

Precision Measurement of the mass of the τ lepton

TAO LUO for the BESIII Collaboration

University of Hawaii

The 13th International Workshop on
Tau Lepton Physics,

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Outline



- Introduction
- Beam Energy Measurement System (BEMS)
- Data samples and Monte Carlo (MC) Simulation
- Event Selection for τ Pair Candidate Events
- Data Analysis
- Systematic Uncertainties
- Summary

Introduction

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- m_τ is a fundamental parameter of SM

$$\frac{B(\tau \rightarrow l\nu\bar{\nu})}{\tau_\tau} = \frac{g_\tau^2 m_\tau^5}{192\pi^3} F_{cor}(m_\tau, m_l)$$

- Determination of m_τ to the highest possible precision → high precision test of the Standard Model.

- Check lepton universality

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau} \left(\frac{m_\mu}{m_\tau}\right)^5 \times \text{Br}(\tau \rightarrow e\nu\bar{\nu}) \times \frac{F_{cor}(m_\mu, m_e)}{F_{cor}(m_\tau, m_e)}$$

g_L is the Fermi weak coupling constant. Phys.R 421, 191 (2005)

F_{cor} : weak(electromagnetic) radiative correction

- Universality is sensitive to: m_τ^5
- For $e, \mu, \Delta m/m \sim 10^{-8}$, for $\tau, \Delta m/m \sim 10^{-4}$, need more precise measurements.

- Methods:

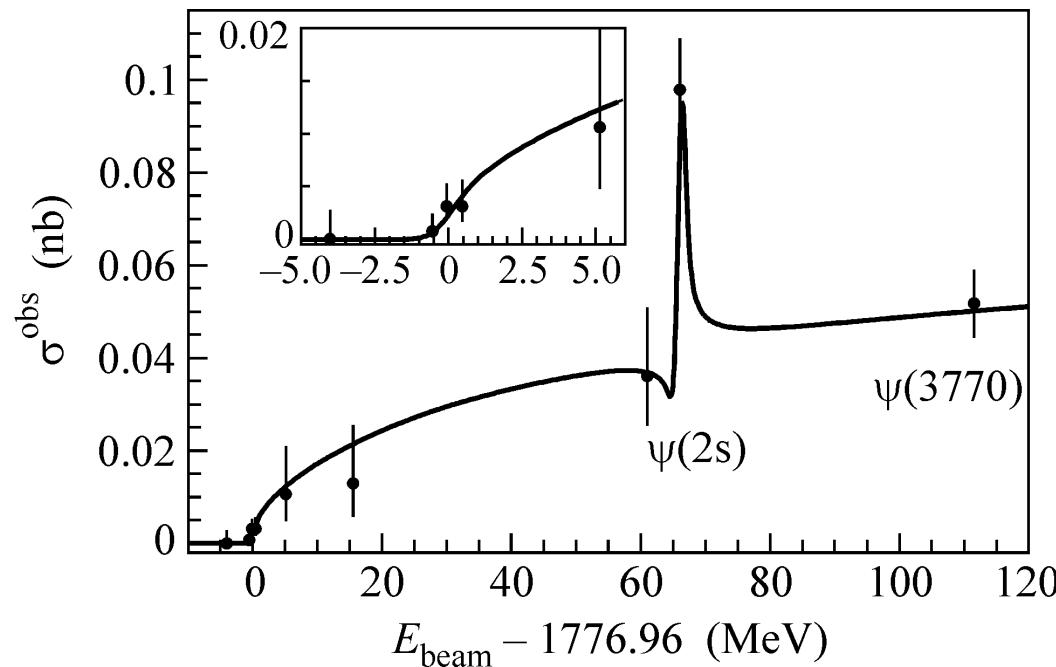
- Pseudomass technique: ARGUS, OPAL, BELLE and BABAR
- Threshold scan method (our focus): DELCO, BES (92, 96), KEDR and BESIII

Threshold scan method

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- Study of the threshold behavior of the τ pair production cross section in e^+e^- collisions
- Extremely important is to determine the beam energy and the beam energy spread precisely

Observed $\tau^+\tau^-$ cross section versus the beam energy

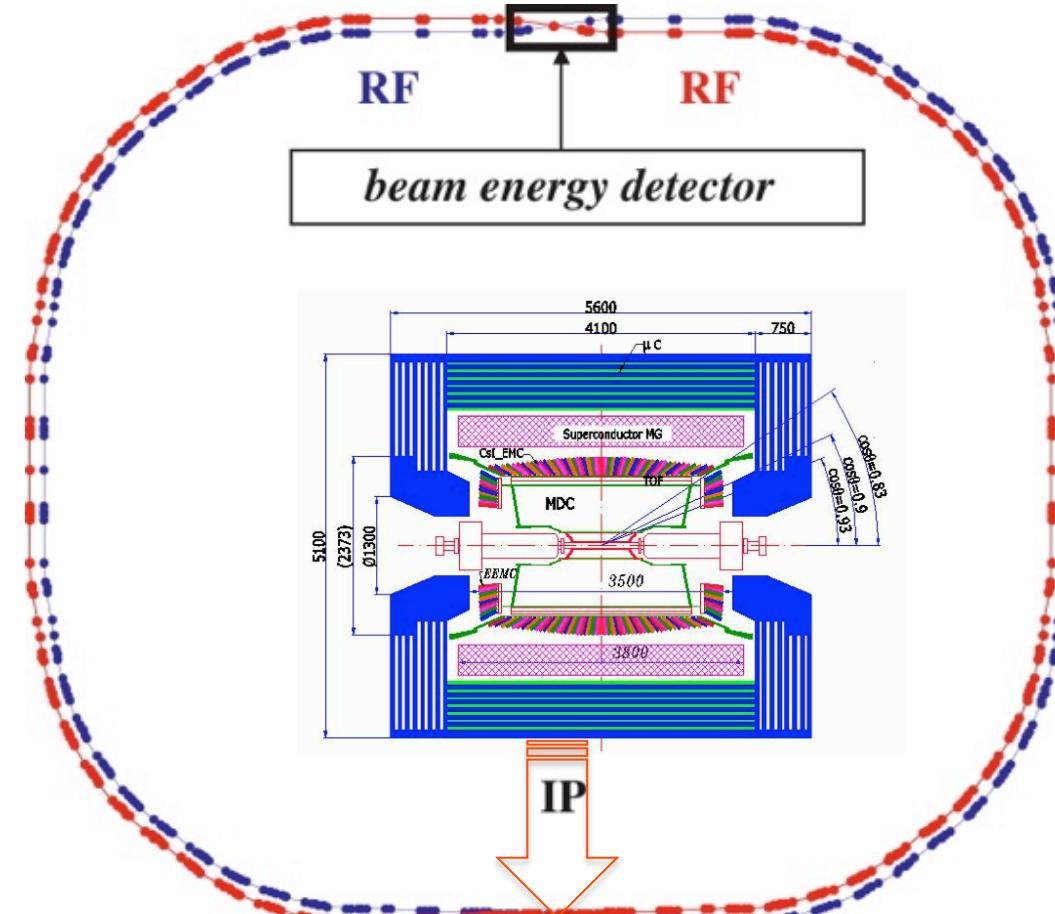


KEDR detector
JETPL 85, 347

Beijing Electron Positron Collider (BEPCII)

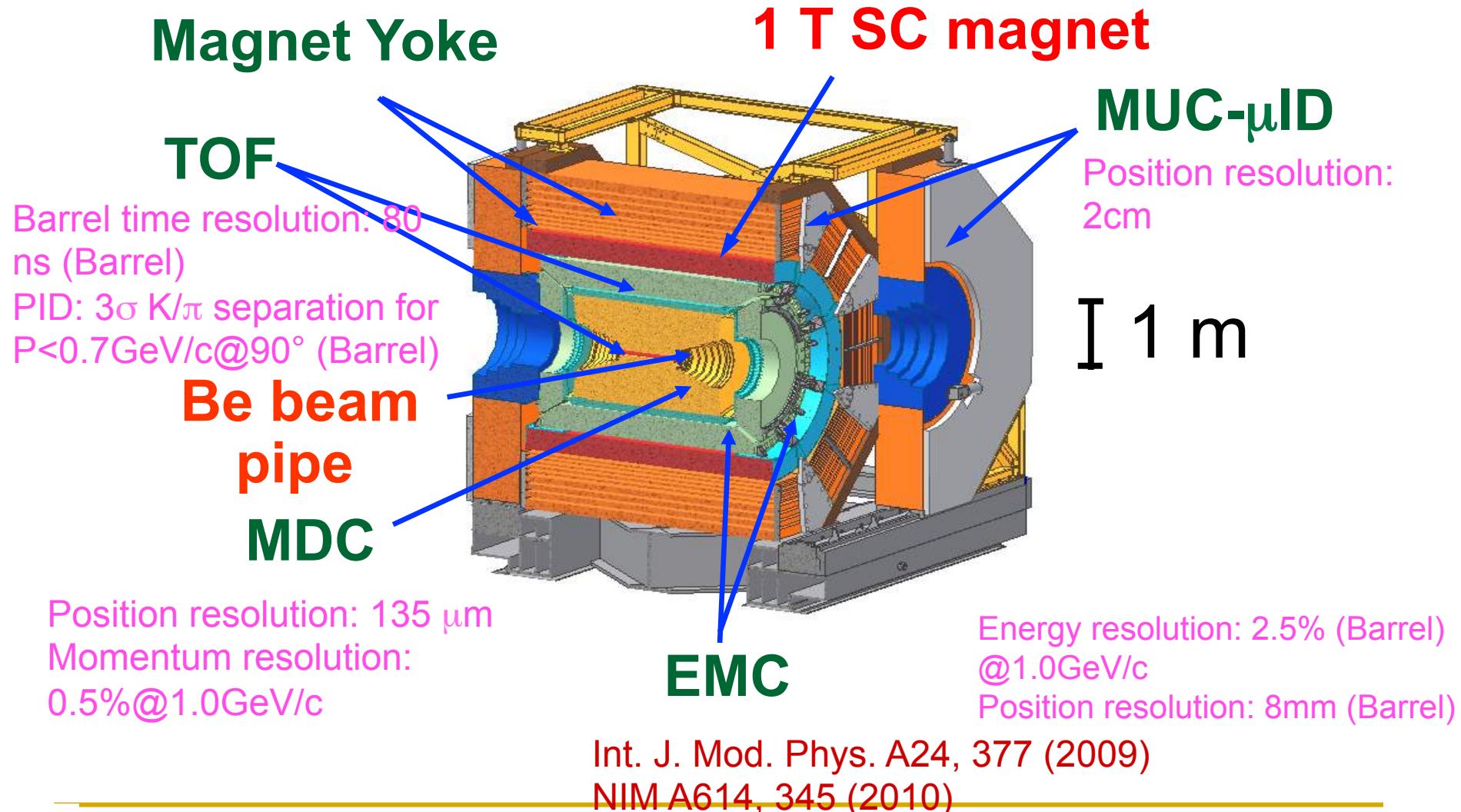
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- Working energy range:
2.0 ~ 4.6 GeV
- Double-ring structure
- Design luminosity: 1 x
 $10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @
1.89GeV
- Achieved luminosity:
 $0.7 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ @
1.89GeV
- Number of bunches:
2×93
- Beam current:
2×0.91A



BESIII Detector

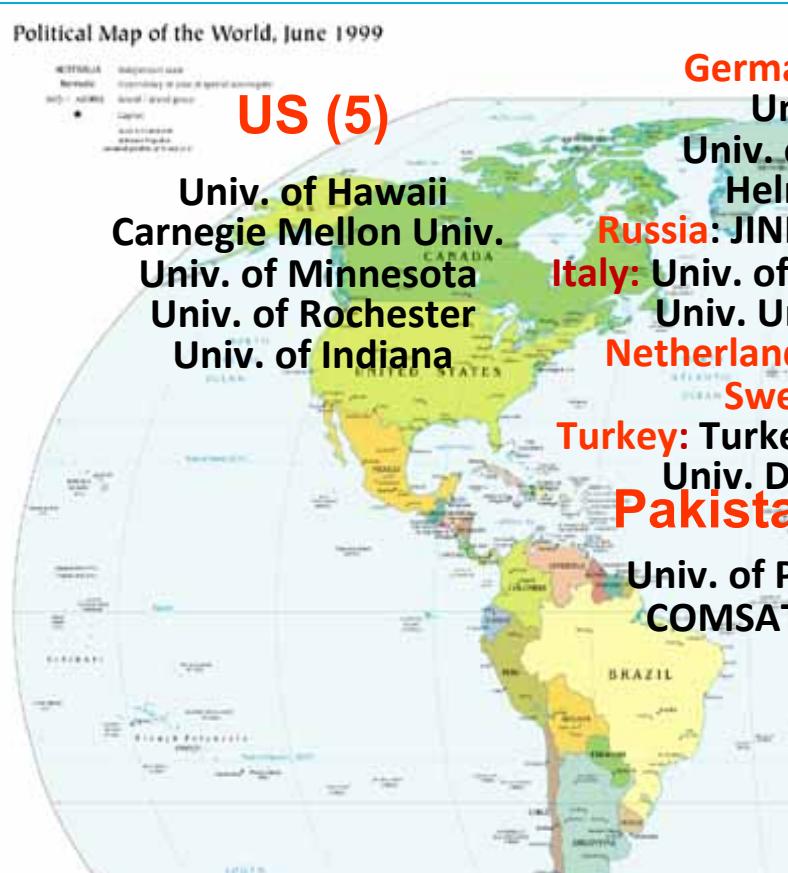
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The BESIII Collaboration

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Europe (15)



~400 members
55 institutions from
11 countries



UH

Germany: Univ. of Bochum,
Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz

Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Turino, Frascati Lab, Ferrara
Univ. Univ. of Eastern Piedmont

Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.

Turkey: Turkey Accelerator Center, Ankara
Univ. Dogus Univ. Uludag Univ.

Pakistan (2)

Univ. of Punjab
COMSAT CIIT

Korea (1)
Seoul Nat. Univ.

Japan (1)
Tokyo Univ.

China(31)

IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ.,
Zhongshan Univ., Shanghai Jiaotong Univ., Nankai
Univ., Beihang Univ.

Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ., Hong
Kong Univ., Hong Kong Chinese Univ.

τ Mass Scan Experiment

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- τ scan experiment done in December 2011
- J/ψ and ψ' resonances were each scanned at seven points
- Four scan point data were collected near τ pair production threshold
 - The first point is below the mass of τ pair
 - The other three are above

Scan	E_{CM} (MeV)	$\mathcal{L}(\text{nb}^{-1})$
J/ψ	3088.7	78.5 ± 1.9
	3095.3	219.3 ± 3.1
	3096.7	243.1 ± 3.3
	3097.6	206.5 ± 3.1
	3098.3	223.5 ± 3.2
	3098.8	216.9 ± 3.1
	3103.9	317.3 ± 3.8
τ	3542.4	4252.1 ± 18.9
	3553.8	5566.7 ± 22.8
	3561.1	3889.2 ± 17.9
	3600.2	9553.0 ± 33.8
ψ'	3675.9	787.0 ± 7.2
	3683.7	823.1 ± 7.4
	3685.1	832.4 ± 7.5
	3686.3	1184.3 ± 9.1
	3687.6	1660.7 ± 11.0
	3688.8	767.7 ± 7.2
	3693.5	1470.8 ± 10.3

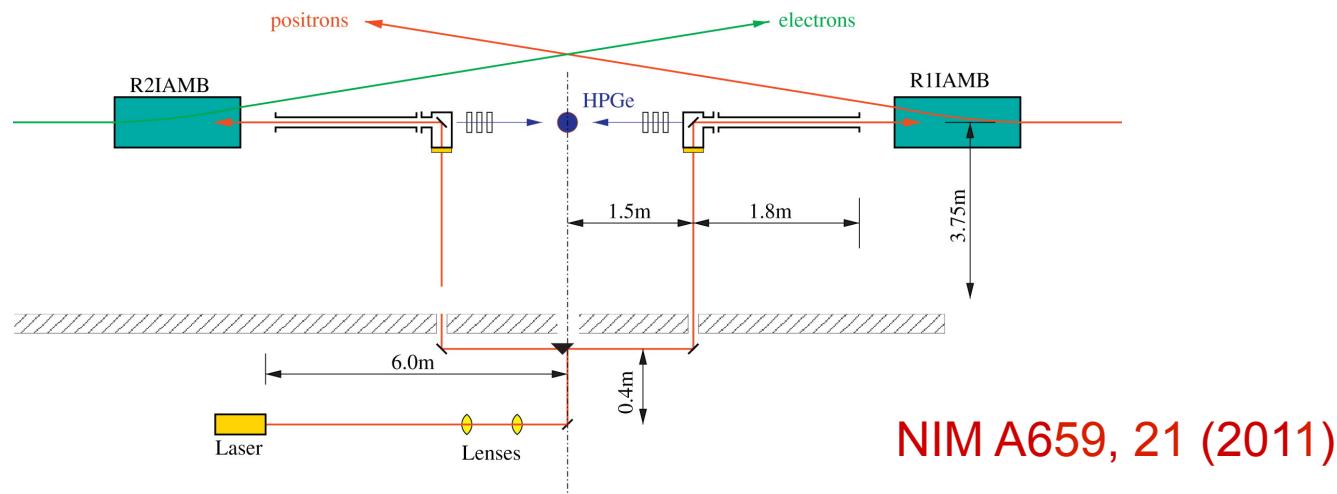
Beam Energy Measurement System (BEMS)

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- Determination of beam energy crucial for τ mass measurement
- The electron energy E_e is related to the maximal energy of the scattered photon E_γ by the kinematics of Compton scattering

$$E_e = \frac{E_\gamma}{2} \left[1 + \sqrt{1 + \frac{m_e^2}{\epsilon_\gamma E_\gamma}} \right] \rightarrow E_{CM} = 2 \times \sqrt{\bar{E}_{e^+} \times \bar{E}_{e^-}} \times \cos\left(\frac{\theta_{e^+e^-}}{2}\right)$$

- $\sigma(\text{Energy}) \sim 10^{-5}$, $\Delta (\text{Energy spread}) / \text{Energy spread} \sim 6\%$



Scan point energies from BEMS

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All units are in MeV

Beam energy	Runs	E_{e^-}	ΔE_{e^-}	E_{e^+}	ΔE_{e^+}	E_{CM}	ΔE_{CM}
1554.0	24937	1544.542	0.135	1544.312	0.217	3088.667	0.256
1547.7	24938-24942	1547.917	0.099	1547.548	0.106	3095.278	0.145
1548.1	24943-24949	1548.692	0.103	1548.171	0.086	3096.676	0.135
1548.5	24959-24966	1549.079	0.109	1548.714	0.075	3097.606	0.133
1548.9	24967-24971	1549.451	0.081	1549.014	0.114	3098.278	0.140
1549.3	24972-24975	1549.566	0.101	1549.438	0.083	3098.817	0.131
1552.0	24976-24978	1552.186	0.088	1551.936	0.107	3103.934	0.139
1771.0	24983-25015	1771.558	0.067	1771.069	0.053	3542.413	0.085
1777.0	25016-25094	1777.307	0.060	1776.730	0.046	3553.822	0.075
1780.4	25100-25141	1780.926	0.055	1780.431	0.065	3561.142	0.085
1800.0	25143-25243	1800.526	0.044	1799.878	0.044	3600.186	0.062
1838.0	25244-25251	1838.183	0.256	1837.940	0.157	3675.901	0.300
1841.9	25252-25262	1842.234	0.112	1841.642	0.281	3683.653	0.303
1842.5	25264-25270	1842.825	0.201	1842.511	0.112	3685.113	0.230
1843.1	25271-25295	1843.560	0.113	1843.000	0.152	3686.337	0.189
1843.8	25325-25337	1844.148	0.126	1843.648	0.095	3687.573	0.158
1844.5	25299-25314	1844.700	0.177	1844.342	0.140	3688.819	0.226
1847.0	25315-25322	1847.141	0.189	1846.597	0.156	3693.515	0.245

Beam energy spread from BEMS **BESIII**

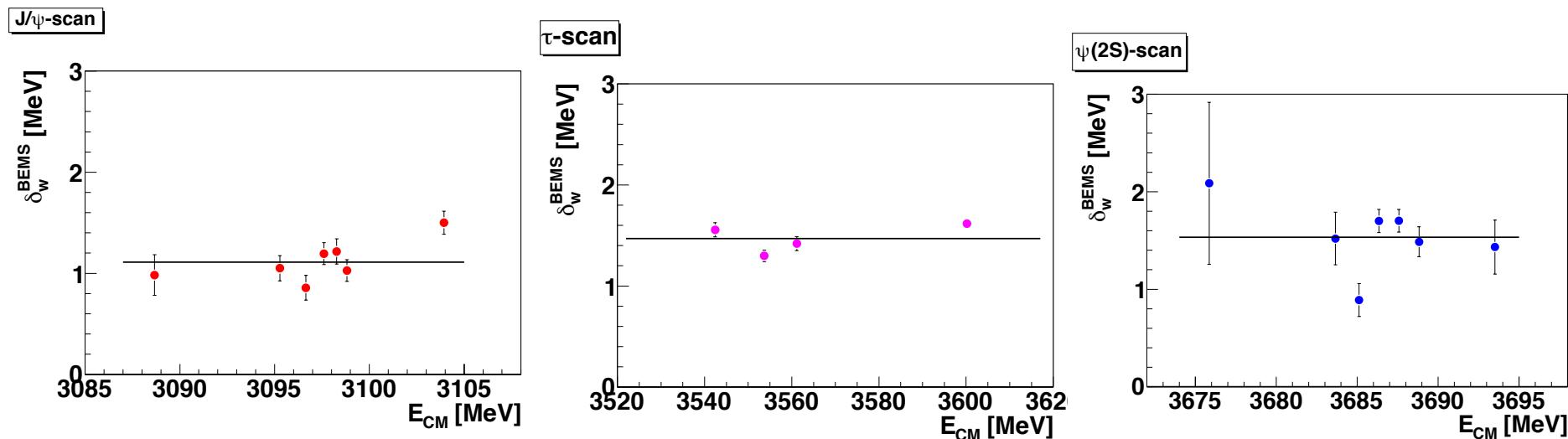
- Total energy spread (MeV) of a scan point, δ_w^{BEMS} , is calculated from the average electron and positron spreads using

$$\delta_w^{\text{BEMS}} = \sqrt{\delta_{e^-}^2 + \delta_{e^+}^2}$$

- Error from error propagation:

$$\Delta(\delta_w^{\text{BEMS}}) = \sqrt{\delta_{e^-}^2 \times \Delta^2(\delta_{e^-}) + \delta_{e^+}^2 \times \Delta^2(\delta_{e^+})} / \delta_w^{\text{BEMS}}$$

Scan	δ_w^{BEMS}	$\Delta(\delta_w^{\text{BEMS}})$
J/ψ	1.112	0.070
τ	1.469	0.064
ψ'	1.534	0.109



Data Samples and MC Simulation

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- Bhabha events and two gamma events ($ee \rightarrow \gamma\gamma(\gamma)$) → determination of luminosities
 - Babayaga 3.5 generator
- Hadronic events in J/ψ and ψ' scan → study of J/ψ and ψ' hadronic cross-section line shapes
 - data @ 3.097GeV, @ 3.686GeV, @ 3.650GeV used for signal /background assessment.
 - inclusive MC @ 3.097GeV and @ 3.686GeV
- 13 two-prong τ pair final states are used → determination of τ mass
 - $ee, e\mu, e\pi, eK, \mu\mu, \mu\pi, \mu K, \pi K, \pi\pi, KK, e\rho, \mu\rho$ and $\pi\rho$ (with accompanying neutrinos implied)
 - KKMC + BesEvtGen

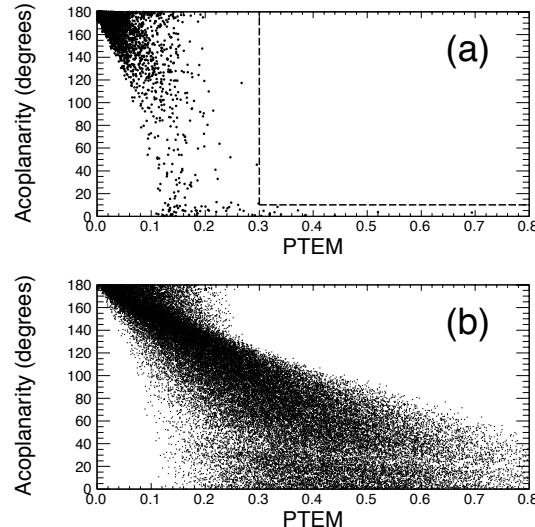
- Good shower in EMC
 - $E > 25\text{MeV}$ (50MeV) for $|\cos\theta| < 0.8$ (for $0.86 < |\cos\theta| < 0.92$)
 - $0 < t < 750 \text{ ns}$, t is the time information from the EMC
- Number of good photon: 0 or 2
- Number of charged tracks: 2
- Cuts on Acoplanarity angle (θ_{acop}) and PTEM

$$PTEM = \frac{P_T}{E_{miss}^{\max}} = \frac{(c\vec{P}_1 + c\vec{P}_2)_T}{W - |c\vec{P}_1| - |c\vec{P}_2|},$$

- PID selection criteria

Event selection details

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Background from the first scan point data

Signal τ pair ee event from the second scan point MC

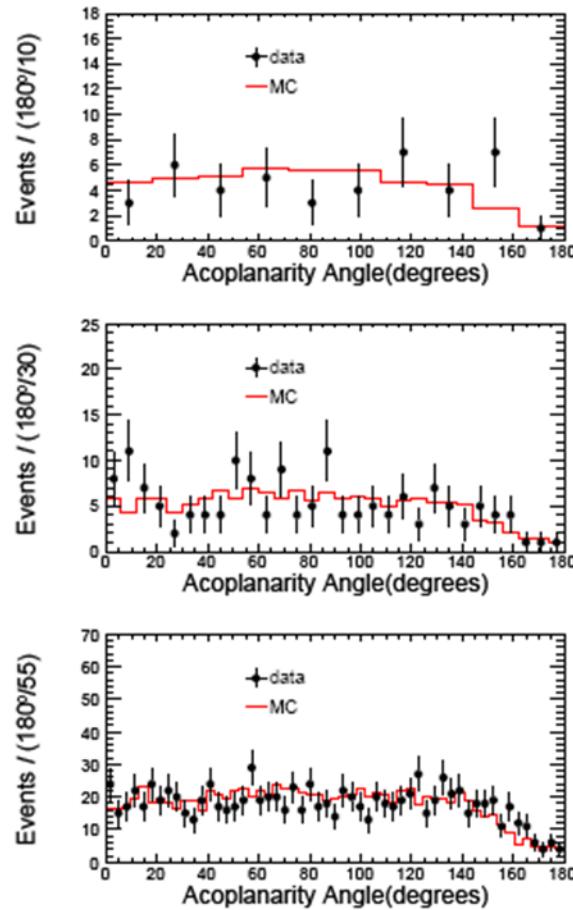
final state	θ_{acop}	PTEM
ee	$>10^\circ$	>0.3
$e\mu$	$<160^\circ$	>0.1
$e\pi$	$<170^\circ$	>0.1
eK	$<170^\circ$	
$\mu\mu$	$<140^\circ$	
μh	$<140^\circ$	
hh	$<160^\circ$	
$e\rho$	$<170^\circ$	
$\mu\rho$	$<150^\circ$	
$\pi\rho$		

PID	p (MeV/c)	EMC	TOF	MUC	other
e	$p_{min} < p < p_{max}$	$0.8 < E/cp < 1.05$	$ \Delta TOF(e) < 0.2$ ns 0 ns $< TOF < 4.5$ ns		
μ	$p_{min} < p < p_{max}$	$E/cp < 0.7$ $0.1 < E < 0.3$	$ \Delta TOF(\mu) < 0.2$ ns	$(D > (80 \times p - 50) \text{ cm or } D > 40 \text{ cm})$ and $N_h > 1$	
π	$p_{min} < p < p_{max}$	$E/cp < 0.6$	$ \Delta TOF(\pi) < 0.2$ ns 0 ns $< TOF < 4.5$ ns		not μ
K	$p_{min} < p < p_{max}$	$E/cp < 0.6$	$ \Delta TOF(K) < 0.2$ ns 0 ns $< TOF < 4.5$ ns		not μ

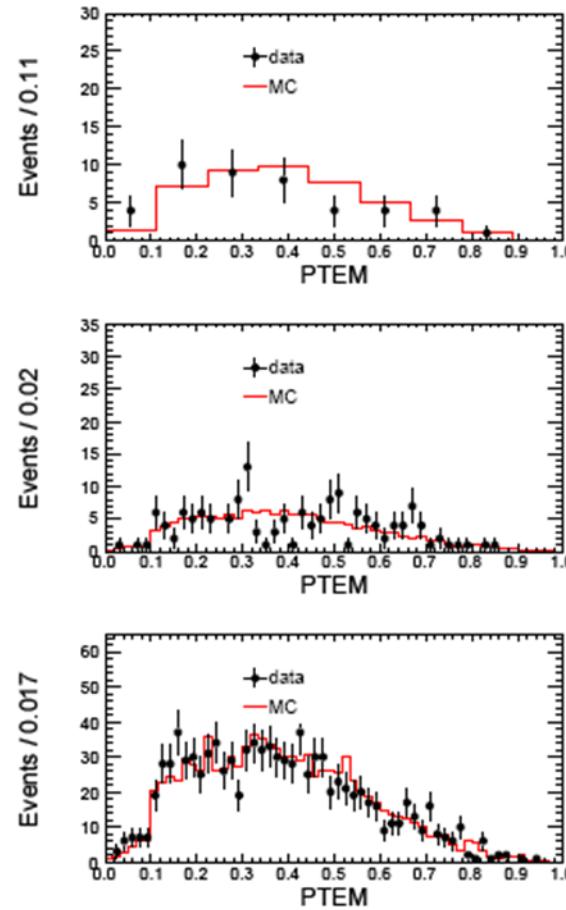
Comparison of the data and Equivalent MC Samples

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Acoplanarity angle



PTEM



1st – point below threshold

2nd – point

$$E_{cm} = 3553.8 \text{ MeV}$$

3rd – point

$$E_{cm} = 3561.1 \text{ MeV}$$

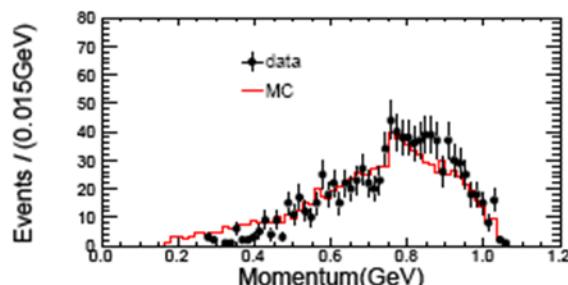
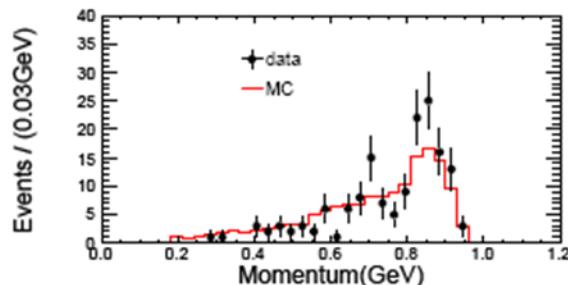
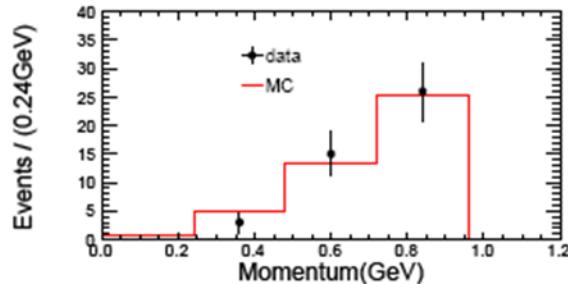
4th – point

$$E_{cm} = 3600.2 \text{ MeV}$$

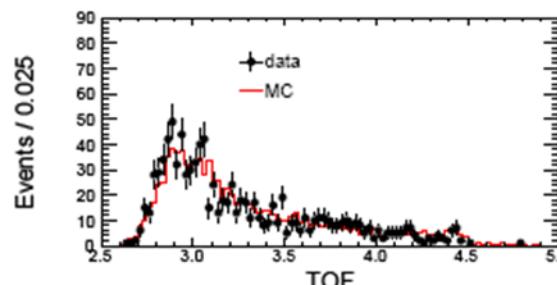
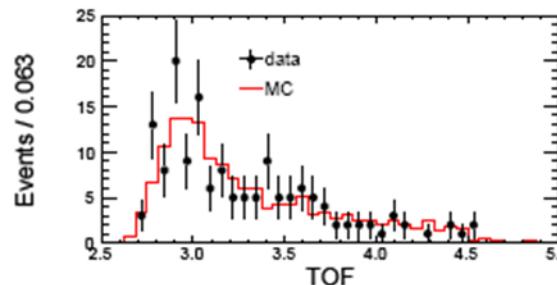
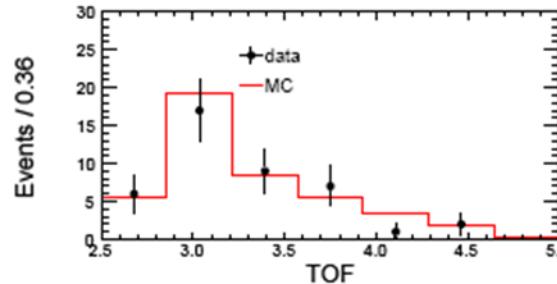
Comparison of the data and Equivalent MC Samples (Continued

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Momentum of charged tracks



TOF of charged tracks
1st – point below threshold



2nd – point
 $E_{cm} = 3553.8\text{MeV}$

3rd – point
 $E_{cm} = 3561.1\text{MeV}$

4th – point
 $E_{cm} = 3600.2\text{MeV}$

Numerical comparison between data and normalized MC



The numbers of normalized MC events have been multiplied by the ratio of the overall efficiencies for identifying τ pair events for data and MC simulation

Final state	1		2		3		4		Total	
	Data	MC	Data	MC	Data	MC	Data	MC	Data	MC
ee	0	0	4	3.7	13	12.2	84	76.1	101	92.0
$e\mu$	0	0	8	9.1	35	31.4	168	192.6	211	233.1
$e\pi$	0	0	8	8.6	33	29.7	202	184.4	243	222.6
eK	0	0	0	0.5	2	1.8	16	16.9	18	19.3
$\mu\mu$	0	0	2	2.9	8	9.2	49	56.3	59	68.4
$\mu\pi$	0	0	4	3.9	11	14.1	89	86.7	104	104.7
μK	0	0	0	0.2	3	0.8	7	9.0	10	10.1
$\pi\pi$	0	0	1	2.0	5	7.7	57	54.0	63	63.8
πK	0	0	1	0.3	0	0.8	10	8.2	11	9.3
KK	0	0	0	0.0	1	0.1	1	0.3	2	0.4
$e\rho$	0	0	3	6.1	19	20.6	142	132.0	164	158.7
$\mu\rho$	0	0	8	3.3	8	11.8	52	63.3	68	78.5
$\pi\rho$	0	0	5	3.4	15	10.8	97	96.0	117	110.2
Total	0	0	44	44.2	153	151.2	974	975.7	1171	1171.0

Agree well

Data Analysis – Determination of luminosity **BESIII**

- Correction for interference effect has been considered.
- $\Delta \mathcal{L} / \mathcal{L} < 2\%$ for most energy points

Scan	E_{CMS} (GeV)	\mathcal{L}_{Bhabha} (nb $^{-1}$)	$\mathcal{L}_{\gamma\gamma}$ (nb $^{-1}$)	$\mathcal{L}_{Bhabha}/\mathcal{L}_{\gamma\gamma}$
J/ψ	3.0887	77.95 ± 0.81	78.5 ± 1.9	0.993 ± 0.026
	3.0953	223.6 ± 2.6	219.3 ± 3.1	1.020 ± 0.019
	3.0967	247.4 ± 2.1	243.1 ± 3.3	1.018 ± 0.016
	3.0976	202.6 ± 1.8	206.5 ± 3.1	0.981 ± 0.017
	3.0983	223.2 ± 2.2	223.5 ± 3.2	0.999 ± 0.017
	3.0988	213.9 ± 2.2	216.9 ± 3.1	0.986 ± 0.018
	3.1039	312.9 ± 2.4	317.3 ± 3.8	0.986 ± 0.014
τ	3.5424	4283.4 ± 26.5	4252.1 ± 18.9	1.007 ± 0.008
	3.5538	5595.9 ± 34.4	5566.7 ± 22.8	1.005 ± 0.007
	3.5611	3873.0 ± 24.0	3889.2 ± 17.9	0.996 ± 0.008
	3.6002	9581.3 ± 58.5	9553.0 ± 33.8	1.003 ± 0.007
ψ'	3.6759	788.2 ± 5.5	787.0 ± 7.2	1.001 ± 0.012
	3.6837	835.4 ± 6.2	823.1 ± 7.4	1.015 ± 0.012
	3.6851	836.7 ± 6.0	832.4 ± 7.5	1.005 ± 0.012
	3.6863	1209.4 ± 8.0	1184.3 ± 9.1	1.021 ± 0.010
	3.6876	1672.8 ± 11.1	1660.7 ± 11.0	1.007 ± 0.009
	3.6888	788.7 ± 5.6	767.7 ± 7.2	1.027 ± 0.012
	3.6935	1497.3 ± 9.8	1470.8 ± 10.3	1.018 ± 0.010

Data Analysis – J/ ψ and ψ' Hadronic Cross-section Line Shape

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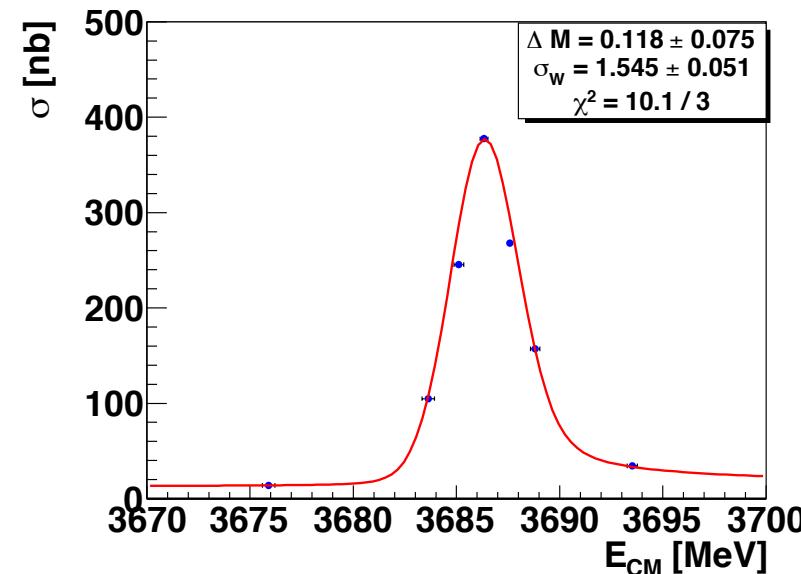
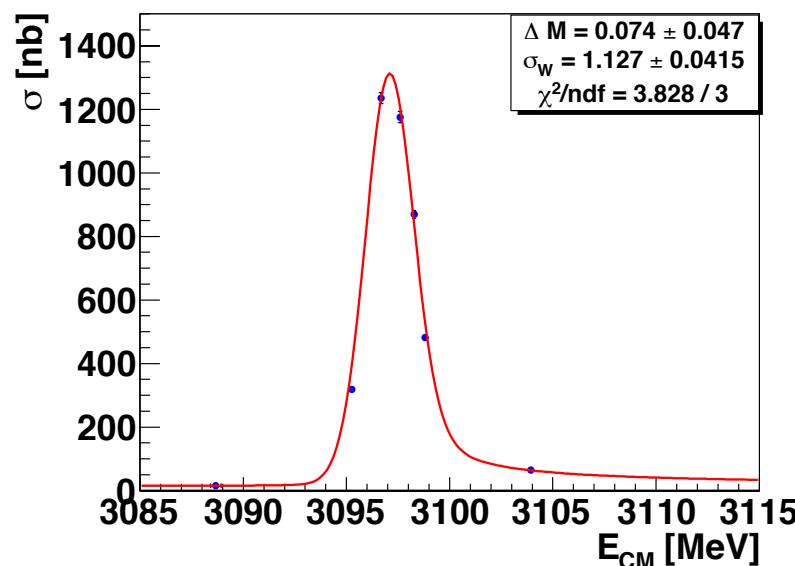
Fit parameters of resonances:

ΔM : the difference between fitted ψ mass and normal value from PDG

δ_w : energy spread

Scan	ΔM	(MeV /c ²)	δ_w	(MeV)
J/ψ	$0.074 \pm 0.047 \pm 0.043$	$1.127 \pm 0.042 \pm 0.050$		
ψ'	$0.118 \pm 0.076 \pm 0.021$	$1.545 \pm 0.051 \pm 0.069$		

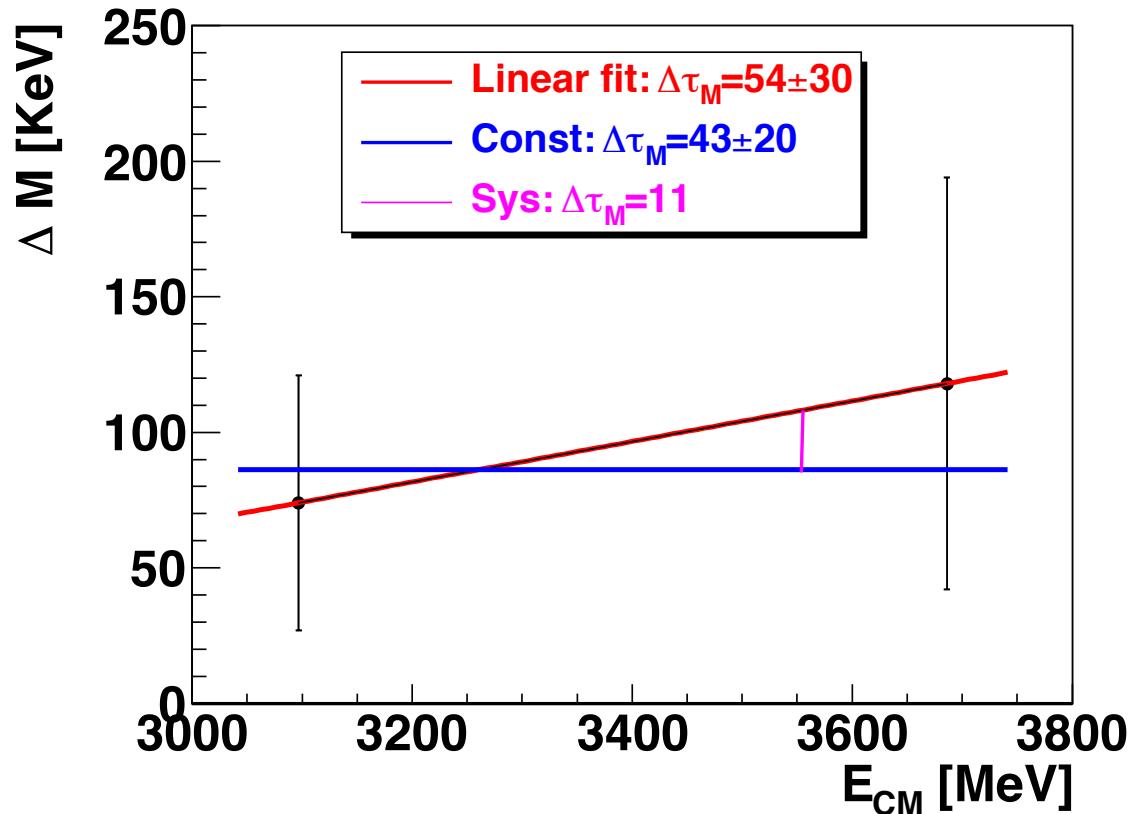
$$\chi^2 = \sum_{i=1}^N \frac{(N_i^h - \sigma_{had}^i \mathcal{L}_i)^2}{N_i^h(1 + N_i^h (\Delta \mathcal{L}_i / \mathcal{L}_i)^2)},$$



Extrapolate the energy correction to the τ -mass

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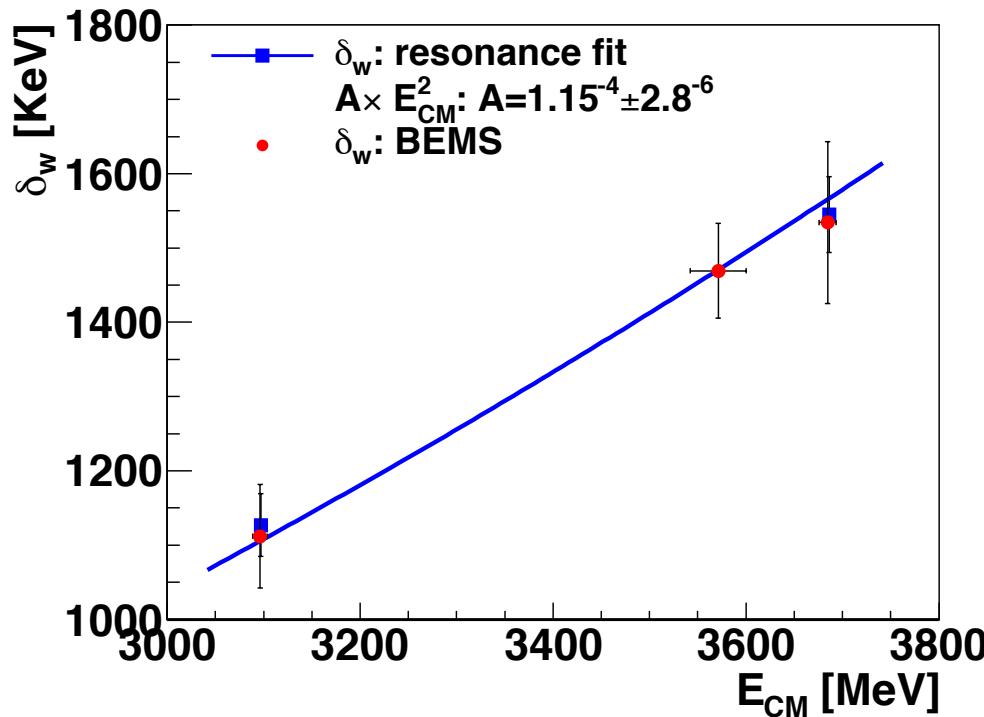
- If the correction has a linear dependence on the energy (red line) :
 $\Delta m_\tau = (0.054 \pm 0.030)$ MeV
- If the correction is constant (blue line) :
 $\Delta m_\tau = (0.043 \pm 0.020)$ MeV
- The difference :
 $\Delta m_\tau = (0.054 \pm 0.030 \pm 0.012)$ MeV



Extrapolate the the J/ ψ and ψ' energy spreads to the τ region

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- Quadratic dependence of δ_w on energy, extrapolate the the J/ ψ and ψ' energy spreads to the τ region (blue line):
$$\delta_w = (1.471 \pm 0.040) \text{ MeV}$$
- BEMS results are plotted by red points.



Data Analysis – τ mass determination

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- The likelihood function for the maximum likelihood fitting:

$$L(m_\tau, R_{Data/MC}, \sigma_B) = \prod_{i=1}^4 \frac{\mu_i^{N_i} e^{-\mu_i}}{N_i!},$$

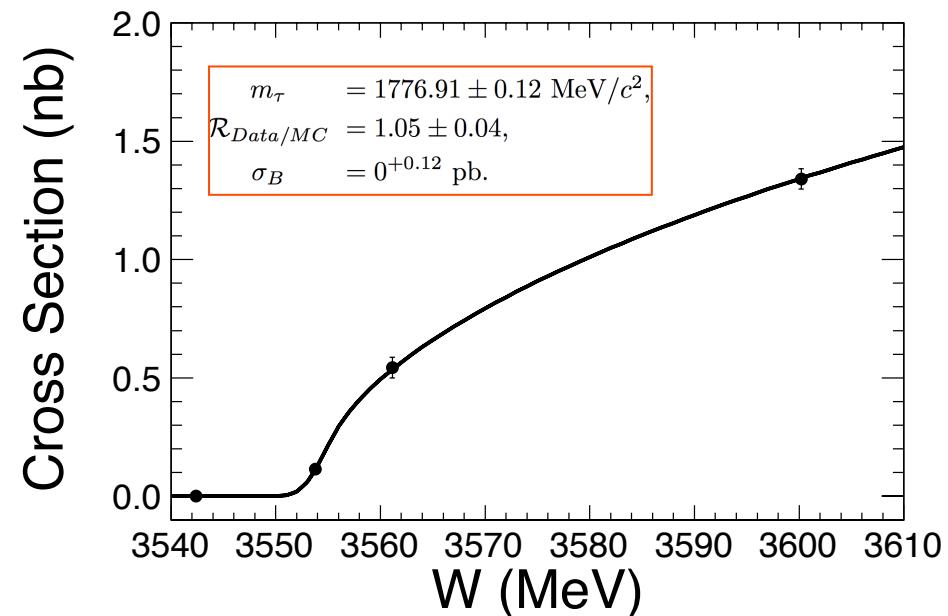
$$\mu_i = [R_{Data/MC} \times \varepsilon_i \times \sigma(E_{CM}^i, m_\tau) + \sigma_B] \times l_i$$

$$\varepsilon_i = Br_j \varepsilon_{ij},$$

i represents energy points, j represent channels

- In carrying out the ML fit, m_τ , $R_{data/MC}$, σ_B are floated

The CM energy dependence of the τ pair cross section resulting from the likelihood fit (curve), compared to the data (Poisson errors)



Systematic Uncertainties

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Source	Δm_τ (MeV/c ²)
Theoretical accuracy	0.010
Energy scale	+0.022 -0.086
Energy spread	0.016
Luminosity	0.006
Cut on number of good photons	0.002
Cuts on PTEM and acoplanarity angle	0.05
mis-ID efficiency	0.048
Background shape	0.04
Fitted efficiency parameter	+0.038 -0.034
Total	+0.094 -0.124

Summary

- $m_\tau = 1776.91 \pm 0.12^{+0.10}_{-0.13} \text{ MeV}/c^2$
- Calculate g_τ with $B(\tau \rightarrow e\bar{\nu}\nu)$ and τ_τ from PDG

$$g_\tau = (1.1650 \pm 0.0034) \times 10^{-5} \text{ GeV}^{-2}$$

- The ratio of squared coupling constants:

$$\left(g_\tau / g_\mu \right)^2 = 1.0016 \pm 0.0042$$

PRD 90, 012001

Compatible with previous determination
Dominant uncertainty still comes from Δm_τ

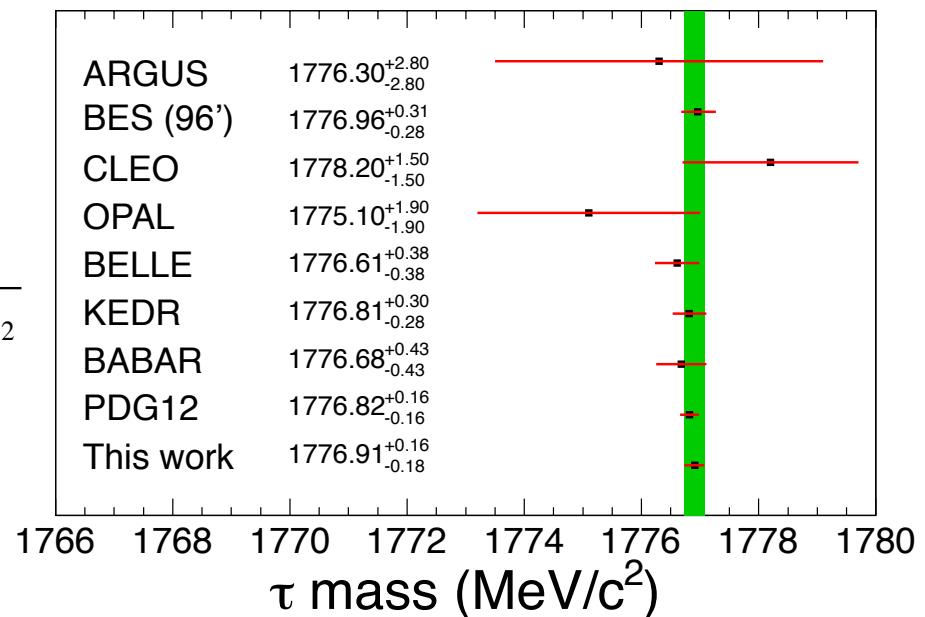
agrees at the 0.4σ level !

- Yoshio Koide equality testing

$$m_e + m_\mu + m_\tau = \frac{2}{3} (\sqrt{m_e} + \sqrt{m_\mu} + \sqrt{m_\tau})^2$$

$$\Delta f_m = \sqrt{\sum_{i=e,\mu,\tau} (m_i - \frac{2}{3} \sum_{k=e,\mu,\tau} \sqrt{m_i m_k})^2 \times \left(\frac{\delta m_i}{m_i}\right)^2}$$

$$\text{The error: } \Delta f_m \approx \frac{1}{3} \delta m_\tau \approx 60 \text{ keV}$$



danke

Bask up slides

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Pseudomass technique

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- Based on the kinematics of multihadronic τ decays, such as :

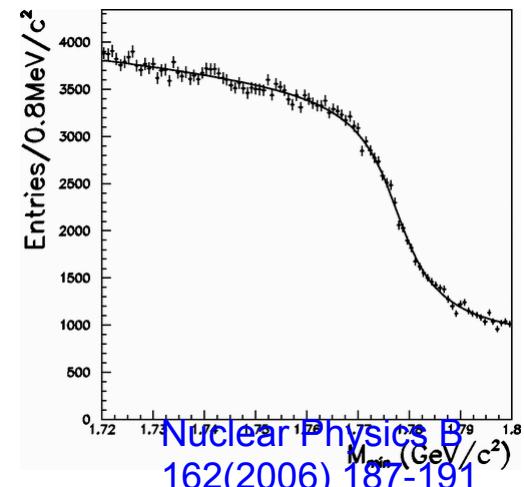
$$\begin{aligned} e^+e^- &\rightarrow \tau^+\tau^- \rightarrow \pi^-\pi^-\pi^+\nu_\tau \\ &\rightarrow e^+\nu_e\nu_\tau, \mu^+\nu_\mu\nu_\tau \end{aligned}$$

$$m_\tau^2 = E_\tau^2 - p_\tau^2$$

Three Assumptions

$$\left\{ \begin{array}{l} \cos(\vec{p}_\tau, \vec{p}_{3\pi}) \approx 1 \\ \tau \text{ momentum region: } p_\tau^* = p_{3\pi} + p_{\nu_\tau} \\ p_{\nu_\tau} = \sqrt{E_{\nu_\tau}^2 - m_{\nu_\tau}^2} \quad m_{\nu_\tau} \text{ neglect,} \end{array} \right.$$

$$m_\tau^{*2} = E_\tau^2 - p_\tau^{*2} = 2(E_\tau - E_{3\pi})(E_{3\pi} - p_{3\pi}) + m_{3\pi}^2$$



Large sample, 3 assumptions

τ mass can be extracted from the fitting

Theoretical τ pair production cross section

BESIII

$$\sigma(W) = \frac{1}{\sqrt{2\pi}\Delta_E} \int_0^{+\infty} dW' e^{-(W'-W)^2/2\Delta_E^2} \int_0^{\beta^2} dx F_i(x, W') \sigma^0(W' \sqrt{1-x})$$

Energy Spread

ISR correction

Coulomb Correction

FSR Correction

Vacuum Polarization
Correction

$$\sigma^0(W) = \frac{4\pi\alpha^2}{3W^2} \frac{\beta(3-\beta^2)}{2} \frac{F_c(\beta)F_r(\beta)}{[1-\Pi(W)]^2}$$