Search for CP violation in $\psi(3686) \rightarrow \pi^+\pi^- J/\psi$

Jingxu Zhang, Shuangshi Fang, Xiongfei Wang
Lanzhou University && IHEP

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Outline

- Motivation
- Data sets
- Event selection
- Results
- Systematic uncertainty
- Summary

Motivation

- Exploration for novel sources of CP violation beyond the standard model (SM) stands as an interesting endeavor in particle physics.
- The **colored EDM (CEDM) of the *c* quark** is proposed as a new source of CP violation. The effective interaction Lagrangian is defined as[1]

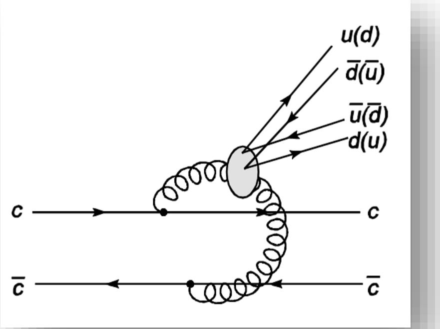
$$\mathcal{L}_{\text{CEDM}} = -\frac{i}{2} d'_c \bar{\psi}_c \sigma^{\mu\nu} \gamma_5 \frac{\lambda_a}{2} \psi_c G^a_{\mu\nu},$$

- The CEDM contributes to the static potential between c and $\bar{c}$, which causes the **mixing between CP-even and CP-odd $c\bar{c}$ bound states**, like $\psi(3686)$ and J/ψ. A CP observable can be defined by CP odd operator $\mathcal{O}$.

$$A_{\mathcal{O}} \equiv \frac{N_{\text{events}}(\mathcal{O} > 0) - N_{\text{events}}(\mathcal{O} < 0)}{N_{\text{events}}(\mathcal{O} > 0) + N_{\text{events}}(\mathcal{O} < 0)}.$$

[1] Phys. Rev. D, 85, 114010 (2012), by Y. P. Kuang.

Motivation



- The CP symmetry of $\psi(3686) \to \pi^+\pi^- J/\psi$ was studied in BESII[2].

$$\boldsymbol{CP}\ A\left(p_{\pi^+}, p_{\pi^-}, p_{J/\psi}\right) = A(-p_{\pi^-}, -p_{\pi^+}, -p_{J/\psi})$$

- Three CP-odd operators correlation of the final-state particles are defined to study CP violation in unpolarized e^+ and e^- c.m. system:

This work → $\boxed{\mathcal{O}(q_{zz}) = \left(p^z_{\pi^+} - p^z_{\pi^-}\right) \cdot (p_{\pi^+} \times p_{\pi^-})^z}$

$$\mathcal{O}(q_2) = (p_{e^+} \times p_{\pi^+}) \cdot p_{\pi^-}$$

$$\mathcal{O}(q_{EE}) = p^E_{\pi^+} - p^E_{\pi^-}$$

$$A_{CP}(q_{zz}) = -0.004 \pm 0.005 \pm 0.007$$

$$A_{CP}(q_2) = 0.011 \pm 0.005 \pm 0.009$$

$$A_{CP}(q_{EE}) = -0.007 \pm 0.005 \pm 0.010$$

BESII results

- CP violation effect in $\psi(3686) \to \pi^+\pi^- J/\psi$ is predicted to be **$\sim 10^{-5}$ by SM model**[3].
- With large events of $\psi(3686)$ collected at BESIII, the precision can be improved significantly.

[2] Fu C. D. (2005). [doctoral dissertation]. IHEP, CAS.
[3] arXiv:hep-ph/0001314 2018, by J. J. Zhu.

Motivation

- The expectation values of the CP-odd operator is linear in d'_c, in the assumption of CEDM of charm quark [1]. It shows:

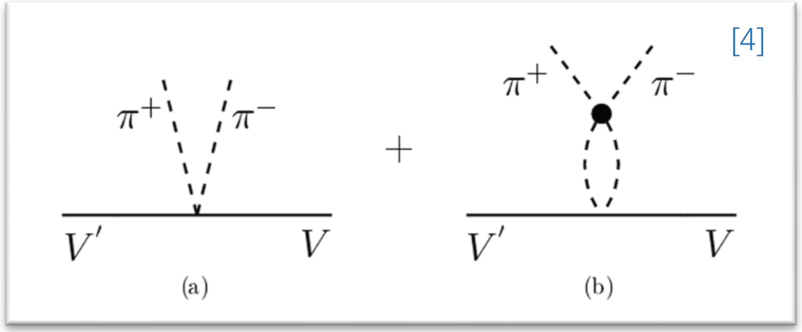
$$\begin{aligned}\langle O\rangle \quad &= \frac{\mathcal{A}}{\Gamma(\psi'\to J/\psi\pi\pi)}\{\mathcal{K}_{M1CEDM1}\mathcal{I}_{E1E1-M1CEDM1}+\mathcal{K}_{E1CEDM2}\mathcal{I}_{E1E1-E1CEDM2}\\ &+C/\mathcal{A}[\mathcal{K}_{E1M1}\mathcal{I}_{E1E1-E1M1}+\mathcal{K}_{M1CEMD1}\mathcal{I}_{E1E1-M1CEDM1}+\mathcal{K}_{E1CEDM2}\mathcal{I}_{E1E1-E1CEDM2}]\}d'_c\cdot m_c,\end{aligned}$$

Here, $\mathcal{A},\mathcal{C}$ are the constant parameters, the $\mathcal{K}s$ are the hadronization factor coefficients at soft-pion approach, the $\mathcal{I}s$ are the phase-space integrations of the interference terms.

- We can then get the correlation with model dependent[1]:
  - $<\mathcal{O}>= 0.00933 * \boldsymbol{d'_c}\cdot m_c$ in SM,
  - $<\mathcal{O}>= 0.00693 * \boldsymbol{d'_c}\cdot m_c$ in Cornell model.

The m_c is the mass of charm quark. It can help to extract the strength of CEDM contribution.

Decay amplitude for $\psi(3686) \to \pi^+\pi^- J/\psi$



I. Chiral perturbation theory (ChPT) [5]

$$\mathcal{A}(\Psi' \to \Psi\pi^+\pi^-) = -\frac{4}{F_0^2}\left\{\underbrace{\left[\frac{g}{2}(m_{\pi\pi}^2 - 2M_\pi^2) + g_1 E_{\pi^+}E_{\pi^-}\right]}_{\text{S-Wave}} \epsilon_\Psi^* \cdot \epsilon_{\Psi'} + \underbrace{g_2\left[p_{\pi^+\mu}p_{\pi^-\nu} + p_{\pi^+\nu}p_{\pi^-\mu}\right]}_{\text{D-Wave (ignored)}} \epsilon_\Psi^{*\mu}\epsilon_{\Psi'}{}^\nu\right\}$$

A^{tree}

$$Amp = A^{tree} + A^{1-loop}$$

II. The chiral unitary approach (CHUA) is used to study the dipion transitions. (Final states interaction, FSI)

The $\pi\pi$ S-wave scattering amplitude is:

$$T(q^2) = V(q^2)[1 - G(q^2)V(q^2)]^{-1}$$

- Where, $q^2 = m_{\pi\pi}^2$
- Where, $V = \frac{1}{F_\pi^2}\begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix}$
  - $V_{11} = M_{\pi^0}^2/2$
  - $V_{12} = \frac{q^2 - M_{\pi^0}^2}{\sqrt{2}} = V_{21}$
  - $V_{22} = [q^2 + 4(M_{\pi^+}^2 - M_{\pi^0}^2)]/2$
  - F_π is pion decay constant

- Where, $G = diag(G_{00}, G_{+-})$

$$G_{00(+-)} = -\frac{1}{16\pi^2}\left[\gamma + \sigma_{0(+)} log\left(\frac{\sigma_{0(+)} + 1}{\sigma_{0(+)} - 1}\right)\right]$$

- γ is a subtraction parameter to regularize the loop
- μ is the mass of ρ meson
- $\sigma_{0(+)} = \sqrt{1 - \frac{4M_{\pi^{0(+)}}}{q^2}}$

The 1-loop amplitude in the CHUA is: [6]

$$A^{1-loop} = A^{tree}[1 + G_{00}T_{12} + \sqrt{2}G_{+-}T_{22}]$$

[4] Nucl.Phys.A761:269-282,2005 by F.K. GUO
[5] Z.Phys. C73 (1997) 541-546 by Mannel
[6] Eur. Phys. J. C (2013) 73:2284 by X.H. LIU

Data sets

BLIND ANALYSIS

Nature volume 526, pages187–189 (2015)

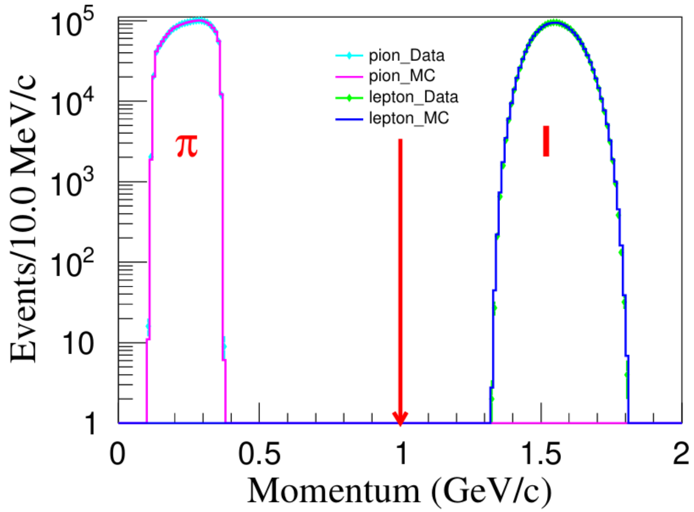
- BOSS 7.0.9
- Data sample:
  - **Semi-Data** of 2009, 2012 and 2021
- MC sample:
  - All years Inclusive MC

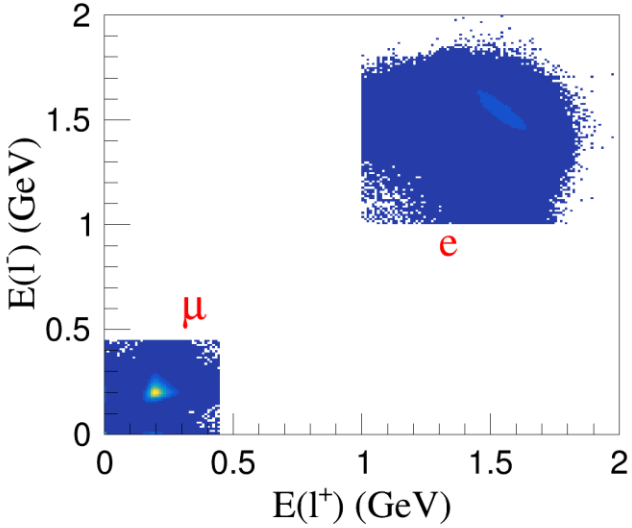
Decay mode	Generator	NR of events
$\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	PHSP	40 Million
	DIY, PHOTOS, VLL	42.8 Million
$\psi(3686) \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	PHSP	40 Million
	DIY, PHOTOS, VLL	42.8 Million

The exclusive MC is corrected by helix parameters.

Event selection

- **Charged tracks**
  - $|cos\theta| < 0.93$;
  - $|R_{xy}| < 1.0$ cm && $|R_z| < 10.0$ cm;
  - $N_{positive} = 2$ && $N_{negative} = 2$.
- **PID**
  - Use momentum to identify pions and leptons;
  - $p_\pi < 1.0\ \mathrm{GeV}/c$, $p_l > 1.0\ \mathrm{GeV}/c$;
  - $N_{\pi^-} = 1 \&\& N_{\pi^+} = 1 \&\& N_{l^+} = 1 \&\& N_{l^-} = 1$.
- **e, μ identification**
  - Deposited energy of EMC
  - Electron: $E_{emc}^{e^+} > 1.0$ GeV && $E_{emc}^{e^-} > 1.0$ GeV;
  - Muon: $E_{emc}^{\mu^+} < 0.45$ GeV && $E_{emc}^{\mu^-} < 0.45$ GeV.





Event selection

Vertex fit

- All final states require to be from same vertex;
- Vertex fit: Successful;

4C kinematic Fit

- Fit to pi+ pi- l+ l-;
- $\chi^2_{4C} < 100$;

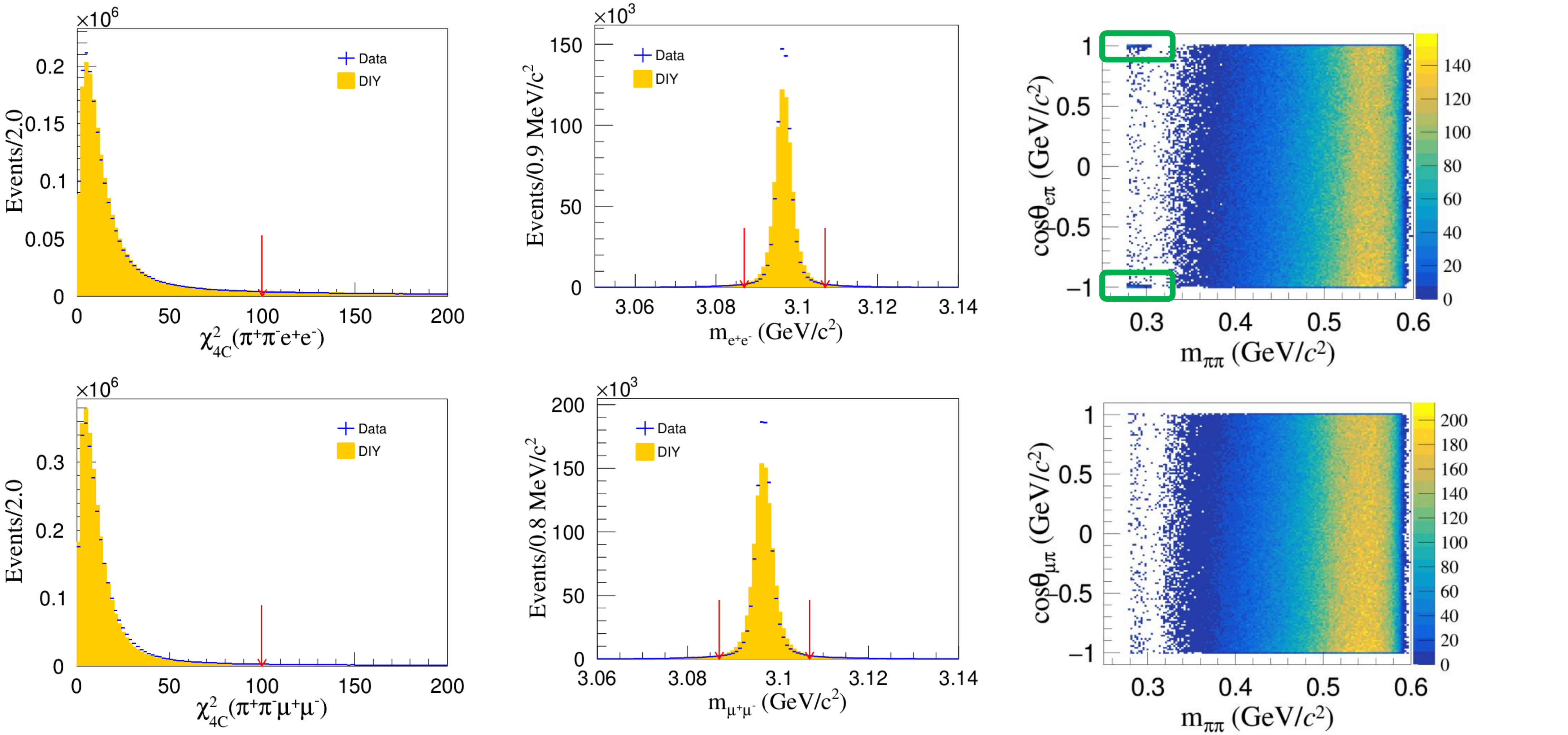
Further selection

- Select J/ψ: $|m_{l^+l^-} - 3.097| < 0.01\ \mathrm{GeV}/c^2$;
- $|q_{zz}| < 0.011$, $|q_2| < 0.058$, $|q_{EE}| < 0.2$;
- $|cos\theta_{\pi l}| > 0.95 \&\& m_{\pi\pi} < 0.32\ \mathrm{GeV}/c^2$.

Data and MC

e^+e^-

$\mu^+\mu^-$

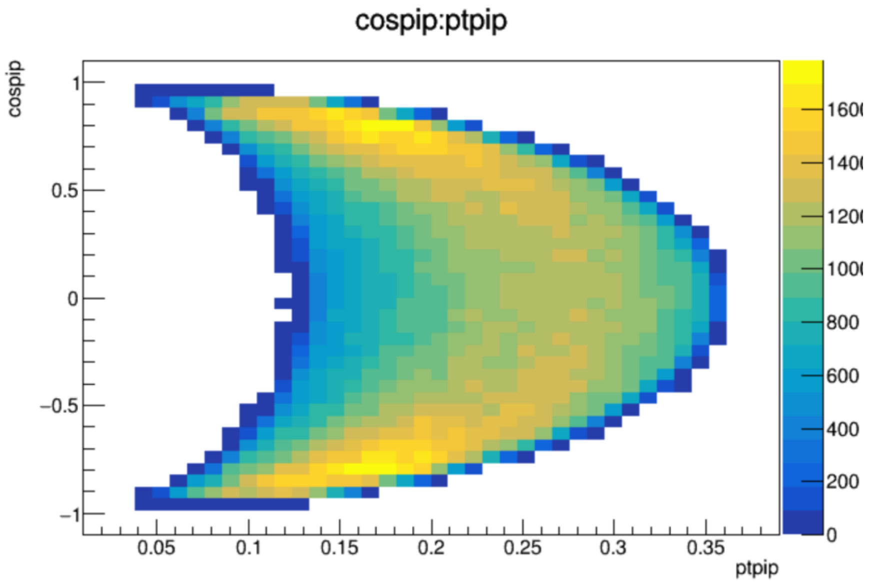


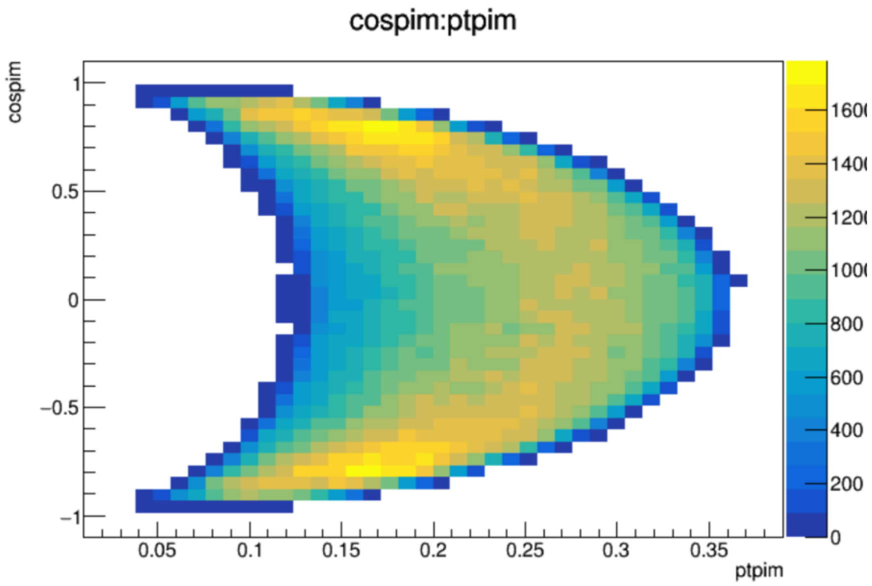
$\chi^2_{4C} < 100$ $\quad |m_{l^+l^-} - 3.097| < 0.01\ \text{GeV}/c^2$ $\quad |cos\theta_{\pi l}| > 0.95\&\&m_{\pi\pi} < 0.32\ \text{GeV}/c^2$

Tracking efficiency correction

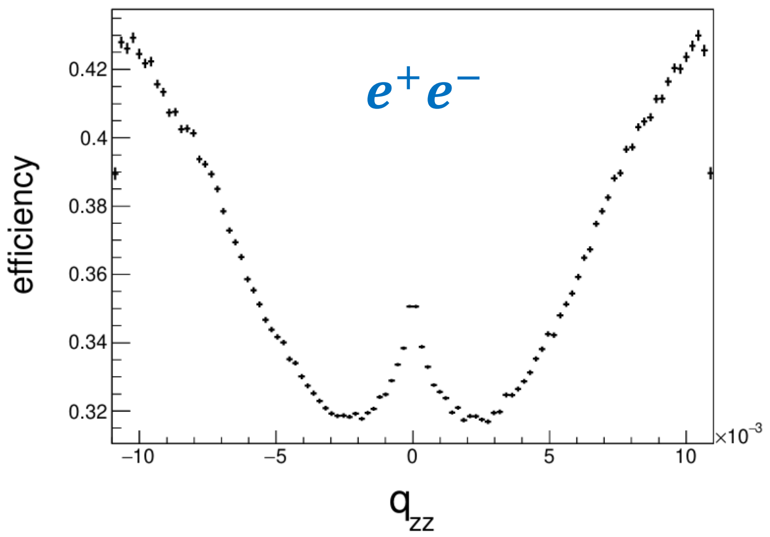
To improve the agreement between data and MC samples, the pion tracking efficiency are corrected for the CP operators. The $\pi^+\pi^-$ efficiency is quoted from BAM-00504, as the control sample is $J/\psi \to \pi^+\pi^-\pi^0$. The definition of correction factor is:

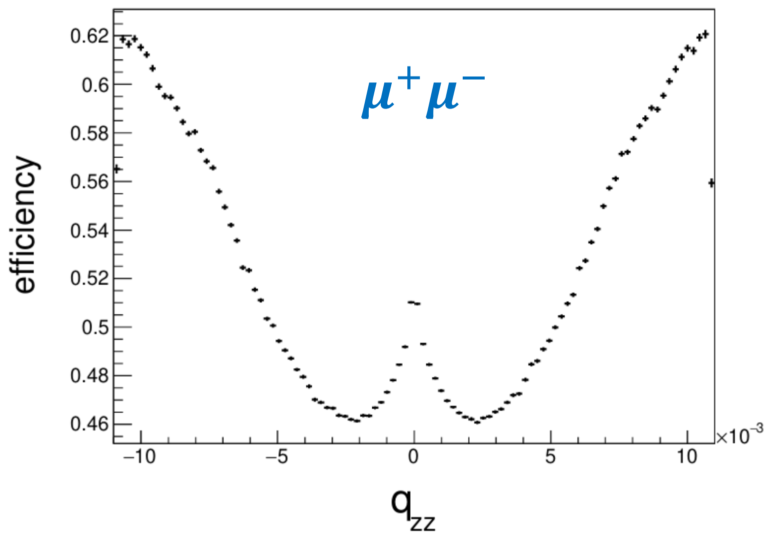
$$R(pt, cos\theta) = \frac{\epsilon_{data}^{\pi^+} \times \epsilon_{data}^{\pi^-}}{\epsilon_{MC}^{\pi^+} \times \epsilon_{MC}^{\pi^-}}$$





MC Efficiency





- Efficiency

$$\epsilon^i = \frac{N^i_{rec}}{N^i_{truth}}$$

Source	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$
Total events	4.28E+07	4.28E+07
Initial selection	40.37%	48.41%
EMC energy	37.38%	48.28%
$\chi^2_{4C} < 100$	30.04%	43.73%
J/ψ mass window	28.95%	42.07%
Cut Range	25.59%	37.19%

$$\mathbf{Err} = \sqrt{\frac{\boldsymbol{\epsilon * (1-\epsilon)}}{\boldsymbol{N_{tot}}}} = \mathbf{0.01\%}$$

Background study

- 0.02% (e^+e^-) and 0.3% ($\mu^+\mu^-$) background level based on inclusive MC.
- 467 (e^+e^-) and 449 ($\mu^+\mu^-$) events survived of 3.65 GeV data, corresponding to 410 pb-1.

$$f = \frac{\mathcal{L}_{\psi(3686)}}{\mathcal{L}_{3650}} \times \frac{s_{3650}}{s_{\psi(3686)}},$$

Table 2: Topology analysis from inclusive MC for e^+e^- decay channel.

rowNo	Decay chain	nEtr
1	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	14575864
2	$\psi' \to \eta J/\psi, \eta \to \pi^+\pi^-, J/\psi \to e^+e^-$	338
3	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \pi^+\pi^-$	74
4	$\psi' \to \pi^0\pi^0 J/\psi, J/\psi \to e^+e^-$	60
5	$\psi' \to e^+e^-$	50
6	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	45

Table 3: Topology analysis from inclusive MC for $\mu^+\mu^-$ decay channel.

rowNo	Decay chain	nEtr
1	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \mu^+\mu^-$	21156043
2	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to e^+e^-$	39309
3	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \pi^+\pi^-$	21791
4	$\psi' \to \pi^+\pi^- J/\psi, J/\psi \to f_0(2100)\gamma, f_0(2100) \to \pi^+\pi^-$	844
5	$\psi' \to \eta J/\psi, \eta \to \pi^+\pi^-, J/\psi \to \mu^+\mu^-$	459

Extract parameters in DIY model

$$Amp = A^{tree} + A^{1-loop}$$

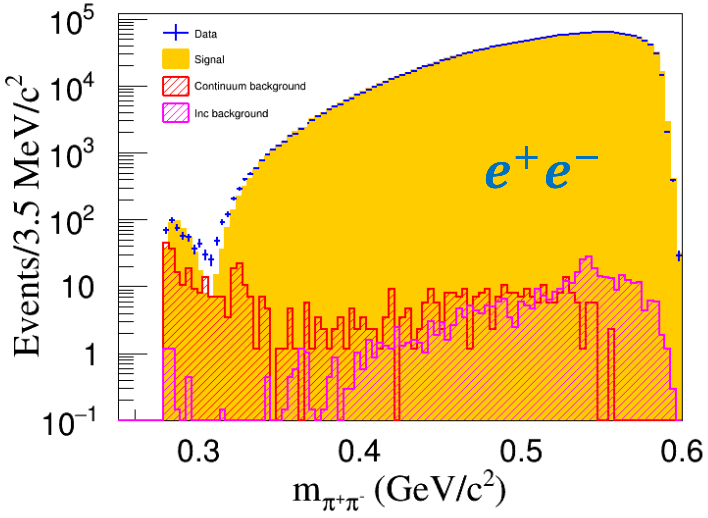
Likelihood Function:

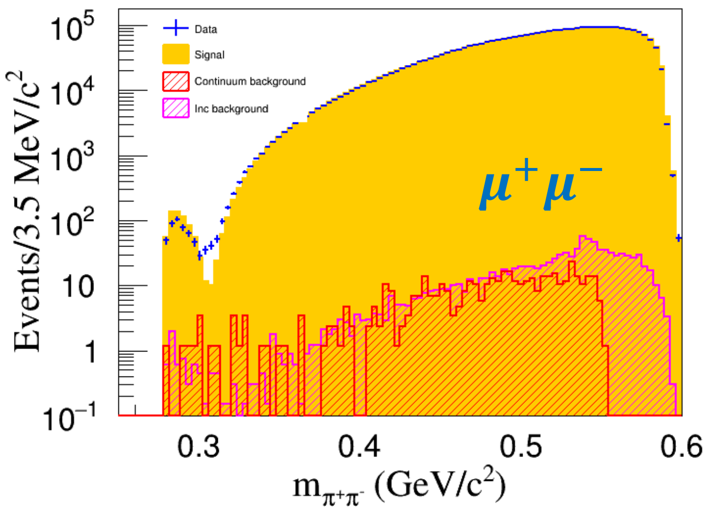
$$\mathcal{L} = \prod_{i=1}^{N} \frac{\mathcal{W}(\xi_i; g0, g1, g2, \gamma)\epsilon(\xi_i)}{\frac{1}{N_{MC}}\sum_{j=1}^{N_{MC}} \mathcal{W}(\xi_j; g0, g1, g2, \gamma)\epsilon d\xi_j}$$

Minimum Function:

$$\mathcal{S} = -ln\mathcal{L}_{data}$$

Parameters	Values
g0	0.2897 ± 0.0002
g1	-0.1085 ± 0.0001
g2	0
γ	-2.934 ± 0.004





A_{CP} measurements

$$q_{zz} = \left(p_z^{\pi^+} - p_z^{\pi^-}\right)\left(p_x^{\pi^+} p_y^{\pi^-} - p_x^{\pi^-} p_y^{\pi^+}\right)$$

- To extract the true nature of physics, it is necessary to do the efficiency correction to **the observed data samples (N^{obs}).**
- It helps to remove the effects on detector resolution and reconstructed processes.
- **The binned MC efficiency (ϵ^i)** is used to correct the observed data samples to the true physics level.
- **The true events of data (N_{data})** is:

$$N_{data}^i = \frac{N_{obs}^i}{\epsilon^i}$$

◆ The binned operator is summed together into two parts, N_{data}^+ with $\mathcal{O} > 0$ and N_{data}^- with $\mathcal{O} < 0$. Then, the A_{CP} observable is defined as:

$$A_{CP} = \frac{N_{data}^+ - N_{data}^-}{N_{data}^+ + N_{data}^-}$$

A_{CP} measurements – Operator distributions

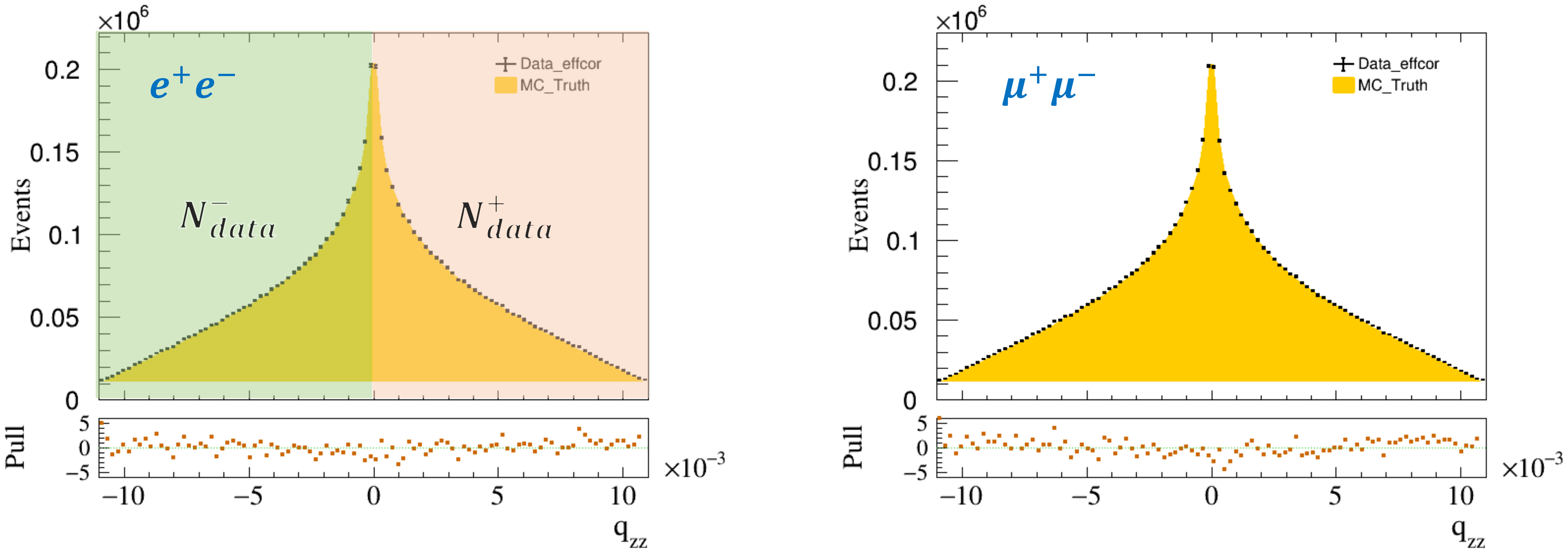


Table 6: The results for number of events N_{obs}, detection efficiency ϵ and A_{CP} values of q_{zz} in e^+e^- and $\mu^+\mu^-$ channels.

Channel	N^-_{obs}	N^+_{obs}	ϵ (%)	A_{CP} ($\times 10^{-4}$)
e^+e^-	1,060,050 ± 1030	1,060,660 ± 1030	25.59 ± 0.01	8.2 ± 7.2
$\mu^+\mu^-$	1,590,560 ± 1261	1,589,190 ± 1261	37.19 ± 0.01	-4.4 ± 5.8

Systematic uncertainty I

◆ Tracking efficiency

Quote ee efficiency from BAM−00543, $\mu\mu$ efficiency is from the same efficiency as $\pi\pi$. By defining the reweight factor, $reweight = \frac{\epsilon_{data}}{\epsilon_{MC}}$, the corrected MC samples are used to give the results. The difference between nominal results and corrected results is taken as systematic uncertainty.

For $\pi\pi$ tracking, the difference between nominal results and not-corrected results is taken as systematic uncertainty.

Table 8: Systematic uncertainty of A_{CP} from tracking efficiencies.

$\times 10^{-4}$	$J/\psi \to e^+e^-$			$J/\psi \to \mu^+\mu^-$		
Tracking	e^-	e^+	π	μ^-	μ^+	π
A_{CP}	0.1	0.3	0.1	0.0	0.0	0.2

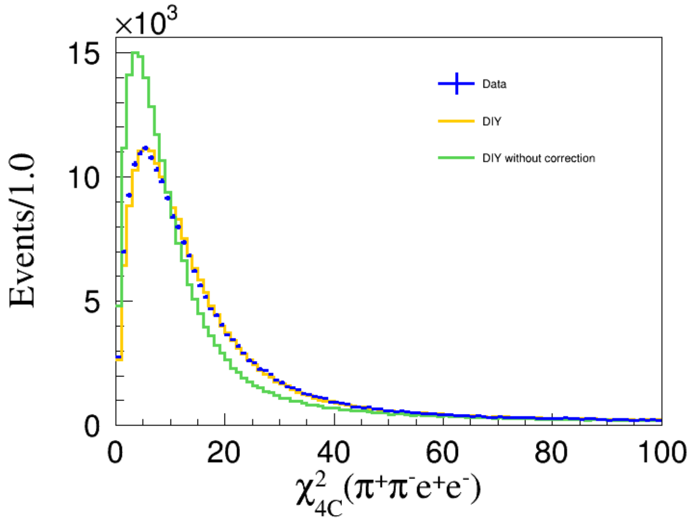
Systematic uncertainty II

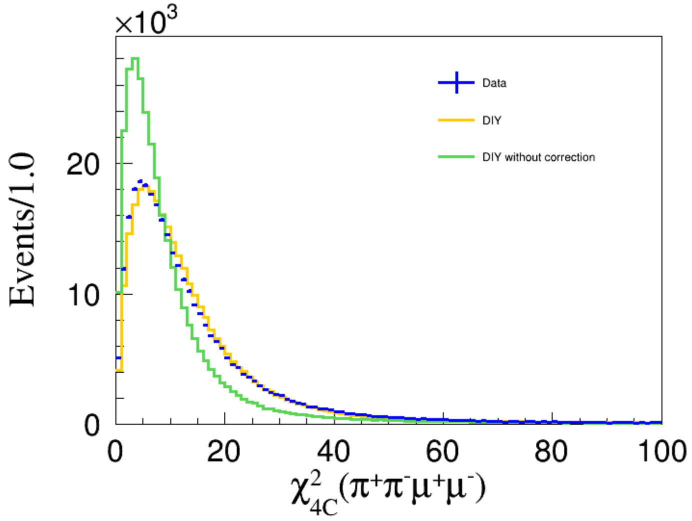
◆ **Kinematic fit**

The difference of results between with and without helix parameters correction is taken as systematic uncertainty.

Table 9: Systematic uncertainty of A_{CP} from 4C kinematic fit.

$\times 10^{-4}$	Nominal result	No helix correction	Difference
$J/\psi \to e^+e^-$	8.2	8.3	0.1
$J/\psi \to \mu^+\mu^-$	-4.4	-4.6	0.2





Systematic uncertainty III

◆ **Mass window of $m_{l^+l^-}$**

By changing the mass window range of ± 1 MeV (nominal 10 MeV), the maximum difference is taken as the systematic uncertainty.

◆ **Cut range for q_{zz}**

By changing the cut range of ± 0.0002, the maximum difference is taken as the systematic uncertainty.

Table 11: Systematic uncertainty of A_{CP} from mass window of $m_{J/\psi}$ and cut of q_{zz} distributions.

$\times 10^{-4}$	$J/\psi \to e^+e^-$		$J/\psi \to \mu^+\mu^-$	
Requirement	Cut $m_{e^+e^-}$	Cut q_{zz}	Cut $m_{\mu^+\mu^-}$	Cut q_{zz}
A_{CP}	0.9	1.0	0.6	0.4

Systematic uncertainty IV

$$A_{CP} = \frac{(N^{+}_{Data} - N^{+}_{Bkg}) - (N^{-}_{Data} - N^{-}_{Bkg})}{(N^{+}_{Data} - N^{+}_{Bkg}) + (N^{-}_{Data} - N^{+}_{Bkg})}.$$

◆ **Background**

When considering the background events, the measurement for the A_{CP} should be modified. The difference of results between with and without considering the backgrounds is regarded as the systematic uncertainty due to backgrounds. The **continuum backgrounds** are taken into account.

Table 10: Systematic uncertainty of A_{CP} from continuum backgrounds.

$\times 10^{-4}$	Nominal result	N^{-}_{QED}	N^{+}_{QED}	QED result	Difference
$J/\psi \to e^+e^-$	8.2	765	828	8.1	0.1
$J/\psi \to \mu^+\mu^-$	-4.4	442	473	-4.4	0.0

Summary of systematic uncertainty

Table 7: The systematic uncertainties of the A_{CP} measurements in decay channels $\psi(3686) \to \pi^+\pi^- J/\psi$, $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$. The absolute errors are at level of $\times 10^{-4}$, and relative errors are in parentheses.

Source	$J/\psi \to e^+e^-$	$J/\psi \to \mu^+\mu^-$
Tracking for l^-	0.1 (1.6%)	0.0 (1.1%)
Tracking for l^+	0.3 (3.1%)	0.0 (0.9%)
Tracking for π	0.1 (1.0%)	0.2 (3.5%)
Mass window for $m_{l^+l^-}$	0.9 (10.9%)	0.6 (14.0%)
Cut range for q_{zz}	1.0 (11.8%)	0.4 (9.4%)
Kinematic fit	0.1 (1.1%)	0.2 (5.0%)
Background	0.1 (1.1%)	0.0 (1.1%)
Summary	1.4 (16.5%)	0.8 (18.9%)

Summary

Table 12: The results of A_{CP} measurement. The first uncertainty is statistical and the second systematic.

	$J/\psi \to e^+e^-$ ($\times 10^{-4}$)	$J/\psi \to \mu^+\mu^-$ ($\times 10^{-4}$)
A_{CP}	8.2 ± 7.2 ± 1.4	-4.4 ± 5.8 ± 0.8

- We study the measurements of A_{CP} in $\psi(3686) \to \pi^+\pi^- J/\psi$ process using semi-data of $\psi(3686)$ samples, according to decay modes $J/\psi \to e^+e^-$ and $J/\psi \to \mu^+\mu^-$.
- By combining two channels, the $\boldsymbol{A_{CP}^{q_{zz}}} = (\mathbf{0.6 \pm 4.5}) \times \mathbf{10^{-4}}$, which indicates CP conservation.
- The strength of CEDM is $\boldsymbol{d_c'} = (\mathbf{0.3 \pm 2.3}) \times \mathbf{10^{-16}} \boldsymbol{e \cdot cm}$ in SM, $\boldsymbol{d_c'} = (\mathbf{0.3 \pm 3.1}) \times \mathbf{10^{-16}} \boldsymbol{e \cdot cm}$ in Cornell model.
- *The memo has passed by the new physics group review.*

Thank you ~

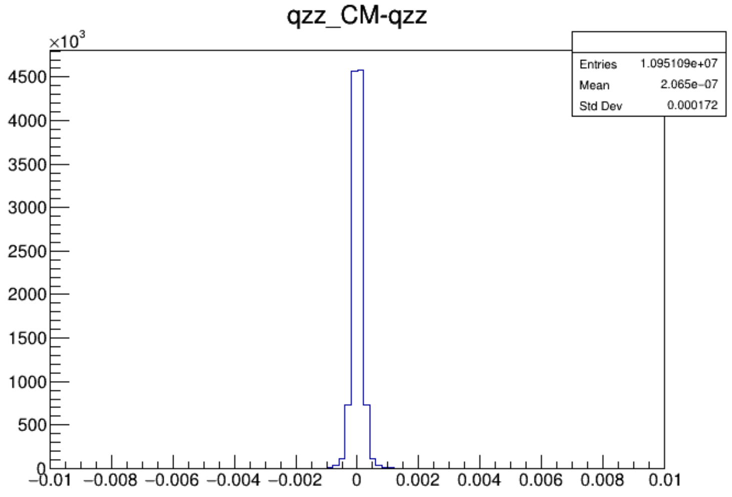
Back up

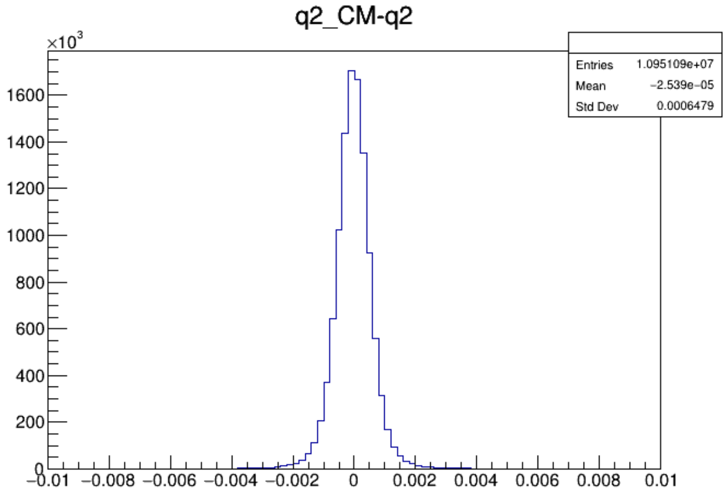
Resolution (Rec - Truth)

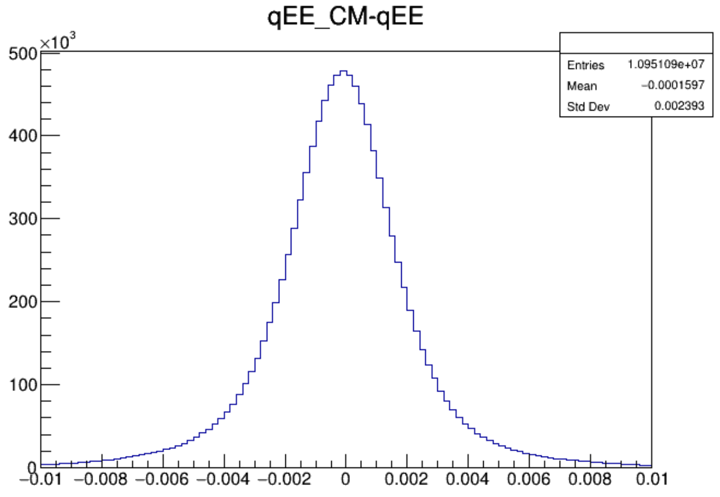
	qzz	q2	qEE
Resolution	10^-7	10^-5	10^-4
Range	0.01	0.05	0.2

CP-odd operators:

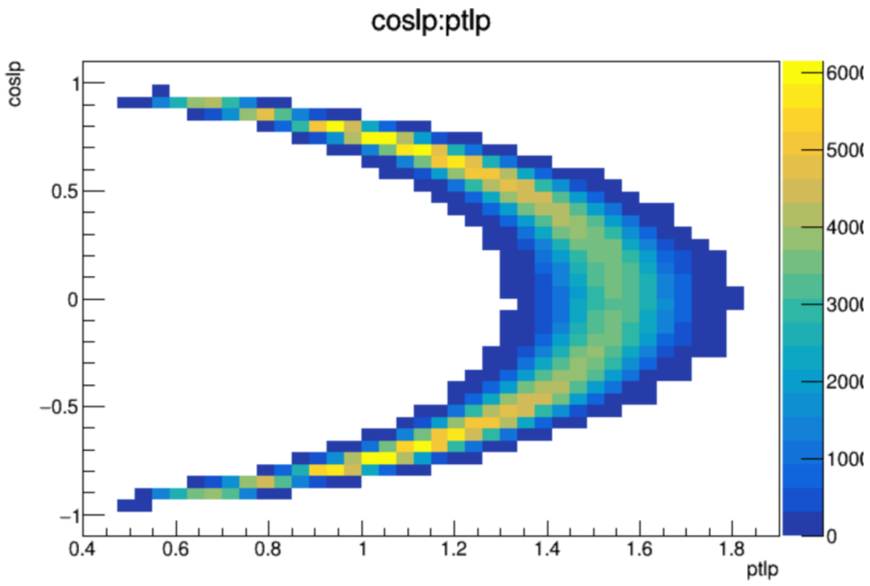
- $q_{zz} = (p_z^{\pi^+} - p_z^{\pi^-})(p_x^{\pi^+} p_y^{\pi^-} - p_x^{\pi^-} p_y^{\pi^+})$
- $q_2 = p_x^{\pi^+} p_y^{\pi^-} - p_x^{\pi^-} p_y^{\pi^+}$
- $q_{EE} = E^{\pi^+} - E^{\pi^-}$

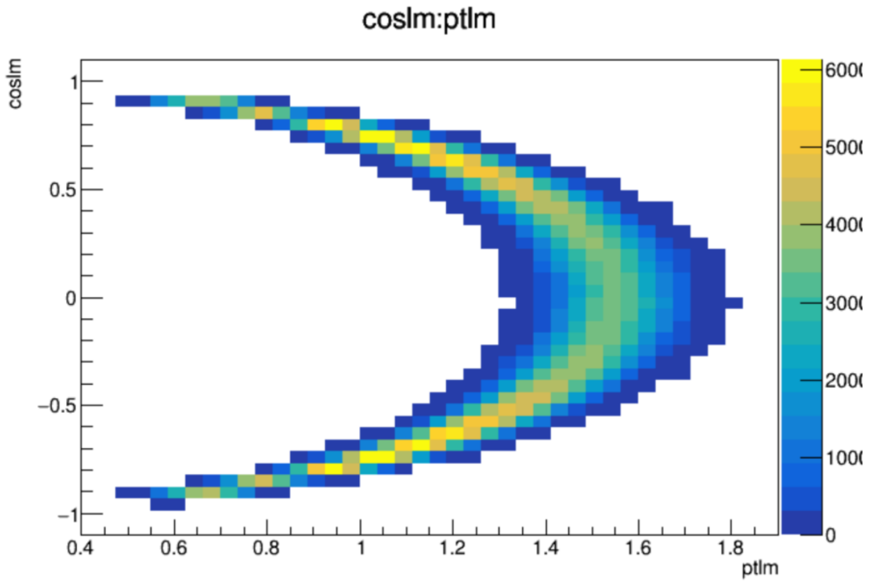


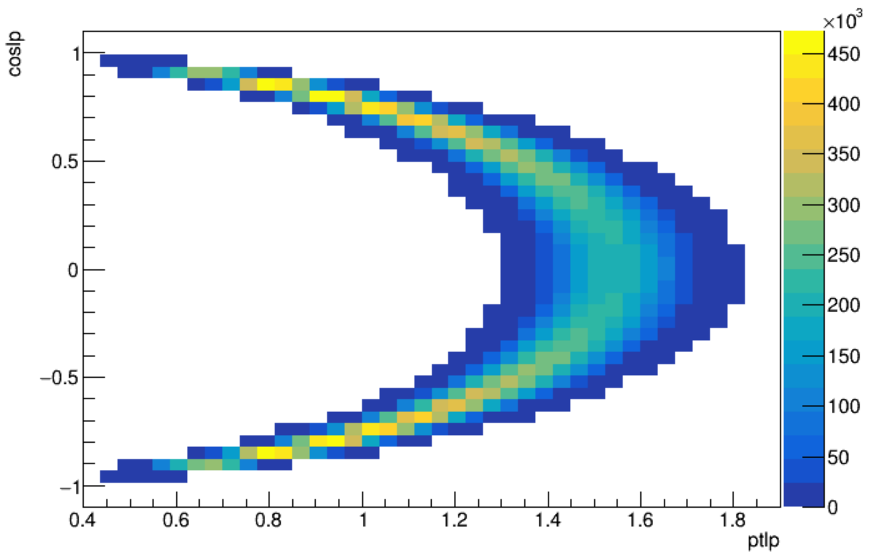


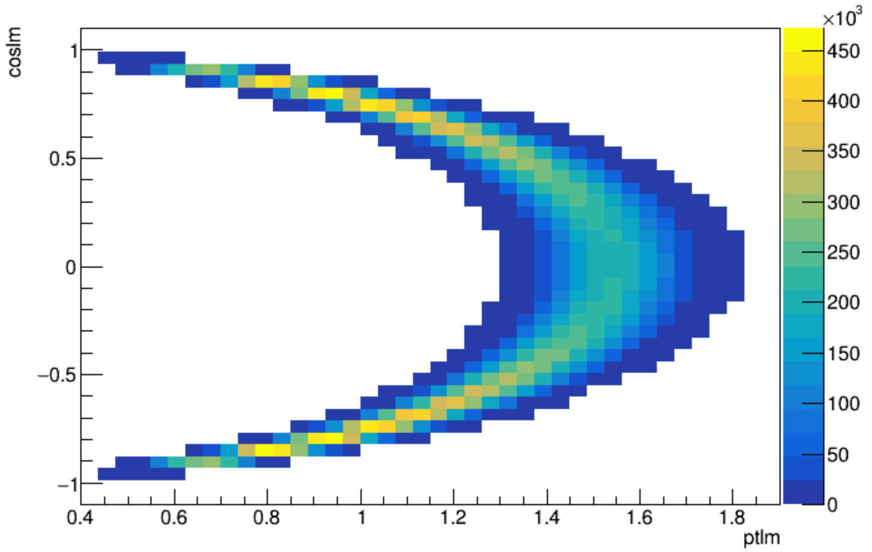


$cos\theta$ v.s. $pt - e^{+}e^{-}$

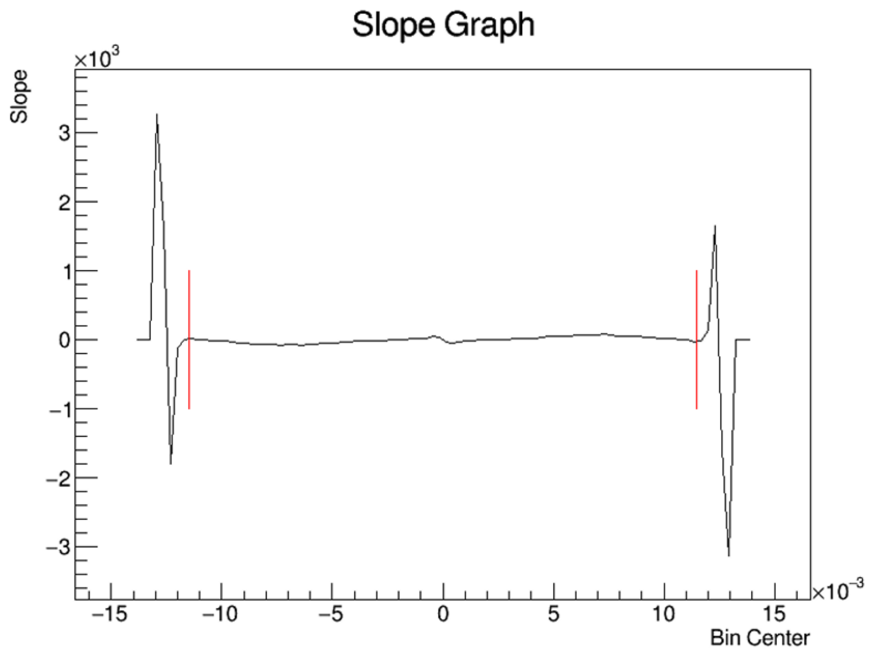


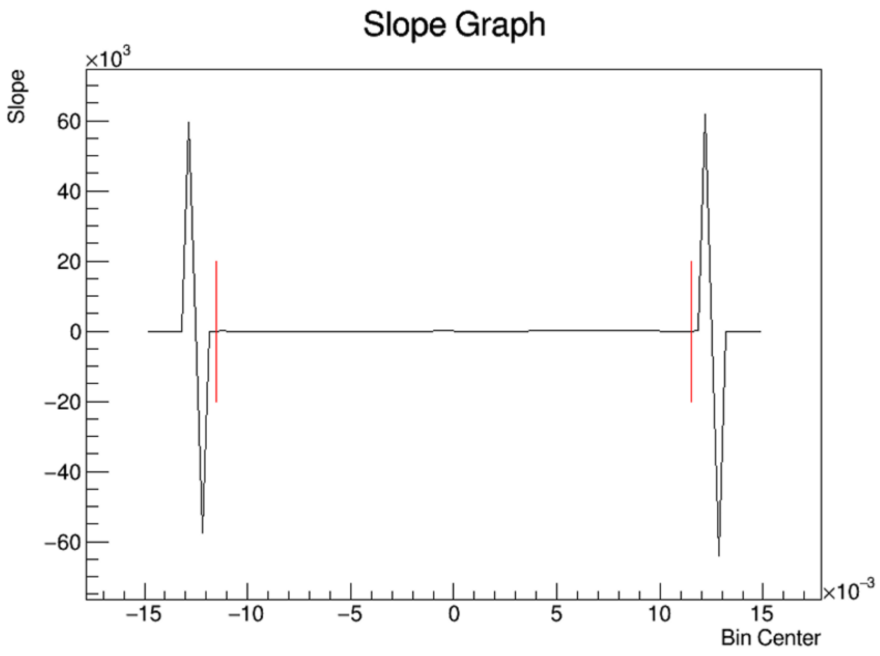






Determination of cut range for qzz, q2, qEE





Cut range [-0.011, 0.011] both in ee and mumu

$$Slope(B) = \frac{A + C}{2}$$

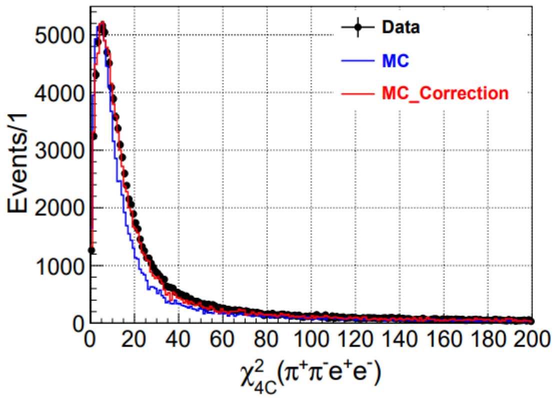
Helix tracking parameters

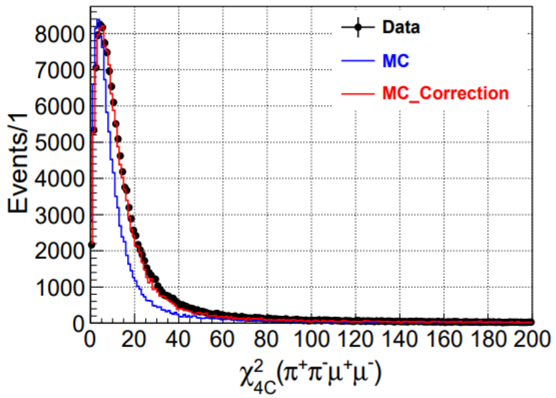
Table 4: Correction factors extracted from pull distributions in the process $e^+e^- \to \pi^+\pi^-e^+e^-$ ($\sqrt{s} = 3.686GeV$)

	ϕ_0		κ		$tg\lambda$	
	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$
π^+	-0.042	1.145	0.146	1.118	-0.119	1.055
π^-	0.025	1.155	-0.134	1.156	-0.124	1.099
e^+	-0.079	1.236	0.308	1.001	-0.152	1.045
e^-	0.067	1.235	-0.334	1.036	-0.130	1.039

Table 5: Correction factors extracted from pull distributions in the process $e^+e^- \to \pi^+\pi^-\mu^+\mu^-$ ($\sqrt{s} = 3.686GeV$)

	ϕ_0		κ		$tg\lambda$	
	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$	$m^{data} - m^{MC}$	$\sigma^{data}/\sigma^{MC}$
π^+	-0.047	1.246	0.144	1.207	0.124	1.177
π^-	-0.037	1.257	-0.118	1.195	-0.153	1.152
μ^+	-0.088	1.301	0.249	1.114	-0.199	1.133
μ^-	0.056	1.306	-0.267	1.132	-0.169	1.091





[Helix_Correction.pdf (ihep.ac.cn)]

Control sample: $e^+e^- \to \pi^+\pi^-J/\psi$
Data set: 2012 year ψ' (305M)
Boss version: 664p03

Continuum background in $cos\theta_{l\pi}$ v.s. $m_{\pi\pi}$