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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(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, $D^+_{(s)} \to K^0_S h^+$ to correct $A_{\epsilon_{h^+}}$

This talk: MC15rd(Last talk: MC15ri)

Selection criteria before BDT

We observed pionIDNN on $D^+_{(s)} \to \eta\pi^+$ and $\eta \to \pi^+\pi^-\pi^0$ $\to$ increase efficiency with similar background level

Particles	Selection Criteria
Hard $\pi^\pm$	In CDC acceptance $dr < 1$, $\|dz\| < 3$ $\mathcal{L}_{\pi,NN} > 0.6$ $p > 0.4$GeV
$K^\pm$	In CDC acceptance $dr < 1$, $\|dz\| < 3$ $\mathcal{L}_K > 0.6, \mathcal{L}_\pi < 0.01$ $p > 0.4$GeV
Normal $\pi^\pm$ in $\eta_{3\pi}$	In CDC acceptance $dr < 1$, $\|dz\| < 3$ $\mathcal{L}_{\pi,NN} > 0.1$
γ of η	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E > 0.1$GeV
γ of π^0	clusterNHits>1.5 0.2967< clusterTheta < 2.6180 $E > 0.055$GeV or beamBackgroundSuppression> 0.5 fakePhotonSuppression> 0.1
π^0	$0.120 < M[\text{GeV}] < 0.145$ kFit(mass): reject if fit fails $\|\Delta\phi(\gamma_1, \gamma_2)\| < 1.5$ $\sphericalangle(\gamma_1, \gamma_2) < 1.4$
$\eta_{\gamma\gamma}$	$0.52 < M[\text{GeV}] < 0.57$ $p > 0.4$GeV
$\eta_{3\pi}$	$0.535 < M[\text{GeV}] < 0.57$ $p > 0.4$GeV

D^+	$1.6 < M(D^+)[\text{GeV}] < 2.1$ $p^* > 2.5$GeV Vertex TreeFit: Min(confidence level) = 0.001 IP constraint η, π^0 mass constraint

particles	selection criteria
γ_{roe}	$\|\text{clusterTiming}\| < 200ns$ $\left\|\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\right\| < 2.0$ clusterNHits > 1.5 $E > 55$MeV beamBackgroundSuppression > 0.5 fakePhotonSuppression > 0.1

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

MVA(BDT) study

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

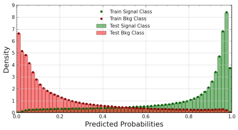
Train variables

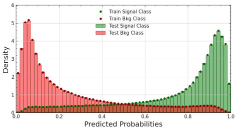
- $D^+_{(s)} \to \eta_{\gamma\gamma} h^+$: 6 variables
  $dr(\pi^+), \cos\theta_{XY}(D^+), |\frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}}|,$
  $\Delta\phi(\gamma_1, \gamma_2), p(\eta) + p(\pi^+),$
  cosHelicityAngleMomentum(D^+)
- $D^+_{(s)} \to \eta_{3\pi} h^+$: 4 variables
  $dr(\pi^+),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

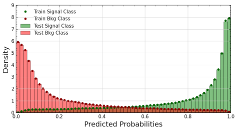
No significant correlations(in backup slides)

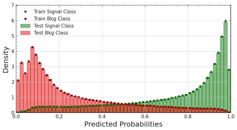
Performed grid search

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





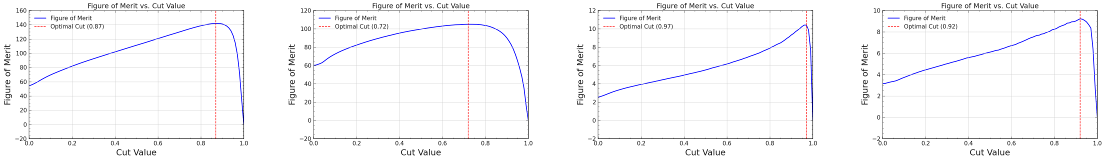




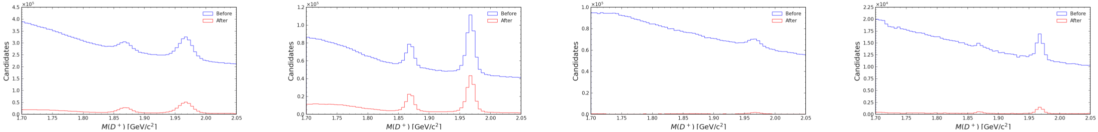
Cut optimization

Optimized variable: BDT in D^+ signal region(might not be optimal to D_s^+)

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

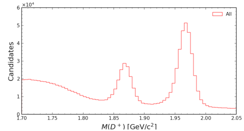


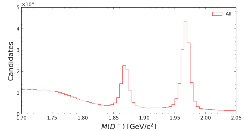
Before vs. after cut

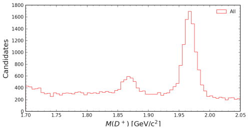


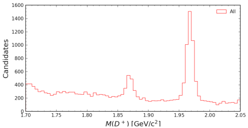
$M(\eta h^+)$ distribution

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

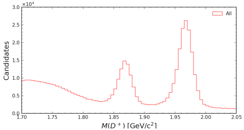


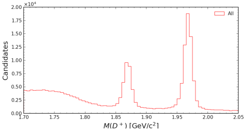


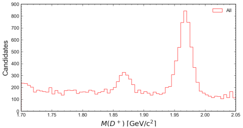


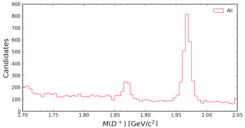


Last talk(MC15ri study)









Signal efficiency

(%), MC15rd is more optimzed

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

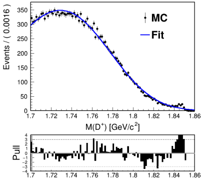
$D_s^+ \to (\rho^+ \to \pi^+ \cancel{\pi^0})\eta$ pdf

Extract pdf in real data(now in MC)

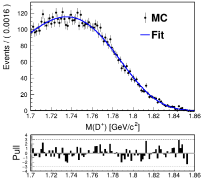
- Pdf is non-trivial and hard to discriminate from other combinatorial
- Pre-selection with $M(\eta\pi^+)$
- With additional π^0, reconstruct $M(\eta\pi^+\pi^0)$
- Cut on $M(\pi^+\pi^0)$ and $M(\eta\pi^+\pi^0)$ to satisfy $m(\rho^+)$ and $m(D_s^+)$ peak region respectively
- Cuts: $|M(\pi^+\pi^0) - m(\rho^+))|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

Pdf

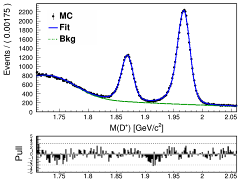
- $\eta_{\gamma\gamma}$ mode, Novosibirsk



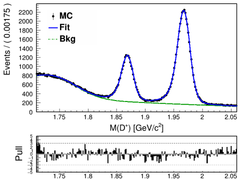
- $\eta_{\pi^+\pi^-\pi^0}$ mode, Novosibirsk



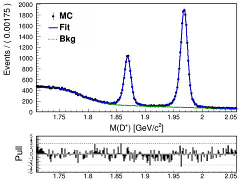
Fit result



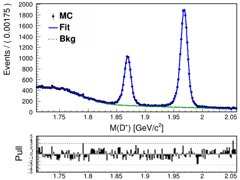
(a) $M(\eta_{\gamma\gamma}\pi^{+})$



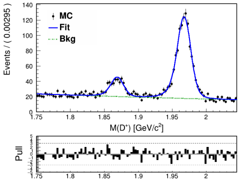
(b) $M(\eta_{\gamma\gamma}\pi^{-})$



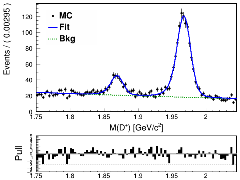
(e) $M(\eta_{3\pi}\pi^{+})$



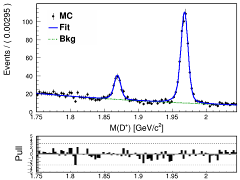
(f) $M(\eta_{3\pi}\pi^{-})$



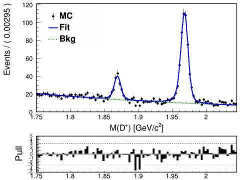
(c) $M(\eta_{\gamma\gamma}K^{+})$



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

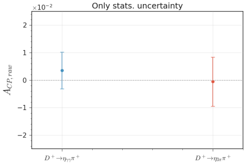


(g) $M(\eta_{3\pi}K^{+})$

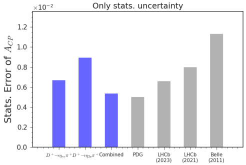


(h) $M(\eta_{3\pi}K^{-})$

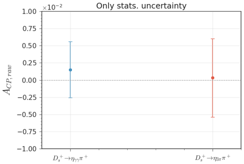
Acp fit result



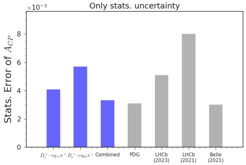
(a) $A_{CP,raw}(D^+ \to \eta\pi^+)$



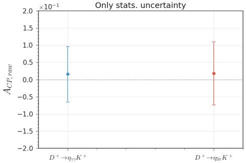
(b) Stat. unc.



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

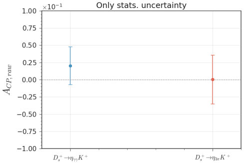


(f) Stat. unc.

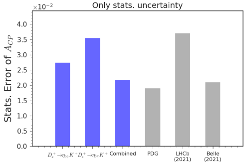


(c) $A_{CP,raw}(D^+ \to \eta K^+)$

(d) Stat. unc.



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



(h) Stat. unc.

Acp fit result

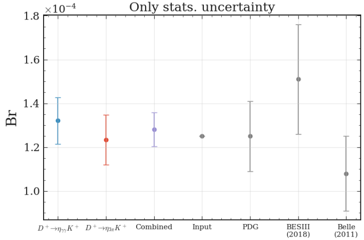
Comparison to most precise single experiment.
(Might be worse after corrected, but not change order)

- $A_{CP,raw}(D^+ \to \eta\pi^+)$: $(0.21 \pm 0.53)\%$
  - 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

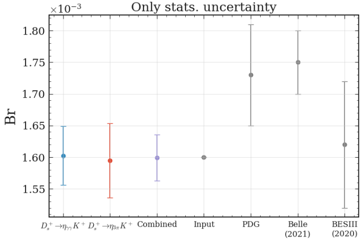
Note: Belle analysis(2021) found data/MC discrepancy of generic background level, about $1.4 \sim 1.5$ times larger than for both $M(\eta\pi^+)$ and $M(\eta K^+)$.
According to Belle note, Belle analysis estimated 10% better precision during MC study.

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,

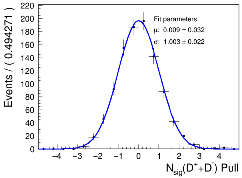
- $Br(D^+ \to \eta K^+)$: 54% improved compared to Belle(2011).
- $Br(D_s^+ \to \eta K^+)$: comparable to Belle(2021).

Examine experimental sensitivity?

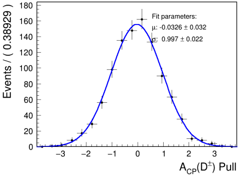
Could we check and analyze full data to examine statistical sensitivity?
Target measurements= $D^+_{(s)} \to \eta\pi^+$: A_{CP}, $D^+_{(s)} \to \eta K^+$: A_{CP}, Br

- $M(\eta\pi^+)$: 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

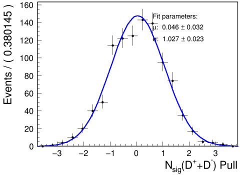
ToyMC study of $D^+_{(s)} \to \eta\pi^+$



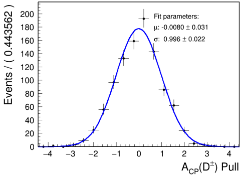
(a) $N_{\text{total}}(D^{\pm}), \eta_{\gamma\gamma}$



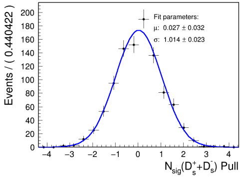
(b) $A_{CP,raw}(D^{\pm}), \eta_{\gamma\gamma}$



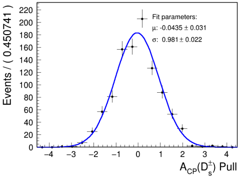
(e) $N_{\text{total}}(D^{\pm}), \eta_{3\pi}$



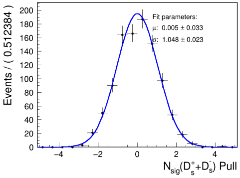
(f) $A_{CP,raw}(D^{\pm}), \eta_{3\pi}$



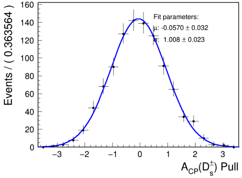
(c) $N_{\text{total}}(D_s^{\pm}), \eta_{\gamma\gamma}$



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

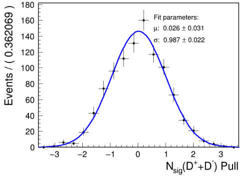


(g) $N_{\text{total}}(D_s^{\pm}), \eta_{3\pi}$

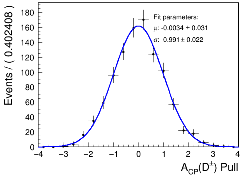


(h) $A_{CP,raw}(D_s^{\pm}), \eta_{3\pi}$

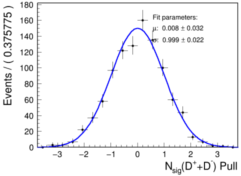
ToyMC study of $D^+_{(s)} \to \eta K^+$



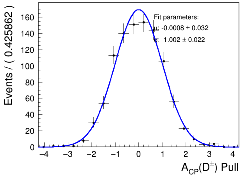
(a) $N_{\text{total}}(D^{\pm}), \eta_{\gamma\gamma}$



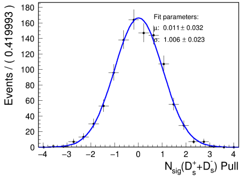
(b) $A_{CP,raw}(D^{\pm}), \eta_{\gamma\gamma}$



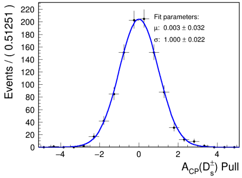
(e) $N_{\text{total}}(D^{\pm}), \eta_{3\pi}$



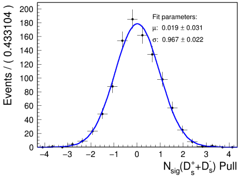
(f) $A_{CP,raw}(D^{\pm}), \eta_{3\pi}$



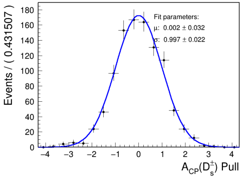
(c) $N_{\text{total}}(D_s^{\pm}), \eta_{\gamma\gamma}$



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

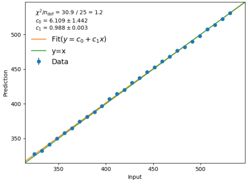


(g) $N_{\text{total}}(D_s^{\pm}), \eta_{3\pi}$

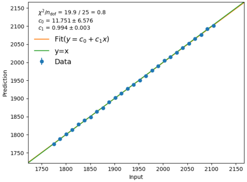


(h) $A_{CP,raw}(D_s^{\pm}), \eta_{3\pi}$

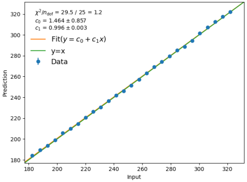
Linearity test



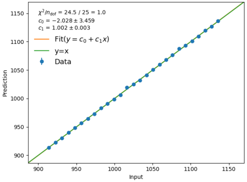
(a) $D^+ \to \eta_{\gamma\gamma} K^+$



(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

A_{CP} control modes

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

Mode	A_{CP}	Br	Decay types
$D^+ \to K^0_S \pi^+$	-0.0041 ± 0.0009	$(1.562 \pm 0.031)\%$	CF
$D^+_s \to K^0_S \pi^+$	0.0020 ± 0.0018	$(1.09 \pm 0.05) \cdot 10^{-3}$	SCS
$D^+ \to K^0_S K^+$	-0.0001 ± 0.0007	$(3.04 \pm 0.09) \cdot 10^{-3}$	SCS
$D^+_s \to K^0_S K^+$	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

A_{CP} control modes

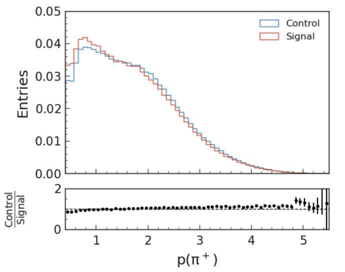
Mode	A_{CP}	Br	Decay types
$D^+ \to K_S^0 \pi^+$	-0.0041 ± 0.0009	$(1.562 \pm 0.031)\%$	CF
$D_s^+ \to K_S^0 K^+$	0.0009 ± 0.0026	$(1.450 \pm 0.035)\%$	CF

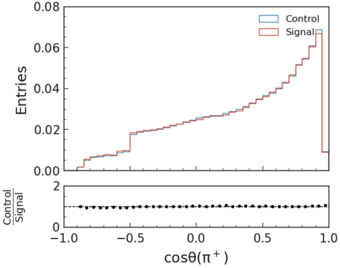
- Currently ongoing & same BDT per signal will be applied
  - $D^+_{(s)} \to \eta\pi^+$ - $D^+ \to K_S^0 \pi^+$
  - $D^+_{(s)} \to \eta K^+$ - $D_s^+ \to K_S^0 K^+$

- $A'_{raw} = \frac{A_{raw}(\cos\theta^* < 0) + A_{raw}(\cos\theta^* > 0)}{2}$
  - $A_{\text{raw}} = A_{CP} + A_{FB} + A_{\epsilon_h^+}$
  - $A'_{\text{raw}} \approx A_{\text{CP}} + A_{\epsilon_h^+}$
  - $A'_{\text{raw, ref}} \approx A_{\text{CP, ref}} + A_{\epsilon_h^+,\text{ref}} + A_{K_{mix}}$ $A_{K_{mix}} \approx (0.070)\%$, well-known.
- $A_{\text{CP}} = A'_{\text{raw}} + A_{\text{CP, ref}} - A'_{\text{raw, ref}}$

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

After applying BDT, MC-matched (just for checking)
Matched well in this case.





If needed, $(p, \cos\theta)$ will be reweighted with sWeighted signals.

Summary & Plans

Summary

Using MC15rd samples(1/4 scaled),

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

Might be a bit worse after A_{ref} correction.

- $Br(D^+ \to \eta K^+)$: $(1.281 \pm 0.078) \cdot 10^{-4}$ - 54% improved than $\sigma_{\text{stats.}} = 0.17 \cdot 10^{-4}$ at Belle(2011).
- $Br(D_s^+ \to \eta K^+)$: $(1.600 \pm 0.036) \cdot 10^{-3}$ - comparable to $\sigma_{\text{stats.}} = 0.05 \cdot 10^{-3}$ Belle(2021).

Plans

- If possible, check statistical significance with blinded data and fitting method
- A_{CP} control sample study with sPlot
- Start systematics study

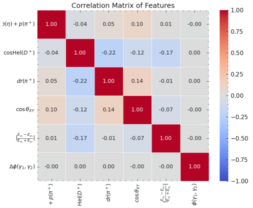
Comments or questions

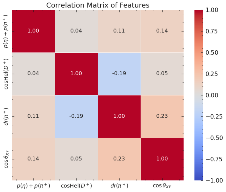
- BDT
  - One was interested in the composition of generic background. ex. mostly from D^+? $\rightarrow$ For what? anyway, I will investigate it
  - Impact parameter of $D^+_{(s)}$? $\rightarrow$ π^+ is highly correlated. And $dz(D^+)$ is not helpful, too
  - $\eta_{\gamma\gamma}$: how about to try angle cuts in advance and make BDT simpler? $\rightarrow$ seems reasonable, retraining
  - $\eta_{3\pi}$: maybe one can try to suppress background of π^+, π^- tracks, like using impact parameters or whatever $\rightarrow$ indeed, dr of 2 tracks help to improve FoM
- Fitting region
  - $M(\eta\pi^+)$: did you try cutting out the lower region? $\rightarrow$ tried from 1.75 & 1.80, hard to converge
- To check blinded data
  - Please ensure the method the blind central $A_{CP,raw}$ value before opening data. $\rightarrow$ confirmed method with one convenor. skimming data is done
- Linearity test
  - c_0 deviated from 0 is fine? Could you explain? $\rightarrow$ include to systematics
- One is already using $D^+ \rightarrow K^0_S\pi^+$ (Yifan, A_{CP}, $D^+ \rightarrow \pi^+\pi^0$) $\rightarrow$ different momentum cuts, so didn't contact

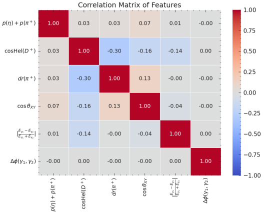
Backup

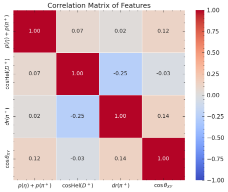
BDT

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

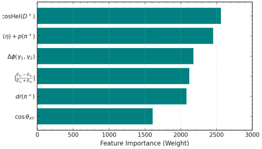


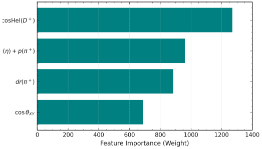


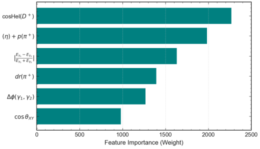


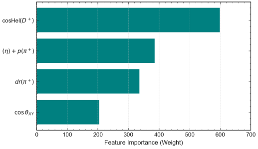


Variable importance









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)	-	$(1.62 \pm 0.10 \pm 0.03 \pm 0.05) \cdot 10^{-3}$