Tau physics at BESIII

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Outline

- Introduction
- BEPCII and BESIII
- Tau physics at BESIII
  - Tau mass measurement
  - some topics
- Summary

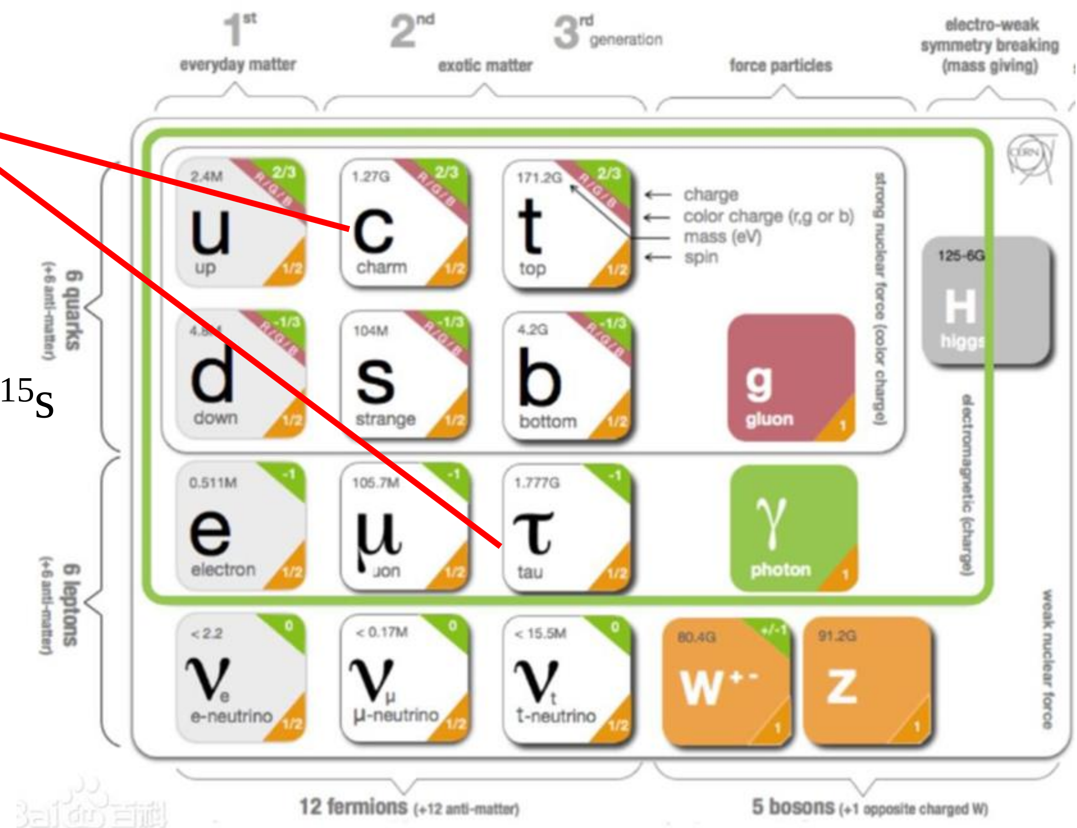
Introduction

BEPCII, BESIII

Found by MARKI in 1975

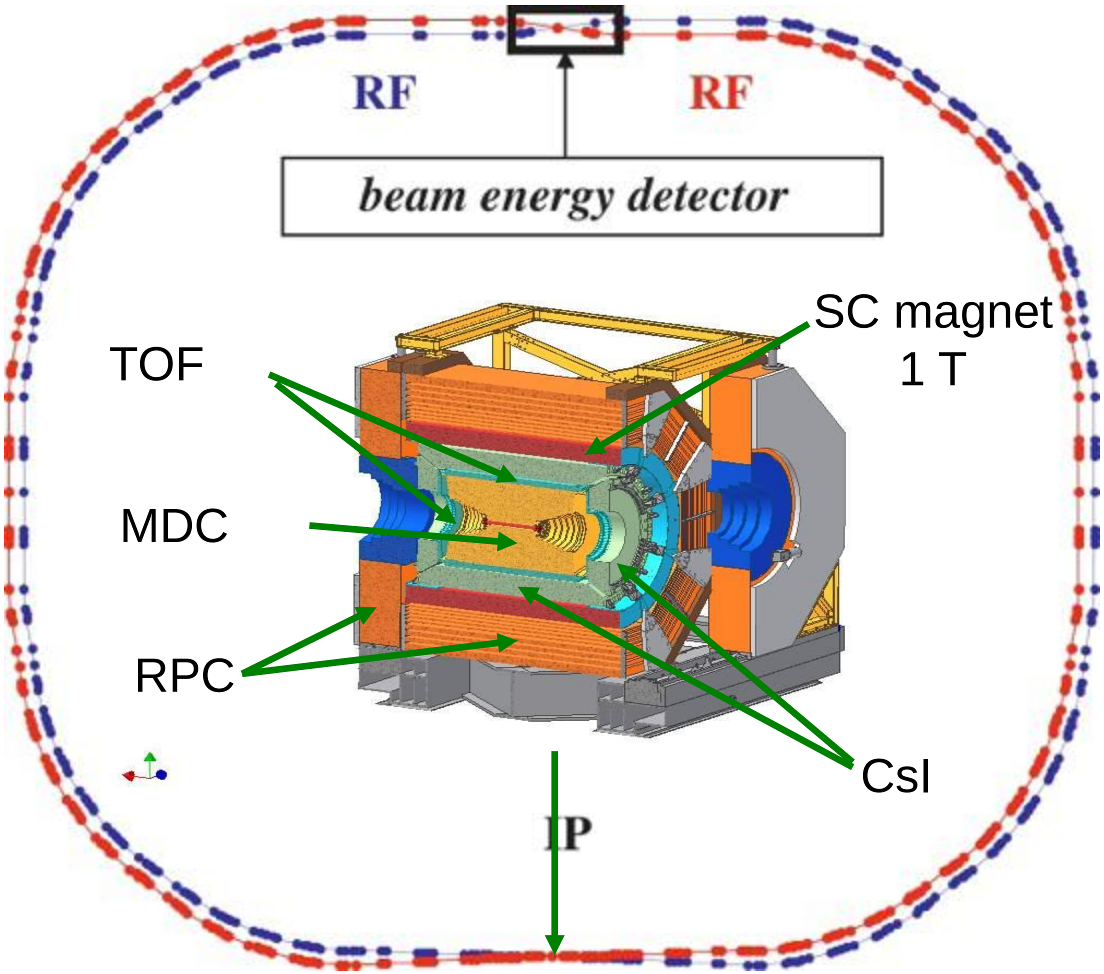
Mean life: $(290.3 \pm 0.5) \times 10^{-15}$s

$m_\tau = 1776.86 \pm 0.12$ MeV



- The heaviest lepton
- Provide plenty of tests to standard model and beyond

BEPCII and BESIII



BEPCII

Energy region: 2.0 ~ 4.6GeV
Luminosity: 10^{33} $cm^{-2}s^{-1}$ @1.89GeV
bunch: 2×93
current: 2×0.91A

BESIII

DC: position: 135 μm,
momentum: 0.5%@1GeV,
$\sigma_{dE/dx}$: 6%

EMC: 2.5%@1GeV
6 (9) mm

TOF: ~70 ps (B)
~70 ps (EC)

μ counter : 9 layers (B)
8 layers (EC)

Advantage and challenge

- Running near threshold of tau pair production
- Background simple
- Systematic uncertainty easy to control

- Statistics is limited

Tau physics at BESIII

- Tau mass measurement at BESIII
  - Motivation
  - Bean Energy Measurement System at BEPCII
  - Tau mass measurement
- Some topics
  - $D^- \rightarrow \tau^- \nu_\tau$
  - $\Psi(2S) \rightarrow \tau\tau$
  - Second-class currents decays
  - $\tau \rightarrow KKK$
  - ……

Tau mass measurement

- Tau lepton mass is a foundamental parameter of the Standard Model

$m_e = 0.5109989461 \pm 0.0000000031$ MeV (6.1×10^{-9}) ; PDG(2018)

$m_\mu = 105.6583745 \pm 0.0000024$ MeV (2.3×10^{-8}) ;

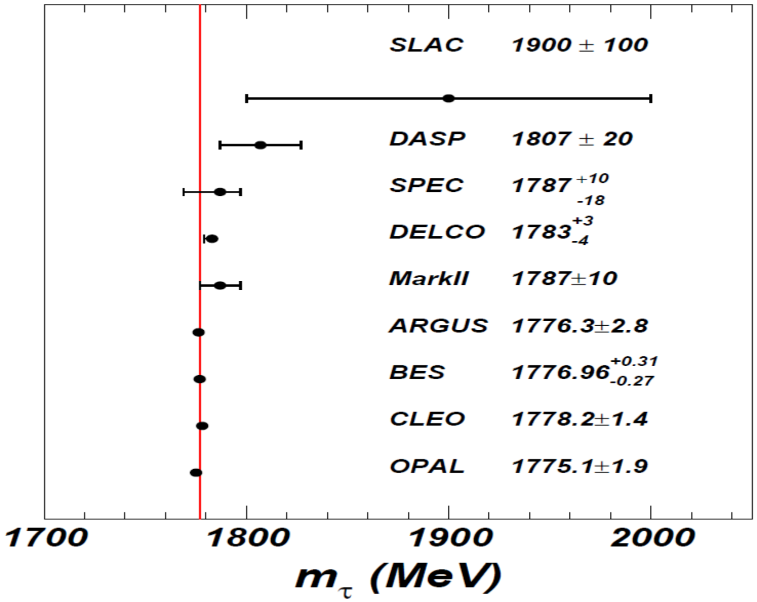
$m_\tau = 1776.86 \pm 0.12$ MeV (6.8×10^{-5})

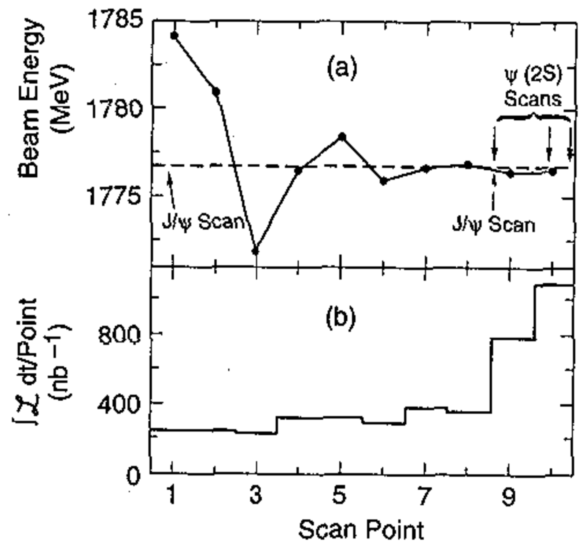
- Leptonic universality test

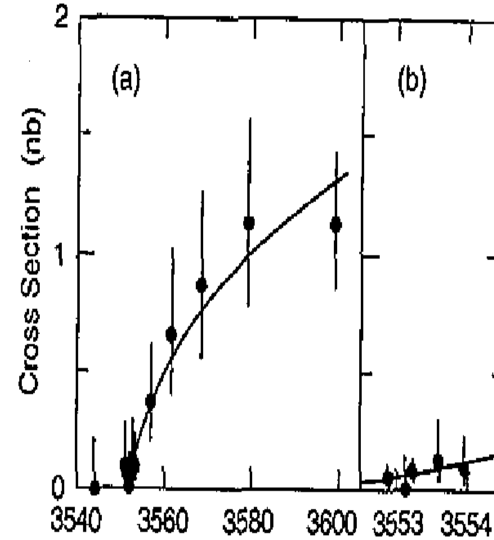
$$\left(\frac{g_\tau}{g_\mu}\right)^2 = \frac{\tau_\mu}{\tau_\tau}\left(\frac{m_\mu}{m_\tau}\right)^5 \frac{B(\tau \to e\nu_e\nu_\tau)}{B(\mu \to e\nu_e\nu_\mu)}(1+\Delta_e)$$

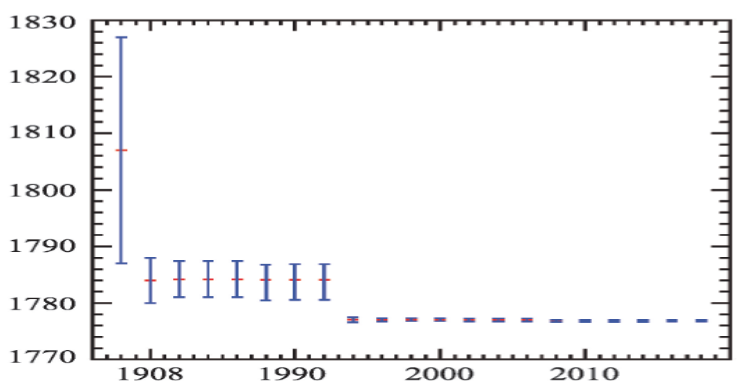
τ mass is sensitive to universality: m_τ^5

History of M_τ measurement





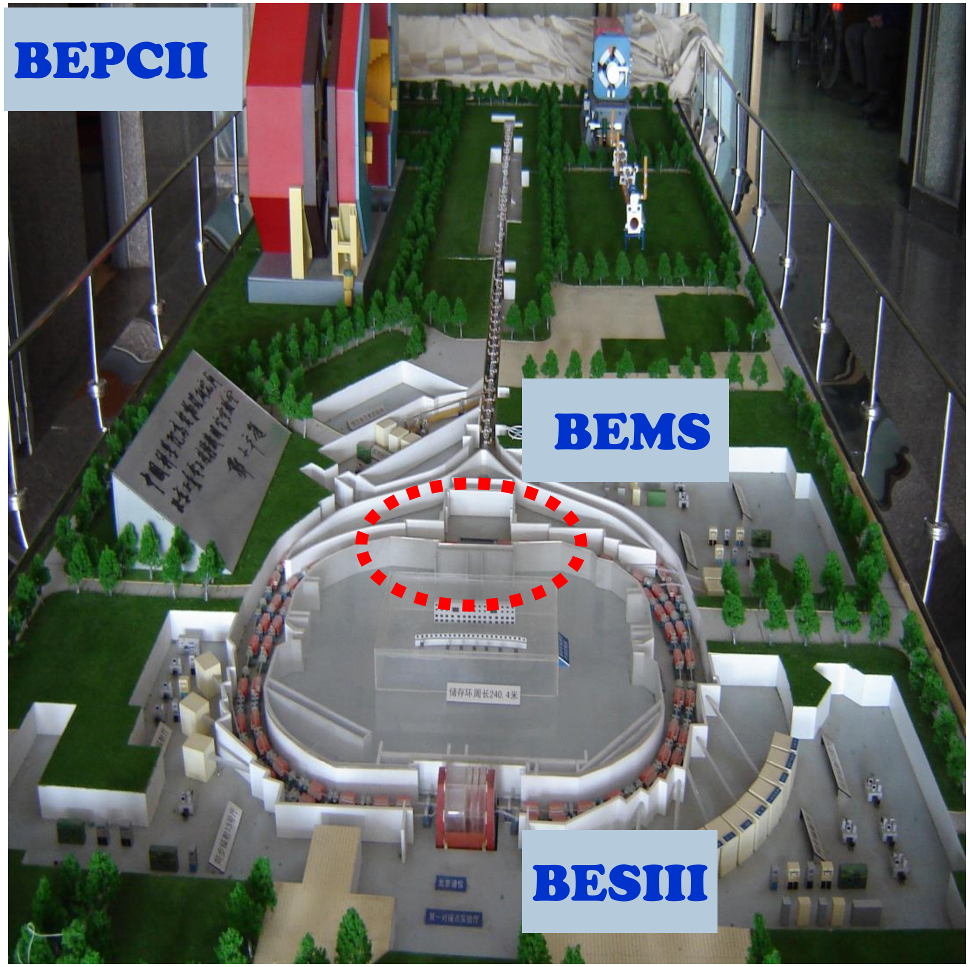




Measurement results of m_τ in the 21 century.

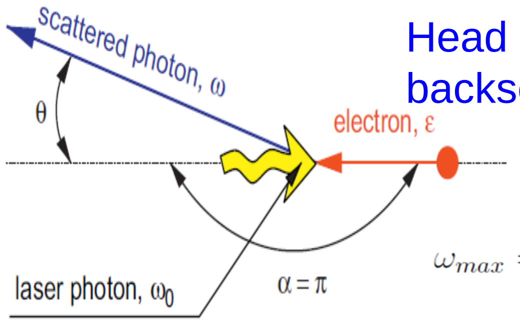
Measured m_τ (value+statistic+systematic)	Year	Exp. Group	Data sample	Method
$1776.91 \pm 0.12^{+0.10}_{-0.13}$	2014	BESIII	23.26 pb^{-1}	Threshold-scan
$1776.68 \pm 0.12 \pm 0.41$	2009	Babar	423 fb^{-1}	Pseudo-mass
$1776.81^{+0.25}_{-0.23} \pm 0.15$	2007	KEDR	6.7 pb^{-1}	Threshold-scan
$1776.61 \pm 0.13 \pm 0.35$	2007	Belle	414 fb^{-1}	Pseudo-mass

Beam Energy Measurement System (BEMS)



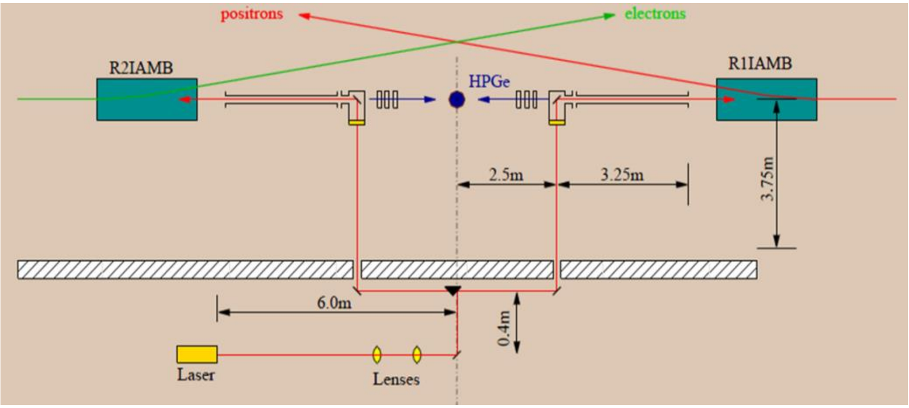
- In 2007 BEMS is started to design by:
  - **Budker Institute of Nuclear Physics SB RAS**
  - **University of Hawaii,**
  - **Institute of High Energy Physics CAS**
- The system was put to operation in December 2010.
- The uncertainty is better than 2×10^{-5}

Beam energy measurement system (BEMS)



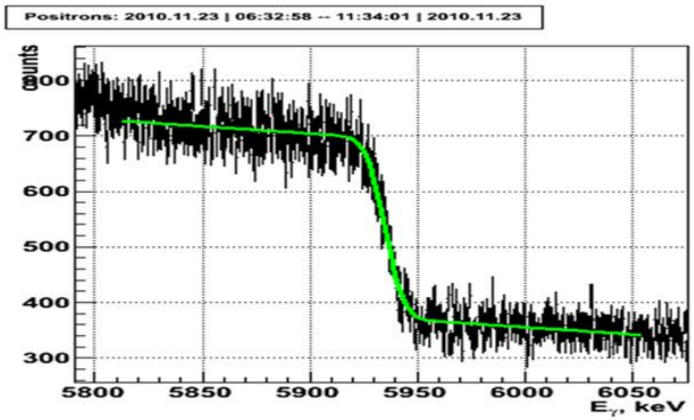
Head on collision, backscattered photons

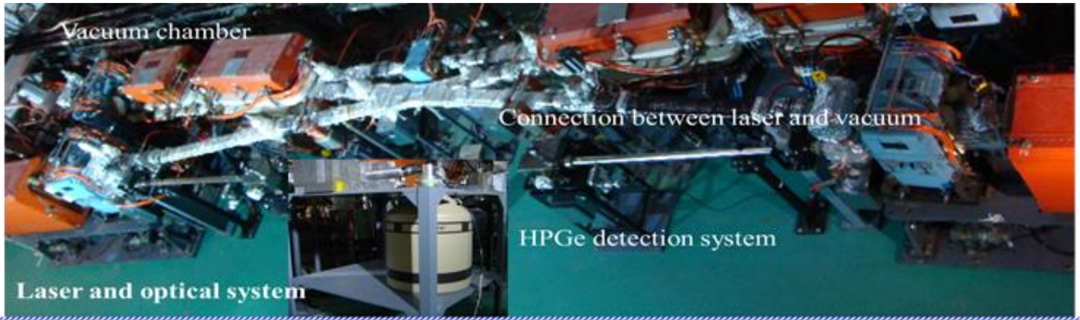
$$\omega_{max} = \frac{\varepsilon^2}{\varepsilon + m_e^2/4\omega_0^2},$$



Beam energy：

$$\varepsilon = \frac{\omega_{max}}{2}\left[1 + \sqrt{1 + \frac{m_e^2}{\omega_0 \omega_{max}}}\right].$$

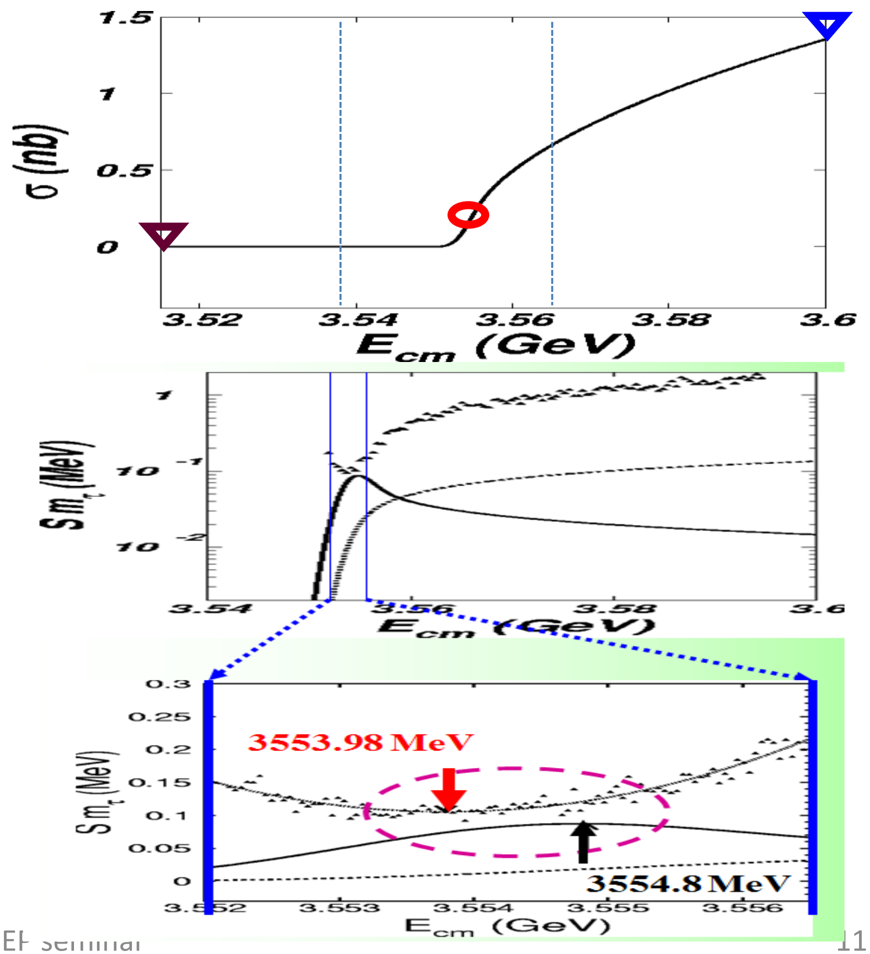




Statistical optimization of M_τ

$$\mu_i(m_\tau, s_i) = \mathcal{L}_i \cdot \left(\varepsilon \cdot \mathcal{B}_f \cdot \sigma_{obs}(m_\tau, s_i) + \sigma_{BG}\right)$$

Assume： M_τ is known



To find :

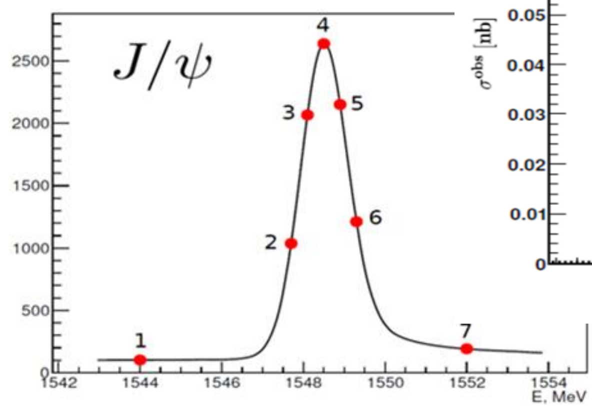
1. What's the optimal distribution of data taking point;
2. How many points are needed in scan experiment;
3. How much luminosity is required for certain precision.

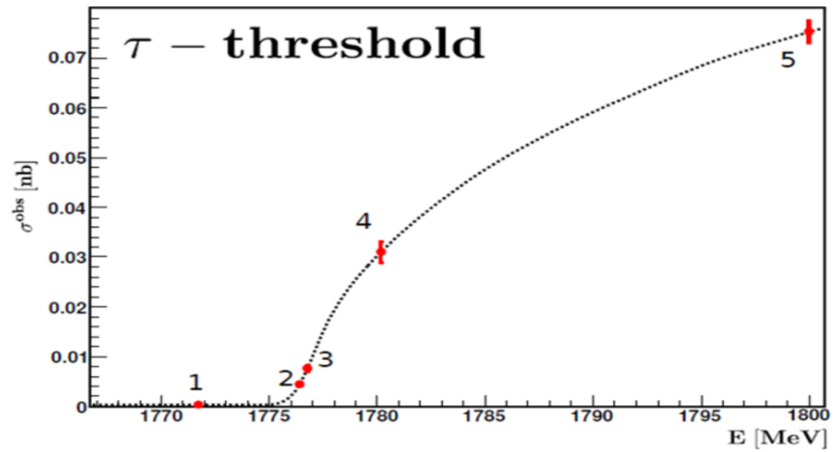
Data taking scenario

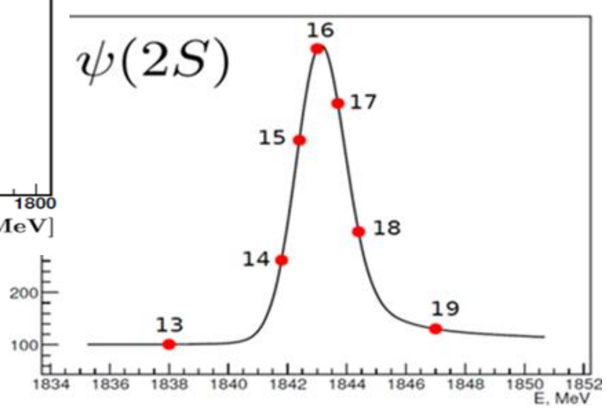
Three stages:

- J/ψ scan, 7 points, determine $M_{J/\psi}$ and σ_E
- Tau mass threshold scan
- ψ' scan, 7 points, determine $M_{\psi'}$ and σ_E

Total lum. ~100pb^{-1}, uncertainty: 0.1MeV





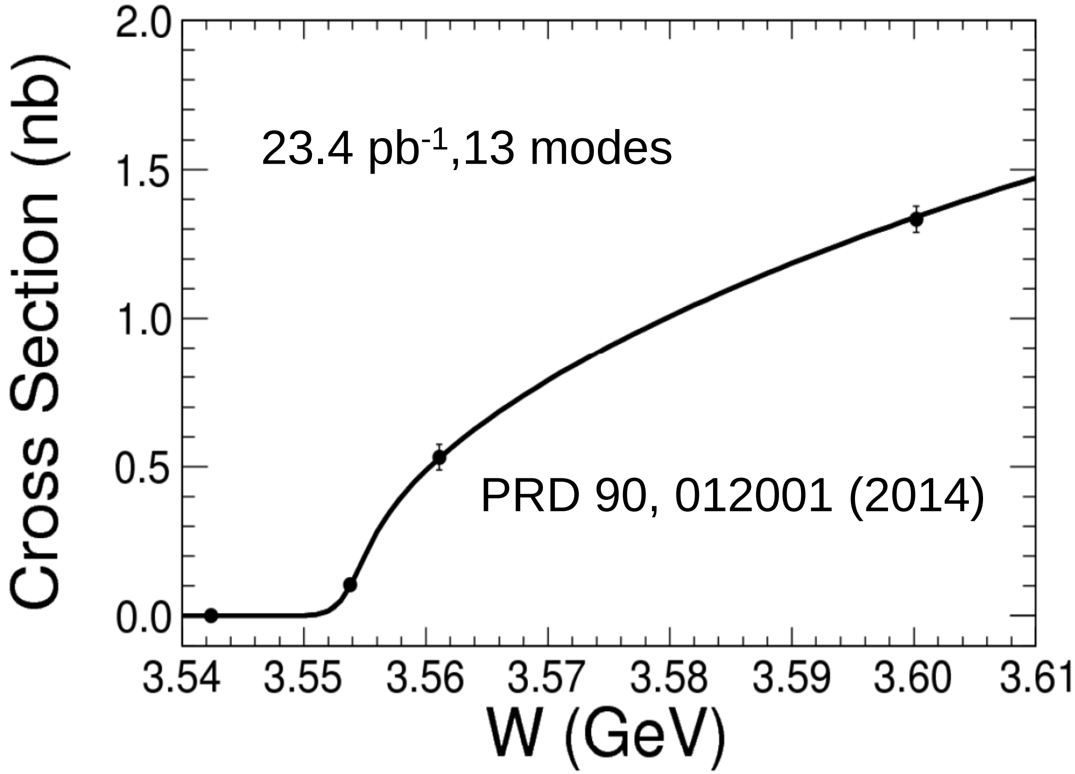


points	ΔE_1	ΔE_2	ΔE_3	ΔE_4	ΔE_5
ΔE_i/MeV	−5	−0.325	+0.075	+3.5	+15
L_i%	14	39	26	7	14

$\Delta E_i = E_i - M_\tau$

Tau scan in 2011

Scan	E_{CM} (MeV)	$\mathcal{L}(\mathrm{nb}^{-1})$
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



$$M_\tau = 1776.91 \pm 0.12 \,^{+0.10}_{-0.13}\ \mathrm{MeV}$$

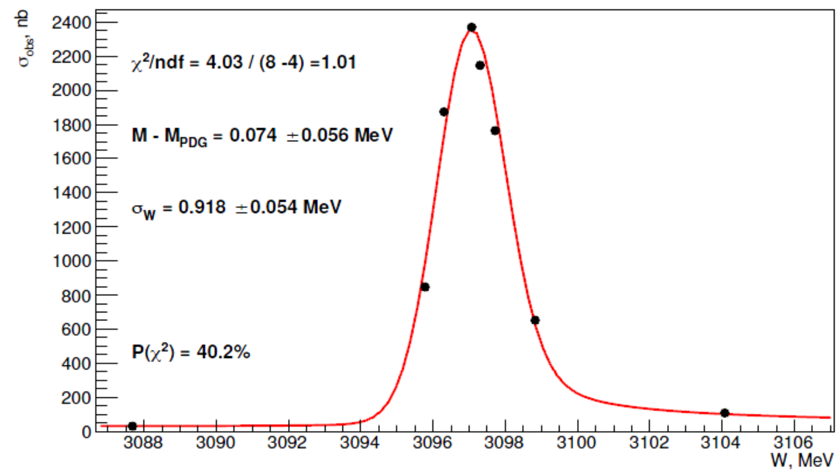
PDG2012: 1776.82 ± 0.16 MeV

Tau scan in 2011(II)

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	18	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

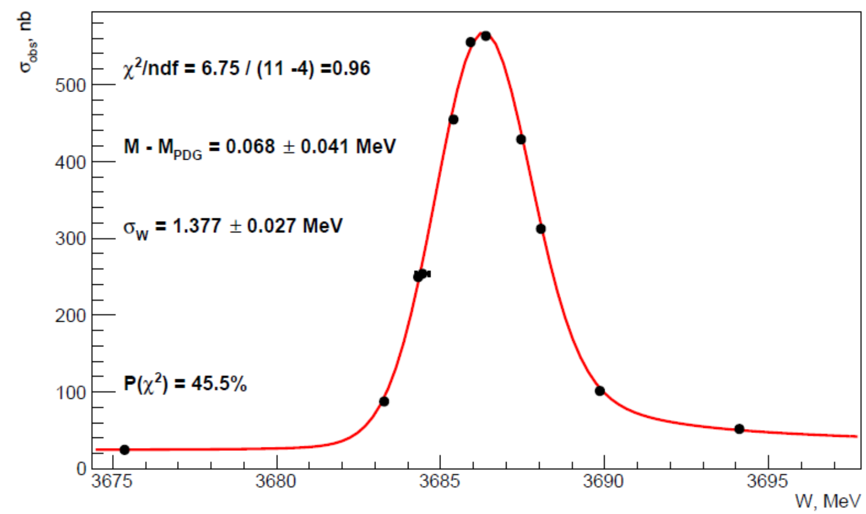
Tau scan in 2018

#	L, pb^{-1}	W_{cm}, MeV
1	2.5	3087.67 ± 0.078
2	3.0	3095.78 ± 0.082
3	6.1	3096.30 ± 0.075
4	3.0	3097.07 ± 0.087
5	1.9	3097.30 ± 0.103
6	4.8	3097.72 ± 0.086
7	5.6	3098.83 ± 0.083
8	5.7	3104.07 ± 0.087
total	32.6	



$\psi(2S)$ scan

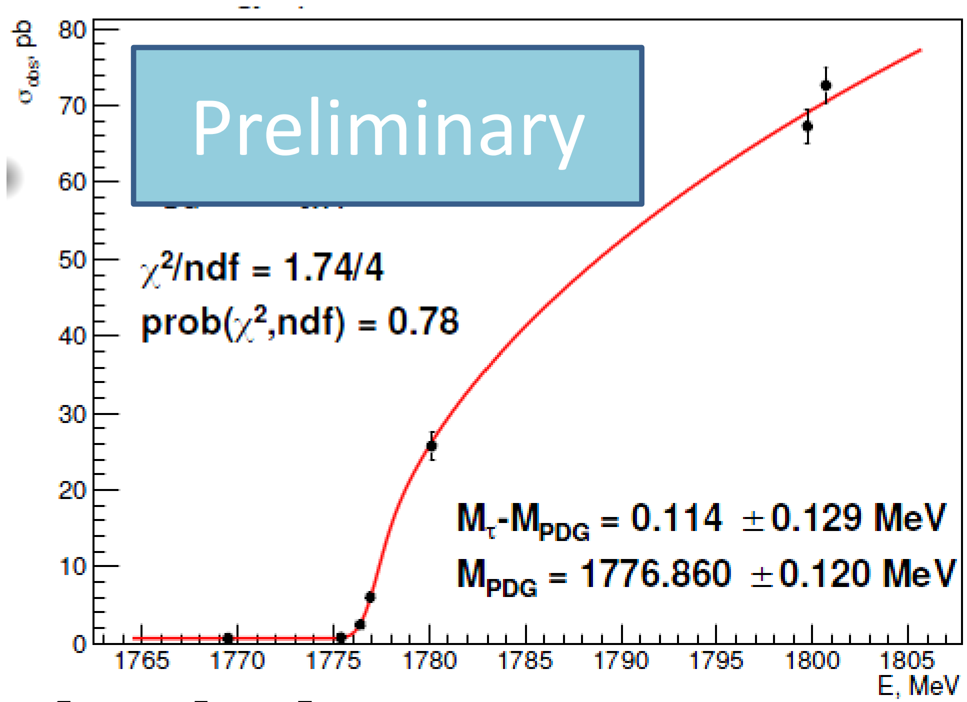
#	L, pb^{-1}	W_{cm}, MeV
1	5.2	3675.37 ± 0.13
2	16.4	3683.28 ± 0.10
3	3.4	3684.45 ± 0.21
4	3.6	3684.32 ± 0.12
5	4.6	3685.39 ± 0.10
6	6.7	3685.92 ± 0.10
7	6.1	3686.38 ± 0.10
8	5.1	3687.45 ± 0.10
9	5.1	3688.06 ± 0.10
10	6.0	3689.85 ± 0.10
11	5.0	3694.11 ± 0.10
total	67.2	



Tau mass scan in 2018 (II)

τ-threshold scan

1	23.8	3539.07 ± 0.05
1'	4.0	3550.87 ± 0.18
2	42.6	3552.87 ± 0.07
3	27.1	3553.93 ± 0.08
4	9.2	3560.36 ± 0.16
5	15.0	3599.57 ± 0.12
5'	14.9	3601.51 ± 0.12
total	136.6	

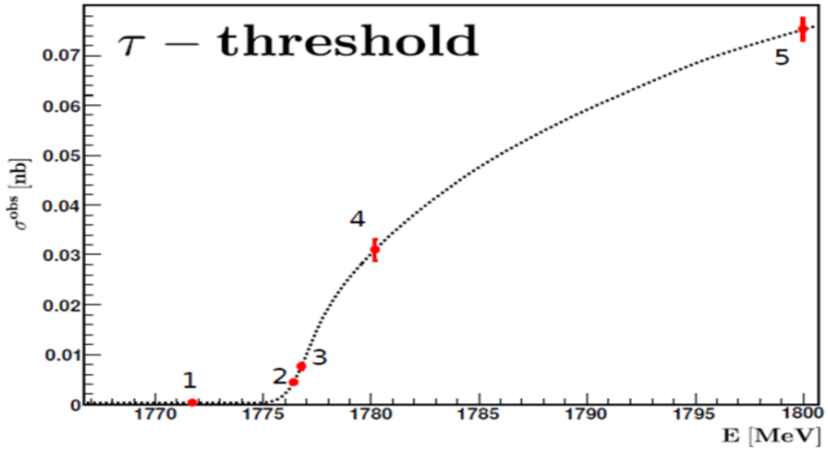


- The analysis is almost finished
- Uncertainty of M_τ will be less than 0.1MeV

Data comparison between 2011 scan and 2018 scan

Sample	P1	P2	P3	P4	P5	total
2011 scan	$4.3pb^{-1}$		$5.6pb^{-1}$	$3.9pb^{-1}$	$9.6pb^{-1}$	$23.4pb^{-1}$
2018 scan	$27.8pb^{-1}$	$42.6pb^{-1}$	$27.1pb^{-1}$	$35.6pb^{-1}$	$29.9pb^{-1}$	$136.6pb^{-1}$

Sample	J/ψ	ψ'
2011 scan	$1.5pb^{-1}$	$7.5pb^{-1}$
2018 scan	$38pb^{-1}$	$68pb^{-1}$



Suggestion from IRC of BESIII White book

✓We recommend to expand the section for tau physics studies other than tau mass measurement ;
✓We recommend to look into the existing data at and just above the tau production threshold and investigate the background sources;
✓We encourage the group to apply beam energy measurement method for other particles' mass measurements at meson and baryon-pair production thresholds, for example, Ds*, Ds0, Ds1, Λc, Σc...

$D^+ \rightarrow \tau^+ \nu_\tau$

$$\Gamma(D^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} f_{D+}^2 |V_{cd}|^2 m_\ell^2 M_{D+} \left(1 - \frac{m_\ell^2}{M_{D+}^2}\right)^2$$

$$R_{\tau/\mu} = \frac{\Gamma(D^+ \to \tau^+ \nu_\tau)}{\Gamma(D^+ \to \mu^+ \nu_\mu)} = \frac{m_\tau^2 \left(1 - \frac{m_\tau^2}{M_{D^+}^2}\right)^2}{m_\mu^2 \left(1 - \frac{m_\mu^2}{M_{D^+}^2}\right)^2} = 2.67,$$

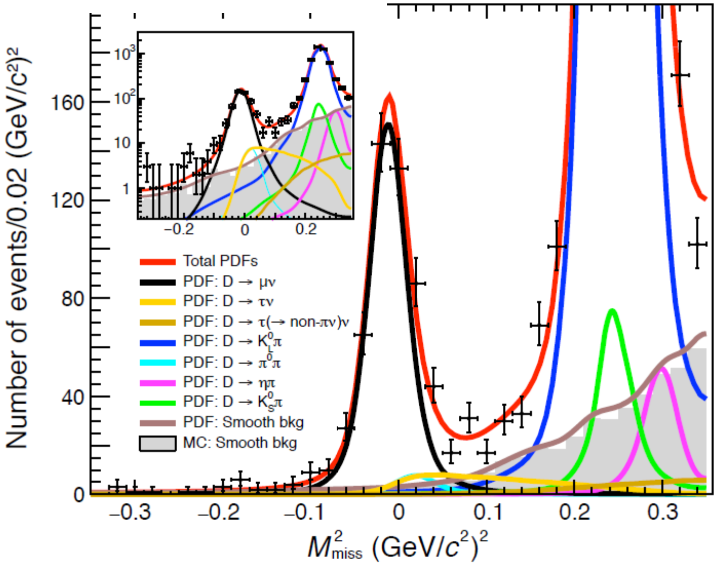
Using 2.93 fb^{-1} charm data

$B_{\tau\nu}$: $(1.20 \pm 0.24 \pm 0.12) \times 10^{-3}$

$B_{\mu\nu} = (3.74 \pm 0.17) \times 10^{-4}$ (PDG)

$R_{\tau/\mu} = 3.21 \pm 0.64 \pm 0.43$

Consistent with SM prediction 2.67



$D^+ \to \tau^+ \nu_\tau$

$$\Gamma(D^+ \to \ell^+ \nu_\ell) = \frac{G_F^2}{8\pi} f_{D+}^2 |V_{cd}|^2 m_\ell^2 M_{D+} \left(1 - \frac{m_\ell^2}{M_{D+}^2}\right)^2$$

- Taking the average values from PDG, |Vcd| = 0.22438 ± 0.00044

  f_{D+} = 224.5 ± 22.8 ± 11.3 ± 0.9 MeV

  consistent with LQCD prediction 212.6 ± 0.6 MeV

- Taking the average prediction for f_{D+},

  |Vcd|= 0.237 ± 0.024 ± 0.012 ± 0.001,

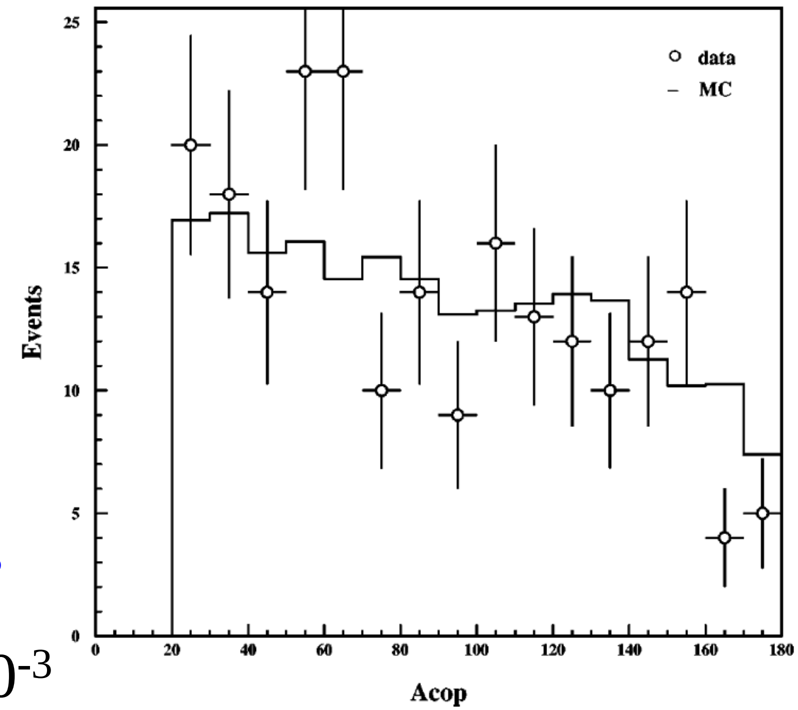
  consistent with the world average |Vcd| = 0.218 ± 0.004

- The Luminosity of charm data will be 20 fb^{-1}, the precision of $B_{\mu\nu}$, f_{D+}, and |Vcd| will be expected much higher.

$\psi(2S) \rightarrow \tau\tau$

- The $\psi(2S)$ provides a unique opportunity to compare the three lepton generations by studying the leptonic decays $\psi(2S) \rightarrow ee, \mu\mu, \tau\tau$

3.96M



$$\frac{B_{ee}}{v_e(\frac{3}{2}-\frac{1}{2}v_e^2)} = \frac{B_{\mu\mu}}{v_\mu(\frac{3}{2}-\frac{1}{2}v_\mu^2)} = \frac{B_{\tau\tau}}{v_\tau(\frac{3}{2}-\frac{1}{2}v_\tau^2)}$$

$$v_l = [1-(4m_l^2/M_{\psi(2S)}^2)]^{1/2}$$

$$B_{ee} \simeq B_{\mu\mu} \simeq \frac{B_{\tau\tau}}{0.3885} \equiv B_{ll}$$

$$B_{\tau\tau} = (2.71 \pm 0.43 \pm 0.55) \times 10^{-3}$$

$\boldsymbol{B_{\tau\tau}}$ /0.3885= $(7.0 \pm 1.1 \pm 1.4) \times 10^{-3}$

SM prediction: $\boldsymbol{B_{ll}} = (8.4 \pm 1.0) \times 10^{-3}$

$\psi(2S) \rightarrow \tau\tau$

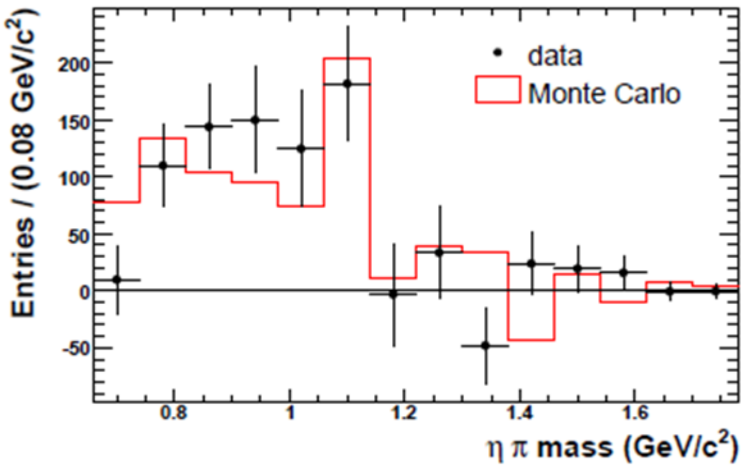
- In 2018, BESIII perform fine $\psi(2S)$ scan at 10 points with totally 67 pb^{-1} data. With this large sample, we can measure B_{ee}, $B_{\mu\mu}$, and $B_{\tau\tau}$ separately and test the relation between them.
- With lots of scan points, the interference between the continuum and resonance parts can be measured directly, and even the phase angle between them.
- The number of $\psi(2S)$ events will be 3 billion, the precision of B_{ll} will be expected much higher.

Second-class currents decay

- In hadronic τ decays, the first-class currents, $J^{PC} = 0^{++}$, 0^{--}, 1^{+-} and 1^{-+} are expected to dominate.
- The second-class currents, $J^{PC} = 0^{+-}$, 0^{-+}, 1^{++} and 1^{--} are associated with a matrix element proportional to the mass difference between up and down quarks. They vanish in the limit of perfect isospin symmetry but is not prohibited by SM, the branching fractions at the order of 10^{-5}.
- The tau lepton provides a clean means to search for second-class currents, through the decay mode $\tau^- \rightarrow \pi^- \eta \nu_\tau$. The $\pi\eta$ final state must have either $J^{PC} = 0^{+-}$ or 1^{--}, can only be produced via second-class currents.

Second-class currents decay

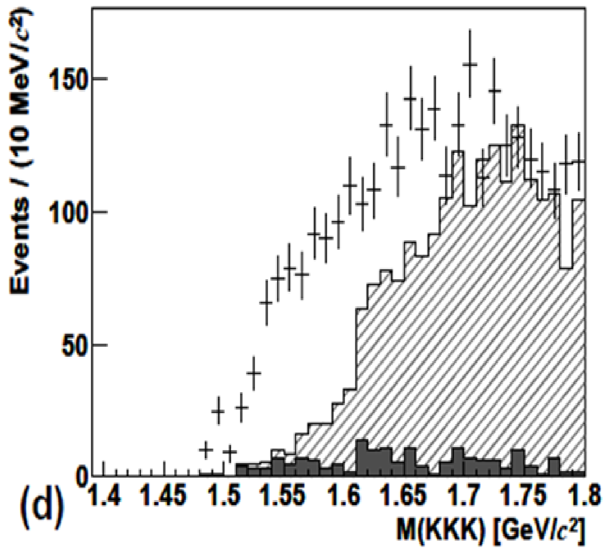
- The CLEO collaboration analyzed 3.5 fb^{-1} data @10.6 GeV, had produced the most stringent limit, and set an upper limit of $B(\tau^- \to \pi^- \eta \nu_\tau) < 1.4 \times 10^{-4}$ at the 95% C.L..
- The BaBar collaboration analyzed 470 fb^{-1} data @10.6 GeV, and set an upper limit of $B(\tau^- \to \pi^- \eta \nu_\tau) < 0.99 \times 10^{-4}$ at the 95% C.L.



- $B(\tau^- \to \pi^- \eta \nu_\tau)$ could be improved if BESIII has large data samples.

$\tau^- \rightarrow K^- K^+ K^- \nu_\tau$

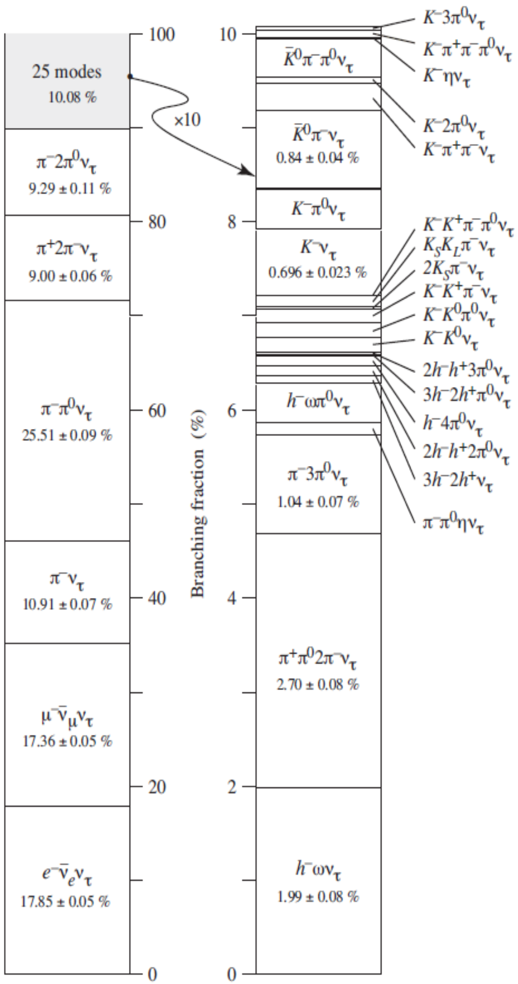
- Provide information on hadronic form factors, the Wess-Zumino anomaly, and also can be used for studies of CP violation in the leptonic sector.
- Provide a direct determination of the strange quark mass and the CKM matrix element |Vus|.
- The BaBar: $B(\tau^- \rightarrow K^- K^+ K^- \nu_\tau)$:
  $(1.58 \pm 0.13 \pm 0.12) \times 10^{-5}$, 342 fb^{-1} data
  at 10.58 GeV.
- The Belle: $B(\tau^- \rightarrow K^- K^+ K^- \nu_\tau)$:
  $(3.29 \pm 0.17 \pm 0.20) \times 10^{-5}$, 666 fb^{-1} data
  at 10.58 GeV.
- The difference between the two measurements is larger than 3 standard deviations.
- BESIII expect more data to check this decay

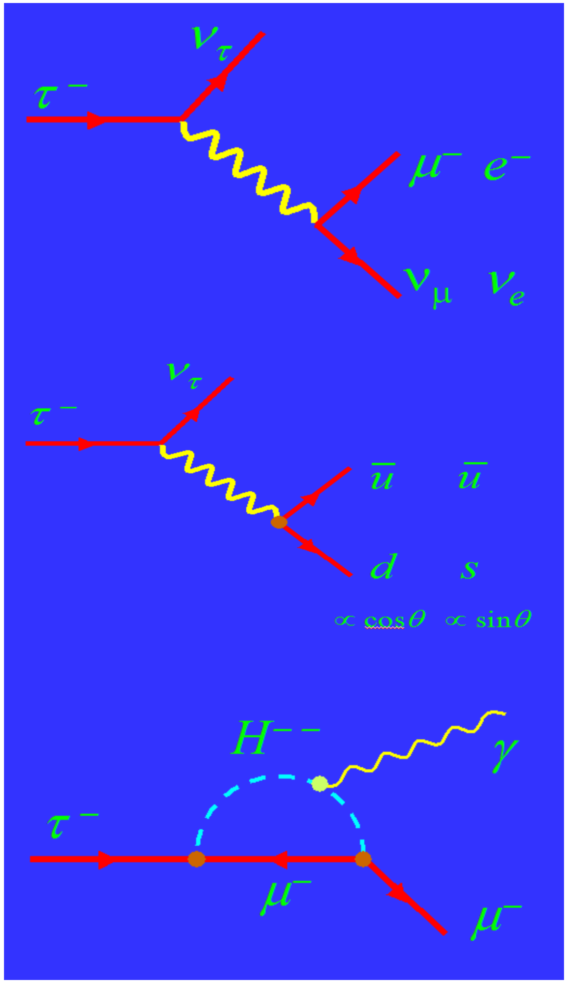


Mass measurement for some hadrons

- BEPCII beam energy improvement from 2.3 to 2.45 GeV.
- Mass of hadrons such as Ds*, Ds0, Ds1, Λc, Σc could be determined by near threshold scan using BEMS
- Wide energy region HPGe is necessary
- The ratio of signal to noise should be optimized

Branch ratio of tau decay





- **Pure leptonic**
  - $\tau^- \to \mu^- \nu_\mu \nu_\tau$ (<0.3%)
- **Semi-leptonic**
  - **Cabibbo favoured**
    $\tau^- \to \pi^- \nu_\tau$ (<0.5%)
  - **Cabibbo suppressed**
    $\tau^- \to K^- \nu_\tau$ (<1.5 %)
- **Rare and forbidden**
  - **Lepton Flavor V**
    $\tau^- \to \mu^- \gamma$ ($<10^{-8}$)
  - **Lepton Number V**
    $\tau^- \to \mu^+ \pi^+ \pi^-$ ($<10^{-8}$)
  - **Baryon Number V**
    $\tau^- \to \bar{p}\, \gamma$ ($<10^{-6}$)

Summary

- BEMS was designed, constructed and put into operation at BEPCII
- Mass of tau lepton has been determined in 2014 as

$$M_\tau = 1776.91 \pm 0.12 \,^{+0.10}_{-0.13}\ \mathrm{MeV}$$

- More precise measurement of mass of tau lepton will be available soon
- Analysis ~150 pb^{-1} tau threshold data and other data to perform the tau related measurement to test the SM and beyond
- We will suggest BESIII experiment to collect more data near tau threshold region

Thank you for your attention!