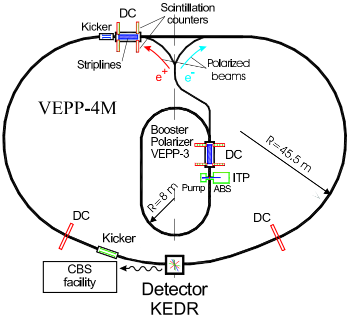
Measurement of R between 1.84 and 3.72 GeV at the KEDR detector

KEDR collaboration

October 2016

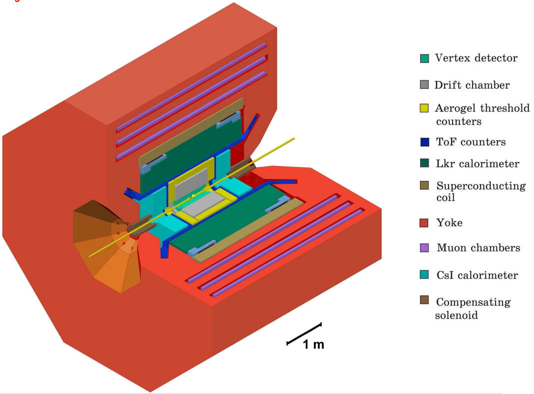
VEPP-4M and KEDR



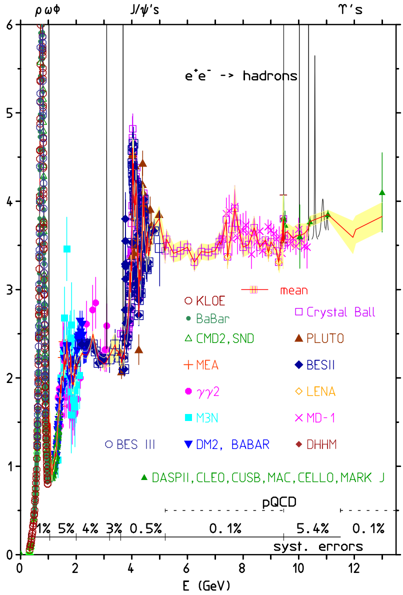
Beam energy	$1 \div 5$ GeV
Number of bunches	2×2
Luminosity 1.8 GeV	1.5×10^{30} cm^{-2} c^{-1}

Energy measurement:

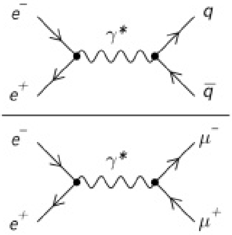
- Resonant depolarization method $10 \div 30$ keV
- Compton backscattering method ~ 100 keV



$R(s)$ measurement



$$R = \frac{\sigma(e^-e^+ \to \text{hadrons})}{\sigma(e^-e^+ \to \mu^-\mu^+)} \approx$$



F. Jegerlehner arXiv:1511.0447

In first approximation:

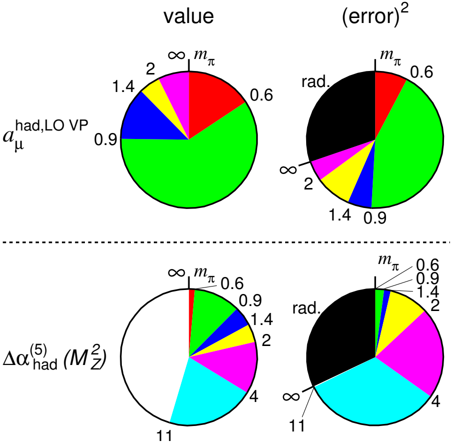
$$R(s) \simeq 3 \sum e_q^2$$

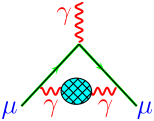
$R(s)$ is used to determine:

- $\alpha_s(s)$
- $(g_\mu - 2)/2$
- $\alpha(M_Z^2)$

R contribution in a_μ and $\alpha(M_Z^2)$

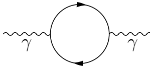
$$a_\mu^{exp} = (g_\mu - 2)/2$$





$$a_\mu^{LO\ VP} = \frac{\alpha^2}{3\pi^2}\int_{m_\pi^2}^{\infty}\frac{K(s)R(s)}{s}ds$$

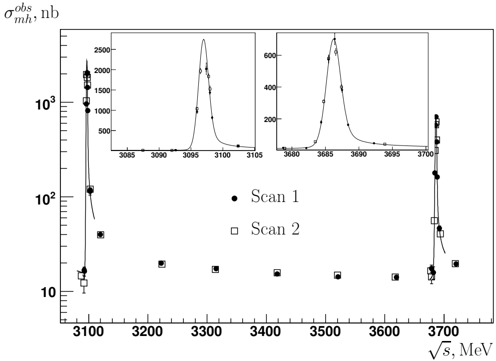
$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha(s)}$$

$$\Delta\alpha = \sum_f$$  $$= \Delta\alpha_{\mathbf{lep}}(s) + \Delta\alpha_{\mathbf{had}}(s)$$

$$\Delta\alpha^{(5)}(M_Z^2) = -\frac{\alpha M_Z^2}{3\pi}\,\mathrm{Re}\int_{m_\pi^2}^{\infty}\frac{R(s)ds}{s(s-M_Z^2-i\epsilon)}$$

K.Hagiwara et al. arxiv:1105.3149

R measurement between J/ψ and $\psi(2S)$



- The c.m. energy range between 3.12 and 3.72 GeV studied
- An integrated luminosity of 1.4 pb^{-1} collected at 7 equidistant points with a step of $\sim$ 0.1 GeV: 3.12, 3.22, . . ., 3.72 GeV
- $(2-3)\cdot 10^3$ events per point, $\sim 18\cdot 10^3$ in total
- Simulation of the *uds* continuum based on the tuned JETSET 7.4 generator, alternatively used LUARLW (H.M. Hu and A. Tai, hep-ex/0106017)

V.V. Anashin et al., Phys.Lett. B753,533 (2016)

Analysis

The way that we are measuring R:

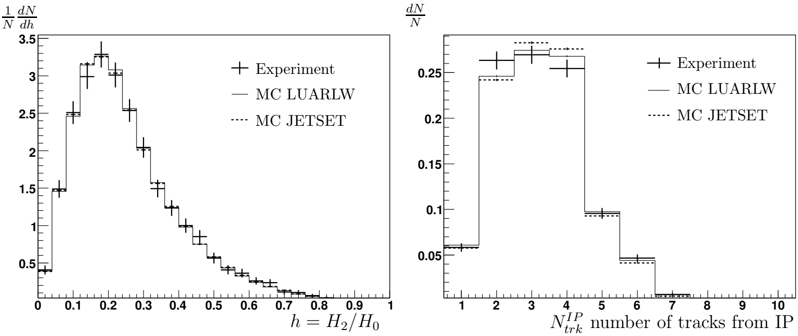
$$R = \frac{\sigma_{obs}(s) - \sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s) - \sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)}{\varepsilon(s)(1+\delta(s))\sigma_{\mu\mu}^{0}} \quad (1)$$

with $\sigma_{obs}(s) = \frac{N_{mh} - N_{res.bg.}}{\int \mathcal{L}dt}$ where N_{mh} represent all events pass hadronic selection criteria, $N_{res.bg.}$ – residual machine background
$\sum \varepsilon_{\psi}^{tail}(s)\sigma_{\psi}^{tail}(s)$ – is contribution from J/ψ and $\psi(2S)$ resonances
$\sum \varepsilon_{bg}^{i}(s)\sigma_{bg}^{i}(s)$ – is contribution from physical processes: $e^+e^- \to l^+l^-$, $\gamma\gamma$-processes.
$\varepsilon(s)$ – multihadron efficiency.

$$1 + \delta(s) = \int dx \frac{1}{1-x} \frac{\mathcal{F}(s,x)}{\left|1 - \tilde{\Pi}(s(1-x))\right|^2} \frac{\tilde{R}(s(1-x))\varepsilon(s(1-x))}{R(s)\varepsilon(s)} \quad (2)$$

$\mathcal{F}(s,x)$ – radiative correction kernel (E.A.Kuraev, V.S.Fadin Sov.J.Nucl.Phys.41(466-472)1985) Here $\tilde{\Pi}$ and $\tilde{R}$ does not includes J/ψ and $\psi(2S)$ resonances.

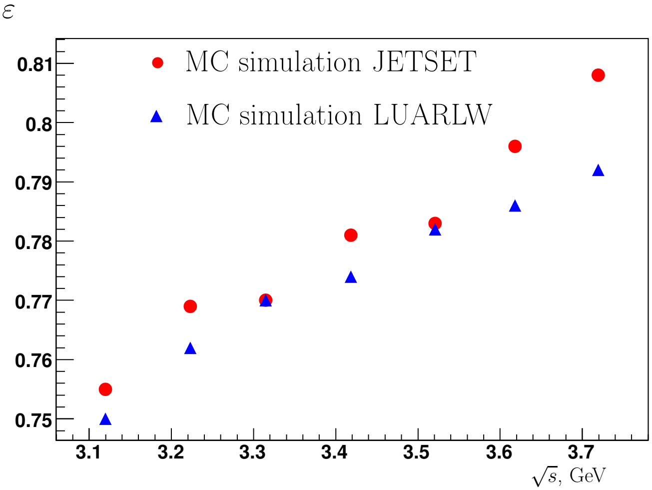
Simulation: JETSET and LUARLW



Ratio of Fox-Wolfram moments, number of tracks

Experimental distribution and two variants of MC simulation based on LUARLW and JETSET are plotted ($\sqrt{s} = 3.12$ GeV).

Simulation: JETSET and LUARLW

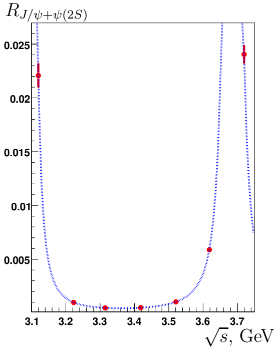


Detection efficiency for *uds* contiuum (Scan 1)

Systematic uncertainty

Source	Syst. error, %
Luminosity	1.1
Rad. corr.	$0.4 \div 0.6$
uds simulation	$1.4 \div 2.1$
J/ψ	$0.1 \div 2.7$
$\psi(2S)$	1.4 at 3.72 GeV
l^+l^-	$0.1 \div 0.2$
e^+e^-X	$0.1 \div 0.2$
Trigger	0.2
Nuclear interaction	0.2
Machine background	$0.7 \div 1.1$
Cuts	0.6
Total	$2.1 \div 3.5$

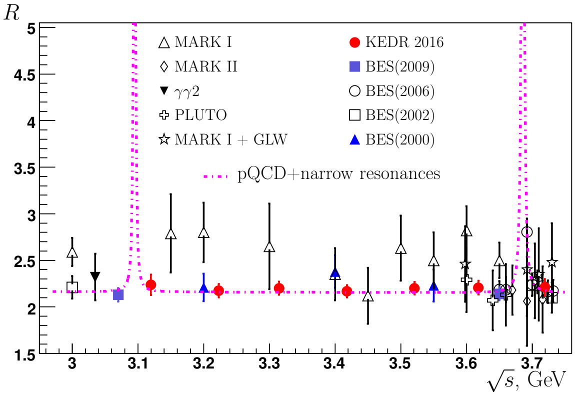
R for $\sqrt{s} = 3.12 - 3.72$ GeV



Using J/ψ **and** $\psi(2S)$ **parameters, we obtain** $R_{uds}(s) + R_{J/\psi+\psi(2S)} \Longrightarrow R(s)$

$\sqrt{s}$, MeV	$R_{uds}(s)$	$R(s)$
3119.9 ± 0.2	$2.215 \pm 0.089 \pm 0.066$	$2.237 \pm 0.089 \pm 0.066$
3223.0 ± 0.6	$2.172 \pm 0.057 \pm 0.045$	$2.173 \pm 0.057 \pm 0.045$
3314.7 ± 0.7	$2.200 \pm 0.056 \pm 0.043$	$2.200 \pm 0.056 \pm 0.043$
3418.2 ± 0.2	$2.168 \pm 0.050 \pm 0.042$	$2.168 \pm 0.050 \pm 0.042$
3520.8 ± 0.4	$2.200 \pm 0.050 \pm 0.044$	$2.201 \pm 0.050 \pm 0.044$
3618.2 ± 1.0	$2.201 \pm 0.059 \pm 0.044$	$2.207 \pm 0.059 \pm 0.044$
3719.4 ± 0.7	$2.187 \pm 0.068 \pm 0.060$	$2.211 \pm 0.068 \pm 0.060$

Comparison with others experiments



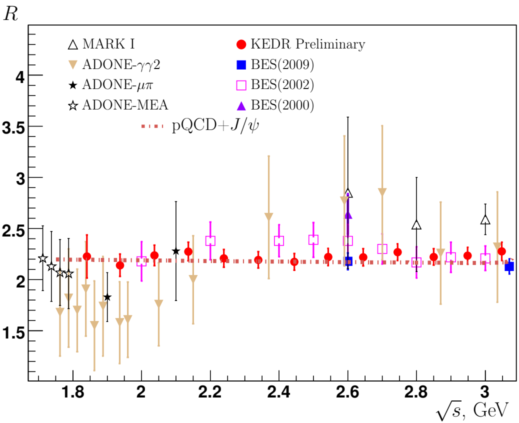
$\overline{R}_{uds}^{KEDR} = 2.189 \pm 0.022 \pm 0.042$ $\qquad$ $R_{uds}^{pQCD} = 2.16 \pm 0.01$

Measurement of R between 1.84 and 3.05 GeV at KEDR

- The c.m. energy range between 1.84 and 3.05 GeV studied
- An integrated luminosity 0.66 pb^{-1} collected at 13 equidistant with a step ~ 0.1 GeV: 1.841, 1.937 ... 3.048 GeV
- $\sim 10^3$ hadronic events per point, $14.8 \cdot 10^3$ events in total
- Simulation of the *uds* continuum based on the tuned LUARLW generator, H.M. Hu and A. Tai, hep-ex/0106017
- JETSET 7.4 alternatively used at 6 points for a cross-check

$$R = \frac{\sigma_{obs}(s) - \sum \varepsilon^i_{bg}(s)\sigma^i_{bg}(s)}{\varepsilon(s)(1+\delta(s))\sigma^0_{\mu\mu}}$$

Preliminary R for the energy range 1.84–3.05 GeV.



The main systematic uncertainties in the R:

Source	Error,%
Luminosity	1.2
Rad. corr.	$0.5 \div 2.0$
uds simulation	$1.2 \div 6.6$
l^+l^-	$0.6 \div 0.3$
e^+e^-X	0.2
Trigger	0.3
Nuclear interaction	0.4
Machine background	$0.4 \div 0.9$
Cuts	0.7
Total	$2.1 \div 7.1$

Conclusion

We have measured the values of R at seven points of the center-of-mass energy between 3.12 and 3.72 GeV. The total achieved accuracy is about or better than 3.3% at most of energy points with a systematic uncertainty of about 2.1%.

We have determined the values of R at thirteen points of the center-of-mass energy between 1.84 and 3.05 GeV. The achieved accuracy is about or better than 3.9% at most of energy points with a systematic uncertainty less than 2.4%.

At the moment it is the most accurate measurement of $R(s)$ in the energy range $1.84 \div 3.72$ GeV.

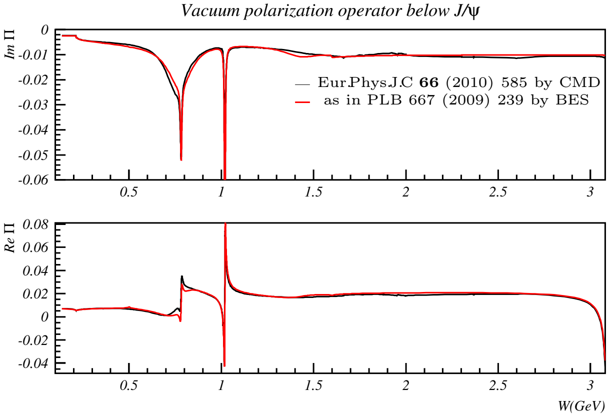
BACKUP SLIDES

Selection criteria

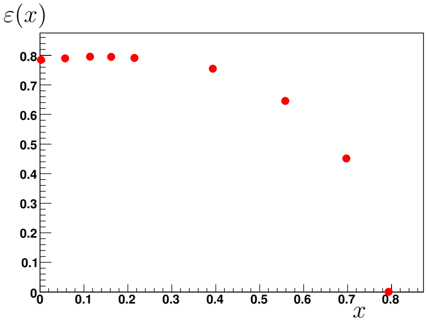
Selection criteria for hadronic events which were used by AND.

Variable	Allowed range	
	3.12-3.72 GeV	1.84 - 3.05 GeV
$N_{\rm track}^{\rm IP}$	≥ 1	≥ 1
$E_{\rm obs}$	> 1.6 GeV	> 1.4 GeV
$E_{\gamma}^{\rm max}/E_{\rm beam}$	< 0.8	< 0.8
$E_{\rm obs} - E_{\gamma}^{\rm max}$		> 1.2 GeV
$E_{\rm cal}^{\rm tot}$	> 0.75 GeV	> 0.55 GeV
H_2/H_0	< 0.85	< 0.9
$\lvert P_z^{\rm miss}/E_{\rm obs}\rvert$	< 0.6	< 0.7
$E_{\rm LKr}/E_{\rm cal}^{\rm tot}$	> 0.15	> 0.15
$\lvert Z_{\rm vertex}\rvert$	< 20.0 cm	< 15.0 cm
	$N_{\rm particles} \geq 4$ or $\tilde{N}_{\rm track}^{\rm IP} \geq 2$	$N_{\rm particles} \geq 3$ or $\tilde{N}_{\rm track}^{\rm IP} \geq 2$

Π(s) calculation



Radiation correction calculation



3 $\varepsilon(x)$ (scan 1, $\sqrt{s} = 3.52$ GeV).

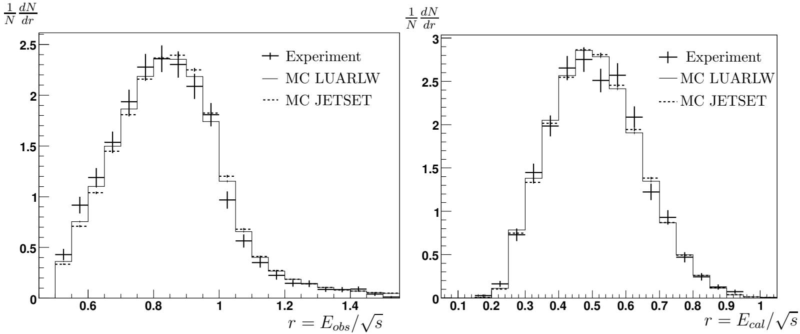
$$1+\delta(s) = \int \frac{dx}{1-x} \frac{\mathcal{F}(s,x)}{|1-\tilde{\Pi}((1-x)s)|^2} \frac{\tilde{R}((1-x)s)\varepsilon((1-x)s)}{R(s)\varepsilon(s)}$$

$$R(s) = -\frac{3}{\alpha} \, \mathrm{Im}\, \Pi_{hadr}(s)$$

Vacuum polarization according to CMD-2 data compilation: Eur. Phys. J. C66 (2010) 585

Point	Scan 1	Scan 2$1+\delta$	Uncertainty,%				Total
			$\Pi(s)$	δR	$\delta\varepsilon$	$\delta_{calc.}$	
1	1.0941 ± 0.0066	1.1074 ± 0.0066	0.3	0.5	0.2	0.2	0.6
2	1.0949 ± 0.0055	1.1049 ± 0.0055	0.1	0.4	0.2	0.2	0.5
3	1.0959 ± 0.0055	1.1100 ± 0.0056	0.1	0.4	0.2	0.2	0.5
4	1.0982 ± 0.0044	1.1094 ± 0.0044	0.1	0.3	0.2	0.2	0.4
5	1.1032 ± 0.0044	1.1102 ± 0.0044	0.1	0.3	0.2	0.2	0.4
6	1.1021 ± 0.0044	1.1098 ± 0.0044	0.1	0.3	0.2	0.2	0.4
7	1.1049 ± 0.0055	1.1067 ± 0.0055	0.4	0.3	0.2	0.2	0.5

Simulation: JETSET and LUARLW



Total observed energy, sum of cluster energies

Experimental distribution and two variants of MC simulation based on LUARLW and JETSET are plotted ($\sqrt{s} = 3.12$ GeV).

pQCD calculation

$R(s)$, obtained in:
P.A.Baikov *et al.* **Nucl. and Part. Phys. Proceed. 261-262(2015)**:

$$R^{n_f=3}(s) = 2\left[1 + \frac{\alpha_s}{\pi} + 1.6398\left(\frac{\alpha_s}{\pi}\right)^2 - 10.2839\left(\frac{\alpha_s}{\pi}\right)^3 - 106.8798\left(\frac{\alpha_s}{\pi}\right)^4\right].$$

α_s obtained in **K.G.Chetyrkin, B.A.Kniehl, M.Steinhauser PRL 79 (1997)**

$$\alpha_s = \frac{1}{\beta_0 L} - \frac{1}{(\beta_0 L)^2}\frac{\beta_1}{\beta_0}\ln L + \frac{1}{(\beta_0 L)^3}\left[\left(\frac{\beta_1}{\beta_0}\right)^2(\ln^2 L - \ln L - 1) + \frac{\beta_2}{\beta_0}\right]$$
$$+ \frac{1}{(\beta_0 L)^4}\left[\left(\frac{\beta_1}{\beta_0}\right)^3\left(-\ln^3 L + \frac{5}{2}\ln^2 L + 2\ln L - \frac{1}{2}\right) - 3\frac{\beta_1\beta_2}{\beta_0^2}\ln L + \frac{\beta_3}{2\beta_0}\right]$$

for $n_f = 3$ $\beta_0 = \frac{9}{4}, \beta_1 = 4, \beta_2 = \frac{3863}{384}, \beta_3 = \frac{445}{32}\zeta(3) + \frac{140599}{4608}, L = \ln^2\frac{Q^2}{\Lambda^2_{\overline{MS}}}$

$\alpha_s(m_\tau^2) = 0.331 \pm 0.013$ (**A.Pich Nucl. and Part. Phys. Proceed. 260 (2015) 61-69**) allow to get $R^{pQCD}_{uds} = 2.16 \pm 0.01$ in energy range $3.1 \div 3.7$ GeV.

$\sigma^{e^+e^-\to\text{hadrons}}$ and $\sigma^{e^+e^-\to e^+e^-}$ nearby a narrow resonance

Analytical expression for the annihilation cross section nearby a narrow resonance in the soft photon approximation was first obtained in

Ya.I. Azimov *et al.* **JETP Lett. 21 (1975) 172**

With up-today modifications one has

$$\sigma^{e^+e^-\to\text{hadr}}(s) = \sigma^{e^+e^-\to\text{hadr}}_{\text{continuum}} + \frac{12\pi}{s}\,(1+\delta_{sf})\left[\frac{\Gamma_{ee}\tilde{\Gamma}_h}{\Gamma M}\,\text{Im}\,f(s) - \frac{2\alpha\sqrt{R\,\Gamma_{ee}\tilde{\Gamma}_h}}{3\sqrt{s}}\,\lambda\ \text{Re}\,\frac{f^*(s)}{1-\Pi_0}\right],$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee} = \left(\frac{d\sigma}{d\Omega}\right)^{ee\to ee}_{\text{QED}} + \frac{1}{s}\left\{\frac{9}{4}\frac{\Gamma_{ee}^2}{\Gamma M}(1+\cos^2\theta)\,(1+\delta_{sf})\,\text{Im}\,f - \frac{3\alpha}{2}\frac{\Gamma_{ee}}{M}\left[(1+\cos^2\theta) - \frac{(1+\cos^2\theta)^2}{(1-\cos\theta)}\right]\text{Re}\,\frac{f^*}{1-\Pi_0}\right\}$$

$$\delta = \frac{3}{4}\beta + \frac{\alpha}{\pi}\left(\frac{\pi^2}{3}-\frac{1}{2}\right) + \beta^2\left(\frac{37}{96}-\frac{\pi^2}{12}-\frac{L}{72}\right),\quad L = \ln\left(s/m_e^2\right),$$

$$\beta = \frac{2\alpha}{\pi}(L-1),\qquad f(s) = \frac{\pi\beta}{\sin\pi\beta}\left(\frac{s}{M^2 - s - iM\Gamma}\right)^{1-\beta}$$

Γ_{ee}, Γ, M – 'dressed' parameters including corrections to the vacuum polarization, $\Gamma_{ee} = \Gamma_{ee}^{(0)}/|1-\Pi_0|^2$, λ–parameter controls the resonance–continuum interference, $\tilde{\Gamma}_h \neq \Gamma_h$

Numerical convolution with the collision energy distribution is used to fit resonance.

Interference effects in the inclusive hadronic cross section

If strong and electromagnetic decays of the resonance do not interfere $\lambda = \sqrt{R\mathcal{B}_{ee}/\mathcal{B}_h}$ otherwise for an exclusive mode m contributing R_m to the R ratio the partial width is

$$\Gamma_m = R_m\Gamma_{ee} + \Gamma_m^{(s)} + 2\sqrt{R_m\Gamma_{ee}\Gamma_m^{(s)}}\,\langle\cos\phi_m\rangle_\Theta\,,$$

The brackets $\langle\rangle_\Theta$ denote averaging over the phase space.

$$\lambda = \sqrt{\frac{R\mathcal{B}_{ee}}{\mathcal{B}_h}} + \sqrt{\frac{1}{\mathcal{B}_h}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\cos\phi_m\rangle_\Theta$$

where $b_m = R_m/R$ is the branching fraction for the continuum, $\mathcal{B}_m^{(s)} = \Gamma_m^{(s)}/\Gamma$.

$$\tilde{\Gamma}_h = \Gamma_h \times \left(1 + \frac{2\alpha}{3(1-\mathrm{Re}\,\Pi_0)\mathcal{B}_h}\sqrt{\frac{R}{\mathcal{B}_{ee}}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\sin\phi_m\rangle_\Theta\right)$$

Γ_m ambiguity: fit gives $\tilde{\Gamma}_m$ and $\cos\phi_m$, the sign of $\sin\phi_m$ required for Γ_m determination is not known