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

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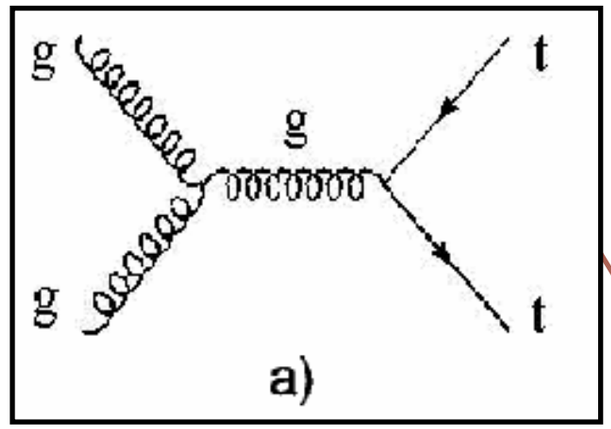
Introduction

- Heaviest fundamental particle: m_t = 173.34±0.76 GeV [arXiv: 1403.4427].
- Short lifetime ~10^{-25} s.
  - Decays before hadronization takes place.
  - Spins cannot decorrelate and the spin info. gets passed on to decay particles.
- Special role in EWSB?: $\lambda_t \sim 1$.



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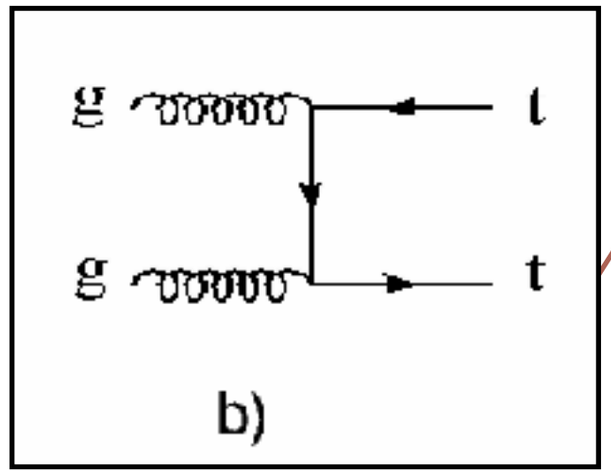

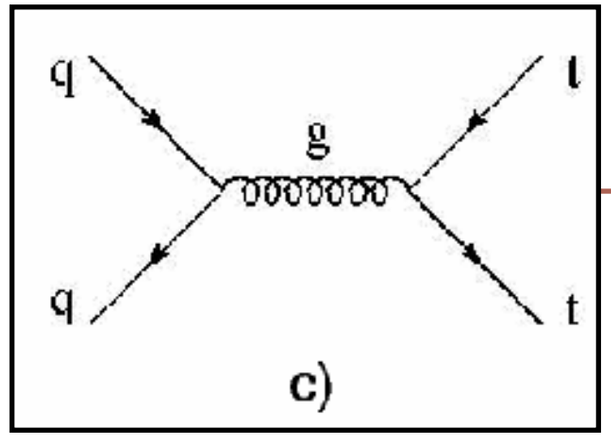

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Study of top properties:

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

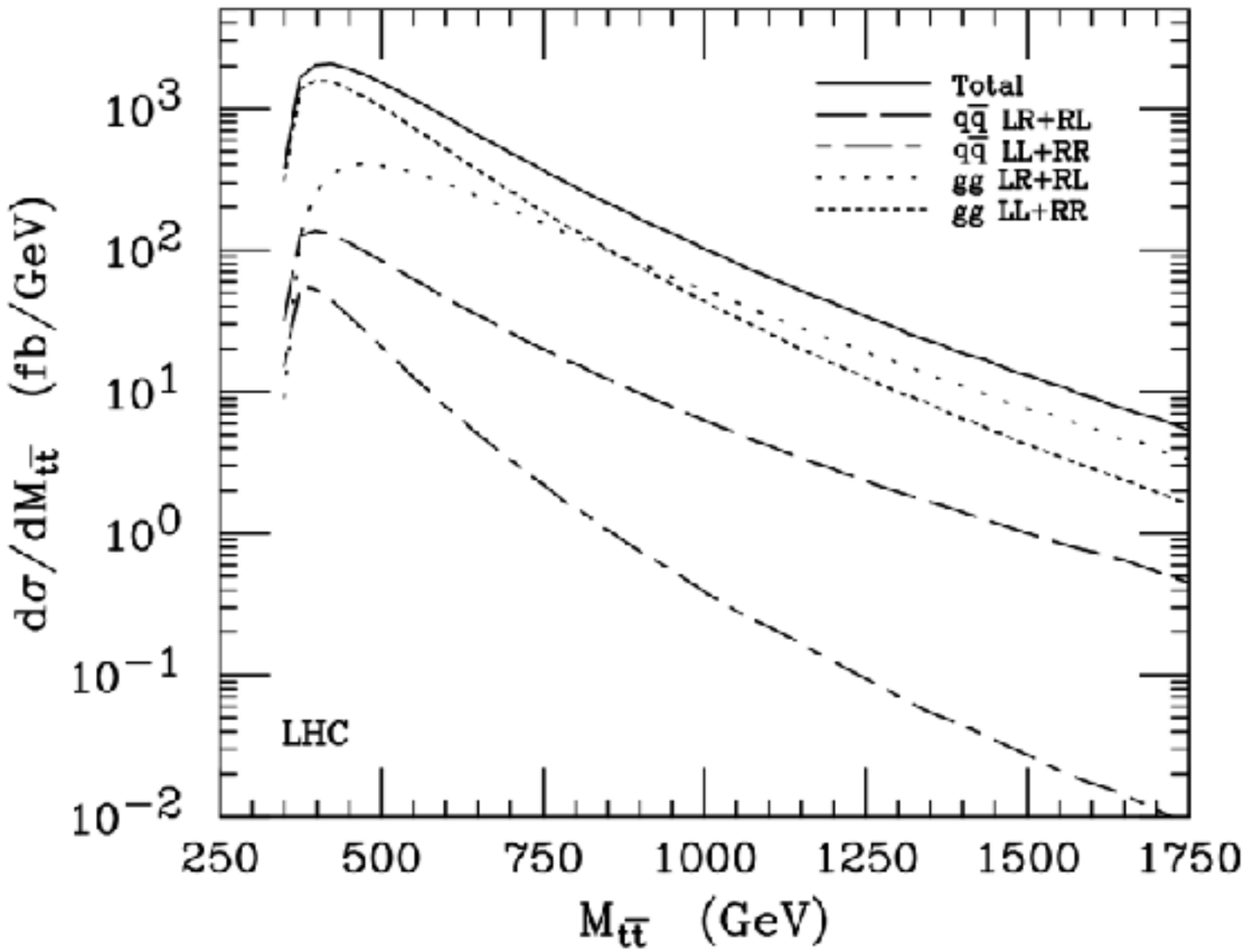
★ provides constraint for BSM models with resonances decaying to top and SUSY stops produced via similar mechanism as SM top.

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.

★ Therefore, we want to measure entire spin density matrix, which includes the polarization.



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

- Time taken for top quark to change its spin by radiating a gluon > lifetime of top. Decay products carry the top spin information.

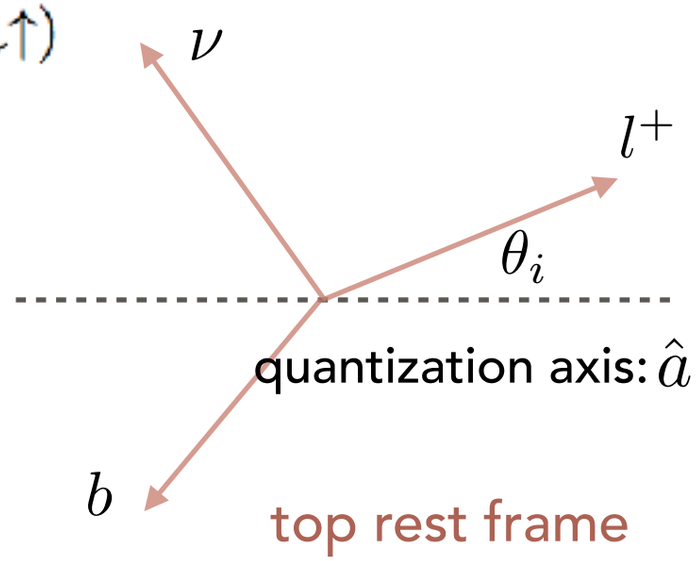
- The $t\bar{t}$ differential cross section:

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

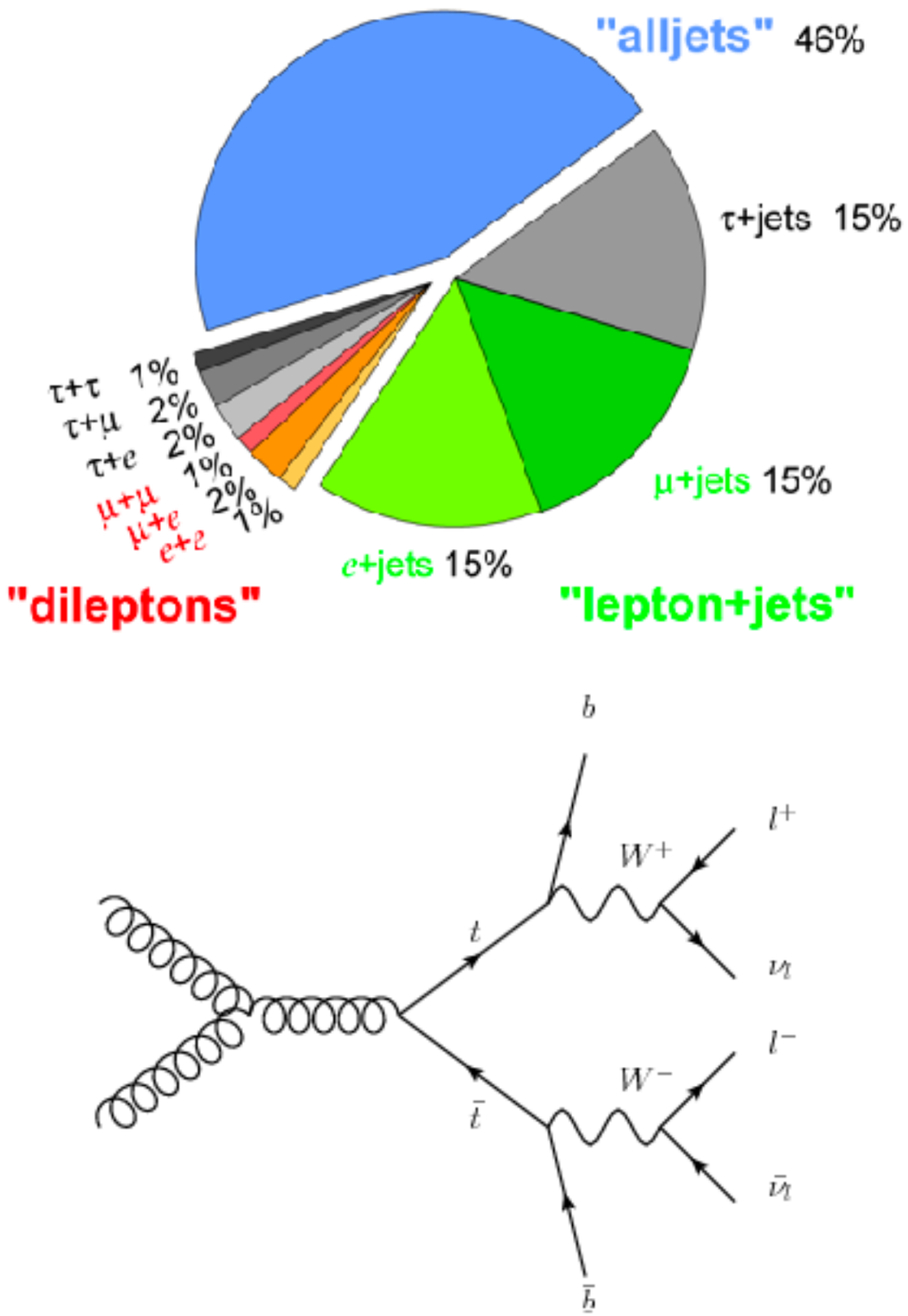
- $B_1, B_2,$ and C are the polarization and spin correlation in quantization axis $\hat{a}$ and $\hat{b}$.

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

- 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.
- 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

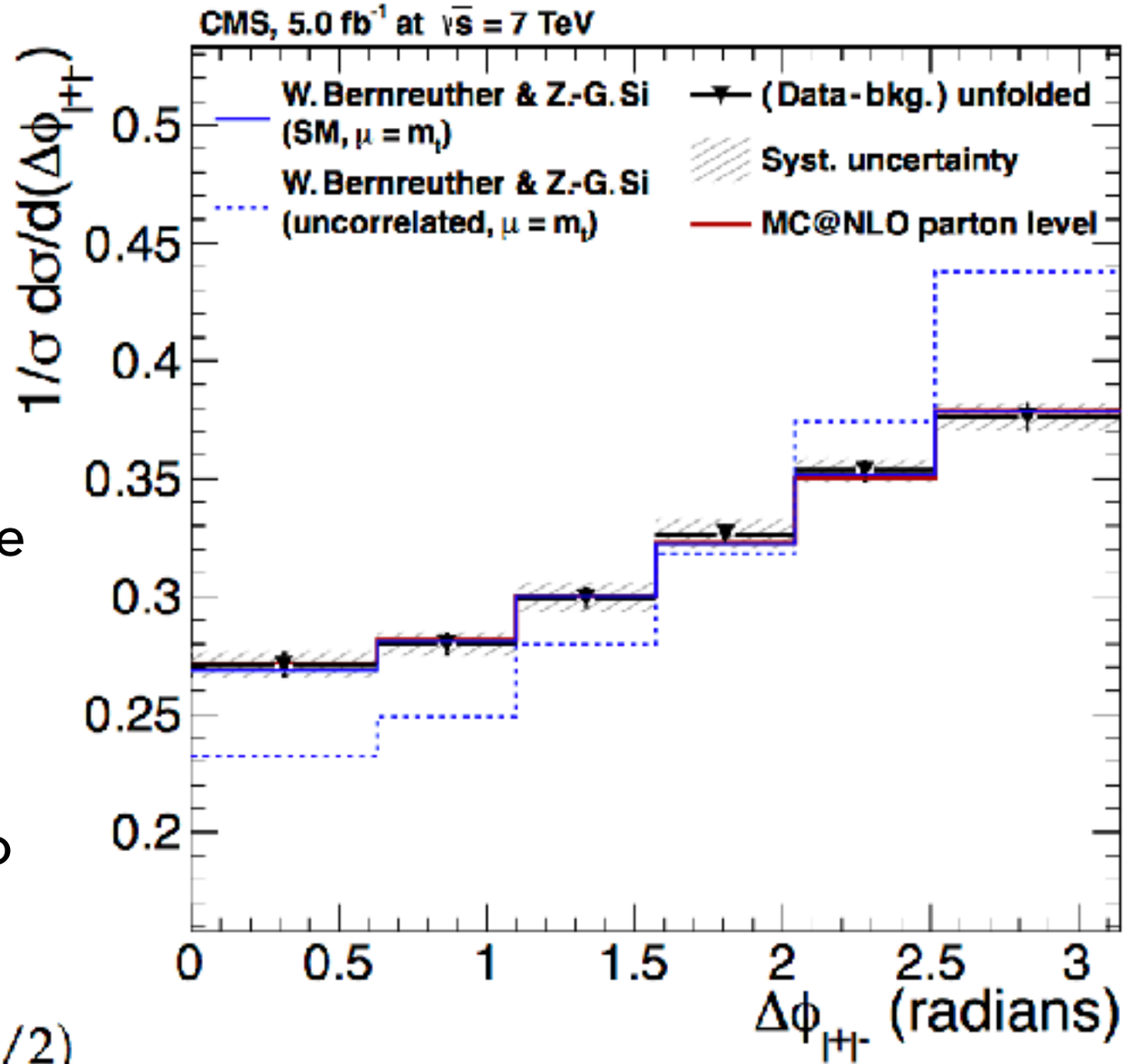
★ Azimuthal angle between two leptons $\Delta\phi(l^+l^-)$ in the final state of ttbar decay allows to probe spin correlation without reconstructing ttbar system.

★ 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:

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



PRL 112 (2014) 182001

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.

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

Quantization axis

Phys. Rev. D **95**, 011101(R)

★ Commonly used basis:

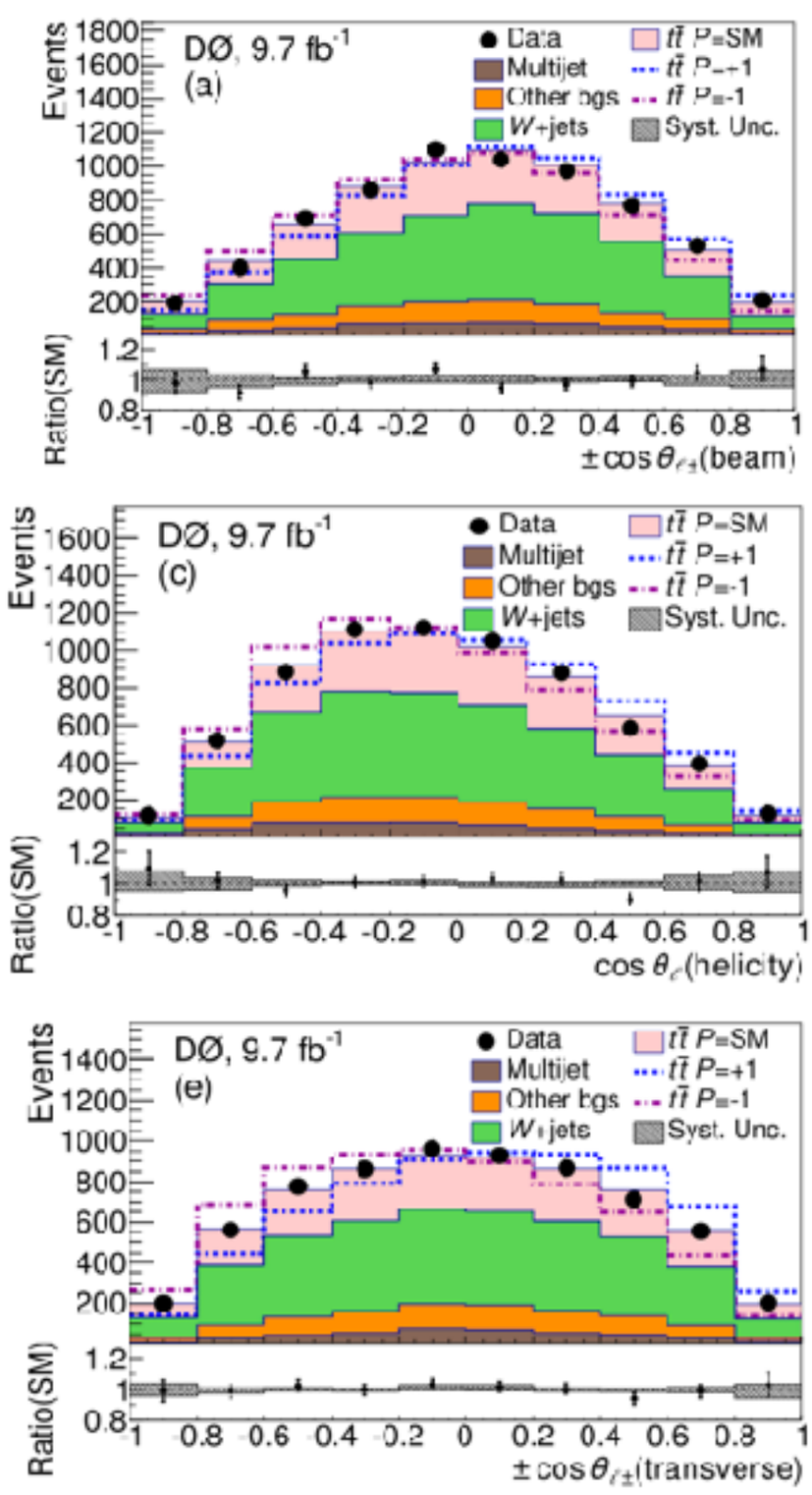
* Beam - direction of one of the beams in lab frame (good at Tevatron).

* Helicity - direction of the flight of top(anti-top) in the pair's CM frame. (good at LHC).

* Transverse - perpendicular to plane defined by proton and parent top direction (higher for Tevatron).

* Off-diagonal - axis w.r.t which the spins of top and anti-top produced by qqbar annihilation are 100 % correlated (No such basis for gg).

Combined e+jets and mu+jets for l+3jets events.



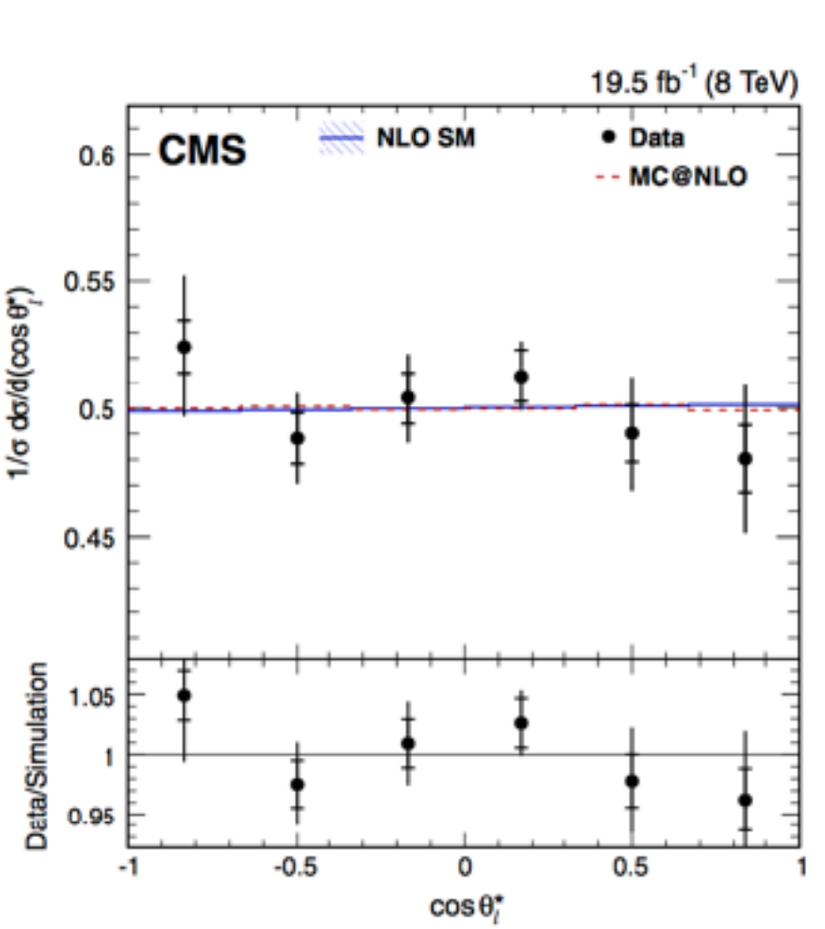
Typical event selection

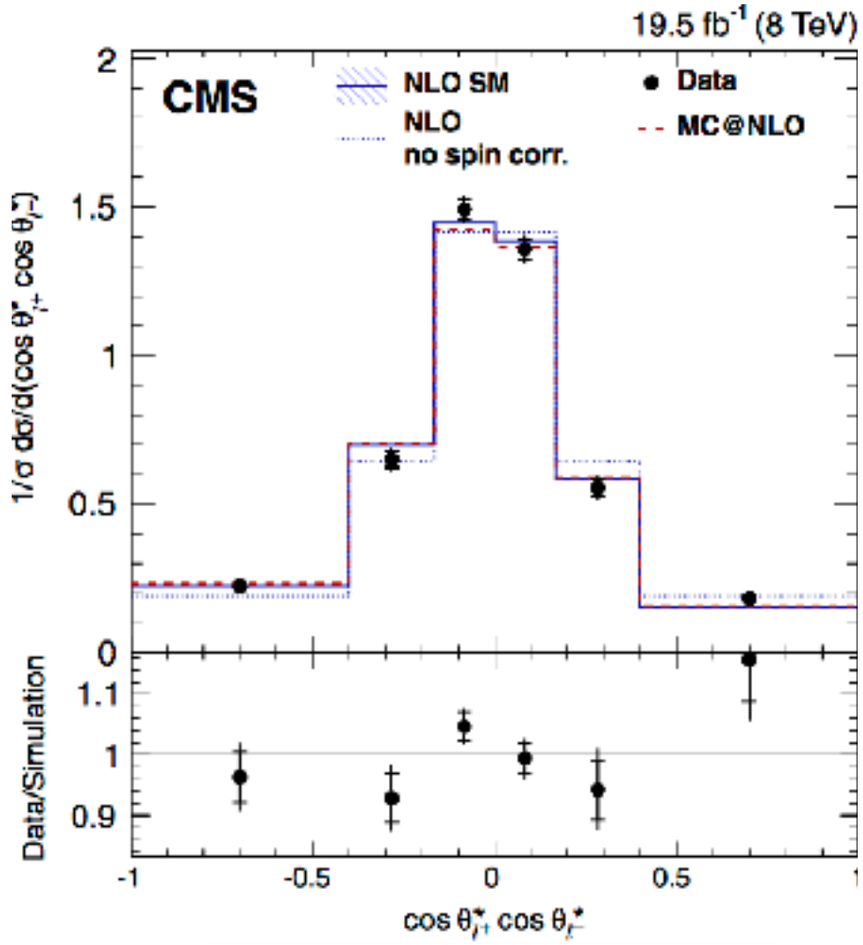
- Signal characterized by
  - 2 oppositely charged isolated leptons (also from τ lepton decay)
  - 2 jets with at least one b-tagged jet.
- Reject DY by applying lepton invariant mass around Z peak and less than 20 GeV.
- Cuts on missing E_T to further suppress DY in the case of same flavor lepton final states.
- Because of two neutrinos in the final state, kinematics reconstruction is done by applying constraints from from missing E_T, two W masses (obtained from generated mass) and two top quark masses (172.5GeV).

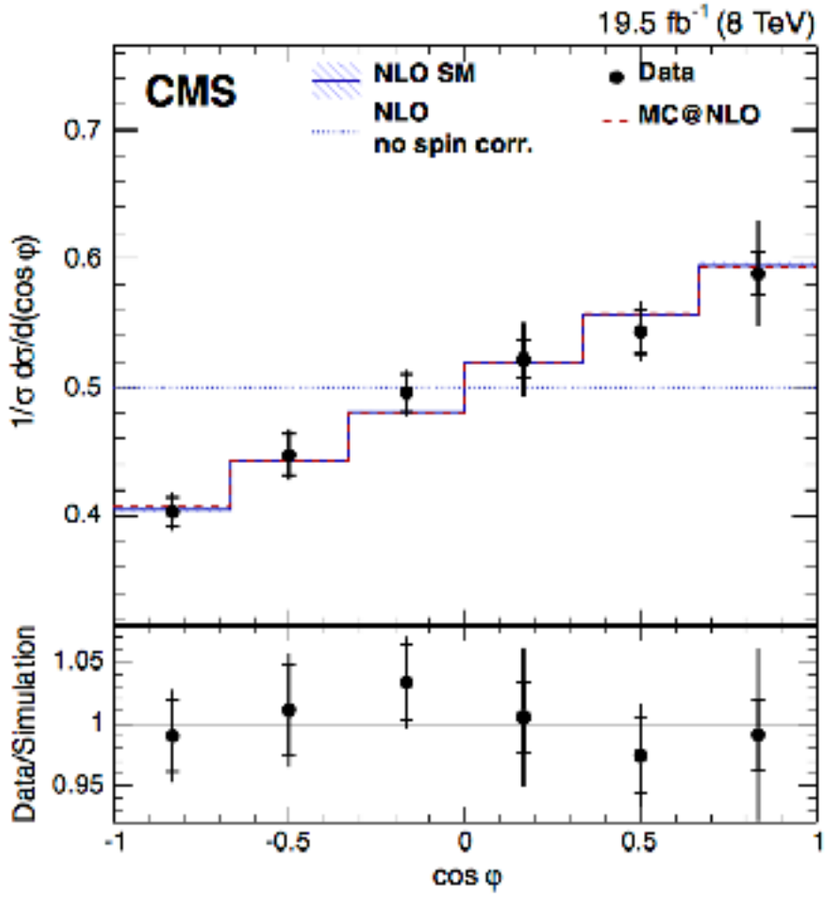
CMS 8 TeV results (helicity basis)

- 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: C_{hel} = 0.278+/-0.084, P = -0.022+/-0.058.



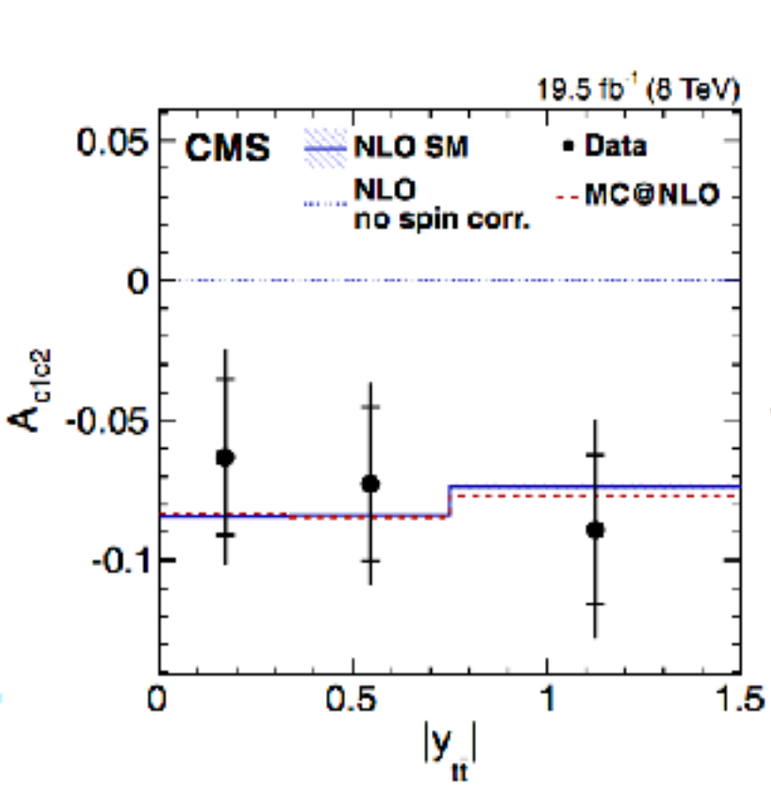


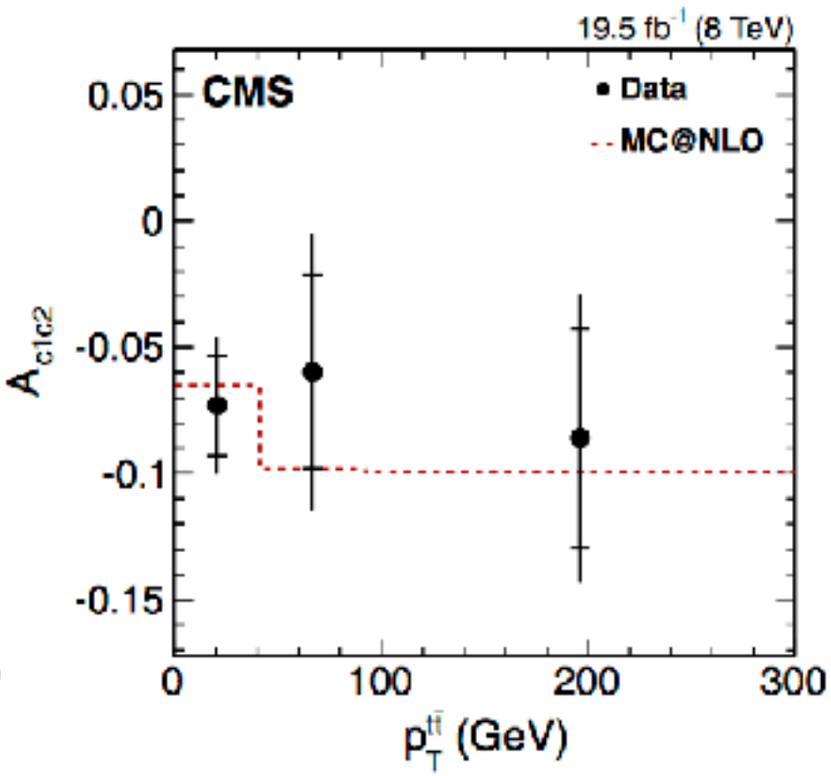


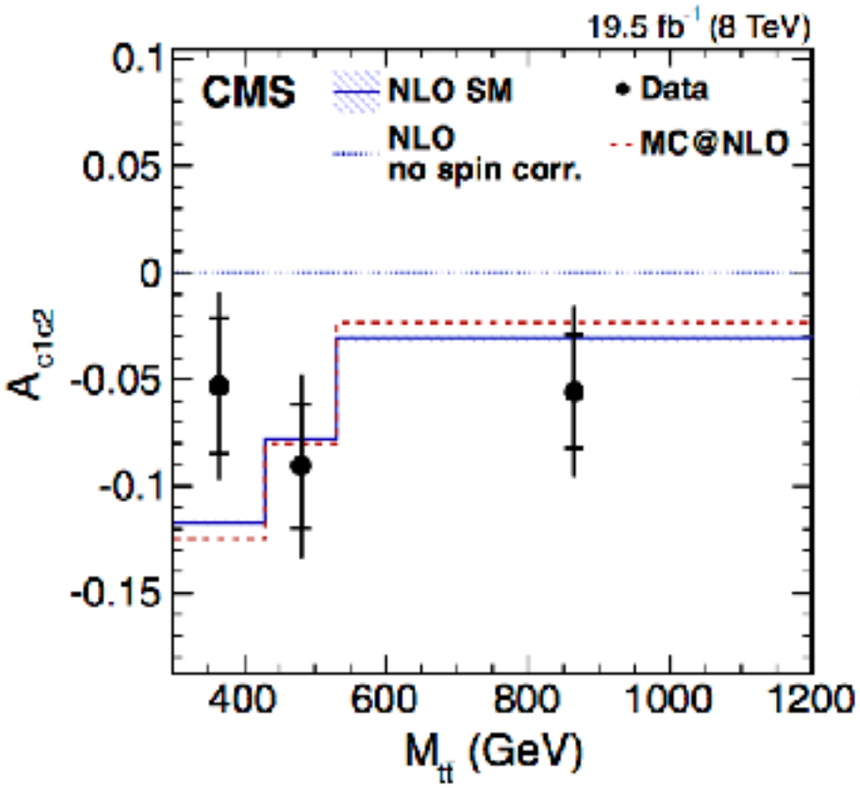
Phys. Rev. D 93, 052007 (2016)

CMS 8 TeV results (helicity basis)

- Asymmetry as a function of invariant mass, pT and pseudo-rapidity of the ttbar system were also studied and found to be consistent with SM.







Phys. Rev. D 93, 052007 (2016)

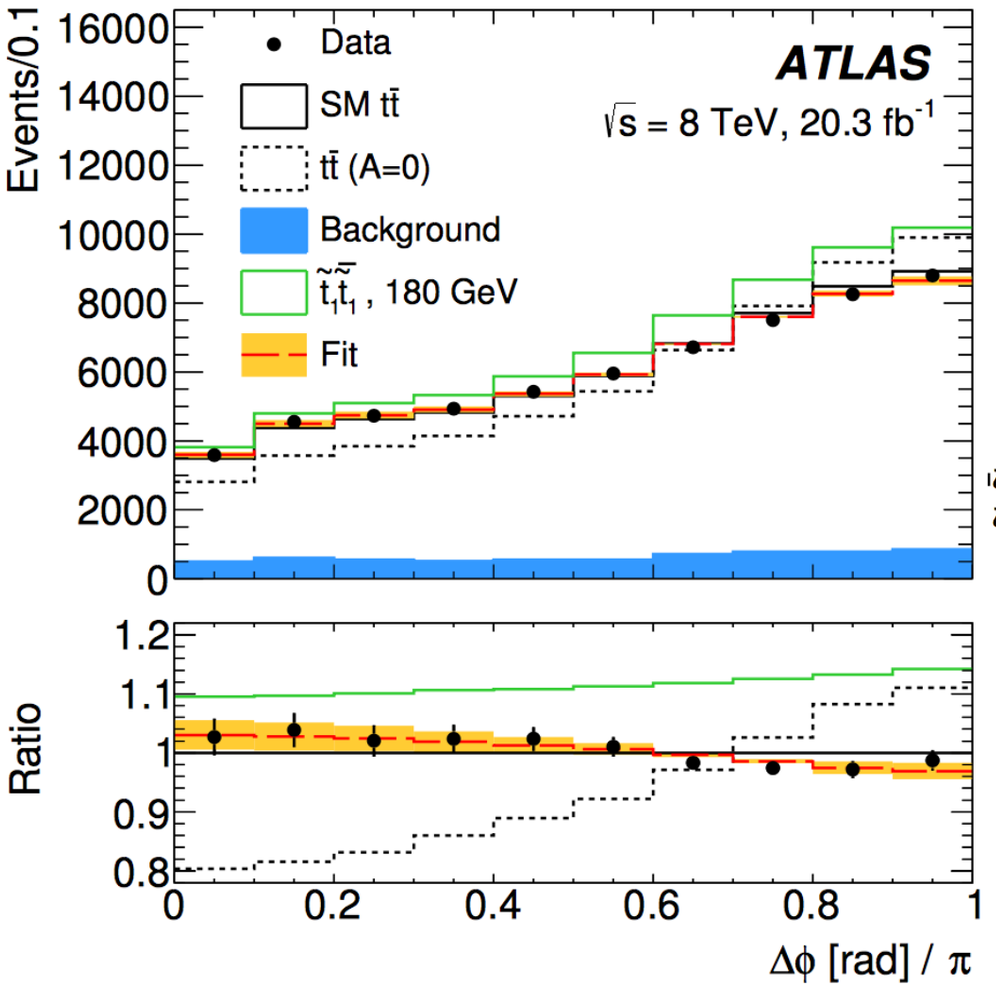
- Spin correlation as a function of mass related variables can help constrain the top quark partner phase-space.

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.

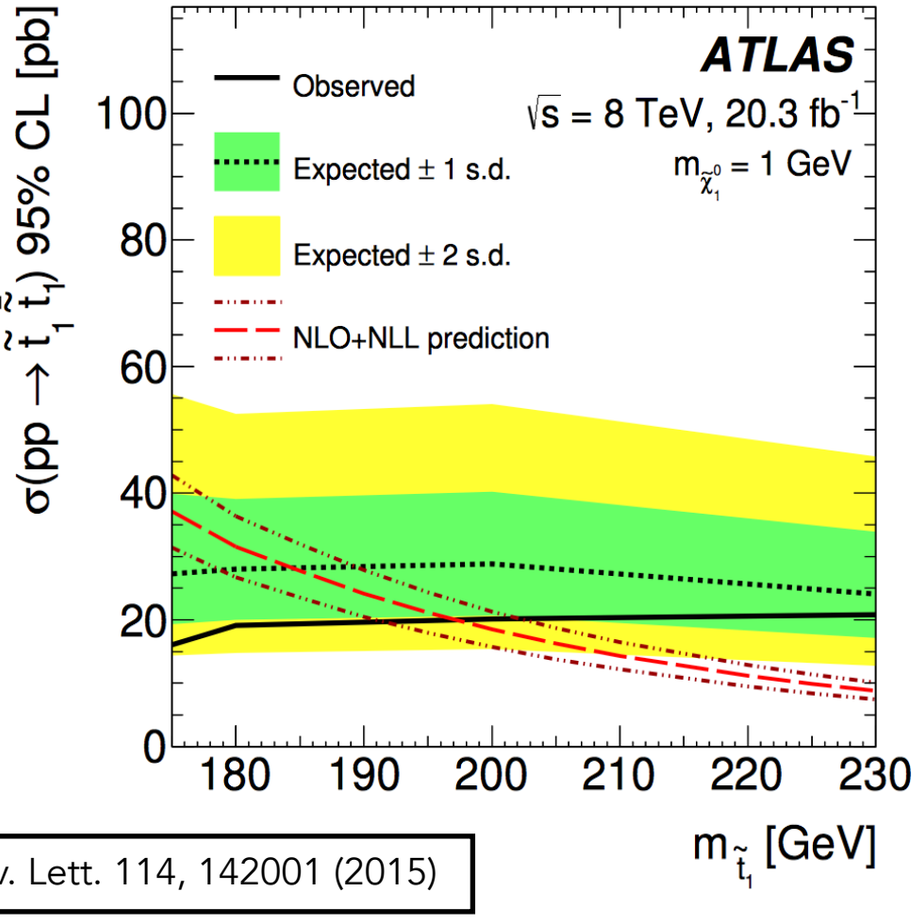
★ $\tilde{t}\bar{\tilde{t}}$ events can be distinguished from SM $t\bar{t}$ events through an increase of the measured $t\bar{t}$ cross section.

Likelihood fit of the spin/ polarization distributions with two templates (with spin correlation(SM) and without spin correlation (A=0), can be used to constrain BSM models.



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

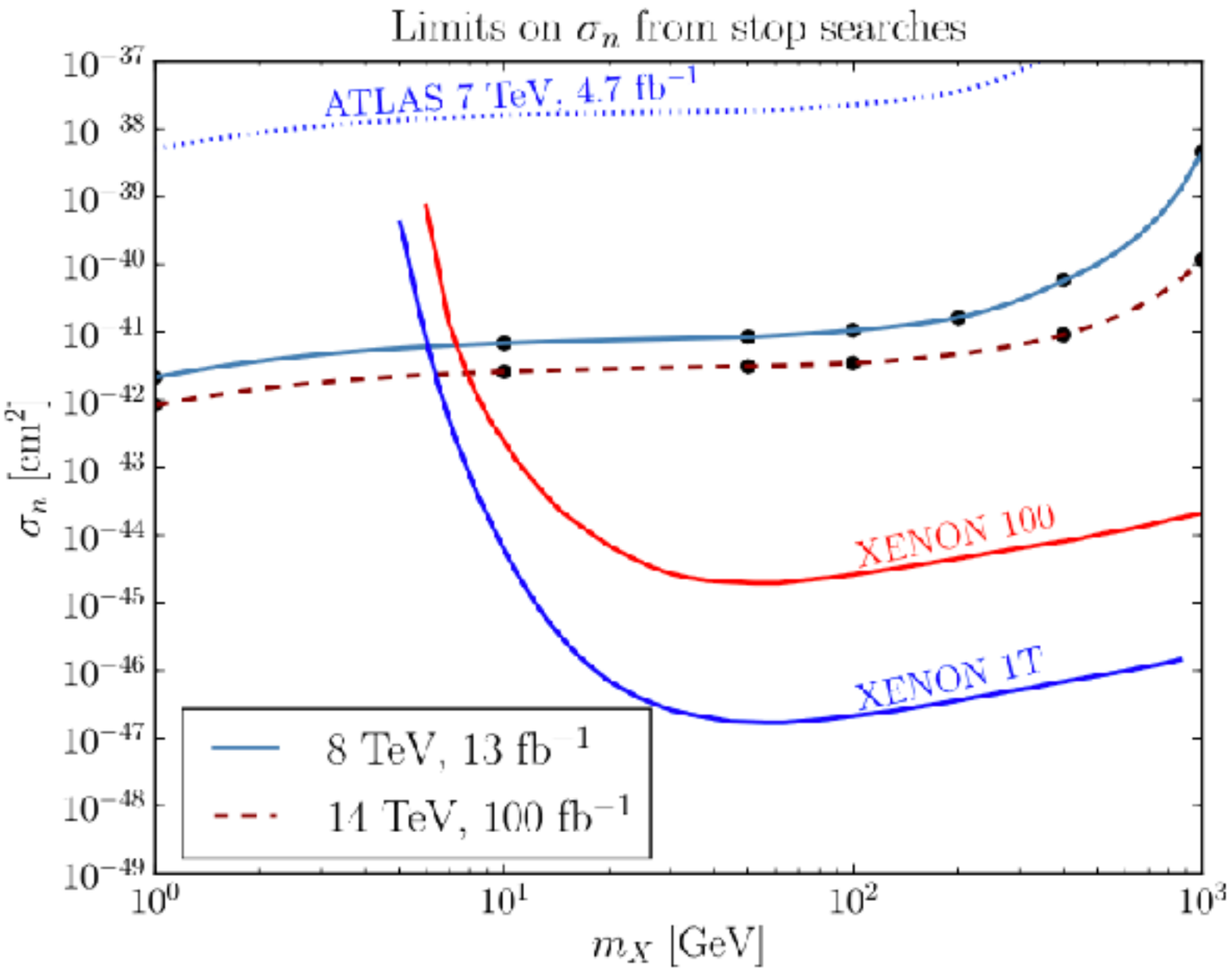
$$\text{Chargino} : \tilde{t}_1 \to b\tilde{\chi}^+ \to b(W^+\tilde{\chi}^0)$$



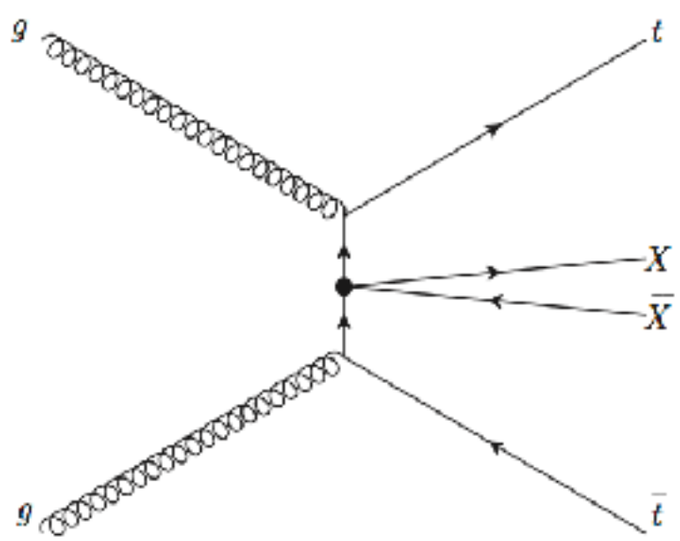
Phys. Rev. Lett. 114, 142001 (2015)

Search for dark matter with top spin correlation

Associated production of dark matter with $t\bar{t}$ pair can alter the $t\bar{t}$ spin correlation.

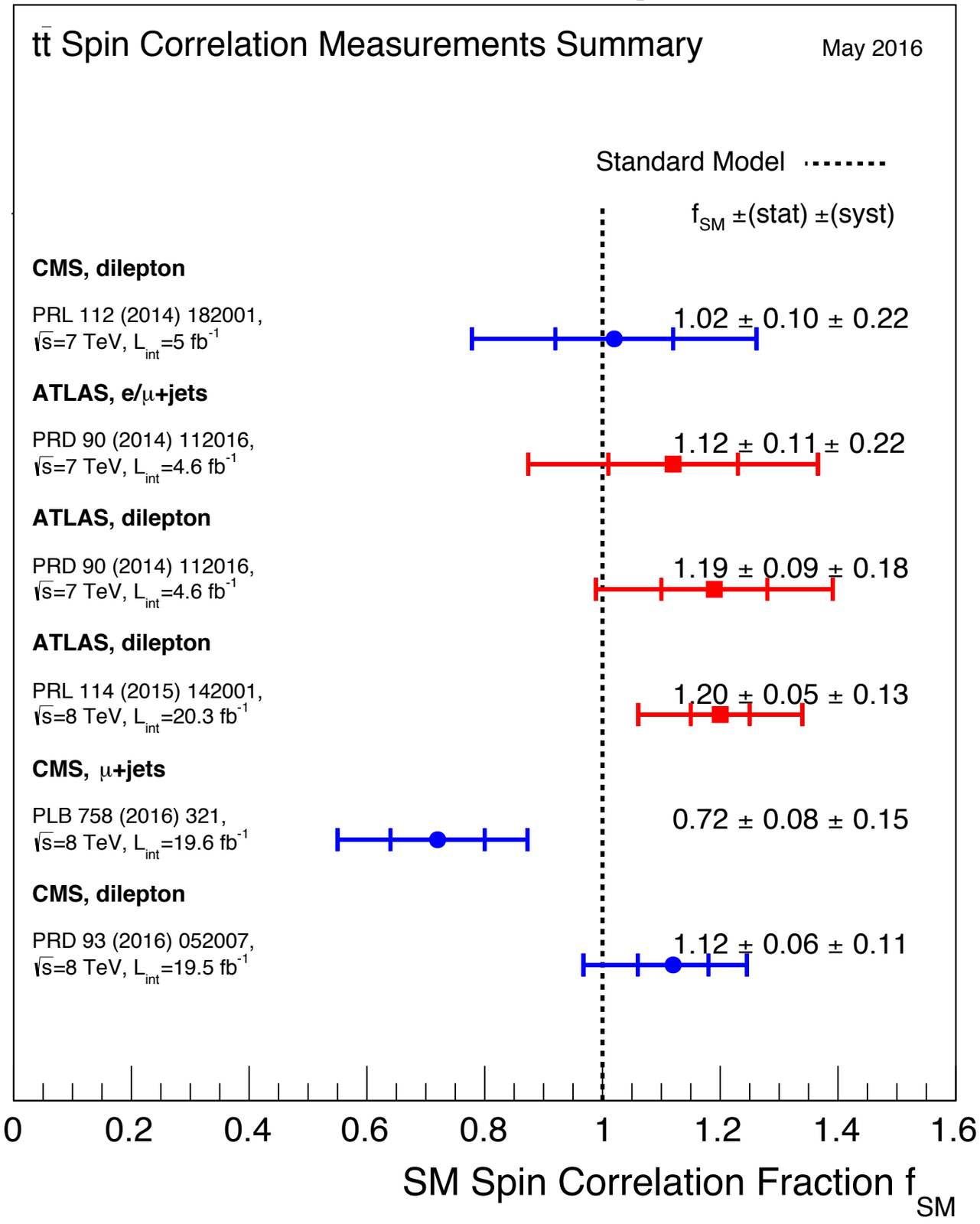


arXiv: 1303.6638



Parameter space for DM-nucleon scattering cross section that is not well constrained by direct searches may be constrained with searches having $t\bar{t}$+ missing E_T in the final state at the LHC.

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: 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].

Plans for 2016 dataset at 13TeV

- Include more observables to probe all the independent coefficient functions of top-spin dependent parts of the $t\bar{t}$ 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!

Kinematic reconstruction

★ Because of two neutrinos in the final state, kinematics is not constrained.

★ Constraints from missing transverse energy in the transverse direction, two W masses (obtained from generated mass) and two top quark masses (172.5GeV).

★ Set of six independent kinematic equations with six unknowns is constructed.

★ Solution proposed by L. Sonnenschein results in a quartic equation for one of the neutrino momenta components, which can have up to four solutions [Phys. Rev. D 73 , 054015 (2006)].

★ The solution with lowest ttbar invariant mass can be taken as solution - has been found through simulation to give correct solution 60% of the time.

★ It has already been used in CMS-TOP-12-028, CMS-TOP-14-013 and CMS-TOP-16-011.

★ Other methods such as neutrino weighting technique (ATLAS 7TeV) [Phys. Rev. Lett. **80**, 2063-2068] have been used in the past.