PWA for $\psi(3686) \to \phi\pi^+\pi^-(\phi K^+K^-)$

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Outline

- Motivation
- Data and MC sample
- Event selection
- PWA
- Summary

Motivation

- Search for strangeness partner of Zc(3900) in phi K channel, as well as other possible resonances.
- Measure the branching fractions of various $\psi(3686)$ decay processes with high precision.

Data and MC sample

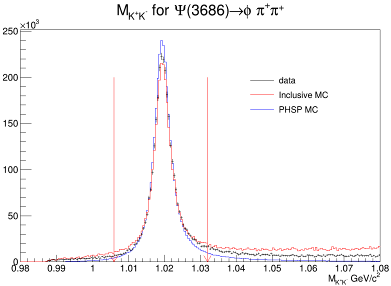
- BOSS version 7.0.9.p01
- Data sample
  - 2021 2.26B $\psi(3686)$ sample
- Official inclusive MC sample including
  - $\psi(3686) \to K^+K^-\pi^+\pi^-$ (0.08×10^6)
  - $\psi(3686) \to K^+K^-K^+K^-$ (1.72×10^6)
- Exclusive MC sample
  - PHSP generate $\psi(3686) \to \phi\pi^+\pi^-, \phi \to K^+K^-(6 \times 10^8)$
  - PHSP generate $\psi(3686) \to \phi K^+K^-, \phi \to K^+K^-(5 \times 10^8)$

Event selection

- Good charged Track:
  - $|V_r| < 1.0$ cm and $|V_z| < 10.0$ cm
  - $|\cos\theta| < 0.93$
- 4 good charged tracks & net charge is 0
- PID (TOF and dE/dx)
  - Kaon:$\mathrm{Prob(K)} > \mathrm{Prob}(\pi)$ and $\mathrm{Prob(K)} > 0.001$
  - Pion:$\mathrm{Prob}(\pi) > \mathrm{Prob(K)}$ and $\mathrm{Prob}(\pi) > 0.001$

Event selection for $\psi(3686) \to \phi\pi^+\pi^-$

- PID and charge: $K^+K^-\pi^+\pi^-$
- 4C fit: $\chi^2_{4c} < 200$
- ϕ Signal region: $1.006 < M_{K^+K^-} < 1.032 \mathrm{GeV/c^2}$ with signal purity at 80% level

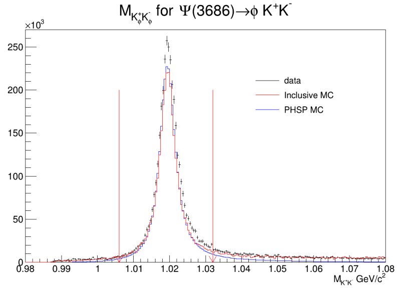


Event selection for $\psi(3686) \to \phi K^+ K^-$

- PID and charge: $K^+K^-K^+K^-$
- 4C fit: $\chi^2_{4c} < 200$
- Two kaons are labeled with subscript ϕ as the mass of them is closest to that of ϕ, that is $K^+_\phi K^-_\phi K^+ K^-$
- ϕ Signal region:

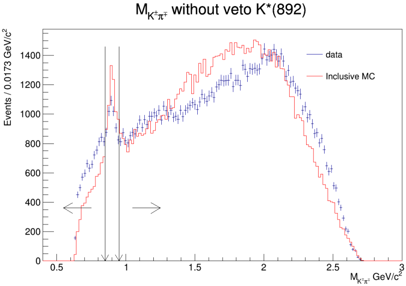
  $1.006 < M_{K^+_\phi K^-_\phi} < 1.032 \mathrm{GeV/c^2}$

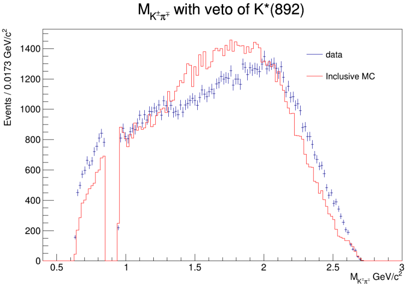
  with signal purity at 80% level



Veto $K^*(892) \to K^\pm \pi^\mp$ for $\psi(3686) \to \phi\pi^+\pi^-$

- $M_{K^\pm\pi^\mp} < 0.85$ or $M_{K^\pm\pi^\mp} > 0.95$ is required





Background study

Inclusive MC sample is used to study potential backgrounds. After applying above cuts, topology analysis is performed based on the inclusive MC. The main decay channels of backgrounds shows in Appendix(II)

- Peaking backgrounds in $\psi(3686) \to \phi\pi^+\pi^-$:
  - mainly from $k^*(892) \to (K\pi)^{+-}$: 2%
- Other small backgrounds levels
  - in $\psi(3686) \to \phi\pi^+\pi^-$: 3%
  - in $\psi(3686) \to \phi K^+K^-$: 0.3%

Continuum background

Non-ϕ background levels in topology analysis:

- $\psi(3686)$ directly to $K^+K^-\pi^+\pi^-$: 5.4%
- $\psi(3686)$ directly to $K^+K^-K^+K^-$: 5.3%

Backgrounds above can be further suppressed in ϕ reweight,and then will fix in the fit of PWA as backgrounds.

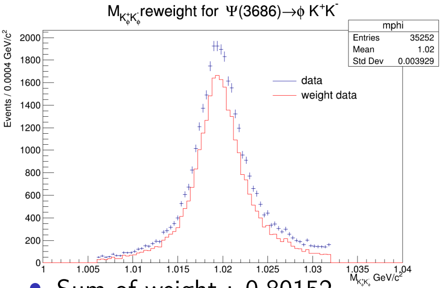
$\phi(1020)$ reweight

Backgrounds above can be further suppressed in ϕ reweight,and then will fix in the fit of PWA as backgrounds.

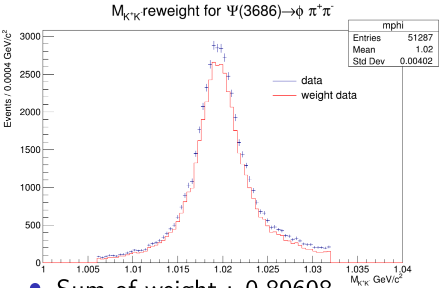
Fit the remaining data with a double-Gaussian function for signal and second-order polynomial for background.The probability density function(PDF) is described as

$$Q_i = \frac{F_s\left(\xi_r^i, \hat{\alpha}_i\right)}{F_s\left(\xi_r^i, \hat{\alpha}_i\right) + F_b\left(\xi_r^i, \hat{\alpha}_i\right)}$$

- Reference :M.Williams,M.Bellis&C.A.Meyer,Journal of Instrument -ation,4(10), P10003(2009) reweight results



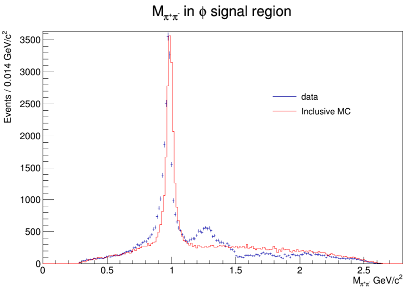
- Sum of weight : 0.80152

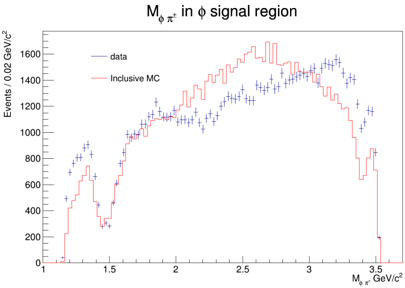


- Sum of weight : 0.89698

The summed weights is consistent with the number of signal events in the inclusive MC.

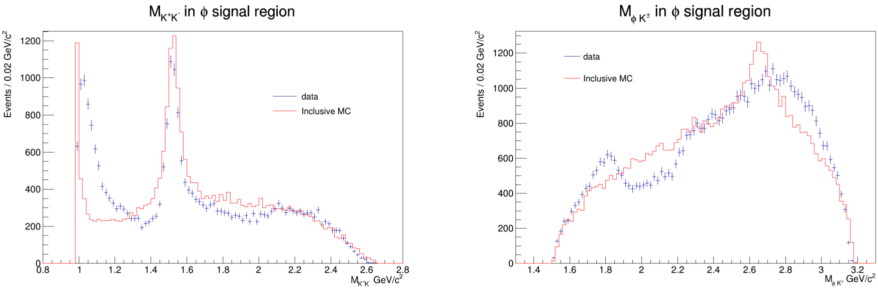
$M_{f_{\pi^+\pi^-}}$ and $M_{b_{\phi\pi^\pm}}$ for $\psi(3686) \to \phi\pi^+\pi^-$





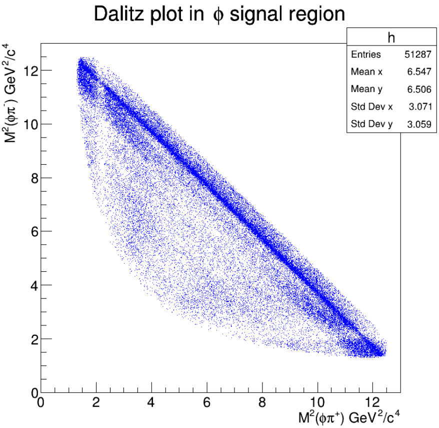
- Some difference between data and MC is observed

$M_{f_{K^+K^-}}$ and $M_{b_{\phi K^\pm}}$ for $\psi(3686) \to \phi K^+ K^-$

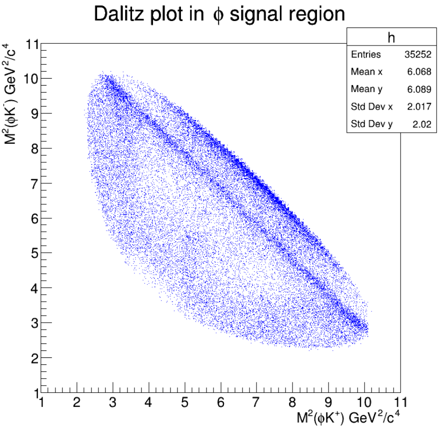


- Some difference between data and MC is observed.

Dalitz plots for $\psi(3686) \to \phi\pi^+\pi^-$



Dalitz plots for $\psi(3686) \to \phi\pi^+\pi^-$



Dalitz plots for $\psi(3686) \to \phi K^+ K^-$

- The amplitudes are composed with covariant tensors

$$\frac{d\sigma}{d\Phi} = \frac{1}{2}\sum_{\mu=1}^{2} A^{\mu} A^{*\mu} = \frac{1}{2}\sum_{i,j}\Lambda_i\Lambda_j^{*}\sum_{\mu=1}^{2} U_i^{\mu} U_j^{*\mu}$$

  - reference: B.S.Zou and D.V.Bugg,Eur.Phys.J.A 16,537-547(2003)

- Most propagators are modeled using relativistic Breit-Wigner function.

$$f = \frac{1}{m_0^2 - m^2 - i m_0 \Gamma_0}$$

- Propagator for $f_0(980)$ is modeled using the Flatté formula

$$f = \frac{1}{m_0^2 - m^2 - i m_0 \left(\Gamma_{\pi\pi} + \Gamma_{K\bar{K}}\right)}$$

PWA: likelihood functions

$$\ln L = \sum_{i=1}^{N} \ln N_{\mathrm{gen}} \sum_{\mu=1}^{2} A^{\mu}(\xi_i, \alpha) A^{*\mu}(\xi_i, \alpha) - N \ln \sum_{j=1}^{N_{\mathrm{acc}}} \sum_{\mu=1}^{2} A^{\mu}(\xi_j, \alpha) A^{*\mu}(\xi_j, \alpha)$$

A^{μ}–amplitude under given parameters α and phase space point ξ
N–number of observed events
$N_{\mathbf{gen}}$–number of events generated by simulation
$N_{\mathbf{acc}}$–number of accepted events after detector acceptance simulation.
Non-ϕ backgrounds are described by add resonance with infinite width into the fit, which is expressed in the likelihood function as:

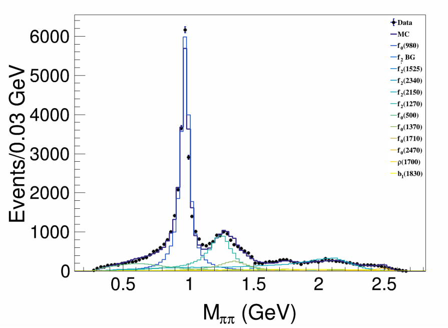
$$\ln L(\mathrm{signal}) = \ln L(\mathrm{data}) - \ln L(\mathrm{background})$$

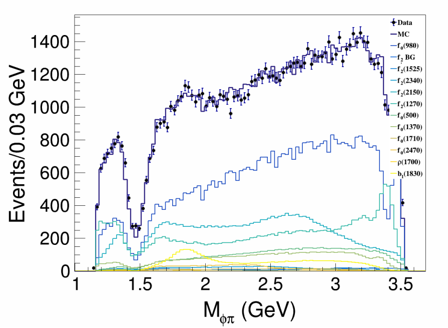
PWA :fit strategy

- Strategy to add resonances
  - First a baseline solution from knowledge and eyes
  - Add resonance considering significance
- Simultaneous fit on K^+K^- and $\pi^+\pi^-$ modes
  - Constraint on: mass & width of resonances, relative amplitude ratios ,total fraction of all resonances
- PWACG - Partial Wave Analysis Code Generator
  - GitHub[https://github.com/caihao/PWACG]

PWA baseline for $\psi(3686) \to \phi\pi^+\pi^-$

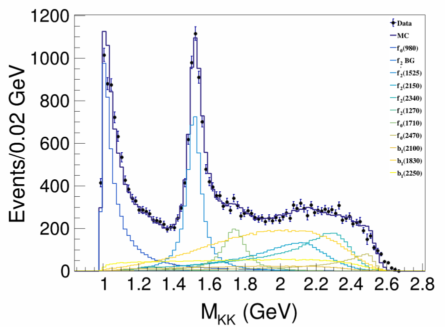
- *Error bar is data; blue line is the result of PWA*

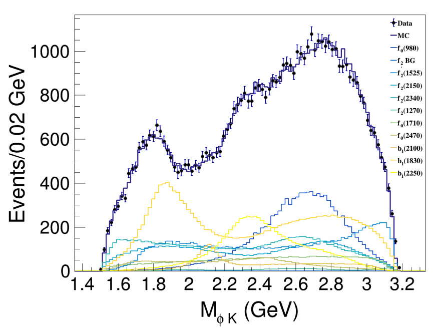




PWA baseline for $\psi(3686) \to \phi K^+K^-$(I)

- *Error bar is data; blue line is the result of PWA*





PWA baseline $\psi(3686) \to \phi\pi^+\pi^-$

mode name	fraction(%)	mass(MeV)	PDG mass	width(MeV)	PDG width	significance
$f_0(980)$	49.08	972.42±0.49	990.0±20	-	-	>10
$f_2(1950)$	23.60	2149.5±5.6	1936 ±12	436.1±1.0	464±24	>10
$f_2(1270)$	19.81	1275.6±2.8	1275 ±0.8	197.6±5.1	$186.6^{+2.8}_{-2.2}$	>10
$f_0(500)$	7.569	535.4±9.0	400 - 800	643±21	100 - 800	>10
$f_0(1370)$	6.404	1350±12	1200 - 1500	265.4±9.0	200 - 500	>10
$b_1(1830)$	5.251	1833.9±5.8	-	320.7±6.2	-	>10
$f_0(2470)$	3.158	2521.4±4.8	2346^{+6}_{-7}	114.0±1.4	75^{+14}_{-12}	>10
$f_2(2340)$	2.004	2358±16	2346^{+21}_{-10}	322±23	331^{+27}_{-18}	>10
$f_0(1710)$	0.9106	1742.9±3.4	1733^{+8}_{-7}	140.1±7.5	150^{+12}_{-10}	>10
$f_2'(1525)$	0.8256	1512.0±1.3	1517±2.4	86.2±2.6	86.0±4	9.74
$\rho(1900)$	0.1089	1851.4±7.8	1880±10	131±24	69±15	7.10
BG	1.137	-	-	-	-	-
sum fraction	119.9	-	-	-	-	-

PWA baseline $\psi(3686) \to \phi K^+ K^-$

mode name	fraction(%)	mass(MeV)	PDG mass	width(MeV)	PDG width	significance
$b_1(1830)$	30.35	1833.9±5.8	-	320.7±6.2	-	>10
$f_2(2340)$	15.19	2358±16	2346^{+21}_{-10}	322±23	331^{+27}_{-18}	>10
$f_2'(1525)$	14.04	1512.0±1.3	1517±2.4	86.2±2.6	86.0±4	>10
$f_0(980)$	11.93	972.42±0.49	990.0±20	-	-	>10
$b_1(2250)$	11.62	2309±39	-	380±18	-	>10
$f_2(1950)$	10.82	2149.5±5.6	2095^{+17}_{-19}	436.1±1.0	287^{+32}_{-24}	>10
$f_0(2470)$	9.970	2521.4±4.8	2346^{+6}_{-7}	114.0±1.4	75^{+14}_{-12}	>10
$f_0(1710)$	4.829	1742.9±3.4	1733^{+8}_{-7}	140.1±7.5	150^{+12}_{-10}	>10
$b_1(2100)$	3.543	2109±22	-	135±23	-	7.56
$f_2(1270)$	0.6639	1275.6±2.8	1275±0.8	197.6±5.1	$186.6^{+2.8}_{-2.2}$	9.67
BG	$<10^{-8}$	-	-	-	-	-
sum fraction	113.0	-	-	-	-	-

- $f_0(980)$ Faltte parameters fit result $g_1 = 63.8 \pm 1.2\mathrm{MeV}$, $g_2 = 1.31 \pm 0.13$

Discussion about b_1 states

According to B.S.Zou's article, there are speculations about $(s\bar{s}q\bar{q})$ four-quark states which could decay to ϕK or $\phi\pi$.
Partial wave amplitudes for $\psi(2s) \to X\pi(K), X \to \phi\pi(K)$:

- For X being a $\rho'(1^{--})$state, there is only one independent amplitude since both $\psi(2s) \to \rho'\pi(K)$ and $\rho' \to \phi\pi(K)$ are limited to a P wave
- For X being a $b_1(1^{+-})$state, there are four independent amplitudes since $\psi(2s) \to b_1\pi(K)$ and $b_1 \to \phi\pi(K)$ both can have both S and D waves

b_1 possible J^P assignments

Possible J^P assignments 1^-and1^+, for all b_1 resonance are tested statistical significance

mode	1+ over 1-			1- over 1+		
	$\Delta \ln \mathrm{L}$	Δndf	sig.	$\Delta \ln \mathrm{L}$	Δndf	sig.
$b_1(1830)$	857.9	20	>30	49.35	8	8.61
$b_1(2100)$	42.75	10	7.56	26.53	4	6.50
$b_1(2250)$	277.9	10	22.6	45.79	4	8.89

The significance tests favor all b_1 resonances are 1^+ states.

Signal efficiency

0.7×10^6 $\psi(3683) \rightarrow \phi K^+K^-$ and 1.17×10^6 $\psi(3683) \rightarrow \phi\pi^+\pi^-$ MC samples with amplitude information were generated to estimate the detector response and event selection efficiency.

Cut	before	after	efficiency(%)
detector response	1170823	410618	35.07
$M_{K^+K^-} \in (1.006, 1.032)\mathrm{MeV}/c^2$	410618	376488	91.68
$M_{K^\pm\pi^\mp} \notin (0.85, 0.95)\mathrm{MeV}/c^2$	376488	346238	91.94
total	1170823	346238	29.57

Cut	before	after	efficiency(%)
detector response	705882	199484	28.26
$M_{K^+K^-} \in (1.006, 1.032)\mathrm{MeV}/c^2$	199484	183602	92.03
total	705882	183602	26.01

Branch Fraction Measurement(preliminary)

Calculate the branching ratio

$$\frac{\Gamma(f \to K^+K^-)}{\Gamma(f \to \pi^+\pi^-)} = \frac{B(f \to K^+K^-)}{B(f \to \pi^+\pi^-)} \times \frac{\varepsilon_2 N(\psi' \to \phi K^+K^-)}{\varepsilon_1 N(\psi' \to \phi\pi^+\pi^-)}$$

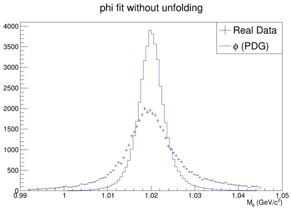
Where ε_1 represents the signal efficiency of $\psi' \to \phi K^+K^-$,ε_2 represents the signal efficiency of$\psi' \to \phi\pi^+\pi^-$, N is the total number of events after selection for the corresponding process, and B represents the branch ratio for a certain resonance in all$\psi' \to \phi K^+K^-$or $\psi' \to \phi\pi^+\pi^-$progress.

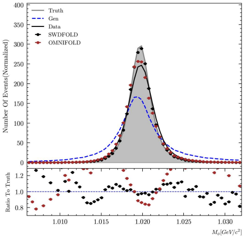
Branch Fraction Measurement(preliminary)

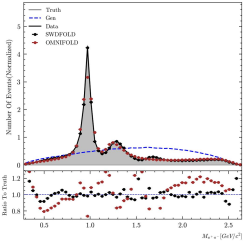
mode	$B(f \to K^+K^-)/\%$	$B(f \to \pi^+\pi^-)/\%$	$\frac{\Gamma(f\to K^+K^-)}{\Gamma(f\to\pi^+\pi^-)}$	pdg value
$f_0(980)$	11.93	49.08	0.19	0.52
$f_2(1270)$	0.6639	19.81	0.026	0.054
$f_2'(1525)$	14.04	0.8256	13	13
$f_0(1710)$	4.829	0.9106	4.2	4.3
$f_2(1950)$	10.82	23.60	0.36	-
$f_2(2340)$	15.19	2.004	5.9	-
$f_0(2470)$	9.970	3.158	2.5	-
$b_1(1830)$	30.35	5.251	4.5	-

Data Unfolding

Due to the significant impact of detector resolution on the real data of ϕ,current fitting method for ϕ involves fixing values to the PDG values.The next step will be to apply unfolding to the real ϕ data in order to achieve a more accurate fit.







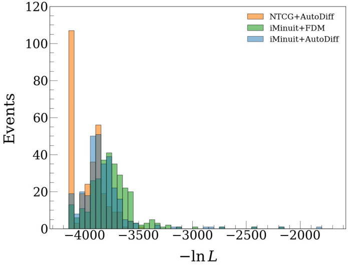
- arXiv[https://doi.org/10.48550/arXiv.2406.01635]

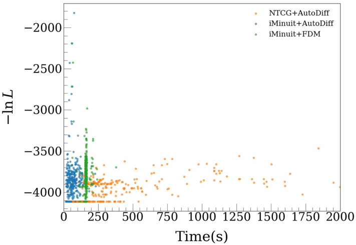
Summary and to-do list

- The baseline is determined and the fit is stable.
- The branching ratio is calculated.
- Three b_1 states have been observed significantly in the $\phi\pi$ and ϕK system.
- Estimate systematic errors and calculate statistical errors.
- Calculate the branching ratio error.
- Using data unfolding in our fit.

PWACG - Partial Wave Analysis Code Generator

- PWA program based on JAX tensor calculation
- Multi-threaded GPU computation and low memory use
- jinja2 code generator: building programs flexibly





- arXiv[https://doi.org/10.48550/arXiv.2403.09225]

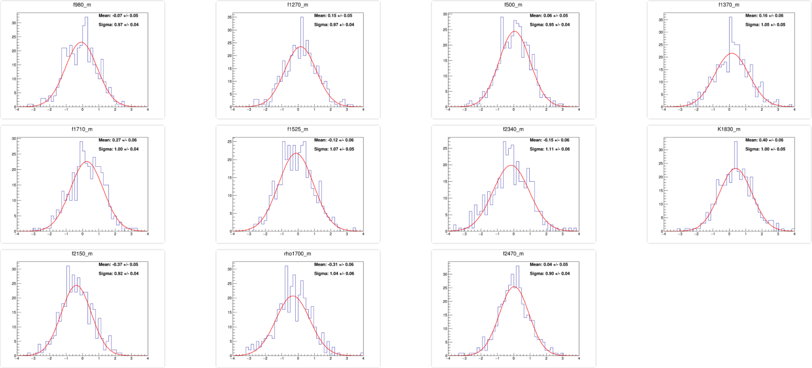
Appendix(II): topoanalysis result for $\psi(3686) \to \phi\pi^+\pi^-$

No.	iDcyTr	nEtr	Decay Chain
1	1	16334	$\psi(2S) \to \pi^+\pi^-\phi, \phi \to K^+K^-$
2	2	13949	$\psi(2S) \to \phi f_0(980), \phi \to K^+K^-, f_0(980) \to \pi^+\pi^-$
3	0	1885	$\psi(2S) \to \pi^+\pi^-K^+K^-$
4	6	734	$\psi(2S) \to \rho^0 K^+K^-, \rho^0 \to \pi^+\pi^-$
5	8	483	$\psi(2S) \to \phi f_0(1710), \phi \to K^+K^-, f_0(1710) \to \pi^+\pi^-$
6	3	251	$\psi(2S) \to \phi f_0(980), \phi \to K^+K^-, f_0(980) \to \pi^+\pi^-\gamma_f$
7	4	234	$\psi(2S) \to \pi^-\overline{K}^{*0}K^+, \overline{K}^{*0} \to \pi^+K^-$
8	5	220	$\psi(2S) \to \pi^+K^{*0}K^-, K^{*0} \to \pi^-K^+$
9	11	135	$\psi(2S) \to \pi^+K_2^{*0}K^-, K_2^{*0} \to \pi^-K^+$
10	7	132	$\psi(2S) \to \pi^+\pi^-\phi\gamma_f, \phi \to K^+K^-$
11	12	123	$\psi(2S) \to \pi^-\overline{K}_2^{*0}K^+, \overline{K}_2^{*0} \to \pi^+K^-$
12	18	83	$\psi(2S) \to \phi f_2', \phi \to K^+K^-, f_2' \to \pi^+\pi^-$
13	13	24	$\psi(2S) \to \pi^+\pi^-a_0, a_0 \to K^+K^-$
14	-	197	modes less than 20 entries

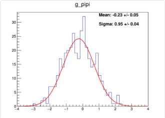
Appendix(II): topoanalysis result for $\psi(3686) \to \phi K^+ K^-$

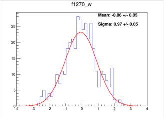
No.	iDcyTr	nEtr	Decay Chain
1	0	24240	$\psi(2S) \to K^+K^-\phi, \phi \to K^+K^-$
2	1	7320	$\psi(2S) \to \phi f_2', \phi \to K^+K^-, f_2' \to K^+K^-$
3	2	3342	$\psi(2S) \to \phi f_0(980), \phi \to K^+K^-, f_0(980) \to K^+K^-$
4	3	2007	$\psi(2S) \to K^+K^+K^-K^-$
5	4	477	$\psi(2S) \to \phi f_0(1710), \phi \to K^+K^-, f_0(1710) \to K^+K^-$
6	5	47	$\psi(2S) \to K^+K^-\phi\gamma_f, \phi \to K^+K^-$
7	12	39	$\psi(2S) \to \phi f_2', \phi \to K^+K^-, f_2' \to K^+K^-\gamma_f$
8	7	18	$\psi(2S) \to K^+K^-f_2', f_2' \to K^+K^-$
9	-	30	modes less than 20 entries

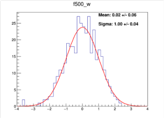
Appendix(III):pull distribution of fit parameters in $\phi\pi^+\pi^-$

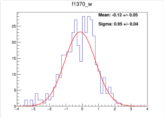


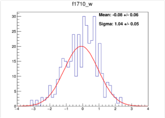
Appendix(III):pull distribution of fit parameters in $\phi\pi^+\pi^-$

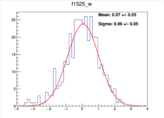


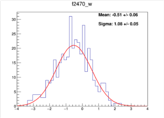


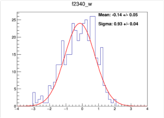


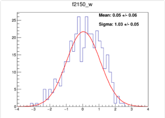


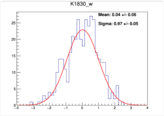


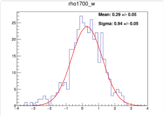




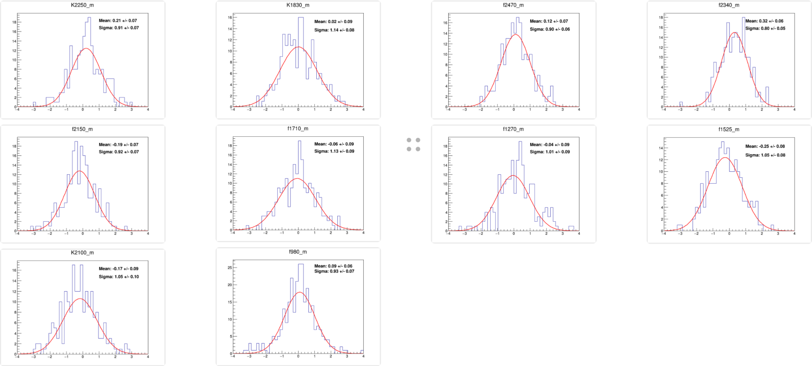




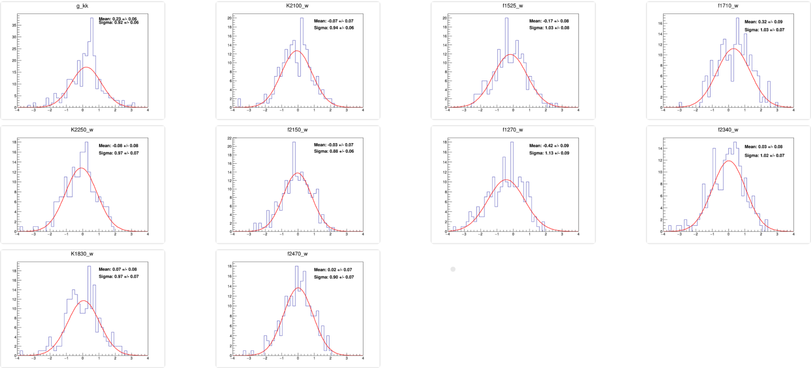




Appendix(III):pull distribution of fit parameters in ϕK^+K^-



Appendix(III):pull distribution of fit parameters in ϕK^+K^-



Thanks!