Measurement of the hadronic cross sections at KLOE with ISR and their impact to the muon anomaly and U-boson search

A. Passeri, on behalf of the KLOE and KLOE-2 collaborations
Reminder: test of the SM with $a_\mu$

Theoretical calculation of the muon anomaly $a_\mu = (g_\mu - 2)/2$ are currently $\sim 3.5 \sigma$ away from its direct measurement.

Calculations and their error depend on hadron vacuum polarization (HLO) and light by light scattering (LBL).

At low $q^2$, HLO evaluation relies on the hadronic cross section measurements

75% of the value and 40% of the error of $a_\mu^{\text{had,LO}}$ comes from the region of $q^2 < 1 \text{ GeV}^2$
Reminder/2: the ISR technique

Neglecting final state radiation (FSR):

\[
\frac{d\sigma(e^+ e^- \rightarrow \text{hadrons} + \gamma)}{dM_{\text{hadr}}^2} = \frac{\sigma(e^+ e^- \rightarrow \text{hadrons}, M_{\text{hadr}}^2)}{s} H(s, M_{\text{hadr}}^2)
\]

Theoretical input: precise calculation of the radiation function \(H(s, M_{\text{hadr}}^2)\)

\(\Rightarrow\) PHOKHARA MC Generator

Binner, Kühn, Melnikov; Phys. Lett. B 459, 1999
(exact next-to-leading order QED calculation of the radiator function)

KLOE first used the ISR technique to precisely measure \(\sigma(e^+e^- \rightarrow \pi^+\pi^-)\) using 140 pb\(^{-1}\) collected in 2001
observing a 3\(\sigma\) discrepancy between \(a_\mu^{\text{SM}}\) and \(a_\mu^{\text{exp}}\): PLB606 (2005)12
KLOE @ DAFNE

DAFNE is an e⁺e⁻ collider in Frascati INFN lab operated at √s=M_φ~1020 MeV

With the ISR technique the KLOE detector can measure σ_{ππ} from threshold up to 1 GeV

KLOE has published 4 such measurements:

- **KLOE05 measurement**
  (PLB606(2005)12) was based on 140pb⁻¹ of 2001 data!

- **KLOE08 measurement**
  (PLB670(2009)285) was based on 240pb⁻¹ from 2002 data!

- **KLOE10 measurement** (PLB700 (2011)102) based on 233 pb⁻¹ of 2006 data (at 1 GeV, different event selection)

- **KLOE12 measurement** (PLB720(2013)336) using ππγ/μμγ ratio in 240 pb⁻¹ 2002 data
The KLOE detector

Large volume Drift Chamber (13K cells, He gas mixt.):

- 4m-∅, 3.75m-length, all-stereo
- $\sigma_p/p = 0.4\%$ (tracks with $\theta > 45^\circ$)
- $\sigma_x^{\text{hit}} = 150\text{ μm (xy)}, 2\text{ mm (z)}$
- $\sigma_x^{\text{vertex}} \sim 1\text{ mm}$  $\sigma_{M\pi\pi} \sim 1\text{ MeV}$

Pb-SciFi Calorimeter (barrel + endcap, 15 $X_0$ depth, 98% solid angle coverage):

- $\sigma_E/E = 5.7\% / \sqrt{E}(\text{GeV})$
- $\sigma_T = 54\text{ ps} / \sqrt{E}(\text{GeV}) \oplus 50\text{ ps}$

- PID capabilities mostly from TOF

Interaction region:
Instrument quadrupoles, Al-Be spherical beam pipe
Selection with ISR photon at Small Angle (SA): KLOE08

- 2 tracks with $50^\circ < \theta_{\text{track}} < 130^\circ$
- small angle (not detected) $\gamma$ ($\theta_{\pi^\pm} < 15^\circ$ or $>165^\circ$)

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

- high statistics for ISR
- low relative FSR contribution
- suppressed $\phi \rightarrow \pi^+\pi^-\pi^0$ wrt the signal

Measurement based on 240 pb$^{-1}$ collected in 2002 at the $\phi$ peak:

$3.1 \times 10^6$ evts between 0.35 and 0.95 GeV$^2$
Selection with ISR photon at Large Angle (LA): KLOE10

2 pion tracks at large angles
50° < θπ < 130°

Photons at large angles (i.e. detected!)
50° < θγ < 130°
✓ independent complementary analysis
✓ threshold region (2mπ)² accessible

However:
✓ lower signal statistics
✓ larger contribution from FSR events
✓ larger φ → π⁺π⁻π⁰ background contamination
✓ irreducible background from φ decays (φ → f₀ γ → ππ γ)
Event selection

Main backgrounds come from:

- $\phi \rightarrow \pi^+\pi^-\pi^0$
- $\phi \rightarrow \pi^+\pi^-\pi^0$
- $\phi \rightarrow \pi^+\pi^-\pi^0$

We define the “trackmass” variable assuming there are only 1 photon + 2 charged particles of same mass $M_{trk}$ and requiring 4-momentum conservation:

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

- Different final states are nicely separated in the $M_{trk}$-$M_{\pi\pi}$ plane
- Calorimeter time of flight is also used to improve radiative bhabha rejection
KLOE measures $L$ with Bhabha scattering

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

55° < $\theta$ < 125°
acollinearity < 9°
p ≥ 400 MeV

F. Ambrosino et al. (KLOE Coll.)

generator used for $\sigma_{\text{eff}}$

BABAYAGA (Pavia group):
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>
KLOE08 : Small Angle technique, $\sqrt{s}=1020$ MeV

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction Filter</td>
<td>negligible</td>
</tr>
<tr>
<td>Background</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trackmass/Miss. Mass</td>
<td>0.2%</td>
</tr>
<tr>
<td>p/e-ID and TCA</td>
<td>negligible</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>Acceptance ($\theta_{\pi\pi}$)</td>
<td>0.2%</td>
</tr>
<tr>
<td>Acceptance ($\theta_{\pi}$)</td>
<td>negligible</td>
</tr>
<tr>
<td>Unfolding</td>
<td>negligible</td>
</tr>
<tr>
<td>Software Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>$\sqrt{s}$ dep. Of H</td>
<td>0.2%</td>
</tr>
<tr>
<td>Luminosity($0.1_{th} \oplus 0.3_{exp}$)%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

**Note:**

- **Experimental fractional error on $a_\mu = 0.6\%**
- **Theoretical fractional error on $a_\mu = 0.6\%**

\[
a_\mu^{\pi\pi} = \int_{x_1}^{x_2} \sigma_{ee \rightarrow \pi\pi}(s)K(s)ds
\]

\[
a_\mu^{\pi\pi}(0.35-0.95 \text{GeV}^2) = (387.2 \pm 0.5_{\text{stat}} \pm 2.4_{\text{sys}} \pm 2.3_{\text{theo}}) \cdot 10^{-10}
\]

A. Passeri
KLOE10: Large Angle technique, $\sqrt{s}=1000$ MeV


**Table of systematic errors on $a_\mu^{\pi\pi}(0.1-0.85 \text{ GeV}^2)$:**

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction Filter</td>
<td>negligible</td>
</tr>
<tr>
<td>Background</td>
<td>0.5%</td>
</tr>
<tr>
<td>$f_0+fp$</td>
<td>0.4%</td>
</tr>
<tr>
<td>Omega</td>
<td>0.2%</td>
</tr>
<tr>
<td>Trackmass</td>
<td>0.5%</td>
</tr>
<tr>
<td>p/e-ID and TCA</td>
<td>negligible</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3%</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.2%</td>
</tr>
<tr>
<td>Acceptance</td>
<td>0.5%</td>
</tr>
<tr>
<td>Unfolding</td>
<td>negligible</td>
</tr>
<tr>
<td>Software Trigger</td>
<td>0.1%</td>
</tr>
<tr>
<td>Luminosity($0.1_{th} \oplus 0.3_{exp}$)%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

**Experimental fractional error on $a_\mu = 1.0\%$**

- FSR treatment: 0.8%
- Radiator H: 0.5%
- Vacuum polarization: 0.1%

**Theoretical fractional error on $a_\mu = 0.9\%$**

$$a_\mu^{\pi\pi}(0.1-0.85 \text{ GeV}^2) = (478.5 \pm 2.0_{\text{stat}} \pm 5.0_{\text{sys}} \pm 4.5_{\text{theo}}) \cdot 10^{-10}$$

0.4% 1.0% 0.9%
Pion Form Factor:

\[ |F_{\pi}(s)|^2 = \frac{3}{\pi} \frac{s}{\alpha^2 \beta_{\pi}^3} \sigma_{\pi\pi(\gamma)}(s)(1+\delta_{VP})(1-\eta_{\pi}) \]

**KLOE08 vs KLOE10**

Fractional difference:

Excellent agreement with KLOE08, especially above 0.5 GeV^2

Combination of KLOE08 and KLOE10:

\[ a_{\mu,\pi}(0.1-0.95 \text{ GeV}^2) = (488.6 \pm 6.0) \cdot 10^{-10} \]

KLOE covers \(~70\%\) of total \( a_{\mu,\pi}^{\text{HLO}} \) with a fractional total error of 1.2\%
KLOE10 vs CMD-2 / SND

CMD and SND results compared to KLOE10: Fractional difference

Below the $\rho$ peak good agreement with CMD-2/SND.
Above the $\rho$ peak KLOE10 slightly lower (as KLOE08)

**KLOE10 vs BaBar**

BaBar results compared to KLOE10: Fractional difference

**BaBar** derives the pion form factor from the $\pi\pi\gamma/\mu\mu\gamma$ ratio

Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above

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A. Passeri
New measurement based on the ratio $\pi\pi\gamma/\mu\mu\gamma$

The pion form factor can be obtained from the ratio of the $\pi\pi\gamma$ to $\mu\mu\gamma$ yields, without any absolute normalization to Bhabha events:

$$|F_\pi(s')|^2 \approx \frac{4(1 + 2m^2_\mu/s')\beta_\mu}{\beta^3_\pi} \frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

**kinematic factor**

$$\frac{\sigma(Born)_{\mu\mu}}{\sigma(Born)_{\pi\pi}}$$

**meas. quantities**

**Most radiative corrections drop out!**
- Radiator Function
- Integrated Luminosity
- Vacuum polarization

**Same data sample as the KLOE08 measurement with SA (undetected photon) selection**

$\pi/\mu$ efficiently separated using $M_{TRK}$:
- $M_{TRK} < 115$ MeV $\rightarrow 0.87 \times 10^6 \mu\mu\gamma$ events
- $M_{TRK} > 130$ MeV $\rightarrow 3.4 \times 10^6 \pi\pi\gamma$ events

$\rho$ region is critical ($\sigma_{\pi\pi} \gg \sigma_{\mu\mu}$)
ππγ / μμγ analysis

- Selection efficiencies (TRG, TRK, PID) evaluated on data
- 1% control of μμγ selection, even in the ρ region
- π/μ separation checked with 3 independent methods (M_{TRK}, Kin fit, σ_{MTRK})
- Excellent data/MC agreement on M_{TRK} and several other distributions

φ→π⁺π⁻π⁰ used as control sample to precisely estimate ππγ efficiency and contamination in the μμγ sample
- Backgrounds estimated from MC shapes fitted to M_{TRK} data distribution
- All efficiencies above 96%, with data/MC corrections ~ 1%
\[ \frac{d\sigma_{\mu\mu\gamma}^{\text{obs}}}{dM_{\mu\mu}^2} = \frac{\Delta N_{\text{Obs}} - \Delta N_{\text{Bkg}}}{\Delta M_{\mu\mu}} \cdot \frac{1}{\varepsilon_{\text{Sel}}} \cdot \frac{1}{\int Ldt} \]

\[ \frac{d\sigma_{\mu\mu\gamma}^{\text{DATA}}}{d\sigma_{\mu\mu\gamma}^{\text{MC}}} = 0.998 \pm 0.001_{\text{stat}} \pm 0.011_{\text{sys}} \]

The systematic error has been averaged on \( M_{\mu\mu}^2 \)

Good agreement with PHOKHARA MC (NLO Calculation)

Consistency check of Radiator function, Luminosity, etc…
Results

Cross section is directly obtained from the bin-by-bin ratio of the measured distribution (independently from radiator functions, VP and luminosity!):

\[ \Delta a_\mu^{\pi\pi} = \int_{s_{\text{min}}}^{s_{\text{max}}} \sigma_{\pi\pi(\gamma)}^0(s) \cdot K(s) \, ds \]

0.35 < \( M_{\pi\pi}^2 \) < 0.95 GeV\(^2\)

\[ 385.1 \pm 1.1^{\text{stat}} \pm 2.7^{\text{sys\&theo}} \text{ for this measurement:} \]

KLOE08: 387.2 ± 0.5\(^{\text{stat}} \) ± 3.3\(^{\text{sys\&theo}}\)

KLOE10: 377.4 ± 1.1\(^{\text{stat}} \) ± 2.7\(^{\text{sys\&theo}}\)

0.35 < \( M_{\pi\pi}^2 \) < 0.85 GeV\(^2\)

\[ 376.6 \pm 0.9^{\text{stat}} \pm 3.3^{\text{sys\&theo}} \text{ for this measurement:} \]

KLOE08: 387.2 ± 0.5\(^{\text{stat}} \) ± 3.3\(^{\text{sys\&theo}}\)

KLOE10: 376.6 ± 0.9\(^{\text{stat}} \) ± 3.3\(^{\text{sys\&theo}}\)
**Systematic errors**

- New measurement has different systematic error sources with respect to past ones
- Very little dependence on acceptance and on theory corrections!

<table>
<thead>
<tr>
<th>Contribution to systematics</th>
<th>KLOE12</th>
<th>KLOE08</th>
<th>KLOE10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background subtraction</td>
<td>0.6</td>
<td>0.3</td>
<td>0.5</td>
</tr>
<tr>
<td>$f_0 + p\pi$</td>
<td>negligible</td>
<td>negligible</td>
<td>0.4</td>
</tr>
<tr>
<td>$\Omega$ cut</td>
<td>-</td>
<td>-</td>
<td>0.2</td>
</tr>
<tr>
<td>Particle mass/PID</td>
<td>0.2</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>Tracking</td>
<td>0.1</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>Acceptance</td>
<td>negligible</td>
<td>0.2</td>
<td>0.5</td>
</tr>
<tr>
<td>L3 Trigger</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Luminosity</td>
<td>-</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Total experimental</td>
<td>0.7</td>
<td>0.6</td>
<td>1.0</td>
</tr>
<tr>
<td>FSR treatment</td>
<td>0.2</td>
<td>0.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Radiator H</td>
<td>-</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Vacuum polarization</td>
<td>-</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Total theoretical</td>
<td>0.2</td>
<td>0.6</td>
<td>0.9</td>
</tr>
<tr>
<td>Total systematics</td>
<td>0.7%</td>
<td>0.9%</td>
<td>1.1%</td>
</tr>
</tbody>
</table>
• excellent agreement with previous KLOE results
• reasonable agreement with SND CMD-2
• fair agreement with BaBar
New result confirms 3.5 $\sigma$ discrepancy with direct measurement

Our extrapolation based on DHMYZ10
Dark photon searches

After recent astrophysical observations (PAMELA, ATIC, Hess, FERMI, AMS...) many theoretical models postulate the existence of a secluded gauge sector: a DARK FORCE!

The dark sector should be mediated by a low mass gauge boson, the U boson (with $m_U < 2m_{\text{proton}}$), and should be kinetically coupled to the SM photon. The kinetic mixing parameter $\epsilon$ expected to be $\leq 10^{-3}$

At DAFNE the processes $\phi \rightarrow \eta U$ and $e^+e^- \rightarrow U\gamma$ can be studied.

U boson can show up as a peak in the $\mu\mu\gamma$ spectrum
Upper limits from $\mu\mu\gamma$ spectrum

High precision in the $\mu\mu\gamma$ spectrum and excellent agreement with PHOKARA montecarlo in the region $0.6 < \sqrt{s} < 1.0$ GeV allow to extract an upper limit in terms of number of events per bin.

This correspond to a sensitivity to $\varepsilon \sim 10^{-3}$
Analysis of $\phi \to \eta ee$ allowed KLOE to set limits in the region $50 < M_\Upsilon < 400$ MeV (PLB 720,111)

In the region $60 < M_\Upsilon < 200$ our limit rules out the hypothesis that a dark photon could originate the $a_\mu$ discrepancy

The $\mu \mu \gamma$ spectrum allows KLOE to explore higher $M_\Upsilon$ masses. Work is in progress to improve and extend this method.
Conclusions

• KLOE has performed a new measurement of $\sigma_{\text{had}}$ below 1 GeV from the $\pi\pi\gamma/\mu\mu\gamma$ spectra ratio

• Systematic uncertainties of this measurement are smaller and from different sources with respect to the past

• The result confirms the previous measurements and the $a_\mu$ discrepancy

• The $\mu\mu\gamma$ spectrum can be used also to put interesting limits on the existence of the so called “U boson”
SPARES
Radiative Corrections

Radiator-Function $H(s,s_p)$ (ISR):
- ISR-Process calculated at NLO-level
  PHOKHARA generator
  Precision: 0.5%
  \[ s \cdot \frac{d\sigma_{\pi\pi\gamma}}{ds_\pi} = \sigma_{\pi\pi}(s_\pi) \times H(s,s_\pi) \]

Radiative Corrections:

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

ii) FSR
   Cross section $s_{pp}$ must be incl. for FSR
   for use in the dispersion integral of $a_m$

FSR corrections have to be taken into account
in the efficiency eval. (Acceptance, $M_{\text{Trk}}$) and in
the mapping $s_\pi \rightarrow s_{\gamma^*}$
\[ \frac{d\sigma(e^+e^- \rightarrow \pi\pi\gamma)}{dM^2} = \frac{\sigma^0_{\pi\pi(\gamma)}(M^2)}{\sigma^0_{\mu\mu}(M^2)} \]
Cross check of $\pi\pi\gamma/\mu\mu\gamma$ separation

- The $\pi/\mu$ separation has been crosschecked with two different (and independent) methods:
- A kinematic fit (KF), in the hypothesis of 2 body+$1\gamma$ (ISR) events.
- A cut on the quality of the fitted tracks, parametrized by $\sigma_{\text{MTRK}}$.

\begin{align*}
\text{MC } \mu\mu\gamma + \pi\pi\gamma \text{ (blue) and data (black).}
\end{align*}

\begin{align*}
\sigma_{\text{MTRK}} \text{ cut (red) on MC } \mu\mu\gamma \text{ and } \pi\pi\gamma \text{ distr.}
\end{align*}

\begin{align*}
\text{MC MTRK distributions with } \sigma_{\text{MTRK}} \text{ cut (red).}
\end{align*}
Results of $\sigma_{\text{MTRK}}$ and KF cross checks

$\pi/\mu$ separation obtained with these methods well in agreement with the standard one.

The ratio of the muon yields from kinematic fit method with $\chi^2_{\mu\mu} < 10$ to the muon yields from standard method, fitted with the constant. Yellow bar the systematic error of the kinematic fit method.

Black dots are the difference of $\mu^+\mu^-\gamma$ yields obtained with std and $\sigma_{\text{MTRK}}$ methods; Red line is the total systematic error of the difference.
CMD2 2007:
$361.5 \pm 1.7_{\text{STAT}} \pm 2.9_{\text{SYST}}$

SND 2006:
$361.0 \pm 2.0_{\text{STAT}} \pm 4.7_{\text{SYST}}$

KLOE 2008:
$356.7 \pm 0.4_{\text{STAT}} \pm 3.1_{\text{SYST}}$

KLOE 2012:
$355.2 \pm 1.1_{\text{STAT}} \pm 2.6_{\text{SYST}}$

BABAR 2009:
$365.2 \pm 1.9_{\text{STAT}} \pm 1.9_{\text{SYST}}$
CMD2 2007:
$361.5\pm1.7_{\text{STAT}}\pm2.9_{\text{SYST}}$

SND 2006:
$361.0\pm2.0_{\text{STAT}}\pm4.7_{\text{SYST}}$

KLOE 2012:
$355.2\pm1.1_{\text{STAT}}\pm2.6_{\text{SYST}}$

BABAR 2009:
$365.2\pm1.9_{\text{STAT}}\pm1.9_{\text{SYST}}$