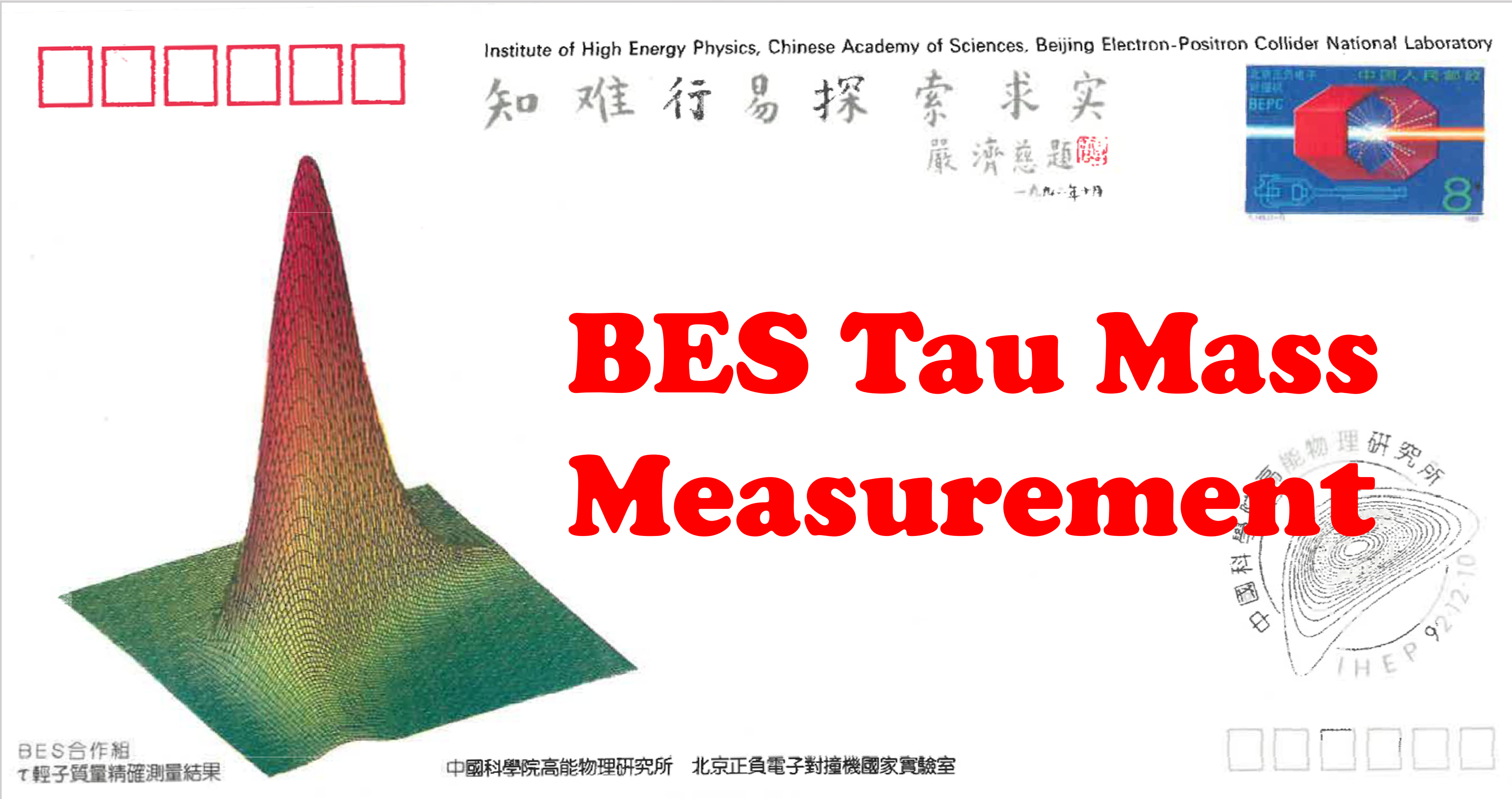
BES Tau Mass Measurement



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Introduction to Tau Leptons

Standard Model (SM) has basic matter and antimatter constituents and forces

1. The fundamental matter particles and antiparticles are
   - 6 quarks and 6 leptons
   - 6 antiquarks and 6 antileptons
2. Leptons=3 charged + 3 neutral and Antileptons=3 charged + 3 neutral, assuming neutrinos are Dirac particles.
3. The 3 charged leptons and 3 charged antileptons are
   - $e^-/\mu^-/\tau^-$ and $e^+/\mu^+/\tau^+$
4. The charged leptons are massive with,
   - M_e=0.5110 MeV, M_μ=105.66 MeV, M_τ=1776.9 MeV
   - Lepton Masses are parameters in SM and not predicted

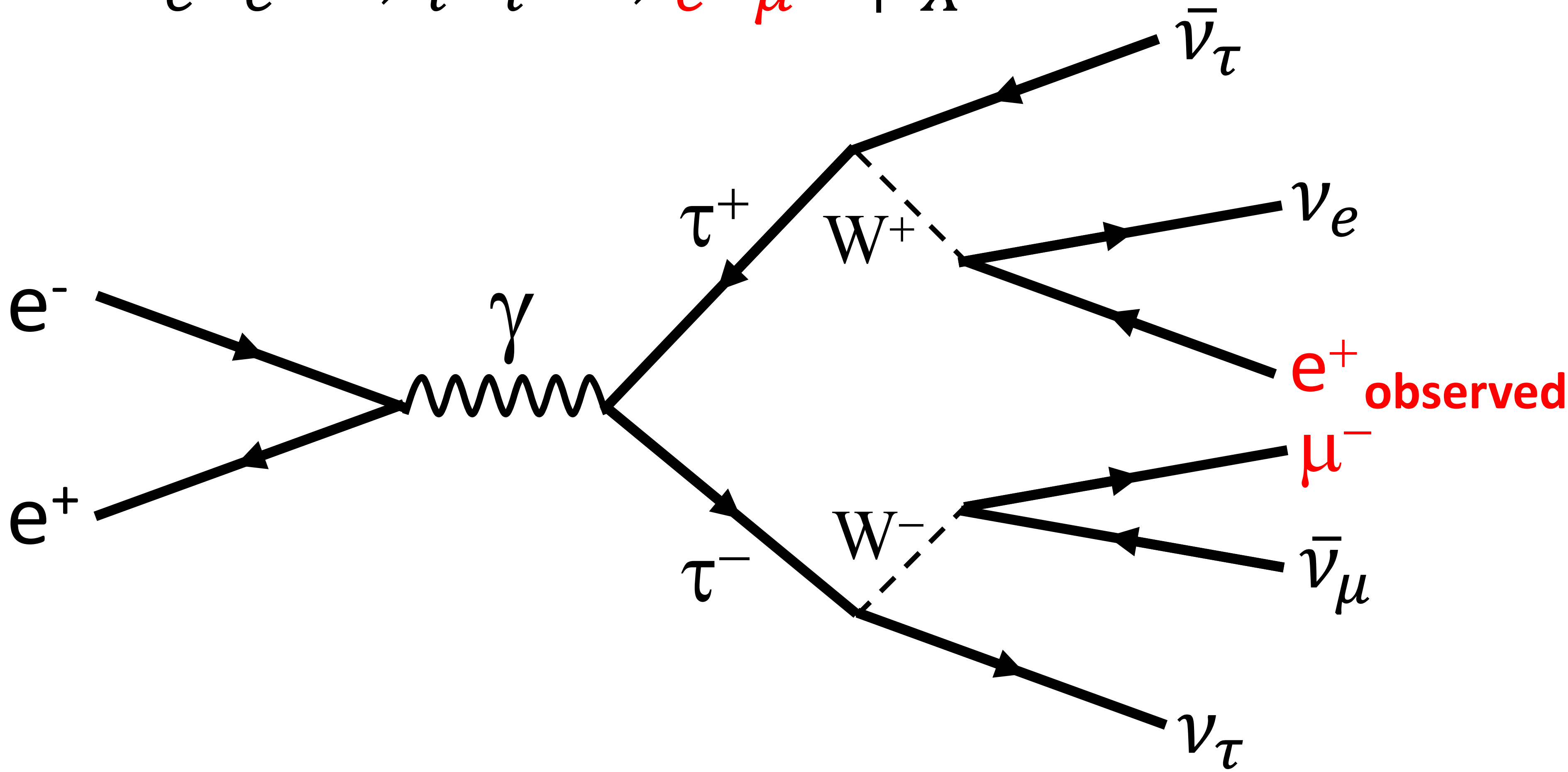
Discovery and Early Measurements

1. Properties of a heavy lepton were anticipated in 1971 by Yung-su Tsai (PRD,v9,2821,1971)
2. In 1975, Martin Perl and the Mark I collaboration at SLAC published evidence for anomalous $e^+e^- \rightarrow e^\pm\mu^\mp$ events.
   - First evidence (PRL,v35,1489,1975) of such a fundamental discovery was controversial*, however by 1977 the evidence was very conclusive. *A possible explanation for these events is the production and decay of a pair of new particles, each having a mass in the range of 1.6 to 2.0 GeV/c^2* [last sentence in PRL].
3. Measurements of key Tau properties by 1992 were made by Mark II, DELCO and DASP.
   1. Mass; 1783+4-3 MeV (1978 DELCO)
   2. Leptonic Branching ratios 17.85±.29%(1992 average)
   3. Lifetime 308±13 pS (1991 OPAL)

*only the 4th quark (charm) had been discovered by 1974.

Mark I Expt Observed Decay mode (1975)

$$e^{+}e^{-} \rightarrow \tau^{+}\tau^{-} \rightarrow e^{\pm}\mu^{\mp} + X$$



Mark I scan of tau production

$$e^+e^- \rightarrow \tau^+\tau^- \rightarrow e^\pm\mu^\mp + X$$

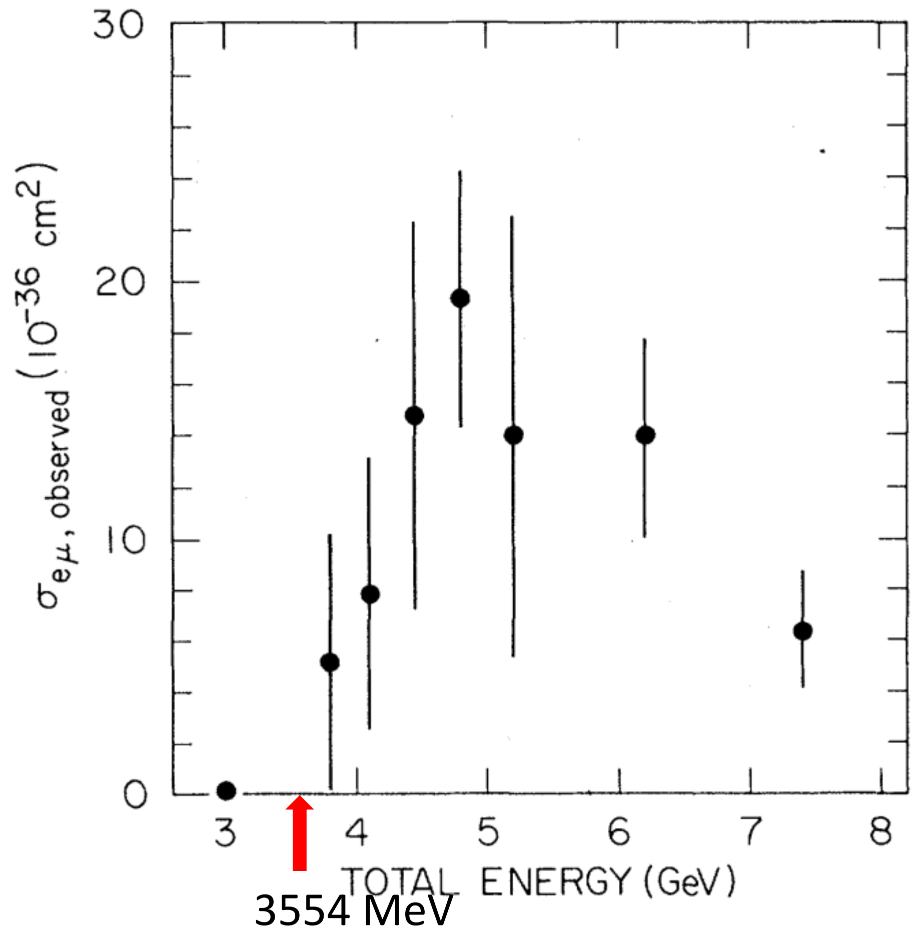
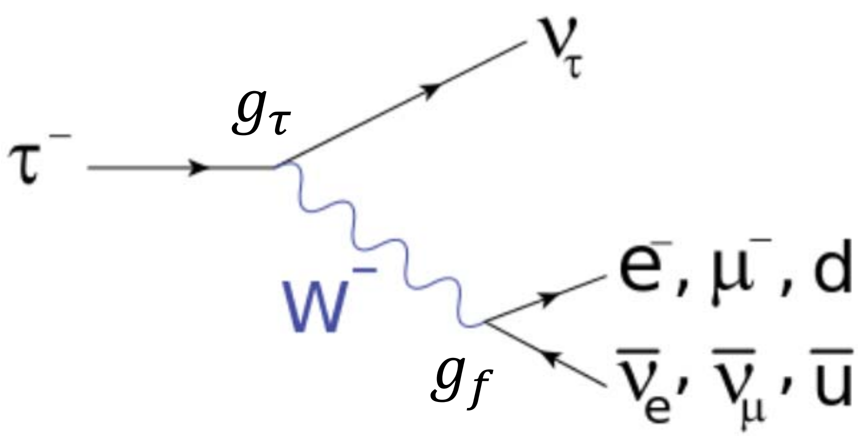


FIG. 2. The *observed* cross section for the signature e-μ events.

Observed ee production cross section was consistent with a heavy lepton mass ~1.8 GeV

Key Predictions of Tau decays



$$\Gamma_X(X \rightarrow e\bar{\nu}_e \nu_X) = \frac{g_X^2 g_e^2 m_X^5}{6144\pi^3 M_W^4} f(y)$$

$$f(y) = 1 - 8y + 8y^3 - y^4 - 12y^3 \ln y$$

$$y = m_e^2 / m_X^2$$

1992 Particle Data Group

τ MASS

VALUE (MeV)	EVTS	DOCUMENT ID		TECN
$1784.1^{+2.7}_{-3.6}$ OUR AVERAGE				
1787 ±10		BLOCKER	80	MRK2
1783^{+3}_{-4}	692	[1] BACINO	78B	DLCO
1787^{+10}_{-18}	299	[2] BARTEL	78	SPEC
1807 ±20		BRANDELIK	78	DASP

τ MEAN LIFE

VALUE (10^{-12} s)	EVTS	DOCUMENT ID		TECN
0.305±0.006 OUR AVERAGE				
0.314±0.023±0.009		ABREU	91D	DLPH
0.308±0.013		ACTON	91C	OPAL
0.309±0.023±0.030	2817	ADEVA	91F	L3
0.301±0.029	3780	KLEINWORT	89	JADE
0.288±0.016±0.017	807	AMIDEI	88	MRK2

τ

Table 1. Branching fractions of the τ (%)

Decay Mode	World Average
B_1	85.94 ± 0.23
B_3	14.06 ± 0.20
$e^- \bar{\nu}_e \nu_\tau$	17.85 ± 0.29
$\mu^- \bar{\nu}_\mu \nu_\tau$	17.45 ± 0.27

Problems with Lepton universality before 1992

Using the Tau leptonic BR, the mass and the lifetime, the ratio of Tau g_τ and muon g_μ couplings squared $\neq 1$ by 2σ. This was pointed out in 1990 by Bill Marciano (PRL, 1990).

$$\frac{g_\tau^2}{g_\mu^2} = 0.941 \pm 0.025$$

Lepton coupling universality violation >2σ !!

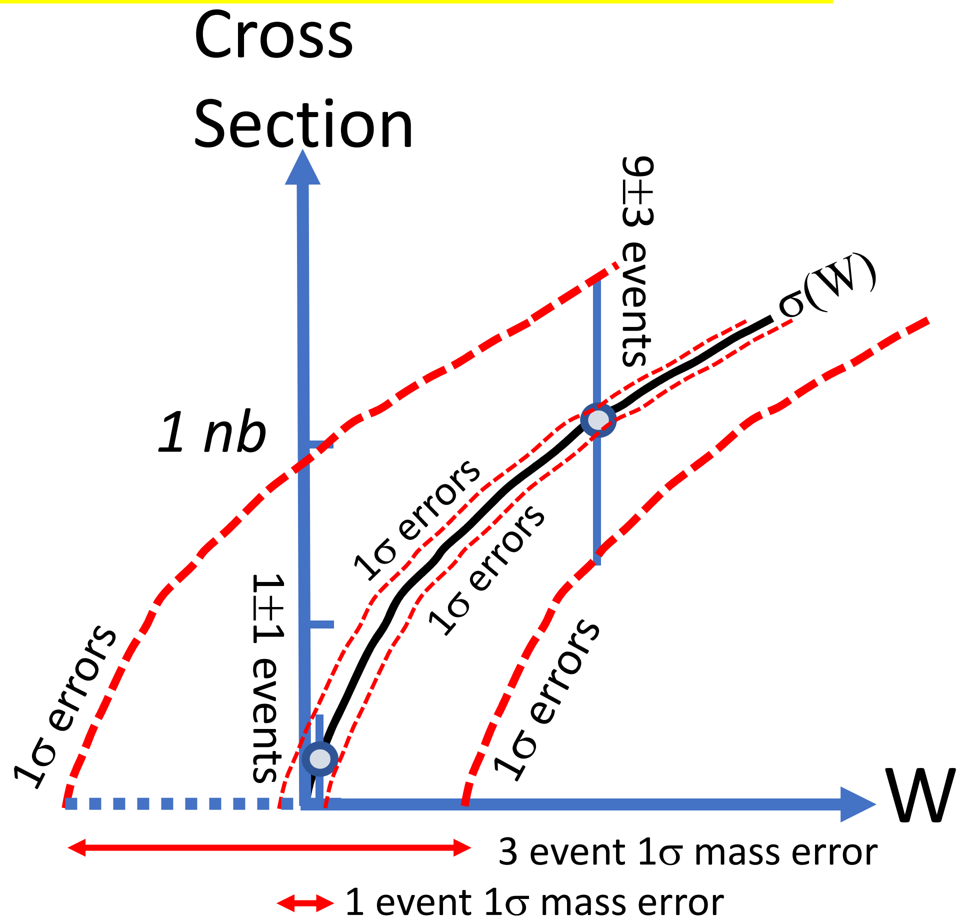
Comparison of Mass Measurement Precision Near threshold for 1 and 9 events.

Consider the production cross section of $ee \rightarrow \tau\tau$ vs W the center mass energy. The cross section is the black line.

Let's consider 2 measurements with the the same luminosity. One is very near threshold where 1 event is produced and another is at a higher energy that has 9 times the cross section and should produce 9 ± 3 events.

We see that the measurement of 1 ± 1 is much better than 9 ± 3 to determine the 1σ errors on a tau mass. This occurs since the cross section is steeply falling at threshold.

$\Rightarrow$ **Measure tau mass very near threshold**



BES Search Method

- The precision of the tau mass measurement depends on the colliding beam energy.
- The best measurement occurs just above $\tau^+\tau^-$ threshold!! However, if we run below threshold we get zero events. At the start of the experiment, we did not know the tau mass, except from the PGD average mass of 1784 which was dominated by the DELCO measurement.
- A "data driven" method, originally proposed by Frank Porter, was devised. Start by assuming $m(\tau)$ =1784 MeV, take 250-400 pb^{-1} of integrated luminosity and then re-evaluate a new m_τ based on using ALL accumulated data, then reset the beam energy just above the revised $\tau^+\tau^-$ threshold and run again. Repeat the process. There were many spirited discussions between BES collaborators about this strategy!!
- This search method was checked by Monte Carlo. This is very different from a "blind analysis" where using MC, we optimize and fix cuts (usually #signal/sqrt(#bkgd)) and then looked at the data. The Tau mass search method re-optimized after each scan point and changed the beam energy.
- In the Tau mass search, it is analogous to running MINUIT where the beam energy is a single stepped parameter and the "minimized function" is actually the expt data. After each data point is taken, we calculate the likelihood fit to all the available data and re-evaluate a new Tau mass, then the beam energy is reset just above threshold. As we iterate and add more data points the likelihood, using all data points as a function of Tau mass, becomes narrower.

Likelihood

The likelihood $\mathcal{L}$ of the measuring n_i events with mean values μ_i at scan point i is a joint Poisson probability of

$$\mathcal{L} = \prod_i \frac{e^{-\mu_i}\ {\mu_i}^{n_i}}{n_i!}$$

and the mean number of events is given as,

$$\mu_i = [\epsilon\sigma(E_i, m_\tau) + \sigma_B]\Phi_i$$

where the symbols are

ε=detection and reconstruction efficiency

σ=Tau production cross section (including beam smearing)

E_i=2 x beam energy

m_τ=Tau mass

σ_B=background cross section

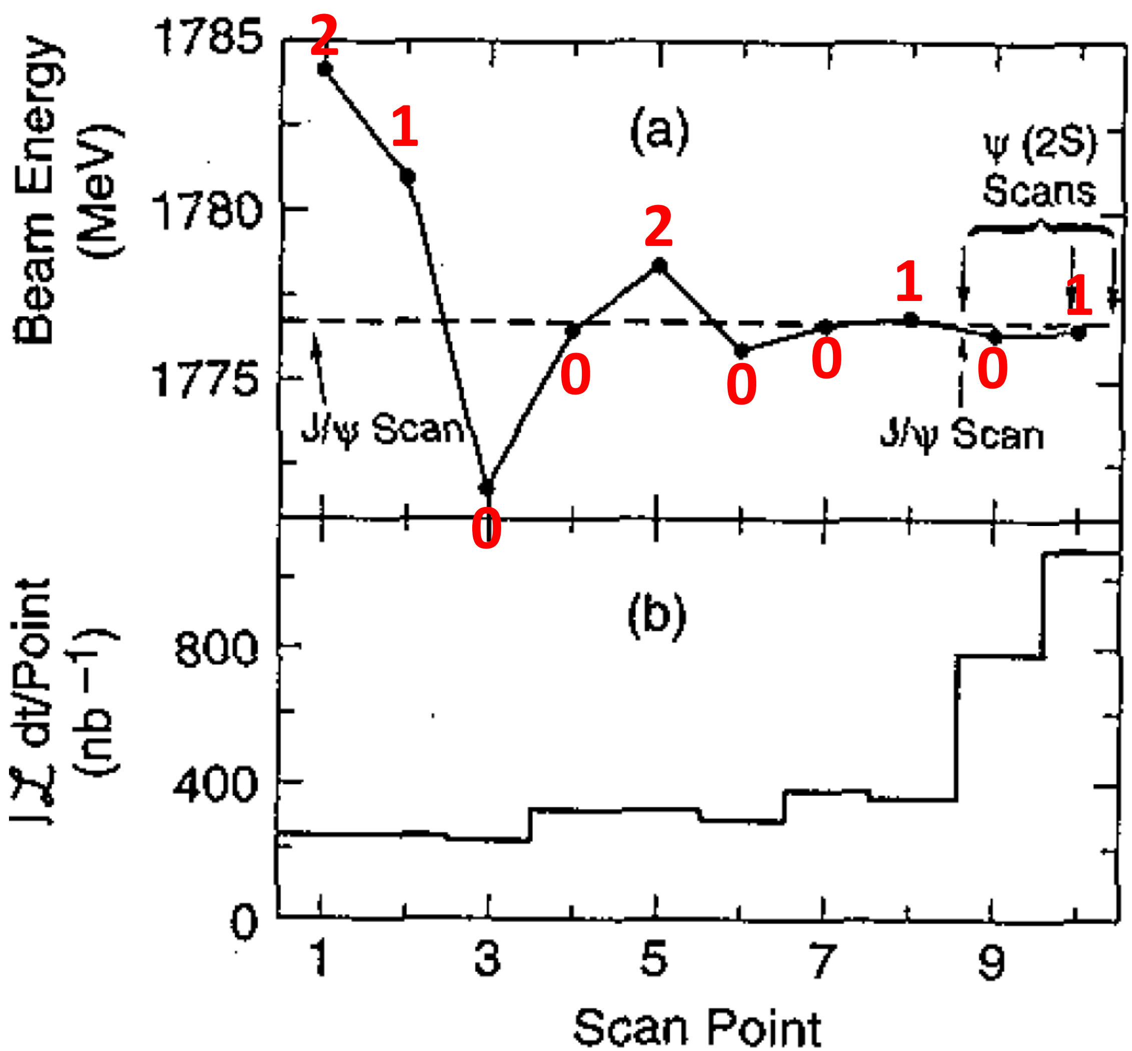
Φ_i=integrated flux

1992 Scan Results with μe events

Scan point	$W/2$ (MeV)	Δ (MeV)	$\mathcal{L}$ (nb^{-1})	N ($e\mu$ events)
1	1784.19	1.34	245.8	2
2	1780.99	1.33	248.9	1
3	1772.09	1.36	232.8	0
4	1776.57	1.37	323.0	0
5	1778.49	1.44	322.5	2
6	1775.95	1.43	296.9	0
7	1776.75	1.47	384.0	0
8	1776.98	1.47	360.8	1
9	1776.45	1.44	794.1	0
10	1776.62	1.40	1109.1	1
11	1799.51	1.44	499.7	5
12	1789.55	1.43	250.0	2

Remarks; Step #1&#2 observe events, so step #3 lower energy but gets no events. Then #4 increases the energy, but sees no events, so step #5 increases energy and sees 2 events. Step #6 lowers energy and gets no events. Step #7 increases energy, but no gets events. Step #8 Increases and gets 1 events. Step #9 decreases energy, but get no events. Ste #10 increases the energy and gets 1 events.

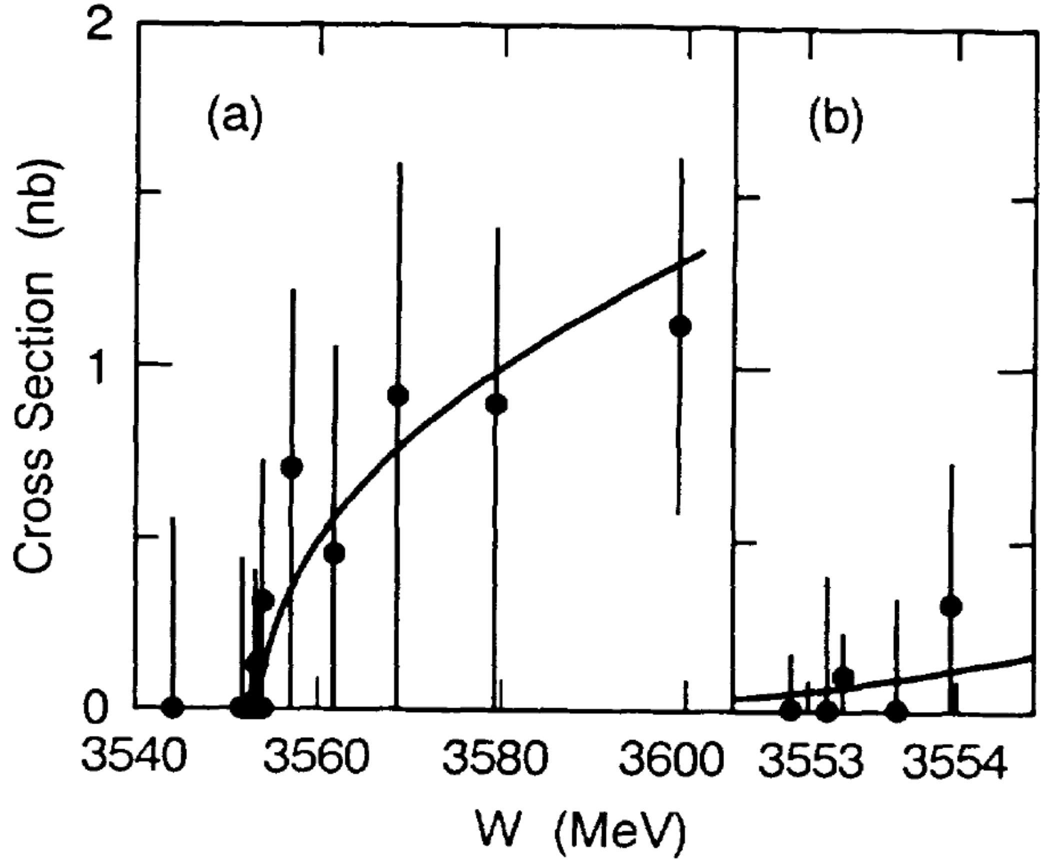
Beam Energy by scan point with #events



In **RED** are number of events reconstructed at each scan point

Near the end of the scan, the J/ψ and ψ(3680) peaks were scanned to check the beam energy.

First 1992 analysis using $e^+e^- \rightarrow e^{\pm}\mu^{\mp}$ +X



1992 Likelihood fit to tau mass

$M_\tau = 1776.9^{+0.4}_{-0.5} \pm .2\ MeV$

BES 1996 Extended Analysis using other modes

Although the e-μ decay modes were very clean, other "anomalous" combinations and hadronic modes were added. The hadron modes included single track charged pion and kaon. There were now six final states,

$$e^{\pm}\mu^{\mp}, e^{\pm}h^{\mp}, \mu^{\pm}h^{\mp}, e^{\pm}e^{\mp}, \mu^{\pm}\mu^{\mp}, h^{\pm}h^{\mp}$$

The final results (1996 PRD) were $\mathbf{1776.96^{+.18+.25}_{-.21-.17}}$ MeV, where the 1st errors are stat. And the 2nd errors at syst. The 1992 results were confirmed.

The muon and tau coupling to electronic decays were compared. The results produced remarkable agreement for the coupling.

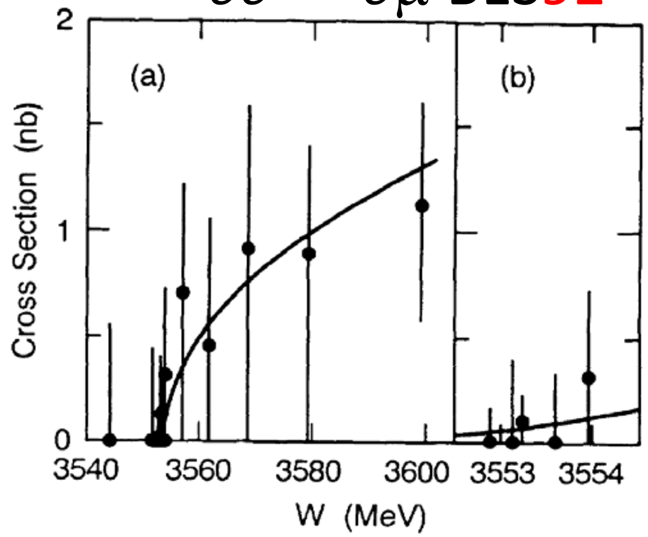
$$\frac{g_\tau^2}{g_\mu^2} = 0.9886 \pm 0.0085$$

In my humble opinion, this was the most important HEP result in 1992. A KEY test of the Standard Model was successfully achieved.

In 2014, BESIII performed a beautiful precision measurement, obtaining $1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV/c^2. The BESIII result has a factor ~2 reduction in errors.

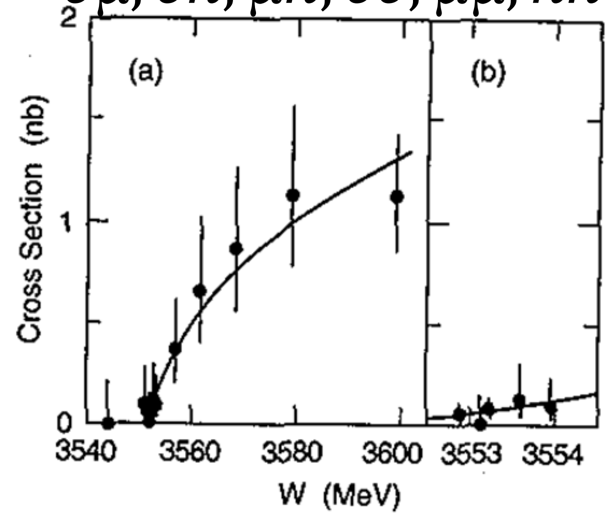
1996 Analysis Results

$ee \rightarrow e\mu$ BES92



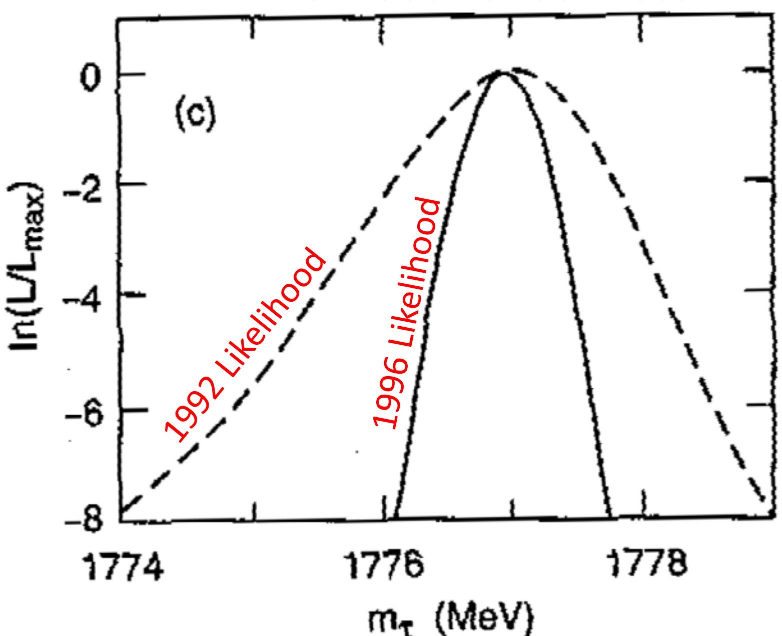
PRL, v69, 3021 (1992)

$ee \rightarrow e\mu, eh, \mu h, ee, \mu\mu, hh$ BES96

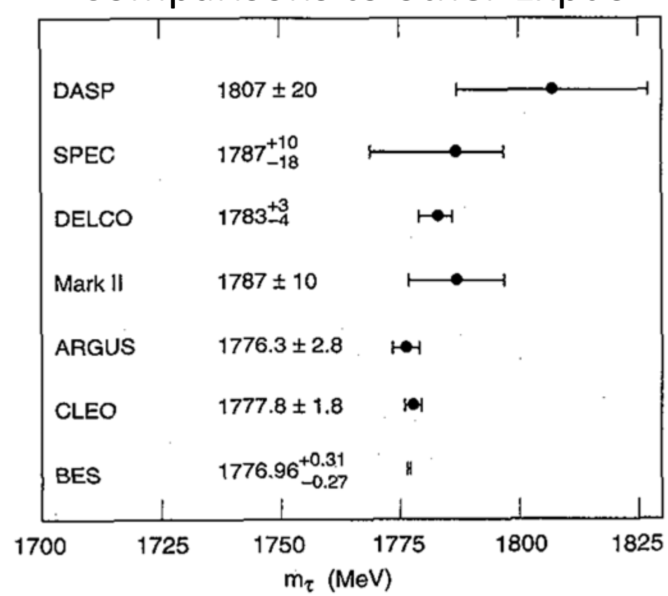


PRD, v53, 20 (1996)

Likelihood vs Tau Mass



Comparisons to other Expt's



Other Impacts of the BES tau mass measurement

In 1971, Y. Koide found an empirical formula* with the electron, muon and tau masses.

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

$$\frac{.510998946 + 105.6583745 + \underline{1784}}{(\sqrt{.510998946} + \sqrt{105.6583745} + \sqrt{\underline{1784}})^2} = 0.667062777118$$

After the BES measurement the numbers improved the formula,

$$\frac{.510998946 + 105.6583745 + \underline{1776.86}}{(\sqrt{.510998946} + \sqrt{105.6583745} + \sqrt{\underline{1776.86}})^2} = 0.666660512412$$

Maybe this formula is numerology or maybe this is the new Balmer series????

*geometrical meaning; the vector of sqrt(masses) is 45° w.r.t. (1,1,1)

$$\cos(45°) = \frac{\left(\sqrt{m_e}, \sqrt{m_\mu}, \sqrt{m_e}\right)}{\left\|\sqrt{m_e}, \sqrt{m_\mu}, \sqrt{m_e}\right\|} \cdot \frac{(1,1,1)}{\|(1,1,1)\|}$$

Other Ideas for "Data Driven" Experiments

1. The BES expt varied the beam energy to optimize the mass measurement. Are there other expt's that might vary a parameter during data taking to optimize a measurement?

2. Consider long baseline neutrino expt's to measure CP violation by measuring P($\nu_\mu \rightarrow \nu_e$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$). This requires separate neutrino and antineutrino beam running.

3. CP violation is proven if P($\nu_\mu \rightarrow \nu_e$) $\neq$ P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$). The sensitivity to this test depends on the unknown value of δ_{CP} AND the amounts of neutrino and antineutrino beam running . Currently T2K is consistent with $-\pi/2$, but NOVA does not find a peak value. In a future DUNE experiment, the choice of neutrino and antineutrino running could be optimized following a similar data driven run.

4. The recipe would be to run neutrino beam and then antineutrino beam, evaluate δ_{CP}. Then find the optimum ratio of neutrino/antineutrino beam running based on this δ_{CP}. The take more antineutrino or neutrino beam running based on this ratio. Iterate this procedure again and again.

SUMMARY

1) 1992 and 1996 BES measurements achieved most precise tau mass measurements when published.

2) Universality of leptonic Mu-Tau coupling, which appeared to be failing in early 1992, was validated to be correct by the BES measurement.

3) The BES results are consistent within errors with the recent and very precise 2014 BESIII measurements, $1776.91 \pm 0.12^{+0.10}_{-0.13}$ MeV/c^2.