A precise KLOE measurement of $\sigma(e^+ e^- \rightarrow \pi^+ \pi^-)$ and extraction of $\alpha_{\mu}^{\pi\pi}$ between 0.35 and 0.95 GeV$^2$

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(for the KLOE collaboration)

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$\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ with ISR:

Particle factories have the opportunity to measure the cross section $\sigma(e^+e^-\rightarrow\pi^+\pi^-)$ as a function of the pionic c.m. energy $s_\pi = M_{\pi\pi}^2$ using initial state radiation (radiative return to energies below the collider energy $s$).

\[
s \cdot \frac{d\sigma(e^+e^-\rightarrow\pi^+\pi^-+\gamma)}{ds_\pi} = \sigma(e^+e^-\rightarrow\pi^+\pi^-) H(s, s_\pi)
\]

requires precise calculation of the radiator $H(s, s_\pi)$

$\Rightarrow$ EVA + PHOKHARA MC Generator

(S.Binner, J.H.Kühn, K.Melnikov, PLB459,1999)

Advantages:
- overall energy scale $\sqrt{s}$ is well known and applies to all values of $s_\pi$
- syst. errors from luminosity, $\sqrt{s}$, rad. corrections enter only once, don’t have to be studied for each point of $s_\pi$
- data comes as together with the standard physics program of the experiment

Requirements:
- precise evaluation of radiator function
- good suppression, or understanding, of Final State Radiation (FSR)
- large integrated luminosity

1st KLOE publication (based on 140 pb$^{-1}$)
A. Aloisio et al., PLB606(2005)12
DEAR SIDDHARTA

e$^+$e$^-$ collider with $\sqrt{s} = m_\Phi \approx 1.0195$ GeV

Peak Luminosity $L_{\text{peak}} = 1.4 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$
Total KLOE int. Luminosity: $\int L \, dt \sim 2500$ pb$^{-1}$ (2001 - 05)

New result is based on 240 pb$^{-1}$ from 2002 data

2006:
• Energy scan with 4 points around $m_\Phi$-peak
• 225 pb$^{-1}$ at $\sqrt{s} = 1$ GeV
KLOE Detector

Driftchamber

\[ \sigma_p/p = 0.4\% \text{ (for } 90^0 \text{ tracks)} \]
\[ \sigma_{xy} \approx 150 \mu m, \sigma_z \approx 2 \text{ mm} \]

Excellent momentum resolution
KLOE Detector

Electromagnetic Calorimeter

\[ \sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})} \]

\[ \sigma_T = 54 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 50 \text{ ps} \]

(Bunch length contribution subtracted from constant term)

Excellent timing resolution
Event Selection

2 pion tracks at large angles
$50^\circ < \theta_{\pi} < 130^\circ$

Photons at small angles
$\theta_{\gamma} < 15^\circ$ or $\theta_{\gamma} > 165^\circ$

✓ high statistics for ISR events
✓ low relative FSR contribution
✓ suppression of $\phi \rightarrow \pi^+\pi^-\pi^0$ background

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

.statistics: 242pb$^{-1}$
3.5 Million Events

[Graph showing distribution of $s_{\pi}$ and $n_{\pi}$]
Event selection

- Experimental challenge: control backgrounds from
  - $\phi \rightarrow \pi^+\pi^-\pi^0$
  - $e^+e^- \rightarrow e^+e^-\gamma$
  - $e^+e^- \rightarrow \mu^+\mu^-\gamma$,
removed using kinematical cuts in trackmass $M_{Trk}$ and Missing Mass $M_{miss}$

$M_{Trk}$:
  defined by 4-momentum conservation under the hypothesis of 2 tracks with equal mass and one $\gamma$

\[
\left(\sqrt{s} - \sqrt{p_1^2 + M_{trk}^2} - \sqrt{p_2^2 + M_{trk}^2}\right)^2 - (p_1 + p_2)^2 = 0
\]

$M_{miss}$:
  defined by 4-momentum conservation under the hypothesis of $e^+e^- \rightarrow \pi^+\pi^-\gamma$

\[
M_{miss} = \sqrt{E_X^2 - p_X^2}
\]

To further clean the samples from radiative Bhabha events, we use a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight.
Radiative corrections

Radiator-Function $H(s,s_\pi)$ (ISR):

- ISR-Process calculated at NLO-level
  \textit{PHOKHARA} generator

**Precision:** $0.5\%$

\[
\frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi)
\]

Radiative Corrections:

i) **Bare Cross Section**
   divide by Vacuum Polarisation $\delta(s) = (\alpha(s)/\alpha(0))^2$
   $\rightarrow$ from F. Jegerlehner

ii) **FSR**
   Cross section $\sigma_{\pi\pi}$ must be incl. for FSR
   for use in the dispersion integral of $a_\mu$

   FSR corrections have to be taken into account in the efficiency eval. (SA Acceptance, $M_{\text{Trk}}$) and in the passage $s_\pi \rightarrow s_{\gamma*}$

KLOE measures $L$ with Bhabha scattering

$55^\circ < \theta < 125^\circ$

acollinearity $< 9^\circ$

$p \geq 400$ MeV

$$\int L \, dt = \frac{N_{obs} - N_{bkg}}{\sigma_{eff}}$$

F. Ambrosino et al. (KLOE Coll.)


BABAYAGA (Pavia group):

C. M.C. Calame et al., NPB584 (2000) 459

New: C. M.C. Calame et al., NPB758 (2006) 22

new version (BABAYAGA@NLO) gives

0.7% decrease in cross section,
and better accuracy: 0.1%

<table>
<thead>
<tr>
<th>Systematics on Luminosity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
<td>0.1 %</td>
</tr>
<tr>
<td>Experiment</td>
<td>0.3 %</td>
</tr>
<tr>
<td>TOTAL</td>
<td>0.1 % th $\oplus$ 0.3% exp = 0.3%</td>
</tr>
</tbody>
</table>
Improvements

- New generator \textbf{BABAYAGA@NLO}, error on $\sigma_{\text{Bhabha}}$ from 0.5% to 0.1%
- 30% inefficiency (veto of cosmic rays) recovered by introducing 3rd level trigger
  - improvements (vertex requirement dropped) in the selection
- Improved offline-event filter reduces systematic uncertainty to < 0.1%
- Improved machine conditions (luminosity and background) in the new data set

### Table

<table>
<thead>
<tr>
<th>Category</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction filter</td>
<td>0.6%</td>
</tr>
<tr>
<td>Background</td>
<td>0.3%</td>
</tr>
<tr>
<td>$M_{\text{trk}}$ cuts</td>
<td>0.2%</td>
</tr>
<tr>
<td>Particle ID</td>
<td>0.1%</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3%</td>
</tr>
<tr>
<td>Vertex</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.3%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.3%</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.2%</td>
</tr>
<tr>
<td>Luminosity ($0.5_{\text{th}} + 0.3_{\text{exp}}$)%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

$\Sigma_{\text{total,2005}} = 1.3\%$

\[
\frac{d\sigma_{\pi\gamma}}{ds_\pi} = \frac{N^{\text{obs}} - N^{\text{bkg}}}{\Delta s_\pi} \cdot \frac{1}{\varepsilon_{\text{sel}}} \cdot \frac{1}{L}
\]
New result from 2002 data:

Systematic errors on $a_\mu^{\pi\pi}$:

<table>
<thead>
<tr>
<th>Source</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offline Filter</td>
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</tr>
<tr>
<td>Background</td>
<td>0.6%</td>
</tr>
<tr>
<td>Trackmass/Miss. Mass</td>
<td>0.2%</td>
</tr>
<tr>
<td>$\pi/e$-ID</td>
<td>0.3%</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>Acceptance ($\theta_{\text{miss}}$)</td>
<td>0.1%</td>
</tr>
<tr>
<td>Acceptance ($\theta_\pi$)</td>
<td>negligible</td>
</tr>
<tr>
<td>Unfolding</td>
<td>0.2%</td>
</tr>
<tr>
<td>Software Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>Luminosity($0.1_{\text{th}} \oplus 0.3_{\text{exp}}$)%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

Experimental fractional error on $a_\mu = 0.9$ %

\[
\sigma_{\pi\pi}(s_\pi) = \frac{\pi\alpha^2 \beta^3}{3s} |F_\pi(s_\pi)|^2
\]

\[
\sum_{\text{Total}} = 1.0\%
\]
Evaluating $a_{\mu}^{\pi\pi}$

Dispersion integral for $2\pi$-channel in energy interval $0.35 < M_{\pi\pi}^2 < 0.95$ GeV$^2$

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


$$a_{\mu}^{\pi\pi}(0.35-0.95\text{GeV}^2) = (388.7 \pm 0.8_{\text{stat}} \pm 3.5_{\text{sys}} \pm 3.5_{\text{theo}}) \cdot 10^{-10}$$

Applying update for trigger eff. and change in Bhabha-cross section used for luminosity evaluation:

$$a_{\mu}^{\pi\pi}(0.35-0.95\text{GeV}^2) = (384.4 \pm 0.8_{\text{stat}} \pm 3.5_{\text{sys}} \pm 3.0_{\text{theo}}) \cdot 10^{-10}$$

2008:

$$a_{\mu}^{\pi\pi}(0.35-0.95\text{GeV}^2) = (389.4 \pm 0.6_{\text{stat}} \pm 3.3_{\text{sys}} \pm 2.0_{\text{theo}}) \cdot 10^{-10}$$
Summary of the results:

**KLOE 2005 published result:**
388.7$^{±0.8}_{\text{STAT}}$$^{±4.9}_{\text{SYST}}$

**KLOE 2005 updated:**
384.4$^{±0.8}_{\text{STAT}}$$^{±4.6}_{\text{SYST}}$

**KLOE 2008:**
389.4$^{±0.6}_{\text{STAT}}$$^{±3.9}_{\text{SYST}}$
$a_{\mu}^{\pi\pi}$ comparison:

Comparison with $a_{\mu}^{\pi\pi}$ from CMD2 and SND in the range 0.630-0.958 GeV:


**CMD2 2007:**

$361.5^{+1.7}_{-2.0}^{\text{STAT}}^{+2.9}_{-3.0}^{\text{SYST}}$

**SND 2006:**

$361.0^{+2.0}_{-1.8}^{\text{STAT}}^{+4.7}_{-4.4}^{\text{SYST}}$

**KLOE 2008:**

$358.4^{+0.6}_{-0.6}^{\text{STAT}}^{+3.5}_{-3.5}^{\text{SYST}}$

KLOE result in agreement with CMD2 and SND
$|F_\pi|^2$ comparison:

- Only statistical errors are shown.

Light grey band: KLOE stat. error
Dark grey band: KLOE total error (stat. + syst.)

Data points: CMD and SND results compared to KLOE value extrapolated to the corresponding $s_\pi$ (only stat. error shown)
Large angle analysis:

- Independent complementary analysis
- Threshold region \((2m_\pi)^2\) accessible
- \(\gamma_{\text{ISR}}\) photon detected
  (4-momentum constraints)

- Lower signal statistics
- Larger contribution from FSR events
- Large \(\phi \rightarrow \pi^+\pi^-\pi^0\) background contamination
- Irreducible background from \(\phi\) decays \((\phi \rightarrow f_0\gamma \rightarrow \pi\pi\gamma)\)

Threshold region non-trivial due to irreducible FSR-effects, which have to be estimated from MC using phenomenological models (interference effects unknown)

Pion tracks: \(50^\circ < \theta_\pi < 130^\circ\)

At least 1 photon with \(50^\circ < \theta_\gamma < 130^\circ\) and \(E_\gamma > 50\) MeV \(\Rightarrow\) photon detected

2002 data
485000 events
\(L = 240\) pb\(^{-1}\)

Preliminary

\[\phi, \rho \rightarrow \pi\gamma \& f_0 \rightarrow \pi\pi\gamma\]

FSR

\(\rightarrow\) important!

\(\rho\pi, \rho^0\pi\)
Large angle analysis:

**Dedicated selection cuts:**

- Exploit kinematic closure of the event
  - Cut on angle $\Omega$ btw. ISR-photon and missing momentum

- Kinematic fit in $\pi^+\pi^-\pi^0$ hypothesis using 4-momentum and $\pi^0$-mass as constraints

- FSR contribution added back to cross section (estimated from PHOKHARA generator)

- Reducible Background from $\pi^+\pi^-\pi^0$ and $\mu^+\mu^-\gamma$ well simulated by MC

Dominating uncertainty from model dependence of irreducible background $\phi \rightarrow f_0\gamma \rightarrow \pi^+\pi^-\gamma$.

Using different models for $f_0$-decay and using input from dedicated KLOE $\phi \rightarrow f_0\gamma$ analyses

(with $f_0 \rightarrow \pi^+\pi^-$ and $f_0 \rightarrow \pi^0\pi^0$)

$\Rightarrow$ Difference between the MC models contributes to systematic uncertainty
Conclusions and Outlook:

We have evaluated the contribution to $a_{\mu}^{\pi\pi}$ in the range between 0.35 - 0.95 GeV$^2$ using cross section data obtained via ISR events with photon emission at small angles.

- The result from new data agrees with the updated result from the published KLOE analysis
- KLOE results also agree with recent results on $a_{\mu}^{\pi\pi}$ from the CMD2 and SND experiments at VEPP-2M in Novosibirsk
- better agreement in spectrum between different experiments than in the past

Independent analysis is in progress using detected photons emitted at large angle

- Syst. uncertainty dominated by model-dependence of scalar mesons

We are also measuring the pion form factor using the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

Finally we are measuring pion form factor from data taken at $\sqrt{s} = M_\phi - 20$ MeV (1000 MeV)

- suppression of background from $\phi$-decays
- determination of $f_0$-parameters