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CPV in Higgs di-tau decays and energy correlators

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4 Questions

1. Scientific Question

- Can the four-point energy-energy correlators (E4C) be use to improve the sensitivity to CPV in Higgs di-tau decays in the rho chain?

2. Importance

- Define new observables that can probe CPV from NP with more sensitivity at future electron-positron colliders.
- Connect the CPV from NP to baryogenesis.

3. What's New?

- First work exploiting the concept of E4C in the context of CP asymmetries in Higgs di-tau decays.

4. Implications

- Probe or rule out NP models based on their particular CPV signatures at future colliders.

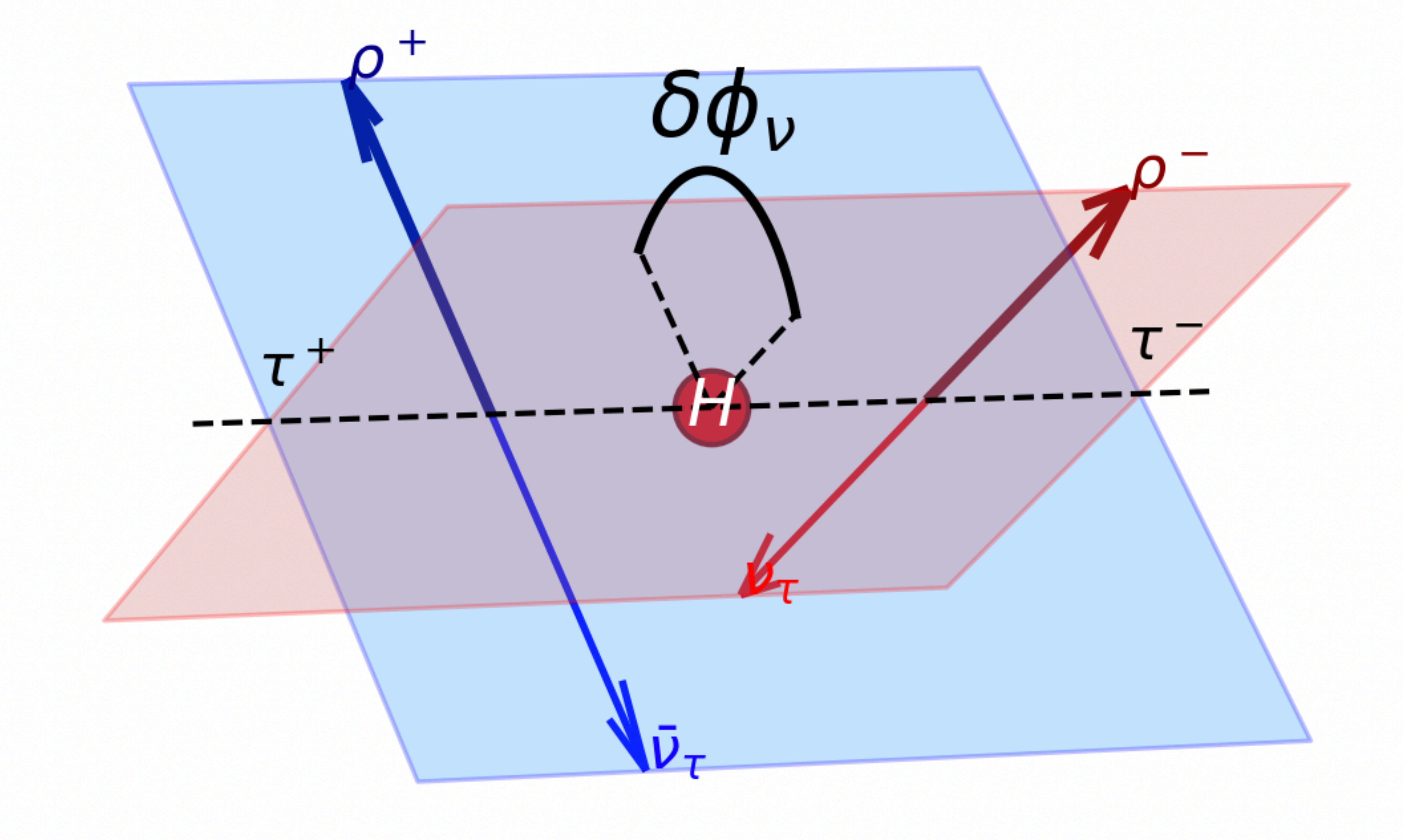
CPV in Higgs to di-taus decay

We want to study CP violation in Higgs di-tau decays $h \to \tau^+\tau^-$ (we follow MJRM et al arXiv:2012.13922):

$$\mathcal{L}_{h\tau\tau} = -\kappa_\tau \frac{m_\tau}{v} \bar{\tau}(\cos\Delta + i\gamma_5 \sin\Delta)\tau h$$

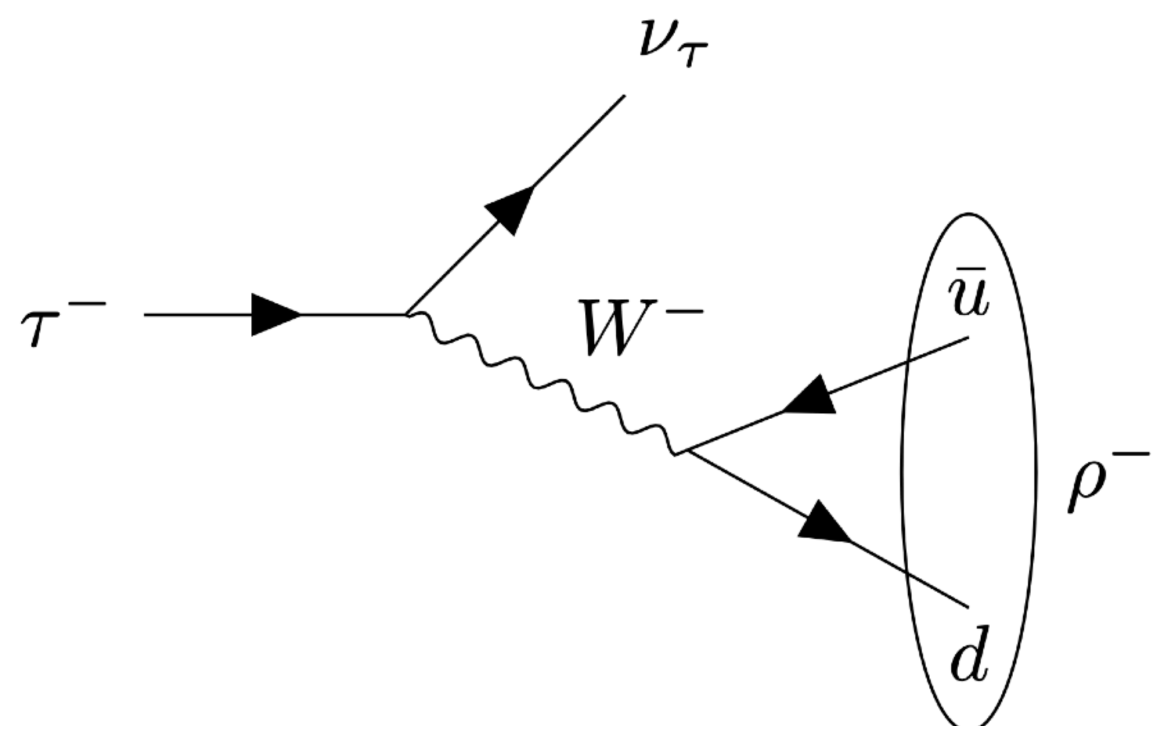
with κ_τ being real and positive by definition, and $\Delta \in [0, 2\pi)$ in general.

For each τ decay, a decay plane can be formed by its decay products. The generic azimuthal angle difference $\delta\phi$ between the two decay planes is a good observable for probing Δ



Dominant channel:

$\tau^\pm \to \rho^\pm \nu_\tau (\approx 25.5\%)$



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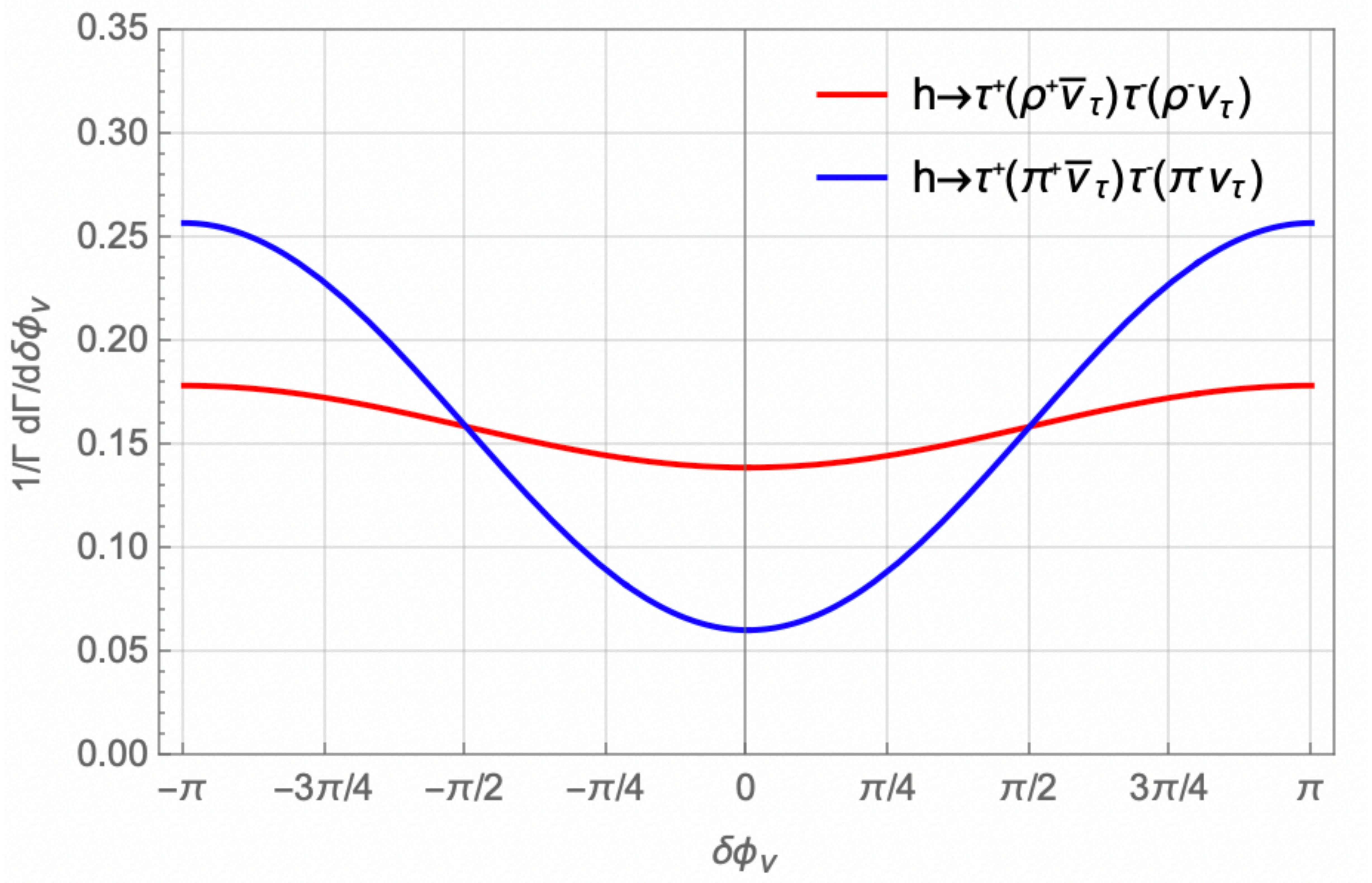
Neutrino azimuthal angle difference

The differential decay rate of the Higgs to di-taus can be expressed as

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$



For $\tau^{\pm} \to \pi^{\pm}\nu_{\tau}(\approx 10.8\%)$ (spin 0 meson)

$$|A| = \frac{\pi^2}{16} \approx 0.62$$

For $\tau^{\pm} \to \rho^{\pm}\nu_{\tau}(\approx 25.5\%)$ (spin 1 meson)

$$|A| = \frac{\pi^2}{16}\left(\frac{m_\tau^2 - 2\,m_\rho^2}{m_\tau^2 + 2\,m_\rho^2}\right)^2 \approx 0.12$$

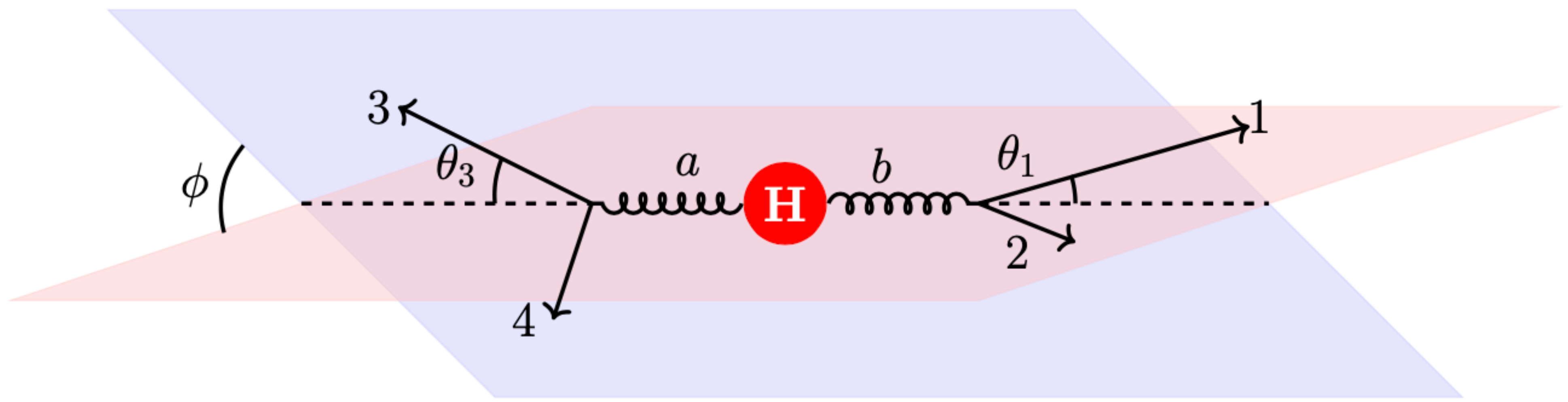
Sensitivity loss

Energy correlators

Following arXiv:2601.22248

$H \to gg$: Two gluons are produced in an entangled helicity state. Each gluon splits into a pair of partons

$$g \to q\bar{q} \quad \text{or} \quad g \to gg \qquad z = E_{daughter}/E_{parent}$$



Taken from arXiv:2601.22248

We can define a cut such that $z > z_{cut} = x$ is infrared safe and the azimuthal angle ϕ between the splitting planes defines a Lund observable:

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

where Δ is the CP-violating phase of the Hgg vertex.

Issue: Spin dependence in $A_{\mathrm{Lund}}(x)$ disappears for soft splittings as it is proportional to $z(1-z)$.

Energy correlators

Following arXiv:2601.22248

Solution: Four-point energy-energy correlator (E4C)

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

with $x = n$ and $\mathcal{N}(x) = \int_0^\pi d\phi\, \mathrm{E4C}(\phi, x)$.

E4C is given by ($n \geq 1$)

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

$\{E_i, E_j\}$ correspond to the energies of the particles $\{i, j\}$ in one jet with energy Q_1 (similarly for Q_2).

Key point: The energy weighting selects hard, spin-retaining configurations, making $A_{\mathrm{E4C}}(x = n)$ grow with n, boosting the sensitivity to Δ.

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Neutrino azimuthal angle difference

For $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau}(\approx 25.5\%)$ (spin 1 meson)

$$\frac{1}{\Gamma}\frac{d\Gamma(h\to\rho^+\rho^-\nu_\tau\bar{\nu}_\tau)}{d\delta\phi_\nu} = \frac{1}{2\pi}\left[1-\frac{\pi^2}{16}\left(\frac{m_\tau^2-2m_\rho^2}{m_\tau^2+2m_\rho^2}\right)^2\cos(2\Delta-\delta\phi_\nu)\right] \qquad |A| = \frac{\pi^2}{16}\left(\frac{m_\tau^2-2\,m_\rho^2}{m_\tau^2+2\,m_\rho^2}\right)^2 \approx 0.12$$

We would like to enhance |A| for the dominant decay channel $\tau^{\pm} \rightarrow \rho^{\pm}\nu_{\tau}$

Energy correlators idea:

Find $A \rightarrow A_n$ such that $A_0 = \frac{\pi^2}{16}\left(\frac{m_\tau^2-2\,m_\rho^2}{m_\tau^2+2\,m_\rho^2}\right)^2$

$A_n > |A_0|$ for $n = 1,2,3,4,\ldots$

Neutrino azimuthal angle difference

In the $H \rightarrow gg$ case

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

$A_{\mathrm{Lund}}(x)$ is proportional to

$$z(1-z) = \frac{E_{daugh}}{E_{parent}}\left(1 - \frac{E_{daugh}}{E_{parent}}\right) \propto \frac{E_i^2}{Q^2}$$

making the simple energy weight E_i^2 (or $E_i^n\,E_j^n$) good enough for amplifying the spin correlation.

Does the same energy weight in $H \rightarrow gg$ work for the $h \rightarrow \tau^+\tau^-$ case?

We need to understand the energy dependence of the amplitude A for the $h \rightarrow \tau^+\tau^-$ decay

Q: Where does this expression come from?

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

Neutrino azimuthal angle difference

Q: Where does this expression come from?

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

Following arXiv:1805.10552, for a single $\tau \to V\nu$ decay

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} \propto 1 + \alpha_V h_\tau \cos\theta$$

Where a dilution factor α_V is defined (also called analysing power)

$$\alpha_V = \frac{|M_L|^2 - |M_T|^2}{|M_L|^2 + |M_T|^2} = \frac{\Gamma_L - \Gamma_T}{\Gamma_L + \Gamma_T} = f_L - f_T = 2f_L - 1$$

Neutrino azimuthal angle difference

Following arXiv:1805.10552, for a single $\tau \to V\nu$ decay

$$\boxed{\alpha_V = \frac{\Gamma_L - \Gamma_T}{\Gamma_L + \Gamma_T} = 2f_L - 1}$$

For $h \to \tau^+\tau^-$ we have to take the square of α_V and integrate over the polar angle θ:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

$$\boxed{A = -\frac{\pi^2}{16}\alpha_V^2}$$

Which we can match from our earlier expression

$$\frac{\Gamma_L}{\Gamma_T} = \frac{m_\tau^2}{2m_\rho^2} \qquad \to \qquad |A| = \frac{\pi^2}{16}\left(\frac{m_\tau^2 - 2\,m_\rho^2}{m_\tau^2 + 2\,m_\rho^2}\right)^2$$

Neutrino azimuthal angle difference

Following arXiv:1805.10552, for a single $\tau \to V\nu$ decay

$$\boxed{\alpha_V = \frac{\Gamma_L - \Gamma_T}{\Gamma_L + \Gamma_T} = 2f_L - 1}$$

We need to amplify the longitudinally polarised ρ's!

For $h \to \tau^+\tau^-$ we have to take the square of α_V and integrate over the polar angle θ:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right]$$

$$\boxed{A = -\frac{\pi^2}{16}\alpha_V^2}$$

What's the energy dependence of the distribution for ρ_L?

Which we can match from our earlier expression

$$\frac{\Gamma_L}{\Gamma_T} = \frac{m_\tau^2}{2m_\rho^2} \qquad \to \qquad |A| = \frac{\pi^2}{16}\left(\frac{m_\tau^2 - 2\,m_\rho^2}{m_\tau^2 + 2\,m_\rho^2}\right)^2$$

Neutrino azimuthal angle difference

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τ POLARIZATION MEASUREMENTS AT LEP AND SLC

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To distinguish whether the $\rho^{\pm}$ is in a transversely or longitudinally polarized state we must observe the $\rho^{\pm}\to\pi^{\pm}\pi^{0}$ decay and study the $\pi^{\pm}$ spectrum as a function of $x\equiv E_{\pi}/E_{\rho}$. We have

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x}(\rho_{\mathrm{T}}\to\pi\pi)\sim\tfrac{1}{2}\sin^{2}\hat{\theta}\,,$$

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}x}(\rho_{\mathrm{L}}\to\pi\pi)\sim\cos^{2}\hat{\theta}\,, \qquad (21)$$

where

$$\cos\hat{\theta}=\frac{2x-1}{\sqrt{1-4m_{\pi}^{2}/m_{\rho}^{2}}} \qquad (22)$$

Inspection of eq. (21) shows that transverse ρ's favor equal splitting of the ρ energy between the two decay pions, while longitudinal ρ's lead to large $\pi^{-}\pi^{0}$ energy differences. This combined with the strong enhancement of hard longitudinal ρ's for $P_{\tau}=+1$ and soft transverse ρ's for $P_{\tau}=-1$ leads us to expect the pion energy difference compared to the beam energy,

$$y=\frac{|E_{\pi^{0}}-E_{\pi^{-}}|}{E_{\mathrm{beam}}}\,, \qquad (23)$$

to be a good τ polarization analyzer. The y distribu-

This means that instead of using $\dfrac{E_i^n\,E_j^n}{Q_1^{2n}}\,\dfrac{E_k^n\,E_l^n}{Q_2^{2n}}$

We could use $\dfrac{|E_{\pi^0}-E_{\pi^-}|^n}{E_{\mathrm{beam}}^n}\,\dfrac{|E_{\pi^0}-E_{\pi^+}|^n}{E_{\mathrm{beam}}^n}$

For boosting up the longitudinal ρ's in

$$h\to\tau^+\tau^-\to\rho^+\rho^-\nu\bar{\nu}\to\pi^+\pi^0\pi^-\pi^0\nu\bar{\nu}\,!$$

Current progress

- Selected easiest azimuthal observable to implement the E4C idea.
- Identified strategy for enhancing the CP sensitivity in $h \to \tau^+\tau^-$ decays.
- Found the energy dependence of the longitudinally polarised ρ's. ✅
  - Exploit the energy dependency for defining the E4C for $h \to \tau^+\tau^-$. ✅
  - Define A_n for dominant decay chain $h \to \tau^+(\rho^+\bar{\nu}_\tau)\,\tau^-(\rho^-\nu_\tau)$. ⛔

Backup

Neutrino azimuthal angle difference

$$\boxed{\alpha_V = 2f_L - 1, \qquad f_L = \frac{\Gamma_L}{\Gamma_L + \Gamma_T}}$$