Study of SCS radiative D^0 decays, $D^0 \to V\gamma$ at Belle II

Jaeyoung Kim[1], Youngjoon Kwon[1]

[1]Yonsei University
Seoul, Korea

Saga-Yonsei Joint Workshop

Introduction & motivation

Introduction

Signal decays: $D^0 \to V\gamma, (V = \phi, \rho^0, \omega)$
(Charge-conjugated decays are also included)

- $D^0 \to \phi(\to K^+K^-)\gamma$
- $D^0 \to \rho^0(\to \pi^+\pi^-)\gamma$
- $D^0 \to \omega \to (\pi^+\pi^-\pi^0)\gamma$

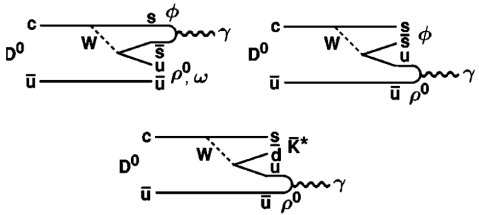


Figure: Feynman diagrams [PRD 58, 092001(1998)]

$D^0 \to \bar{K}^{*0}(\to K^-\pi^+)\gamma$: π^0 veto calibration

Motivations

$D^0 \to V\gamma$

- Previous results at Belle (see below table)
  - $\Delta Br \sim \mathcal{O}(10\%), \Delta A_{CP} \sim \mathcal{O}(10^{-2})$
  - No evidence so far of non-zero A_{CP}
- Sensitive to NP in A_{CP} measurement
  - SM prediction: $\mathcal{O}(10^{-3})$ [James Lyon and Roman Zwicky, PRD 106, 053001(2022)]
  - SM extension with chromomagnetic dipole operators: up to $\mathcal{O}(10^{-2})$ for $V = \phi, \rho^0$ [Gino Isidori and Jernej F. Kamenik, PRL 109, 171801(2012)]
- $D^0 \to \omega\gamma$ not yet been measured
- Table of Belle results [T.Nanut *et al.*(Belle), PRL 118, 151801(2017)]

Channels	Br	A_{CP}
$D^0 \to \rho^0\gamma$	$(1.77 \pm 0.30 \pm 0.07) \times 10^{-5}$	$+0.056 \pm 0.152 \pm 0.066$
$D^0 \to \phi\gamma$	$(2.76 \pm 0.19 \pm 0.10) \times 10^{-5}$	$-0.094 \pm 0.066 \pm 0.001$
$D^0 \to \bar{K}^{*0}\gamma$	$(4.66 \pm 0.21 \pm 0.21) \times 10^{-4}$	$-0.003 \pm 0.020 \pm 0.000$

Motivations

Expectation for Belle II

Table 113: A_{CP} results of the Belle study and extrapolation of the statistical uncertainty to Belle II, for different values of integrated luminosity.

	Int. luminosity		
		$A_{CP}(D^0 \to \rho^0\gamma)$	
Belle result	1 ab^{-1}	$+0.056$ ±0.152	±0.006
	5 ab^{-1}	±0.07	
Belle II statistical error	15 ab^{-1}	±0.04	
	50 ab^{-1}	±0.02	
		$A_{CP}(D^0 \to \phi\gamma)$	
Belle result	1 ab^{-1}	-0.094 ±0.066	±0.001
	5 ab^{-1}	±0.03	
Belle II statistical error	15 ab^{-1}	±0.02	
	50 ab^{-1}	±0.01	
		$A_{CP}(D^0 \to \overline{K}^{*0}\gamma)$	
Belle result	1 ab^{-1}	-0.003 ±0.020	±0.000
	5 ab^{-1}	±0.01	
Belle II statistical error	15 ab^{-1}	±0.005	
	50 ab^{-1}	±0.003	

[The Belle II Physics Book, PTEP 123C01(2019)]

D^* flavour tagging (D^0 or $\bar{D}^0$?)

D^* flavour tagging (D^0 or $\bar{D}^0$?)

- Useful in charm meson analysis,
  - Provide a clean sample of flavor-tagged D^0, used extensively at B factories
  - Determine the flavor of D^0 or $\bar{D}^0$ through the charge of pion emitted in D^* decay

$$D^{*+} \to D^0 \pi^+$$
$$D^{*-} \to \bar{D}^0 \pi^-$$

- $\Delta m = M(D^{*+}) - M(D^0)$
  - Shows sharply peaking distribution,
  - Belle II achieved Δm resolution of $180\mathrm{keV/c^2}$
  - Eliminates considerable background
- Typical $\epsilon_{D*} = 80\%$
- Typical mis-taggin rate $= 0.2\%$

Dominant background from π^0

Dominant background from π^0

Sources

- $D^0 \to V\pi^0(\to \gamma\not{\gamma})$

Features

- Background peak in $M(D^0)$ overlaps with signal peak
- Branching fraction [R.L. Workman et al. (Particle Data Group), Prog.Theor.Exp.Phys.2022, 083C01(2022)]

V	$D^0 \to V\pi^0$	$D^0 \to V\gamma$
ϕ	$(6.6 \pm 0.4) \cdot 10^{-4}$	$(2.81 \pm 0.19) \cdot 10^{-5}$
ρ^0	$(3.86 \pm 0.23) \cdot 10^{-3}$	$(1.82 \pm 0.32) \cdot 10^{-5}$
$\bar{K}^{*0}$	$(1.95 \pm 0.24) \cdot 10^{-2}$	$(4.1 \pm 0.7) \cdot 10^{-4}$
ω	$(1.17 \pm 0.35) \cdot 10^{-4}$	$< 2.4 \cdot 10^{-4}$(C.L. 90%)

Analysis procedure

1. Pre-selection
2. Dedicated π^0 veto (MVA)
3. Signal extraction with additional cuts
4. Check and calibrate data/MC discrepancy of π^0 veto (plan)
5. Calculation of Br and A_{CP} with normalization modes (plan)

V	$D^0 \to V\gamma$	Normalization mode
ϕ	$D^0 \to \phi(\to K^+K^-)\gamma$	$D^0 \to K^+K^-$
ρ^0	$D^0 \to \rho^0(\to \pi^+\pi^-)\gamma$	$D^0 \to \pi^+\pi^-$
$\bar{K}^{*0}$	$D^0 \to \bar{K}^{*0}(\to K^-\pi^+)\gamma$	$D^0 \to K^-\pi$
ω	$D^0 \to \omega(\to \pi^+\pi^-\pi^0)\gamma$	$D^0 \to \pi^+\pi^-\pi^0$

Event selection & background study

Pre-selection

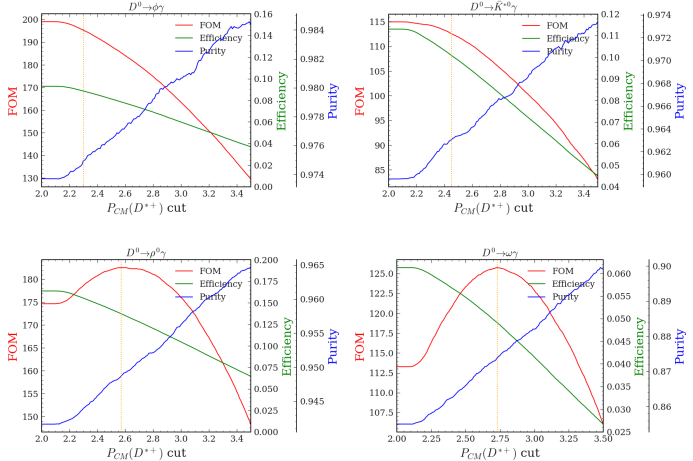
Criteria

Particles	selection criteria
$K^{\pm}$	in CDC acceptance $\mathcal{L}_{K\pi} > 0.5$ $dr < 1.5, \lvert dz\rvert < 3.5$
hard $\pi^{\pm}$	in CDC acceptance $\mathcal{L}_{\pi K} > 0.5$ $dr < 1.5, \lvert dz\rvert < 3.5$
slow π^{+}	in CDC acceptance $dr < 1.5, \lvert dz\rvert < 3.5$
π^0	eff30_May2020
$\lvert M(V) - m(V)\rvert$	$\phi :< 0.02$GeV $\bar{K}^{*0} :< 0.22$GeV $\rho^0 :< 0.245$GeV $\omega :< 0.04$GeV

γ	$E > 300$MeV clusterE9E21 > 0.95 clusterNHits ≥ 5 clusterSecondMoment ≤ 1.5
D^0	$p_{CM} > 2$GeV
D^{*+}	$\Delta m = M(D^{*+}) - M(D^0) < 0.160$GeV vertex treeFit: min(confidence level)=0.001 IP constraint

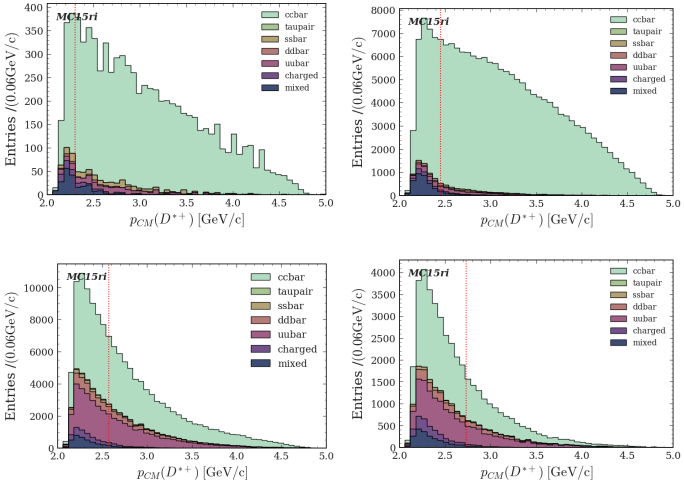
$p_{CM}(D^{*+})$ cut

- 1. Maximize FOM($N_{sig}/\sqrt{N_{sig}+N_{bkg}}$)
- 2. Suppress the combinatorial bkg from $B^0\bar{B}^0, B^+B^-$ & $q\bar{q}(u\bar{u}, d\bar{d}, s\bar{s})$



$p_{CM}(D^{*+})$ cut

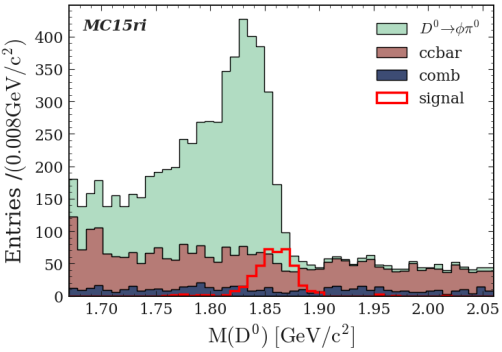
- 1. Maximize FOM($N_{sig}/\sqrt{N_{sig}+N_{bkg}}$)
- 2. Suppress the combinatorial bkg from $B^0\bar{B}^0, B^+B^-$ & $q\bar{q}(u\bar{u}, d\bar{d}, s\bar{s})$



After additional cuts for signal extraction

	ϕ	$\bar{K}^{*0}$	ρ^0	ω	all
$\lvert M(V) - m_{nominal}(V)\rvert$	< 11MeV	< 60MeV	< 125MeV	< 15MeV	
$\lvert Q - Q_{\text{nominal}}\rvert$					< 0.6MeV
$p_{\text{CM}}(D^{*+})$	> 2.3GeV	> 2.45GeV	> 2.57GeV	> 2.73GeV	

Bkg constituents of $D^0 \to \phi\gamma$ in $\int \mathcal{L}dt$ =1/ab MC

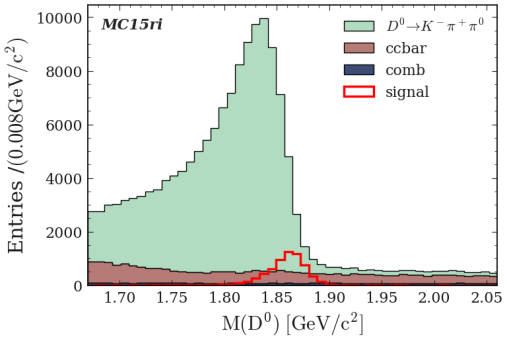


$Q = M(D^{*+}) - M(D^0) - M(\pi^+) = \Delta m - M(\pi^+)$

After additional cuts for signal extraction

	ϕ	$\bar{K}^{*0}$	ρ^0	ω	all
$\lvert M(V) - m_{nominal}(V)\rvert$	< 11MeV	< 60MeV	< 125MeV	< 15MeV	
$\lvert Q - Q_{\text{nominal}}\rvert$					< 0.6MeV
$p_{\text{CM}}(D^{*+})$	> 2.3GeV	> 2.45GeV	> 2.57GeV	> 2.73GeV	

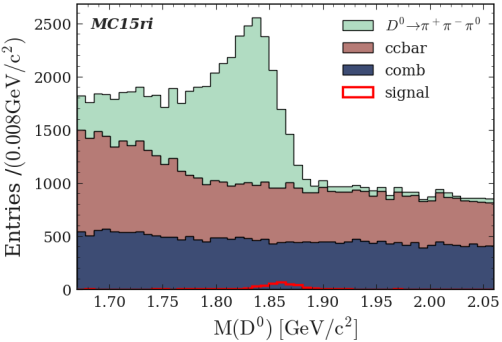
Bkg constituents of $D^0 \to \bar{K}^{*0}\gamma$ in $\int \mathcal{L}dt$ =1/ab MC



After additional cuts for signal extraction

	ϕ	$\bar{K}^{*0}$	ρ^0	ω	all
$\lvert M(V) - m_{nominal}(V)\rvert$	< 11MeV	< 60MeV	< 125MeV	< 15MeV	
$\lvert Q - Q_{\text{nominal}}\rvert$					< 0.6MeV
$p_{\text{CM}}(D^{*+})$	> 2.3GeV	> 2.45GeV	> 2.57GeV	> 2.73GeV	

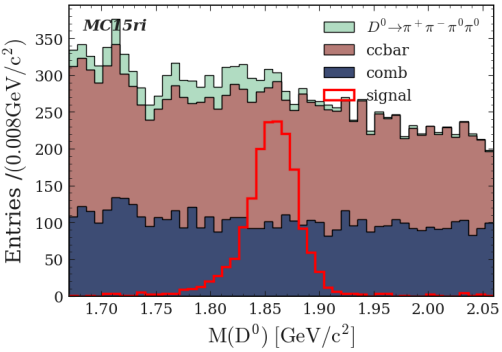
Bkg constituents of $D^0 \to \rho^0\gamma$ in $\int \mathcal{L}dt$ =1/ab MC



After additional cuts for signal extraction

	ϕ	$\bar{K}^{*0}$	ρ^0	ω	all
$\lvert M(V) - m_{nominal}(V)\rvert$	< 11MeV	< 60MeV	< 125MeV	< 15MeV	
$\lvert Q - Q_{\text{nominal}}\rvert$					< 0.6MeV
$p_{\text{CM}}(D^{*+})$	> 2.3GeV	> 2.45GeV	> 2.57GeV	> 2.73GeV	

Bkg constituents of $D^0 \to \omega\gamma$ in $\int \mathcal{L}dt$ =1/ab MC, **(caution: upper limit!)**



Not included: $D^0 \to \omega(\pi^0 \to \gamma\gamma), D^0 \to \omega(\eta \to \gamma\gamma), D^0 \to \pi^+\pi^-\pi^0(\eta \to \gamma\gamma)$ in bkg MC

An issue for $D^0 \to \omega\gamma$

- Not included main bkg($D^0 \to \omega\pi^0$, $D^0 \to \omega\eta$, $D^0 \to \pi^+\pi^-\pi^0\eta$) in bkg MC
  Adding according to PDG value
  $Br(D^0 \to \omega\pi^0)_{2016,BESIII} = (1.17 \pm 0.35) \cdot 10^{-4}$
  $Br(D^0 \to \omega\eta)_{2018,BESIII} = (1.98 \pm 0.18) \cdot 10^{-3}$
  $Br(D^0 \to \pi^+\pi^-\pi^0\eta)_{2020,BESIII} = (3.23 \pm 0.22) \cdot 10^{-3}$
- We will add these 3 decays.

π^0 veto

π^0 veto (MVA)

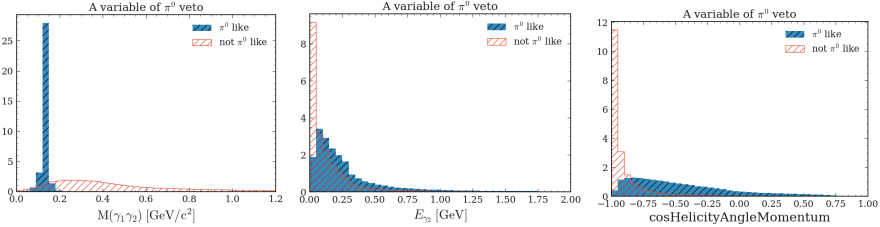
- Purpose: suppression of dominant background, $D^0 \to V\pi^0(\to \gamma_1\cancel{\gamma_2})$
  - not π^0-like vs. π^0-like
- Tool: BDT(Boosted Decision Tree)
- Training variables: $M(\gamma_1\gamma_2), E(\gamma_2)$, cosHelicityAngleMomentum
  - γ_1: primary candidate in $D^0 \to V\gamma$ reconstuction
  - γ_2: any photons except γ_1 remained in each event
    signal: $D^0 \to V\gamma_1$, bkg: $D^0 \to V\pi^0(\to \gamma_1\cancel{\gamma_2})$
- Selection of photons

particles	selection criteria
γ_1	$\lvert\text{clusterTiming}\rvert < 200ns$ $\lvert\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\rvert < 2.0$ $E > 300$MeV clusterE9E21≥ 0.95 clusterNHits≥ 5 clusterSecondMoment≤ 1.5
γ_2	$\lvert\text{clusterTiming}\rvert < 200ns$ $\lvert\frac{\text{clusterTiming}}{\text{clusterErrorTiming}}\rvert < 2.0$ in forward, $E > 25$MeV in barrel, $E > 20$MeV in backward, $E > 20$MeV clusterNHits≥ 2

π^0 veto training

- Samples
  - not π^0 like: pre-selected 1M signal MC of 4 channels($\phi, \rho^0, \bar{K}^{*0}, \omega$) (required grand-daughter of D^{*+} and daughter of D^0)
  - π^0 like: true π^0 in pre-selected background MC

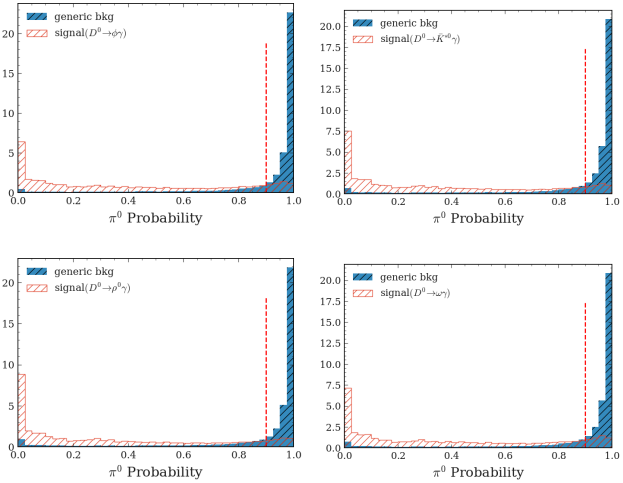
- Distribution of training variables
  $M(\gamma_1\gamma_2), E(\gamma_2)$, cosHelicityAngleMomentum



$\cos\theta$: θ between the line defined by the $\vec{p}_2 - \vec{p}_1$ in π^0 frame and $\vec{p}(\pi^0)$ in lab frame ($\pi^0 \to \gamma_1\gamma_2$)

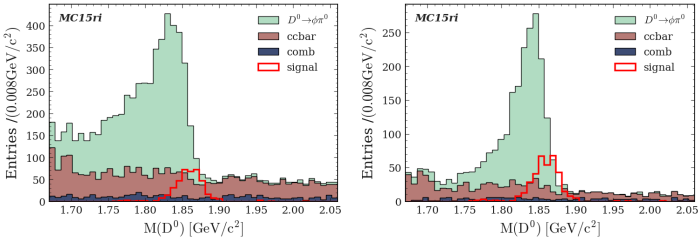
π^0 veto results

- MVA output for each channel
  (bkg: true daughter of π^0 in 1ab^{-1} bkg MC, signal: 1M true signal MC)

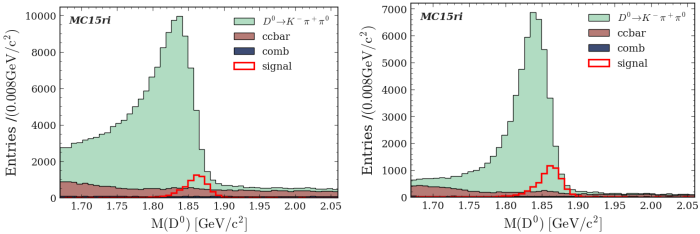


After π^0 veto (π^0 probability < 0.9)

- Bkg constituents of $D^0 \to \phi\gamma$: before vs. after

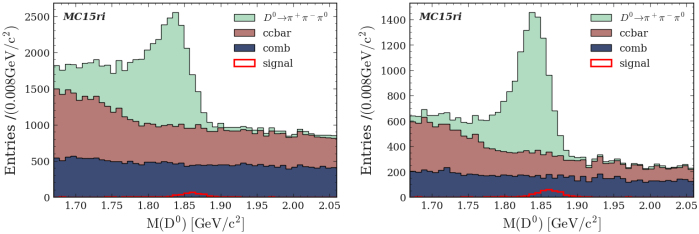


- Bkg constituents of $D^0 \to \bar{K}^{*0}\gamma$: before vs. after

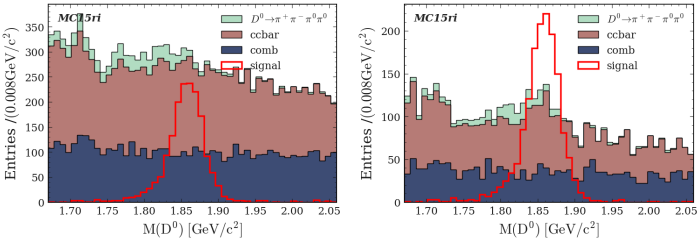


After π^0 veto (π^0 probability < 0.9)

- Bkg constituents of $D^0 \to \rho^0\gamma$: before vs. after



- Bkg constituents of $D^0 \to \omega\gamma$: before vs. after ,(caution: upper limit!)



Future plans

Plan1:check and calibrate π^0 veto

- Using $D^0 \to \bar{K}^{*0}\gamma$, check π^0 veto data/MC discrepancy between $D^0 \to \bar{K}^{*0}(\to K^-\pi^+)\pi^0$ and $D^0 \to \bar{K}^{*0}(\to K^-\pi^+)\gamma$
- Compare $\epsilon_{\text{veto}} = \frac{N_{after\ veto}}{N_{before}}$ of data & MC
- For ideal case, $R \equiv \epsilon_{veto,MC}/\epsilon_{veto,data} = 1$

Plan2:extract signal

- Do 2D fitting($M(D^0), \cos\theta_H$)
- Calculation $Br\&A_{CP}$ with normalization modes,

V	$D^0 \to V\gamma$	Normalization mode
ϕ	$D^0 \to \phi(\to K^+K^-)\gamma$	$D^0 \to K^+K^-$
ρ^0	$D^0 \to \rho^0(\to \pi^+\pi^-)\gamma$	$D^0 \to \pi^+\pi^-$
$\bar{K}^{*0}$	$D^0 \to \bar{K}^{*0}(\to K^-\pi^+)\gamma$	$D^0 \to K^-\pi$
ω	$D^0 \to \omega(\to \pi^+\pi^-\pi^0)\gamma$	$D^0 \to \pi^+\pi^-\pi^0$

For example, $Br(D^0 \to \phi\gamma) = Br(D^0 \to K^+K^-)\frac{N_{rec,D^0\to\phi\gamma}/\epsilon_{D^0\to\phi\gamma}}{N_{rec,D^0\to K^+K^-}/\epsilon_{D^0\to K^+K^-}}$

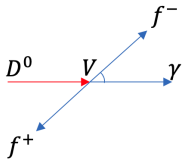
Thank you for your attention!

Backup

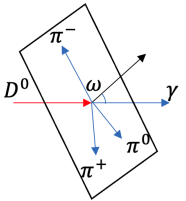
$cos\theta_H$

$D^0 \to V\gamma, (V = \phi, \rho^0, \bar{K}^{*0}, \omega)$

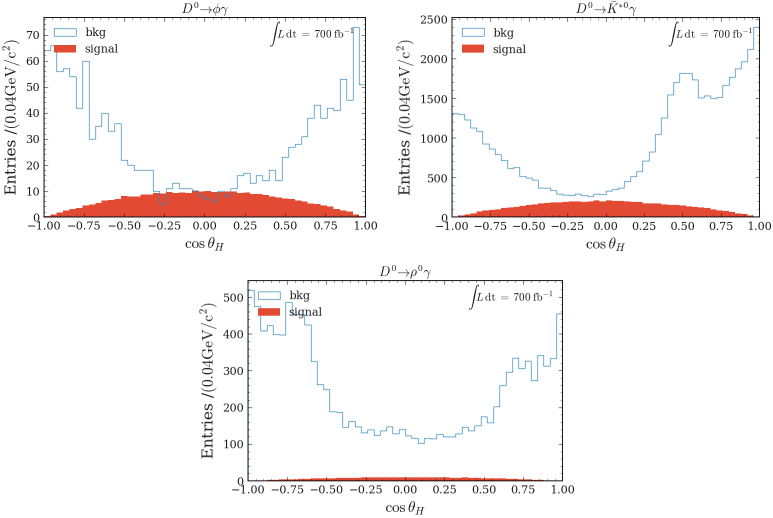
- For $V = \phi, \rho^0, \bar{K}^{*0}$ in $D^0 \to V(\to f^+f^-)\gamma$
  $cos\theta_H$



- For $V = \omega$
  $cos\theta_H$

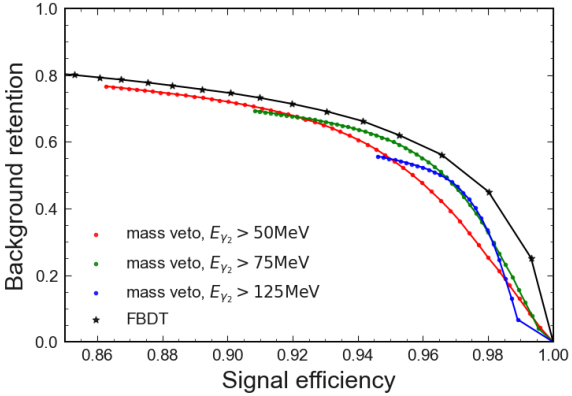


$cos\theta_H$ distribution



π^0 veto results

- ROC curve



- Mass veto: remove the region of near $m(\pi^0)$ (details are in backup)
- BDT is the best until now

Mass veto

- Select one primary photon
- Make pair with other photons in ROE
- Choose one candidate where $M(\gamma_1\gamma_2)$ is nearest to nominal mass(π^0: 0.135GeV)