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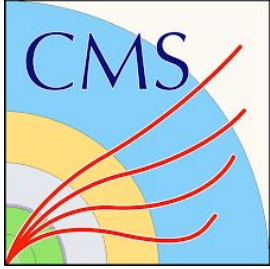

Entanglement & More at the CMS

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QuantumTANGO
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Overview

- Entanglement
- Current Analysis Strategy for Entanglement
  - Reconstruction-level extraction
  - Unfolded parton-level extraction
- Current Status on Entanglement Measurement
- Analysis Strategy for Bell's Inequality & Full Quantum Tomography
  - Initial state dependence → classifier
  - $m_{t\bar{t}}$ and θ dependence → ML reconstruction

D < -⅓ → Entangled!

Entanglement

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

- Degree of entanglement is highly phase-dependent
- Focus on low mttbar region → high statistics
- Can perform simple cut on $m_{t\bar{t}}$ to extract degree of entanglement

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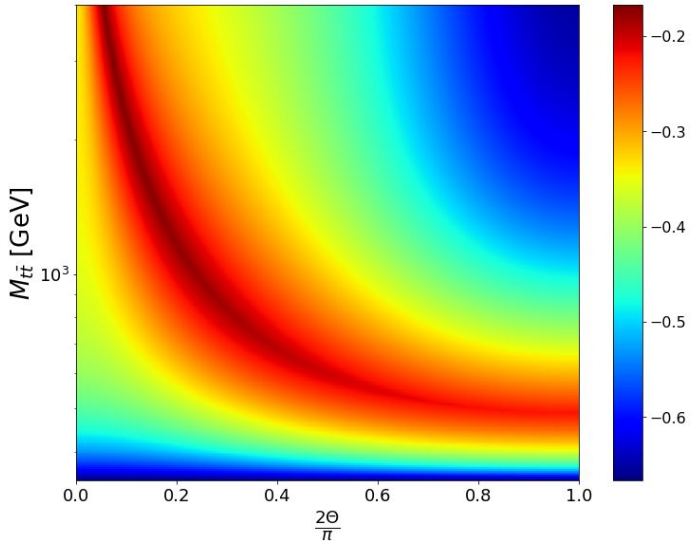

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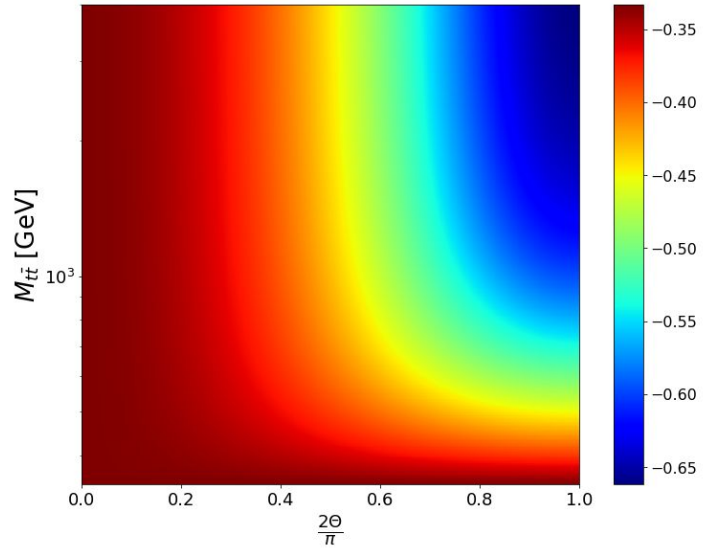
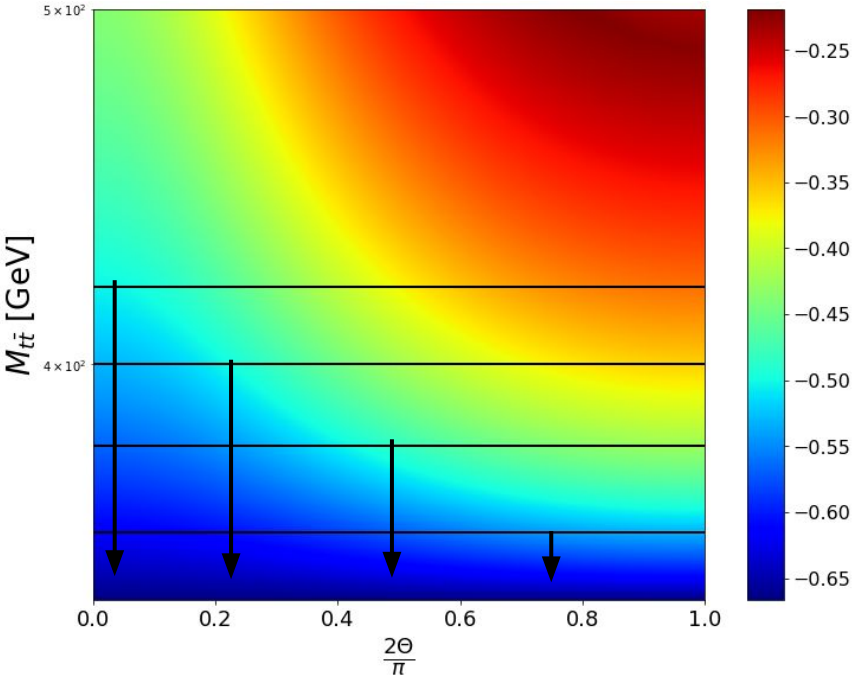


Analysis Strategy

- Reconstruction Level Extraction
  - Measure D at reconstruction level using forward-backward asymmetry in cos(ϕ) distribution
  - Potentially measure in 4 different bins
  - Determine effects of acceptance x efficiency on entanglement criteria by computing D_{reco} and comparing to same $D_{gen}^{\text{full phase space}}$
- Unfolded parton-level extraction
  - Follow same method of [spin correlation measurement in CMS] [arXiv:1907.03729] using TUnfold



Reconstruction-level Extraction

- At generator level D < -⅓ = D_{ent} → entangled
- However, at reconstruction level this will change due to acc x eff effects and migrations
- Need D < X → entangled at reconstruction level
  - Evaluated D at reco level using MC as a function of cut on $m_{t\bar{t}}$
  - Threshold for entanglement: $D_{ent}^{reco} = \frac{D^{reco}}{D^{gen}} D_{ent}^{gen}$
  - N_i = Number of events in bin i

$$A_{FB}^{(i)} = \frac{N_{6-i} - N_i}{N_{6-i} + N_i} \qquad D = \frac{-\frac{6}{5}A_{FB}^{(1)} - 2A_{FB}^{(2)} - 6A_{FB}^{(3)}}{3}$$

Unfolding Procedure [arXiv:1907.03729]

- Use matrix-based unfolding with Tikhonov regularization on curvature
- Functional form of cos(ϕ) differential distribution is known → can force distribution to be linear in variable of interest
  - For D this is already fine since it is a linear distribution already
  - Showed in our 2016 data analysis that this was unbiased to injected differences in spin coefficient values from [SM - 0.5, SM + 0.5] in steps of 0.05
- Finer binning to mitigate bias introduced via binning and re-binned to resolution-based binning after unfolding
- Scan on regularization strength is performed via minimum of global correlation coefficient in the rebinned distribution
- Systematics are evaluated as alternative response matrices

Current Status on Entanglement

- Currently in review
- No issues seen thus far in unfolding procedure
- Currently only performing 2D unfolding with $m_{t\bar{t}}$ vs D
  - Idea is 3D will be saved for full quantum tomography
- Still need to finish performing our battery of unfolding bias checks
  - Linearity tests

Future Analysis Strategy

- We would like to perform a full quantum tomography [arXiv:2003.02280] of the ttbar system
- Attempts at initial state classifier are thus far unsuccessful
- Bell's ineq strategy (was initial focus):
  - Initially perform eigenvalue calculation $m_{t\bar{t}}$
    Stat ⊗ Syst error propagation is being performed via uncertainties package
  - However, now we have J. A. Aguilar-Saavedra and J. A. Casas result [arXiv:2205.00542] suggesting |C_ii +/- C_jj| is better
- ML-based reconstruction is on-going work

Questions?

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Backup

Kinematic Reconstruction

- Fix mass of top quarks and W bosons and solve resulting quartic equation
- Smear leptons and b-jets within resolution and swap b-jets to get multiple solutions
- Use mlb distribution to perform weighted average of solutions
- mlb > 180 smears are discarded
- Lowest mttbar solution is always considered as correct solution