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Measurements of top quark properties in CMS

$t\bar{t}$ spin density matrix, quantum entanglement & magic

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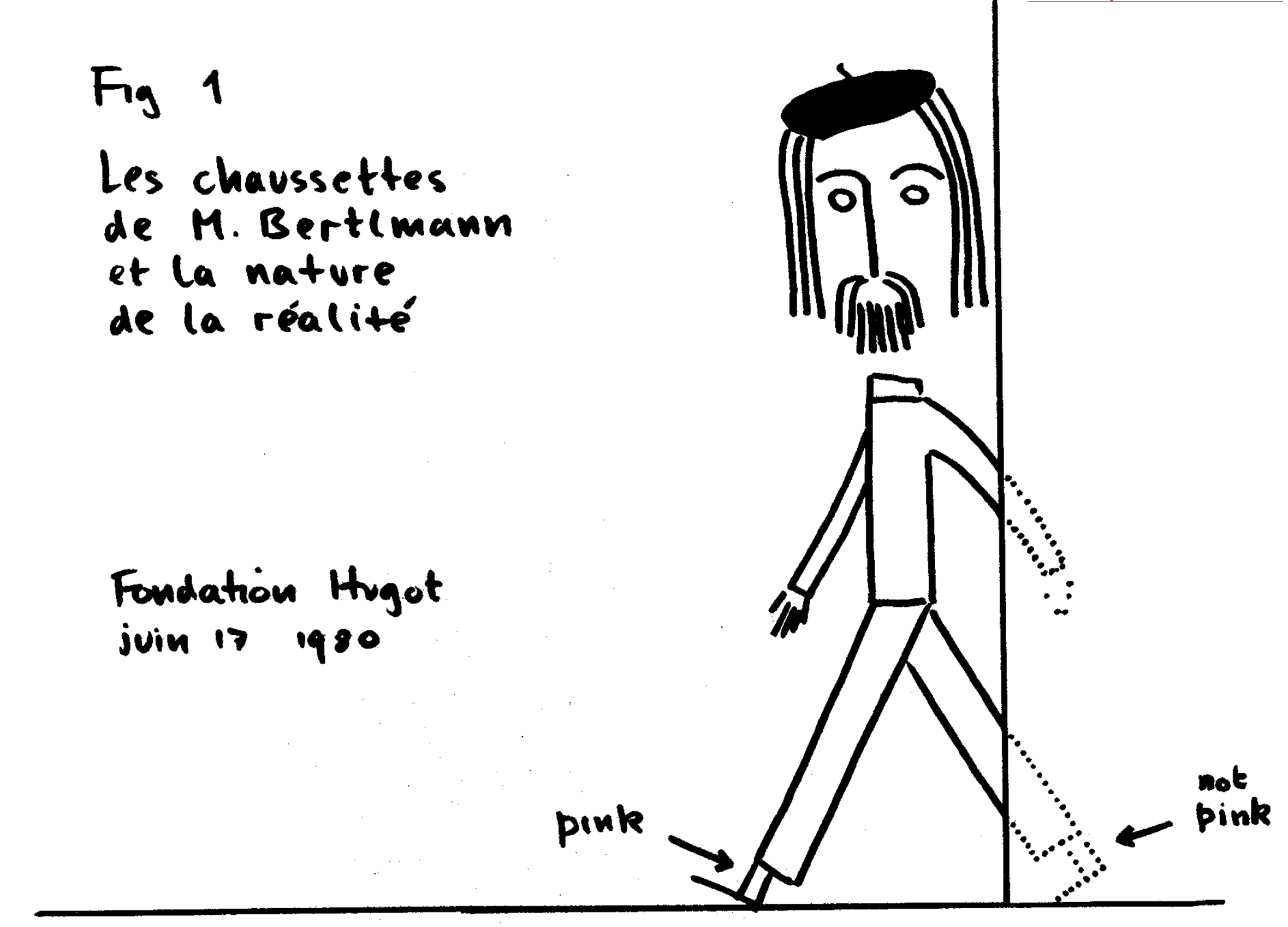

The top quark

* **Most massive** elementary particle known to date — **very short lifetime.**

$$\tau_t = \frac{1}{\Gamma_t} \approx 10^{-25}s < \frac{1}{\Lambda_{QCD}} \approx 10^{-24}s < \frac{m_t}{\Lambda_{QCD}^2} \approx 10^{-21}s \ll \tau_b$$

Decays before hadronization spin de-correlation

* Top-antitop spins stay correlated — could be inferred from the decay products' angular distributions.

* Polarization and spin correlation measurements provide tests of the **Standard Model.**

  * But also, new ways to **test Quantum Theory with unstable particles** (quarks) at high energies in **specific phase regions.**

Full Spin density matrix measurement in the e/μ+jets events

* Differential cross section

$$\Sigma_{tot}(\phi_{p(\bar{p})}, \theta_{p(\bar{p})}) = \frac{d^4\sigma}{d_{\phi_p} dcos(\theta_p) d_{\phi_{\bar{p}}} dcos(\theta_{\bar{p}})}$$

$$= \sigma_{norm}(1 + \kappa \mathbf{P} \cdot \mathbf{\Omega} + \bar{\kappa}\bar{\mathbf{P}} \cdot \bar{\mathbf{\Omega}} - \kappa\bar{\kappa}\mathbf{\Omega} \cdot (C\bar{\mathbf{\Omega}}))$$

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

Ω: unit vector in helicity basis.
P: polarization vector.
C: 3x3 spin correlation matrix
κ: spin analyzing power

Lepton and d-type quark (from W) for max top quark spin transfer to decay products: $\kappa \to 1$.

* $t\bar{t}$ spin dependence fully characterised by 15 coefficients
  $Q_m = \{P_n, P_r, P_k, \bar{P}_n, \ldots, C_{nn}, C_{nr}, \ldots, C_{kk}\}$ **all probed by angular distributions**
  $\Sigma_m = \sigma_{norm}\{\kappa \sin\theta_p \cos\phi_p, \ldots, \kappa\bar{\kappa} \cos\theta_p \cos\theta_{\bar{p}}\}$

* Detector-level templates (T_m) from reweighting $t\bar{t}$ gen-level Σ_m for each Q_m.

* Weights $w_i = \Sigma_m/\Sigma_{tot}$ based on gen-level values of $\theta_{p(\bar{p})}, \phi_{p(\bar{p})}, m(t\bar{t})$ vs $|\cos\theta|$.

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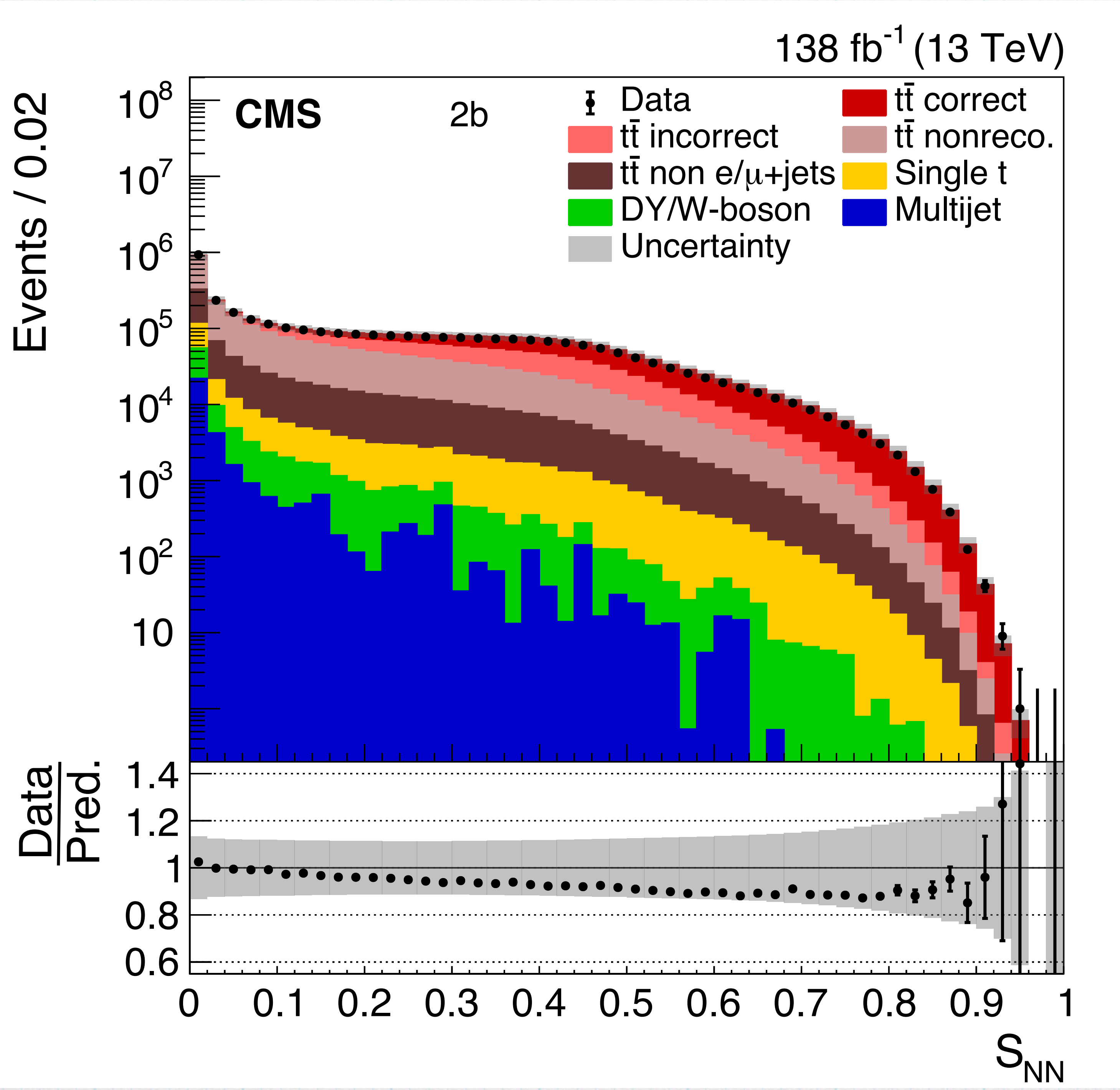
Spin density matrix measurement in the e/μ+jets events

* $t\bar{t}$ signal: POWHEG+Pythia8+EWK corrections from HATHOR & uncertainties for higher order QCD from POWHEG MINNLO. Decays and correlations simulated at leading order.
* Machine learning for top reconstruction including **d-type quark id**.
    * Inputs: lepton kinematics, missing energy, jet kinematics, b-tagging scores.



Event categories: lepton flavor, number of b-tags, S_{NN} score

Reject low fraction of correctly reconstructed events for $S_{NN} < 0.1$

$$S_{high}(1b): \quad S_{NN} > 0.30$$

$$S_{high}(2b): \quad S_{NN} > 0.36$$

optimized to minimize uncertainties in spin density matrix.

Fraction of correctly assigned jets (including d-type id):
$\sim 40 - 50\,\%$ for $S_{high}(2b)$

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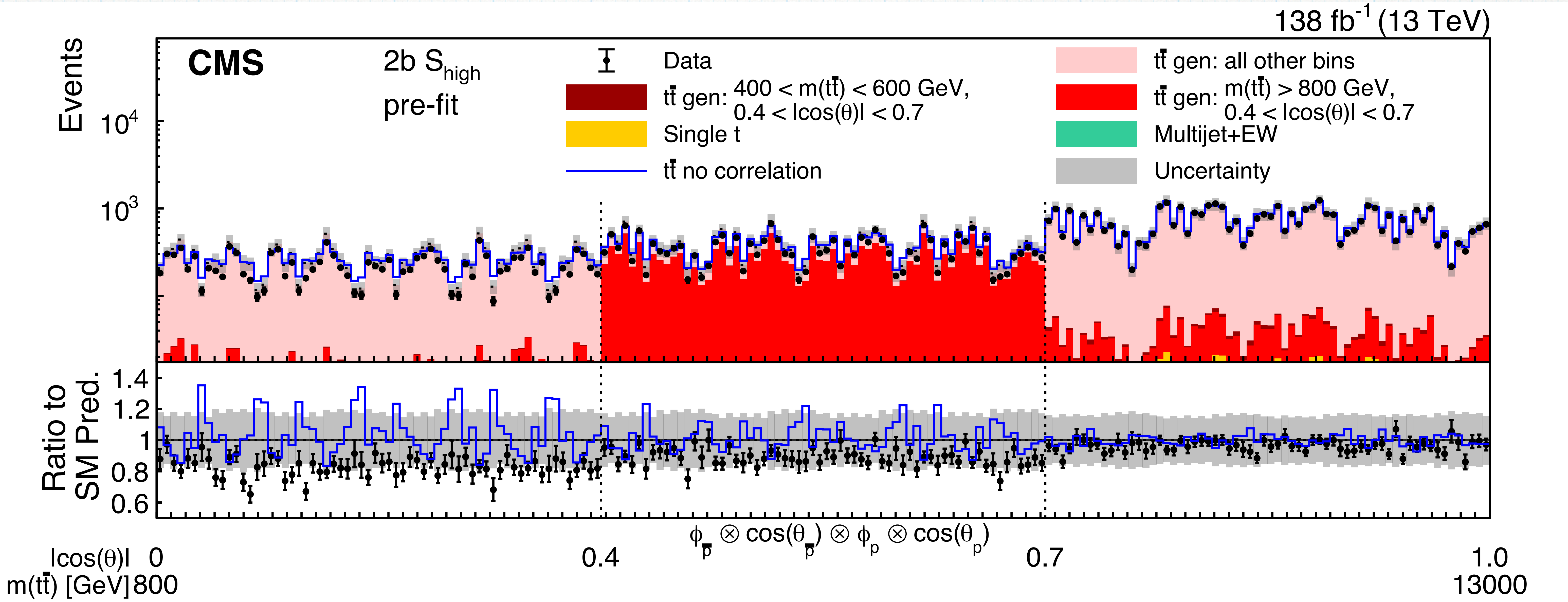
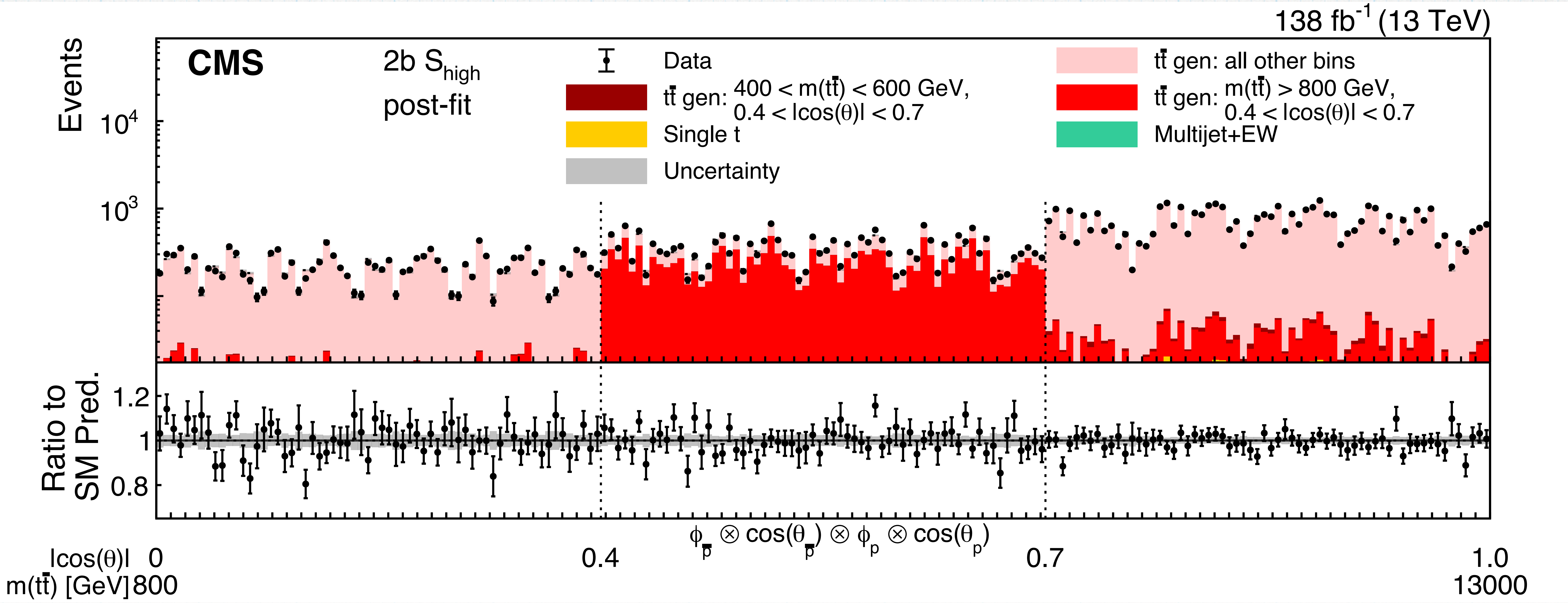
Full matrix measurement in bins of $m(t\bar{t})$ vs $|\cos\theta|$

* Binned likelihood fit in various regions of phase space to reco-level templates
  * simultaneously fitting data in 16 categories: $(2b,1b) \times (S_{high}, S_{low})$ x4 data-taking periods.



prefit



postfit

x-axis: unrolled distribution of $\phi_{\bar{p}}, \cos(\theta_{\bar{p}}), \phi_p, \cos(\theta_p)$ in each $m(t\bar{t})$ vs $|\cos\theta|$ bin.

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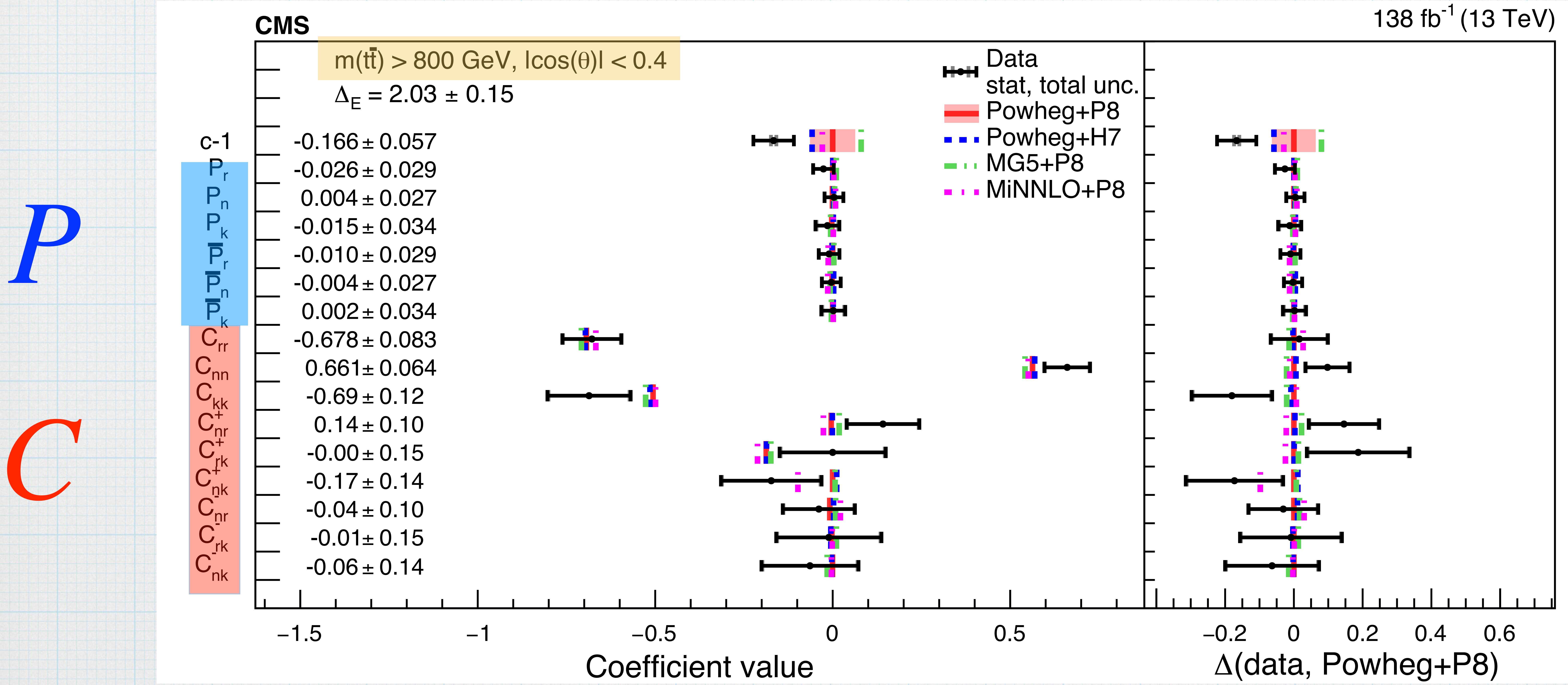
Spin density matrix coefficients

- Measured inclusively & differentially in bins of $m(t\bar{t}), |\cos(\theta)|$ & $p_T(t)$



POWHEG+PYTHIA with ME scale & PDF uncertainties.

PhysRevD 110 (2024) 112016

- Good agreement w/ SM and CMS dilepton channel result [PhysRevD 100 (2019) 072002]
- First at high $m(t\bar{t})$

Quantum entanglement from $t\bar{t}$ spin density matrix

* Peres-Horodecki criterion [Afik, De Nova, EPJPlus 136 (2021) 907] provides sufficient condition for entanglement

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

* Spin-singlet state (expected from $gg \to t\bar{t}$ at production threshold)

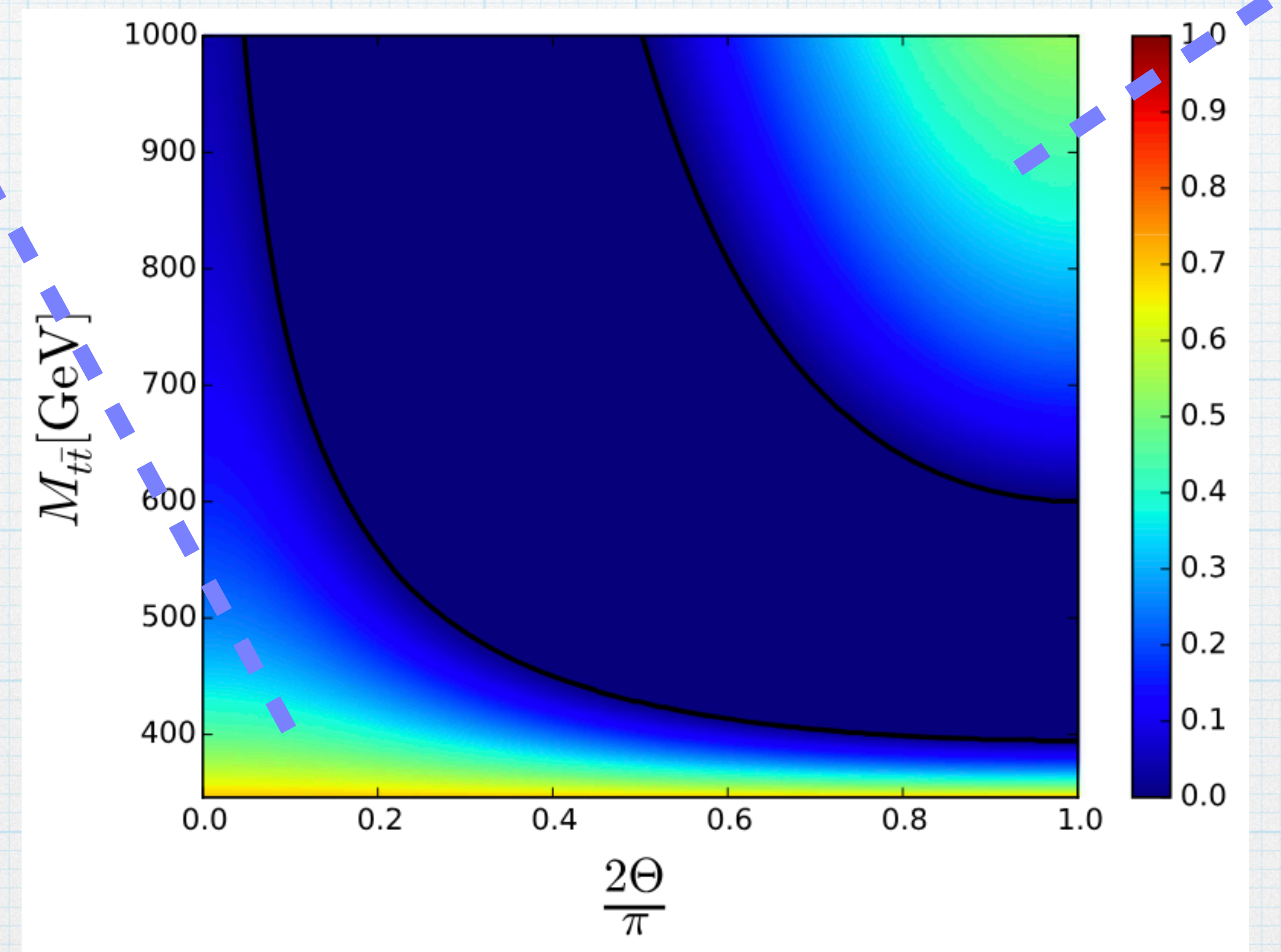
$$\frac{d\sigma}{d\cos(\chi)} = \sigma_{norm}(1 + D\kappa\bar{\kappa}\cos(\chi))$$

where $D = -\frac{1}{3}Tr(C)$

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

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

Extract D using χ: opening angle between two decay products in the helicity basis, $\cos\chi = \Omega \cdot \bar{\Omega}$



Afik, De Nova, EPJPlus 136 (2021) 907

* Spin-triplet state (expected from both $q\bar{q}, gg \to t\bar{t}$ at high $m(t\bar{t})$ and low $|\cos\theta|$)

$$\tilde{D} = \frac{1}{3}(C_{nn} - C_{rr} - C_{kk})$$

When $p_T(t) \sim m_t$,

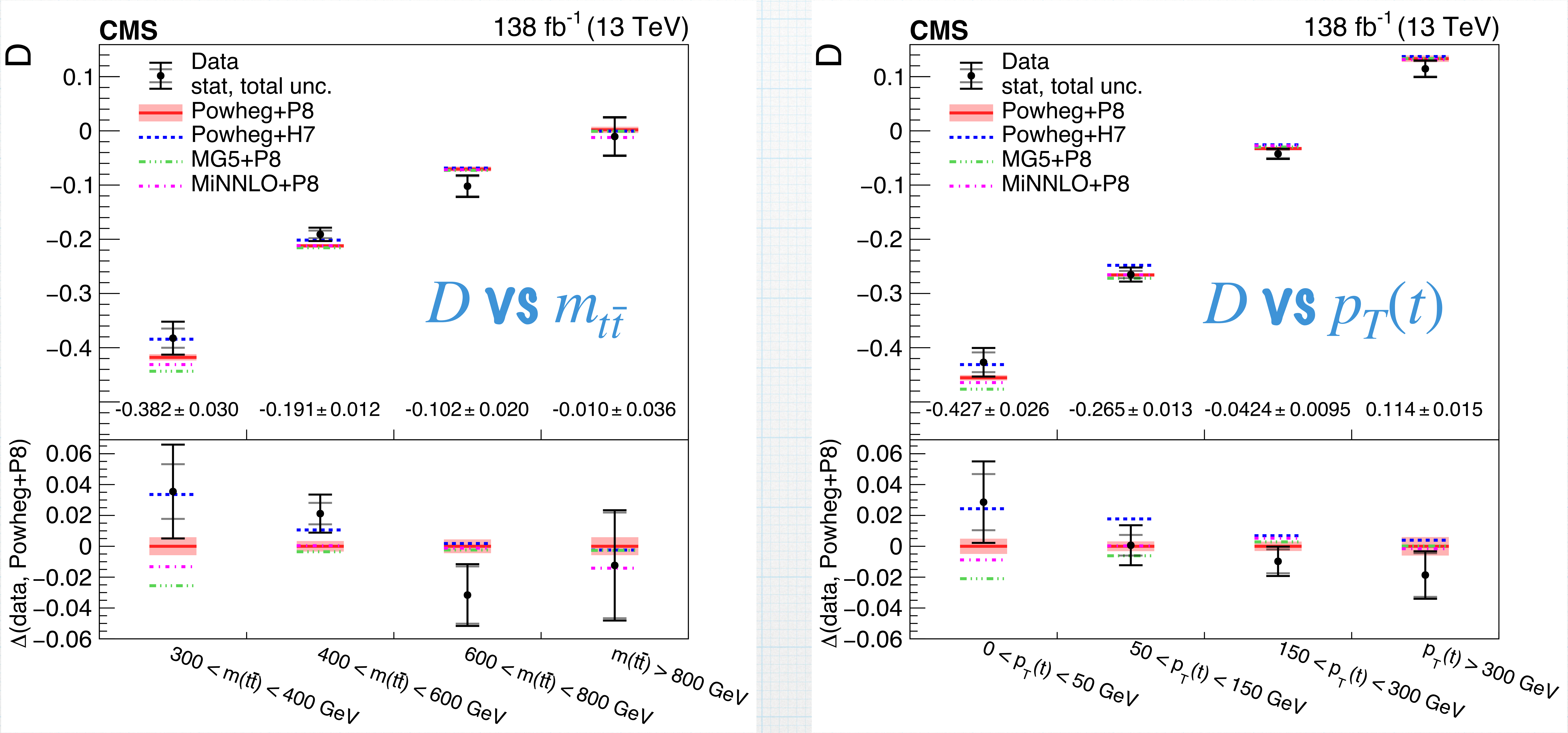
$$C_{rr}, C_{kk} < 0$$

$$\Delta_E = 3\tilde{D} > 1$$

Extract $\tilde{D}$ using

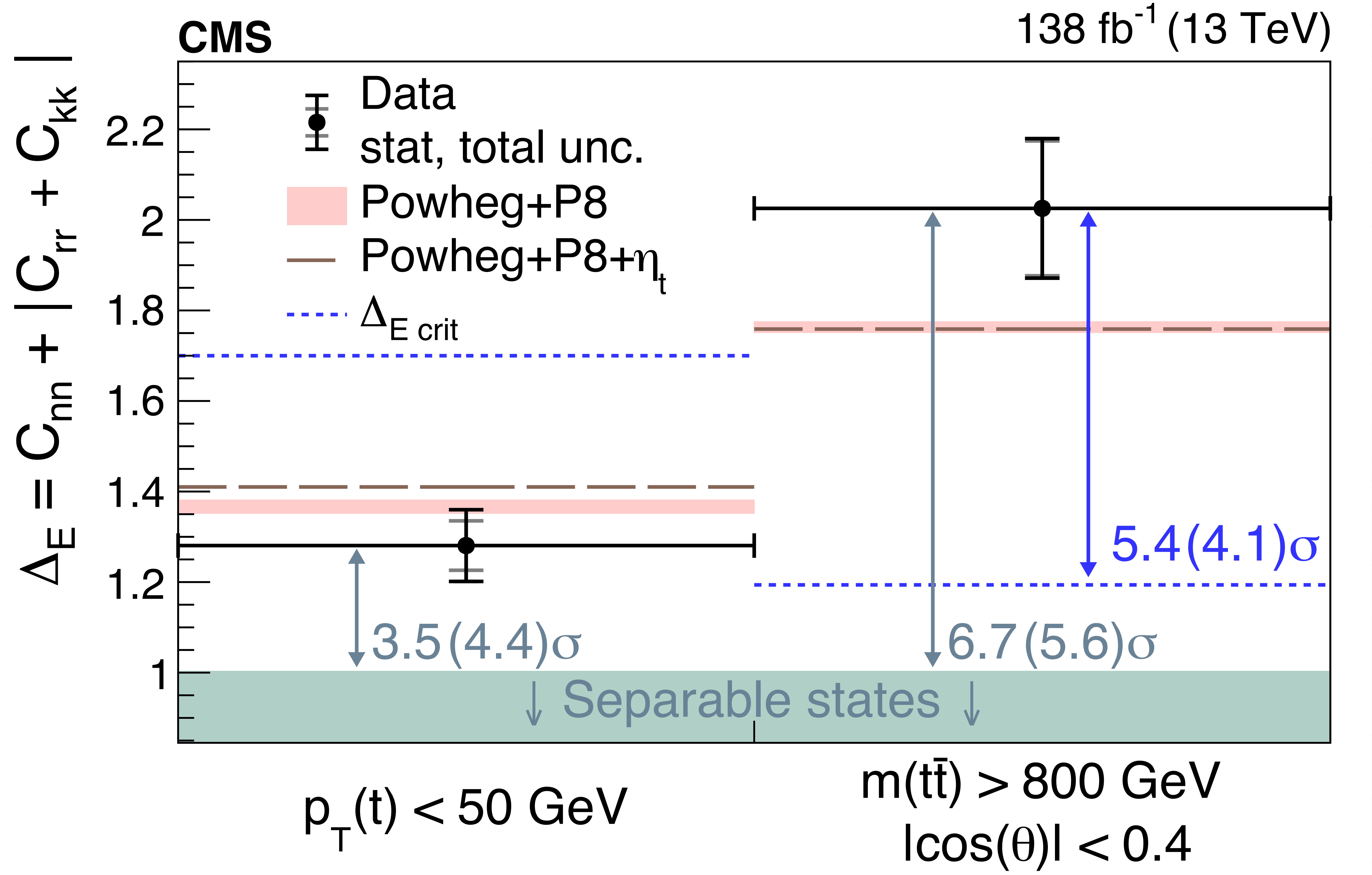
$\tilde{\chi} = -\Omega_n\bar{\Omega}_n + \Omega_r\bar{\Omega}_r + \Omega_k\bar{\Omega}_k$

Quantum entanglement from $t\bar{t}$ spin density matrix



- Good agreement with predictions.

Quantum entanglement from $t\bar{t}$ spin density matrix



- **First observation of entanglement at high $m(t\bar{t})$ where ~90% of observed $t\bar{t}$ are space-like separated.**

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Quantum « magic »

- Quantum Magic quantifies computational advantage of quantum over classical states.
  - Entanglement by itself doesn't guarantee this.

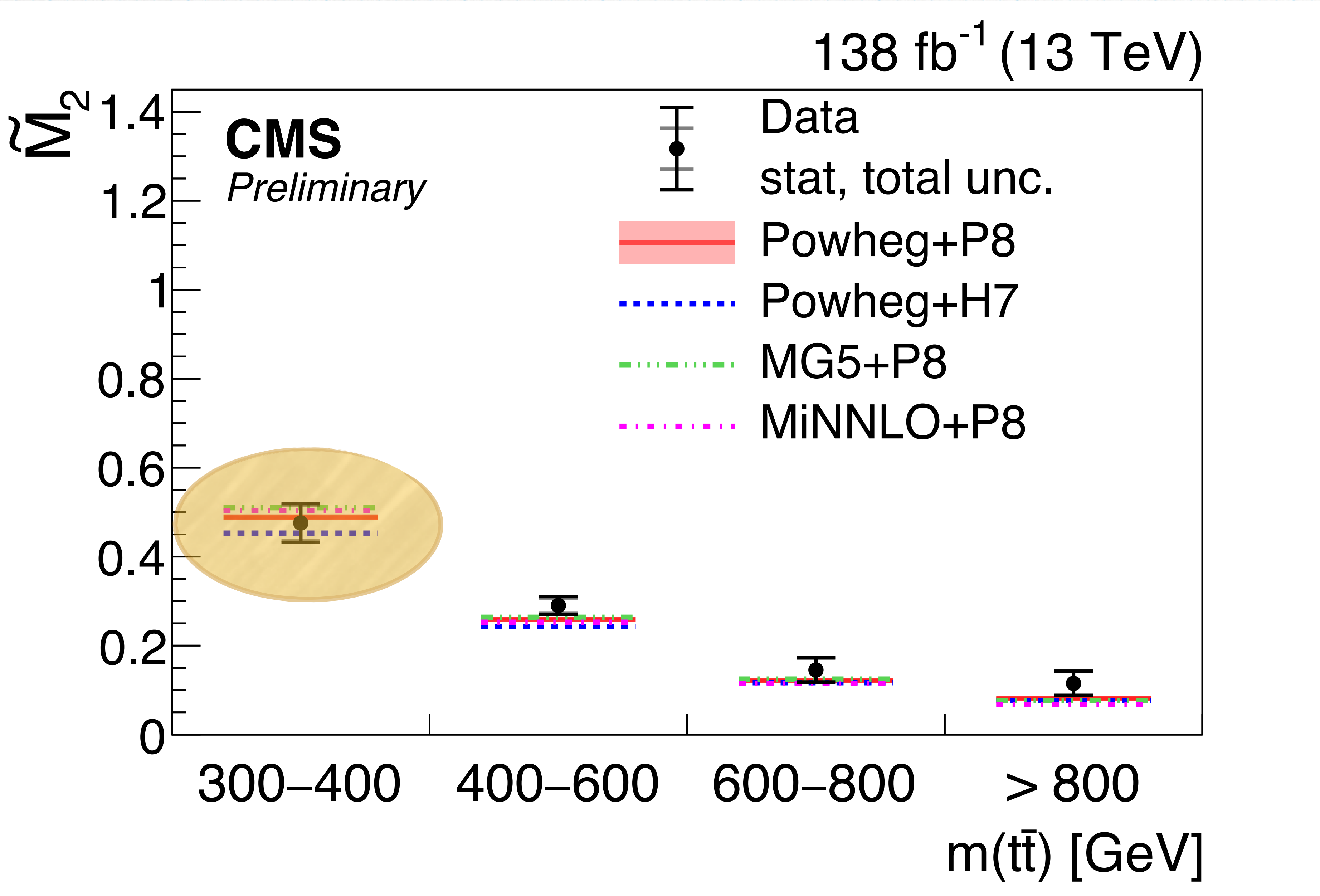
For mixed states (e.g. two-qubit $t\bar{t}$ system):

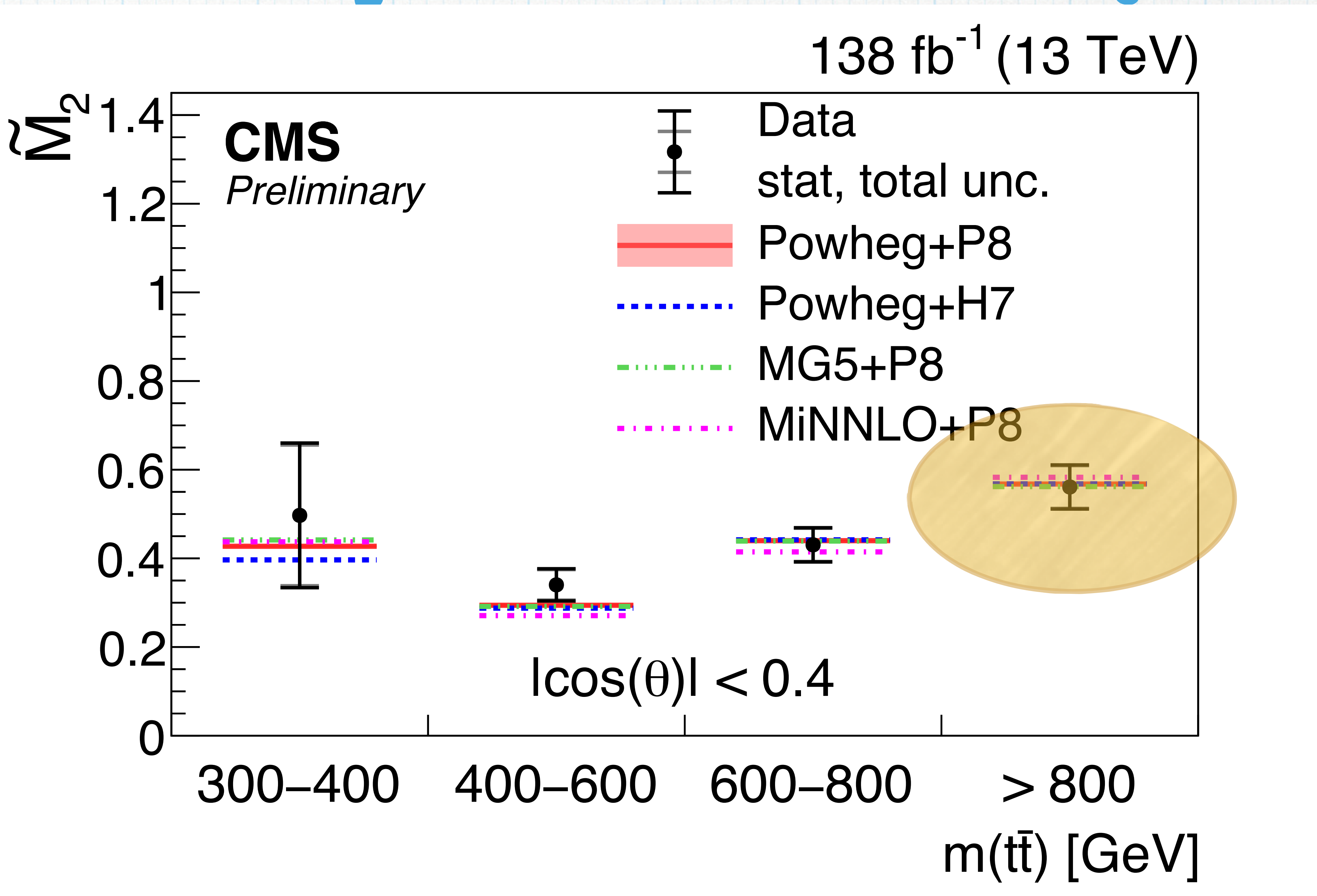
$$\tilde{M}_2 = -\,log_2\left(\frac{1 + \Sigma_{i\in n,k,r}[(P_i^4 + \bar{P}_i^4)] + \Sigma_{i,j\in n,k,r}C_{ij}^4}{1 + \Sigma_{i\in n,k,r}[(P_i^2 + \bar{P}_i^2)] + \Sigma_{i,j\in n,k,r}C_{ij}^2}\right)$$

- Zero magic $\leftrightarrow$ classical computer.
- $\tilde{M}_2$ is nonlinear and phase-space dependent: nonzero magic from $pp \to t\bar{t}$ doesn't mean the same thing for individual processes $qq \to t\bar{t}$ and $gg \to t\bar{t}$ b/c.

CMS-PAS-TOP-25-001

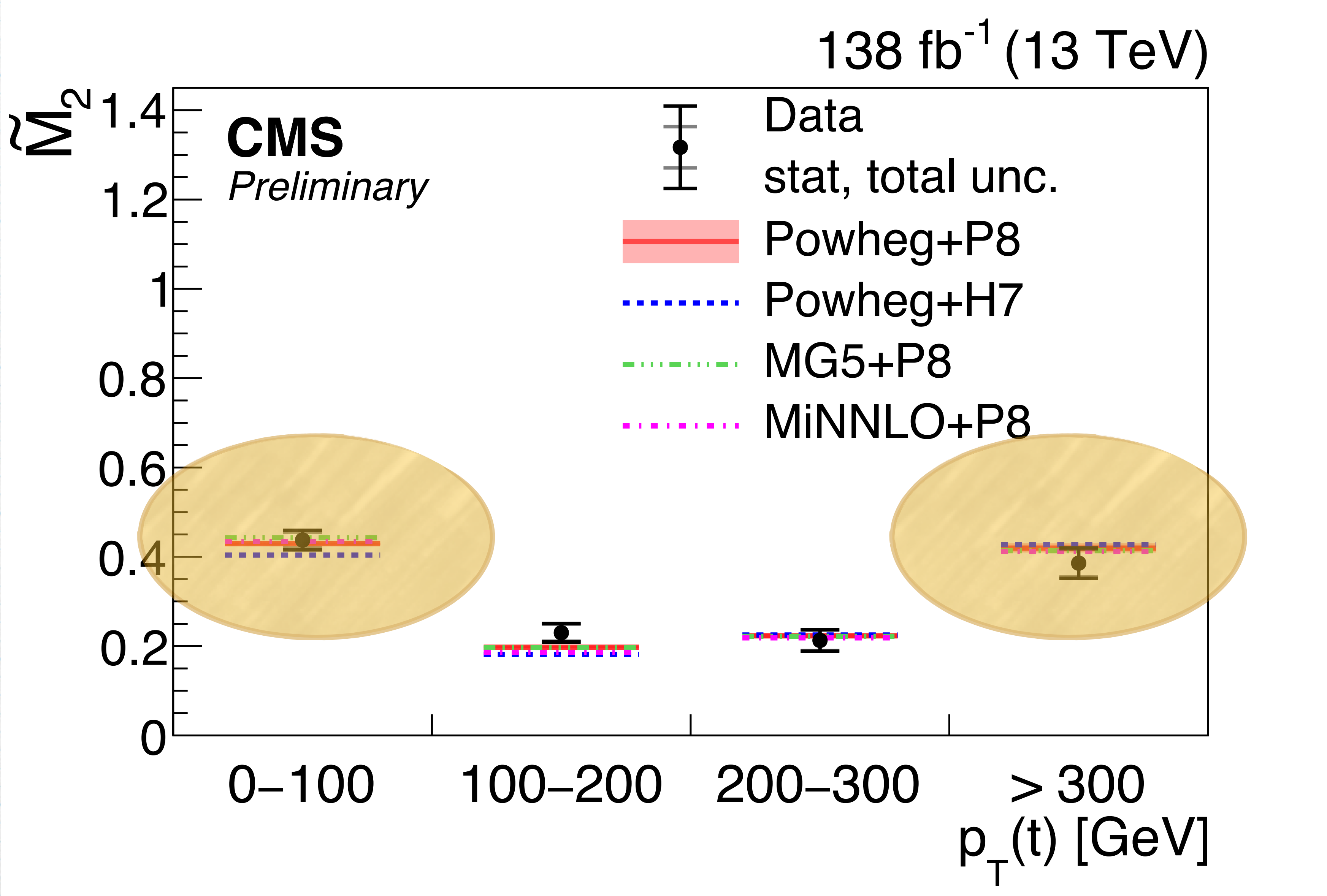
Quantum « magic » from $t\bar{t}$ spin density matrix





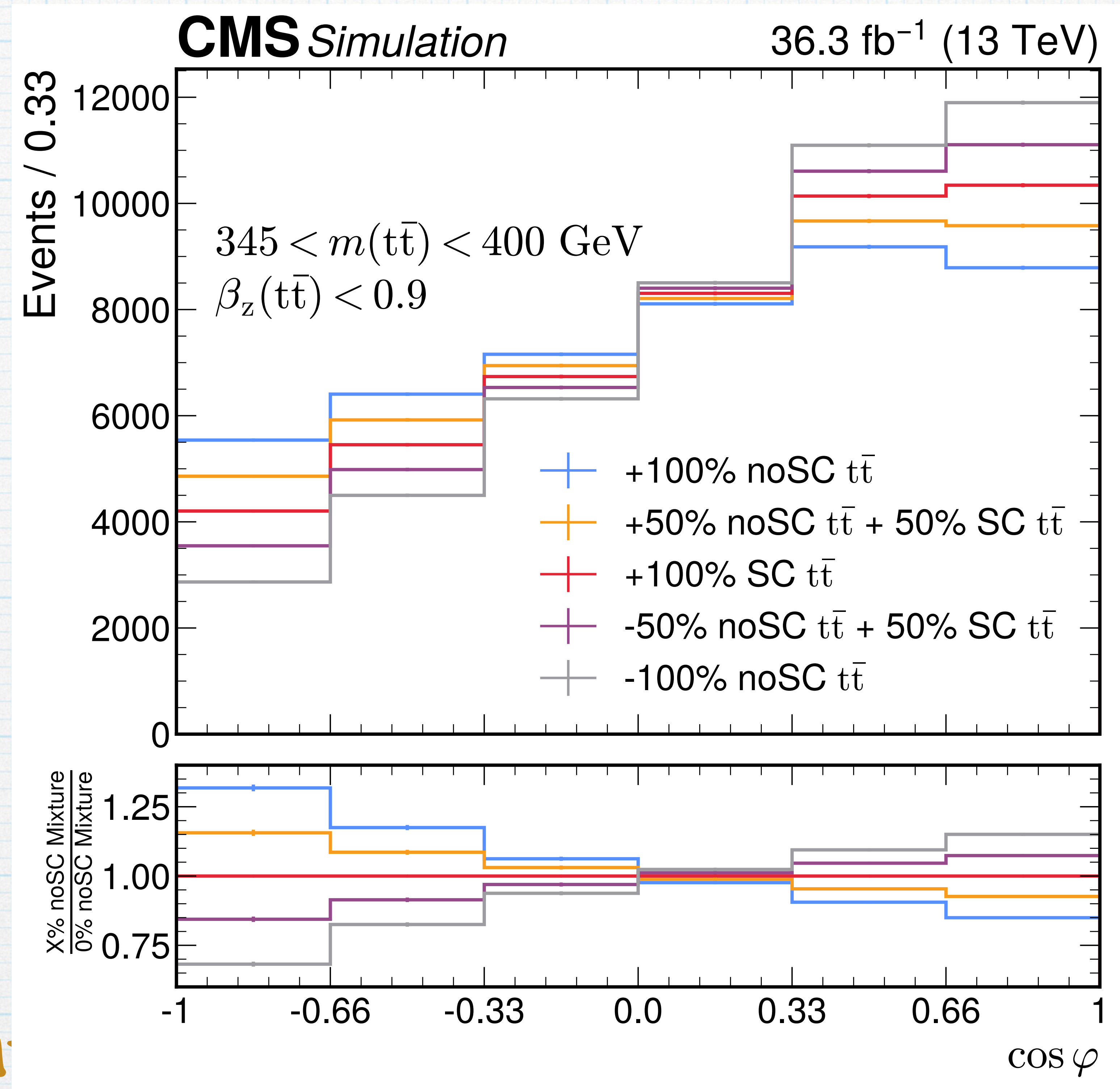
- Calculation uses the spin density matrix measurement from the lepton+jets channel [PhysRevD 110 (2024) 112016]
- First magic measurement from $t\bar{t}$ spin density matrix → $\tilde{M}_2 > 0$
- Depends on phase space region.
- Good agreement with predictions.
- Statistical uncertainties dominant.

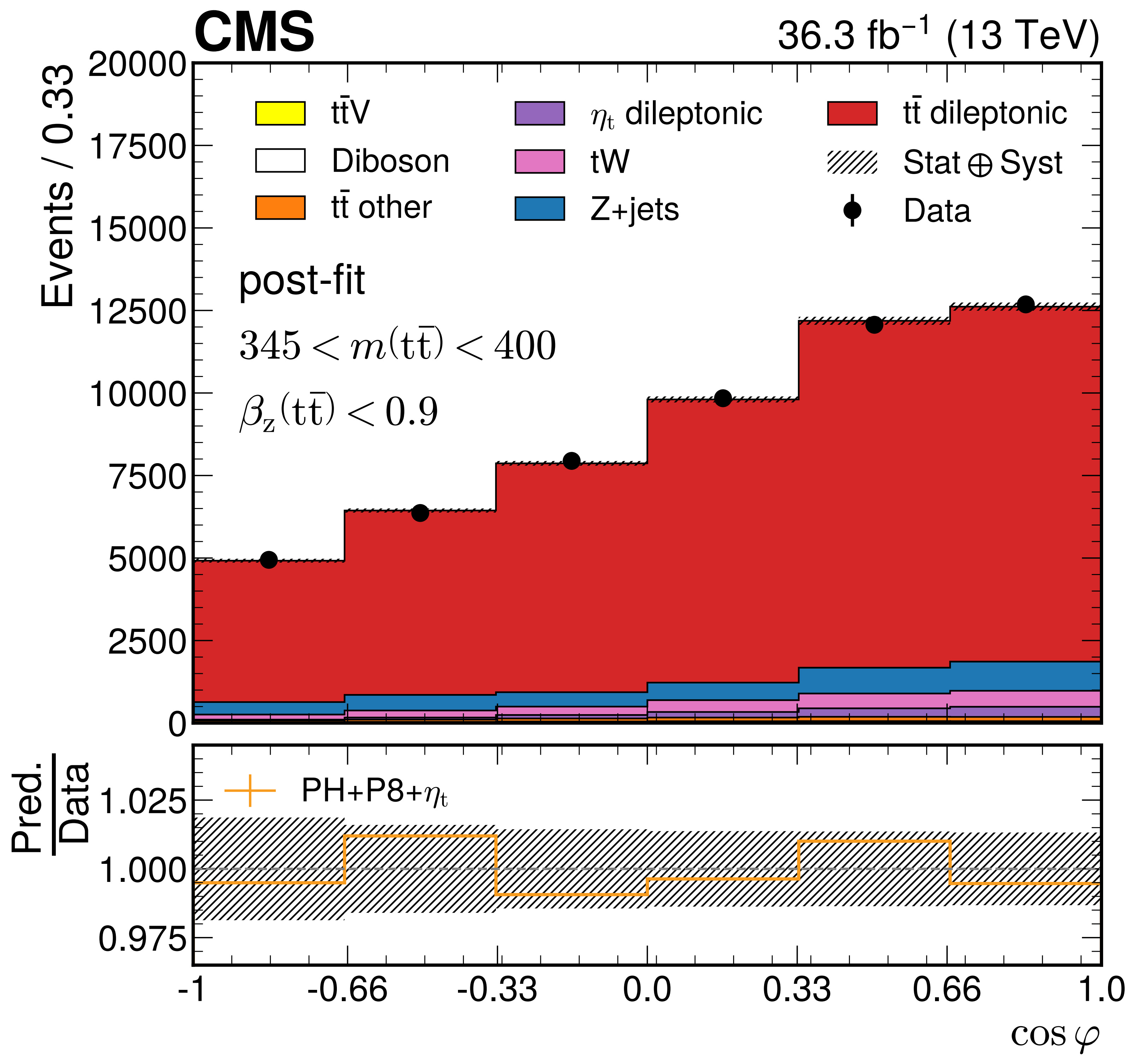
CMS-PAS-TOP-25-001



Spin correlation in dilepton channel

- Top reconstruction
- D variations from samples w/ different degrees of SM and no-spin correlation assumptions.
- D measurement from binned-profile likelihood fit of $\cos\varphi$.
- Fits including (and not) a ground state « **toponium** » (η_t):
  - Non-relativistic QCD quasi-bound sta[te] model at 343 GeV, cross section=6.4 pb.





$$t\bar{t} + \eta_t$$

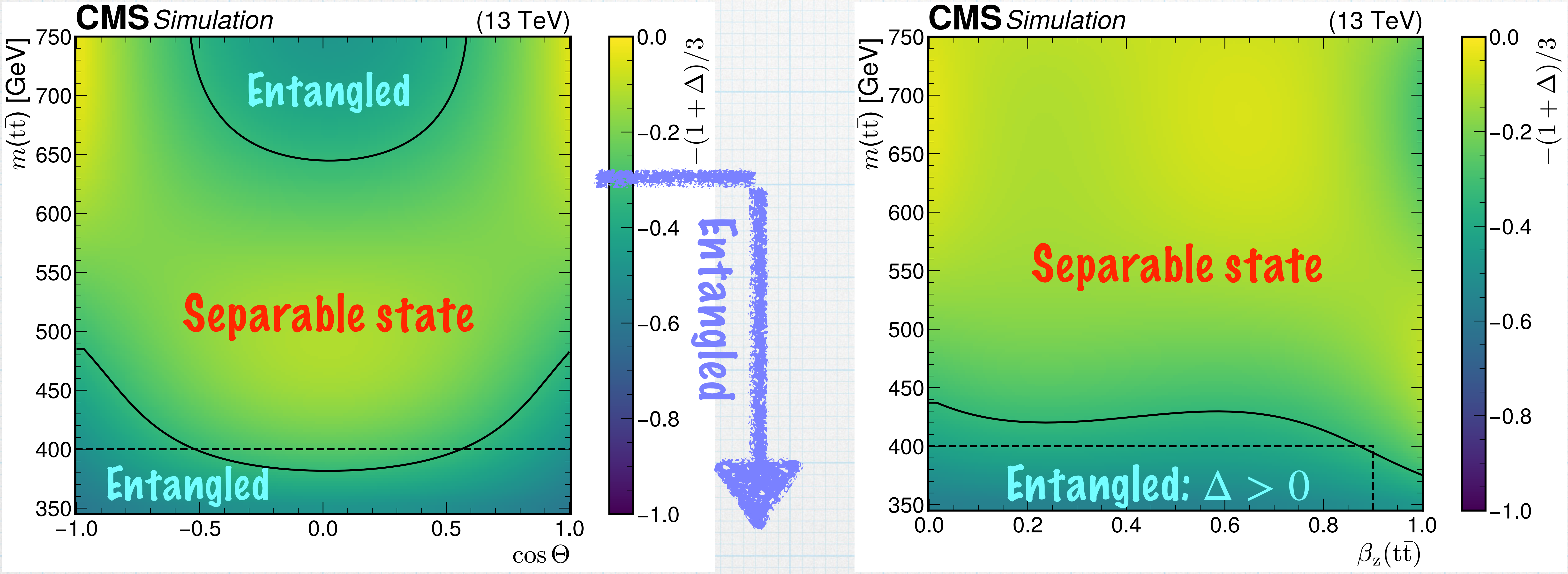
Rep. Prog. Phys. 87 (2024) 117801

Details in the next two contributions in this session by C. Schwanenberger & H. Li.

Quantum entanglement: dilepton channel

- At $m(t\bar{t}) \sim 350$ GeV: $D = -\frac{1}{3}\Delta_E$, $\frac{d\sigma}{d\cos\varphi} = \sigma_{norm}(1 - D\cos\varphi)$
- $D = 0 \leftrightarrow$ no spin correlation.

Helicity angle: $\cos\varphi = \hat{\ell}^{+} \cdot \hat{\ell}^{-}$



$$\beta_z(t\bar{t}) = \left| \frac{p_z^t + p_z^{\bar{t}}}{E^t + E^{\bar{t}}} \right|$$

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

J.A. Aguilar-Saavedra, J.A. Casas EPJC 82 (2022) 666

- Focus on $345 < m(t\bar{t}) < 400$ GeV, $\beta_z(t\bar{t}) < 0.9$
- Obtain D from 2-bin asymmetry: $A_D = \frac{N(\cos\varphi > 0) - N(\cos\varphi < 0)}{N(\cos\varphi > 0) + N(\cos\varphi < 0)} \rightarrow D = -2A_D$

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Quantum entanglement: dilepton channel

- > 5σ observation of entanglement irrespective of η_t.
- Including η_t improves the data/simulation agreement.

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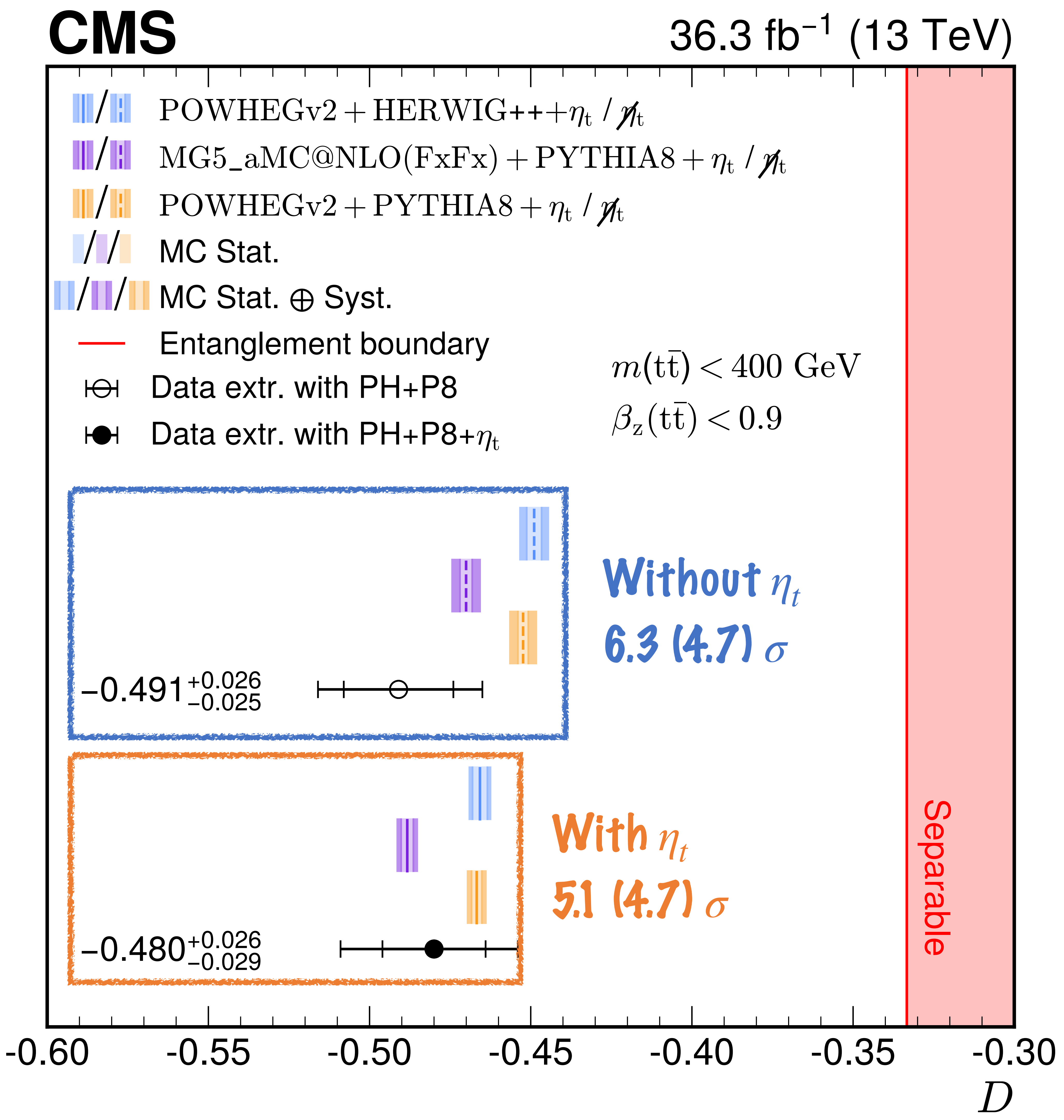
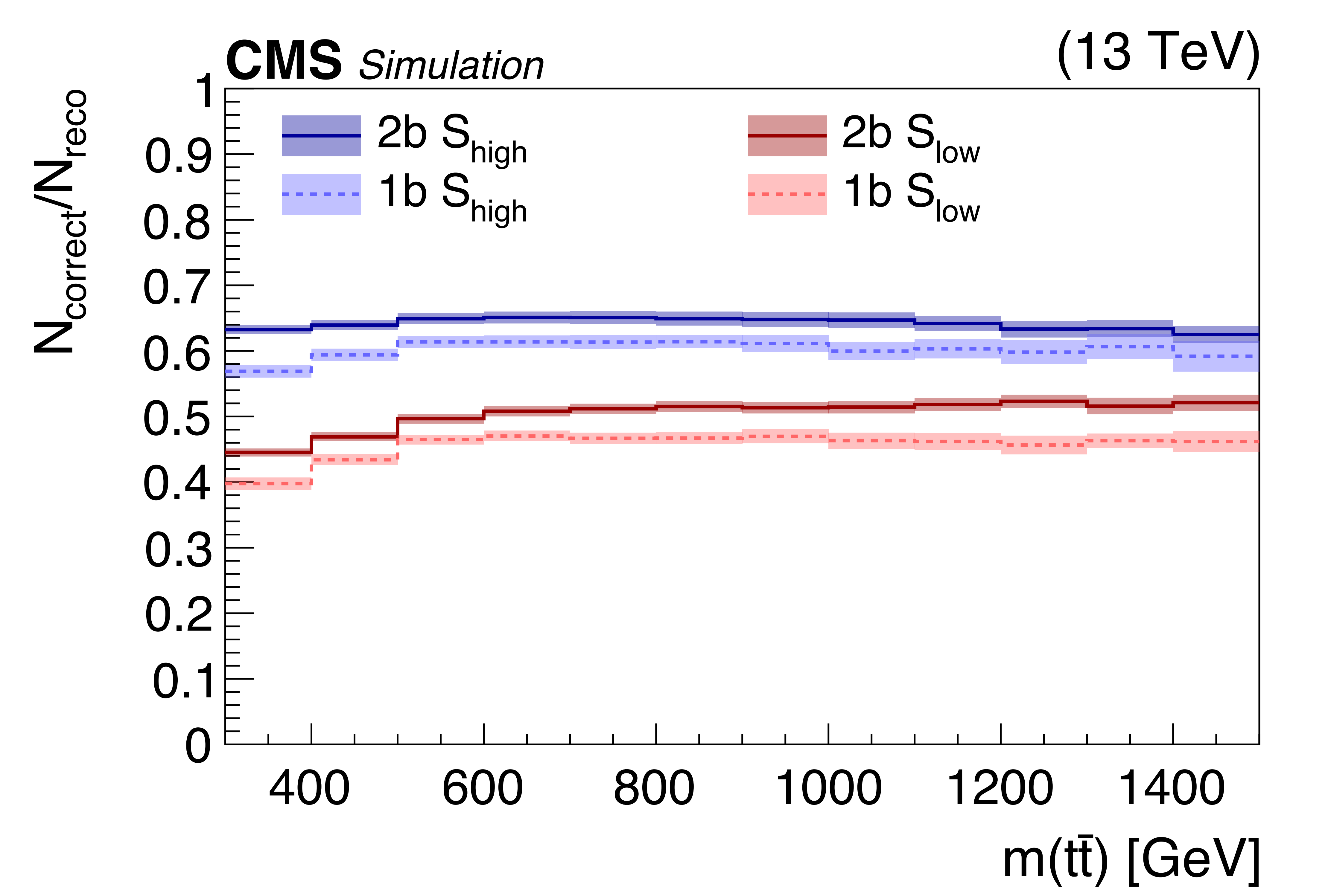


Summary

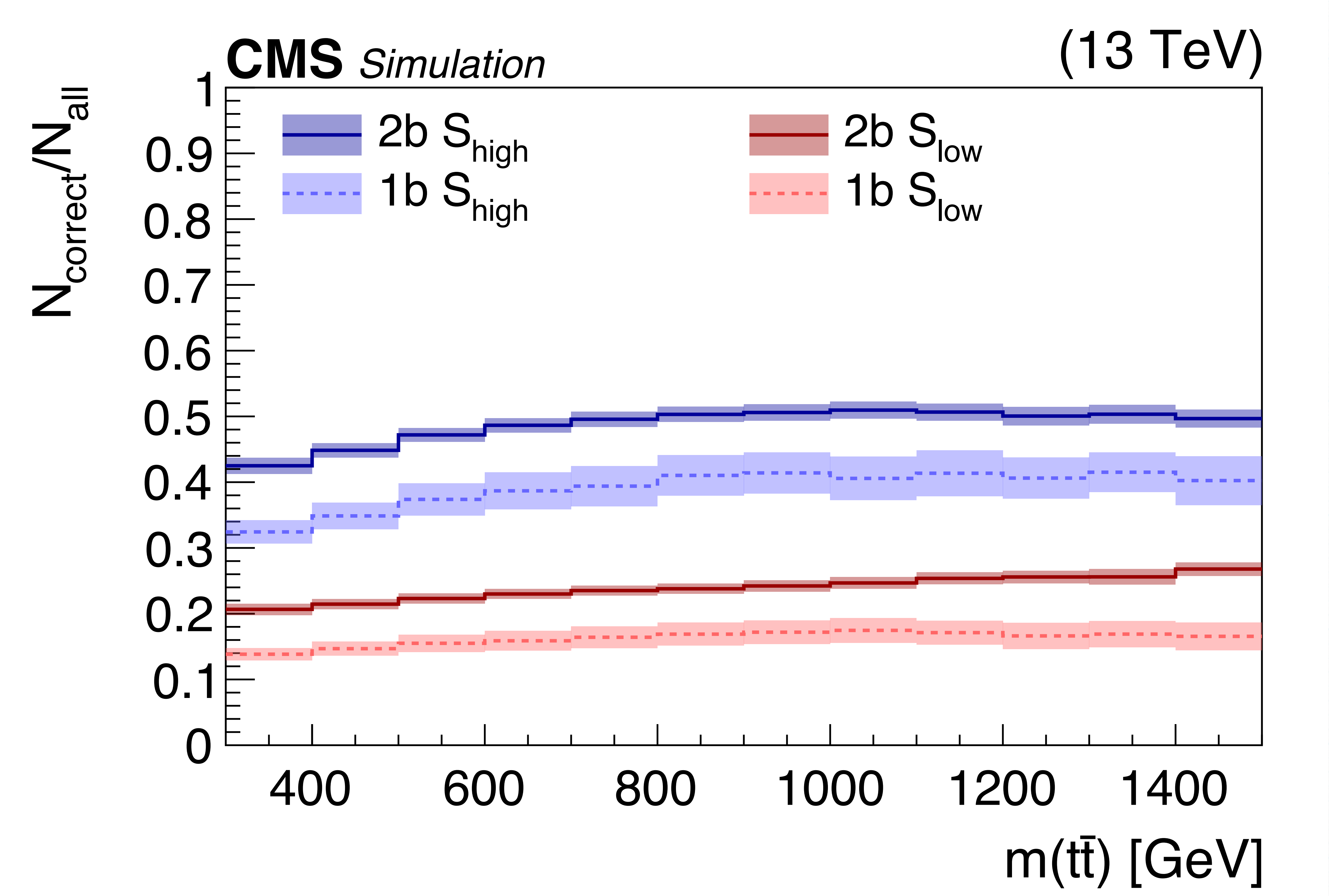
* $t\bar{t}$ spin correlation measurements in dilepton and lepton+jets channels in agreement with SM expectations.
    * Full spin-density matrix in the lepton+jets channel.
    * First observations of entanglement between top quarks in top pair production.
        * At production threshold in dilepton and high $m(t\bar{t})$ in lepton+jets channel.
    * Quantum Magic measurement
        * one of the first connections between quantum information science and particle physics.
        * shows the potential of collider experiments for investigating foundations of quantum mechanics.

Backup

Spin density matrix measurement in the e/μ+jets events

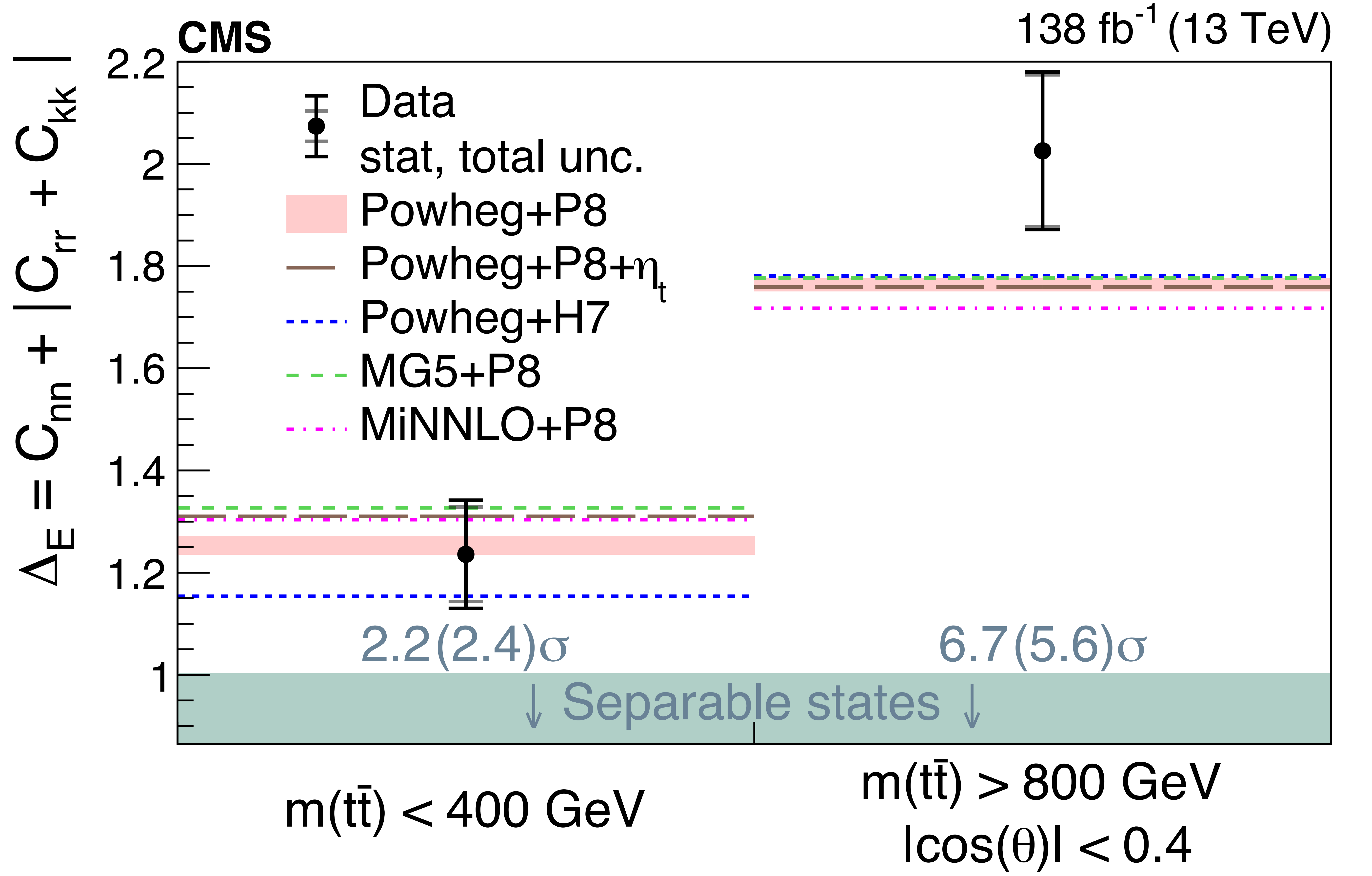


Reconstruction efficiency of the NN

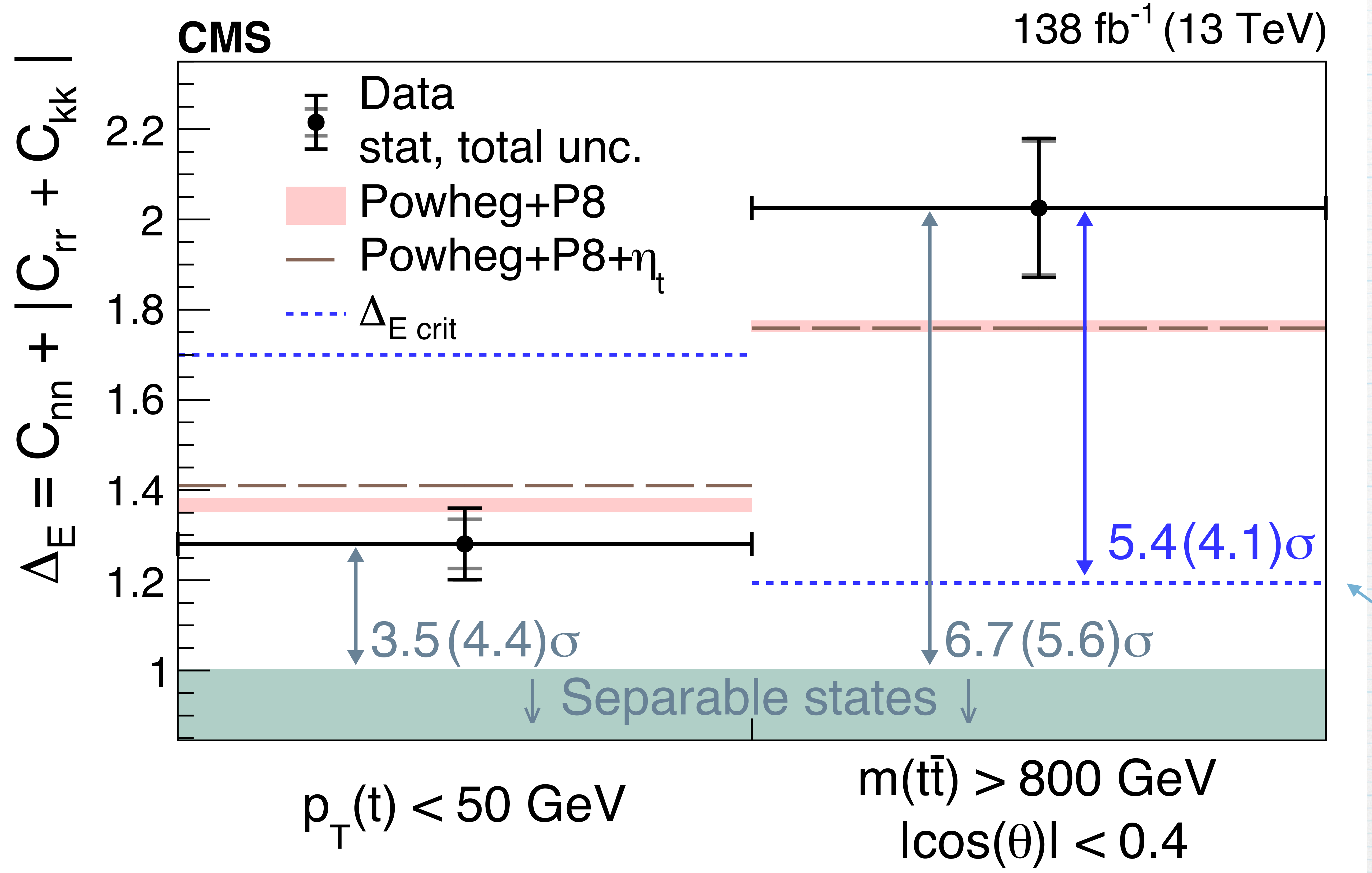


Fraction of correctly reconstructed events

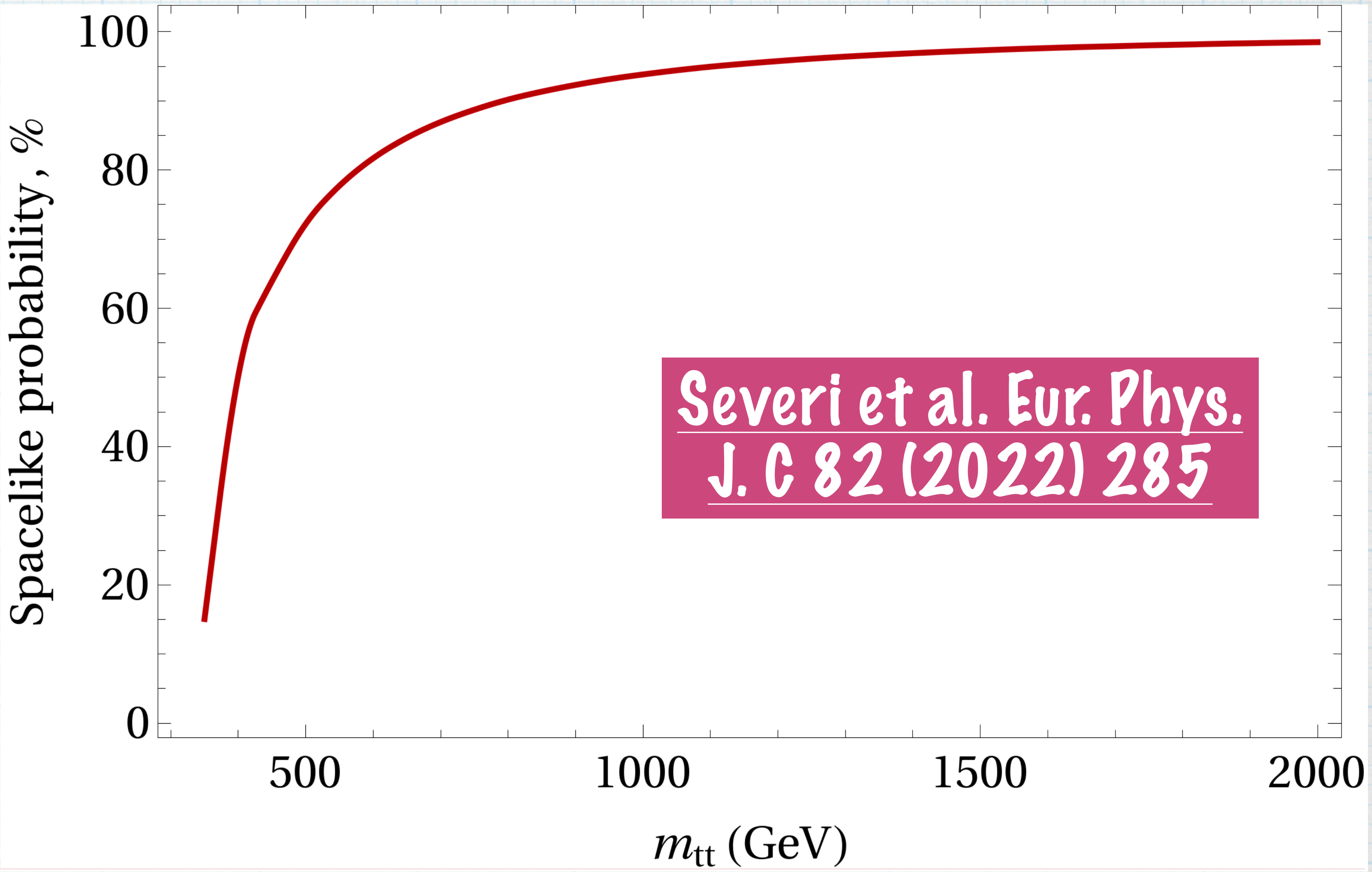
Quantum entanglement (l+jets)



Quantum entanglement from $t\bar{t}$ spin density matrix



- **First observation of entanglement at high $m(t\bar{t})$ where ~90% of observed $t\bar{t}$ are space-like separated.**



$\Delta_{E\ crit}$ = max level of entanglement explained classically by exchange of info between t and $\bar{t}$ at the speed of light.

f = fraction of spacelike sep. events

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

Assume timelike sep. evts. w/ max entanglement: $\Delta_{E\ crit}=3$ & spalike sep. Events $\Delta_{E\ sep}=1$.

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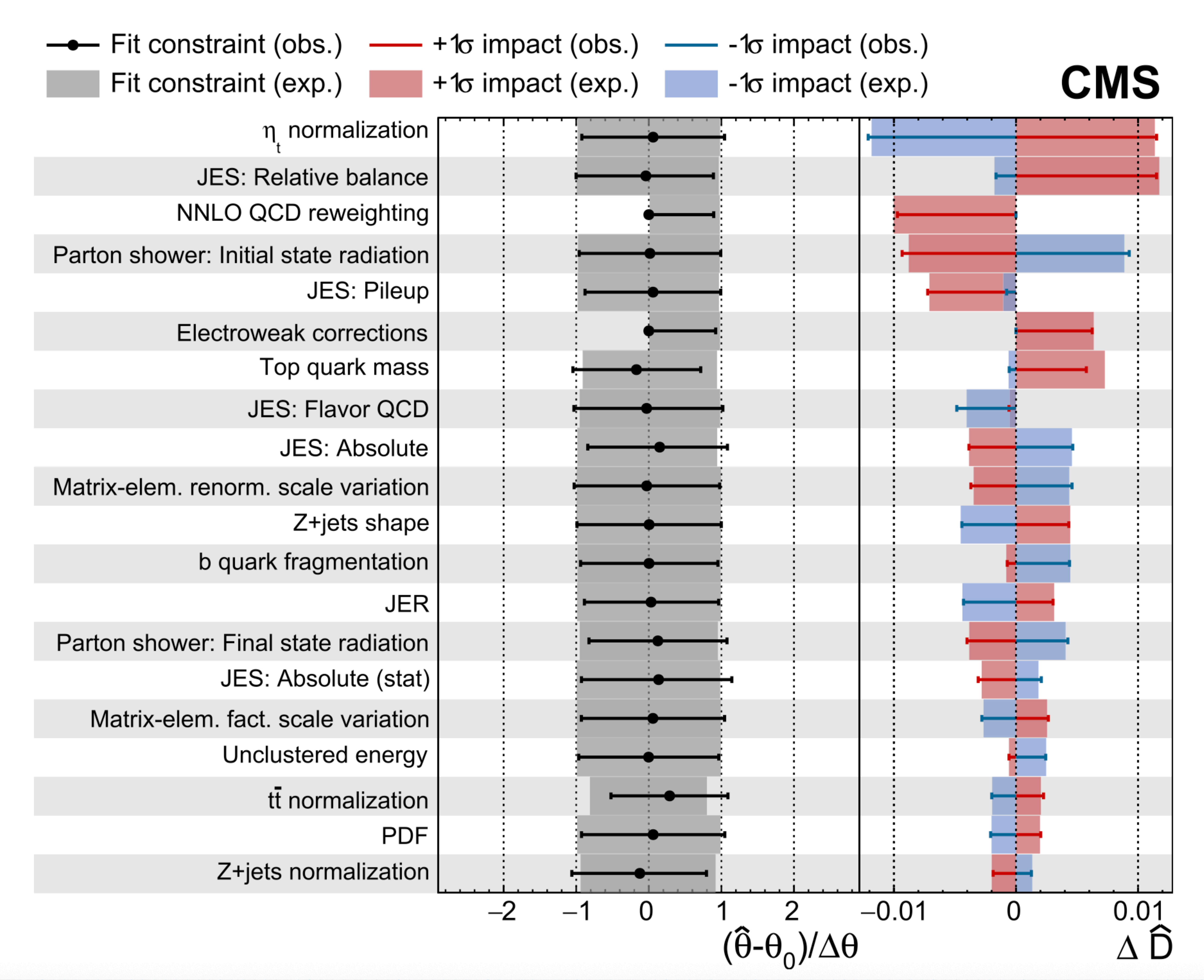
Quantum entanglement: dilepton channel



* Systematic uncertainties: toponium
  * cross section variation +/-50% to account for missing octet contributions.
  * binding energy variation +/-0.5 GeV.

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