Study of $D^{\mathbf{0}} \to K^+K^-\omega$ and $K_S^0 - K_L^0$ asymmetry in $D^0 \to \omega K_S^0/K_L^0$ decays on BESIII

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Thesis Proposal Talk

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Outline

- Introduction
- Partial wave analysis of $D^0 \to K^+K^-\omega$
- Study of $K_S^0 - K_L^0$ asymmetry in the decays $D^0 \to \omega K_S^0$ and $D^0 \to \omega K_L^0$
- Summery and Prospects

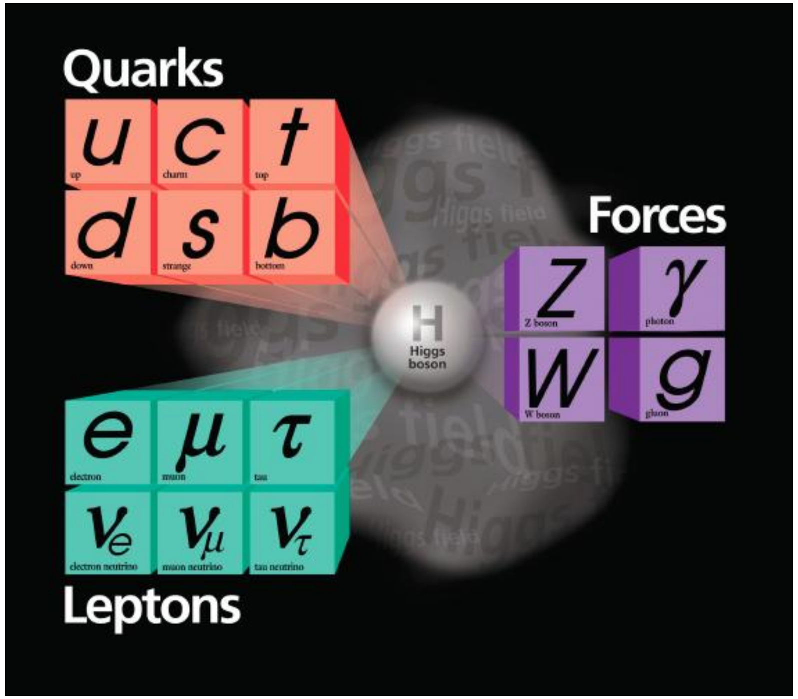
Standard Model（SM）

- SM describes the fundamental particles that make up the visible world of matter and how they interact with each other.
  - Still need to explain:

    Dark matter and dark energy

    Mass of neutrinos

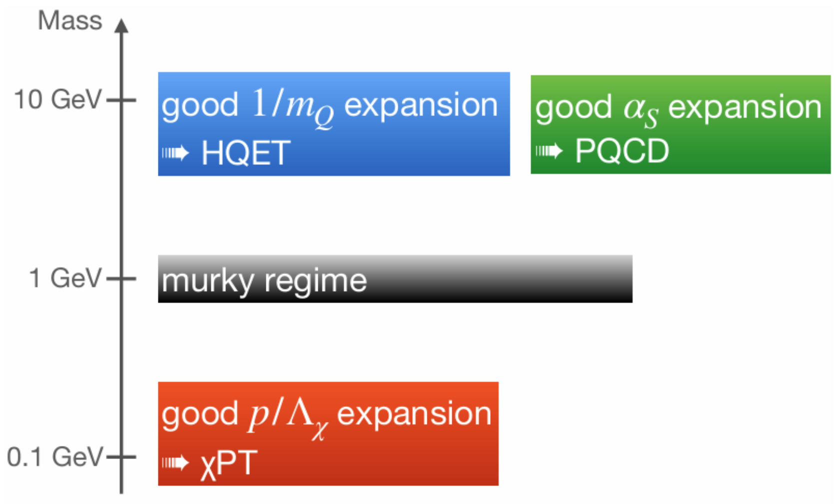
    … …



Experiments: test of SM, search for new physics beyond SM

SM phenomenology: Bridge between SM and experiments

Peculiarities of Charm



- m_c ~1.3 GeV/c^2, neither heavy enough to allow for a sensible heavy quark mass expansion nor light enough for an application of chiral perturbation theory.

- (semi-)leptonic D decays: lattice QCD
- D decay dominantly into hadronic final states

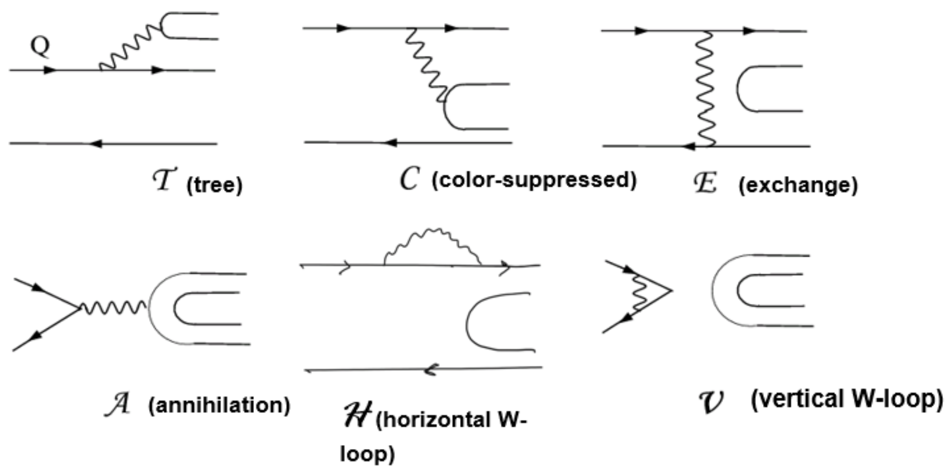
but no D meson hadronic decay theory based on QCD yet….

Mode	BR
PP	$\sim 10\%$
VP	$\sim 28\%$
VV	$\sim 10\%$
SP	$\sim 4.2\%$
AP	$\sim 10\%$
TP	$\sim 0.3\%$
2-body	$\sim 63\%$
hadronic	$\sim 84\%$
semileptonic	$\sim 16\%$

P: pseudoscalar meson
V: vector meson
A: axial vector meson
T: tensor meson

D Meson Decays

- Powerful theoretical models for charm hadronic decays: factorization-assisted topological-amplitude(FAT)approach, flavor or topological diagram approach (TDA)
  - Topological information → Extract from experiments
  - FSIs and non-factorizable contribution
  - Predictions of observable quantities → Test by experiments

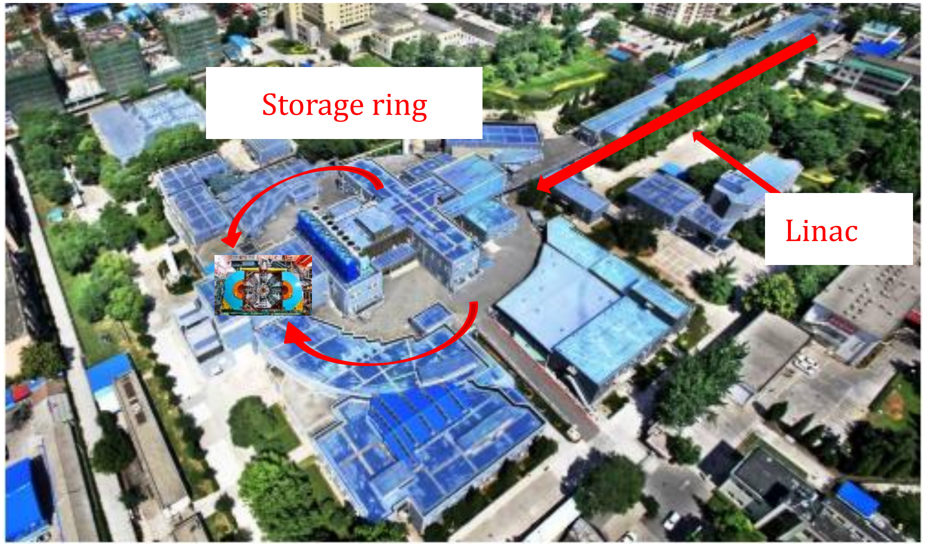


- Precise measurements to test theories and further understanding:
  - Polarization puzzles in $D \to VV$
  - $K_S^0 - K_L^0$ asymmetries in $D \to K^0 M$

  … …

- $D^0\bar{D}^0$samples produces at BESIII
  - 20.3 fb^{-1} @ 3.773 GeV
  - Near DD threshold
  - ~73.4M $D^0\bar{D}^0$ pairs

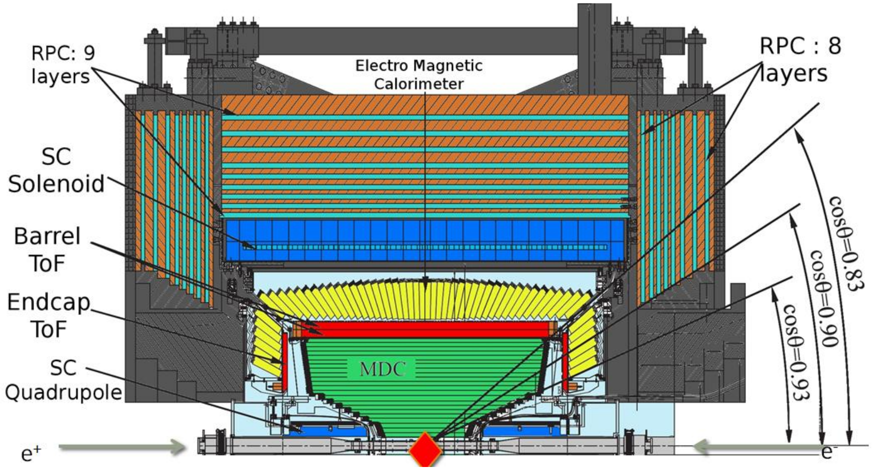
BEPCII and BESIII



Double ring: e^+ and e^-
Cross angle: 22 mrad
E$_{cm}$: $1.84 - 4.95$ GeV
Peak luminosity: $1.1 \times 10^{33}\ \mathrm{cm^{-2}s^{-1}}$ @ $\psi(3770)$

Electromagnetic Calorimeter
CsI(Tl): L = 28 cm
- Barrel $\sigma_E/E = 2.5\%$ @ 1 GeV
- Endcap $\sigma_E/E = 5.0\%$ @ 1 GeV

Muon Counter RPC
Barrel: 9 layers
Endcaps: 8 layers
- $\sigma_{\mathrm{spatial}} = 1.48$ cm



- BESIII Detector

Main Drift Chamber
Small cell, 43 layer
- $\sigma_{xy} = 130\ \mu\mathrm{m}$
- $\mathrm{d}E/\mathrm{d}x \sim 6\%$
- $\sigma_p/p = 0.5\%$ @ 1 GeV/c

Time Of Flight
Plastic scintillator
- $\sigma_T(\mathrm{barrel}) = 68$ ps
- $\sigma_T(\mathrm{endcap}) = 110$ ps

(update to 60 ps with MRPC)

Work I

Partial wave analysis of $D^0 \rightarrow K^+K^-\omega$

Motivation

- **Polarization puzzles in $M \to VV$:**
  - $B \to VV$[1][2]: ($V = \phi, K^*, \rho$ and ω)
    - Tree-dominated: Transverse polarization amplitudes suffer from the helicity-flipping suppression at the order of Λ_{QCD}/m_b. $f_L^{\text{theor.}} \sim 1 - O(\Lambda_{\text{QCD}}/\text{m}_\text{b})$ confrimed by $B^0 \to \rho^+\rho^-, B^+ \to \rho^+\rho^0$; indicated the helicity conservation in $B \to VV$.
    - Penguin-dominated or FSI : $f_L^{B\to\phi K^*} \sim 0.5$.

Comparison of the FAT approach experimental results

Mode	$\mathcal{B}(10^{-6})$	$f_L(\%)$	$f_\perp(\%)$	$\phi_\parallel$ (rad)	$\phi_\perp$ (rad)
$B^- \to \rho^-\rho^0$	21.7 ± 5.1	95.5 ± 1.5	2.22 ± 0.64	-0.09 ± 0.05	-0.09 ± 0.05
Expt.	24.0 ± 1.9	95 ± 1.6			
$\overline{B}_0 \to \rho^+\rho^-$	29.5 ± 6.5	92.6 ± 1.6	3.65 ± 0.91	-0.27 ± 0.08	-0.27 ± 0.08
Expt.	27.7 ± 1.9	$99.0^{+2.1}_{-1.9}$			
$\overline{B}^0 \to \rho^0\rho^0$	0.94 ± 0.49	81.7 ± 10.8	9.21 ± 5.50	-0.04 ± 0.44	-0.03 ± 0.44
Expt.	0.96 ± 0.15	71^{+8}_{-9}			

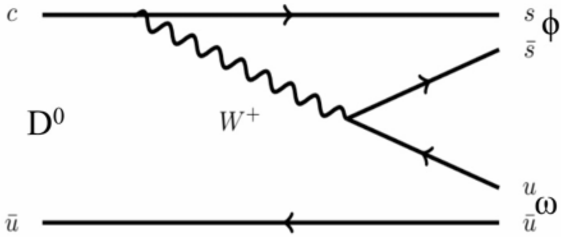
    - consist between experiment measurements and theoretical predictions

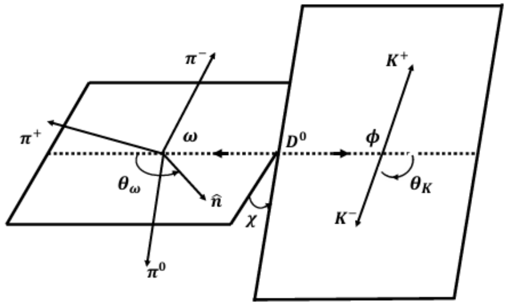
[1] PRL 91,171802(2003), [2] PRL 91,201801(2003)

Motivation

- $D \to VV$:

- Perturbative QCD not valid, naive factorization model [3] and Lorentz invariant-based symmetry model [4] predict f_L not dominant in $D \to VV$ process: $f_L^{\text{theor.}} \sim 0.5^{[3]} 0.33^{[4]}$: $D^0 \to \bar{K}^{*0}\rho^0$.
- $f_L^{D^0 \to \rho^0\rho^0\,[5]} = 0.71 \pm 0.04 \pm 0.02$(FOCUS Collaboration) → [D] wave dominant.
- In $D^0 \to \omega\phi$[6], $f_L = 0.00 \pm 0.10 \pm 0.08$, $f_L^{U.L.} < 0.24$(95% C.L.) are given by fitting to angular distributions(BESIII Collaboration) and shows larger difference from $D^0 \to \rho^0\phi$.





- FSI through $K^{*+}\,K^{*-}$ or flavor-singlet contributions can lead to different, a more precise PWA result can help to confirm the theoretical models.

[3] PRD 59,114013(1999), [4] JHEP 03,042 (2014) , [5] PRD 75,052003(2007), [6] PRL 128,011803(2022).

Motivation

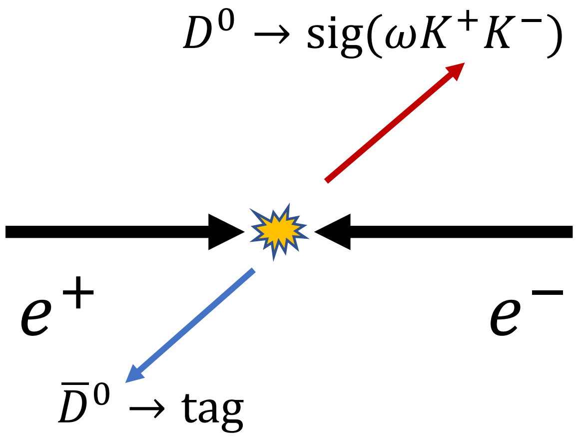
- Still lack of knowledge about some crucial pieces of dynamics in D decay mechanisms. Polarization of $D \to VV$ provide valuable information to further understand D decays and non-perturbative QCD. Longitudinal polarization fraction(f_L) is important to test models.

- 20 fb^{-1} e^+e^- annihilation data @ 3.773 GeV.
  - Larger $D^0\bar{D}^0$samples → more precise results
  - Double-tag method → lower background level
  - Extract the S,P,D amplitudes of $D^0 \to \omega\phi$

- Other resonant on invariant mass structures

Dataset

- Quantum correlated $D^0\bar{D}^0$ produced at BESIII
  - Data:20.3 fb^{-1} @ $E_{cm}=3.773$ GeV
  - Inclusive MC: 40× for background study
  - Signal PHSP MC: 100× for amplitude analysis
  - Signal DIY MC: 200× for amplitude analysis



- Double tag method
  - Reconstruct both of $D^0\bar{D}^0$
  - Tag mode: $\bar{D}^0 \to K^+\pi^-, K^+\pi^-\pi^0, K^+\pi^+\pi^-\pi^-$(~25% of D^0 decay)

Event Selection - Preliminary Selection

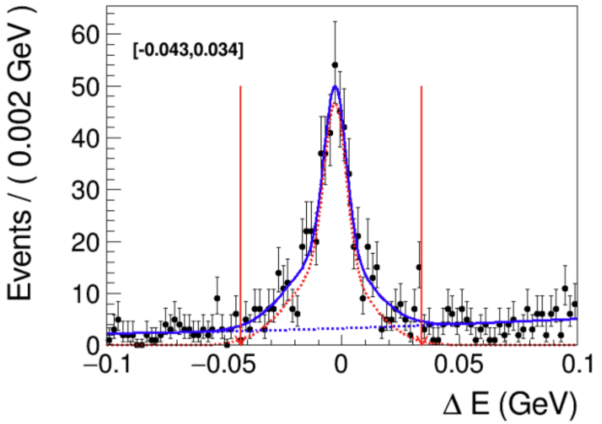
- **Good charged tracks:**
  - |Rxy| ≤ 1 cm, |Rz| ≤ 10 cm, $|\cos\theta| \leq 0.93$
- **Good Photons :**
  - Barrel: E > 25 MeV, $|cos\theta| \leq 0.8$
  - Endcap: E > 50 MeV, $0.86 \leq |cos\theta| \leq 0.92$
  - EMC time cut: 0 ≤ T ≤ 14 (50ns)
  - Angle between shower and charged tracks larger than 10°
- **PID(SimplePID package):**
  - π: Prob(π) > Prob(K)
  - K: Prob(K) > Prob(π)

- **π^0 Candidates:**
  - $0.115 < M_{\gamma\gamma} < 0.150$ GeV$/c^2$, $\chi^2_{1c} < 50$
- **Cosmic rays rejection for $\bar{D}^0 \to K^+\pi^-$**
  - **Tag D Reconstruction:**
  - $\Delta E = E_D - E_{Beam}$, $M_{BC} = \sqrt{\left(E_{Beam}{}^2 - p_D^2\right)}$;
  - Minimum |ΔE| is used to selected best candidate
- **Ks veto for $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$ tag mode:**
  - $|M_{\pi^+\pi^-} - 0.4976| > 0.03$ GeV$/c^2$.
- **The ST requirement follow the official document (MEMO_D_ST_v4.0.pdf (ihep.ac.cn))**

Event Selection - Further Selection

Case 1(Full Reconstruction)

- π^0 candidate: Minimum |ΔE| to selected best candidate
- $1C(M_{D^0}^{PDG})$ kinematic fit performed



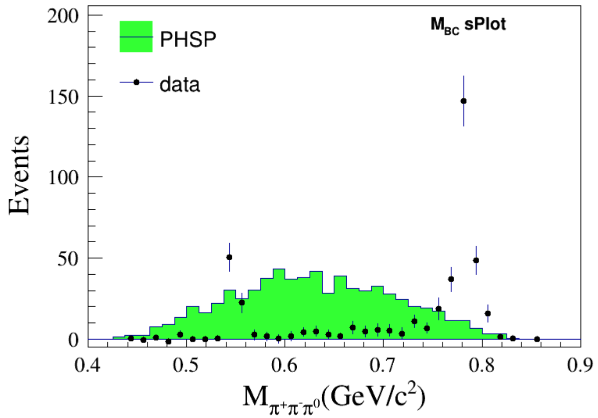
- ΔE requirement: (-0.043, 0.035) GeV

Case 2(Miss one Kaon)

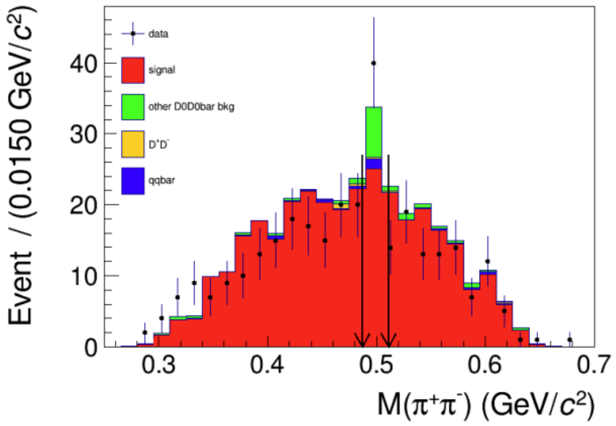
- π^0 candidate: Minimum χ^2_{1c} to selected best candidate
- M_{BC}^{tag} requirement: (1.859, 1.873) GeV/c^2
- Rrecoiled D^0:
  $\vec{P}_{D^0}$ direction is opposite to ST $\vec{P}_{\bar{D}^0}$

$$|\vec{P}_{D^0}|=\sqrt{(E_{beam}{}^2 - M_{D^0}^2)},\ E_{D^0} = E_{beam}$$

- $4C(\vec{P}_{D^0}, E_{D^0})$ kinematic fit performed
- $M_{D^0} - M_{found} > 0$



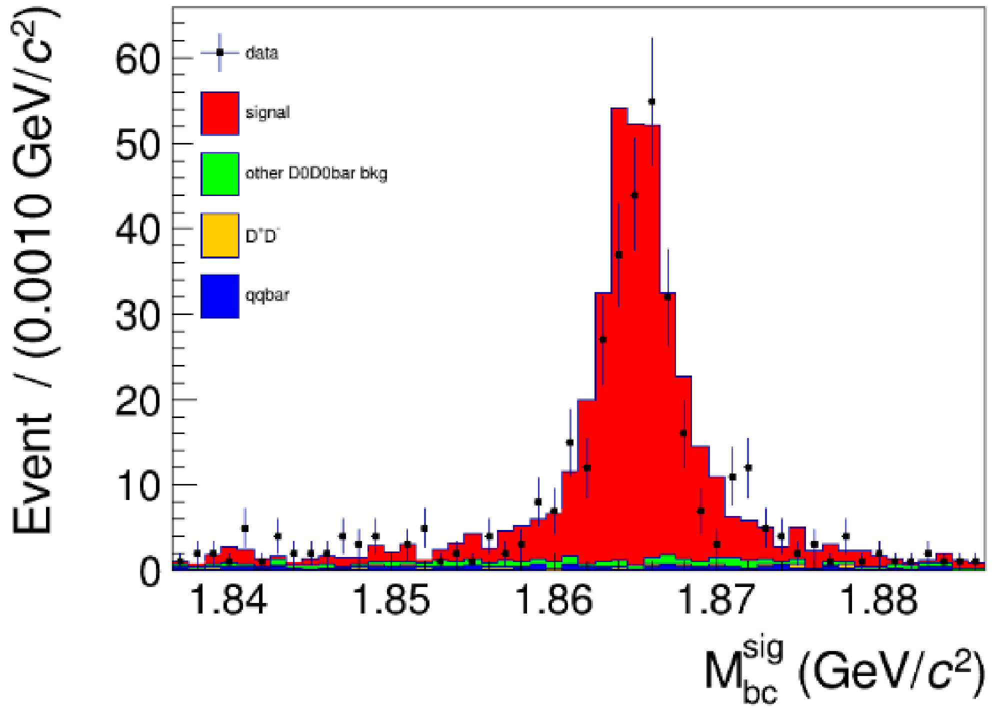
- $M_{\pi^+\pi^-\pi^0} > 0.69\ \mathrm{GeV}/c^2$



- Reject $M_{\pi^+\pi^-} \in (0.487, 0.511)\ \mathrm{GeV}/c^2$

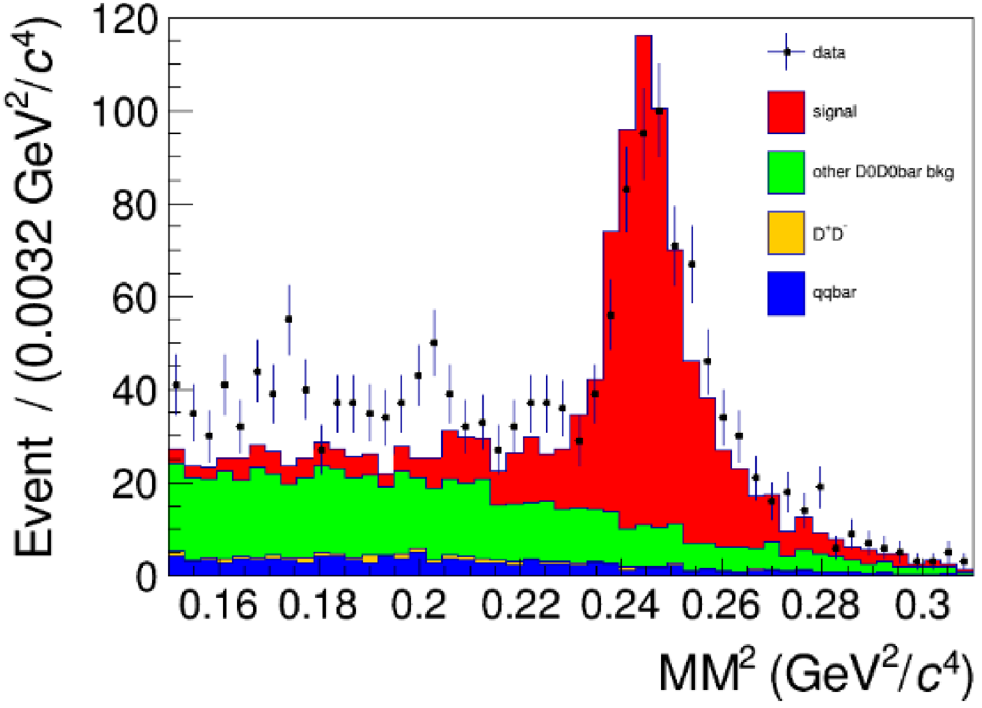
Background Analysis

Case 1(Full Reconstruction)



- Signal region: (1.859,1.873); purity~90%
- Extract signal from M_{BC}.

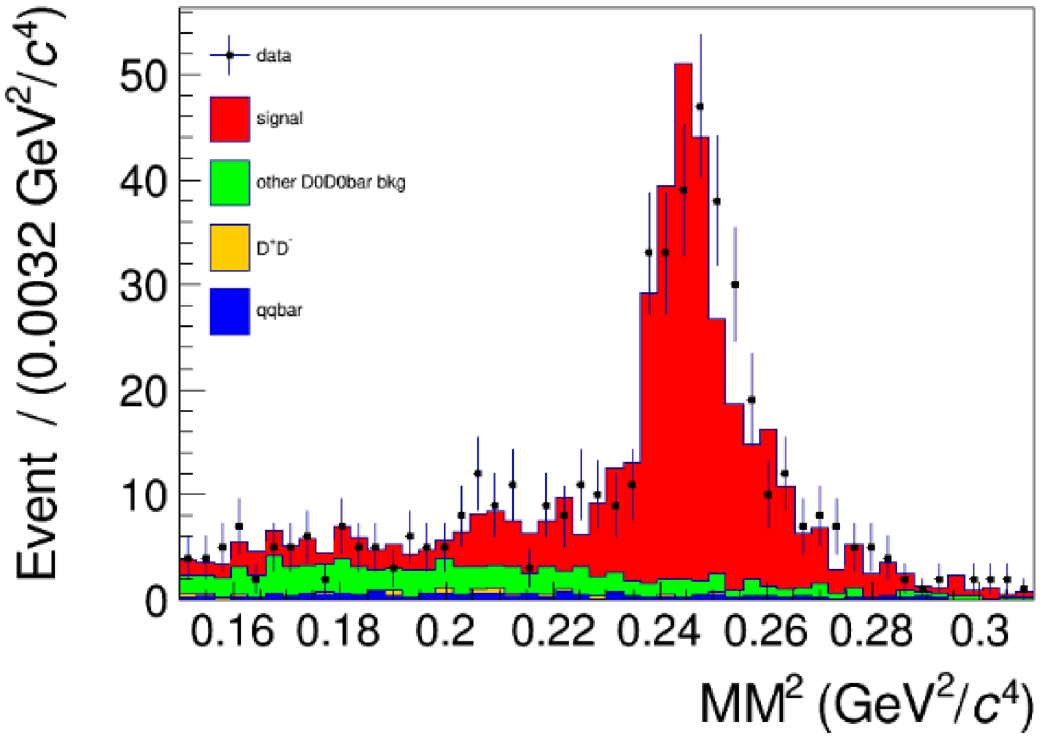
Case 2(Miss one Kaon)



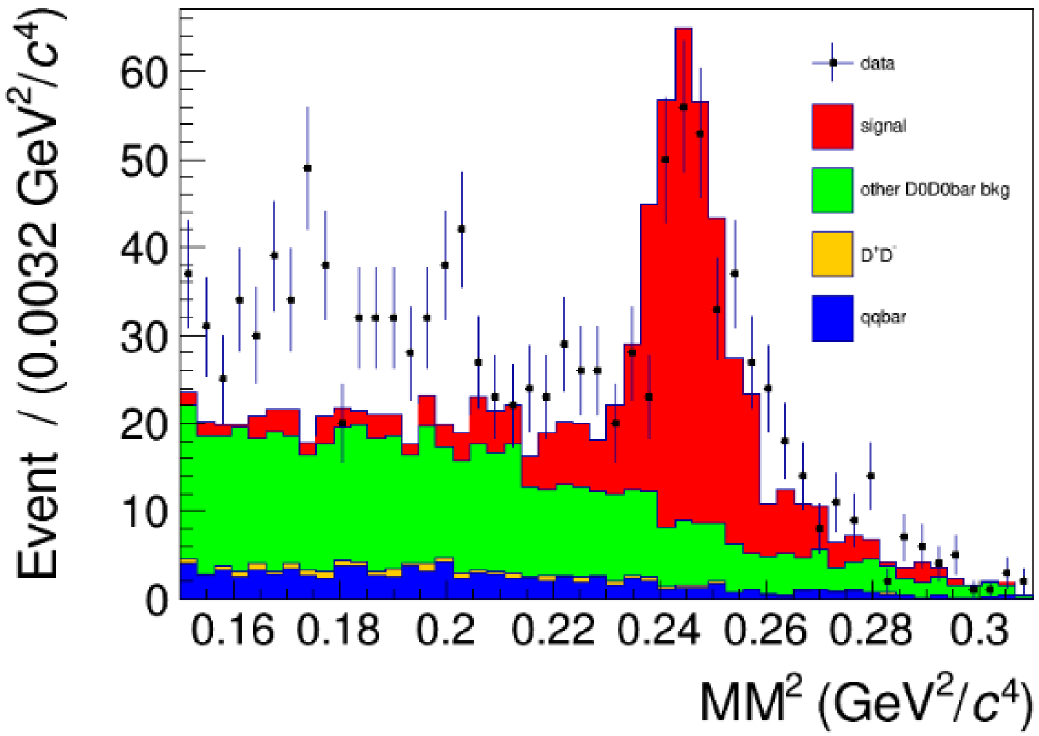
- Signal region: (0.215,0.275); purity~50%
- Extract signal from M_{miss}^2.

Background Analysis

Case 2_A(Miss one Kaon)



Case 2_B(Miss one Kaon)



- Charge of founded $K(C^{sig}_{\text{found }K})$ = charge of tag side K (C_K^{tag})
- Signal region: (0.215,0.275); purity~80%

- Charge of founded $K(C^{sig}_{\text{found }K}) \neq$ charge of tag side K (C_K^{tag})
- Signal region: (0.215,0.275); purity~40%

Introduction of PWA

Likelihood Formula:

- $\ln\mathcal{L} = \sum_{i=1}^{3}\sum_{k}^{N_{Data,i}} \ln[\omega_{sig}^{i} f_s(p_j^k) + (1-\omega_{sig}^{i}) f_B^i(p_j^k)]$
  - f_s:signal p.d.f
  - ω_{sig}: fraction of signal(signal purity)
  - p_j: four-momenta of daughter particles
  - f_B:background p.d.f

Signal PDF:

MC integral

- $f_s(p) = \frac{\boxed{\epsilon_s(p)|A_D(p)|^2 R_3(p)}}{\int \epsilon_s(p)|A_D(p)|^2 R_3(p)dp}$
  - $\epsilon_s(p)$:signal efficiency
  - $R_3(p)$:phase space factor

Amplitude Construction:

- Constructed by covariant tensor method

$$A_{D^0}(p) = \sum_i \Lambda_i U_i(p)$$

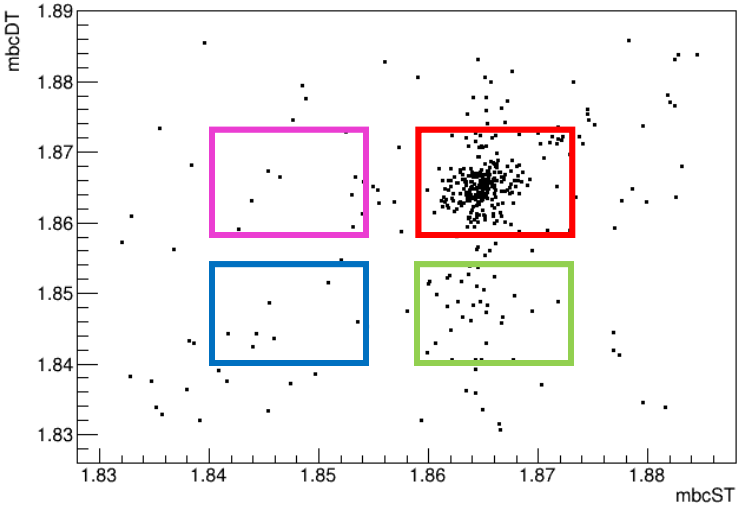
  - Λ_i: coupling factor

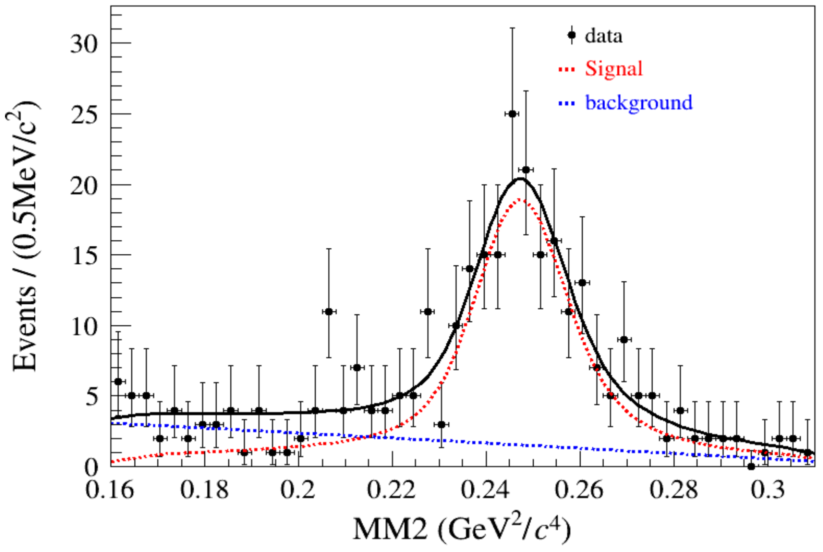
- $U_i(p) = B_{L_D}(p)P_{R_1}(p)B_{L_{R_1}}(p)P_{R_2}(p)B_{L_{R_2}}(p)S_i(p)$
  - B_L : Blatte-Weisskopf barrier factor
  - P_R : Propagator of resonance R
  - S_i : Spin factor of i-th decay amplitude

- $A_{\bar{D}^0}(p) = \sum_i \Lambda_i \bar{U}_i(p) = \sum_i \Lambda_i U_i(\bar{p})$
  - $\bar{p}$: CP-conjugate of phase space point p

Background Estimation

- **BKG Consistency** between Data and Inclusive MC in side-bands. And consistency of inclusive MC(without signal process) in signal region and side-bands is obtained.





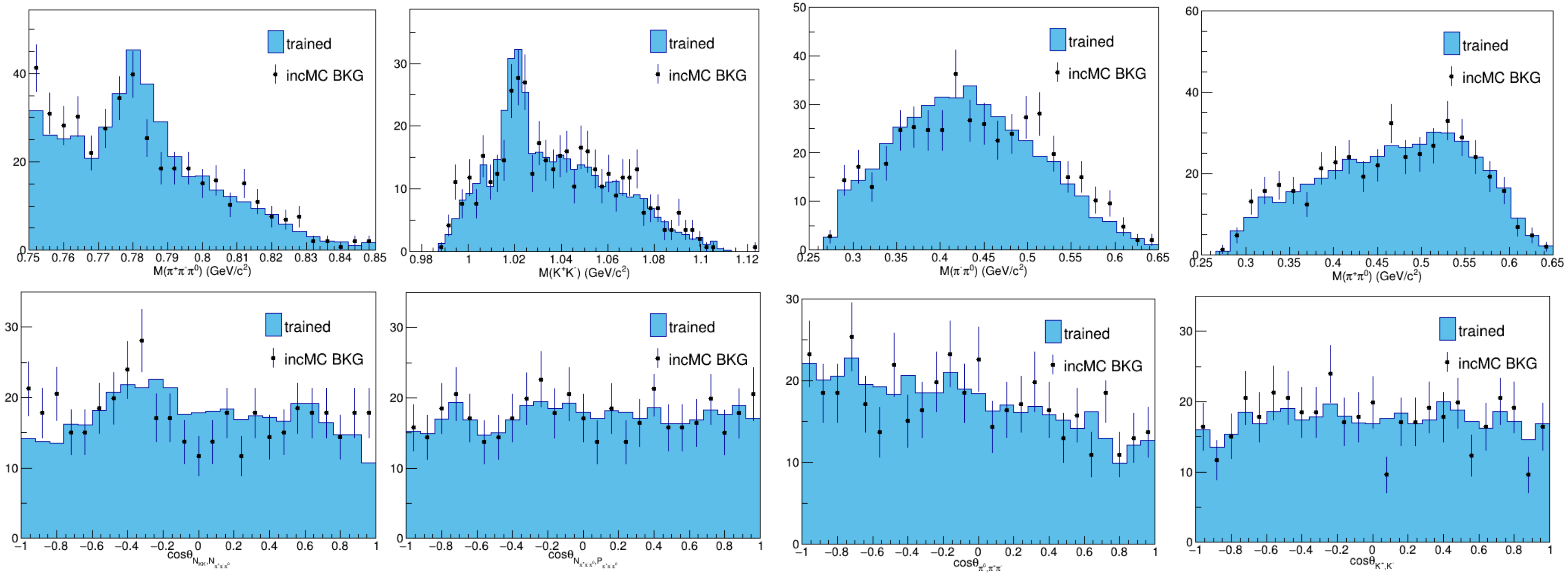
- **By Mixed-sample Method:**
  - $M_{K^+K^-}, M_{\pi^+\pi^-\pi^0}, M_{\pi^+\pi^0}, M_{\pi^-\pi^0},$
    $\theta_{N_{KK},N_{\pi^+\pi^-\pi^0}}, \theta_{N_{\pi^+\pi^-\pi^0},P_{\pi^+\pi^-\pi^0}}, \theta_{P_{\pi^0},P_{\pi^+\pi^-}}, \theta_{P_{K^+},P_{K^-}}$

χ of Data & IncMC	Full reconstruction	Miss one K
$\bar{D}^0 \to K^+\pi^-$	-	0.84
$\bar{D}^0 \to K^+\pi^-\pi^0$	0.67	-0.33
$\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$	1.93	-0.83

Background Estimation

- p.d.f of background $f_B(p)$ is described with Inclusive MC, by performing Machine Learning on DIY MC.

- Eight Variables used :
  - $M_{K^+K^-}, M_{\pi^+\pi^-\pi^0}, M_{\pi^+\pi^0}, M_{\pi^-\pi^0}, \theta_{N_{KK},N_{\pi^+\pi^-\pi^0}}, \theta_{N_{\pi^+\pi^-\pi^0},P_{\pi^+\pi^-\pi^0}}, \theta_{P_{\pi^0},P_{\pi^+\pi^-}}, \theta_{P_{K^+},P_{K^-}}$



Signal Purity

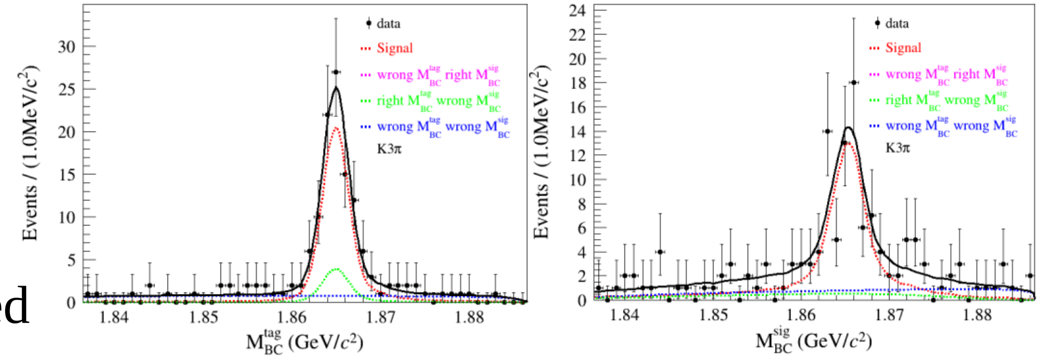
- **Signal**: right tag and right signal D^0, described by DIY MC shape.

- **BKGI**: background with right tag and wrong signal, described by $A_{x1}(x1;\ m_{x1}, z_{x1}, \rho_{x1}) \times S_{x2}$.

- **BKGII**: background with wrong tag and right signal, described by $A_{x2}(x2;\ m_{x2}, z_{x2}, \rho_{x2}) \times S_{x1}$

- **BKGIII**: background in diagonal region. $T(x_1 - x_2; \mu, \sigma(x_1 + x_2), n) \times A_{x1}(x1;\ m_{x1}, z'_{x1}, \rho'_{x1}) \times A_{x2}(x2;\ m_{x2}, z'_{x2}, \rho'_{x2})$

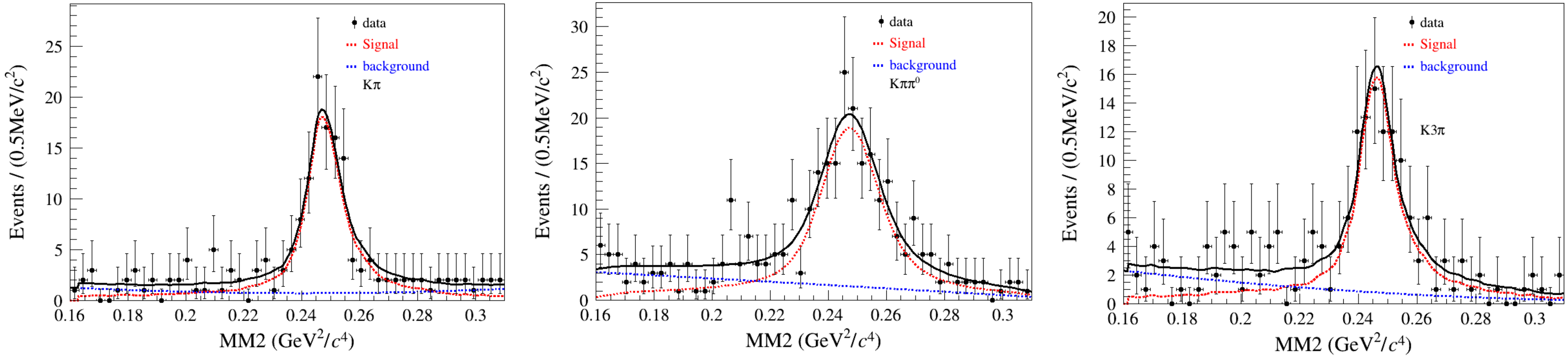
$$T(y; \mu, \sigma, n) = \frac{\Gamma(n/2+0.5)}{\sigma\sqrt{n\pi}\Gamma(n/2)}\left[1 + \frac{1}{2}\left(\frac{y-\mu}{\sigma}\right)^2\right]^{-\frac{n+1}{2}}$$



Tag Mode	N^{sig} (signal region)	Purity(%)
$K^+\pi^-$	93.5 ± 9.6	99.9 ± 0.0
$K^+\pi^-\pi^0$	154.0 ± 14.2	92.0 ± 6.4
$K^+\pi^-\pi^+\pi^-$	70.8 ± 8.4	85.4 ± 10.6

Signal Purity

- **Signal**: DIY MC shape $S \otimes$ Gauss function G .
- **Background**: continuum background, described by $2nd$ −order Chebyshev polynomials.



Tag Mode	$K^+\pi^-$	$K^+\pi^-\pi^0$	$K^+\pi^-\pi^+\pi^-$
N^{sig}(signal region)	114.7 ± 14.0	181.3 ± 26.2	104.9 ± 14.8
Purity(%)	88.3 ± 5.4	85.2 ± 6.6	87.2 ± 5.8

Amplitude Construction

- Spin factor of $\omega \to \pi^+\pi^-\pi^0$:

$$A_\mu(\omega) = \varepsilon_{\mu\nu\rho\sigma} p_\omega^\sigma [t^\rho(\pi^+\pi^0,\pi^-) t^\nu(\pi^+\pi^0) - t^\rho(\pi^+\pi^-,\pi^0) t^\nu(\pi^+\pi^-) + t^\rho(\pi^0\pi^-,\pi^+) t^\nu(\pi^0\pi^-)]$$

$D \to S\omega, S \to P_1P_2$	$t^\mu(D)A_\mu(\omega)$
$D[S] \to V\omega, V \to P_1P_2$	$P^{\mu\nu}(D)t_\mu(V)A_\nu(\omega)$
$D[P] \to V\omega, V \to P_1P_2$	$\varepsilon_{\mu\nu\rho\sigma}p_D^\sigma t^\rho(D)t_\mu(V)A_\nu(\omega)$
$D[D] \to V\omega, V \to P_1P_2$	$t_{\mu\nu}(D)t^\mu(V)A^\nu(\omega)$
$D[P] \to T\omega, T \to P_1P_2$	$P^{\mu\nu\rho\sigma}(D)t_{\mu\nu}(T)t_\rho(D)A_\nu(\omega)$
$D[D] \to T\omega, T \to P_1P_2$	$\varepsilon_{\mu\nu\rho\sigma}p_D^\sigma t^{\rho\alpha}(D)t_\alpha^\nu(T)A^\mu(\omega)$
$D[F] \to T\omega, T \to P_1P_2$	$t_{\mu\nu\rho}(D)t^{\mu\nu}(T)A^\rho(\omega)$
$D \to PP_1, P[P] \to \omega P_2$	$t^\mu(P)A_\mu(\omega)$
$D \to AP_1, A[S] \to \omega P_2$	$t^\mu(D)P_{\mu\nu}(A)A^\nu(\omega)$
$D \to AP_1, A[D] \to \omega P_2$	$t^\mu(D)t_{\mu\nu}(A)A^\nu(\omega)$
$D \to VP_1, V[P] \to \omega P_2$	$t^\mu(D)\varepsilon_{\mu\nu\rho\sigma}p_V^\sigma t^\nu(V)A^\nu(\omega)$
$D \to PT\ P_1, PT[P] \to \omega P_2$	$t^{\mu\nu}(D)P_{\mu\nu\rho\sigma}(PT)t^\rho(PT)A^\sigma(\omega)$
$D \to PT\ P_1, PT[F] \to \omega P_2$	$t^{\mu\nu}(D)t_{\mu\nu\rho}(PT)A^\rho(\omega)$
$D \to TP_1, T[D] \to \omega P_2$	$t^{\mu\alpha}(D)\varepsilon_{\mu\nu\rho\sigma}p_T^\sigma t_\alpha^\rho(T)A^\nu(\omega)$

- **Spin projection operator**

$$P^{(0)}(p_a) = 1\,,$$

$$P^{(1)}_{\mu\mu'}(p_a) = -g_{\mu\mu'} + \frac{p_{a\mu}p_{a\mu'}}{p_a^2}\,,$$

$$P^{(2)}_{\mu\nu\mu'\nu'}(p_a) = \frac{1}{2}[P^{(1)}_{\mu\mu'}(p_a)P^{(1)}_{\nu\nu'}(p_a) + P^{(1)}_{\mu\nu'}(p_a)P^{(1)}_{\nu\mu'}(p_a)] - \frac{1}{3}P^{(1)}_{\mu\nu}(p_a)P^{(1)}_{\mu'\nu'}(p_a)\,.$$

- **Blatt-Weisskopf barrier factor**

$$B_0(q) = 1$$

$$B_1(q) = \sqrt{\frac{2}{q^2 + q_0^2}}$$

$$B_2(q) = \sqrt{\frac{13}{q^4 + 3q^2q_0^2 + 9q_0^4}}$$

q: breakup momentum
$q_0 = 0.197321/R\ GeV/c$
$R = 5 * 0.197321 \approx 1\ fm$ for D0
$R = 3 * 0.197321 \approx 0.6\ fm$ for other resonance

- **Propagator**

Gounaris-Sakurai(GS) formula: $\rho(770)$

Relative Breit-Wigner(RBW): $f_2(1270)$

RBW with constant width $\Gamma(s)$: Other resonances

QC Correction

- Neglect $D^0 - \overline{D}^0$ mixing and CPV, the decay rates:

$$\frac{\mathrm{d}\Gamma(f;g)}{\mathrm{d}\Phi} \propto |A_{f\bar{g}}|^2 = |A_f\bar{A}_g - \bar{A}_f A_g|^2$$

- g Tag mode, f Signal mode, the decay rate of signal $D \to f$:

$$\frac{\mathrm{d}\Gamma(D^0 \to f)}{\mathrm{d}\Phi_f} \propto |A_f|^2 \int |\bar{A}_g|^2 \mathrm{d}\Phi_g + |\bar{A}_f|^2 \int |A_g|^2 \mathrm{d}\Phi_g - A_f\bar{A}_f^* \int \bar{A}_g A_g^* \mathrm{d}\Phi_g - A_f^*\bar{A}_f \int \bar{A}_g^* A_g \mathrm{d}\Phi_g$$

[1] Eur. Phys. J. C 81, no.3, 226 (2021)
[2] JHEP 05, 164 (2021)

- Decay rate of $D \to f$ can be rewritten:

$$r_g^2 = \frac{\int |\bar{A}_g|^2 \mathrm{d}\Phi_g}{\int |A_g|^2 \mathrm{d}\Phi_g}, \qquad R_g e^{-i\delta_g} = \frac{\int A_g^* \bar{A}_g \mathrm{d}\Phi_g}{\sqrt{\int |A_g|^2 \mathrm{d}\Phi_g \int |\bar{A}_g|^2 \mathrm{d}\Phi_g}}$$

$$\frac{\mathrm{d}\Gamma(D^0 \to f)}{\mathrm{d}\Phi_f} \propto |A_f|^2 + r_{\bar{g}}^2|\bar{A}_f|^2 - r_{\bar{g}}R_{\bar{g}}e^{i\delta_{\bar{g}}}A_f\bar{A}_f^* - r_{\bar{g}}R_{\bar{g}}e^{-i\delta_{\bar{g}}}A_f^*\bar{A}_f$$
$$= \boxed{|A_f - r_{\bar{g}}R_{\bar{g}}e^{-i\delta_{\bar{g}}}\bar{A}_f|^2 + r_{\bar{g}}^2(1 - R_{\bar{g}}^2)|\bar{A}_f|^2}.$$

Mode	$r(\%)$	R	$\delta(^\circ)$
$K^-\pi^+$	5.86 ± 0.02[1]	1	$192.1^{+8.6}_{-10.2}$[1]
$K^-\pi^+\pi^0$	4.41 ± 0.11[2]	0.79 ± 0.04[2]	$196 \pm +11$[2]
$K^-\pi^+\pi^-\pi^+$	5.50 ± 0.07[2]	$0.44^{+0.09}_{-0.10}$[2]	161^{+28}_{-18}[2]

Fitting Results

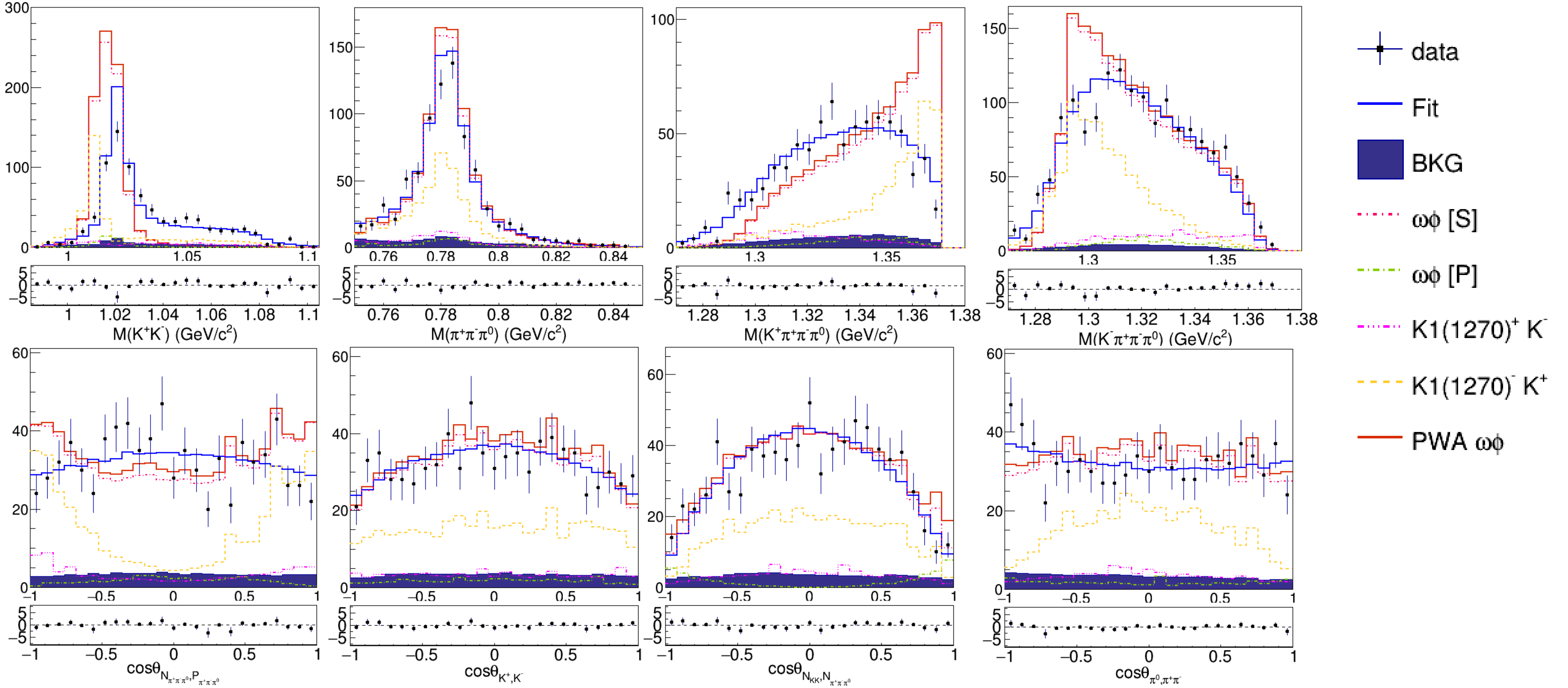
J^{PC}	K^+K^- resonance
0^{++}	$a_0(980), f_0(980), f_0(1370), KK$
1^{--}	$\phi(1020), \rho(1450), KK$
2^{++}	$f_2(1270)$

J^P	$K\omega$ resonance
0^-	$K(1460)$
1^+	$K_1(1270), K_1(1400), K_1(1650)$
1^-	$Kst(1410)$
2^-	$K_2(1580)$
2^+	$Kst(1430)$

Amplitude	significance
$\omega\phi[S]$	$> 10\sigma$
$\omega\phi[P]$	3.5σ
$\omega\phi[D]$	2.0σ
$K_1(1270)^+K^-[S]$	5.1σ
$K_1(1270)^-K^+[S]$	8.1σ

Resonance	FF(%)	mag	phase
$\omega\phi[S]$	85.35	1	0
$\omega\phi[P]$	2.11	0.052	0.022
$K_1(1270)^+K^-[S]$	3.70	0.999	-1.602
$K_1(1270)^-K^+[S]$	10.69	1.978	1.286

Fitting Results



Polarization of $D \to VV$

- For $D \to VV$ decay modes, these decays have a richer structure, as they have three partial-wave or helicity states.
- The polarized decay amplitudes can be expressed in several different but equivalent bases **helicity basis**(H_0, H_+, H_-), **transverse basis(**$\boldsymbol{A_0, A_\perp, A_\parallel}$**)** and can be related to the partial wave amplitudes$[S]$,$[P]$,$[D]$.

$$A_0 = H_0 = -\frac{1}{\sqrt{3}} S + \sqrt{\frac{2}{3}} D \ ,$$

$$A_\parallel = \frac{1}{\sqrt{2}}(H_+ + H_-) = \sqrt{\frac{2}{3}} S + \frac{1}{\sqrt{3}} D$$

$$A_\perp = \frac{1}{\sqrt{2}}(H_+ - H_-) = P \ ,$$

$$S = \frac{1}{\sqrt{3}}(-A_0 + \sqrt{2} A_\parallel) = \frac{1}{\sqrt{3}}(-H_0 + H_+ + H_-)$$

$$P = A_\perp = \frac{1}{\sqrt{2}}(H_+ - H_-),$$

$$D = \frac{1}{\sqrt{3}}(\sqrt{2} A_0 + A_\parallel) = \frac{1}{\sqrt{6}}(2H_0 + H_+ + H_-),$$

Polarization of $D^0 \to \omega\phi$

- $H_{\pm} = \sqrt{\frac{1}{3}}g_{00} \pm \sqrt{\frac{1}{2}}Wrg_{11} + \sqrt{\frac{1}{6}}r^2 g_{22}, F_0 = \gamma_1\gamma_2(-\sqrt{\frac{1}{3}}g_{00} + \sqrt{\frac{2}{3}}r^2 g_{22})$

Longitudinal polarization fraction: $f_L = \frac{|H_0|^2}{|H_+ + H_0 + H_-|^2}$ $\qquad r = 2|q|$

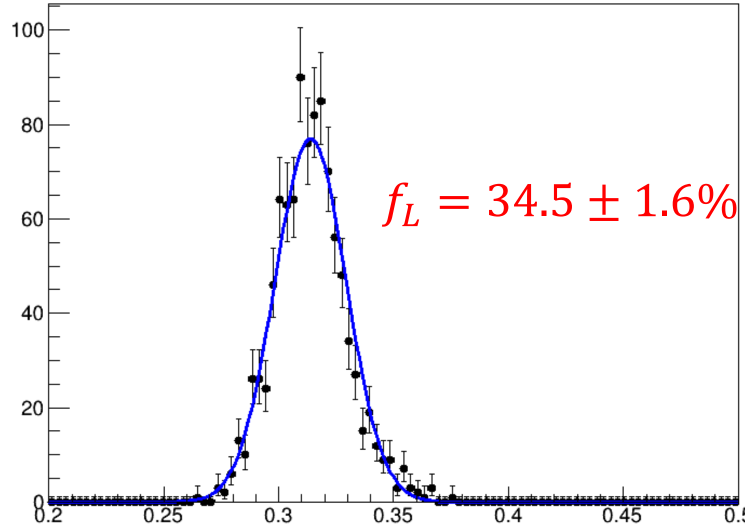
$|q|$: momentum of V in D rest frame $\qquad \gamma$: Lorentz factor of V in D rest frame $\qquad W$:mass of D

The LS coupling parameters α_i in **covariant tensor** formula can be used by **covariant helicity** formula.

Covariant tensor: $\Sigma_{\sigma_1\sigma_2}|\alpha_0 A(0,0) + \alpha_1 A(1,1) + \alpha_2 A(2,2)|^2$

Covariant helicity : $g_{ii} = f_i\alpha_i \ \rightarrow H_{\pm} = \sqrt{\frac{1}{3}}f_0\alpha_0 \pm \sqrt{\frac{1}{2}}Wrf_1\alpha_1 + \sqrt{\frac{1}{6}}r^2 f_2\alpha_2,$

$$H_0 = \gamma_1\gamma_2(-\sqrt{\frac{1}{3}}f_0\alpha_0 + \sqrt{\frac{2}{3}}r^2 f_2\alpha_2)$$



$f_L = 34.5 \pm 1.6\%$

Summary and next to do

- Summary:
  - ✓ Event Selection and Background estimation
  - ✓ Simultaneous Fit with DIY MC
  - ✓ Calculation of f_L based on PWA result

- Next to do:
  - ➢ Iteration of DIY MC
  - ➢ Finish IO check
  - ➢ Study of systematic uncertainty

Work II

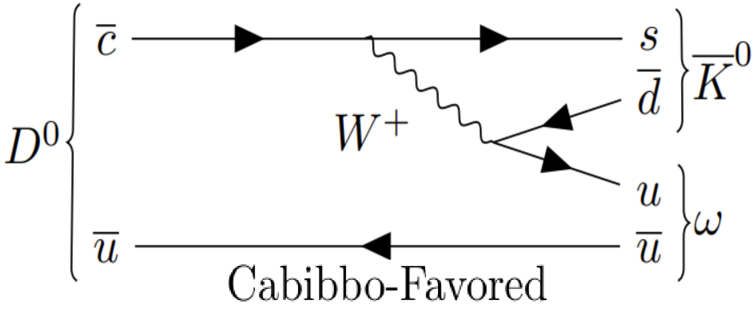
Study of $K_S^0 - K_L^0$ asymmetry in the decays $D^0 \to \omega K_S^0$ and $D^0 \to \omega K_L^0$

Motivation

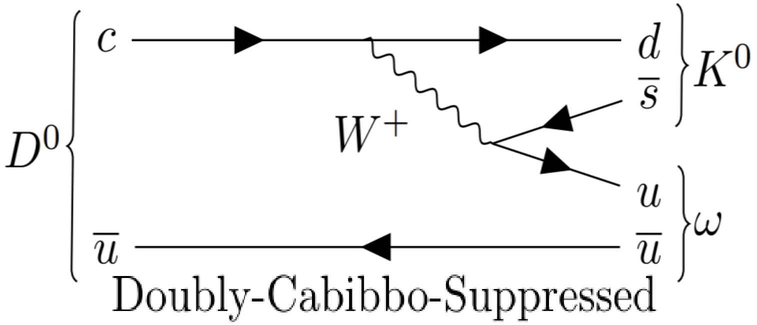
□ The (quasi-)two-body D meson decays are important for understanding D decay mechanism, according to Glashow-Iliopoulos-Maiani (GIM): $V_{cd}^{*}V_{ud} + V_{cs}^{*}V_{us} + V_{cb}^{*}V_{ub} = 0 \nRightarrow$ CPV in D decays.

PLB 349,363366(1995)

- For the processes that involving a neutral K meson, Bigi and Yamamoto pointed out that interference between CF and DCS amplitudes in $D \to K^0 M$ can lead to experimentally observable $K_S^0 - K_L^0$ asymmetries .



Cabibbo-Favored



Doubly-Cabibbo-Suppressed

- CPV associated with those interference between CF and DCS amplitudes is studied to be $\sim 10^{-3}$.

PRL 119.181802(2017)

- Measurement of $K_S^0 - K_L^0$ asymmetry $R(D^0) = \frac{\mathcal{B}(D^0 \to K_S^0 X) - \mathcal{B}(D^0 \to K_L^0 X)}{\mathcal{B}(D^0 \to K_S^0 X) + \mathcal{B}(D^0 \to K_L^0 X)} \simeq 2r_f cos\delta_f$, can enable us to determine the amplitude of DCS processes and promote study of CPV.

Motivation

- Compare of $R(D^0;X)$ from theories and experiments
  - Different theoretical predictions (FAT, TDA…) of $R(D^0;X)$ show good consist with $D \to PP$ process but differ from $D \to VP$ process.
  - $R(D^0;\omega)$ is calculated with $\mathcal{B}(D^0 \to K_L^0\omega)$ measured by BESIII using 2.93 fb^{-1} data and $\mathcal{B}(D^0 \to K_S^0\omega)$ from CLEO, the result shows large difference from FAT and TDA predictions.
  - Measurement of $\mathcal{B}(D^0 \to K_S^0\omega)$ and $\mathcal{B}(D^0 \to K_L^0\omega)$ using a larger data sample can provide more precise results and provide important test of theoretical models.

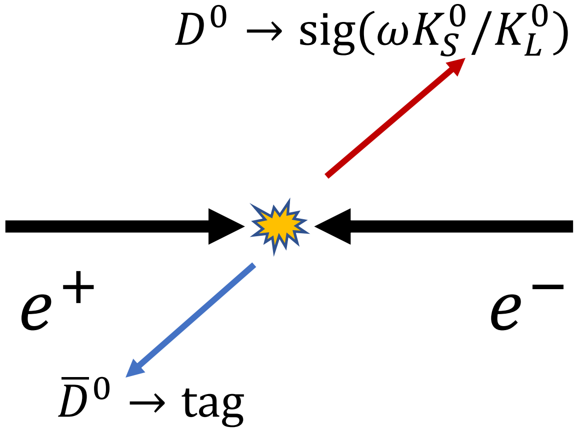
	$D \to PP$		$D \to VP$	
$X = \pi^0, \eta, \eta', \phi, \omega$	π^0	η/η'	ϕ	ω
$R(D^0;X)_{\mathrm{FAT}}^{[1]}(\%)$	11.3 ± 0.1			
$R(D^0;X)_{\mathrm{F4}}^{[2]}(\%)$	10.7		10.1 ± 2.9	10.6 ± 3.4
$R(D^0;X)_{\mathrm{F1'}}^{[2]}(\%)$	10.7		4.1 ± 2.9	8.9 ± 3.5
$R(D^0;X)_{exp.}(\%)$	10.8 ± 3.5[3]	8 ± 2.3[4]	-0.1 ± 4.7[4]	-2.4 ± 3.1[4]

Large difference between theory predictions and experiment measurement

[1] PRD 95,073007(2017), [2] PRD 109,073008(2024), [3] PRL 100,091801(2008), [4] PRD 105,092010(2022).

Analysis Strategy

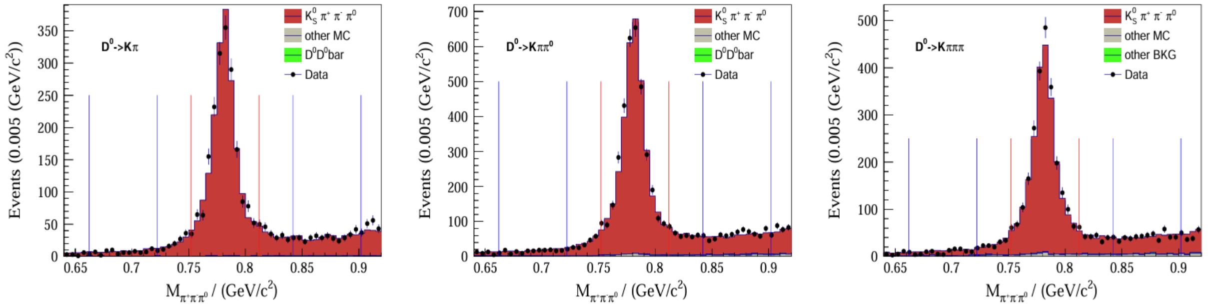
- Data set: 7.93 fb^{-1} at 3.773 GeV:
  - High precise measure of $\omega K_S^0/K_L^0$.
  - Cancel part systematic uncertainties.



- Double Tag Method: $D^0\bar{D}^0$ pair production.
  - $\bar{D}^0$ reconstructed by tag mode i. (ST)
  - D^0 reconstructed by sig mode $\mathrm{f}(\omega K_S^0/K_L^0)$. (DT)
  - $\mathcal{B}_{\mathrm{f}}^{\mathrm{i}} = \dfrac{\mathrm{N}_{\mathrm{DT}}^{\mathrm{i}}\cdot\epsilon_{\mathrm{tag}}^{\mathrm{i}}}{\mathrm{N}_{\mathrm{ST}}^{\mathrm{i}}\cdot\epsilon_{\mathrm{tag,sig}}^{\mathrm{i}}\cdot[1-\frac{2\mathrm{r_i R_i}\cos\delta^{\mathrm{i}}}{1+\mathrm{r_f^2}}(2\mathrm{F_+^f}-1)]}$; $f_{\mathrm{QC}}^{\mathrm{f}} = \dfrac{1}{1-\frac{2\mathrm{r_i R_i}\cos\delta^{\mathrm{i}}}{1+\mathrm{r_i^2}}(2\mathrm{F_+^f}-1)}$.
  - Tag mode: $\bar{D}^0 \to K^+\pi^-$, $\bar{D}^0 \to K^+\pi^-\pi^0$, $\bar{D}^0 \to K^+\pi^-\pi^+\pi^-$.

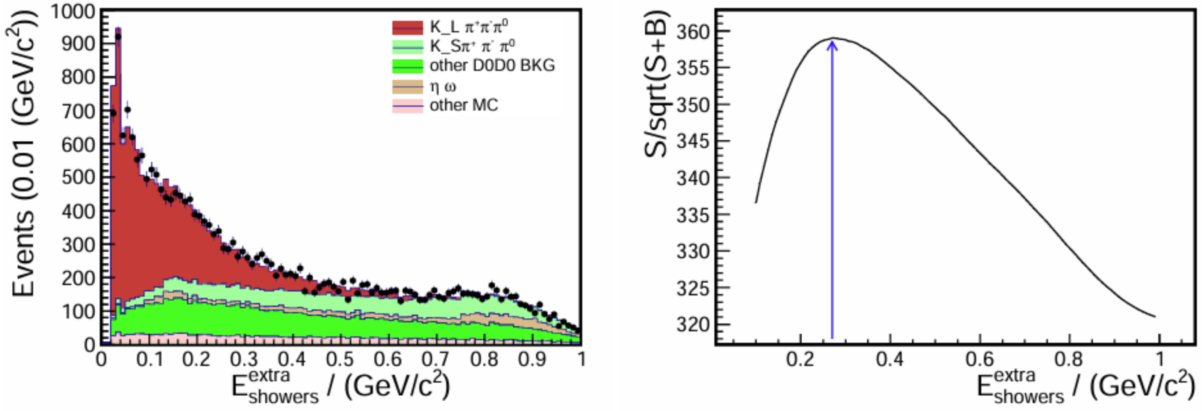
Background Analysis

- $D^0 \to \omega K_S^0$
  - Low background level



  - Peaking backgrounds non-ω resonance $K_S^0\pi^+\pi^-\pi^0$ processes
  - Peaking backgrounds: wrong reconstruction of a soft γ of π^0

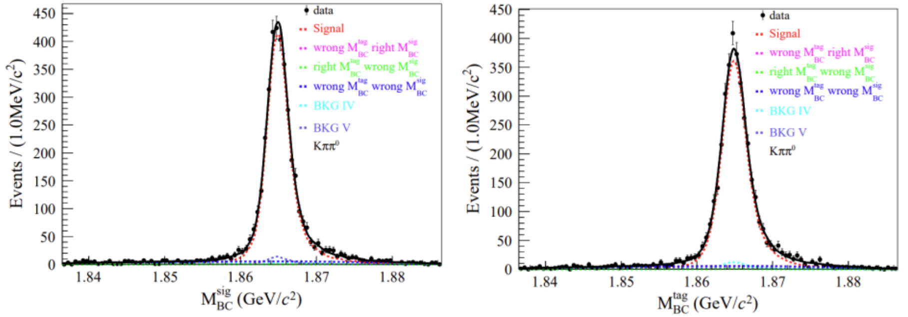
- $D^0 \to \omega K_L^0$



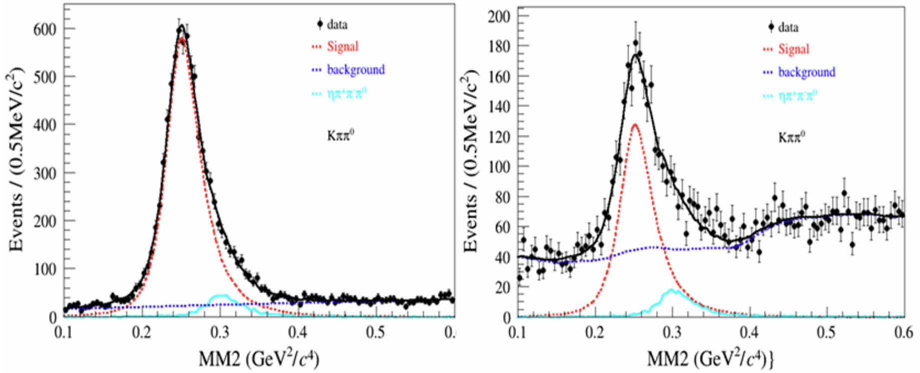
  - Suppress background by requiring $E_{showers}^{extra}$
  - Peaking backgrounds $\omega\eta$
  - Peaking backgrounds ωK_S^0
  - Peaking backgrounds non-ω resonance $K_{S/L}^0\pi^+\pi^-\pi^0$ processes
  - Peaking backgrounds from $q\bar{q}$ process

DT Fitting Method & Results

- $D^0 \to \omega K_S^0$: Fully reconstructed; 2D-fit to M_{BC}^{sig} $v.s. M_{BC}^{tag}$.
  - Peaking BKGs from $D^0 \to K_S^0\pi^+\pi^-\pi^0$: $M_{\pi^+\pi^-\pi^0}$ side-band.
  - Wrong reconstruction of a soft γ of π^0 :MC simulation.
  - Signal shape modeled by MC.



- $D^0 \to \omega K_L^0$: Missing mass method; fitting to $M_{miss}^2(MM2)$.
  - Lateral peaks from η: MC simulation.
  - Peaking BKGs from $D^0 \to K_{S/L}^0\pi^+\pi^-\pi^0$: $M_{\pi^+\pi^-\pi^0}$ side-band.
  - Peaking BKGs from $q\bar{q}$: estimated by M_{BC}^{tag} side-band and MC simulation.



Systematic Uncertainty

Source	$D^0 \to K_S^0\omega(\%)$	$D^0 \to K_L^0\omega(\%)$
$\pi^\pm$ tracking	1.0	0.8
$\pi^\pm$ PID	0.2	0.2
π^0 reconstruction	1.1	1.1
K_S^0 reconstruction	1.1	–
ST Yields	0.1	0.1
DT Fit	0.5	0.7
QC-correction	0.6	0.5
ω Mass window	0.5	0.7
$N_{\text{charged}}^{\text{extra}} = 0$	–	0.9
$E_\gamma^{extra} < 0.27$ GeV	–	0.4
MC Statistics	0.3	0.3
Quoted BFs	0.7	0.7
Total	2.2	2.2

- Interference between the processes with and without ω intermediate state are not considered.
- A MC study indicates that this interference will affect the BFs of $D^0 \to \omega K_{S/L}$ with a factor of 3.96%, ,which will be regarded as the third uncertainties in the measurement.

Summary of $D^0 \to \omega K^0_{S\backslash L}$

Results	$\mathcal{B}(D^0 \to K^0_S\omega) \times 10^{-3}$	$\mathcal{B}(D^0 \to K^0_L\omega) \times 10^{-3}$	$\boldsymbol{R(D^0;\omega) \times 10^{-2}}$
This work	$11.91 \pm 0.19 \pm 0.26 \pm 0.47$	$10.97 \pm 0.15 \pm 0.28 \pm 0.44$	$4.21 \pm 0.99 \pm 0.88 \pm 2.80$
Previous results	$11.2 \pm 0.4 \pm 0.5$	$11.64 \pm 0.22 \pm 0.28$	-2.4 ± 3.1
F1′	12.7 ± 0.6	10.3 ± 0.5	10.6 ± 3.4
F4	12.5 ± 0.6	10.5 ± 0.5	8.9 ± 3.5

- Summary
  - ✓ Measurements of $\mathcal{B}(D^0 \to K^0_S\omega)$, $\mathcal{B}(D^0 \to K^0_L\omega)$ and $\boldsymbol{R(D^0;\omega)}$.
  - ✓ Draft already finished and under BESIII referees reviewing
- Next to do
  - ➢ Finish the draft review and submit

Summary and Prospects

- Work I:PWA of $D^0 \to \omega K^+ K^-$
  - ✓ Obtained amplitude model
  - ➢ IO Check & systemic uncertainty ongoing
- Work II:$D^0 \to \omega K_S^0$ and $D^0 \to \omega K_L^0$
  - ✓ Draft under BESIII reviewing.

- Prospects:
  - ➢ Study of other $D \to VV$ process, e.g. $D^0 \to \omega\omega$

Thank you !

Back UP

- **Covariant helicity amplitude** for $D \to \phi\omega \to (K^+K^-)(\rho\pi) \to (K^+K^-)(\pi\pi_2\pi_3)$:

$$H_{\lambda_\phi,\lambda_\omega} = F^{JD}_{\lambda_\phi,\lambda_\omega} D^{JD}_{\lambda_D,\lambda_\phi-\lambda_\omega}(\Omega_D) \cdot T_\phi(m_\phi) F^{J\phi}_{\lambda_{K^+},\lambda_{K^-}}\left(\Omega_\phi^{\{D\}}\right) \cdot T_\omega(m_\omega) F^{J\omega}_{\lambda_\rho,\lambda_\pi}\left(\Omega_\omega^{\{D\}}\right) D^{J\omega}_{\lambda_\omega,\lambda_\rho-\lambda_\pi}\left(\Omega_\omega^{\{D\}}\right) \cdot T_\rho(m_\rho) F^{J\rho}_{\lambda_{\pi_2},\lambda_{\pi_3}} D^{J\rho}_{\lambda_\rho,\lambda_{\pi_2}-\lambda_{\pi_3}}$$

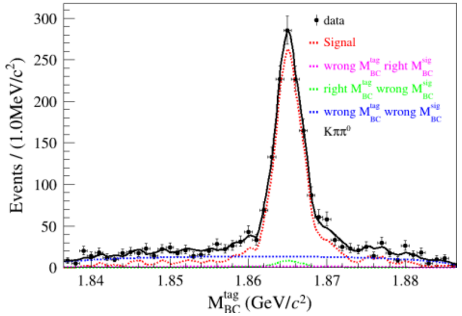
$$J_D = 0 \to \lambda_\phi = \lambda_\omega \to |A|^2 = \left|\sum_{\lambda_\phi\lambda_\omega} H_{\lambda_\phi\lambda_\omega}\right|^2 = |H_{11} + H_{-1-1} + H_{00}|^2$$

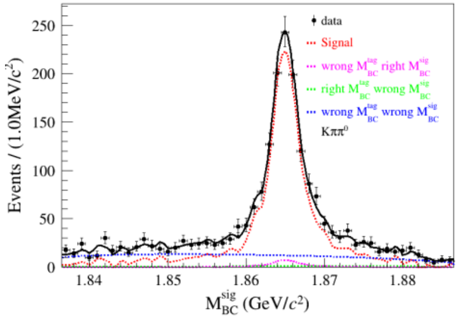
$$F^{J_D}_{\pm1\pm1} = \sqrt{\frac{1}{3}} g_{00} \pm \sqrt{\frac{1}{2}} W r g_{11} + \sqrt{\frac{1}{6}} r^2 g_{22}, \quad F^{J_D}_{00} = \gamma_1\gamma_2(-\sqrt{\frac{1}{3}} g_{00} + \sqrt{\frac{2}{3}} r^2 g_{22}), \quad r + 2|q|$$

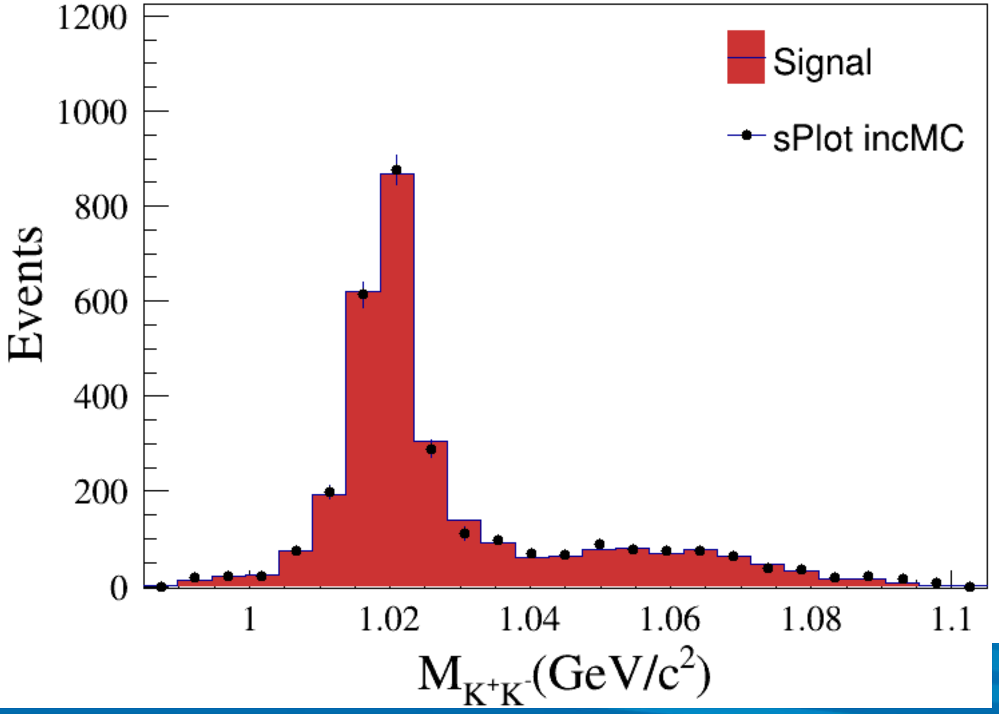
$|q|$: momentum of V in D rest frame γ: Lorentz factor of V in D rest frame W:mass of D

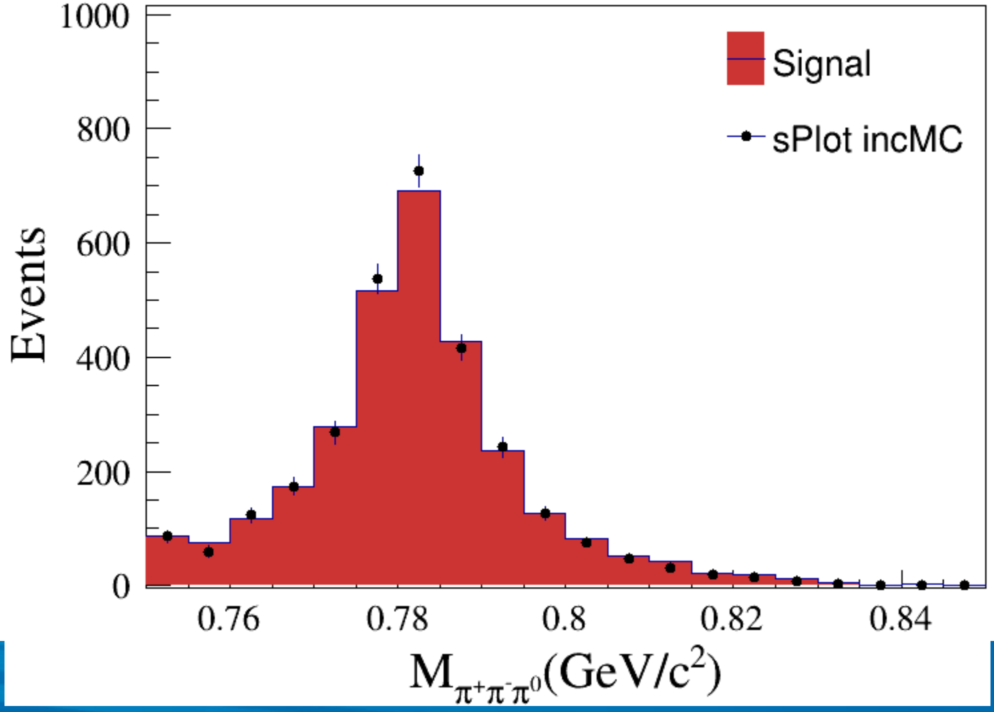
sPlosPlot on MC — Full Reconstructiont

- To check the reliability of sPlot, 2-D M_{BC} fits are performed on inclusive MC samples. The comparisons between the signal components of inclusive MC and sPlot are shown below.

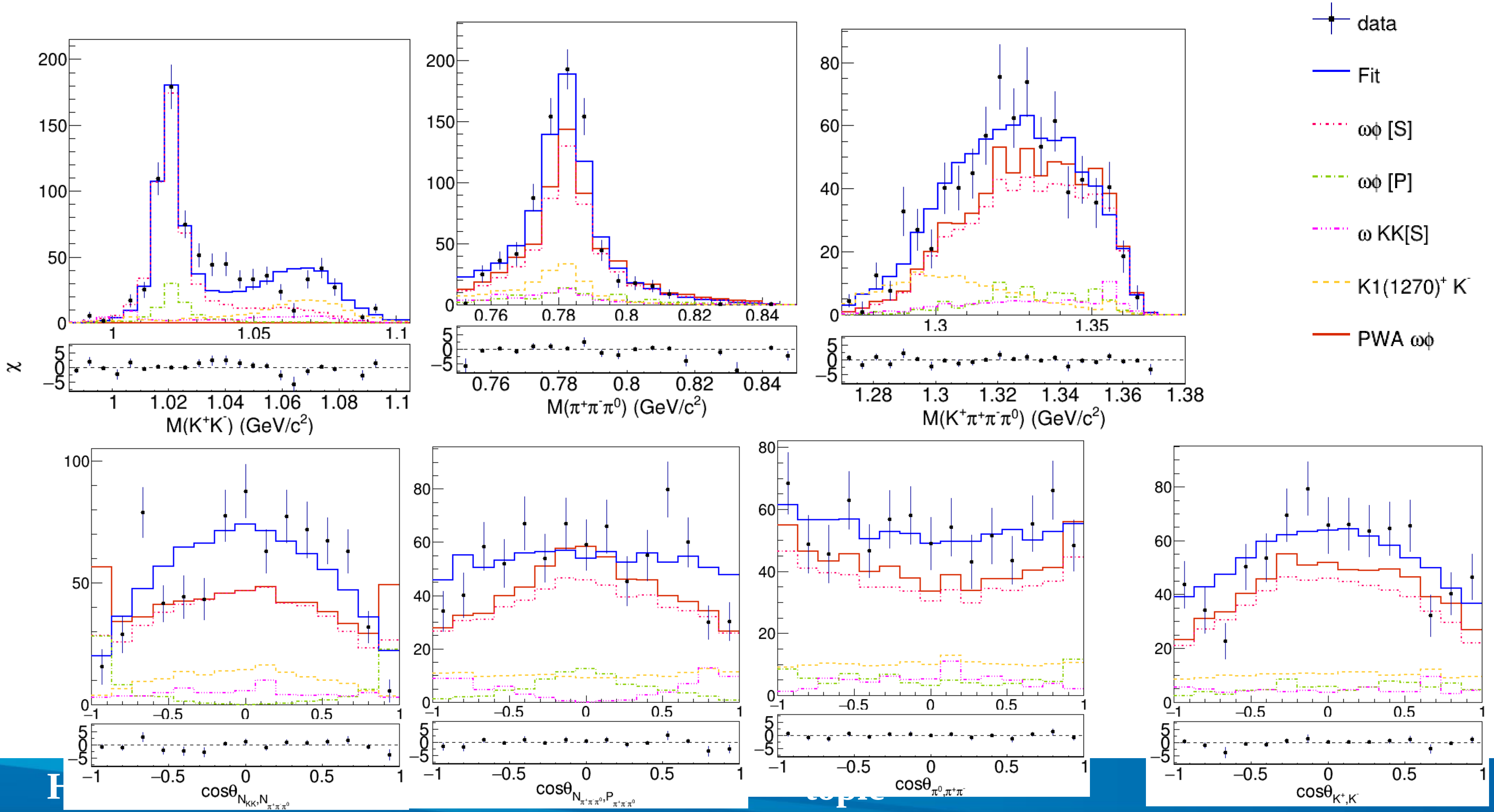




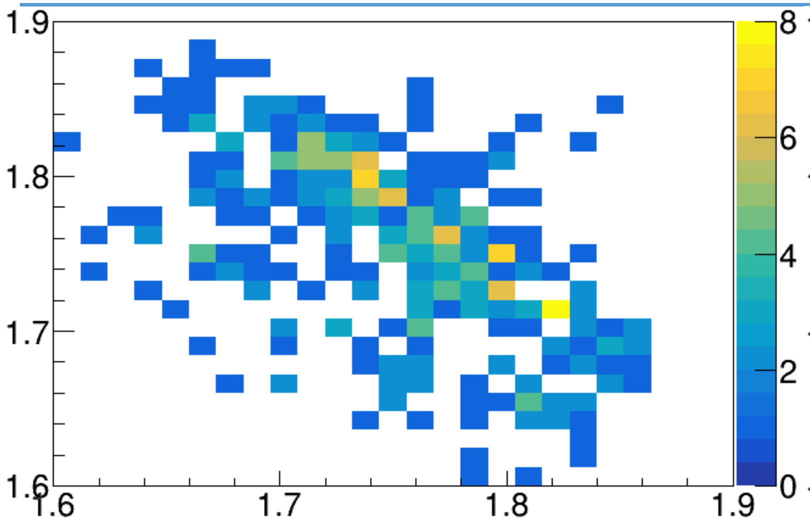


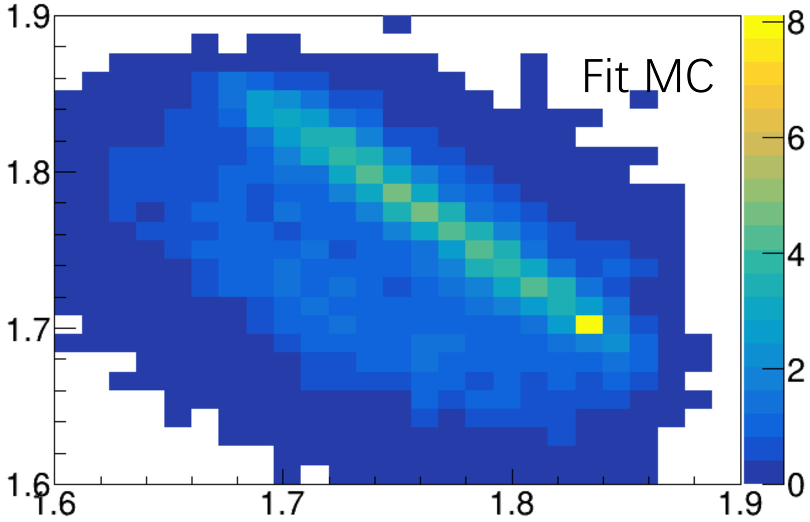


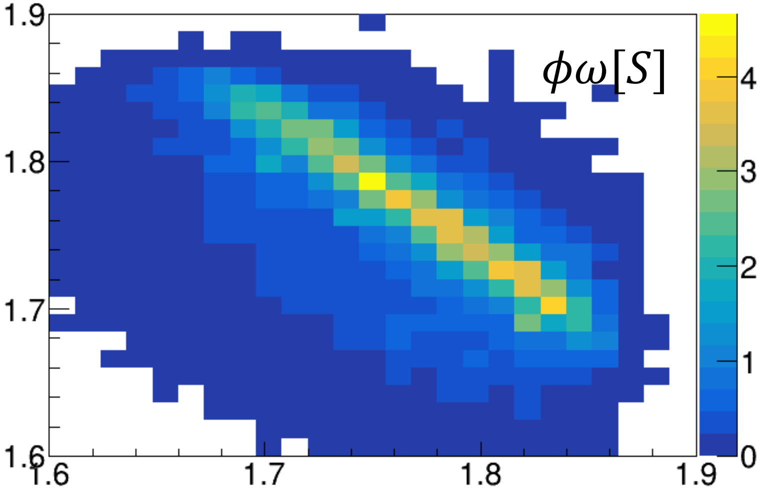
Fit on sPlot — Full reconstruction

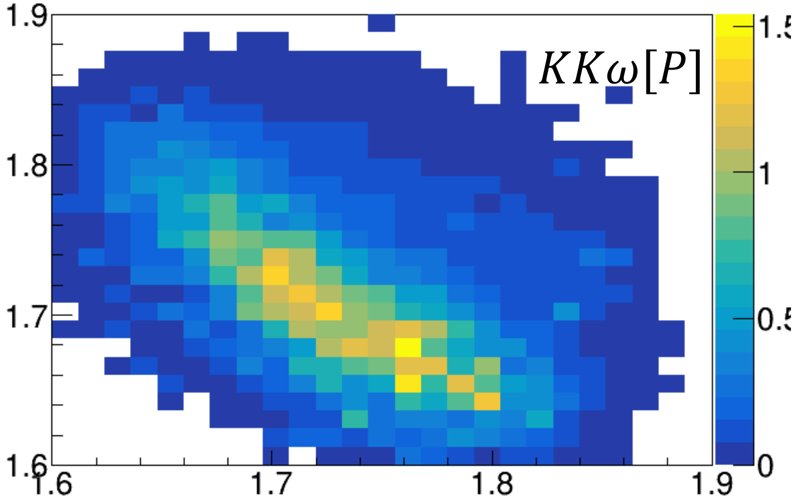


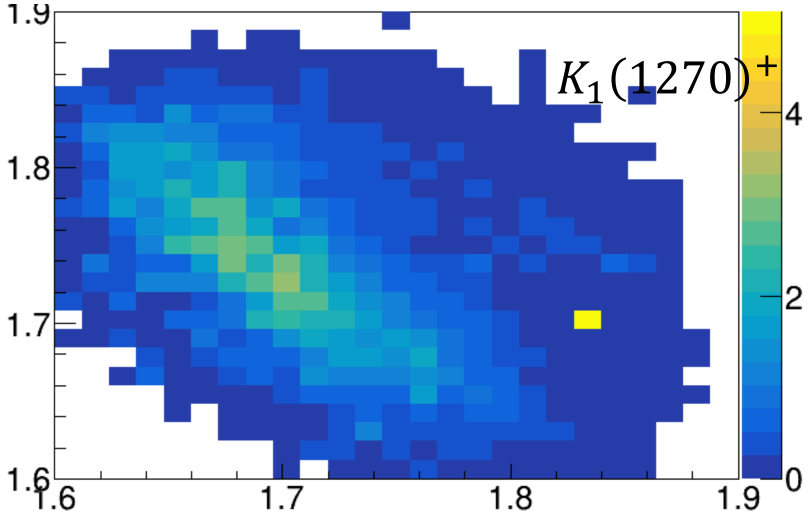
$M^2_{K^-\pi^+\pi^-\pi^0}$ $v.s.$ $M^2_{K^+\pi^+\pi^-\pi^0}$



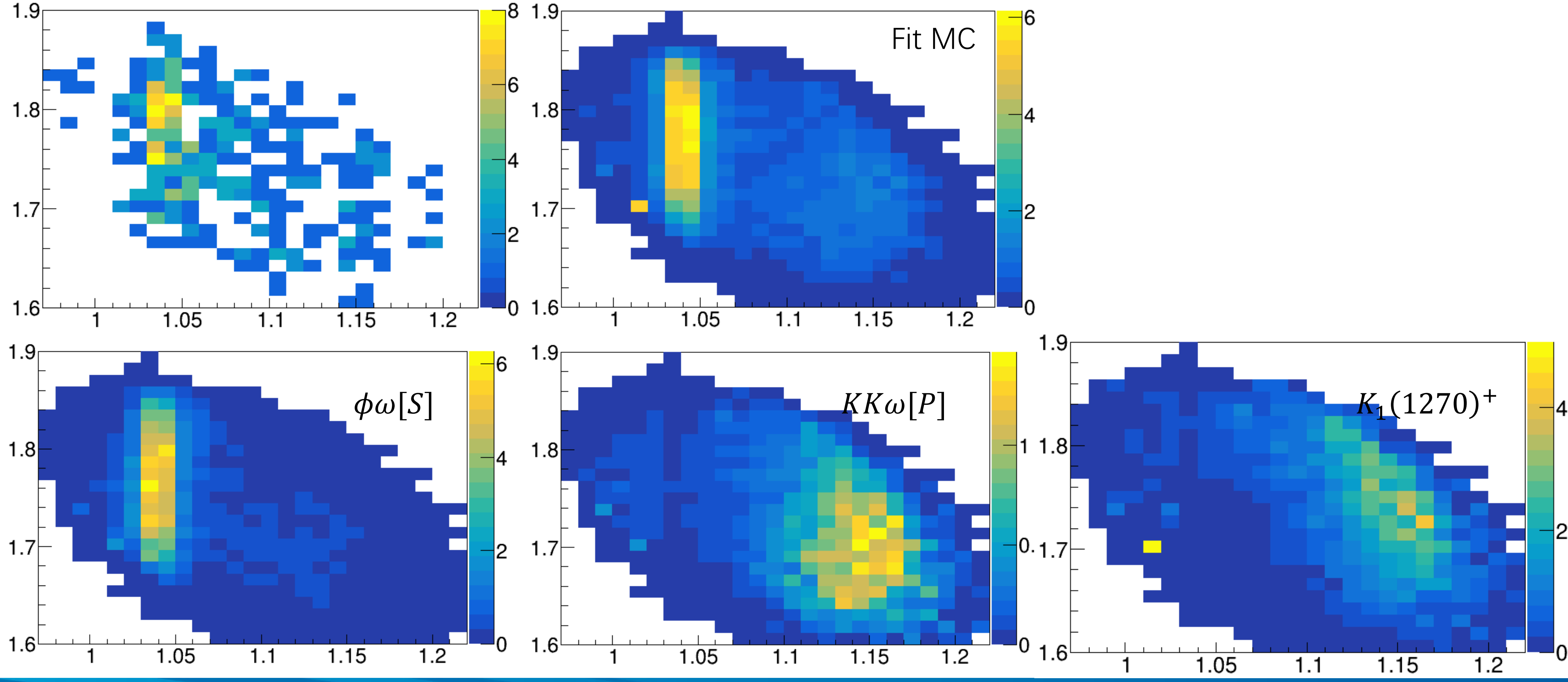








$M^2_{K^-\pi^+\pi^-\pi^0}$ $v.s.$ $M^2_{K^+K^-}$



Amplitude	$\lvert\tilde{c}_k\rvert$	$\arg(\tilde{c}_k)$ [rad]	Fit fraction [%]
$D^0 \to [\phi(1020)\rho(770)^0]_{L=0}$	1 (fixed)	0 (fixed)	$92.55 \pm 0.46 \pm 0.28$
$D^0 \to [\phi(1020)\omega(782)]_{L=0}$	$0.114 \pm 0.004 \pm 0.003$	$1.30 \pm 0.04 \pm 0.04$	$1.42 \pm 0.11 \pm 0.04$
		Sum of fit fractions	$93.96 \pm 0.40 \pm 0.28$
$D^0 \to [\phi(1020)\rho(770)^0]_{L=1}$	1 (fixed)	0 (fixed)	$83.11 \pm 4.11 \pm 1.70$
$D^0 \to [\phi(1020)\omega(782)]_{L=1}$	$0.254 \pm 0.052 \pm 0.018$	$1.32 \pm 0.19 \pm 0.07$	$4.33 \pm 1.58 \pm 0.52$
		Sum of fit fractions	$87.45 \pm 2.99 \pm 1.78$
$D^0 \to [\phi(1020)\rho(770)^0]_{L=2}$	1 (fixed)	0 (fixed)	$94.64 \pm 1.69 \pm 0.78$
$D^0 \to [\phi(1020)\omega(782)]_{L=2}$	$0.162 \pm 0.032 \pm 0.014$	$1.50 \pm 0.17 \pm 0.06$	$0.71 \pm 0.27 \pm 0.12$
		Sum of fit fractions	$95.35 \pm 1.54 \pm 0.79$
$D^0 \to [K^+K^-]_{L=0}\rho(770)^0$	1 (fixed)	0 (fixed)	$85.41 \pm 5.89 \pm 3.49$
$D^0 \to [K^+K^-]_{L=0}\omega(782)$	$0.494 \pm 0.098 \pm 0.098$	$-0.95 \pm 0.19 \pm 0.15$	$9.24 \pm 3.26 \pm 3.64$
		Sum of fit fractions	$94.65 \pm 5.03 \pm 5.04$
$K_1(1270)^+ \to [\rho(770)^0 K^+]_{L=0}$	1 (fixed)	0 (fixed)	$139.03 \pm 1.98 \pm 3.81$
$K_1(1270)^+ \to [\omega(782) K^+]_{L=0}$	$0.159 \pm 0.012 \pm 0.011$	$1.36 \pm 0.07 \pm 0.06$	$1.52 \pm 0.22 \pm 0.19$
		Sum of fit fractions	$140.55 \pm 1.90 \pm 3.81$

AMPs from LHCb
J. High Energy Phys. 02 (2019) 126.

confirm that $\boldsymbol{Br(D^0 \to \omega\phi) < Br(D^0 \to \rho^0\phi)}$