Top-antitop spin correlation and entanglement

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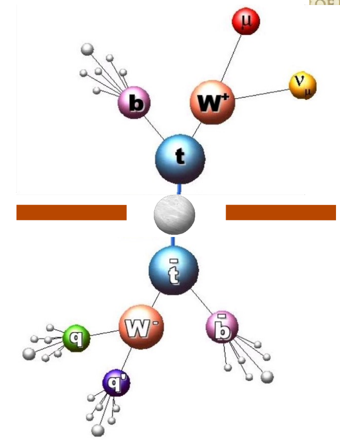
Spin correlation and entanglement



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

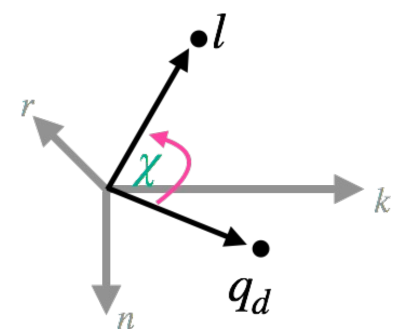
2×3(P)+3×3(C) =**15 coefficients Q_m**

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

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

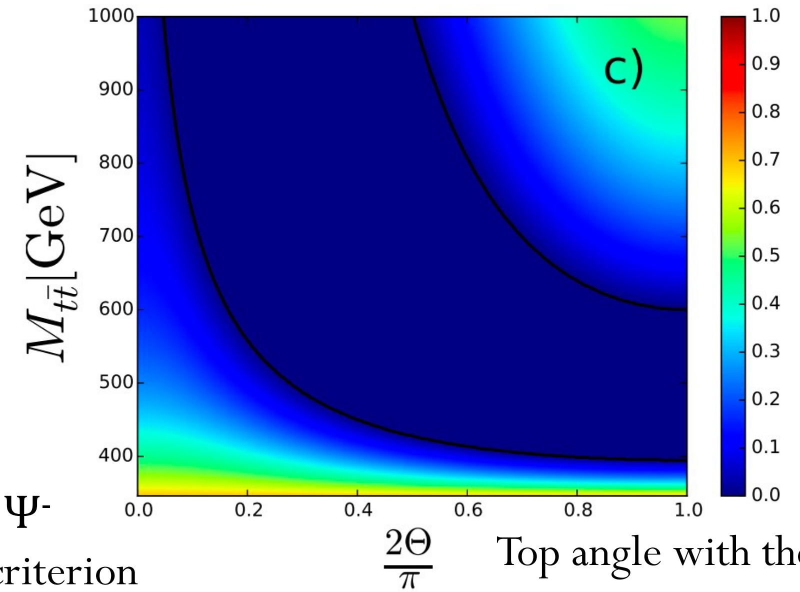
$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\downarrow\rangle \pm |\downarrow\uparrow\rangle\right).$$

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

Peres-Horodecki criterion

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

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



Top angle with the beam axis

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

Peres-Horodecki criterion

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

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

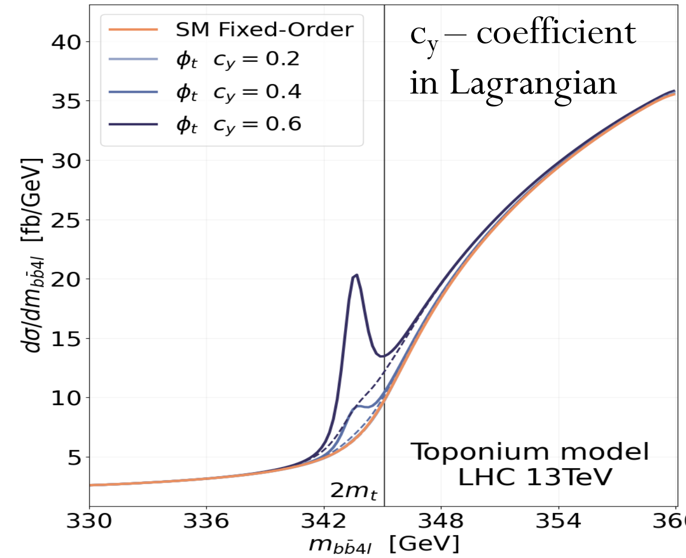
Plot from Afik, De Nova EPJP136(2021)9,907 hep-ph:2003.02280

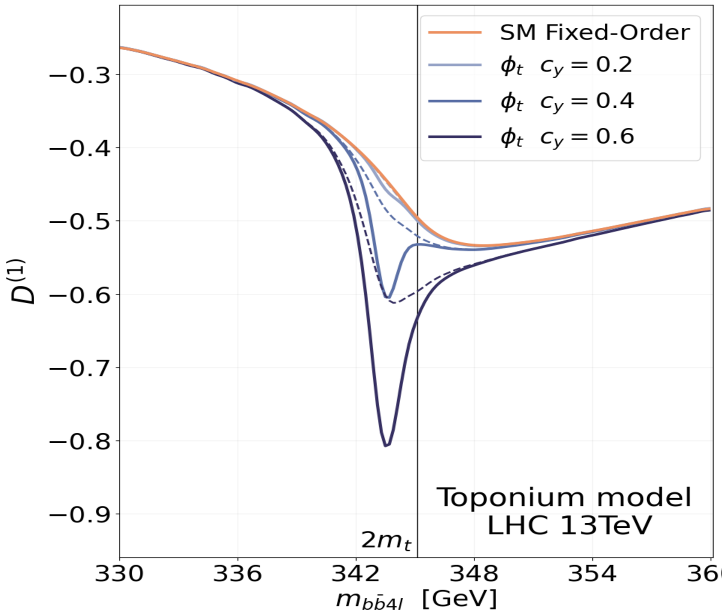
Dilepton vs l+jets channels

- Dilepton based on PRD 100 (2019) 072002
  - 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**
  - **CMS Top-23-001**
- 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**
- **CMS Top-23-007**

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
- Add "toponium" (pseudo-scalar color singlet predicted by non-relativistic QCD)
  - 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

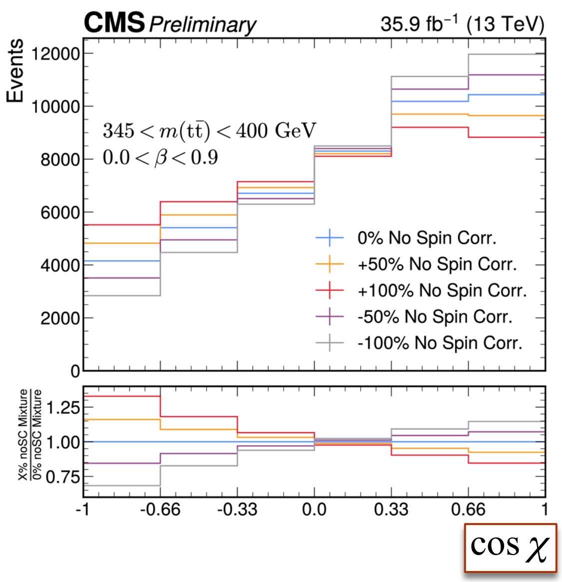
Dilepton channel

To extract D we measure the distribution in the sensitive variable – cos χ

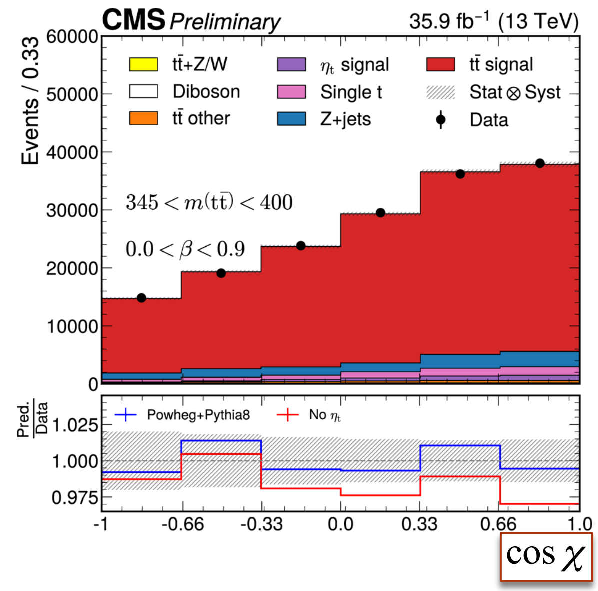
$$\frac{d\sigma}{d\cos\chi} = A(1 + D\kappa\bar{\kappa}\cos\chi)$$

Optimize M_{tt} cut to maximize sensitivity to entanglement

Determine the effect of acceptance and efficiency by comparing $D_{reco}(M_{reco})$ *vs* D_{gen} *(*M_{gen} *full phase space)*

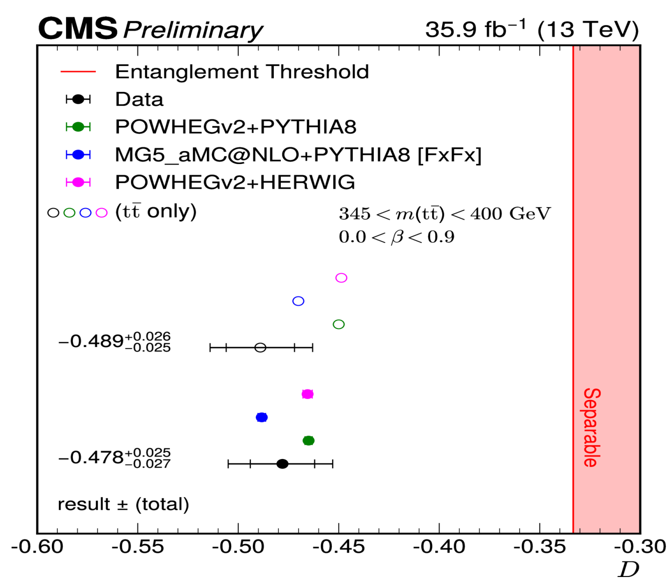


The ttbar entanglement is observed at > 5.0 σ level for 345<Mtt<400 GeV, β<0.9



w/out **Toponium**

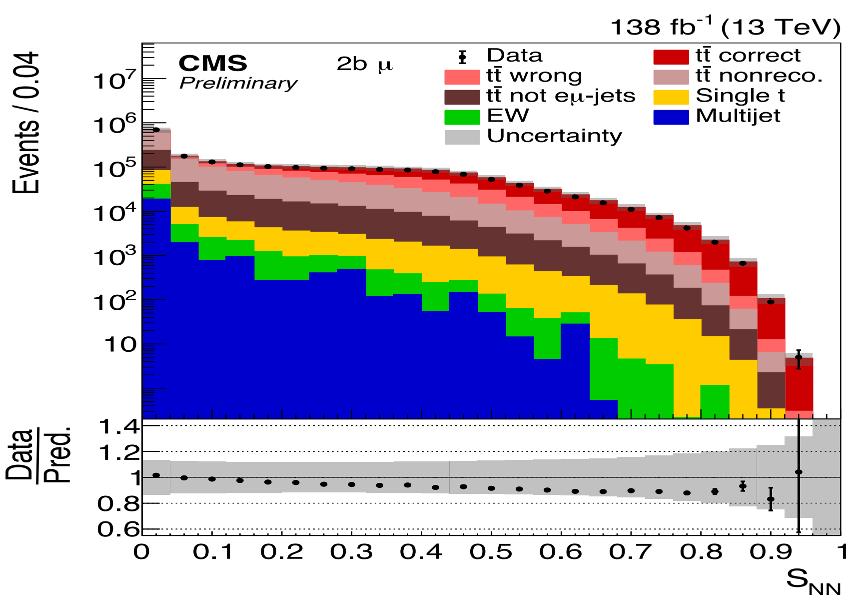
w/ **Toponium**



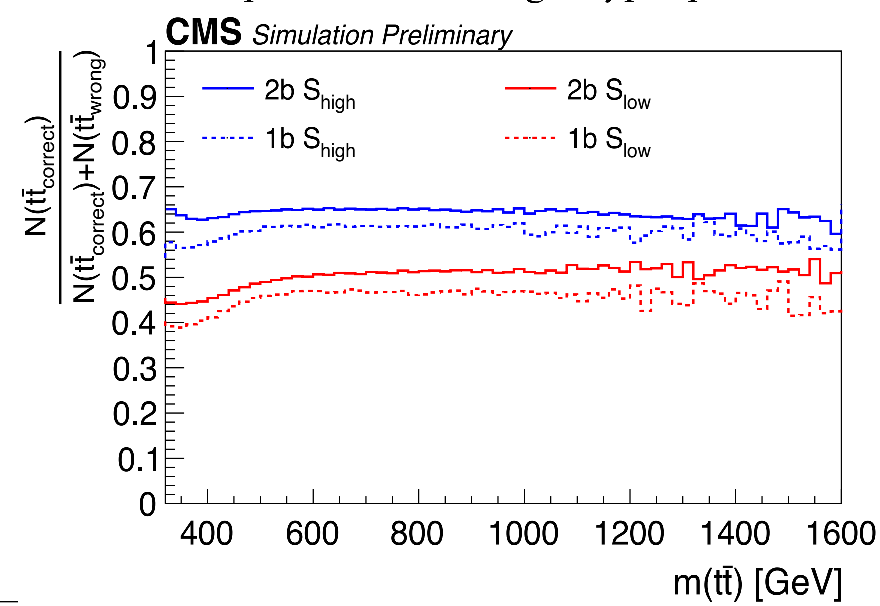
~1.5σ tension with the expectation if toponium is not included

L+jets channel

- We pursue both strategies – evaluation of the full correlation matrix C and polarization vectors P as well as D and $\tilde{D}$ measurements
- The measurements are done inclusively and differentially in bins of M_{tt}, $cos\theta$ and top quark p_T
- Event reconstruction (jet-parton assignment) is performed using NN
- Remove events with NN score $S_{NN}<0.1$;
- Divide events into categories based on lepton flavor, number of b-tags, and NN score



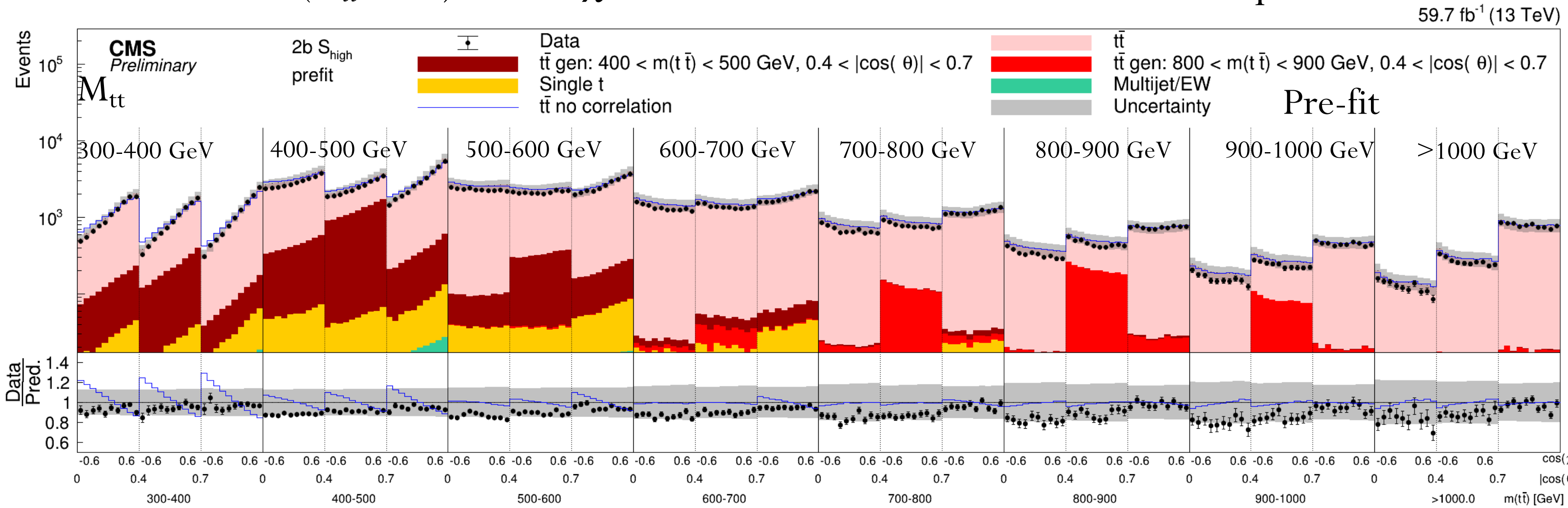
Fraction of *tt* events with correctly assigned jets to partons including *d*-type quark

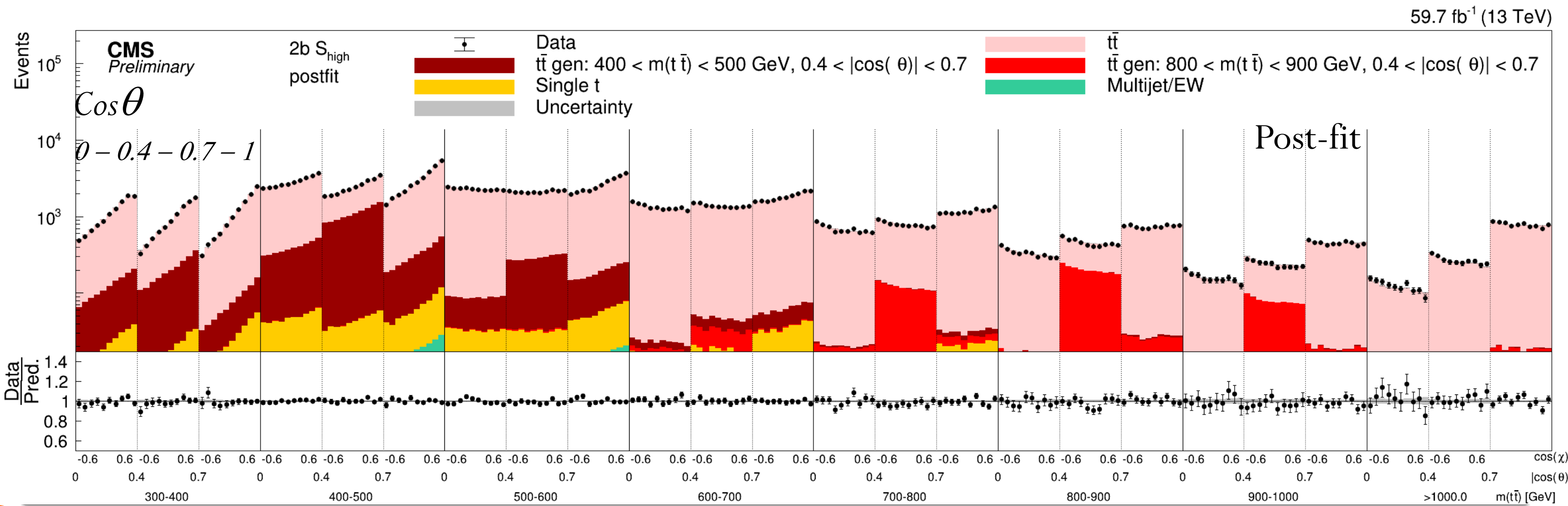


Regina Demina, University of Rochester

L+jets: Example of the fit

- In each (M_{tt}, $cos\theta$) bin $cos\chi$ distribution is fit to the reco-level templates





L+jets – 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

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

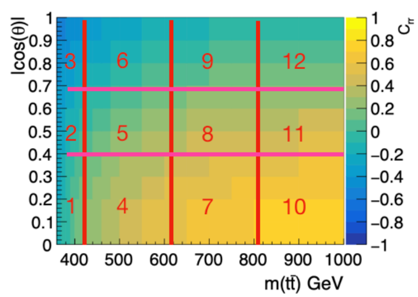
- The total cross section is a linear combination of these templates with coefficients Q_m that are the components of P and C

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

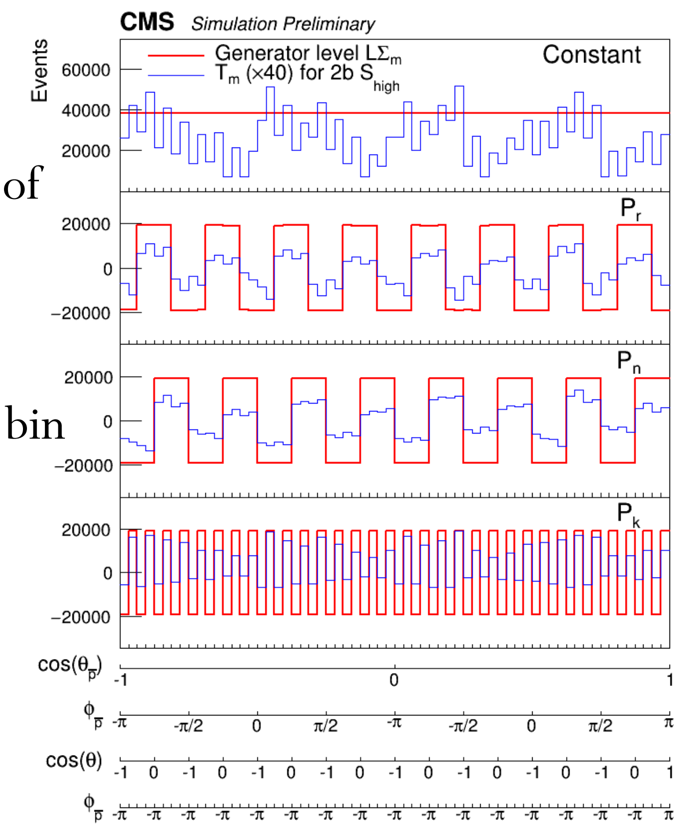
- The templates T_m are defined at the reco level.

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

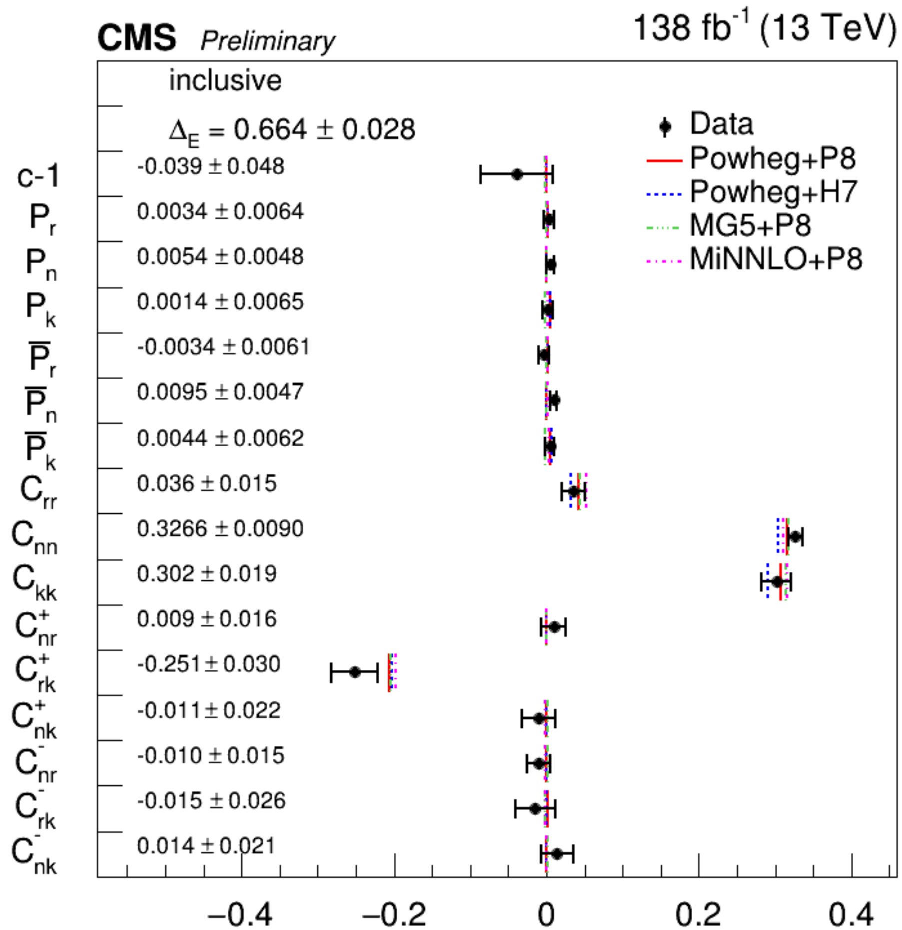


Gen level Σ_m and reco level T_m



L+jets – spin correlation matrix measurement

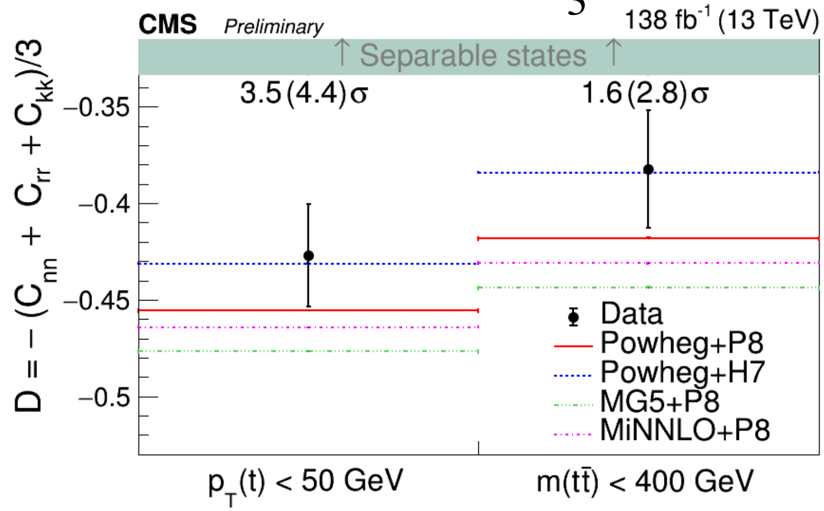
- Full measurement of the *P* and *C* is performed inclusively and differentially in bins of M_{tt}, $cos\theta$ and top p_T
- Full covariance matrix will be provided with the published result
- A good agreement with the SM prediction is observed



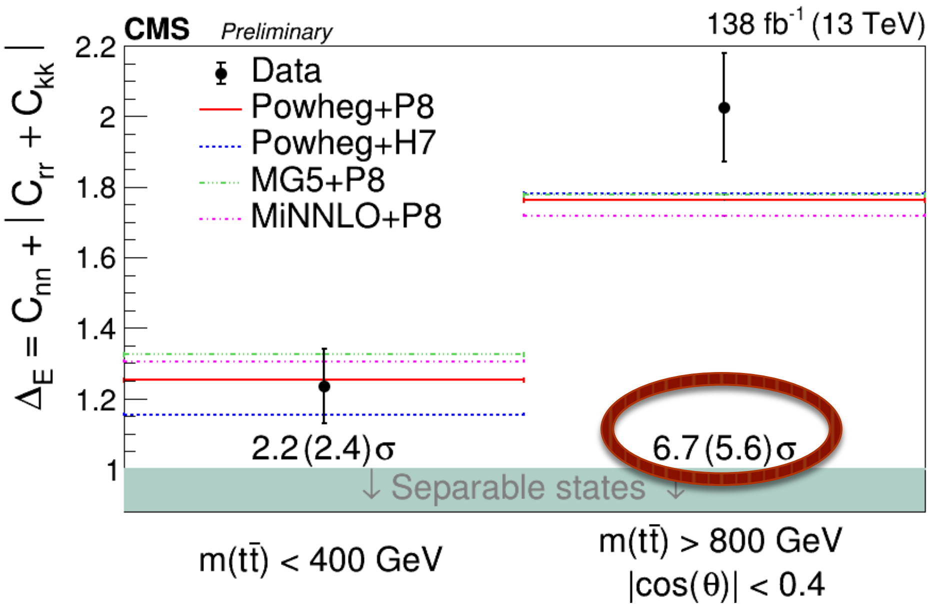
L+jets – entanglement results

- We quantify the entanglement using Peres Horodecki criterion
- Significant entanglement is observed in the high M_{tt} region

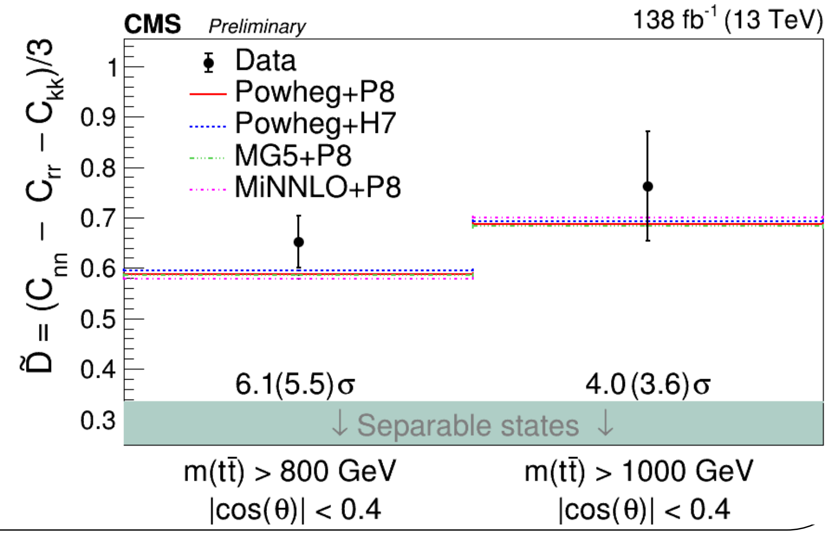
Low M_{tt} $\quad D < -\frac{1}{3}$



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

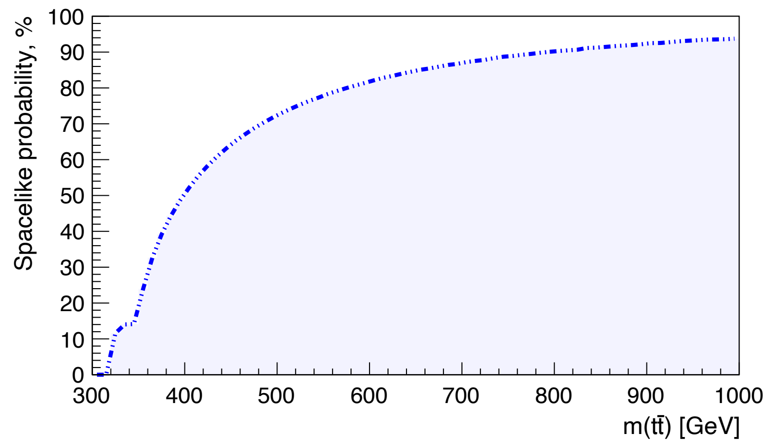


High M_{tt} $\quad \tilde{D} > \frac{1}{3}$



Excluding classical explanation

- What is the maximum value of Δ_E that can still be explained by the non-quantum communication ($v \leq c$)?
- In this case only top and antitop decays separated by a **time-like interval** are entangled
- The rest of the events must be separable
- Since top and antitop decay vertices are not observed, the fraction of space-like events, f, can only be determined statistically

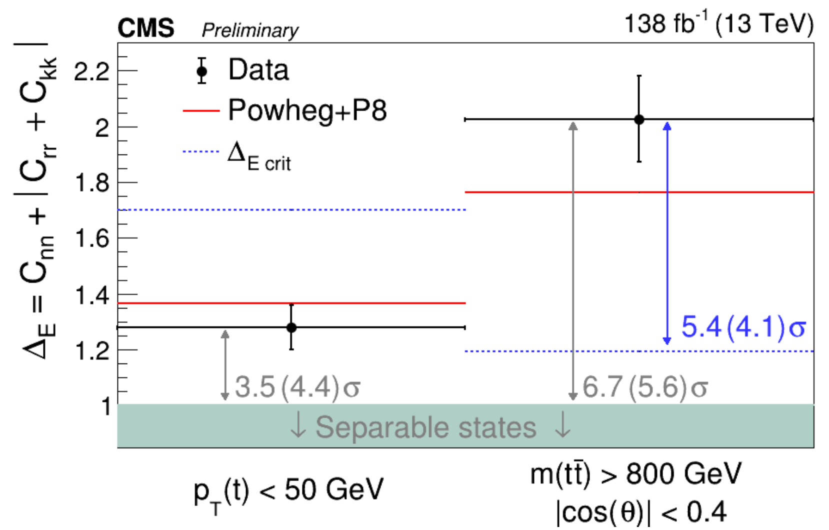


All ttbar events → In space-like interval (f) → Separable $Max(\Delta_E)=1$

All ttbar events → In time-like interval ($1-f$) → Entangled $Max(\Delta_E)=3$

$$Max(|C_{ii}|) = 1$$

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



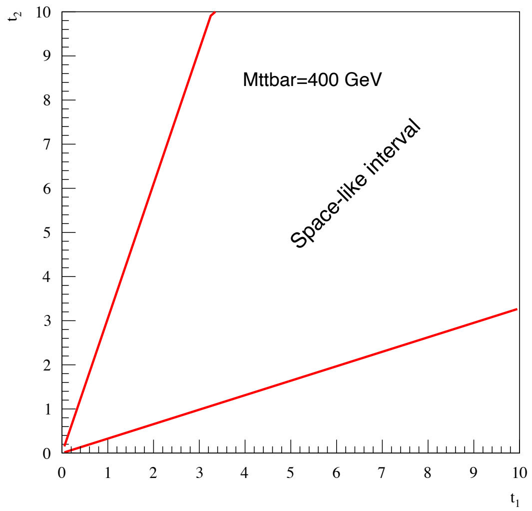
Observed Δ_E exceeds $\Delta_{Ecritical}$ by >5σ excluding classical explanation

- ArXiv:2110.10112v2 – Fig9 – fraction of space-like events

Summary

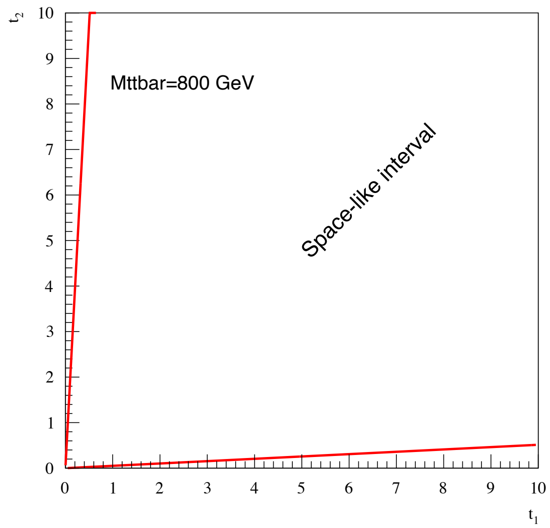
- Angular distributions of the top and antitop quarks were used to measure their **polarization** and **spin correlation matrix**, C_{ij} inclusively and in bins of M_{tt}, $\cos\theta$ and top quark p_T
- In some regions of phase space top and antitop get entangled, which can be demonstrated using **Peres-Horodecki 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}
- Both dilepton and single lepton channels were used for spin correlation studies
  - dilepton channel is more sensitive at the production threshold,
  - l+jets channel is better suited for high M_{tt}
- Based on D measurement in dilepton channel the entanglement was observed at >**5σ** level at low M_{tt}
  - $345 < M_{tt} < 400\ GeV,\ \beta < 0.9$
- Using full matrix measurement the entanglement was observed at **6.7σ** level at high M_{tt}
  - $M_{tt} > 800\ GeV,\ |\cos\theta| < 0.4$
- The later result was found to exceed the maximum entanglement achievable by classical communication by >**5σ**

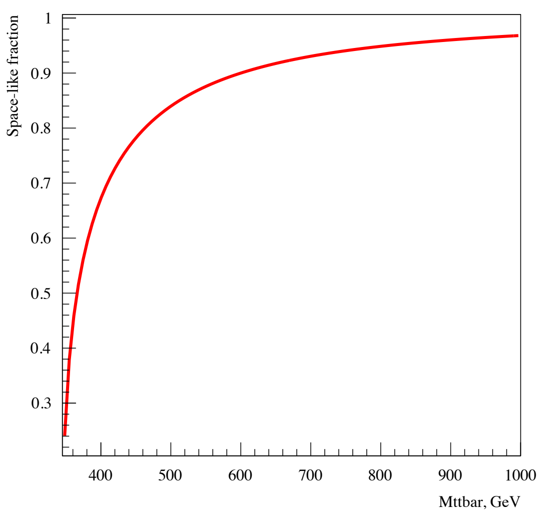
Space-like separated events



Spin correlations are evaluated based on the direction of the top quark decay products. Hence, the time of top (antitop) decays $t_1(t_2)$ is considered to be the moment when the measurements is performed. Events are space-like separated if

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



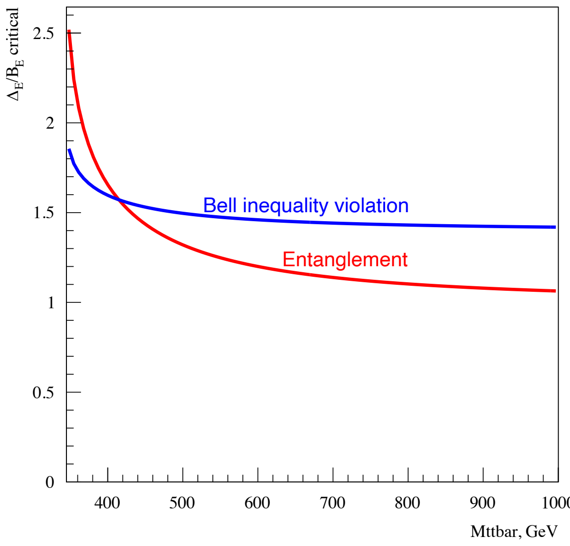


Fraction of space-like events

$$f = \frac{1-\beta}{1+\beta}$$

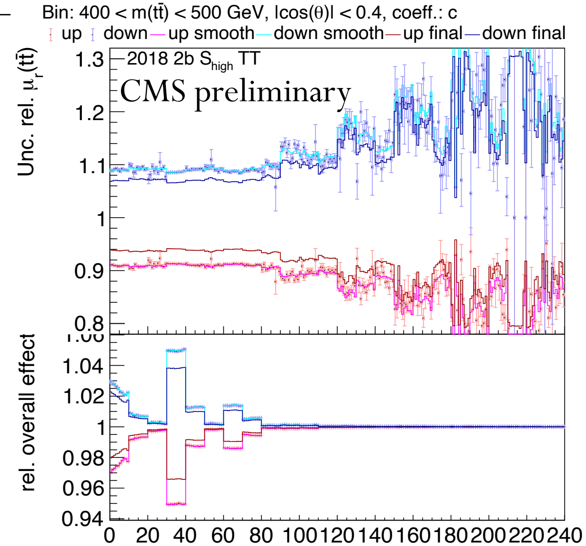
$$\Delta_{Ecritical} = f(\Delta_E = 1) + (1-f)(\Delta_E = 3)$$

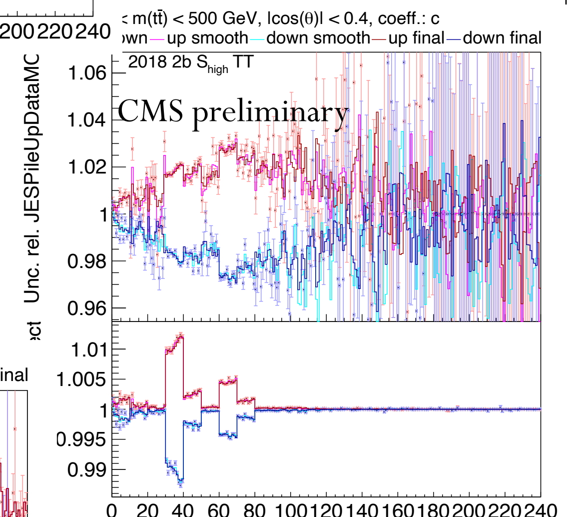
$$B_{Ecritical} = f(B_E = \sqrt{2}) + (1-f)(B_E = 2)$$

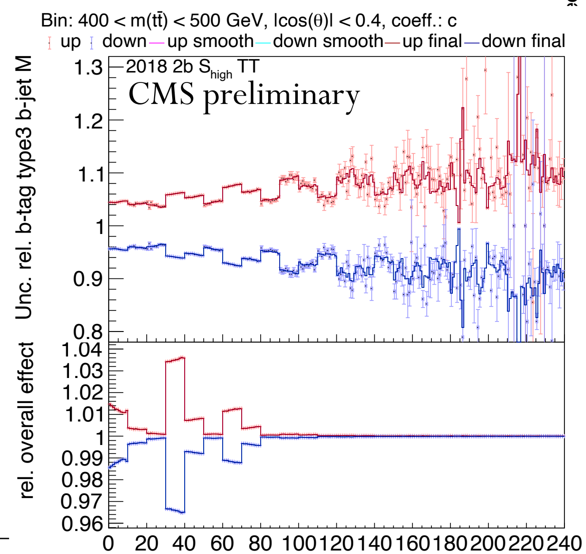


Systematics

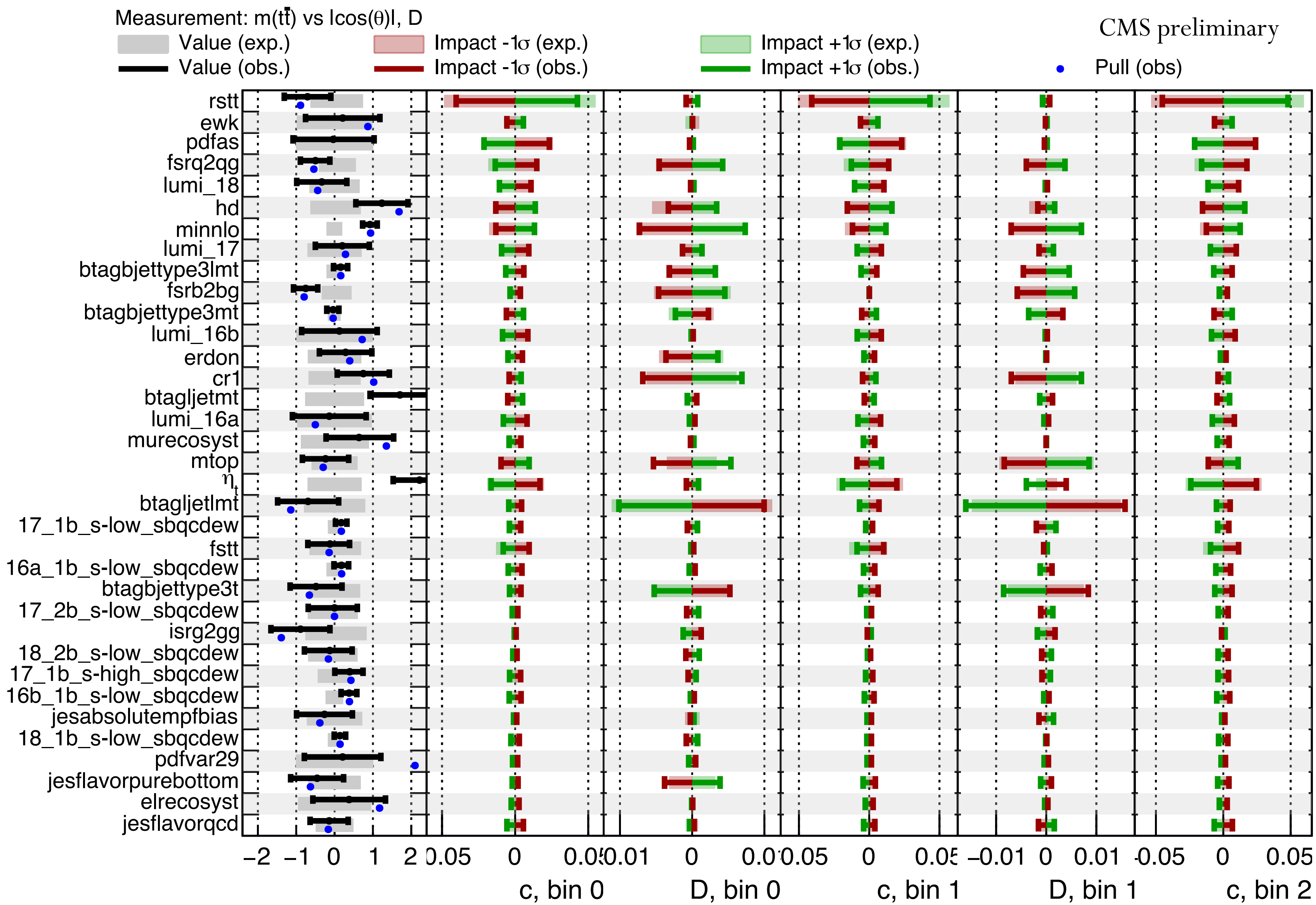
- The analysis is statistics limited
- Theoretical uncertainties
  - Mtop, renormalization/factorization scale, NNLO, EW
  - NB. Toponium effect is small for lepton+jets ~5E-04
- Experimental uncertainties:
  - Jet energy scale, b-tagging efficiency







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
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lumi_16b
erdon
cr1
btagljetmt
lumi_16a
murecosyst
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η_t
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elrecosyst
jesflavorqcd
−2 −1 0 1 2
c, bin 0
D, bin 0
c, bin 1
D, bin 1
c, bin 2