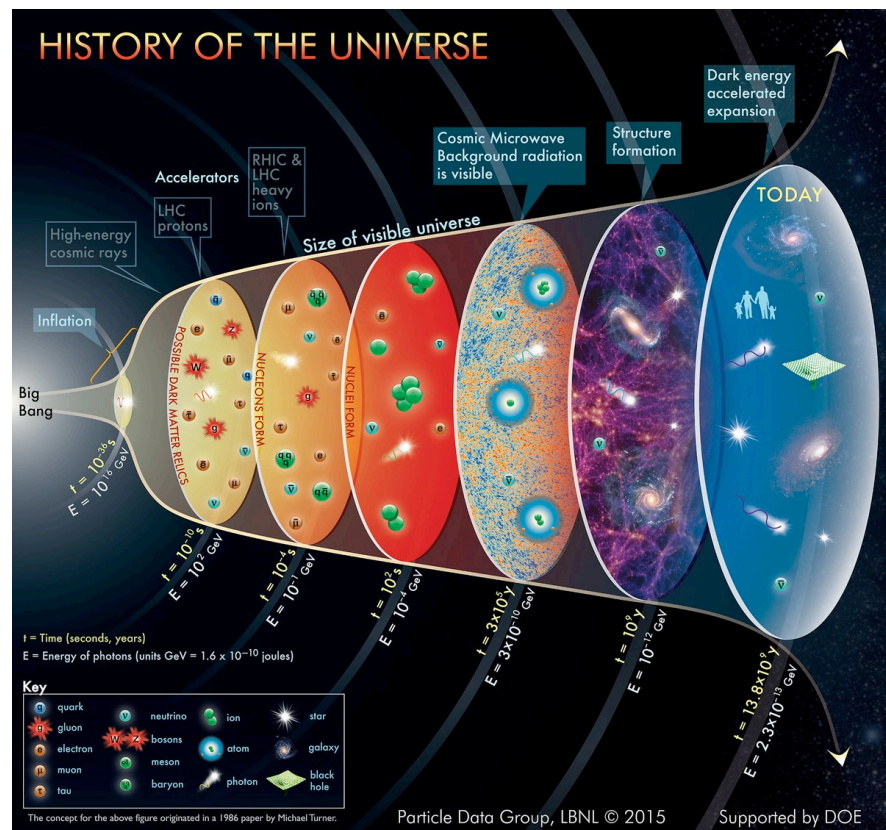
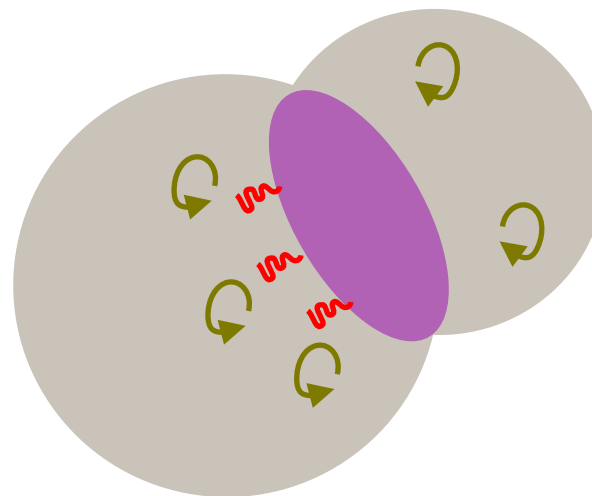
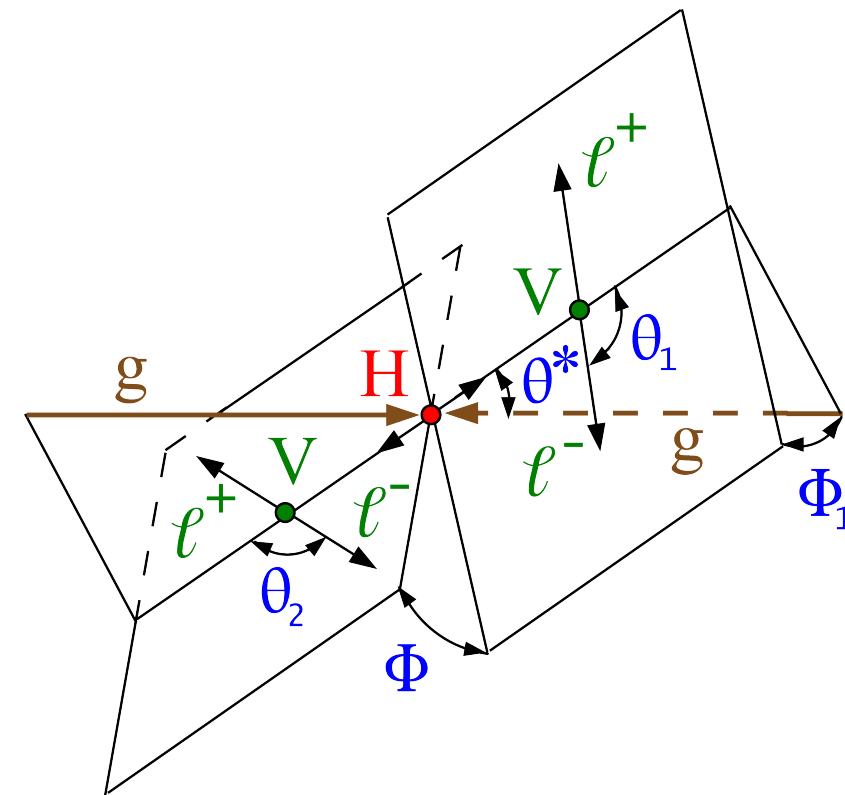




Ying-Ying Li (李英英)

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

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

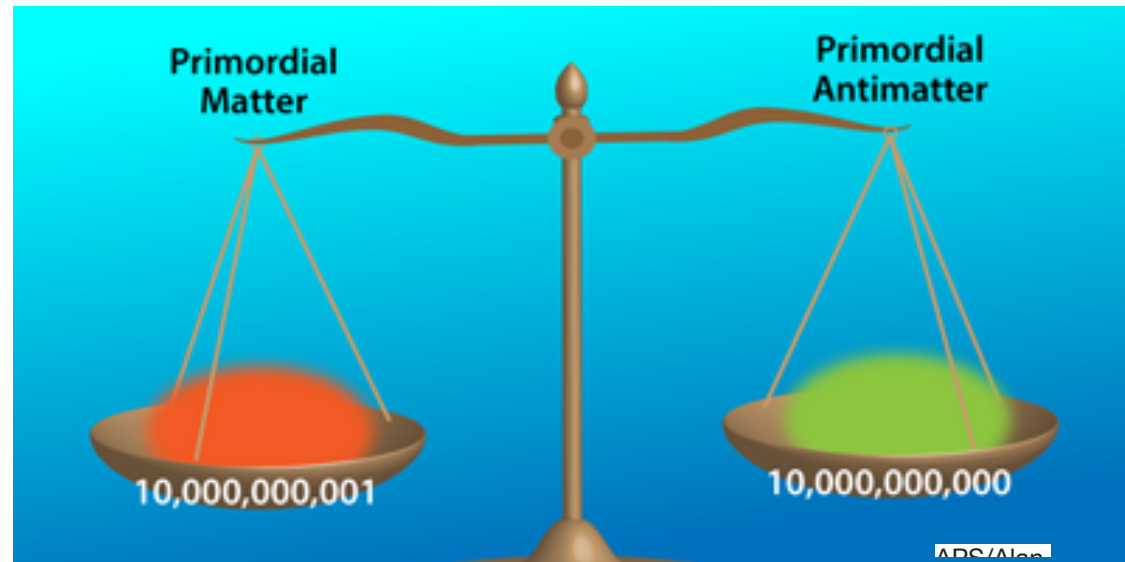
Parton spin correlations and CP properties in Higgs boson decay at future lepton colliders

Oct. 31, 2026 @ 7th Joint Workshop on the SM and Beyond

CP violation and baryogenesis

One observable fact

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



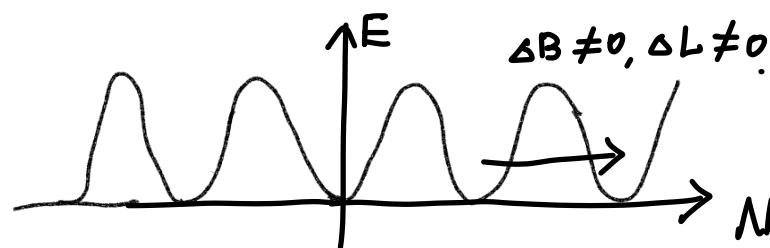
Three conditions(Sakharov conditions)

C- and CP-
violation

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

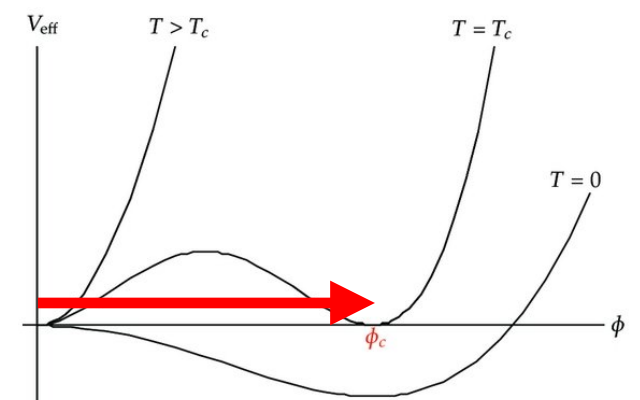
SM, not enough

B-violation



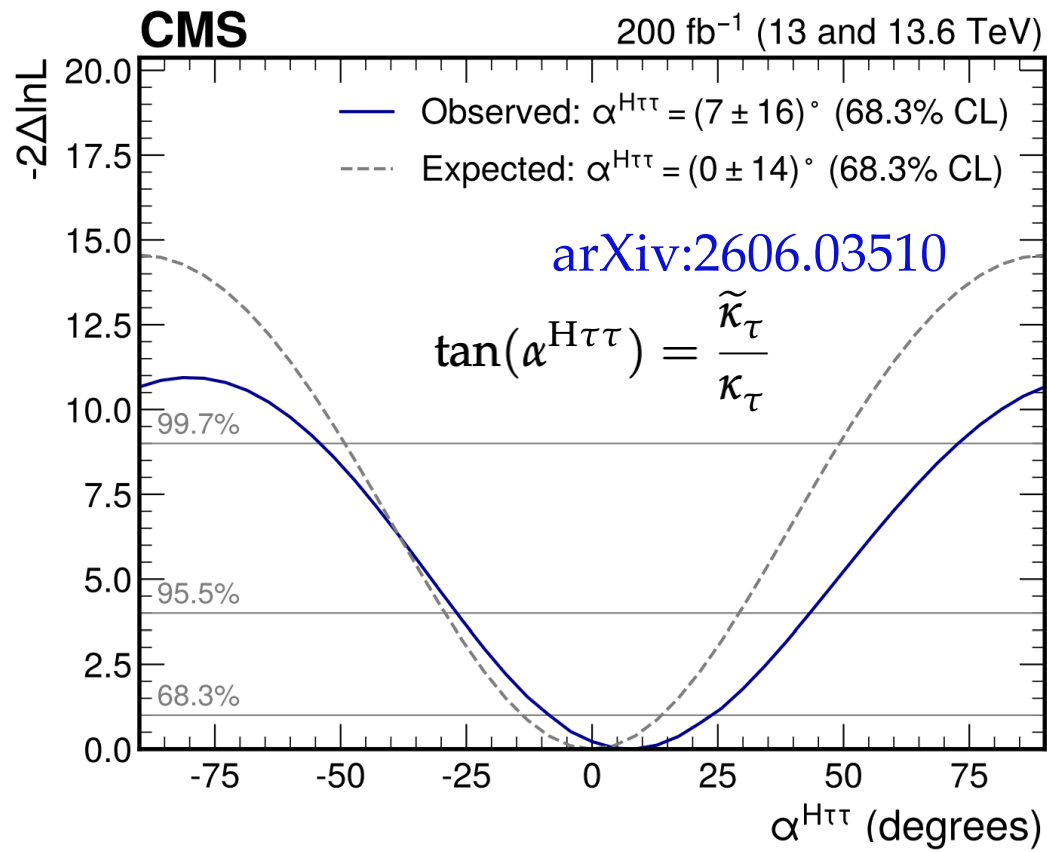
SM

Out of equilibrium

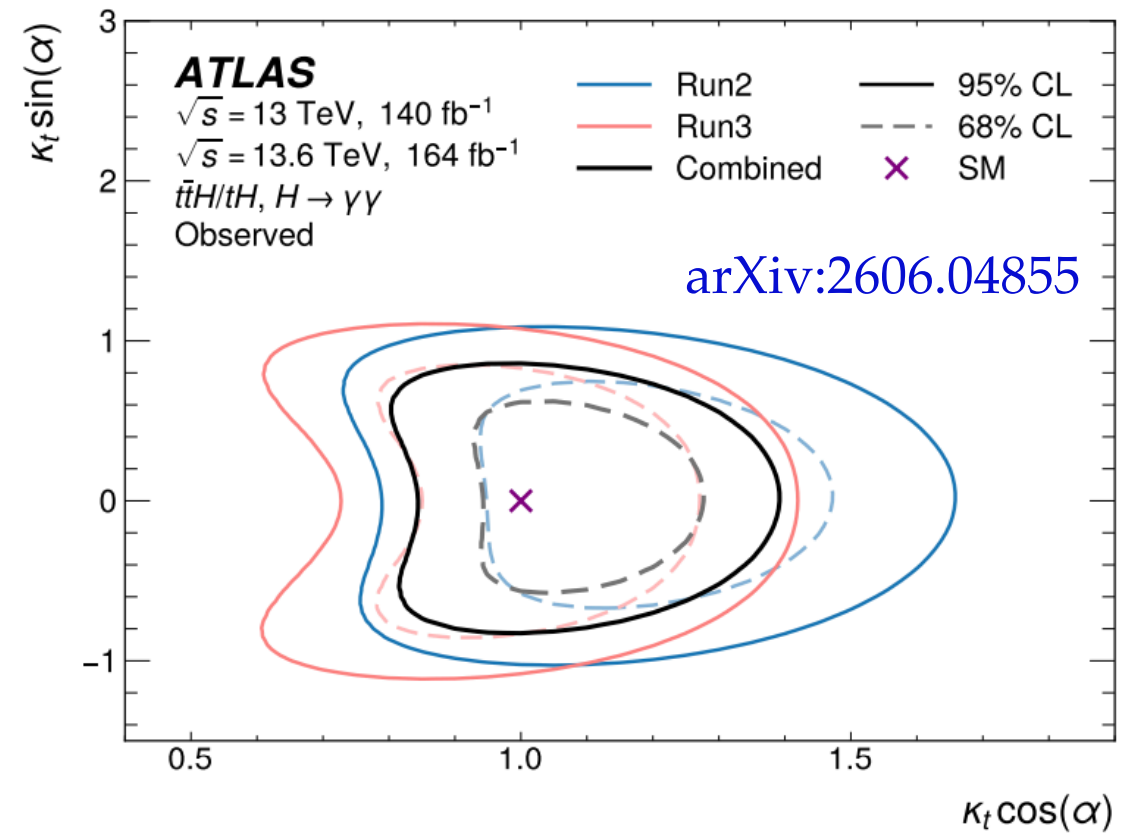


BSM

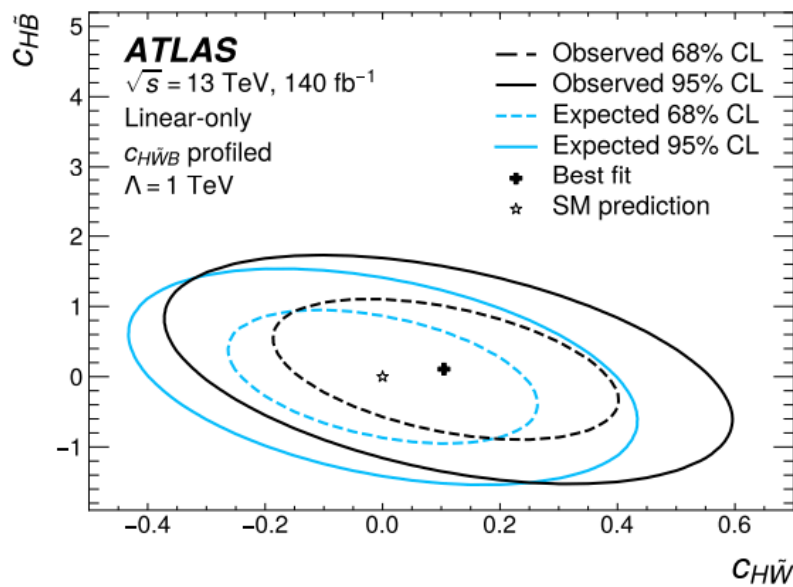
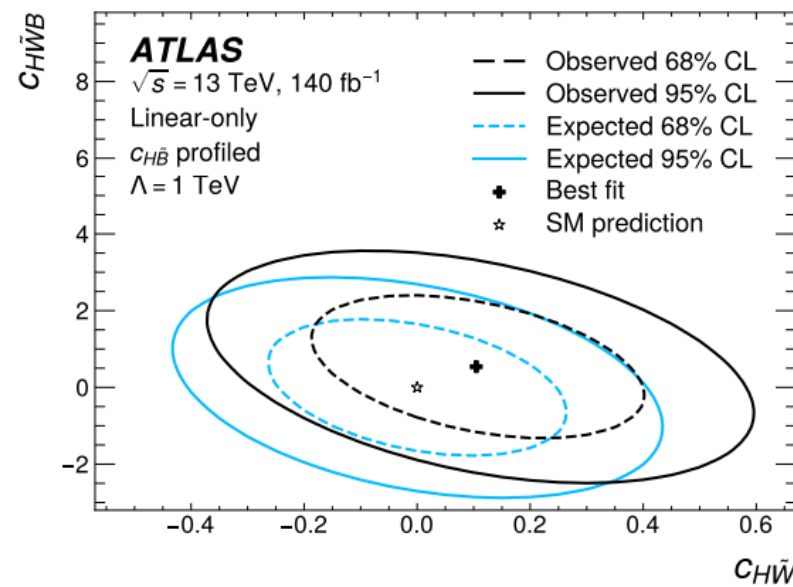
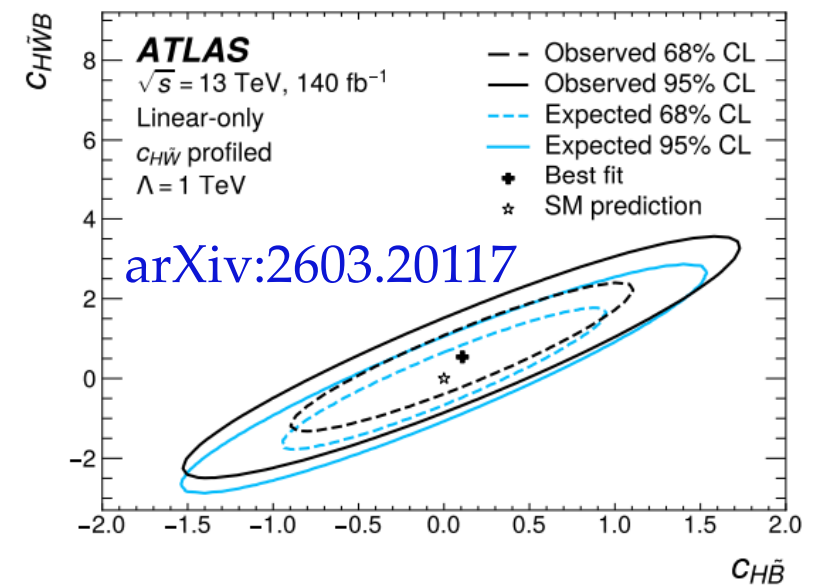
CP violation in Higgs-related couplings



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



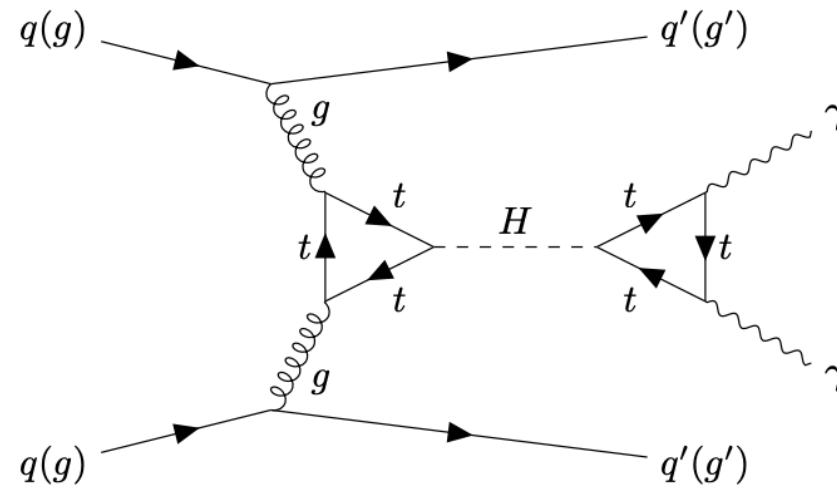
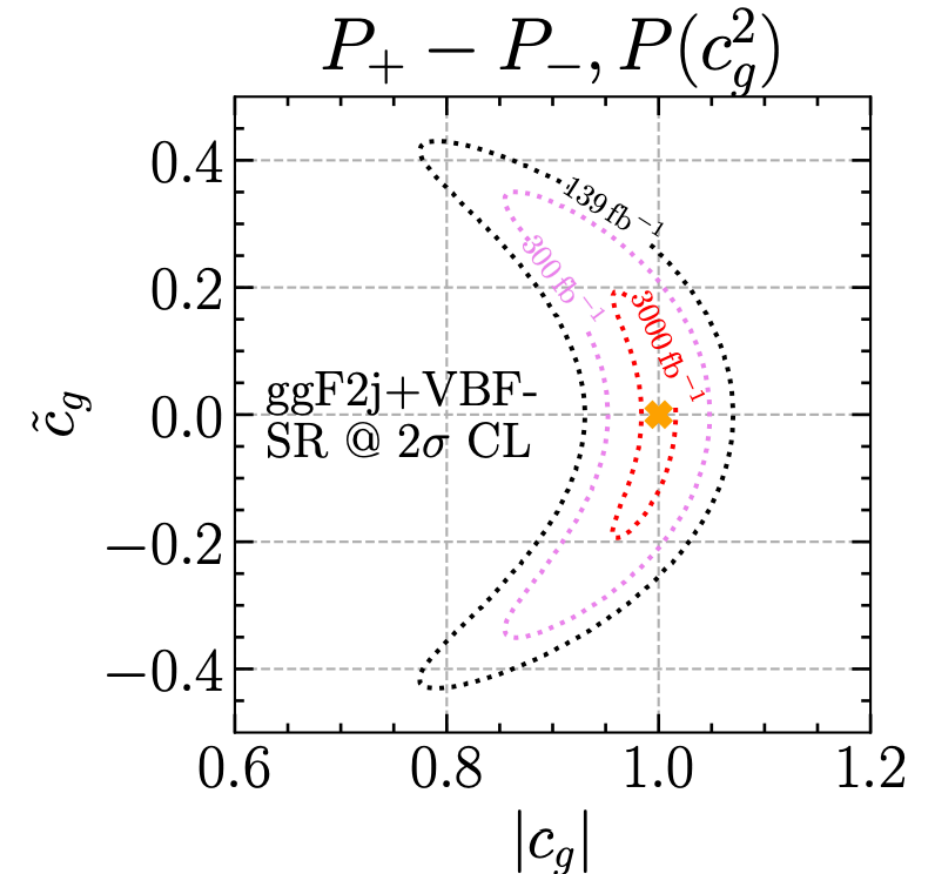
$$\mathcal{L} = -\frac{m_t}{v} \{ \bar{\psi}_t \kappa_t [\cos(\alpha) + i \sin(\alpha) \gamma_5] \psi_t \} H$$



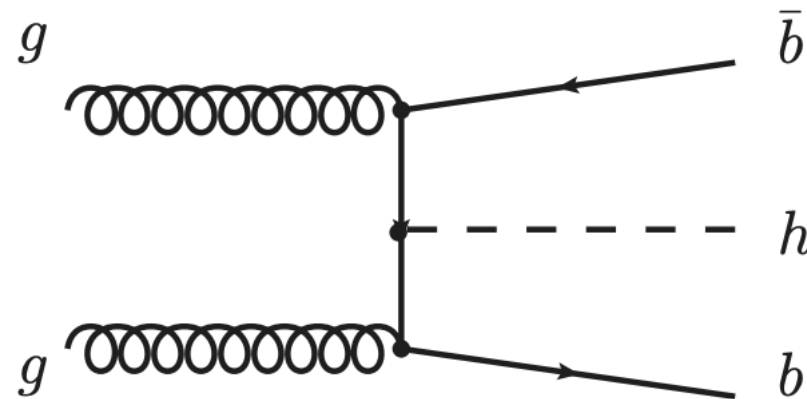
CP violation in Higgs-related couplings

SciPost Phys. Core 8, 006 (2025)

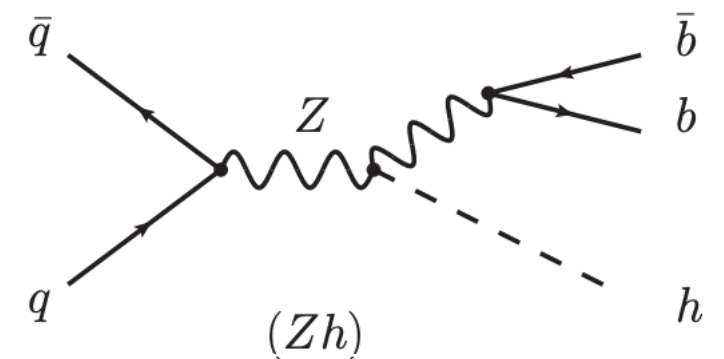
$Hgg?$



$Hb\bar{b}?$



Very large irreducible bg

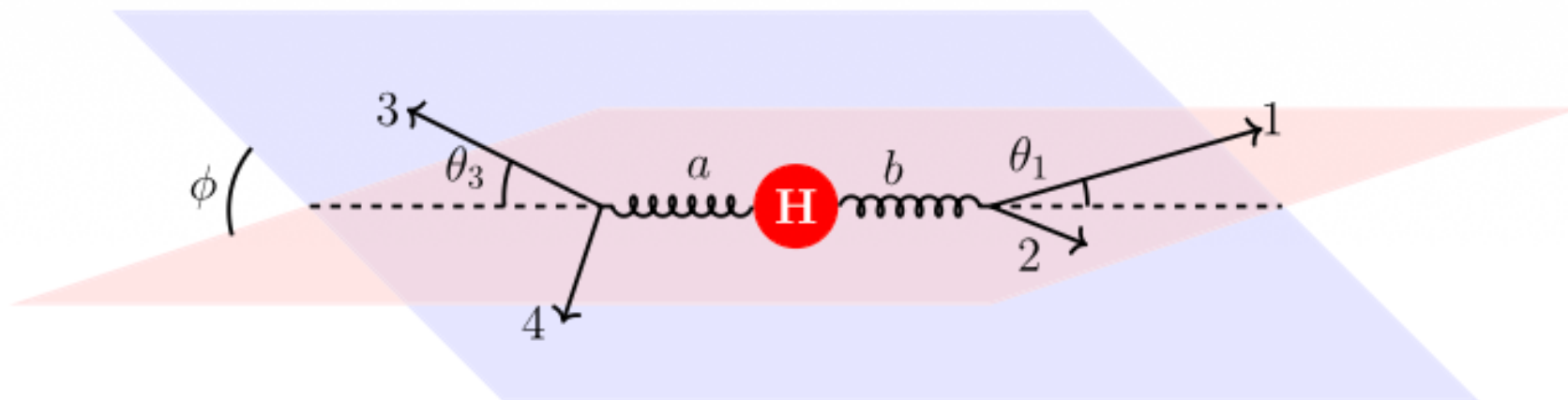


arXiv:2011.13945

CP violation in Higgs -related couplings

What about from the decay?

$Hgg?$
 $Hb\bar{b}?$

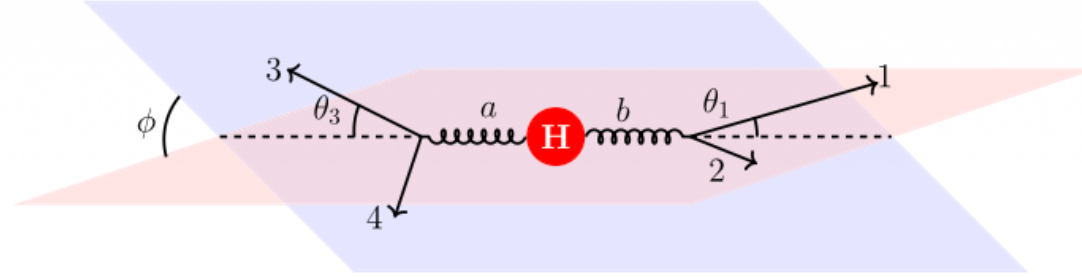


What observables should we look at?

Would CP information be preserved in the showering
and hadronization?

Methods—leading order approximation

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



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

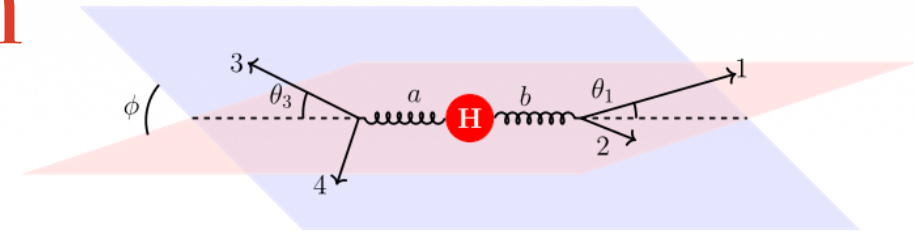
$$|\mathcal{M}|^2 \propto \sum_{h,h'} \mathcal{M}_{h_1 h_2} (\mathcal{M}_{h'_1 h'_2})^\dagger \rho_{\mu\nu}^{h_1 h'_1} P_{a_1 b_1 \leftarrow g_1}^{h_1 h'_1, \mu\nu}(z_1, k_{1\perp}) \rho_{\alpha\beta}^{h_2 h'_2} P_{a_2 b_2 \leftarrow g_2}^{h_2 h'_2, \alpha\beta}(z_2, k_{2\perp})$$

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

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

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

Methods—leading order approximation



IR safe?

Resolution

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

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

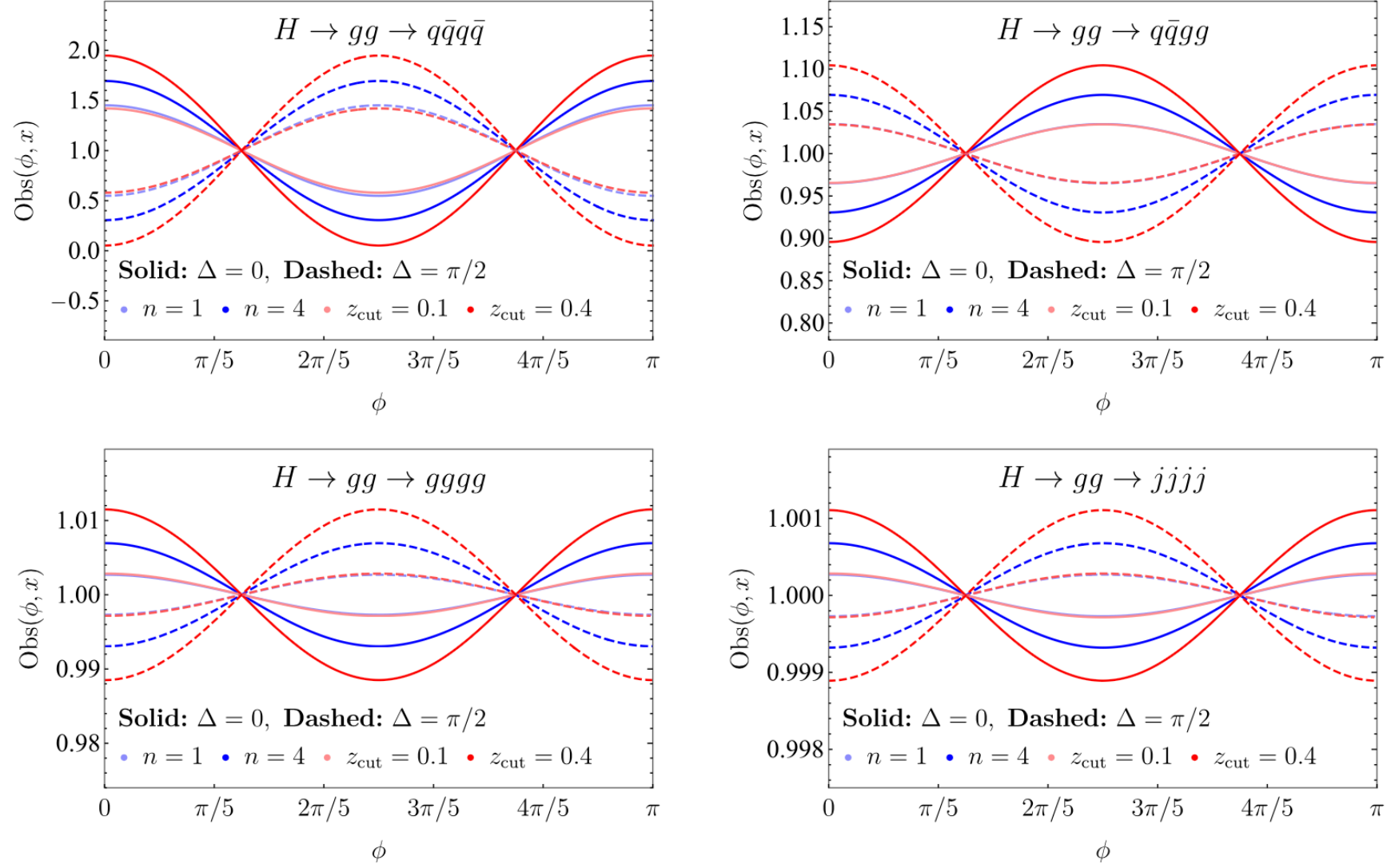
- Use energy-weighted differential cross-section, or energy correlator (EC). Here we extend the idea by introducing the n-power weighting ($E^n C$):

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

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

correlation strength

Methods—leading order approximation



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

Methods—leading order approximation

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

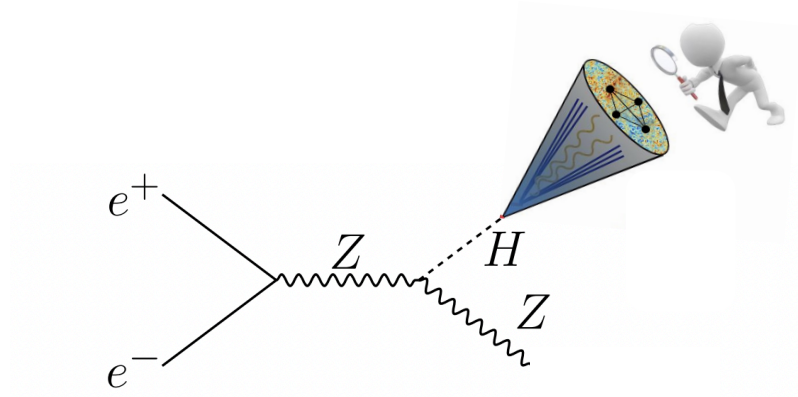
TABLE II. Cut efficiency ϵ_z for $z_{\text{cut}} = 0.1$ and $z_{\text{cut}} = 0.4$ when considering the Lund observable.

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

At lepton colliders, measure spin correlation

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

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

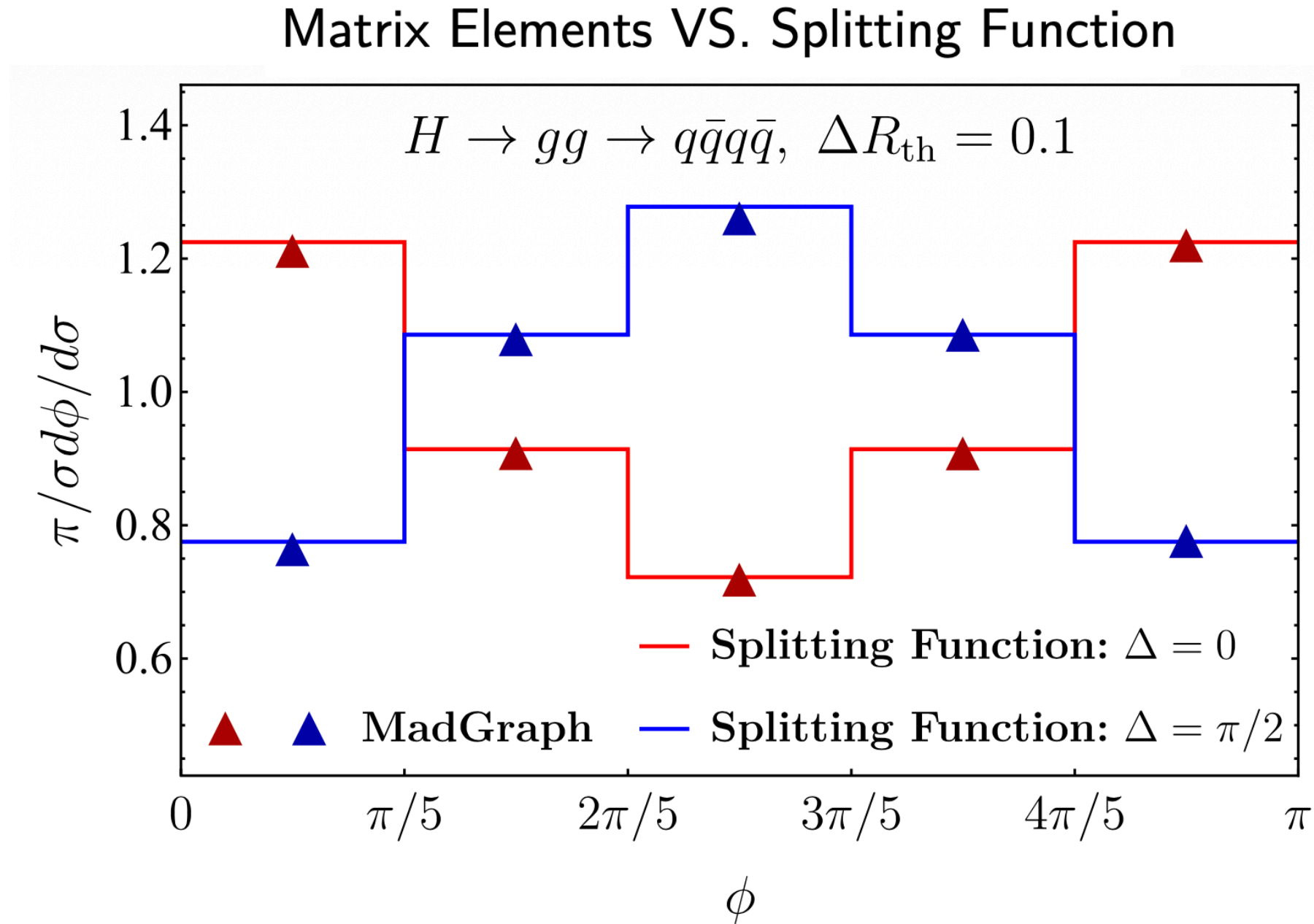


To construct Higgs rest frame...

$$Z \rightarrow l\bar{l}$$

At lepton colliders, measure spin correlation

We use MadGraph to generate parton level events $e^+e^- \rightarrow ZH, H \rightarrow gg \rightarrow a_1b_1a_2b_2$



At lepton colliders, measure spin correlation

Signal event number

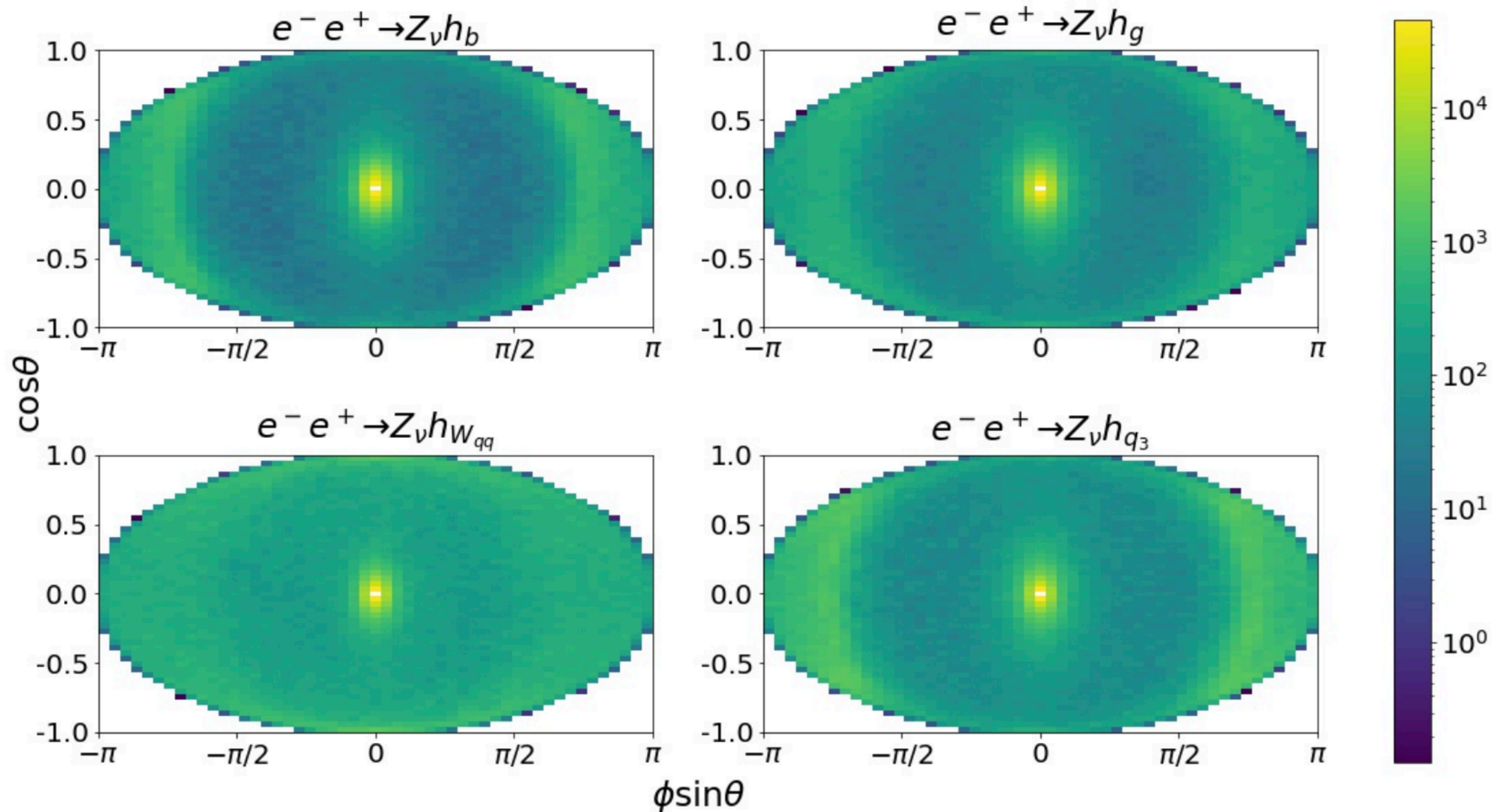
$$N_X = \sigma_{ZH} \mathcal{L} \text{Br}(Z \rightarrow l\bar{l}) \text{Br}(H \rightarrow gg) P_{gg \rightarrow X} \epsilon_z \epsilon_{\text{cut}} \epsilon_{gg}$$

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

ϵ_z : only for Lund variable

At lepton colliders, measure spin correlation

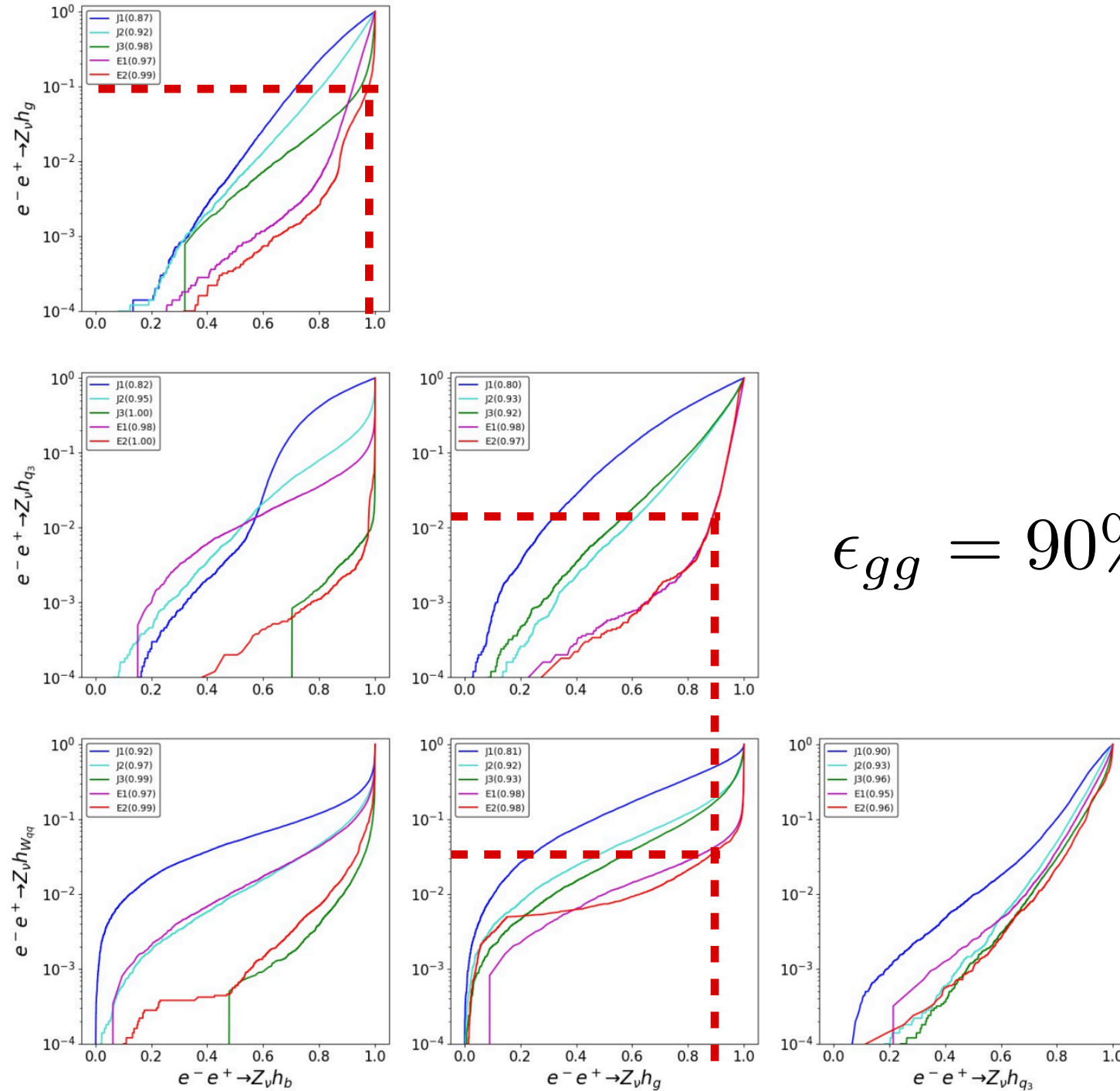
ϵ_{gg} : event level analysis to separate gg events from others



ResNet-50 network

At lepton colliders, measure spin correlation

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



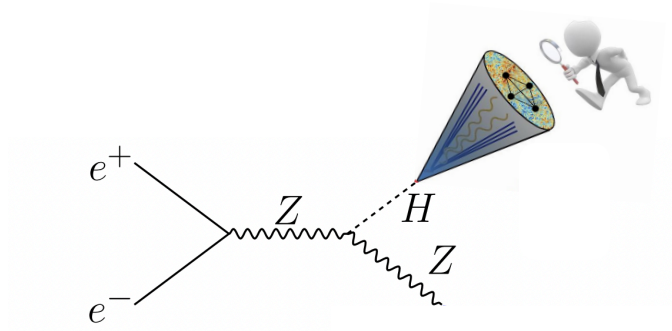
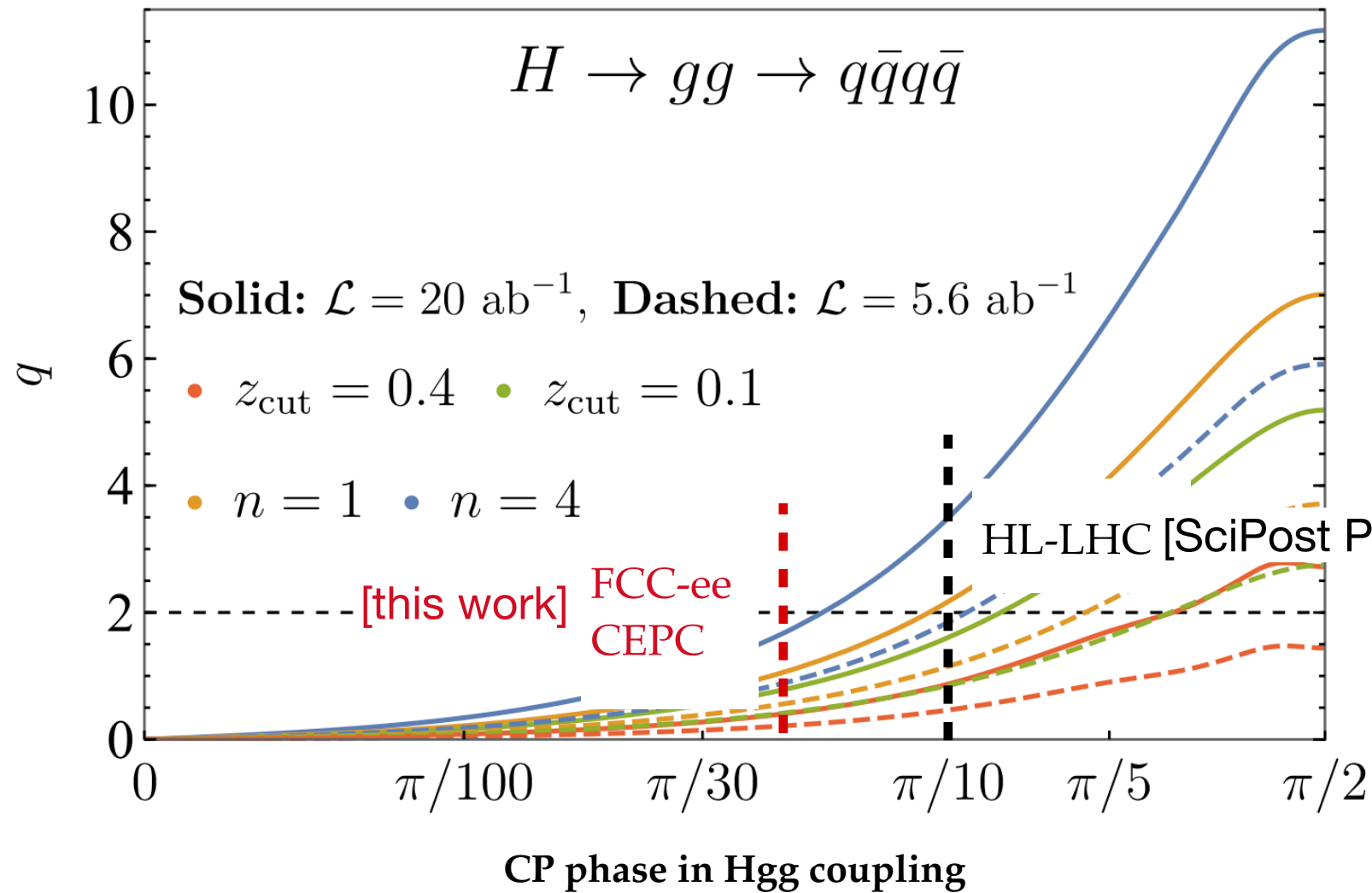
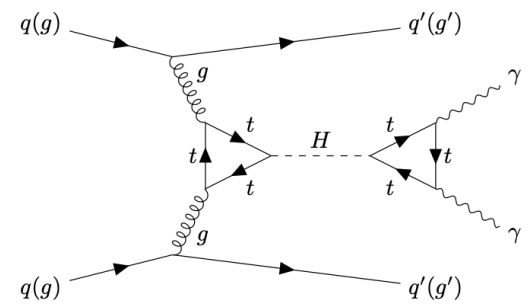
At lepton colliders, measure spin correlation

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

TABLE III. Significance to exclude the uncorrelated hypothesis using the choices of $\text{E4C}(\phi, n = 1)$ and $\text{E4C}(\phi, n = 4)$, 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:

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

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

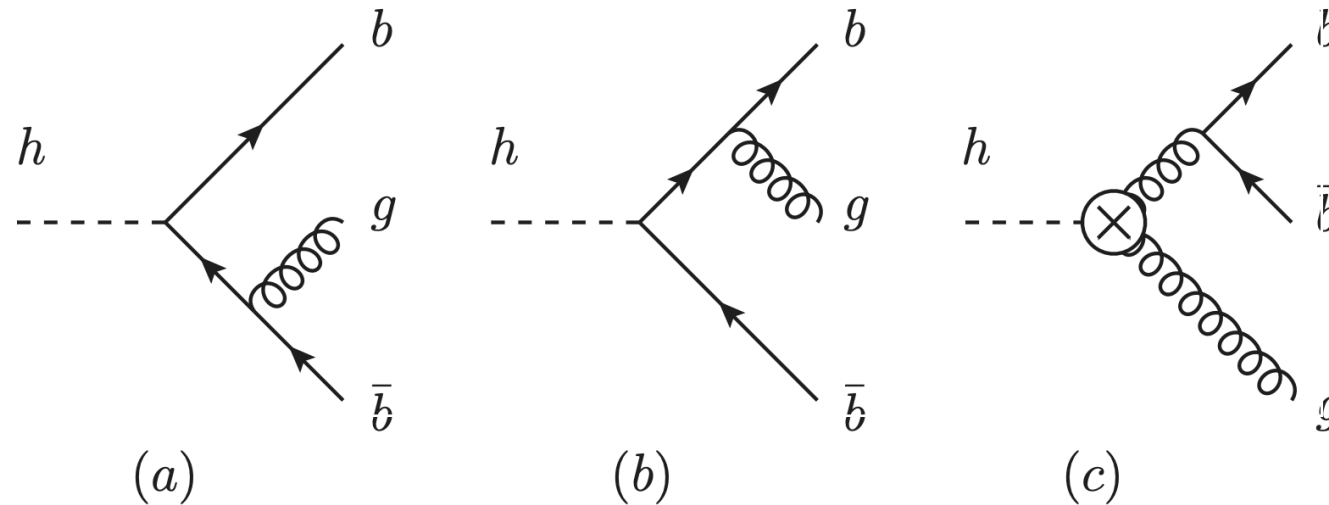
Beyond the collinear approximation, say large ΔR

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

At lepton colliders, CP properties

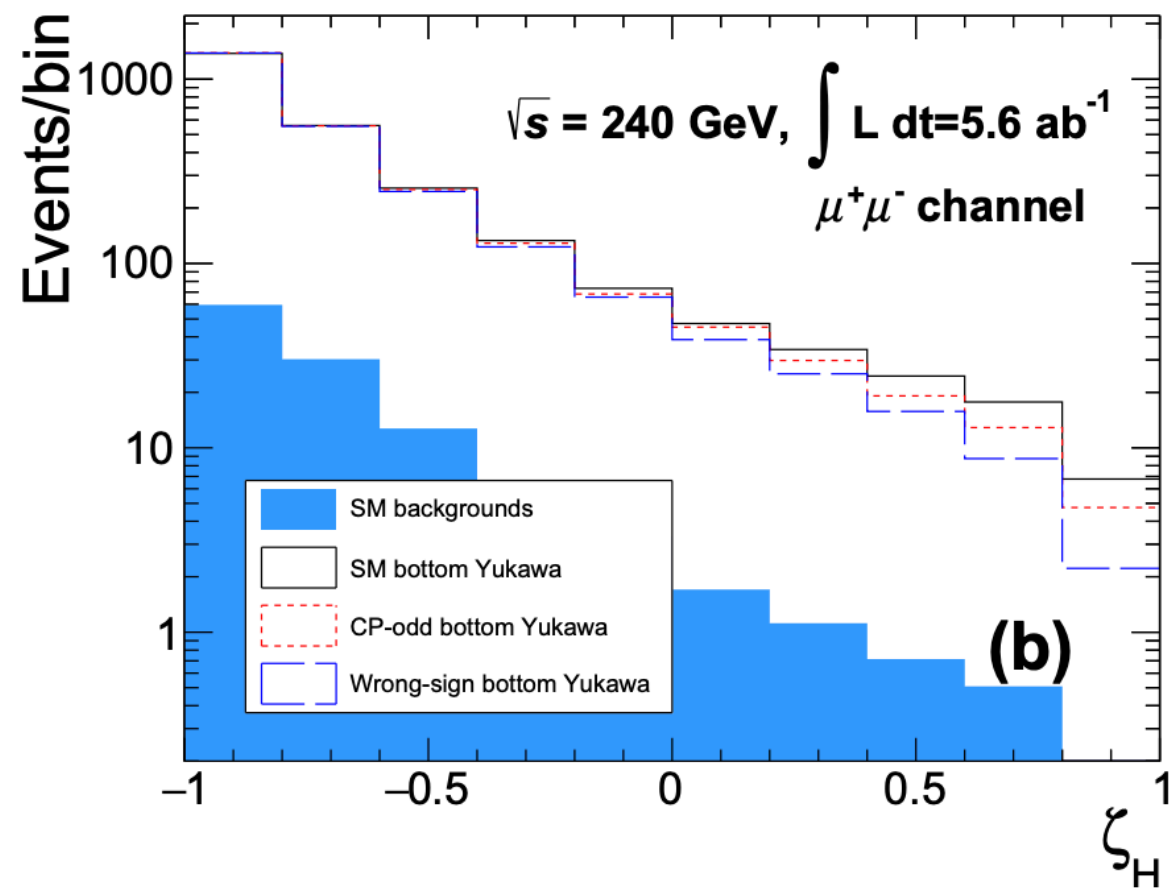
arXiv:2009.02000

$H b \bar{b}$



$b \bar{b}$ is collinear

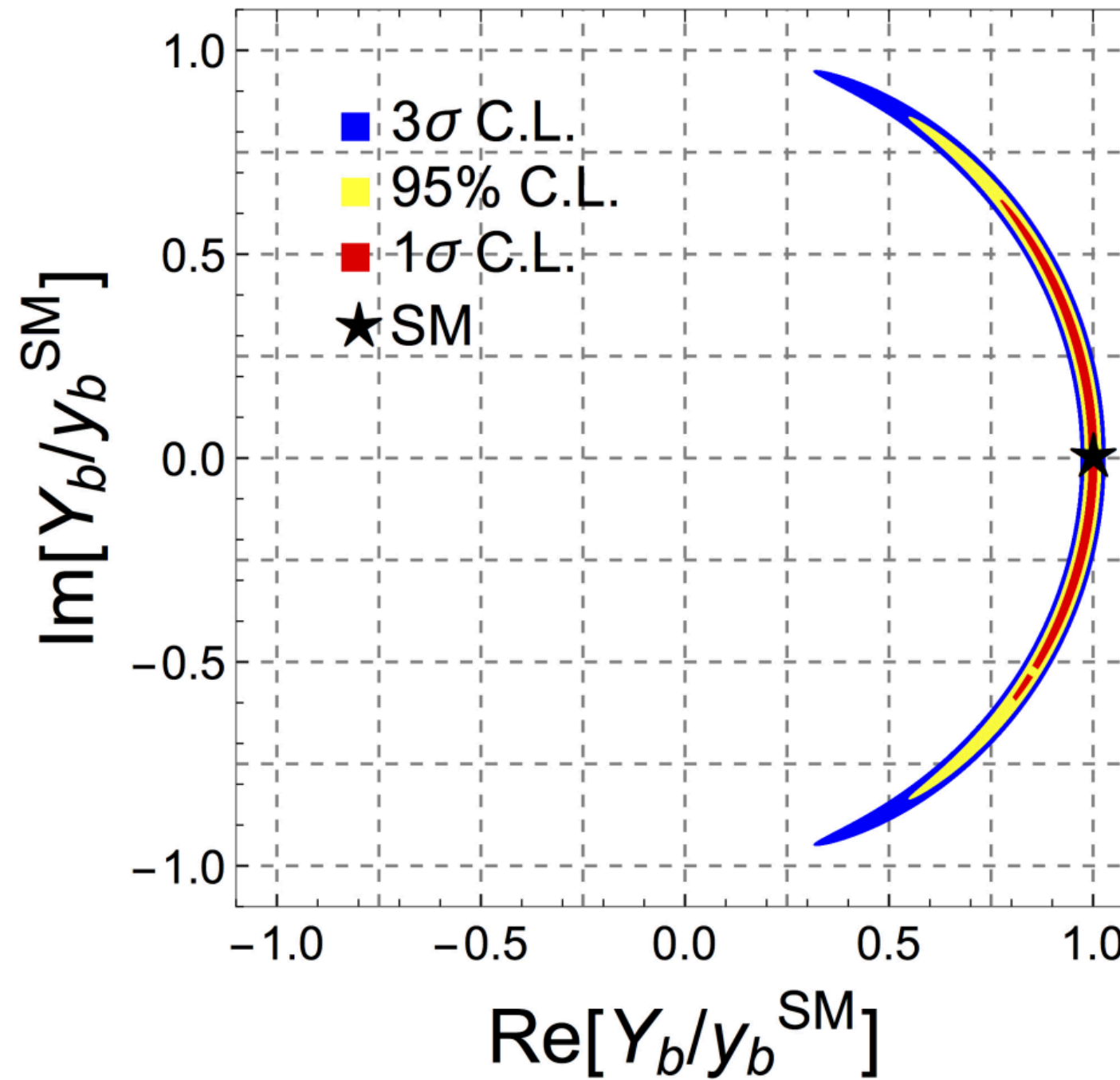
$$\zeta_H \equiv \frac{2E_{b_1} E_{b_2}}{E_{b_1}^2 + E_{b_2}^2} \cos \theta_{b_1 b_2}$$



At lepton colliders, CP properties

arXiv:2009.02000

Hbb?



At lepton colliders, CP properties

Challenges...

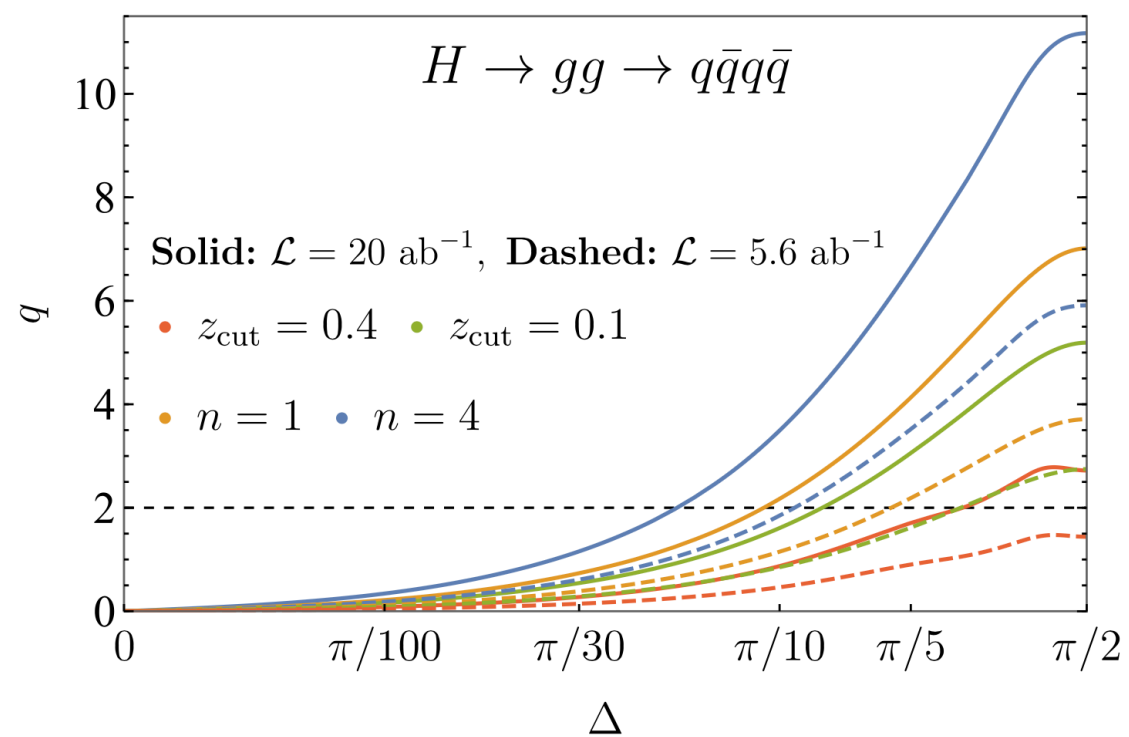
1. Would CP information be preserved in the showering
and hadronization?

more realistic modeling to including showering and hadronization

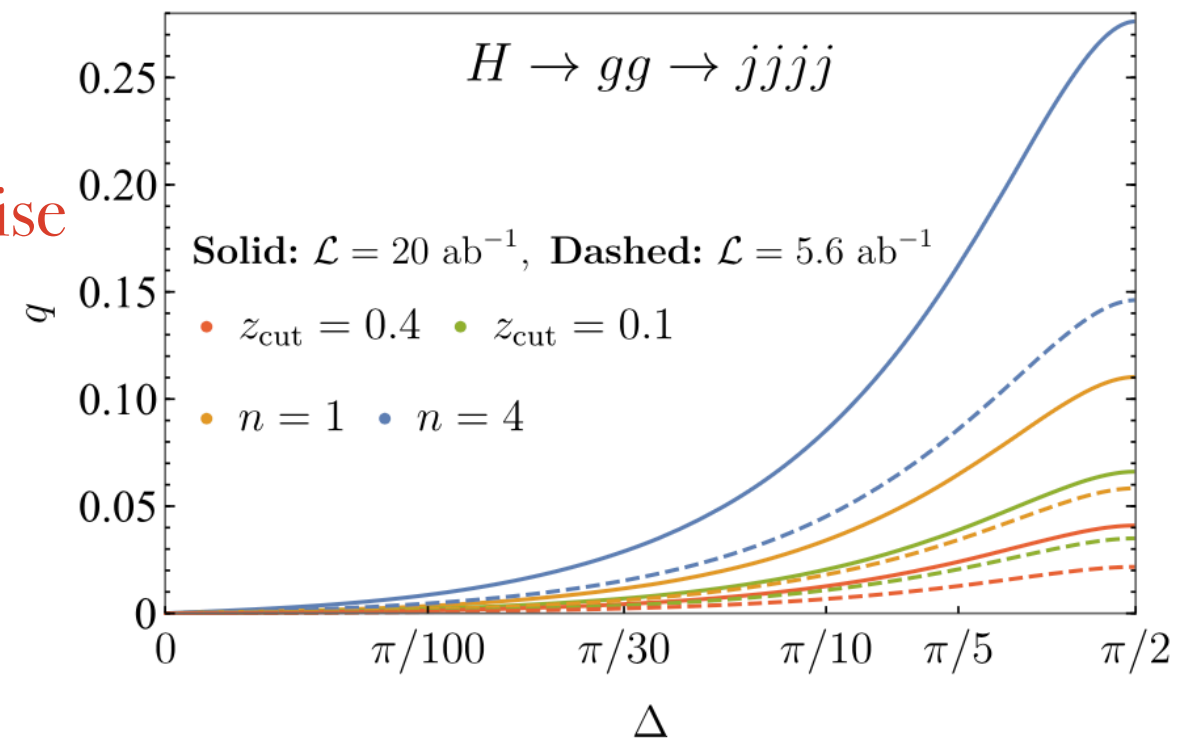
At lepton colliders, CP properties

Challenges...

2. Subjet tagging



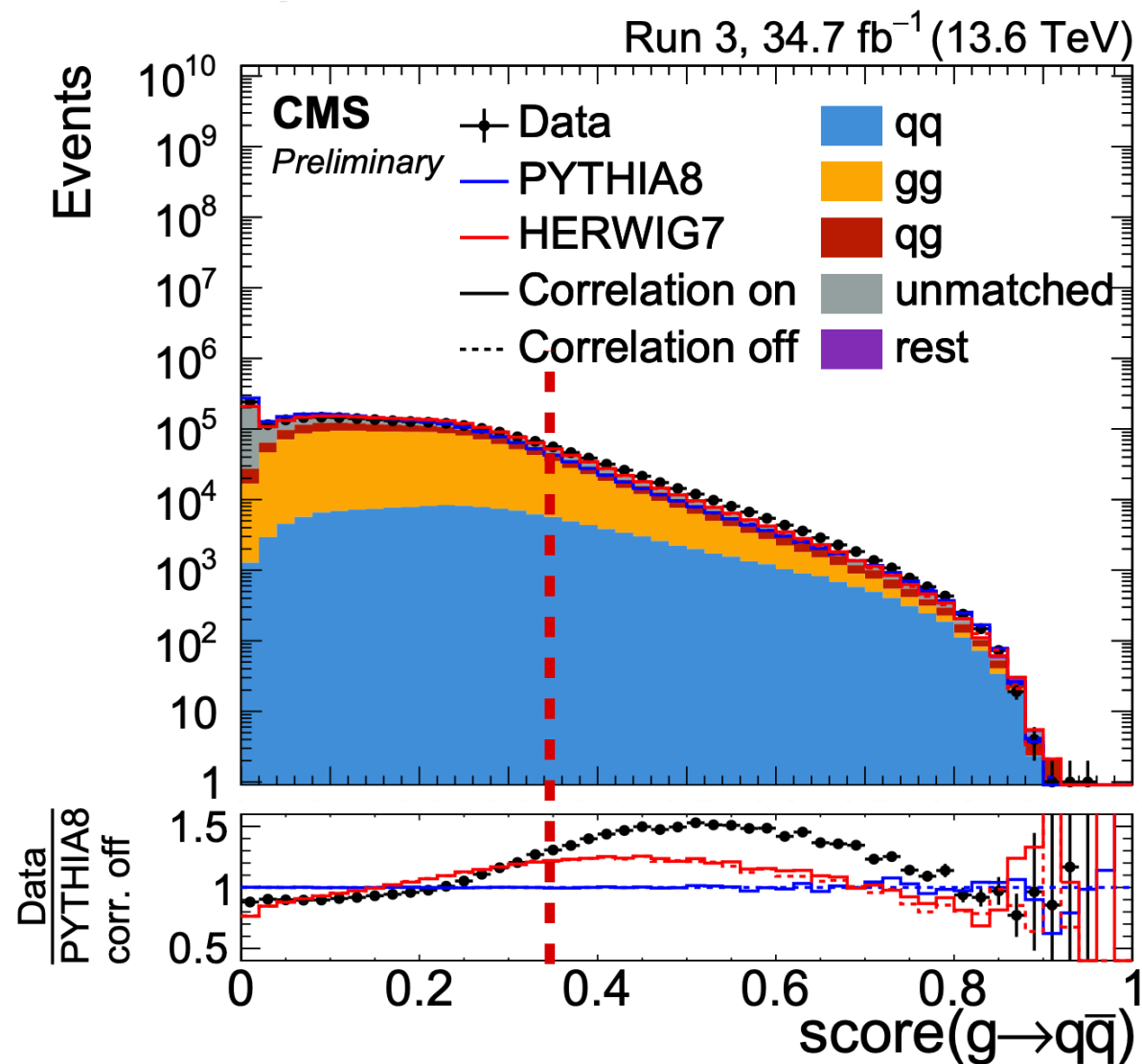
otherwise



At lepton colliders, CP properties

Challenges...

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



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

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

It can be further improved.

Stay tuned..

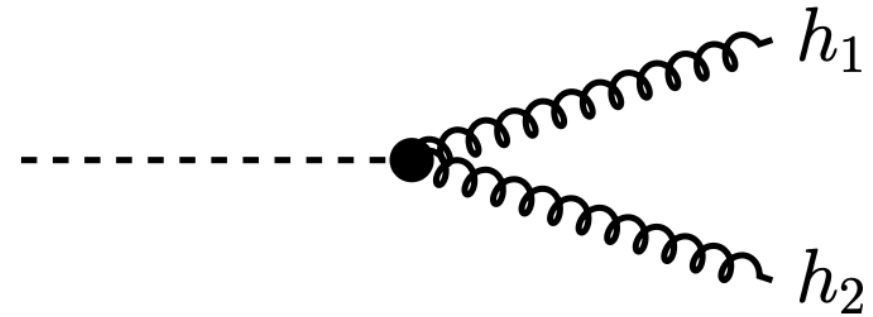
Thank you

CP violation and baryogenesis

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

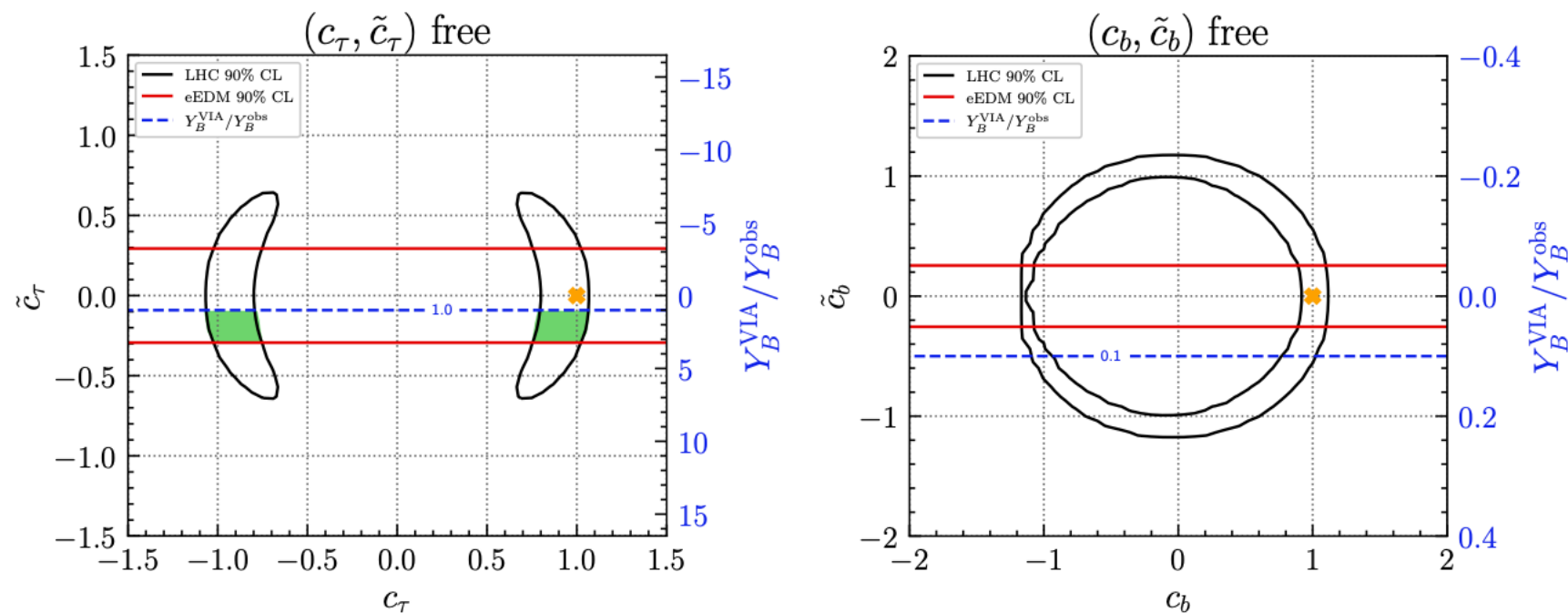
$$|\mathcal{M}|^2 \propto \sum_{h,h'} \mathcal{M}_{h_1 h_2} (\mathcal{M}_{h'_1 h'_2})^\dagger \rho_{\mu\nu}^{h_1 h'_1} P_{a_1 b_1 \leftarrow g_1}^{h_1 h'_1, \mu\nu}(z_1, k_{1\perp}) \rho_{\alpha\beta}^{h_2 h'_2} P_{a_2 b_2 \leftarrow g_2}^{h_2 h'_2, \alpha\beta}(z_2, k_{2\perp})$$

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



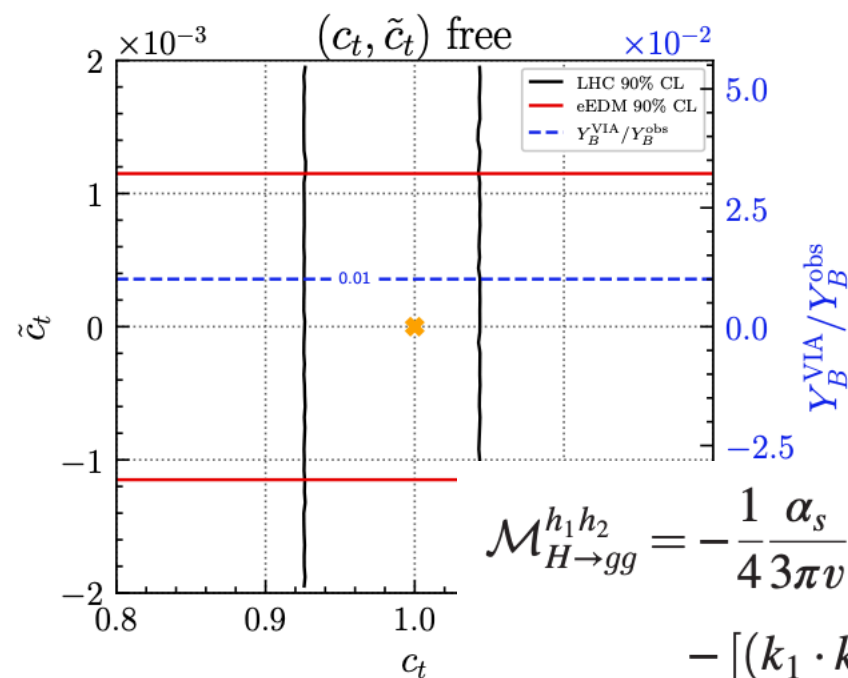
$$\mathcal{M}_{H \rightarrow gg}^{h_1 h_2} = -\frac{1}{4} \frac{\alpha_s}{3\pi v} \left(\epsilon_{\mu\nu\alpha\beta} k_1^\mu k_2^\nu \epsilon_{h_1}^{*\alpha} \epsilon_{h_2}^{*\beta} \sin \Delta \right. \\ \left. - [(k_1 \cdot k_2)(\epsilon_{h_1}^* \cdot \epsilon_{h_2}^*) - (k_1 \cdot \epsilon_{h_2}^*)(k_2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

CP violation and baryogenesis



(a)

(b)



(c)

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