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

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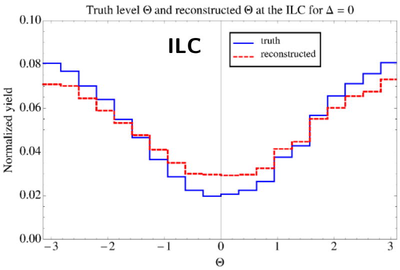
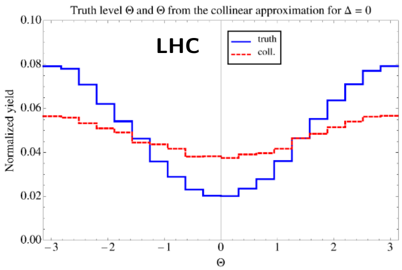
Motivation for studying CP violation:

- CP violation (beyond violations currently observed in electroweak sector) could provide explanation for **matter-antimatter asymmetry**
- Many **recent results implying CP violation** by mesons (strange B, charmed D^0) and neutrinos motivate continued CP violation work
- Higgs sector one of the less-explored sectors for CP violation

Higgs CP Violation:

- Higgs CP violation is a possible source for matter-antimatter asymmetry
- $H \to \tau^+\tau^-$ is ideal for studying CP violation in **leptonic decays**: high branching fraction, polarimeter reconstruction from decay products

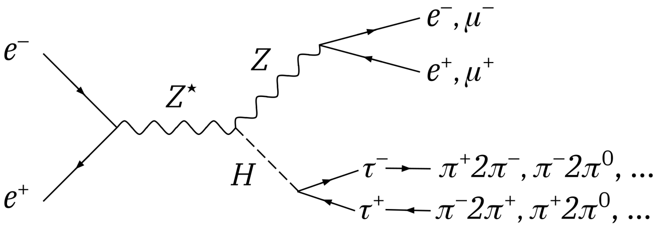




Higgs factory (left) vs approximations possible for LHC (right)
(plots from [Harnik et al., arXiv:1308.1094])

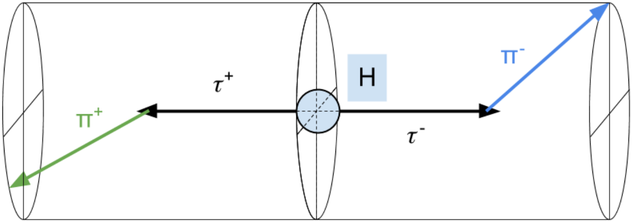
Introduction to Methods and Goals

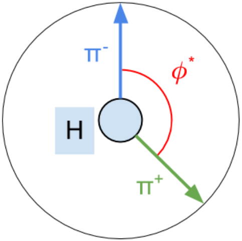
- Past work by Jeans and Wilson [arXiv:1804.01241] focuses on $\tau^{\pm} \to \pi^{\pm}$, $\pi^{\pm}\pi^{0}$ in the ILD detector and uses a series of cuts and CP sensitivity bins
- We develop a new method for SiD with CP sensitivity **weighting** and increased use of **neural networks** for tau event and decay path tagging to **avoid strict cuts**
- We examine the $\tau^{\pm} \to \pi^{\pm}$, $\pi^{\pm}\pi^{0}$, $\ell^{\pm}$, $\pi^{\pm}2\pi^{0}$, $\pi^{\mp}2\pi^{\pm}$ decay modes, allowing **80.6%** of all $H \to \tau^{+}\tau^{-}$ events to be used, compared to **13.2%** for methods only considering $\tau^{\pm} \to \pi^{\pm}$, $\pi^{\pm}\pi^{0}$



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

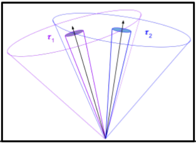




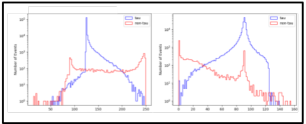
$$\vec{n}_- \equiv \frac{\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}}{\left|\vec{q}_{\pi^-} \times \vec{q}_{\tau^-}\right|} \qquad \vec{n}_+ \equiv \frac{\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}}{\left|\vec{q}_{\pi^+} \times \vec{q}_{\tau^-}\right|}$$

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

Tau Tagging Workflow



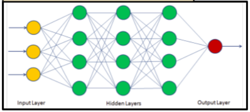
Remove Z daughters, isolate tau cones



Compute event statistics from decay products

Two-neural-network tau tagging with minimal cuts

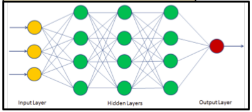
NN1: Tau vs Bkg



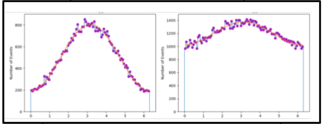
Labelled taus

Remove labelled background events

NN2: Tau Decays

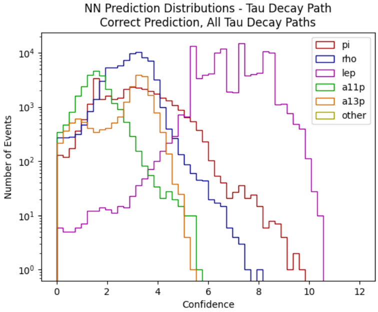


Compute ϕ_{CP} values

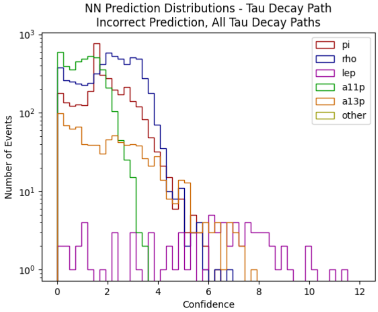


Bin by sensitivity, cosine fit

- 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-labelled** tau decays had **lower NN confidences**, allowing for better binning for CP sensitivity

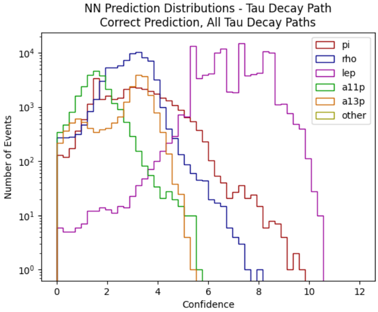


Correct Label

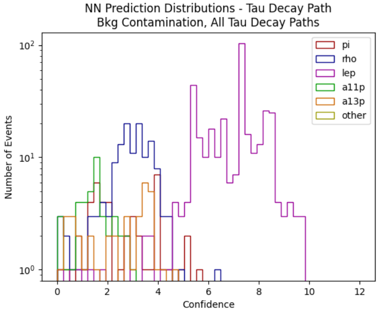


Incorrect Label

- 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 an optimized cutoff for the tau-vs-bkg NN improved background rejection



Correct Label



Background Contamination

Tau Tagging Results

- Used $1ab^{-1}$ of $e_L^- e_R^+$ data, considered the dominant $4f$ background (ZZ, WW), SiD-based Delphes simulation
- **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 provides very **strong background rejection** and gave $S/\sqrt{S+B} = 21.79$
- 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

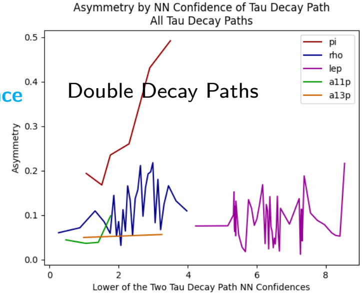
Tau tagging efficiency (%)

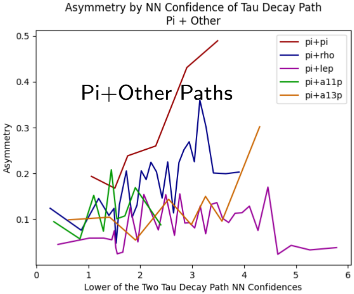
NN tag	Truth event type τ	bkg
τ	65.178	0.006
bkg	34.822	99.994

Decay Path	NN Prediction Cutoff
$\pi^\pm$	0.308
$\pi^\pm\pi^0$	0.169
$\ell^\pm$	0.000
$\pi^\pm 2\pi^0$	0.186
$\pi^\mp 2\pi^\pm$	0.000

Asymmetry Binning Variables: NN Prediction Confidence and Energy

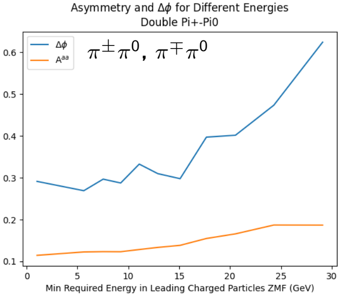
Confidence

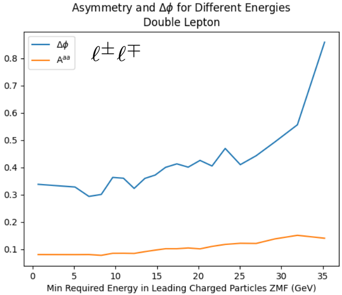




Confidence

Energy

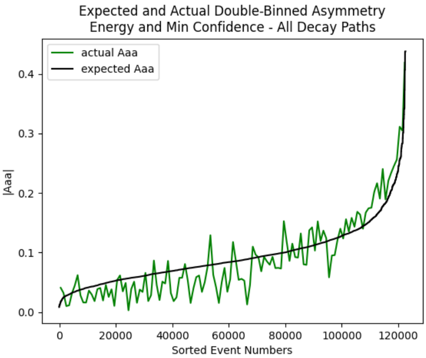




Energy

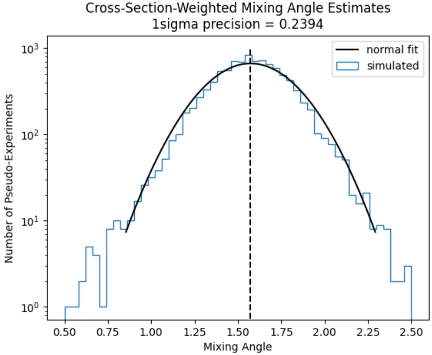
Asymmetry Weighting Results

- 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**



Expected Mixing Angle Precision

- With eLpR polarization, $\boldsymbol{Z \to e^+e^-, \mu^+\mu^-}$, and considering only signal and 4f background, a preliminary expected mixing angle precision of **239.4 mrad** is obtained
- This is very comparable to Jeans and Wilson's result when using the same Z decay paths. However, their final result also includes $\boldsymbol{Z \to qq}$, which greatly improves overall expected precision and which we are **currently working to include**



Summary and Next Steps

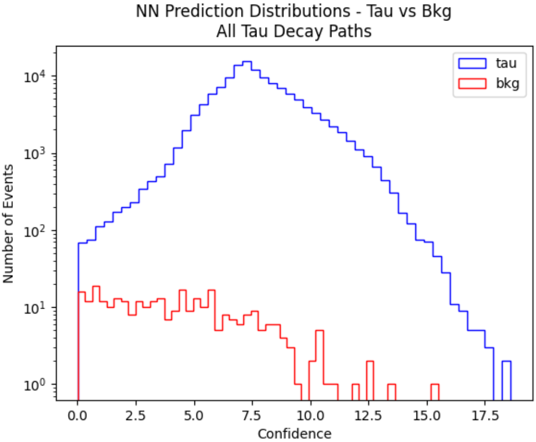
- Here we created a new method for ILC $H \to \tau^+\tau^-$ tagging and CP violation analysis using neural networks and CP sensitivity weighting to avoid strict cuts
- We make use of $\tau^\pm \to \pi^\pm$, $\pi^\pm\pi^0$, $\ell^\pm$, $\pi^\pm 2\pi^0$, $\pi^\mp 2\pi^\pm$ decay modes to consider more tau data in a unified analysis
- Now working to implement $Z \to qq$ cutflow and both polarizations to increase number of usable signal events and improve expected mixing angle precision
- Should have final **full simulation expected mixing angle precision** results soon based on a simulation of the **SiD** experiment

Backup Slides

Full NN Workflow

- 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:** 32 inputs
  - Z invariant mass, recoil mass, total event energy, invariant mass of remaining particles after Z daughters removed
  - **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, as well as for just the charged particles, for each τ (total 4 inputs)
  - For **3-charged-prong decays**, invariant mass of product pair closest to **rho mass**, neutral pion multiplicity, and unpaired photon multiplicity, for each tau (6 inputs)
- **Tau decay separation NN:** 14 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,as well as for just the charged particles (2 inputs)
  - For **3-charged-prong decays**, invariant mass of product pair closest to **rho mass**, neutral pion multiplicity, and unpaired photon multiplicity (3 inputs)
  - Seed is lepton (0) or hadron (1)?
- Preliminary testing using **1 hidden layer** for each NN

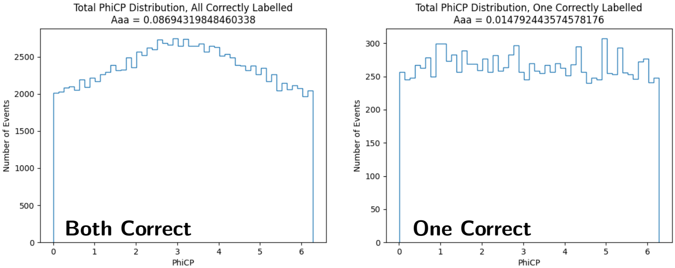
- NN prediction confidence was calculated as the **highest output** from a NN output node minus the **second-highest output**
- **Background events** had **lower NN confidences** than signal events, allowing for improved background rejection

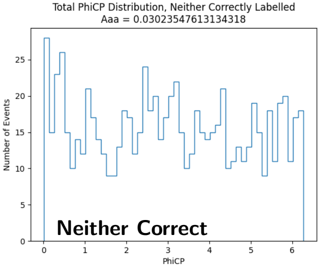


Signal vs Background

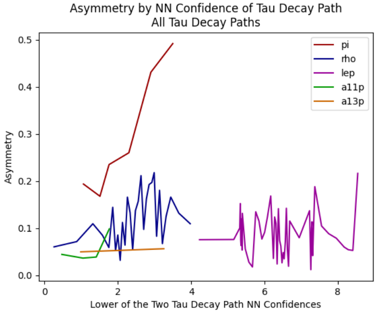
Importance of Removing Incorrectly-Tagged Taus

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

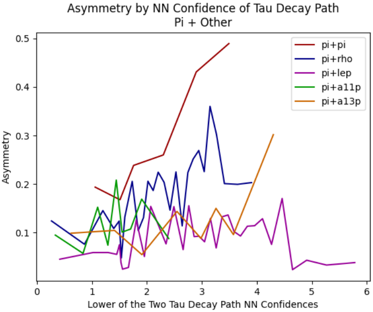




- Groups of 400 events each sorted by NN prediction confidence showed **variable dependence** of asymmetry on NN prediction confidence
- Double π events and $\pi\rho$ events showed strongest asymmetry improvement at high NN prediction confidences of possible decay paths shown here
- Overall, the **confidence-based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



Double Decay Paths



Pi+Other Paths

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