Measurement of τ mass at BESIII

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On behalf of BESIII

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Outline

- **Motivation**
- **Scan method & Data taking**
- **Analysis**
- **Summary**

Motivation of high accurate τ mass measurement

Elementary parameter in SM

$$\frac{B(\tau \rightarrow e\nu_e\nu_\tau)}{\tau_\tau} = \frac{g_\tau^{\,2} m_\tau^{\,5}}{192\pi^3}$$

Yoshio Koideo equation

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

Lepton universality

$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \rightarrow e\nu_e\nu_\tau)}{B(\mu \rightarrow e\nu_e\nu_\mu)}\left(1+\Delta_e\right)\left(1+\Delta_W\right)$$

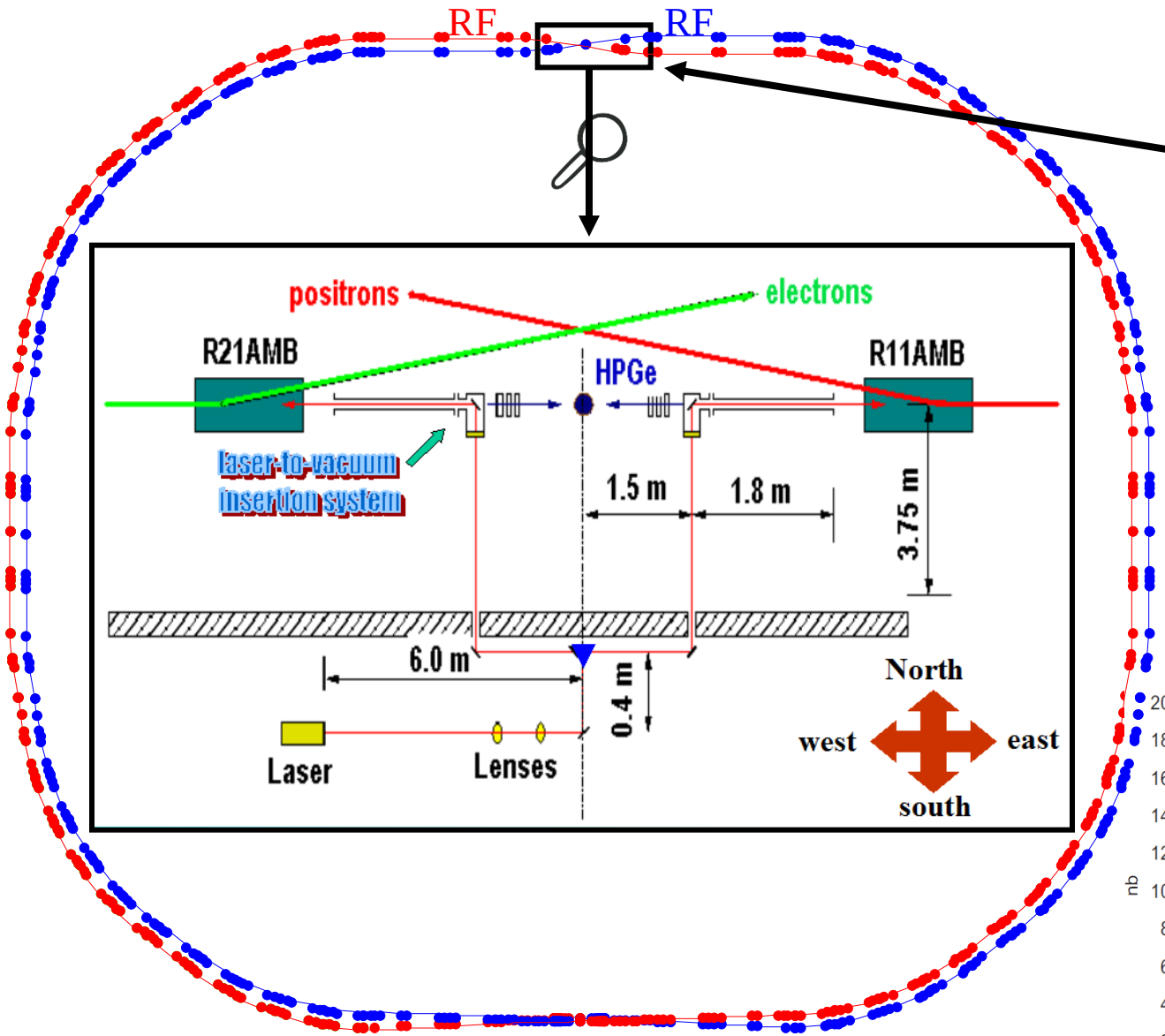
- $M_e = 0.510998910 \pm 0.000000013$ (2.6×10^{-8})
- $M_\mu = 105.658367 \pm 0.000004$ (3.8×10^{-8})
- $M_\tau = 1776.82 \pm 0.16$ (9.0×10^{-5})

PDG 2012

Method: Pseudo-mass and threshold scan

τ lepton mass measurement [value+statistic +systematic error]	Year	Ex. Group	Data sample	Method
$1776.68 \pm 0.12 \pm 0.41$	**2009**	**Babar**	423 fb^{-1}	Pseudo-mass
$1776.81+(+0.25-0.23) \pm 0.15$	**2007**	**KEDR**	6.7 pb^{-1}	Scan
$1776.61 \pm 0.13 \pm 0.35$	**2007**	**Belle**	414 fb^{-1}	Pseudo-mass
$1776.96+(+0.18-0.21)+(+0.25-0.17)$	**1996**	**BES**	5.1 pb^{-1}	Scan

- For threshold scan method precisely determine beam energy and energy spread is extremely important.

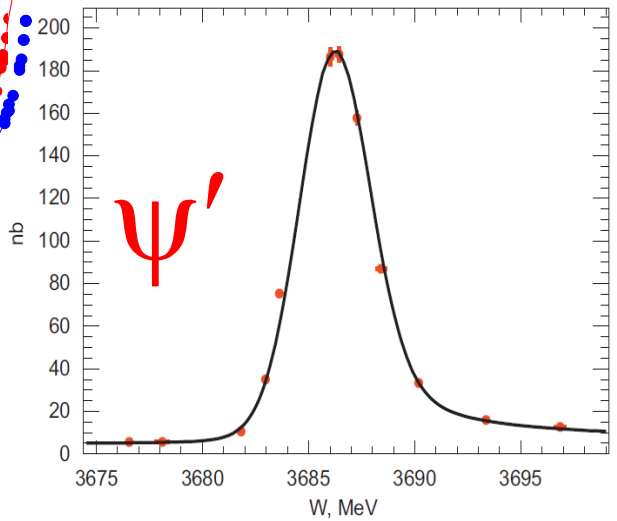


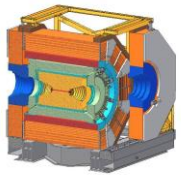
BEMS:

beam energy measurement system

$\delta m_{\psi'}/m_{\psi'} = 2 \times 10^{-5}$

$\delta\Delta / \Delta = 6\%$.





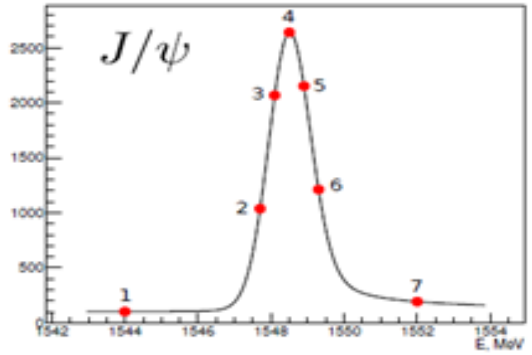
Optimization for scan

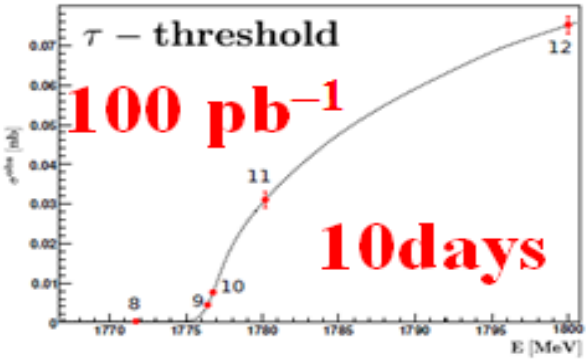
1. **N free parameters fit, N scan points is enough**
2. **The optimized position can be obtained by single parameter scan**
3. **Luminosity allocation can be determined analytically or by simulation method**

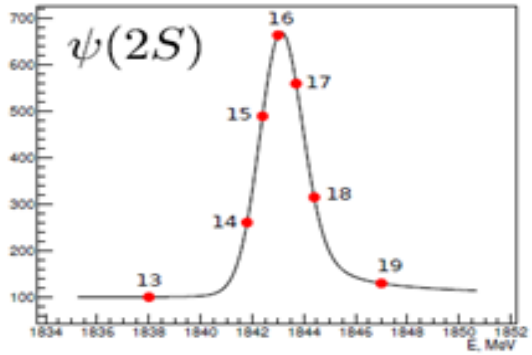
Y.K.Wang, J.Y.Zhang, X.H.Mo, C.Z.Yuan, Chin. Phys. C 2009, 33:501-507

τ scan (plan & done)

plan







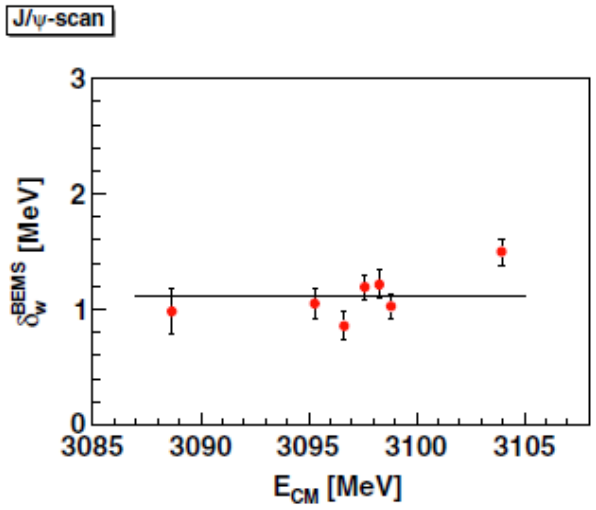
done: $24pb^{-1}$ four points

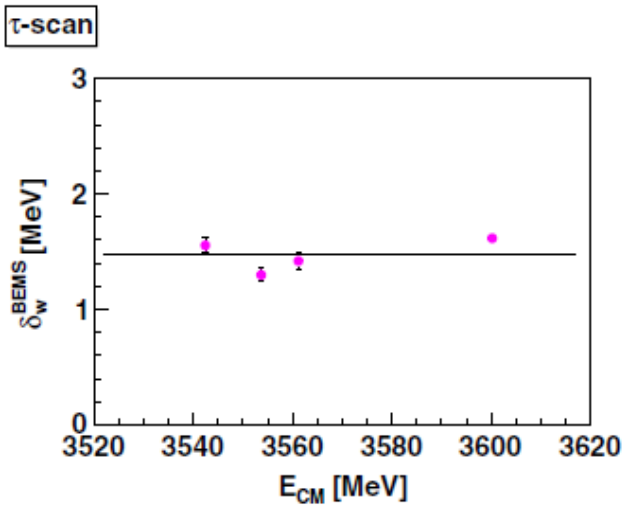
Scan	$E_{\text{c.m.}}$ (MeV)	$\mathcal{L}$ (nb^{-1})
J/ψ	3088.7	78.5 ± 1.9
	3095.3	219.3 ± 3.1
	3096.7	243.1 ± 3.3
	3097.6	206.5 ± 3.1
	3098.3	223.5 ± 3.2
	3098.8	216.9 ± 3.1
	3103.9	317.3 ± 3.8
τ	3542.4	4252.1 ± 18.9
	3553.8	5566.7 ± 22.8
	3561.1	3889.2 ± 17.9
	3600.2	9553.0 ± 33.8
ψ'	3675.9	787.0 ± 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

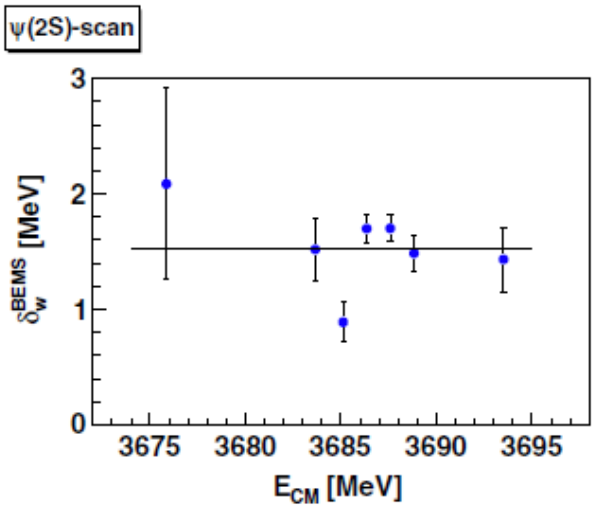
Beam energy from BEMS

Scan 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







Energy spreads (MeV)

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

Data Samples and MC Simulation

- Bhabha and two gamma events → determine luminosities
  - Babayaga 3.5 generator
- Hadronic events in J/ψ and ψ' scan → study 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 → determine τ mass
  - ee, eμ, eπ, eK, μμ, μπ, μK, πK, ππ, KK, eρ, μρ and πρ (with accompanying neutrinos implied)
    - KKMC + BesEvtGen

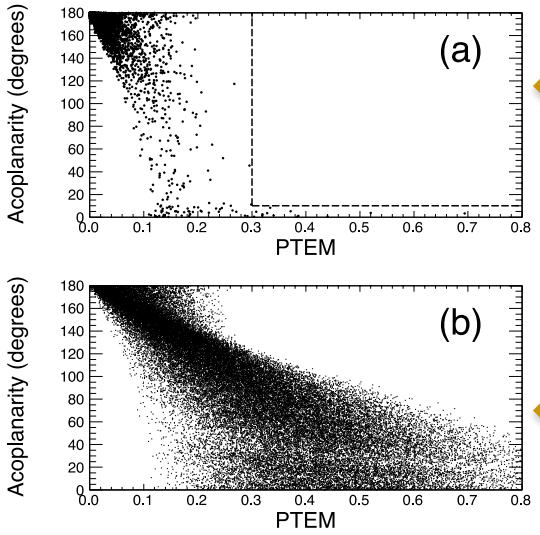
Event Selection for τ pair candidate events

- Good shower in EMC
  - E > 25MeV (50MeV) for $|\cos\theta| < 0.8$ (for $0.86 < |\cos\theta| < 0.92$)
  - 0 < t < 750 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

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

- PID selection criteria

Event selection details



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	$<160^\circ$	
$e\rho$	$<170^\circ$	
$\mu\rho$	$<150^\circ$	
$\pi\rho$		

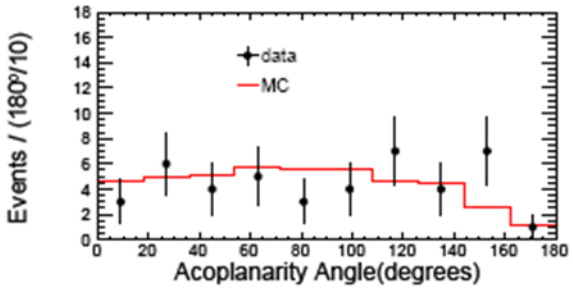
PID	p (MeV/c)	EMC	TOF	MUC	other
e	$p_{min} < p < p_{max}$	$0.8 < E/cp < 1.05$	$\lvert\Delta TOF(e)\rvert$ <0.2 ns 0 ns< TOF <4.5 ns		
μ	$p_{min} < p < p_{max}$	$E/cp < 0.7$ $0.1 < E < 0.3$	$\lvert\Delta TOF(\mu)\rvert$ <0.2 ns	(D >(80×p-50) cm or D >40 cm) and N_h >1	
π	$p_{min} < p < p_{max}$	$E/cp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

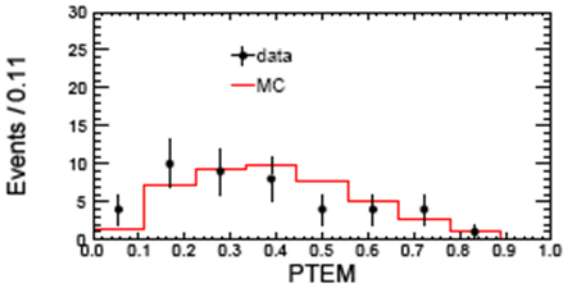
Comparison of the data and MC Samples

Acoplanarity angle

PTEM

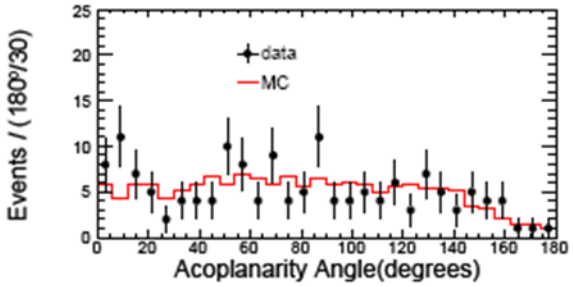
1st – point below threshold

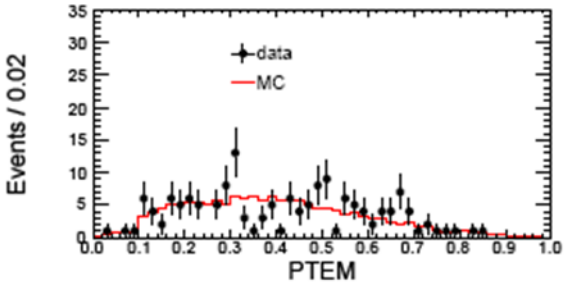




2nd – point

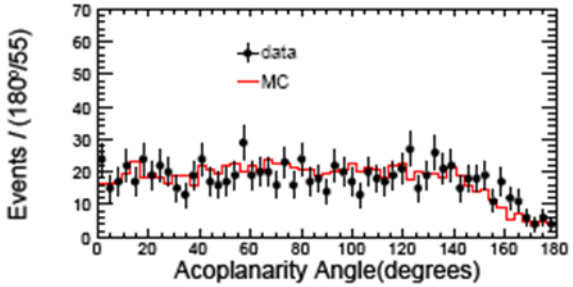
E_{cm} = 3553.8MeV

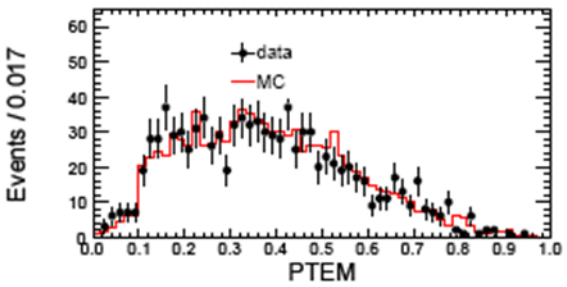




3rd – point

E_{cm} = 3561.1MeV





4th – point

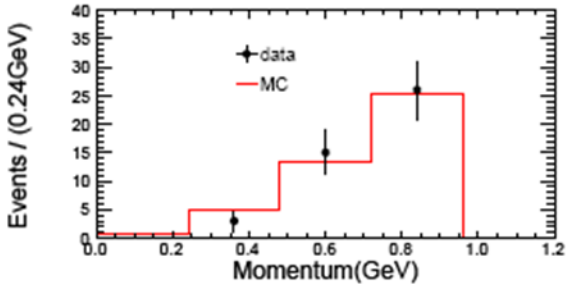
E_{cm} = 3600.2MeV

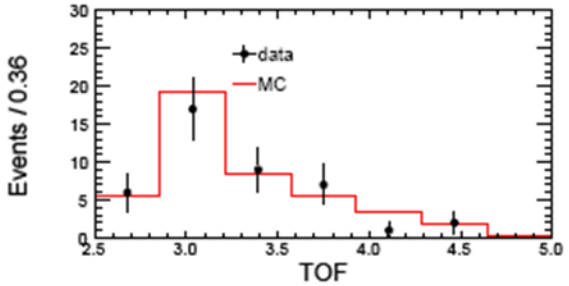
Comparison of the data and MC Samples (Cont.)

Momentum of charged tracks

TOF of charged tracks

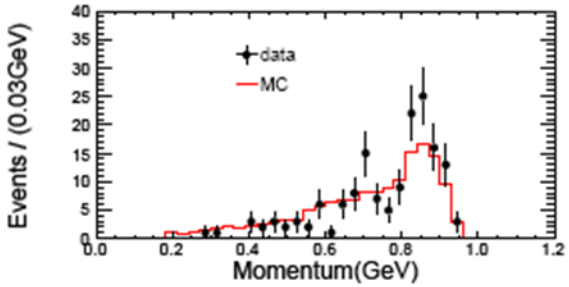
1st – point below threshold

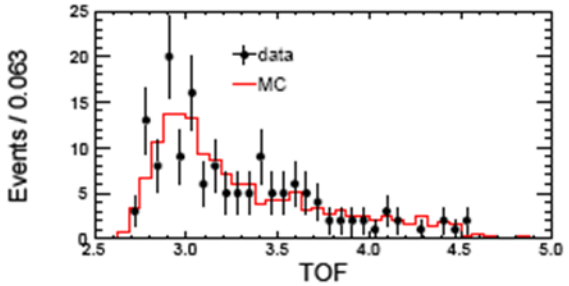




2nd – point

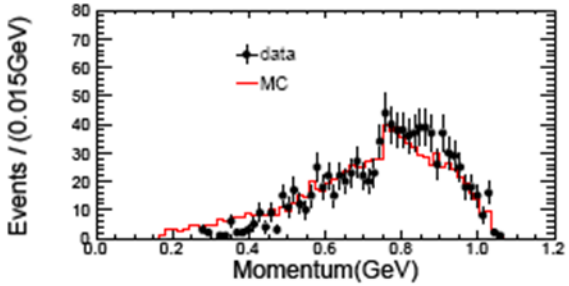
E_{cm} = 3553.8MeV

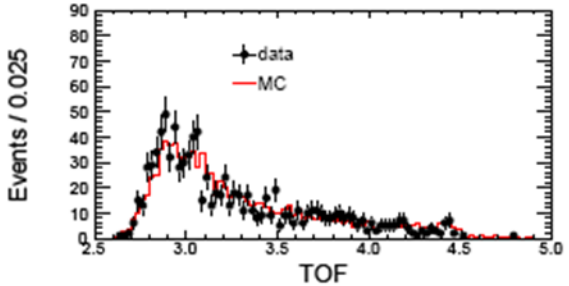




3rd – point

E_{cm} = 3561.1MeV





4th – point

E_{cm} = 3600.2MeV

Data analysis

- Luminosity
- J/ψ and ψ' line shape (calibration of energy scale and spread)
- τ mass measurement

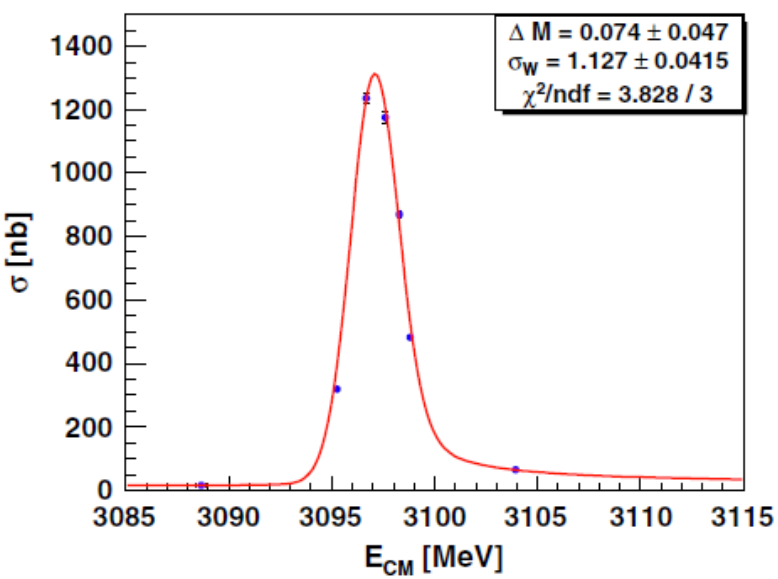
Luminosity

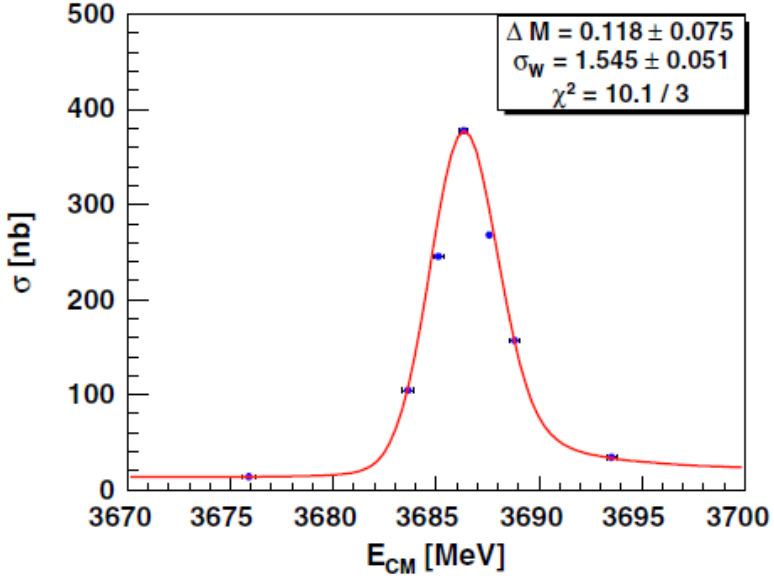
Cross checked by Bhabha and $\gamma\gamma$

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

Most $\delta L/L$ <2 %

J/ψ and ψ' line shape fit



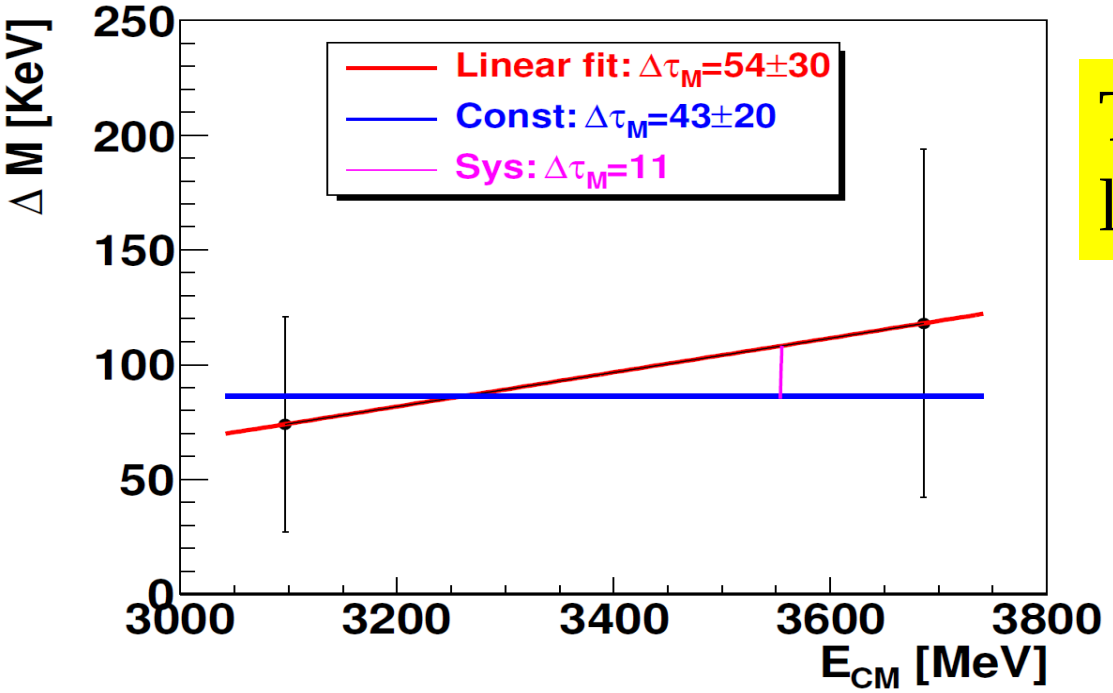


$\Delta M = M_{FIT} - M_{PDG}$ $\delta_w = energy\ spread$

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

MeV

Energy scale extrapolation to τ mass region



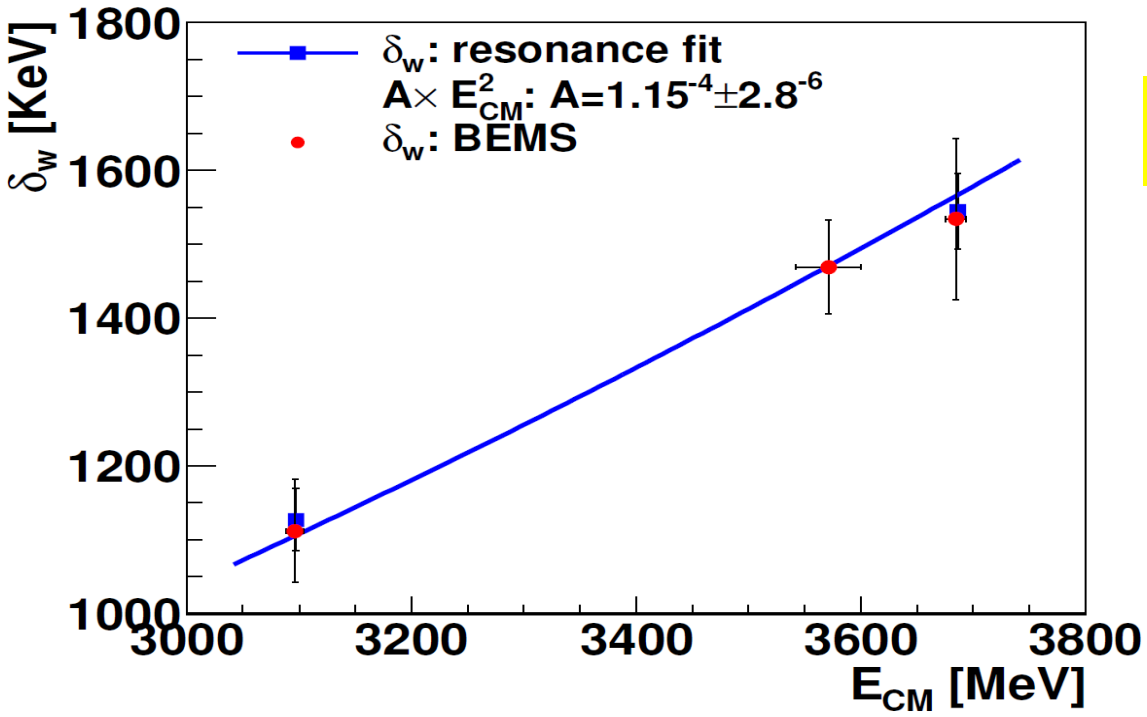
Two assumptions: linear and constant

$\Delta M \approx 90$ keV

$$\Delta M \Rightarrow \delta M_\tau$$

$\delta M_\tau = 54 \pm 30$ (stat.) ± 12 (sys.) keV

Energy spread extrapolation to τ mass region



Quadratic dependence

$$\delta_w = 1.469 \pm 0.064 \pm 0.057 \text{ MeV}$$

Interference is the main contribution to the systematic

$$\Delta\delta_w \Rightarrow \delta M_\tau$$

$$\delta M_\tau = 16 \text{ keV}$$

The number of observed events and that of normalized MC samples

	1		2		3		4		Total	
Final state	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

Formulae prepared for fit

$$L(m_\tau, \mathcal{R}_{\text{data/MC}}, \sigma_B) = \prod_{i=1}^{4} \frac{\mu_i^{N_i} e^{-\mu_i}}{N_i!}$$

$m_\tau, R_{data/MC}, \sigma_B$ are floating

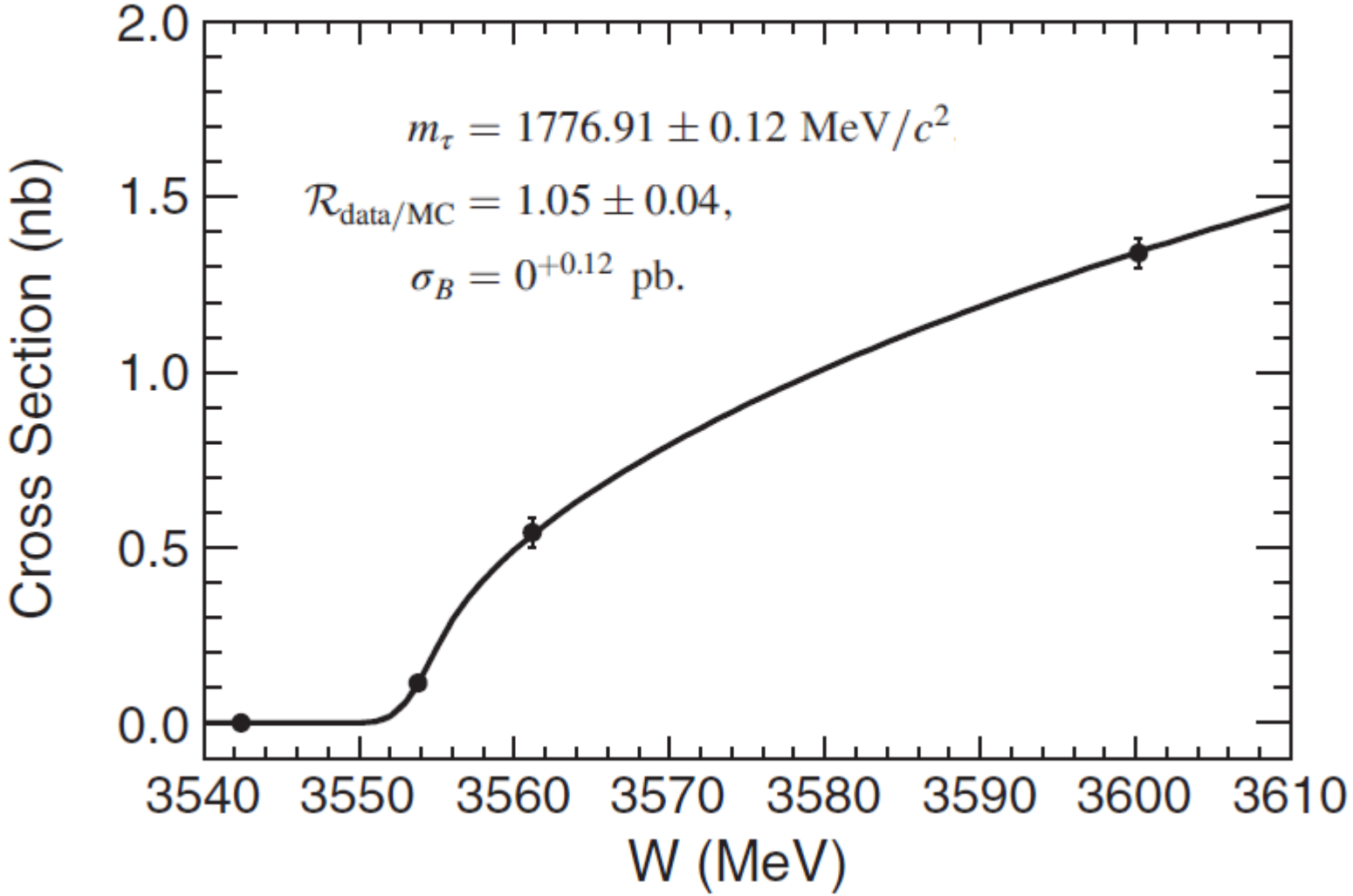
$$\mu_i = [\mathcal{R}_{\text{data/MC}} \times \epsilon_i \times \sigma(E^i_{\text{c.m.}}, m_\tau) + \sigma_B] \times \mathcal{L}_i$$

$$\sigma(E_{\text{c.m.}}, m_\tau, \delta_w^{\text{BEMS}}) = \frac{1}{\sqrt{2\pi}\delta_w^{\text{BEMS}}} \int_{2m_\tau}^{\infty} dE'_{\text{c.m.}} e^{\frac{-(E_{\text{c.m.}}-E'_{\text{c.m.}})^2}{2(\delta_w^{\text{BEMS}})^2}} \int_0^{1-\frac{4m^2}{E'^2_{\text{c.m.}}}} dx F(x, E'_{\text{c.m.}}) \frac{\sigma_1(E'_{\text{c.m.}}\sqrt{1-x}, m_\tau)}{|1-\prod(E_{\text{c.m.}})|^2}$$

Theoretical accuracy of cross section at the level of 0.1%

F(x, $E_{c.m.}$): E.A.Kuraev,V.S.Fadin , Sov.J.Nucl.Phys. 41(1985)466;
$\Pi(E_{c.m.})$: F.A. Berends et al. , Nucl. Phys. B57 (1973)381.

Fit results


$m_\tau = 1776.91 \pm 0.12$ MeV/c^2
$\mathcal{R}_{\rm data/MC} = 1.05 \pm 0.04$,
$\sigma_B = 0^{+0.12}$ pb.
Cross Section (nb)
2.0
1.5
1.0
0.5
0.0
3540
3550
3560
3570
3580
3590
3600
3610
W (MeV)

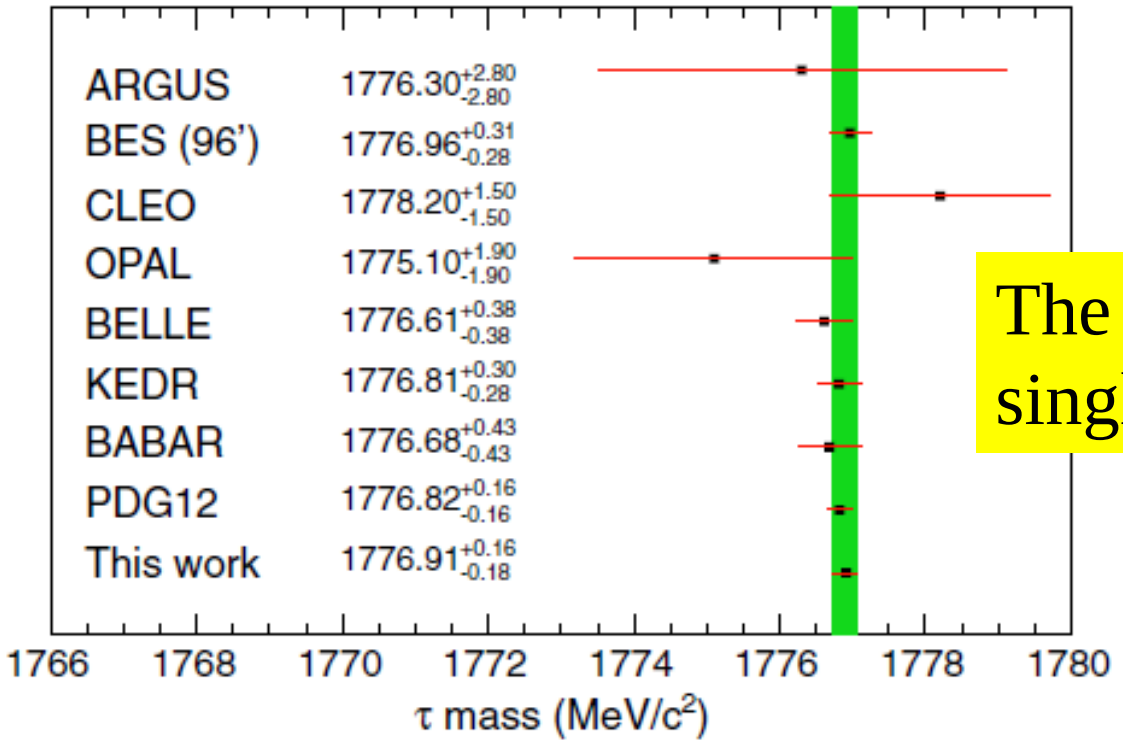
Systematic uncertainties

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

$$m_\tau = (1776.91 \pm 0.12^{+0.10}_{-0.13})\ \mathrm{MeV}/c^2$$

PRD 90, 012001



The most precise single measurement.

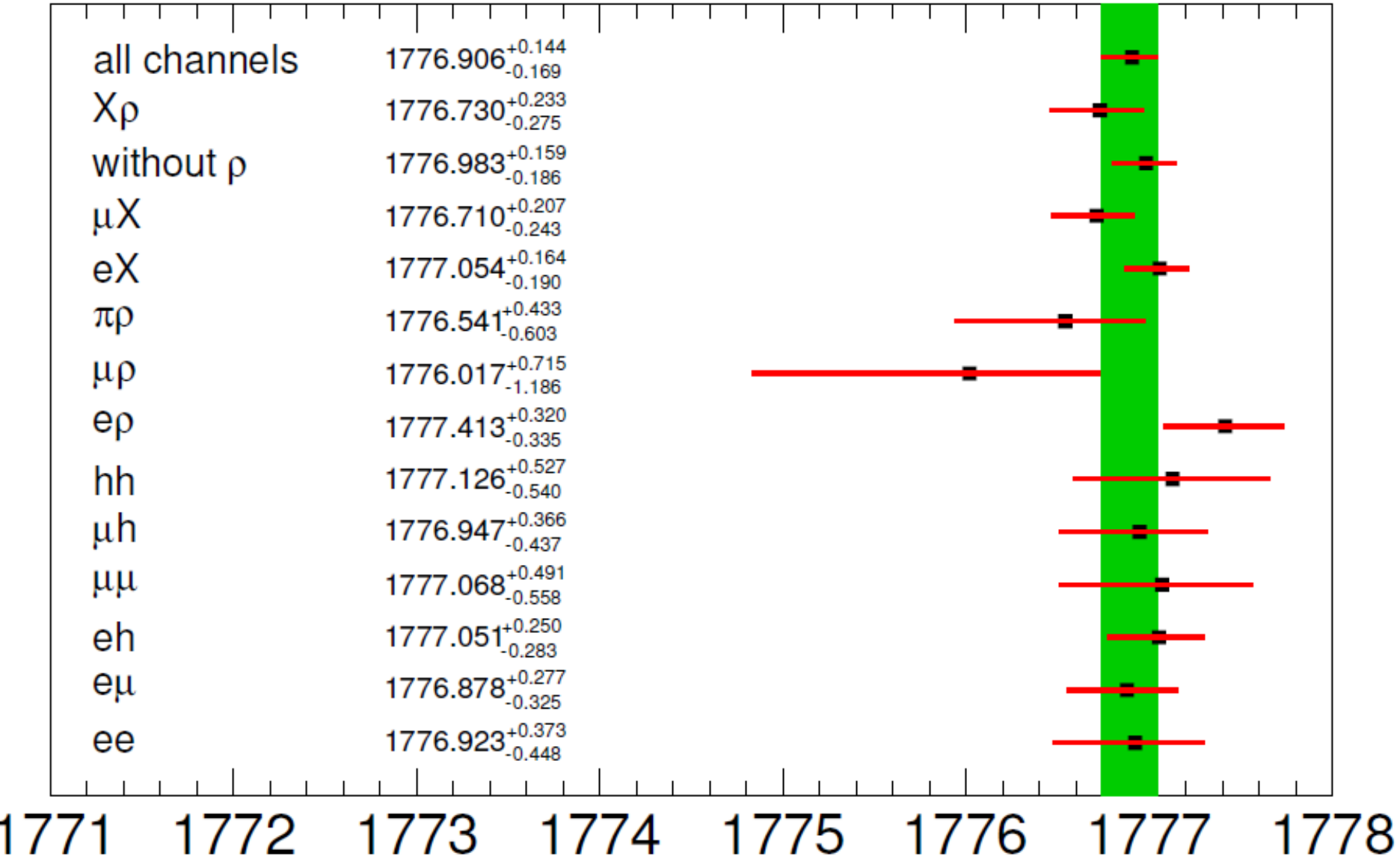
$$\left(\frac{g_\tau}{g_\mu}\right)^2 = 1.0016 \pm 0.0042$$

Lepton universality can be tested at 0.4%

- An updated scan may at BESIII
  - 10 days → 29 days, 24 pb^{-1} → 100 pb^{-1}

Thanks!

Backup


all channels
1776.906 +0.144 -0.169
Xρ
1776.730 +0.233 -0.275
without ρ
1776.983 +0.159 -0.186
μX
1776.710 +0.207 -0.243
eX
1777.054 +0.164 -0.190
πρ
1776.541 +0.433 -0.603
μρ
1776.017 +0.715 -1.186
eρ
1777.413 +0.320 -0.335
hh
1777.126 +0.527 -0.540
μh
1776.947 +0.366 -0.437
μμ
1777.068 +0.491 -0.558
eh
1777.051 +0.250 -0.283
eμ
1776.878 +0.277 -0.325
ee
1776.923 +0.373 -0.448
1771
1772
1773
1774
1775
1776
1777
1778

Tau mass scan is actually an accelerator experiment

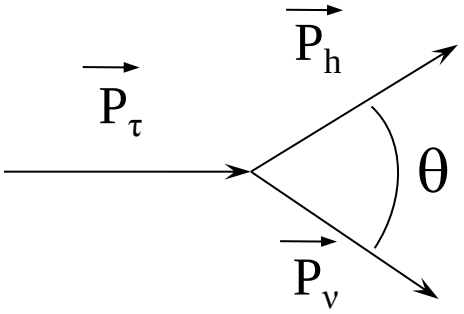
Tau mass scan

Expected luminosity (speed of data accumulation) is 0.3 pb-1/hour. Expected time of hitting to energy point is 1 day (3 steps x 4+4 measurements of electron/positron beam energy). Then it will take about 29 days to do experiment.

Beam energy, Mev	1771.0	1776.6	1777.0	1780.4	1800.0	Psi prime scan	1776.6	1777.0	J/psi scan
Integrated luminosity, pb-1	14	14	14	7	14		25	12	
Time of data aquisition, days	3	3	3	2	3	4	4,5	2,5	4

Old plan 10 days → New plan: 29 days

Pseudomass method



All in CMS

$M_{min} \le M_\tau$

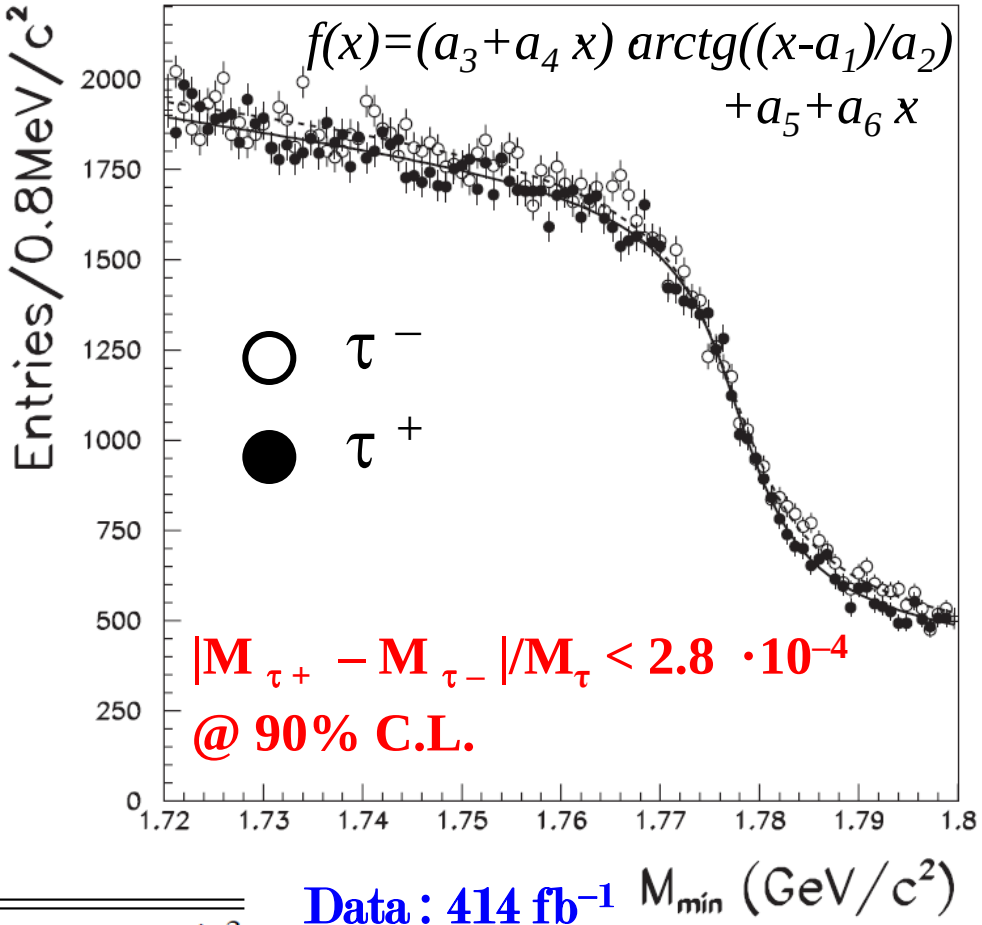
$M_{min}^2 = M_h^2 + 2(E_\tau - E_h)(E_h - P_h)$

$E_\tau = E_{beam}$: beam energy, run dependence is corrected

E_h : hadron system energy

P_h : hadron system momentum

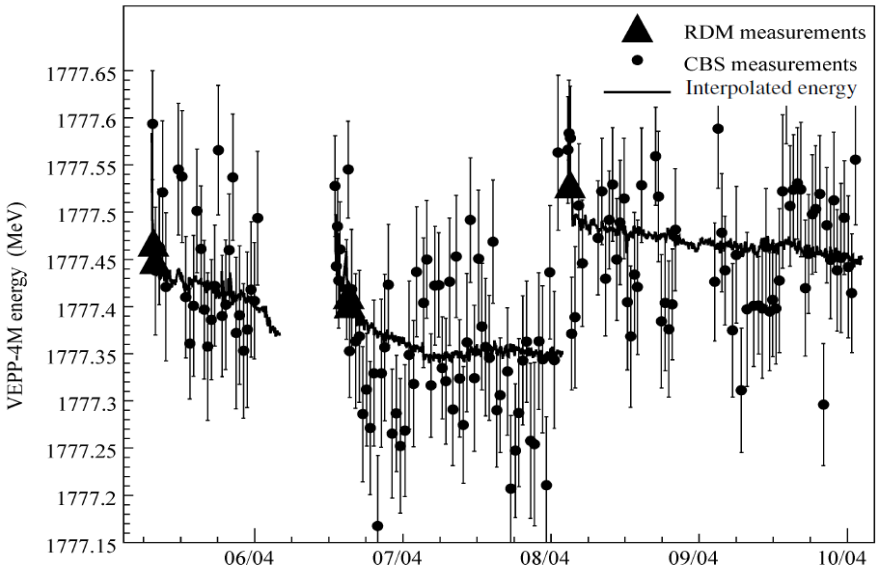
M_h : mass of the hadron system

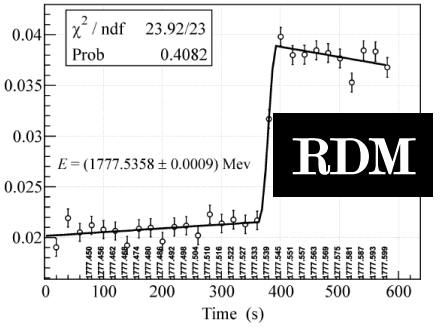


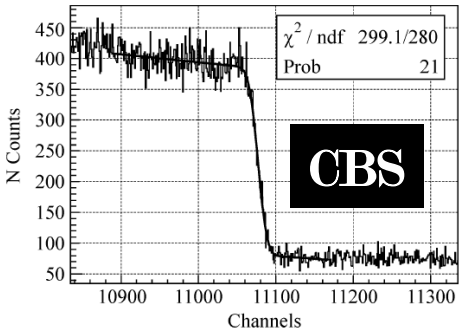
Source of systematics	σ, MeV/c^2
Beam energy and tracking system	0.26
Edge parameterization	0.18
Limited MC statistics	0.14
Fit range	0.04
Momentum resolution	0.02
Model of $\tau \to 3\pi\nu_\tau$	0.02
Background	0.01
Total	0.35

M_τ = 1776.61
$\pm$ 0.13(stat.)
$\pm$ 0.35(sys.) MeV
(Belle:PRL99,011801)

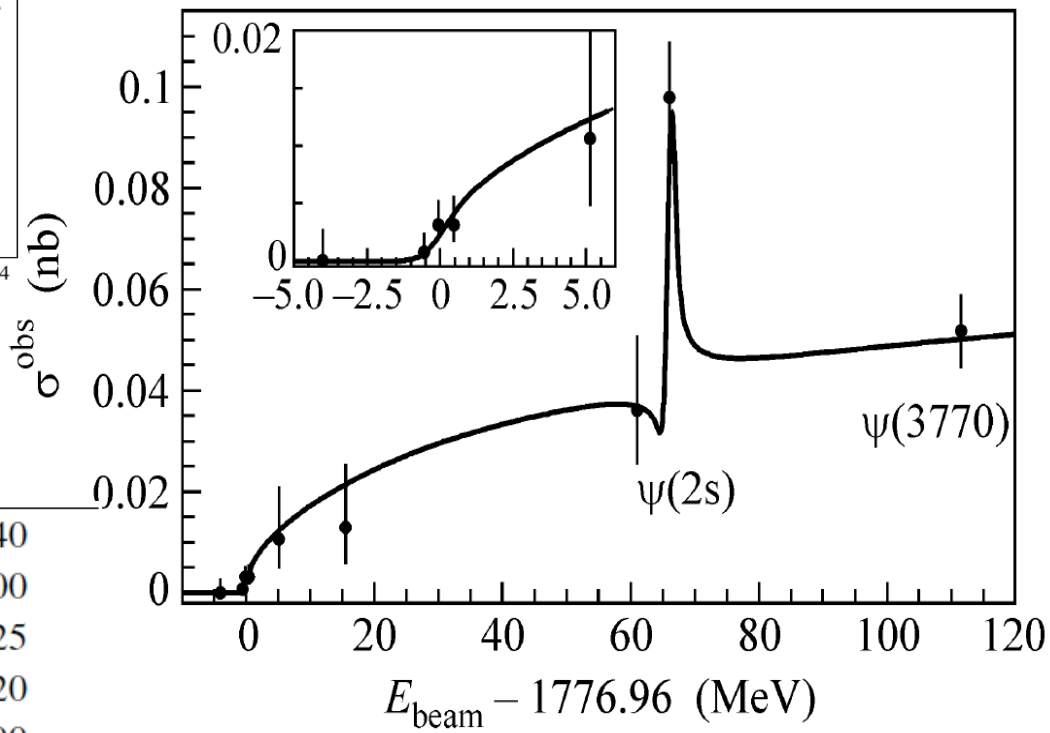
Threshold scan method







8 points, 6.7 pb^{-1}, for τ
1 points, 0.8 pb^{-1}, at ψ′



Beam energy determination	40
Detection efficiency variations	100
Energy spread determination accuracy	25
Energy dependence of the background	20
Luminosity measurement instability	90
Beam energy spread variation	15
Cross section calculation (r.c., interference)	30
Sum in quadrature	150

$$M_\tau = 1776.81^{+0.25}_{-0.23} \pm 0.15 \text{ MeV}$$

$$\sigma M_\tau / M_\tau = 1.64 \times 10^{-4}$$

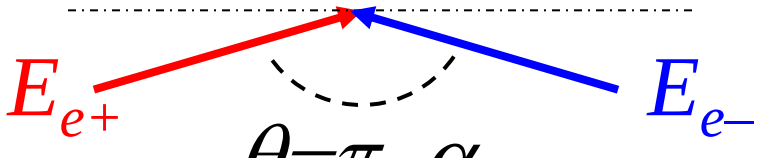
KDER : JETPL85_347

CM energy setting

$$S=(E_{e^+}+E_{e^-})^2-(p_{e^+}+p_{e^-})^2$$

$$E_{cm}^{AA}=(E_{e^+}+E_{e^-})\cdot\cos\frac{\alpha}{2}$$

$$E_{cm}^{GA}=2\sqrt{E_{e^+}E_{e^-}}\cdot\cos\frac{\alpha}{2}$$

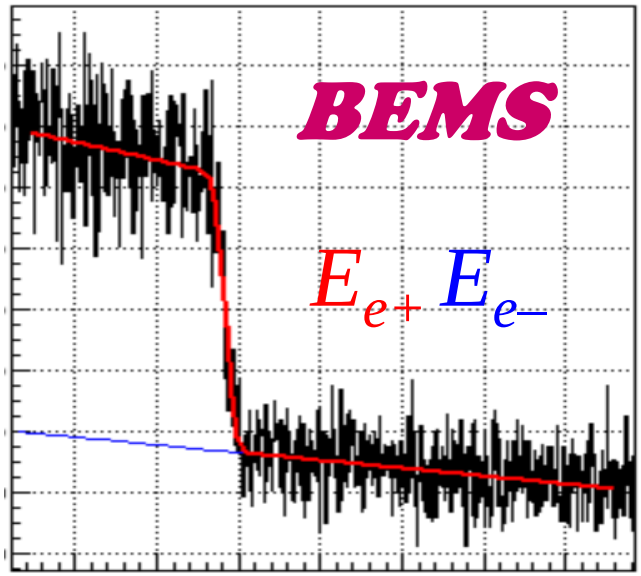


$$\theta=\pi-\alpha$$

$$\alpha\approx 22\text{mrad}$$

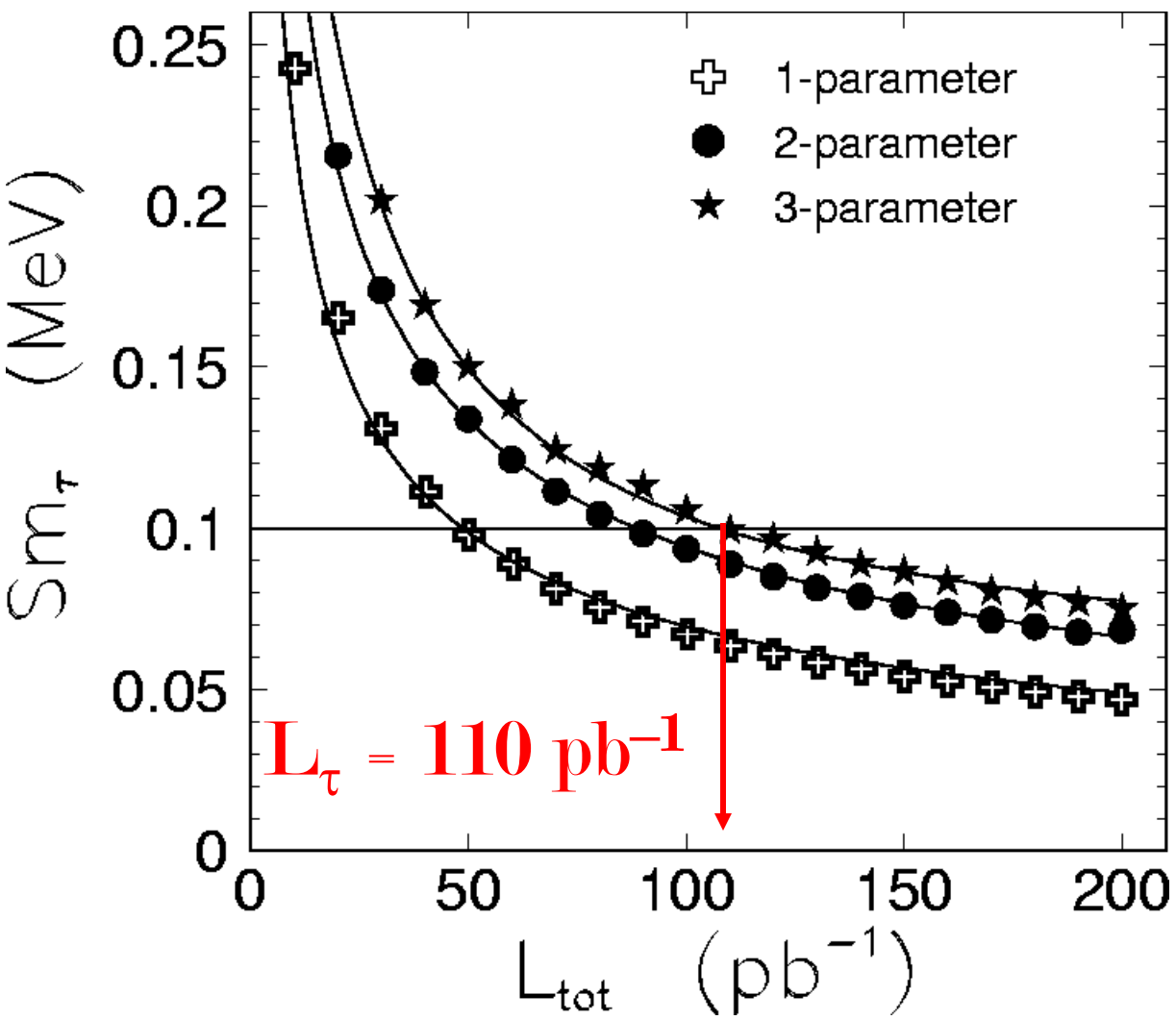
$$E_{cm}^{GA}\approx E_{cm}^{GA}\approx 2E_{beam}\left(1-\frac{\alpha^2}{8}\right)$$

$E_{cm}^{GA}\approx E_{cm}^{GA}\approx E_{cm}^{\sqrt{S}}$
α-effect $\approx 6\times10^{-5}$,
0.11MeV @τ threshold



$$E_{cm}^{\sqrt{S}}\approx 2E_{beam}\left(1-\frac{\alpha^2}{8}\right)$$

$$E_{cm}^{\sqrt{S}}=\sqrt{2m_e^2+2E_{e^+}E_{e^-}-2\sqrt{E_{e^+}^2-m_e^2}\sqrt{E_{e^-}^2-m_e^2}\cdot\cos(\pi-\alpha)}$$



Optimization study:
Chin. Phys. C 2009, 33:501-507 ;
Y.K.Wang,
J.Y.Zhang,
X.H.Mo,
C.Z.Yuan.

Only based on e μ event !!
Only Statistics uncertainty !!

$1=M_\tau$, $2=\varepsilon$, $3=\sigma_{BG}$;

L_1: L_2 = 3:1 , L_1: L_{tot} = 10% , $\delta M_\tau \propto (\sqrt{L})^{-1}$;

Theoretical accuracy of cross section at the level of 0.1%

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

Energy Spread

ISR correction

Coulomb Correction

FSR Correction

Vacuum Polarization Correction

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