Enhancing Higgs CP sensitivity with energy correlators at lepton colliders

With : Ying-Ying Li, Michael J. Ramsey-Musolf and Cristian Sierra, Yi-Lin Wang

CEPC 2026, Shanghai

Anjan Kumar Barik, 22/10/2026

National Natural Science Foundation of China

International Collaboration Fund for Creative Research Teams

Precision Calculations for Electron-Positron Colliders

Michael Ramsey-Musolf [1]

Xiao-Gang He[1] Hai-Jun Yang[1] Jun Guo[1] Manqi Ruan[2] Sven Heinemeyer[3] Alessandro Vicini[4]

[1]Shanghai Jiao Tong University | *[2]Institute of High Energy Physics, CAS*

[3]Instituto de Fisica Teorica, Madrid | *[4]University of Milan*

January 2025 – December 2027

CP Violating Higgs boson di-tau decay

Scientific Question : How can energy correlators be used to probe CP violating Higgs boson decays into tau lepton pairs?

Importance : Determining the CP nature of the Higgs boson is one of the central goals of current and future collider experiments.

Uniqueness: The study explores whether energy correlators can provide cleaner and more experimentally stable probes compared to conventional angular observables.

Implications: This observables may provide new strategies for precision Higgs CP measurements at future colliders such as CEPC.

CP Violating Higgs boson di-tau decay

- Tau yukawa coupling can be parametrized as

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

SM limit : Δ=0, κ_τ=1

Pion Mode

$$\tau^\pm \rightarrow \pi^\pm \nu_{\tau^\pm}$$

Branching Fraction:10.82%

Rho Mode

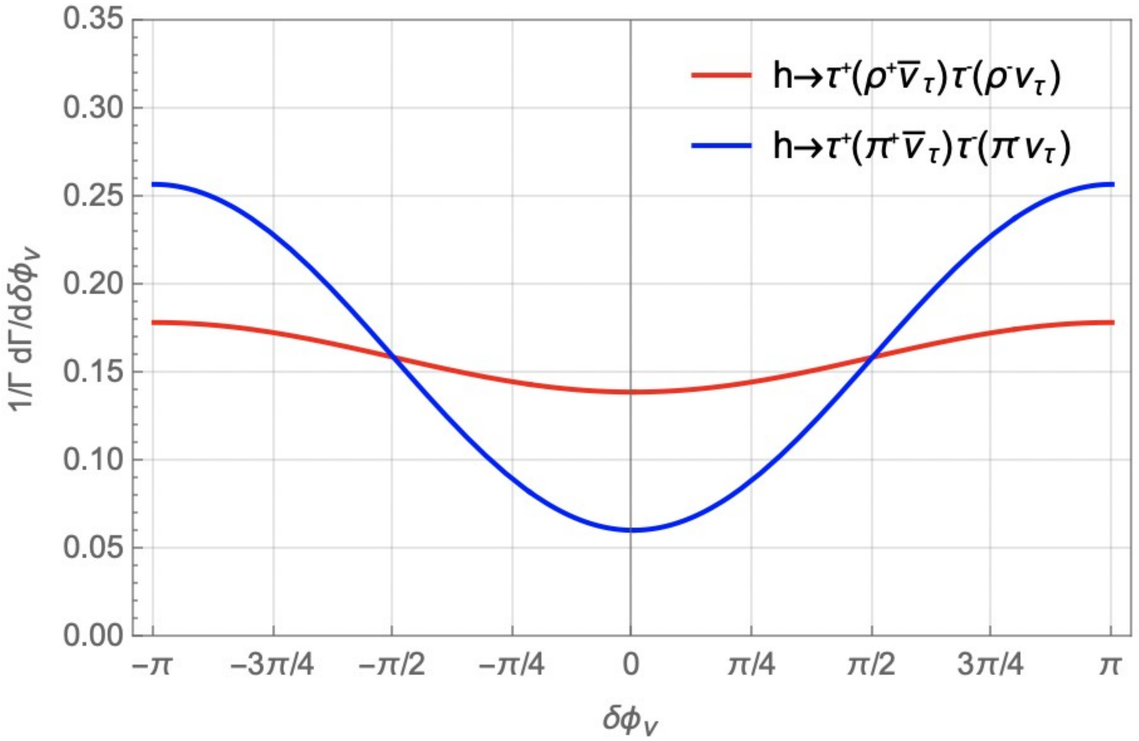
$$\tau^\pm \rightarrow \rho^\pm \nu_{\tau^\pm} \rightarrow \pi^\pm \pi^0 \nu_{\tau^\pm}$$

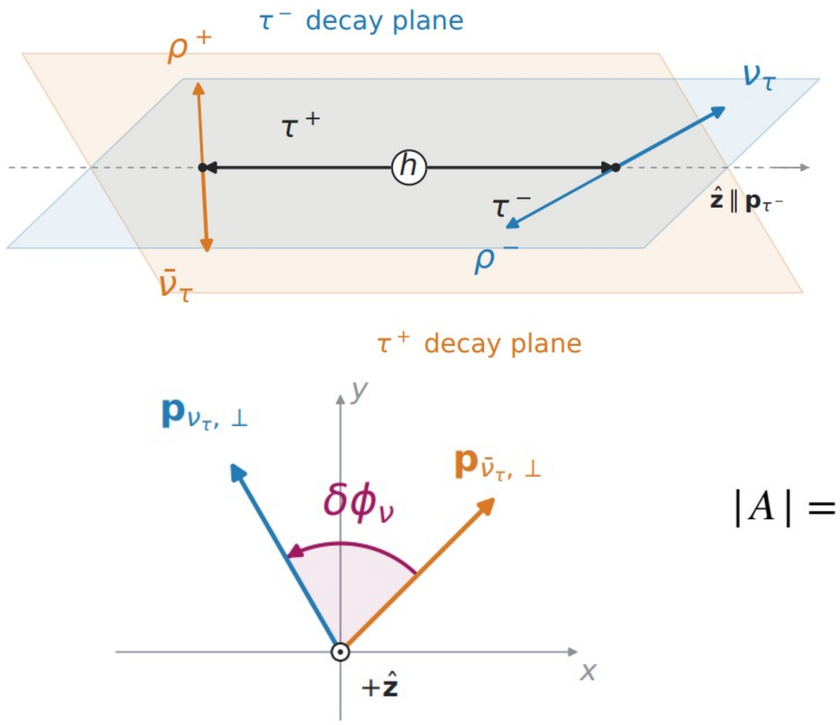
Branching Fraction: 25.49%

Neutrino azimuthal angle difference

- The differential distribution of Higgs to di-tau decay 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 pion mode

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

For rho mode

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

Issue: Sensitivity loss. **Rest of the slides deal with this!**

Polarization analysing power

- The differential distribution of Higgs to di-tau decay can be expressed as

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

- Analysing power is given by

$$d_\rho = \frac{m_\tau^2 - 2m_\rho^2}{m_\tau^2 + 2m_\rho^2} \;=\; 2f_L \,-\, 1 \simeq \;0.449$$

- The longitudinal fraction of ρ

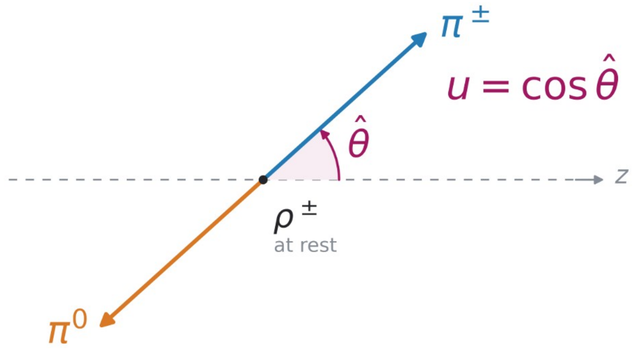
$$f_L = \frac{m_\tau^2}{m_\tau^2 + 2m_\rho^2} \;\simeq\; 0.724$$

- The Longitudinal and the transverse component of ρ contribute to the analysing power with opposite sign

Pion energy difference and Rho polarization

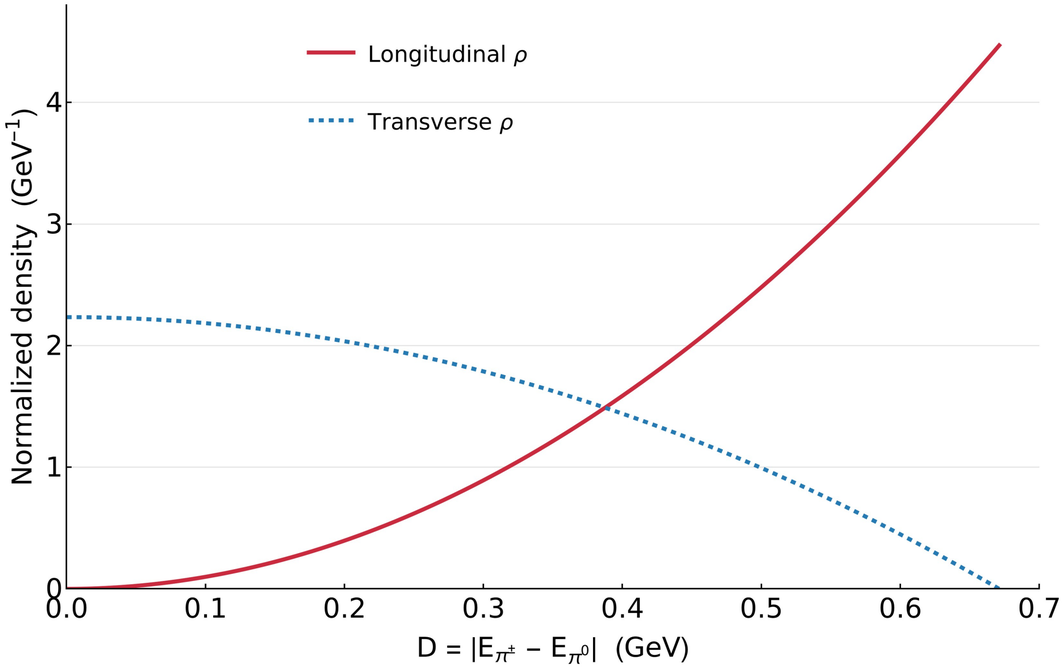
- Normalized pion angular distribution

$$P_L(u) = \frac{3}{2}u^2, \qquad P_T(u) = \frac{3}{4}(1-u^2)$$



- Absolute energy difference in pions

$$\frac{|E_{\pi^\pm} - E_{\pi^0}|}{m_\rho} = \frac{\beta_\rho E_\rho}{m_\rho}\,|u| = \frac{m_\tau^2 - m_\rho^2}{2\,m_\tau m_\rho}\,|u| \simeq 0.93\,|u|$$



- Longitudinally polarized ρ's lead to large energy difference between pions

HAGIWARA, MARTIN, and ZEPPENFELD (1990)

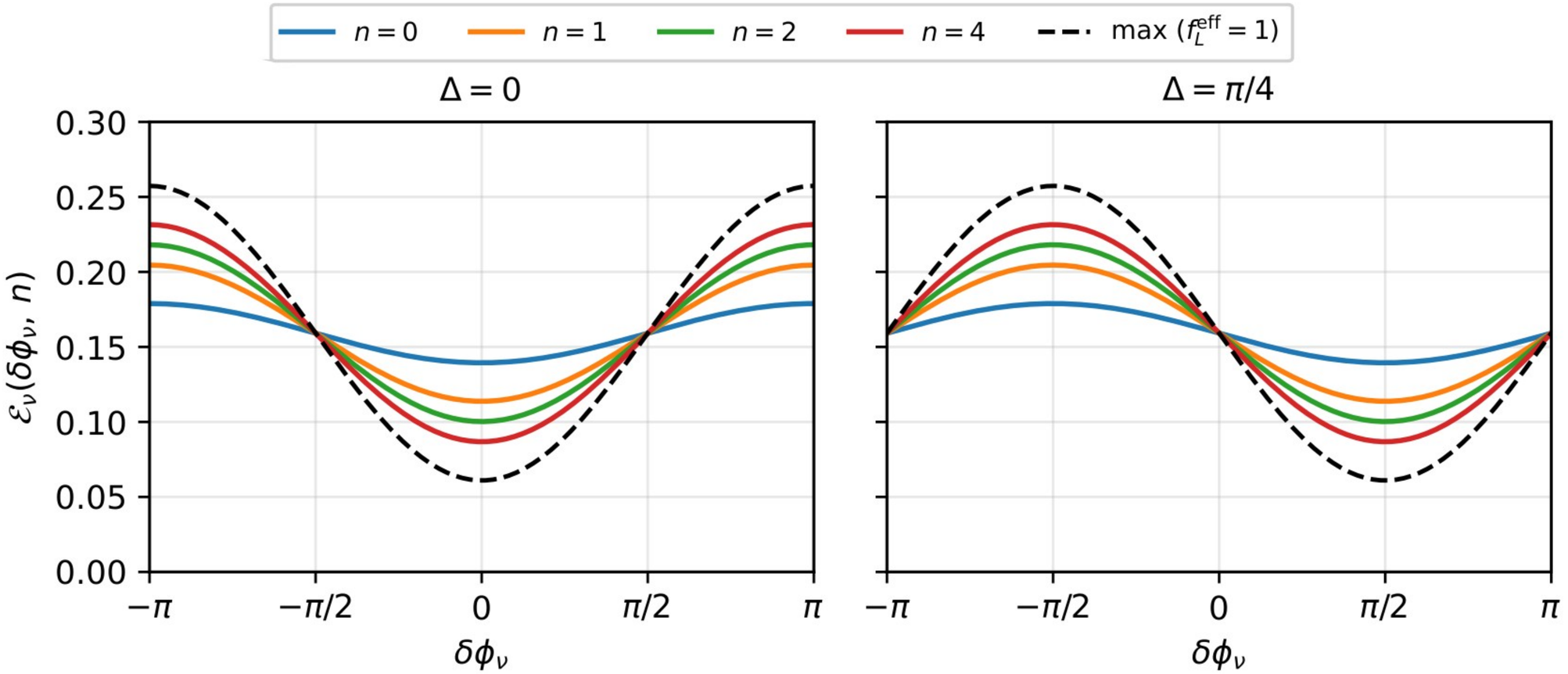
Energy correlators

- Four point Energy weight (E4C)

$$w_n \equiv \left(\frac{|E_{\pi^+} - E_{\pi^0}|}{m_\rho}\right)^n_{\tau^+} \times \left(\frac{|E_{\pi^-} - E_{\pi^0}|}{m_\rho}\right)^n_{\tau^-}$$

- The EC-weighted observable is then defined as

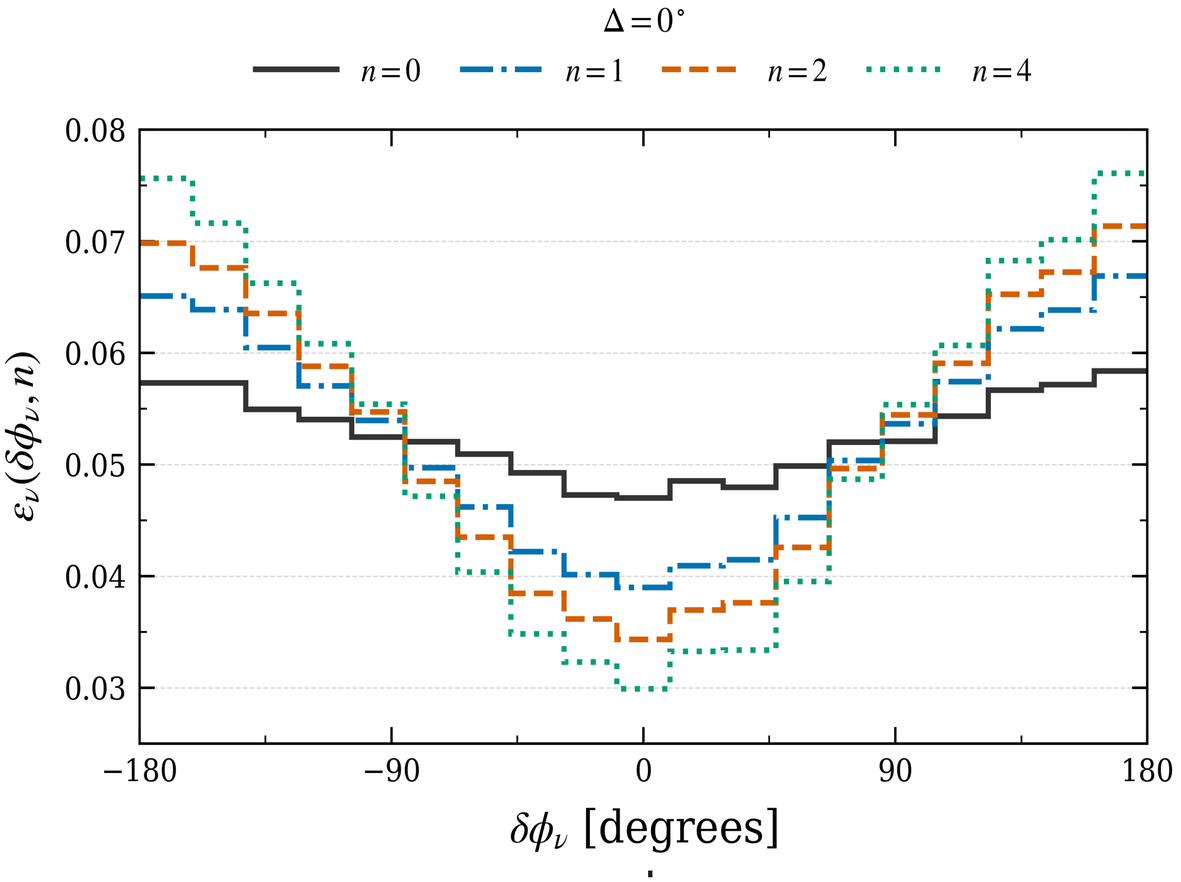
$$\mathcal{E}_\nu(\delta\phi_\nu, n) \equiv \frac{\int d\Gamma\ w_n\ \delta\big(\delta\phi_\nu - (\phi_\nu - \phi_{\bar{\nu}})\big)}{\int d\Gamma\ w_n}$$

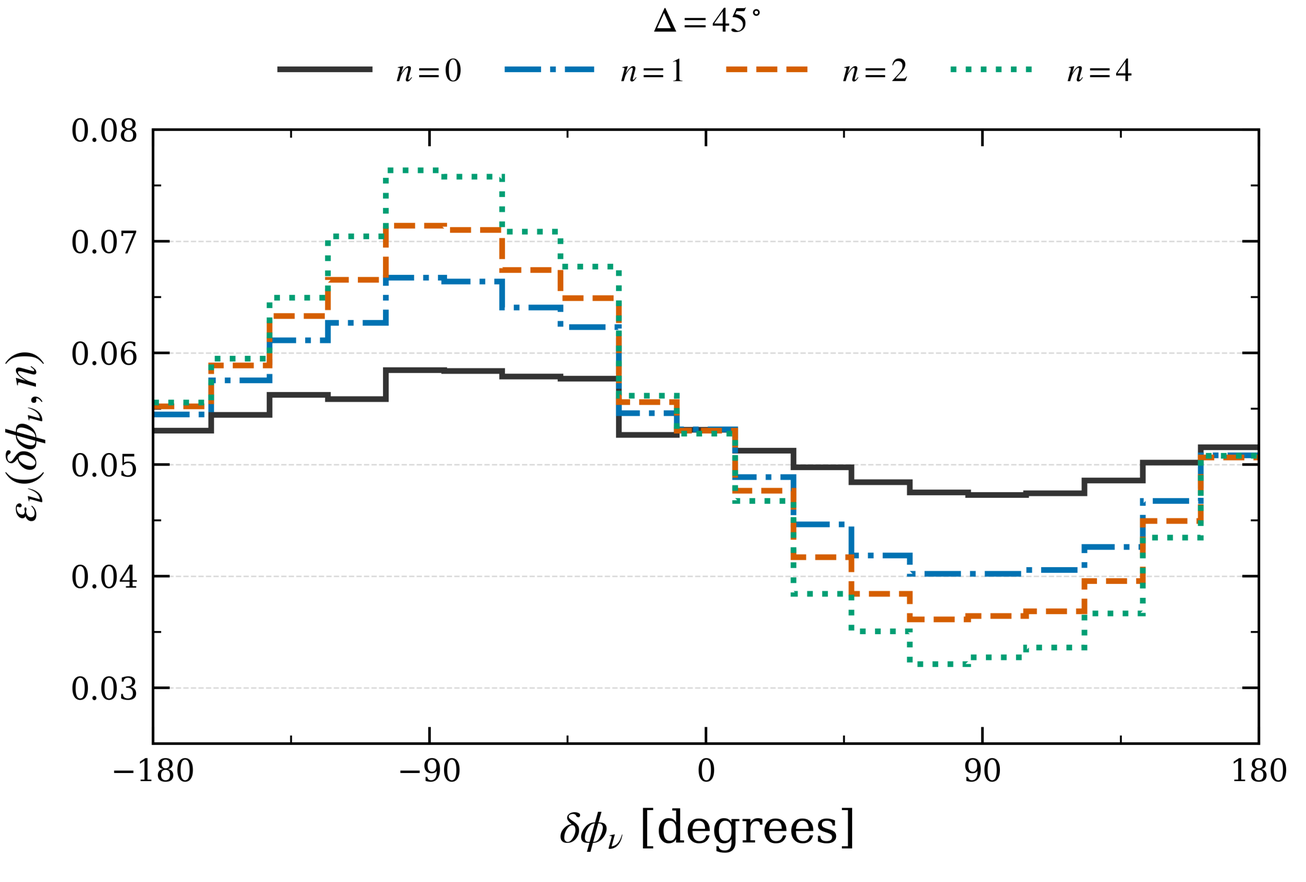


Energy correlators MC simulation

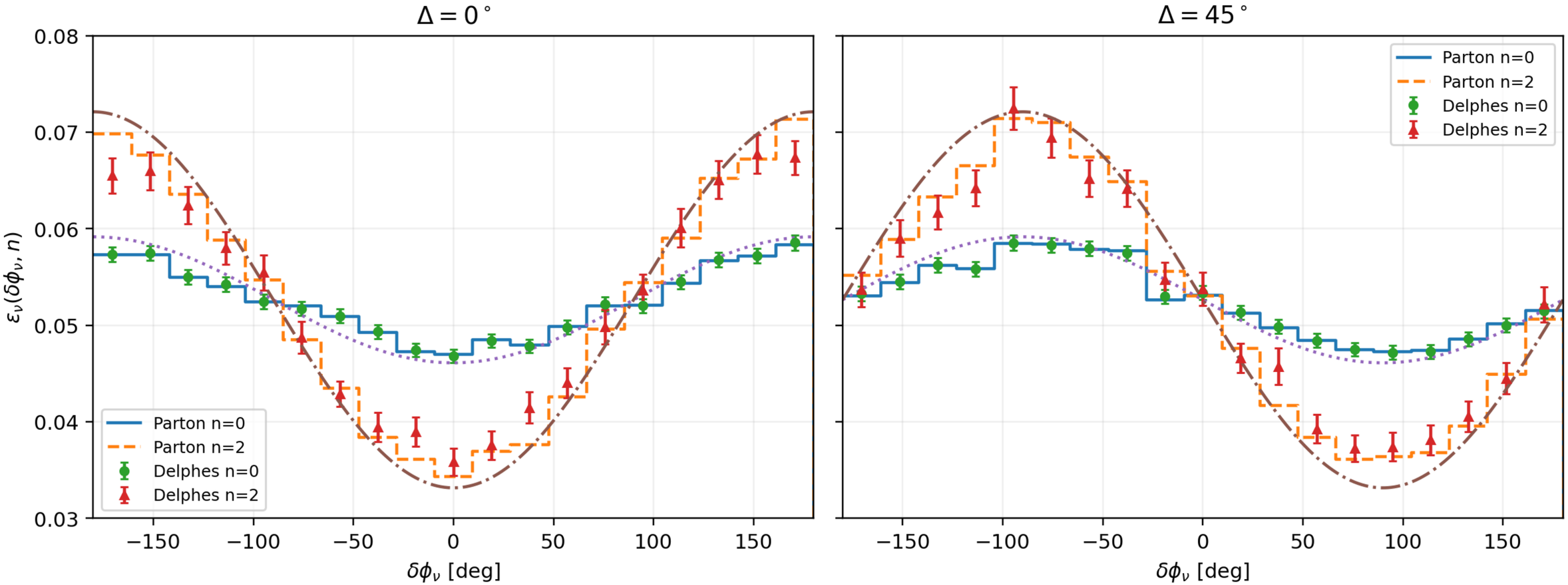
Will the E4C enhancement be realized in a real experiment ?

$$e^+e^- \to Zh, \qquad h \to (\rho^+ \bar{\nu}_\tau)(\rho^- \nu_\tau) \qquad \sqrt{s} = 240\ \text{GeV}$$





Detector Simulation



- Detector simulation also preserve the theoretical prediction.

Conclusion

- The mixture of longitudinal and transverse ρ polarizations dilutes the CP-sensitive modulation of $\delta\varphi_v$ in τ to ρ ν decay.
- Approximately 72% of the ρ mesons are longitudinally polarized, in the τ decay.
- Longitudinal ρ decays favor larger charged–neutral pion energy differences in the τ rest frame.
- Weighting events by powers of these energy differences enriches the longitudinal contribution and enhances the CP-sensitive modulation.

PCEPC Scientific Thrusts

Theory

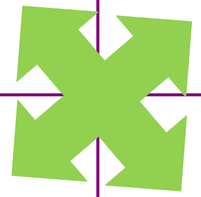
Theory

I. $e^+e^- \rightarrow f\,f$ @ NNLO

- MJRM, A. Vicini
- 2 post-docs
- 2 PhD students

II. $e^+e^- \rightarrow Zh$ @ NLO

- MJRM, XG He, S. Heinemeyer
- 3 Post-docs
- 2 PhD students



III. Theory-Expt Pipeline

- H. Yang, M. Ruan, J. Guo
- 2 post-docs
- 2 PhD students

IV. Novel EW Observables

- XG He, MJRM, M. Ruan
- 2 post-doc
- 2 PhD students

Experiment

Total team: 22 = 7 Senior + 7 post-docs + 8 PhD students

Theory + Experiment

Effective analyzing power

- The effective longitudinal fraction after weighting

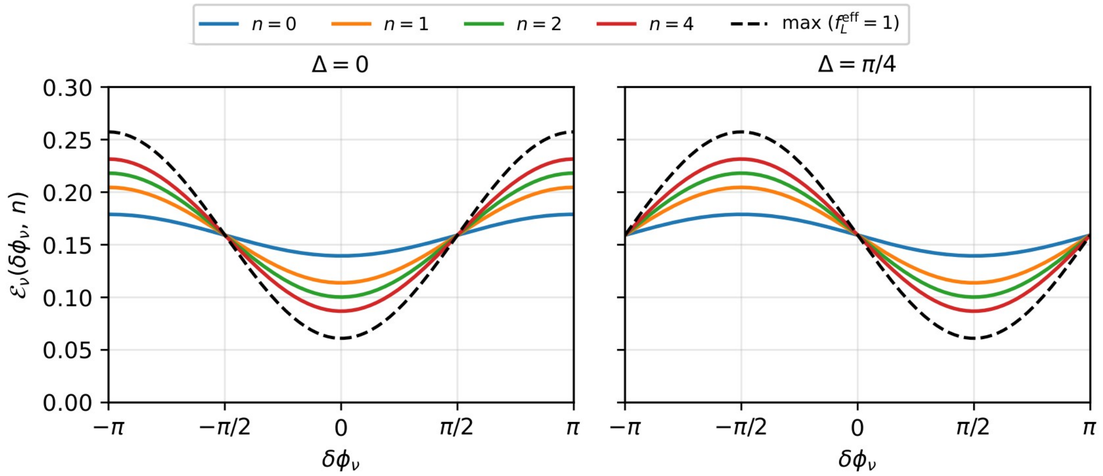
$$f_L^{\text{eff}}(n) = \frac{f_L\, I_L(n)}{f_L\, I_L(n) + (1 - f_L)\, I_T(n)}$$

$$I_L(n) \equiv \int_{-1}^{1} P_L(u)\, |u|^n\, du = \frac{3}{n+3},$$

$$I_T(n) \equiv \int_{-1}^{1} P_T(u)\, |u|^n\, du = \frac{3}{(n+1)(n+3)}$$

- The effective analyzing power

$$d_\rho^{\text{eff}}(n) = 2 f_L^{\text{eff}}(n) - 1 = \frac{f_L I_L(n) - (1 - f_L) I_T(n)}{f_L I_L(n) + (1 - f_L) I_T(n)}$$



- The Normalized E4C-weighted distributions

$$\mathcal{E}_\nu(\delta\phi_\nu, n) = \frac{1}{2\pi}\left[1 - A_n \cos(2\Delta - \delta\phi_\nu)\right] \quad \text{with} \quad A_n = \frac{\pi^2}{16}\left(d_\rho^{\text{eff}}(n)\right)^2$$

Statistical cost

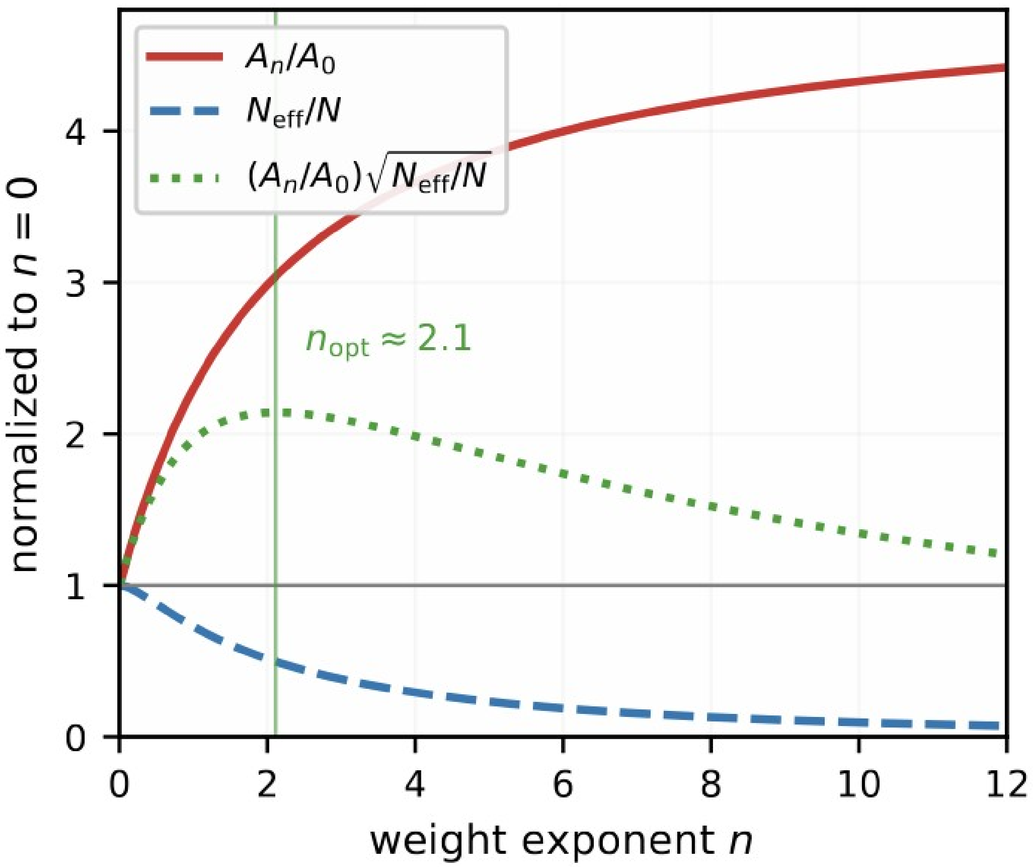
For the weighted events, the extracted uncertainty for the phase is (from Fisher information)

$$\sigma_\Delta \propto 1/(A_n\sqrt{N_{\mathrm{eff}}})$$

where is the effective sample size for weighted events.

The Figure of Merit is then given by (normalised to)

$$\mathrm{FOM}(n) \propto A_n \sqrt{\frac{N_{\mathrm{eff}}(n)}{N}}.$$



We obtain an optimal value of n