$H \to \tau^+\tau^-$ CP Violation Analysis for SiD

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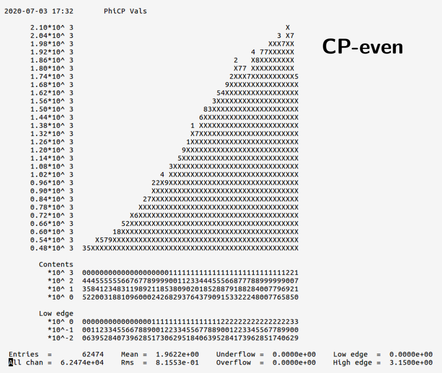
Tau-Based Analysis of Higgs CP Violation - Overview

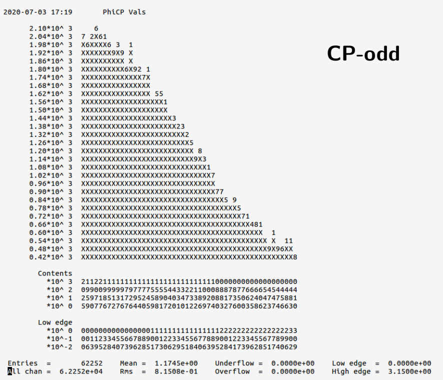
- **Motivation:** Is the 125GeV Higgs purely CP even, odd, or a mix? How precisely can we measure the Higgs CP mixing angle? ILD achieves ∼75 mrad.

$$h_{125} = h^0_{even} sin(\phi_{mix}) + A^0_{odd} cos(\phi_{mix})$$

- Higgs is fully **CP-odd** if $\phi_{mix} = 0$, fully **CP-even** if $\phi_{mix} = \frac{\pi}{2}$
- Find ϕ_{mix} with a fit $C_0 + C_1 cos(\phi^* - 2\phi_{mix})$ to a CP-sensitive distribution ϕ^*

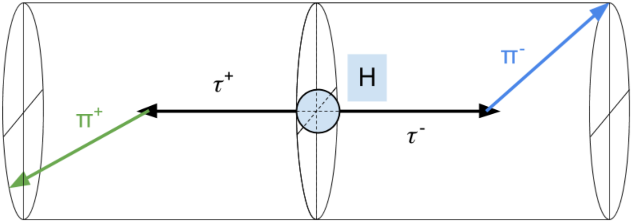
Example of how distribution is supposed to work:

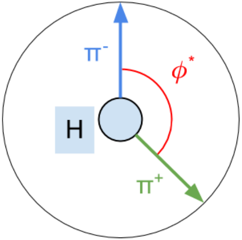




Tau-Based Analysis of Higgs CP Violation - Methodology

- General methodology: extract **polarimeter vector** from analyzing tau decay; find **azimuthal angle** between τ^+ and τ^- polarimeter vectors
- Polarimeter vectors vary with tau decay; $\tau^\pm \to \pi^\pm \nu_\tau$ (below) and $\tau^\pm \to \pi^\pm \pi^0 \nu_\tau$ are the simplest to analyze, but using **higher-multiplicity decays** would allow for **more events** to be used





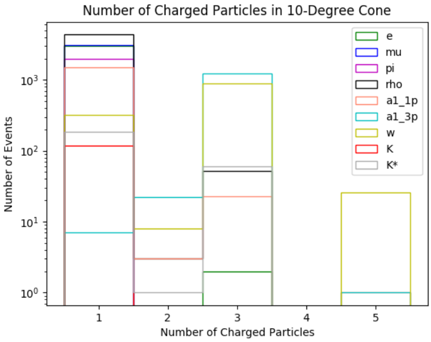
$$\vec{n}_- \equiv \frac{\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}}{|\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}|} \qquad \vec{n}_+ \equiv \frac{\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}}{|\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}|}$$

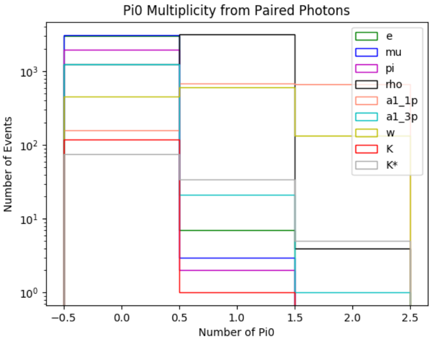
$$\cos(\phi^*) \equiv \vec{n}_- \cdot \vec{n}_+$$

Key Areas of Active Work

- **Higher-multiplicity τ tagging:** new NN-based tagging for all relevant τ decays (as opposed to low-multiplicity tagging used before)
- **Continuous CP sensitivity analysis:** energy-based binning and asymmetry-based weighting for $\Delta\phi$ improvement
- **Preliminary CP violation analysis with a_1 decays:** implementing and testing methods of a_1 polarization state separation

- Many previous τ-tagging methods used **energy and multiplicity cuts** to tag mostly **low-multiplicity** decays
- New double-neural-network τ-tagging method to **tag higher-multiplicity decays** allows for more complete CP violation analysis with $H \to \tau^+\tau^-$
- Require $e^+e^-/\mu^+\mu^-$ Z-daughter pair, then use **two highest-energy, opposite-charge** charged particles as seeds and divide rest of particles based on angular proximity to seeds
- Compute several distributions to separate **background** from $H \to \tau^+\tau^-$ and to distinguish τ **decay paths** (below and next slide)



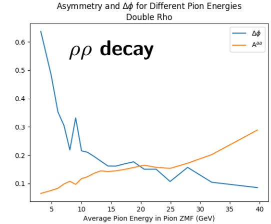


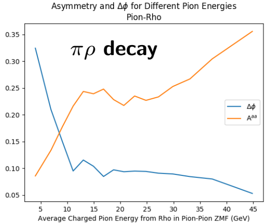
Input Distributions for Higher-Multiplicity Decay Tagging

- Group all **charged particles** closest to each seed inside and outside of 10° cone around seed
- Pair all photons to reconstruct **neutral pions** (requiring $0.12 < m_{\gamma\gamma} < 0.15$); assign to closest seed
- **Tau-vs-background NN:** 23 inputs
  - Z invariant mass, recoil mass, total event energy, invariant mass of remaining particles after Z daughters removed (total 4 inputs)
  - **Angle** between charged seeds
  - Energy and multiplicity of **charged particles** inside and outside of 10° cone for each τ (total 8 inputs)
  - Energy and multiplicity of π^0 and unpaired **photons** for each τ (total 8 inputs)
  - Total **visible invariant mass** of charged particles within 10° cone and all assigned π^0 and photons for each τ (total 2 inputs)
- **Tau decay separation NN:** 10 inputs
  - Energy and multiplicity of charged particles inside and outside of 10° cone (4 inputs)
  - Energy and multiplicity of π^0 and unpaired photons (total 4 inputs)
  - Total visible invariant mass of charged particles within 10° cone and all assigned π^0 and photons (1 input)
  - Seed is lepton (0) or hadron (1)?
- Preliminary testing using **1 hidden layer** for each NN

Energy-Based Event Weighting for $\Delta\phi$ Calculation

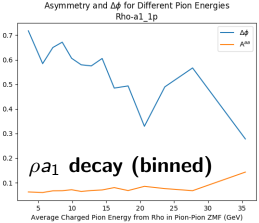
- For events containing ρ, ℓ, and/or a_1, CP **sensitivity varies with energy**
- Plotting distributions of $\Delta\phi$ and asymmetry $|A^{aa}| = 4C_1/(2\pi C_0)$ from events **binned by energy** lets us weight events by energy

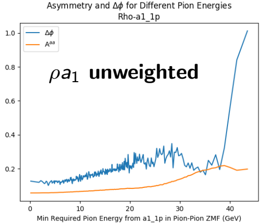


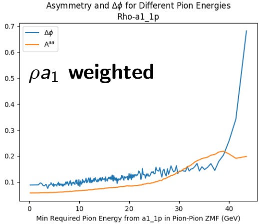


$\Delta\phi$, $|A|^{aa}$

- From plotting minimum-energy-vs-$\Delta\phi$ instead of binning by energy, weighting each ϕ_{mix} value by $|A^{aa}|^2$ greatly improves $\Delta\phi$ values and seems to make strict energy cuts unnecessary

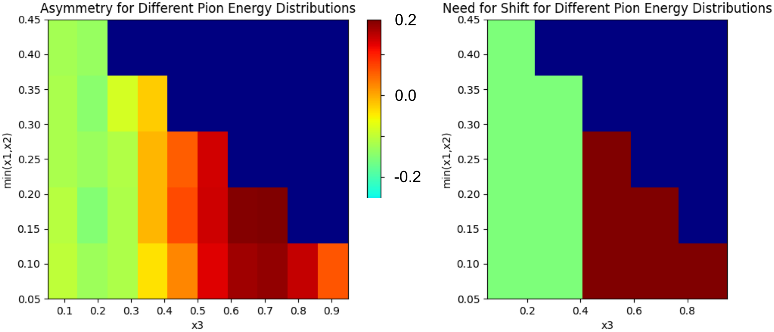






Separation of a_1 Polarization States

- Distributions of ϕ^* for a_1^T and a_1^L are **out of phase;** must be **separated**
- Effective **rough cut**: shift ϕ^* values by π for events with $x_3 > 0.4$ with $x_3 = E_{opp}/E_{a_1}$, where E_{opp} is energy of pion with **different charge** from other two



$a_1^{\pm} \to \pi^{\pm} 2\pi^0$

shift, **no shift**

Next Steps

- Debug and finish developing high-multiplicity NN tagger
- Improve a_1 polarization analysis methods
- Run full tagging and CP violation analysis with full SiD reconstruction (have been using MC truth and fast MC simulations)