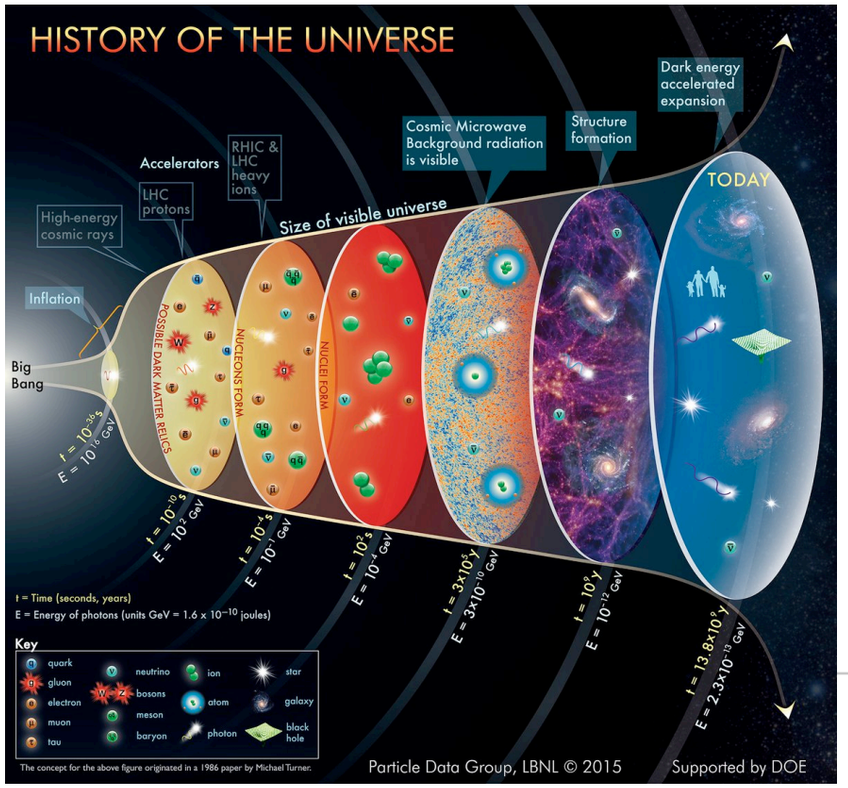
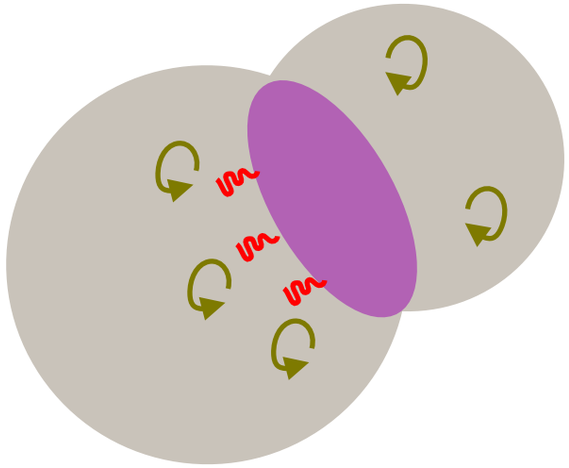
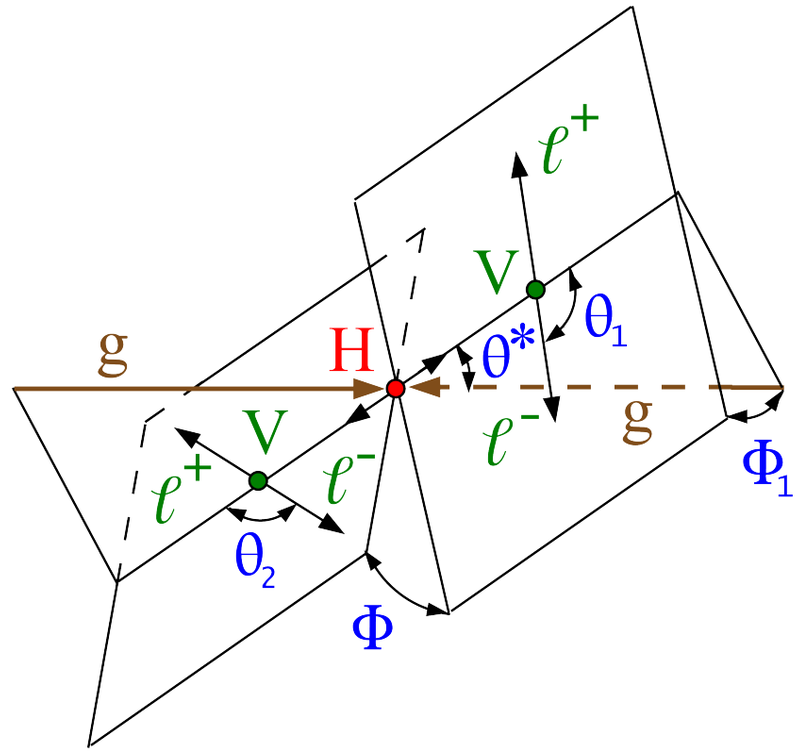






中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences

Ying-Ying Li (李英英)

Phys.Rev.D 114 (2026) 1, 016006

In collaboration with Yi-Lin Wang, Jun Gao, Hua Xing Zhu

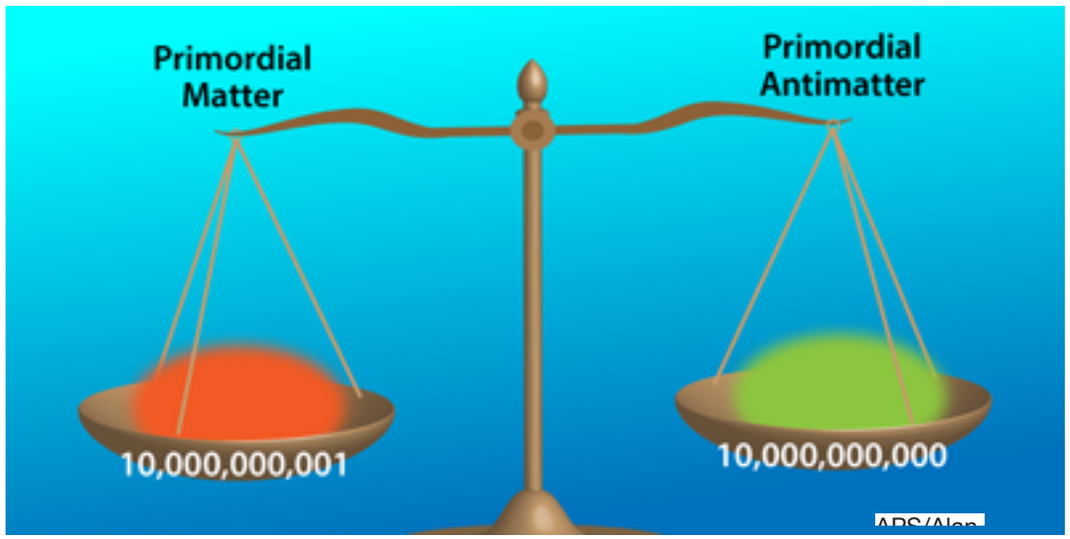
Parton spin correlations and CP properties in Higgs boson decay at future lepton colliders

Oct. 22, 2026 @ CEPC 2026

CP violation and baryogenesis

One observable fact

$$\frac{n_B - n_{\bar{B}}}{n_\gamma} \sim 10^{-10}$$



Three conditions(Sakharov conditions)

C- and CP-violation

$$\begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix}$$

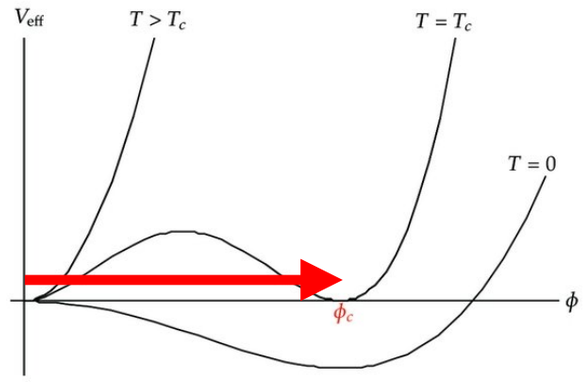
SM, not enough

B-violation



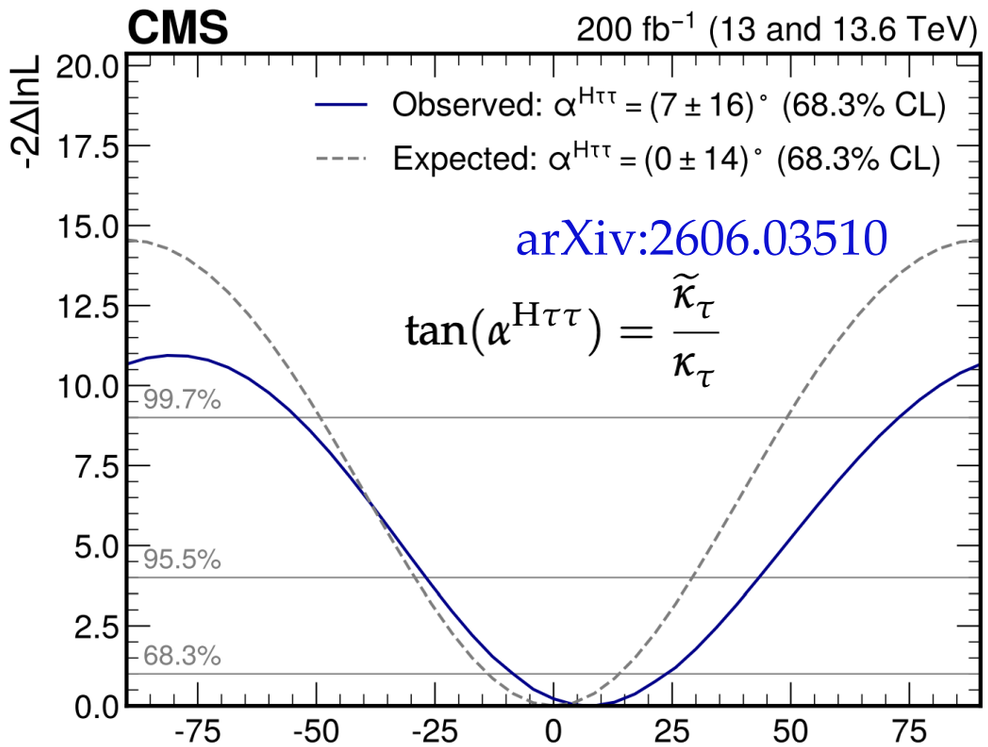
SM

Out of equilibrium

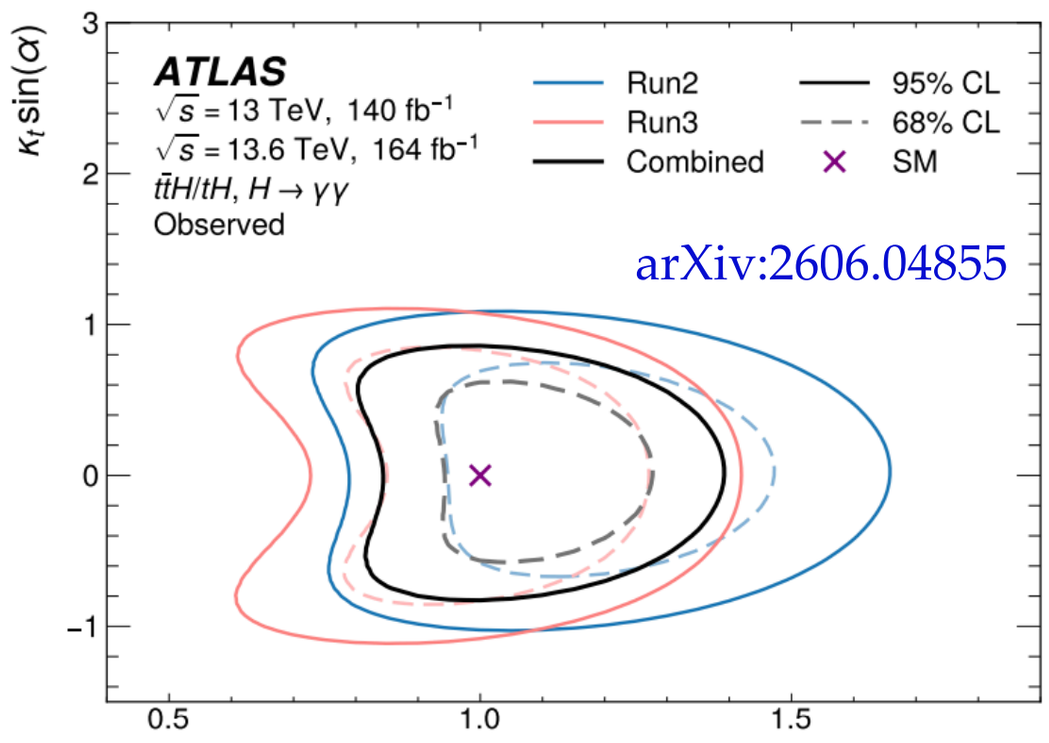


BSM

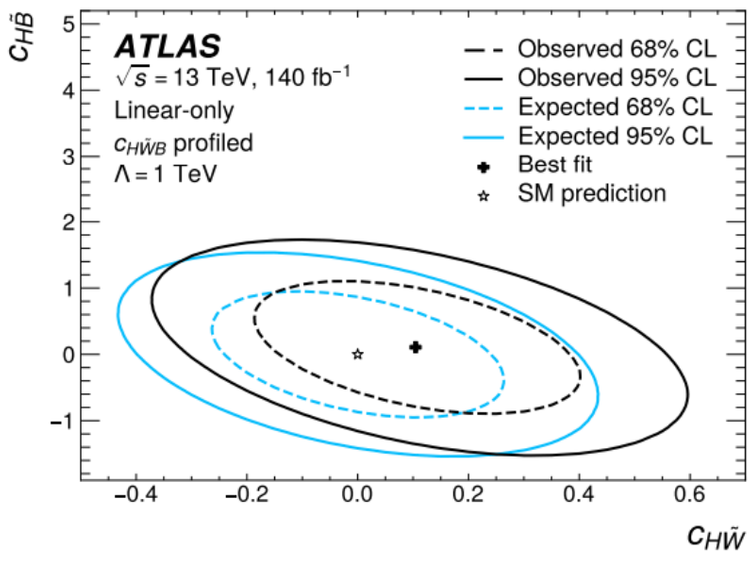
CP violation in Higgs-related couplings

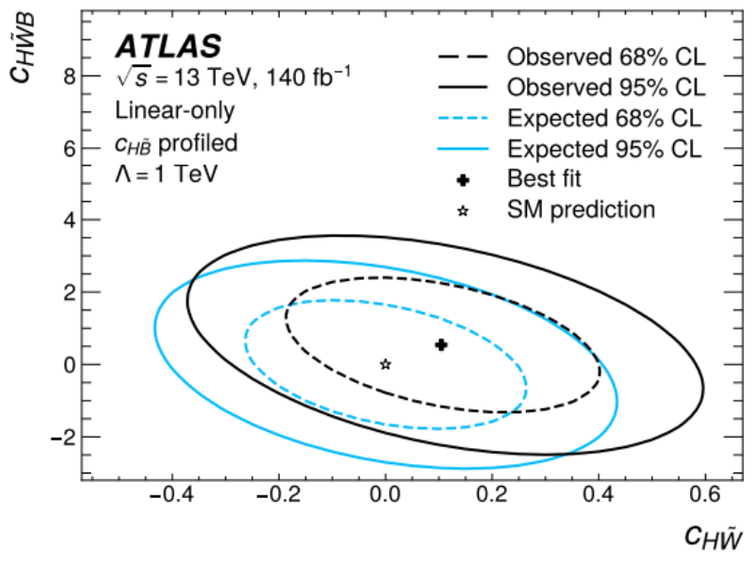


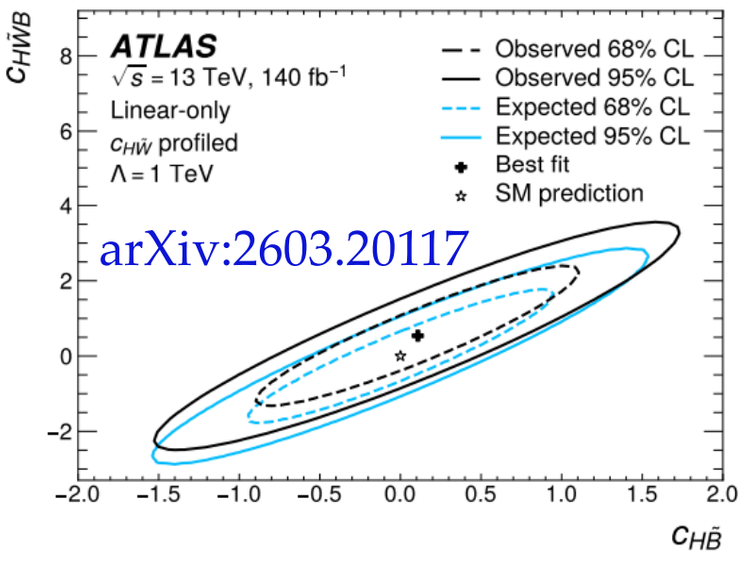
$$\mathcal{L}_Y = -\frac{m_\tau}{v} H(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i\gamma_5 \tau)$$



$$\mathcal{L} = -\frac{m_t}{v}\left\{\bar{\psi}_t \kappa_t \left[\cos(\alpha) + \mathrm{i}\sin(\alpha)\gamma_5\right]\psi_t\right\} H$$

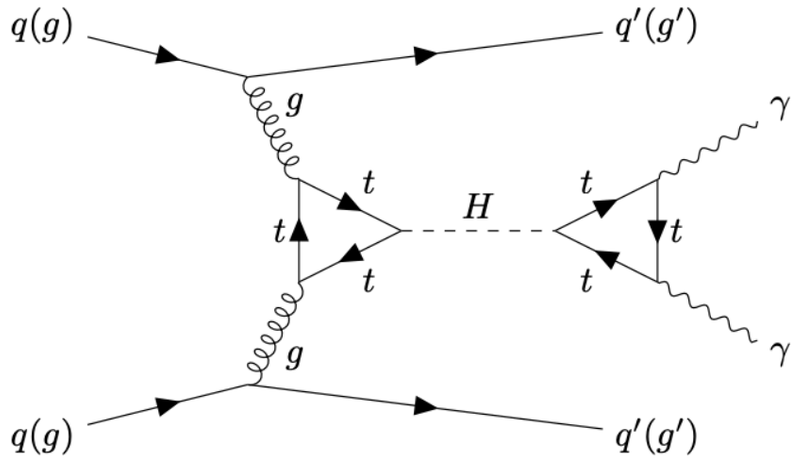




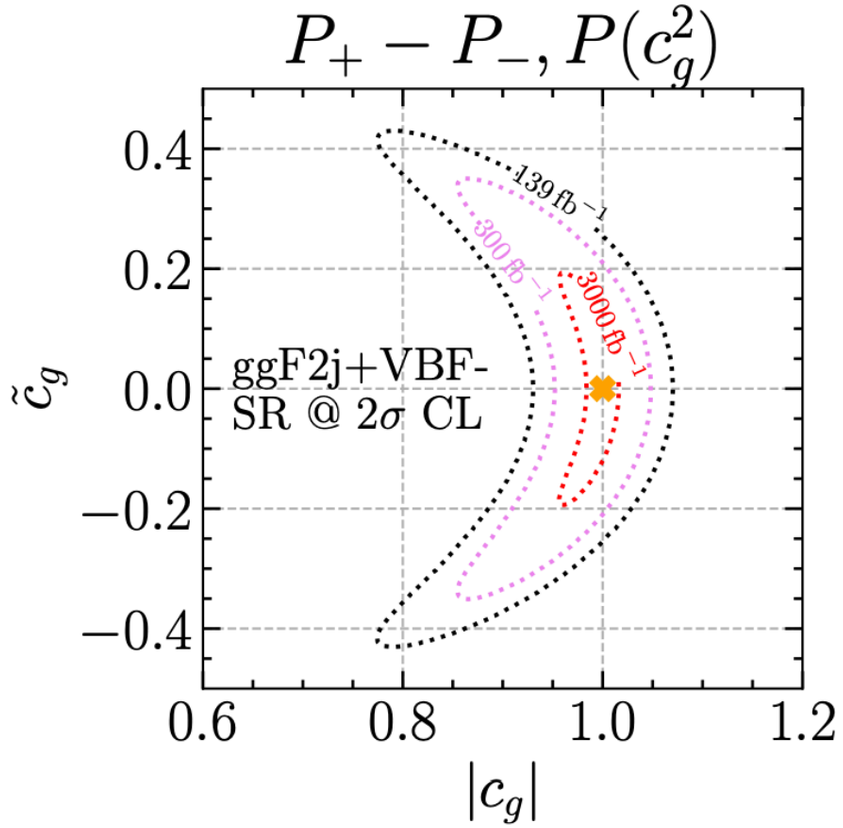


CP violation in Higgs-related couplings

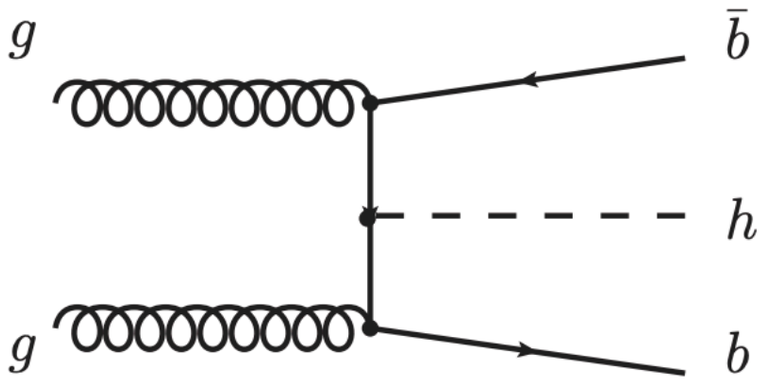
Hgg?



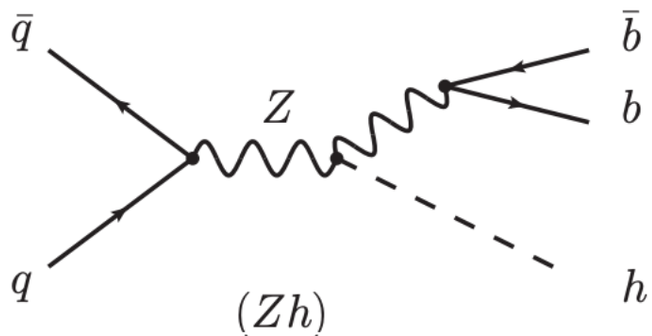
SciPost Phys. Core 8, 006 (2025)



$Hb\bar{b}$?



Very large irreducible bg



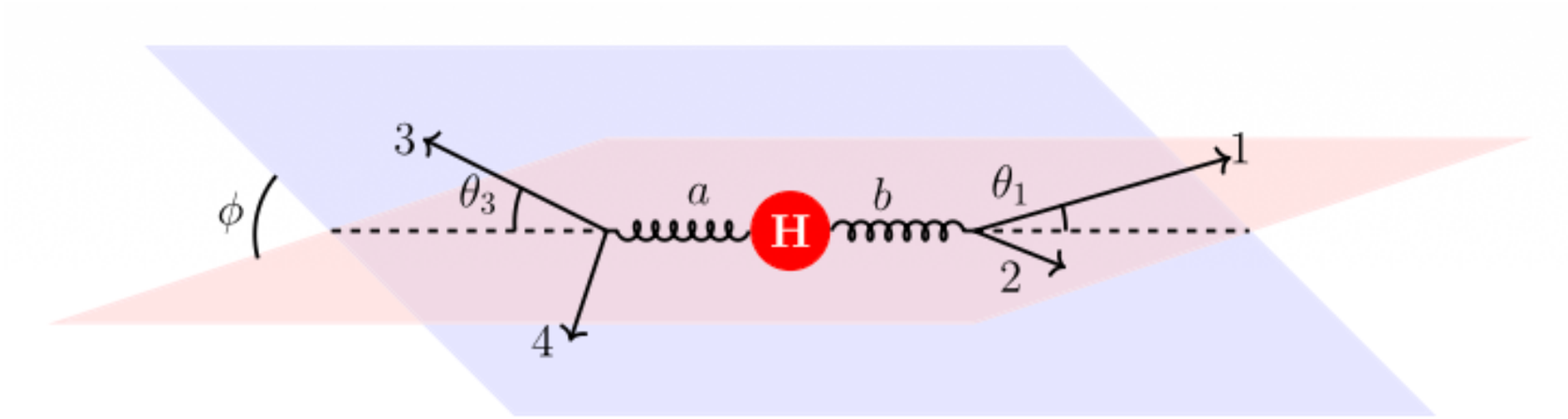
arXiv:2011.13945

CP violation in Higgs -related couplings

What about from the decay?

Hgg?

Hbb̄?

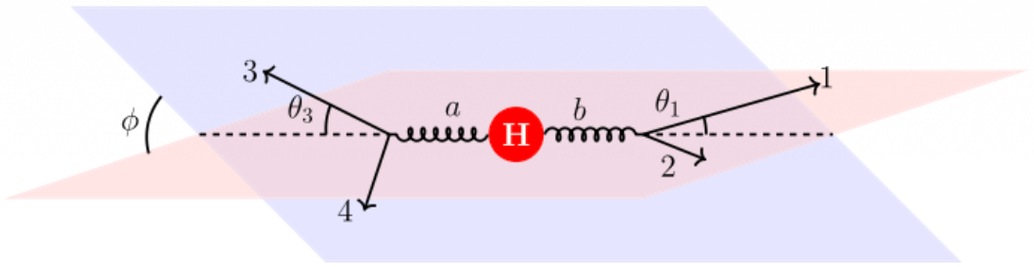


What observables should we look at?

Would CP information be preserved in the showering and hadronization?

Methods–leading order approximation

$$\mathcal{L}_{\text{eff}} = \frac{1}{4}\frac{\alpha_s}{3\pi}\frac{h}{v}(\cos\Delta G^a_{\mu\nu}G^{a,\mu\nu} + \sin\Delta G^a_{\mu\nu}\tilde{G}^{a,\mu\nu})H$$



Factorization of $H \to g_1 g_2,\ g_1 \to a_1 b_1,\ g_2 \to a_2 b_2$

$$|\mathcal{M}|^2 \propto \sum_{h,h'} \mathcal{M}_{h_1 h_2}(\mathcal{M}_{h'_1 h'_2})^\dagger \rho_{\mu\nu}^{h_1 h'_1} P^{h_1 h'_1,\mu\nu}_{a_1 b_1 \leftarrow g1}(z_1, k_{1\perp}) \rho_{\alpha\beta}^{h_2 h'_2} P^{h_2 h'_2,\alpha\beta}_{a_2 b_2 \leftarrow g2}(z_2, k_{2\perp})$$

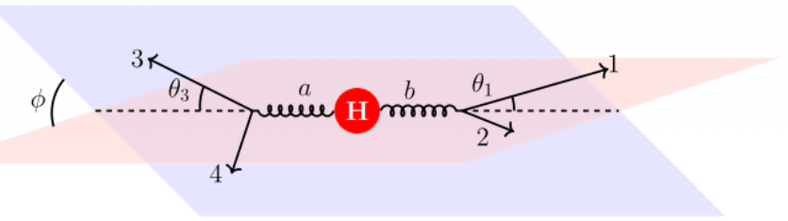
$\rho_{\mu\nu}^{hh'}$: Gluon polarization matrix and $P^{hh',\mu\nu}$ is spin-unaveraged gluon splitting function:

$$\hat{P}^{\mu\nu}_{q\bar{q}\leftarrow g}(z, k_\perp) = \hat{P}^{\mu\nu}_{\bar{q}q\leftarrow g}(z, k_\perp) = T_R\left[-g^{\mu\nu} + 4z(1-z)\frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2}\right],$$

$$\hat{P}^{\mu\nu}_{gg\leftarrow g}(z, k_\perp) = 2C_A\left[-g^{\mu\nu}\left(\frac{z}{1-z} + \frac{1-z}{z}\right) - 2z(1-z)\frac{k_\perp^\mu k_\perp^\nu}{k_\perp^2}\right]$$

[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

Methods–leading order approximation



IR safe?

Resolution

- Adding z_{cut} to the soft parton in one splitting branch, a cut on the Lund plane.

$$\mathrm{Obs}(\phi, x) \equiv \frac{\pi}{\sigma}\frac{d\sigma}{d\phi} = 1 + A_{\mathrm{Lund}}(x)\cos(2\phi - 2\Delta)$$

- Use energy-weighted differential cross-section, or energy correlator (EC). Here we extend the idea by introducing the n-power weighting (E^nC):

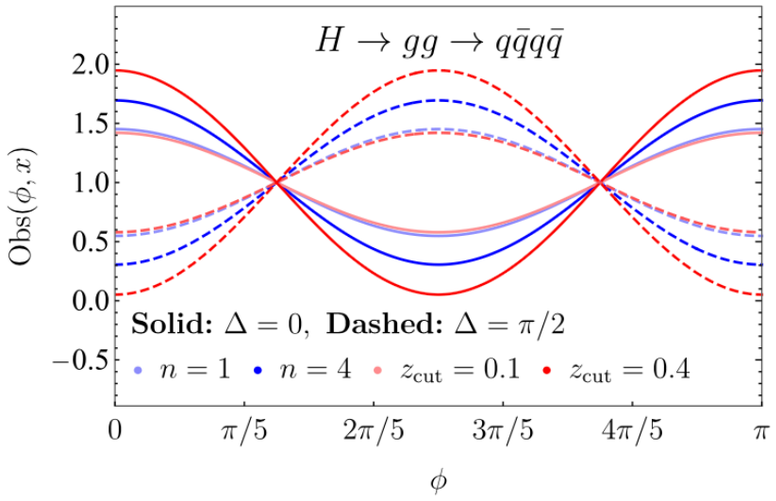
$$\mathrm{E4C}(\phi, n) = \sum_{ij,kl}\int \frac{d\sigma}{\sigma}\frac{E_i^n E_j^n}{Q_1^{2n}}\frac{E_k^n E_l^n}{Q_2^{2n}}\delta(\phi - \phi_{(ij,kl)})$$

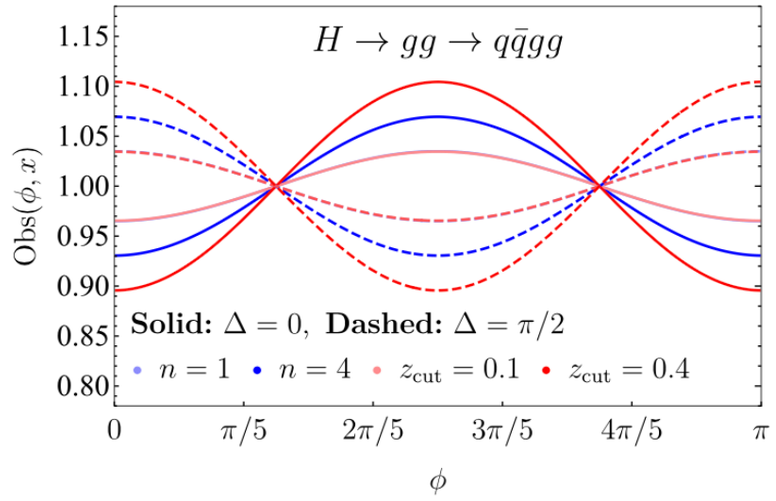
$$\mathrm{Obs}(\phi, x) \equiv \frac{\mathrm{E4C}(\phi, x)}{\mathcal{N}(x)} = 1 + A_{\mathrm{E4C}}(x)\cos(2\phi - 2\Delta)$$

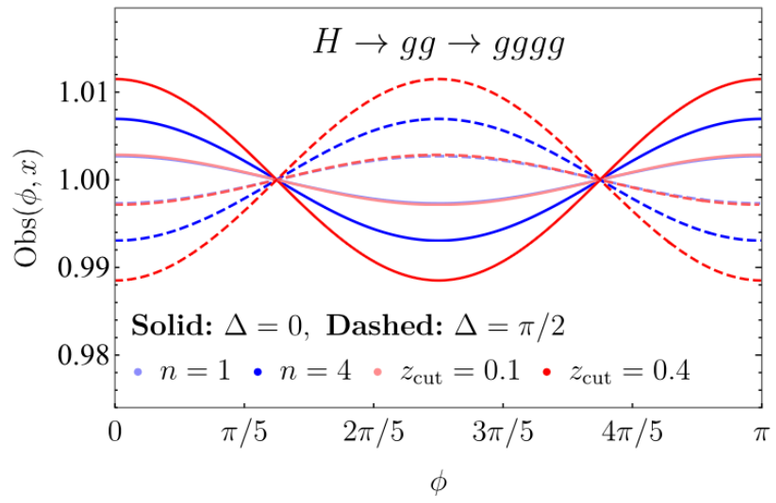
correlation strength

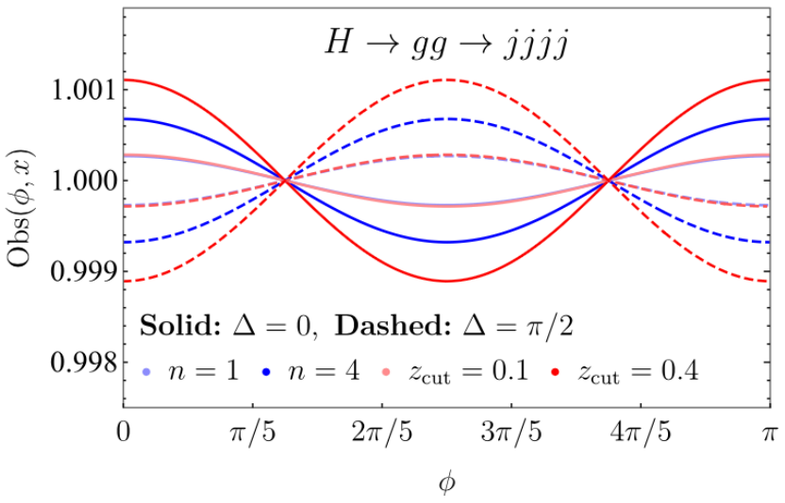
[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

Methods–leading order approximation









Correlation strength	$q\bar{q}q\bar{q}$	$gggg$	$q\bar{q}gg$	$jjjj$
$A_{\mathrm{Lund}}(z_{\mathrm{cut}} = 0.1)$	0.4204	0.0028	−0.0346	0.0003
$A_{\mathrm{Lund}}(z_{\mathrm{cut}} = 0.4)$	0.9481	0.0115	−0.1044	0.0011
$A_{\mathrm{E4C}}(n = 1)$	0.4516	0.0027	−0.0349	0.0003
$A_{\mathrm{E4C}}(n = 4)$	0.6944	0.0070	−0.0695	0.0007

[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

Methods–leading order approximation

Correlation strength	$q\bar{q}q\bar{q}$	$gggg$	$q\bar{q}gg$	$jjjj$
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But…

TABLE II. Cut efficiency ϵ_z for $z_{\text{cut}} = 0.1$ and $z_{\text{cut}} = 0.4$ when considering the Lund observable.

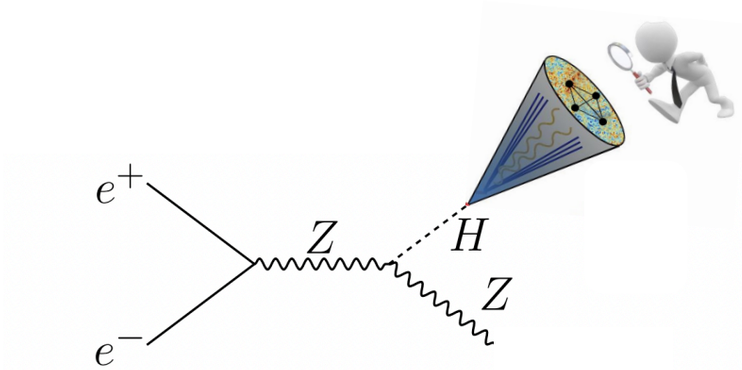
ϵ_z	$qqqq$	$gggg$	$q\bar{q}gg$	$jjjj$
$z_{\text{cut}} = 0.1$	0.64	0.32	0.45	0.33
$z_{\text{cut}} = 0.4$	0.07	0.02	0.01	0.02

[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

At lepton colliders, measure spin correlation

Lepton Colliders: CEPC & FCC-ee, Higgs factory.
We choose $e^+e^- \to ZH$ as Higgs production chann

- Largest cross section at $\sqrt{s} = 240$ GeV



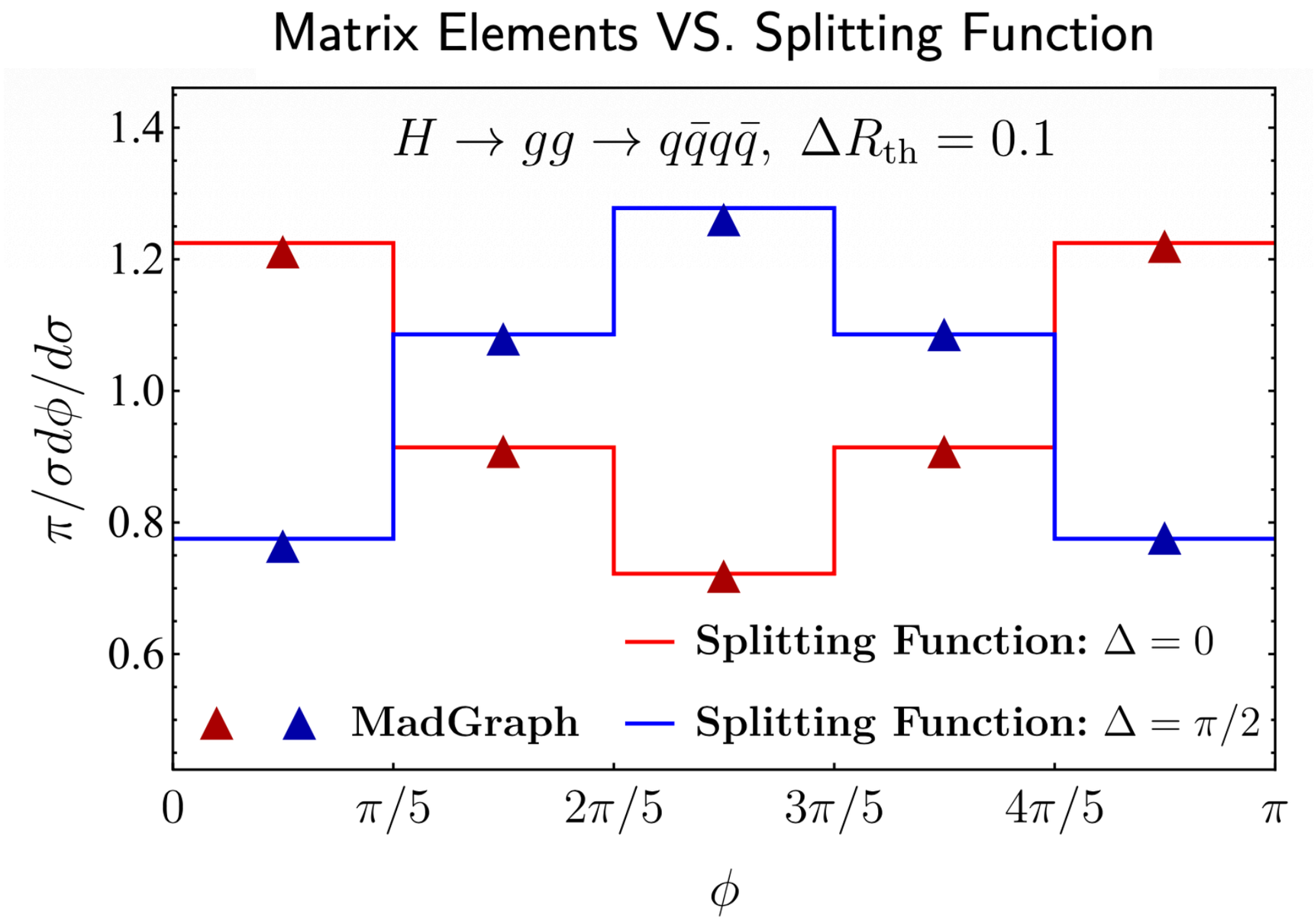
To construct Higgs rest frame...

$$Z \to l\bar{l}$$

[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

At lepton colliders, measure spin correlation

We use MadGraph to generate parton level events $e^+e^- \to ZH, H \to gg \to a_1 b_1 a_2 b_2$



[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

At lepton colliders, measure spin correlation

Signal event number

$$N_X = \sigma_{ZH}\mathcal{L}\mathrm{Br}(Z \to l\bar{l})\mathrm{Br}(H \to gg)P_{gg\to X}\epsilon_z\epsilon_{\mathrm{cut}}\epsilon_{gg}$$

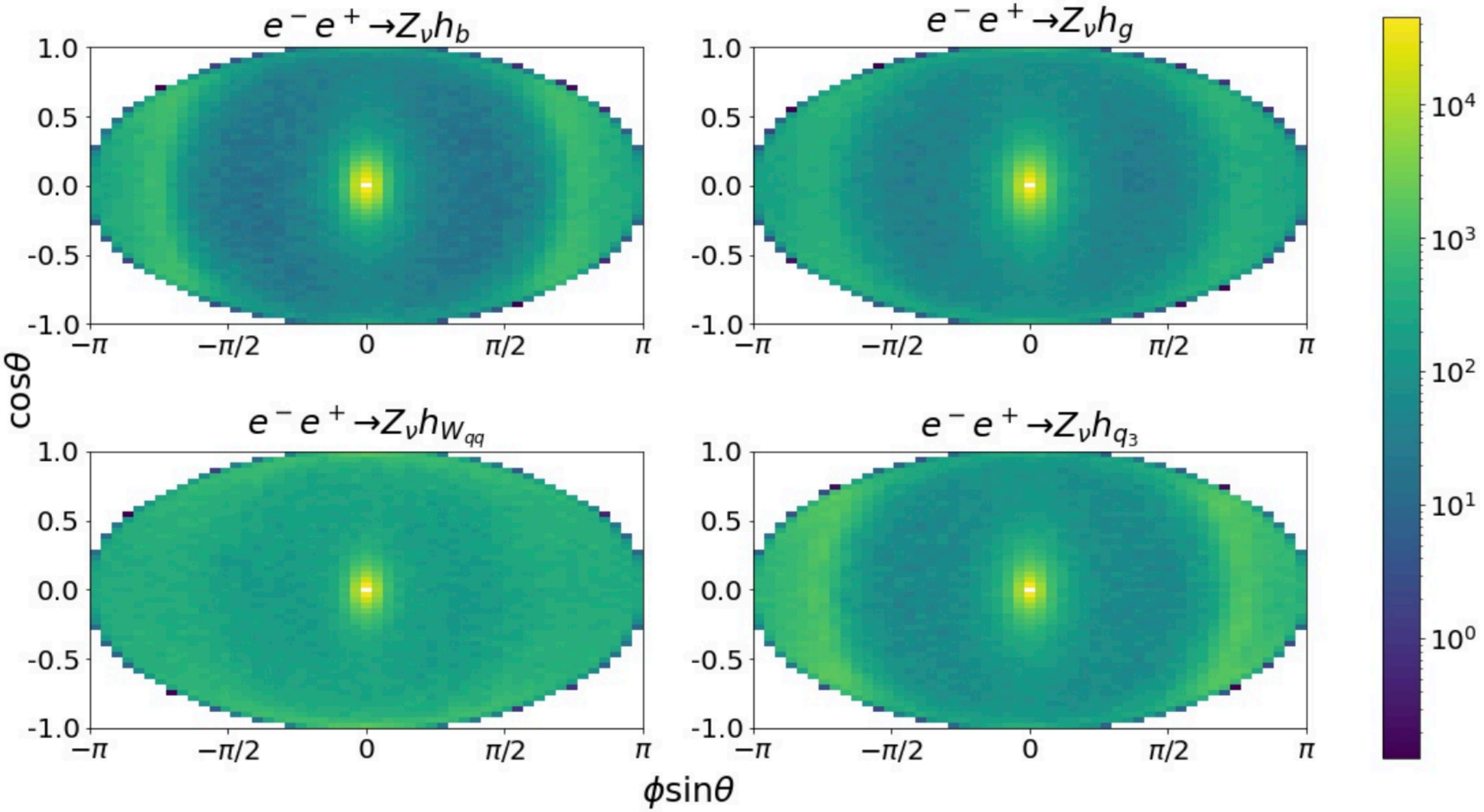
$$\epsilon_{\mathrm{cut}}: \quad \begin{aligned} &\text{parton } p_T \geq 20\mathrm{GeV}, \eta < 5 \text{ and } \Delta R > 0.4 \\ &\text{lepoton } p_T \geq 10\mathrm{GeV}, \eta < 2.5 \text{ and } \Delta R > 0.4 \end{aligned}$$

ϵ_z : only for Lund variable

[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

At lepton colliders, measure spin correlation

ϵ_{gg} : event level analysis to separate gg events from others

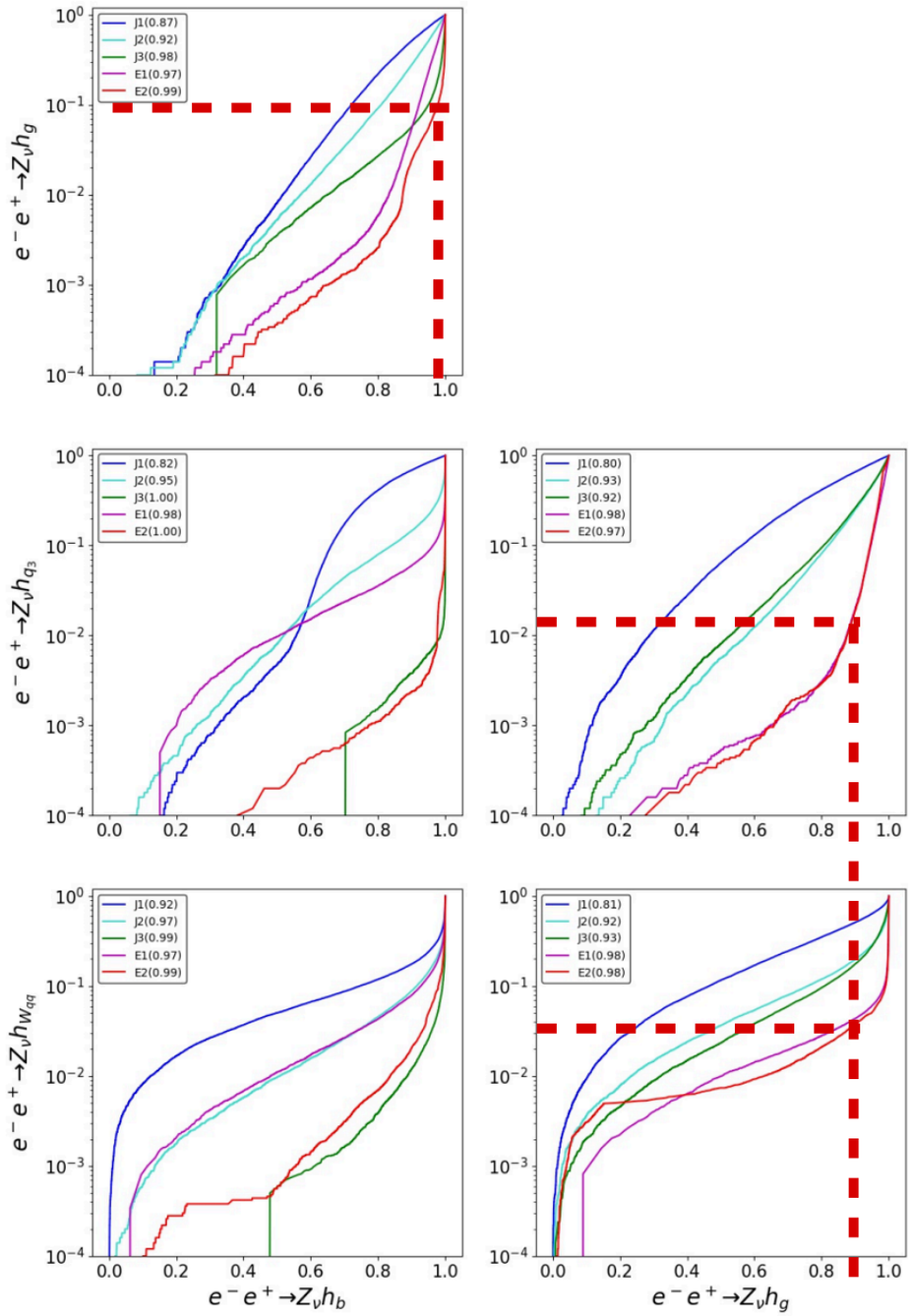


ResNet-50 network

[*JHEP* 10 (2020) 018, LL, **YYL**, TL, SJX]

At lepton colliders, measure spin correlation

ϵ_{gg} : event level analysis to separate gg events from others



$$\epsilon_{gg} = 90\%$$

[*JHEP* 10 (2020) 018, LL, **YYL**, TL, SJX]

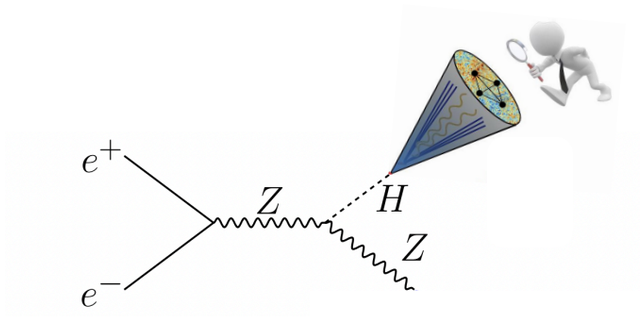
At lepton colliders, measure spin correlation

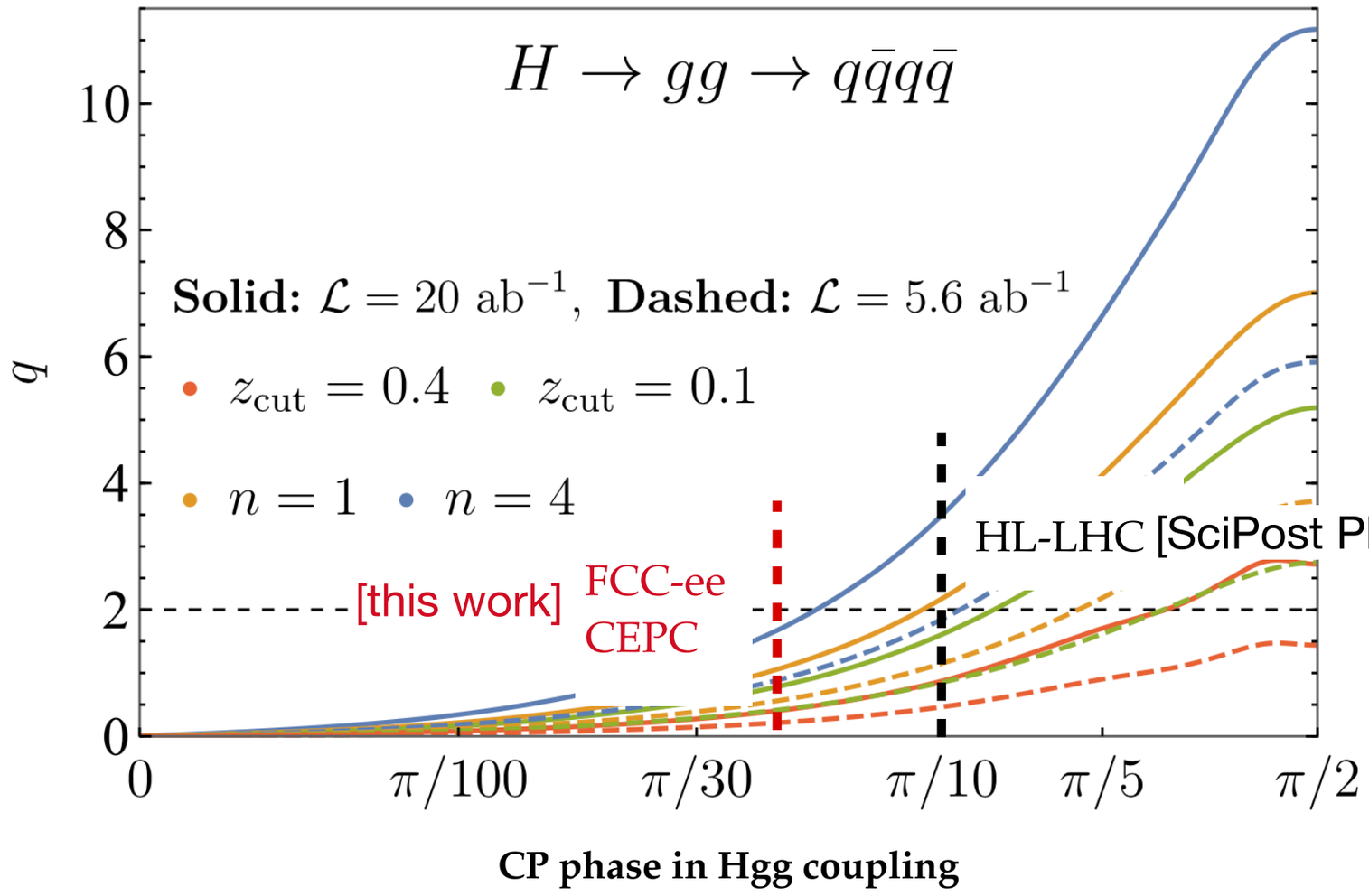
$$q = \sqrt{-2\sum_{i=1}^{M} N_i^{\text{obs}} - N_i + N_i^{\text{obs}} \log \frac{N_i}{N_i^{\text{obs}}}}$$

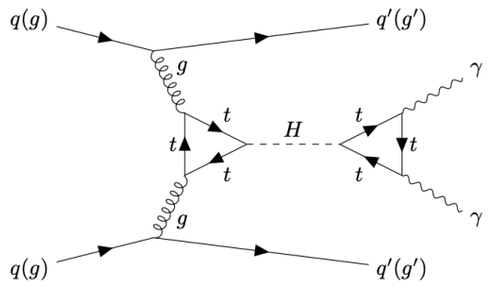
TABLE III. Significance to exclude the uncorrelated hypothesis using the choices of E4C($\phi, n = 1$) and E4C($\phi, n = 4$), and the Lund observable with $z_{\text{cut}} = 0.1$ and $z_{\text{cut}} = 0.4$, at $\mathcal{L} = 5.6\ \text{ab}^{-1}$.

q	$q\bar{q}q\bar{q}$	$gggg$	$q\bar{q}gg$	$jjjj$
$z_{\text{cut}} = 0.1$	1.3608	0.1661	0.6688	0.0175
$z_{\text{cut}} = 0.4$	0.6847	0.1047	0.3646	0.0108
$n = 1$	1.836	0.2795	1.007	0.0292
$n = 4$	2.8812	0.7204	2.005	0.0731

At lepton colliders, CP properties







[*Phys.Rev.D* 114 (2026) 1, 016006, YLW, **YYL**, JG, HXZ]

At lepton colliders, CP properties

$Hb\bar{b}$?

The splitting function for quarks:

$$\hat{P}^{ss'}_{qg\leftarrow q}(z,k_\perp) = \hat{P}^{ss'}_{\bar{q}g\leftarrow \bar{q}}(z,k_\perp) = \delta_{ss'} C_F \frac{1+z^2}{1-z},$$

$$\hat{P}^{ss'}_{gq\leftarrow q}(z,k_\perp) = \hat{P}^{ss'}_{g\bar{q}\leftarrow q}(z,k_\perp) = \delta_{ss'} C_F \frac{1+(1-z)^2}{z}$$

Spin terms is trivial, thus no spin correlation at collinear region.

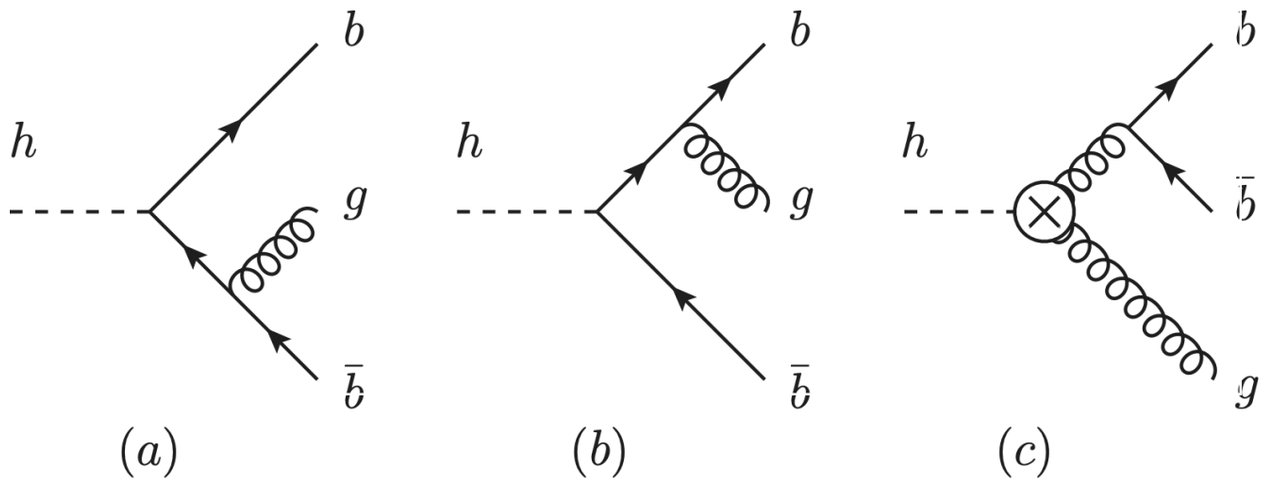
Beyond the collinear approximation, say large ΔR

$$A < 10^{-3}$$

At lepton colliders, CP properties

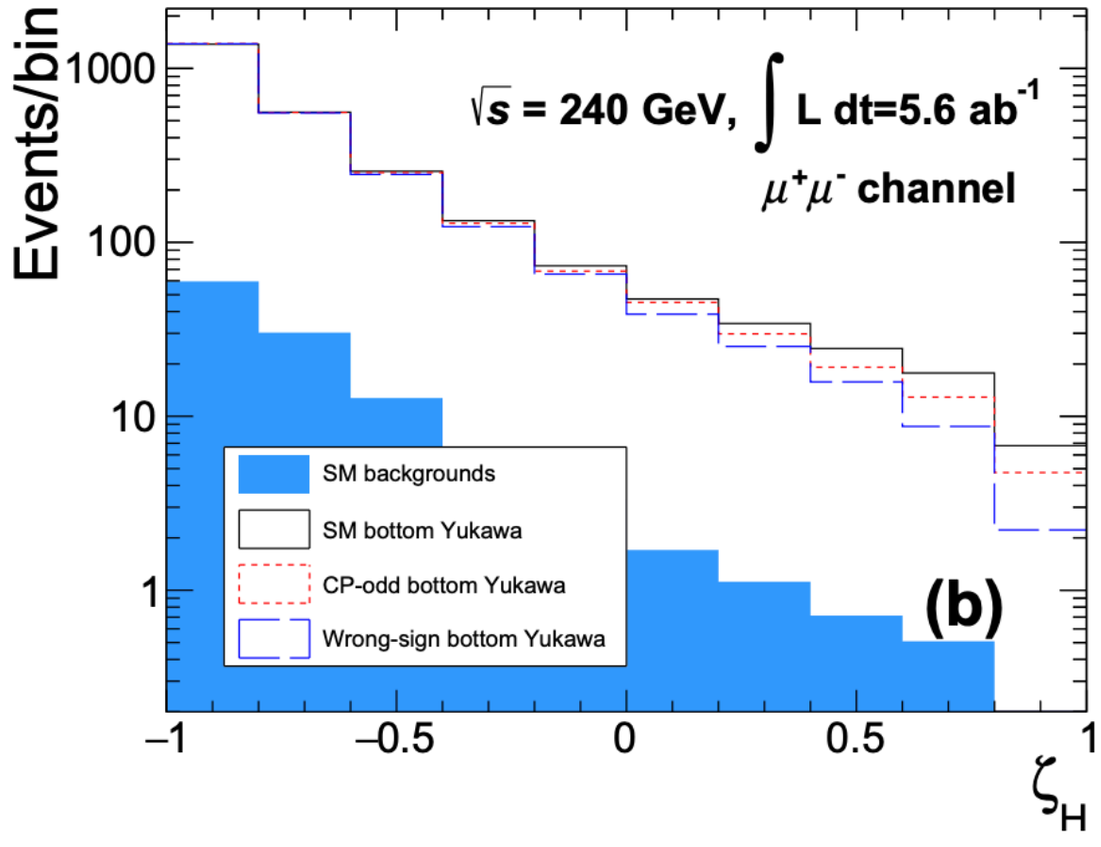
arXiv:2009.02000

$Hb\bar{b}$



$b\bar{b}$ is collinear

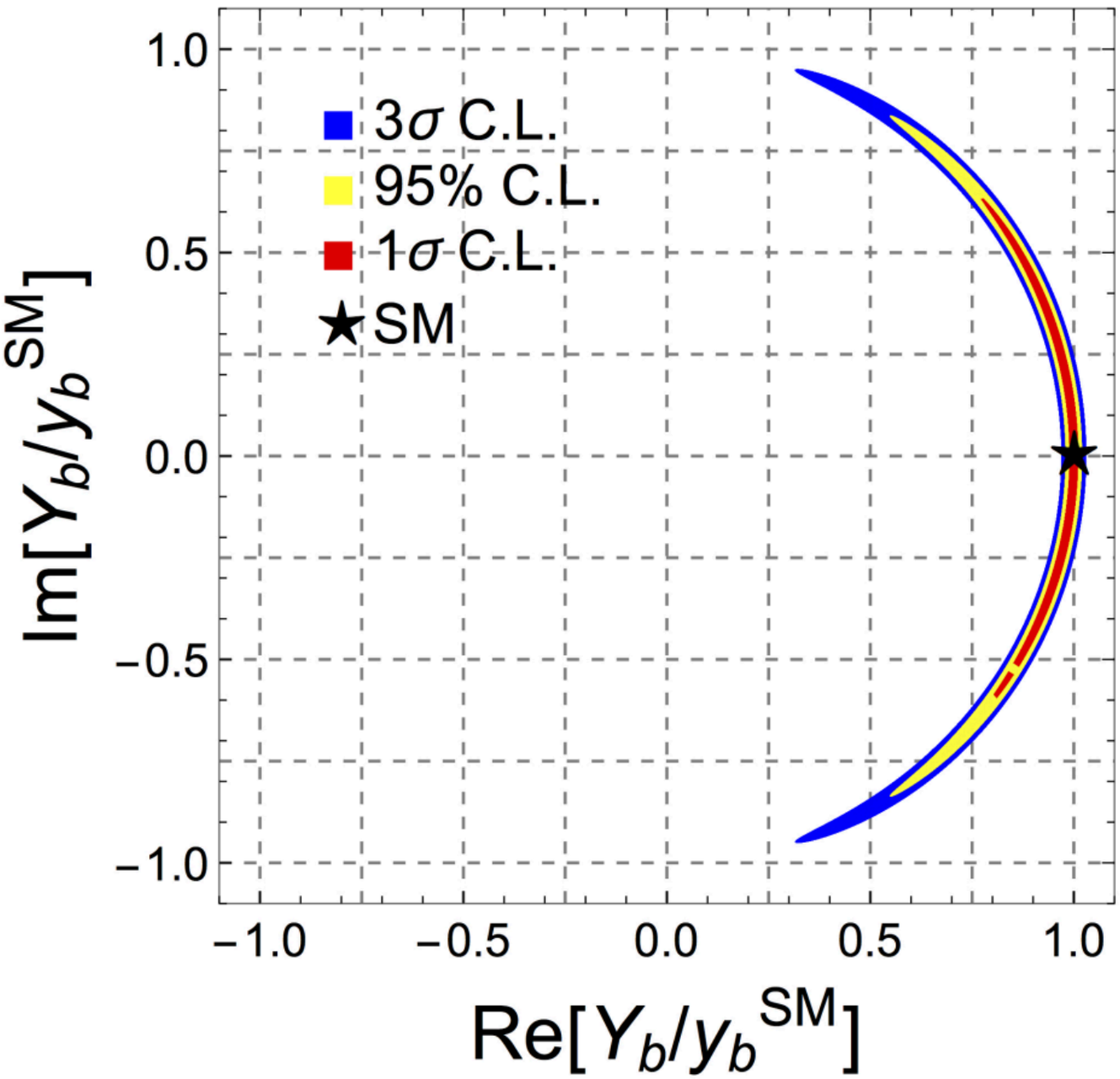
$$\zeta_H \equiv \frac{2E_{b_1}E_{b_2}}{E_{b_1}^2 + E_{b_1}^2}\cos\theta_{b_1 b_2}$$



At lepton colliders, CP properties

arXiv:2009.02000

Hbb?



At lepton colliders, CP properties

Challenges…

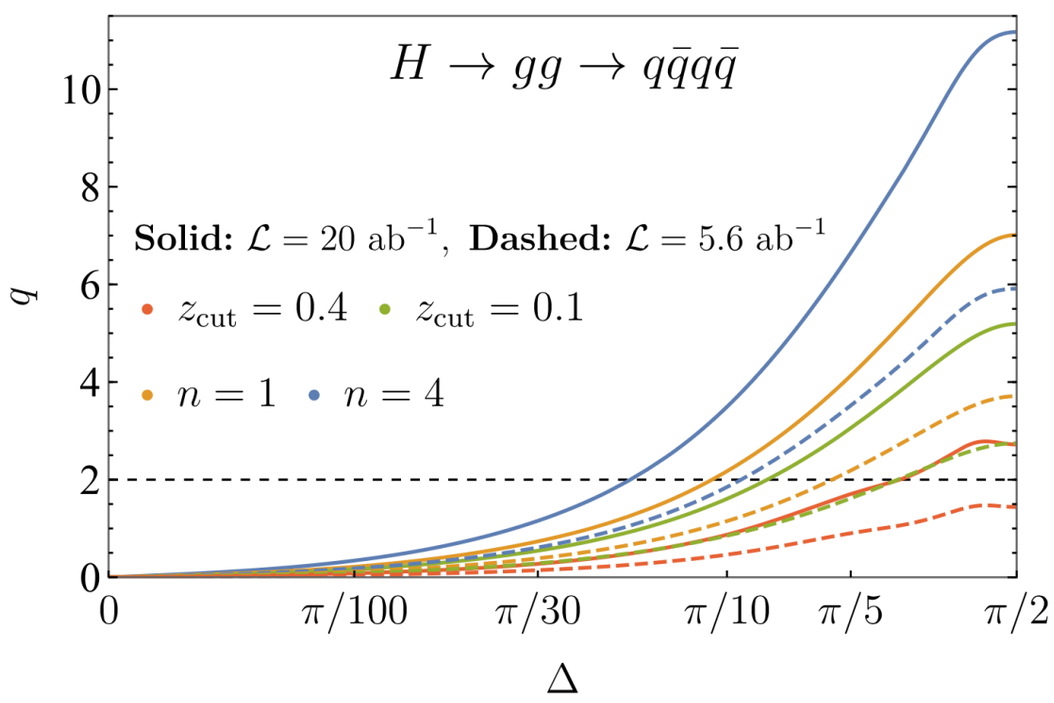
1. Would CP information be preserved in the showering and hadronization?

more realistic modeling to including showering and hadronization

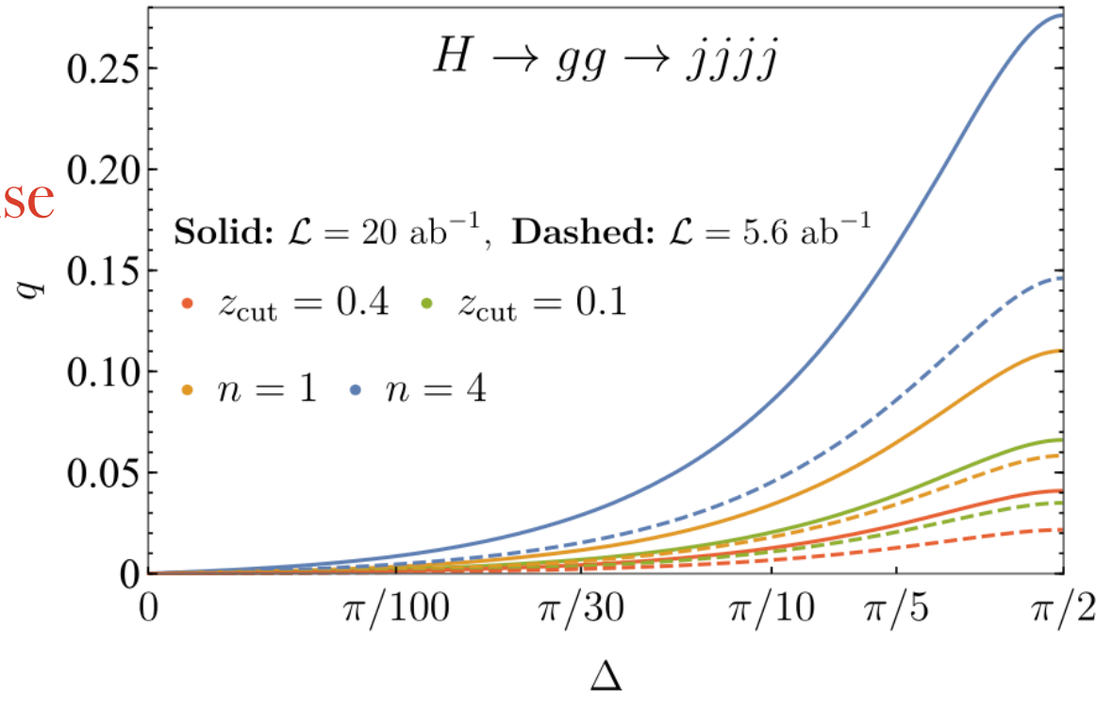
At lepton colliders, CP properties

Challenges…

2. Subjet tagging



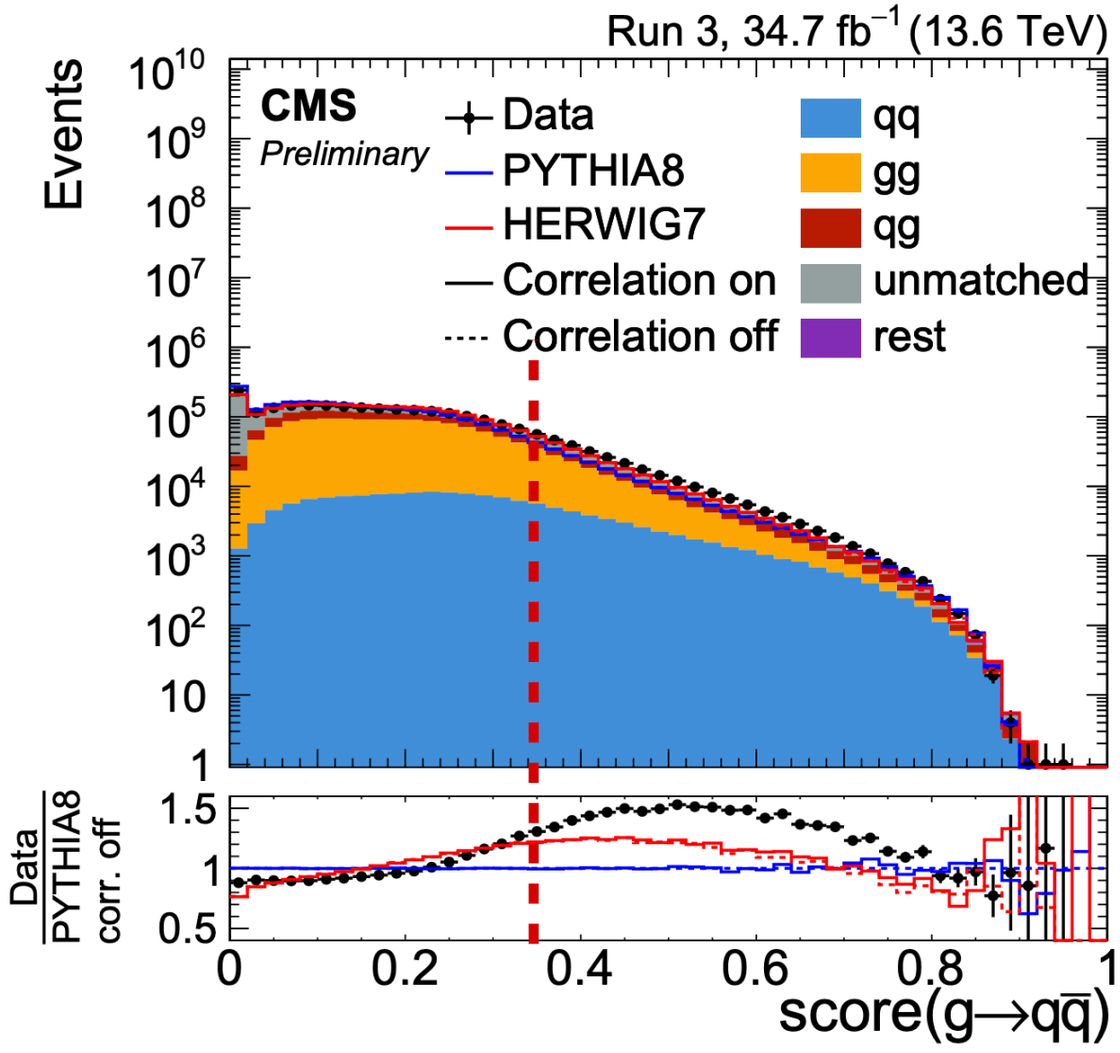
otherwise



At lepton colliders, CP properties

Challenges…

2. Subjet tagging $X \to Xg, g \to q\bar{q}(gg)$ CMS PAS SMP-25-006



$$\text{score}(g \to q\bar{q}) > 0.35$$

$$\text{purity}(ggq\bar{q}) : 0.07 \to 0.24$$

It can be further improved.

Stay tuned..

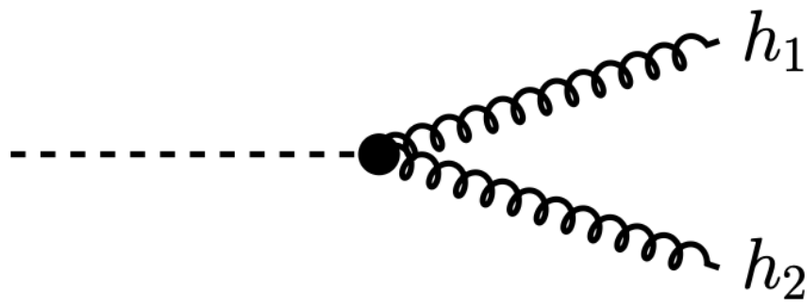
Thank you

CP violation and baryogenesis

Factorization of $H \to g_1 g_2,\ g_1 \to a_1 b_1,\ g_2 \to a_2 b_2$

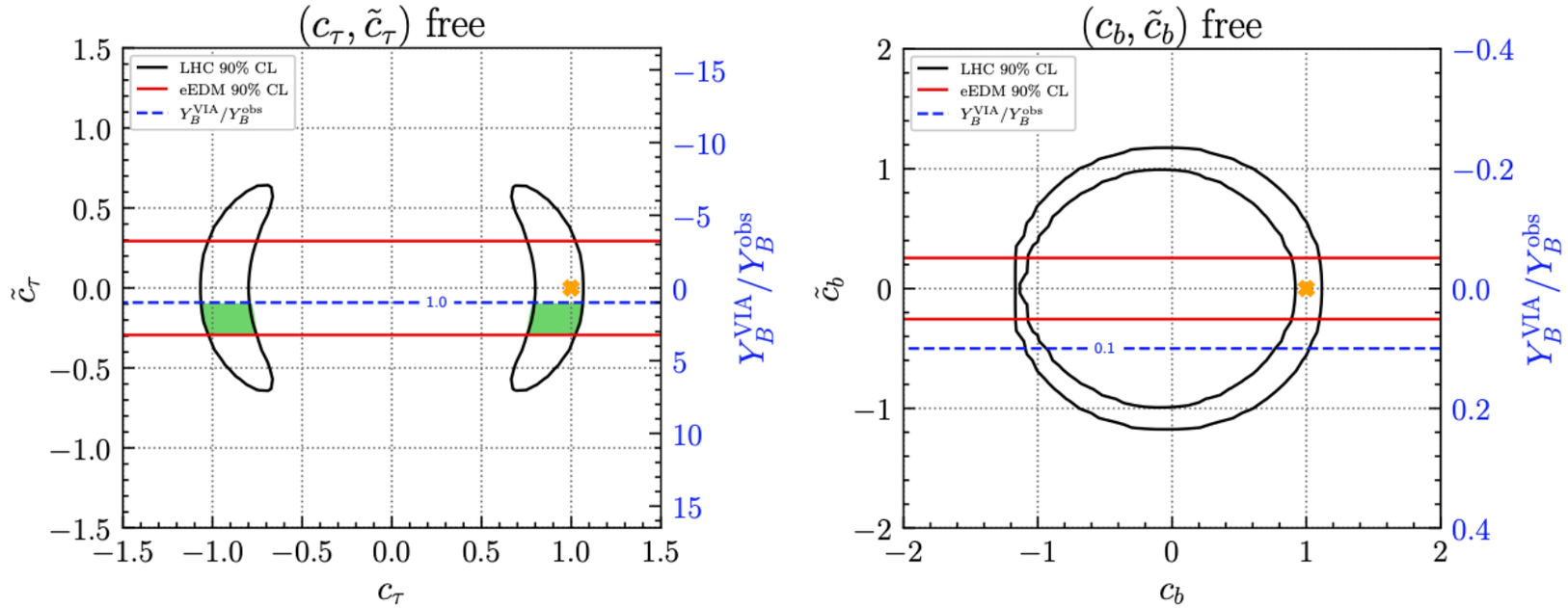
$$|\mathcal{M}|^2 \propto \sum_{h,h'} \mathcal{M}_{h_1 h_2} (\mathcal{M}_{h'_1 h'_2})^\dagger \rho_{\mu\nu}^{h_1 h'_1} P^{h_1 h'_1, \mu\nu}_{a_1 b_1 \leftarrow g1}(z_1, k_{1\perp}) \rho_{\alpha\beta}^{h_2 h'_2} P^{h_2 h'_2, \alpha\beta}_{a_2 b_2 \leftarrow g2}(z_2, k_{2\perp})$$

$\mathcal{M}_{h_1 h_2}$ is $H \to gg$ helicity amplitude:



$$\mathcal{M}^{h_1 h_2}_{H\to gg} = -\frac{1}{4}\frac{\alpha_s}{3\pi v}\Big(\epsilon_{\mu\nu\alpha\beta} k_1^\mu k_2^\nu \epsilon_{h_1}^{*\alpha} \epsilon_{h_2}^{*\beta} \sin\Delta$$
$$- \left[(k_1 \cdot k_2)(\epsilon^*_{h_1} \cdot \epsilon^*_{h_2}) - (k_1 \cdot \epsilon^*_{h_2})(k_2 \cdot \epsilon^*_{h_1})\right] \cos\Delta\Big)$$

CP violation and baryogenesis



$$\mathcal{M}^{h_1 h_2}_{H\to gg} = -\frac{1}{4}\frac{\alpha_s}{3\pi v}\Big(\epsilon_{\mu\nu\alpha\beta}k_1^\mu k_2^\nu \epsilon_{h_1}^{*\alpha}\epsilon_{h_2}^{*\beta}\sin\Delta - [(k_1\cdot k_2)(\epsilon_{h_1}^*\cdot\epsilon_{h_2}^*) - (k_1\cdot\epsilon_{h_2}^*)(k_2\cdot\epsilon_{h_1}^*)]\cos\Delta\Big)$$