https://cms-results.web.cern.ch/cms-results/public-results/publications/TOP-23-007/index.html

Spin correlation, entanglement and causality connection in top-antitop events

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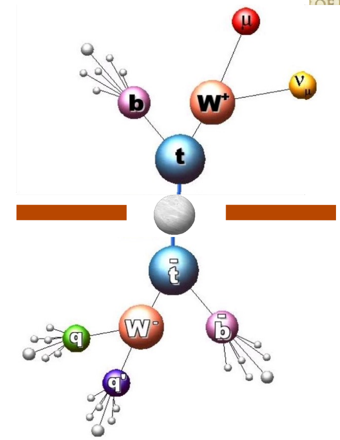
Spin correlation and entanglement

Polarization, P and spin correlation matrix, C determine the angular distribution of the decay products in the helicity basis as in [1212.4888]



$$\frac{d\sigma}{d\Omega d\bar{\Omega}} = \sigma_{norm}(1+\kappa\vec{P}\cdot\Omega+\bar{\kappa}\vec{\bar{P}}\cdot\bar{\Omega}-\kappa\bar{\kappa}\Omega\cdot C\cdot\bar{\Omega})$$

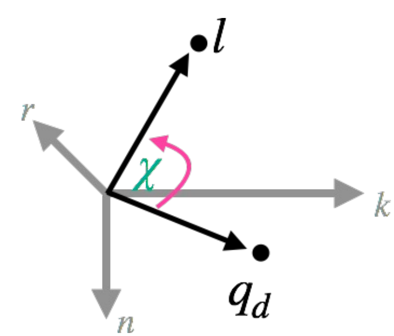
κ - spin analyzing power of top/antitop decay products

Ω – unit vector in the direction of the decay product

2x3(P)+3x3(C) =**15 coefficients collectively called Q_m**

Alternatively, we can define χ -opening angle between the two decay products, then

$$\frac{d\sigma}{d\cos\chi} = A(1+D\kappa\bar{\kappa}\cos\chi) \qquad C_{nn}+C_{rr}+C_{kk}=Tr(C)=-3D$$



and $\tilde{\chi}$, where the sign of n-component in one of the decay products is inverted

$$\frac{d\sigma}{d\cos\tilde{\chi}} = A(1+\tilde{D}\kappa\bar{\kappa}\cos\tilde{\chi}) \qquad C_{nn}-C_{rr}-C_{kk}=3\tilde{D}$$

The system is considered **separable** if its density matrix can be factored into that of individual states $\rho=\sum_n p_n\rho_n^t\rho_n^{\bar{t}}$

Otherwise, it is considered **entangled** → **Peres-Horodecki criterion** [2003.02280]

Entanglement is a result of spin correlation.

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

Two approaches – both presented

- Use full angular information of two decay products (e.g. charged leptons, or a lepton and a d-type quark) to measure the full matrix C and then construct Δ_E
- Use the distribution in χ and $\tilde{\chi}$ to measure D and $\tilde{D}$

Spin correlation and entanglement

There are four maximally entangled states

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

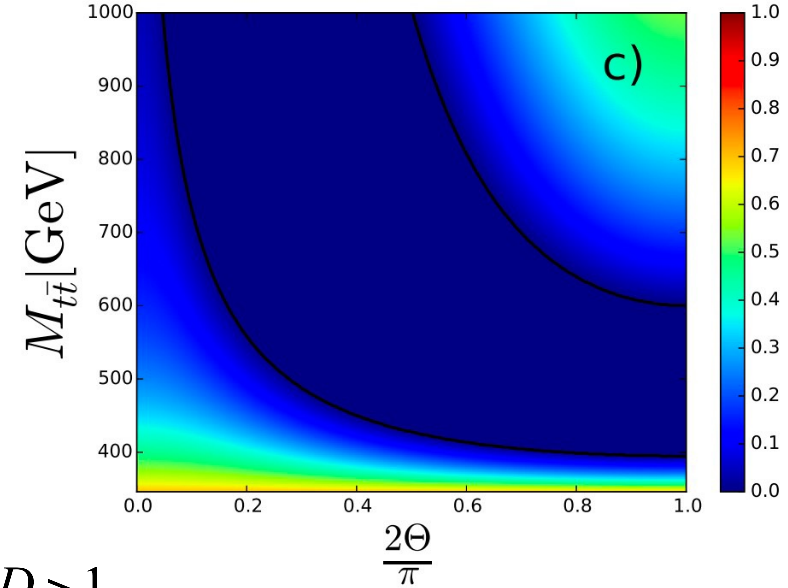
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\big(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\big).$$

at low $M_{t\bar{t}}$ **singlet** pseudoscalar state Ψ^-

$C_{nn}, C_{rr}, C_{kk} > 0$

$$\Delta_E = Tr(C) = -3D > 1$$

$$D < -\frac{1}{3}$$



at high $M_{t\bar{t}}$ **triplet** vector state (Φ^+-Φ^-, Ψ^+, Φ^++Φ^-)

$C_{nn} > 0$

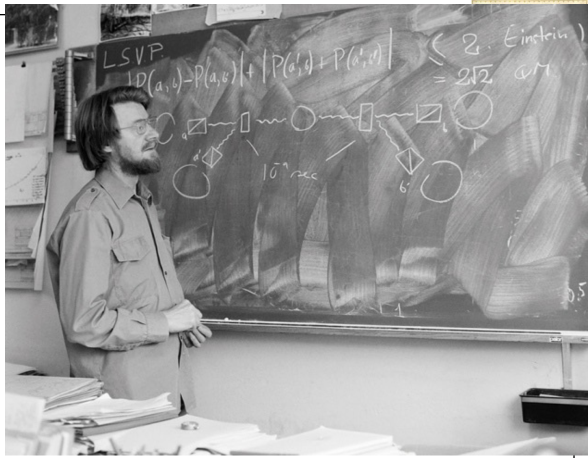
$C_{rr}, C_{kk} < 0$

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

$$\tilde{D} > \frac{1}{3}$$

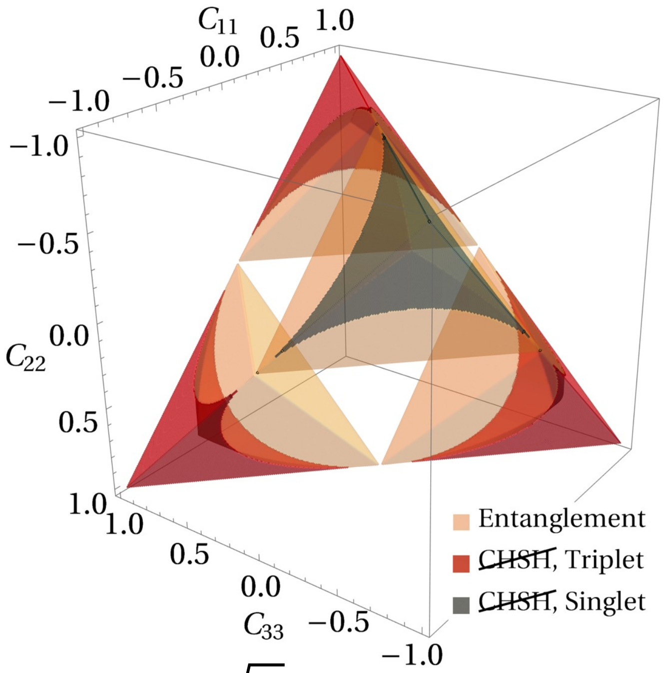
Plot from Afik, De Nova EPJP136(2021)9,907 hep-ph:2003.02280

Bell inequality



- **Bell inequality** is formulated based on conventional logic, which is violated in QM
- Entanglement is a necessary but not sufficient condition for Bell inequality violation
- It can be phrased in terms of Clauser, Horne, Shimony, and Holt (CHSH) inequality [PRL, 23(15), 1969] which states that measurements a, a' and b, b' on subsystems A and B, respectively (with absolute values <=1) classically must satisfy:

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



- For ttbar system the CHSH can formatted as

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

$$B_1 = |C_{rr} - C_{nn}| > \sqrt{2}$$

$$B_2 = |C_{rr} + C_{kk}| > \sqrt{2}$$

C Severi et al. arXiv:2110.10112v2 [hep-ph]

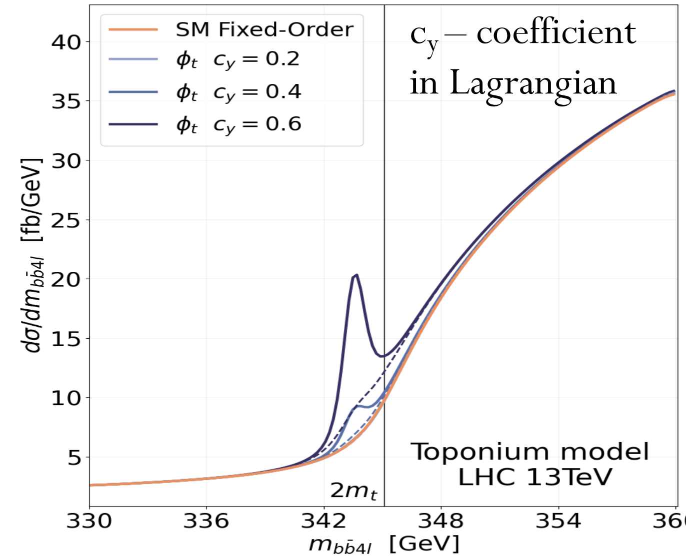
Dilepton vs l+jets channels

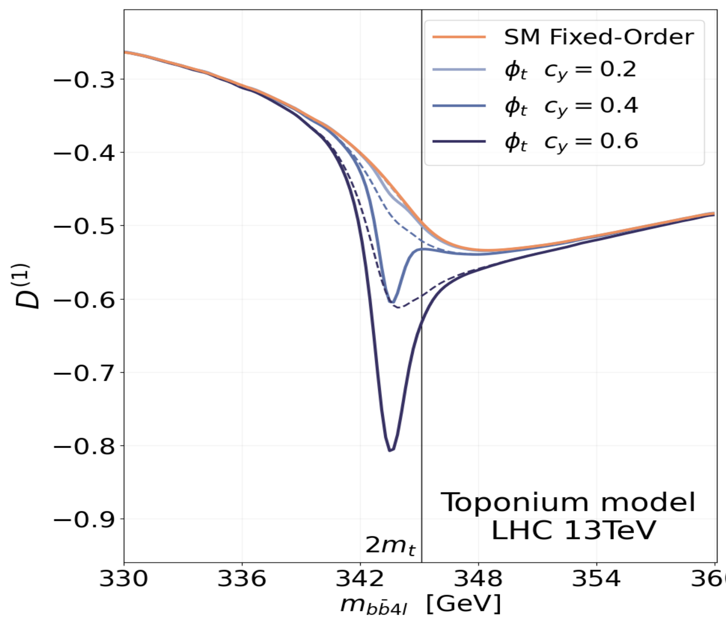
- Dilepton
- Lower branching ratio
- |κ|=1 for charged leptons, which are easy to ID →Ideal channel for spin correlation
- Lower p_T cuts for leading/subleading lepton (25/20 GeV) → higher efficiency at the threshold
- Worse M_{tt} resolution, not ideal for differential measurement
- Best for threshold
  - high entanglement
  - potential for "toponium" observation
  - mostly time-like separated events

- Lepton+jets
  - Higher branching ratio
  - |κ|=1 for down-type quarks, but they are harder to identify – employ AI (~66%)
  - 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_{tt}
  - Better M_{tt} resolution, good for differential measurement
- Advantage for high M_{tt}
  - high entanglement
  - potential for observation of Bell Inequality Violation
  - mostly space-like separated events

Signal modeling

- NLO POWHEG+Pythia8
- Include EW corrections with HATHOR (*Comput. Phys. Commun. 182 (2011) 10)*
- NNLO (*Phys. Rev. Lett. 127 (2021) 062001)*
  - Dilepton: p_T reweighting to match the top quark p_T spectrum from a fixed order ME calculation at NNLO
  - Lepton+jets: NN-based reweighting to match NNLO distributions at reco level
- Include "toponium" (pseudo-scalar color singlet predicted by non-relativistic QCD) as an uncertainty +-100%
  - M(toponium)-344 GeV, σ=~6.5pb
    - Sumino, Fujii, Hagiwara, Murayama & Ng (PRD`93)
    - Jezabek, Kuhn & Teubner (Z.Phys.C`92)
    - B. Fuks et al. (PRD 104 (2021) 034023)
  - affects the invariant mass distribution and the **spin correlations** at the threshold

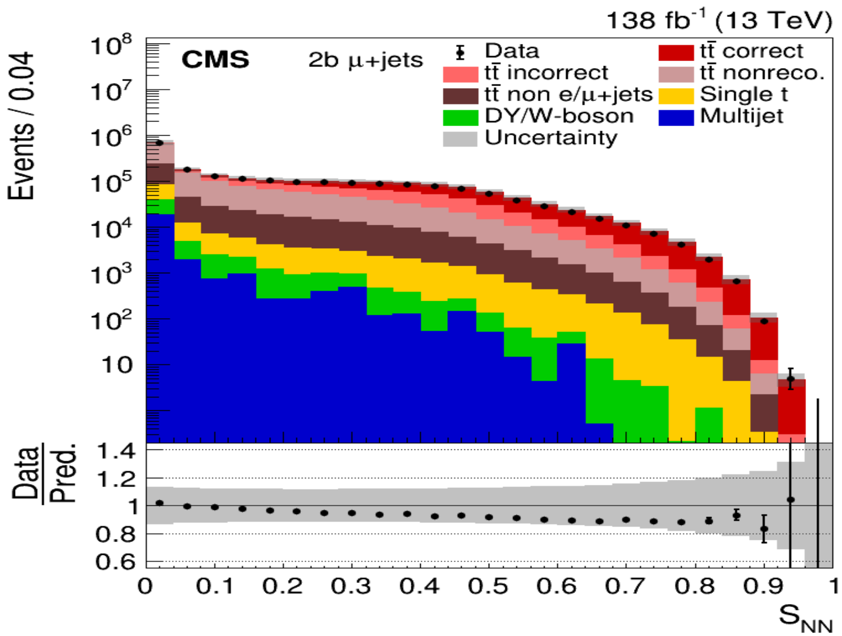




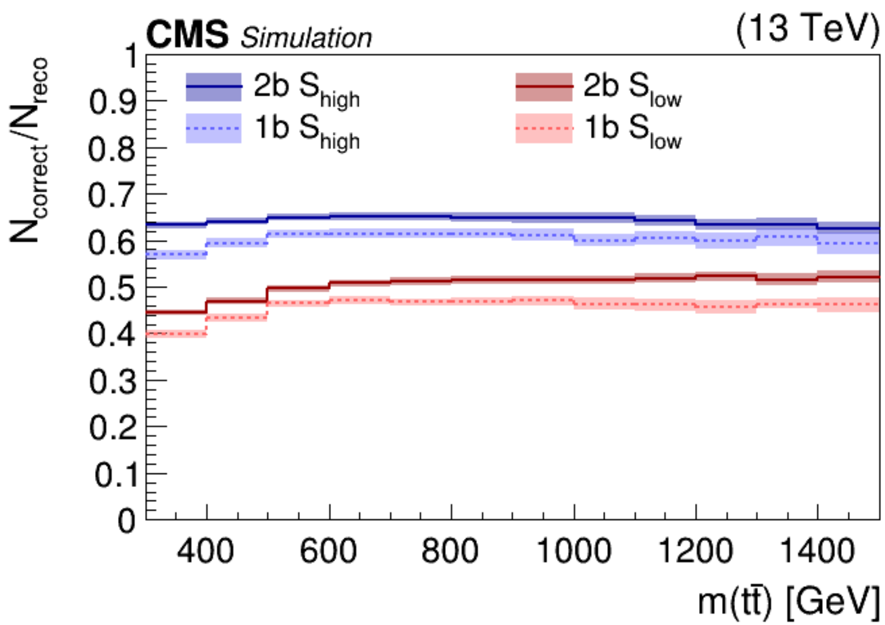
 F. Maltoni et al. JHEP03(2024)099

L+jets system reconstruction

- The measurements are done inclusively and differentially in M_{tt}, $cos\theta$ and p_T (t)
- **Jet-parton assignment, including d-type quark is performed using NN**
  - **Input – jet 4-vectors, b-tagging score (it carries some info about charm jets)**
- Remove events with NN score S_{NN}<0.1;
- Divide events into categories based on lepton flavor, number of b-tags, and NN score



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



Full matrix measurement

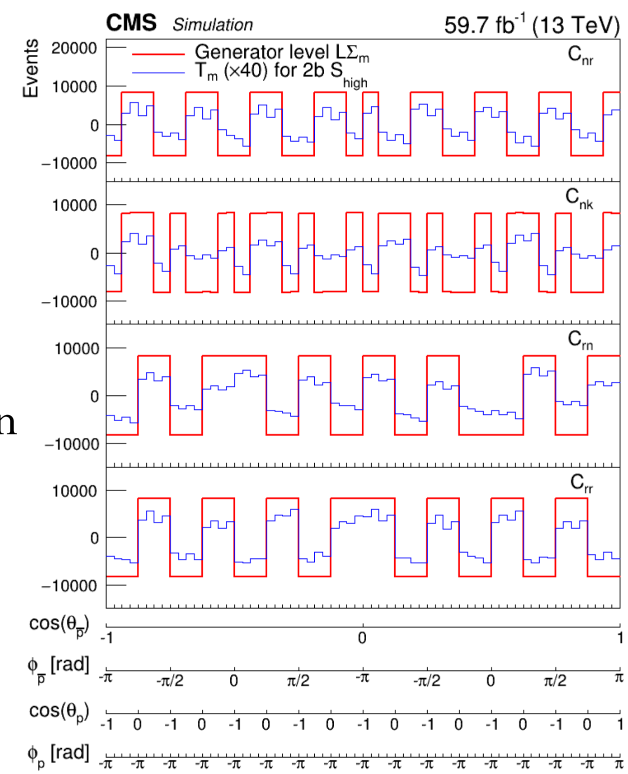
- Full measurement of the vectors P and matrix C is performed using templates defined based on the functions of angles of top and antitop decay products

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

- The total cross section is a linear combination of these templates with coefficients Q_m that are the components of P and C

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

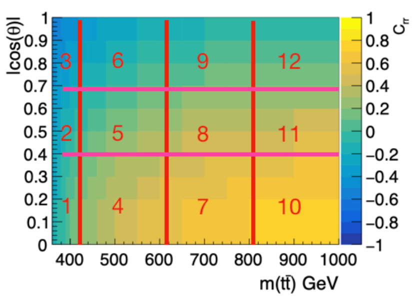
Gen level Σ_m and reco level T_m



- **The templates T_m are defined at the reco level.**

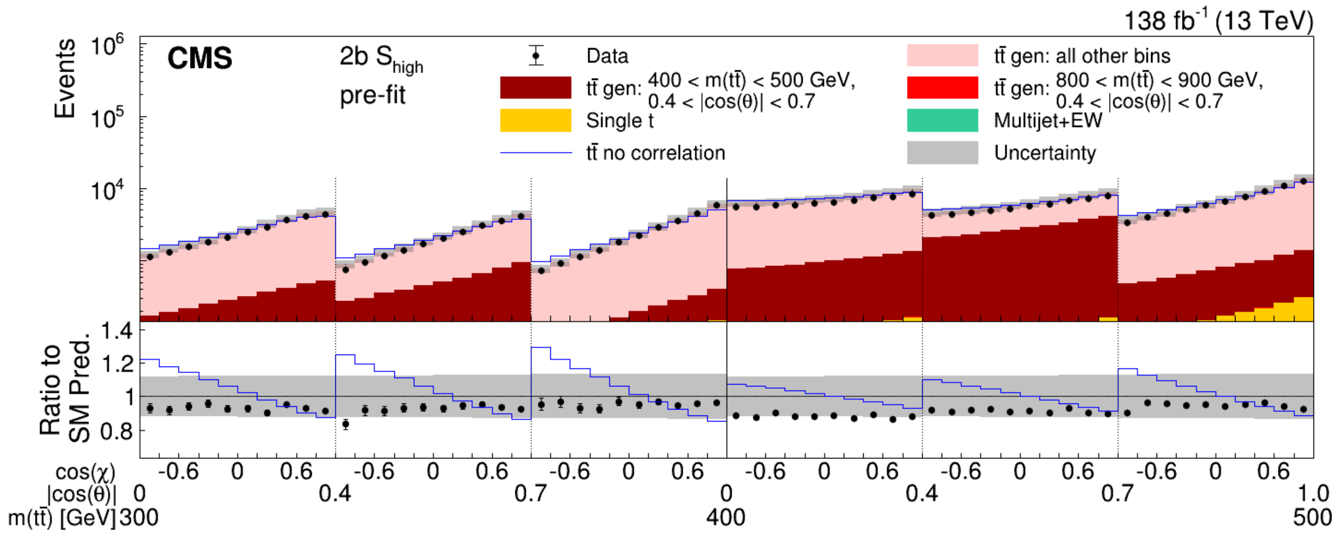
To avoid generating events with every possible combination of Q_m the events are reweighted with weights defined at the gen level $w_i = \frac{\Sigma_i}{\Sigma_{tot}}$

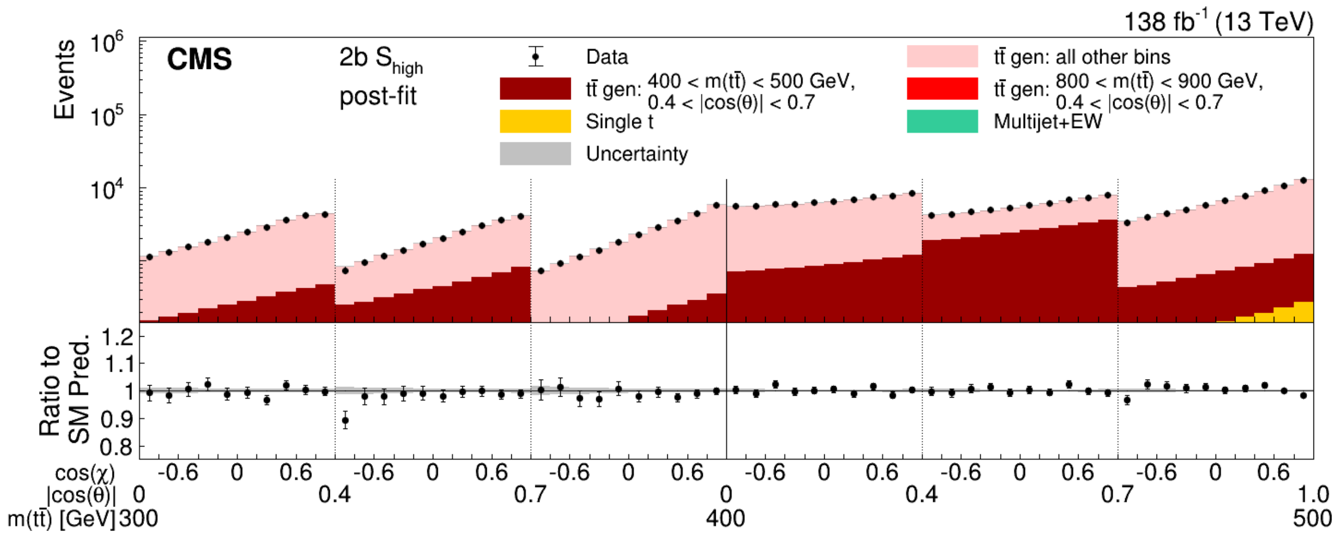
To minimize the bias due to variation of Q_m or T_m within the bin we perform the measurement in finer bins in M_{tt} and $\cos\theta$, then combine



Example of the fit

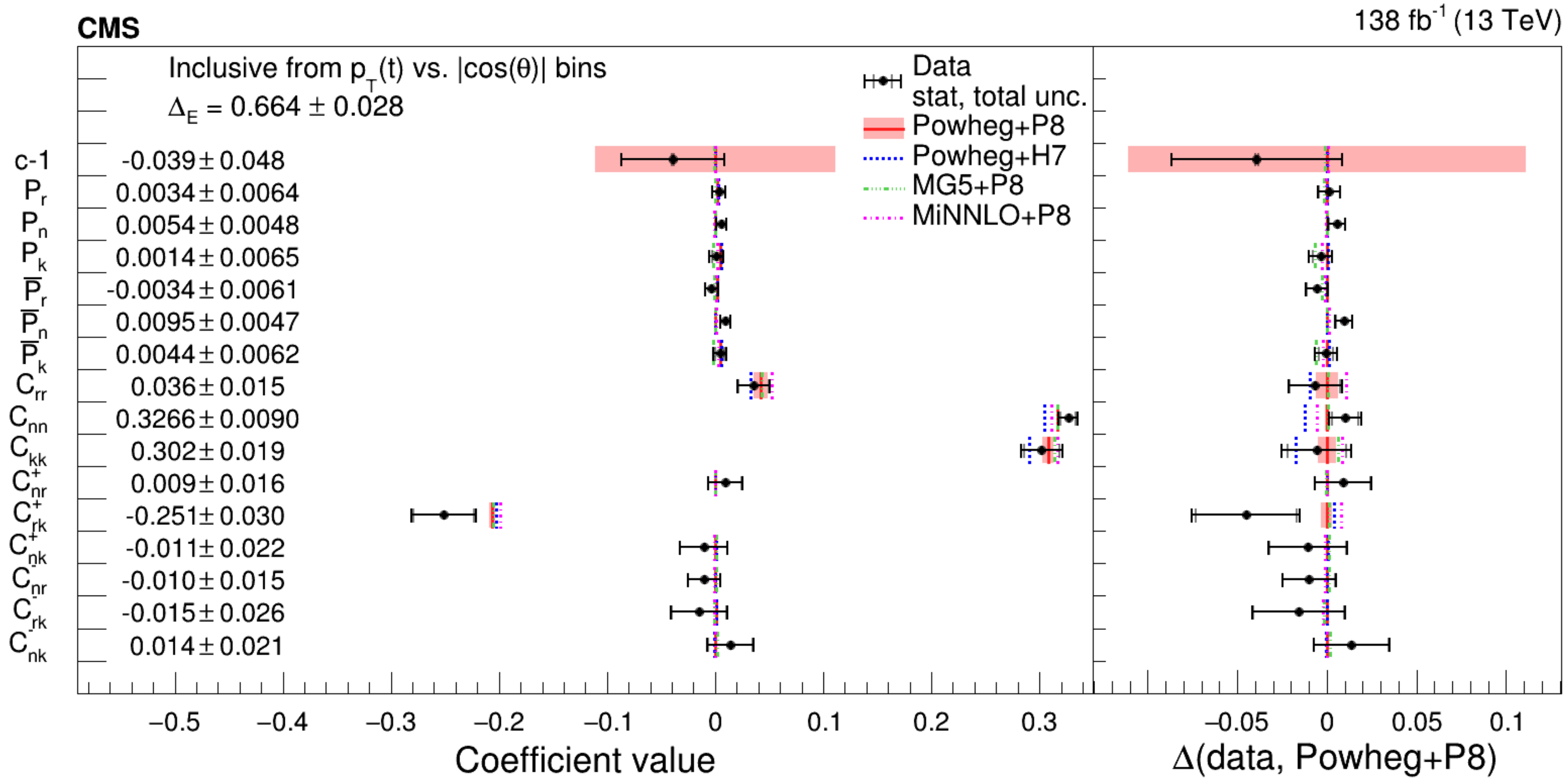
Fit is performed in different categories (e.g. 2b Shig, 1b Slow…) simultaneously.
Bins are defined at the reconstruction level,
But contributions from all bins at gen level are included and fit for (different shades of red).
Thus, we present the result in bins of gen level variables.





Polarization, spin correlation measurement

- Full measurement of the P and C is performed inclusively and differentially in bins of M_{tt}, $cos\theta$ and top p_T
- Include uncertainty on Powheg+p8 (in pink), the other models have similar uncertainties
- Full covariance matrix is provided
- A good agreement with the SM prediction is observed



Differential measurement

- You can see the transition from singlet to triplet state

at low p_T **singlet**

pseudoscalar state Ψ^-

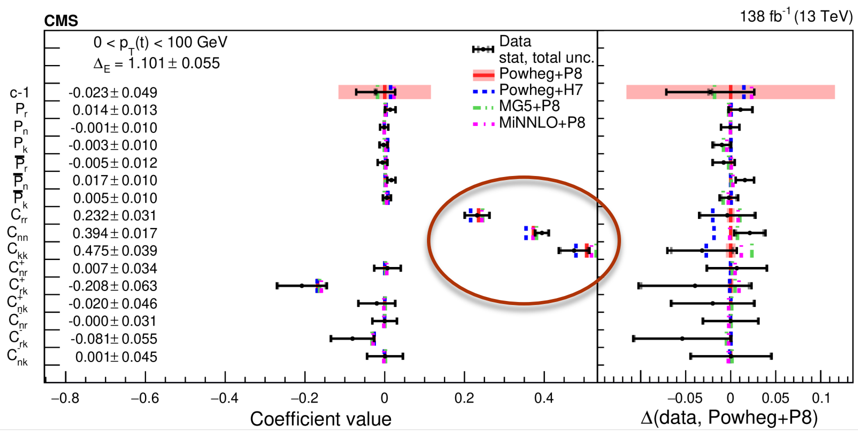
$C_{nn}, C_{rr}, C_{kk} > 0$

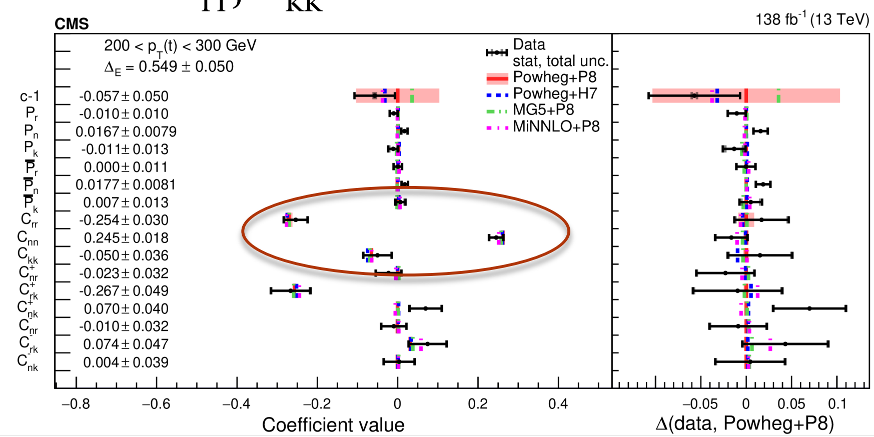
at high p_T **triplet** vector state

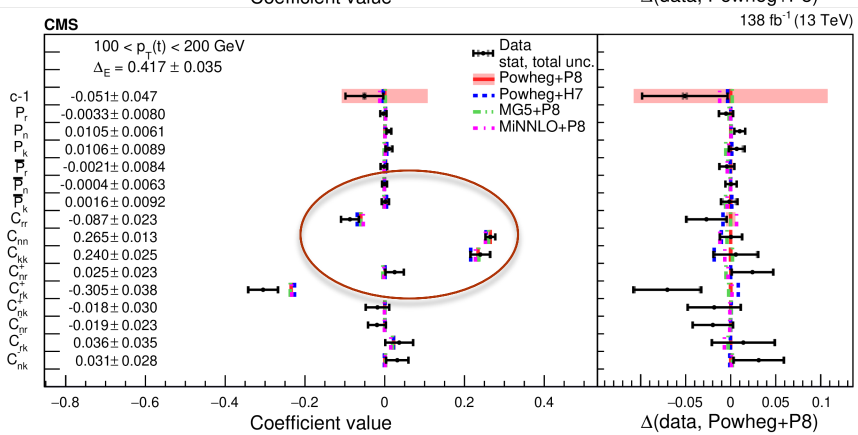
$(\Phi^+ - \Phi^-, \Psi^+, \Phi^+ + \Phi^-)$

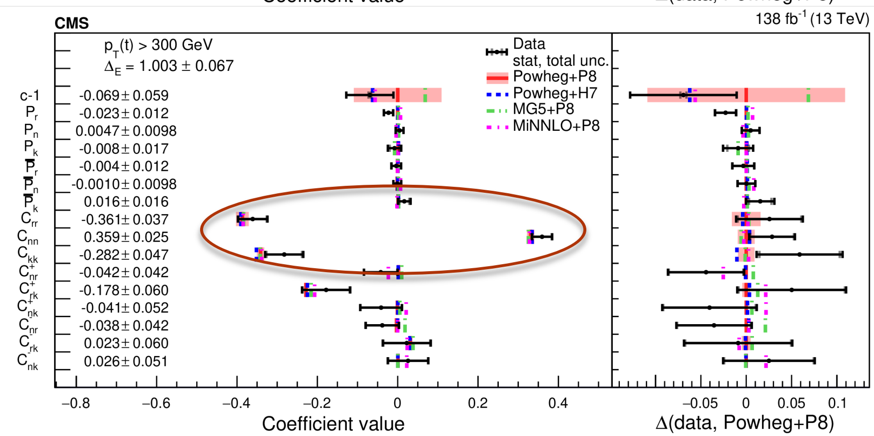
$C_{nn} > 0$

$C_{rr}, C_{kk} < 0$



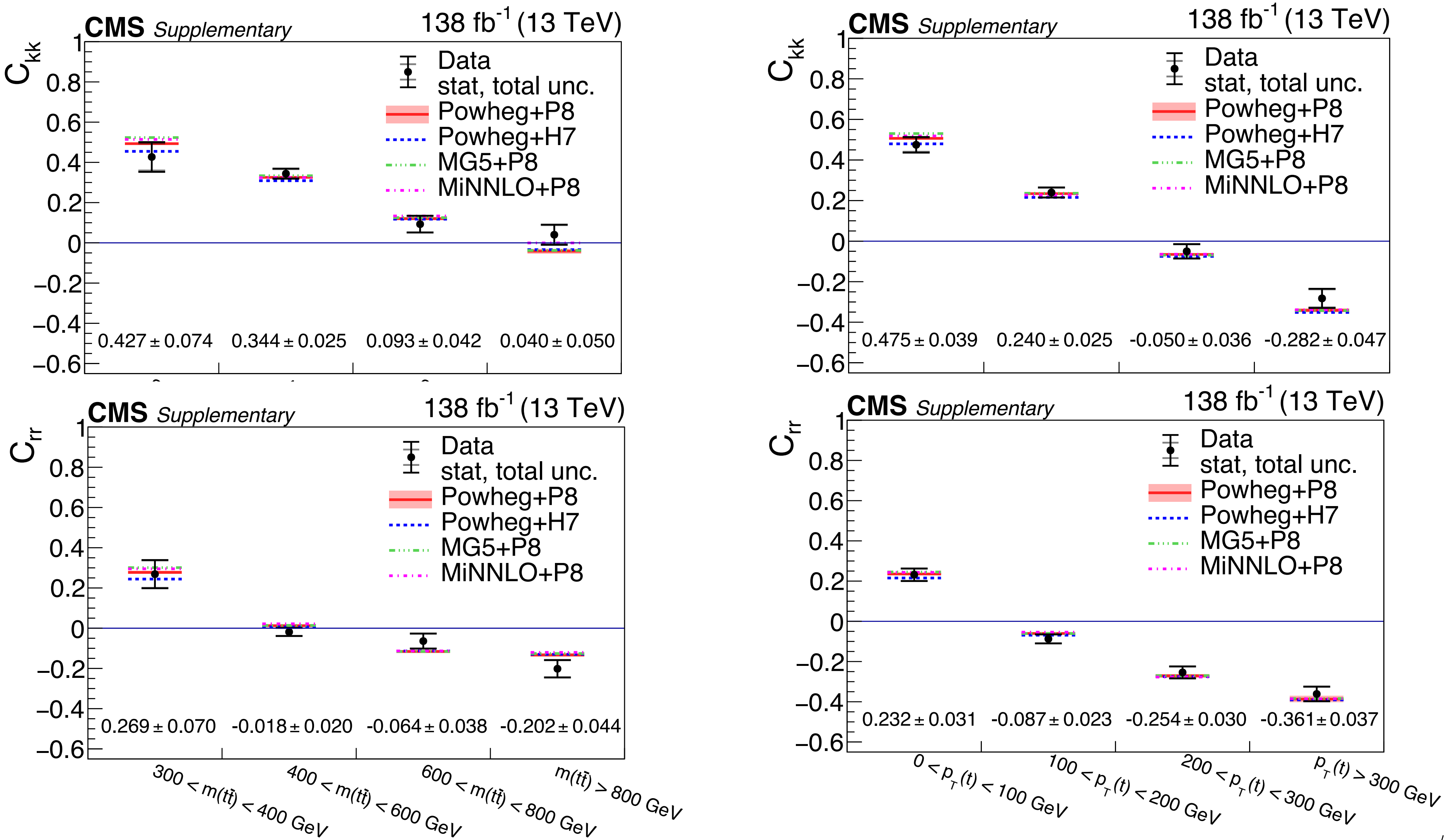






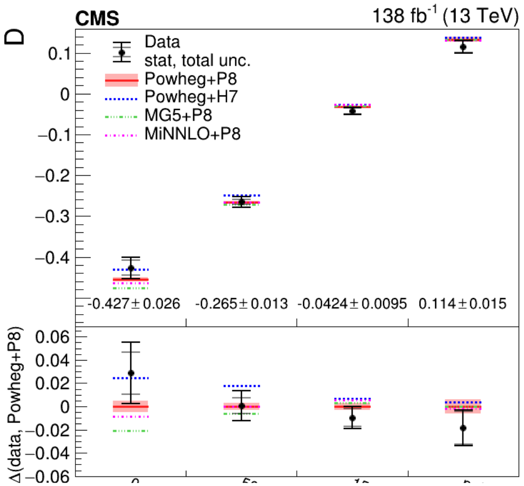
Differential measurement – diagonal elements

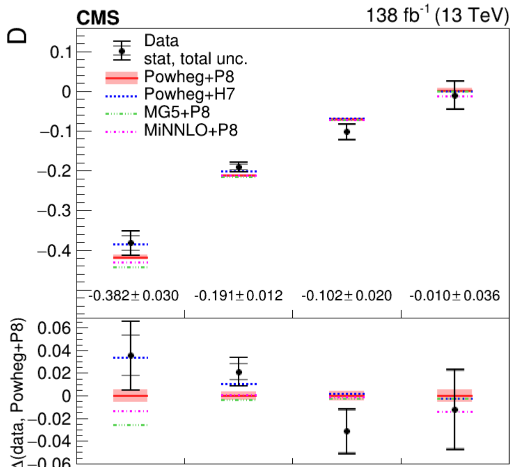
- You can see the transition from singlet to triplet state

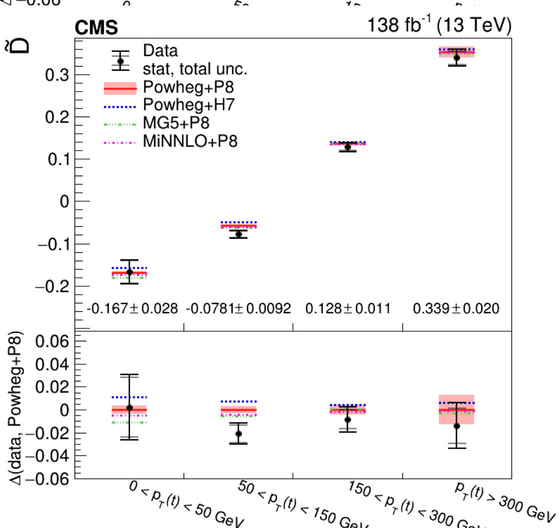


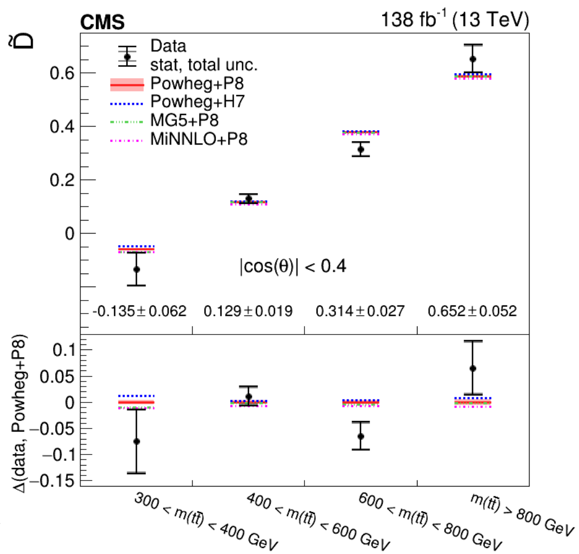
D and D~ measurements

- Full measurement of the P and C is performed inclusively and differentially in bins of M_{tt}, $cos\theta$ and top p_T
- Full covariance matrix will be provided with the published result
- A good agreement with the SM prediction is observed

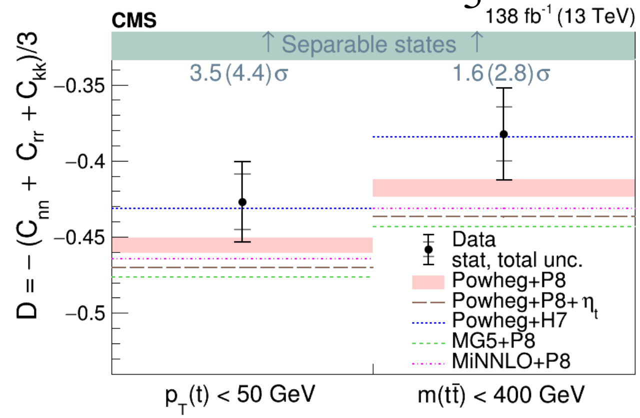




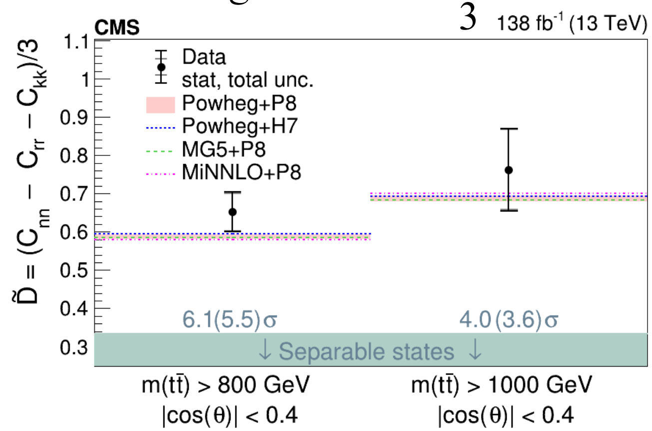




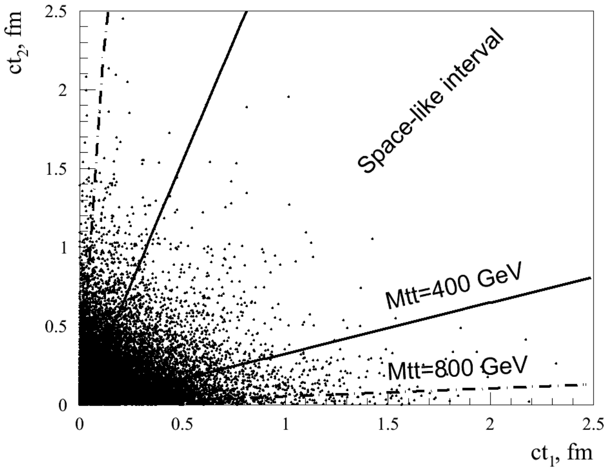
Low M_{tt} $D < -\frac{1}{3}$



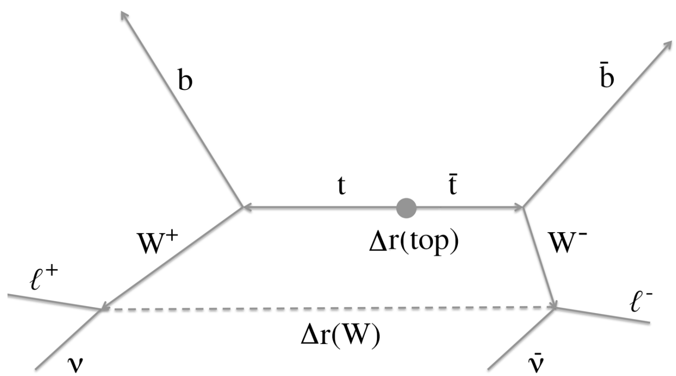
High M_{tt} $\tilde{D} > \frac{1}{3}$

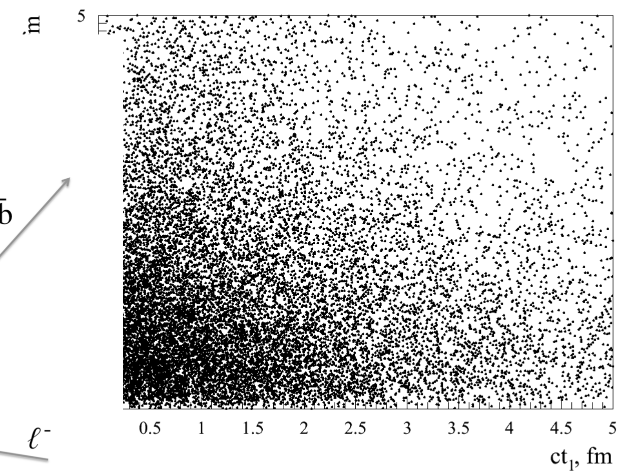


Causal connection in ttbar events



$$\frac{1-\beta}{1+\beta}t_1 < t_2 < \frac{1+\beta}{1-\beta}t_1$$



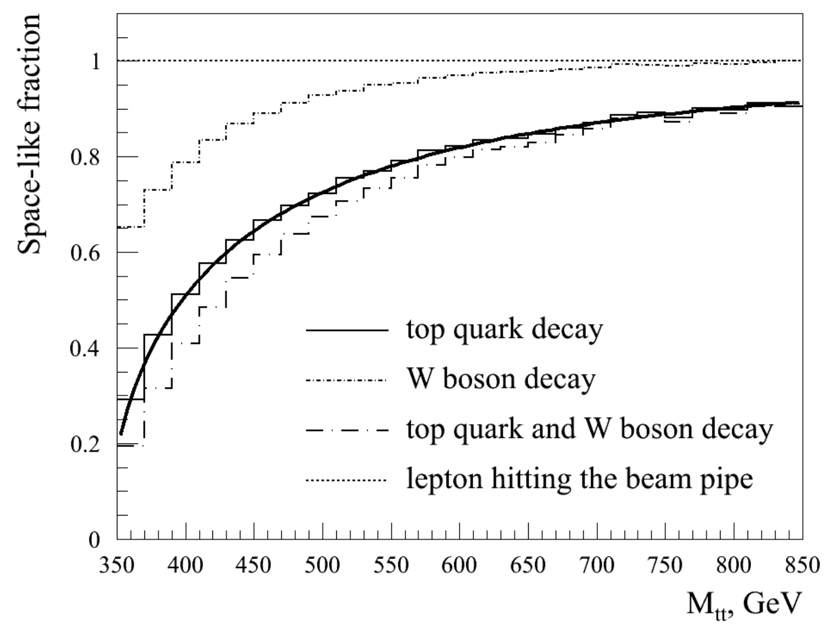


Could top and antitop or their decay products have communicated?

Consider separation between:

- Top and antitop
- W+ and W-
- Both tops and Ws are separated
- Leptons contact with macroscopic device

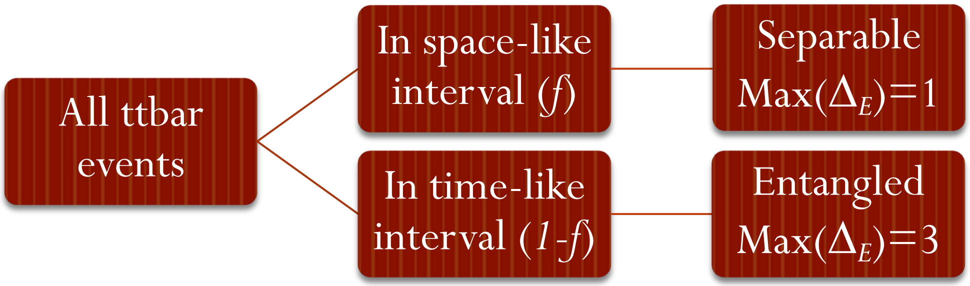
RD, G. Landi arXiv2407.15223v1



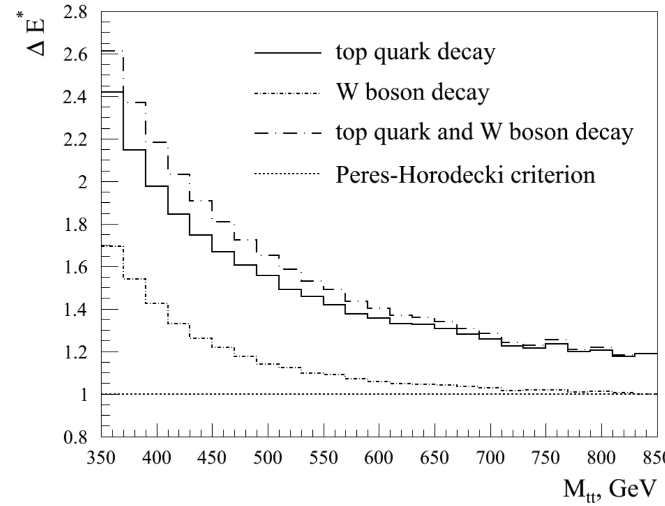
Causal connection in ttbar events

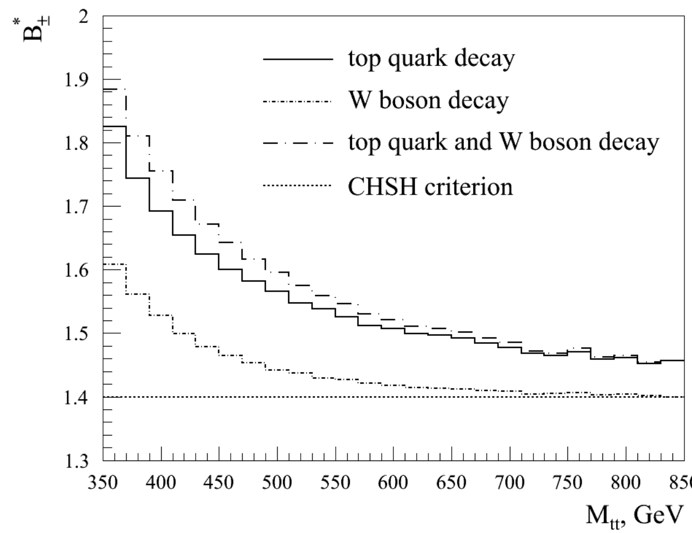
f- fraction of space-like separated top and antitop

$$\Delta_{Ecritical} = f(\Delta_E = 1) + (1 - f)(\Delta_E = 3)$$



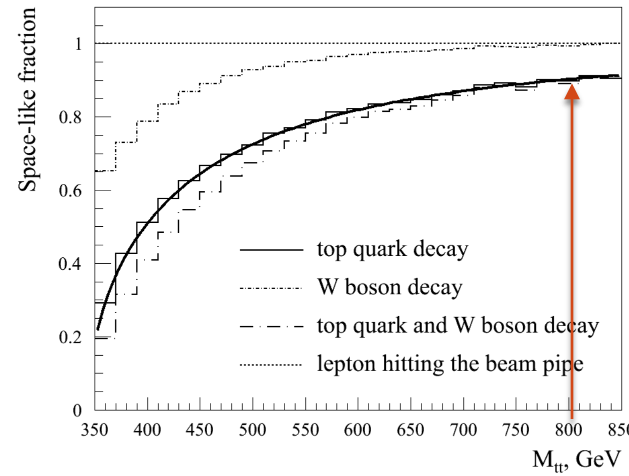
$$B_{Ecritical} = f(B_E = \sqrt{2}) + (1 - f)(B_E = 2)$$



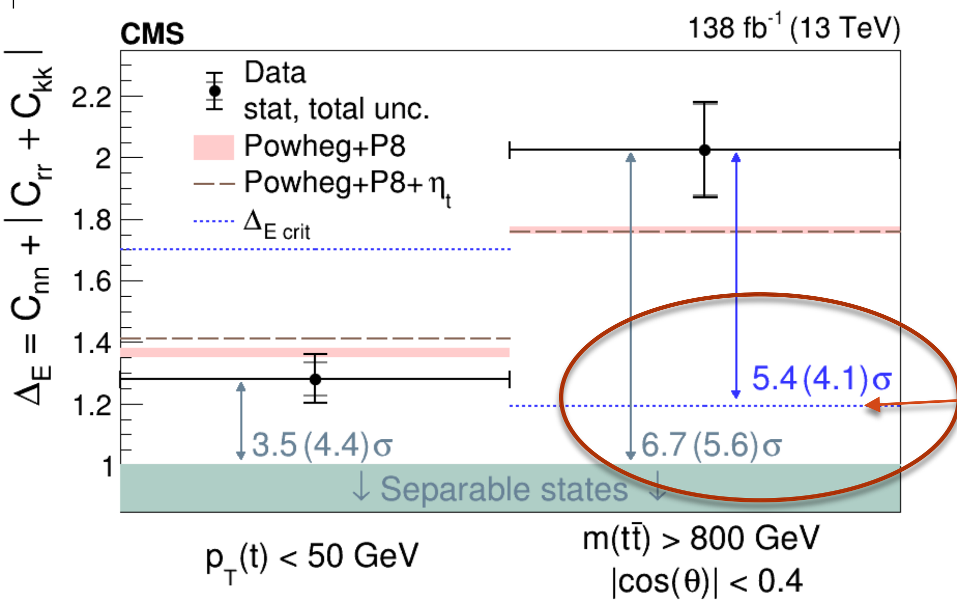


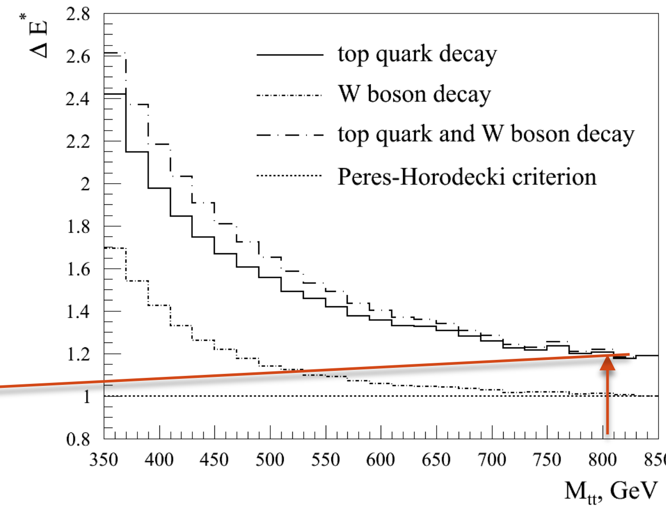
Entanglement results

- We quantify the entanglement using Peres Horodecki criterion
- Significant entanglement is observed in the M_{tt} >800 GeV region
- Apply the Demina-Landi criterion to see if this entanglement could be explained by classical communication



Based on full matrix $\Delta_E = C_{nn} + |C_{rr} + C_{kk}| > 1$



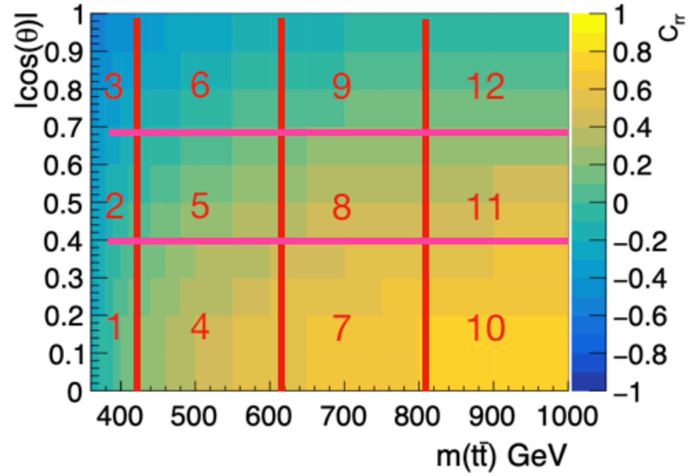


Summary

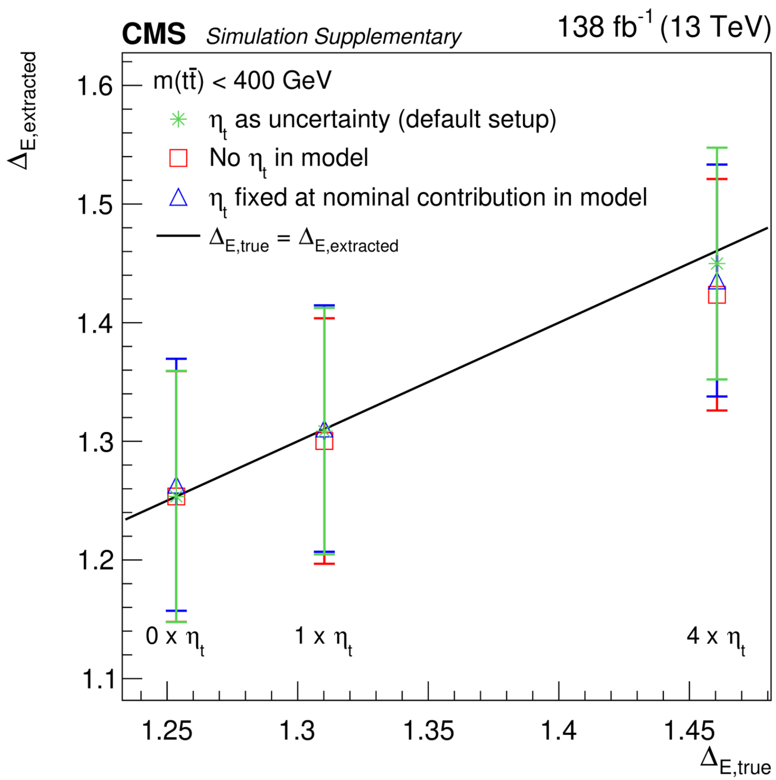
- Angular distributions of the top and antitop quarks were used to measure their **polarization** and **spin correlation matrix**, C_{ij} inclusively and in bins of M_{tt}, $cos\theta$ and top quark p_T
- In some regions of phase space top and antitop get entangled, which can be demonstrated using **Peres-Horodecki criterion** based on their spin correlation matrix
- Maximally entangled states are a singlet produced at the threshold, and a triplet produced at high M_{tt}
- Using full matrix measurement the entanglement was observed at **6.7σ** level in $M_{tt} > 800\ GeV,\ |cos\theta| < 0.4$ region
- The later result was found to exceed the maximum entanglement achievable by classical communication between top and antitop decays by **>5σ**

Calibration

To minimize the bias due to variation of Q_m or T_m within the bin we perform the measurement in finer bins in M_{tt} and *cos q*, then combine

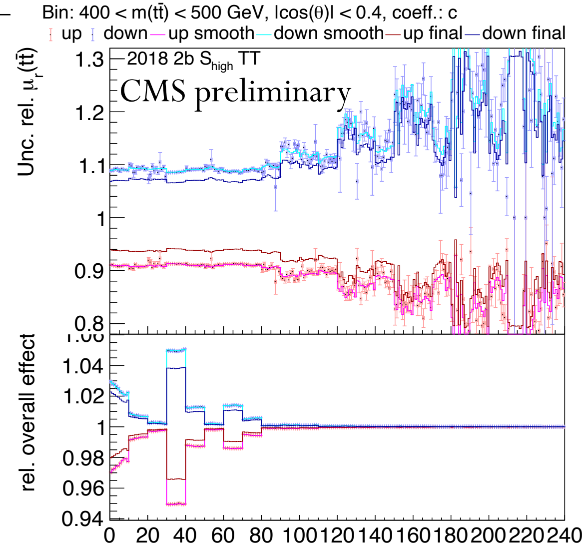


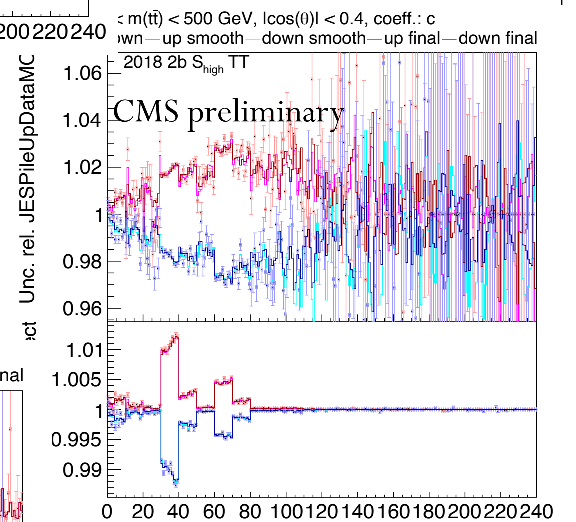
We perform calibration of the procedure by injecting the variation of Q_m different from the SM, e.g. using h_t model:

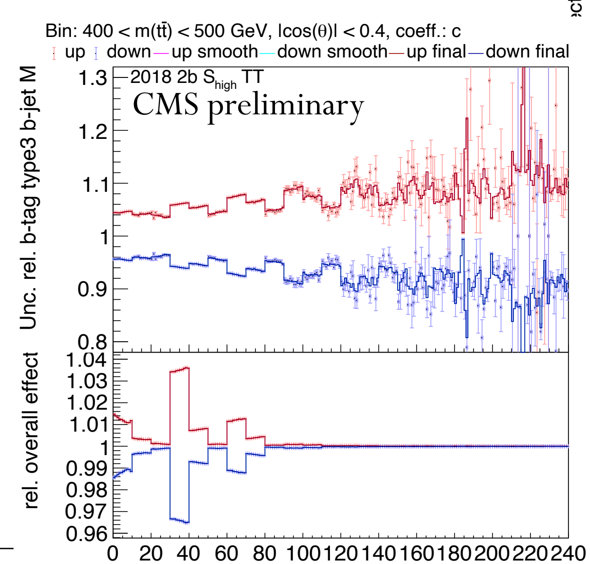


Systematics

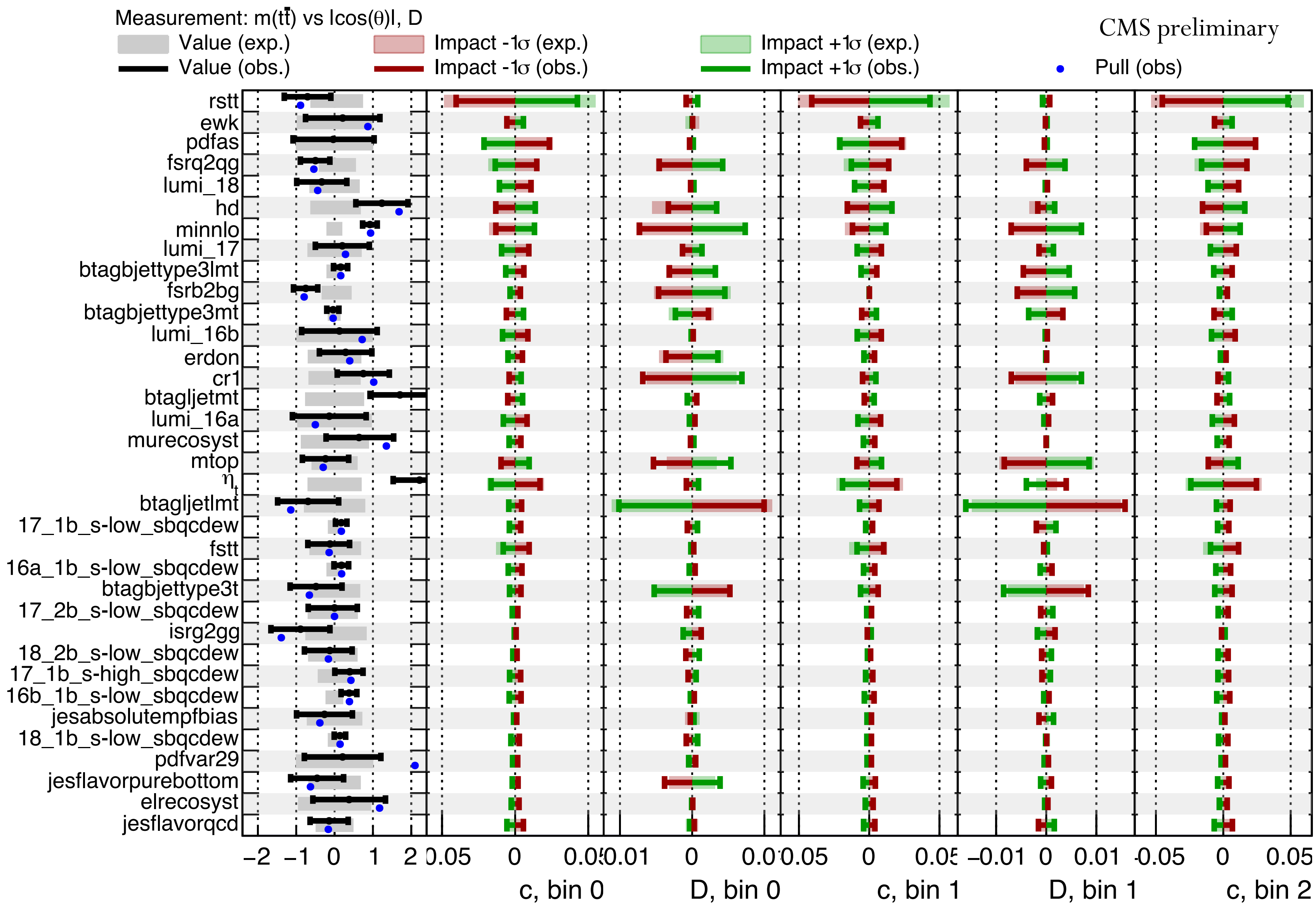
- The analysis is statistics limited
- Theoretical uncertainties
  - Mtop, renormalization/factorization scale, NNLO, EW
  - NB. Toponium effect is small for lepton+jets ~5E-04
- Experimental uncertainties:
  - Jet energy scale, b-tagging efficiency







Impacts



Measurement: m(tt̄) vs |cos(θ)|, D
Value (exp.)
Value (obs.)
Impact -1σ (exp.)
Impact -1σ (obs.)
Impact +1σ (exp.)
Impact +1σ (obs.)
CMS preliminary
Pull (obs)
rstt
ewk
pdfas
fsrq2qg
lumi_18
hd
minnlo
lumi_17
btagbjettype3lmt
fsrb2bg
btagbjettype3mt
lumi_16b
erdon
cr1
btagljetmt
lumi_16a
murecosyst
mtop
ηt
btagljetlmt
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fstt
16a_1b_s-low_sbqcdew
btagbjettype3t
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isrg2gg
18_2b_s-low_sbqcdew
17_1b_s-high_sbqcdew
16b_1b_s-low_sbqcdew
jesabsolutempfbias
18_1b_s-low_sbqcdew
pdfvar29
jesflavorpurebottom
elrecosyst
jesflavorqcd
−2 −1 0 1 2
c, bin 0
D, bin 0
c, bin 1
D, bin 1
c, bin 2