Unraveling the CP phase of top Yukawa coupling at LHC

Pankaj Sharma

The University of Adelaide

In collaboration with

Saurabh D. Rindani and Ambresh Shivaji

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OUTLINE

- **Introduction**

  ⇒ CP phase in top Yukawa coupling

- **Constraints**

  ⇒ EDM Constraints

  ⇒ Constraints from LHC

- **Top Polarization**

- **Associated production of Higgs and top.**

- **Asymmetries.**

- **Conclusions.**

INTRODUCTION

- Characterization of Higgs is an important task in Run II LHC,
  ⇒ May provide unique information about BSM physics
- Determination of spin and parity is crucial,
  ⇒Consistent with spin 0 particle with SM like couplings,
  ⇒Also pure pseudoscalar is disallowed,
- However, a CP admixture is still allowed,
- It is of fundamental importance to explore this information,
- Yukawa couplings of third generation fermions, particularly top quarks, are of particular interest,
- Fermionic couplings are more democratic to CP odd Higgs compared to EW gauge bosons

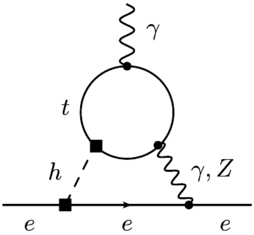
CP violating top Yukawa coupling

The most general top Yukawa coupling without imposing CP invairance can be written as

$$\mathcal{L}_{t\bar{t}h} = -y_t \; \bar{t} \; (\cos\zeta_t + i \; \gamma_5 \;\; \sin\zeta_t) t \; h.$$

- ζ_t is the CP violating phase,
- $\zeta_t = 0$ or $\zeta_t = \pi \Rightarrow$ a pure scalar state,
- $\zeta_t = \pi/2 \Rightarrow$ a pure pseudoscalar state,
- $0 < \zeta_t < \pi/2$, or $\pi/2 < \zeta_t < \pi$ signals CP violation,
- $\zeta_t = \pi/4$ denotes a maximally CP violating case.

Constraints from Low Energy Experiments



- Upper bound on electron-EDM is $|d_e/e| < 8.7 \times 10^{-29}$ cm,
- Leads to $|\zeta_t| < 0.01$,
- However, it assumes $\kappa_e = 1$ (SM-like)
- Bound vanishes in the limit $\kappa_e \to 0$

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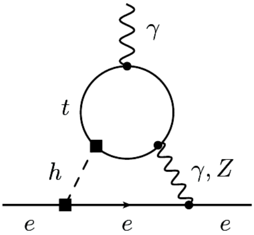

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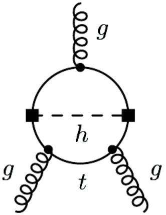
- Bound vanishes in the limit $\kappa_e \to 0$

- Other low energy bound comes from neutron EDM,
- Even if $\kappa_{e,d,u} = 0$,
- Gluon operator contributes in such a scenario,
- Bound is two order magnitude weaker than electron EDM

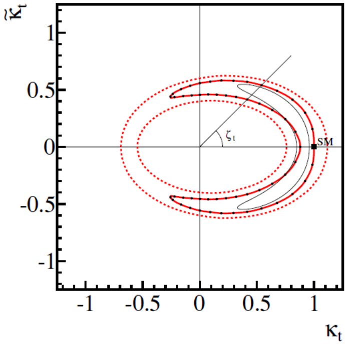


[Brod,Haisch,Zupan], JHEP 11, 180 (2013)

Constraints from LHC

- Modifications in $t\bar{t}h$ couplings affects both $gg \to h$ production as well as $h \to \gamma\gamma$ decays,
- Effective Hgg and $H\gamma\gamma$ couplings obtained from LHC provides stringent constraints,
- Assumption: $\kappa_f = 1$ and $\kappa_W = \kappa_Z = 1$,
- Negative value of the top Yukawa still allowed by the data

[Boudjema,Godbole,Guadagnoli,Mohan]
[Kobakhidze,Wu,Yue]
[Ellis,Hwang,Sakurai,Takeuchi]



Top Polarization

- Life time $\sim 5 \times 10^{-25}$s which is smaller than $\Lambda_{QCD} \sim 3 \times 10^{-24}$s
- In the top-rest frame, the distribution of its decay products is

$$\frac{1}{\Gamma}\frac{d\Gamma_f}{d\cos\theta_f} = \frac{1}{2}\left(1 + \kappa P_t \cos\theta_f\right)$$

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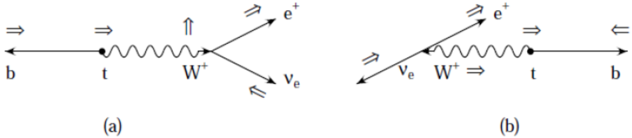

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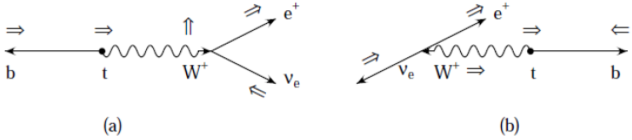

- The ℓ^+ and d quark are the best spin analyzers with $\kappa_{\ell+} = \kappa_{\bar{d}} = 1$,
- Thus the ℓ^+ or d have the largest probability of being emitted in the direction of the top spin,

Pankaj Sharma
The University of Adelaide

Top Polarization Contd

A issue

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- Reconstruction of top-rest frame is difficult at LHC

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Our Prescription

- We study lab-frame distributions of top-decay products,
- Decay-lepton angular distribution is insensitive of anomalous tbW couplings at linear order,

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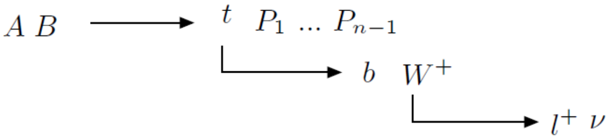
Our Prescription

- We study lab-frame distributions of top-decay products,
- Decay-lepton angular distribution is insensitive of anomalous tbW couplings at linear order,

Thus, we have a pure and clean looking glass for top polarization.

$\Rightarrow$ New Physics

A generic top-production process



Lepton angular distributions are independent of anomalous tbW couplings under following assumptions:

[Godbole, Rindani], [Grzadkowski]

A generic top-production process

$$A\,B \longrightarrow t\;\; P_1 \,\ldots\, P_{n-1}$$
$$t \longrightarrow b\;\; W^+$$
$$W^+ \longrightarrow l^+\;\nu$$

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[Godbole, Rindani], [Grzadkowski]

- top is on-shell; narrow-width approximation for top,

$$|\mathcal{M}|^2 = \frac{\pi\delta(p_t^2 - m_t^2)}{\Gamma_t m_t} \sum_{i,j} \rho(\lambda, \lambda')\Gamma(\lambda, \lambda')$$

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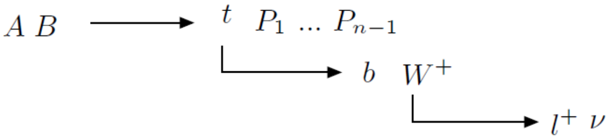

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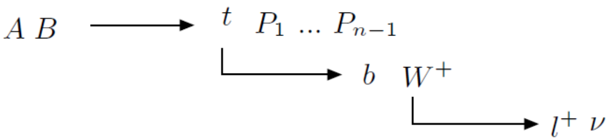

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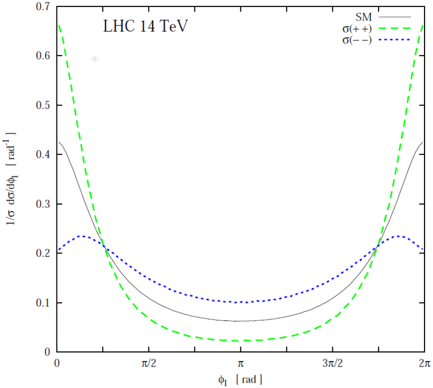
- $t \to bW(\ell\nu_\ell)$ is the only decay channel,
- couplings f_{1R}, f_{2L} and f_{2R} are small,

Azimuthal distribution

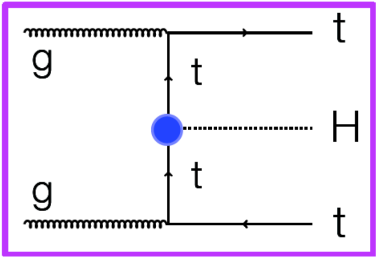


- Construct top production plane using top p_T and beam axis,
- x-component of top p_T must be positive,
- No need to reconstruct top rest frame

We define an asymmetry

$$\mathcal{A}_\phi^\ell = \frac{\sigma(\cos\phi_\ell > 0) - \sigma(\cos\phi_\ell < 0)}{\sigma(\cos\phi_\ell > 0) + \sigma(\cos\phi_\ell < 0)},$$

Associated Production of top and Higgs



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- Would be a good direct probe of CP violating phase ζ_t,
- Cross section drops with ζ_t
- Not sensitive to sign of top Yukawa

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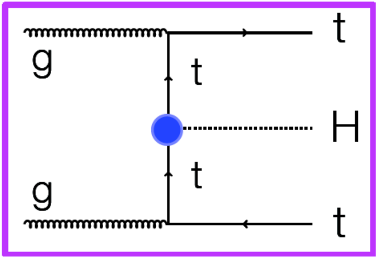

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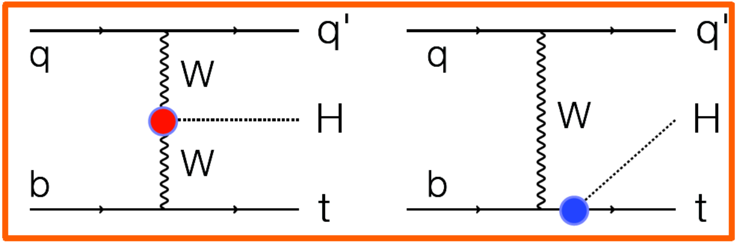

- Single top with Higgs has much smaller cross section
- Interference is largely destructive

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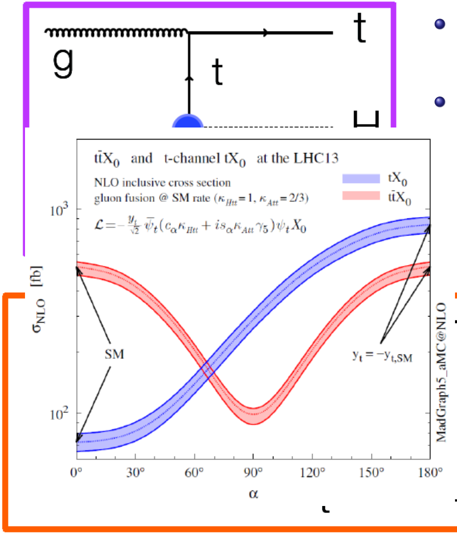

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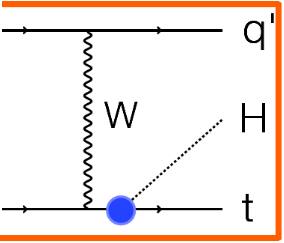

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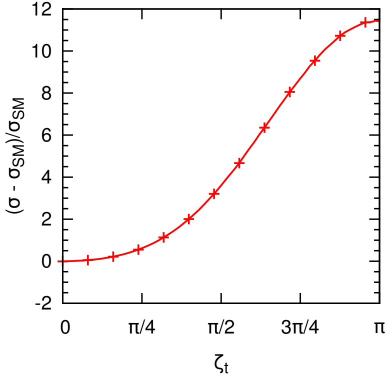
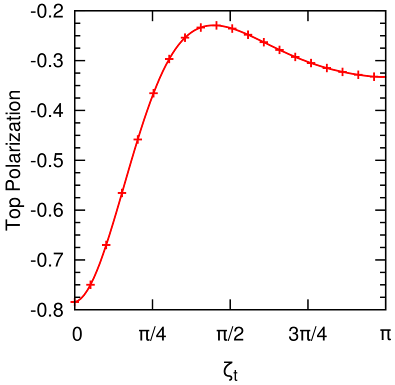
Cross section for thj production



- Cross section, $\sigma \sim 72$ fb (SM),
- May be discovered in Run II LHC with full data set of 3 ab^{-1},
- However, cross section rises sharply with ζ_t
- Quite sensitive to sign of top Yukawa

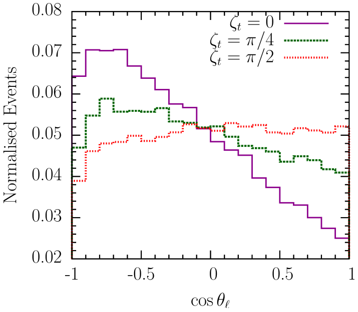
- Search strategy for thj heavily relies on the very forward light jet in the process,
- Putting a $|\eta_j| > 2.5$ helps in suppressing the background,
- Main backgrounds are top pair and $tj\gamma\gamma$

Polarization as a fuction of ζ_t



- Polarization is obtained by calculating left and right helicity cross sections,
- Higgs emission from top changes the top helicity,
- While Higgs emitted from W does not effect top helicity,
- This plot is the theoretical expectation for P_t,
- P_t is quite sensitive to CP phase ζ_t

Distributions in the rest frame



- $\ell^{\pm}$ distribution is sensitive to phase ζ_t in the rest frame of top quark,
- For $\zeta_t = \pi/2$, distribution is flat due to pure pseudoscalar coupling,
- Need to reconstruct top full momentum

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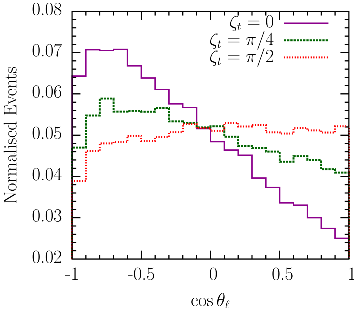

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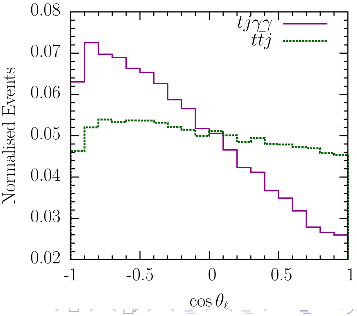
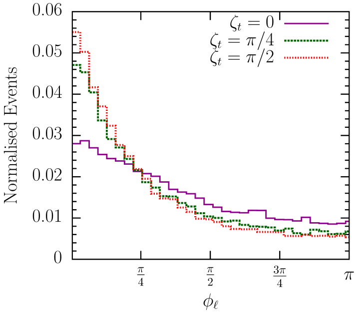
- Due to parity conserving coupling, $t\bar{t}j$ distribution is flat
- $tj\gamma\gamma$ arise from EW coupling leading to large slope in the distribution,
- Slope of the distribution $\propto$ top polarization.



Distributions in the laboratory frame

- Lab frame azimuthal distributions are insensitive to any new physics in decay,
- Thus probe the polarization without any impurity,
- Distribution for $\zeta_t = 0$ and $\zeta_t = \pi/4$ are quite distinct,



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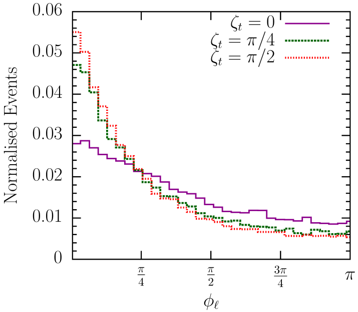
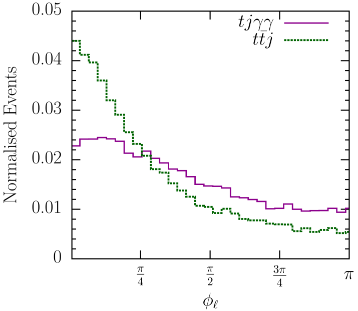
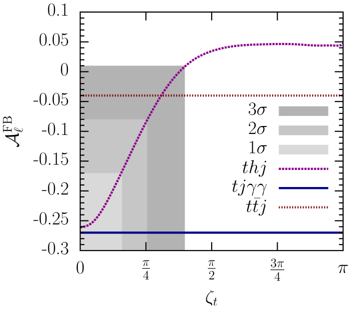




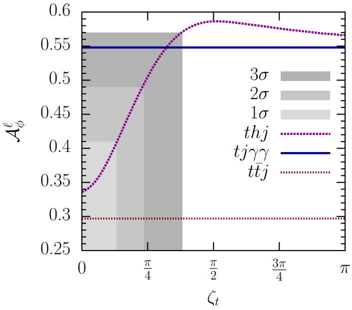
- Distributions are very asymmetric in the left and right portion of the detector,
- Background asymmetry are much smaller than the signal for most of the parameter space,

Asymmetries



- 1,2,3σ bands of statistical uncertainty are shown,
- Limits are evaluated with 3000 fb^{-1} of luminosity,
- Rest frame asymmetry is more difficult to reconstruct

- Also contributions from backgrounds are shown
- Lab frame asymmetry can determine ζ_t upto $\pi/8$ with 3000 fb^{-1},
- Without having to reconstruct top rest frame



Conclusions

- Determining the CP properties of the Higgs boson is a task of fundamental importance,
- Can only be probed in the associated production mechanism,
- Apart from cross section, top polarization may provide another handle to probe CP phase of the top Yukawa coupling,
- Lab frame observable, apart from being easily measurable, are also more sensitive to the phase,
- It will require a full 14 TeV data set to put a limit on the CP phase from the direct search

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