Measurement of the $t\bar{t}$ spin correlations and top quark polarization in dileptonic channel

AJEETA KHATIWADA

PURDUE UNIVERSITY

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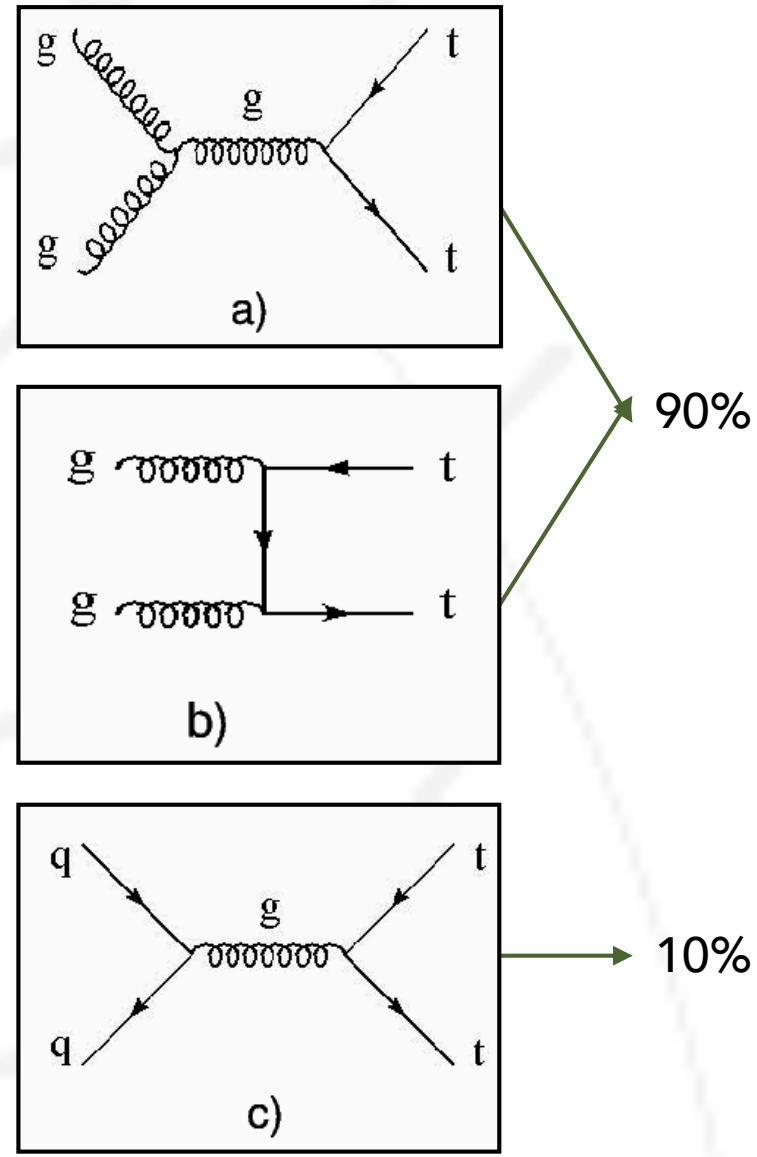
Introduction

- Heaviest fundamental particle: m_t = 173.34±0.76 GeV [arXiv: 1403.4427].
- Short lifetime ~10^{-25} s.
  - Decays before hadronization takes place.
  - Time taken for top quark to change its spin by radiating a gluon > lifetime of top. Spins cannot decorrelate and the spin info. gets passed on to decay particles.
- Special role in EWSB?: λ_t ~ 1.



Study of top properties:

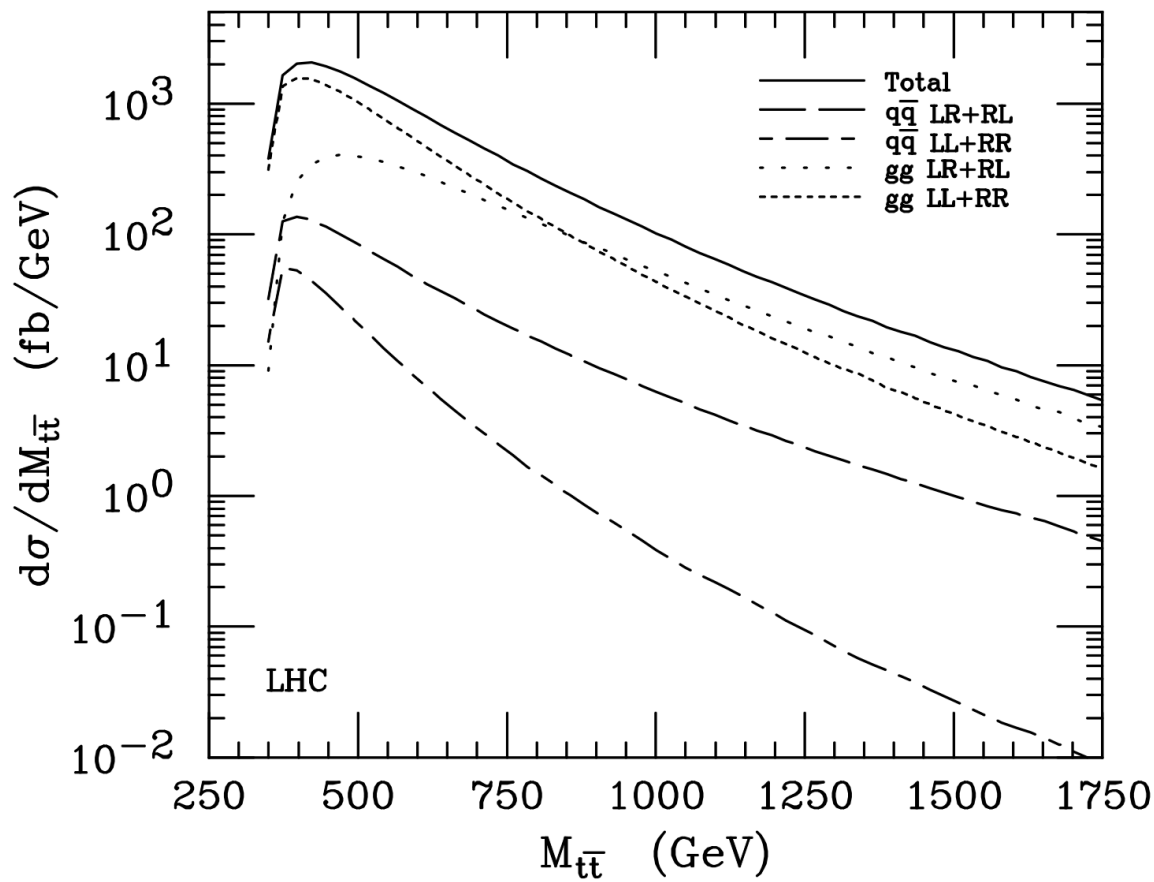
✦ provides precision test of top quark production and decay, and

✦ provides constraint for BSM models with resonances decaying to top and SUSY stops produced via similar mechanism as SM top.

Top quark spin correlation

- In SM: Top quarks produced by strong interaction are unpolarized but QCD causes top-quark spins to be correlated at production.

- BSM scenarios can also cause tops to be polarized in addition to modifying spin correlation.



Phys.Rev. D53 (1996) 4886-4896

At low(high) invariant mass, top anti-top pair production is dominated by like(unlike) helicity gluon fusion.

Probing the spin correlation

- The $t\bar{t}$ differential cross section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_+ d\cos\theta_-} = \frac{1}{4}\Big(1 + B_1\,\cos\theta_+ + B_2\,\cos\theta_- - C\,\cos\theta_+\cos\theta_-\Big)$$

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- $B_1, B_2,$ and C are the polarization and spin correlation in quantization axis $\hat{a}$ and $\hat{b}$.

$$C(\hat{\mathbf{a}},\hat{\mathbf{b}}) = \kappa_\ell^2\,\frac{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)-\sigma(\uparrow\downarrow)-\sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)+\sigma(\uparrow\downarrow)+\sigma(\downarrow\uparrow)}$$

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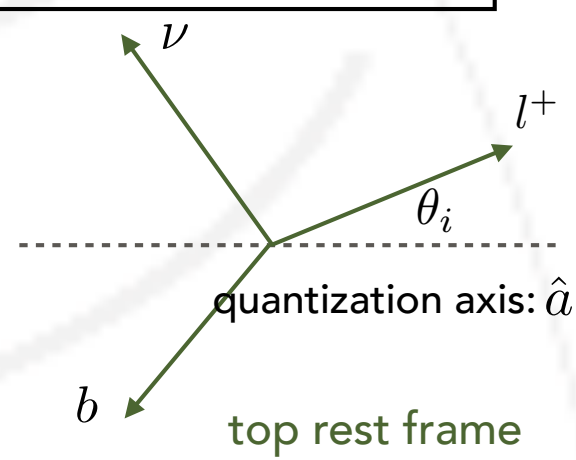
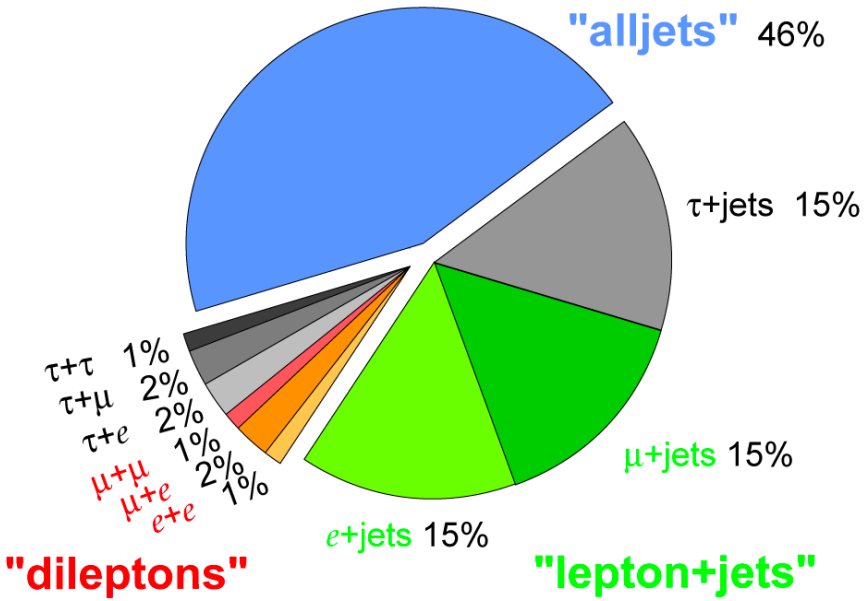
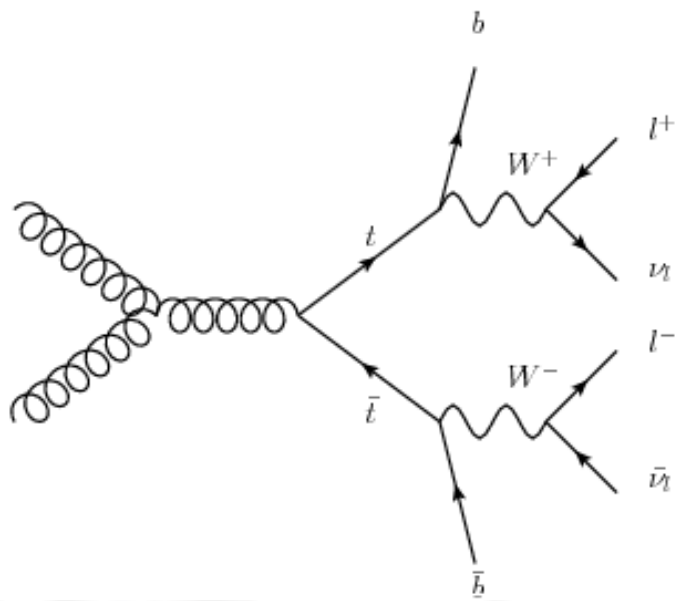
- κ_l is the spin analyzing power (of charged lepton). +1.0 for charged lepton/down quark, -0.41 for bottom quark, -0.31 for up quark and neutrino in top decays [Phys.Lett. B411 (1997) 173-179], [arXiv:hep-ph/9706304v1].
- θ_i is the angle between spin quantization direction and momentum of decay particle in the rest from of its parent top.



Top quark pair decay modes





- All-hadronic
  * Largest BR
  * Large QCD Background
  * Event fully constrained
- Semi-leptonic
  * High BR
  * Medium background
  * Event constrained
- Dileptonic
  * Small BR
  * S/B good
  * Event under-constrained

Small BR is okay - Large $\sigma_{t\bar{t}}$ at 13 TeV ~ 830 pb.

Observables

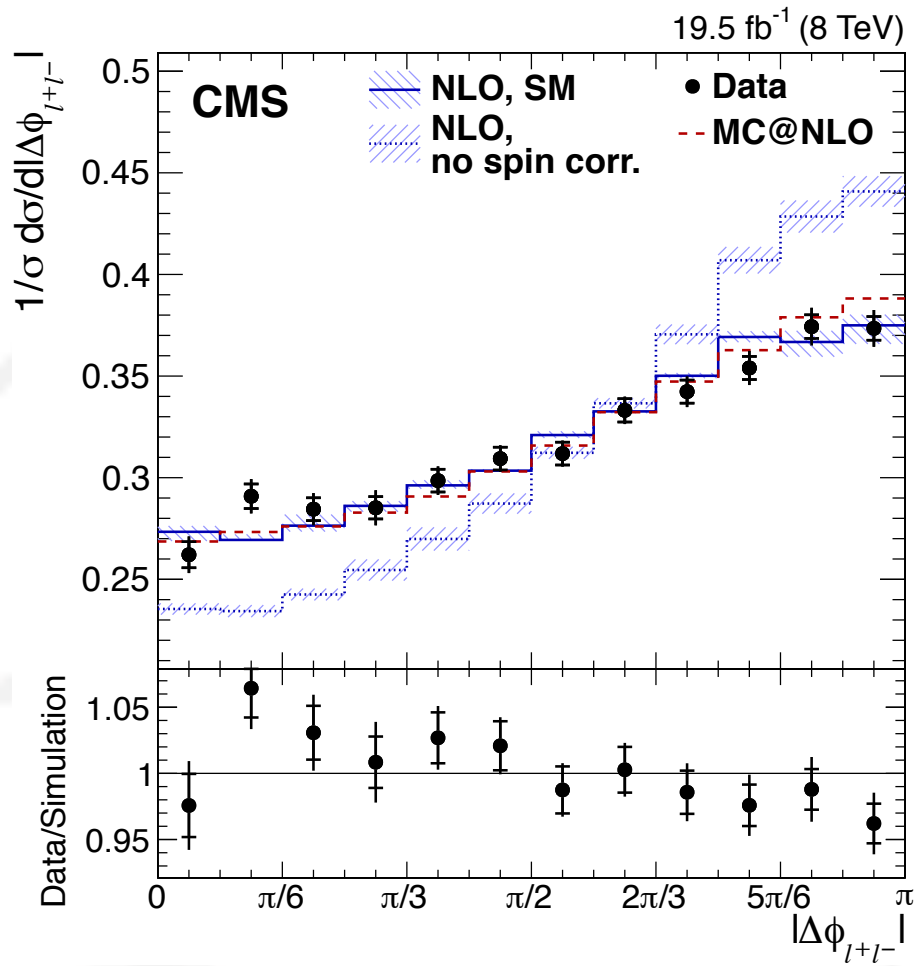
- Azimuthal angle between two leptons $\Delta\phi(l^+l^-)$ in the final state of ttbar decay allows to probe spin correlation without reconstructing ttbar system.

- The $\Delta\phi(l^+l^-)$ variable has been used in almost all past analyses: CMS/ATLAS 7/8 TeV.

- The parton level differential cross section is estimated by unfolding the background subtracted angular distributions.

- Corresponding asymmetries are also estimated at parton level:

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



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Observables

- With the ttbar system fully reconstructed:
  - Opening angle (ϕ) between the lepton momenta measured in their parent top quarks' rest frame is sensitive to spin correlation.
  - $\cos\theta_l$ gives information about the top quark spin where θ_l is the angle of a charged lepton in the rest frame of its parent top quark(antiquark) in a particular basis.
  - Top quark polarization is related to A_p:

$$A_p = \frac{N[\cos\theta_l > 0] - N[\cos\theta_l < 0]}{N[\cos\theta_l > 0] + N[\cos\theta_l < 0]}$$

  - $\cos\theta_{l+}\cos\theta_{l-}$ gives information about the spin correlation.
  - $A_{c_1c_2}$ is related to correlation strength which is dependent on the choice of quantization axis.

$$A_{c_1c_2} = \frac{N(c_1c_2 > 0) - N(c_1c_2 < 0)}{N(c_1c_2 > 0) + N(c_1c_2 < 0)}.$$

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Event selection at 8 TeV

- Exactly 2 oppositely charged isolated leptons with p_T >20 GeV and letal <2.4.
- Reject DY by applying lepton invariant mass cut of less than 20 GeV.
- Missing E_T > 40 GeV and cut on invariant mass within 15 GeV of Z peak to further suppress DY in the case of same flavor lepton final states.
- At least 2 anti-k_T (R=0.5) jets (at least one b-tagged) with p_T >30 GeV and l etal<2.4.
- Jets need to be separated from selected leptons by deltaR>0.4.
- Analytical solutions for the 2 neutrino's 4-momenta are obtained by applying constraints on missing E_T, two W masses (obtained from generated mass) and two top quark masses (172.5GeV) [J. High Energy Phys. 07 (2011) 049], [Nucl.Instrum. Methods Phys. Res. Sect. A 736, 169 (2014)], [Phys. Lett. B 287, 225 (1992)].

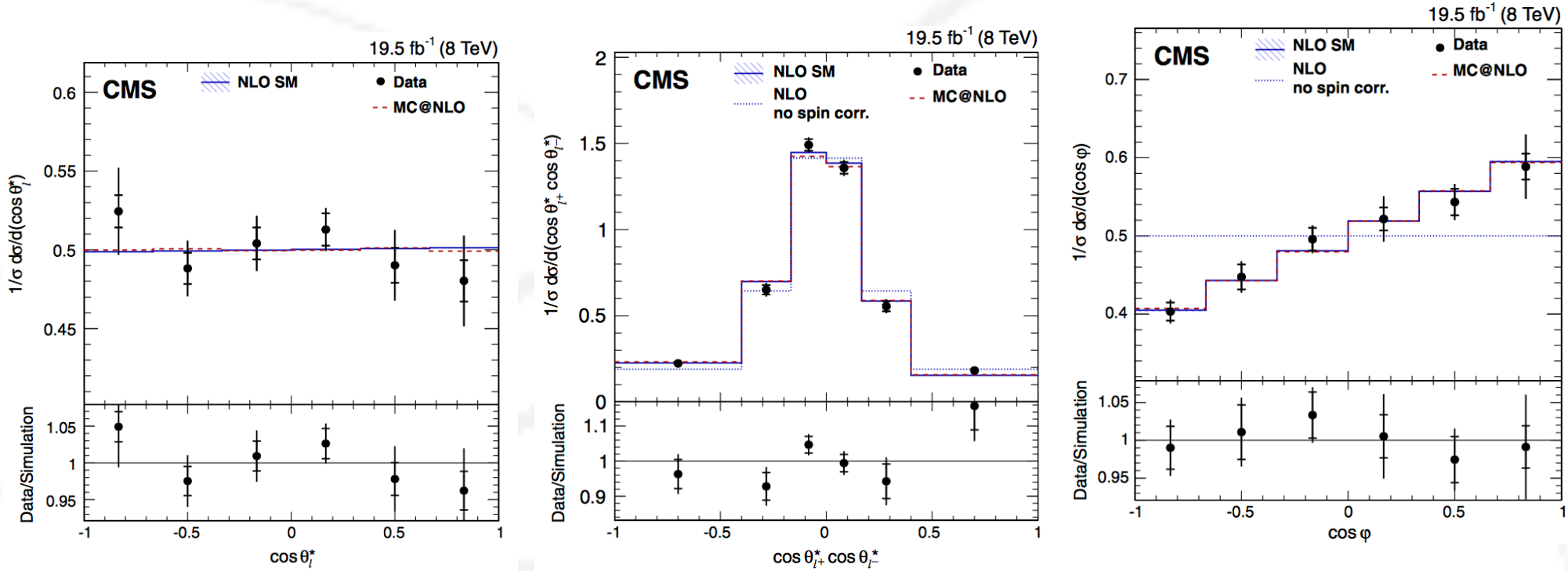
CMS 8 TeV results

- Measured spin correlation and polarization distributions were found to be in agreement with the SM prediction.

- Spin correlation/polarization coefficients were measured in helicity basis (direction of top in the pair's CM frame):

  $C_{hel} = -4A_{C1C2} = 0.278 +/- 0.084$, $D = -2A_{\cos\phi} = 0.205 +/- 0.031$.

  $C^{CPV} = (A_{P+} - A_{P-}) = 0.000 +/- 0.016$, $P = 2A_P = -0.022 +/- 0.058$.



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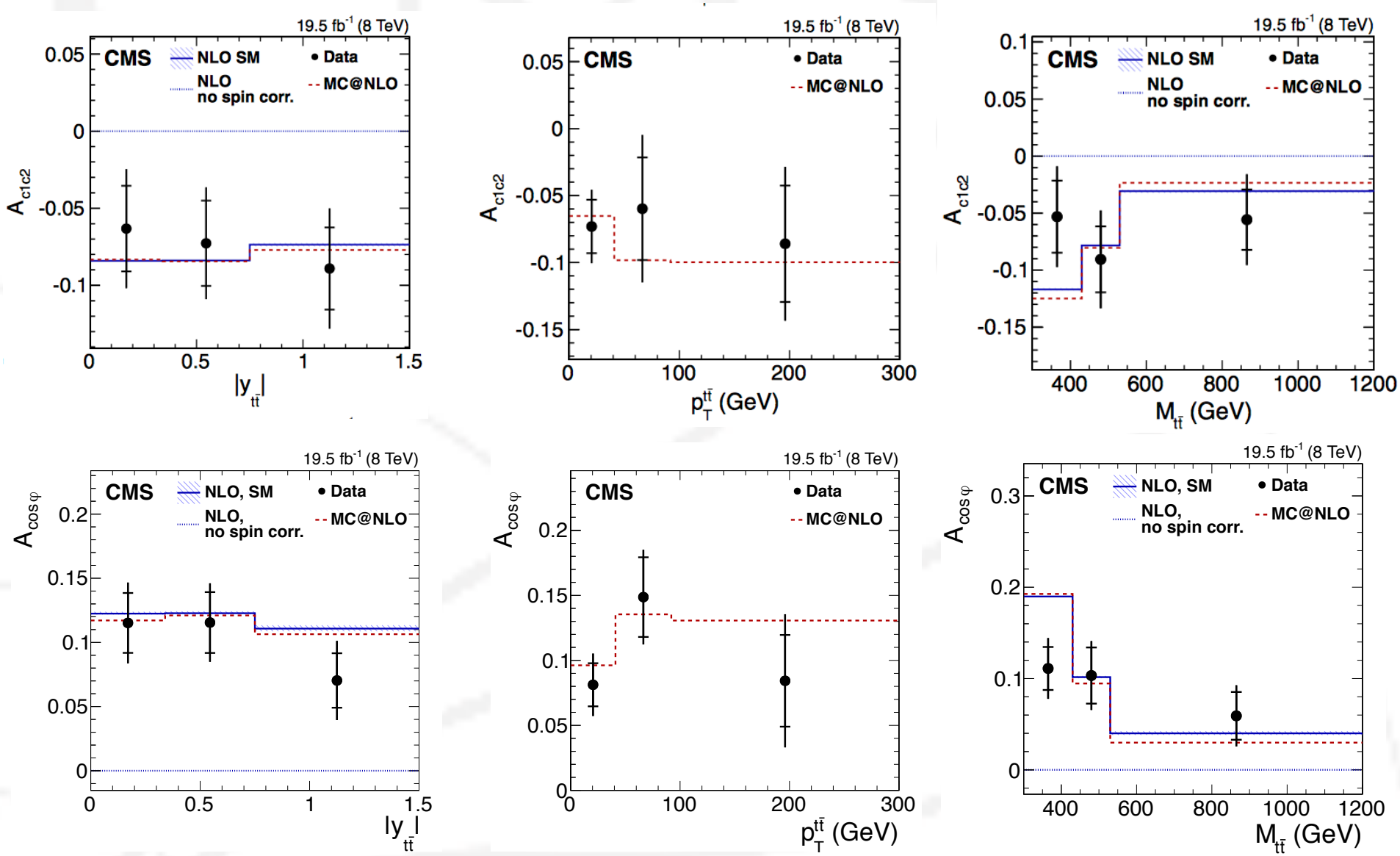
CMS 8 TeV results

- Asymmetry as a function of invariant mass, p_T and eta of the ttbar.



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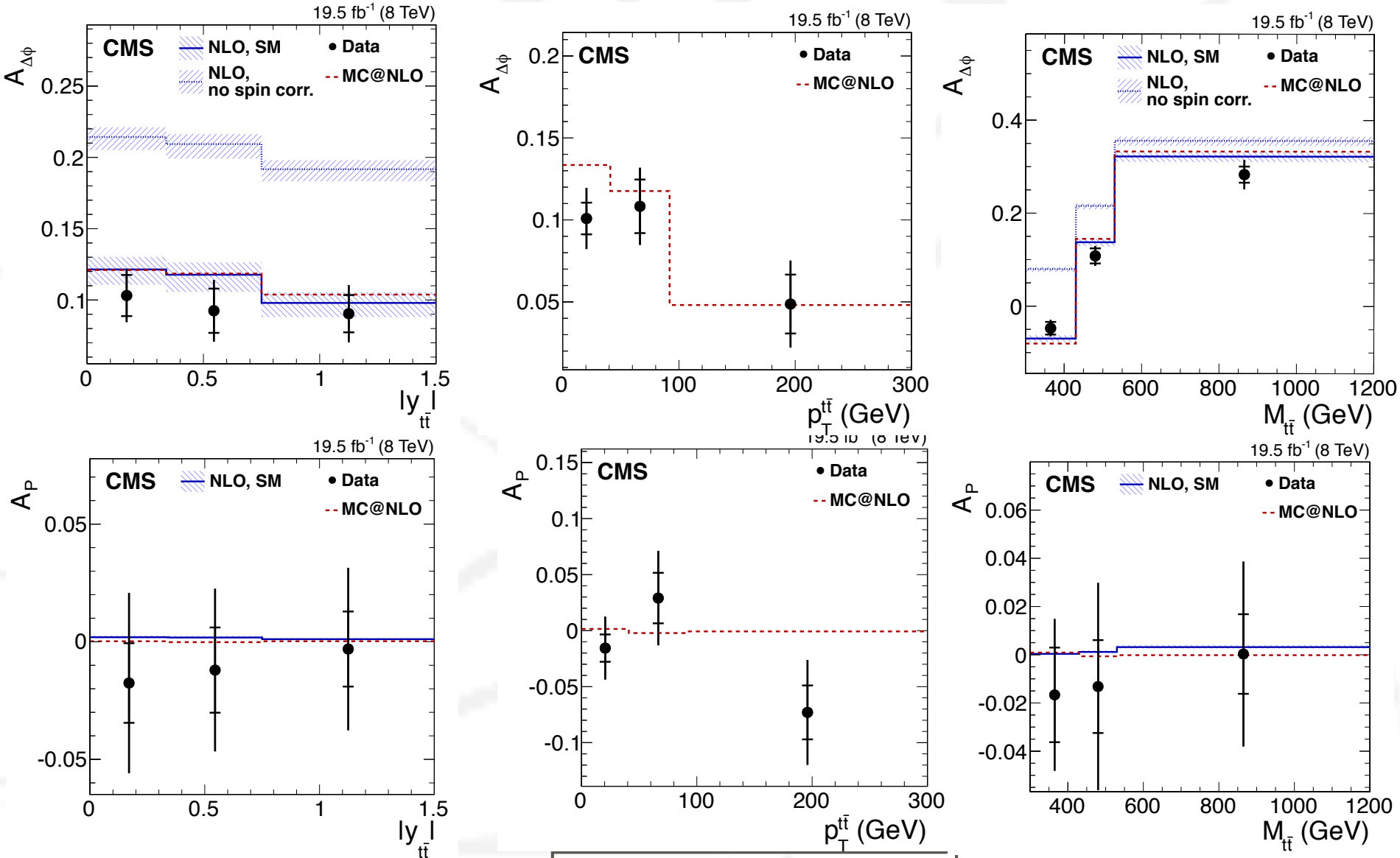
CMS 8 TeV results (helicity basis)

- Asymmetry as a function of invariant mass, p_T and eta of the ttbar.



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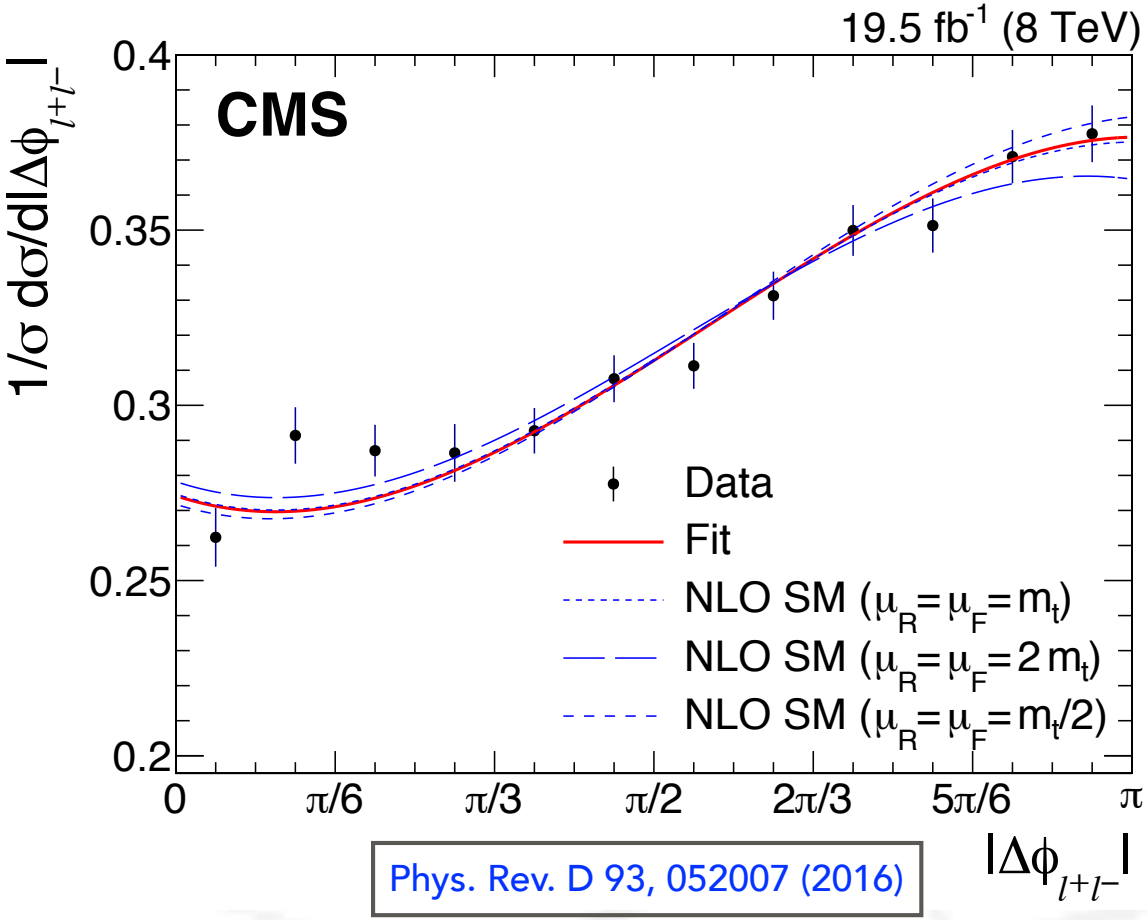
Search for top quark anomalous couplings (8 TeV)



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- Parametric template fit of the delta phi distribution (in the bins of ttbar invariant mass to reduce top p_T modeling uncertainty).
- SM and NP templates are parametrized by polynomial function.
- No evidence of NP observed.

- Exclusion limits on an effective model of chromo-magnetic dipole moment (CMDM) and chromo-electric dipole moment (CEDM) were set:
- $-0.053 < Re(\hat{\mu}_t) < 0.026$ (CP conserving CMDM) and $-0.068 < Im(\hat{d}_t) < 0.067$ (imaginary part of CP violating CEDM) excluded at 95% CL.

Spin correlation and polarization at 13 TeV

- At 13 TeV we want to measure all the independent coefficients of spin density matrix, which includes the polarization.
  - $|\mathcal{M}|^2 \sim Tr[\rho R \bar{\rho}]$

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

    ρ: decay density matrix.

JHEP12(2015)026

  - *R* can be decomposed in spin spaces of top(anti-top) as:

$$R = A\mathbb{I} \times \mathbb{I} + B_i^+ \sigma^i \times \mathbb{I} + B_i^- \sigma^i \times \mathbb{I} + C_{ij} \sigma^i \times \sigma^j$$

  - B_i and C_{ij} are further decomposed in terms of orthonormal basis ($\hat{k}/\hat{p}$: direction of top/incoming parton in $t\bar{t}$ ZMF):

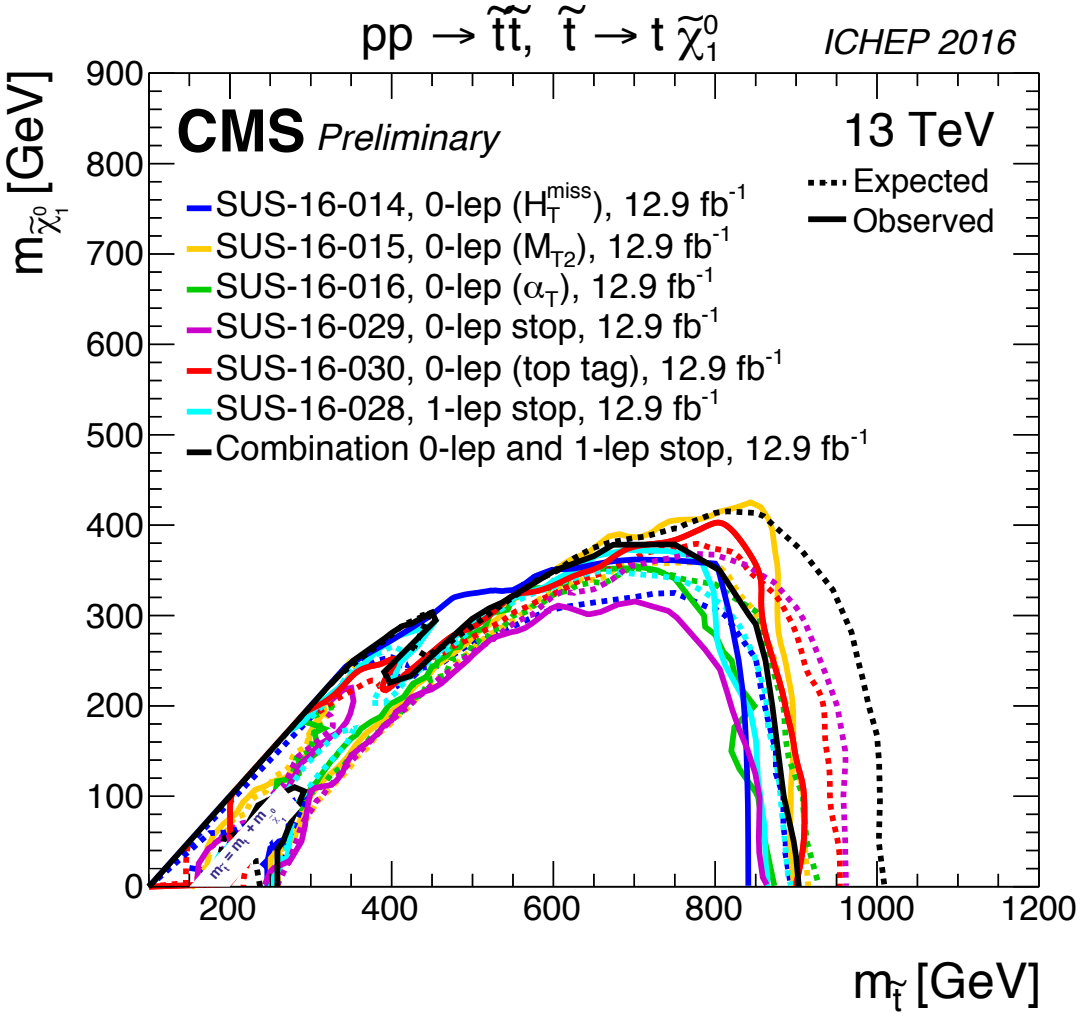
$$\{\hat{r}, \hat{k}, \hat{n}\} : \hat{r} = \frac{1}{r}(\hat{p} - y\hat{k}), \hat{n} = \frac{1}{r}(\hat{p} \times \hat{k}), y = \hat{k}.\hat{p}, r = \sqrt{1 - y^2}$$

  - Coefficients can be classified w.r.t P, CP, T and Bose symmetry.

BSM search via precision measurements of top-quark pairs

- Stop decays in both the top quark and the chargino channels are very sensitive to spin-correlations and polarization information.

$$\text{Top} : \tilde{t}_1 \to t\tilde{\chi}^0 \to (W^+b)\tilde{\chi}^0$$
$$\text{Chargino} : \tilde{t}_1 \to b\tilde{\chi}^+ \to b(W^+\tilde{\chi}^0)$$



- $\tilde{t}\bar{\tilde{t}}$ events can be distinguished from SM $t\bar{t}$ events through an increase of the measured cross section.

- Likelihood fit of the spin/polarization distributions with two templates (with spin correlation(SM) and without spin correlation, can be used to constrain BSM models (in particular SUSY model at stop mass -> top mass).

Conclusion and plans for 13 TeV

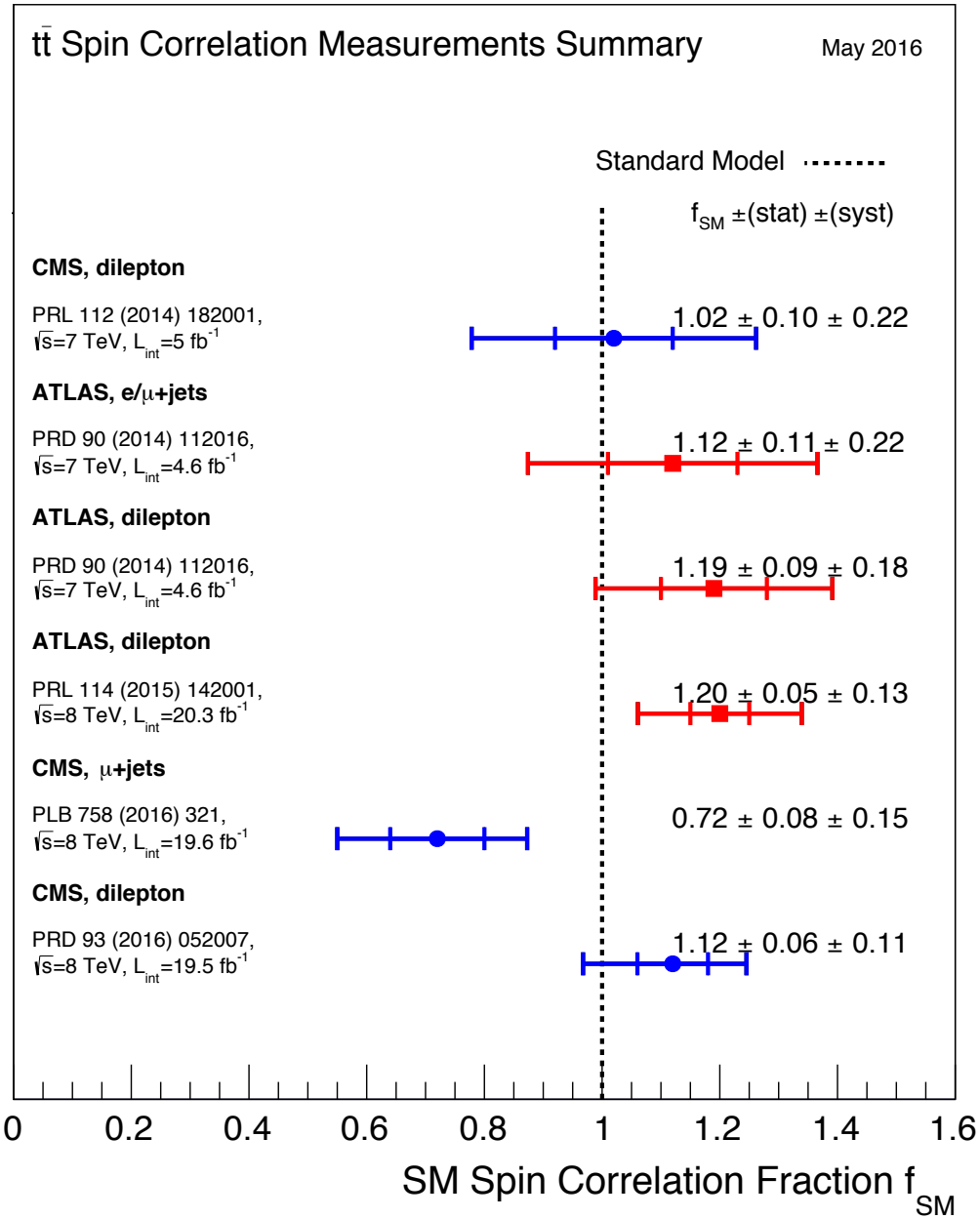
- At 8 TeV, four spin correlation observables and the 2D distributions of associated asymmetries w.r.t variables related to ttbar were studied.
- Results at 8 TeV show agreement with the SM and search for top quark anomalous couplings showed no evidence of new physics.
- At 13 TeV, plan to include more observables to probe all the $t\bar{t}$ independent coefficients of top-spin dependent parts of the production spin density matrices as described in Bernreuther et. al. [JHEP12(2015)026].
- Likelihood fit of the spin-correlation distributions with templates from SUSY+SM or other BSM models+SM in order to constrain new physics scenarios.
- 2D differential cross section measurements to probe for new physics and better handle on systematics.

THANK YOU!

Sources of uncertainty

ttbar modeling uncertainties	Experimental Systematic Uncertainties
Top quark pT	Jet energy scale
Parton distribution functions	Jet energy resolution
Factorization and renormalization scales	Lepton energy scale
Top quark mass	Background
Hadronization	Pileup
Unfolding (simulation statistical)	b tagging efficiency
Unfolding (regularization)	Lepton selection

Summary of previous measurements



Likelihood fit of the angular distributions using SM template and no correlation template:

$$f_{SM} = \frac{N_{SM}^{t\bar{t}}}{N_{SM}^{t\bar{t}} + N_{UnCorr}^{t\bar{t}}}$$

- f_{SM} = 1: Strength of spin correlations same as SM prediction.
- f_{SM} = 0: Uncorrelated events.
- New: Most precise measurement in the lepton+jet channel (full matrix element method to construct event and sample likelihoods): f_{SM}=0.72 +/- 0.08 +/- 0.15 - compatible with SM with 2.2 sigma and with uncorrelated with 2.9 sigma. [Phys. Lett. B 758 (2016) 321].