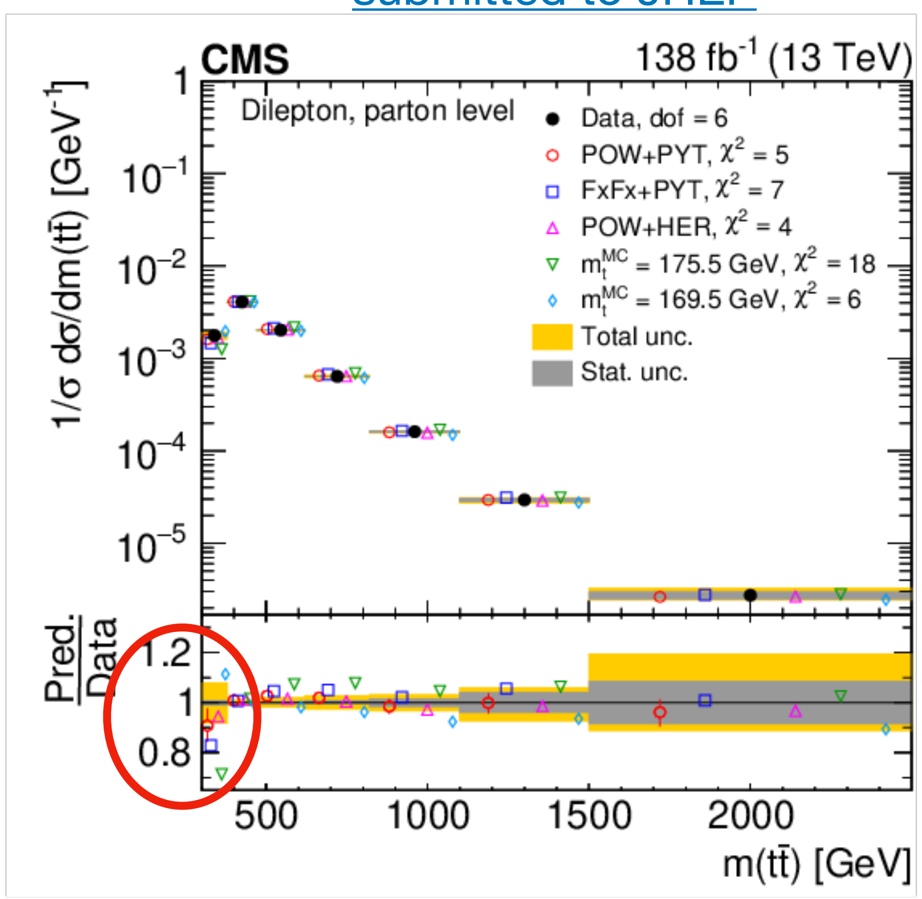
**>5 standard deviations observation of top quarks being entangled at $t\bar{t}$ threshold !**



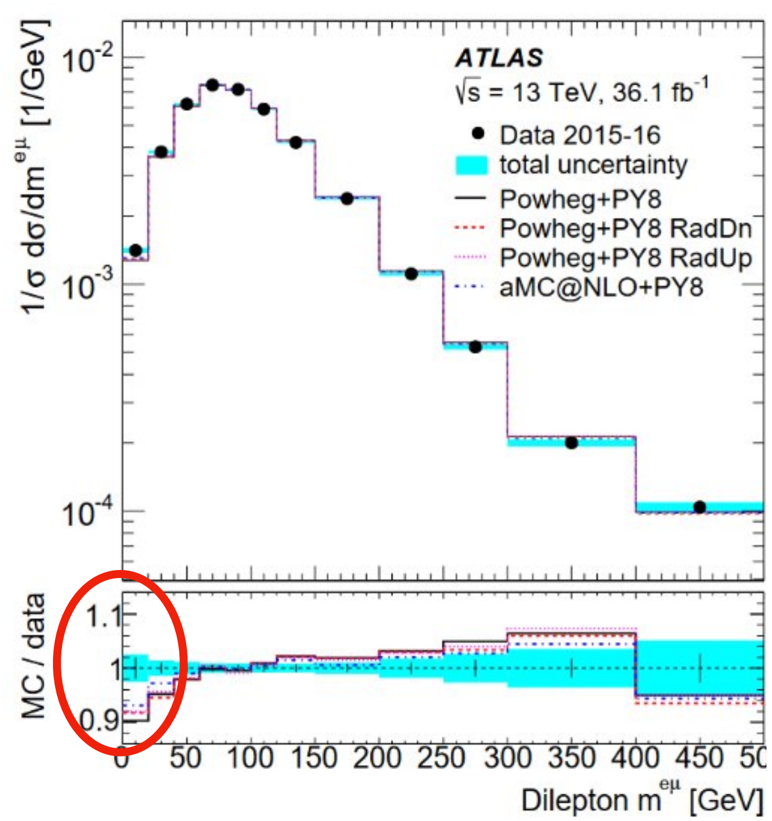
# Threshold region

- **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**

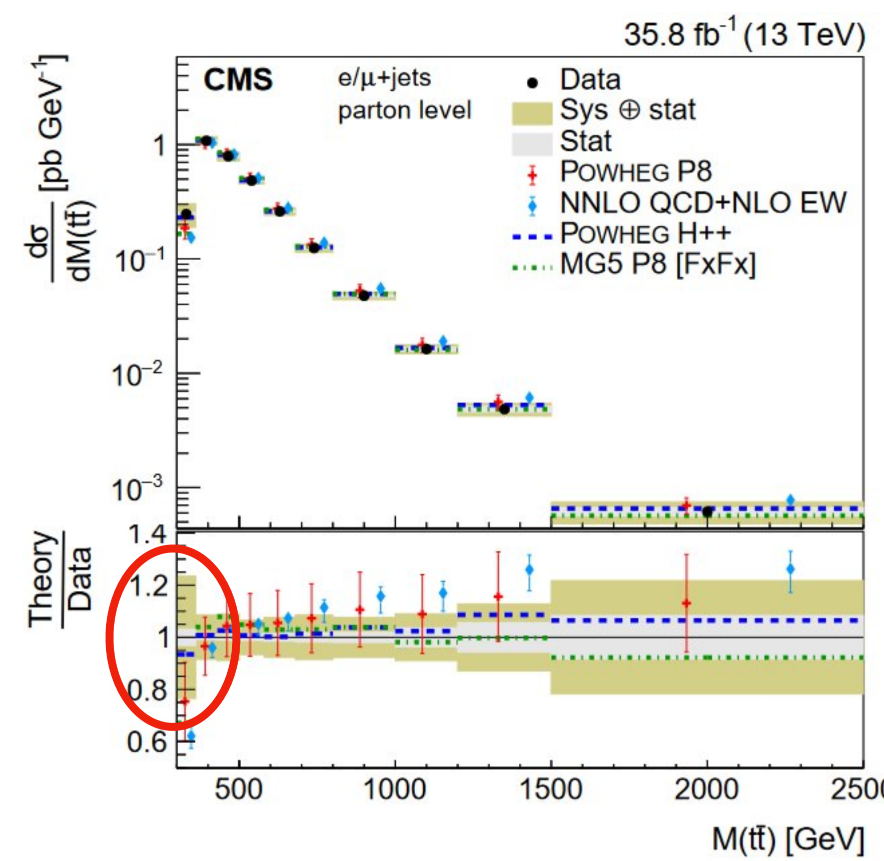
arXiv:2402.08486, submitted to JHEP




EPJ C 80, 6




Phys. Rev. D 97, 112003

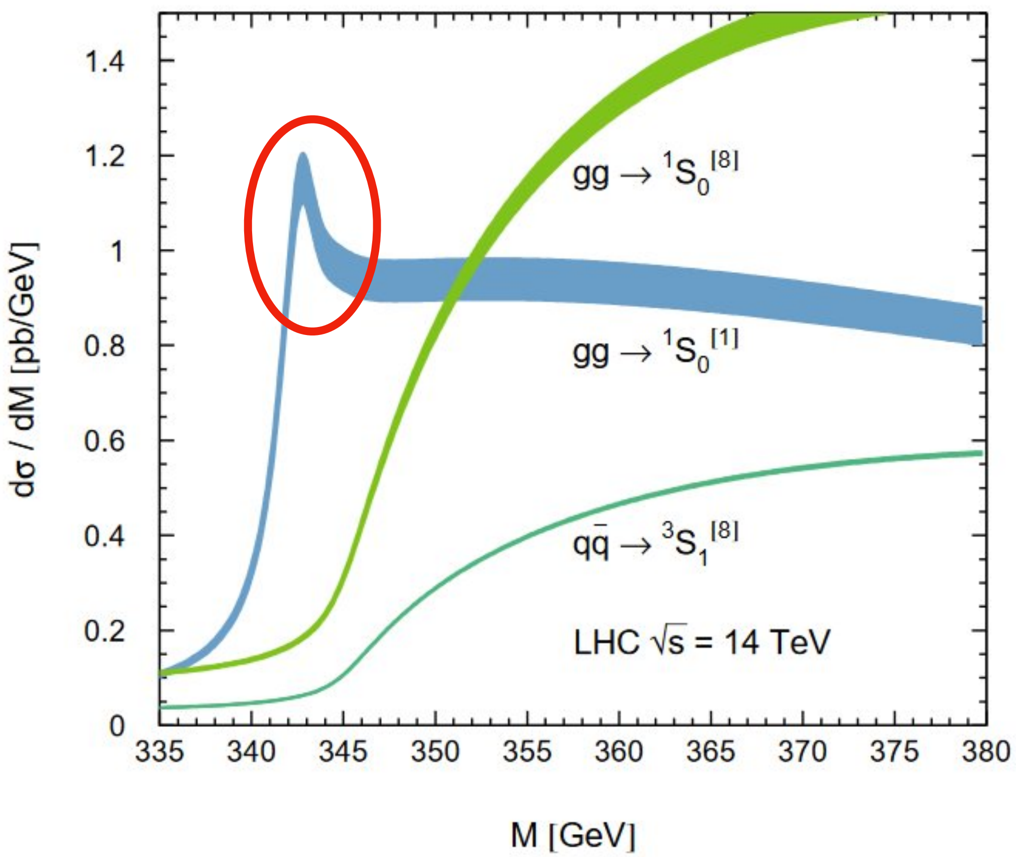


# Threshold region

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

- **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 ?**

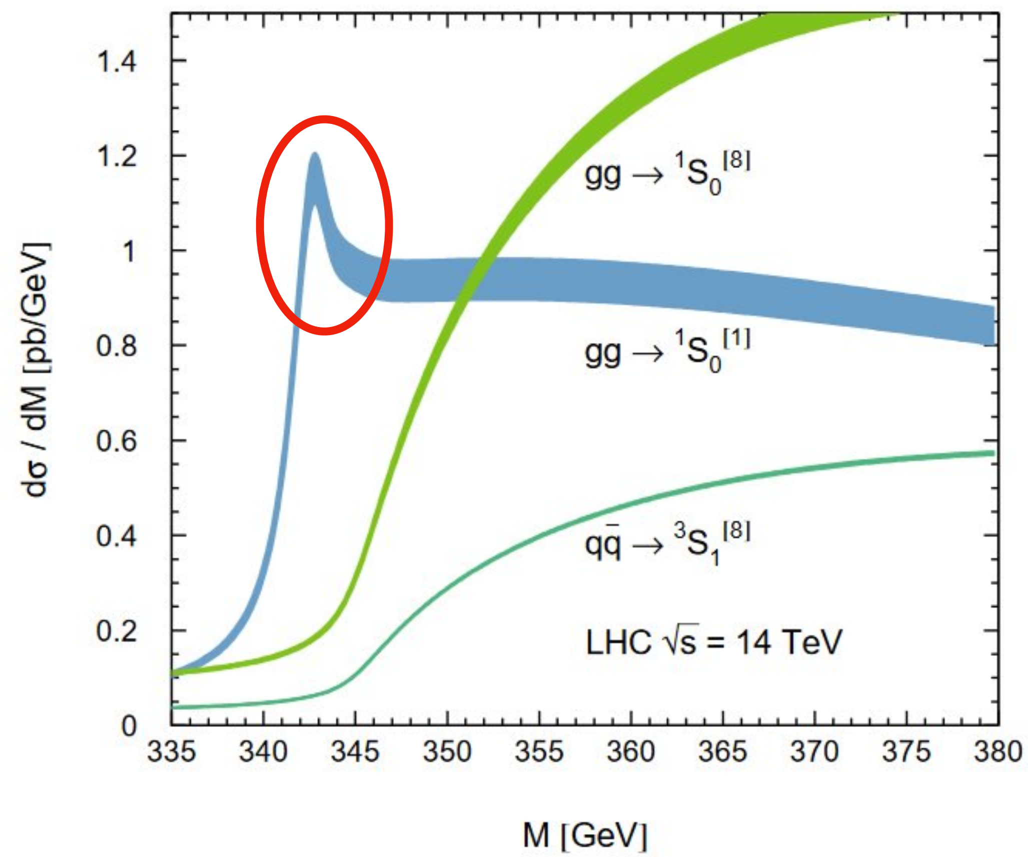


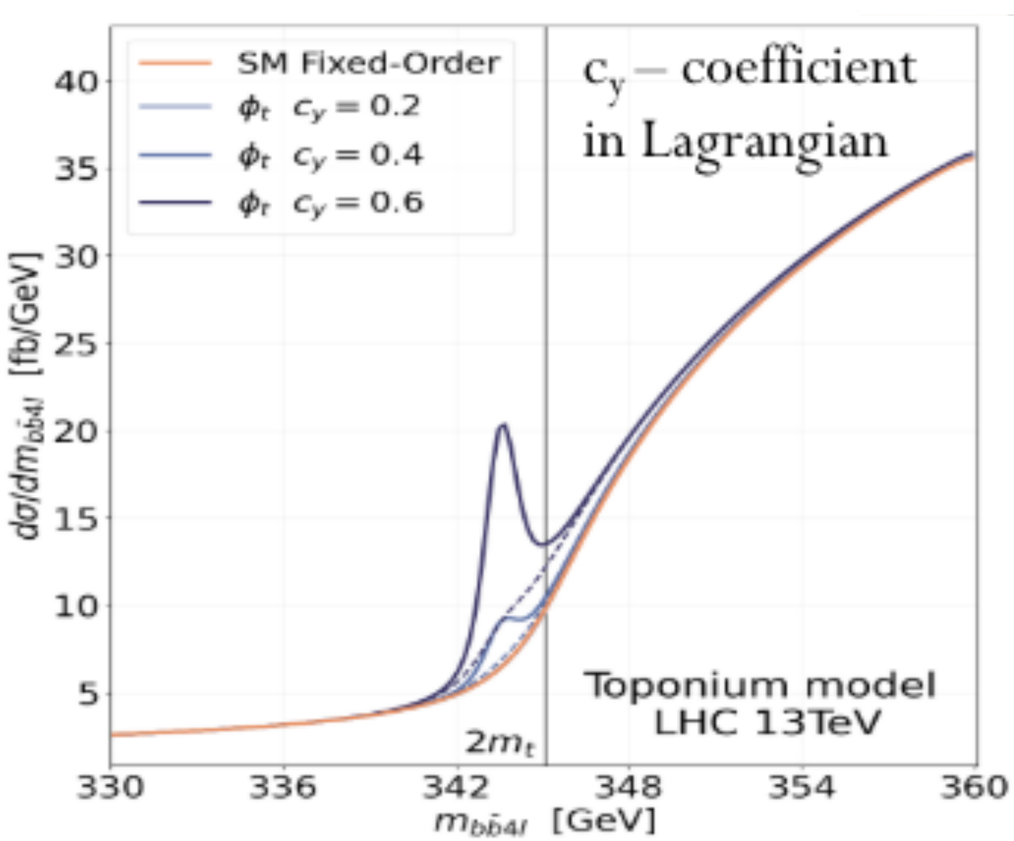
# Threshold region

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

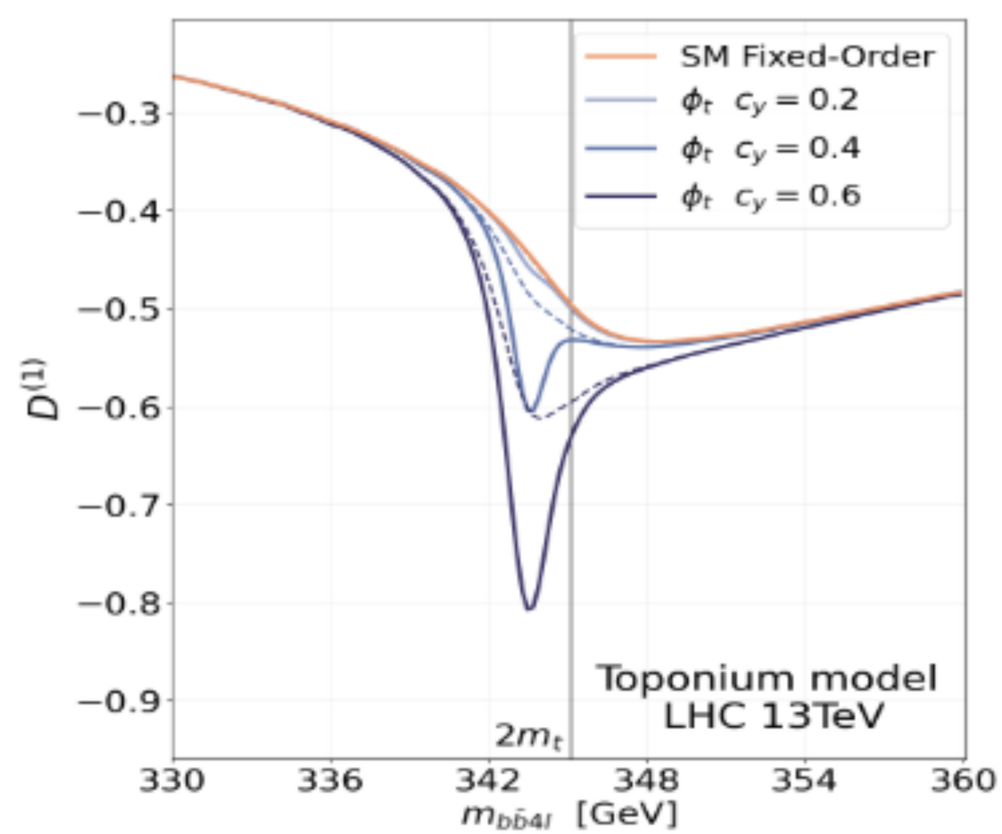
- **NRQCD contributions close to threshold**
  - **toponium:** predicted top quark-antiquark quasi-bound state with a mass of 343 GeV and a width of 7 GeV
- **Excess seen could come from toponium ?**
- It affects the invariant mass distribution and the spin correlations at threshold

→ **inclusion of toponium ($\eta_t$) contributions in our signal model**



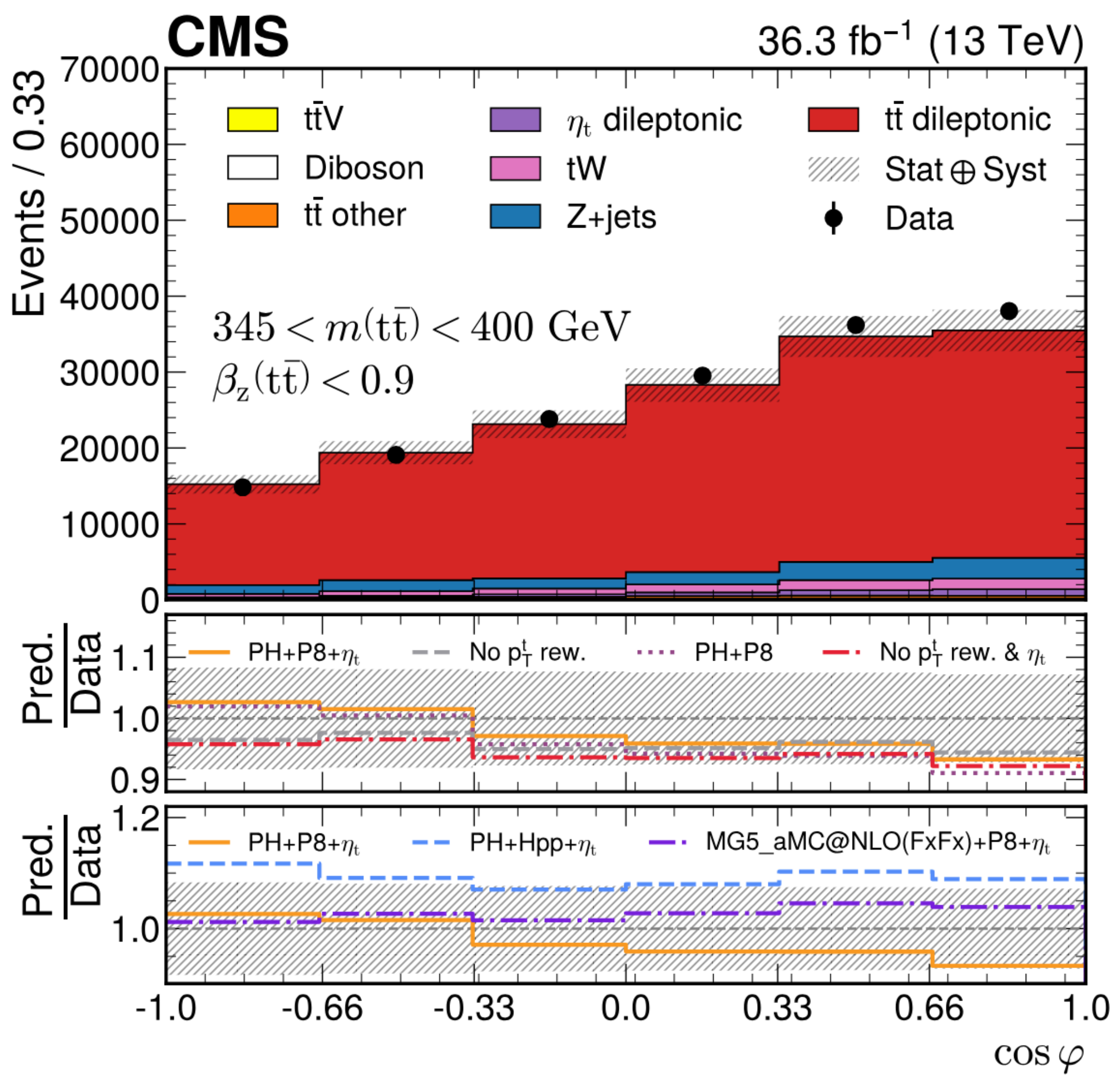

F. Maltoni et al.
JHEP03(2024)099



# Signal model

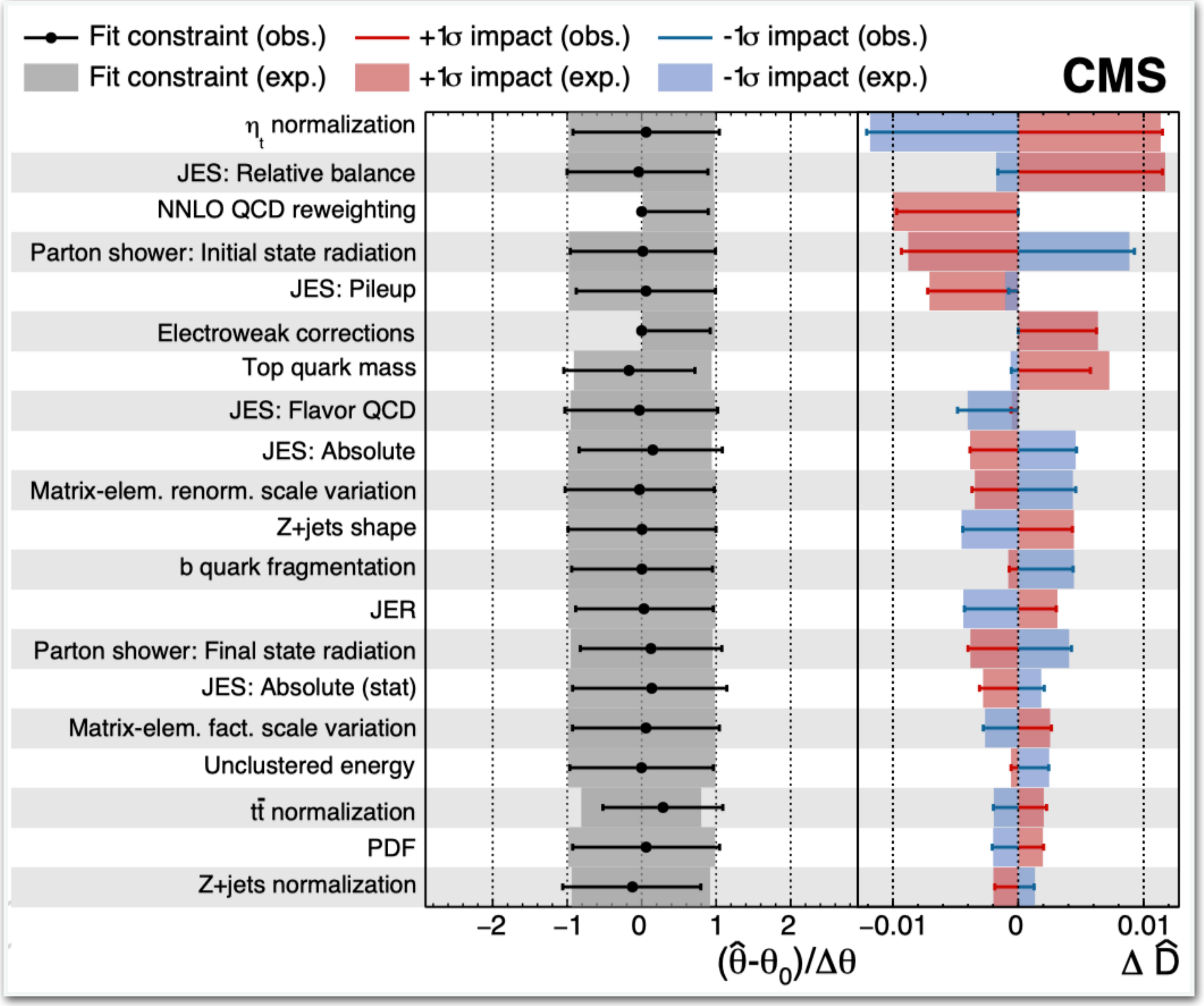
- **Combined signal model: $t\bar{t}$ + toponium ($\eta_t$)**
  - PowhegBox+Pythia8 (NLO) as **nominal $t\bar{t}$ sample**
  - **toponium model** generated with MG5 aMC@NLO(LO)+Pythia8

    B. Fuks et al.
    Phys Rev D 104 034023
    - $337 < m_{\eta_t} < 349$ GeV
    - only pseudoscalar colour singlet and spin-0 $\eta_t$ state accounted for
    - $\eta_t$ improves data modeling in the threshold region



# Dilepton: systematic uncertainties

- **Same uncertainties considered in 2016 spin corr analysis + additional ones for toponium:**
    - *toponium cross section varied by 50%* due to missing octet contributions
    - *binding energy uncertainty varied by ±0.5 GeV*
- **Leading theory-based uncertainties:**
    - Toponium normalization
    - NNLO QCD reweighing
    - Parton Shower
- **Leading experimental uncertainties:**
    - Jet energy scale



# Dilepton results with $\eta_t$

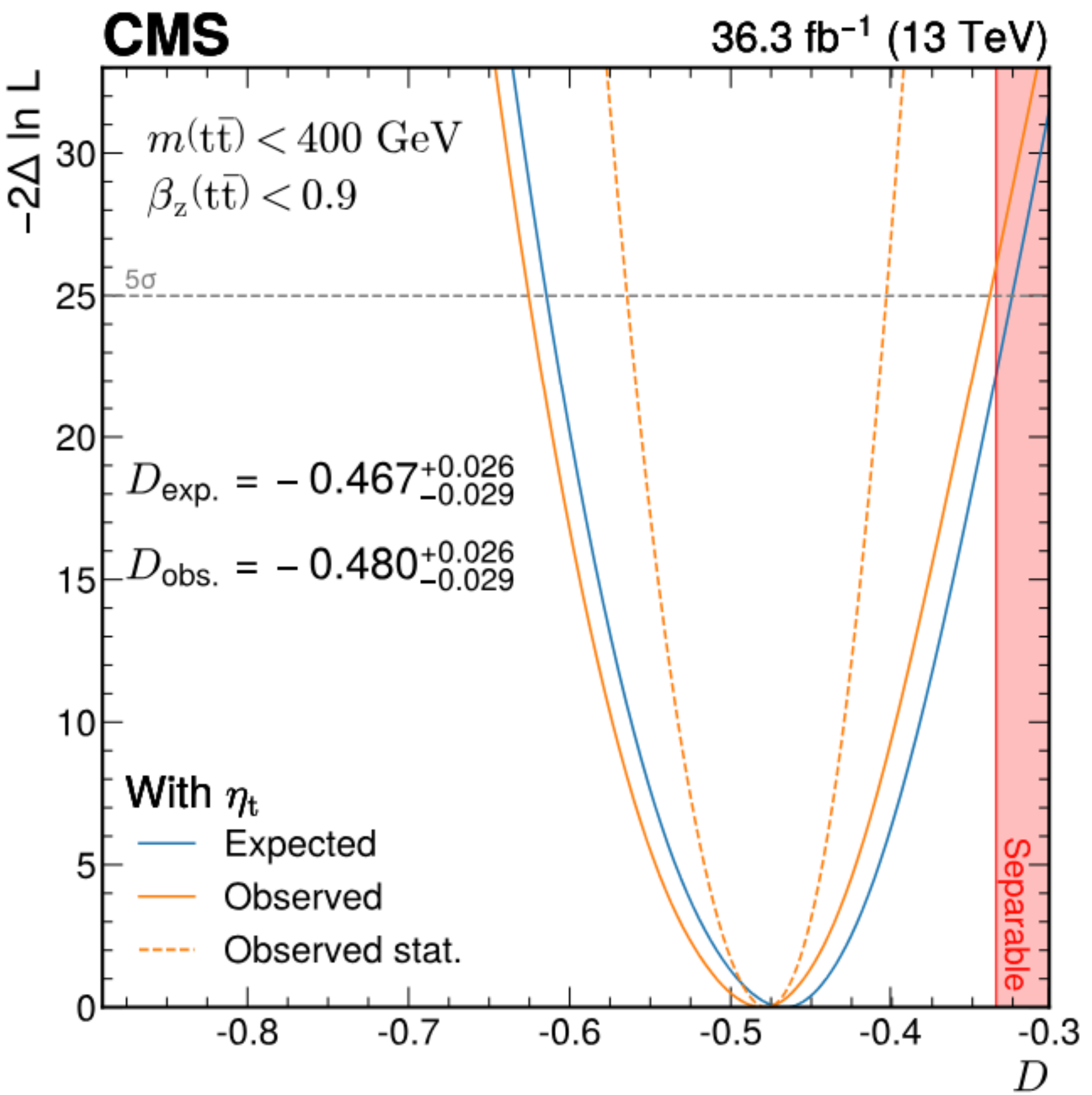
- **Scan of the $-2\Delta lnL$ distribution yields $D$ at parton level, accounting for all detector effects**

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

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

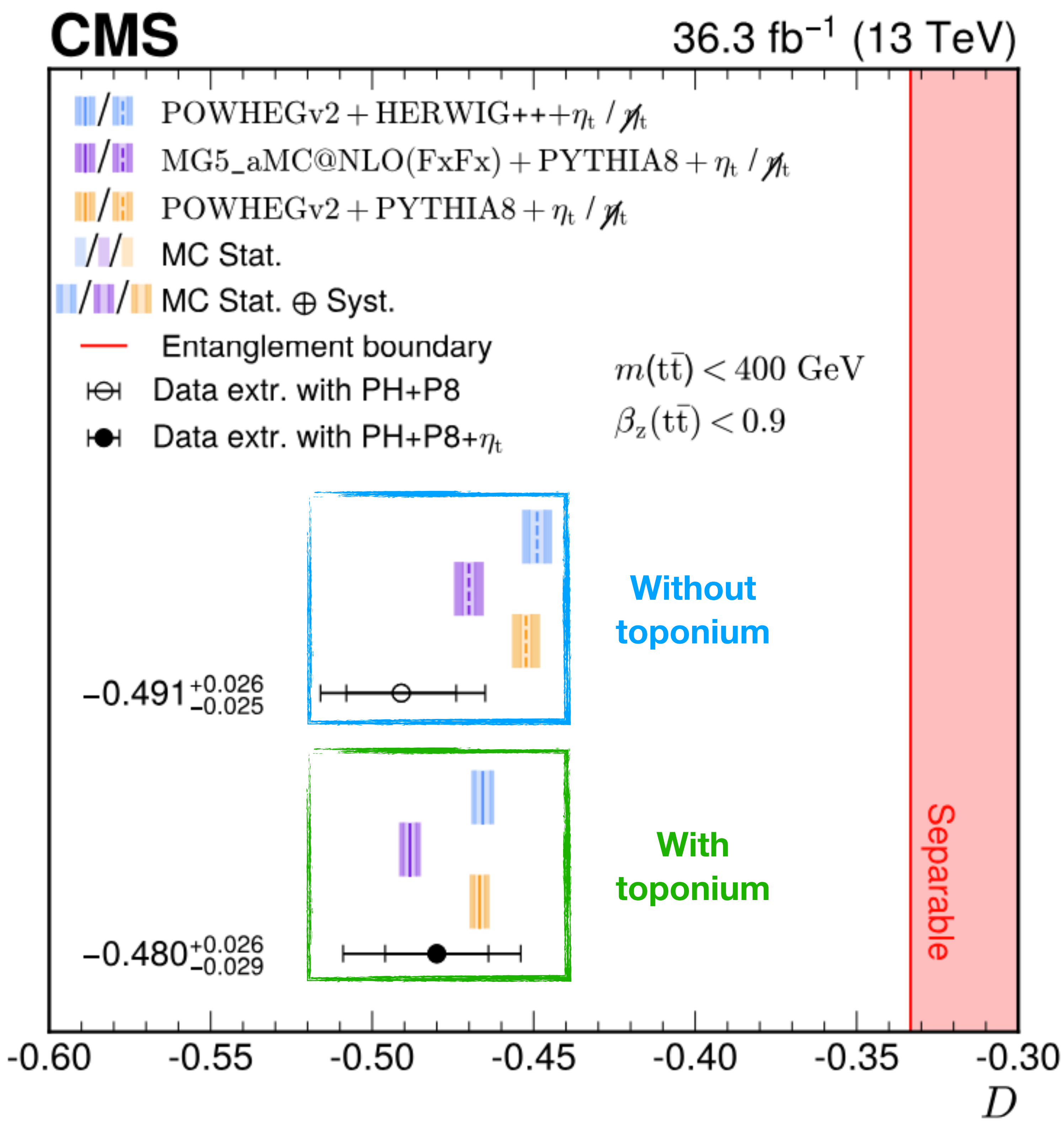
- **Significance: 5.1$\sigma$ obs (4.7$\sigma$ exp.)**

**Reduction of significance but observation > 5$\sigma$ !**

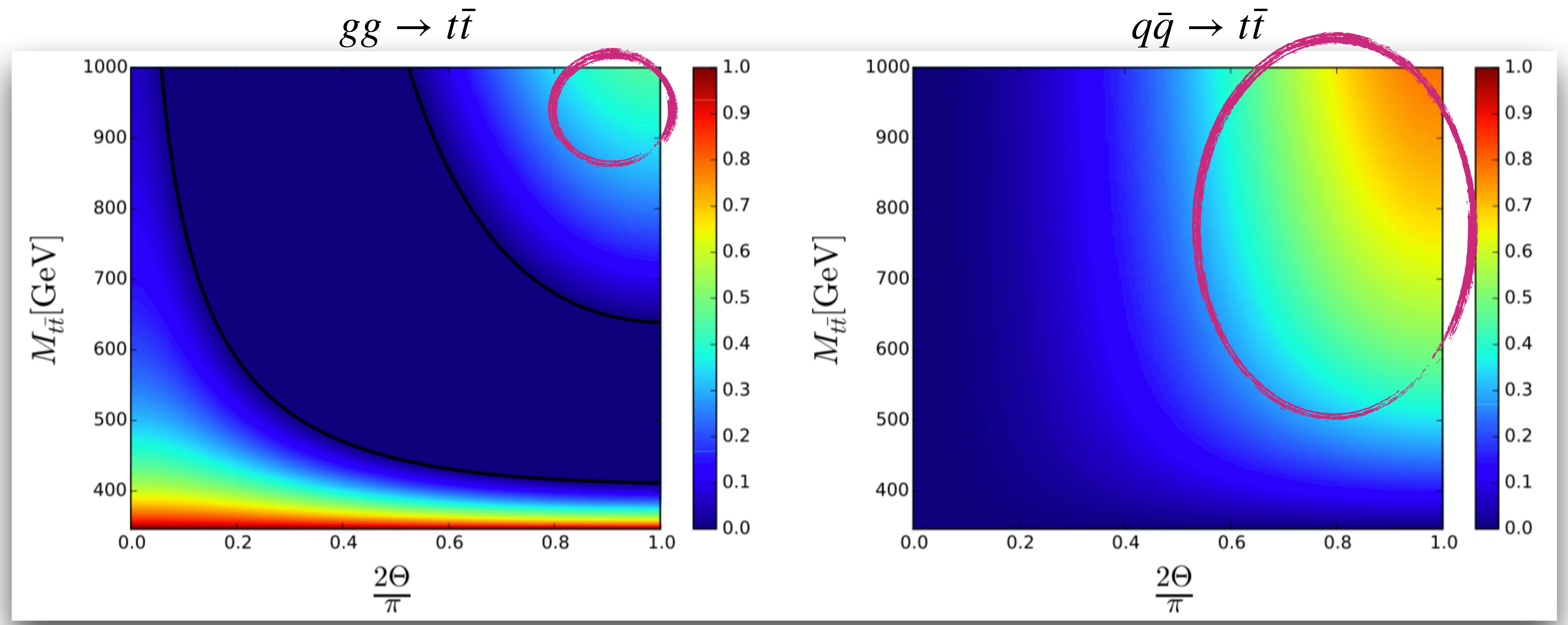


# Dilepton results - summary

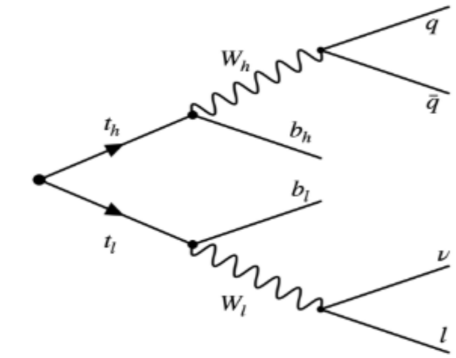
- **Good agreement with SM predictions**
  - **significantly improved with $\eta_t$ inclusion**
  - ~1.5$\sigma$ with the expectation if toponium is not included



# Lepton + jets analysis



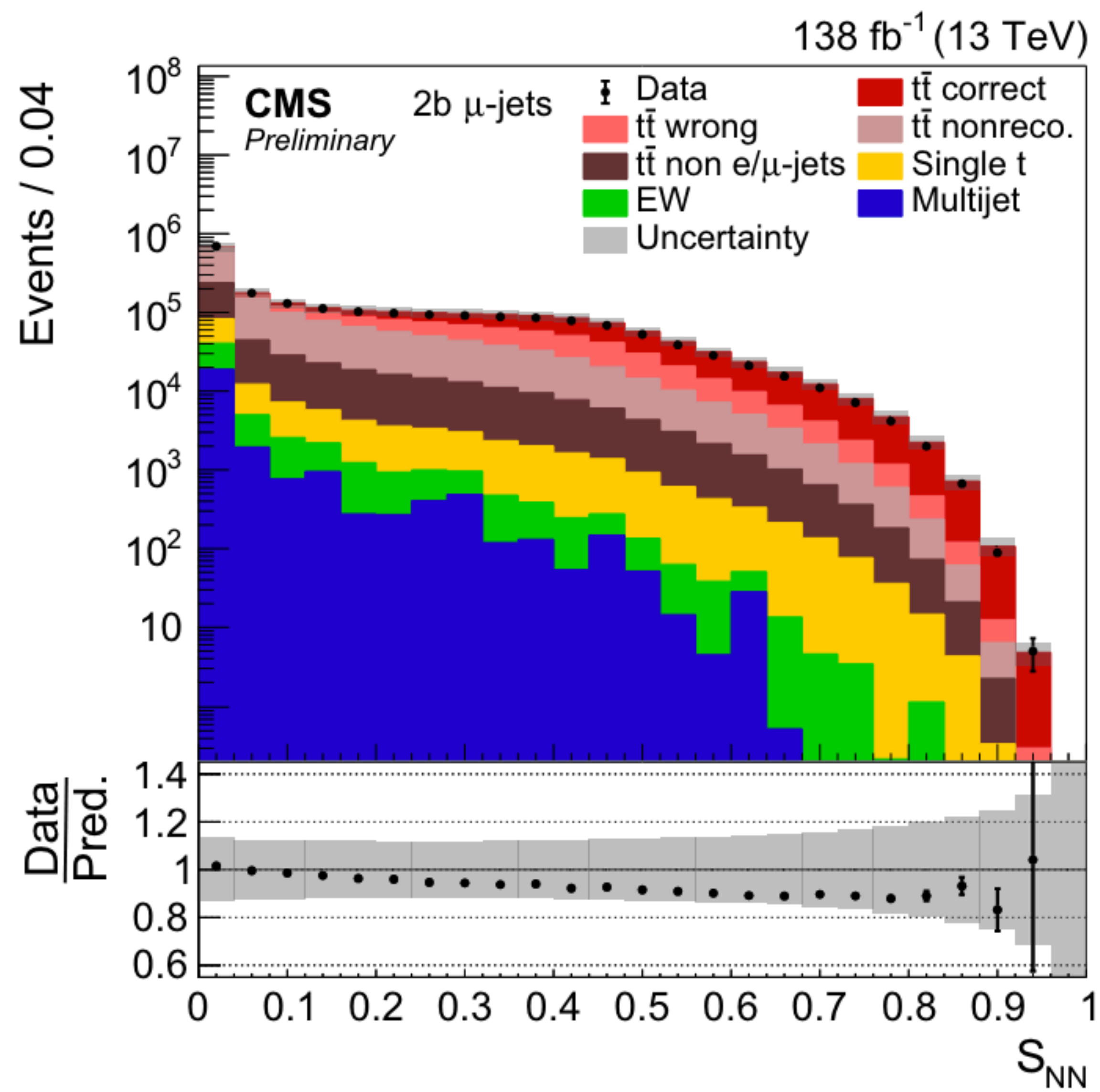
# Lepton + jets: strategy



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

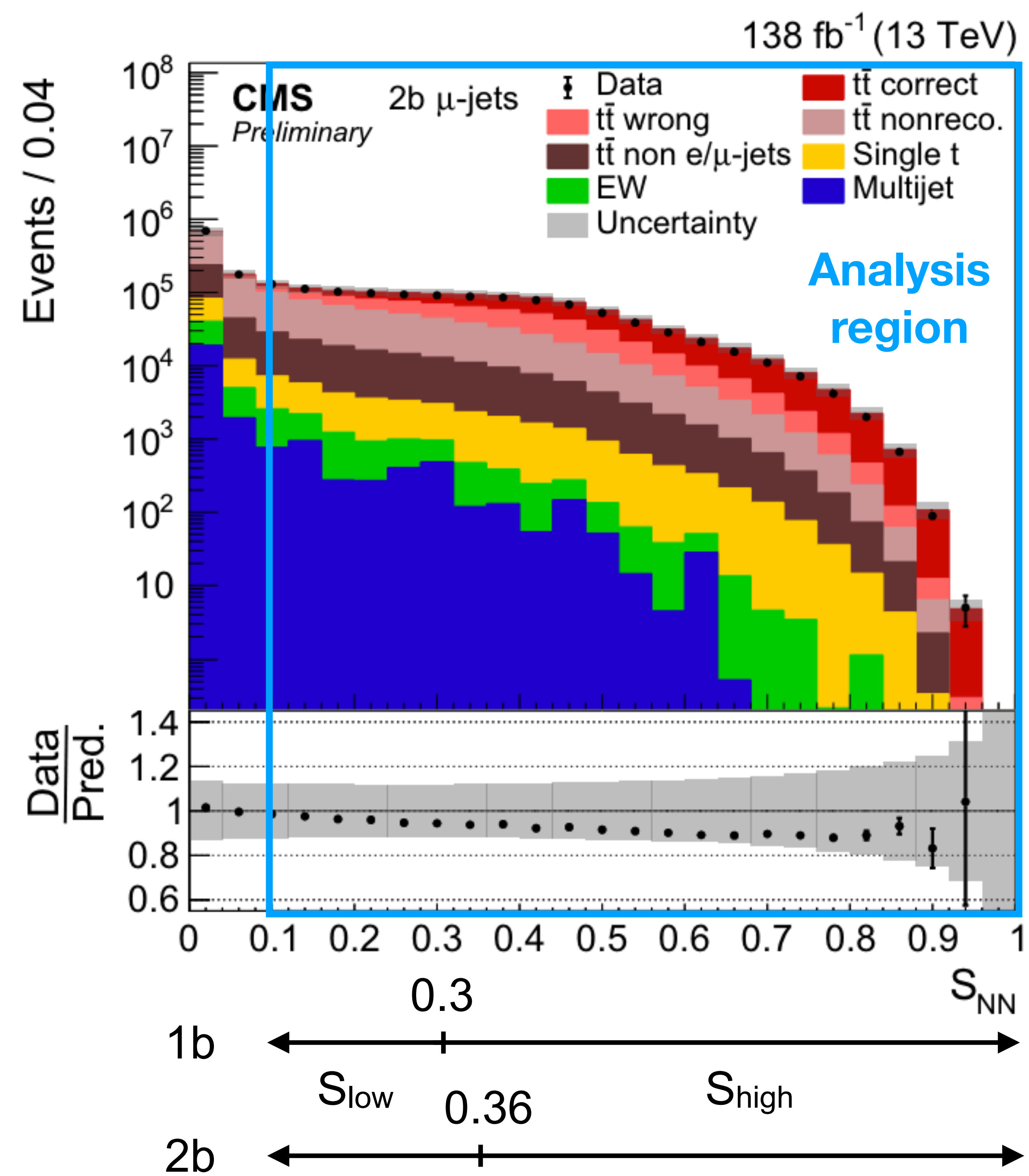
- PowhegBox+Pythia8 (NLO) as **nominal $t\bar{t}$ sample**
  - inclusion of **EWK corrections at NLO** with HATHOR [Comput. Phys. Commun. 182 (2011) 10]
  - **reweighting to NNLO QCD calculations** [PRL 127 (2021) 062001]
    - NN-based reweighting to match NNLO distributions at reconstruction level

- **Main background sources:**
  - single top quark
  - DY+jets
  - W+jets
  - QCD multijet production



# Lepton + jets: strategy

- **Artificial NN used to reconstruct the $t\bar{t}$ system in each event**
- **Remove events with NN score $S_{NN}$<0.1**
  - due to the low fraction of correctly reconstructed events and the large contribution of background processes
- Events divided into **categories based on lepton flavor, number of b-tags, and NN score**



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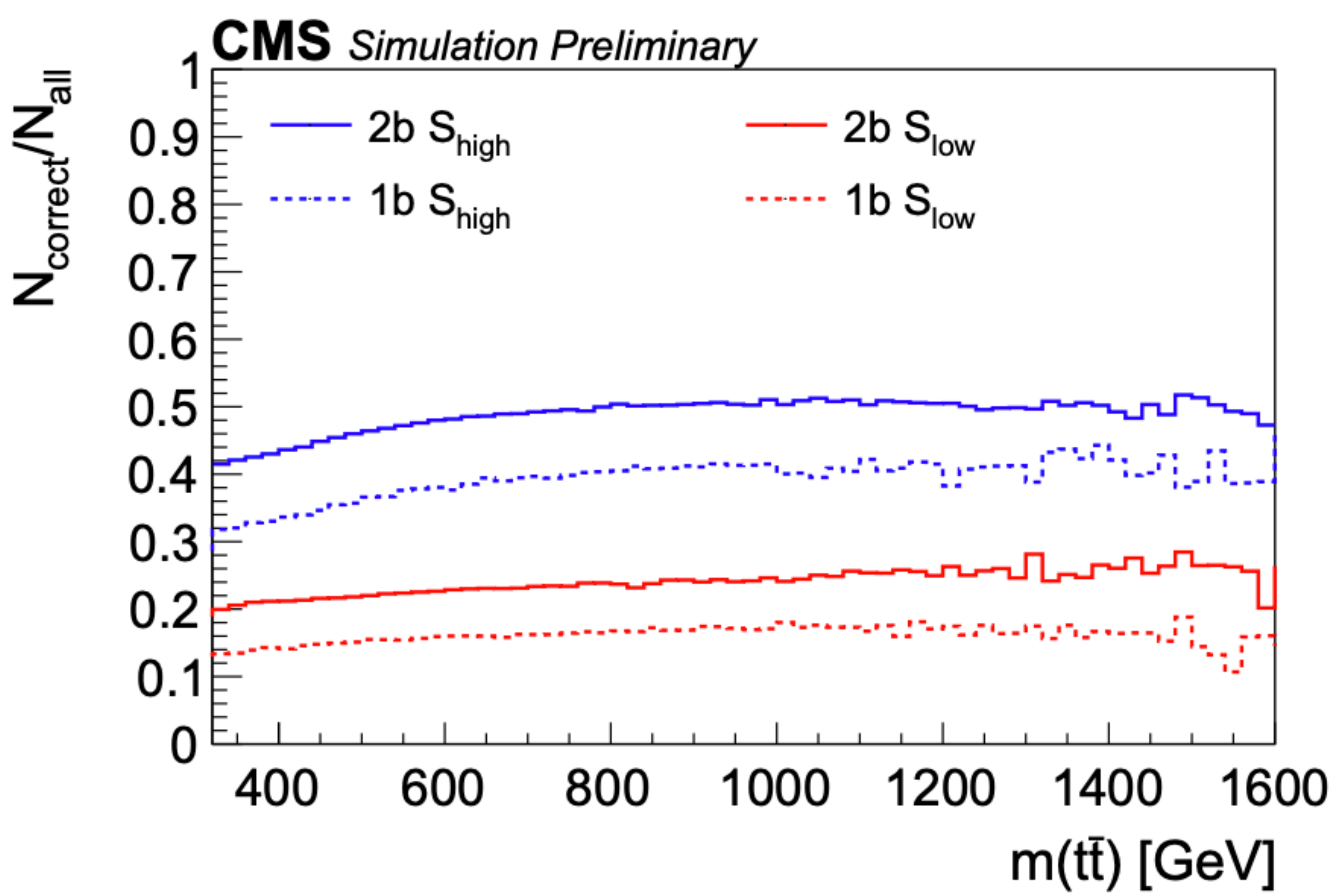
- **Artificial NN used to reconstruct the $t\bar{t}$ system in each event**
- **Remove events with NN score $S_{NN}$<0.1**
  - due to the low fraction of correctly reconstructed events and the large contribution of background processes
- Events divided into **categories based on lepton flavor, number of b-tags, and NN score**
- **50% correct jet assignment** (including correct d-type quark) **in 2b $S_{high}$ region**
- All polarization and spin correlation coefficients extracted simultaneously by performing a binned **maximum likelihood fit** to the data

Fraction of events reconstructed with correctly assigned jets to partons including d-type quark



# Lepton + jets: fit strategy

- The total cross section is a **linear combination of $\Sigma_m$ templates** with P and C coefficients $Q_m$:

$$\Sigma_{tot} = \Sigma_0 + \Sigma_{m=1}^{15} Q_m \Sigma_m$$

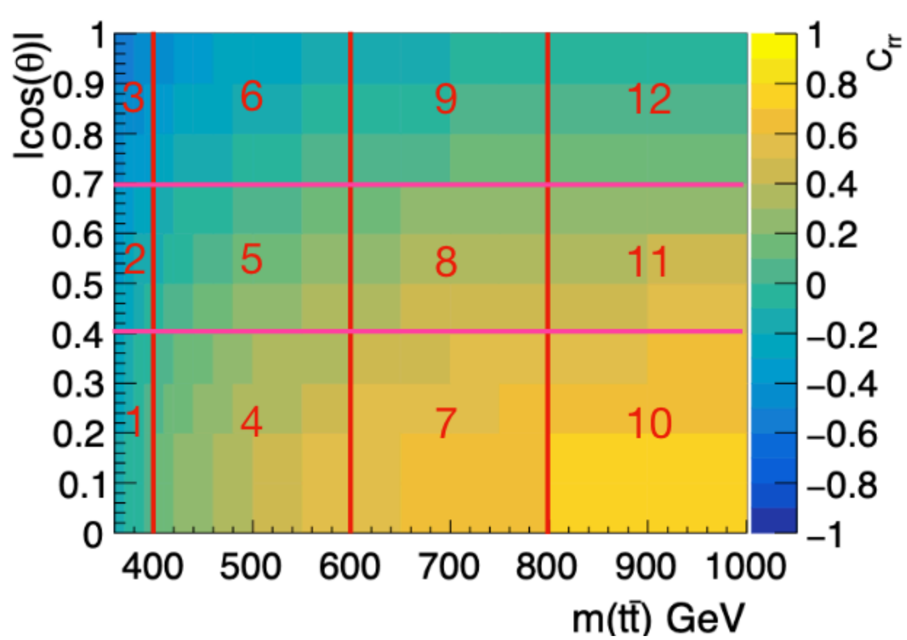
$$\Sigma_m = \sigma_{norm}\{\sin\theta_p \cos\phi_p, \sin\theta_p \sin\phi_p, \ldots, \cos\theta_p \cos\theta_{\bar{p}}\}$$

$Q_m$ can be extracted by fitting $\Sigma_{tot}$

- **Events are reweighted at the generator level**

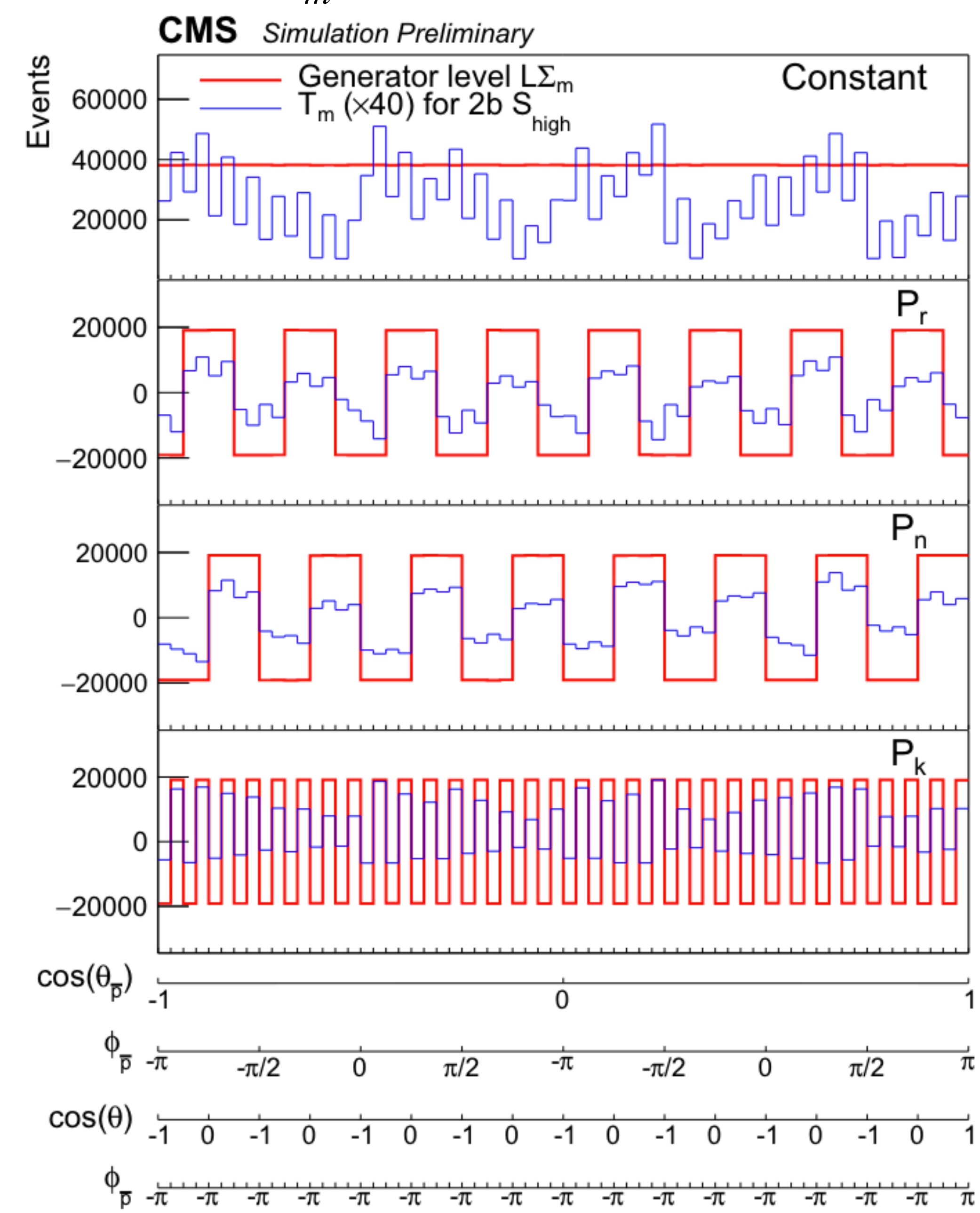
$$w_m = \frac{\Sigma_m}{\Sigma_{tot}}$$

- To minimize bias due to variations of $T_m$ within a bin, measurements are performed in **sufficiently small bins**

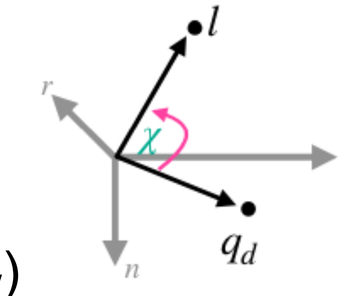



$L\Sigma_m$ = templates used at gen level

$T_m$ = templates defined at reco level

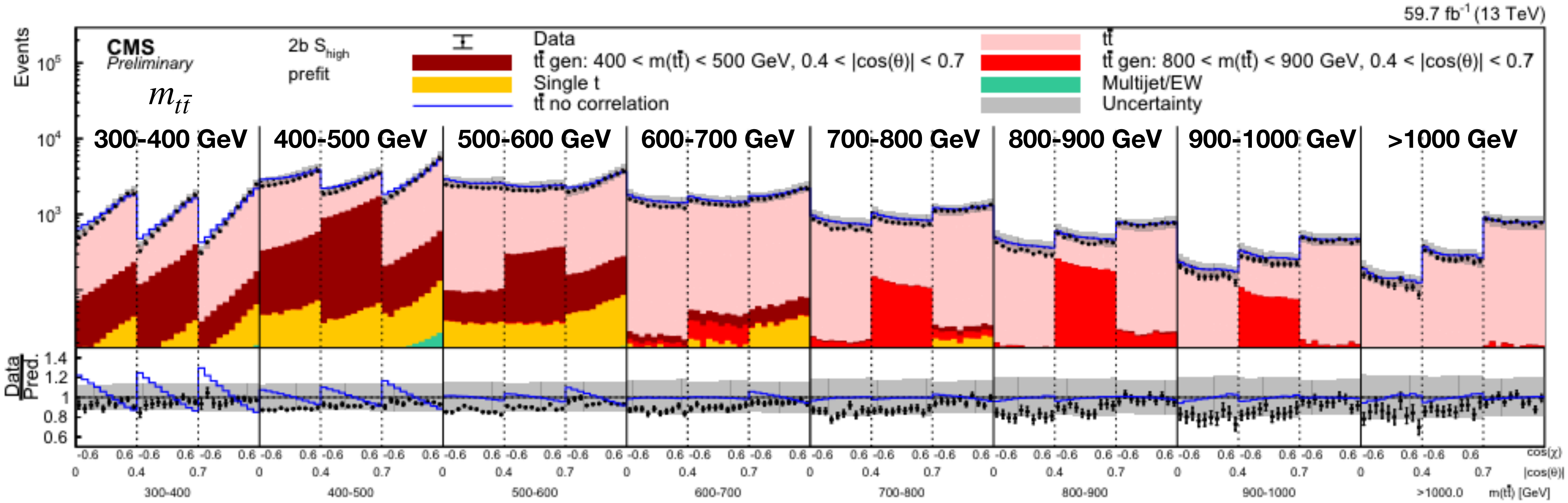


# Lepton+jets: fit




- **Maximum likelihood fit** combining information of the four 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

**Prefit**

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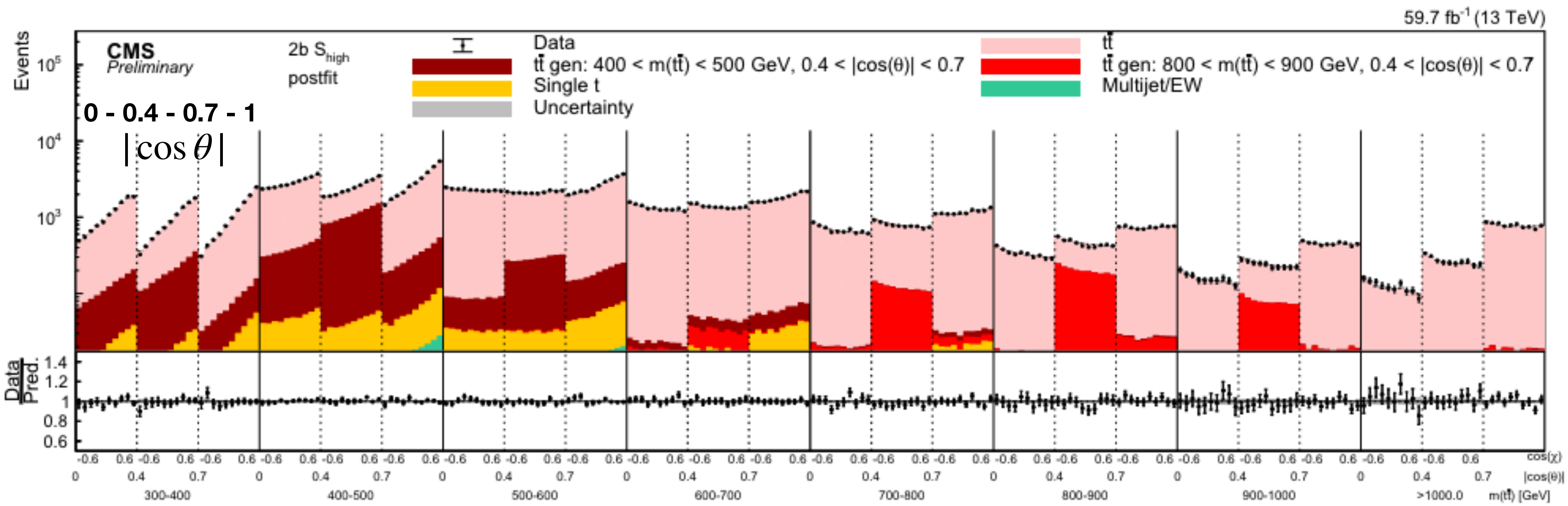
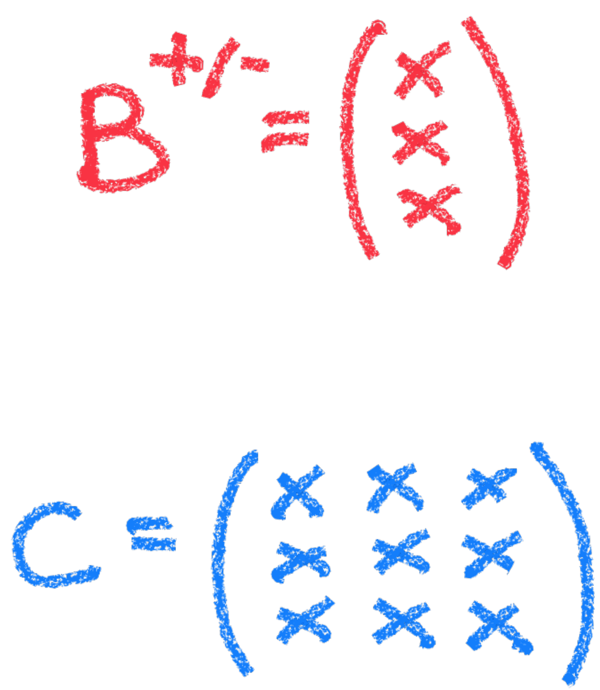
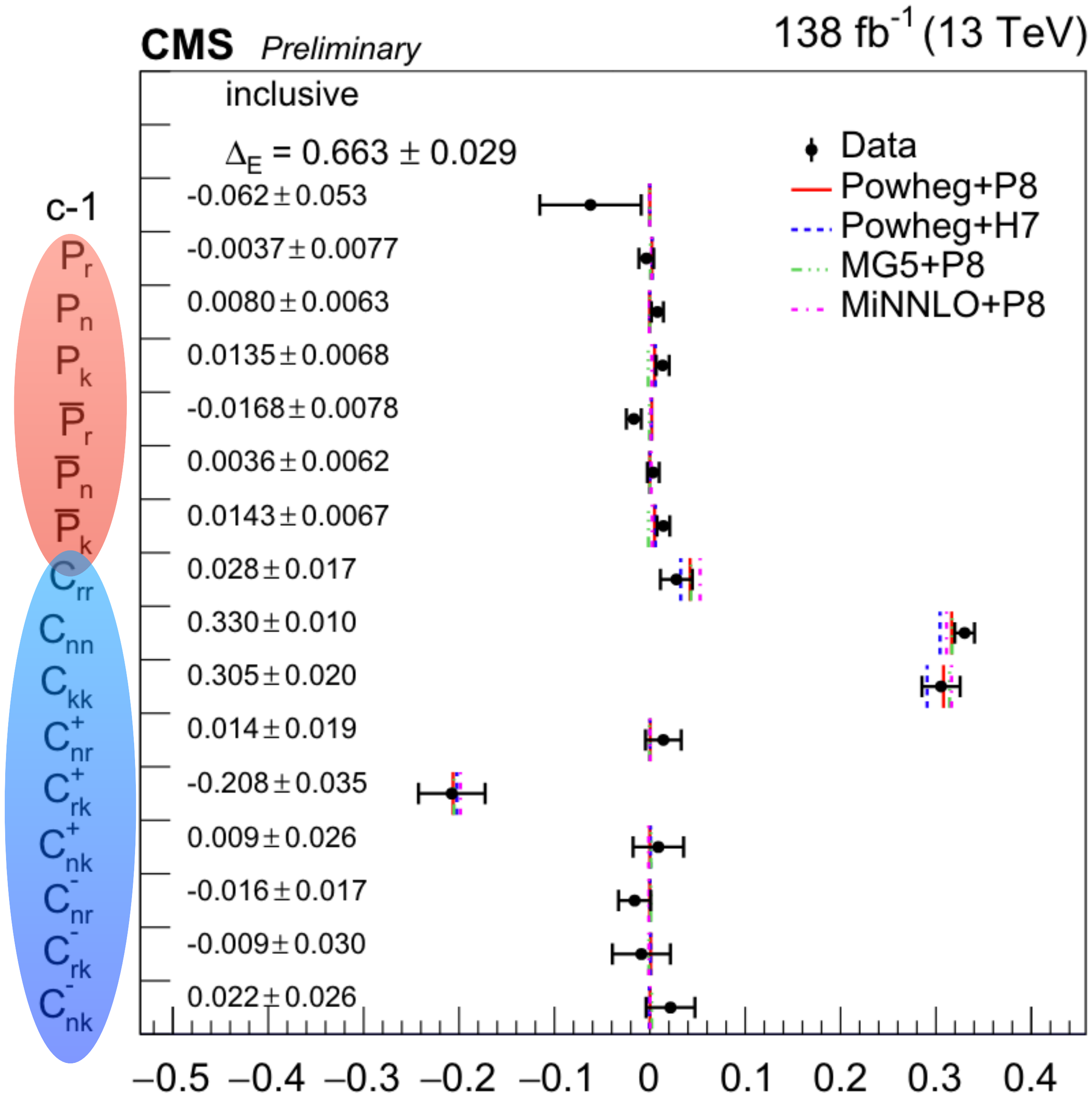
**Postfit**



# Lepton+jets results: full matrix

- **Full measurement of P and C performed inclusively and differentially**
- **Good agreement with SM prediction**

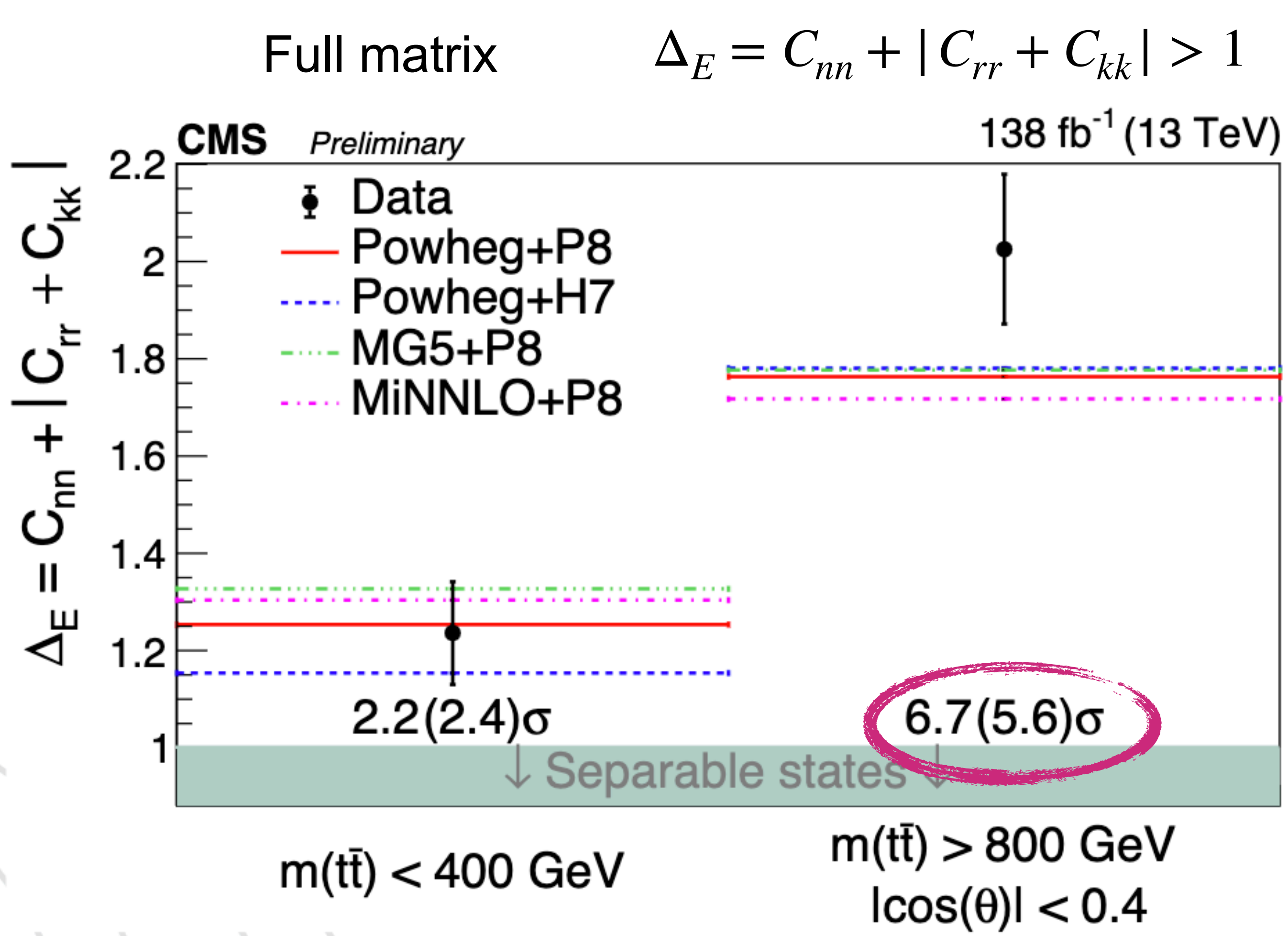



Inclusive from $m_{t\bar{t}}$ vs $|\cos\theta|$

# Lepton+jets: entanglement

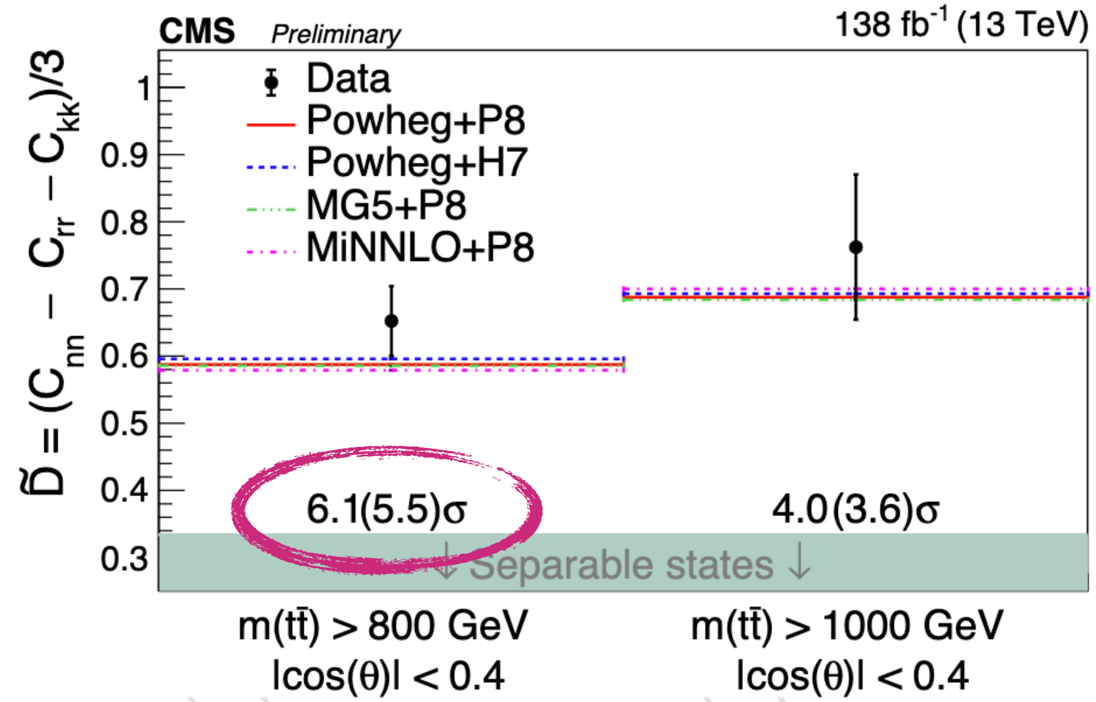
- **Entanglement observed for first time in space-like separated events!**



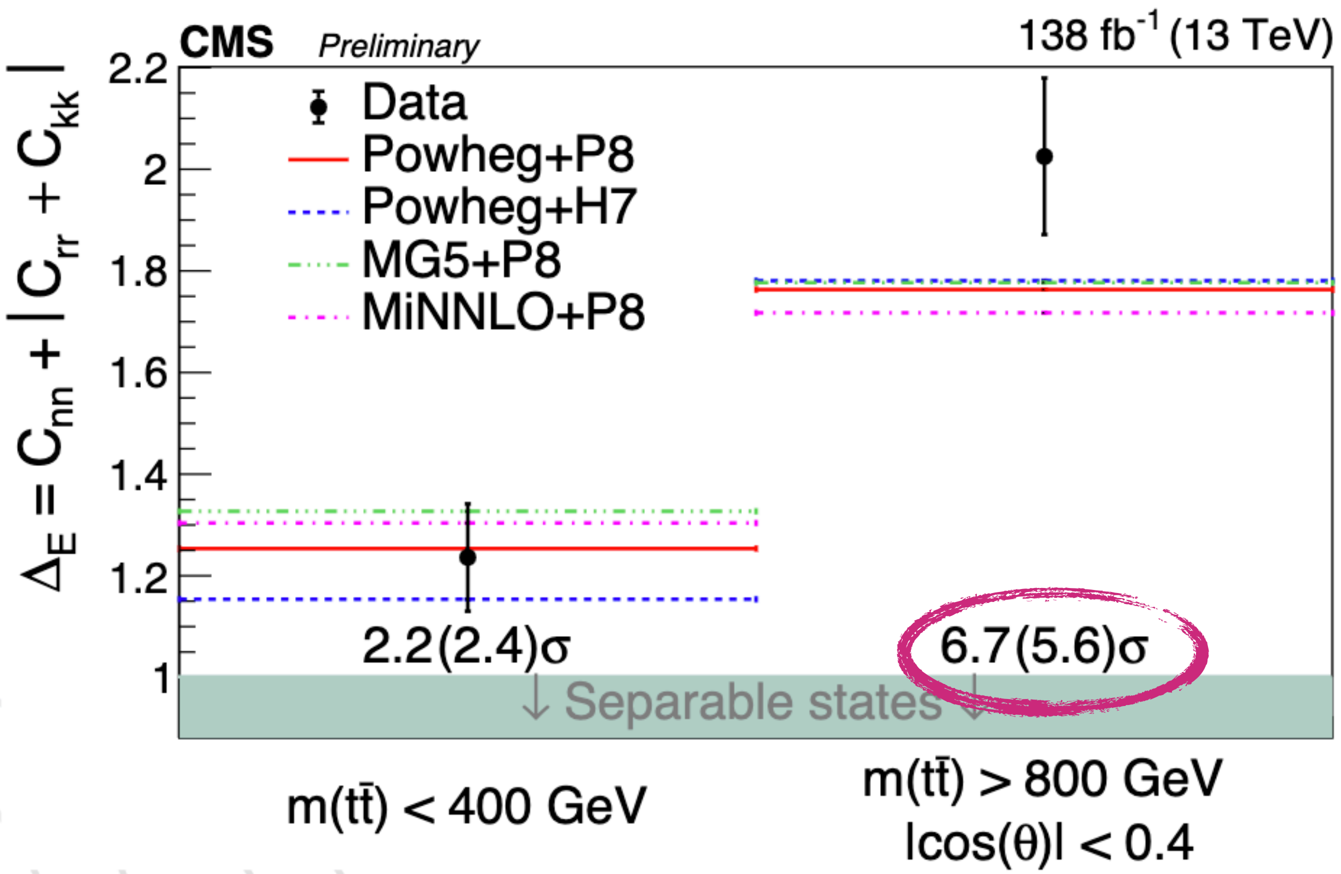
# Lepton+jets: entanglement

- **Entanglement observed for first time in space-like separated events!**
  - highest sensitivity in full matrix measurement

High $m_{t\bar{t}}$ $\tilde{D} > 1/3$



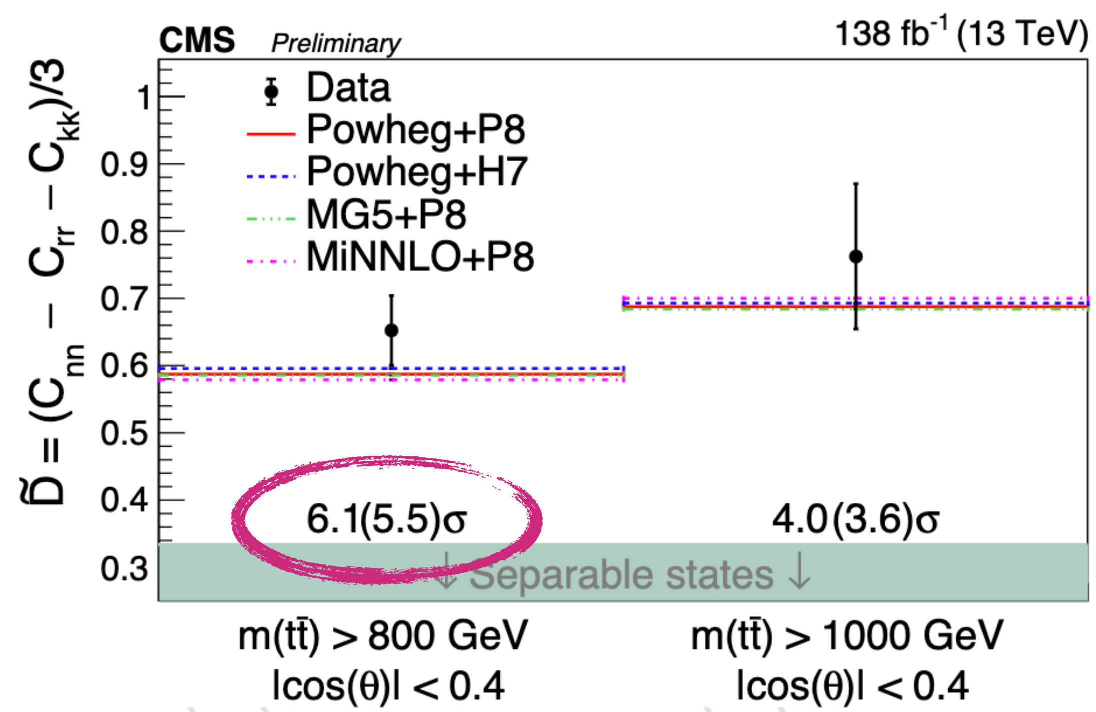

Full matrix $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$



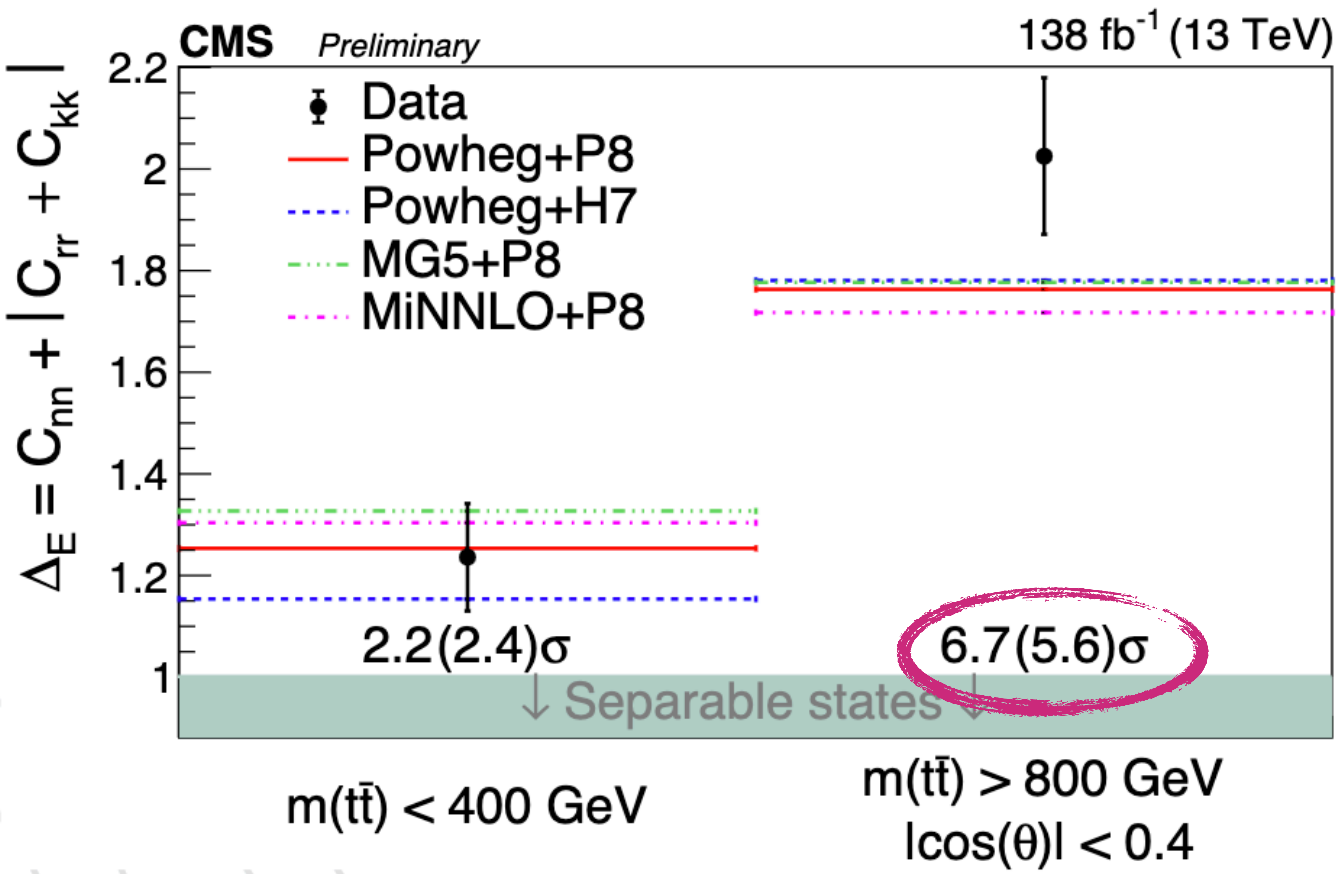
# Lepton+jets: entanglement

- **Entanglement observed for first time in space-like separated events!**
  - highest sensitivity in full matrix measurement
- No sensitivity in low $m_{t\bar{t}}$ region

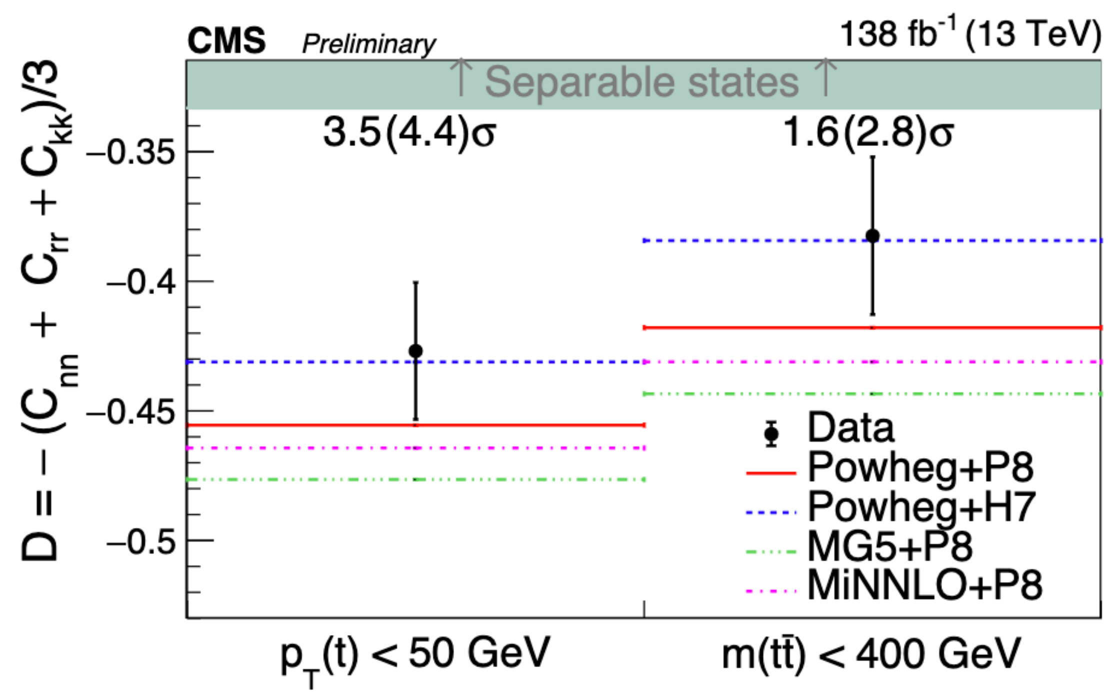
High $m_{t\bar{t}}$ $\tilde{D} > 1/3$




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

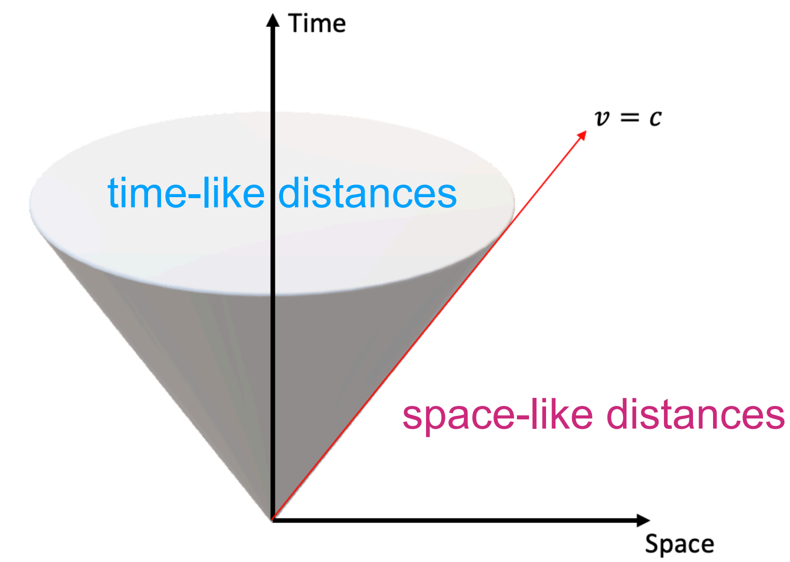



Low $m_{t\bar{t}}$ $D < -1/3$



# Excluding classical explanation

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

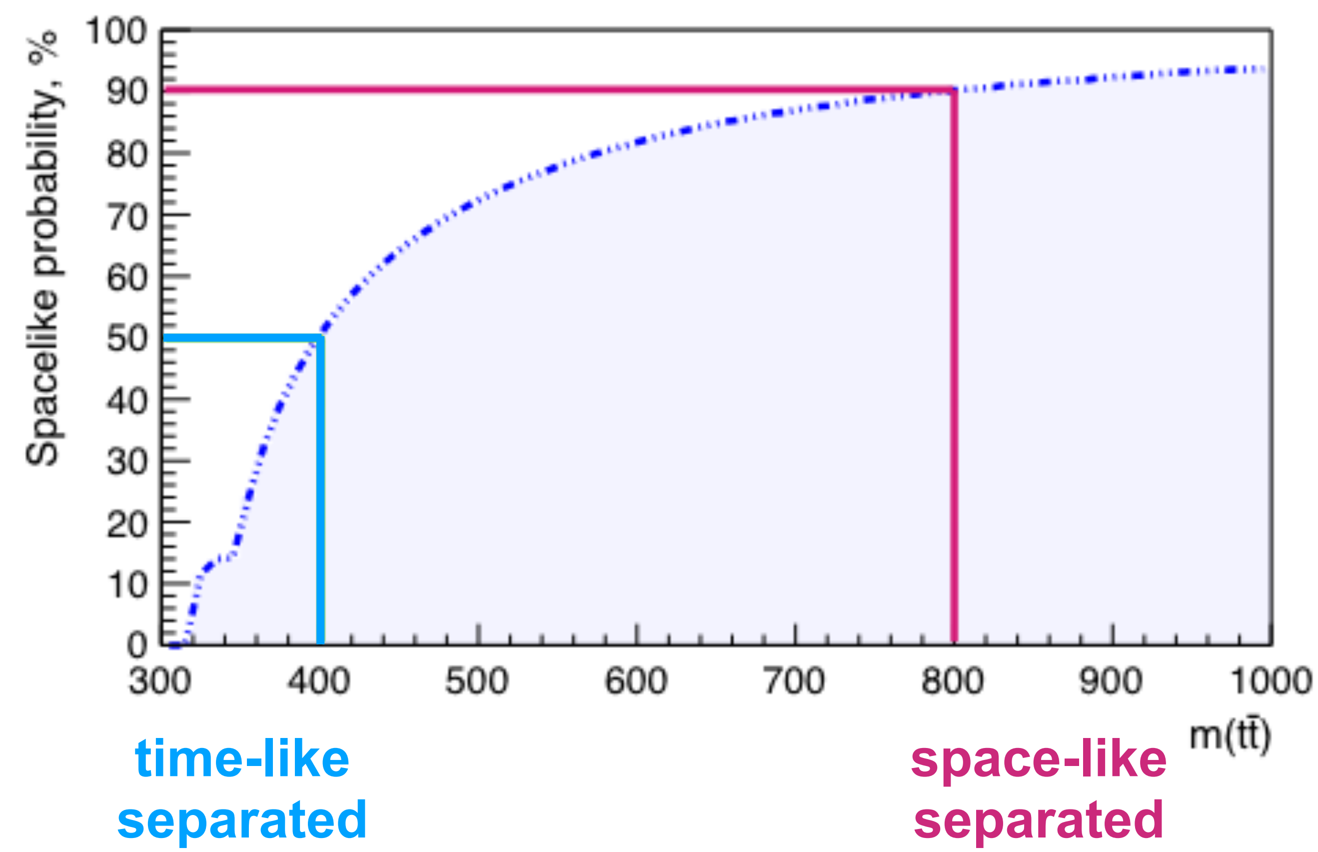



- What is the maximum value of $\Delta_E$ that can still be explained by non-quantum communication ($v \leq c$)?
  - time-like separated events: ΔE max = 3 ($C_{ii}$ = 1)
  - space-like separated events: ΔE sep = 1

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

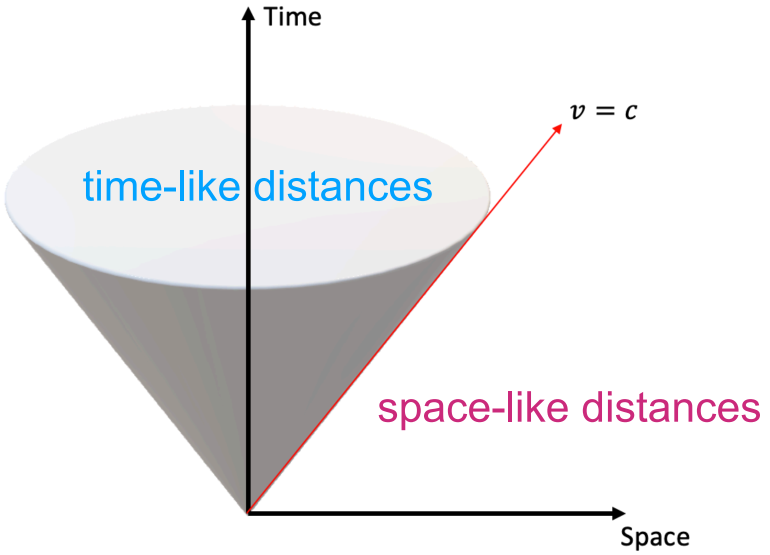
$$\Delta_{\mathrm{E\,crit}} = f\Delta_{\mathrm{E\ sep}} + (1-f)\Delta_{\mathrm{E\ max}}$$

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



# Excluding classical explanation

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

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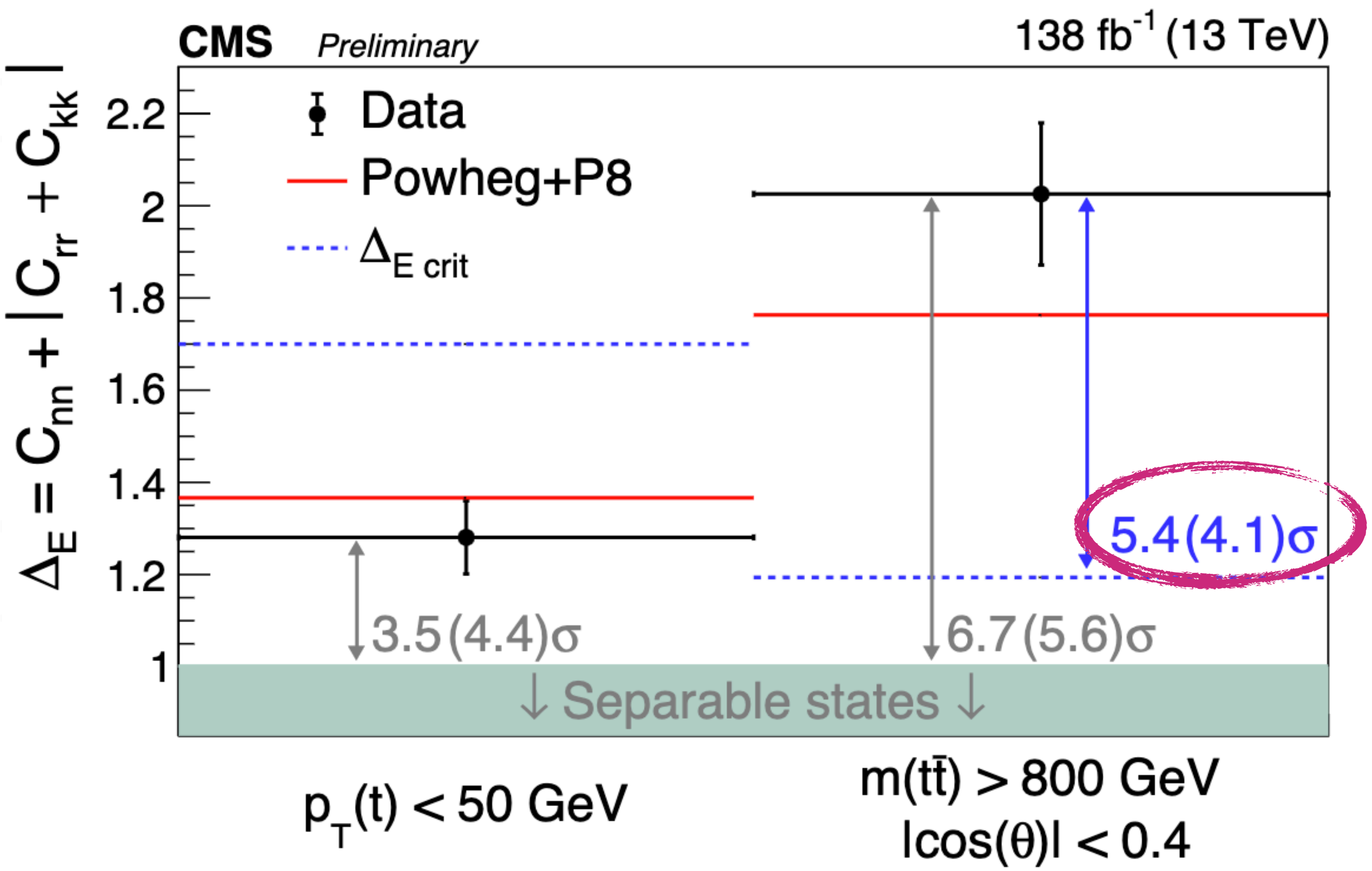
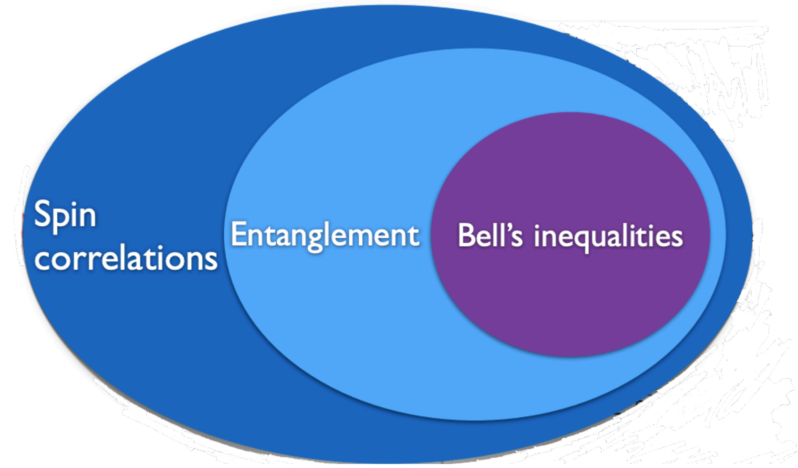
$$\Delta_{\mathrm{E\,crit}} = f\Delta_{\mathrm{E\ sep}} + (1-f)\Delta_{\mathrm{E\ max}}$$

**Observed $\Delta_E$ exceeds $\Delta_{E\ critical}$ by >5 $\sigma$**

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



# Outlook




- This is just the beginning…
- Threshold region
  - potential to probe toponium
- High mass region
  - potential for observation of Bell's Inequality violation
- BI expressed by Clauser, Horne, Simony, Holt (CHSH) inequality = measurements a, a' and b, b' on subsystems A and B must classically satisfy:

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

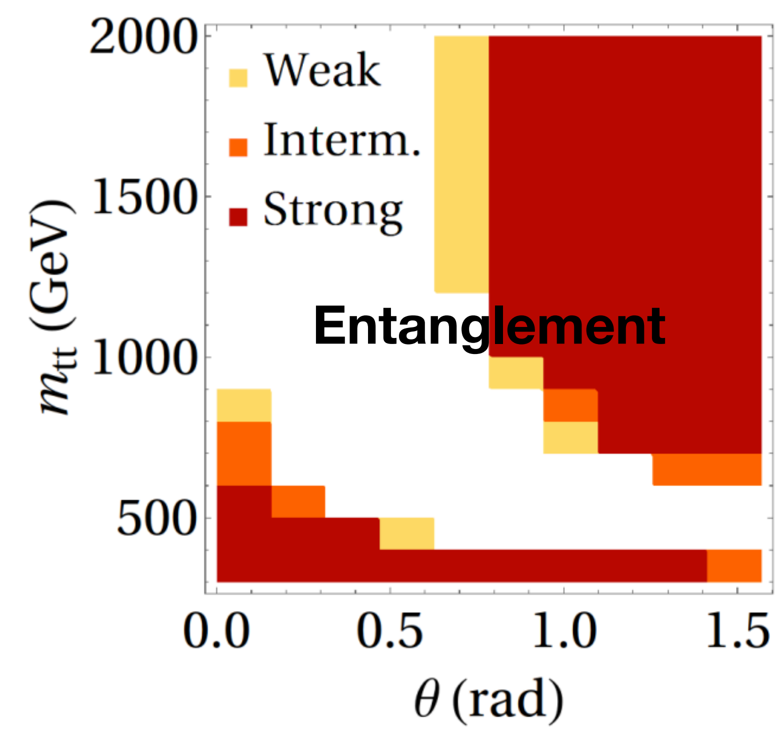
- For $t\bar{t}$ system it can be written in terms of C matrix as

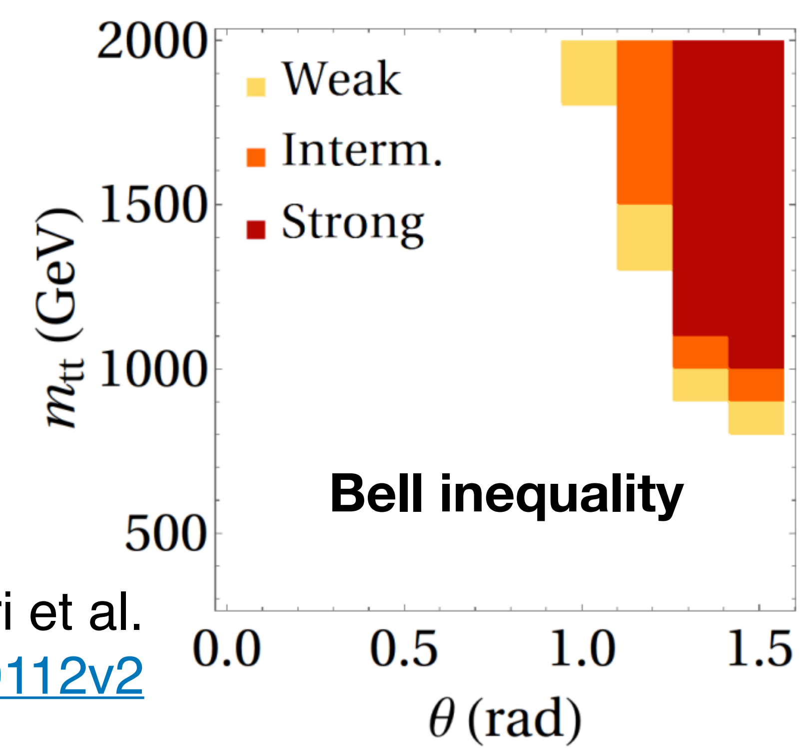
$$|C(a_1, b_1) - C(a_1, b_2) + C(a_2, b_1) + C(a_2, b_2)| \leq 2$$

- or more simply as:

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

- Expected to happen at even higher $m_{t\bar{t}}$
  - more statistics is needed to measure it

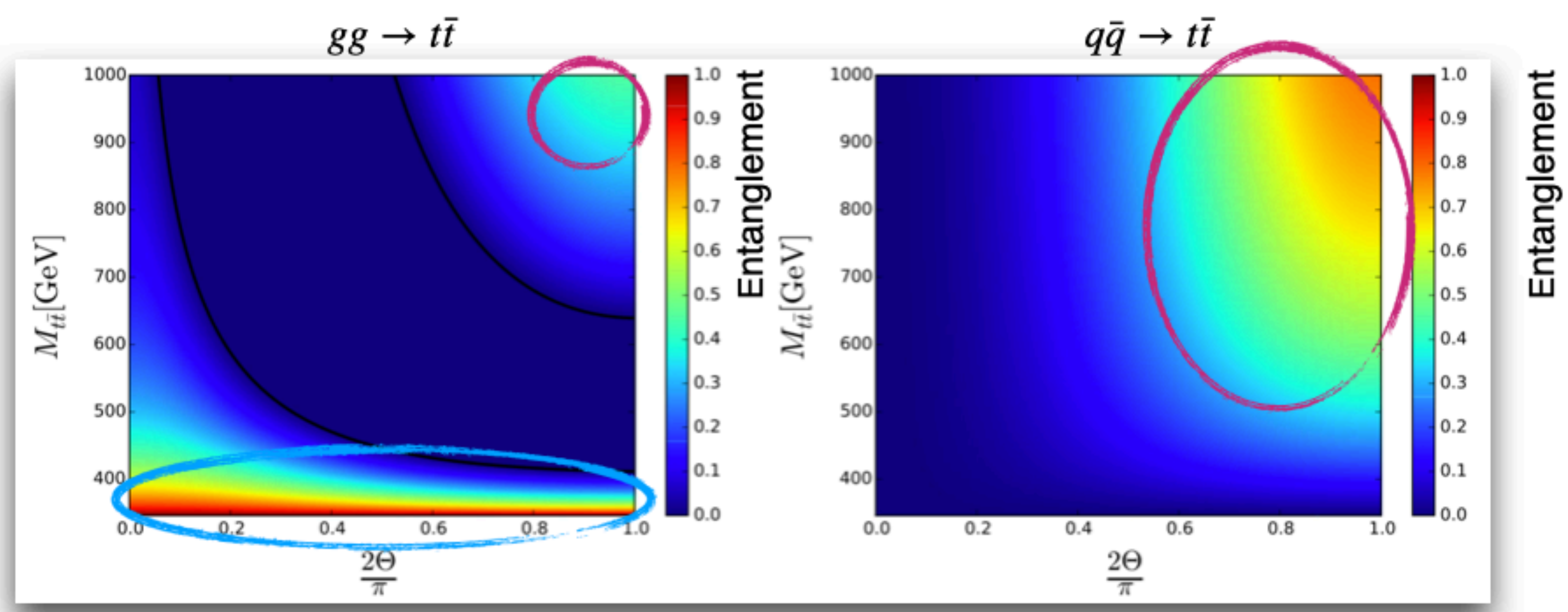



C Severi et al.
arXiv:2110.10112v2

# Conclusions

- **First observation of entanglement between top quarks with CMS data in dilepton analysis**
- **Even in presence of a "toponium" bound state, we confirm the existence of entanglement in the $t\bar{t}$ system with > 5 $\sigma$**
- A better modeling next to the production threshold is required → theory community is working on improving the prediction of mainstream generators for precision measurements
- **First observation of entanglement between casually separated top quarks in lepton+jets analysis**
  - full spin matrix measurement
- **We observe more entanglement than what is achievable by classical exchange of information**
- **More exciting results to come!**



# BACKUP

# Spin correlations: basis of spin quantization axes

Phys. Rev. D 100 (2019) 072002

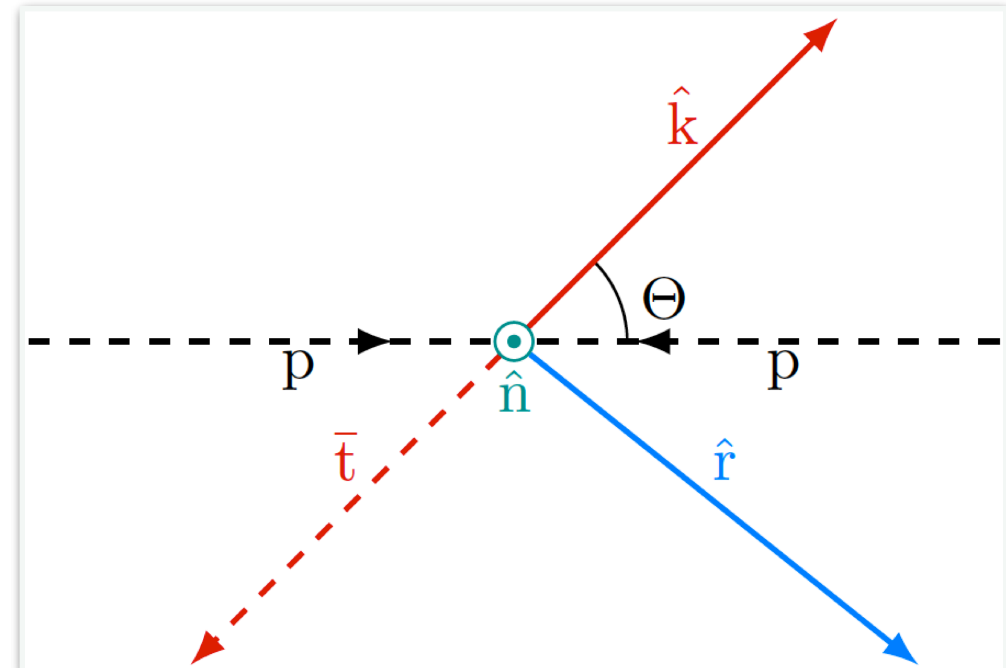
- B and C coefficients:
  - functions of $\sqrt{s}$ and of the top quark scattering angle
  - written in terms of **orthonormal basis** $\{\hat{k}, \hat{r}, \hat{n}\}$:
    - helicity $\hat{k}$-axis: top quark direction in ttbar rest frame
    - transverse $\hat{n}$-axis: transverse to production (ttbar scattering) plane

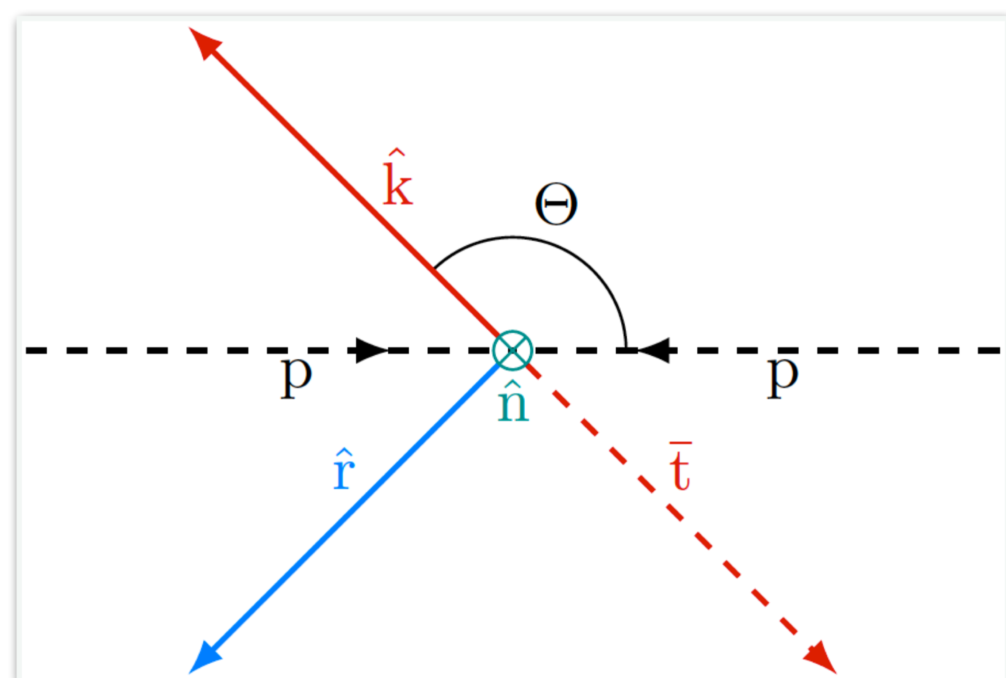
$$\hat{n} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} \times \hat{k})$$

    - $\hat{r}$-axis: orthogonal to the other 2 axes (normal to k in ttbar scattering plane)

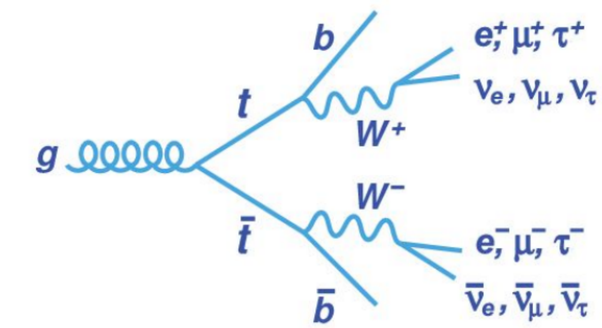
$$\hat{r} = \frac{sign(cos\Theta)}{sin\Theta}(\hat{p} - \hat{k}cos\Theta)$$

    - $\hat{p}$ = direction of the incoming parton, i.e. direction of the proton beam (z-direction in the laboratory frame)
    - $\Theta$ = top quark scattering angle in ttbar rest frame

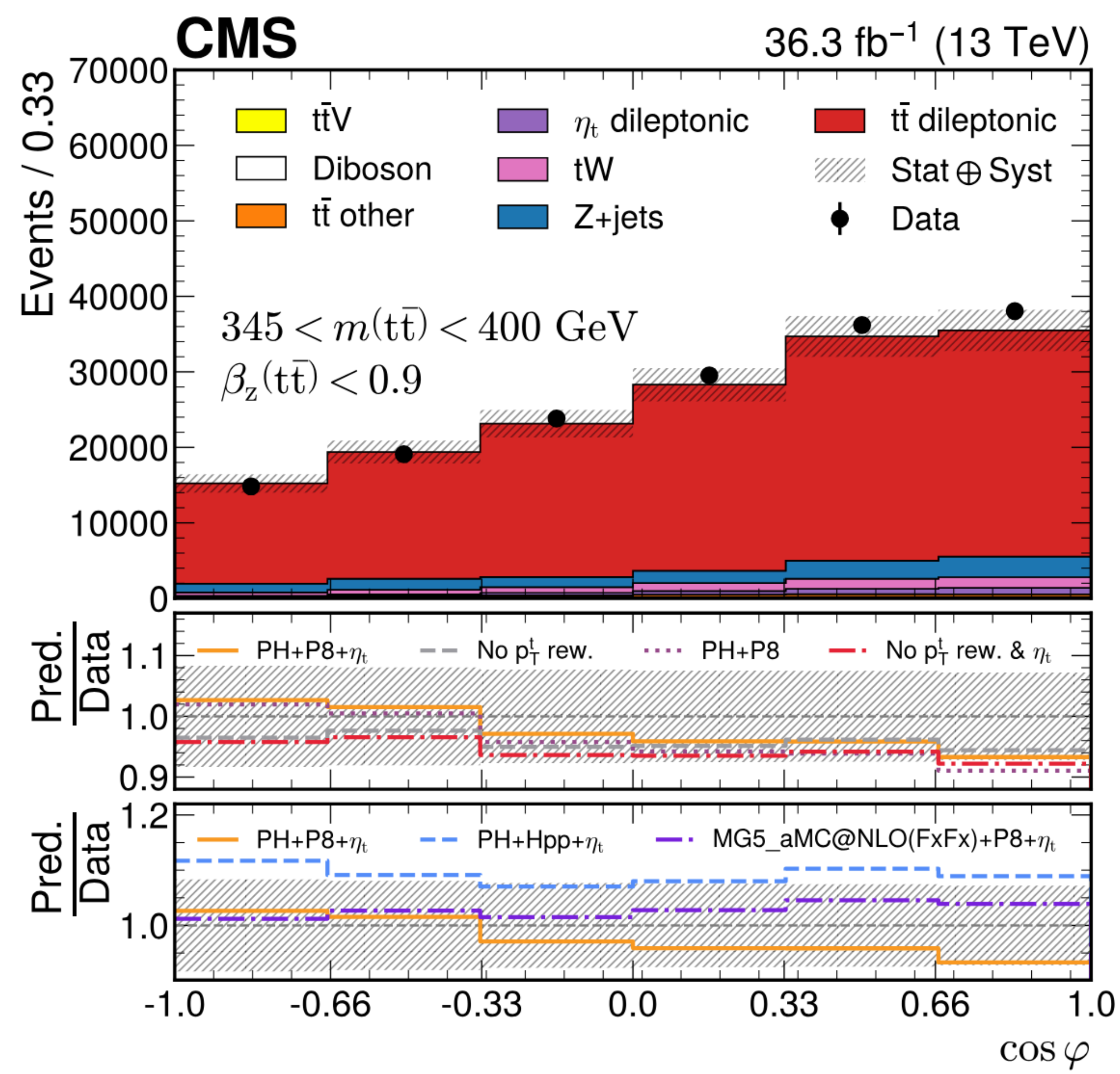


# Dilepton: event selection




- = 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
  - 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($\ell$, jet) > 0.4
- ee, μμ channels:
  - $E^T_{\text{miss}}$ > 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 $m_{t\bar{t}}$



# Dilepon: 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

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

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

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

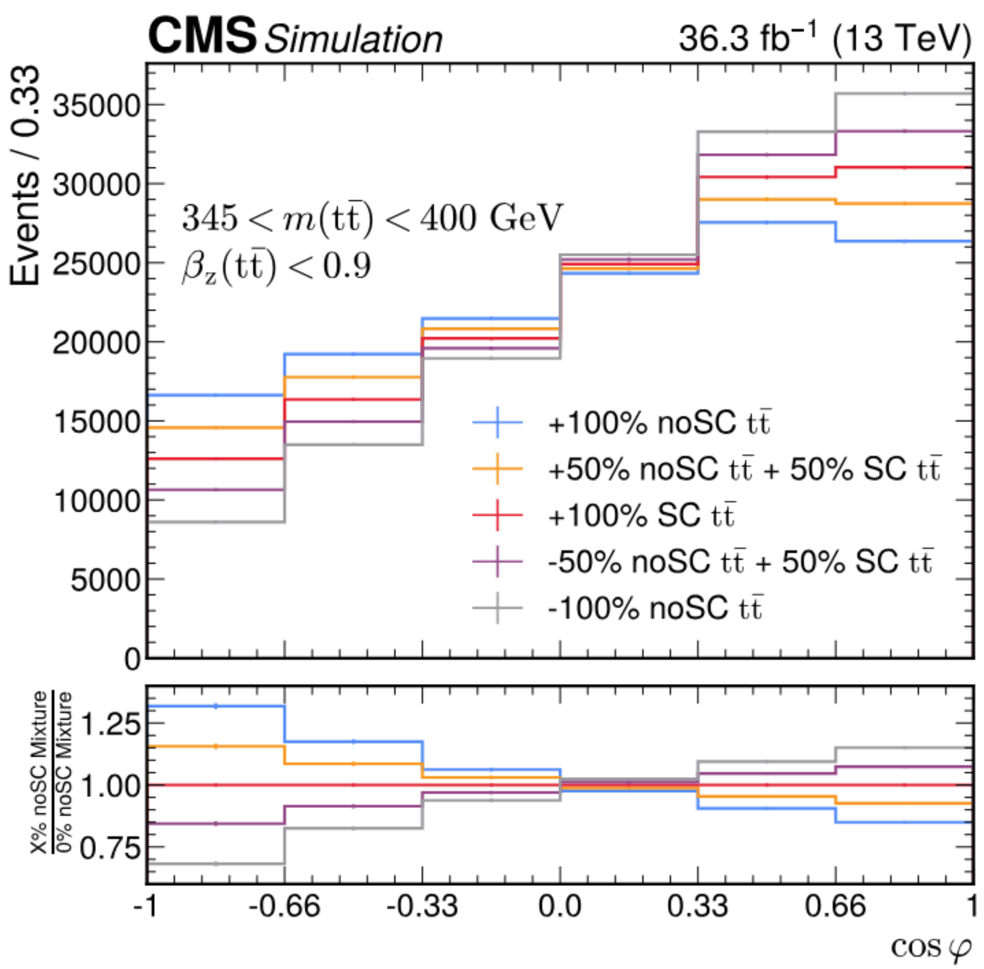
# Mixtures of SC and noSC

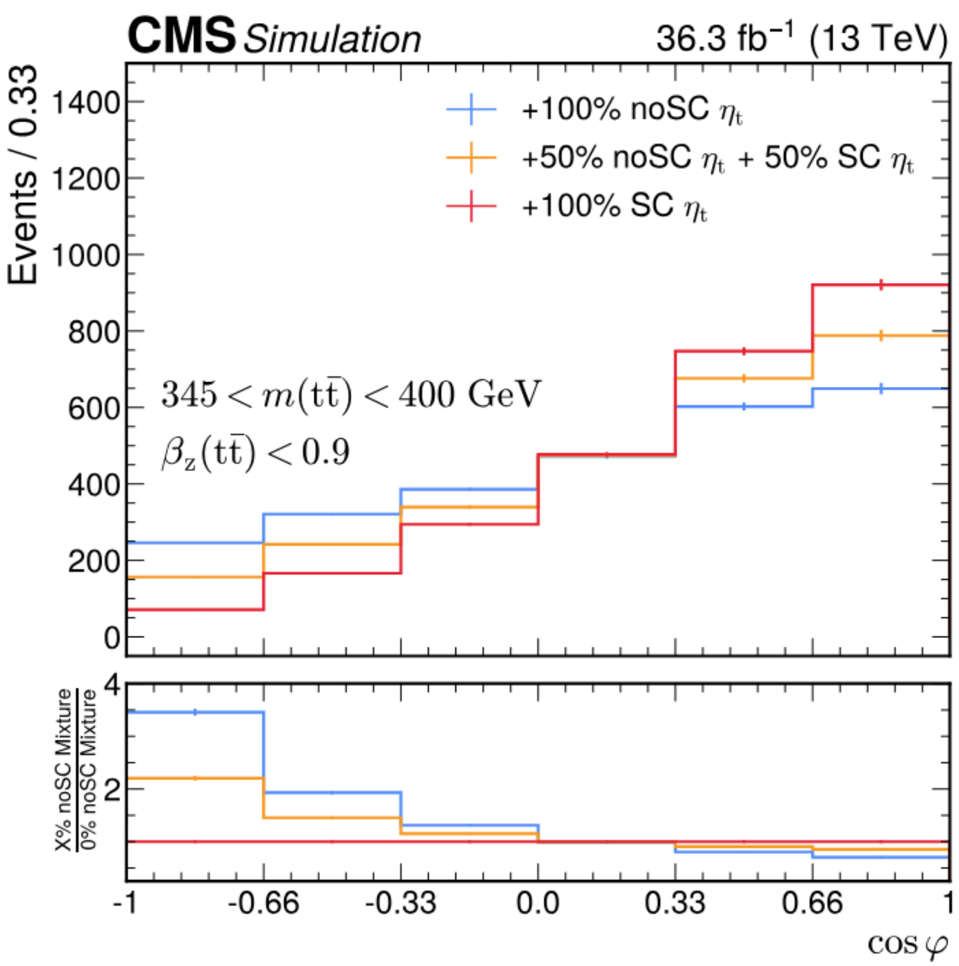
- In order to have templates implementing an alternative value of the entanglement proxy D, we employ the noSC sample and "mix" it in steps ranging from −100% to 100% with the combined signal model SM template
- The negative mixtures are created mirroring the corresponding positive mixtures around the 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 $\eta_\mathrm{t}$.



# Comparison with ATLAS

- **Entanglement in top quark observed by both ATLAS and CMS with >5 standard deviations!**
  - despite different analyses…

| | **ATLAS** | **CMS** |
|---|---|---|
| Dataset | Full Run 2 (140 $fb^{-1}$) | 2016 (35.9 $fb^{-1}$) |
| $t\bar{t}$ decay | Dilepton: eμ | Dilepton: ee, eμ and μμ |
| $t\bar{t}$ reconstruction | Ellipse method | Weighting method |
| Main selections | $340 < m(t\bar{t}) < 380$ GeV | $345 < m(t\bar{t}) < 400$ GeV, beta <0.9 |
| Triggers | Single lepton | Single lepton + dilepton |
| Corrected to | Particle-level | Parton-level |
| Fit type | No fit, calibration curve | Profile likelihood template fit |
| Alternative hypothesis D | Reweighting | Mixing samples with/without spin corr |
| Threshold effects | Neglected | Considered (toponium contribution) |
| Nominal MC | PowhegBox+Pythia8 | PowhegBox+Pythia8 |
| Alternative MC | PowhegBox+Herwig7, bb4l | PowhegBox+Herwig++, MG5_AMC@NLO |
| **Significance** | **>> 5 standard deviations** | **> 5 standard deviations** |

$$D_{obs} = -0.547 \pm 0.002(\text{stat}) \pm 0.021(\text{syst})$$
$$D_{exp} = -0.470 \pm 0.002(\text{stat}) \pm 0.018(\text{syst})$$

$$D_{obs} = -0.480^{+0.016}_{-0.017}(\text{stat})^{+0.020}_{-0.023}(\text{syst})$$
$$D_{exp} = -0.467^{+0.016}_{-0.017}(\text{stat})^{+0.021}_{-0.024}(\text{syst})$$

# Comparison with ATLAS

- No clear preference for a specific MC prediction

- **Both analyses are dominated by systematic uncertainty**
  - total (stat.) unc. is an order of magnitude larger in the CMS analysis
  - total (syst.) unc. is similar between ATLAS & CMS, but different systematics are considered

$$D_{obs} = -0.547 \pm 0.002(\text{stat}) \pm 0.021(\text{syst})$$
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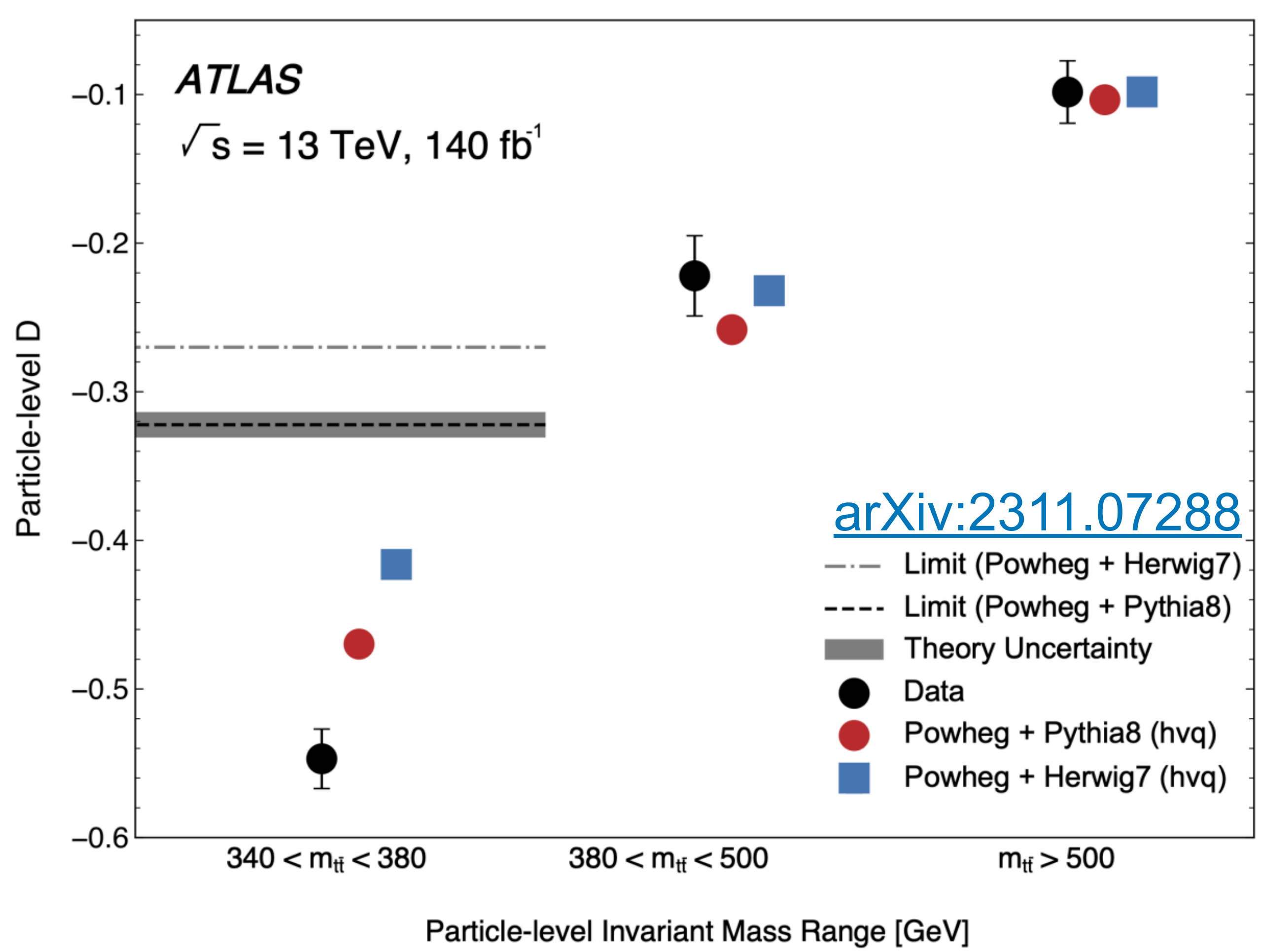
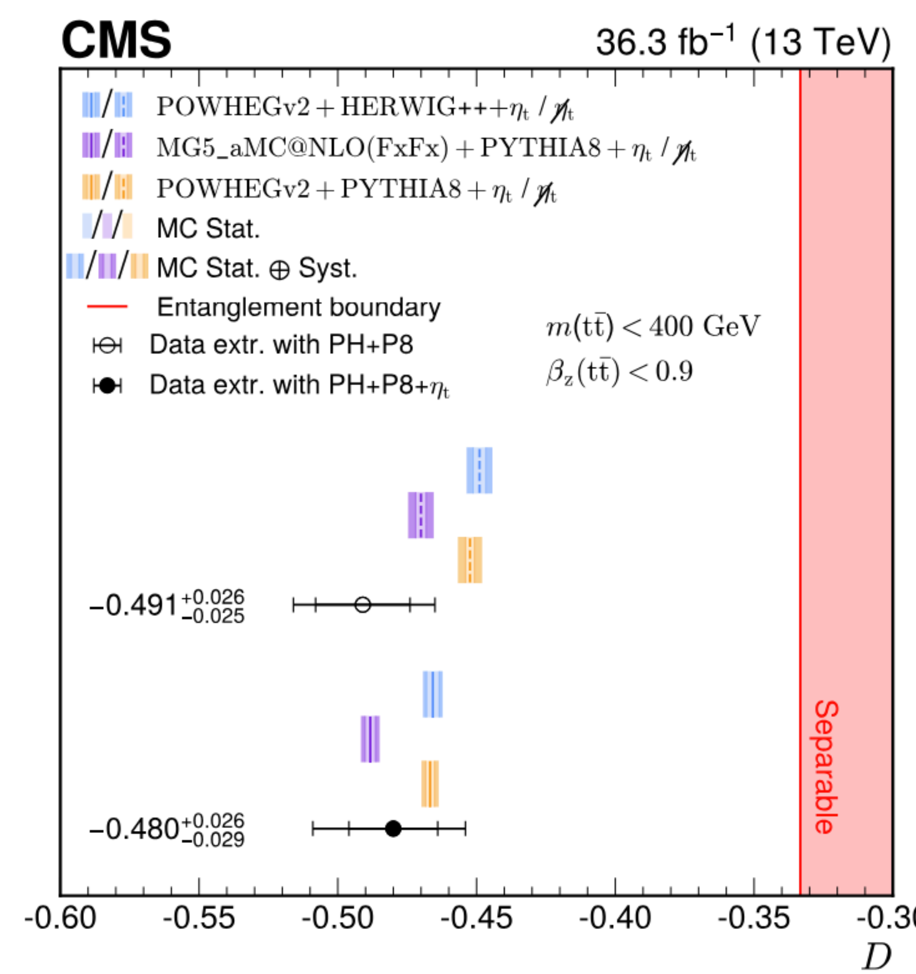



ATLAS: limit of D = −1/3 is folded from parton to **particle-level**

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

# Lepton + jets: event selection

**For muons:** $p_T > 30$ GeV and $|\eta| < 2.4$ (tracker coverage). Standard tight selection. Isolated if particle-flow (PF) isolation $I_{PF}/p_T(\mu) < 0.15$

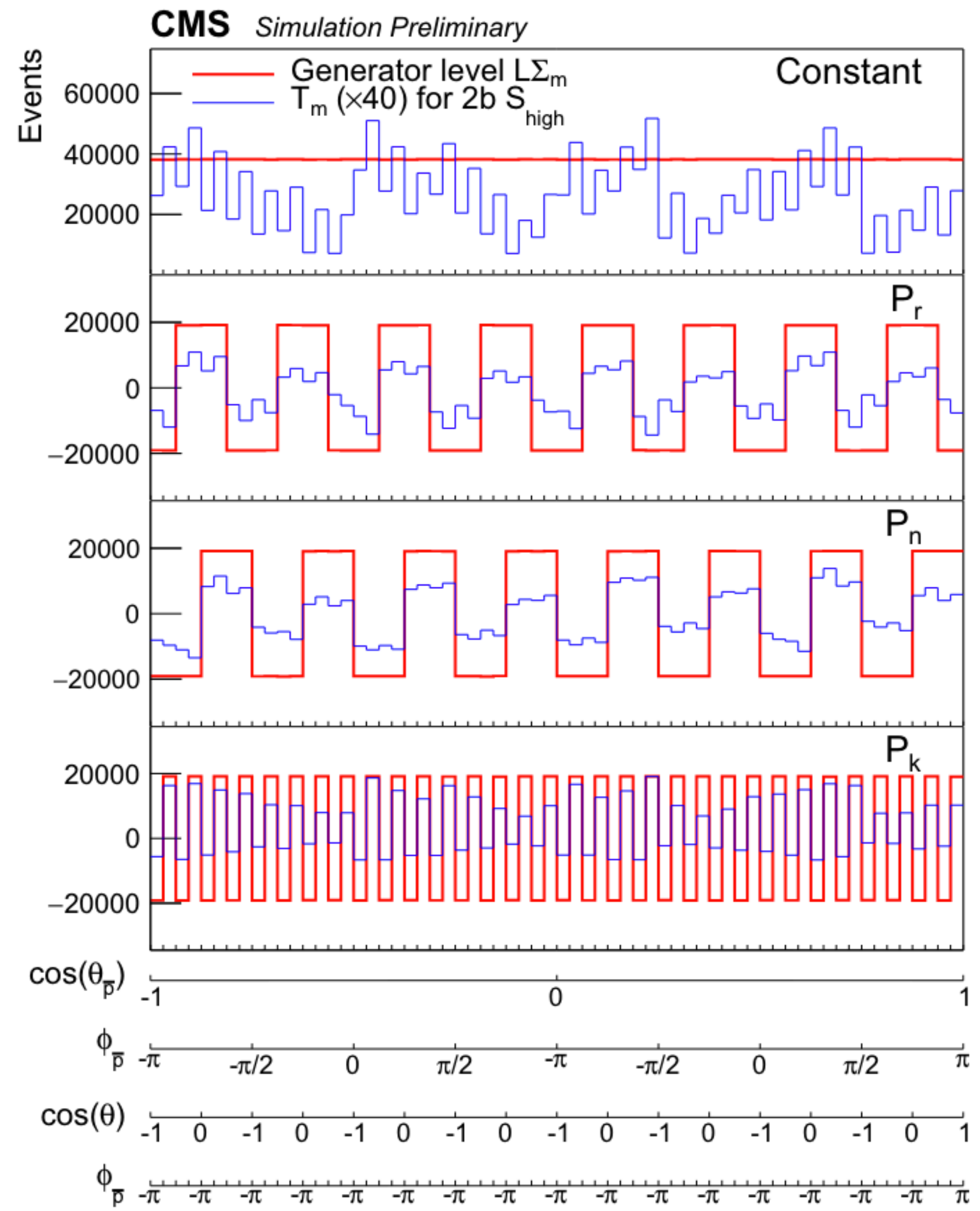
**For electrons:** $p_T > 30$ GeV for 2016, 2017 ($p_T > 34$ GeV for 2018). $|\eta| < 2.4$. Tight selection.

- Exactly one electron or muon per event.
- Events with more than one isolated lepton satisfying $p_T > 15$ GeV and $|\eta| < 2.4$ are discarded.
- At least **4** jets using the anti-$k_T$ jet algorithm with a distance parameter of 0.4 (*AK4s*), with $p_T > 30$ GeV and $|\eta| < 2.4$.
- DeepJet b-tagging algorithm is used for the identification of b jets. Information about the b-tagging WPs provided to the neural network.
  - Two categories defined by b-tagging criteria are used: two b-jet candidates passing the medium WP criterion (2b) and only one b-jet candidate passing the medium WP criteria (1b).

- To enhance fraction of correctly reconstructed events and reduce background contributions
  - $|m(t_l) - 172.5$ GeV$| < 50$ GeV
  - $|m(t_h) - 172.5$ GeV$| < 50$ GeV
  - $|m(W) - 80.4$ GeV$| < 30$ GeV

# Lepton + jets: strategy

- At generator level, $\Sigma_m$ never change because they do not depend on the kinematics of the top quarks
  - calculation of $\Sigma_{tot}$ uses the average values of $Q_m$ in each bin
- At detector level, $T_m$ change as a function of top quark kinematics due to selection requirements and detector effects
  - if they vary significantly within a fitted bin, the measured $Q_m$ could be biased
- To mitigate this effect, measurements are performed in sufficiently small bins such that either $Q_m$ or $T_m$ are approximately constant within each bin




$L\Sigma_m$ = templates used at gen level
$T_m$ = templates defined at reco level

# Lepton+jets: syst. uncertainties

- **Analysis is limited by statistical uncertainties**

- **Leading theoretical uncertainties:**
  - **top quark mass**
  - **renormalization/factorization scale**
  - **NNLO QCD reweighing**
  - **EW corrections**

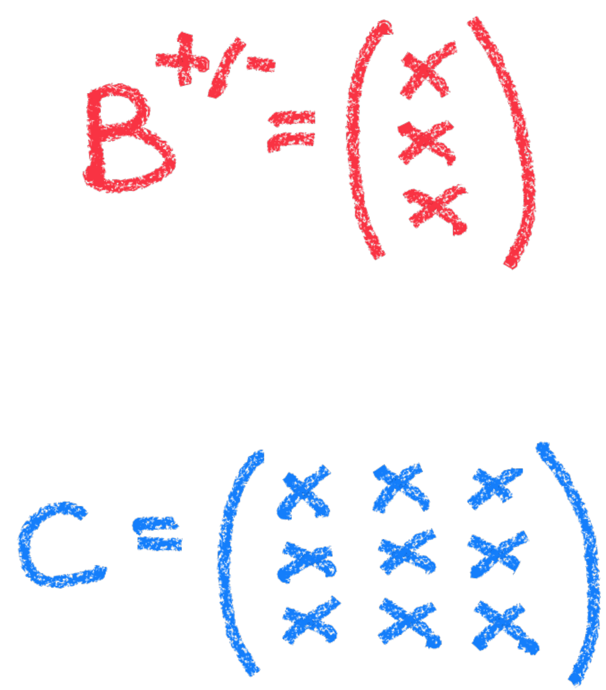
  - **NB: toponium effect is small for lepton+jets (~5E-04 )**

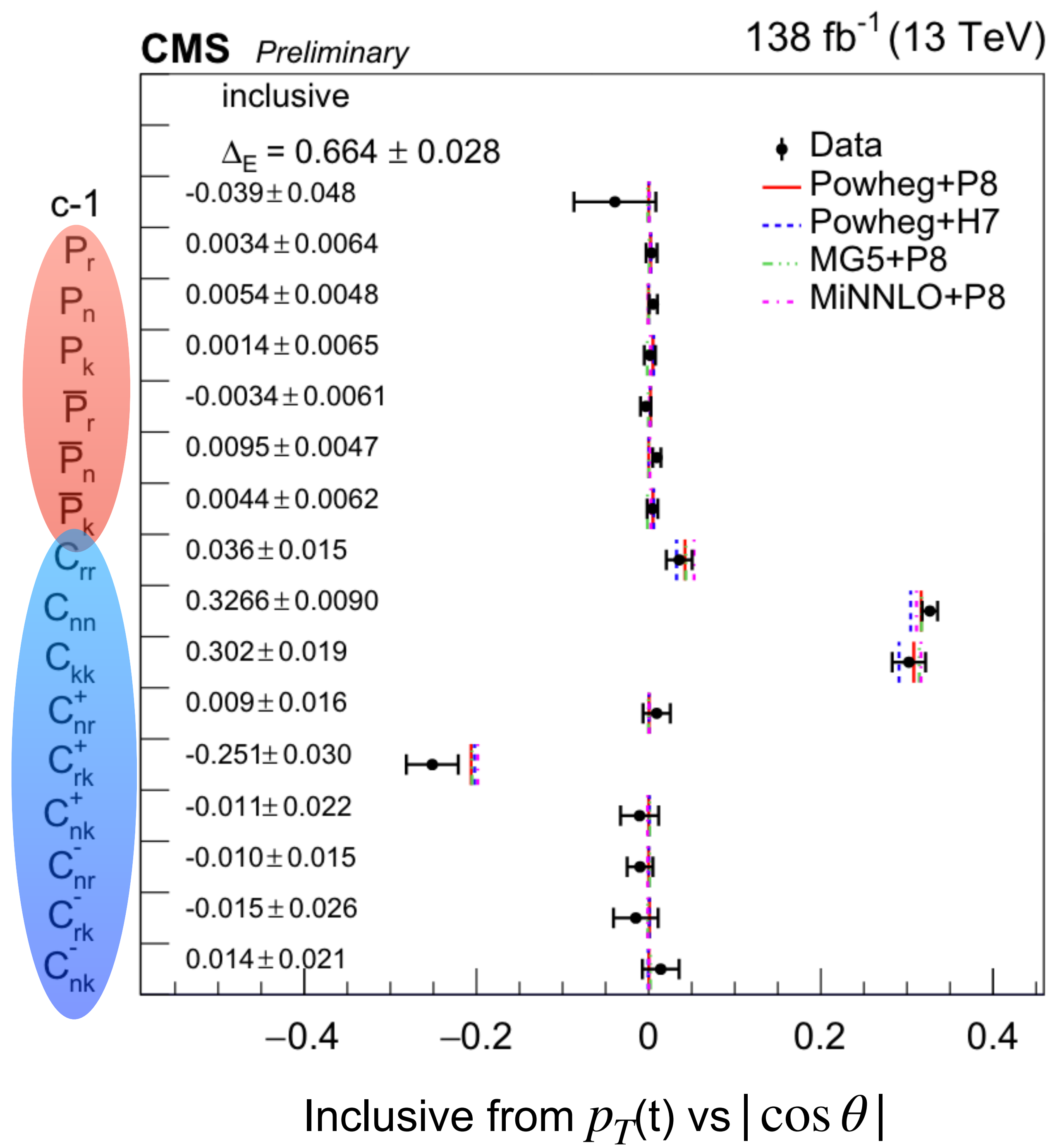
- **Leading experimental uncertainties:**
  - **Jet energy scale**
  - **b-tagging efficiency**

# Lepton+jets results: full matrix

- **Full measurement of P and C performed inclusively and differentially**
  - in bins of $m_{t\bar{t}}$ vs $|\cos\theta|$ or $p_T$(t) vs $|\cos\theta|$

- **Good agreement with SM prediction**



# Lepton+jets results: $D$ and $\tilde{D}$

- **Measurement of $D$, $\tilde{D}$ performed inclusively and differentially** in bins of $m_{t\bar{t}}$ vs $|\cos\theta|$ or $p_T$(t) vs $|\cos\theta|$
- **Good agreement with SM prediction**

Inclusive $D$, $\tilde{D}$ measurements

| Coeff. | Data | POWHEG+P8 | POWHEG+H7 | MG5+P8 | MINNLO+P8 |
|---|---|---|---|---|---|
| | Inclusive from $m(t\bar{t})$ *vs.* $|\cos(\theta)|$ binning | | | | |
| $c$ | $0.905 \pm 0.061$ | 1 | 1 | 1 | 1 |
| $D$ | $-0.209 \pm 0.011$ | -0.2222 | -0.2092 | -0.2251 | -0.226 |
| | Inclusive from $p_T(t)$ *vs.* $|\cos(\theta)|$ binning | | | | |
| $c$ | $0.973 \pm 0.056$ | 1 | 1.0002 | 0.999 | 1.0006 |
| $D$ | $-0.2233 \pm 0.0098$ | -0.2222 | -0.2092 | -0.2251 | -0.226 |
| | Inclusive from $m(t\bar{t})$ *vs.* $|\cos(\theta)|$ binning | | | | |
| $c$ | $0.918 \pm 0.062$ | 1 | 1 | 1 | 1 |
| $\tilde{D}$ | $-0.0172 \pm 0.0077$ | -0.0113 | -0.0063 | -0.0136 | -0.018 |
| | Inclusive from $p_T(t)$ *vs.* $|\cos(\theta)|$ binning | | | | |
| $c$ | $0.949 \pm 0.055$ | 1 | 1.0002 | 0.999 | 1.0006 |
| $\tilde{D}$ | $-0.0289 \pm 0.0066$ | -0.0113 | -0.0063 | -0.0136 | -0.018 |

$D$ measurements in $m_{t\bar{t}}$ bins

| Coeff. | Data | POWHEG+P8 | POWHEG+H7 | MG5+P8 | MINNLO+P8 |
|---|---|---|---|---|---|
| | $300 < m(t\bar{t}) < 400$ GeV | | | | |
| $c$ | $0.934 \pm 0.067$ | 1 | 1.0058 | 0.9318 | 1.0045 |
| $D$ | $-0.382 \pm 0.030$ | -0.4179 | -0.3843 | -0.4434 | -0.4311 |
| | $400 < m(t\bar{t}) < 600$ GeV | | | | |
| $c$ | $0.890 \pm 0.060$ | 1 | 0.9998 | 1.0045 | 0.9957 |
| $D$ | $-0.191 \pm 0.012$ | -0.2121 | -0.2015 | -0.2157 | -0.2118 |
| | $600 < m(t\bar{t}) < 800$ GeV | | | | |
| $c$ | $0.906 \pm 0.064$ | 1 | 0.9955 | 1.0427 | 1.0015 |
| $D$ | $-0.102 \pm 0.020$ | -0.0705 | -0.0687 | -0.0729 | -0.0717 |
| | $m(t\bar{t}) > 800$ GeV | | | | |
| $c$ | $0.930 \pm 0.070$ | 1 | 0.9926 | 1.0689 | 1.0186 |
| $D$ | $-0.010 \pm 0.036$ | 0.0019 | -0.0005 | -0.0007 | -0.0123 |