Measurements of Top Quark Polarizations and ttbar Spin Correlations in Dileptonic Final States with CMS Detector at LHC

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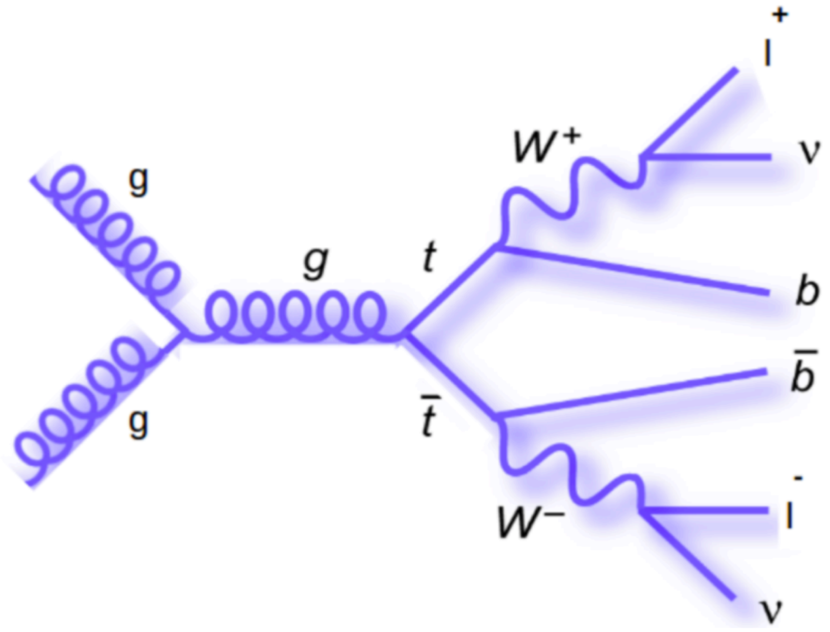
CMS

Top Quark - Introduction

- Heaviest fundamental particle: $m_t = 172.44 \ \pm 0.13 \ \pm 0.47 \text{ GeV}$
- Decay time (10^{-25} s) < hadronization time (~10^{-24} s) < spin decorrelation time(10^{-21}s) .
  - Spin related information is passed on to the angular distributions of decay products. Ideal system to study spin correlation of fundamental particles.

- Produced primarily via gluon fusion(gg->tt) at 13 TeV LHC.
- This analysis focuses on the dileptonic decay channel of ttbar.
  - 9% branching ratio is okay since $\sigma_{t\bar{t}}$ at 13 TeV ~830 pb.
  - Clean signal i.e. good S/B ratio.



Top Quark Spin Correlation

- The spins of top quark pairs produced from ttbar, generated from proton proton collisions have their spins correlated.
- Beyond Standard Model(BSM) theories can cause polarization of top quarks and modify spin correlation between top quarks.
- To search for BSM, measuring polarization and spin density matrix can be very useful.
- Measuring spin density matrix at different ttbar invariant masses is also interesting.

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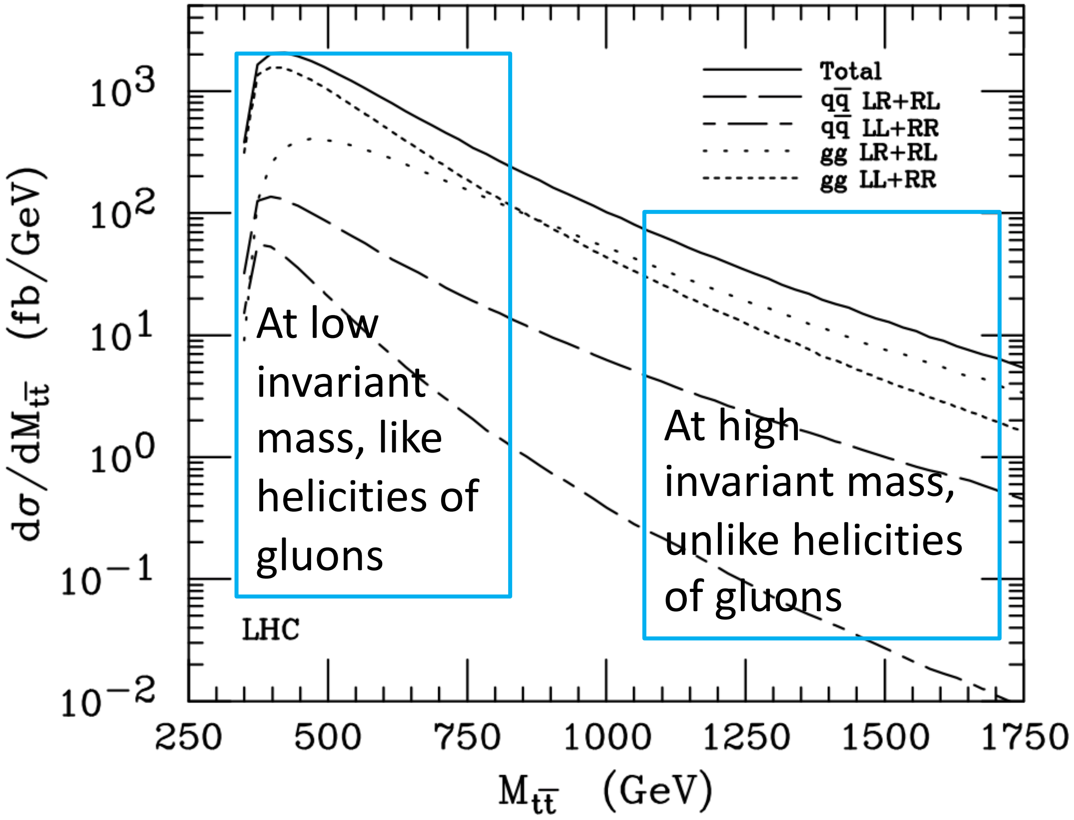


The helicities of gluons which produce ttbar pair are dependent on invariant mass.

Ttbar Spin Density Matrix

- The square of the matrix element for ttbar production and decay to two leptons:

$$\left|\mathrm{M}\left(q\bar{q}/gg \ \rightarrow t\bar{t} \ \rightarrow \ l^{+}\nu b l^{-}\bar{\nu}\bar{b}\right)\right|^{2} \propto \ \rho R \bar{\rho}$$

R is the spin density matrix of ttbar production, ρ is the decay density matrix

- R can be decomposed into different components:

$$R \ \propto \ \tilde{A}\, \mathrm{I} \otimes \mathrm{I} \ + \ \tilde{B}_i^{+} \sigma^{i} \otimes \mathrm{I} \ + \ \tilde{B}_i^{-} \mathrm{I} \otimes \sigma^{i} \ + \tilde{C}_{ij}\, \sigma^{i} \otimes \sigma^{j}$$

The total ttbar production cross-section and the top quark kinematic distributions ($\tilde{A}\, \mathrm{I} \otimes \mathrm{I}$)

Top/anti-top quark polarizations ($\tilde{B}_i^{+} \sigma^{i} \otimes \mathrm{I} + \tilde{B}_i^{-} \mathrm{I} \otimes \sigma^{i}$)

Spin correlations between top and anti-top quarks ($\tilde{C}_{ij}\, \sigma^{i} \otimes \sigma^{j}$)

- Goal of the analysis: Measure all independent coefficients [second and third terms in above equation] of the spin-dependent parts of the ttbar production density matrix.

Single differential cross-sections and corresponding coefficients

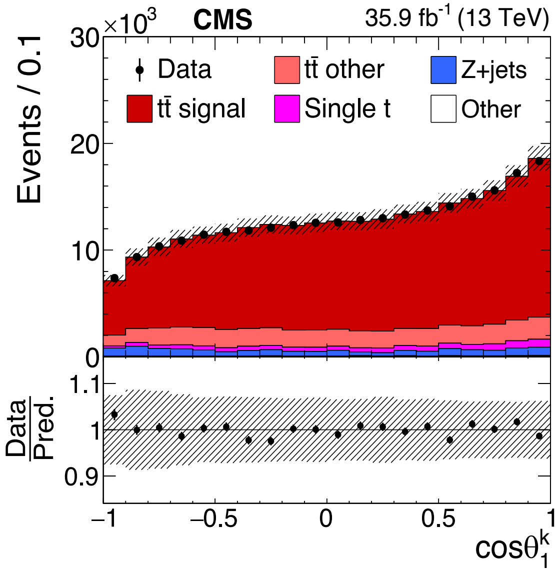
- After integrating out azimuthal angles, double-differential angular distribution becomes

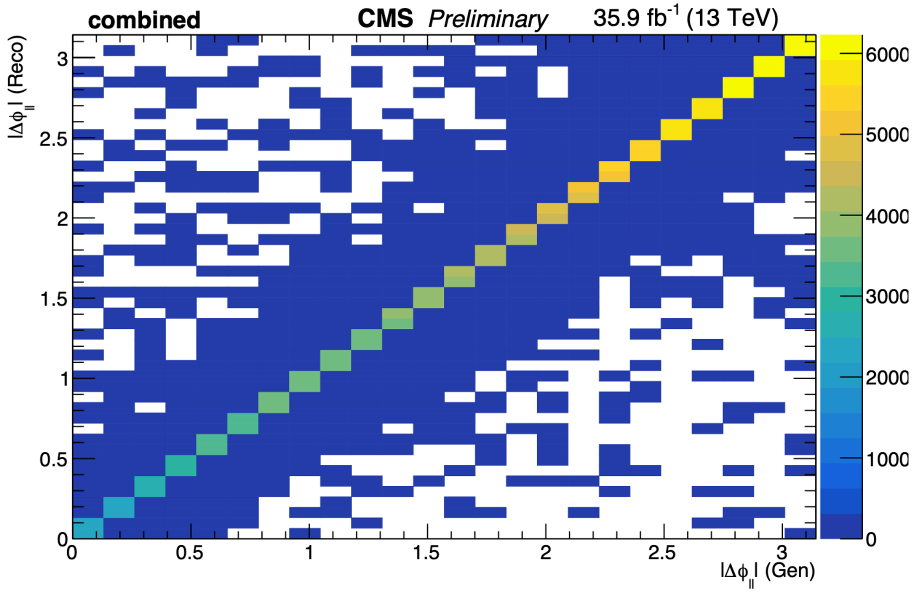
$$\frac{1}{\sigma}\frac{d^2\sigma}{d\cos\theta_1^i d\cos\theta_2^j} = \frac{1}{4}\left(1 + B_1^i \cos\theta_1^i + B_2^j \cos\theta_1^i - C_{ij}\cos\theta_1^i \cos\theta_2^j\right)$$

- Single-differential cross-sections can be derived by integrating out certain angles and changing variables.
  - Measure polarizations: $\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i \cos\theta_1^i\right)$
- Measure spin correlation coefficient D
  - $\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi); \cos\varphi = \widehat{l_1}.\widehat{l_2}; D = -\frac{Trace[C]}{3} = -\frac{(C_{kk}+C_{rr}+C_{nn})}{3}$
- Measure $A_{\Delta\phi_{l\bar{l}}} = \frac{N(|\Delta\phi_{ll}|>\pi/2) - N(|\Delta\phi_{ll}|<\pi/2)}{N(|\Delta\phi_{ll}|>\pi/2) + N(|\Delta\phi_{ll}|<\pi/2)}$, where $\Delta\phi_{l\bar{l}}$ is absolute angle between two leptons in lab frame.

Strategy for the measurement

- Object and event selection
- Kinematic reconstruction of ttbar system
- Binned measurements of single and double differential cross sections
- Background subtraction, normalization of data and simulations.
- Simultaneous unfolding of distributions for acceptance, efficiency and migration.
  - Obtain parton level differential cross sections and extrapolate to full phase space.
- Use covariance matrix from the analysis to constrain EFT operators.

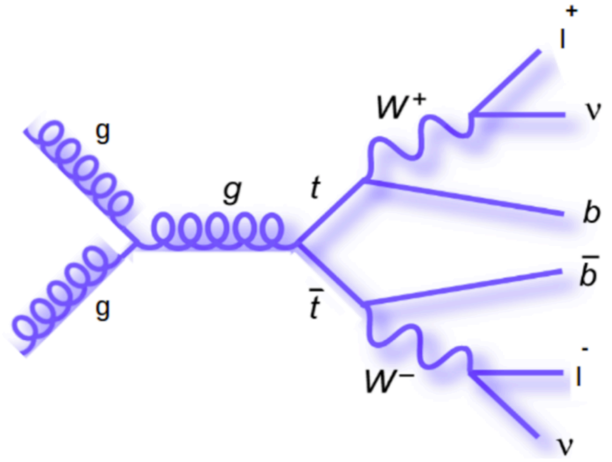




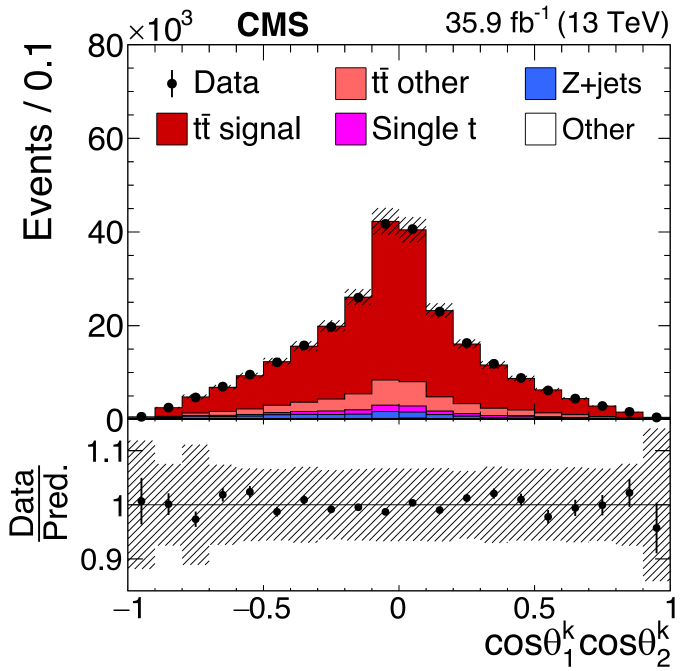
Signal, Backgrounds and Uncertainties

$$t\bar{t} \rightarrow l^{+}\nu b l^{-}\bar{\nu}\bar{b}$$

- Signal:
  - ➢Two charged leptons(ee/emu/mumu) from W boson decays, not from tau decays.
  - ➢Two jets from hadronization of b-quarks.



- Background:
  - ➢Ttbar events with leptonically decaying tau leptons.
  - ➢Single top quarks produced with a W boson.
  - ➢Z+jets, W+jets, diboson.
- Systematic Uncertainties(Main ones for C_{kk} measurement)
  - ➢Background cross-section (6%)
  - ➢B-fragmentation (5%)
  - ➢Jet energy scale (4%)



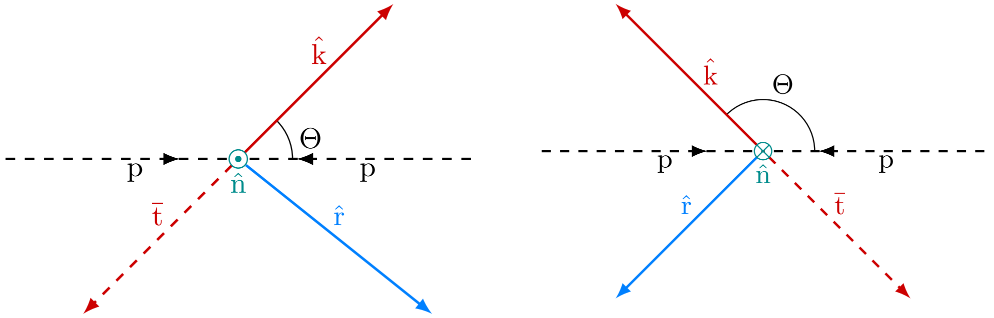
Results: D coefficient

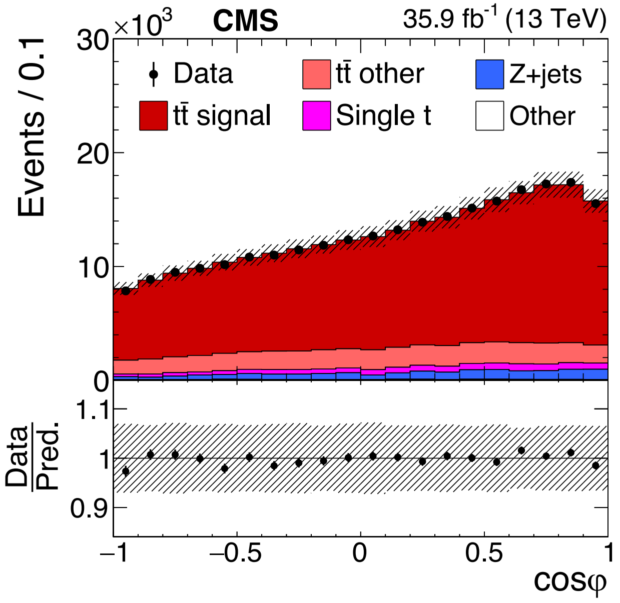
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi); \quad \cos\varphi = \widehat{l_1}.\widehat{l_2};$$

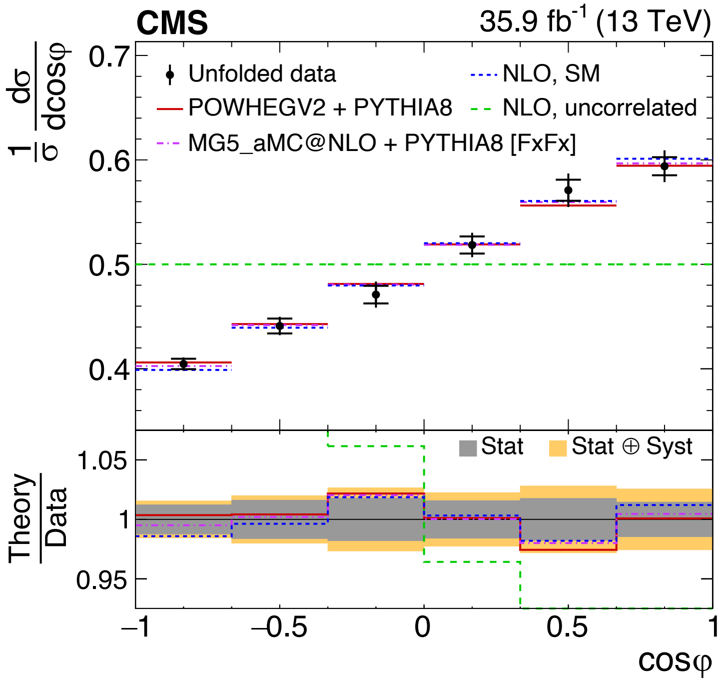
$$D = -\frac{Trace[C]}{3} = -\frac{(C_{kk} + C_{rr} + C_{nn})}{3}$$

D = −0.237 ± 0.007 ± 0.009

SM NLO: - 0.243







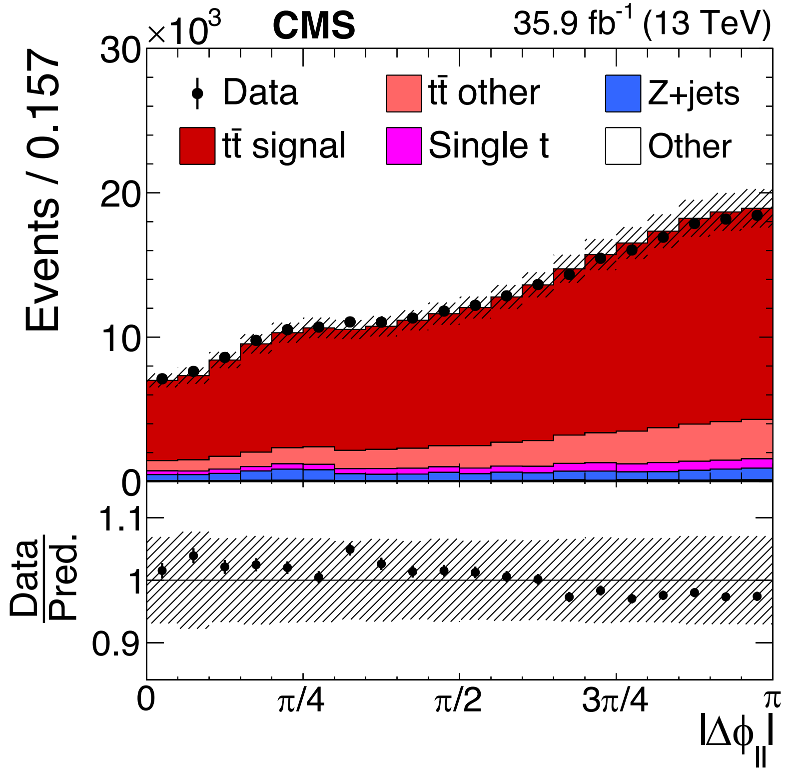
- $\hat{n}$ axis: $\hat{n} = \frac{sign(\cos\Theta)}{\sin\Theta}(p \times \hat{k})$
- $\hat{k}$ axis: Direction of top quark in ttbar rest frame
- $\hat{r}$ axis: $\hat{k} = \frac{sign(\cos\Theta)}{\sin\Theta}(p - \hat{k}\cos\Theta)$
- $\hat{p}$ direction: direction of incoming proton /beam axis
- Θ : Angle between top quark and incoming parton in ttbar rest frame.

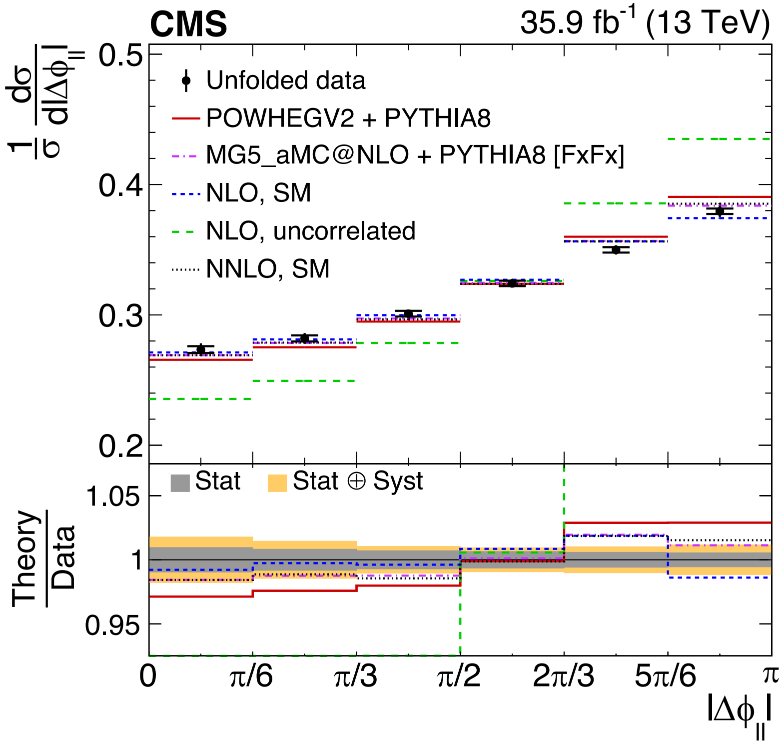
Results: A coefficient

$$A_{\Delta\phi_{l\bar{l}}} = \frac{N(|\Delta\phi_{ll}| > \pi/2) - N(|\Delta\phi_{ll}| < \pi/2)}{N(|\Delta\phi_{ll}| > \pi/2) + N(|\Delta\phi_{ll}| < \pi/2)}$$

$A_{\Delta\phi_{l\bar{l}}}$ = 0.103 ± 0.003 ± 0.007

SM NNLO: 0.115





$\Delta\phi_{ll}$ variable is more interesting for double differential distributions when the shape changes depending on invariant mass of ttbar.

Full Run2 measurement

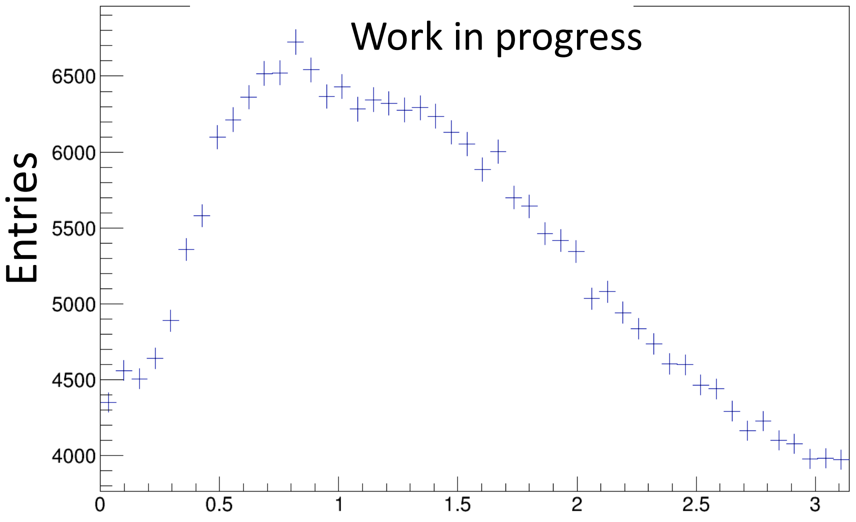
- Run analysis using data recorded by CMS detector during 2016, 2017 and 2018.
- Extension with new measurements.

1. Double differential distributions
   - Angular variables like $\Delta\phi_{l\bar{l}}$ and spin correlation variables in bins of $m_{t\bar{t}}$, pT_{top} etc.
2. Single and double differential distributions of angular variables of jets
   - $\Delta\phi, \Delta\eta, \Delta\phi\ vs\ \Delta\eta$ of additional jets for SUSY interpretations.
3. Introduce linear combinations of c_{ii} to avoid steep slopes in their distributions.
4. Same strategy as the one explained previously. The public results are available only for 2016 data.

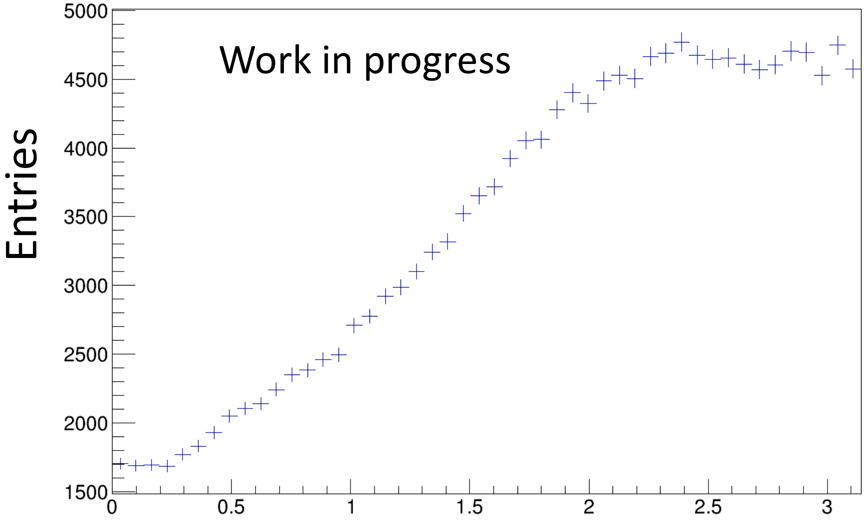
Double differential distributions

- $\Delta\phi_{l\bar{l}}$ distribution changes depending on m_{ttbar} .
- Interesting since helicity of ttbar pair produced at LHC is dependent on its invariant mass.
- $\Delta\phi_{l\bar{l}}$ vs m_{ttbar} distributions have not been studied yet with data collected by CMS detector.

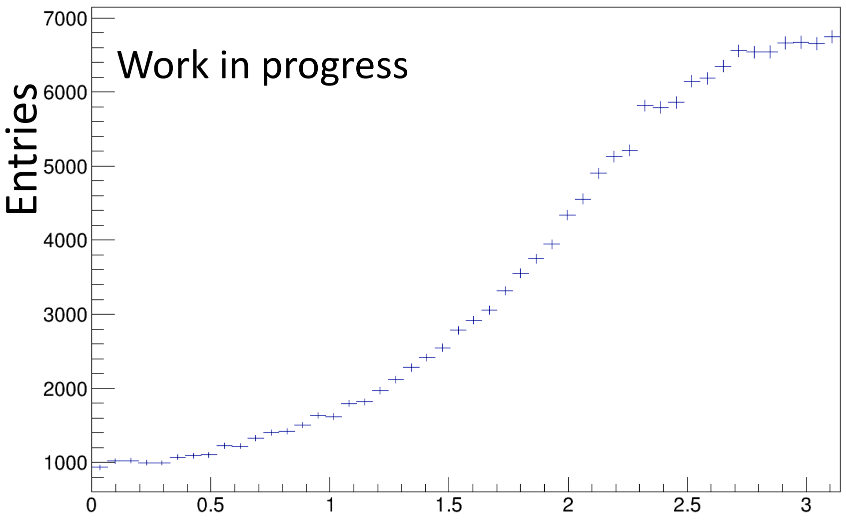
$0 < m_{ttbar} < 450$ GeV



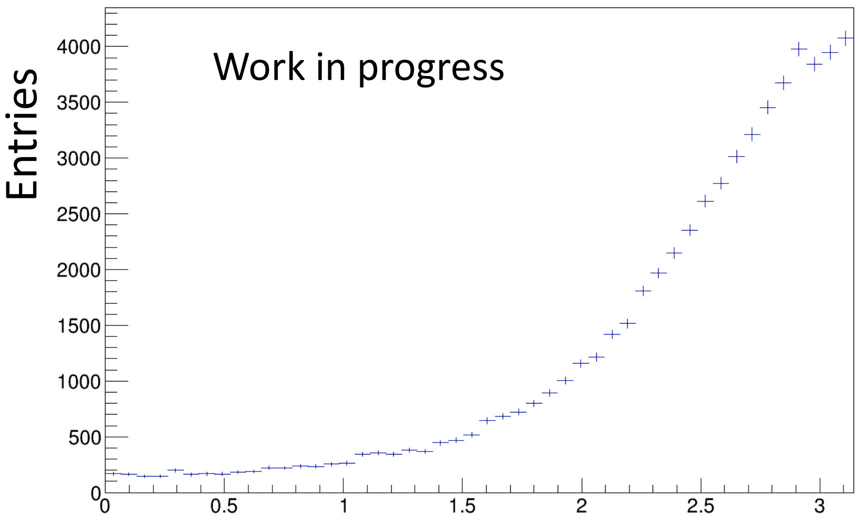
$450 < m_{ttbar} < 550$ GeV



$550 < m_{ttbar} < 800$ GeV

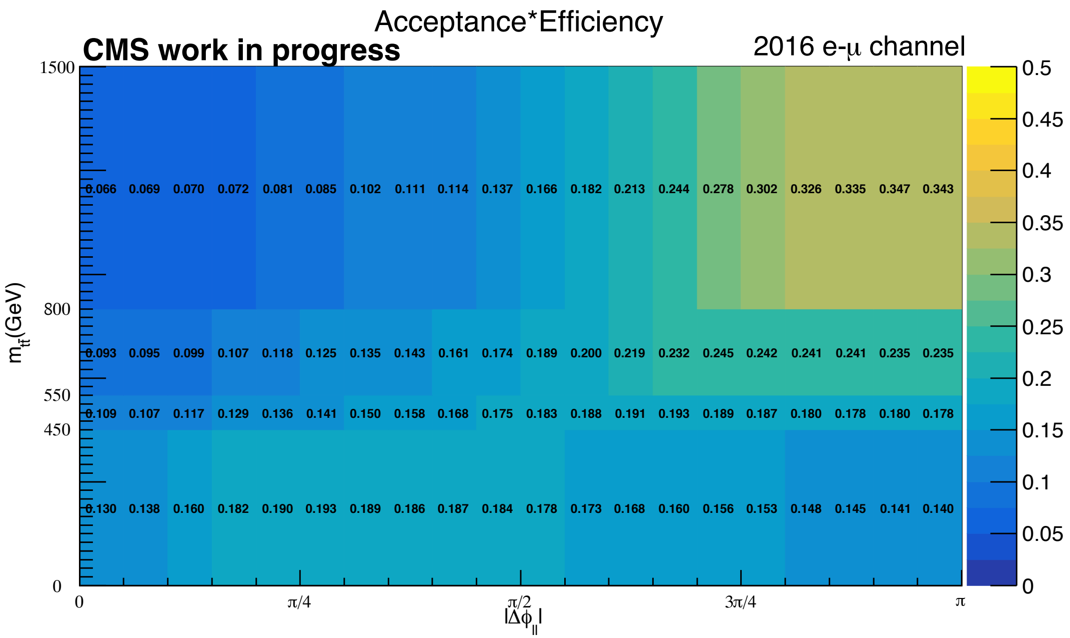


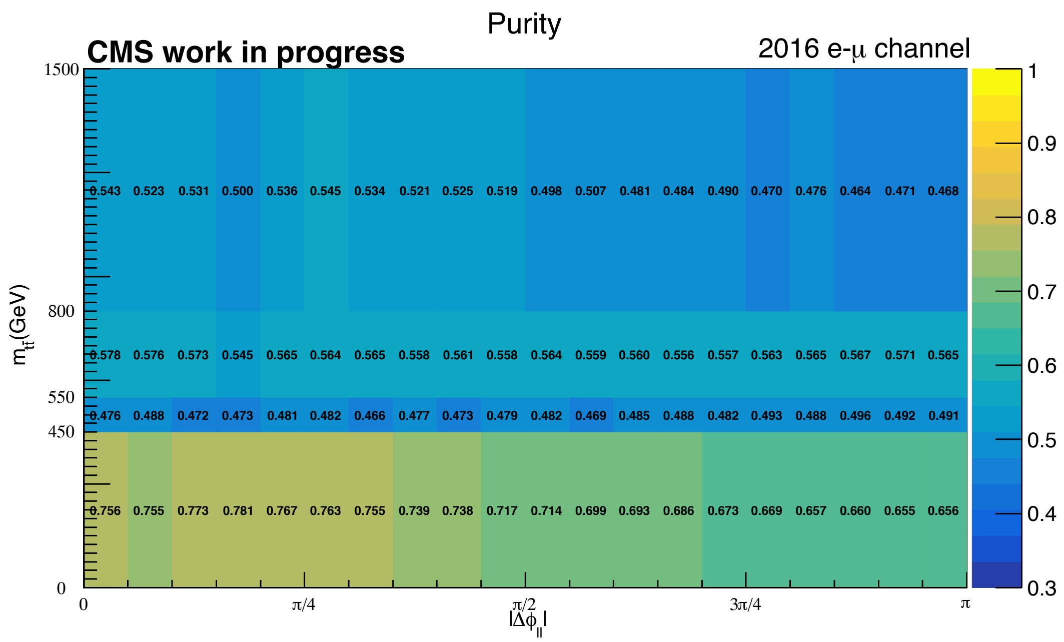
800 GeV $< m_{ttbar}$



Unfolding double differential distributions-1

- Study acceptance, efficiency to study the performance of CMS detector at different regions of phase space.
- Study resolution, purity and stability to study migration effects of double differential distributions to choose optimal binnings.

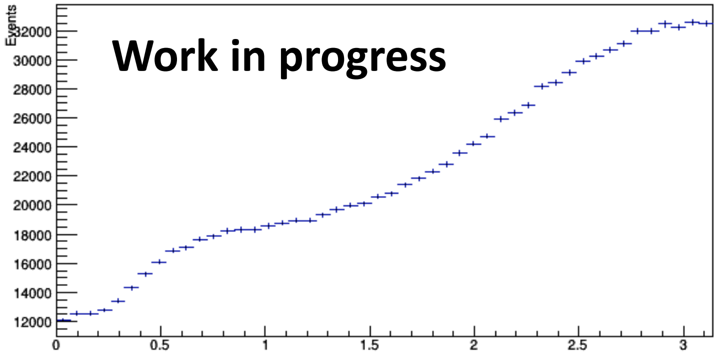




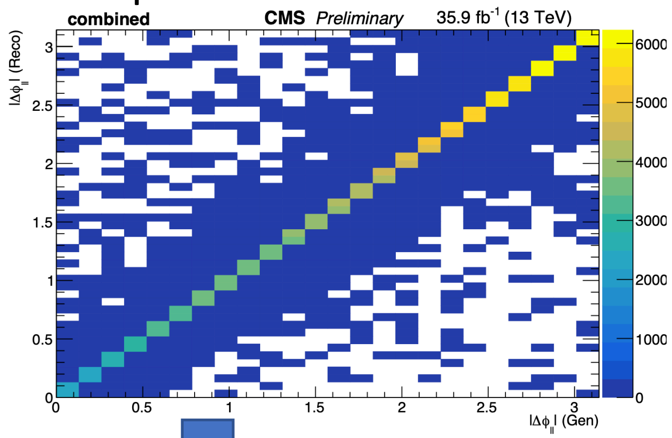
Unfolding double differential distributions-2

- Detector can measure events only in certain regions of the phase space.
- Reconstruction of events results in shifting of physical quantities measured.
- Extrapolating the reconstructed events to the full phase space precisely is extremely important for the measurement.
- Any migration effects need to be corrected.

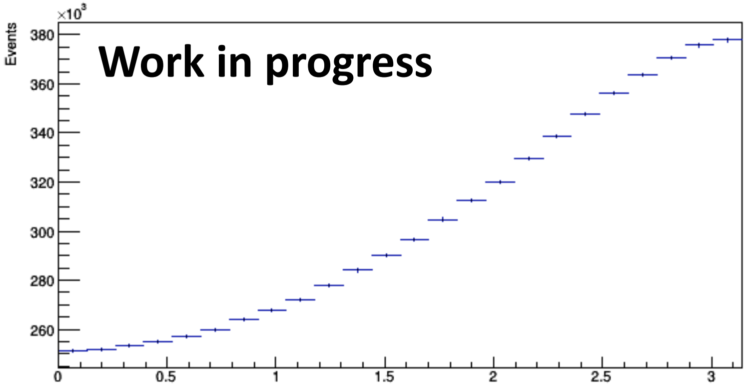
Reconstructed events



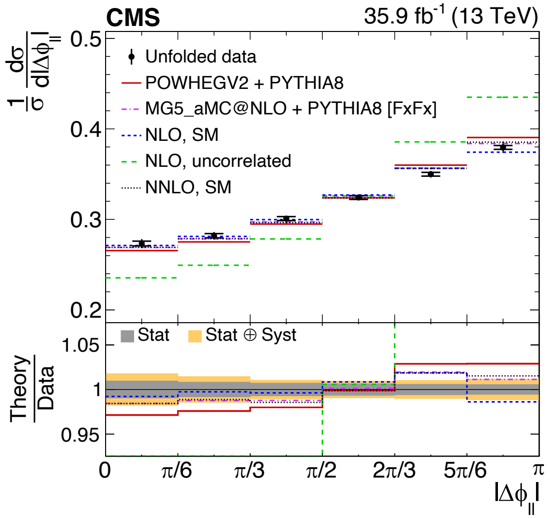
Response matrix



True events (generator)

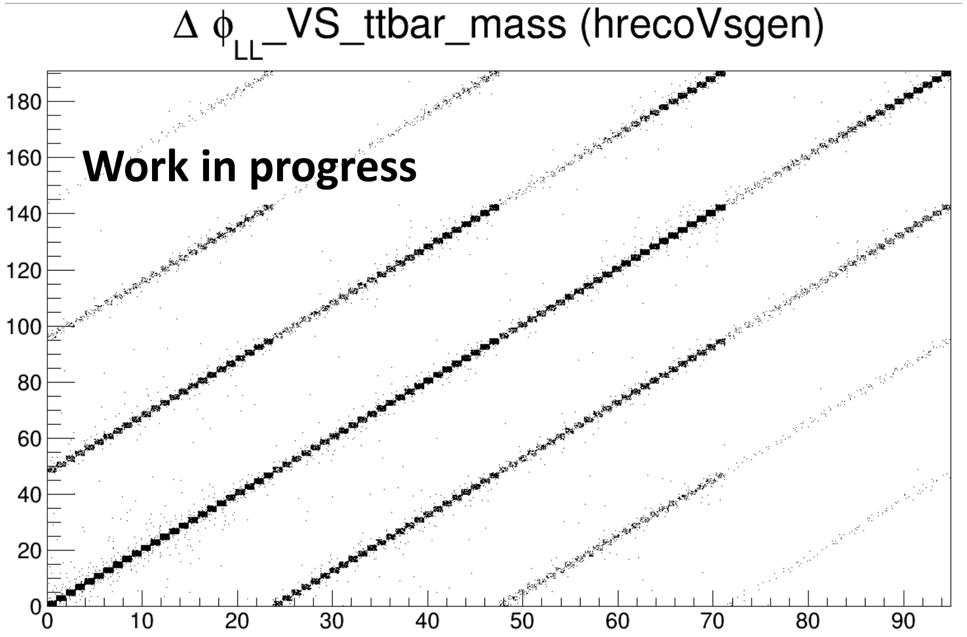


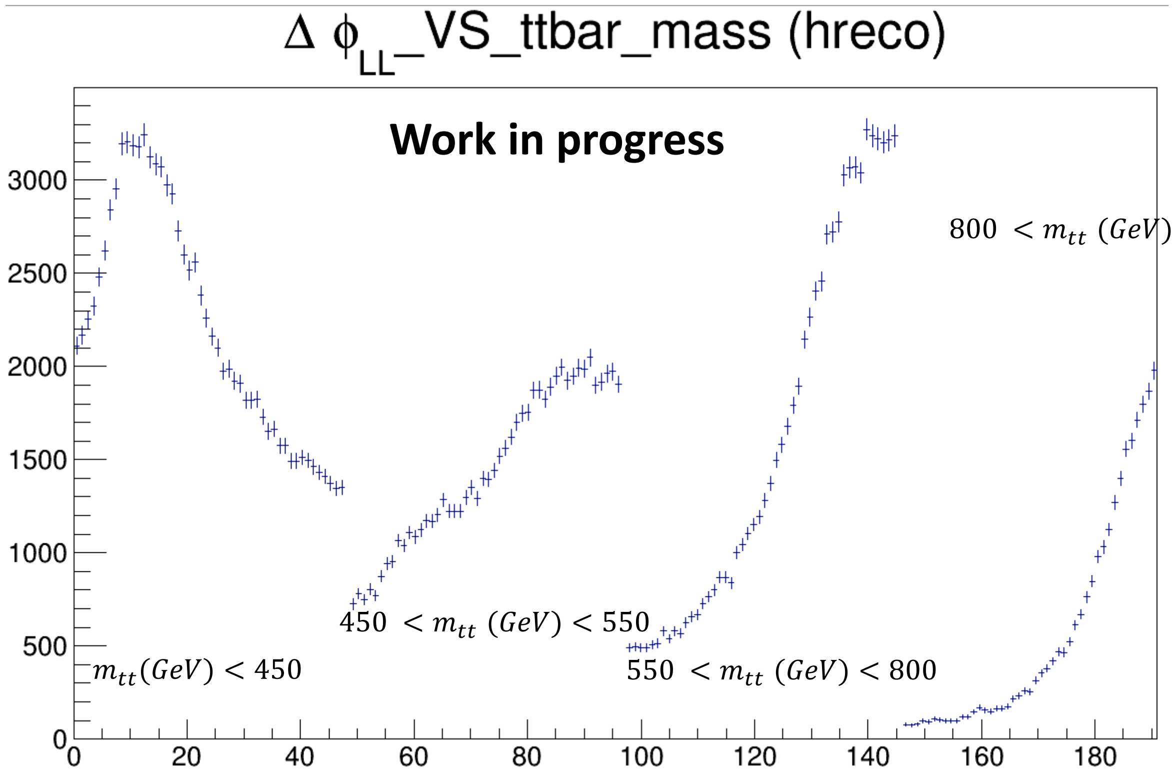
Measurement vs predictions



Unfolding double differential distributions-3

- Roll out double differential distributions into longer single differential distributions for matrix unfolding since there is a known solution for the problem.

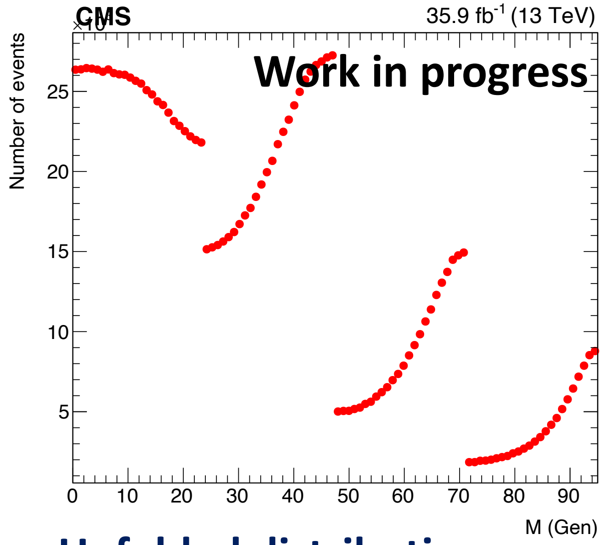




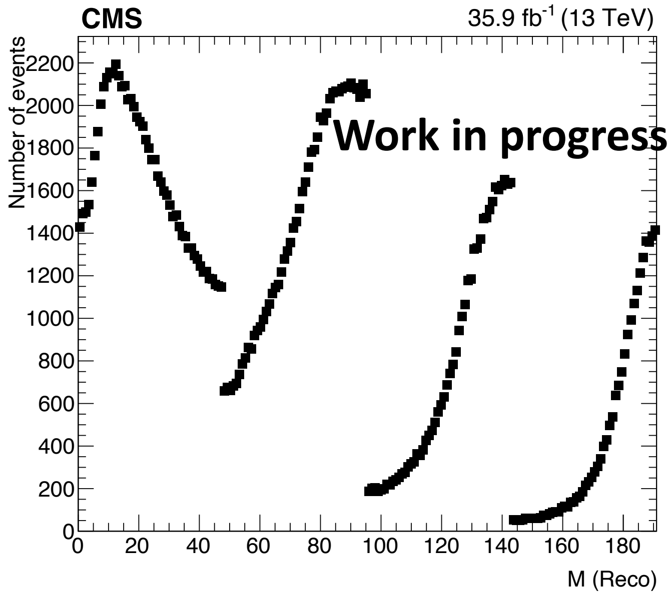
Unfolding double differential distributions-4

Reco level distribution is unfolded to pull phase space true level distribution using response matrix. For comparison, true level distribution from MC is also shown.

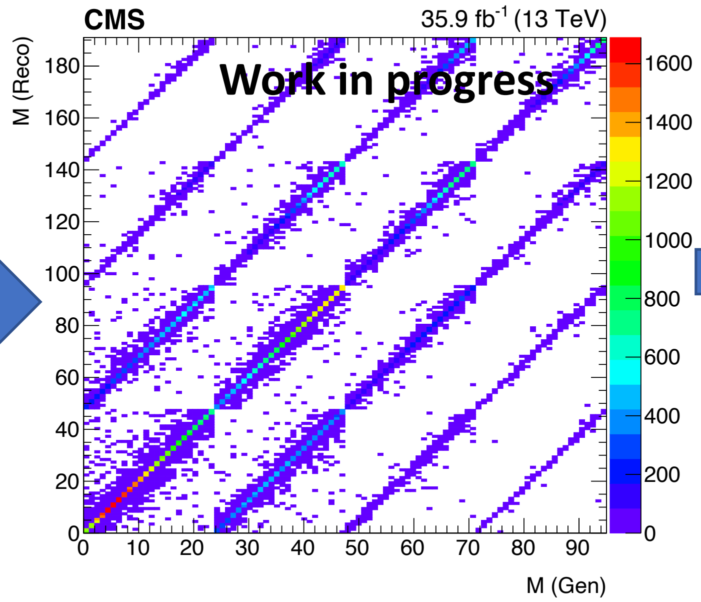
True level (MC)



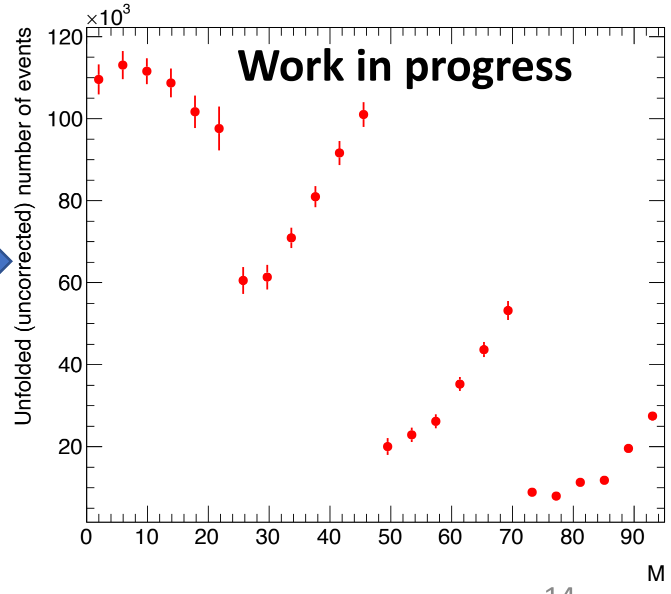
Reconstructed level



Response matrix



Unfolded distribution



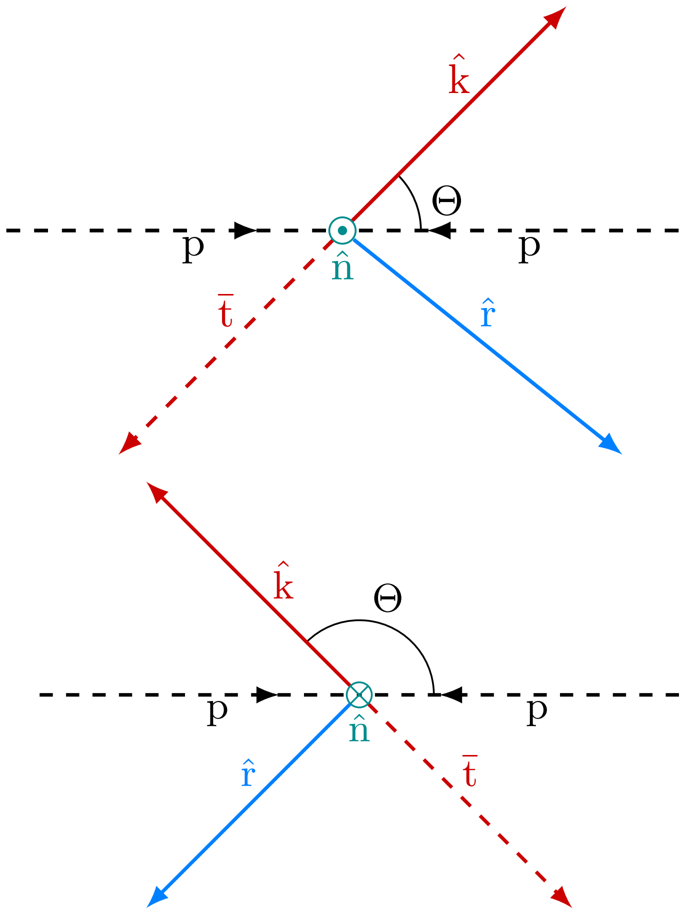
Conclusion and summary of ongoing work

- Measurement of top quark polarization and ttbar spin correlation using full run 2 data is progressing.
  - Double differential distributions of various pairs of variables are being studied.
  - Include more variables like angular variables of jets.
- Study of which pairs of variables work for double-differential studies and optimization of binning has been done.
- Unfolding of double-differential distributions is ongoing.
- Now working on systematics uncertainties.

BACKUP

Helicity Basis: Spin Quantization Axes{k,n,r}

- $\hat{k}$ axis: Direction of top quark in ttbar rest frame
- $\hat{n}$ axis: $\hat{n} = \frac{sign(\cos\Theta)}{\sin\Theta}(p \times \hat{k})$
- $\hat{r}$ axis: $\hat{k} = \frac{sign(\cos\Theta)}{\sin\Theta}(p - \hat{k}\cos\Theta)$
- $\hat{p}$ direction: direction of incoming proton /beam axis
- Θ : Angle between top quark and incoming parton in ttbar rest frame.



Event and Object Selection Details

Triggers: Single-lepton and dilepton paths – maximize trigger efficiency

Leptons: Exactly two isolated electrons or muons of opposite electric charge

$p_T > 25(20)\ GeV$ for leading (trailing) candidate, $|\eta| < 2.4$, Relative isolation criteria (I_{rel}),

$1.44 < |\eta_{cluster}| < 1.57$ excluded in ECAL, Identification requirements,

$m_{l^+l^-} < 20$ GeV and $76 < m_{l\bar{l}} < 106$ GeV excluded

Jets: At least two jets, with at least one b-tagged

$p_T > 30\ GeV$, $|\eta| < 2.4$, anti-k_t jets ($R = 0.4$), Jet Cleaning: $\Delta R(l, jet) > 0.4$

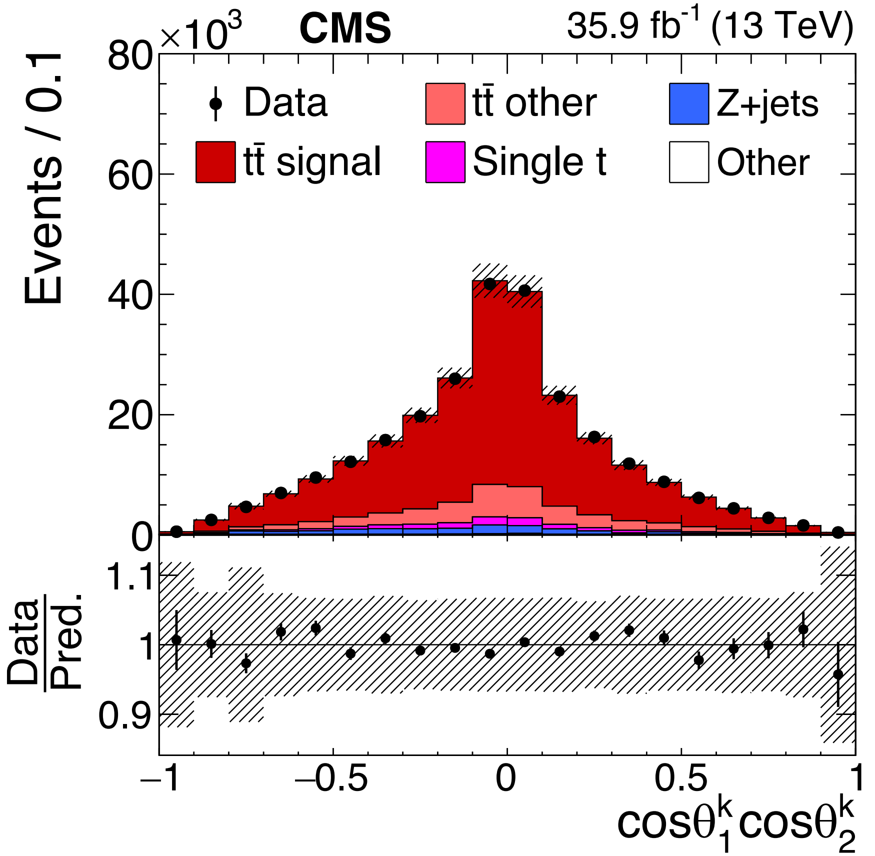
E_T^{miss}: $p_T^{miss} > 40\ GeV$

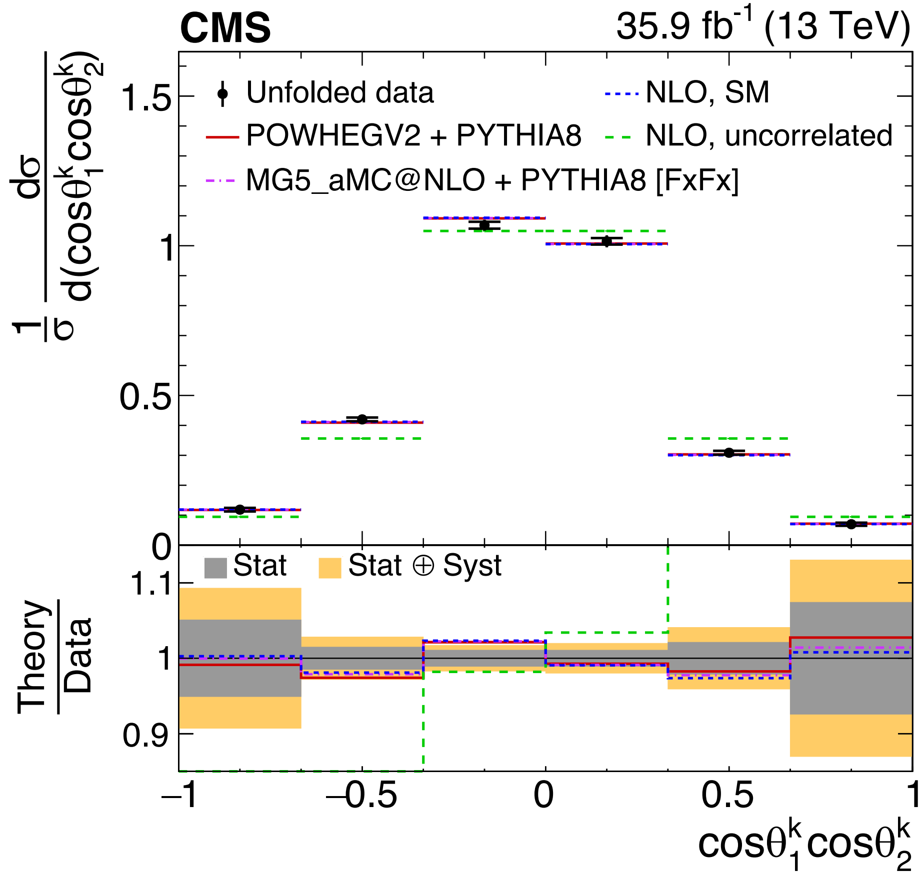
Results: C coefficient

$$\frac{1}{\sigma}\frac{d\sigma}{d\left(\cos\theta_1^i\cos\theta_2^i\right)} = \frac{1}{2}\left(1 - C_{ii}\left(\cos\theta_1^i\cos\theta_2^i\right)\right)\ln\frac{1}{\left|\cos\theta_1^i\cos\theta_2^i\right|}$$

C_{kk} = 0.30 ± 0.02 ± 0.03

SM NLO: 0.33



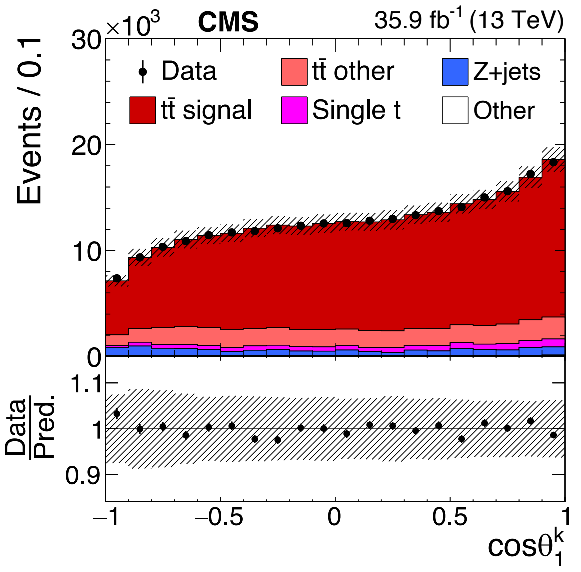


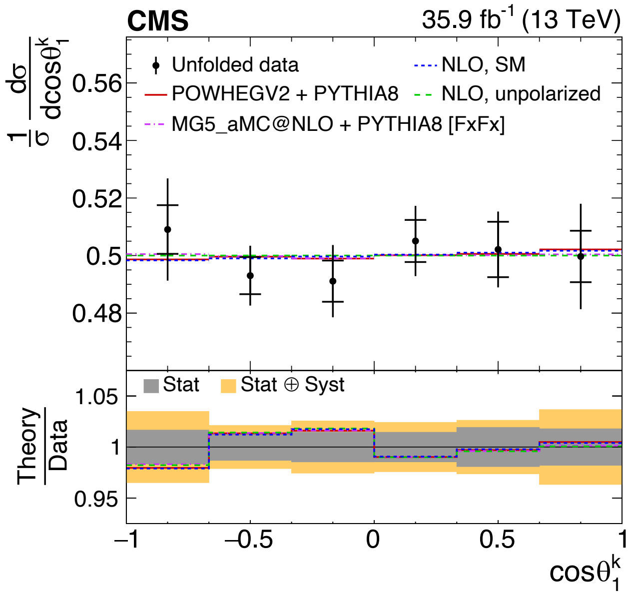
Results: B coefficient

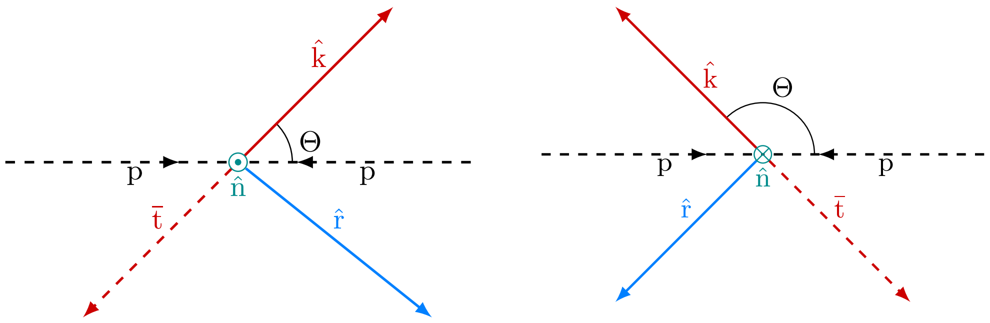
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_1^i} = \frac{1}{2}\left(1 + B_1^i \cos\theta_1^i\right)$$

B^k_i= 0.005 ± 0.010 ± 0.021
SMO: 0.004

- $\hat{k}$ axis: Direction of top quark in ttbar rest frame
- $\hat{n}$ axis: $\hat{n} = \frac{sign(\cos\Theta)}{\sin\Theta}(p \times \hat{k})$
- $\hat{r}$ axis: $\hat{k} = \frac{sign(\cos\Theta)}{\sin\Theta}(p - \hat{k}\cos\Theta)$
- $\hat{p}$ direction: direction of incoming proton /beam axis
- Θ : Angle between top quark and incoming parton in ttbar rest frame.

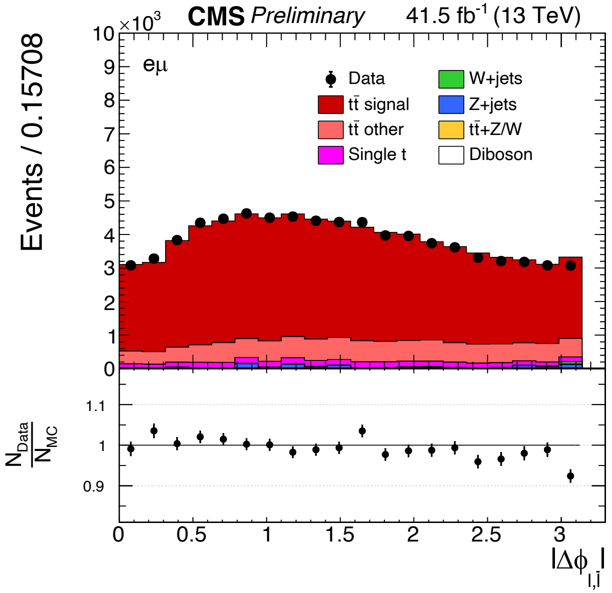




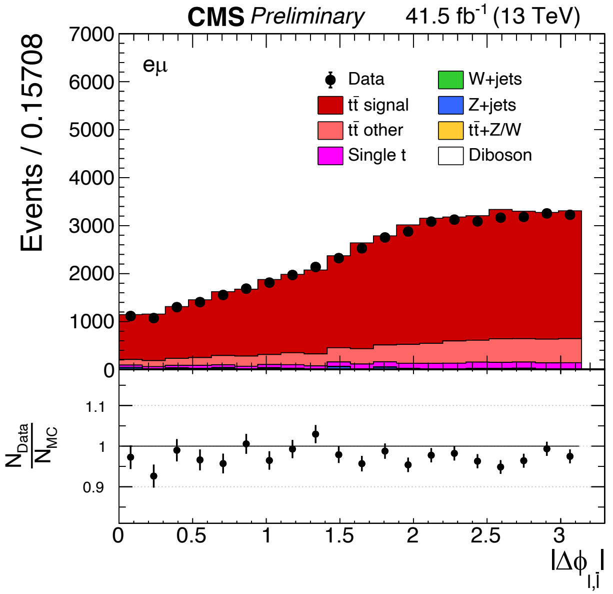


deltaPhi_llbar control plots in e-mu channel in bins of mass of ttbar [0-450], [450-550], [550-800], [800-infinity] Gev (binning used by ATLAS)

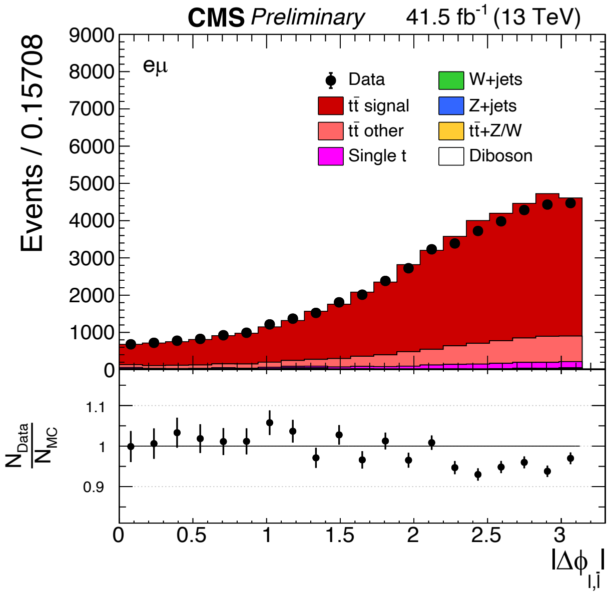
M_{ttbar} < 450 Gev



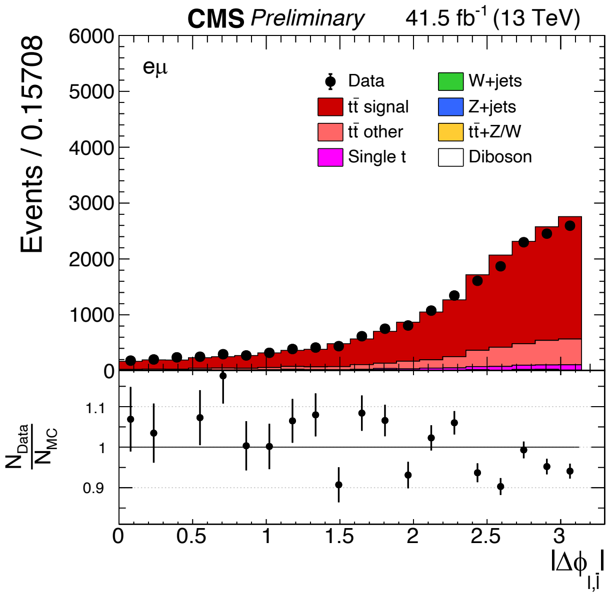
450 < M_{ttbar} < 550 Gev



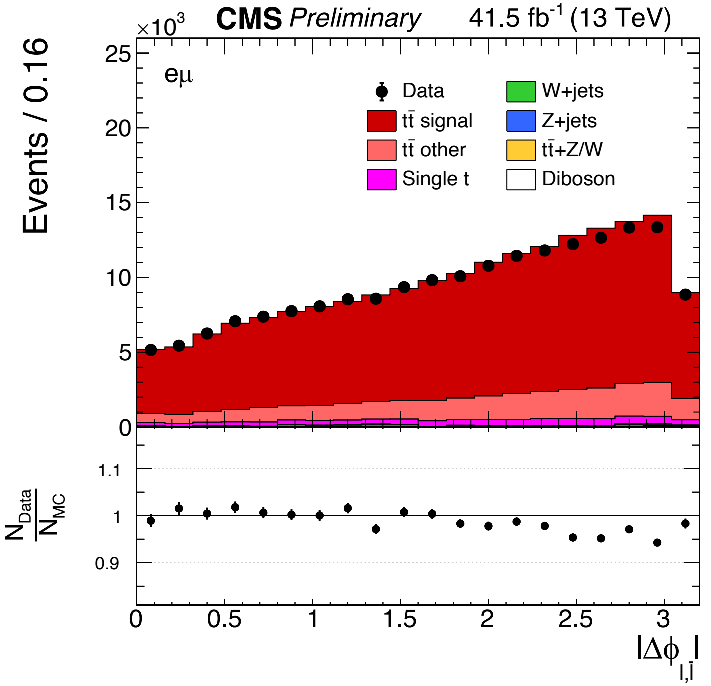
550 < M_{ttbar} < 800 Gev



800 GeV < M_{ttbar}



Control plot with all e-mu events



Constraining the Top Quark Anomalous CDMD Operator Coefficient

- Several Beyond Standard Model (BSM) theories predict an anomalous top quark Chromo-Magnetic Dipole Moment(CMDM) that would affect ttbar kinematics and top spin correlation coefficients.
- We use covariance matrix from the measurement to constrain $\frac{C_{tG}}{\lambda^2}$ (Wilson coefficient of CMDM operator).
- Chi-squared is calculated using:
  $$\chi^2\left({}^{C_{tG}}/_{\lambda^2}\right) = \sum_{i=1}^{N}\sum_{j=1}^{N}(data_i - pred_i)\cdot\left(data_j - pred_j\right)\cdot Cov_{i,j}^{-1}$$
- More independently measured variables results in better constraint.
- Best fit value (from 2016 data): ${}^{C_{tG}}/_{\lambda^2} = 0.04\,TeV^{-2}$
  95% confident limit: $-0.07 < {}^{C_{tG}}/_{\lambda^2} < 0.16\,TeV^{-2}$