Determining the CP Property of the $ht\bar{t}$ Coupling via a Gluon Jet Anisotropy Substructure

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Higgs *CP* property

❑ Higgs identity

- Scalar. $m_H = 125$GeV.
- More tests are needed to confirm it as the SM Higgs
- *CP* property $\Longrightarrow$ baryogenesis

❑ Higgs-top interaction

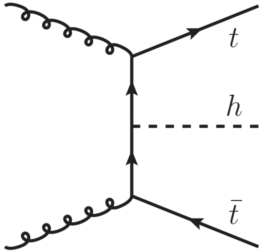
$$\mathcal{L} \supset -\frac{m_t}{v}\, h\, \bar{t}\,(\kappa + i\,\widetilde{\kappa}\,\gamma_5)\, t$$

CP-even *CP*-odd

$$\boxed{(\kappa, \widetilde{\kappa}) = \kappa_t\,(\cos\alpha, \sin\alpha)}$$

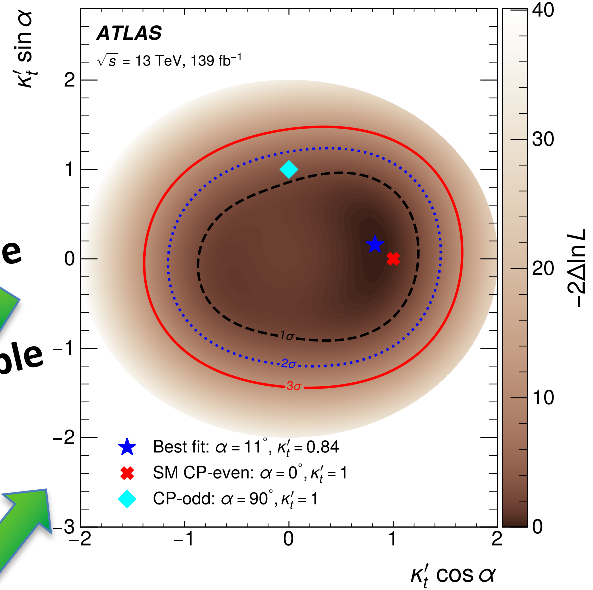
$$\mathcal{L} \supset -\kappa_t \frac{m_t}{v}\, h\, \bar{t}\,(\cos\alpha + i\,\sin\alpha\,\gamma_5)\, t$$

- κ_t: Scales the overall rate
- α: *CP* phase. $\alpha \neq 0 \Longrightarrow$ *CP* violation



CP-sensitive observable

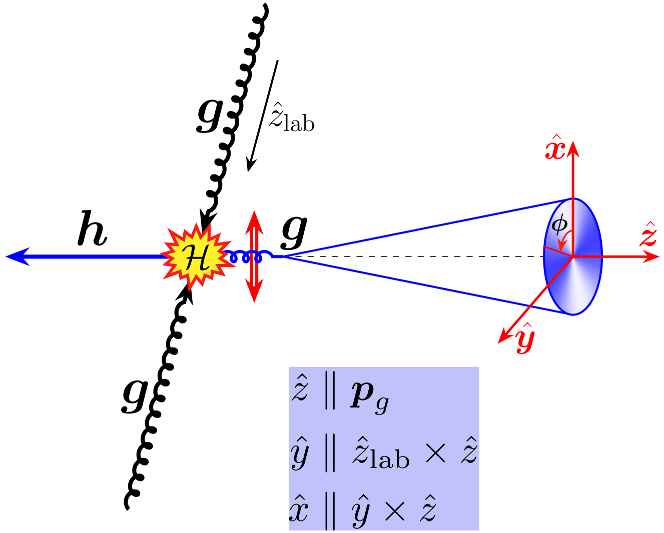
CERN-EP-2022-208



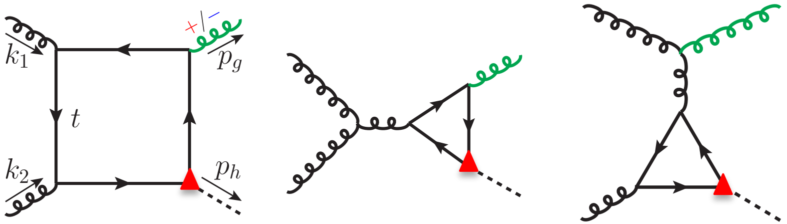
See also: CMS-HIG-21-006

<u>Using *CP-odd* observables can enhance the sensitivity!</u>

Linearly polarized gluon jet in $gg \to hg$ process

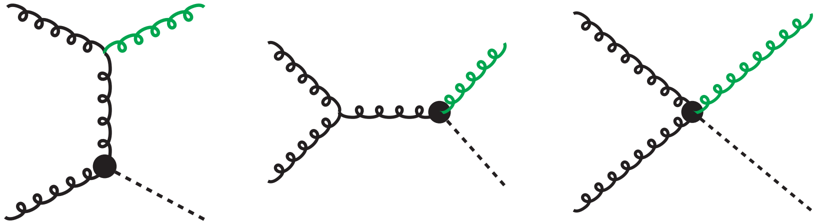


SM + *CP*-odd



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

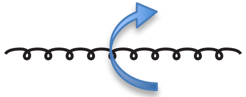
EFT ($m_t \to \infty$)

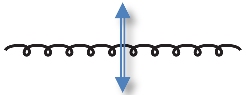


$$\mathcal{L}_{\rm EFT} \supset -\frac{h}{4v}\left(\lambda\, G^a_{\mu\nu} G^{a\mu\nu} + \widetilde{\lambda}\, G^a_{\mu\nu} \widetilde{G}^{a\mu\nu}\right)$$

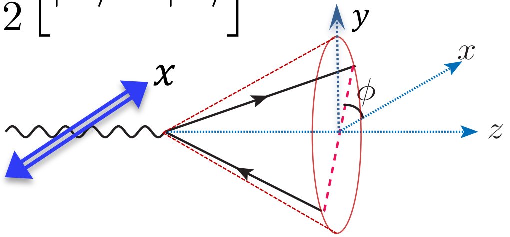
Linear polarization of a gluon

❑ Linear polarization vs. helicity/circular polarization

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

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

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



❑ Gluon polarization density matrix

$$\rho_{\lambda\lambda'} = \frac{1}{2}(1 + \boldsymbol{\xi}\cdot\boldsymbol{\sigma})_{\lambda\lambda'} = \frac{1}{2}\begin{array}{cc} + & - \\ \end{array}\left(\begin{array}{cc} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{array}\right)\begin{array}{c} + \\ - \end{array}$$

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

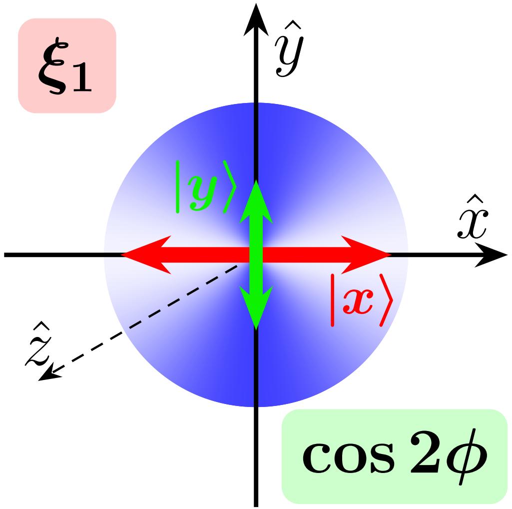
$\boldsymbol{\xi_{1,2} \sim \rho_{+-}}$ **helicity *<u>interference</u>*** → **Two independent linear pol. dof**

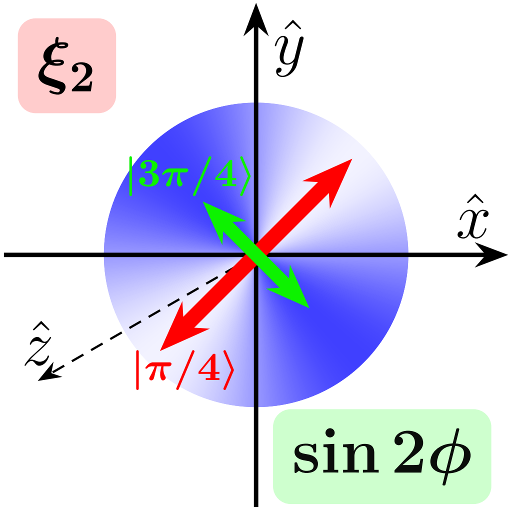
Linear gluon polarization: azimuthal asymmetry

$$\rho_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$

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

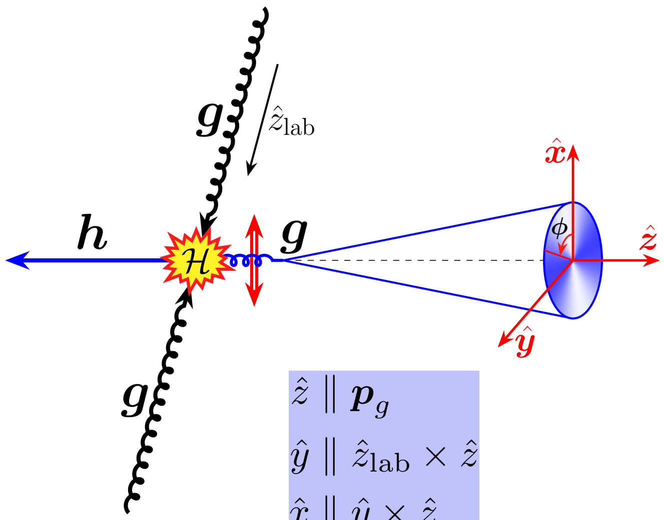
$$\xi_2 = \langle 3\pi/4|\rho|3\pi/4\rangle - \langle \pi/4|\rho|\pi/4\rangle = \rho_{\frac{3\pi}{4},\frac{3\pi}{4}} - \rho_{\frac{\pi}{4},\frac{\pi}{4}}$$





Linearly polarized gluon jet: Production

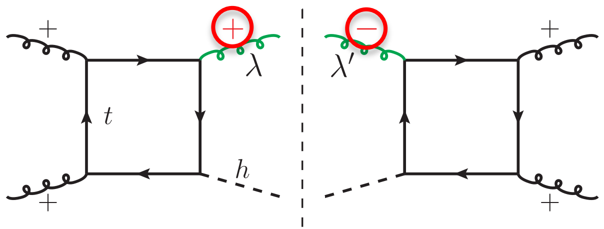
$$\boldsymbol{gg \to hg}$$



$\hat{z} \parallel \boldsymbol{p}_g$
$\hat{y} \parallel \hat{z}_{\text{lab}} \times \hat{z}$
$\hat{x} \parallel \hat{y} \times \hat{z}$

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

1. **Production of polarized gluon (ξ_1, ξ_2, ξ_3)**

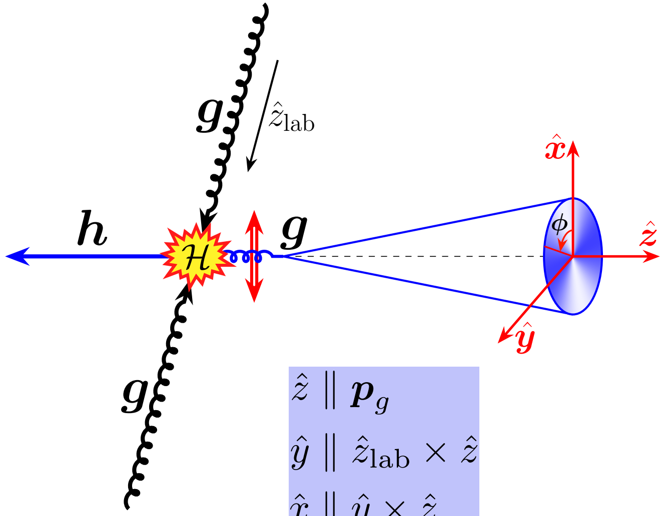


$$\sum_{\lambda_1, \lambda_2} \mathcal{M}_{\lambda_1 \lambda_2 \lambda} \mathcal{M}^*_{\lambda_1 \lambda_2 \lambda'} \equiv \rho_{\lambda\lambda'}(\boldsymbol{\xi}) \cdot \overline{|\mathcal{M}|^2}$$

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

Linearly polarized gluon jet: Fragmentation

$$\boxed{gg \to hg}$$



$$\hat{z} \parallel \boldsymbol{p}_g$$
$$\hat{y} \parallel \hat{z}_{\text{lab}} \times \hat{z}$$
$$\hat{x} \parallel \hat{y} \times \hat{z}$$

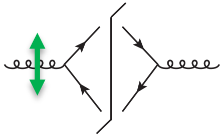
Linear polarization can be measured!

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

1. **Production of polarized gluon (ξ_1, ξ_2, ξ_3)**
2. **Fragmentation of polarized gluon jet**

$$\frac{dJ}{d\phi} = \frac{1}{2\pi N_{c,g}(k\cdot n)^2} \sum_X \int d^4x\, e^{ik\cdot x}\, \left[\rho_{\lambda\lambda'}(\boldsymbol{\xi})\, O(\phi, X)\right]$$
$$\times\, \varepsilon^*_{\lambda'\nu}(p_g) \langle 0 | W_{ac}(\infty, x; n)\, n_\sigma G_c^{\sigma\nu}(x) | X\rangle$$
$$\times\, \varepsilon_{\lambda\mu}(p_g) \langle X | W_{ab}(\infty, 0; n)\, n_\rho G_b^{\rho\mu}(0) | 0\rangle$$

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



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

Linear gluon polarization: *CP* property

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

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

$$\rho_{\lambda\lambda'} = \frac{1}{2}\begin{pmatrix} 1+\xi_3 & \xi_1 - i\,\xi_2 \\ \xi_1 + i\,\xi_2 & 1-\xi_3 \end{pmatrix}$$

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

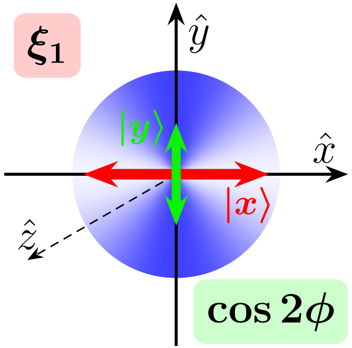
$$\hat{P}|x\rangle = |x\rangle \qquad \hat{P}|\pi/4\rangle = |3\pi/4\rangle$$

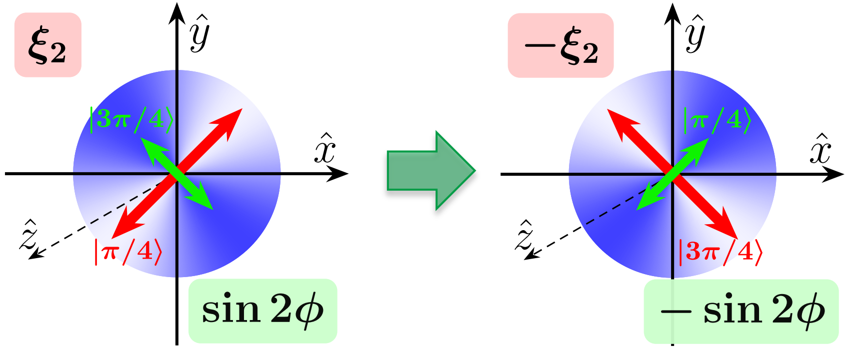
$$\hat{P}|y\rangle = |y\rangle \qquad \hat{P}|3\pi/4\rangle = |\pi/4\rangle$$

$\xi_1 \to \xi_1$: *CP* even

$\xi_2 \to -\xi_2$: *CP* odd

$\cos 2\phi \rightarrow \cos 2\phi$





$\sin 2\phi \rightarrow -\sin 2\phi$

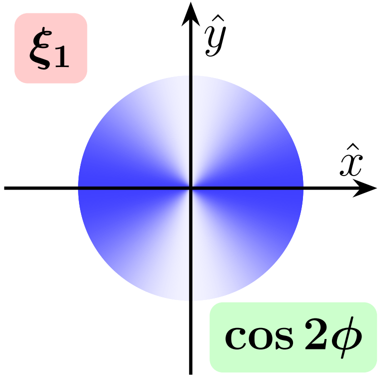
A *NEW* type of *CP*-odd observable!

Gluon jet anisotropy and CP violation

➢ ***CP*** **conserving:**

$$(\xi_1, \xi_2) = (\beta, 0)$$

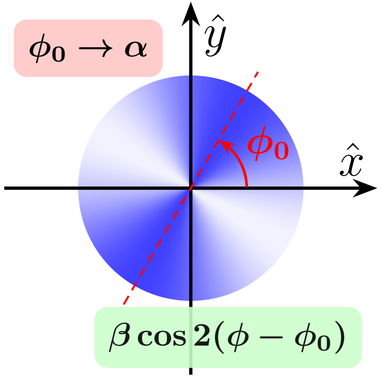
$$\Rightarrow \quad \frac{d\sigma}{d\phi} \sim \beta \, \cos 2\phi$$



➢ ***CP*** **violating (α):**

$$(\xi_1, \xi_2) = \beta(\cos 2\alpha, \sin 2\alpha)$$

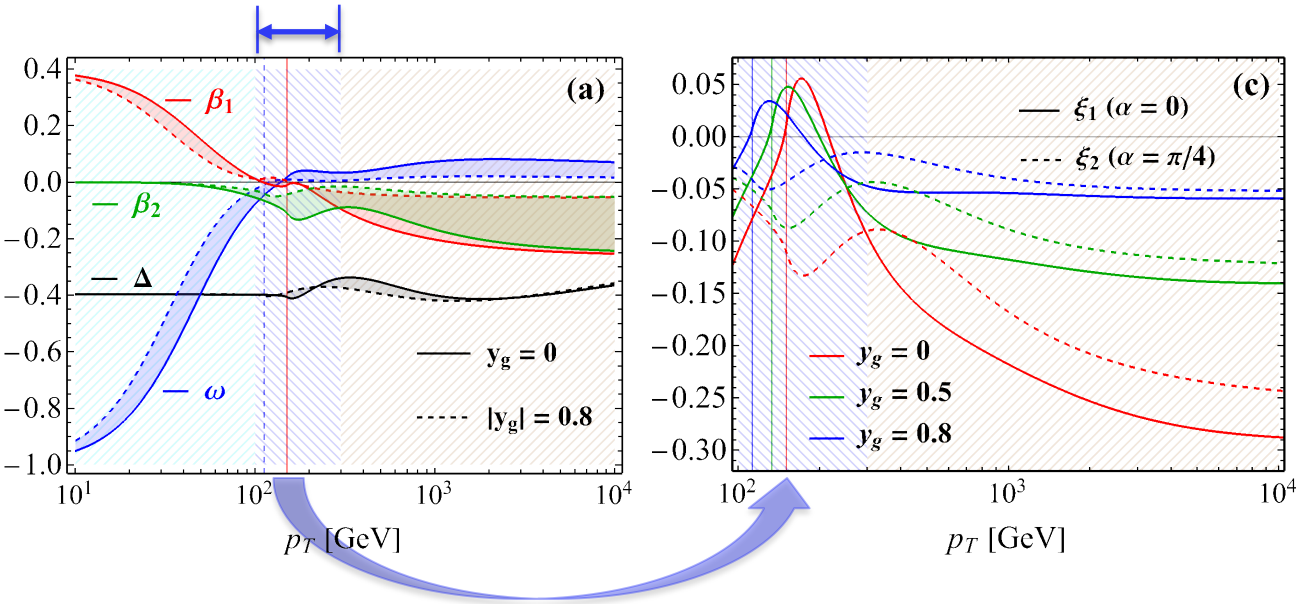
$$\Rightarrow \quad \frac{d\sigma}{d\phi} \sim \beta \, \cos 2(\phi - \alpha)$$

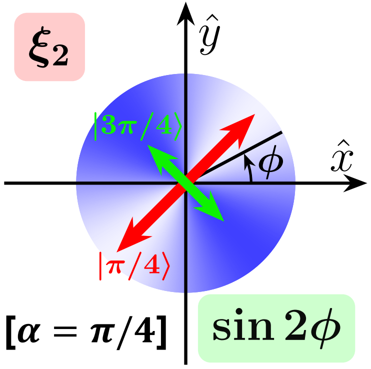


Polarization at intermediate region (transition region)

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

- **Small ξ_1**
- **Increasing ξ_2**
- ***α-sensitive***



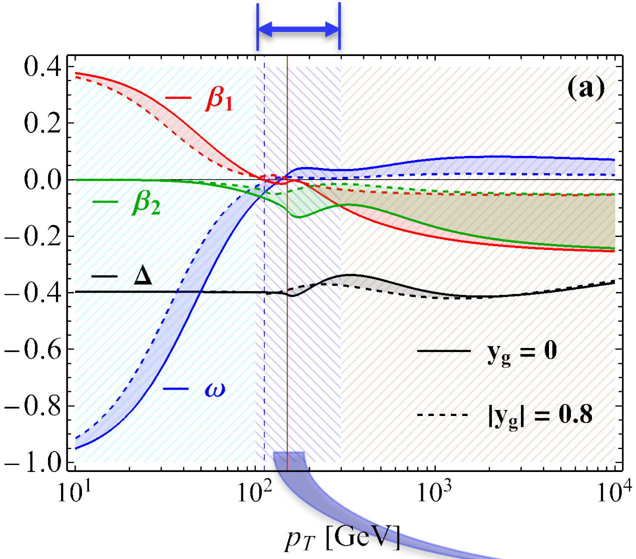


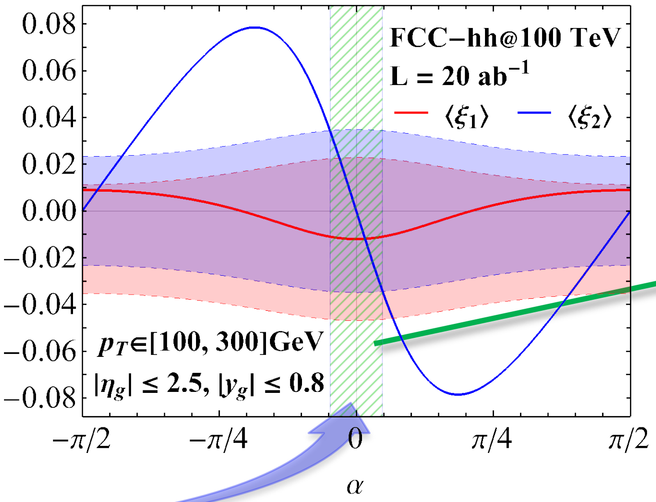
$p_T \in (100, 300)$GeV

Constraining the *CP* phase

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

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





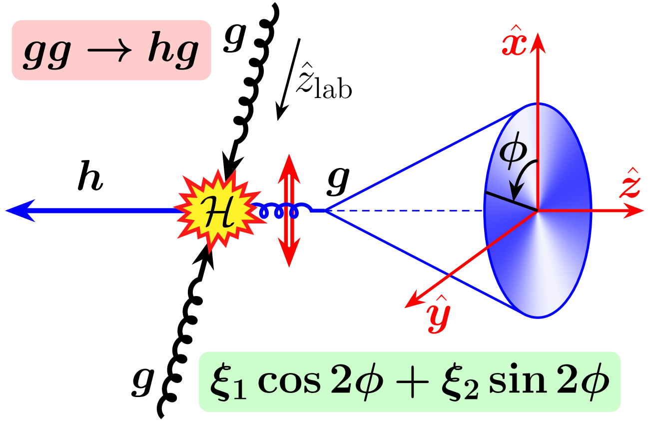
- ***h*** $\rightarrow$ ***γγ*** **channel**
- ***g*** $\rightarrow$ $\boldsymbol{b\bar{b}, c\bar{c}}$

$|\alpha| \leq 8.6°$

Conclusion

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

- **Linearly polarized gluon jet**
- ξ_1: ***CP*** **even** $\Longrightarrow \cos 2\phi$
- ξ_2: ***CP*** **odd** $\Longrightarrow \sin 2\phi$
- ***CP*** **phase** α **causes an oscillation of** ξ_1 **and** ξ_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!

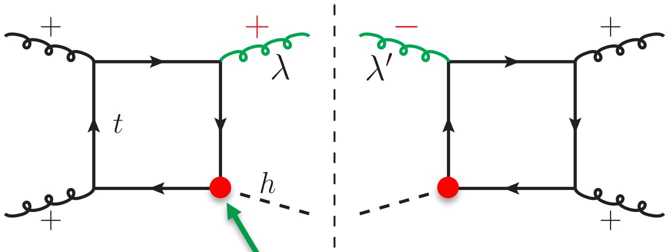
Backup

Polarization production in $gg \to hg$

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

$$\xi_1 = 2\,\mathrm{Re}(\rho_{+-}) \sim \kappa^2 - \widetilde{\kappa}^2 \propto \cos 2\alpha$$ ← ***CP*-even**

$$\xi_2 = -2\,\mathrm{Im}(\rho_{+-}) \propto \kappa \cdot \widetilde{\kappa} \propto \sin 2\alpha$$ ← ***CP*-odd**



$$\mathcal{L} \supset -\kappa_t \frac{m_t}{v} h\,\bar{t}\,(\cos\alpha + i\,\sin\alpha\,\gamma_5)\,t$$

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

- **For a small α**

$$(\xi_1,\ \xi_2) = \left(\frac{\omega + \beta_1}{1+\Delta},\ \frac{2\beta_2\,\alpha}{1+\Delta}\right) + \mathcal{O}(\alpha^2)$$

⇒ **ξ_2 is more sensitive to *small* α, including its *sign***

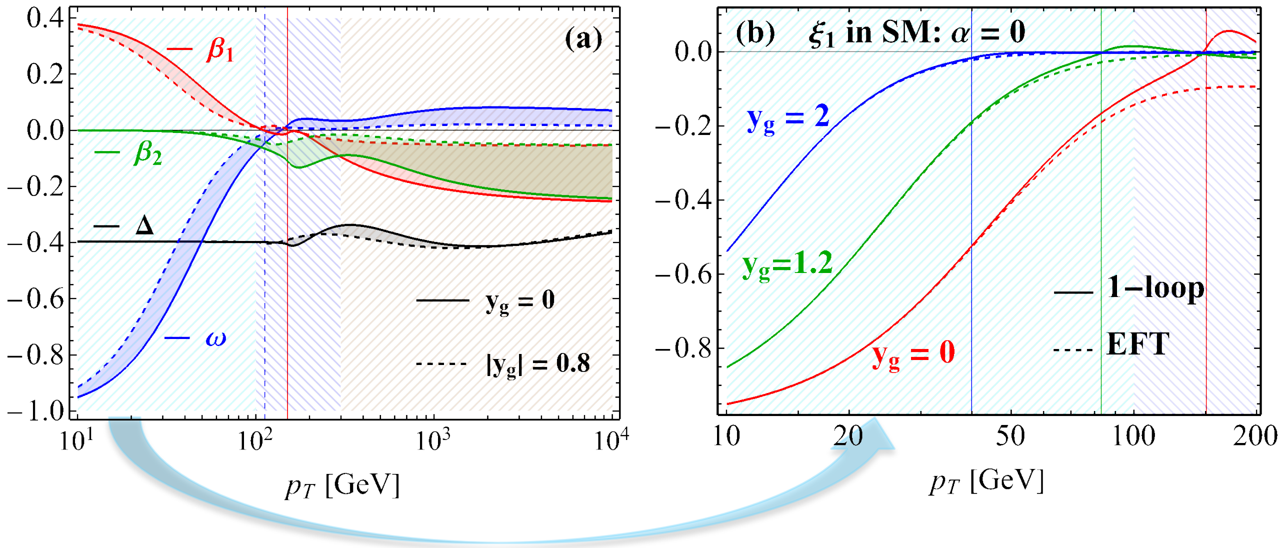
- **For a large α**
  - **$\xi_{1,2}$ oscillate with α**
  - **Controlled by $\beta_{1,2}$**

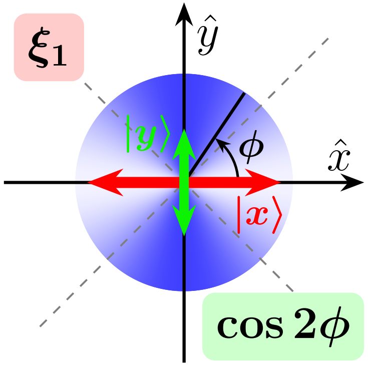
⇒ **$\beta_{1,2}$ quantifies the *CP* sensitivity**

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 ξ_1**
- **Vanishing ξ_2**
- **SM dominance**



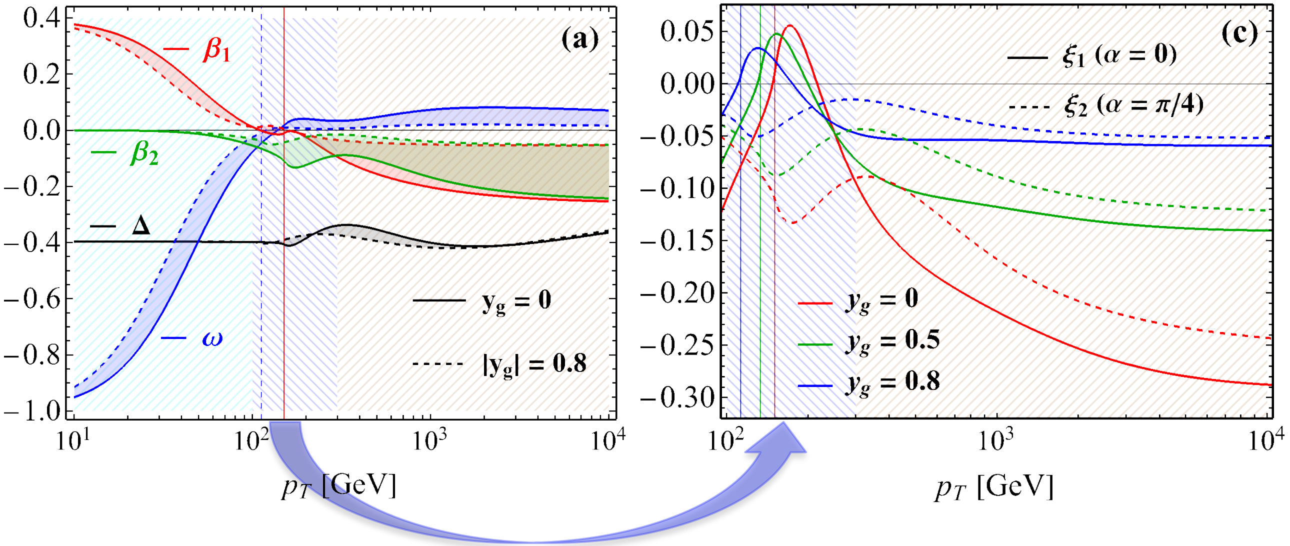


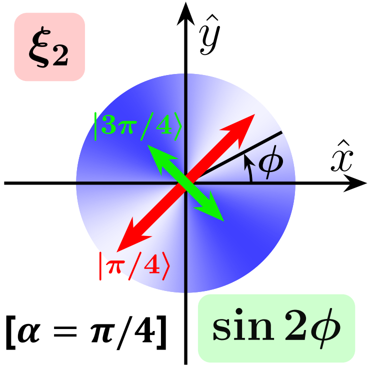
$p_T < 100$GeV

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 ξ_1**
- **Increasing ξ_2**
- ***α-sensitive***





$p_T \in (100, 300)$GeV

Polarization at high-p_T region

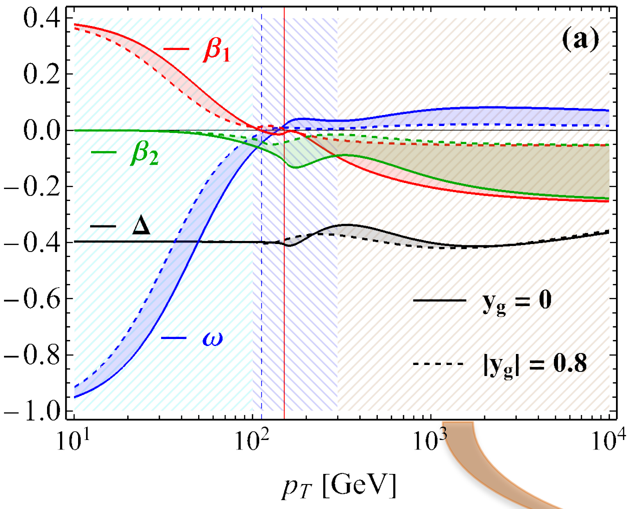
$$\xi_1 = \frac{\omega + \beta_1 \cos 2\alpha}{1 + \Delta \cos 2\alpha}, \quad \xi_2 = \frac{\beta_2 \sin 2\alpha}{1 + \Delta \cos 2\alpha}$$

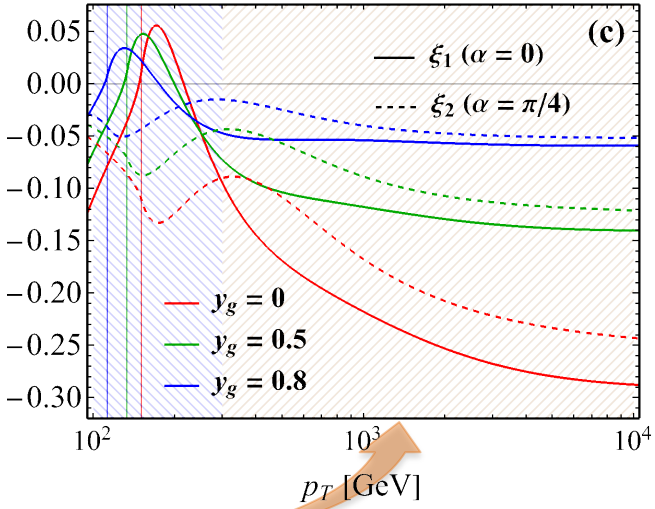
- **Large $\beta_1 \simeq \beta_2 \to \beta$**
- **Small ω**
- **Direct *CP* probe**

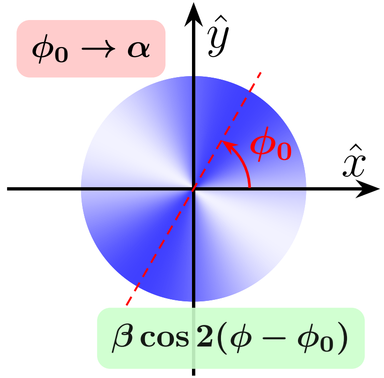
Neglecting ω, Δ

$$\xi_1 \cos 2\phi + \xi_2 \sin 2\phi$$

$$\beta \cos 2(\phi - \alpha)$$







$p_T \geq 300$GeV