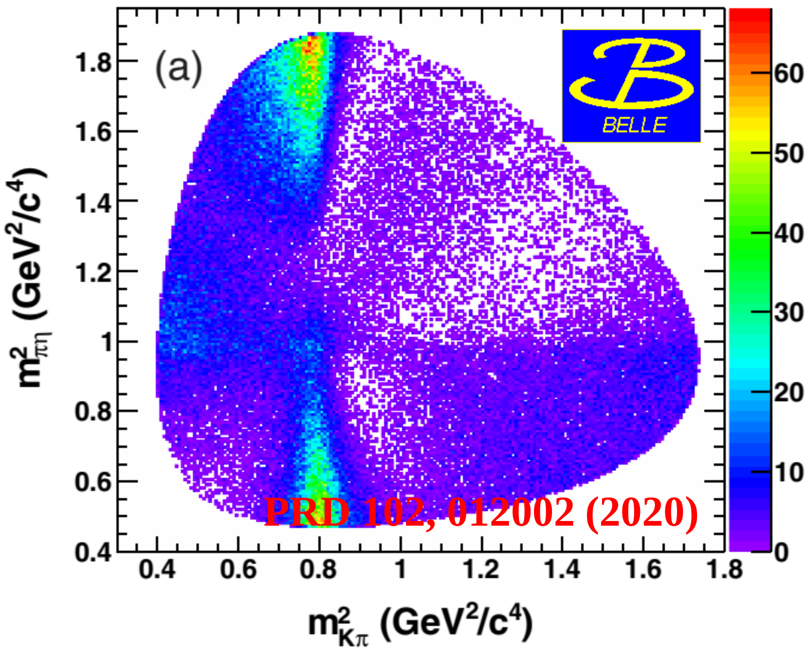
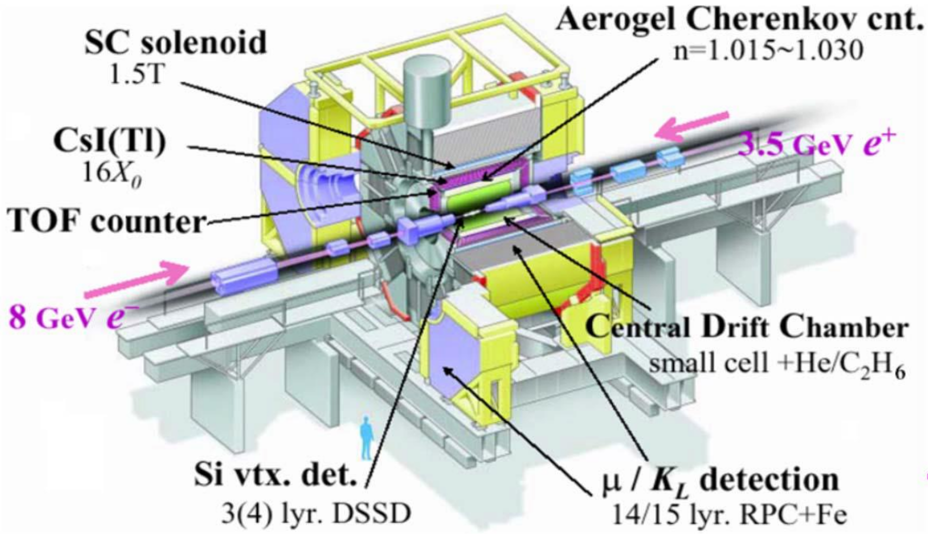
Dalitz plot analysis of $D^0 \to K^- \pi^+ \eta$

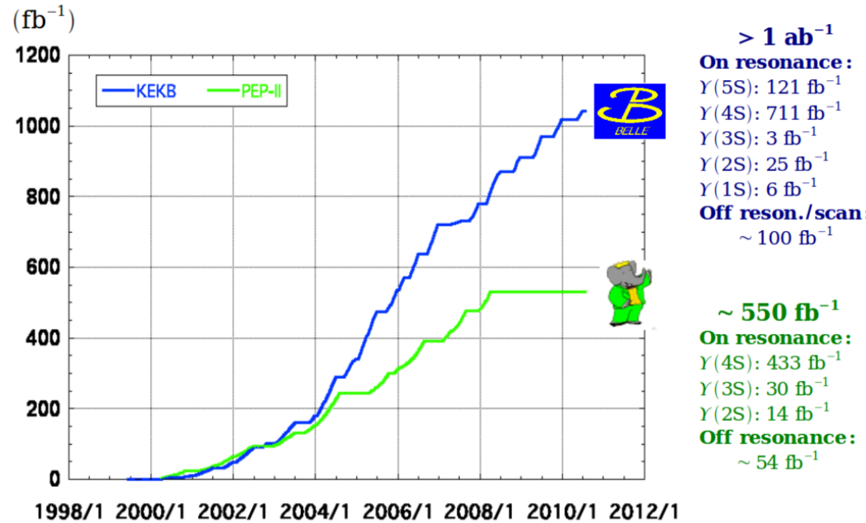
鄢文标 (中国科学技术大学)



第二届“强子物理和重味物理理论与实验联合研讨会”, 2021.03.28, 兰州

KEKB accelerator & Belle Detector



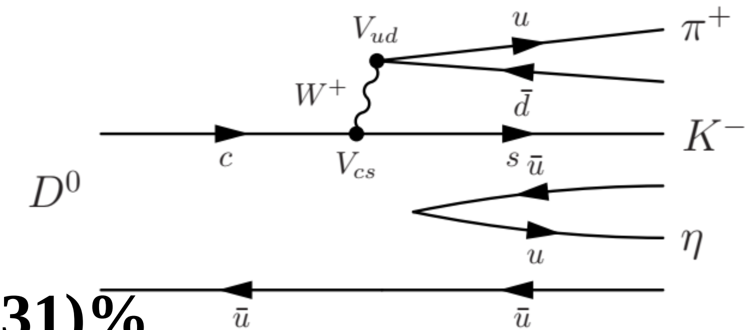


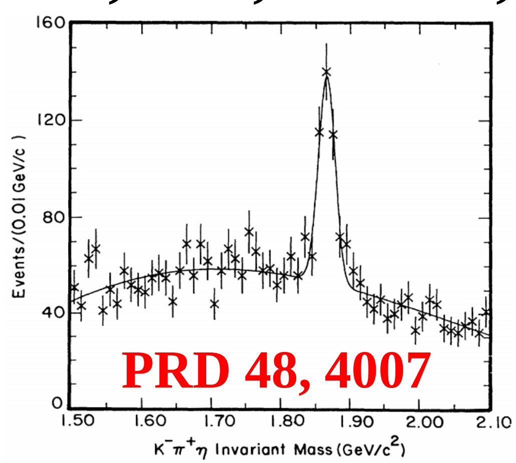
- **Asymmetric e^+e^- collider**
  - **8 GeV(e^-); 3.5GeV(e^+)**
  - **Around 10.58GeV ↔ Y(4S)**
- **B factory, also tau-charm factory**

Process	σ (nb) @ Y(4S)
$b\bar{b}$	1.1
$c\bar{c}$	1.3
$q\bar{q}$ (q=u,d,s)	2.1
$\tau^+\tau^-$	0.93

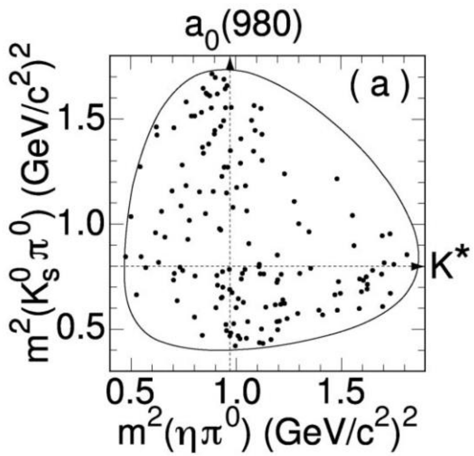
$D^0 \to K^- \pi^+ \eta$

- $D^0 \to K^- \pi^+ \eta$ process
  - Cabibbo favored via $c \to s\, u\, \bar{d}$
  - Firstly observed by CLEO
  - BESIII: Br=(1.853±0.025±0.031)%
- $D^0 \to K^{*0} \eta$: W-exchange diagram
  - $D^0 \to K_S{}^0 \pi^0 \eta$: (1.02 ± 0.30)%
  - Theory calculation: RR D81, 074021; D86, 036012; D89, 054006;





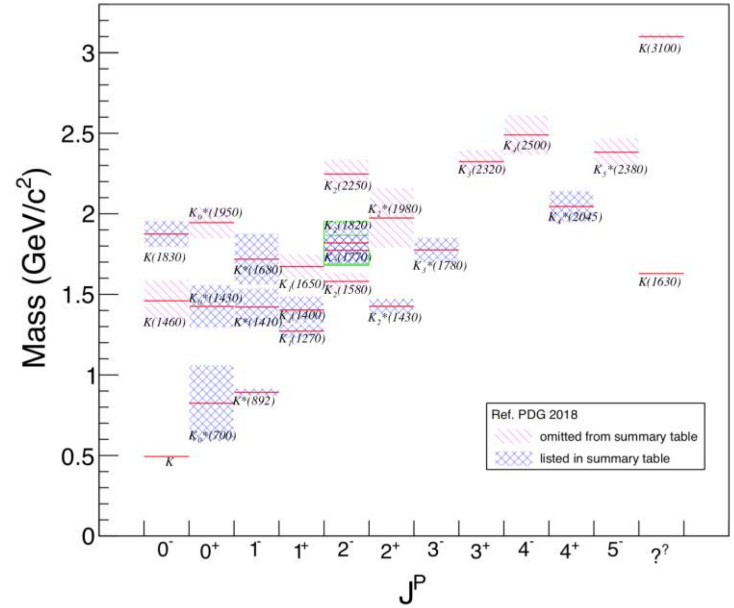
PRD 48, 4007



PRL 93, 111801

D^0 -> $K^- \pi^+ \eta$

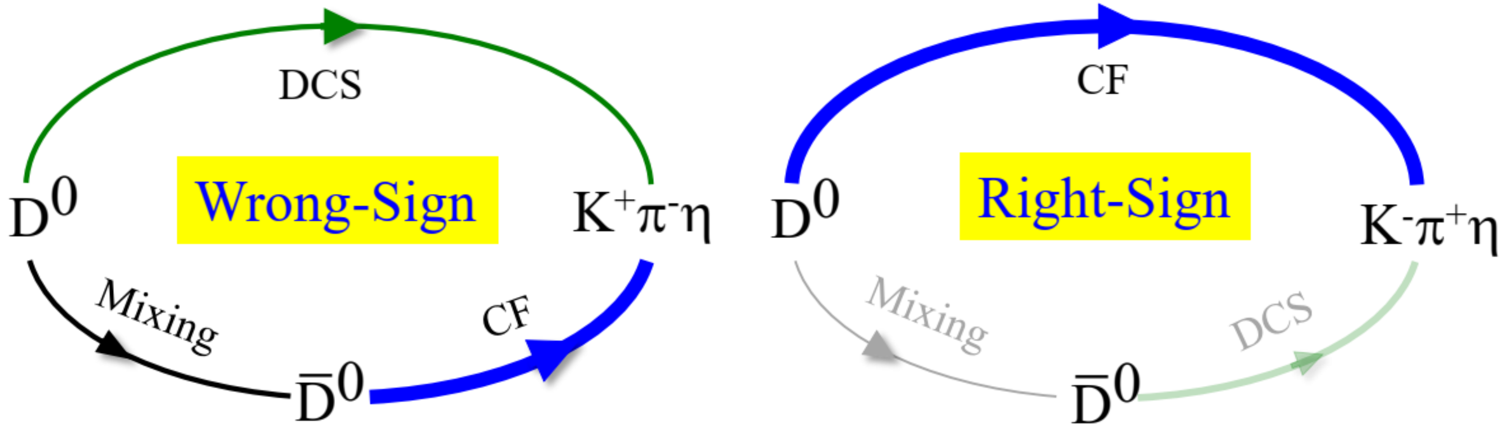
- **D three-body hadronic decay**
  - ☐ **study light hadron spectrum**
- **Kaon spectrum**
  - ☐ **PDG2020: 25 kaon states below 3.1 GeV/c^2**
  - ☐ **Only 13 states well established, 12 states need confirmation**
  - ☐ **Little progress in past 30 years**



- **K* @ Kπ & Kη**
  - ☐ **Search K*(1410), K*(1680) and K_2*(1980) @ Kη**
  - ☐ **K*(1680) as pure 1^3D_1 state**
  - ☐ **K*(1410) & K*(1680): mixture 2^3S_1 and 1^3D_1**

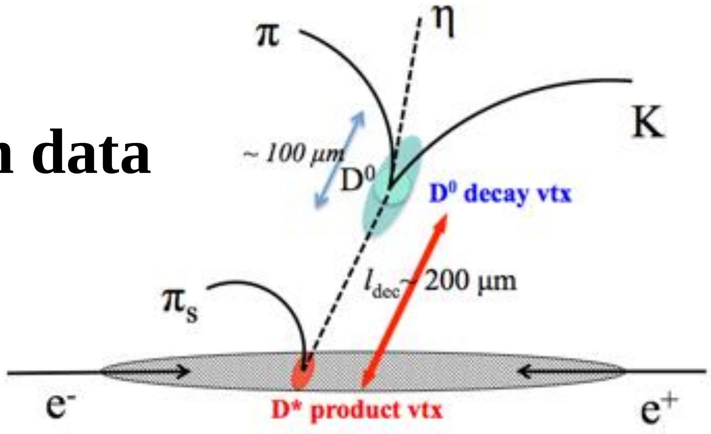
D^0 -> $K^- \pi^+ \eta$

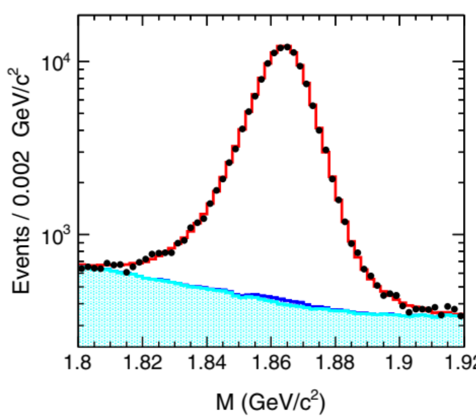
- **Wrong-sign decays have important role on D^0-$\bar{D}^0$ mixing & CP violation**
- **Wrong-sign D^0 -> $K^+ \pi^- \eta$ for D^0-$\bar{D}^0$ mixing: not yet**
- **With 50 ab^{-1} data @ Belle II, Time-dependent Dalitz analysis of D^0 -> $K^+ \pi^- \eta$: possible**
- **Right-sign D^0 -> $K^- \pi^+ \eta$: necessary input for D^0 -> $K^+ \pi^- \eta$**

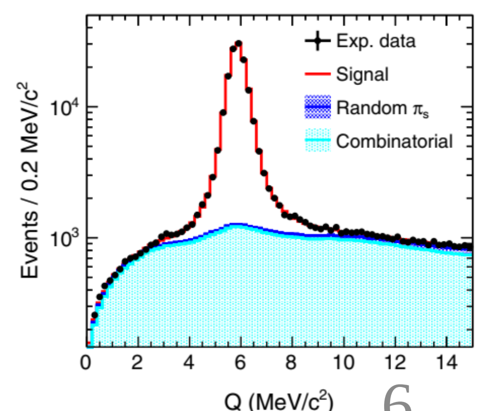


$D^0 \rightarrow K^- \pi^+ \eta$ @ Belle

- **Belle data: total 953 fb^{-1}**
  - □ **Y(nS) with n=[1, 5] & continuum data**
- **$e^+e^- \rightarrow \gamma^* \rightarrow D^{*+} + X$**
  $D^{*+} \rightarrow D^0 \pi_s +$ and $D^0 \rightarrow K^- \pi^+ \eta$
  - □ **$D^0/\bar{D}^0$ tagged by π_s of D***
  - □ **Veto D^{*+} from B decay**
- **M-Q two-dimension fit:**
  - □ **$M \equiv M_{K\pi\eta}$ and $Q \equiv M_{K\pi\eta\pi s} - M_{K\pi\eta} - m_{\pi s}$**
  - □ **105197 ± 60 events at signal region, with purity (94.6 ± 0.9)%**





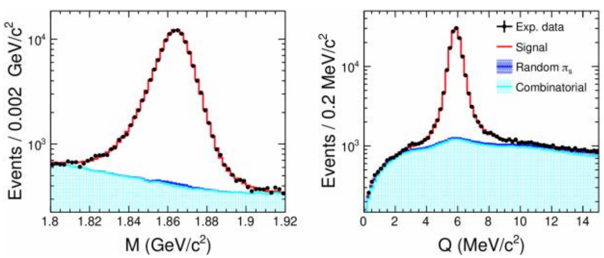


Generalization of Dalitz analysis

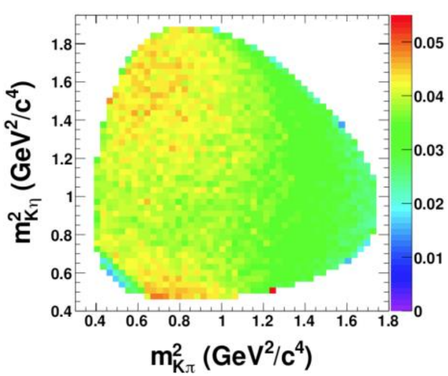
- **Unbinned maximum likelihood method**

$$-2ln\mathcal{L}(m^2_{AB}, m^2_{BC}) = -2\sum_{i=1}^{n} ln[f^i_{sig}p_{sig}(m^2_{AB,i}, m^2_{BC,i}) + f^i_{bkg}p_{bkg}(m^2_{AB,i}, m^2_{BC,i})]$$

M-Q 2D fit

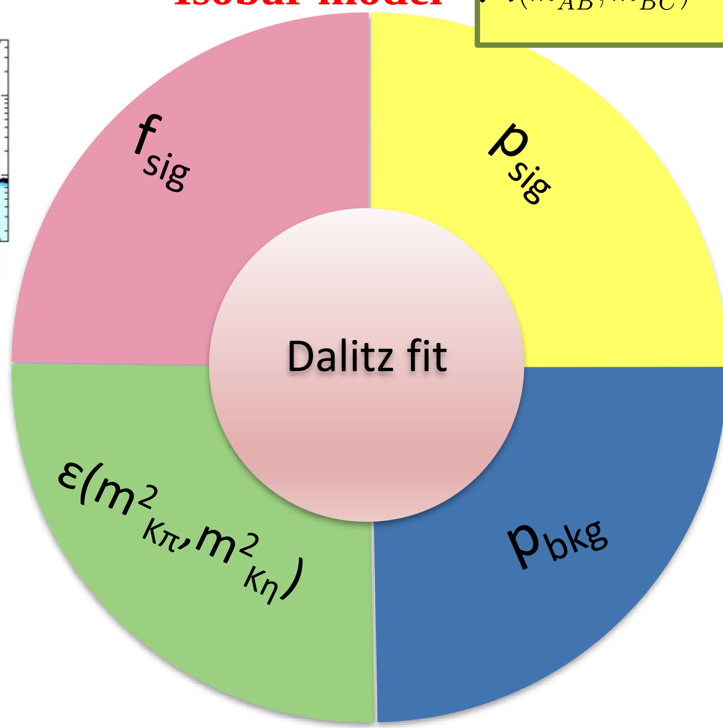


Efficiency plane



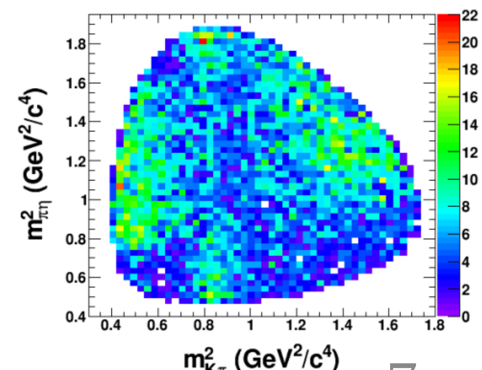
Isobar model

$$\mathcal{M}(m^2_{AB}, m^2_{BC}) = a_{NR}e^{i\phi_{NR}} + \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m^2_{AB}, m^2_{BC})$$



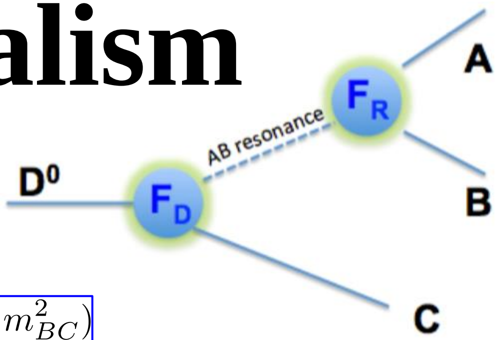
Background PDF

- D^0 √, π_s ×
- D^0 ×, π_s √
- D^0 ×, π_s ×
- M sideband @ Q signal



$$p_{sig} = \frac{\sum |\mathcal{M}(m^2_{12,i}, m^2_{23,i})|^2 \epsilon_j(m^2_{12,i}, m^2_{23,i})}{\sum \iint_{DP} dm^2_{12} dm^2_{23} |\mathcal{M}(m^2_{12}, m^2_{23})|^2 \epsilon_j(m^2_{12}, m^2_{23})}$$

Dalitz analysis formalism



- **Dalitz standard form** $d\Gamma = \frac{1}{(2\pi)^3}\frac{1}{32M^3}|\mathcal{M}|^2 dm_{AB}^2 dm_{BC}^2$
- **Isobar model** $\mathcal{M}(m_{AB}^2, m_{BC}^2) = a_{NR}e^{i\phi_{NR}} + \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_{AB}^2, m_{BC}^2)$
- **Matrix element A_r** $\mathcal{A}(ABC|r) = F_D \times F_r \times T_r \times \Omega_J$
  - **Blatt-Weisskopf centrifugal barrier factor: F_r, F_D**
  - **Angular distribution function Ω_J by Zemach tensor**
  - **Dynamical function T_r**
    - ✓ **most of resonances by relativistic Breit-Wigner**
    - ✓ **$a_0(980)$ by Flatte model**

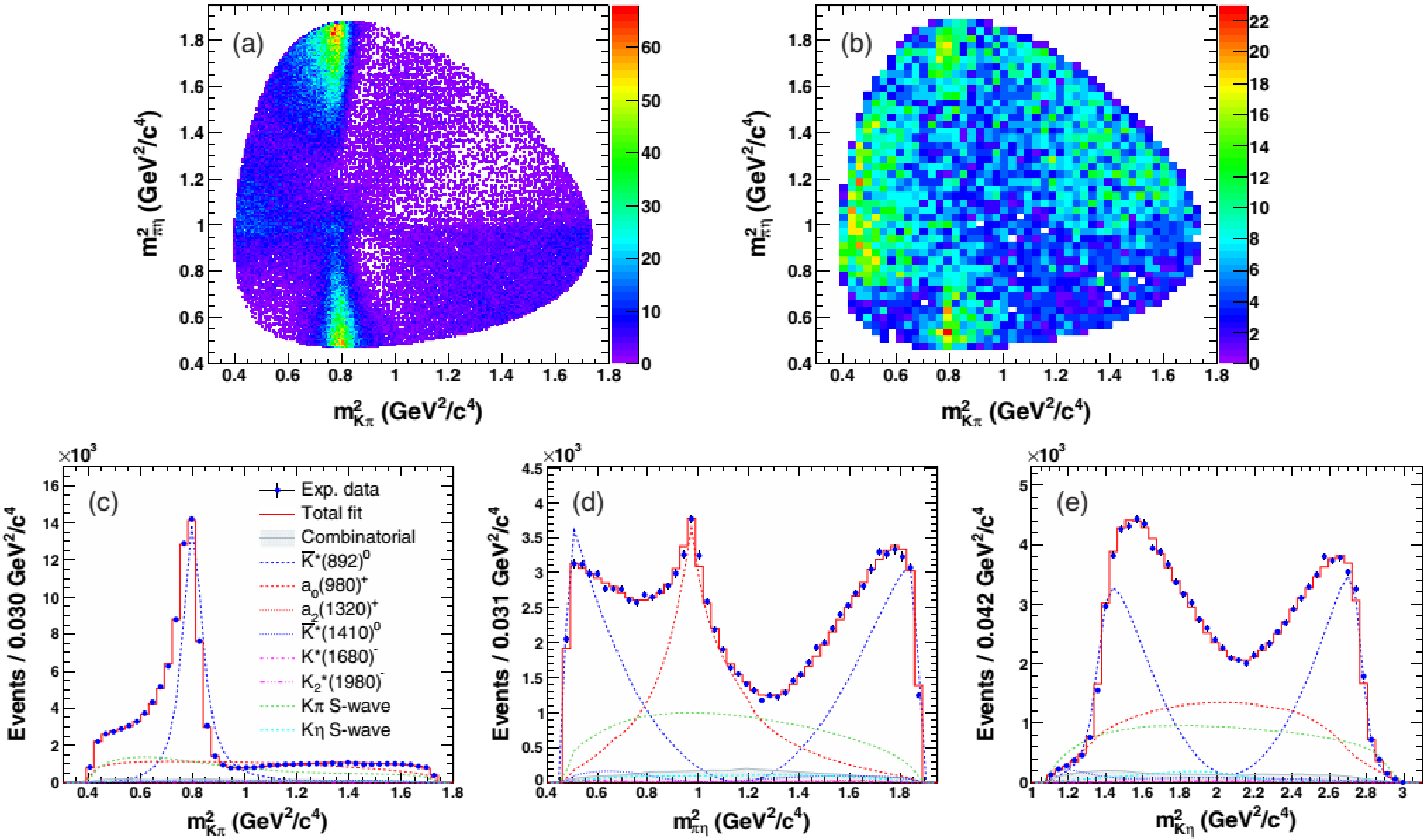
$$T_R(s) = \frac{1}{m_{a_0}^2 - s - i(g_{\pi\eta}^2\rho_{\pi\eta} + g_{\bar{K}^0K}^2\rho_{\bar{K}^0K} + g_{\pi\eta'}^2\rho_{\pi\eta'})}$$

- ✓ **Kπ & Kη S-wave contribution by LASS model**

$$\mathcal{A}_{g\mathrm{LASS}}(s) = \frac{\sqrt{s}}{2q}\cdot[B\sin(\delta_B+\phi_B)e^{i(\delta_B+\phi_B)} + \sin(\delta_R)e^{i(\delta_R+\phi_R)}e^{2i(\delta_B+\phi_B)}],$$

Non-resonant and K_0*(1430) components

Dalitz plot fit results



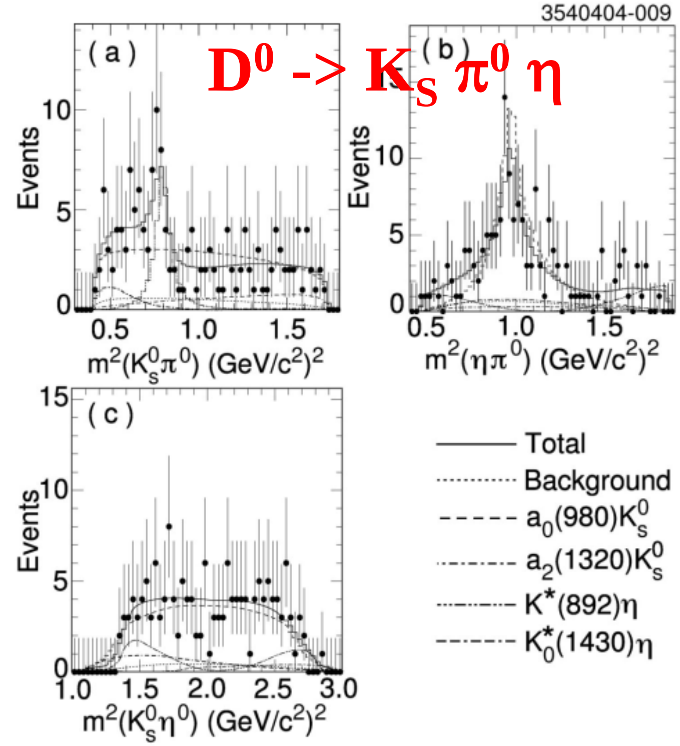
- **The fit quality χ^2/d.o.f = 1638/(1415-24) = 1.18**

Dalitz plot fit results

Component	Magnitude	Phase (°)	Fit fraction (%)
$\bar{K}^*(892)^0$	1	0	$47.61 \pm 1.32^{+0.24+3.64}_{-0.49-2.71}$
$a_0(980)^+$	2.779 ± 0.032	310.3 ± 1.1	$39.28 \pm 1.50^{+1.58+4.38}_{-0.51-3.30}$
$K\pi$ S-wave	10.82 ± 0.23	50.0 ± 5.7	$31.92 \pm 1.21^{+1.47+2.75}_{-0.53-2.87}$
$K\eta$ S-wave	1.70 ± 0.082	113.8 ± 13.6	$3.37 \pm 0.50^{+0.77+3.20}_{-0.27-1.21}$
$a_2(1320)^+$	1.27 ± 0.079	283.4 ± 4.7	$0.74 \pm 0.09^{+0.06+0.37}_{-0.04-0.17}$
$\bar{K}^*(1410)^0$	4.84 ± 0.36	352.7 ± 2.8	$6.94 \pm 0.85^{+0.55+2.37}_{-1.61-3.22}$
$K^*(1680)^-$	2.56 ± 0.18	232.2 ± 6.6	$1.07 \pm 0.16^{+0.11+0.58}_{-0.10-0.36}$
$K_2^*(1980)^-$	9.29 ± 0.69	207.7 ± 4.0	$1.13 \pm 0.15^{+0.05+0.88}_{-0.05-0.98}$
Sum			$132.1 \pm 3.4^{+1.6+8.3}_{-0.7-4.5}$

$D^0 \to K^+ \pi^- \eta$

$D^0 \to K_S \pi^0 \eta$



- **Dominant components: $\bar{K}^*(892)^0$ and $a_0(980)^+$**
- **Kη S-wave with $K_0^*(1430)$: > 30σ**
- **$K^*(1680)^-/K_2^*(1980)^- \to K^- \eta$ are observed for the first time**

With 16σ /17σ

$B(D^0 \to K^- \pi^+ \eta)$

- **Normalized mode $D^0 \to K^- \pi^+$, fit M @ Q signal region**

$$\frac{\mathcal{B}(D^0 \to K^-\pi^+\eta)\mathcal{B}(\eta \to \gamma\gamma)}{\mathcal{B}(D^0 \to K^-\pi^+)} = \frac{N_1/\epsilon_1}{N_2/\epsilon_2}$$

$$\frac{\mathbf{B(D^0 \to K^-\pi^+\eta)}}{\mathbf{B(D^0 \to K^-\pi^+)}} = \mathbf{0.500 \pm 0.002(stat) \pm 0.020(syst) \pm 0.003(PDG)}$$

- **PDG2018: $B(D^0 \to K^- \pi^+) = (3.950 \pm 0.031)\%$, then**

$$\mathbf{B(D^0 \to K^-\pi^+\eta) = 1.973 \pm 0.009(stat) \pm 0.079(syst) \pm 0.018(PDG)}$$

- **BESIII: $B(D^0 \to K^- \pi^+ \eta) = (1.853 \pm 0.025(stat) \pm 0.031(sys))\%$**

Branching fractions @ $D^0 \to K^- \pi^+ \eta$

- **Combine Dalitz fit results and $B(D^0 \to K^- \pi^+ \eta)$, then have**
- $B\left(D^0 \to K^*(892)^0\eta \to K^-\pi^+\eta\right) = (0.94 \pm 0.03 \pm 0.08 \pm 0.01)\%$
  - □ **PDG: $B(K^*(892)^0 \to K^-\pi^+) = (66.503 \pm 0.014)\%$ @ PDG**
  - □ $B(D^0 \to K^*(892)^0\eta) = \left(1.41 \pm 0.04^{+0.12}_{-0.11} \pm 0.01\right)\%$
  - □ **PDG: $B(D^0 \to \bar{K}^*(892)^0 \eta) = (1.02 \pm 0.30)\%$**
  - □ **Theory prediction: (0.51-0.92)%**
  - □ **deviates theory prediction with significance of more than 3σ**
- $B\left(D^0 \to K^*(1680)^-\pi^+ \to K^-\eta\pi^+\right) = \left(2.11 \pm 0.32^{+1.16}_{-0.72} \pm 0.02\right)\times 10^{-4}$
  - □ $B\left(D^0 \to K^*(1680)^-\pi^+ \to K^-\pi^0\pi^+\right) = (0.19 \pm 0.07)\%$ **@ PDG**
  - □ $\frac{B(K^*(1680) \to K^-\eta)}{B(K^*(1680) \to K^-\pi)} = 0.11 \pm 0.02^{+0.06}_{-0.04} \pm 0.04$
  - □ **$B(K^*(1680)^- \to K^-\pi^0) = (12.90 \pm 0.83)\%$ @ PDG**
  - □ $B(K^*(1680)^- \to K^-\eta) = \left(1.44 \pm 0.21^{+0.79}_{-0.49} \pm 0.54\right)\%$
- **$B(D^0 \to K_2^*(1980)^-\pi^+ \to K^-\pi^+\eta) = (2.2 +1.7-1.9)\times 10^{-4}$**
  - □ **Strongly suppressed do to phase-space and yet allowed due to large width of $K_2^*(1980)$**

K*(1680)

- K*(1680) as pure 1^3D_1 state
  - $K\pi : K\eta \approx 1.0$ @ theory
  - Belle: $K\pi : K\eta \approx 0.11 \pm 0.07$
  - $K\pi$, $K\rho$, and $K^*(892)\pi$
  - Any idea ?

Mode	EPJC 77, 861	PRD 68, 054014
$\Gamma_{K\pi}$	69.2 MeV	45 MeV
$\Gamma_{K\eta}$	64.4 MeV	53 MeV

±

	EPJC 77, 861	PRD 68, 054014	Experiment
$\Gamma_{K\pi}/\Gamma_{K^*(892)\pi}$	1.66	1.8	2.8 ± 1.1
$\Gamma_{K\rho}/\Gamma_{K\pi}$	0.65	0.58	1.2 ± 0.4
$\Gamma_{K\rho}/\Gamma_{K^*(892)\pi}$	1.07	1.04	1.05+0.27-0.11

- K*(1410) and K*(1680): mixture 2^3S_1 and 1^3D_1
  - $K^*(1410)^- \to K^-\eta$: smaller than 3σ @ Belle

$$\begin{pmatrix} |K^*(1410)\rangle \\ |K^*(1680)\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_{sd} & \sin\theta_{sd} \\ -\sin\theta_{sd} & \cos\theta_{sd} \end{pmatrix} \begin{pmatrix} |1^3D_1\rangle \\ |2^3S_1\rangle \end{pmatrix}$$

Summary

- **Based on 953 fb^{-1} Belle data, Dalitz analysis of $D^0 \to K^- \pi^+ \eta$ is performed for the first time.**
- **$B(D^0 \to K^- \pi^+ \eta)$ is consistent with BESIII's result.**
- **$B(D0 \to \bar{K}^*(892)^0 \eta)=(1.41 +0.13-0.12)\%$, deviates theory prediction with significance of more than 3σ**
- **$K^*(1680)^-/K_2^*(1980)^- \to K^- \eta$ are observed.**
- **$\frac{B(K^*(1680)\to K^-\eta)}{B(K^*(1680)\to K^-\pi)}=0.11\pm0.02(stat)^{+0.06}_{-0.04}(sys)\pm0.04(PDG)$, is not consistent with theory prediction (≈1) under assumption K*(1680) as pure 1^3D_1 state.**

Charm meson data

Experiment	Machine	C.M $\sqrt{s}$	Luminosity	charm sample	efficiency
CLEOc	CESR (e^+e^-)	3.77 GeV	0.8 fb^{-1}	$2.9 \times 10^6(D^0)$ $2.3 \times 10^6(D^+)$	~10-30%
		4.17 GeV	0.6 fb^{-1}	$0.6 \times 10^6(D_s^+)$	
BESIII	BEPC-II (e^+e^-)	3.77 GeV	2.9 fb^{-1}	$10.5 \times 10^6(D^0)$ $8.4 \times 10^6(D^+)$	
		4.18 GeV	3.0 fb^{-1}	$3 \times 10^6(D_s^+)$	
		4.6 GeV	0.6 fb^{-1}	$1 \times 10^5(\Lambda_c^+)$	
BELLE	KEKB (e^+e^-)	10.58 GeV	1 ab^{-1}	$1.3 \times 10^9(D^0)$ $7.7 \times 10^8(D^+)$ $2.5 \times 10^8(D_s^+)$ $1.5 \times 10^8(\Lambda_c^+)$	~5-10%
	PEP-II (e^+e^-)	10.58 GeV	0.5 ab^{-1}	$6.5 \times 10^8(D^0)$ $3.8 \times 10^8(D^+)$ $1.2 \times 10^8(D_s^+)$ $0.7 \times 10^8(\Lambda_c^+)$	
CDF	Tevatron $(p\bar{p})$	1.96 TeV	9.6 fb^{-1}	1.3×10^{11}	<0.5%
LHCb	LHC (pp)	7 TeV 8 TeV	1.0 fb^{-1} 2.0 fb^{-1}	5.0×10^{12}	

D^0-$\bar{D}^0$ mixing

D^0 and $\bar{D}^0$ are flavor eigenstates, propagate and decays according to

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \left(M - \frac{i}{2}\Gamma\right)\begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

D^0 and $\bar{D}^0$ are combinations of mass eigenstates

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\bar{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\bar{D}^0\rangle \end{aligned}$$

The mass eigenstates develop in time as

$$\begin{aligned} |D_{1,2}(t)\rangle &= e_{1,2}(t)|D_{1,2}(0)\rangle \\ e_{1,2}(t) &\equiv e^{\left[-i\left(M_{1,2}-\frac{i}{2}\Gamma_{1,2}\right)t\right]} \end{aligned}$$

Two parameters describe D^0 and $\bar{D}^0$ mixing

$$x \equiv \frac{\Delta M}{\Gamma} \qquad \Delta M \equiv M_1 - M_2$$

$$y \equiv \frac{\Delta\Gamma}{2\Gamma} \qquad \Delta\Gamma \equiv \Gamma_1 - \Gamma_2$$

If either x or y are not zero, mixing occurs

$$|\langle\bar{D}^0|D^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{q}{p}\right|^2 e^{-\Gamma t}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

$$|\langle D^0|\bar{D}^0(t)\rangle|^2 = \frac{1}{2}\left|\frac{p}{q}\right|^2 e^{-\Gamma t}\left[cosh(y\Gamma t) - cos(x\Gamma t)\right]$$

D^0 -> K^- π^+ η