Measurement of the hadronic cross section at KLOE
Status up to July ’04

Dispersion integral for hadronic contribution to $a_\mu$ evaluated for:

a) CMD-2 (Novosibirsk/VEPP-2M) $\pi^+ \pi^-$ channel with 0.6% precision < 1 GeV

b) $\tau$-Data from ALEPH/OPAL/CLEO

$e^+ e^- -$ Data: 2.7 $\sigma$ - Deviation

$\tau$ – Data: 1.4 $\sigma$ - Deviation

Experiment BNL-E821

Values for $\mu^+(2002)$ and $\mu^-(2004)$ in agreement with each other.

Precision: 0.5ppm

$\mathbf{a_\mu = 11659000 (10^{-10})}$
The standard method to measure $\sigma(e^+e^- \rightarrow \text{hadrons})$ is the energy scan, i.e. the syst. variation of c.m. energy of the machine. Since at DAΦNE the collision energy is fixed, we use a complementary approach: looking for $e^+e^- \rightarrow \pi^+\pi^-\gamma$ events, where the photon is emitted in the initial state (ISR), we have a continuous variation of $s_\pi$, the invariant mass of the hadronic system

$$4m_\pi^2 < s_\pi < m_\phi^2$$

Precise knowledge of ISR process
Radiator function $H(Q^2,\theta_\gamma,M^2_\phi)$
MC generator: Phokhara
H. Czyz, A. Grzelinska, J.H. Kühn, G. Rodrigo

$$M^2_{\text{hadr}} \frac{d\sigma(e^+e^- \rightarrow \text{hadrons} + \gamma)}{dM^2_{\text{hadrons}}} = \sigma(e^+e^- \rightarrow \text{hadrons}) H(M^2_{\text{hadr}})$$

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Hadronic cross section @ KLOE
**π⁺π⁻γ selection**

**Pion Tracks** at large angles

\[ 50^\circ < \theta_\pi < 130^\circ \]

**Photons** at small angles

\[ \theta_\gamma < 15^\circ \text{ and } \theta_\gamma > 165^\circ \]

are masked by quadrupoles near the I.P.

*(no photon tagging*)

\[ \vec{p}_\gamma = -\vec{p}_{\text{miss}} = -(\vec{p}_+ + \vec{p}_-) \]

- High Statistics for **ISR** Photons
- Low relative contribution of **FSR**
- Reduced background contamination

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Hadronic cross section @ KLOE
\( \pi^+\pi^-\gamma \) cross section

\[ \frac{dN(\pi^+\pi^-\gamma)}{dM_{\pi\pi}^2} \]

after acceptance cuts

Event analysis:
Efficiencies and background

Normalize to Luminosity

Differential cross section
\[ \frac{d\sigma(\pi^+\pi^-\gamma)}{dM_{\pi\pi}^2} \]

Divide by Radiator Function

Radiative Corrections

Cross section
\[ \sigma(e^+e^- \rightarrow \pi^+\pi^-) \]

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Hadronic cross section @ KLOE

141 pb\(^{-1}\)

No acceptance at threshold region

\( M_{\pi\pi}^2 \) [GeV\(^2\)]
**Step 1**: $e^+e^-\gamma$ are separated from $\pi^+\pi^-\gamma$ by means of a Likelihood method (signature of EmC-clusters and TOF of particle tracks)

**Step 2**: $\phi\rightarrow\pi^+\pi^-\pi^0$ and $e^+e^-\rightarrow\mu^+\mu^-\gamma$ rejected by means “Trackmass”

\[
(M_\phi - \sqrt{|\vec{p}_1|^2 + M_{\text{trk}}} - \sqrt{|\vec{p}_2|^2 + M_{\text{trk}}})^2 - |\vec{p}_1 + \vec{p}_2|^2 - |q_\gamma|^2 = 0
\]
**Step 3**: fit data trackmass distributions with MC ones (signal + background) with free normalization parameters

\[ M_{\pi\pi}^2 \in [0.32, 0.37] \text{ GeV}^2 \]

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Hadronic cross section @ KLOE
KLOE uses **large angle Bhabha events** for the luminosity evaluation:

\[
\int L \, dt = \frac{N}{\sigma_{MC}} (1 - \delta_{Bkg})
\]

\(N\) = events with \(55^\circ < \theta < 125^\circ\)

**Experimental precision**

Excellent agreement data-MC

**Theory precision** (radiative corr.)

- BABAYAGA event generator (Pavia group)
- syst. comparison among other generators (Bhagenf, BHWIDE, VEPP-2M); max. \(\Delta = 0.7\%\)

\(\Rightarrow\) **uncertainty 0.5% = BABAYAGA error**

### Analysis items Luminosity

<table>
<thead>
<tr>
<th>Analysis items</th>
<th>Correction</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptance</td>
<td>-0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td>Knowledge W</td>
<td></td>
<td>0.1%</td>
</tr>
<tr>
<td>Background</td>
<td>+0.5%</td>
<td>0.1%</td>
</tr>
<tr>
<td>Tracking Efficiency</td>
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<td>0.1%</td>
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<tr>
<td>EmC Cluster Efficiency</td>
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<tr>
<td>EmC Calibration Drifts</td>
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<tr>
<td>Cosmic Ray Veto</td>
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</tr>
<tr>
<td>Total exp systematics</td>
<td></td>
<td>+0.6% 0.3%</td>
</tr>
</tbody>
</table>

\begin{align*}
\text{Entries} & = 586920 \\
\text{Mean} & = 90.00 \\
\text{RMS} & = 22.65
\end{align*}

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Hadronic cross section @ KLOE
**Analysis $\sigma(e^+e^-\rightarrow\pi^+\pi^-\gamma)$**

**EFFICIENCIES:**
- Trigger + Cosmic Veto
- Tracking Vertex
- $\pi/e$ separation
- Reconstruction filter
- Trackmass cut
- Unfolding procedure
- Acceptance

**BACKGROUND**
- $e^+e^-\rightarrow e^+e^-\gamma$
- $e^+e^-\rightarrow \mu^+\mu^-\gamma$
- $\phi \rightarrow \pi^+\pi^-\pi^0$

**LUMINOSITY**
- Bhabha at large angles

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**140 pb$^{-1}$ of 2001 data**

1.5 millions events

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$\frac{d\sigma(e^+e^-\rightarrow\pi^+\pi^-\gamma)}{dM_{\pi\pi}^2}$ [nb/GeV$^2$]

$M_{\pi\pi}^2$ [GeV$^2$]

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Hadronic cross section @ KLOE
There is no initial state radiation and the $e^+$ and the $e^-$ collide at the energy $M_\phi \Rightarrow$ the virtual $\gamma$ has $Q^2 = M_\phi^2$

Background

The cross section $e^+e^- \rightarrow \pi^+\pi^-$ has to be inclusive with respect to NLO FSR events:
FSR Treatment

"FSR Inclusive" approach

\[ N(e^+e^- \rightarrow \pi^+ \pi^- \gamma_{ISR} \gamma_{FSR}) \]
add back missing FSR

Event analysis
Phokhara ISR+FSR
Luminosity

\[ \sigma(e^+e^- \rightarrow \pi^+ \pi^- \gamma_{ISR} \gamma_{FSR}) \]

Correction for unshifting

Radiator H

\[ \sigma(e^+e^- \rightarrow \pi^+ \pi^- \gamma_{FSR}) \]

Invariant mass of the system \( \pi^+\pi^- \), \( s_{\pi} \neq \) invariant mass of the virtual photon \( s \)
**FSR uncertainty**

**"FSR Exclusive" approach**

\[ N(e^+e^- \rightarrow \pi^+ \pi^- \gamma_{\text{ISR}} \gamma_{\text{FSR}}) \]

- subtract FSR contribution estimated by MC

**Event analysis**

- Phokhara ISR
- Luminosity

**Radiator H**

\[ \sigma(e^+e^- \rightarrow \pi^+ \pi^- \gamma_{\text{ISR}}) \]

\[ 0.8 \ldots 0.9\% \text{ Schwinger } '90 \]

**The 2 methods are in excellent agreement**

- Higher order FSR corrections negligible
- Proof of Factorization Ansatz

- FSR systematic = 0.3%, coming from 2 contributions
- 0.2% difference **incl-excl correction**
- upper limit of 20% for **scalar QED model**
  (point-like pions): 20% \times 1\% = 0.2%

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 Hadronic cross section @ KLOE
Cross Section $\sigma(e^+e^-\rightarrow\pi^+\pi^-)$

Final spectrum: after the correction for vacuum polarization

$$\sigma_{\text{bare}}(s) = \sigma(s) \cdot \left( \frac{\alpha(0)}{\alpha(M_{\pi\pi}^2)} \right)^2$$

$\Delta\alpha_{\text{had}}(s)$ from F. Jegerlehner, July 2003

<table>
<thead>
<tr>
<th>Acceptance</th>
<th>0.3 %</th>
</tr>
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<tbody>
<tr>
<td>Trigger</td>
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<tr>
<td>Reconstruction Filter</td>
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<tr>
<td>Tracking</td>
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<tr>
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<tr>
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<tr>
<td>Trackmass</td>
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<td>Background subtraction</td>
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<tr>
<td>Unfolding</td>
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<tr>
<td><strong>Total exp systematics</strong></td>
<td>0.9 %</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.6 %</td>
</tr>
<tr>
<td>Vacuum Polarization</td>
<td>0.2 %</td>
</tr>
<tr>
<td>FSR resummation</td>
<td>0.3 %</td>
</tr>
<tr>
<td>Radiation function ($H(s_\pi)$)</td>
<td>0.5 %</td>
</tr>
<tr>
<td><strong>Total theory systematics</strong></td>
<td>0.9 %</td>
</tr>
</tbody>
</table>

Total error = 1.3 %
We have evaluated the dispersion integral for $2\pi$ channel in the energy range $0.35 < s_{\pi\pi} < 0.95 \text{ GeV}^2$

$$a_\mu^{\pi\pi} = \frac{1}{4\pi^3} \int_{0.35\text{GeV}^2}^{0.95\text{GeV}^2} ds \sigma(e^+e^- \rightarrow \pi^+\pi^-) K(s)$$

$$a_\mu^{\pi\pi} = (388.7 \pm 0.8_{\text{stat}} \pm 3.5_{\text{syst}} \pm 3.5_{\text{theo}}) \times 10^{-10}$$

Comparison with CMD-2 in the energy range $0.37 < s_{\pi\pi} < 0.97 \text{ GeV}^2$

- **CMD-2**: $(378.6 \pm 2.7_{\text{stat}} \pm 2.3_{\text{syst+theo}})$
- **KLOE**: $(375.6 \pm 0.8_{\text{stat}} \pm 4.8_{\text{syst+theo}})$

1.3% Error

0.9% Error

At large values of $s_\pi (> m_\rho^2)$ we are consistent with CMD-2 and we confirm the deviation from $\tau$-data.
Conclusion

- KLOE has proven the feasibility to use initial state radiation to measure hadronic cross section (hep-ex 0407048)

- We expect to reduce the systematic error below 1% by repeating the analysis with 2002 data. Improvements from theory are also expected.

- The analysis at large photon angle to study the region near the threshold is going on.

- Evaluation of ratio R – the analysis has already begun
Outlook

- Large angle photon analysis to explore the threshold region
  tagged measurement

- Test of sQED model:
  at large photons angles the amount of FSR is large. Here it is possible to study the charge asymmetry.
  It comes out from the interference between ISR (C-odd) and FSR (C-even)

\[
A(\theta) = \frac{N_{\pi^+}(\theta) - N_{\pi^-}(\theta)}{N_{\pi^+}(\theta) + N_{\pi^-}(\theta)}
\]

Integrating asymmetry we get a difference data-MC of (8.5 ± 1.2)%

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Hadronic cross section @ KLOE
Backup slices
The **smearing matrix “almost” diagonal**
Inversion of smearing matrix possible
A more sophisticated unfolding technique
is obtained by means of the **unfolding package GURU** (A. Höcker et.al./ALEPH).

**Issues:**
- Reliability of MC simulation ✓
- Correct choice of the regularization parameter

**Systematics** studied by varying meaningful values of the regularization parameter:

Due to nature of the dispersion integral
the effect on $a_\mu$ is almost negligible
NLO-FSR unshifting correction
Inclusive approach

Terms not included in Phokhara

Unshifting correction

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Hadronic cross section @ KLOE
Relative contribution of LO-FSR

Relative contribution of NLO-FSR

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Hadronic cross section @ KLOE
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$\frac{d\sigma}{dQ^2} (\pi\pi\gamma)$ with $F_{\pi}=1$

2.106 events

$Q^2 (GeV^2)$

$F_{\pi}$ = 1

$s_\pi (GeV^2)$

Radiator Function

Likelihood effect on $M_{trk}$ distribution

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Hadronic cross section @ KLOE
KLOE & DAΦNE

- $e^+e^-$ collider @ $\sqrt{S} = M_\Phi = 1019.4$ MeV
- achieved peak Luminosity: $8 \times 10^{31}\text{cm}^{-2}\text{s}^{-1}$
- 2000-2002 data set: $\sim 500\text{ pb}^{-1}$

KLOE detector designed for CP violation studies ⇒ good time resolution

$\sigma_t = 57\text{ ps} / \sqrt{E}\text{(GeV)} \oplus 54\text{ ps}$

in calorimeter and high resolution drift chamber ($\sigma_p/p$ is 0.4% for $\theta > 45^\circ$), ideal for the measurement of $M_{\pi\pi}$. 

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