

MEASURING THE CP NATURE OF TOP-HIGGS COUPLINGS

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OUTLINE

- Baseline for future e-p machine
- Single Higgs production with top-quark and formalism
- Simulation and Observables
- Exclusion Limits
- Constraints from LHC and e^+e^- on top-Higgs coupling
- Summary and conclusions

A Baseline for the FCC-he

Oliver Brüning¹ Max Klein^{1,2}, Daniel Schulte¹, Frank Zimmermann¹¹ CERN, ² University of LiverpoolMarch 3rd, 2016

Table 1: Baseline parameters of future electron-proton collider configurations based on the ERL electron linac.

parameter [unit]	LHeC CDR	ep at HL-LHC	ep at HE-LHC	FCC-he
E_p [TeV]	7	7	15	50
E_e [GeV]	60	60	60	60
\sqrt{s} [TeV]	1.3	1.3	1.9	3.5
bunch spacing [ns]	25	25	25	25
protons per bunch [10^{11}]	1.7	2.2	2.2	1
ϵ_p [μm]	3.7	2	2	2.2
electrons per bunch [10^9]	1	2.3	2.3	2.3
electron current [mA]	6.4	15	15	15
IP beta function β_p^* [cm]	10	7	10	15
hourglass factor	0.9	0.9	0.9	0.9
pinch factor	1.3	1.3	1.3	1.3
luminosity [$10^{33}\text{cm}^{-2}\text{s}^{-1}$]	1.3	10.1	15.1	9.2



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Measuring CP nature of top-Higgs couplings at the future Large Hadron electron Collider



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ABSTRACT

We investigate the sensitivity of top-Higgs coupling by considering the associated vertex as CP phase (ζ_t) dependent through the process $p e^- \rightarrow \bar{t} h \nu_e$ in the future Large Hadron electron Collider. In particular the decay modes are taken to be $h \rightarrow b\bar{b}$ and $\bar{t} \rightarrow$ leptonic mode. Several distinct ζ_t dependent features are demonstrated by considering observables like cross sections, top-quark polarisation, rapidity difference between h and \bar{t} and different angular asymmetries. Luminosity (L) dependent exclusion limits are obtained for ζ_t by considering significance based on fiducial cross sections at different σ -levels. For electron and proton beam-energies of 60 GeV and 7 TeV respectively, at $L = 100 \text{ fb}^{-1}$, the regions above $\pi/5 < \zeta_t \leq \pi$ are excluded at 2σ confidence level, which reflects better sensitivity expected at the Large Hadron Collider. With appropriate error fitting methodology we find that the accuracy of SM top-Higgs coupling could be measured to be $\kappa = 1.00 \pm 0.17(0.08)$ at $\sqrt{s} = 1.3(1.8) \text{ TeV}$ for an ultimate $L = 1 \text{ ab}^{-1}$.

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Formalism:

In the Standard Model top and bottom Yukawa Couplings are given as :

CP-even

$$\mathcal{L}_{\text{Yukawa}} = -\frac{m_t}{v} \bar{t} t h - \frac{m_b}{v} \bar{b} b h, \text{ Here } v \equiv (\sqrt{2} G_F)^{-1/2} = 2m_W / g.$$

Beyond the Standard Model top and bottom Yukawa Couplings to study CP-nature of Higgs-boson are given as :

CP Phase

$$\mathcal{L} = -\frac{m_t}{v} \bar{t} [\kappa \cos \zeta_t + i \gamma_5 \sin \zeta_t] t h - \frac{m_b}{v} \bar{b} [\cos \zeta_b + i \gamma_5 \sin \zeta_b] b h.$$

$\zeta_{t,b} = 0$ or π : Pure scalar state

$\zeta_{t,b} = \pi/2$: Pure pseudo scalar state

In the SM $\kappa = 1, \zeta_t = 0$

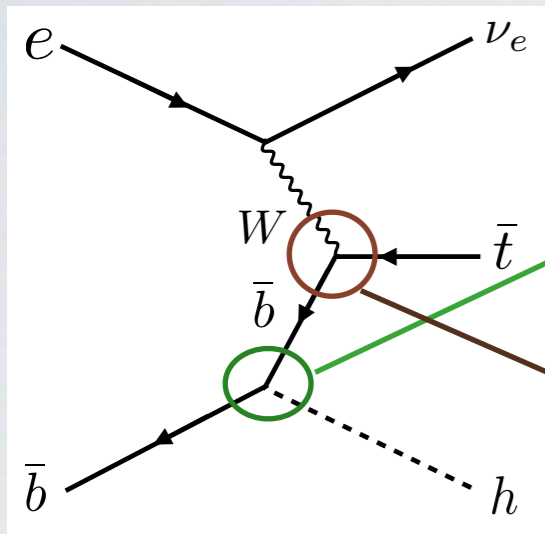
$\zeta_{t,b} \in (0, \pi/2)$ or $(\pi/2, \pi)$: A mixture of different CP states

- In e-p machine, the top-Higgs couplings can be probed via associated production of Higgs-boson with anti-top quark necessarily with 5F proton

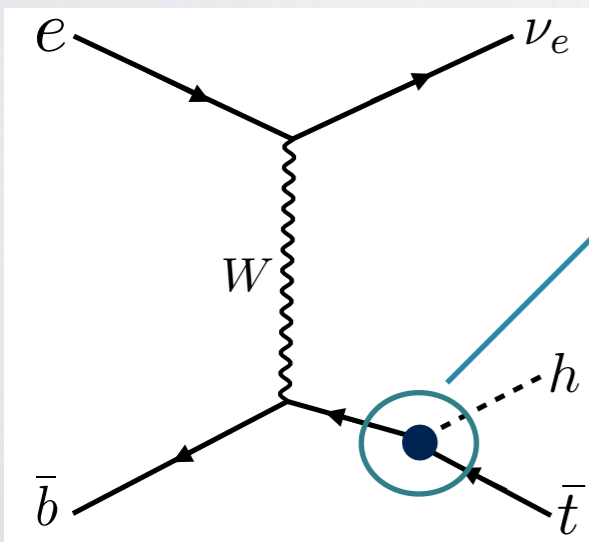
Process

$$p e^{-} \rightarrow \bar{b} e^{-} \rightarrow \bar{t} h \nu_e$$

Feynman Diagrams

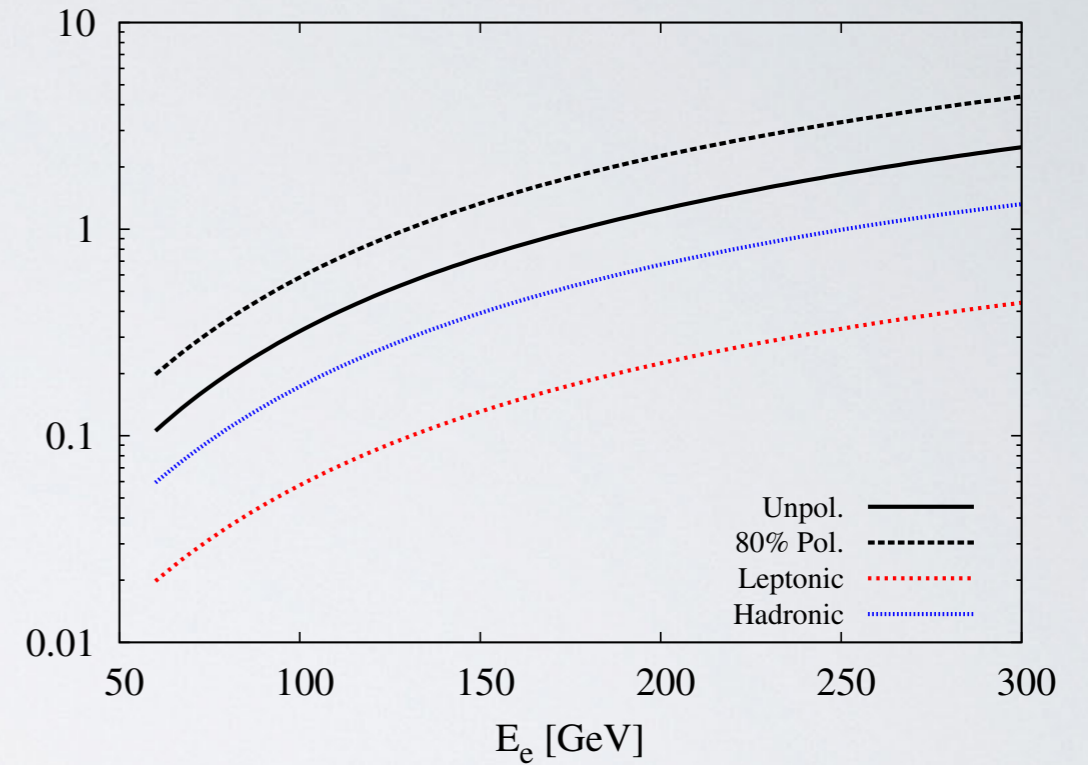
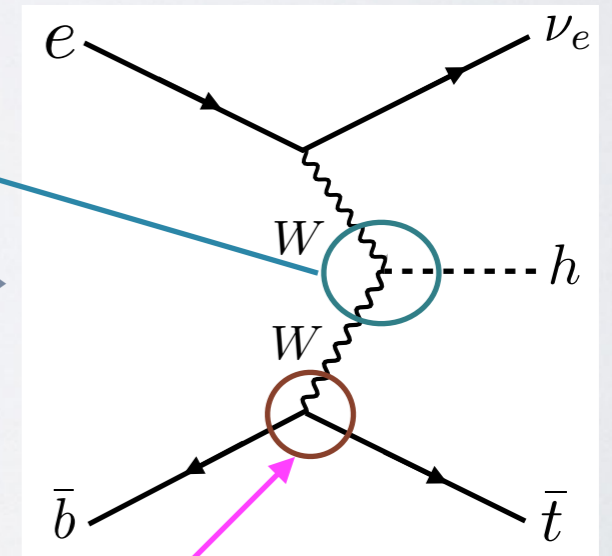


Inensitive to BSM



Sensitive to BSM

Negative Interference



[Eur. Phys. J. C {75}, no. 12, 577 (2015)]

Observables:

From here onwards we only use following Lagrangian in our studies:

$$\mathcal{L} = -\frac{m_t}{v} \bar{t} [\kappa \cos \zeta_t + i\gamma_5 \sin \zeta_t] t h$$

(All analysis at “parton”-level only)

I. Cross section

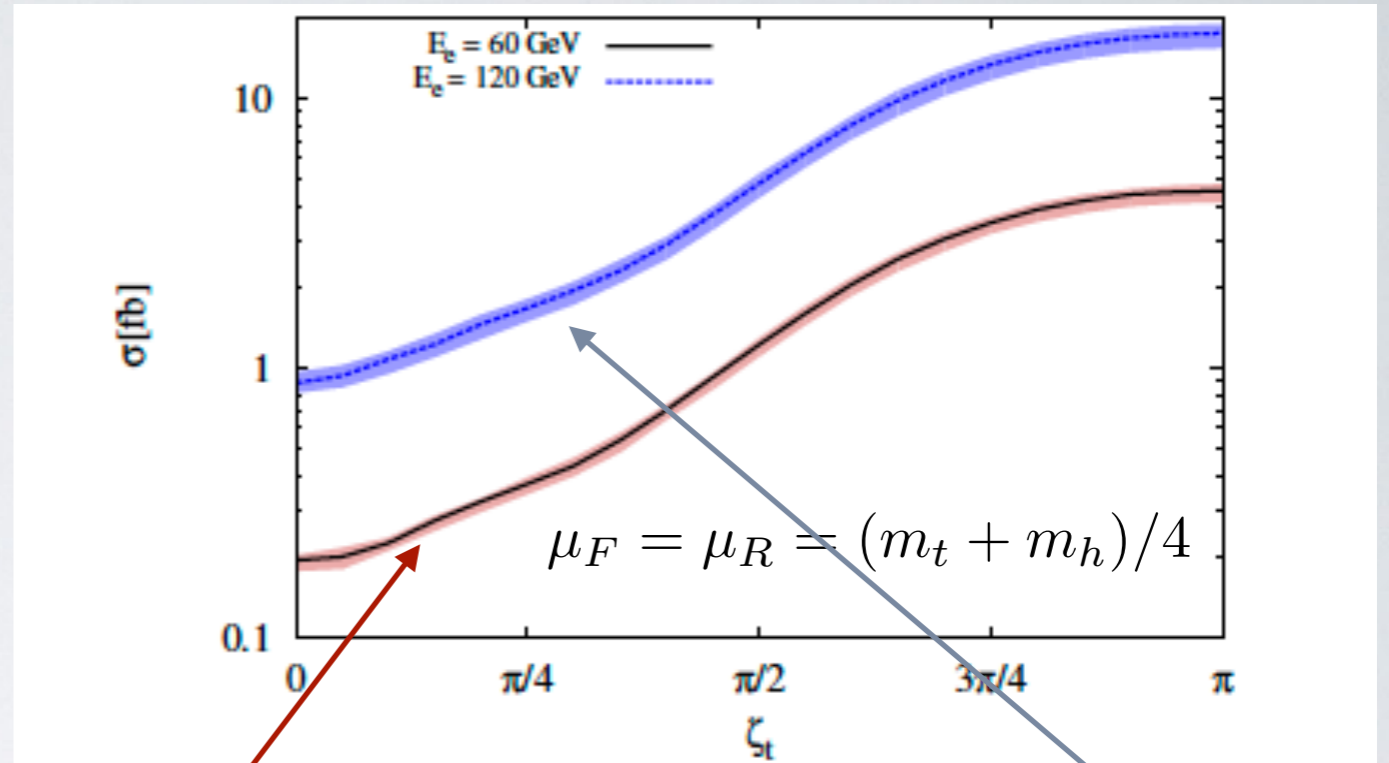


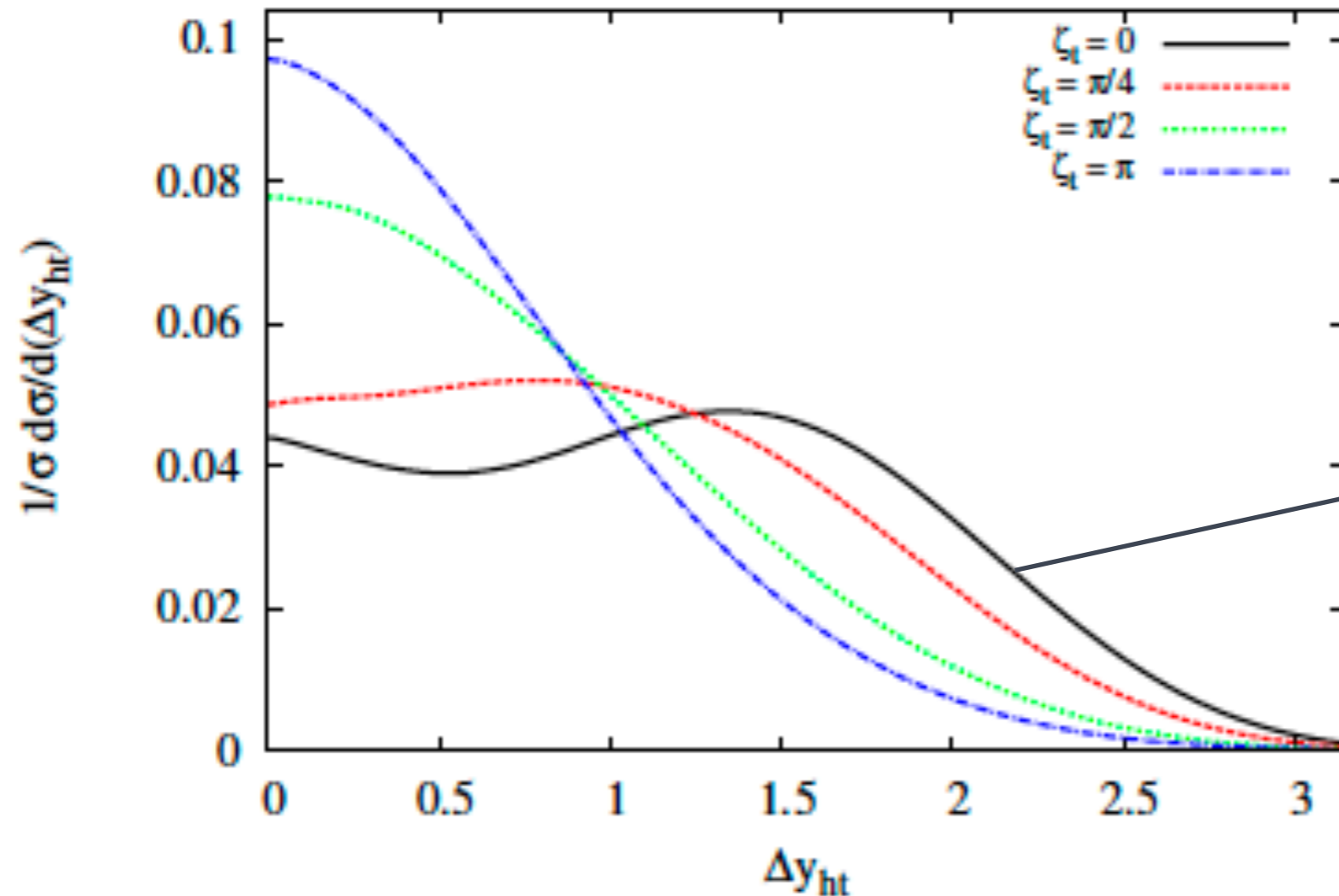
Figure 3: Total cross section as a function of ζ_t with scale uncertainties. The *black solid* and *blue dotted* lines correspond to $E_e = 60$ and 120 GeV respectively for fixed $E_p = 7$ TeV and $\mu_F = \mu_R = (m_t + m_h)/4$.

Cross sections of signal and backgrounds in charged current (CC), neutral current (NC) and photo-production (PHOTO) modes for $E_e = 60$ GeV and $E_p = 7$ TeV as explained in the text. Here X could be either of missing energy or electron and j is all possible combinations of light-, c - and b -quarks and gluons. For this estimation we use basic cuts as mentioned in text and electron polarisation is taken to be -0.8 .

Process	CC (fb)	NC (fb)	PHOTO (fb)
Signal:	1.98×10^{-2}	–	–
$Wjjj + X, \setminus h$	$2.05 \times 10^{+2}$	$3.18 \times 10^{+1}$	$3.40 \times 10^{+3}$
$Wjjj + X, \setminus t$	$4.18 \times 10^{+1}$	$3.16 \times 10^{+1}$	$3.41 \times 10^{+3}$
$Wjjj + X, \setminus th$	$4.16 \times 10^{+1}$	$3.18 \times 10^{+1}$	$3.41 \times 10^{+3}$

Observables:

2. Rapidity difference



Sensitive to
phase angles

SM

Figure 4: The normalised difference between rapidities of top quark and the Higgs boson at some typical values of ζ_t for $E_e = 60$ GeV and $E_p = 7$ TeV. The *black* solid line corresponds to the SM case, while dotted lines correspond to different values of ζ_t .

Observables:

3. Top-Quark Polarisation

$$P_t = \frac{N_+ - N_-}{N_+ + N_-} \equiv \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Information of top-spin reflect to its decay product:

$$\frac{1}{\Gamma_f} \frac{d\Gamma_F}{d \cos \theta_f} = \frac{1}{2} (1 + \alpha_f P_t \cos \theta_f)$$

Partial width of f

For $t \rightarrow b + W^\pm (\rightarrow l^\pm + \nu_l)$
 $\alpha_W = -\alpha_b = 0.39,$
 $\alpha_\nu = -0.3,$
 $\alpha_W = 1$ at LO

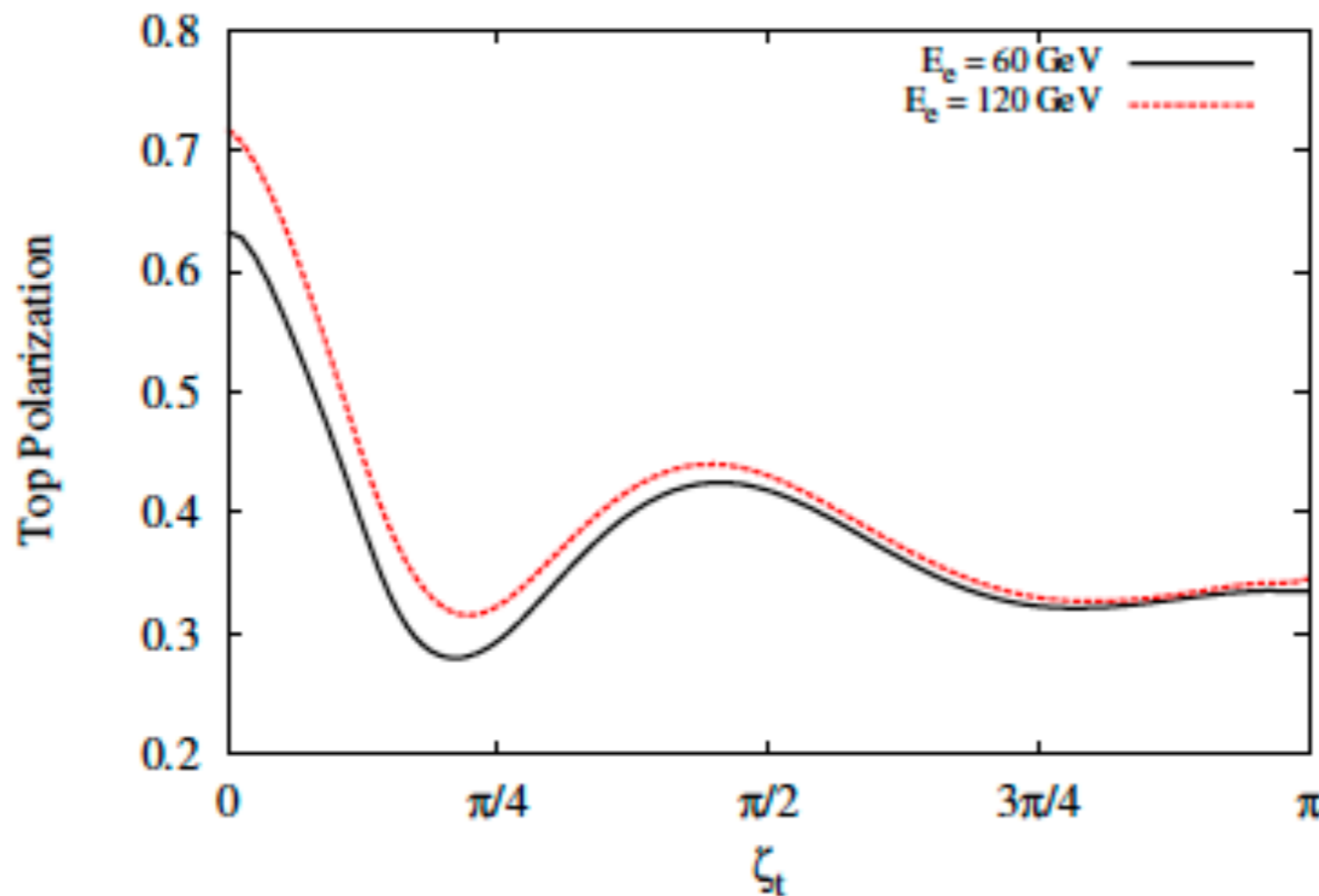


Figure 5: The degree of longitudinal polarisation (P_t) of the top quark against ζ_t . The *black* solid and *red* dotted lines correspond to the $E_e = 60$ and 120 GeV, while E_p is fixed at 7 TeV.

Observables:

Leptonic only:

Full process: $p e^- \rightarrow \bar{t} h \nu_e$,
 $h \rightarrow b\bar{b}, \bar{t} \rightarrow W^- \bar{b}, W^- \rightarrow l^- \nu_l$
 $(l^\pm = e^\pm, \mu^\pm)$

Optimising Events:

- (a) $p_T^{jet} \geq 20 \text{ GeV}, p_T^{lep} \geq 10 \text{ GeV}$,
- (b) $-2 \leq \eta_b \leq 5, 2 \leq \eta_j \leq 5$,
- (c) $\Delta R > 0.4$,
- (d) $\text{MET} > 10 \text{ GeV}$,
- (e) $115 < m_{bb} < 130 \text{ GeV}$,
- (f) $160 < m_t < 177 \text{ GeV}$.

$$m_t^2 = (m_T + m_{b_1})^2,$$

$$m_T = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\phi_l - \phi_\nu))}$$

b – tagging efficiency is assumed to be 70%, fake rates from c – initiated jets and light jets to the b -jets to be 10% and 1%.

4. Asymmetries

$$A_{\theta_{ij}} = \frac{N_+^A(\cos \theta_{ij} > 0) - N_-^A(\cos \theta_{ij} < 0)}{N_+^A(\cos \theta_{ij} > 0) + N_-^A(\cos \theta_{ij} < 0)},$$

$$A_{\Delta\phi_{ij}} = \frac{N_+^A(\Delta\phi_{ij} > \pi/2) - N_-^A(\Delta\phi_{ij} < \pi/2)}{N_+^A(\cos \theta_{ij} > 0) + N_-^A(\cos \theta_{ij} < 0)},$$

$$\delta_\alpha = \sqrt{\frac{1 - A_\alpha^2(\zeta_t)}{\sigma_{\zeta_t} \cdot L}}, \quad (\alpha = \theta_{ij}, \Delta\phi_{ij})$$

Follow the top-quark polarisation pattern

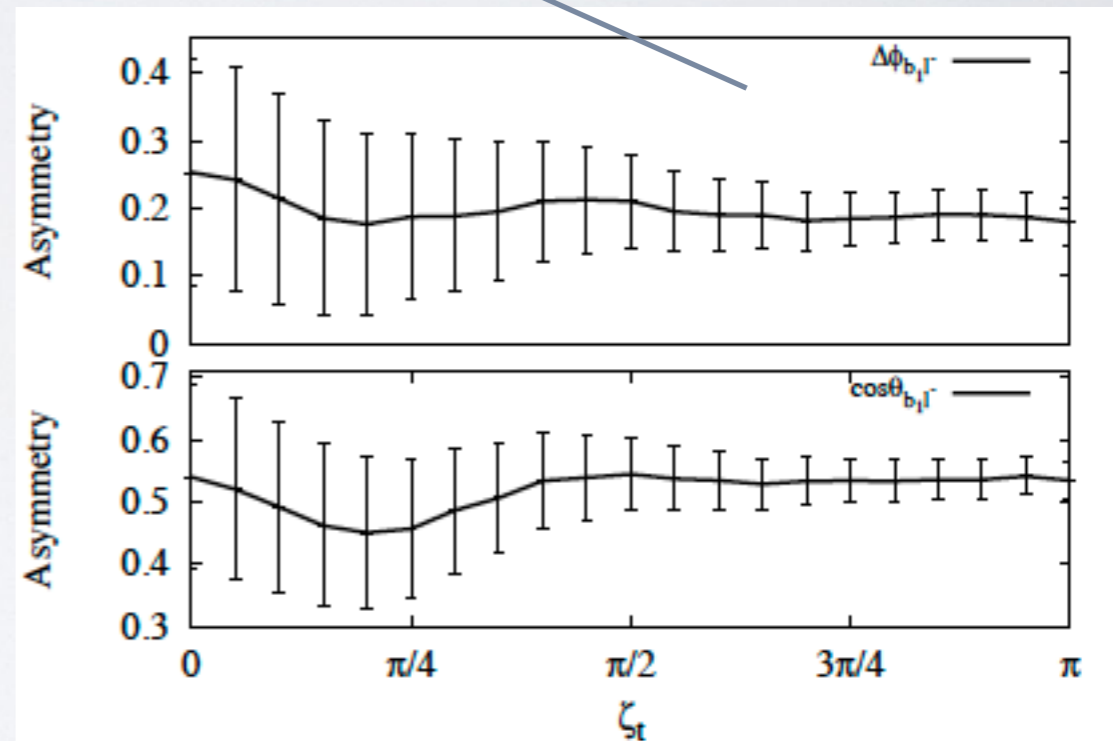


Figure 6: Variation of angular asymmetries between the leading b -tagged jet and the charged lepton in the differential azimuthal and polar angle ($\Delta\phi_{b_1 l^-}$ and $\cos\theta_{b_1 l^-}$) distributions with respect to ζ_t for $E_e = 60 \text{ GeV}$ and $E_p = 7 \text{ TeV}$. The error bars correspond to the uncertainties in asymmetry measurement at $L = 1 \text{ ab}^{-1}$.

Exclusion Limits:

Based on Asymmetry

Uncertainty

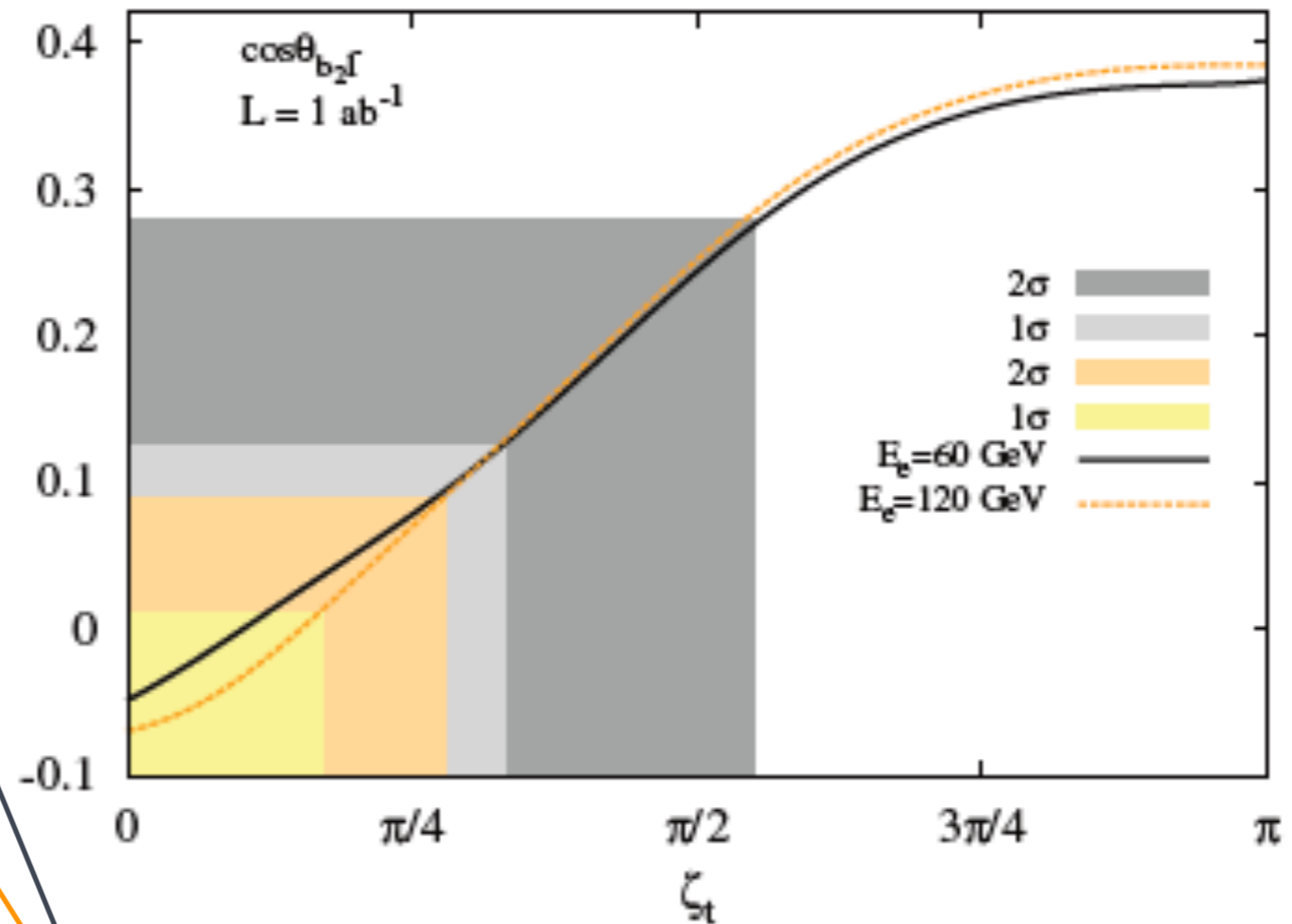
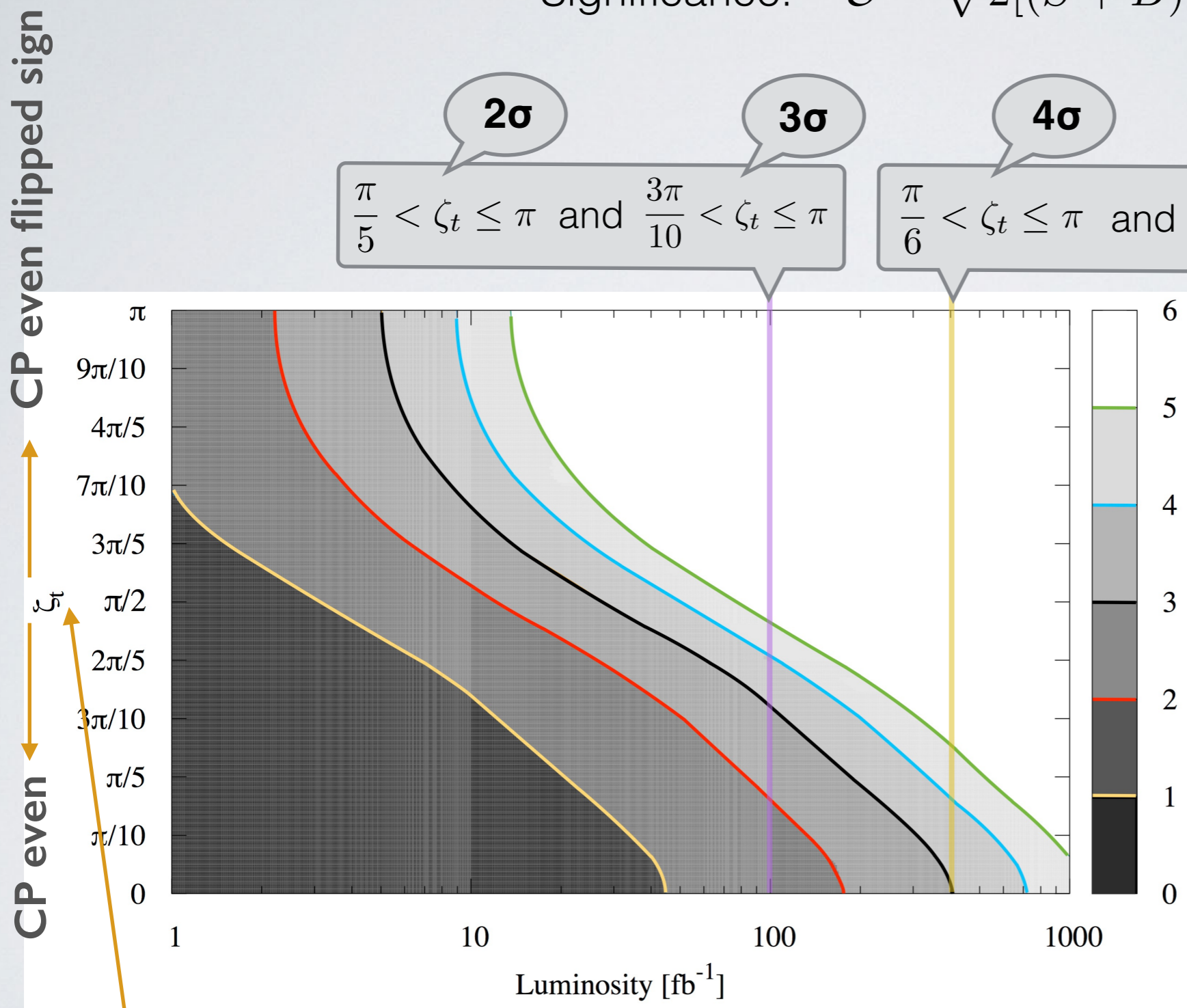


Figure 7: Variation of the angular asymmetry between the subleading b -tagged jets and charged leptons in the differential polar angle ($\cos \theta_{b_2 l^-}$) distribution with respect to ζ_t for $E_e = 60$ GeV (*black solid line*) and $E_e = 120$ GeV (*orange dashed line*) with $E_p = 7$ TeV. The shaded regions *grey (orange)* and *light grey (yellow)* corresponds to 2σ and 1σ of statistical uncertainty in the measurement of the asymmetry in the SM for $E_e = 60$ (120) GeV at $L = 1 \text{ ab}^{-1}$ respectively.

$$\delta A_{\cos \theta_{b_2 l^-}} = \sqrt{\frac{1 - (A_{\cos \theta_{b_2 l^-}}^{\text{SM}})^2}{\sigma_{\text{SM}} \cdot L}}$$

Exclusion Contour

Significance: $\mathcal{S} = \sqrt{2[(S + B) \log(1 + S/B)] - S}$



2σ
 $\frac{\pi}{5} < \zeta_t \leq \pi$ and $\frac{3\pi}{10} < \zeta_t \leq \pi$

3σ
 $\frac{\pi}{6} < \zeta_t \leq \pi$ and $\frac{\pi}{4} < \zeta_t \leq \pi$

4σ
 $\frac{\pi}{6} < \zeta_t \leq \pi$ and $\frac{\pi}{4} < \zeta_t \leq \pi$

5σ
 $\frac{\pi}{6} < \zeta_t \leq \pi$ and $\frac{\pi}{4} < \zeta_t \leq \pi$

For higher $E_e = 120 \text{ GeV}$, the cross section for **signal** (**background**) is enhanced approximately by a factor of **4** (**3**).

The luminosity required for exclusion is smaller compared to the $E_e = 60 \text{ GeV}$

At Lum. $L=100 \text{ fb}^{-1}$

$\frac{\pi}{20} < \zeta_t \leq \pi$ **4σ**

$\frac{\pi}{6} < \zeta_t \leq \pi$ **5σ**

$E_e = 60 \text{ GeV}$ and $E_p = 7 \text{ TeV}$.

The exclusion contour with respect to integrated luminosities at various phase angles by considering significance based on fiducial cross section.

Sensitivity of tth Coupling

$$\kappa = \frac{\sqrt{S+B}}{2S} \quad \mathcal{L} = 1 \text{ ab}^{-1}$$

$$\zeta_t = 0$$

$E_e = 60 \text{ GeV}$

$$\kappa = 1.00 \pm 0.17$$

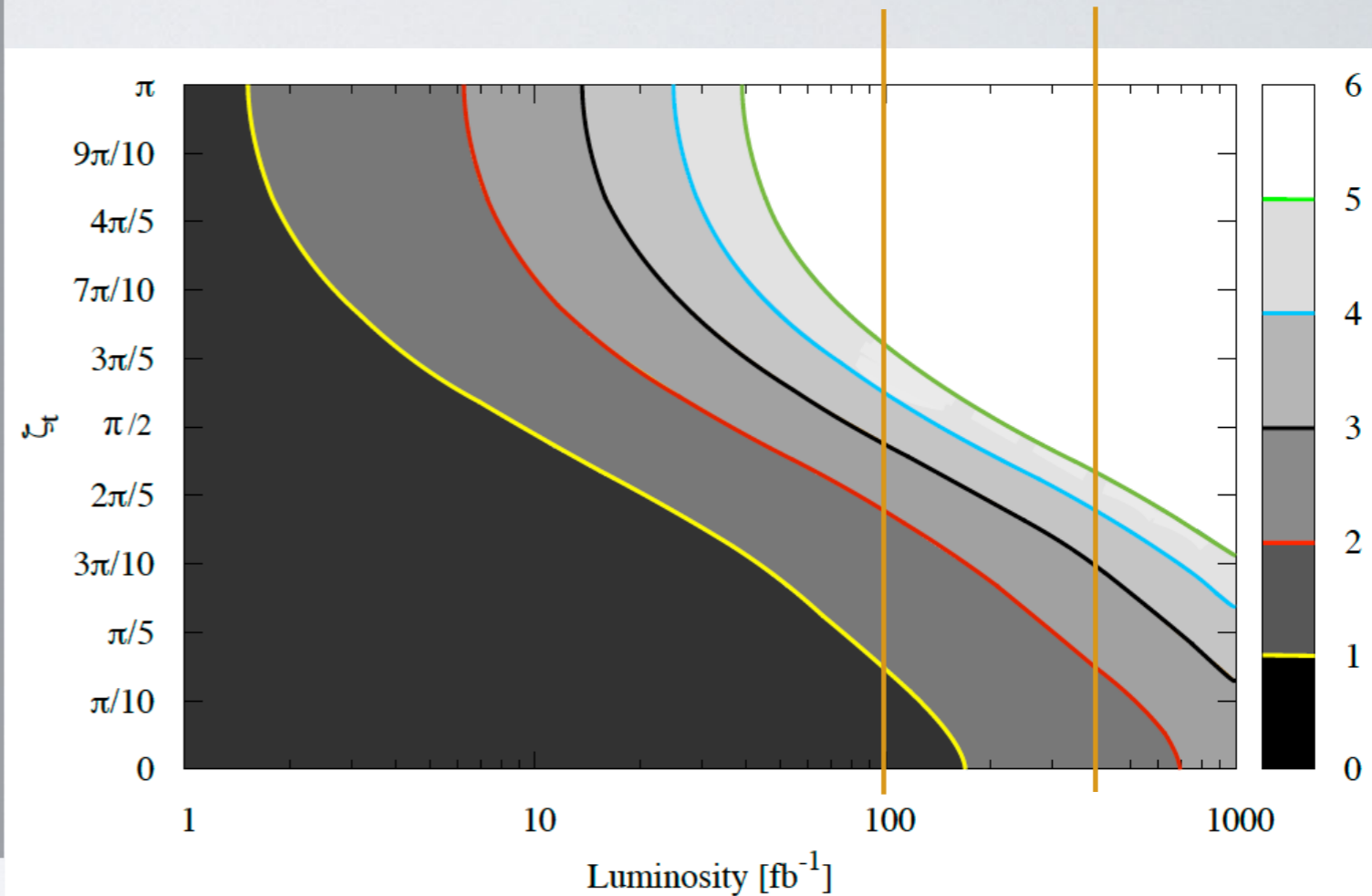
$E_e = 120 \text{ GeV}$

$$\kappa = 1.00 \pm 0.08$$

$E_e = 40 \text{ GeV}$

$$\kappa = 1.00 \pm 0.31$$

Exclusion Contour



$E_e = 40 \text{ GeV}$ and $E_p = 7 \text{ TeV}$.

The exclusion contour with respect to integrated luminosities at various phase angles by considering significance based on fiducial cross section.

Constraint from e+e- and LHC

Denoting the CP-even (odd) couplings as: C_t^S (C_t^P)

- LHC Run-I and Run-II Higgs data set:

$$0.85 < C_t^S < 1.20, |C_t^P| < 0.37$$

- Stronger than LHC Run-I data set:

$$0.68 < C_t^S < 1.20, |C_t^P| < 0.54$$

- Future e+e- at 240 GeV $e^+e^- \rightarrow h\gamma$

[arXiv:1610.06676]

$$|C_t^P| < 0.19 \text{ with } 0.5\% \text{ accuracy}$$

Converting in terms of Phase angle : $\zeta_t = \tan^{-1} \left(\frac{C_t^P}{C_t^S} \right)$

One can realise better sensitivity at the LHeC

Summary

- Large top-Yukawa coupling provide a unique opportunity to characterise Higgs-boson at colliders, namely, at the LHC and future e^+e^- or e - p colliders.
- Nominal cross section and clean signature at e - p collider shows advantages over other machines.
- Different observables like top-polarisation ,the difference between rapidities of anti-top quark and Higgs-boson provides unique features that are clearly distinct from the pure scalar type couplings.
- By considering the leptonic decay mode of the anti-top quark and Higgs into b -quark pair, we constructed the asymmetry observables and constrain the top-Yukawa couplings at different possible energies for e - p configuration.
- We find that almost all values of ζ_t can be excluded at 2σ (4σ) with an integrated luminosity of 200 /fb (700 /fb) for c.m.e. of 1.3 TeV. These limits are superior to those found in studies at the HL-LHC.
- The cross section measurement combined with accurate measurements of the kinematic observables can be a powerful probe at the LHeC to uncover the finer details of the nature of the top-Higgs couplings.