Measurements of Top Quark Polarizations and $t\bar{t}$ Spin Correlations in Dilepton Final States

Top Quark Physics at APS Division of Particles and Fields
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The Top Quark

- Heaviest known fundamental particle: \( m_t = 172.44 \pm 0.13 \pm 0.47 \text{ GeV} \)
- Extremely short lifetime: \( \frac{1}{m_t} \sim \mathcal{O}(10^{-27} \text{ s}) \ll \frac{1}{\Gamma(t \to Wb)} \sim \mathcal{O}(10^{-25} \text{ s}) \ll \frac{1}{\Lambda_{\text{QCD}}} \sim \mathcal{O}(10^{-24} \text{ s}) \ll \frac{m_t}{\Lambda^2} \sim \mathcal{O}(10^{-21} \text{ s}) \)

Production | Decay | Hadronization | Spin Decorrelation

- Spin information of the top quark is preserved in the angular distribution of its decay products
- Produced dominantly in pairs via gluon fusion (gg \( \to \) t\(\bar{t}\)) at 13 TeV LHC
- This analysis targets the dilepton final states (\(\sim 9\%\) BF) of t\(\bar{t}\) decay:

\[
\begin{align*}
t\bar{t} & \rightarrow (b \ W^+) (\bar{b} \ W^-) \rightarrow (b \ \ell^+ \ \nu_\ell) (\bar{b} \ \ell^- \ \bar{\nu}_\ell)
\end{align*}
\]
**t\bar{t} Spin Density Matrix (R) at Parton Level**

- Squared matrix element for the $t\bar{t}$ production and decay:

$$|\mathcal{M}(gg/q\bar{q}) \rightarrow t\bar{t} \rightarrow (l^+vb)(l^-\bar{v}\bar{b})|^2 \sim Tr[\rho R\bar{\rho}]$$

- Spin density matrix $R$ related to on-shell $t\bar{t}$ production

- Decay density matrix $\rho/\bar{\rho}$

- $R$ can be decomposed into the spin space of $t$ and $\bar{t}$ using a basis of Pauli matrices:

$$R \propto \tilde{A} \mathbb{1} \otimes \mathbb{1} + \tilde{B}^+_i \sigma^i \otimes \mathbb{1} + \tilde{B}^-_i \mathbb{1} \otimes \sigma^i + \tilde{C}_{ij} \sigma^i \otimes \sigma^j$$

- Constant that characterizes spin-averaged production cross-section at parton level

- 3-vectors that characterize the net degree of **top quark/antiquark polarization** along each of the axes

- 3 x 3 matrix elements that characterizes the **correlation between the top/anti-top spins** along each pair of axes

**Aim:** Measurement of all the independent coefficients of the spin-dependent parts of the $t\bar{t}$ production density matrix in the dileptonic channel
Helicity Basis: Spin Quantization Axes \( \{\hat{k}, \hat{r}, \hat{n}\} \)

- **Helicity** \( \hat{k} \)-axis: top quark direction in \( t\bar{t} \) rest frame

- **Transverse** \( \hat{n} \)-axis: transverse to production plane

\[
\hat{n} = \frac{\text{sign} \left( \cos \Theta \right)}{\sin \Theta} \left( \hat{p} \times \hat{k} \right)
\]

- **\( \hat{r} \)-axis**: orthogonal to the other two axes

\[
\hat{r} = \frac{\text{sign} \left( \cos \Theta \right)}{\sin \Theta} \left( \hat{p} - \hat{k} \cos \Theta \right)
\]

- **\( \hat{p} \)**: direction of the incoming parton, i.e. the direction of the proton beam (z-direction in the laboratory frame)

- **\( \Theta \)**: top quark scattering angle in \( t\bar{t} \) rest frame
Differential Cross Sections

- The polar angle double-differential distributions:

\[
\frac{1}{\sigma} \frac{d\sigma}{d\cos \theta_1^i \, d\cos \theta_2^j} = \frac{1}{4} (1 + B_1^i \cos \theta_1^i + B_2^j \cos \theta_2^j - C_{ij} \cos \theta_1^i \cos \theta_2^j)
\]

- A change of variable, if necessary, and integrating out one of the angles yield single-differential cross sections:

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_1^i} = \frac{1}{2} (1 + B_1^i \cos \theta_1^i) \quad \text{Measure polarizations}
\]

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\cos \theta_1^i \cos \theta_2^j)} = \frac{1}{2} [1 - C_{ii} (\cos \theta_1^i \cos \theta_2^j)] \ln \left| \frac{1}{\cos \theta_1^i \cos \theta_2^j} \right| \quad \text{Measure diagonal spin correlations}
\]

- For today’s talk, we will focus only on the measurements of \(B_1^k, C_{kk}, D,\) and \(A_{\Delta \phi \mu}\) from \(|\Delta \phi \mu| = \left| \left| \phi_{\mu_1} - \phi_{\mu_2} \right| - \pi - \pi \right|\)
Recent & Exciting Results from ATLAS

$|\Delta \Phi_{ll}|$ distribution in data (parton level, full phase space)

$$|\Delta \Phi_{ll}| = \left| |\phi_{l_1} - \phi_{l_2}| - \pi \right| - \pi$$

- Provides an indirect measurement of spin correlations; does not require a full reconstruction of $t$ and $\bar{t}$
- Shape comes from top kinematics and depends partly on the spin correlation coefficients

- Asymmetry:

$$A_{\Delta \Phi_{ll}} = \frac{N(|\Delta \Phi_{ll}| > \frac{1}{2}) - N(|\Delta \Phi_{ll}| < \frac{1}{2})}{N(|\Delta \Phi_{ll}| > \frac{1}{2}) + N(|\Delta \Phi_{ll}| < \frac{1}{2})}$$

- Discrepancy between data and NLO simulations ($\sim 3 \sigma$)
Measurement Strategy

- Object and Event Selection
- Kinematic Reconstruction of $t\bar{t}$ system
- Binned Measurements of Single Differential Cross-Sections
- Background Subtraction and Normalization
- Simultaneous Unfolding of the Distributions using TUnfold to Correct for Migration and Acceptance
  - Obtain Parton-level, Normalized Differential Cross-Sections Extrapolated to the Full Phase Space
- Extraction of the $A_{\Delta\phi_{ll}}$, B, C, and D Coefficients
- Interpretation: Comparison to SM Simulation, EFT, SUSY
Signal, Backgrounds, and Event Yields

Signal:
\[ t\bar{t} \rightarrow (b\ell^+\nu_\ell)(\bar{b}\ell^-\bar{\nu}_\ell) \]
- Two charged leptons (\( e^+e^- \) or \( e^\pm\mu^\mp \) or \( \mu^+\mu^- \)) originating from W boson decays, but not from \( \tau \) decays
- Two jets originating from the hadronization of b-quarks (b-jets)
- Large \( E_T^{miss} \)

Main Backgrounds:
- \( t\bar{t} \) events with leptonically decaying \( \tau \) leptons (\( t\bar{t} \) other)
- Single top quarks produced in association with a W boson (\( tW \))
- \( Z/\gamma^* \) bosons produced with additional jets (\( Z+\)jets)

Other Backgrounds:
- W boson production with additional jets (\( W+\)jets)
- Diboson events (\( WW, ZZ, WZ \))
- production of \( t\bar{t} \) in association with \( W \) or \( Z \) boson (\( t\bar{t}+W/Z \))

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t\bar{t} ) Signal</td>
<td>0.788</td>
</tr>
<tr>
<td>( t\bar{t} ) Other</td>
<td>0.129</td>
</tr>
<tr>
<td>( tW )</td>
<td>0.034</td>
</tr>
<tr>
<td>( Z+)jets</td>
<td>0.043</td>
</tr>
<tr>
<td>Other</td>
<td>0.006</td>
</tr>
<tr>
<td>Total MC</td>
<td>1</td>
</tr>
<tr>
<td>Data</td>
<td>0.977</td>
</tr>
</tbody>
</table>

CMS 2016 Data at \( \sqrt{s} = 13 \text{ TeV} \)
\( \mathcal{L} = 35.9 \text{ fb}^{-1} \)
Unfolding with TUnfold

- Need to correct measured distributions for **Migration** and **Acceptance** before comparing to theoretical calculations

\[ \mathbf{x} = \mathbf{M} \cdot \mathbf{A} \cdot \mathbf{\hat{y}} \] to be inverted with regularization  
\[ \mathbf{x} : \text{Measured Bins} \quad \mathbf{\hat{y}} : \text{True Bins} \]

- Statistical extrapolation from fiducial phase space to full phase space

- Suppress statistical fluctuations by regularizing the difference between the unfolded distribution and the gen-level MC distribution of measured bins with respect to the SM expectation

- The distributions we measure are of particularly simple form at parton-level, depending on only one spin coefficient:

\[
\text{i.e.} \quad \frac{1}{\sigma d(\cos \theta_1 \cos \theta_2)} = \frac{1}{2} \left[ 1 - C_{ii}(\cos \theta_1^i \cos \theta_2^i) \right] \ln \left| \frac{1}{\cos \theta_1^i \cos \theta_2^i} \right|
\]

- By multiplying the density by an appropriate factor before regularizing, i.e. \( \left( \ln \frac{1}{| \cos \theta_1^i \cos \theta_2^i |} \right)^{-1} \), we can make the variation with respect to the coefficient exactly linear and therefore the regularization cannot bias the measured coefficient

- Use 6 uniform bins for each distribution, roughly matching the reconstruction resolution
## Systematic Uncertainties

### Experimental

- Background Cross Section: \( \sim 6\% \)
- Jet Energy Scale: \( \sim 4\% \)
- B-Tagging: \( \sim 1\% \)
- Kinematic Reconstruction Efficiency: \( \sim 1\% \)
- Lepton ID and Selection: \( \sim 1\% \)
- Unclustered Energy: \( \sim 1\% \)
- Pile-up Reweighting: \( \sim 0.5\% \)
- Jet Energy Resolution: \( \sim 0.5\% \)
- Trigger Efficiency: \( \sim 0\% \)
- (Luminosity and Branching Fraction)

### Theoretical

- b-fragmentation: \( \sim 5\% \)
- Scales (\( \mu_R \) and \( \mu_F \)): \( \sim 4\% \)
- Top \( p_T \): \( \sim 3\% \)
- UE-tune: \( \sim 3\% \)
- PDF (replicas and \( \alpha_s \)): \( \sim 2\% \)
- Color reconnection: \( \sim 2\% \)
- ME-PS matching: \( \sim 1\% \)
- Semi-leptonic BRs of b hadrons: \( \sim 0\% \)
- Top Mass: \( \sim 0\% \)
- \( \alpha_s \) for ISR and FSR: \( \sim 0\% \)
Results:

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \varphi} = \frac{1}{2} (1 + D \cos \varphi)
\]

\[
\cos \varphi = \hat{l}_1 \cdot \hat{l}_2
\]

\[
D = -\frac{Tr(\tilde{C})}{3} = -\frac{1}{3} [C_{kk} + C_{rr} + C_{nn}]
\]

Most precise single variable!
Dominant systematics: Background and Top $p_T$ modelling

\[
D = -0.237 \pm 0.007 \pm 0.009
\]

SM NLO: -0.243
Results:

\[
\frac{1}{\sigma} \frac{d\sigma}{d(\cos \theta_1^k \cos \theta_2^k)} = \frac{1}{2} \left[ 1 - C_{kk}(\cos \theta_1^k \cos \theta_2^k) \right] \ln \left| \frac{1}{\cos \theta_1^k \cos \theta_2^k} \right|
\]

Spin correlations measurements are consistent with SM expectations.

Dominant systematics: Background & JES

\[ C_{kk} = 0.30 \pm 0.02 \pm 0.03 \]

SM NLO: 0.33
Results:

\[
\frac{1}{\sigma} \frac{d\sigma}{d \cos \theta_1^k} = \frac{1}{2} (1 + B_1^k \cos \theta_1^k)
\]

Not yet sensitive to the small level of polarization in the SM

Dominant systematics: JES, b-quark fragmentation, and Background

\(B_1^k = 0.005 \pm 0.010 \pm 0.021\)

SM NLO: 0.004 \(\pm 0.0017 \pm 0.0012\)
Results: \( |\Delta \phi_{UU}| = \left| \left| \phi_{\ell_1} - \phi_{\ell_2} \right| - \pi \right| - \pi \) to measure \( A_{\Delta \phi_{UU}} = \frac{N(|\Delta \phi_{UU} | > \pi/2) - N(|\Delta \phi_{UU} | < \pi/2)}{N(|\Delta \phi_{UU} | > \pi/2) + N(|\Delta \phi_{UU} | < \pi/2)} \)

CMS observes a similar, but reduced, discrepancy in \( |\Delta \phi_{UU}| \) as ATLAS. Dominant systematics: ME-PS Matching and Top \( p_T \) modelling

\[
A_{\Delta \phi_{UU}} = 0.103 \pm 0.003 \pm 0.007 \\
\text{SM NNLO: } 0.115 \pm 0.005 \pm 0.001
\]
Results Summary:Measured Observables and Coefficients

- **$C_{kk}$**: $0.300 \pm 0.022 \pm 0.031$
- **$-D$**: $0.237 \pm 0.007 \pm 0.009$
- **$A_{\Delta \phi_{\parallel}}$**: $0.103 \pm 0.003 \pm 0.007$

The CMS analysis includes measurements for $C_{kk}$, $-D$, and $A_{\Delta \phi_{\parallel}}$. The plots show comparisons between data and various calculations, with error bars indicating statistical and systematic uncertainties.
Results Summary: Measured Observables and Coefficients
Constraining the Top Quark Anomalous CMDM Operator Coefficient

Several models of physics Beyond SM (BSM) predict an anomalous top quark Chromo-Magnetic Dipole Moment (CMDM) that would induce top chirality flips affecting spin structure and kinematic properties of $t\bar{t}$ events.

$\chi^2$ minimization technique to constrain $\frac{c_{tG}}{\Lambda^2}$ Wilson coefficient of CMDM operator:

$$\chi^2 \left( \frac{c_{tG}}{\Lambda^2} \right) = \sum_{i=1}^{N} \sum_{j=1}^{N} (\text{data}_i - \text{pred}_i) \cdot (\text{data}_j - \text{pred}_j) \cdot \text{Cov}_{i,j}^{-1}$$

Best fit value: $\frac{c_{tG}}{\Lambda^2} = 0.04$ TeV$^{-2}$

95% confidence level limits on $\frac{c_{tG}}{\Lambda^2}$ from simultaneous fit to measured differential cross sections:

$-0.07 < \frac{c_{tG}}{\Lambda^2} < 0.16$ TeV$^{-2}$

Strongest direct constraint to date!
Summary

- First direct measurements at 13 TeV of all spin-dependent coefficients of the $t\bar{t}$ production density matrix are in close agreement with SM predictions.
- Tensions between measured $|\Delta \phi_{t\bar{t}}|$ distribution and NLO MC predictions reduced, but still substantial, with NNLO corrections.
- Precision $t\bar{t}$ spin density matrix measurements are a powerful probe of BSM physics in $t\bar{t}$ production:
  - Simultaneous fit for constraint on top quark anomalous CMDM operator coefficient $c_{tG}/\Lambda^2$.
  - EFT Interpretation: Sensitive to 10 out of the 11 independent dimension-6 operators relevant for hadronic $t\bar{t}$ production.
  - SUSY Interpretation: Limits on light stop squark production.
Helicity Angle

- Helicity angle of a lepton is calculated from the angle between:
  - the lepton momentum in the rest frame of its parent top (primed)
  - the top momentum in the $t\bar{t}$ rest frame (not primed)

\[
\cos \theta_{l^+} = \frac{\vec{p}_{l^+} \cdot \vec{p}_t}{|\vec{p}_{l^+}| |\vec{p}_t|} \quad \cos \theta_{l^-} = \frac{\vec{p}_{l^-} \cdot \vec{p}_t}{|\vec{p}_{l^-}| |\vec{p}_t|}
\]

- Helicity basis is stable with regard to reconstruction errors

- Helicity angle of a lepton can be expressed in terms of Lorentz- invariant quantities:

\[
\cos \theta = \frac{2[m_t^2 (p_t p_{t\bar{t}}) - (p_t p_{t\bar{t}})(p_t p_{\bar{t}})]}{\hat{s} \sqrt{1 - 4m_t^2} / \hat{s} \sqrt{(p_t p_{\bar{t}})^2 - m_t^2 m_{\bar{t}}^2}}
\]

The scalar product of the three vectors $\vec{p}_{l^+}$ & $\frac{\vec{p}_t}{|\vec{p}_t|}$ and the product of the four vectors $(0, \frac{\vec{p}_t}{|\vec{p}_t|})$ & $(E_{l^+}', \vec{p}_{l^+}')$ are identical.
evaluated in the \( t \) ZMF

\( \hat{\ell}^1 \)

i.e. the \( t \) helicity angle

\( \theta_{k}^1 \)

\( \vec{p}_t \) in \( tt \) ZMF

\( \hat{k} \)

\( \Theta = t \) scattering angle

\( \hat{n} \)

\( \perp \) to \( k \) within the \( pp \to tt \) scattering plane

\( \perp \) to the scattering plane

\( \vec{t} \)
Expanding $\tilde{B}^\pm_i$ and $\tilde{C}_{ij}$ in terms of the orthonormal basis $\{\hat{k}, \hat{r}, \hat{n}\}$

$$\tilde{B}^\pm_i = b^\pm_{ik} \hat{k}_i + b^\pm_{ir} \hat{r}_i + b^\pm_{in} \hat{n}_i$$

$$\tilde{C}_{ij} = c_{kk} \hat{k}_i \hat{k}_j + c_{nn} \hat{n}_i \hat{n}_j + c_{rr} \hat{r}_i \hat{r}_j$$

$$+ c_{rk} (\hat{r}_i \hat{k}_j + \hat{k}_i \hat{r}_j) + c_{nr} (\hat{n}_i \hat{r}_j + \hat{r}_i \hat{n}_j) + c_{rn} (\hat{k}_i \hat{n}_j + \hat{n}_i \hat{k}_j)$$

$$+ c_{nk} (\hat{k}_i \hat{n}_j - \hat{n}_i \hat{k}_j) + c_{nr} (\hat{n}_i \hat{r}_j - \hat{r}_i \hat{n}_j) + c_{rk} (\hat{k}_i \hat{r}_j - \hat{r}_i \hat{k}_j)$$

Coefficients are functions of the partonic CM energy and $\cos \Theta$

Large values are only allowed for the P and CP even spin correlations: $c_{kk}, c_{rr}, c_{nn}, c_{rk}$

Any deviation from these expectations would be a sign of BSM production phenomena
\( \bar{t}t \rightarrow bW^+\bar{b}W^- \rightarrow b\ell^+\nu_\ell \bar{b}\ell^-\bar{\nu}_\ell \): Double Differential Distributions

- Normalized fourfold angular distributions for the two leptons (each measured in its parent top quark rest frame):

\[
\frac{1}{\sigma} \frac{d\sigma}{d\Omega_1 d\Omega_2} = \frac{1}{(4\pi)^2} (1 + \vec{B}_1 \cdot \hat{\ell}_1 + \vec{B}_2 \cdot \hat{\ell}_2 - \hat{\ell}_1 \cdot \vec{C} \cdot \hat{\ell}_2)
\]

  Charged lepton directions of flight in the \( t \) and \( \bar{t} \) rest frames respectively

- \( B^i_1 \) and \( B^i_2 \), the top quark and antiquark polarization coefficients with respect to each reference axis \( i \) (sensitive to \( \vec{B}^+_i \) and \( \vec{B}^-_i \))

- \( C_{ii} \), the “diagonal” spin correlation coefficient for each reference axis \( i \) (sensitive to \( \vec{C}_{ij} \))

- \( C_{ij} \), the “cross” spin correlation coefficient for each pair of axes \( i \neq j \) (the sums and differences \( C_{ij} \pm C_{ji} \) are sensitive to \( \vec{C}_{ij} \))
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

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

\[ 1.44 < |\eta_{cluster}| < 1.57 \text{ excluded in ECAL}, \text{ Identification requirements}, \]

\[ m_{l+/-l} < 20 \text{ GeV} \text{ and } 76 < m_{ll} < 106 \text{ GeV excluded} \]

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

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

**\( E_T^{miss} \):** \[ p_T^{miss} > 40 \text{ GeV} \]
Kinematic Reconstruction

- The four momenta of the two neutrinos in the decay are needed to full reconstruct top quark four momenta.

- Analytical solutions are obtained by applying six kinematic constraints:

\[
E_x^{\text{miss}} = p_{x,v} + p_{x,\bar{v}} \\
E_y^{\text{miss}} = p_{y,v} + p_{y,\bar{v}}
\]

\[
m_{W^+}^2 = (E_{l^+} + E_v)^2 - (p_{x,l^+} + p_{x,v})^2 - (p_{y,l^+} + p_{y,v})^2 - (p_{z,l^+} + p_{z,v})^2
\]

\[
m_{W^-}^2 = (E_{l^-} + E_{\bar{v}})^2 - (p_{x,l^-} + p_{x,\bar{v}})^2 - (p_{y,l^-} + p_{y,\bar{v}})^2 - (p_{z,l^-} + p_{z,\bar{v}})^2
\]

\[
m_t^2 = (E_{l^+} + E_v + E_b)^2 - (p_{x,l^+} + p_{x,v} + p_{x,b})^2 - (p_{y,l^+} + p_{y,v} + p_{y,b})^2 - (p_{z,l^+} + p_{z,v} + p_{z,b})^2
\]

\[
m_{\bar{t}}^2 = (E_{l^-} + E_{\bar{v}} + E_{\bar{b}})^2 - (p_{x,l^-} + p_{x,\bar{v}} + p_{x,\bar{b}})^2 - (p_{y,l^-} + p_{y,\bar{v}} + p_{y,\bar{b}})^2 - (p_{z,l^-} + p_{z,\bar{v}} + p_{z,\bar{b}})^2
\]

- Reconstruct each event 100 times smearing W mass, jet and lepton directions and energies by their resolutions.

- Take the top 4-momenta solution as a weighted average of all the solutions for all smearing.

- All lepton-jet combinations are tried, and the one with highest sum of weights is chosen (preferring the one with most b-tags); this selects the one most likely based on kinematics.
Event Yields after Selection and Kinematic Reconstruction

- Yields for the 3 dilepton channels and combined:

<table>
<thead>
<tr>
<th></th>
<th>$e^+e^-$</th>
<th>$e^\pm\mu^\mp$</th>
<th>$\mu^+\mu^-$</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$ Signal</td>
<td>26,764.7</td>
<td>124,539</td>
<td>54,873.5</td>
<td>206,177</td>
</tr>
<tr>
<td>$t\bar{t}$ Other</td>
<td>4,147.05</td>
<td>20,356.6</td>
<td>9,137.69</td>
<td>33,641.3</td>
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<tr>
<td>Single $t$</td>
<td>1,142.39</td>
<td>5,490.33</td>
<td>2,257.13</td>
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<tr>
<td>$Z$+jets</td>
<td>3,135.8</td>
<td>1,305.76</td>
<td>6,881.75</td>
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</tr>
<tr>
<td>Other</td>
<td>227.22</td>
<td>875.22</td>
<td>461.89</td>
<td>1,564.33</td>
</tr>
<tr>
<td>Total MCs</td>
<td>35,417.2</td>
<td>152,567</td>
<td>73,612</td>
<td>261,585</td>
</tr>
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<td>Data</td>
<td>34,890</td>
<td>150,410</td>
<td>70,346</td>
<td>255,646</td>
</tr>
</tbody>
</table>

- Data/MC agreement within uncertainties

- Fraction of Signal events in simulation: 79%
$f_{SM}$ Results

![Graph showing CMS results with standard model and data points for $C_{kk}$, $D$, and $A_{L\Delta\varphi, l}$.]