



# Gluon jet anisotropy as a new observable to probe the $CP$ structure of Higgs-top coupling

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# Higgs $CP$ property

## ❑ Higgs identity

- Scalar.  $m_H = 125\text{GeV}$ .
- More tests are needed to confirm it as the SM Higgs
- $CP$  property  $\Rightarrow$  baryogenesis

## ❑ Higgs-top interaction

$$\mathcal{L} \supset -\frac{m_t}{v} h \bar{t} (\kappa + i \tilde{\kappa} \gamma_5) t$$

  
CP-even      CP-odd

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- $\kappa_t$ : Scales the overall rate
- $\alpha$ :  $CP$  phase.  $\alpha \neq 0 \Rightarrow CP$  violation

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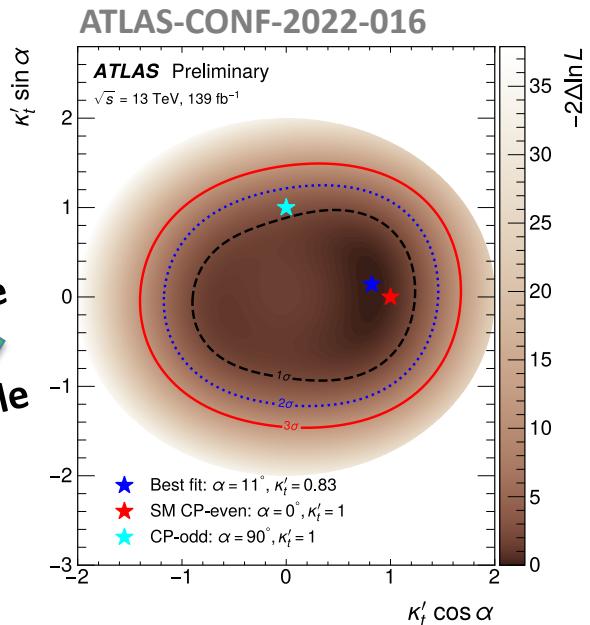
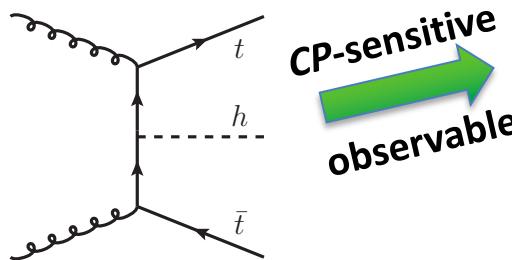
$\downarrow$

**$CP$ -even**       **$CP$ -odd**

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See also: CMS-HIG-21-006

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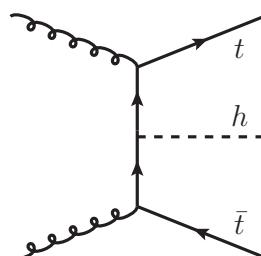
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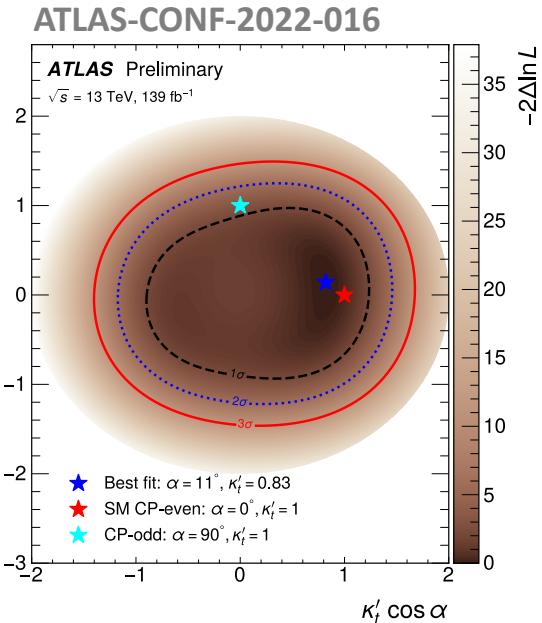
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*CP-sensitive  
observable*

Using *CP-odd* observables  
can enhance the sensitivity!

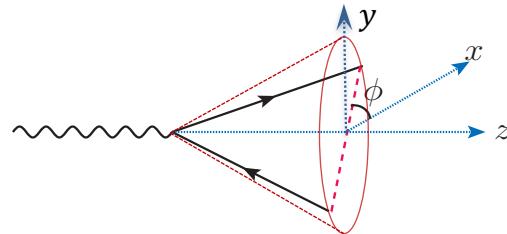


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# Linear polarization of a gluon

## □ Linear polarization vs. helicity/circular polarization

helicity pol.   $|\pm 1\rangle$    $|e^{\pm i\phi}|^2 = 1$





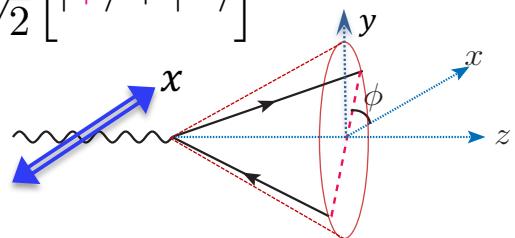
# Linear polarization of a gluon

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linear pol.  $|x\rangle = -\frac{1}{\sqrt{2}}[|+\rangle - |-\rangle], \quad |y\rangle = \frac{i}{\sqrt{2}}[|+\rangle + |-\rangle]$

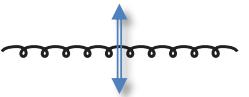
$|e^{+i\phi} \pm e^{-i\phi}|^2 \rightarrow 2(1 \pm \cos 2\phi)$



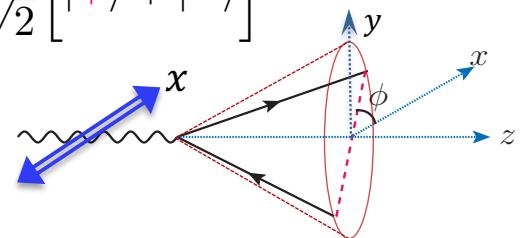
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## □ Gluon polarization density matrix

$$\rho_{\lambda\lambda'} = \frac{1}{2}(1 + \boldsymbol{\xi} \cdot \boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2} \begin{pmatrix} 1 + \xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1 - \xi_3 \end{pmatrix} +$$

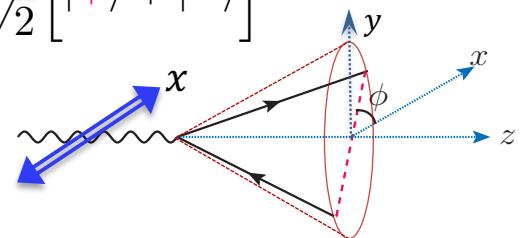
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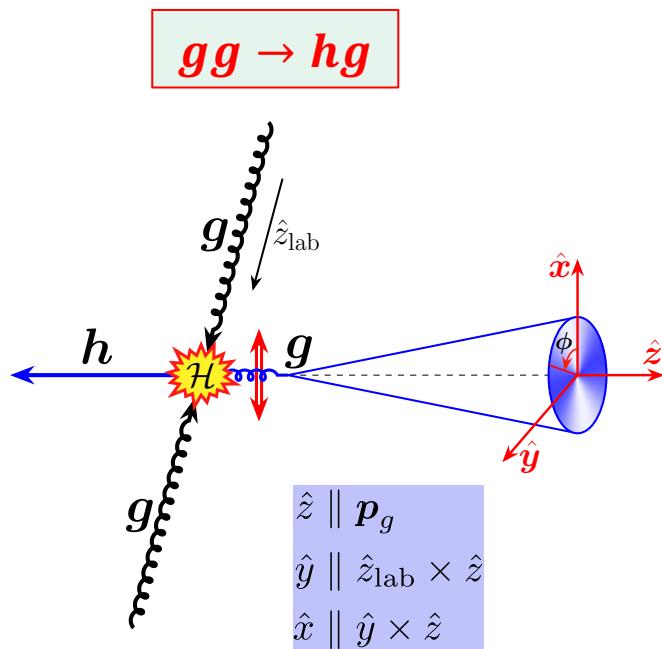
$\xi_3 = \rho_{++} - \rho_{--}$  net helicity

$\xi_{1,2} \sim \rho_{+-}$  helicity interference

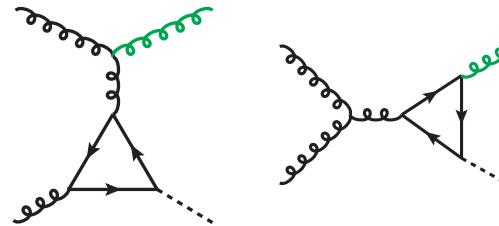
Two independent linear pol. dof



# Linearly polarized gluon jet

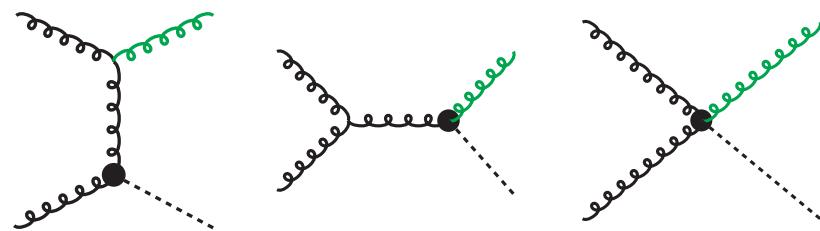


SM + CP-odd



$$\mathcal{L} \supset -\frac{m_t}{v} h \bar{t} (\kappa + i \tilde{\kappa} \gamma_5) t$$

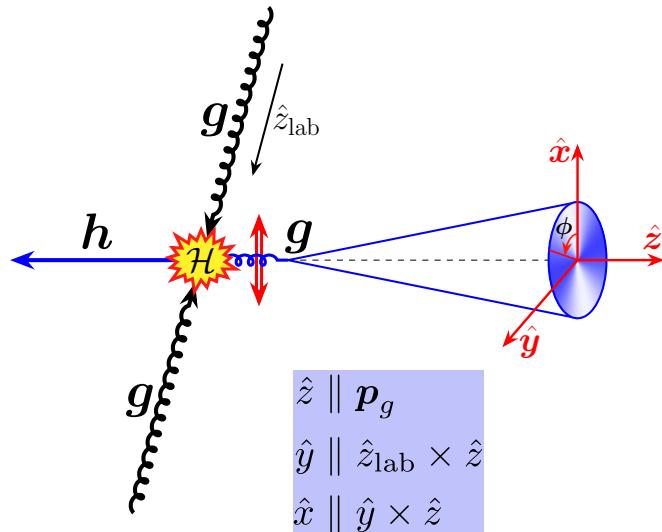
EFT ( $m_t \rightarrow \infty$ )



$$\mathcal{L}_{\text{EFT}} \supset -\frac{h}{4v} \left( \lambda G_{\mu\nu}^a G^{a\mu\nu} + \tilde{\lambda} \tilde{G}_{\mu\nu}^a \tilde{G}^{a\mu\nu} \right)$$

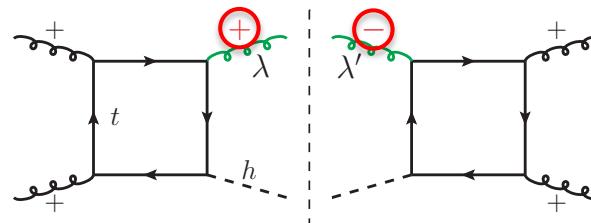
# Linearly polarized gluon jet

$$gg \rightarrow hg$$



$$\frac{d\sigma_w}{dy_g \, dp_T^2 \, dm_J^2 \, d\phi} = \frac{d\hat{\sigma}}{dy_g \, dp_T^2} \frac{dJ(\xi(p_T, y_g), m_J^2, \phi)}{d\phi}$$

## 1. Production of polarized gluon ( $\xi_1, \xi_2, \xi_3$ )

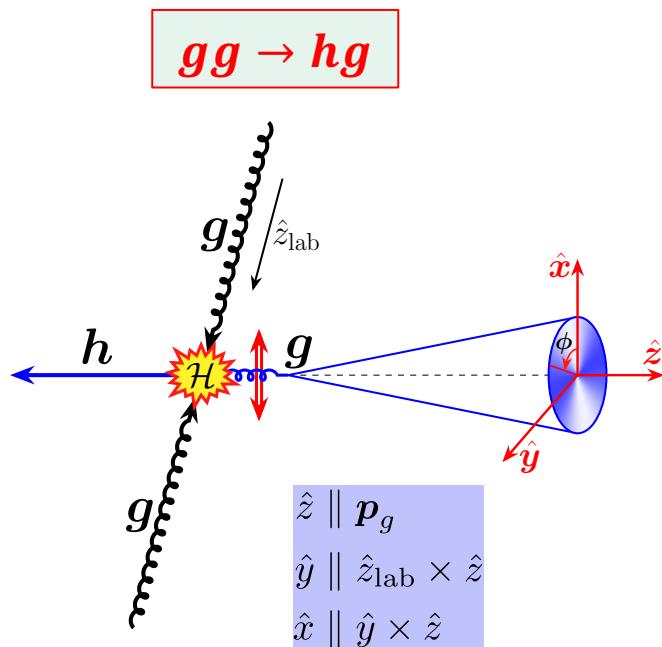


$$\sum_{\lambda_1, \lambda_2} \mathcal{M}_{\lambda_1 \lambda_2} \rho_{\lambda_1 \lambda_2} \mathcal{M}_{\lambda_1 \lambda_2}^* \equiv \rho_{\lambda \lambda'}(\xi) \cdot \overline{|\mathcal{M}|^2}$$

$\xi_{1,2} \sim \rho_{+-} = \underline{\text{helicity interference}}$



# Linearly polarized gluon jet



**Linear polarization can be measured!**

$$\frac{d\sigma_w}{dy_g dp_T^2 dm_J^2 d\phi} = \frac{d\hat{\sigma}}{dy_g dp_T^2} \frac{dJ(\xi(p_T, y_g), m_J^2, \phi)}{d\phi}$$

1. Production of polarized gluon ( $\xi_1, \xi_2, \xi_3$ )
2. Fragmentation of polarized gluon jet

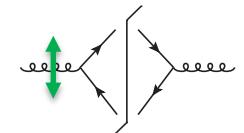
$$\frac{dJ}{d\phi} = \frac{1}{2\pi N_{c,g}(k \cdot n)^2} \sum_X \int d^4x e^{ik \cdot x} [\rho_{\lambda\lambda'}(\xi) O(\phi, X)]$$

$$\times \varepsilon_{\lambda' \nu}^*(p_g) \langle 0 | W_{ac}(\infty, x; n) n_\sigma G_c^{\sigma\nu}(x) | X \rangle$$

$$\times \varepsilon_{\lambda\mu}(p_g) \langle X | W_{ab}(\infty, 0; n) n_\rho G_b^{\rho\mu}(0) | 0 \rangle$$

$$O(\phi, X) = \frac{1}{\sum_{i \in X} p_{i,T}} \sum_{i \in X} p_{i,T} \delta(\phi - \phi_i)$$

$$\frac{dJ^{(q)}}{d\phi} = \frac{\alpha_s T_F}{6\pi^2 m_J^2} \left[ 1 + \frac{1}{2} (\xi_1 \cos 2\phi + \xi_2 \sin 2\phi) \right] \quad (\text{quark tagged})$$

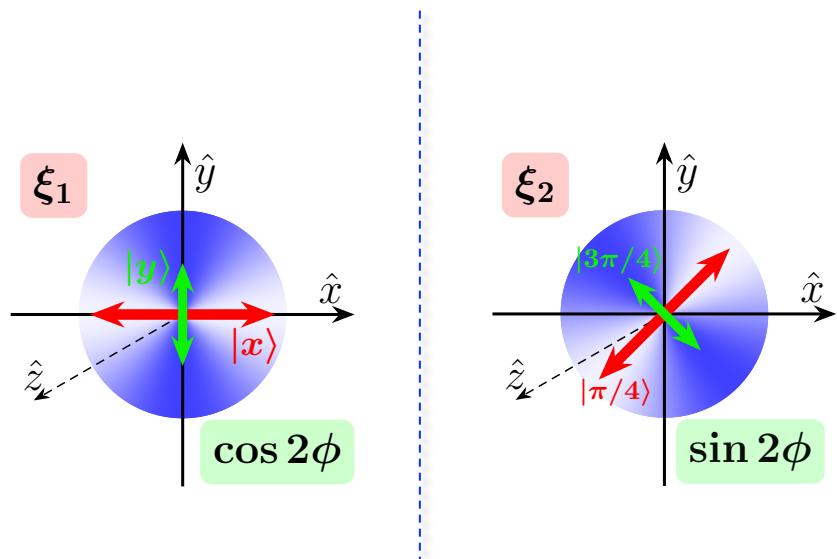


## Linear gluon polarization: $CP$ property

$$\xi_1 = \langle \pi/2 | \rho | \pi/2 \rangle - \langle 0 | \rho | 0 \rangle = \rho_{yy} - \rho_{xx}$$

$$\xi_2 = \langle 3\pi/4 | \rho | 3\pi/4 \rangle - \langle \pi/4 | \rho | \pi/4 \rangle = \rho_{\frac{3\pi}{4}, \frac{3\pi}{4}} - \rho_{\frac{\pi}{4}, \frac{\pi}{4}}$$

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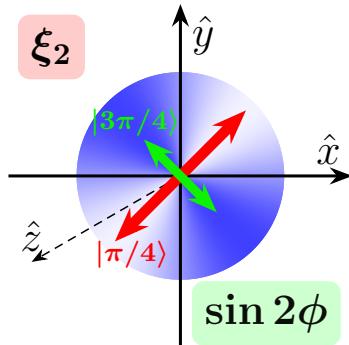
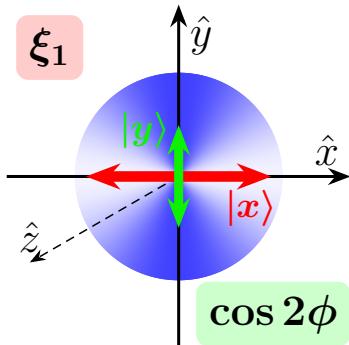
- **C**: keeps momentum and spin
- **P**: reflection about the scattering plane ( $\hat{x}$ - $\hat{z}$ )

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$$\begin{aligned} \hat{P}|x\rangle &= |x\rangle & \hat{P}|\pi/4\rangle &= |3\pi/4\rangle \\ \hat{P}|y\rangle &= |y\rangle & \hat{P}|3\pi/4\rangle &= |\pi/4\rangle \end{aligned}$$

$\xi_1 \rightarrow \xi_1$ : CP even

$$\begin{array}{c} \cos 2\phi \\ \downarrow \\ \cos 2\phi \end{array}$$



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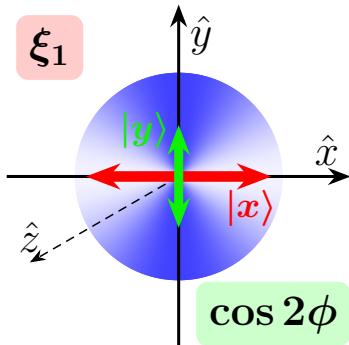
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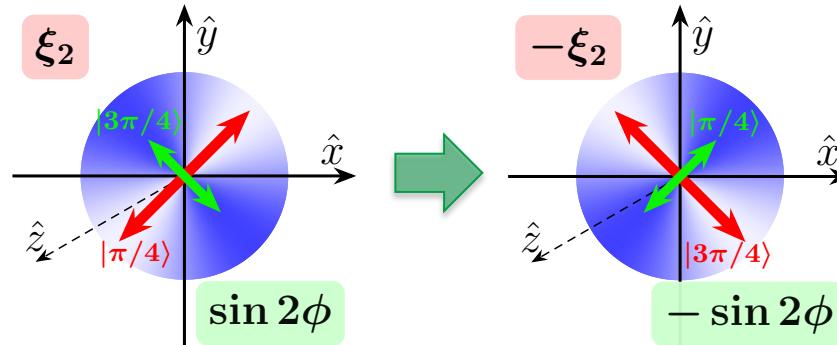
$\hat{P}|x\rangle = |x\rangle$      $\hat{P}|\pi/4\rangle = |3\pi/4\rangle$   
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$\xi_1 \rightarrow \xi_1$ : CP even

$$\begin{matrix} \cos 2\phi \\ \downarrow \\ \cos 2\phi \end{matrix}$$



$\xi_2 \rightarrow -\xi_2$ : CP odd



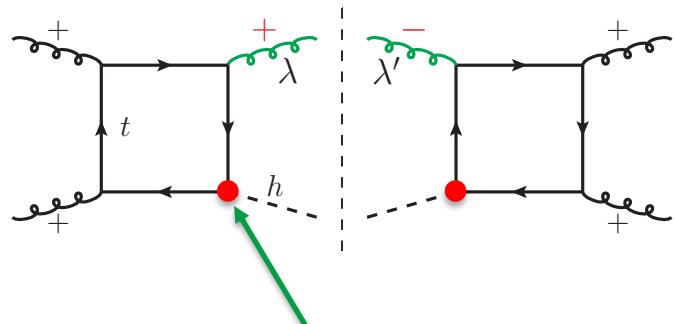
$$\begin{matrix} \sin 2\phi \\ \downarrow \\ -\sin 2\phi \end{matrix}$$

A **NEW** type of CP-odd observable!

# Polarization production in $gg \rightarrow hg$

$$\sum_{\lambda_1, \lambda_2} \mathcal{M}_{\lambda_1 \lambda_2 \lambda} \mathcal{M}_{\lambda_1 \lambda_2 \lambda'}^* = \rho_{\lambda \lambda'}(\xi) |\mathcal{M}|^2$$

$$\begin{aligned} \xi_1 &= 2 \operatorname{Re}(\rho_{+-}) \sim \kappa^2 - \tilde{\kappa}^2 \propto \cos 2\alpha & \xleftarrow{\text{CP-even}} \\ \xi_2 &= -2 \operatorname{Im}(\rho_{+-}) \propto \kappa \cdot \tilde{\kappa} \propto \sin 2\alpha & \xleftarrow{\text{CP-odd}} \end{aligned}$$



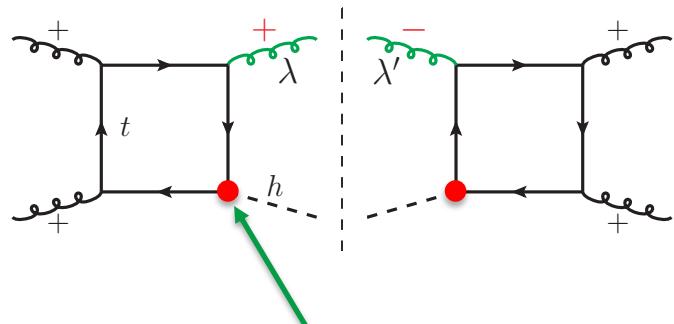
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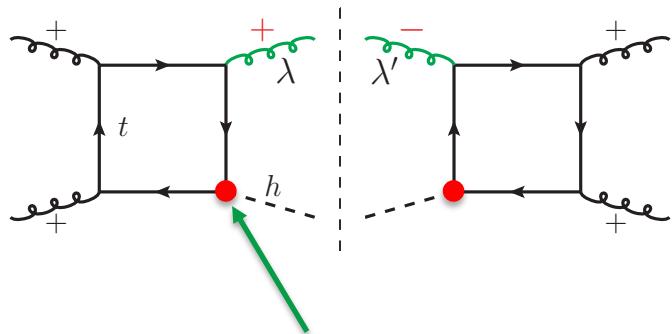
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□ For a small  $\alpha$

$$(\xi_1, \xi_2) = \left( \frac{\omega + \beta_1}{1 + \Delta}, \frac{2\beta_2 \alpha}{1 + \Delta} \right) + \mathcal{O}(\alpha^2) \quad \rightarrow \quad \xi_2 \text{ is more sensitive to } \underline{\text{small }} \alpha, \text{ including its } \underline{\text{sign}}$$



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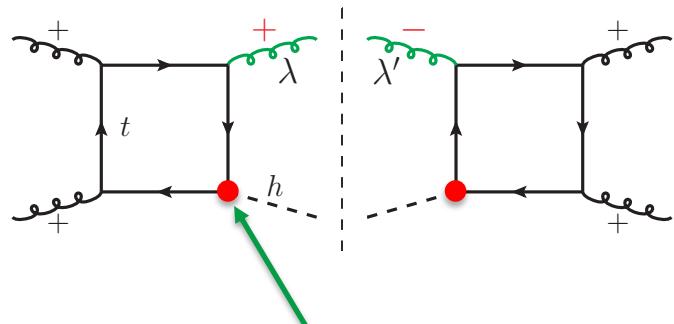


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## □ For a large $\alpha$

- $\xi_{1,2}$  oscillate with  $\alpha$
- Controlled by  $\beta_{1,2}$

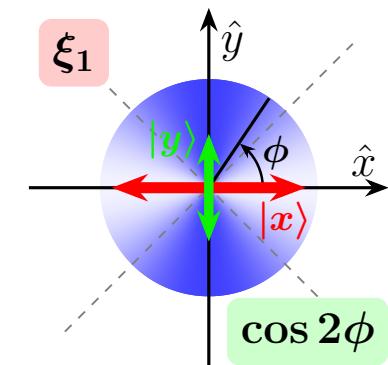
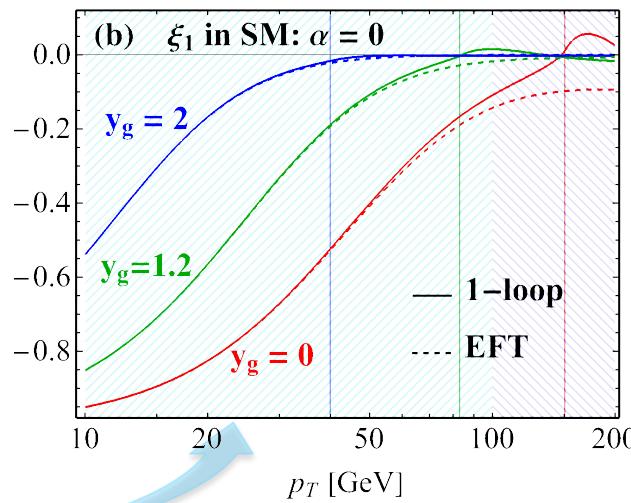
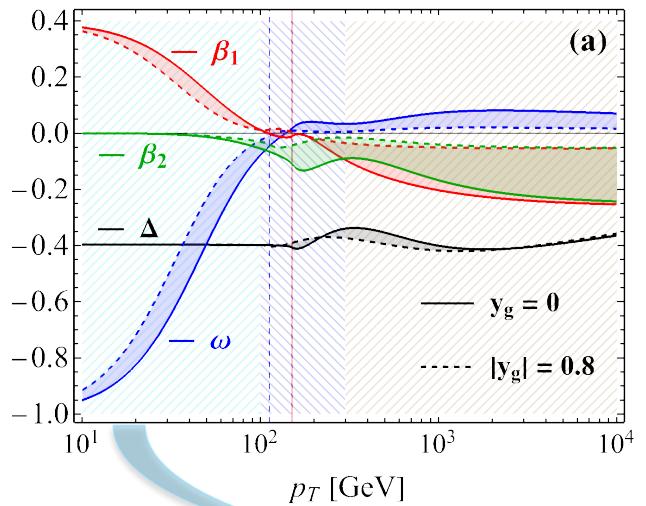


$\beta_{1,2}$  quantifies the CP sensitivity

# Polarization at low- $p_T$ region

$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

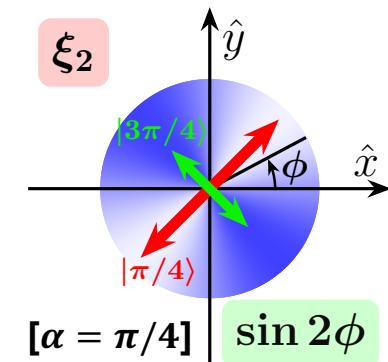
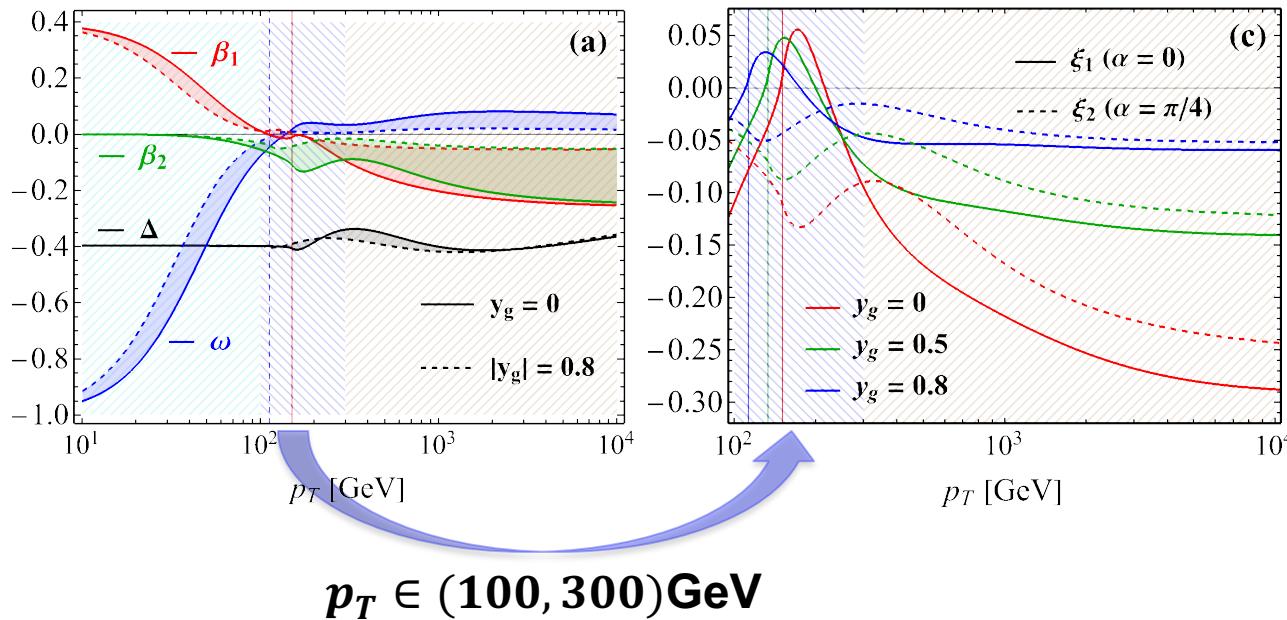
- Large negative  $\xi_1$
- Vanishing  $\xi_2$
- SM dominance



# Polarization at intermediate region (transition region)

$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

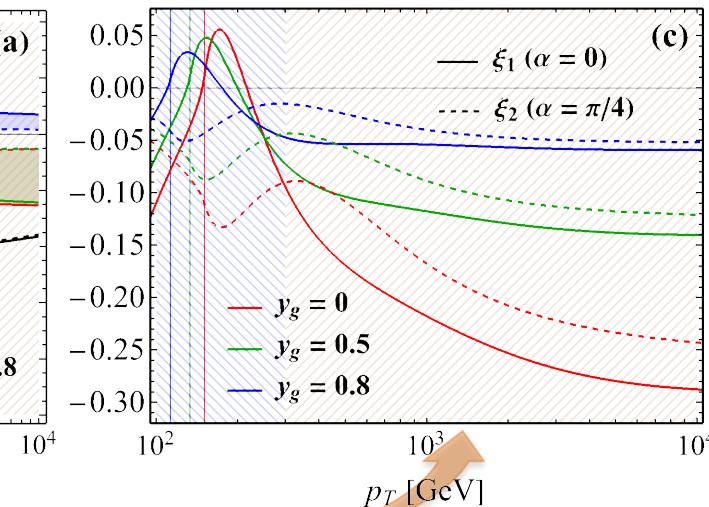
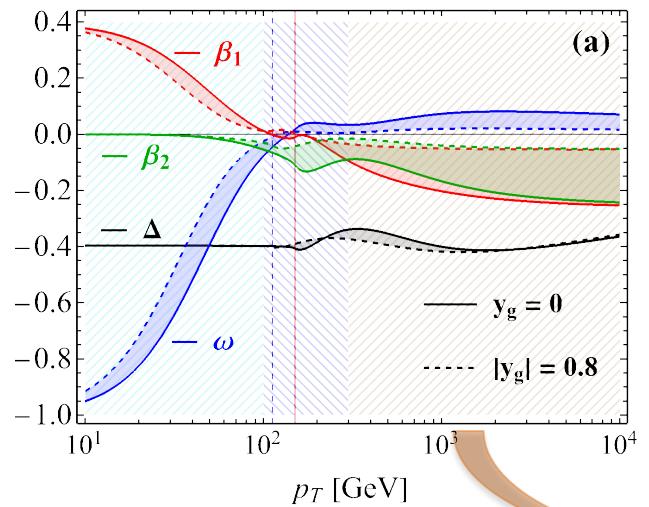
- Small  $\xi_1$
- Increasing  $\xi_2$
- $\alpha$ -sensitive



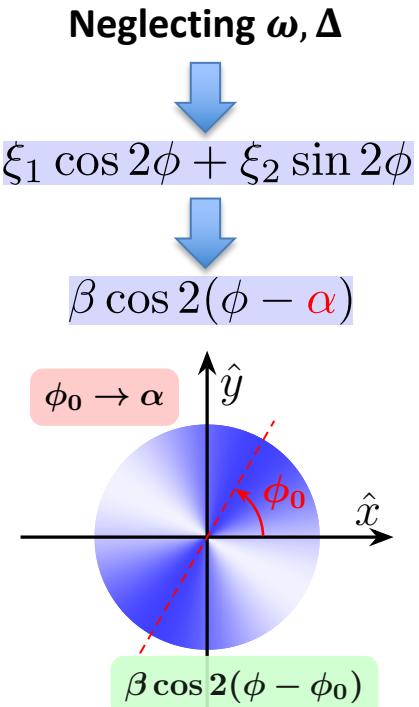
# Polarization at high- $p_T$ region

$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

- Large  $\beta_1 \simeq \beta_2 \rightarrow \beta$
- Small  $\omega$
- Direct  $CP$  probe



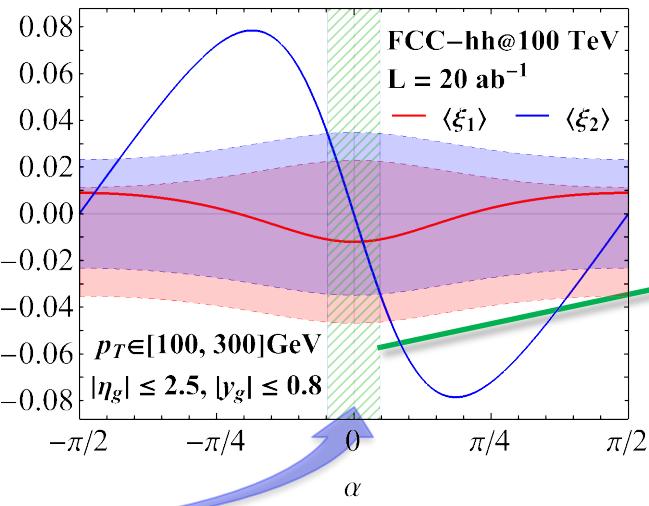
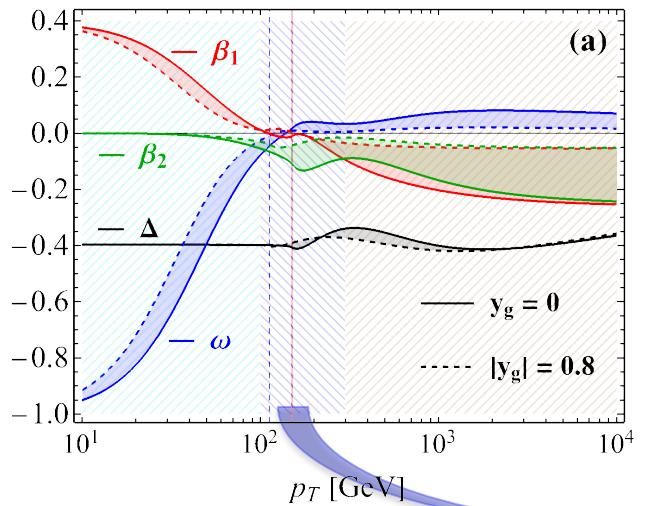
$p_T \geq 300$  GeV



# Constraining the $CP$ phase

$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

$$\langle \xi_i(\alpha) \rangle = \frac{1}{\sigma(\alpha)} \int dy_g dp_T [\xi_i(p_T, y_g, \alpha)] \frac{d\sigma(\alpha)}{dy_g dp_T}$$



- $h \rightarrow \gamma\gamma$  channel
- $g \rightarrow b\bar{b}, c\bar{c}$

$$|\alpha| \leq 8.6^\circ$$

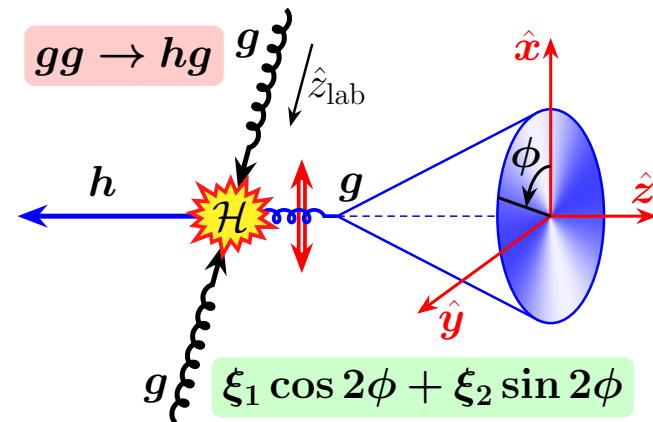
# Conclusion

## ❑ A new observable for probing the $CP$ phase of $h t \bar{t}$ interaction

- Linearly polarized gluon jet
- $\xi_1: CP \text{ even} \Rightarrow \cos 2\phi$
- $\xi_2: CP \text{ odd} \Rightarrow \sin 2\phi$
- $CP$  phase  $\alpha$  causes an oscillation of  $\xi_1$  and  $\xi_2$
- A rough estimate: FCC@100TeV gives  $|\alpha| < 8.6^\circ$

## ❑ Outlook

- Experimental measurement at HL-LHC
- Complementary to the direct  $h-t-\bar{t}$  measurement



Thank you!