Recent results on top-quark physics by CMS: top-quark properties

On behalf of the CMS Collaboration

Reza Goldouzian

UNIVERSITY OF NOTRE DAME

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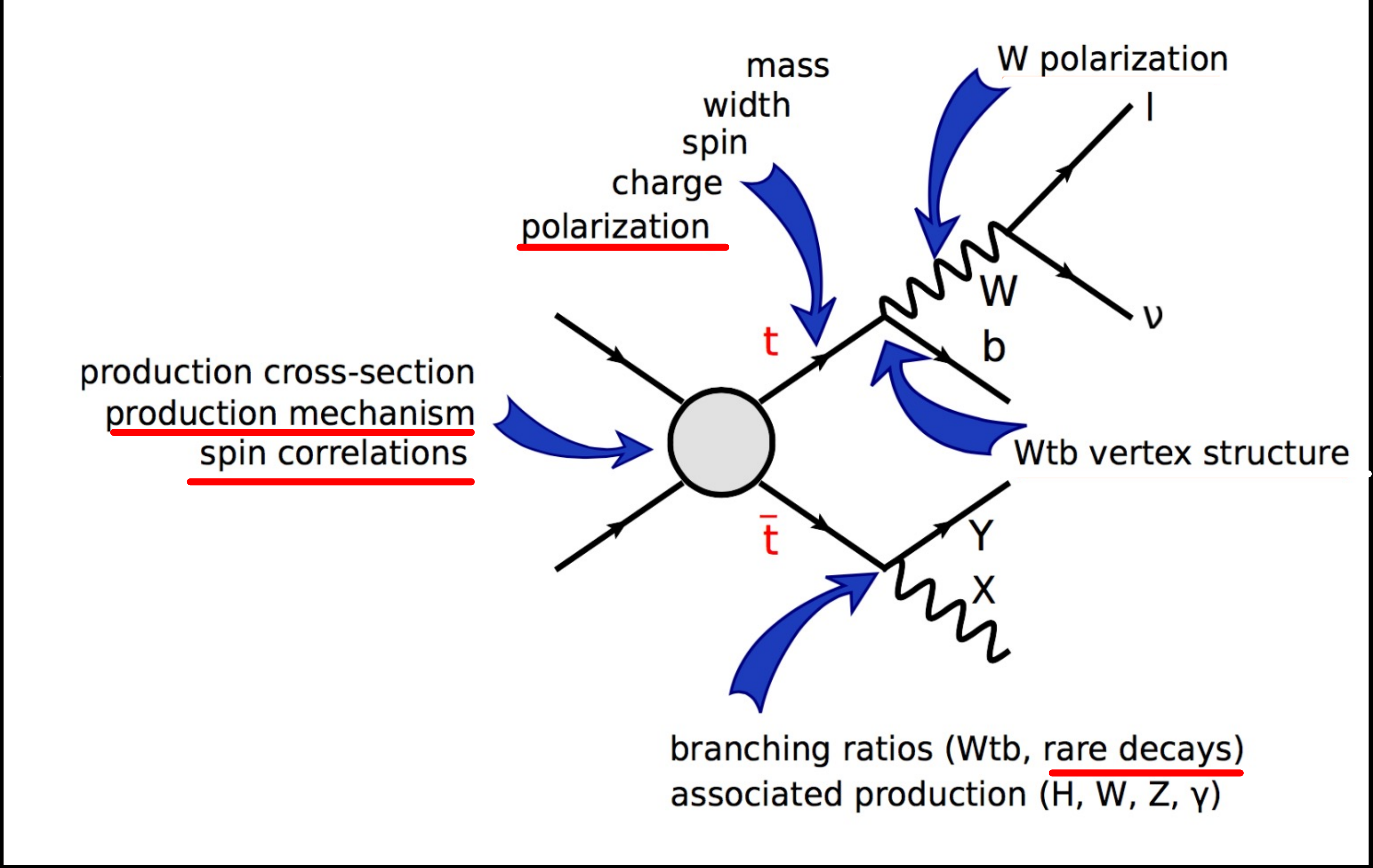
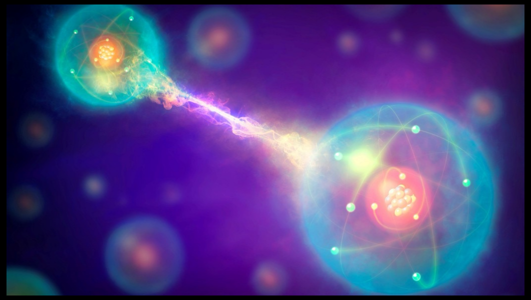
Introduction

- Why study top quark properties?
  - heaviest elementary particles in the SM
  - decays before the spin decorrelates
  - Large coupling to Higgs boson, plays significant role in EWSB

- Properties measurements of top quark test SM and probe new physics
  - Production mechanism and cross section
  - Width, mass, BRs,…
  - Spin polarization, correlation, entanglement,…
  - Rare decays
  - ….
- Focus on most recent results at 13 TeV



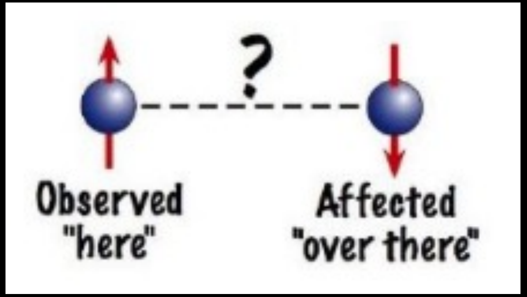
Entanglement in QM



- Qubit = two-level quantum system |0⟩, |1⟩ → most simple quantum system
- Two qubits → most simple example of quantum correlations
- A quantum state of two subsystems A and B is separable when its density matrix:

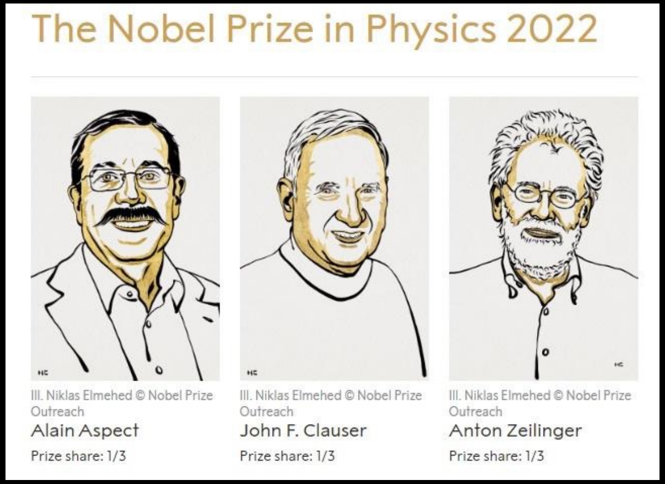
$$\rho_{\rm sep} = \sum_n p_n \rho_n^A \otimes \rho_n^B$$

Non-separability of a quantum state = entanglement



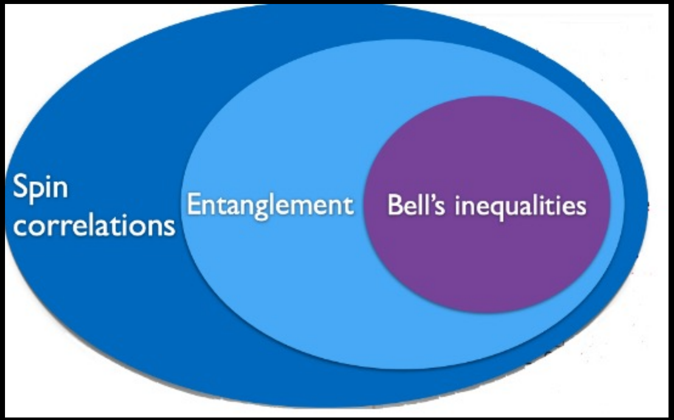
- entangled states cannot be described by independent superpositions
- Measuring particle spin in an entangled system immediately reveals the spin state of the second particle even when casually separated

- "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 states cannot be described by independent superpositions
- 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



Entanglement at the LHC

- LHC can provide a unique environment to study spin correlations, entanglement and violation of Bell's inequalities at high energy
- Simplest process at LHC: $t\bar{t}$ pair
  - Top has 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
    - ~100% transmitted to charged leptons and down type quarks
- Spin correlations are 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

$$B^{+/-} = \begin{pmatrix} \times \\ \times \\ \times \end{pmatrix} \quad C = \begin{pmatrix} \times & \times & \times \\ \times & \times & \times \\ \times & \times & \times \end{pmatrix}$$

- In SM, top are unpolarized in $t\bar{t}$ production, but top spins strongly correlated with antitop spins
- In tt, the trace of the correlation matrix C is a good entanglement witness
  - D = tr[C]/3= −3 ⟨cos φ⟩ is a good variable to be measured experimentally
    - cos φ is the opening angle between leptons in parent top rest frame
  - D<-1/3 is sufficient condition for entanglement
- First observation of entanglement in $t\bar{t}$ by ATLAS at the end of last year

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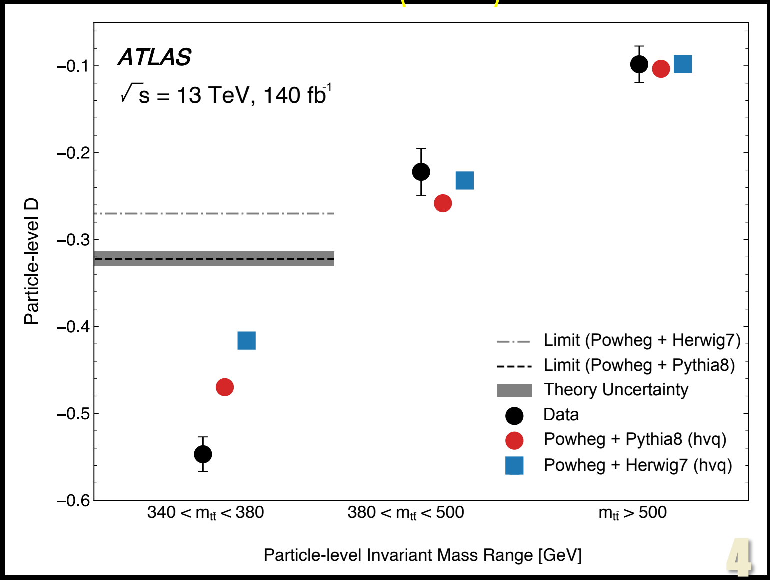
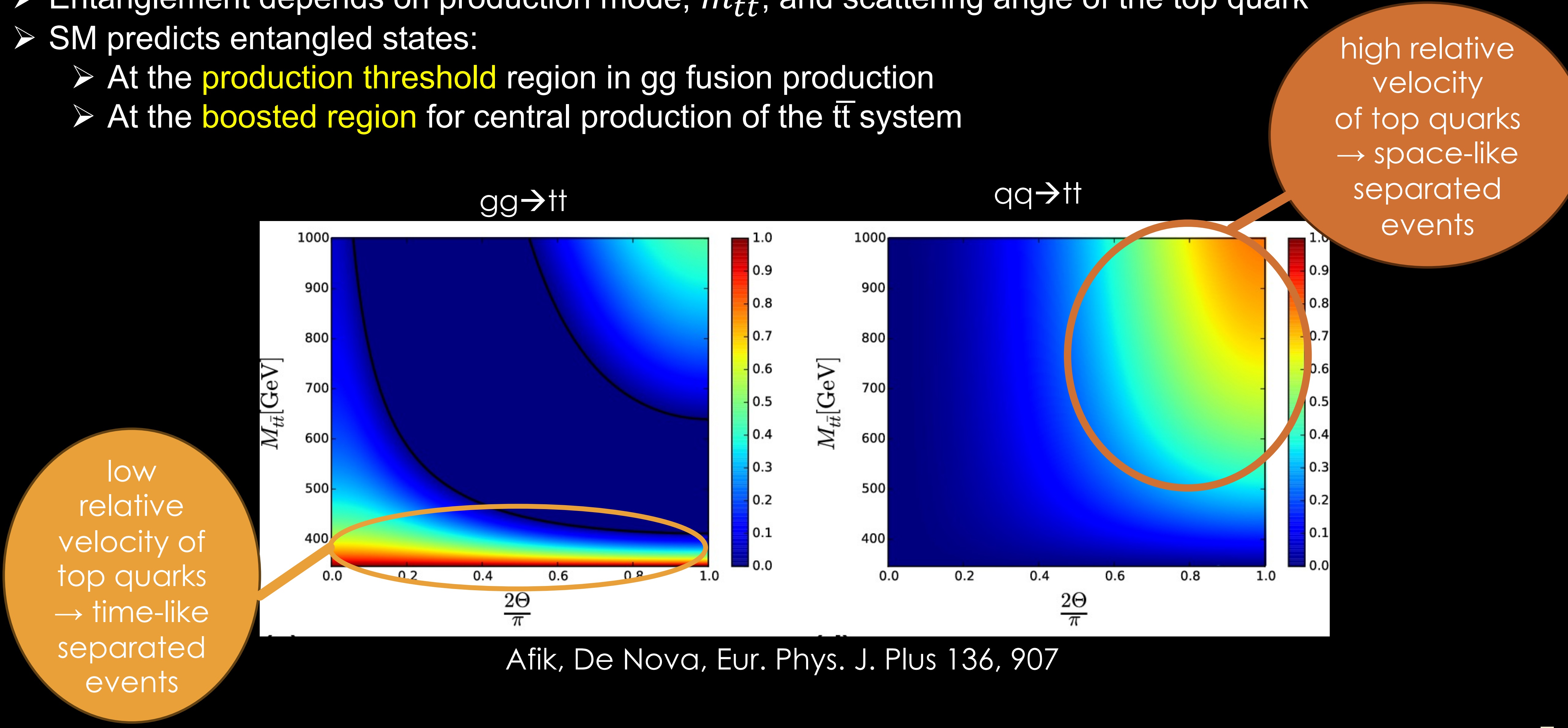


Entanglement and phase space

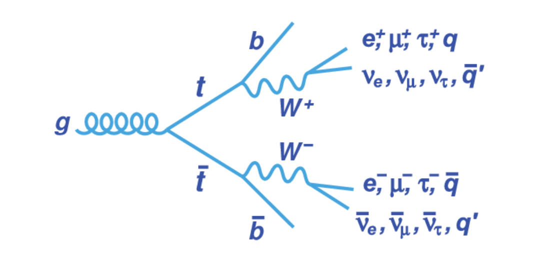
- Entanglement depends on production mode, $m_{t\bar{t}}$, and scattering angle of the top quark
- SM predicts entangled states:
  - At the production threshold region in gg fusion production
  - At the boosted region for central production of the $t\bar{t}$ system



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

CMS entanglement measurements

Single lepton
arXiv:2409.11067
Submitted to PRD



Dilepton
arXiv:2406.03976
Submitted to ROPP

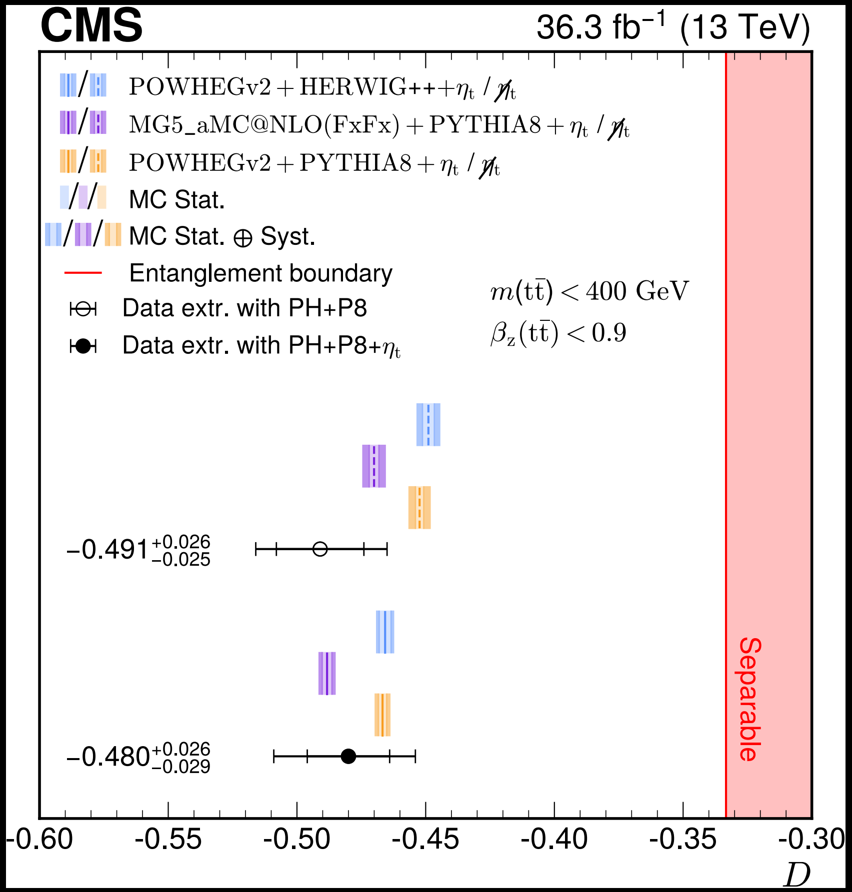
- 138 fb^{-1} of data @13 TeV
- Higher branching ratio
- top spin info ~100 % transmitted to down-type quarks → hard to identify
- Higher cut for single lepton (30 GeV) and for 4 jets (30 GeV) → lower efficiency at the threshold but OK for high $m_{t\bar{t}}$
- Better $m_{t\bar{t}}$ resolution → good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

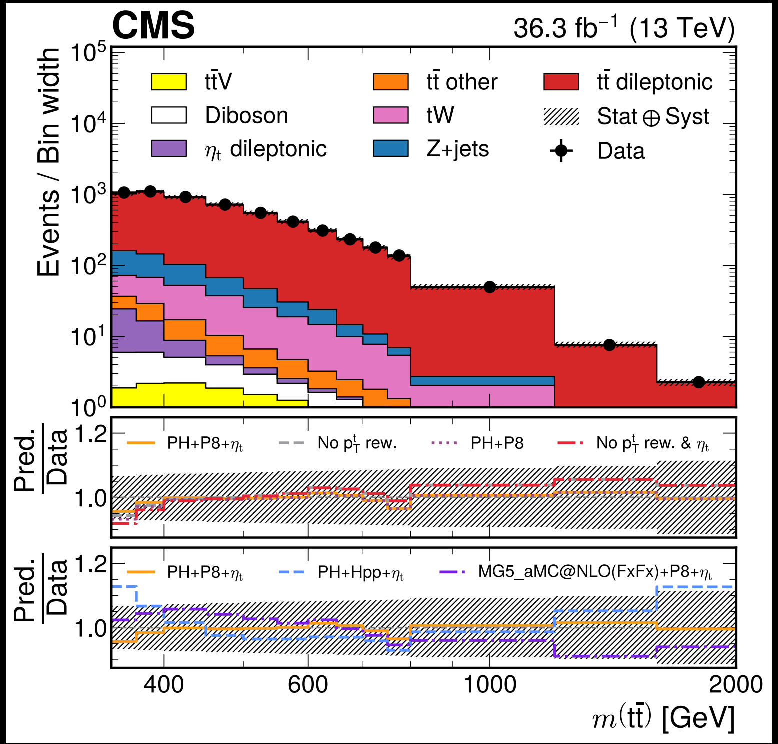
- 36.3 fb^{-1} of 2016 data @13 TeV
  - based on Phys. Rev. D 100, 072002
- Lower branching ratio
- top spin info 100 % transmitted to charged leptons → easy to identify
- Lower cuts for leading/subleading lepton(25/20 GeV) → higher efficiency at the threshold
- Worse $m_{t\bar{t}}$ resolution → not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

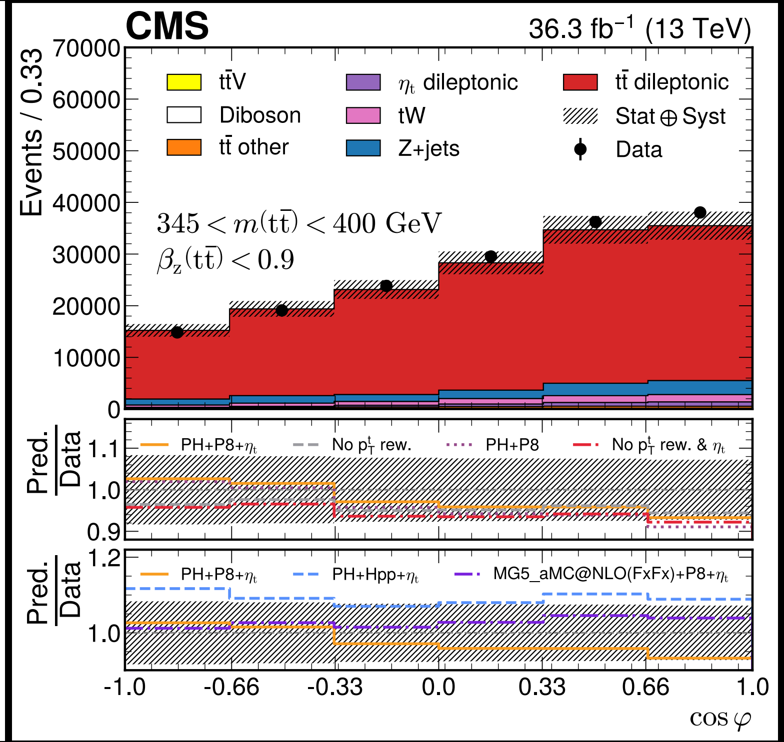
CMS entanglement measurements: Dilepton

Dilepton
arXiv:2406.03976
Submitted to ROPP

- Focus on low-mass region (345< $m_{t\bar{t}}$ <400GeV) to increase entanglement
- Cut on velocity along the beam line of the $t\bar{t}$ system to increase fraction gg/qq
- Top quark reconstructions with m_{lb} weighting method
- Signal modelling: SM $t\bar{t}$ + toponium (η_t)
- The entanglement proxy is extracted with a template fit
- Results:
  - Good agreement with SM predictions
  - Significance: 5.1σ obs (4.7σ exp.)
  - Significantly improved with η_t inclusion





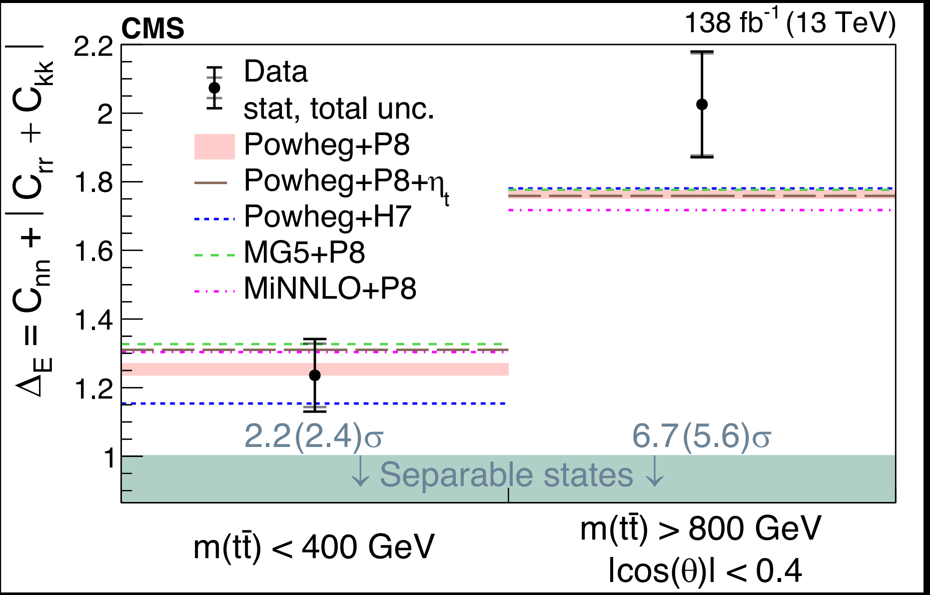


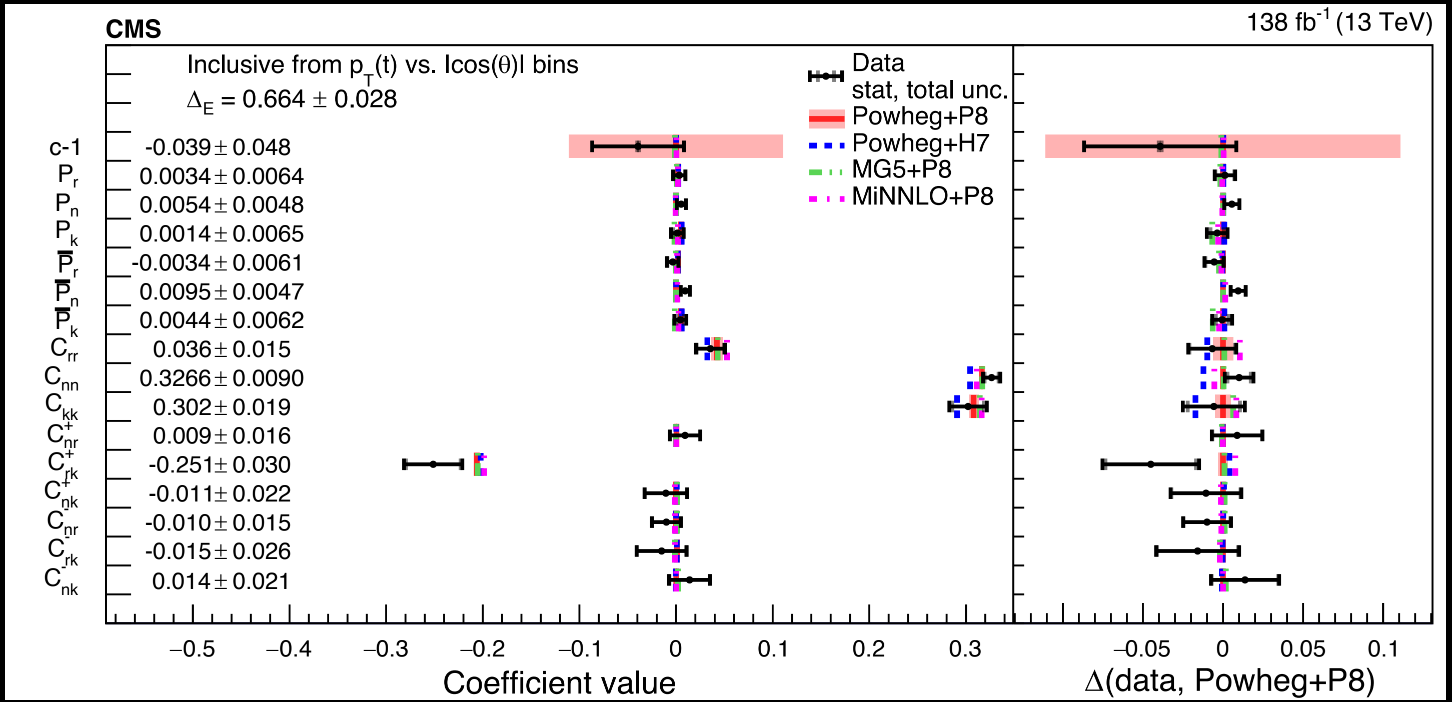
CMS entanglement measurements: Lepton+jets

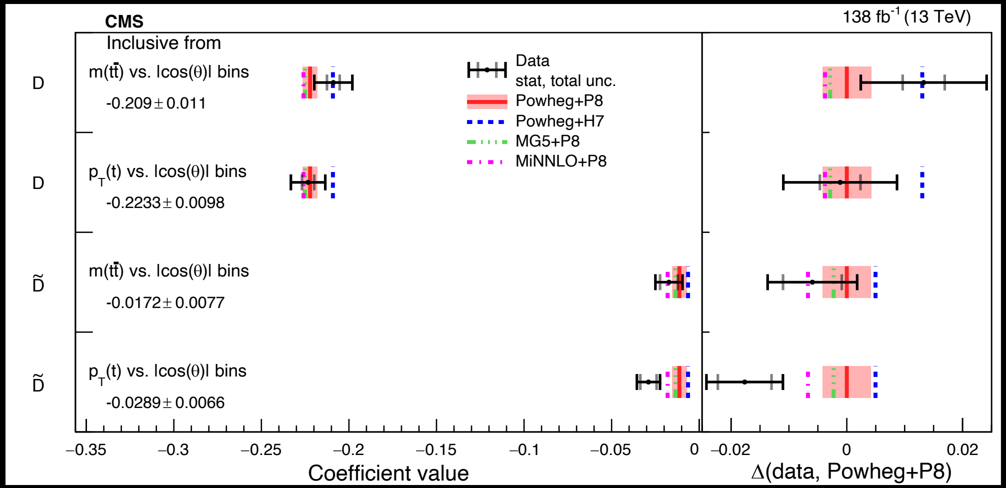
Single lepton
arXiv:2409.11067
Submitted to PRD

- Artificial NN used to reconstruct the $t\bar{t}$ system
- Events divided into categories based on lepton flavor, number of b-tags, and NN score
- All polarization and spin correlation coefficients extracted simultaneously by performing a binned maximum likelihood fit to the data
  - + measurement of D
- Inclusive + differential measurements in bins of $m_{t\bar{t}}, |cos\theta|, p_T(t)$
- Good agreement with SM prediction

Entanglement observed for first time in boosted region





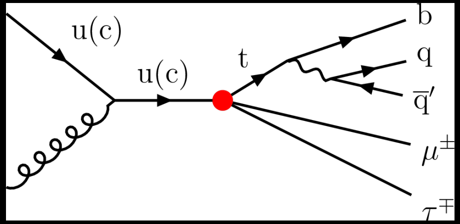


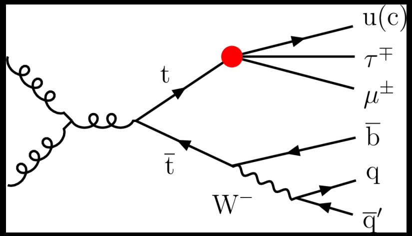
Search for CLFV

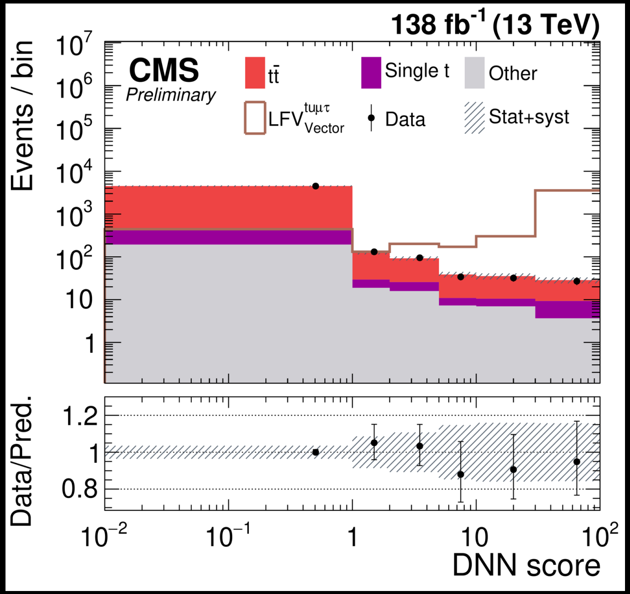
13 TeV (138/fb)

Dilepton (eτ) NEW
CMS-PAS-TOP-22-011

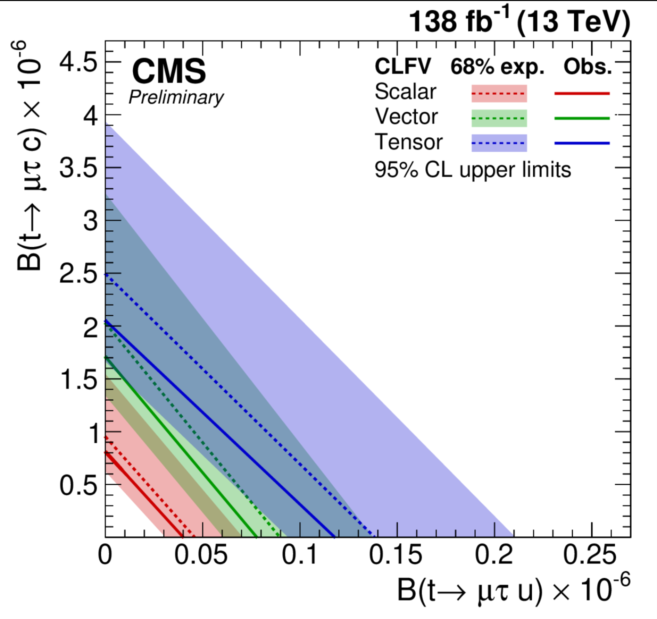
- Charged lepton flavor violation (CLFV) via neutrino oscillations is highly suppressed ($BR \sim 10^{-55}$) → any experimental evidence = indication of new physics
- Model independent EFT approach, scalar, vector and tensor (llqq) operators
- Dilepton **eτ** final state
- LFV in both single top production and decay are included

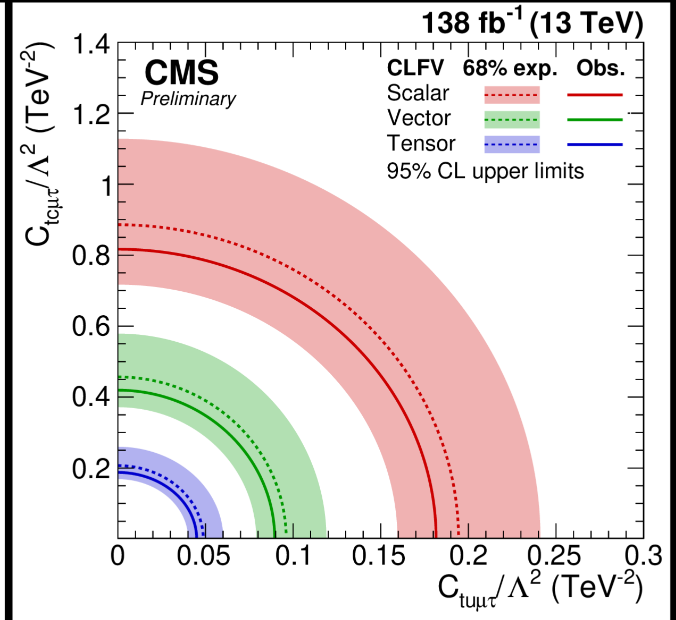






- Background mostly $t\bar{t}$
- Deep neural networks are trained to discriminate signal events from BG





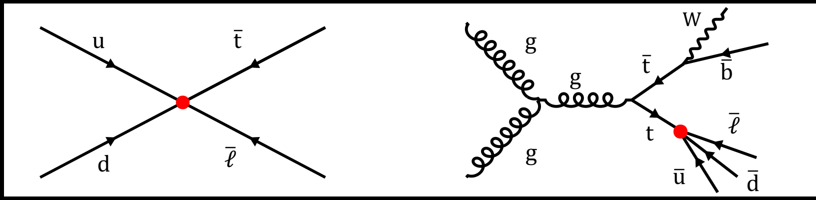
- Data are found to be consistence with the SM expectation
- Limits are set on LFV couplings
  - Translated to the top LFV decay branching fractions

Improvement by factor ~2 on previous limits

Search for BNV

13 TeV (138/fb)

dilepton
Phys. Rev. Lett. 132 (2024) 241802



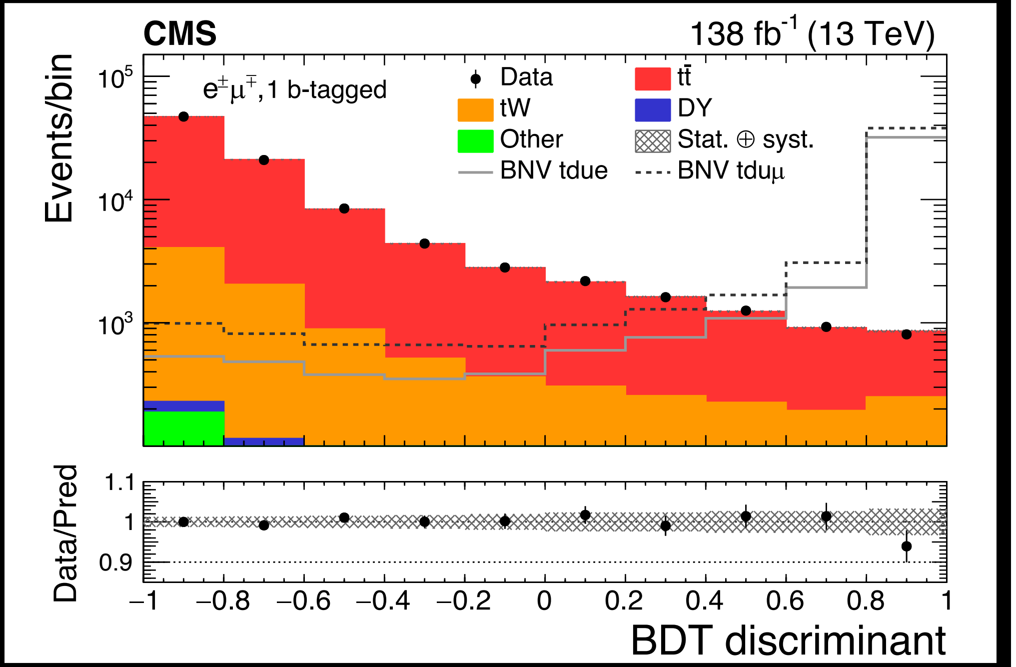
- In the SM, the baryon number violation (BNV) is forbidden at LO
  - Not from a fundamental symmetry in the SM
  - BSM processes can enhance BNV
  - a window to search for new physics
- A model independent effective field theory approach is followed
- Dilepton final states are probed

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{eff}} = \mathcal{L}_{\mathrm{SM}} + \sum_x \frac{C_x}{\Lambda^2} O_x + \ldots ,$$

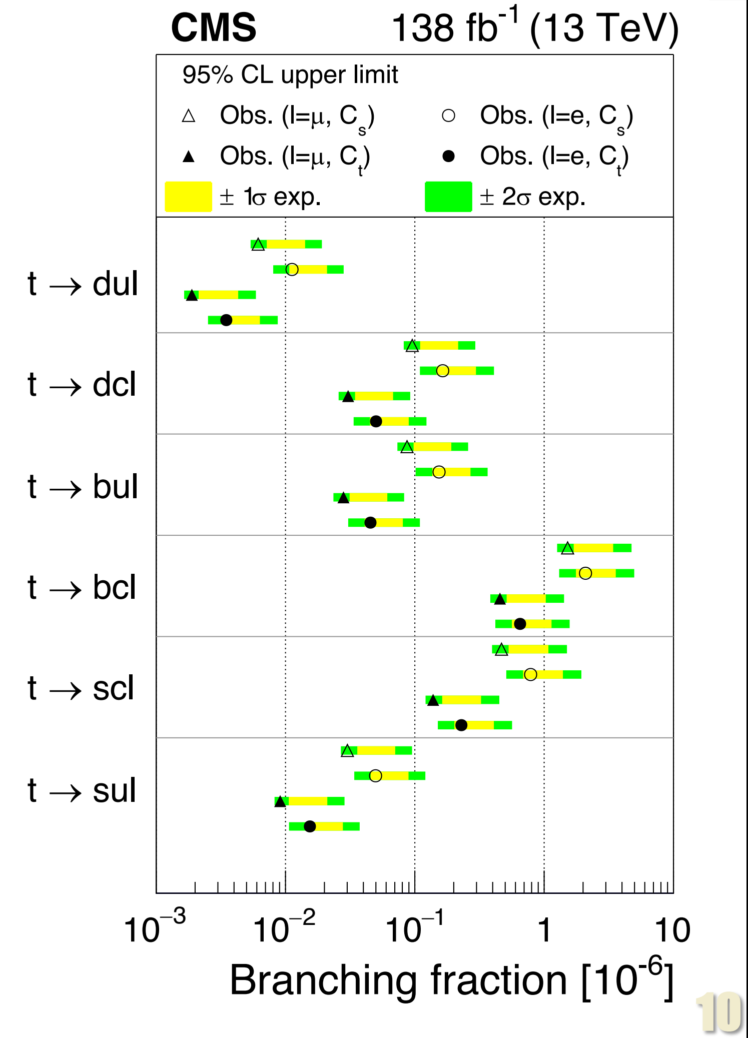
- BNV effects in single top quark production is included for the first time
- BDT is used to discriminate between signal and background events

$$O^{(s)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(aP_L + bP_R)D_\gamma][\overline{U^c_\beta}(cP_L + dP_R)E],$$
$$O^{(t)} \equiv \epsilon^{\alpha\beta\gamma}[\overline{t^c_\alpha}(a'P_L + b'P_R)E][\overline{U^c_\beta}(c'P_L + d'P_R)D_\gamma]$$

- No significant excess of events over the background prediction is observed
- Upper limit are set on the 24 Wilson coefficients



Upper limits on the top quark BNV BRs are multiple orders of magnitude more stringent than the previous limits



Summary

- Top properties are measured with exceptional precision
  - Mass, width, spin correlation,…
- Observation of quantum entanglement by ATLAS and CMS (new!) have brought the foundations of quantum mechanics to colliders
- Multiple searches are performed to probe rare decays of the top quarks (LFV, BNV, FCNC, ….)
  - No sign for deviations beyond the SM
- Only small fraction of recent results were presented today
  - Many more can be found here: Latest CMS results on top quarks
- more results with the Run 2 (+ Run 3) datasets are in the pipeline
  - Stay tuned!

Thanks for your attention