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CPV in Higgs di-tau decays and energy correlators

WG4

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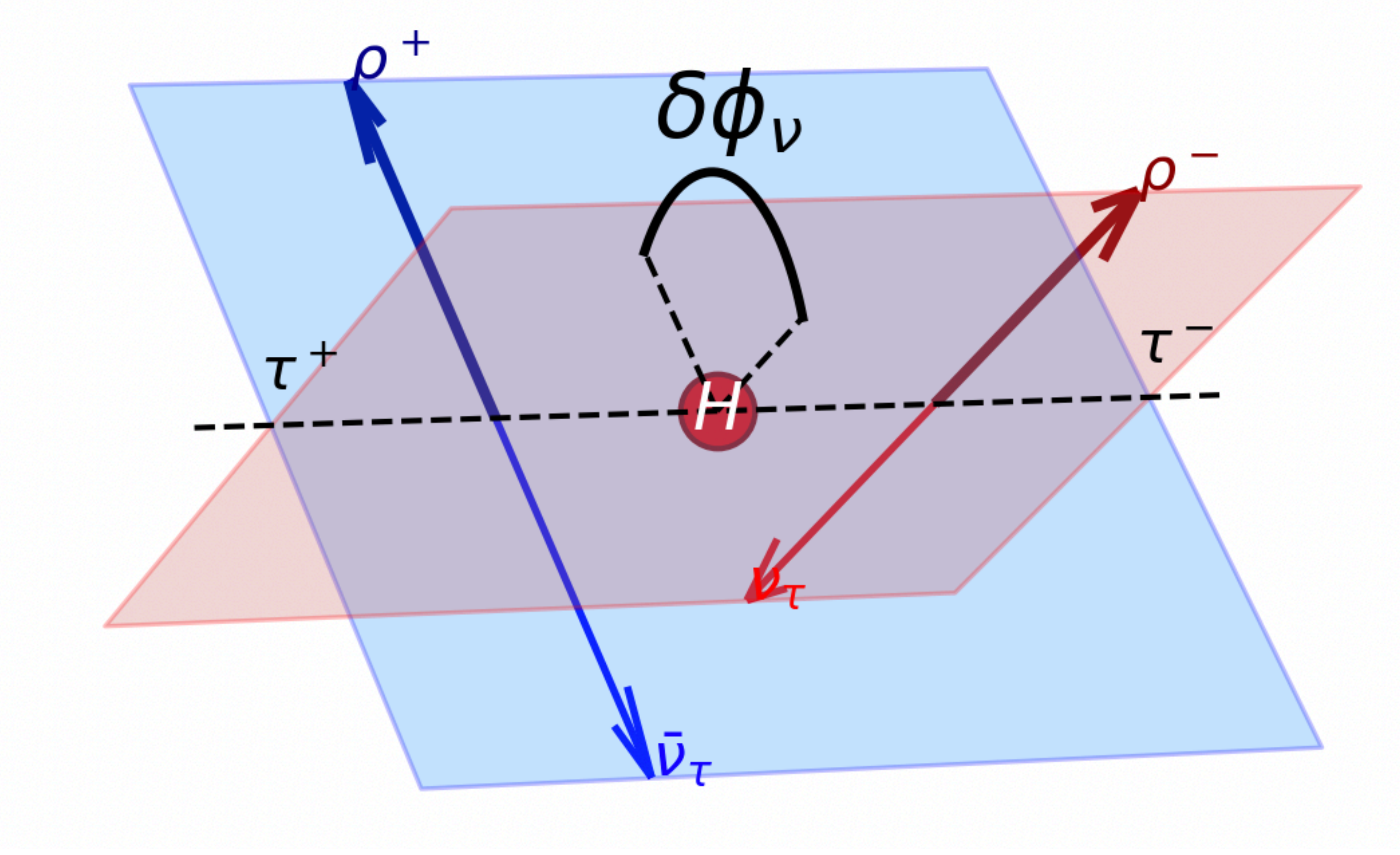
CPV in Higgs to di-taus decay

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

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

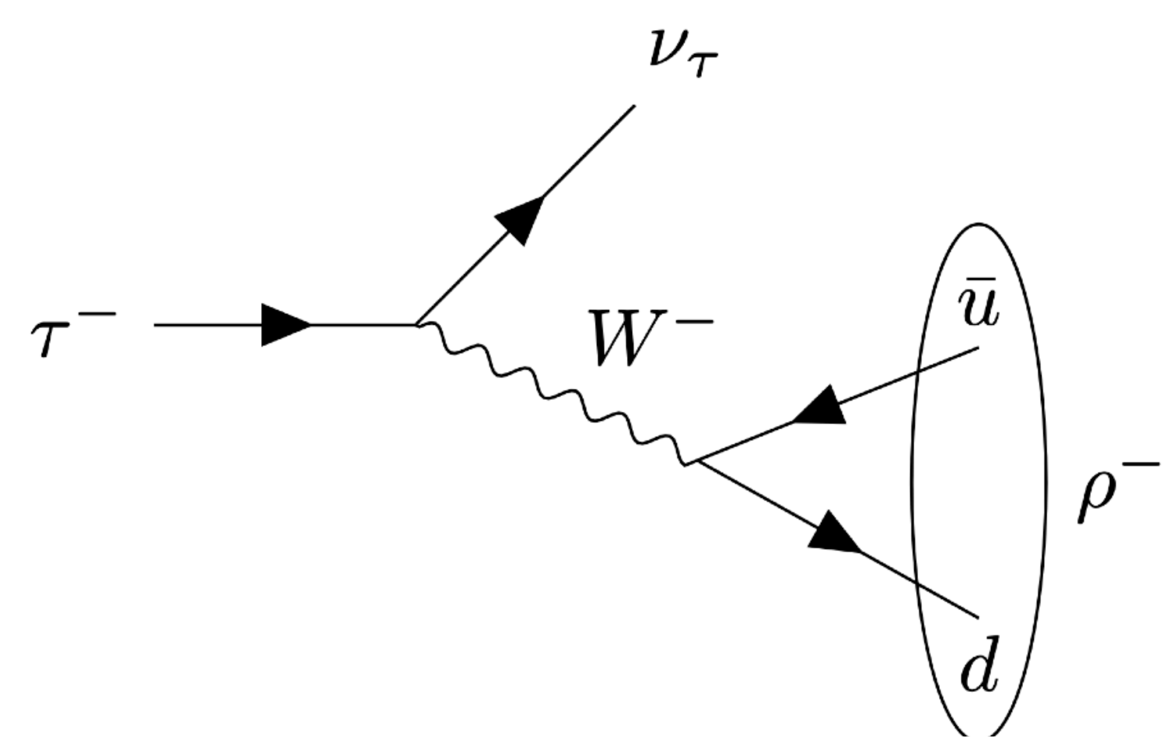
with κ_τ being real and positive by definition, and $\Delta \in [0, 2\pi)$ in general.

For each τ decay, a decay plane can be formed by its decay products. The generic azimuthal angle difference $\delta\phi_\nu$ 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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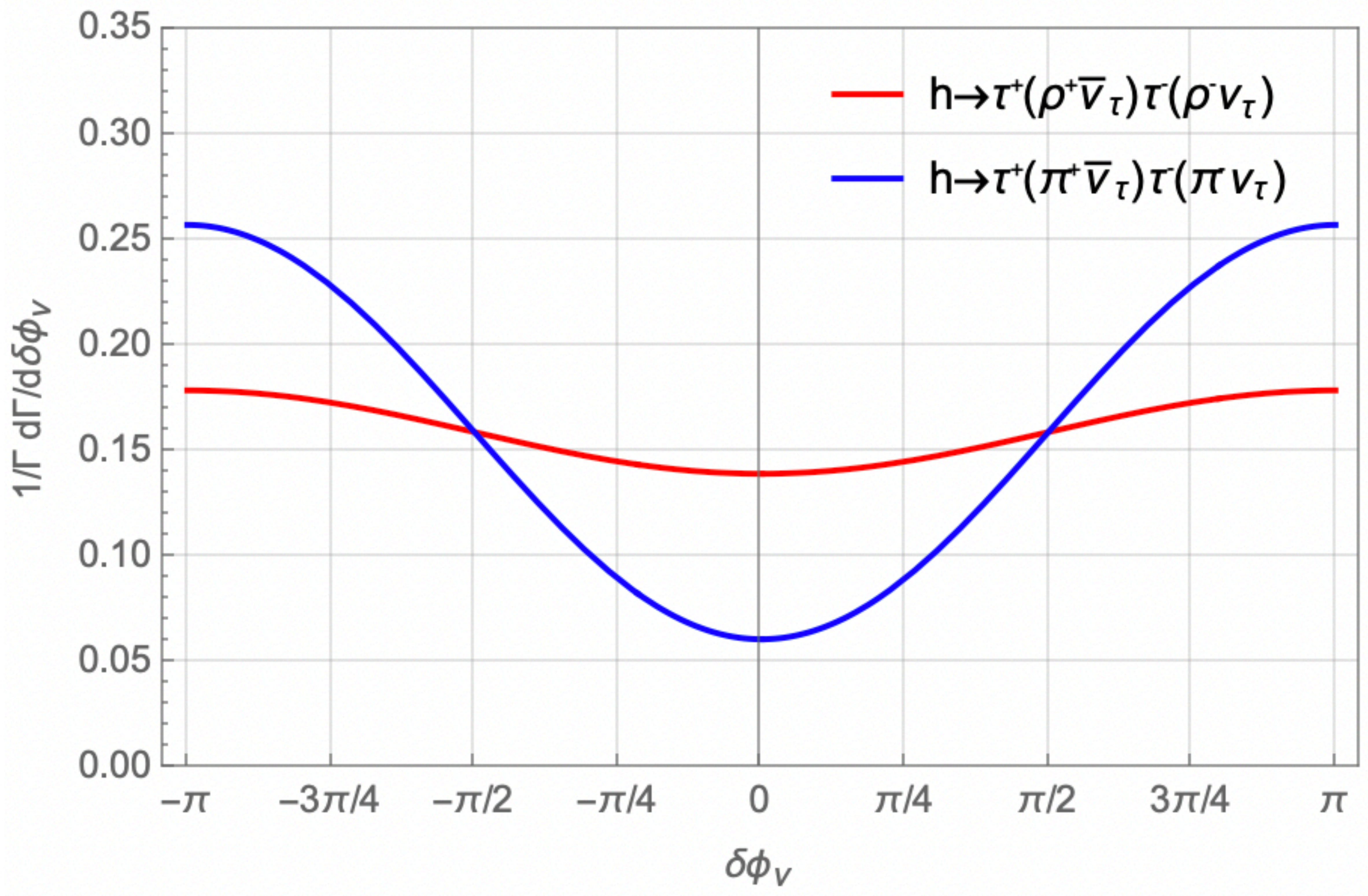
Neutrino azimuthal angle difference

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)

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

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

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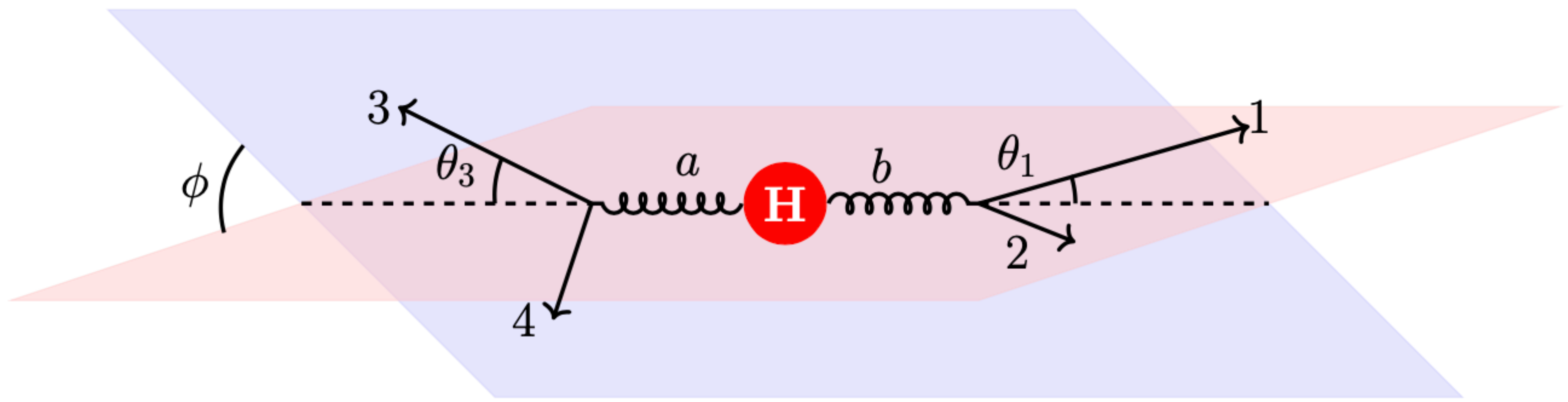
Energy correlators

Following arXiv:2601.22248. **Similar issue** in $H \to gg$

Two gluons are produced in an entangled helicity state. Each gluon splits into a pair of partons

$g \to q\bar{q}$ or $g \to gg$ $z = E_{final}/E_{initial}$



Taken from arXiv:2601.22248

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

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 $z(1-z)$.

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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

In the $H \to gg$ case (following arXiv:2601.22248)

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

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

$$A_{\mathrm{Lund}}(x) \propto z(1-z) = \frac{E_{final}}{E_{initital}}\left(1 - \frac{E_{final}}{E_{initial}}\right) \propto \frac{E_f^2}{Q^2}$$

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 $H \to gg$ work for the $h \to \tau^+\tau^-$ case?

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

Q: Where does this expression come from?

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

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Neutrino azimuthal angle difference

Following arXiv:1805.10552, for a single $\tau \rightarrow V\nu$ 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):

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

We need to amplify the longitudinally polarised ρ's!

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

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\delta\phi} = \frac{1}{2\pi}\left[1 + A\cos(2\Delta - \delta\phi)\right] \longrightarrow \boxed{A = -\frac{\pi^2}{16}\alpha_V^2}$$

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

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 $\boxed{x \equiv E_\pi / E_\rho}$ We have

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

Energy dependence

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

where

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

$$\rho_T: \quad \cos\hat{\theta} = 0 \to 2x - 1 = 0 \to x = 1/2$$

Same energy splitting

$$\rho_L: \quad |\cos\hat{\theta}| = 1 \to 2x - 1 \text{ large} \to x = 1$$

All energy into one pion

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,

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

Key insight

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

Neutrino azimuthal angle difference

This means that instead of using $\frac{E_i^n E_j^n}{Q_1^{2n}} \frac{E_k^n E_l^n}{Q_2^{2n}}$ we could use $w(n) \equiv \frac{|E_{\pi^0} - E_{\pi^-}|^n}{E_{\text{beam}}^n} \frac{|E_{\pi^0} - E_{\pi^+}|^n}{E_{\text{beam}}^n}$:

$$\boxed{E4C(\delta\phi_\nu, n) = \sum_{(i,j)\in\rho^+} \sum_{(k,l)\in\rho^-} \int \frac{d\sigma}{\sigma} \frac{|E_i - E_j|^n}{m_\rho^n} \frac{|E_k - E_l|^n}{m_\rho^n} \delta\left(\delta\phi_\nu - (\phi_\nu - \phi_{\bar{\nu}})\right)}$$

Disclaimer: Not Lorentz invariant, depends on the energies in the τ rest frames.

The CPV Δ phase is encoded in the differential cross section. Carrying out the algebra:

Neutrino azimuthal angle difference

This means that instead of using $\frac{E_i^n E_j^n}{Q_1^{2n}} \frac{E_k^n E_l^n}{Q_2^{2n}}$ we could use $w(n) \equiv \frac{|E_{\pi^0} - E_{\pi^-}|^n}{E^n_{\text{beam}}} \frac{|E_{\pi^0} - E_{\pi^+}|^n}{E^n_{\text{beam}}}$:

$$\boxed{E4C(\delta\phi_\nu, n) = \sum_{(i,j)\in\rho^+} \sum_{(k,l)\in\rho^-} \int \frac{d\sigma}{\sigma} \frac{|E_i - E_j|^n}{m_\rho^n} \frac{|E_k - E_l|^n}{m_\rho^n} \delta\big(\delta\phi_\nu - (\phi_\nu - \phi_{\bar{\nu}})\big)}$$

Disclaimer: Not Lorentz invariant, depends on the energies in the τ rest frames.

The CPV Δ phase is encoded in the differential cross section. Carrying out the algebra:

$$\boxed{\text{Obs}(\delta\phi_\nu, n) \equiv \frac{\text{E4C}(\delta\phi_\nu, n)}{\mathcal{N}(n)} = \frac{1}{2\pi}\Big[1 - A_n \cos(2\Delta - \delta\phi_\nu)\Big], \qquad A_n = \frac{\pi^2}{16}\left(\alpha_\rho^{eff}(n)\right)^2}$$

Where we have defined $\mathcal{N}_\nu(n) \equiv \int_0^{2\pi} \text{E4C}(\delta\phi_\nu, n)\, d\delta\phi_\nu = \frac{1}{\sigma}\int d\sigma\, w(n)$ and $\frac{|E_{\pi^+} - E_{\pi^0}|}{m_\rho} \propto |\cos\hat{\theta}| \equiv |u|$

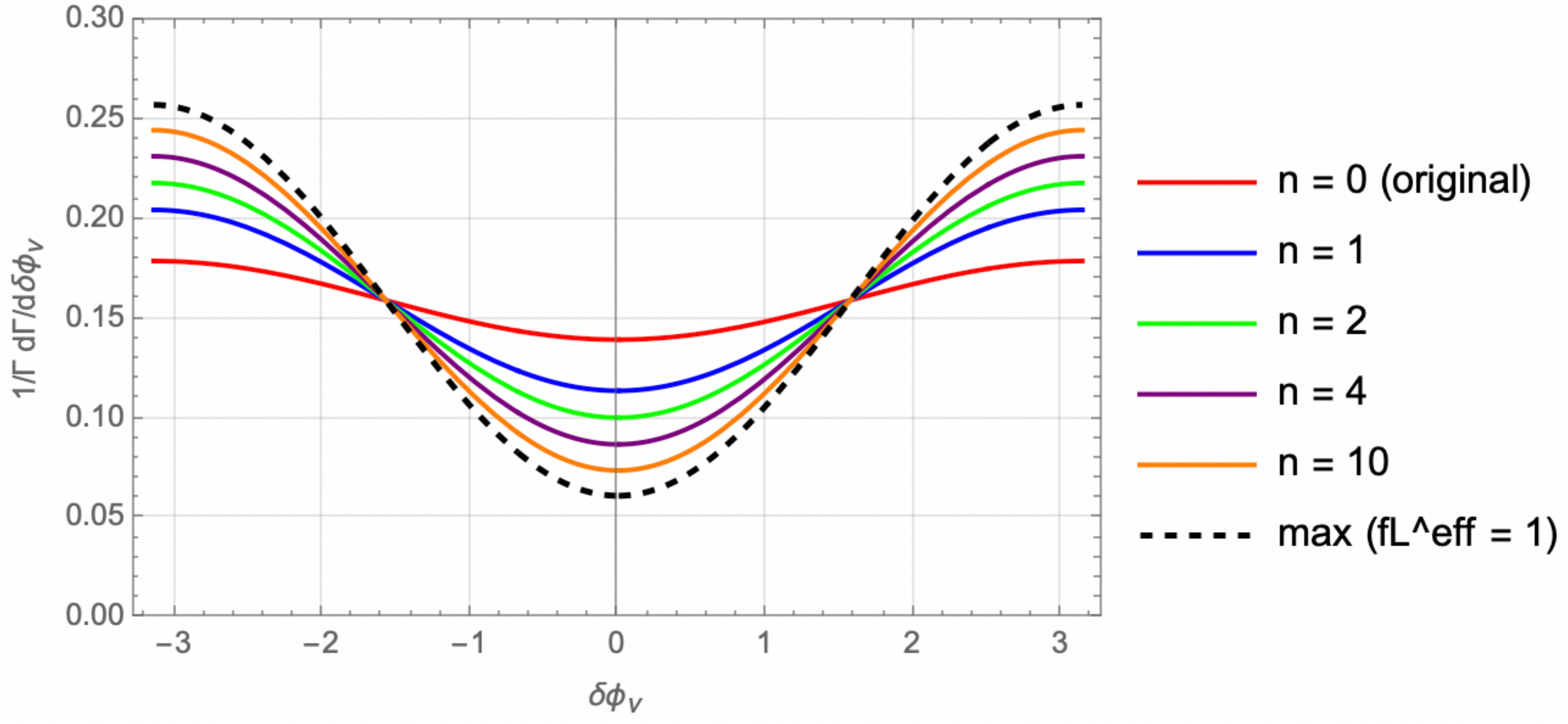
$$\alpha_\rho^{eff}(n) = 2f_L^{eff}(n) - 1, \qquad f_L^{eff}(n) = \frac{f_L \int_{-1}^{1} P_L(u)\,|u|^n du}{f_L \int_{-1}^{1} P_L(u)\,|u|^n du + (1 - f_L)\int_{-1}^{1} P_T(u)\,|u|^n du}.$$

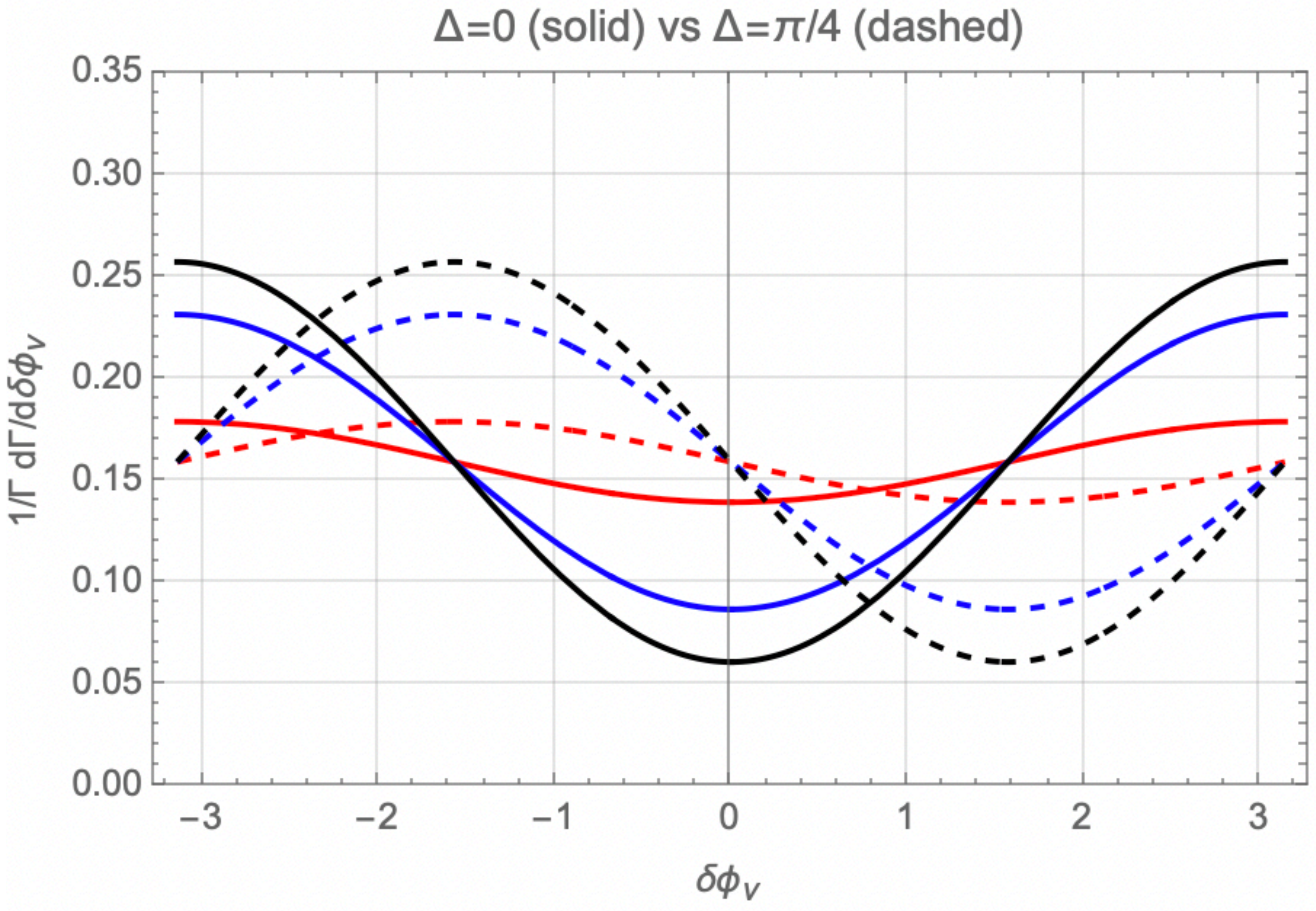
$$P_L(u) = \frac{3}{2}u^2, \qquad P_T(u) = \frac{3}{4}(1 - u^2),$$

Neutrino azimuthal angle difference

n	fL^eff	αρ^eff	A_n
0	0.724254	0.448508	0.124085
1	0.840078	0.680156	0.285363
2	0.887382	0.774764	0.37027
4	0.929242	0.858484	0.454615
10	0.966546	0.933092	0.537067
∞	1.	1.	$\frac{\pi^2}{16}$

$\Delta = 0$



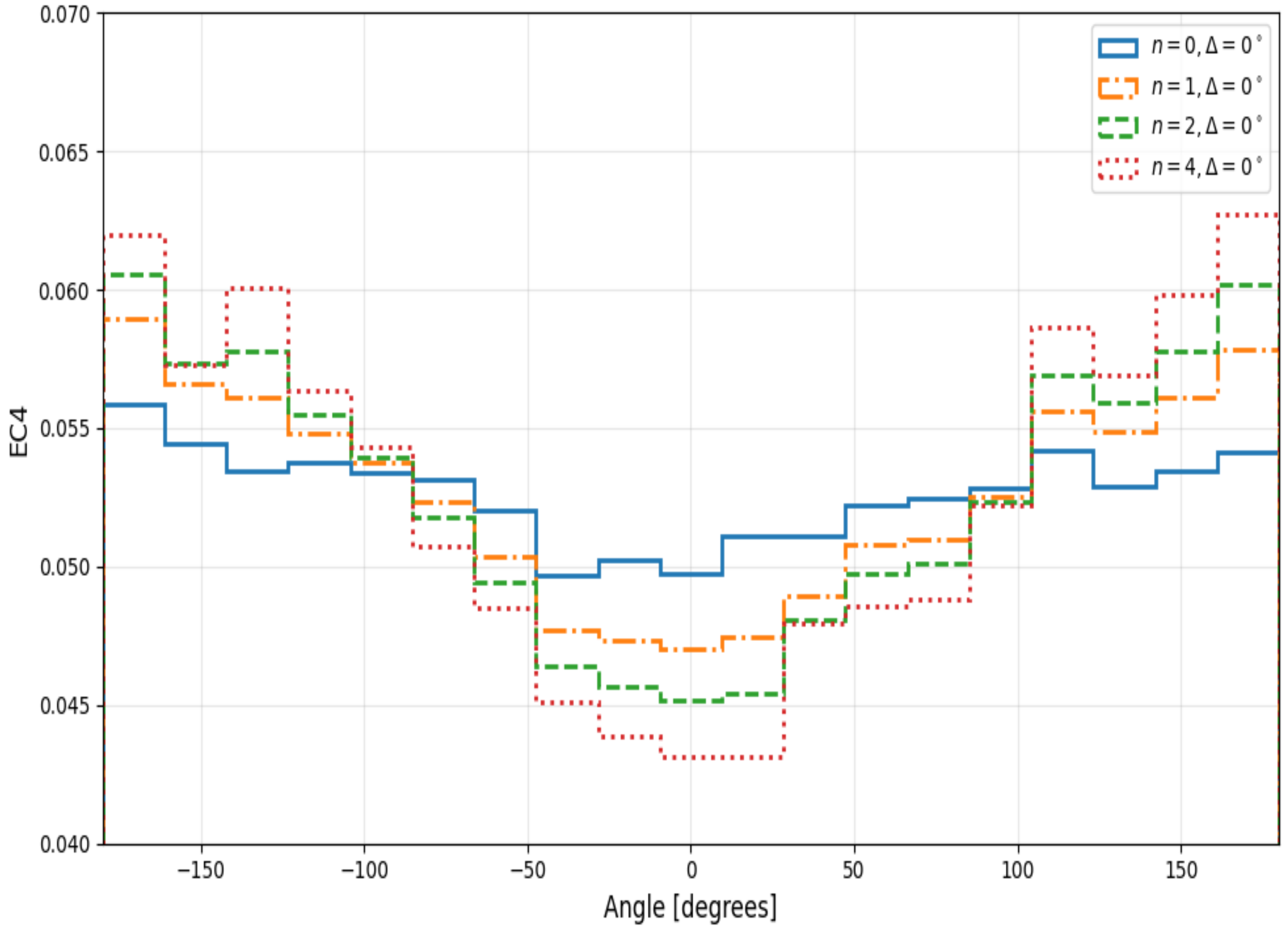


MC distributions (worked by Anjan)

Madgraph ($\sqrt{s}$ = 240 GeV, x0 is Higgs) **(E4C implemented)**

```
import model /home/anjan/heptools/MG5_aMC_v3_4_2/models/HC_UFO__taudec\
ay_UFO
generate e+ e- > z x0, (x0 > ta+ ta-, ta+ > pi+ pi0 vt~, ta- > pi- pi0\
 vt)
output ee_zh_tata_3BD_HC
```

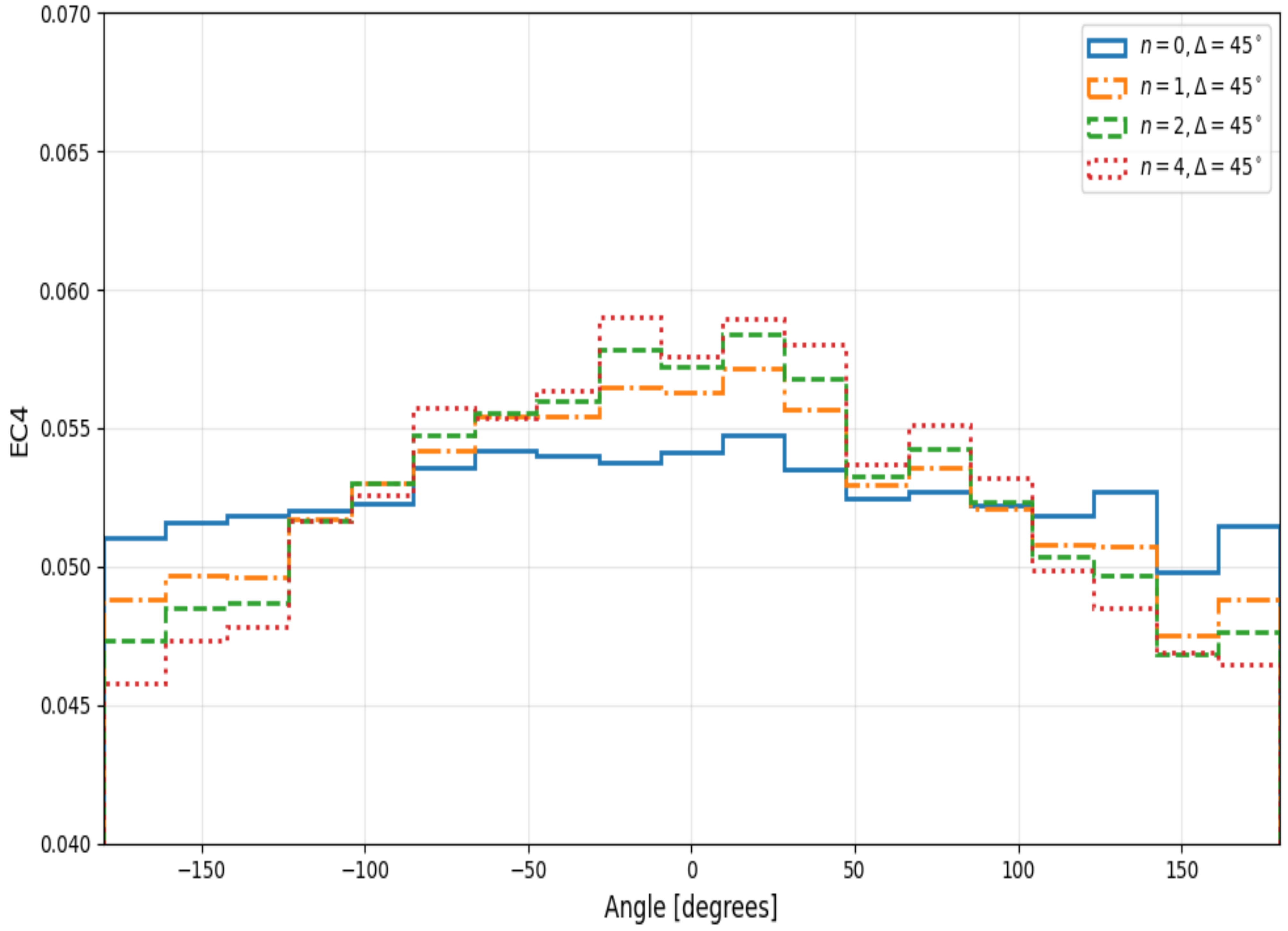
$\Delta = 0$



$\delta\phi_\nu$

Azimuthal angle diff.

$\Delta = \pi/4$



Not matching analytical distribution, debugging in progress

Current progress

- Identified strategy for enhancing the CPV sensitivity in $h \to \tau^+\tau^-$ decays.
- Found the energy dependence of the longitudinally polarised ρ's.
  - Define A_n for dominant decay chain $h \to \tau^+(\rho^+\bar{\nu}_\tau)\,\tau^-(\rho^-\nu_\tau)$.
- Apply same method to others distributions (coplanarity, polarimeter) (**Mohamed**).
- Get Monte Carlo results as in MJRM paper 2012.13922 (**Anjan**).
- Check implications for baryogenesis from the sensitivity to the CPV Δ phase.
- Check implications for measurements of $\sin^2\theta_W$ from A_{FB}.

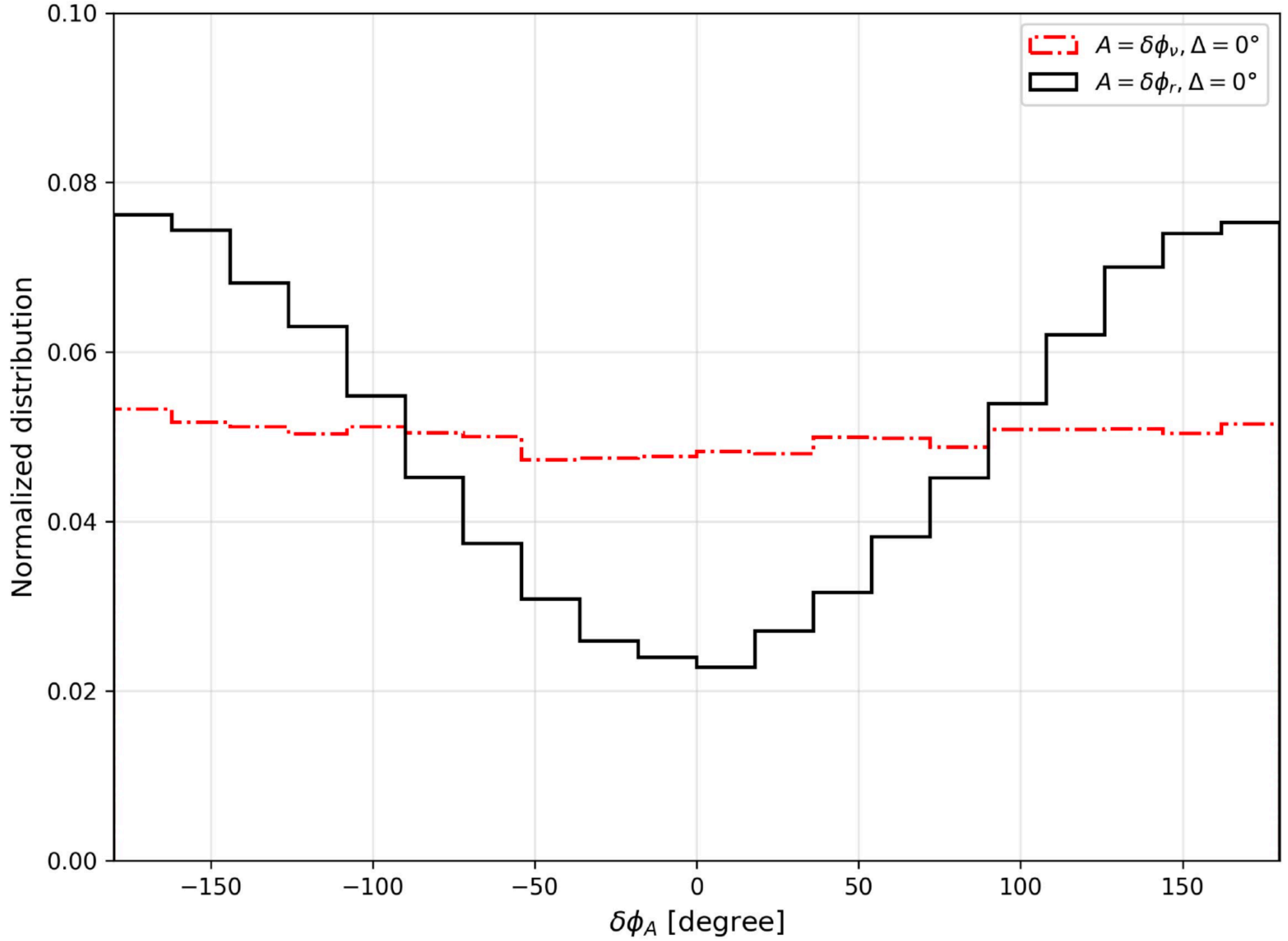
	July	Aug	Sept	Oct	Nov	Dec
WG4	Generalize E4C for other angular distributions.	Implement MC for E4C	Evaluate more pheno within EPC and start draft. Present it at Zhuhai.		Finish pheno and submit paper to arXiv	

Backup

MC distributions (worked by Anjan)

Madgraph ($\sqrt{s}$ = 240 GeV, x0 is Higgs) **(No E4C implemented)**

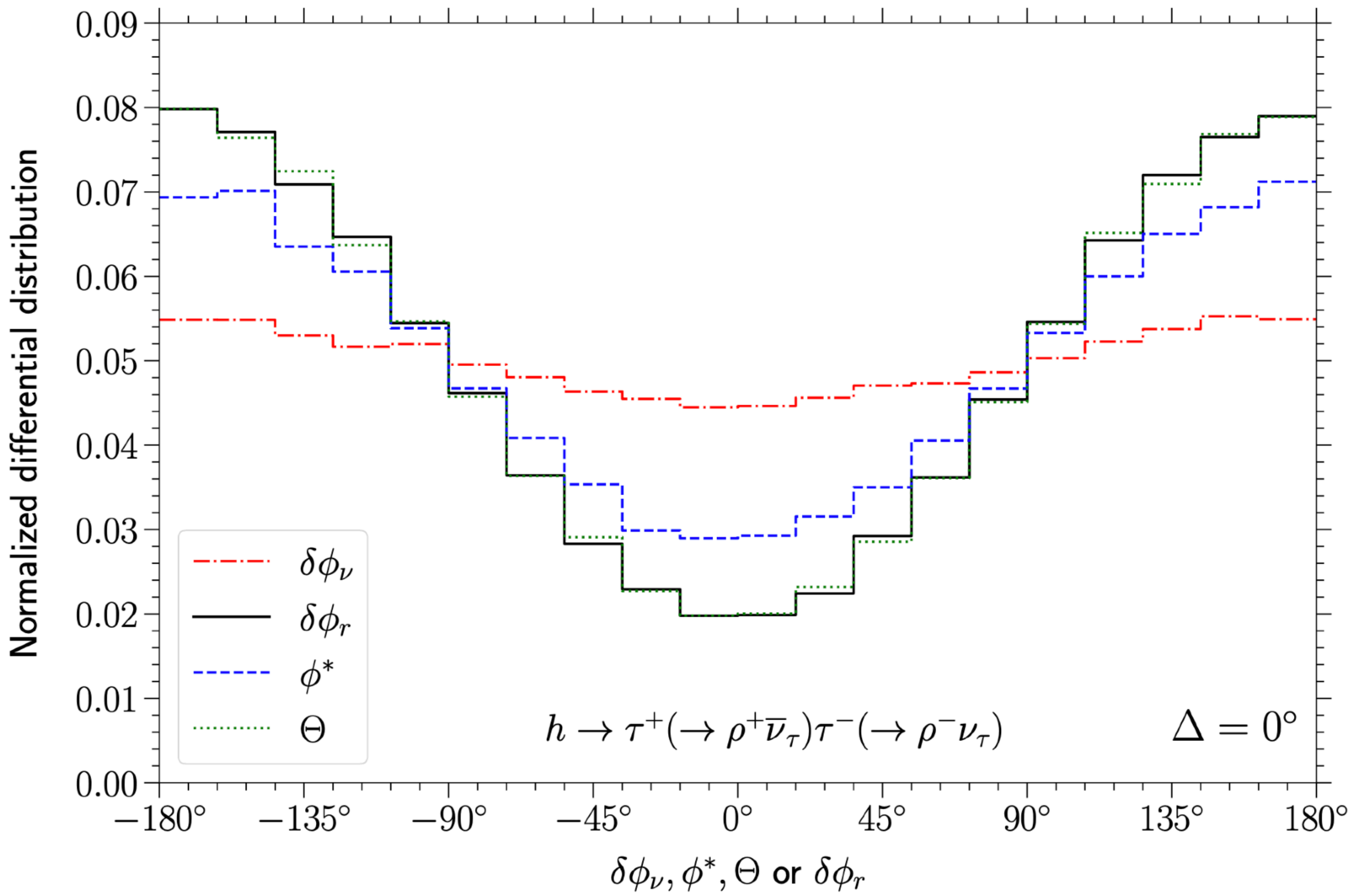
```
import model /home/anjan/heptools/MG5_aMC_v3_4_2/models/HC_UFO__taudec\
ay_UFO
generate e+ e- > z x0, (x0 > ta+ ta-, ta+ > pi+ pi0 vt~, ta- > pi- pi0\
 vt)
output ee_zh_tata_3BD_HC
```



$\delta\phi_\nu$: Azimuthal angle diff. between decay planes

$\delta\phi_r$: Azimuthal angle diff. between polarimeter vectors $r_\pm$

Figure 1 from MJRM et al 2012.13922



The azimuthal angle difference $\delta\phi_r \equiv \phi_{\mathbf{r}_+} - \phi_{\mathbf{r}_-}$ is defined with respect to the z direction, $\mathbf{z} \equiv \hat{\mathbf{p}}_{\tau^-}$. In the Higgs rest frame,

$$\tan \delta\phi_r = \frac{\hat{\mathbf{p}}_{\tau^-} \cdot (\mathbf{r}_+ \times \mathbf{r}_-)}{\mathbf{r}_- \cdot \mathbf{r}_+ - (\mathbf{r}_+ \cdot \hat{\mathbf{p}}_{\tau^-})(\mathbf{r}_- \cdot \hat{\mathbf{p}}_{\tau^-})}.$$

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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.

Neutrino azimuthal angle difference

The equivalent to $\mathrm{Obs}(\phi, x) \equiv \dfrac{\mathrm{E4C}(\phi, x)}{\mathcal{N}(x)}$ for $\tau^{\pm} \to \rho^{\pm}\nu_{\tau}\,(\approx 25.5\%)$ (spin 1 meson) would come from

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

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

Energy correlators idea:

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

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

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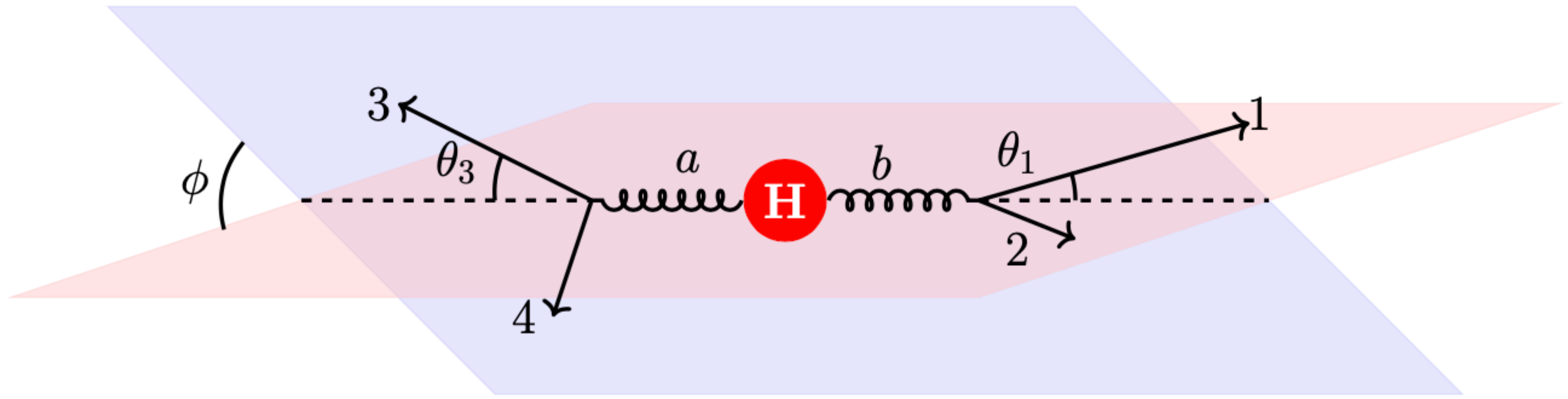
Energy correlators

Following arXiv:2601.22248. **Similar issue** in $H \to \ gg$

Two gluons are produced in an entangled helicity state. Each gluon splits into a pair of partons

$g \to \ q\bar{q}$ or $g \to \ gg$ $\quad z = E_{final}/E_{initial}$



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 $z(1 - z)$.

Neutrino azimuthal angle difference

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

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

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

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

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

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

Neutrino azimuthal angle difference

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

We could use $\frac{|E_{\pi^0} - E_{\pi^-}|^n}{E_{\text{beam}}^n} \frac{|E_{\pi^0} - E_{\pi^+}|^n}{E_{\text{beam}}^n}$

With $E_{\pi^+} + E_{\pi^0} = E_\rho$ we have

$$\frac{|E_{\pi^+} - E_{\pi^0}|}{m_\rho} = \frac{E_\rho}{m_\rho} |2x - 1| \propto |\cos\hat{\theta}| \equiv |u|$$

And the total partial decay width of ρ's into pions is

$$\frac{d\Gamma}{du} = \frac{d\Gamma_L}{du} + \frac{d\Gamma_T}{du} = \Gamma_L P_L(u) + \Gamma_T P_T(u) = \Gamma_\rho \left[f_L P_L(u) + (1 - f_L) P_T(u) \right]$$

With

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