Search for A_{CP} in $D^+_{(s)} \to \eta h^+$ & Br measurement in $D^+_{(s)} \to \eta K^+$ at Belle II

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Lab meeting

(Recap)Introduction

Decays

- $D^+ \to \eta\pi^+$: Singly Cabibbo-suppressed (SCS)
- $D^+ \to \eta K^+$: Doubly Cabibbo-suppressed (DCS)
- $D_s^+ \to \eta\pi^+$: Cabibbo favoured (CF)
- $D_s^+ \to \eta K^+$: SCS
- Using both $\eta \to \gamma\gamma, \eta \to \pi^+\pi^-\pi^0$

Target measurements with Belle II data

- A_{CP} of $D_{(s)}^+ \to \eta h^+ (h = \pi, K)$
- Branch fraction of $D_{(s)}^+ \to \eta K^+$ normalized by $D_{(s)}^+ \to \eta\pi^+$

Analysis methodology

Basic ideas

- Direct reconstruction and fit to $M(\eta_{\gamma\gamma}h^+)$: no D^{*+} tagging
- Train BDT(~~XGboost~~ lightgbm) with grid search: $(\eta_{\gamma\gamma},\pi^+),(\eta_{\gamma\gamma},K^+),(\eta_{3\pi},\pi^+),(\eta_{3\pi},K^+)$
- Before: BDT - signal: $D^+\to\eta h^+$, bkg: ~~$D_s^+\to\eta h^+$ subtracted generic background~~
- Now: BDT - signal: $D^+_{(s)}\to\eta h^+$, bkg: other generic background
  - To improve FoM of $D_s^+\to\eta h^+$
- BDT value is used to optimize with FoM

Branch fraction

- Ratio: $\frac{D^+_{(s)}\to\eta K^+}{D^+_{(s)}\to\eta\pi^+}$, expect to minimize systematics as Belle did

A_{CP}

- Plan: might use control modes, $D^+_{(s)}\to K_S^0 h^+$ to correct $A_{\epsilon_{h^+}}$

This talk: MC15rd(Last talk: MC15ri)

Selection criteria

Before MVA,

Hard π^+: In CDC acceptance, dr<1, |dz|<3, $L_\pi > 0.6$
π^+: In CDC acceptance, dr<1, |dz|<3, $L_\pi > 0.1$
Hard K^+ : In CDC acceptance, dr<1, |dz|<3, $L_K > 0.6$, $L_\pi < 0.01$
γ for η: clusterNHits>1.5, 0.2967< clusterTheta<2.6180, E>0.1
γ for π^0: clusterNHits>1.5, 0.2967< clusterTheta<2.6180, E>0.055,
beamBackgroundSuppression > 0.5, fakePhotonSuppression > 0.1

π^0 for η: 0.12<M<0.145, -1.5<daughterDiffOfPhi(0,1)<1.5, daughterAngle(0,1)<1.4
$\eta_{\gamma\gamma}$: 0.52 < M < 0.57, p > 0.4 GeV
$\eta_{3\pi}$: 0.535 < M < 0.57, p>0.4 GeV

D^+: $p_{CMS} > 2.5$, treefit chiProb > 0.001 (π^0, η mass constraint)

particles	selection criteria
γ_{ROE}	$\lvert\text{clusterTiming}\rvert < 200ns$ $\lvert\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\rvert < 2.0$ clusterNHits> 1.5 $E > 55\text{MeV}$ beamBackgroundSuppression > 0.5 fakePhotonSuppression > 0.1

particles	selection criteria
$\lvert M(\gamma\gamma_{ROE}) - m_{\pi^0)}\rvert$	$> 0.011\text{GeV/c}^2$

MVA(BDT) study

Trained BDTs among different final states: $(\eta_{\gamma\gamma}, \pi^+), (\eta_{\gamma\gamma}, K^+), (\eta_{3\pi}, \pi^+), (\eta_{3\pi}, K^+)$

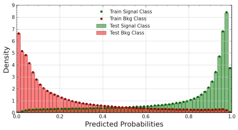
Train variables

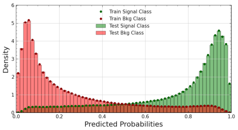
- $D^+_{(s)} \to \eta_{\gamma\gamma} h^+$: 6 variables
  $dr(\pi^+), \cos\theta_{XY}(D^+), |\frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}}|,$
  $\Delta\phi(\gamma_1, \gamma_2), p(\eta) + p(\pi^+),$
  cosHelicityAngleMomentum(D^+)
- $D^+_{(s)} \to \eta_{3\pi} h^+$: 4 variables
  $dr(\pi^+), \cos\theta_{XY}(D^+),$
  $p(\eta) + p(\pi^+),$
  cosHelicityAngleMomentum(D^+)

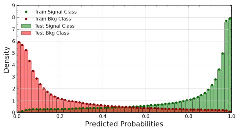
No significant correlations(in backup slides)

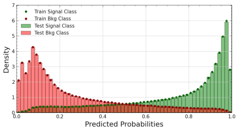
Performed grid search

$D^+ \to \eta_{\gamma\gamma}\pi^+, D^+ \to \eta_{3\pi}\pi^+, D^+ \to \eta_{\gamma\gamma}K^+, D^+ \to \eta_{3\pi}K^+$



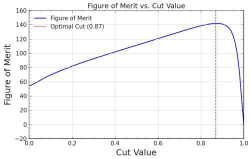


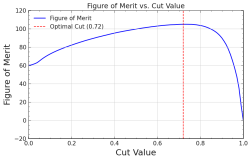


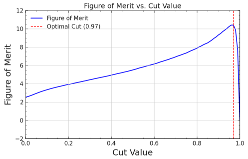


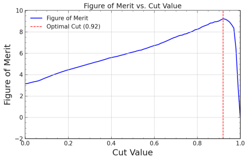
Cut optimization

Optimized variable: BDT in D^+ signal region(might not be optimal to D_s^+)
$D^+ \to \eta_{\gamma\gamma}\pi^+, D^+ \to \eta_{3\pi}\pi^+, D^+ \to \eta_{\gamma\gamma}K^+, D^+ \to \eta_{3\pi}K^+$

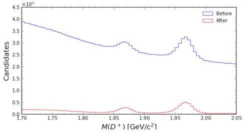


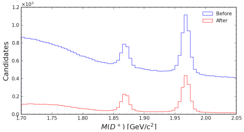


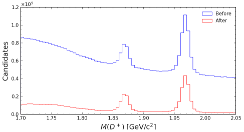


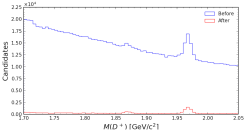


Before vs. after cut



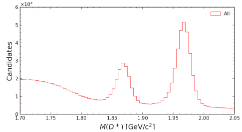


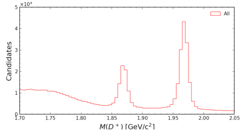


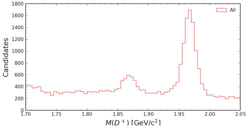


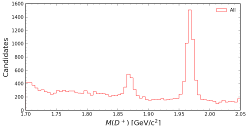
$M(\eta h^+)$ distribution

Full MC15rd: $D^+ \to \eta_{\gamma\gamma}\pi^+, D^+ \to \eta_{3\pi}\pi^+, D^+ \to \eta_{\gamma\gamma}K^+, D^+ \to \eta_{3\pi}K^+$

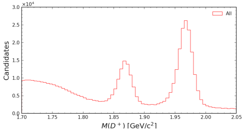


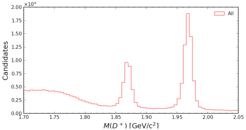


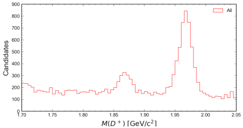


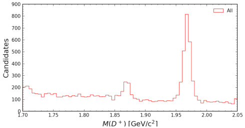


Last talk(MC15ri study)









Signal efficiency

(%), MC15rd is more optimzed

- pionIDNN on $D^+_{(s)} \to \eta\pi^+$ and $\eta \to \pi^+\pi^-\pi^0$) $\to$ increase efficiency for π^+ modes
- Put D^+_s as signal in BDT training $\to$ increase a bit for D_s modes

Mode	Belle II(MC15rd) more optimized	Belle II(MC15ri)	Belle (2011)	Belle (2021)
$D^+ \to \eta_{\gamma\gamma}K^+$	3.41 ± 0.01	3.42 ± 0.01		
$D^+ \to \eta_{\pi\pi\pi}K^+$	3.55 ± 0.01	3.28 ± 0.01	1.35 ± 0.01	
$D^+_s \to \eta_{\gamma\gamma}K^+$	2.37 ± 0.01	2.04 ± 0.01		7.42 ± 0.05
$D^+_s \to \eta_{\pi\pi\pi}K^+$	2.15 ± 0.01	2.02 ± 0.01		4.04 ± 0.02
$D^+ \to \eta_{\gamma\gamma}\pi^+$	9.50 ± 0.01	8.85 ± 0.02		
$D^+ \to \eta_{\pi\pi\pi}\pi^+$	8.06 ± 0.01	6.17 ± 0.02	1.68 ± 0.02	
$D^+_s \to \eta_{\gamma\gamma}\pi^+$	8.47 ± 0.01	7.54 ± 0.02		10.84 ± 0.02
$D^+_s \to \eta_{\pi\pi\pi}\pi^+$	7.08 ± 0.01	5.29 ± 0.02		6.50 ± 0.03

Fitting

Simultaneous fit($D^+_{(s)} + D^-_{(s)}$)

- Set fitting range to cover D^+ and D^+_s

Fit method

- Signals: $D^+_{(s)} \to \eta h^+$
  - pdf: double-sided cystall ball convoluted with gaussian(mean=0)
  - MC fixed: double-sided cystall ball
  - Floating: gaussian
- Backgrounds
  - $M(\eta\pi^+)$: $D^+_s \to (\rho^+ \to \pi^+\pi^0)\eta$, fixed shape with Novosibirsk function(next slide)
  - Other combinatorial
    - $M(\eta\pi^+)$: exponential
    - $M(\eta K^+)$: exponential

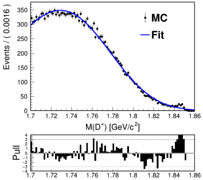
$D_s^+ \to (\rho^+ \to \pi^+\pi^0)\eta$ pdf

Extract pdf in real data(now in MC)

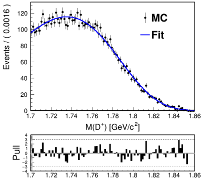
- Pdf is non-trivial and hard to discriminate from other combinatorial
- Pre-selection with $M(\eta\pi^+)$
- With additional π^0, reconstruct $M(\eta\pi^+\pi^0)$
- Cut on $M(\pi^+\pi^0)$ and $M(\eta\pi^+\pi^0)$ to satisfy $m(\rho^+)$ and $m(D_s^+)$ peak region respectively
- Cuts: $|M(\pi^+\pi^0) - m(\rho^+))| < 250MeV$ & $(1.94GeV < M(\pi^+\pi^0\eta) < 1.99GeV)$
- Apply BDT

Pdf

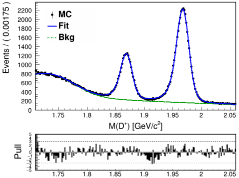
- $\eta_{\gamma\gamma}$ mode, Novosibirsk



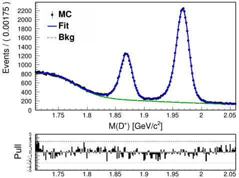
- $\eta_{\pi^+\pi^-\pi^0}$ mode, Novosibirsk



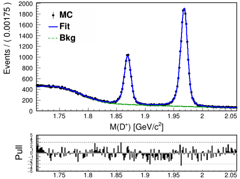
Fit result



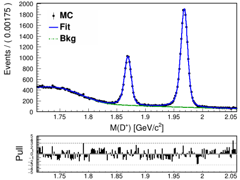
(a) $M(\eta_{\gamma\gamma}\pi^{+})$



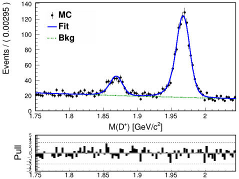
(b) $M(\eta_{\gamma\gamma}\pi^{-})$



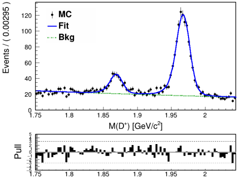
(e) $M(\eta_{3\pi}\pi^{+})$



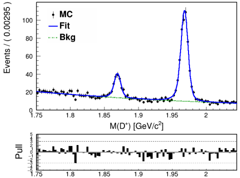
(f) $M(\eta_{3\pi}\pi^{-})$



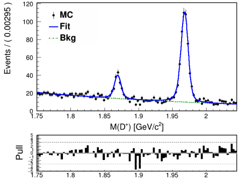
(c) $M(\eta_{\gamma\gamma}K^{+})$



(d) $M(\eta_{\gamma\gamma}K^{-})$

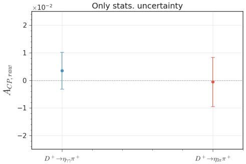


(g) $M(\eta_{3\pi}K^{+})$

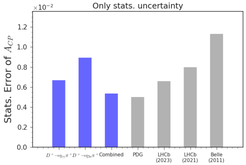


(h) $M(\eta_{3\pi}K^{-})$

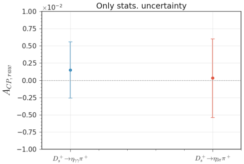
Acp fit result



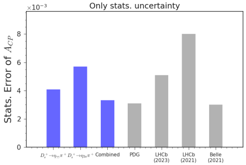
(a) $A_{CP,raw}(D^+ \to \eta\pi^+)$



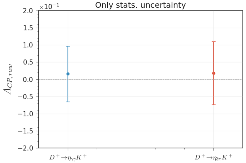
(b) Stat. unc.



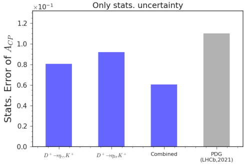
(e) $A_{CP,raw}(D_s^+ \to \eta\pi^+)$



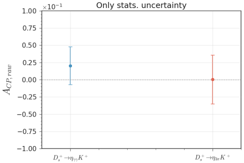
(f) Stat. unc.



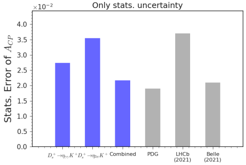
(c) $A_{CP,raw}(D^+ \to \eta K^+)$



(d) Stat. unc.



(g) $A_{CP,raw}(D_s^+ \to \eta K^+)$



(h) Stat. unc.

Acp fit result

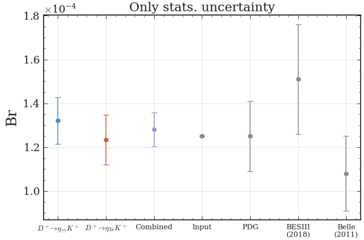
Comparison to most precise single experiment.
(Might be worse after corrected, but not change order)

- $A_{CP,raw}(D^+ \to \eta\pi^+)$: $(0.21 \pm 0.53)\%$
  - Most precise: $\sigma_{\text{stats.}} = 0.66\%$ at LHCb(2023), 25% improved
- $A_{CP,raw}(D_s^+ \to \eta\pi^+)$: $(0.11 \pm 0.33)\%$
  - Most precise: $\sigma_{\text{stats.}} = 0.3\%$ at Belle(2021), comparable
- $A_{CP,raw}(D^+ \to \eta K^+)$: $(1.70 \pm 6.06)\%$
  - Most precise: $\sigma_{\text{stats.}} = 11\%$ at LHCb(2021), 82% improved(but still large uncertainty)
- $A_{CP,raw}(D_s^+ \to \eta K^+)$: $(1.30 \pm 2.17)\%$
  - Most precise: $\sigma_{\text{stats.}} = 2.1\%$ at Belle(2021), comparable

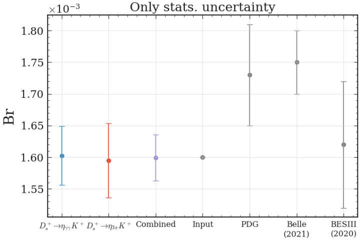
Note: Belle analysis(2021) found data/MC discrepancy of generic background level, about $1.4 \sim 1.5$ times larger than for both $M(\eta\pi^+)$ and $M(\eta K^+)$.
According to Belle note, Belle analysis estimated 10% better precision during MC study.

Branch fraction fit result

To normalize with $\frac{D^+_{(s)} \to \eta K^+}{D^+_{(s)} \to \eta \pi^+}$, BDTs trained by $D^+ \to \eta_{\gamma\gamma} K^+$, $D^+ \to \eta_{3\pi} K^+$ are applied to normalized channels($D^+ \to \eta_{\gamma\gamma}\pi^+$, $D^+ \to \eta_{3\pi}\pi^+$)



(a) $D^+ \to \eta K^+$

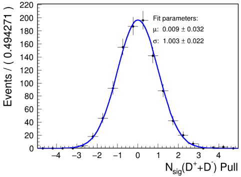


(b) $D_s^+ \to \eta K^+$

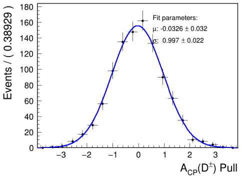
In terms of statistical uncertainties,

- $Br(D^+ \to \eta K^+)$: 54% improved compared to Belle(2011).
- $Br(D_s^+ \to \eta K^+)$: comparable to Belle(2021).

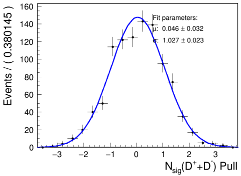
ToyMC study of $D^+ \to \eta\pi^+$



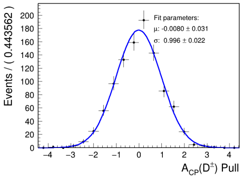
(a) $N_{\text{total}}(D^{\pm}), \eta_{\gamma\gamma}$



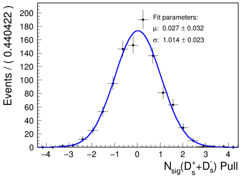
(b) $A_{CP,raw}(D^{\pm}), \eta_{\gamma\gamma}$



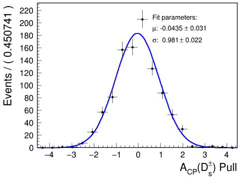
(e) $N_{\text{total}}(D^{\pm}), \eta_{3\pi}$



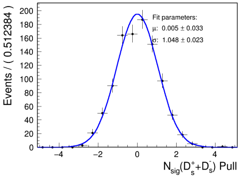
(f) $A_{CP,raw}(D^{\pm}), \eta_{3\pi}$



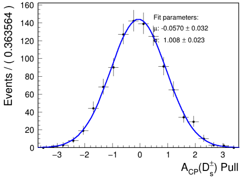
(c) $N_{\text{total}}(D_s^{\pm}), \eta_{\gamma\gamma}$



(d) $A_{CP,raw}(D_s^{\pm}), \eta_{\gamma\gamma}$

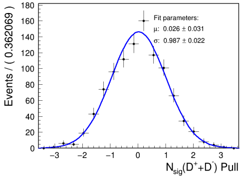


(g) $N_{\text{total}}(D_s^{\pm}), \eta_{3\pi}$

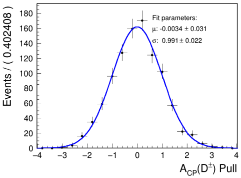


(h) $A_{CP,raw}(D_s^{\pm}), \eta_{3\pi}$

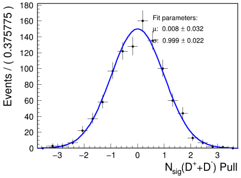
ToyMC study of $D^+ \to \eta K^+$



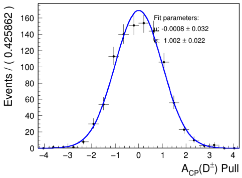
(a) $N_{\text{total}}(D^{\pm}), \eta_{\gamma\gamma}$



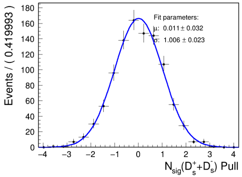
(b) $A_{CP,raw}(D^{\pm}), \eta_{\gamma\gamma}$



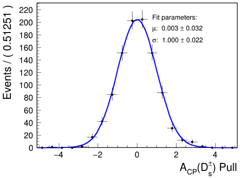
(e) $N_{\text{total}}(D^{\pm}), \eta_{3\pi}$



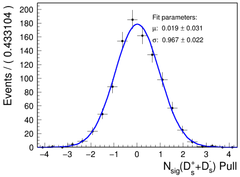
(f) $A_{CP,raw}(D^{\pm}), \eta_{3\pi}$



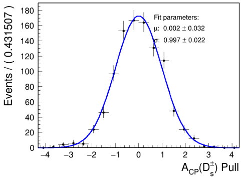
(c) $N_{\text{total}}(D_s^{\pm}), \eta_{\gamma\gamma}$



(d) $A_{CP,raw}(D_s^{\pm}), \eta_{\gamma\gamma}$

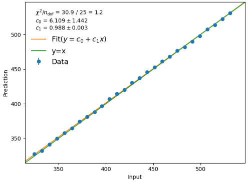


(g) $N_{\text{total}}(D_s^{\pm}), \eta_{3\pi}$

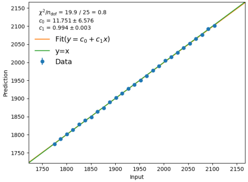


(h) $A_{CP,raw}(D_s^{\pm}), \eta_{3\pi}$

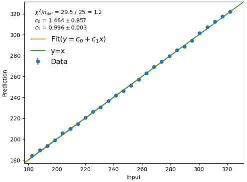
Linearity test



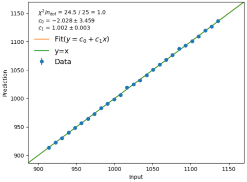
(a) $D^+ \to \eta_{\gamma\gamma} K^+$



(b) $D_s^+ \to \eta_{\gamma\gamma} K^+$



(c) $D^+ \to \eta_{3\pi} K^+$



(d) $D_s^+ \to \eta_{3\pi} K^+$

- Performed linearity test between $\pm 3\sigma$ with respect to fitted N_{sig}
- Each point: 1000 ToyMC

Examine experimental sensitivity?

Could we check and analyze full data to examine statistical sensitivity?
Target measurements= $D^+_{(s)} \to \eta\pi^+$: A_{CP}, $D^+_{(s)} \to \eta K^+$: A_{CP}, Br

- $M(\eta\pi^+)$: full region with blinded central value of $A_{CP,raw}$
  - To check statistical significance
  - To validate fitting method(ex. data driven pdf)
- $M(\eta K^+)$: sideband region(not $M(D^+_{(s)})$ region) due to Br measurement
  - To check statistical significance

A_{CP} control modes

Candidates of A_{CP} control modes(PDG values)

Mode	A_{CP}	Br	Decay types
$D^+ \to K_S^0\pi^+$	-0.0041 ± 0.0009	$(1.562 \pm 0.031)\%$	CF
$D_s^+ \to K_S^0\pi^+$	0.0020 ± 0.0018	$(1.09 \pm 0.05) \cdot 10^{-3}$	SCS
$D^+ \to K_S^0K^+$	-0.0001 ± 0.0007	$(3.04 \pm 0.09) \cdot 10^{-3}$	SCS
$D_s^+ \to K_S^0K^+$	0.0009 ± 0.0026	$(1.450 \pm 0.035)\%$	CF
$D_s^+ \to \phi\pi^+$	-0.0038 ± 0.0027	$(2.21 \pm 0.06)\%$	CF

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$D_s^+ \to \phi\pi^+$	-0.0038 ± 0.0027	$(2.21 \pm 0.06)\%$	CF

- Current ongoing study & same BDT per signal will be applied

$$A_{\text{CP}}(D_s^+ \to \eta\pi^+) = A_{\text{raw}} + A_{\text{CP, raw}}(D_s^+ \to \phi\pi^+) - A_{\text{raw, ref}}$$
$$A_{\text{CP}}(D^+ \to \eta\pi^+) = A_{\text{raw}} + A_{\text{CP, raw}}(D^+ \to K_S^0\pi^+) - A'_{\text{raw, ref}}$$
$$A_{\text{CP}}(D_s^+ \to \eta K^+) = A_{\text{raw}} + A_{\text{CP, raw}}(D_s^+ \to K_S^0 K^+) - A'_{\text{raw, ref}}$$
$$A_{\text{CP}}(D^+ \to \eta K^+)$$
$$= A_{\text{raw}} + A_{\text{CP, raw}}(D_s^+ \to K_S^0 K^+) - A'_{\text{raw}, K_S^0 K^+}$$
$$- A_{\text{CP, raw}}(D_s^+ \to \phi\pi^+) + A_{\text{raw}, \phi\pi^+} + A_{\text{CP, raw}}(D^+ \to K_S^0\pi^+) - A'_{\text{raw}, K_S^0\pi^+}$$

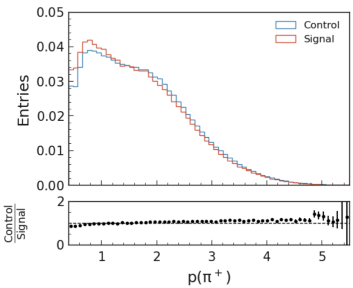
$$A_{\text{raw}} \approx A_{\text{CP}} + A_{\text{FB}} + A_{\epsilon_h^+}$$
$$A_{\text{raw, ref}} \approx A_{\text{CP, ref}} + A_{\text{FB, ref}} + A_{\epsilon_h^+,\text{ref}}$$
$$A_{\text{CP}} = A_{\text{raw}} + A_{\text{CP, ref}} - A_{\text{raw, ref}}$$
' indicates $A_{K_{mix}} \approx (0.070)\%$ corrected

A_{CP} control mode of $D^+ \to \eta K^+$

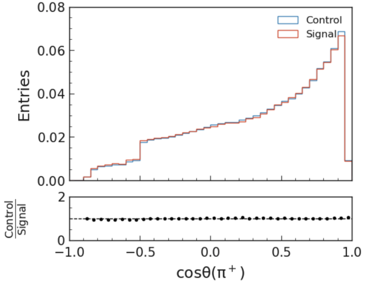
- Two options(3 CF decays or 1 SCS decay)
  1. 3 CF decays
     $A_{\text{CP}}(D^+ \to \eta K^+) = A_{\text{raw}} + A_{\text{CP, raw}}(D_s^+ \to K_S^0 K^+) - A'_{\text{raw},K_S^0 K^+} - A_{\text{CP, raw}}(D_s^+ \to \phi\pi^+) + A_{\text{raw},\phi\pi^+} + A_{\text{CP, raw}}(D^+ \to K_S^0 \pi^+) - A'_{\text{raw},K_S^0 \pi^+}$
  2. 1 SCS decay($D^+ \to K_S^0 K^+$) alone
     $A_{\text{CP}}(D^+ \to \eta K^+) = A_{\text{raw}} + A_{\text{CP, raw}}(D^+ \to K_S^0 K^+) - A'_{\text{raw},K_S^0 K^+}$
- $A_{\text{CP}}(D^+ \to \eta K^+)$ has low statistics since it's DCS.
  - MC15rd study(scaled to 427/fb): $\sigma_{A_{CP,raw}} = (6.08)\%$
  - May fine to use $D^+ \to K_S^0 K^+$. We will check statistical precision for both cases.

A_{CP} control modes, $D^+ \to \eta_{\gamma\gamma}\pi^+$ vs. $D^+ \to K_S^0\pi^+$

After applying BDT



(a) p



(b) cos theta

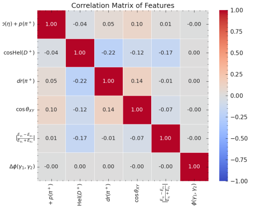
Some control modes will be reweighted with sPlot technique.

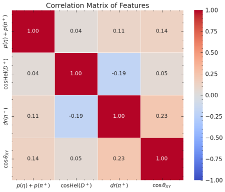
Summary & Plans

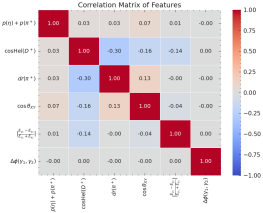
Backup

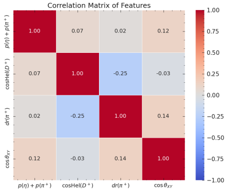
BDT

Variable correlations $D^+ \to \eta_{\gamma\gamma}\pi^+, D^+ \to \eta_{3\pi}\pi^+, D^+ \to \eta_{\gamma\gamma}K^+, D^+ \to \eta_{3\pi}K^+$

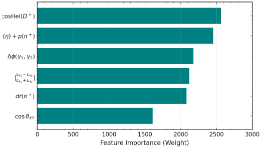


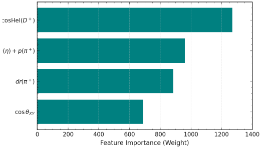


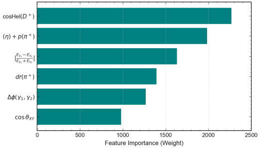


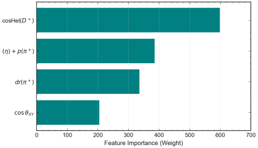


Variable importance









Experimental histories

Decay Mode	Experiment	A_{CP}	Br
$D^+ \to \eta\pi^+$ (SCS)	LHCb (2023)	$(0.34 \pm 0.66 \pm 0.16 \pm 0.05)\%$	-
	LHCb (2021)	$(0.13 \pm 0.50 \pm 0.18)\%$	-
	BESIII (2018)	-	$(37.90 \pm 0.70 \pm 0.68) \cdot 10^{-4}$
	Belle (2011, 791/fb)	$(1.74 \pm 1.13 \pm 0.19)\%$	-
	CLEO (2010)	$(-2.0 \pm 2.3 \pm 0.3)\%$	$(35.4 \pm 0.8 \pm 1.8 \pm 0.8) \cdot 10^{-4}$
$D^+ \to \eta K^+$ (DCS)	LHCb (2021)	$(-6 \pm 10 \pm 4) \cdot 10^{-2}$	-
	BESIII (2018)	-	$(0.151 \pm 0.025 \pm 0.014) \cdot 10^{-3}$
	Belle (2011, 791/fb)	-	$(1.08 \pm 0.17 \pm 0.08) \cdot 10^{-4}$
$D_s^+ \to \eta\pi^+$ (CF)	LHCb (2023)	$(0.32 \pm 0.51 \pm 0.12)\%$	-
	LHCb (2021)	$(0.8 \pm 0.7 \pm 0.5)\%$	-
	Belle (2021, 921/fb)	$(0.2 \pm 0.3 \pm 0.3)\%$	$(19.00 \pm 0.10 \pm 0.59 \pm 0.68) \cdot 10^{-3}$
			More experiments
$D_s^+ \to \eta K^+$ (SCS)	LHCb (2021)	$(0.9 \pm 3.7 \pm 1.1)\%$	-
	Belle (2021, 921/fb)	$(2.1 \pm 2.1 \pm 0.4)\%$	$(1.75 \pm 0.05 \pm 0.5 \pm 0.06) \cdot 10^{-3}$
	BESIII (2020)	-	$(1.62 \pm 0.10 \pm 0.03 \pm 0.05) \cdot 10^{-3}$