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

L. Braun
J. Brau

University of Oregon

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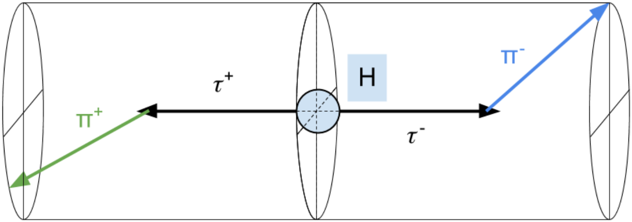
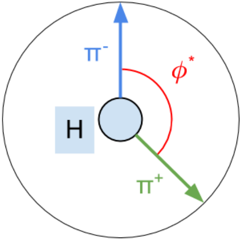
Tau-Based Analysis of Higgs CP Violation

- 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



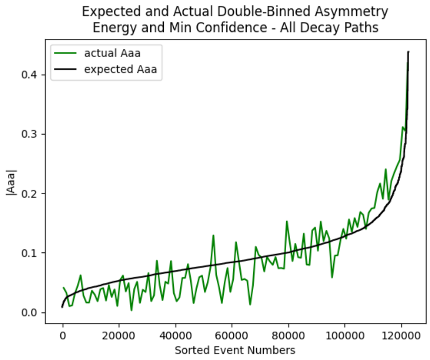


$$\vec{n}_- \equiv \frac{\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}}{|\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}|} \qquad \vec{n}_+ \equiv \frac{\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}}{|\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}|}$$

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

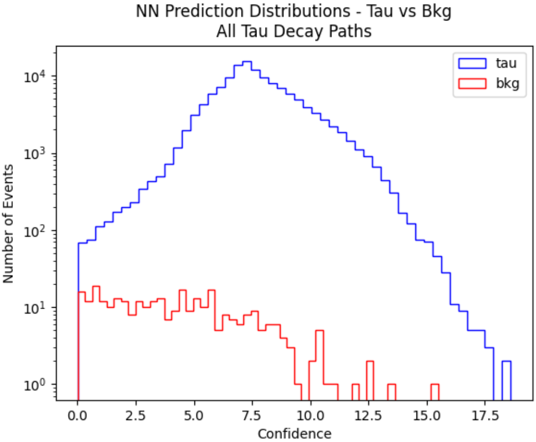
CP Sensitivity Estimation

- To estimate **CP mixing angle precision**, need a unified **CP sensitivity metric**
- ILD's method includes binning for **CP sensitivity** based off of **NN predictions** for tau-vs-bkg and tau decay paths (more confident prediction = more sensitive)
- The **higher-multiplicity** tau tagging system uses a **different NN setup**, but can still help inform CP sensitivity
- Once events are binned across **decay path, NN prediction, and leading charged particle energy**, we can extract a **single CP sensitivity parameter**, and similar-sensitivity bins can be merged for simultaneous cosine fitting
- Result shown here uses combined **energy-based** and **confidence-based asymmetry**. Events are sorted by CP sensitivity (average of these two metrics)



NN Prediction Distributions - Tau vs Background

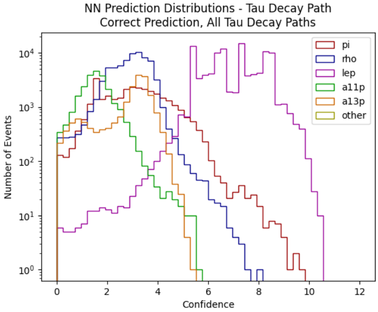
- NN prediction confidence was calculated as the **highest output** from a NN output node minus the **second-highest output**
- **Background events** had **lower NN confidences** than signal events, allowing for improved background rejection



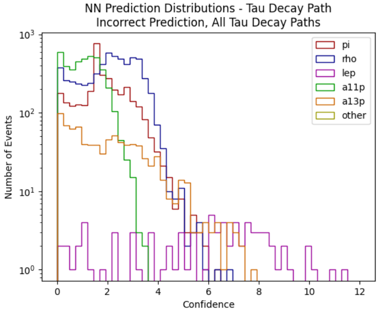
Signal vs Background

NN Prediction Distributions - Tau Decay Paths

- NN prediction confidence was calculated as the **highest output** from a NN output node minus the **second-highest output**
- Different **tau decay paths** had different confidence distributions which strongly correlated with **overall tagging performance**
- **Incorrectly-labeled** tau decays had **lower NN confidences**, allowing for better binning for CP sensitivity

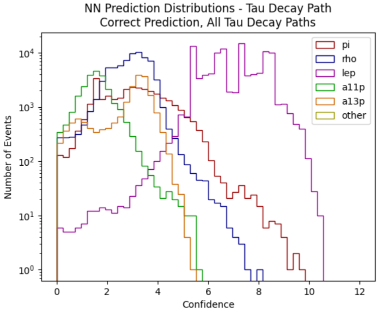


Correct Label

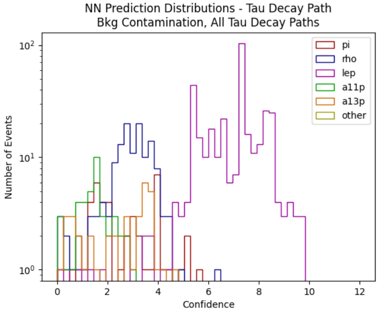


Incorrect Label

- NN prediction confidence was calculated as the **highest output** from a NN output node minus the **second-highest output**
- **Background events** erroneously labelled as taus had **similar prediction distributions** to true taus, but a better cutoff for the tau-vs-bkg NN should improve background rejection enough



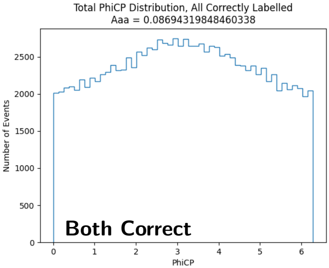
Correct Label

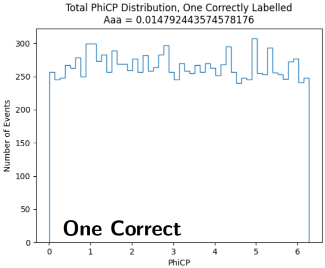


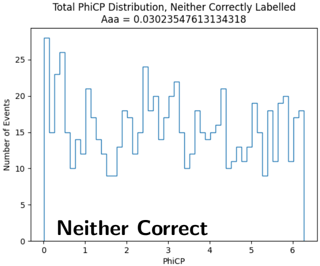
Background Contamination

Importance of Removing Incorrectly-Tagged Taus

- **Negligible asymmetry** for events assigned **incorrect decay path** for one or both taus motivates stricter tau decay path cuts

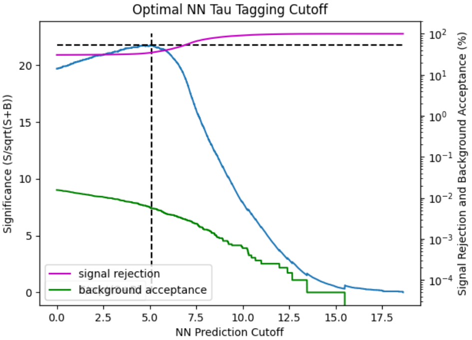






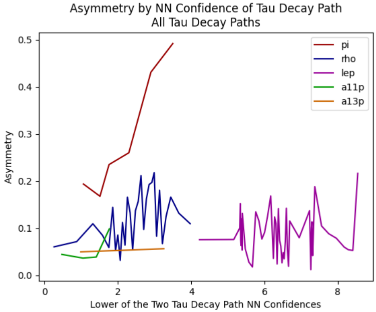
Optimized NN Cutoffs

- **Significance-maximizing** ($S/\sqrt{S+B}$) NN prediction confidence cuts weighted by cross section for both tau-vs-bkg and tau decay path NNs
- Tau-vs-bkg optimization gave a cutoff at about 5.095, which agrees with naive cut estimates
- Tau decay path NNs invariably yielded **very lax cuts**. This is likely due to the much lower number of mislabelled tau decay paths compared to correctly-labelled ones, meaning that signal efficiency is prioritized over background rejection here

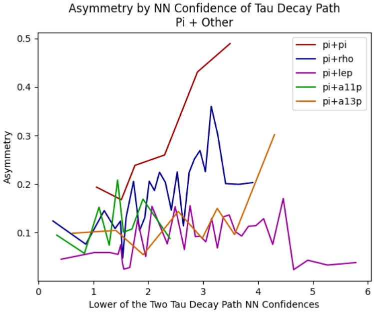


Decay Path	Cutoff
π	0.308
ρ	0.169
ℓ	0.000
$a_{1,1p}$	0.186
$a_{1,3p}$	0.000

- Groups of 400 events each sorted by NN prediction confidence showed **variable dependence** of asymmetry on NN prediction confidence
- Double π events and $\pi\rho$ events showed strongest asymmetry improvement at high NN prediction confidences of possible decay paths shown here
- Overall, the **confidence-based asymmetry** statistic is a sufficient predictor of CP sensitivity to be used in CP sensitivity estimates



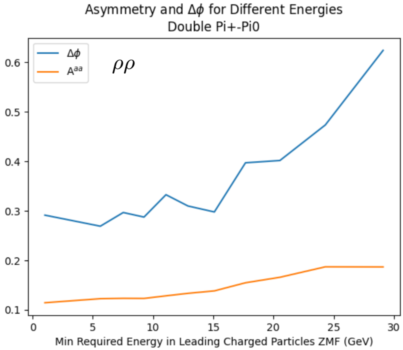
Double Decay Paths

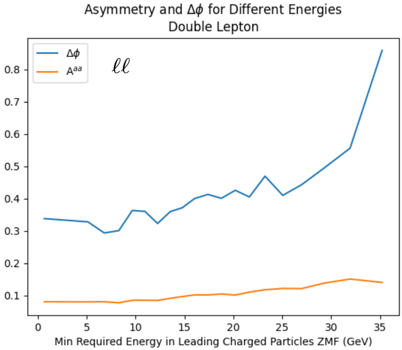


Pi+Other Paths

Review of Energy-Based Asymmetry Binning

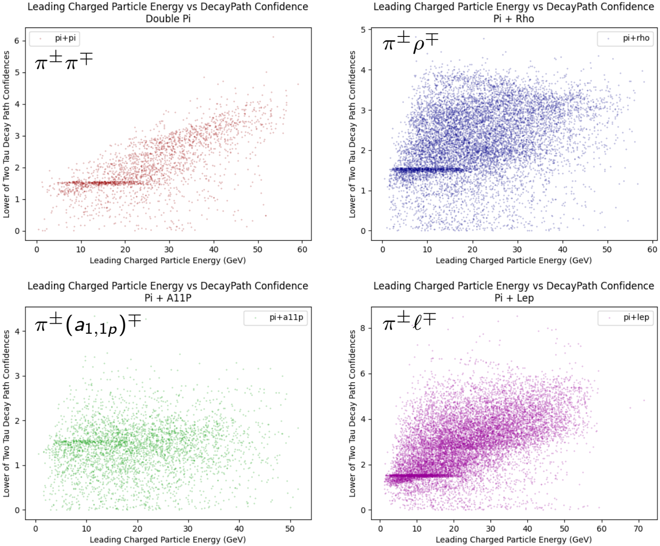
- Previously had established methods for CP sensitivity estimate based on **leading charged particle energy** based on the literature
- Events with higher leading charged particle energies have higher asymmetries for most decay paths, irrespective of NN prediction confidence





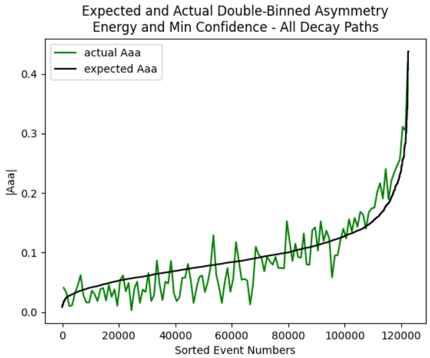
Correlation Between Leading Particle Energy and NN Prediction Confidence

- Due to limited signal sample sizes, a final CP sensitivity must be extracted from separate asymmetry estimates. The variable correlation between energy- and confidence-based methods is small enough that **using both is still worthwhile**



Double-Binned Expected Asymmetry Calculation

- Events binned separately by **leading charged particle energy and NN prediction confidence** for each decay path
- Asymmetry calculated based on cosine fit to groups of **400 events** for each binning process, each event assigned **expected asymmetry (A^{aa})** equal to **average** of fitted asymmetries
- Asymmetries calculated from groups of 1000 events **binned based on expected asymmetry** roughly agreed with expected asymmetry distribution
- Asymmetry distributions **skewed toward high asymmetry values**



Next Steps

- Improve method for **calculating expected asymmetry** from energy-based asymmetry and confidence-based asymmetry
- Using background NN prediction confidence and leading charged particle energies, **simulate repeated cross-section-weighted "experiments"** to include **high background contamination in asymmetry calculation**
- **Simultaneous cosine fitting** based on expected asymmetry: How to group events for simultaneous fitting? (ILD uses three bins and a minimum asymmetry cut)
- CP mixing angle **precision estimates**