Spin correlation and W helicity in top events with CMS

Haryo Sumowidagdo

on behalf of CMS Collaboration

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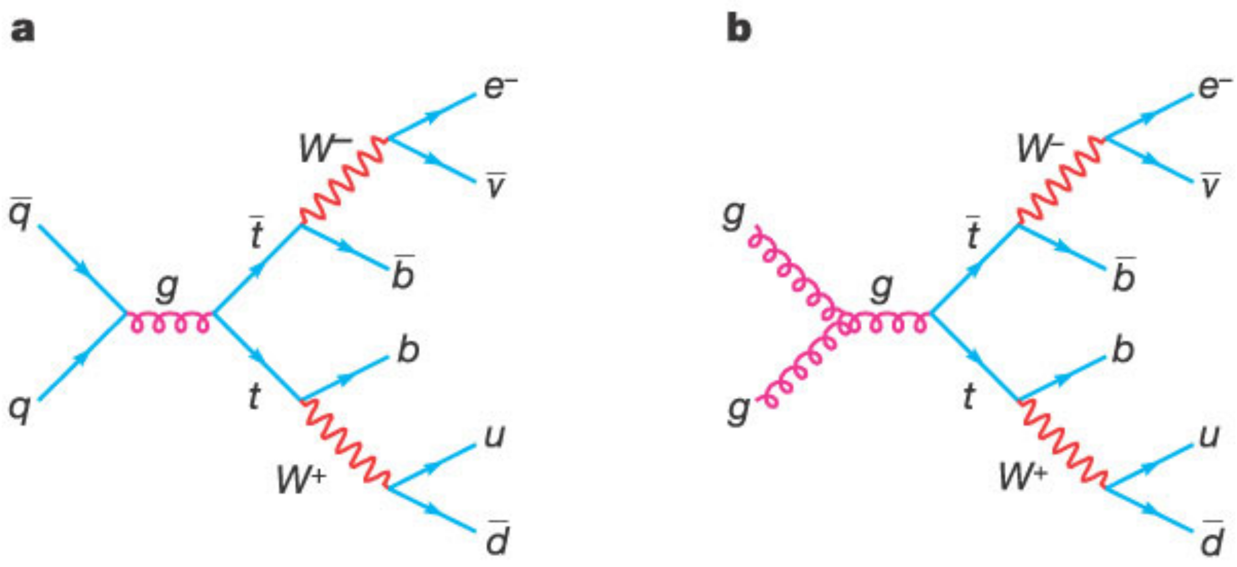
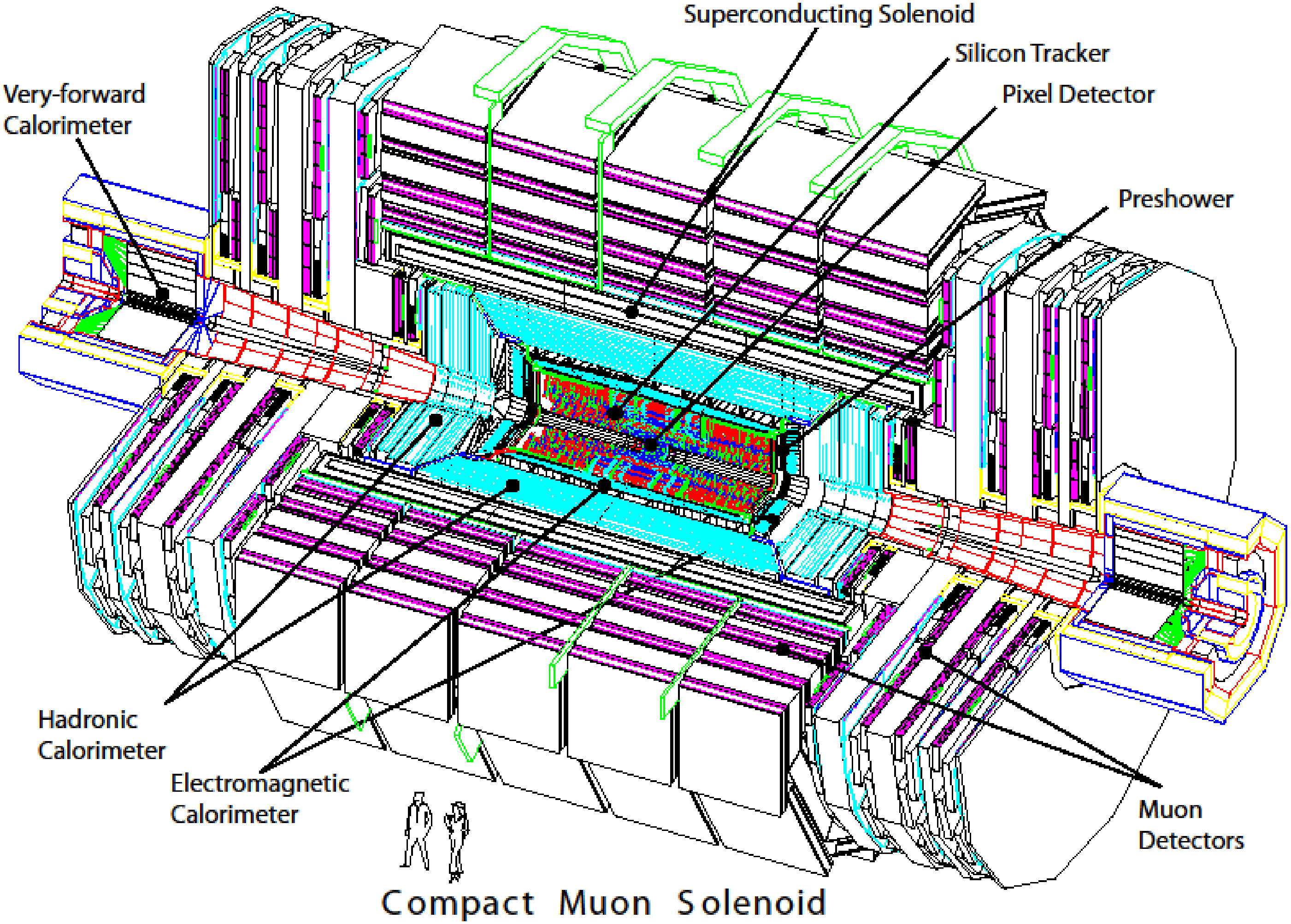
Motivation

- Top quarks have a very short lifetime.
  - Spin information of the top quark is transferred into its decay products.
  - W helicity: The helicity fraction of W bosons from top decays is sensitive to new physics Wtb vertex.
  - Spin correlation: Assuming Standard Model (SM) decay of top quarks, can infer the (non)-existence of spin correlation in ttbar pair -> Probing new physics at the production.



The CMS Detector



W Helicity

- SM predicts accurately the transverse (F_0), left-longitudinal (F_L) and right-longitudinal (F_R) polarization of W boson from top decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = \frac{3}{8}(1-\cos\theta^*)^2 F_L + \frac{3}{8}(1+\cos\theta^*)^2 F_R + \frac{3}{4}\sin^2\theta^* F_0$$

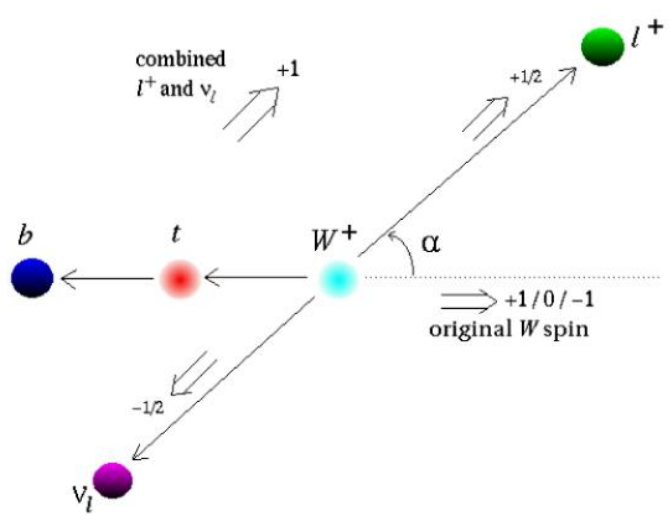


Figure 2. Spins in the W^+ rest frame. The W's helicity from the top frame is preserved as the spin in the right-hand direction. The helicities of the W's decay products are fixed by the weak force and constitute a +1 spin projection in the direction of the l^+, at polar angle α from the original spin axis.

- Measurement is done in the muon+jets channel with 2.2 fb^{-1} of data:
  - The selection follows lepton +jets cross-section with looser muon isolation to reduce the bias at cos θ^* near -1.
  - The complete event kinematics is reconstructed with a kinematic fit.

Monte Carlo Reweighting

- Any helicity configuration can be generated by reweighting on event-by-event basis.
  - At the generator level for a specific helicity configuration, it is assumed the distribution is given by

$$\rho(\cos\theta^*_{gen}) \equiv \frac{1}{N}\frac{dN}{d\cos\theta^*_{gen}} = \frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2$$

  - The weight applied for each event generated with SM fractions thus

$$W(\cos\theta^*_{gen};\vec{F}) \equiv \frac{\rho(\cos\theta^*_{gen})}{\rho^{SM}(\cos\theta^*_{gen})} = \frac{\frac{3}{8}F_L(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0\sin^2\theta^*_{gen} + \frac{3}{8}F_R(1+\cos\theta^*_{gen})^2}{\frac{3}{8}F_L^{SM}(1-\cos\theta^*_{gen})^2 + \frac{3}{4}F_0^{SM}\sin^2\theta^*_{gen} + \frac{3}{8}F_R^{SM}(1+\cos\theta^*_{gen})^2}$$

  - Reconstruction effects and efficiencies are automatically taken into account.

- Fit parameter is **F** = (F_0, F_L, F_R)

Helicity fitting

- Simultaneously fit F_0, F_L and f_{top} (fraction of ttbar events in the data sample)
  - Extract the F_R by constraining the sum of **F** to be 1.
- Define a likelihood function

$$\mathcal{L}(\vec{F}) = \prod_{bin\ i} \frac{N_{MC}(i;\vec{F})^{N_{data}(i)}}{(N_{data}(i))!} \exp\left(-N_{MC}(i;\vec{F})\right),$$

where the various components are defined as:

$$\begin{aligned} \mathrm{N}_{\mathrm{MC}}(i,\vec{F}) &= \mathrm{N}_{\mathrm{BKG}}(i) + \mathrm{N}_{\mathrm{t\bar{t}}}(i;\vec{F}) \\ \mathrm{N}_{\mathrm{t\bar{t}}}(i;\vec{F}) &= \mathcal{F}_{\mathrm{t\bar{t}}} \left[\sum_{\mathrm{t\bar{t}\ events,\ bin}\ i} W(\cos\theta^*_{gen};\vec{F}) \right] \\ \mathrm{N}_{\mathrm{BKG}}(i) &= \mathrm{N}_{\mathrm{W+jets}}(i) + \mathrm{N}_{\mathrm{Drell-Yan+jets}}(i) + \mathrm{N}_{\mathrm{QCD}}(i) + \mathrm{N}_{\mathrm{Single-Top}}(i) \end{aligned}$$

- With MC sample size much larger than data sample, statistical uncertainty is dominated by data.

Results

- Fitting simultaneously F_0, F_L and f_{top} yields:

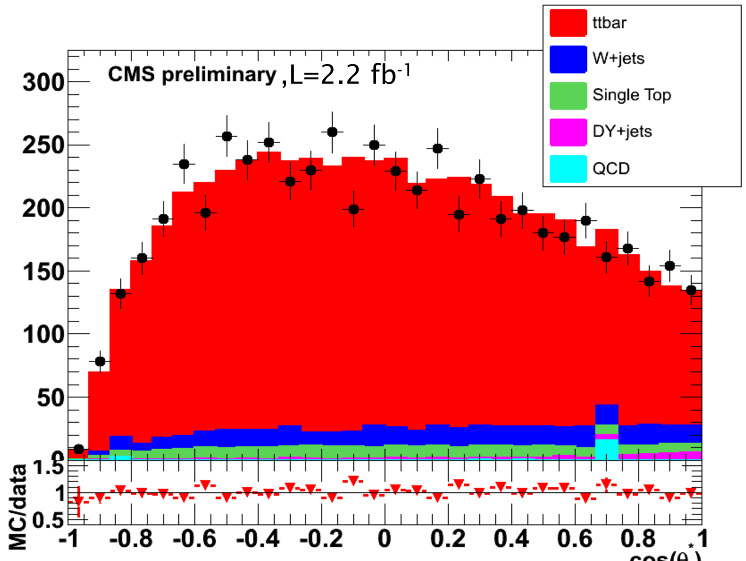
$$F_0 = 0.567 \pm 0.074(\text{stat.}) \pm 0.047(\text{syst.})$$
$$F_L = 0.393 \pm 0.045(\text{stat.}) \pm 0.029(\text{syst.})$$

and

$$F_R = 0.040 \pm 0.035\ (\text{stat.}) \pm 0.044(\text{syst.})$$

- Fitting F_0 and f_{top} with $F_R = 0$.

$$F_0 = 0.643 \pm 0.034(\text{stat.}) \pm 0.050(\text{syst.})$$



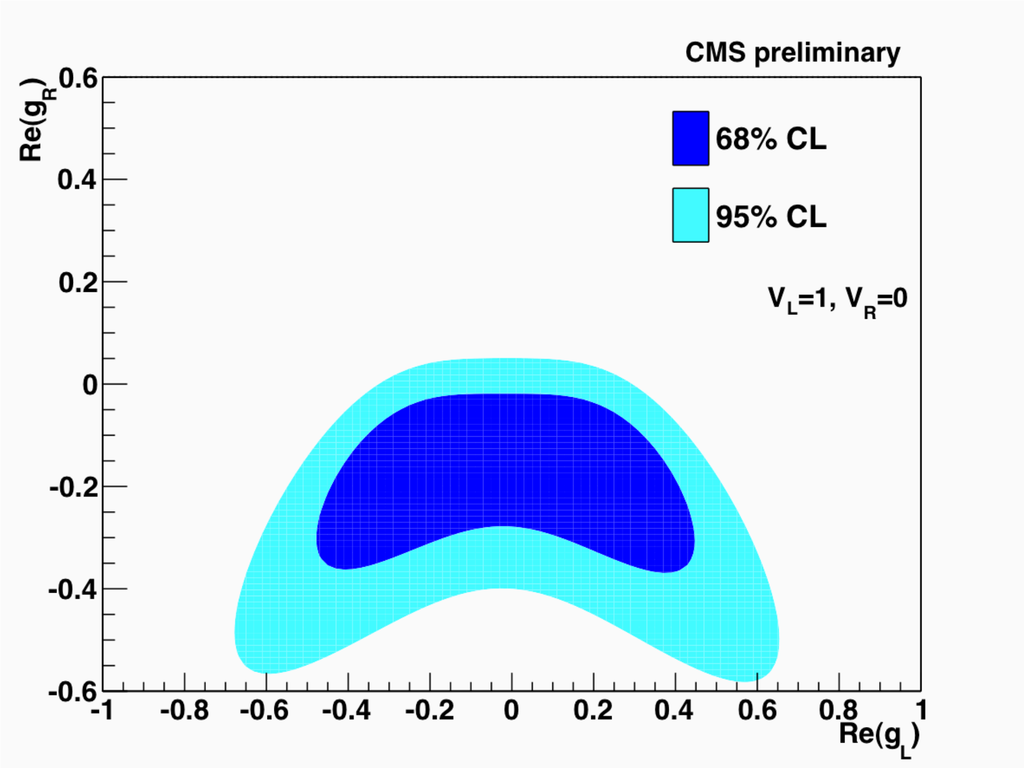
Systematic uncertainties on W helicity

Systematic check	Fitting F_0, F_L and $\mathcal{F}_{t\bar{t}}$ **3D fit**		Fitting F_0 and $\mathcal{F}_{t\bar{t}}$ **2D fit**
	$\pm$ Uncertainty F_0	$\pm$ Uncertainty F_L	$\pm$ Uncertainty F_0
b-Tag ($\frac{\epsilon^{DATA}_{b-tag}}{\epsilon^{MC}_{b-tag}}$)	0.007	0.009	0.010
QCD Norm	0.007	0.002	0.003
Single-t Norm	0.003	0.007	0.010
DY Norm	0.018	0.003	0.010
W+jet Norm	0.020	0.006	0.029
muon (no $\frac{\epsilon^{DATA}_{\mu}}{\epsilon^{MC}_{\mu}}$)	0.002	0.003	0.003
PDF	0.001	0.001	0.002
JES scale	0.018	0.011	0.005
top Q^2 scale	0.014	0.007	0.021
DY,W Q^2 scale	0.022	0.003	0.014
top mass (± 3 GeV/c^2)	0.019	0.021	0.025

Table 2: Summary of the systematic uncertainties, on the **3D fit** analysis, fitting F_0, F_L and $\mathcal{F}_{t\bar{t}}$ (columns 2-3) and on the **2D fit** analysis, fitting F_0 and $\mathcal{F}_{t\bar{t}}$ only (column 4). The numbers given correspond to the absolute uncertainty with respect to the central analysis: $(F^{central} - F^{check})$.

Limits on anomalous couplings

- Following notation of J.A. Aguilar-Saavedra (NPB 812, 181 and NPB 821, 215) with $Re(g_L)$ and $Re(g_R)$ as free parameters of the fit.
- Regions disfavored by CMS single top measurement is excluded.



Spin correlation in top quark-antiquark

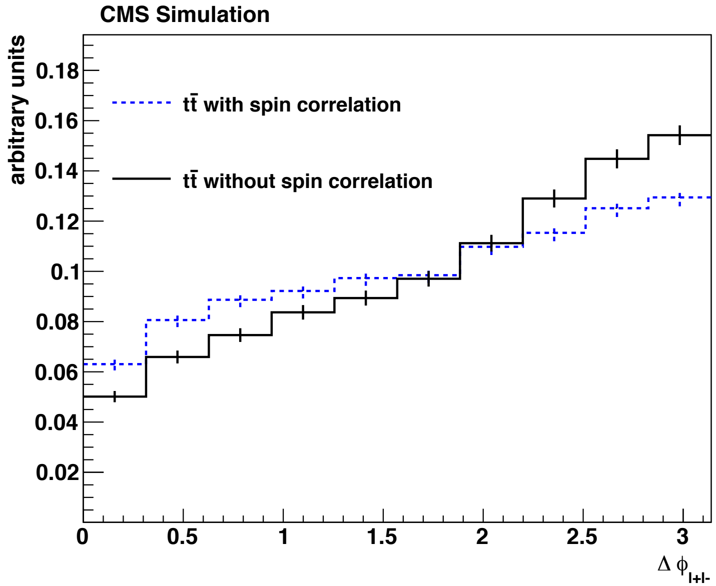
- Given an arbitrary spin quantization axis, the spin correlation coefficient is defined as:

$$A = \frac{N(\uparrow\uparrow) + N(\downarrow\downarrow) - N(\downarrow\uparrow) - N(\uparrow\downarrow)}{N(\uparrow\uparrow) + N(\downarrow\downarrow) + N(\downarrow\uparrow) + N(\uparrow\downarrow)}$$

- It is not a parameter in the Lagrangian.
  - Depends on top quark mass, colliding initial state, collisions energy, production and decay mechanism of the top quark.
- CMS performs two measurements in the dilepton channels with full 2011 dataset of 5.0 fb^{-1}, CMS-PAS-TOP-12-004.
  - $\Delta\varphi$ measurement, using the absolute difference in azimuthal angle between the two charged leptons. Follows suggestion from Mahlon & Parke (PRD 81, 074024)
  - Direct asymmetries measurement using full event reconstruction. Look specifically into higher mass region per suggestion of Krohn et al (PRD 84, 074034). Related to CMS Analysis CMS-TOP-12-016.
  - Selection and background estimation is identical with ttbar cross-section and mass measurements in the dilepton channels (ee, $\mu\mu$,eμ)

$\Delta\varphi_{l+l-}$ analysis

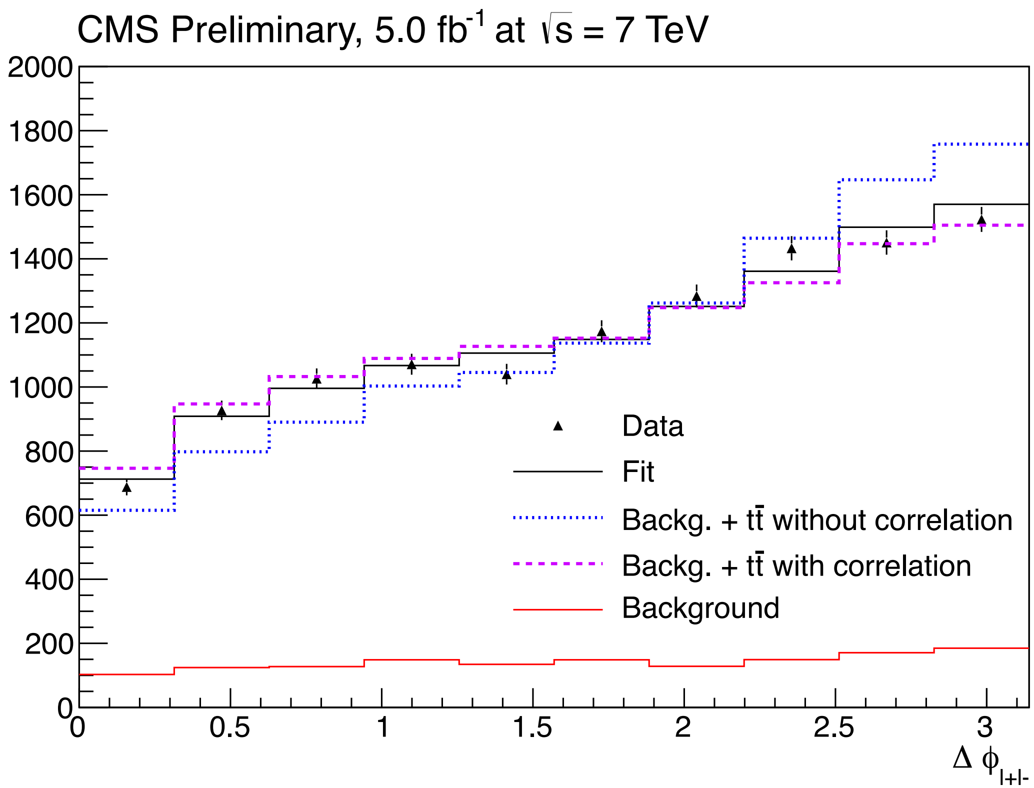
- Fit the $\Delta\varphi_{l+l-}$ between the two charged leptons. No full event kinematics reconstruction is necessary.
- Fit templates:
  - MC@NLO ttbar with and without spin correlations.
  - Background subtraction: combination of MC shape and data-driven yield estimation.
- Fit parameters: Number of ttbar events in each individual channel ee, μμ,eμ and an overall fraction of ttbar with spin correlation.
- Calibration and linearity check using pseudo-experiment confirm the validity of fit procedure.
  - Considered fraction ranges from -1 to 2.
  - Width of the pull distribution is within 10% of unity.



Fit results

- The fitted fraction of ttbar with spin correlation, f, is found to be

  $f = 0.74 \pm 0.08$ (stat) ± 0.24 (syst), correspond to
  $A = 0.24 \pm 0.02$ (stat) ± 0.08 (syst).
  (Expected $f = 1.0$, $A = 0.31$)



Systematics uncertainties on $\Delta\varphi_{l+l-}$

uncertainty Δf	absolute	relative (%)
statistic uncertainty	0.08	11%
MC stat uncertainty	0.07	9%
	experimental	
Lepton selection	0.01	1%
Lepton energy scale	0.01	1%
JES/JER	0.02	3%
all backgrounds	0.07	9%
PU	0.02	3%
b-tagging	0.01	1%
	$t\bar{t}$ modelling	
FastSim vs FullSim	0.06	8%
Fact. and renorm. scales	0.15	20%
τ decay	0.12	16%
top mass	0.02	3%
PDF	0.07	9%

Table 1: Uncertainty on the fraction of events with spin correlation Δf, as predicted by the fit.

Direct measurement of the asymmetry

- Using fully reconstructed events, directly measure the two following asymmetry coefficients

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

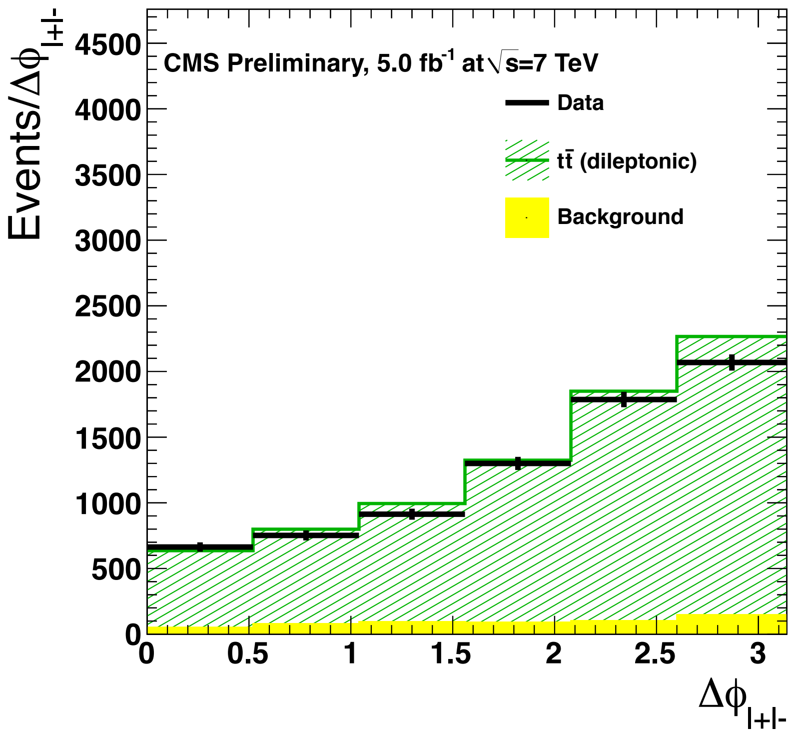
$$A_{c1c2} = \frac{N(\cos(\theta_l^+) \times \cos(\theta_l^-) > 0) - N(\cos(\theta_l^+) \times \cos(\theta_l^-) < 0)}{N(\cos(\theta_l^+) \times \cos(\theta_l^-) > 0) + N(\cos(\theta_l^+) \times \cos(\theta_l^-) < 0)}$$

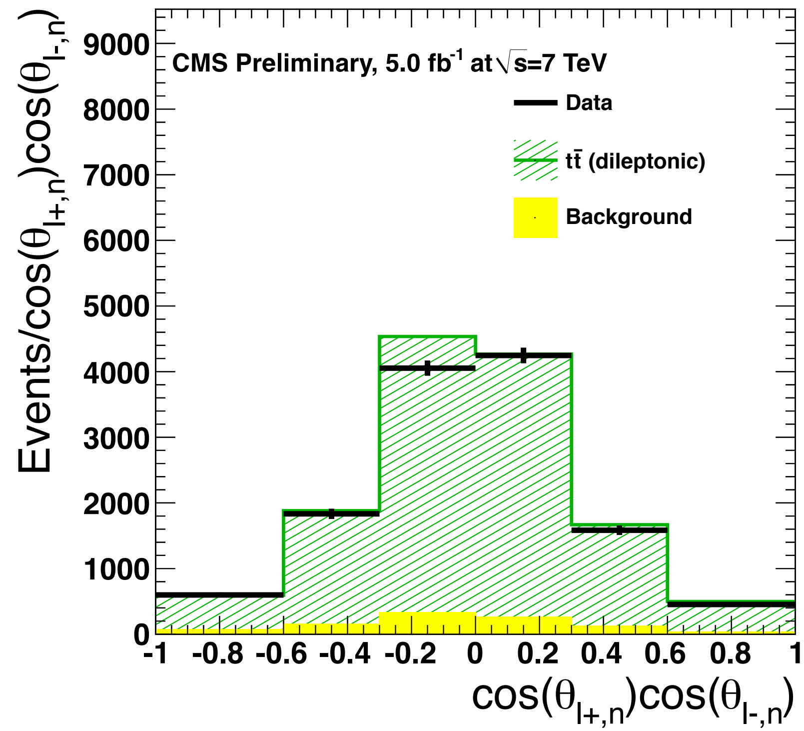
- The analytical matrix weighting technique (AMWT) from CMS top quark mass measurement in the dilepton channels is used.
- Reconstructed asymmetries are unfolded to the parton level.
  - Detailed discussion of unfolding is in CMS-TOP-12-016.
  - First look at Mttbar > 450 GeV before unfolding.
  - Unfolding then is done at the inclusive sample (without Mttbar cut to avoid bias).

Asymmetries at Mttbar > 450 GeV

- No deviation from SM prediction observed at high ttbar invariant mass in both distributions.

$A_{\delta\rho l+l-} = -0.378 \pm 0.019$ (stat) and
$A_{c1c2} = -0.019 \pm 0.016$ (stat).





Unfolding (CMS-TOP-12-016)

- Use a regularized unfolding algorithm based on Singular Value Decomposition, implemented in RooUnfold.
- Verified that the unfolding procedure can correctly unfold distributions with different levels of asymmetry.

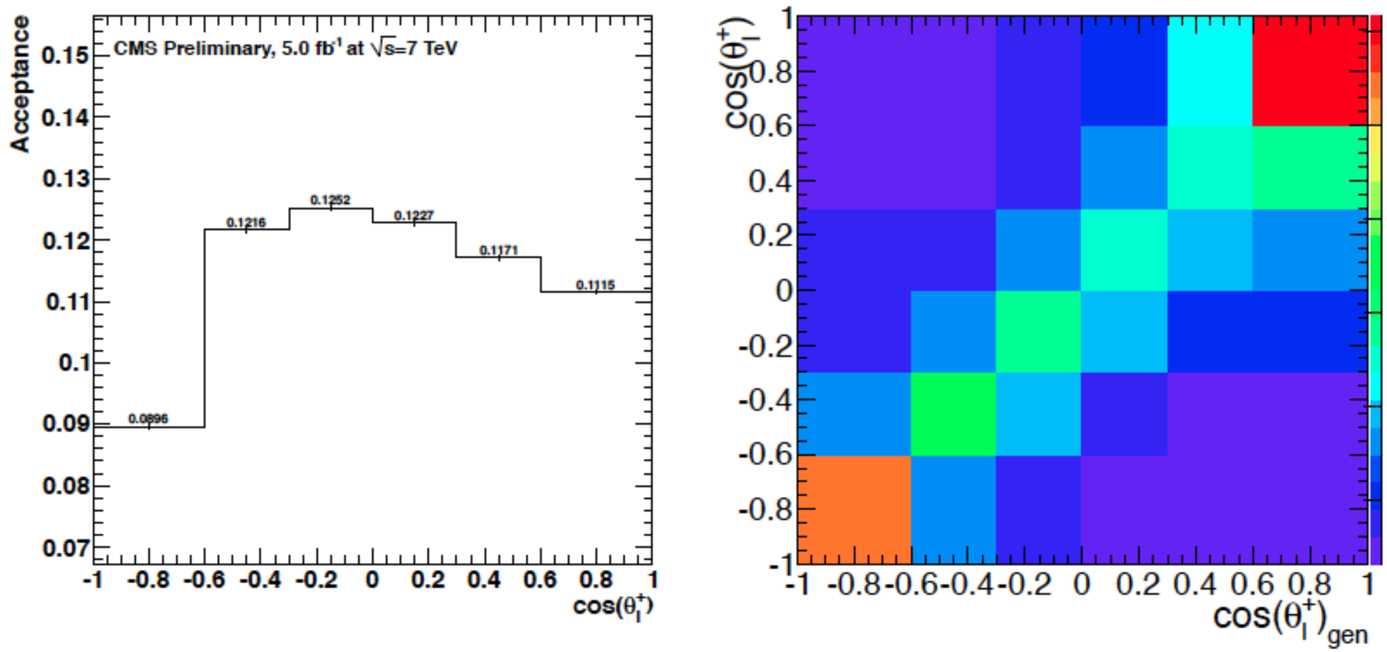
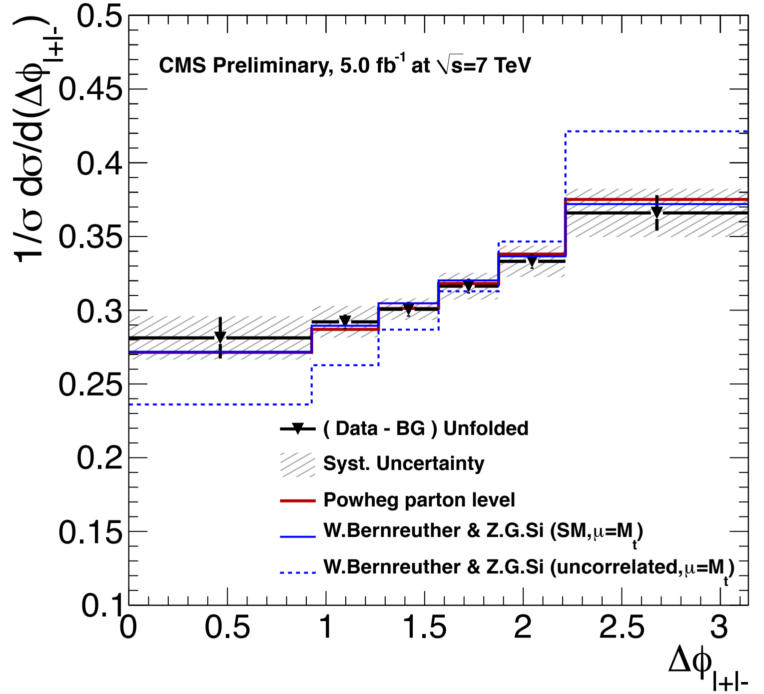


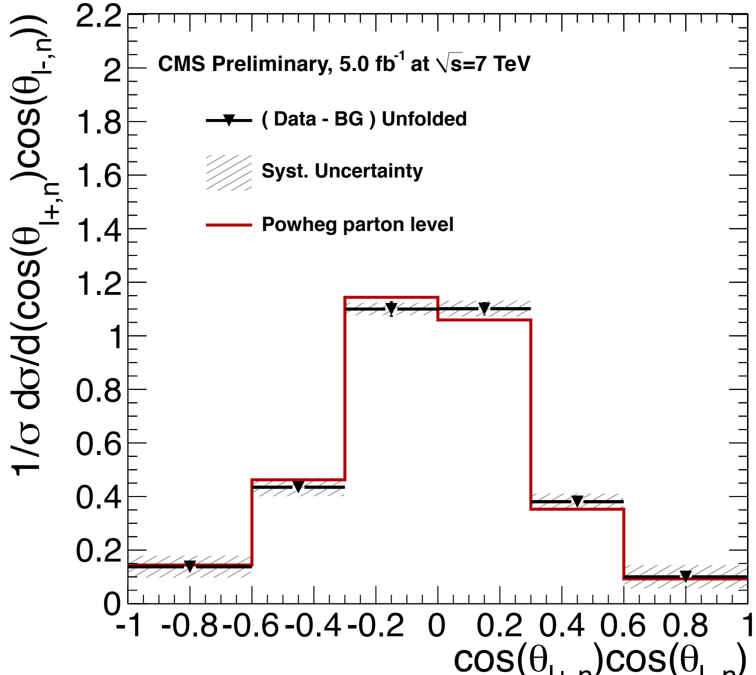
Figure 3: Acceptance matrix bins (left) and smearing effects due to the uncertainties of top reconstruction (right).

Unfolded asymmetries results

- The unfolded asymmetries results are measured to be

$$A_{\delta\rho l+l-} = -0.097 \pm 0.015\ (\text{stat}) \pm 0.036\ (\text{syst}), \text{ and}$$
$$A_{c1c2} = 0.015 \pm 0.037\ (\text{stat}) \pm 0.055\ (\text{syst}).$$





Systematic uncertainties on asymmetries

systematic	$A_{\Delta\phi}$	A_{c1c2}
statistic uncertainty	0.015	0.037
MC stat uncertainty	0.0004	0.0004
	experimental	
Lepton SF	0.0009	0.0002
Lepton energy scale	0.0009	0.0002
JES/JER	0.002	0.016
all backgrounds	0.002	0.010
PU	0.003	0.003
b-tagging	0.001	0.002
	$t\bar{t}$ modelling	
Fact. and renorm. scales	0.030	0.051
τ decay	0.016	0.002
top mass	0.002	0.005
PDF	0.009	0.001

Table 3: Uncertainty on the unfolded values of $A_{\Delta\phi}$ and A_{c1c2}

Top polarization (CMS-TOP-12-016)

- First direct measurement of θ_l^+, the direction of the positively charged lepton in the ttbar rest frame using the helicity spin basis.

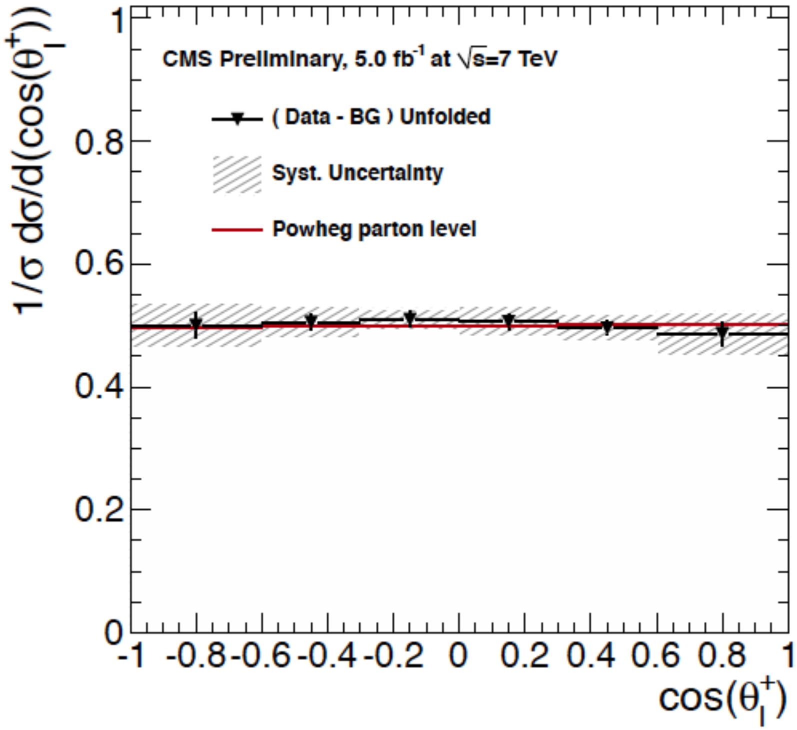


Figure 4: Background-subtracted and unfolded $\cos(\theta_l^+)$ distribution. The error bars represent statistical uncertainties only, while the systematic uncertainty band is represented by the hatched area. Note that the bin values are correlated due to the unfolding.

Summary

- LHC has become a top quark factory that enables precision measurements of top quark couplings and asymmetries.
- CMS first measurement of W helicity in top decays is already competitive with Tevatron's results.

$$F_R = 0.040 \pm 0.035\,(\text{stat.}) \pm 0.044(\text{syst.})$$

- Spin correlation in ttbar events is investigated in the dilepton channel:
  - Fraction of ttbar with spin correlation is measured to be:

    f = 0.74 ± 0.08 (stat) ± 0.24 (syst), correspond to
    A = 0.24 ± 0.02 (stat) ± 0.08 (syst).

  - No deviation observed on the asymmetries at high Mttbar region.

    $A_{\delta\rho l+l-} = -0.378 \pm 0.019$ (stat) and
    $A_{c1c2} = -0.019 \pm 0.016$ (stat).