Energy calibration for the data collected below 2 GeV

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Outline

Motivation

- The 2024 R-QCD scan data is collected from April 4, 2024 to June 7, 2024.
- Data table[1]: 13 energy points below 2 GeV, total luminosity 24.8 pb^{-1}

$E_{\text{c.m.}}$	E_{beam}	Run start	Run end	Day start	Day end	N_{hadron} (online)	Lum (nb^{-1}, online)	N_{runs}	T_{pure}
1.84	0.92	81849	81970	2024-04-04	2024-04-12	95225	1501.16859	113	105:54:4
1.87	0.935	81971	82104	2024-04-12	2024-04-21	134317	2002.61137	131	120:41:25
1.872	0.936	82543	82656	2024-05-16	2024-05-23	123359	2014.243081	112	99:36:12
1.874	0.937	82657	82783	2024-05-23	2024-05-30	126692	2018.925277	107	98:7:44
1.875	0.9375	82835	82909	2024-06-02	2024-06-07	96666	1485.36413	71	69:6:24
1.876	0.938	82105	82203	2024-04-21	2024-04-27	114388	2032.83002	88	89:17:43
1.877	0.9385	82784	82834	2024-05-30	2024-06-02	82078	1340.88419	50	49:21:59
1.878	0.939	82204	82261	2024-04-27	2024-05-01	91678	2020.95641	57	52:53:30
1.882	0.941	82262	82310	2024-05-01	2024-05-04	95556	2032.727	49	47:56:19
1.886	0.943	82311	82358	2024-05-04	2024-05-07	100997	2031.15264	47	43:43:55
1.9	0.95	82359	82404	2024-05-07	2024-05-10	89832	2022.1664	46	44:52:1
1.94	0.97	82405	82462	2024-05-10	2024-05-12	93843	2036.75904	57	46:30:29
1.97	0.985	82463	82530	2024-05-13	2024-05-16	112591	2229.09763	66	56:4:58
total		81849	82909	2024-04-04	2024-06-07	1357222	24768.885778	994	924:6:43

[1] Hao Zhang's talk in Tau-QCD group meeting on Dec. 18, 2024

Motivation

- The interesting physical phenomenon near $N\bar{N}$ threshold[2] need us to calibrate the center-of-mass energy.
- The process $e^+e^- \to \mu^+\mu^-$ is used to calibrate the E_{cms}, and three other channels, $e^+e^- \to K^+K^-$, $e^+e^- \to 2(\pi^+\pi^-)$ and $e^+e^- \to 3(\pi^+\pi^-)$ are used as the cross check.
- We can calibrate the center-of-mass energy by the following formula,

$$M^{cor}_{final\ states} = M^{data}_{final\ states} + M^{mc,off}_{final\ states} - M^{mc,on}_{final\ states}$$

where $M^{data}_{final\ states}$ is the peaking position of data sample and $M^{mc,off}_{final\ states}$($M^{mc,on}_{final\ states}$) is the peaking position of MC sample with ISR/FSR off(on).

[2] Xiaorong Zhou's talk in BESIII Collaboration Meeting on Dec. 4, 2023

Outline

Event selection: $e^+e^- \to \mu^+\mu^-$

- We require exactly 2 good charged tracks with opposite charge satisfying:
  - $|V_z| < 10.0$ cm, $|V_r| < 1.0$ cm
  - $|\cos\theta| < 0.8$
- To remove Bhabha events, we require
  - $E/pc < 0.4$
- To suppress di-muon events with high energy radiative photons as well as cosmic rays, we require
  - $|\Delta\theta| \equiv |\theta_1 + \theta_2 - 180^\circ| < 10^\circ$
  - $|\Delta\phi| \equiv ||\phi_1 - \phi_2| - 180^\circ| < 5^\circ$
  - $|\Delta T| = |t_1 - t_2| < 1.5$ ns

MC samples: generated by Jin Fang

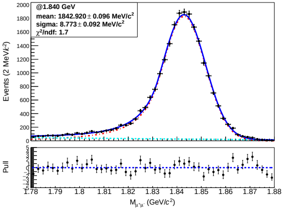
BabayagaNLO is used to generate 2 sets of dimu MC sample:

- ISR/FSR off: BabayagaNLO.PhotonNumber=0;
- ISR/FSR on: BabayagaNLO.PhotonNumber=-1;("-1 means all")

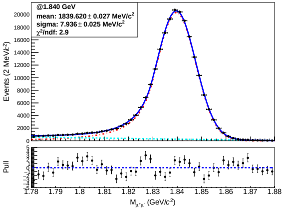
$E_{\rm cms}$ (GeV)	1.84	1.87	1.872	1.874	1.875	1.876	1.877	1.878	1.882	1.886	1.9	1.94	1.97
mc OFF	0.40 M	0.50 M	0.50 M	0.50 M	0.40 M	0.55 M	0.35 M	0.50 M	0.50 M	0.50 M	0.50 M	0.50 M	0.50 M
mc ON	0.42 M	0.54 M	0.55 M	0.55 M	0.40 M	0.55 M	0.36 M	0.55 M	0.55 M	0.55 M	0.53 M	0.52 M	0.55 M

Fit data/MC peak

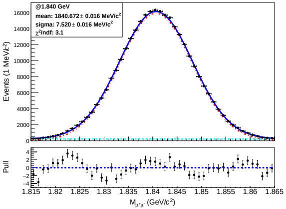
Taking the first energy point, 1.840 GeV sample as an example, the fit results of the data, MC with ISR/FSR on and off, are shown below.



Crystalball fit on data

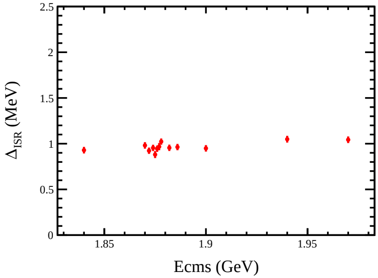


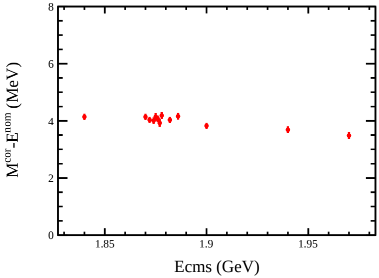
Crystalball fit on MC(ISR/FSR on)



Crystalball fit on MC(ISR/FSR off)

Results: $M^{cor}_{\mu^+\mu^-} = M^{data}_{\mu^+\mu^-} + M^{mc,off}_{\mu^+\mu^-} - M^{mc,on}_{\mu^+\mu^-}$





- $\Delta_{ISR} = M^{mc,off}_{\mu^+\mu^-} - M^{mc,on}_{\mu^+\mu^-}$, and E^{nom} is the requested energy when collecting data.
- The ISR/FSR effect for dimu process is about 1 MeV and a shift of ~ 4 MeV for center-of-mass energy can be found in dimu process.

Outline

Event selection: $e^+e^- \to K^+K^-$

The selection criteria for $e^+e^- \to K^+K^-$ are reffered to a BESIII work[3] by Dong Liu.

- We require exactly 2 good charged tracks with opposite charge satisfying:
  - $|V_z| < 10.0$ cm, $|V_r| < 1.0$ cm
  - $|\cos\theta| < 0.93$
- To remove Bhabha events, we require
  - $E/pc < 1.46674 - 0.444252 \cdot E_{cm} + 0.0623961 \cdot E_{cm}^2$
  - $\cos\theta < 0.8$ for positive charged track, $\cos\theta > -0.8$ for negative charged track
- To suppress the background events from multibody final state and cosmic rays, we require
  - $\theta(K^+, K^-) > 179°$
  - $|\Delta T| = |t_1 - t_2| < 3$ ns
  - $|P_K - P_{exp}| < \sigma_P$, where $P_{\rm exp} = \sqrt{s/4 - m_K^2 c^4}/c$ and $\sigma_P = 0.001171 \cdot E_{\rm cms}^2 + 0.01128 \cdot E_{\rm cms} - 0.013500$ (fitted by Yijing Wang).

[3] PRD 99, 032001 (2019)

MC samples of $e^+e^- \to K^+K^-$

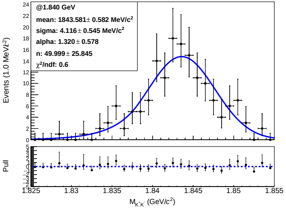
Phokhara is used to generate 2 sets of MC sample: (The FSR is turned off for both samples because Phokhara cannot handle FSR effect for scan mode.)

- ISR off: Phokhara.ScanMode = -1, Phokhara.NLO = 0;
- ISR on: Phokhara.ScanMode = 1, Phokhara.NLO = 1;

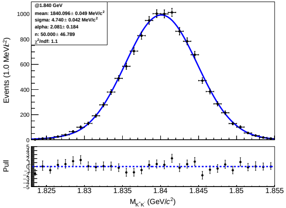
E_{cms} (GeV)	1.84	1.87	1.872	1.874	1.875	1.876	1.877	1.878	1.882	1.886	1.9	1.94	1.97
mc OFF	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M
mc ON	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M

Fit data/MC peak

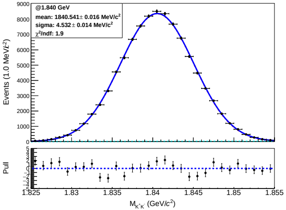
Taking the first energy point, 1.840 GeV sample as an example, the fit results of the data, MC with ISR on and off, are shown below.



Crystalball fit on data

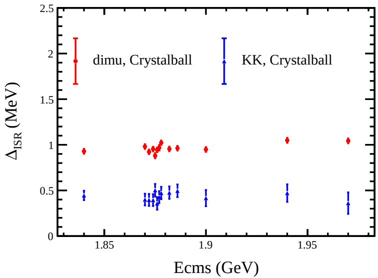


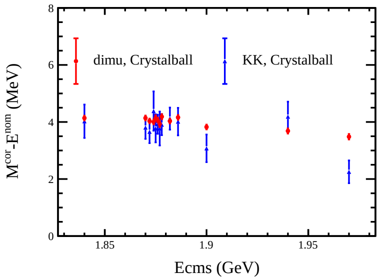
Crystalball fit on MC(ISR/FSR on)



Crystalball fit on MC(ISR/FSR off)

Results: $M^{cor}_{K^+K^-} = M^{data}_{K^+K^-} + M^{mc,off}_{K^+K^-} - M^{mc,on}_{K^+K^-}$





- The ISR effect for $e^+e^- \to K^+K^-$ process is about 0.4 MeV.
- The shift of center-of-mass energy is consistent with dimu process.

Outline

Event selection: $e^+e^- \to 2(\pi^+)2(\pi^-)$

The selection criteria are reffered to 4π channel data quality check by Yijing Wang [4].

- Good charged tracks:
  - $|V_z| < 10.0$ cm, $|V_r| < 1.0$ cm, $|\cos\theta| < 0.93$
  - $E/p \leq 0.85$, $p/E_{\mathrm{beam}} < 0.9$
  - $N_{\mathrm{good}} = 4$
- PID:
  - $Prob(\pi) > Prob(p\&K)$
  - $N_{\pi^+} = 2$, $N_{\pi^-} = 2$
- Vertex Fit: Successful vertex fit for the four charged tracks

[4] BESIII Parallel R-QCD report on July 4, 2024

MC samples of $e^+e^- \to 2(\pi^+\pi^-)$

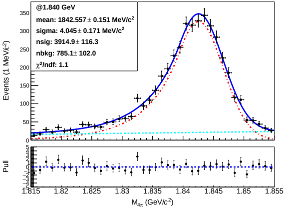
Phokhara is used to generate 2 sets of MC sample: (The FSR is turned off for both samples because Phokhara cannot handle FSR effect for scan mode.)

- ISR off: Phokhara.ScanMode = -1, Phokhara.NLO = 0;
- ISR on: Phokhara.ScanMode = 1, Phokhara.NLO = 1;

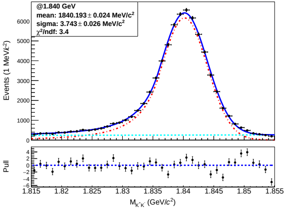
$E_{\rm cms}$ (GeV)	1.84	1.87	1.872	1.874	1.875	1.876	1.877	1.878	1.882	1.886	1.9	1.94	1.97
mc OFF	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M
mc ON	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M

Fit data/MC peak

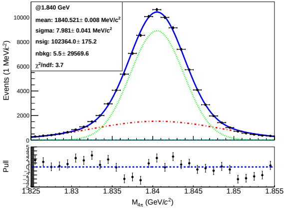
Taking the first energy point, 1.840 GeV sample as an example, the fit results of the data, MC with ISR on and off, are shown below.



Crystalball fit on data

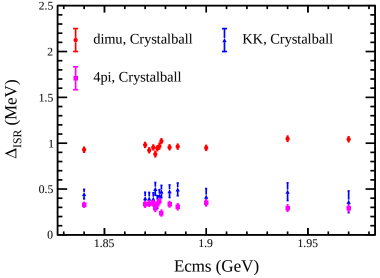


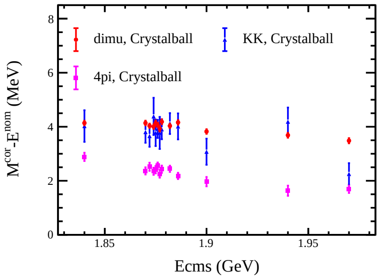
Crystalball fit on MC(ISR/FSR on)



Gauss fit on MC(ISR/FSR off)

Results: $M^{cor}_{4\pi} = M^{data}_{4\pi} + M^{mc,off}_{4\pi} - M^{mc,on}_{4\pi}$





- The ISR effect for $e^+e^- \to 2(\pi^+\pi^-)$ process is about 0.4 MeV.
- The shift of center-of-mass energy for $e^+e^- \to 2(\pi^+\pi^-)$ is about 1.5 MeV smaller than dimu and K^+K^- processes.

MC samples of $e^+e^- \to 2(\pi^+\pi^-)$

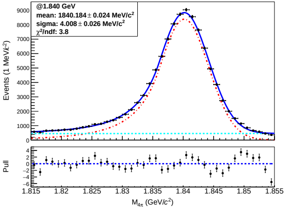
In order to check whether it comes from FSR effect, another generator, ConExc, is used to generate 2 sets of MC samples:

- FSR off: no PHOTOS;
- FSR on: with PHOTOS

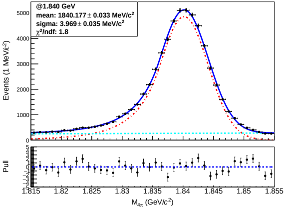
$E_{\rm cms}$ (GeV)	1.84	1.87	1.872	1.874	1.875	1.876	1.877	1.878	1.882	1.886	1.9	1.94	1.97
FSR OFF	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M
FSR ON	0.36 M	0.36 M	0.32 M	0.40 M	0.40 M	0.38 M	0.38 M	0.36 M	0.38 M	0.40 M	0.40 M	0.38 M	0.38 M

Fit data/MC peak

Taking the first energy point, 1.840 GeV sample as an example, the fit results of the ConExc MC with FSR on and off, are shown below.

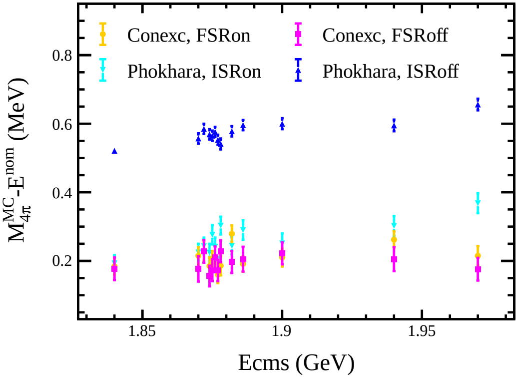


Crystalball fit on MC(FSR on)



Crystalball fit on MC(FSR off)

FSR effect on 4π channel:



- The FSR effect on 4π channel is very small.

Outline

Event selection: $e^+e^- \to 3(\pi^+\pi^-)$

The selection criteria are reffered to 6π channel data quality check by Tiantian Lei and Gaole Peng.

- Good charged tracks:
  - $|V_z| < 10.0$ cm, $|V_r| < 1.0$ cm, $|\cos\theta| < 0.93$
  - $N_{\text{good}} = 6$
- PID:
  - $Prob(\pi) > Prob(p\&K)$
  - $N_{\pi^+} = 3$, $N_{\pi^-} = 3$
- Vertex Fit: Successful vertex fit for the four charged tracks

MC samples of $e^+e^- \to 3(\pi^+\pi^-)$

- ISR off: PHSP;
- ISR on: ConExc with both ISR and Born process

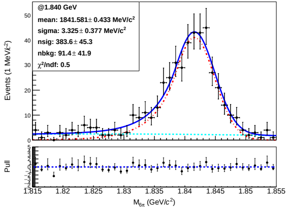
E_{cms} (GeV)	1.84	1.87	1.872	1.874	1.875	1.876	1.877	1.878	1.882	1.886	1.9	1.94	1.97
mc OFF	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M
mc ON	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M	0.2 M

The FSR is turned off for both samples, because the PHOTOS package cannot handle decays into six particle states.

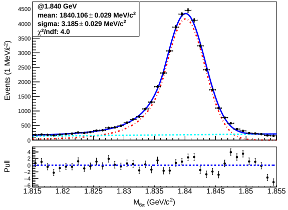
```
 stmt1: select MdcRes,MdcEff from MdcTuning where RunFrom <= 81916 and RunTo >= 81916 and SftVer = "6.6.3"
 cnt = 0
 row = 0
 ********************************************************************************
 *                                                                              *
 * PHOENE: Too much Bremsstrahlung required, PRSOFT =       -0.294012           *
 * Fatal Error Message, I stop this Run !                                       *
 *                                                                              *
 ********************************************************************************
WARNING - Attempt to delete the physical volume store while geometry closed !
WARNING - Attempt to delete the logical volume store while geometry closed !
WARNING - Attempt to delete the solid store while geometry closed !
WARNING - Attempt to delete the region store while geometry closed !
```

Fit data/MC peak

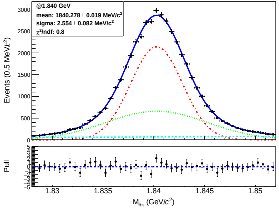
Taking the first energy point, 1.840 GeV sample as an example, the fit results of the data, MC with ISR on and off, are shown below.



Crystalball fit on data

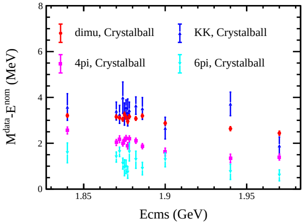


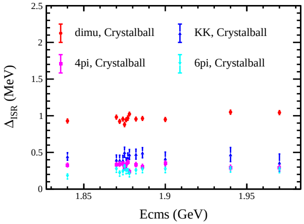
Crystalball fit on MC(ISR/FSR on)

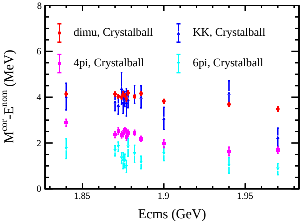


Gauss fit on MC(ISR/FSR off)

Results: $M_{6\pi}^{cor} = M_{6\pi}^{data} + M_{6\pi}^{mc,off} - M_{6\pi}^{mc,on}$





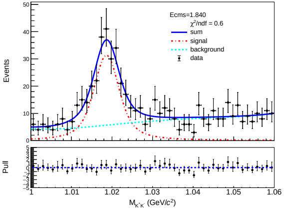


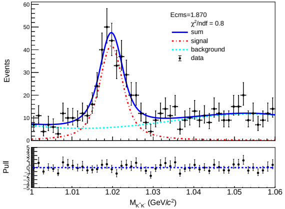
- The results of $e^+e^- \to \mu^+\mu^-$ and $e^+e^- \to K^+K^-$ are consistent.
- The results of $e^+e^- \to 2(\pi^+\pi^-)$ and $e^+e^- \to 3(\pi^+\pi^-)$ are smaller than dimu and K^+K^- processes.

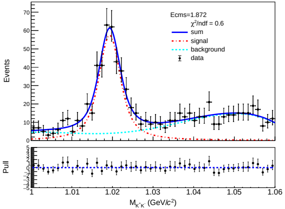
Outline

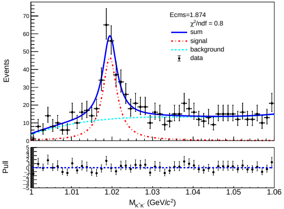
Fit inclusive ϕ peak in each data sample

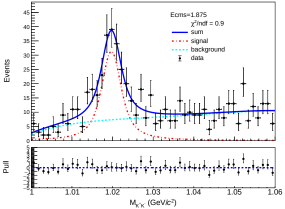
To check the Kaon momentum validation, we select inclusive ϕ in each data sample and fit ϕ peak.

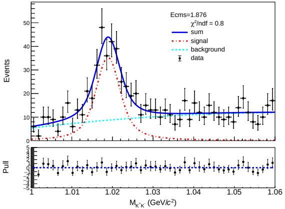






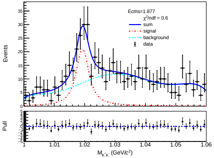


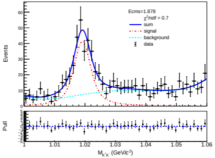


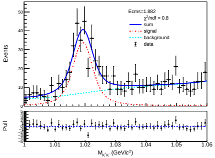


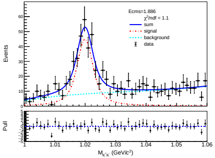
Fit inclusive ϕ peak in each data sample

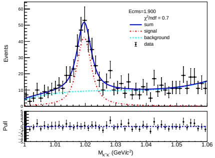
To check the Kaon momentum validation, we select inclusive ϕ in each data sample and fit ϕ peak.

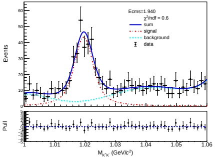


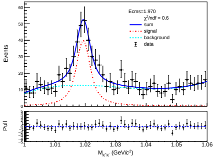








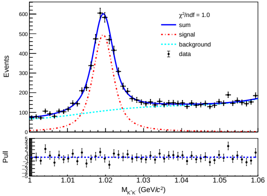


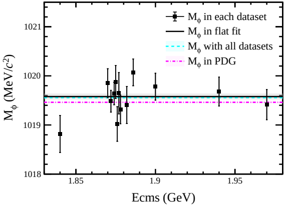


Momentum validation: inclusive ϕ

Momentum validation	M_{PDG} (MeV/c^2)	M_{obs} (MeV/c^2)	diff (MeV/c^2)
$\phi \to K^+K^-$	1019.461 ± 0.016	1019.558 ± 0.086 (overall)	0.10 (1.0σ)
		1019.578 ± 0.058 (mean)	0.12 (1.6σ)

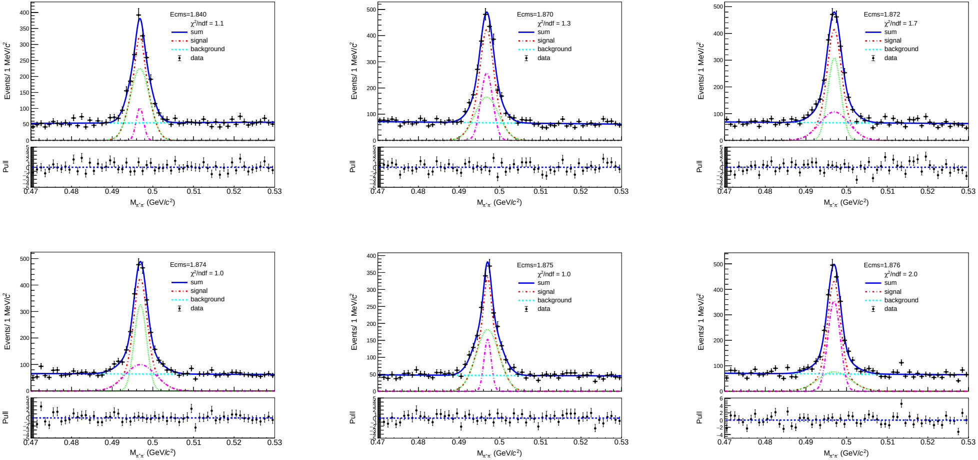
- Selection criteria of inclusive ϕ are reffered to Yuepeng Zhang.
- Fit funtion: BW$\otimes$Gauss + 3rd-Chebyshev polynomial, with the mean value of Gauss is fixed to 0. The results are consistent with the mean value of BW fixed to PDG ϕ mass.





Fit inclusive K_S peak in each data sample

To check the Pion momentum validation, we select inclusive K_S in each data sample and fit K_S peak.



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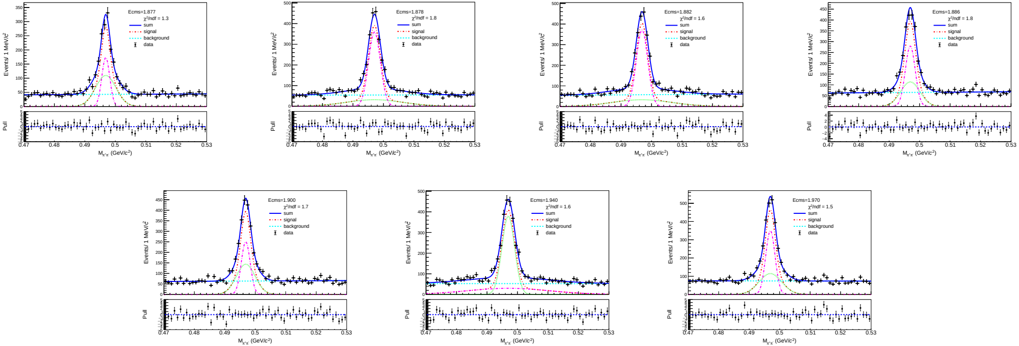
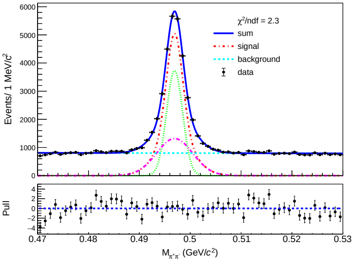
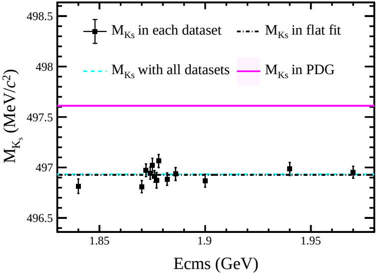


Momentum validation: inclusive K_S

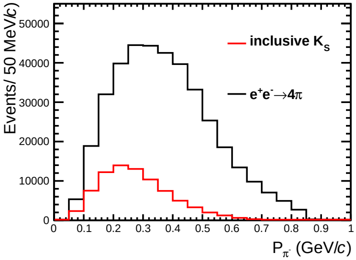
- Selection criteria of inclusive K_S are reffered to Yateng Zhang[5].
- Fit funtion: double-Gauss + 1st-Chebyshev polynomial.
- $\Delta M_{K_S} \sim 0.7\ \mathrm{MeV}$ for data below 2 GeV

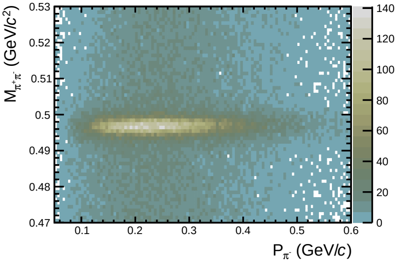




[5] PRL 130.231901 (2023)

π^- momentum distribution

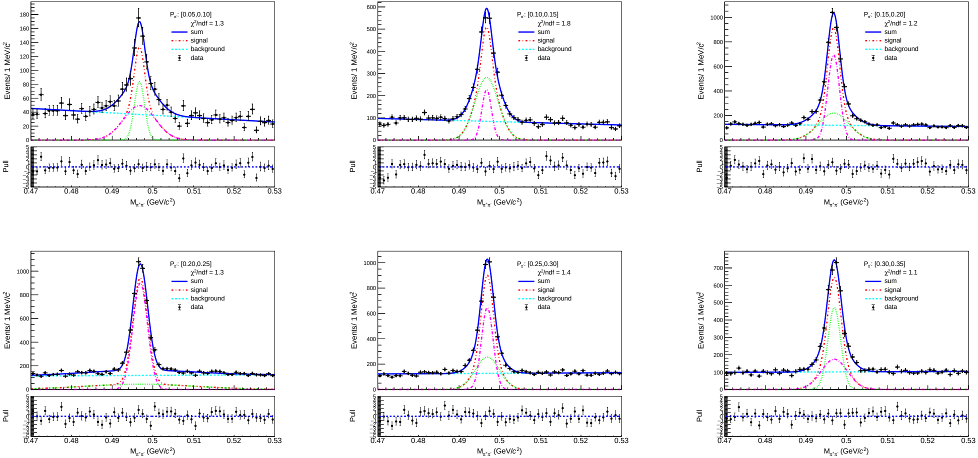




$$0.47 \leq M_{\pi^+\pi^-} \leq 0.53\ \mathrm{GeV}/c^2$$

Fit K_S peak in each π^- momentum bin

Every 50 MeV/c one interval, the momentum of π^- is divided into 11 intervals. The mass of K_S is fitted in each momentum interval.



Fit K_S peak in each π^- momentum bin

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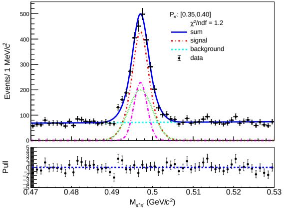
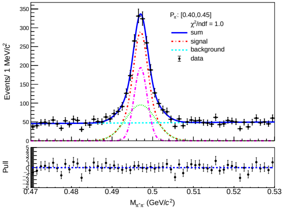
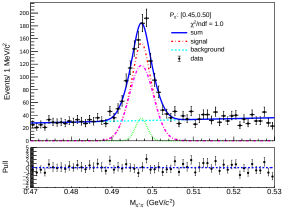
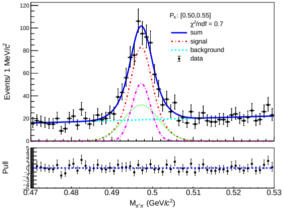
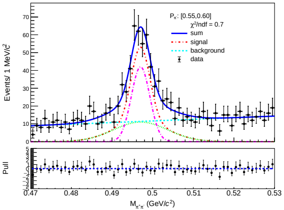




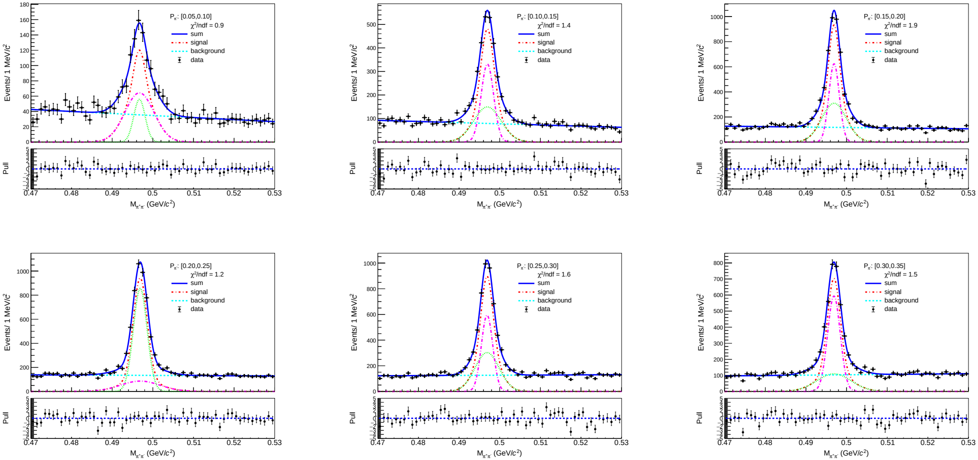






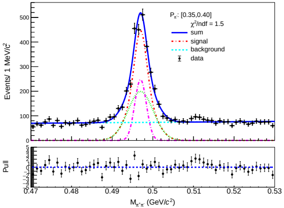
Fit K_S peak in each π^+ momentum bin

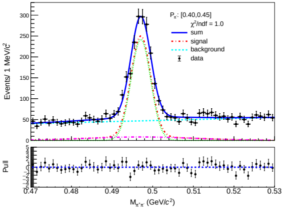
Every 50 MeV$/c$ one interval, the momentum of π^+ is divided into 11 intervals. The mass of K_S is fitted in each momentum interval.

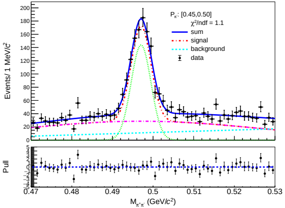


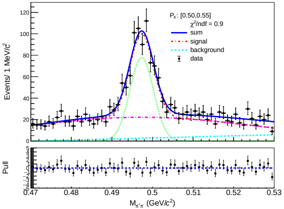
Fit K_S peak in each π^+ momentum bin

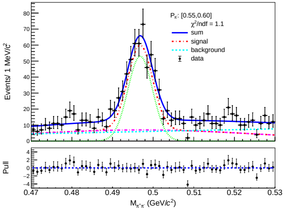
Every 50 MeV$/c$ one interval, the momentum of π^- is divided into 11 intervals. The mass of K_S is fitted in each momentum interval.





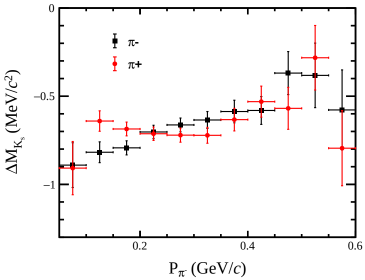


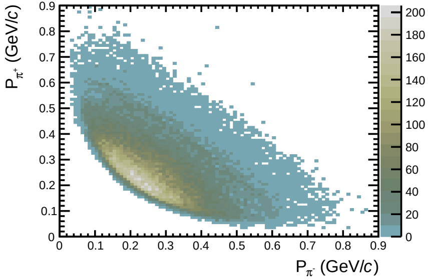




K_S mass shift on P_π

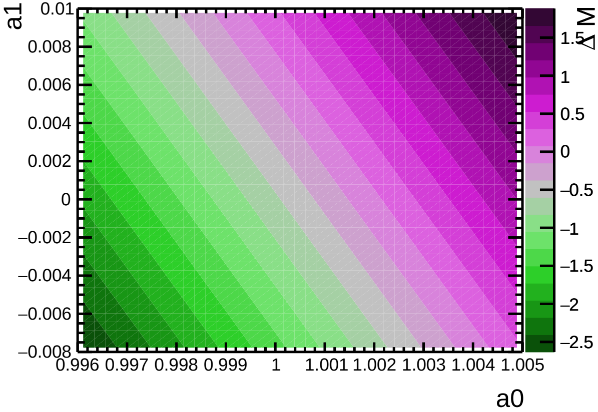
- The mass shift of K_S decreases as P_{π^-} (P_{π^+}) increase.





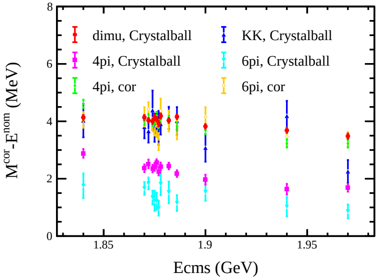
2D scan

- Assume: $f_{\pi^+} = f_{\pi^-} = a_1 \cdot p + a_0$
- Apply the factor to pions and fit K_S mass, and compare with $M_{K_S}^{PDG}$.



Correct 4π and 6π channels

- use $f = 1.003 - 0.004 \cdot p$ (global minimum, $\Delta M_{K_S} = 0.021\ \mathrm{MeV}$)
- $m_{inv} = \sqrt{(\sum E)^2 - (\sum \vec{p})^2} \to m_{inv} = \sqrt{(\sum E')^2 - (\sum f \cdot \vec{p})^2}\ (E' = \sqrt{m^2 + |f \cdot \vec{p}|^2})$

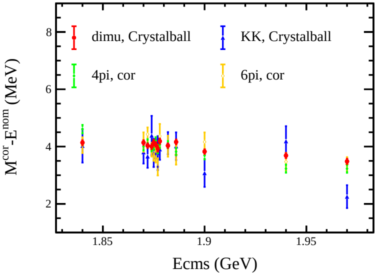


- After correction, the results of the 4 channels are consistent with each other.

Outline

Summary and to do list

- Summary
  - The energy of data below 2 GeV is calibrated by the process $e^+e^- \to \mu^+\mu^-$, $e^+e^- \to K^+K^-$, $e^+e^- \to 2(\pi^+\pi^-)$ and $e^+e^- \to 3(\pi^+\pi^-)$. The results are consistent with each other, and dimu results are shown in the table below.
  - About 4 MeV shifts are found in each data sample.
- To do list:
  - Cross check π momentum validation in Rscan-2015 data and J/ψ data.
  - Study the systematic uncertainties and prepare the memo.



E^{nom} (MeV)	E^{cor} (MeV)
1840	1844.138 ± 0.083
1870	1874.137 ± 0.084
1872	1876.035 ± 0.079
1874	1878.002 ± 0.084
1875	1879.139 ± 0.099
1876	1880.073 ± 0.080
1877	1880.925 ± 0.101
1878	1882.185 ± 0.089
1882	1886.032 ± 0.081
1886	1890.160 ± 0.083
1900	1903.824 ± 0.080
1940	1943.686 ± 0.088
1970	1973.483 ± 0.092