τ Branching fractions measurements

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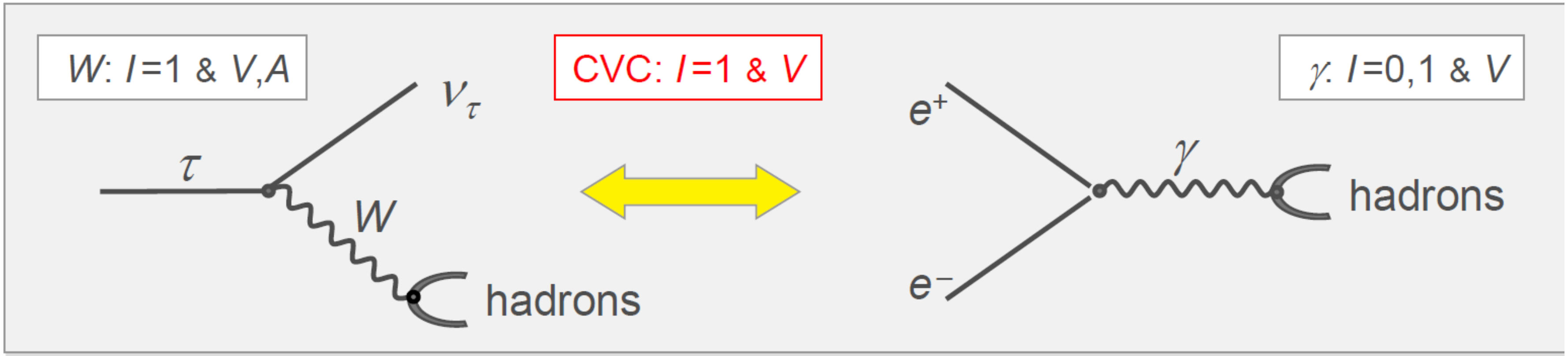
τ miniworkshop, November 8 2024

- Different experimental conditions: LEP, B factories
- ALEPH $\tau^+\tau^-$ sample and impact on τ physics
- Global measurement of branching fractions
- focus on $B_{\pi\pi0}$ and B_e: comparison with other measurements

Spectral functions from hadronic τ decays



Hadronic physics factorizes (spectral Functions)

$$\sigma^{(I=1)}\left[e^+e^- \rightarrow \pi^+\pi^-\right] = \frac{4\pi\alpha^2}{s}\upsilon\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right]$$

$$\upsilon\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right] \propto \frac{BR\left[\tau^- \rightarrow \pi^-\pi^0\nu_\tau\right]}{BR\left[\tau^- \rightarrow e^-\bar{\nu}_e\nu_\tau\right]} \frac{1}{N_{\pi\pi^0}}\frac{dN_{\pi\pi^0}}{ds} \frac{m_\tau^2}{\left(1-s/m_\tau^2\right)^2\left(1+s/m_\tau^2\right)} \frac{R_{IB}(s)}{S_{EW}}$$

branching fractions | mass spectrum | kinematic factor (PS) | Isospin correction

- Analogous to (1) e^+e^- ratio = $\pi^+\pi^-/\mu^+\mu^-$ and (2) ISR method (E_γ spectrum to span mass range from threshold to m_τ)

Different experimental environments

- Measurement of spectral functions from τ hadronic decays:
  - 2π ($\tau \to \pi^- \pi^0 \nu_\tau$) : Z (LEP) ALEPH, OPAL; Υ(4S) (B-factories) CLEO, Belle   dominant
  - 4π ($\tau \to \pi^- \pi^+ \pi^- \pi^0 \nu_\tau$, $\tau \to \pi^- 3\pi^0 \nu_\tau$): ALEPH, OPAL, CLEO +more ALEPH   sub-dominant

- B factories: high luminosity $\Rightarrow$ large statistics, relatively low energy
  $\Rightarrow$ difficult to separate $\tau^+\tau^-$ from q qbar jets, need hard cuts, low efficiency
  $\Rightarrow$ use well-identified clean single tag (leptonic modes)

- LEP: clear signature for $\tau^+\tau^-$ final state: low multiplicity, back-to-back topology, missing energy/momentum (neutrinos), well separated from background
  $\Rightarrow$ high selection efficiency (>90%), small background (~ 1%)
  pure $\tau^+\tau^-$ sample, but lower statistics
  more collimated decays $\Rightarrow$ need detector with good granularity to separate decay modes

- ALEPH detector with excellent calorimeter granularity (γ, π^0 close to charged particle)
  $\Rightarrow$ best detector for τ physics (13 BR classes, not competitive for rare modes <0.1%)
  $\Rightarrow$ only experiment to perform a global analysis of all major decay modes simultaneously, allowing for many cross checks
  specific analyses for 22 modes with kaons ($K^\pm$, K_S, K_L); improved by B-factories

ALEPH: τ Decay channels

Class label	Reconstruction criteria	Generated τ decay	
e	$1\ e$	$\tau \to e^- \overline{\nu}_e\ \nu_\tau$	
μ	$1\ \mu$	$\tau \to \mu^- \overline{\nu}_\mu\ \nu_\tau$	
h	$1\ h$	$\tau \to \pi^-\ \nu_\tau$ $\tau \to K^-\ \nu_\tau$ $\tau \to K^{*-}\ \nu_\tau$	$\tau \to \pi^- K^0 \overline{K}^0\ \nu_\tau$ $\tau \to K^- K^0\ \nu_\tau$
$h\ \pi^0$	$1\ h\ +\ \pi^0$	$\tau \to \rho^-\ \nu_\tau$ $\tau \to \pi^-\pi^0\overline{K}^0\ \nu_\tau$	$\tau \to K^-\pi^0 K^0\ \nu_\tau$ $\tau \to K^{*-}\ \nu_\tau$
$h\ 2\pi^0$	$1\ h\ +\ 2\pi^0$	$\tau \to a_1^-\ \nu_\tau$ $\tau \to K^{*-}\ \nu_\tau$ $\tau \to K^-\ 2\pi^0\ \nu_\tau$	$\tau \to \pi^-\omega\ \nu_\tau$ (2) $\tau \to \pi^- K^0 \overline{K}^0\ \nu_\tau$ $\tau \to K^- K^0\ \nu_\tau$
$h\ 3\pi^0$	$1\ h\ +\ 3\pi^0$	$\tau \to \pi^- 3\pi^0\ \nu_\tau$ $\tau \to \pi^-\pi^0\overline{K}^0\ \nu_\tau$	$\tau \to K^-\pi^0 K^0\ \nu_\tau$ $\tau \to \pi^-\pi^0\eta\ \nu_\tau$ (3)
$h\ 4\pi^0$	$1\ h\ + \geq 4\pi^0$	$\tau \to \pi^- 4\pi^0\ \nu_\tau$ $\tau \to \pi^- K^0\overline{K}^0\ \nu_\tau$	$\tau \to \pi^-\pi^0\eta\ \nu_\tau$ (4)
$3h$	$2-4h$	$\tau \to a_1^-\ \nu_\tau$ $\tau \to K^{*-}\ \nu_\tau$ $\tau \to K^-\pi^+\pi^-\ \nu_\tau$	$\tau \to K^- K^+\pi^-\ \nu_\tau$ $\tau \to \pi^- K^0\overline{K}^0\ \nu_\tau$ $\tau \to K^- K^0\ \nu_\tau$
$3h\ \pi^0$	$2-4h + \pi^0$	$\tau \to 2\pi^-\pi^+\pi^0\ \nu_\tau$ (5) $\tau \to \pi^-\pi^0\overline{K}^0\ \nu_\tau$	$\tau \to K^-\pi^0 K^0\ \nu_\tau$
$3h\ 2\pi^0$	$3h + 2\pi^0$	$\tau \to 2\pi^-\pi^+ 2\pi^0\ \nu_\tau$ (6) $\tau \to \pi^- K^0\overline{K}^0\ \nu_\tau$	$\tau \to \pi^-\pi^0\eta\ \nu_\tau$ (7)
$3h\ 3\pi^0$	$3h + \geq 3\pi^0$	$\tau \to 2\pi^-\pi^+ 3\pi^0\ \nu_\tau$	
$5h$	$5h$	$\tau \to 3\pi^- 2\pi^+\ \nu_\tau$	$\tau \to \pi^- K^0\overline{K}^0\ \nu_\tau$
$5h\ \pi^0$	$5h + \pi^0$	$\tau \to 3\pi^- 2\pi^+\pi^0\ \nu_\tau$	

- Monte Carlo generator KORALZ 07 with TAOLA (Z. Was), FSR generated by PHOTOS
- Reconstruction level:
  - paired γ's (π^0 identified)
  - unpaired γ : π^0 with lost γ or radiative decay (LH identified) or merged γ's (π^0 identified)
  - remaining unpaired γ counted as π^0 in classification
  - account of fake γ from hadron interactions in calorimeter (LH identif.)

2 With $\omega \to \pi^0\gamma$
3 With $\eta \to \gamma\gamma$
4 With $\eta \to 3\pi^0$
5 This channel includes $\tau \to \pi\omega\ \nu_\tau$ with $\omega \to \pi^-\pi^+\pi^0$
6 This channel includes $\tau \to \pi\pi^0\omega\ \nu_\tau$ with $\omega \to \pi^-\pi^+\pi^0$
7 With $\eta \to \pi^-\pi^+\gamma$

ALEPH global BR measurement

$$n_i^{obs} - n_i^{bkg} = \sum_j \varepsilon_{ji} N_j^{prod}$$

$$B_j = \frac{N_j^{prod}}{\sum_j N_j^{prod}}$$

- Efficient $\tau\tau$ selector exploiting topology, missing energy
- Efficiency matrix ε_{ji}: decay generated in class j, reconstructed in class i, 13 classes up to 5 charged hadrons, 3 π^0
- Determined with simulation
- Corrected for data/simulation differences (few per mil)
- FSR included for all channels

	e	μ	h	$h\pi^0$	$h2\pi^0$	$h3\pi^0$	$h4\pi^0$	$3h$	$3h\pi^0$	$3h2\pi^0$	$3h3\pi^0$	$5h$	$5h\pi^0$
e	73.26	0.01	0.41	0.45	0.34	0.25	0.74	0.02	0.02	0.05	0.00	0.00	0.00
μ	0.01	74.49	0.63	0.22	0.07	0.21	0.33	0.01	0.01	0.00	0.00	0.00	0.00
h	0.25	0.75	65.03	3.56	0.34	0.06	0.00	1.44	0.10	0.08	0.00	0.80	0.00
$h\pi^0$	1.02	0.26	4.70	68.19	11.31	2.15	0.49	0.48	1.28	0.62	0.05	0.24	0.00
$h2\pi^0$	0.12	0.01	0.33	5.67	57.68	23.13	7.57	0.08	0.39	1.48	0.24	0.04	0.00
$h3\pi^0$	0.01	0.00	0.07	0.41	6.92	43.06	38.15	0.01	0.10	0.37	0.71	0.04	0.00
$h4\pi^0$	0.00	0.00	0.02	0.05	0.67	6.25	25.26	0.00	0.02	0.11	0.19	0.00	0.00
$3h$	0.01	0.02	0.25	0.07	0.03	0.00	0.00	67.98	6.77	0.80	0.03	22.11	2.52
$3h\pi^0$	0.01	0.01	0.22	0.56	0.27	0.06	0.06	7.29	58.90	16.53	4.46	7.07	16.04
$3h2\pi^0$	0.00	0.00	0.04	0.06	0.10	0.08	0.02	0.41	6.02	40.42	25.02	0.28	0.65
$3h3\pi^0$	0.00	0.00	0.00	0.00	0.00	0.01	0.05	0.02	0.41	6.19	28.98	0.00	0.00
$5h$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	38.70	4.58
$5h\pi^0$	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02	0.03	0.08	2.99	38.72
Class 14	3.27	4.17	6.38	0.73	1.08	1.71	1.75	0.80	3.66	9.96	13.87	5.03	9.75
sum	77.06	79.72	78.08	79.97	78.81	76.97	74.42	78.56	77.71	76.64	73.64	77.30	72.26

- Large selection efficiency: overall 78.9%, 91.7% in polar angle acceptance
- Rather independent of decay channel ($\pm$ 5%)
- Non-τ background (1.2%) subtracted

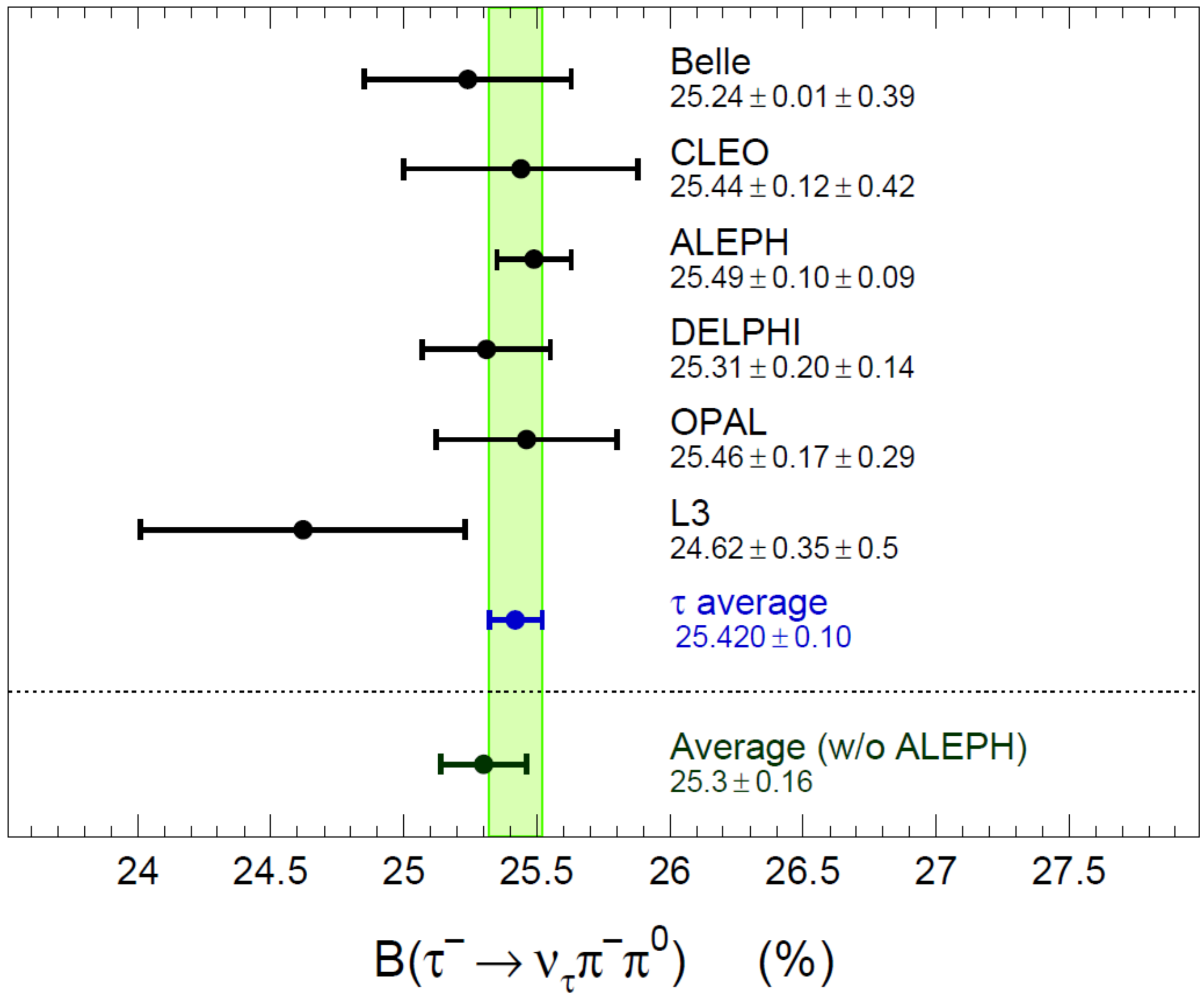
ALEPH τ BR measurements without kaons

- Solve linear equations for individual BR
- For each topology modes with kaon subtracted out

mode	$B \pm \sigma_{stat} \pm \sigma_{syst}$ [%]	
e	$17.837 \pm 0.072 \pm 0.036$	
μ	$17.319 \pm 0.070 \pm 0.032$	
π^-	$10.828 \pm 0.070 \pm 0.078$	
$\pi^-\pi^0$	$25.471 \pm 0.097 \pm 0.085$	
$\pi^-2\pi^0$	$9.239 \pm 0.086 \pm 0.090$	
$\pi^-3\pi^0$	$0.977 \pm 0.069 \pm 0.058$	
$\pi^-4\pi^0$	$0.112 \pm 0.037 \pm 0.035$	
$\pi^-\pi^-\pi^+$	$9.041 \pm 0.060 \pm 0.076$	
$\pi^-\pi^-\pi^+\pi^0$	$4.590 \pm 0.057 \pm 0.064$	
$\pi^-\pi^-\pi^+2\pi^0$	$0.392 \pm 0.030 \pm 0.035$	
$\pi^-\pi^-\pi^+3\pi^0$	$0.013 \pm 0.000 \pm 0.010$	estimate
$3\pi^-2\pi^+$	$0.072 \pm 0.009 \pm 0.012$	
$3\pi^-2\pi^+\pi^0$	$0.014 \pm 0.007 \pm 0.006$	
$\pi^-\pi^0\eta$	$0.180 \pm 0.040 \pm 0.020$	ALEPH [13]
$\pi^-2\pi^0\eta$	$0.015 \pm 0.004 \pm 0.003$	CLEO [27]
$\pi^-\pi^-\pi^+\eta$	$0.024 \pm 0.003 \pm 0.004$	CLEO [27]
$a_1^-(\to \pi^-\gamma)$	$0.040 \pm 0.000 \pm 0.020$	estimate
$\pi^-\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.253 \pm 0.005 \pm 0.017$	ALEPH [13]
$\pi^-\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.048 \pm 0.006 \pm 0.007$	ALEPH [13] + CLEO [26]
$\pi^-2\pi^0\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.002 \pm 0.001 \pm 0.001$	CLEO [27]
$\pi^-\pi^-\pi^+\omega(\to \pi^0\gamma, \pi^+\pi^-)$	$0.001 \pm 0.001 \pm 0.001$	CLEO [27]

$B_{\pi\pi 0}$ measurements

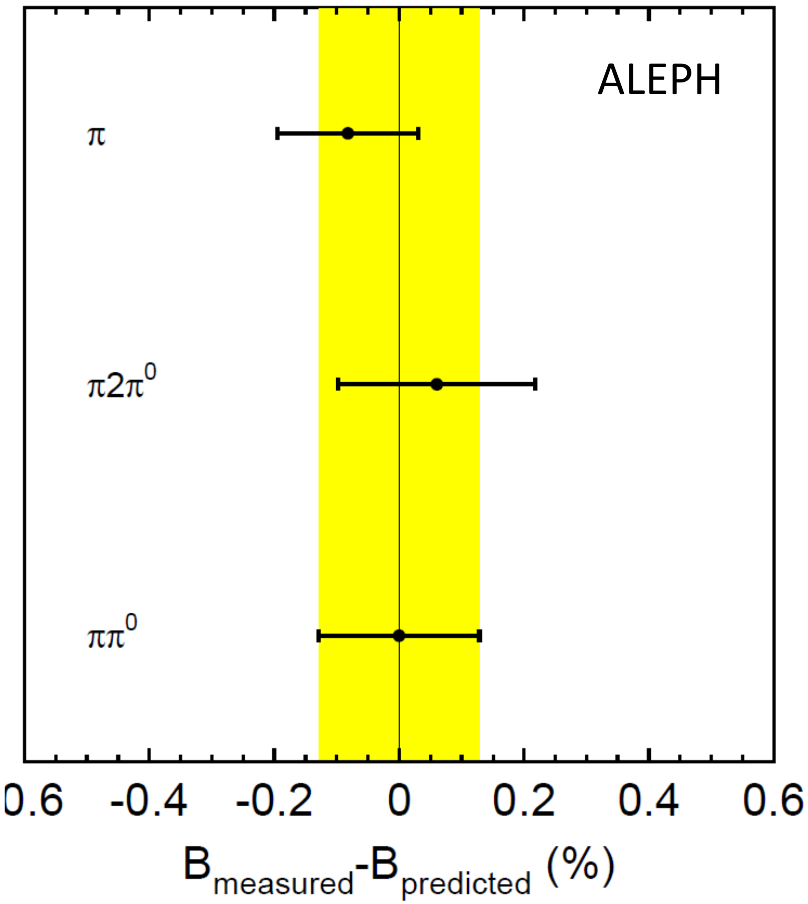
- Strongly dominated by ALEPH
- However average of other measurements consistent with ALEPH with comparable accuracy



2005 Phys.Rep.
plot updated

Consistency check of ALEPH $B_{\pi\pi 0}$ measurement

- Compare measurements of 'adjacent' channels $\tau \to \pi^- \nu_\tau$, $\tau \to \pi^- 2\pi^0 \nu_\tau$ with predictions based on lepton universality and isospin, respectively
- Test of feedthrough in the classification with number of γ/π^0
- Consistent within uncertainties



2005 Phys.Rep.

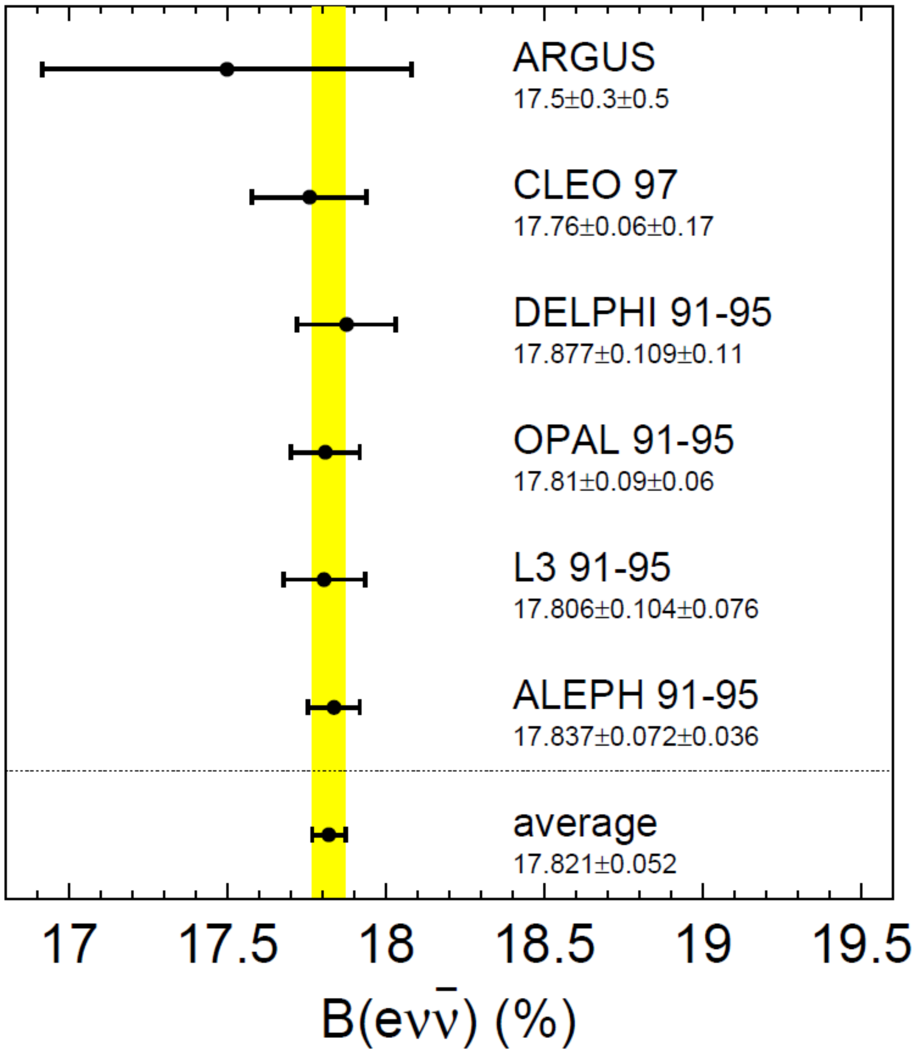
Using leptonic universality

Isospin using BR $\tau \to \pi^- \pi^+ \pi^- \nu_\tau$ + π mass corrections

Measurement

B_e measurements

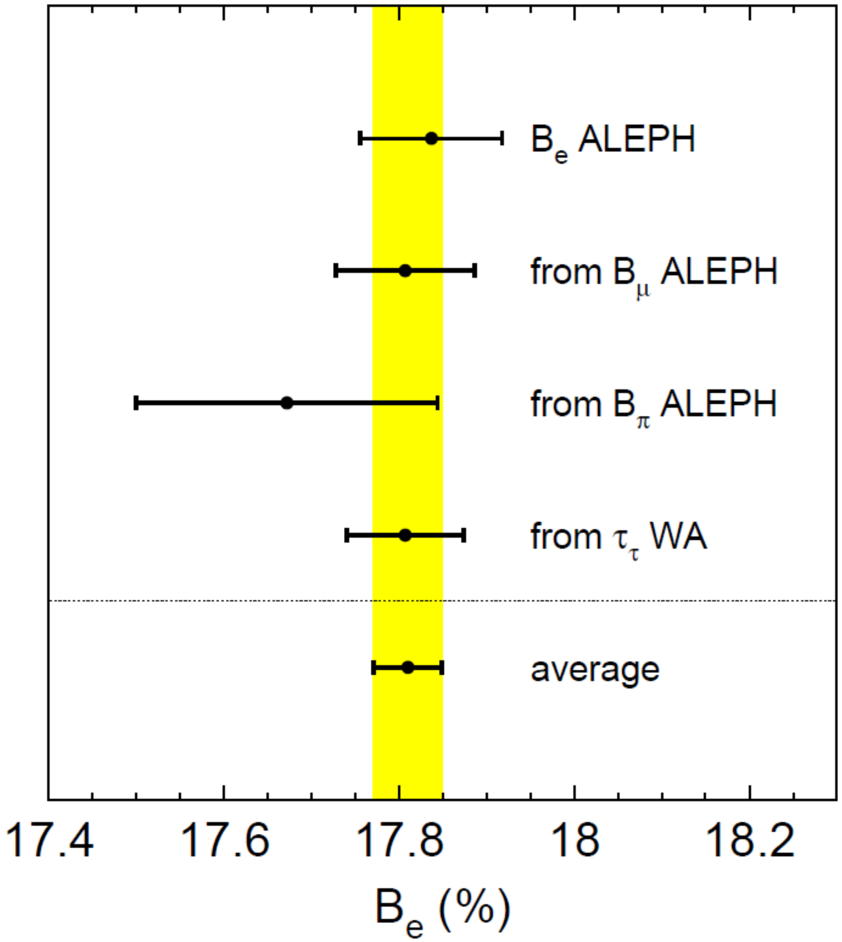
- Dominated by ALEPH
- Average of other measurements (17.809 ± 0.067)% consistent with ALEPH



2005 Phys.Rep.

Consistency of B_e measurements using lepton universality

- Lepton universality tested at per mil level
- Assuming lepton universality: independent determinations of B_e consistent
- Averaging leads to B_e improved value



2005 Phys.Rep.

Not including 2017 Belle lifetime measurement with precision x2 and consistent central value

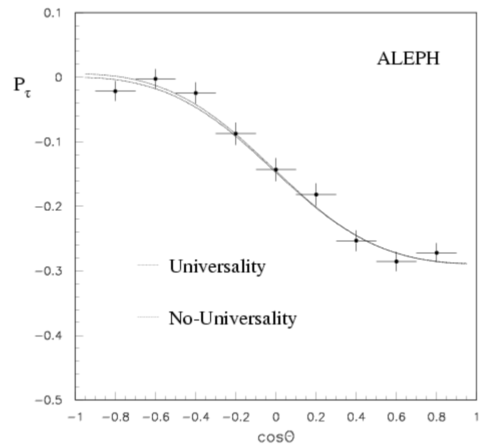
$B_{e\ uni} = (17.818 \pm 0.0032)$ %

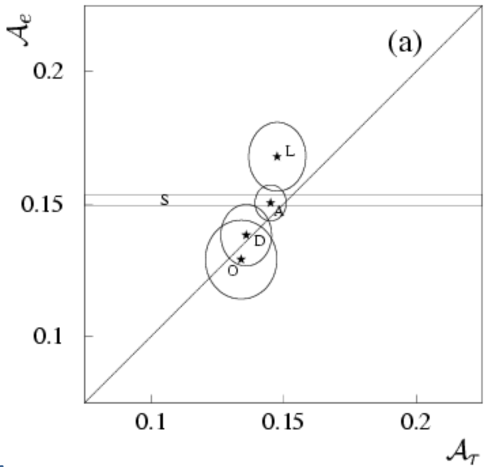
ALEPH $\tau^+\tau^-$ sample used for many precision analyses

- EW precision tests: cross section, FB asymmetry, τ polarization

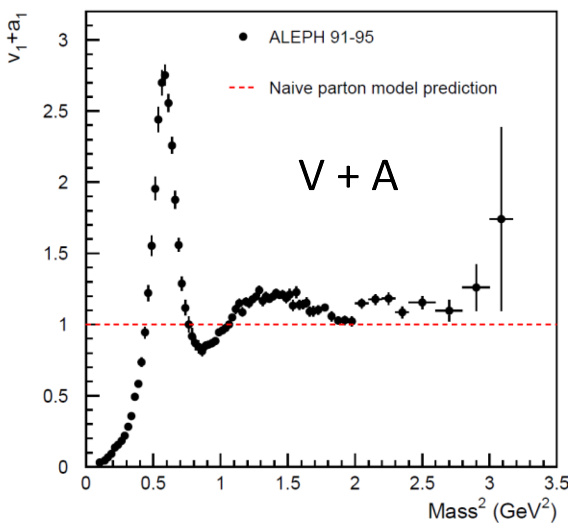
$A_l = 2\, a_l v_l / (a_l^2+v_l^2)$

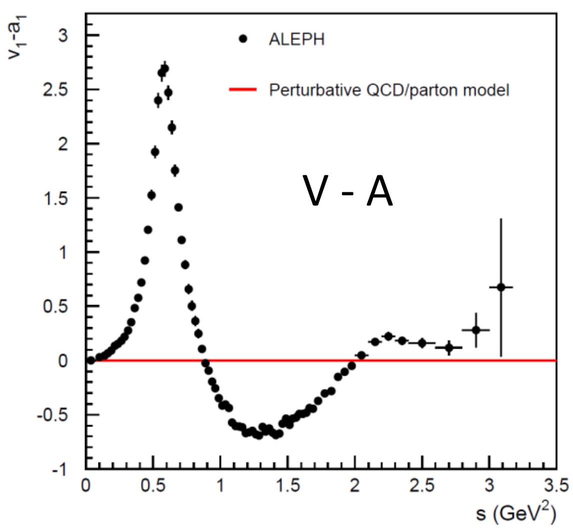
Best single measurement of $\sin^2\theta_{W\,eff}$ at LEP





- V,A spectral functions (using G-parity), duality quark-hadron and QCD analyses





input to many QCD analyses

ALEPH τ branching fractions and spectral functions

- A long-term effort by the Orsay group
- 1991: first BR analysis (Zhiqing Zhang's thesis)
- 1992-2000: refined analyses on final states and BR modes with kaons
- 1997: V,A spectral functions (Andreas Hoecker's thesis)
- 2000-2002: final BR analysis full statistics (Changzheng Yuan postdoc)
- 2005: detailed Phys. Rep. on τ BR : arxiv:0506.072 linked
- 2013: update of spectral functions (new unfolding technique, Bogdan Malaescu)
  arxiv:1312.1501 linked
- Thanks to all !