Measurement of the hadronic cross section at KLOE/KLOE-2

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(for the KLOE/KLOE-2 collaborations)
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International workshop on $e^+e^-$ collisions from $\phi$ to $\psi$
Rome, Italy
09 September 2013
Outline

• Hadronic contribution to $(g-2)_\mu$
• KLOE measurements of $\sigma(e^+e^-\rightarrow\pi^+\pi^-(\gamma))$:
  • Small (photon) angle measurements (KLOE05, KLOE08)
  • Large (photon) angle measurement (KLOE10)
  • Evaluation of $a_{\mu\pi\pi}$ and comparison with CMD-2/SND/BaBar
• New measurement of $\sigma(e^+e^-\rightarrow\pi^+\pi^-(\gamma))$ using $\pi\pi\gamma/\mu\mu\gamma$ ratio (KLOE12) PLB 720 (2013) 336–343
  • Comparison with KLOE08, KLOE10 and evaluation of $a_{\mu\pi\pi}$
  • Preliminary combination of KLOE08, KLOE10, KLOE12 results
Long established discrepancy (>3σ) between SM prediction and BNL E821 exp.

Theoretical error $\delta a_{\mu}^{\text{SM}}$ (~6x10^{-10}) dominated by HLO VP ([4–5]x10^{-10}) and HLbL ([2.5–4]x10^{-10}).

A twofold improvement on $\delta a_{\mu}^{\text{SM}}$ from 2001 (thanks to new $e^+e^-$ measurements)!

Experimental error $\delta a_{\mu}^{\text{EXP}}$ ~6x10^{-10}(E821).
Plan to reduce it to 1.6x10^{-10} by the new g-2 experiments at FNAL and J-PARC.

$\mu$ anomaly

In 2001 $a_{\mu}^{\text{EXP}} - a_{\mu}^{\text{TH}} = (23 \pm 16) \cdot 10^{-10}$, $\sim 3.4\sigma$

$\delta a_{\mu}^{\text{HLO}} \sim 0.7\%$

$\delta a_{\mu}^{\text{HLbL}} \sim 25-40\%$

$\delta a_{\mu}^{\text{HLO}} = (690.9 \pm 4.4) \times 10^{-10}$
[Eidelman, TAU08]

$\delta a_{\mu}^{\text{HLbL}} = (10.5 \pm 2.6) \times 10^{-10}$
[Prades, dR&V. 08]

$= (11 \pm 4) \times 10^{-10}$ (Jegerlehner, Nyffler)

$\frac{a_{\mu}}{2} = \frac{(g_{\mu} - 2)}{2}$

$T.\text{Teubner}, \text{PHIPS}108$
L.O. Hadronic contribution to $a_\mu$ can be estimated by means of a dispersion integral:

$$a_\mu^{\text{had}} = \left( \frac{\alpha m_\mu}{3 \pi} \right)^2 \int \frac{ds}{s^2} \frac{R(s) \hat{K}(s)}{4m_\pi^2}$$

$R(s) = \frac{\sigma_{\text{tot}}(e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q} \rightarrow \text{hadrons})}{\sigma_{\text{tot}}(e^+e^- \rightarrow \gamma^* \rightarrow \mu^+\mu^-)}$

- $K(s) = \text{analytic kernel-function}$
- above a sufficiently high energy value, typically $2\ldots5$ GeV, we can use $pQCD$

**Input:**

a) *hadronic electron-positron cross section data* (G.dR 69, E.J.95, A.D.H.’97,....)

b) *hadronic $\tau$- decays*, which can be used with the help of the CVC-theorem and an isospin rotation (plus isospin breaking corrections)

(Alemany, Davier, Hoecker ‘97)
ISR: Initial State Radiation

Neglecting final state radiation (FSR):

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

measured cross section  \hspace{1cm} resulting cross section  \hspace{1cm} radiator function

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

\(\rightarrow\) EVA + PHOKHARA MC Generator

Binner, Kühn, Melnikov; Phys. Lett. B 459, 1999


(exact next-to-leading order QED calculation of the radiator function)

IN 2005 KLOE has published the first precision measurement of \(\sigma(e^+e^- \rightarrow \pi^+\pi^-)\) with ISR using 2001 data (140pb\(^{-1}\)) PLB606(2005)12 \(\Rightarrow\) \(-3\sigma\) discrepancy btw \(a^\text{SM}_\mu\) and \(a^\text{exp}_\mu\)
DAΦNE: A $\phi$-Factory in Frascati (near Rome)
e$^+$e$^-$ collider with $\sqrt{s} = m_\phi \approx 1.0195$ GeV

Integrated Luminosity

Total KLOE int. Luminosity: $\int L \, dt \sim 2500$ pb$^{-1}$ (2001 - 05)

Peak Luminosity $L_{\text{peak}} = 1.5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$

KLOE05 measurement (PLB606(2005)12) based on 140pb$^{-1}$ of 2001 data

KLOE10 measurement (PLB700 (2011)102) based on 233 pb$^{-1}$ of 2006 data (at 1 GeV, different event selection)

KLOE08 measurement (PLB670(2009)285) was based on 240pb$^{-1}$ of 2002 data

KLOE12 measurement (PLB720(2013)336) based on 240 pb$^{-1}$ of 2002 data (from $\pi\pi\gamma/\mu\mu\gamma$ ratio)
Drift chamber

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

**Excellent momentum resolution**

Full stereo geometry, 4m diameter, 52140 wires 90% Helium, 10% iC_4H_{10}
Electromagnetic Calorimeter

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

\[ \sigma_T = 54 \text{ ps} / \sqrt{E(\text{GeV})} \oplus 100 \text{ ps} \]

(Bunch length contribution subtracted from constant term)

Excellent timing resolution

Pb / scintillating fibers (4880 PMTs)
Endcap - Barrel - Modules
Event Selection: Small Angle (SA)

Pion tracks at large angles
\[ 50^\circ < \theta_\pi < 130^\circ \]

a) Photons at small angles
\[ \theta_\gamma < 15^\circ \text{ or } \theta_\gamma > 165^\circ \]

→ Photon momentum from kinematics:
\[ \vec{p}_\gamma = \vec{p}_{\text{miss}} = - (\vec{p}_+ + \vec{p}_-) \]

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination
Event Selection: Large Angle (LA)

Pion tracks at large angles

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

a) Photons at small angles

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

\[ \rightarrow \text{Photon momentum from kinematics:} \]

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

- High statistics for ISR photons
- Very small contribution from FSR
- Reduced background contamination

b) Photons at large angles

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

\[ \rightarrow \text{Photon is explicitly measured in the detector!} \]

- Threshold region accessible
- Lower signal statistics
- Increased contribution from FSR and \[ \phi \rightarrow \pi^+ \pi^- \pi^0 \] (use off-peak data)
Luminosity:

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°
$p \geq 400$ MeV

Generator used for $\sigma_{\text{eff}}$: BABAYAGA (Pavia):

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>
</tr>
</thead>
<tbody>
<tr>
<td>Theory</td>
</tr>
<tr>
<td>Experiment</td>
</tr>
<tr>
<td>TOTAL</td>
</tr>
</tbody>
</table>

\[0.1 \% \text{ th} \oplus 0.3 \% \text{ exp} = 0.3\%\]
Luminosity:

KLOE measures $L$ with Bhabha scattering

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

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

acollinearity $< 9^\circ$

$p \geq 400$ MeV
**KLOE08: Small Angle ($\sqrt{s}= 1020$ 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>

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

<table>
<thead>
<tr>
<th>Source</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSR treatment</td>
<td>0.3%</td>
</tr>
<tr>
<td>Radiator H</td>
<td>0.5%</td>
</tr>
<tr>
<td>Vacuum polarization</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

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

$$a_\mu^{\pi\pi} = \int_{s_1}^{s_2} \sigma_{ee\to\pi\pi}(s)K(s)ds$$

$$a_\mu^{\pi\pi}(0.35-0.95\text{GeV}^2) = (387.2 \pm 0.5_{\text{stat}} \pm 2.4_{\text{syst}} \pm 2.3_{\text{theo}}) \cdot 10^{-10}$$
KLOE10: Large Angle (√s= 1000 MeV)

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

<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>$f_0 + \rho \pi$</td>
<td>0.4%</td>
</tr>
<tr>
<td>$\Omega$ cut</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$<em>{\text{th}}$ ⊕ 0.3$</em>{\text{exp}}$)%</td>
<td>0.3%</td>
</tr>
<tr>
<td>FSR treatment</td>
<td>0.8%</td>
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<tr>
<td>Radiator H</td>
<td>0.5%</td>
</tr>
<tr>
<td>Vacuum polarization</td>
<td>0.1%</td>
</tr>
</tbody>
</table>

Experimental fractional error on $a_{\mu} = 1.0\%$

Theoretical fractional error on $a_{\mu} = 0.9\%$

\[
a_{\mu \pi \pi}(0.1\text{-}0.85 \text{ GeV}^2) = (478.5 \pm 2.0^{\text{stat}} \pm 5.0^{\text{syst}} \pm 4.5^{\text{theo}}) \cdot 10^{-10}
\]
Comparison of results: KLOE10 vs KLOE08

KLOE08 result compared to KLOE10:

Fractional difference:

Good agreement with KLOE08, especially above 0.5 GeV^2

Combination of KLOE08 and KLOE10:
\[ a_\mu^{\pi\pi}(0.1-0.95 \text{ GeV}^2) = (488.6 \pm 6.0) \cdot 10^{-10} \]

KLOE covers ~70% of total \( a_\mu^{\text{HLO}} \) with a fractional total error of 1.2%
Comparison of results: 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.

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference

Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above 0.6 GeV.
KLOE12: New $\sigma_{\pi\pi}$ measurement from $\pi\pi\gamma/\mu\mu\gamma$

An alternative way to obtain $|F_\pi|^2$ is the bin-by-bin ratio of pion over muon yields (instead of using absolute normalization with Bhabhas).

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

Many systematic effects drop out:

- radiator function
- int. luminosity from Bhabhas
- Vacuum polarization

Data Sample:

- 239.2 pb$^{-1}$ of 2002 data (the same used in KLOE08 analysis)
- photon at small angle
- 0.87 Million $\mu\mu\gamma$ events
- 3.4 Million $\pi\pi\gamma$ events
Important to get a good $\pi/\mu$ separation, especially in the $\rho$ region where $\sigma_{\pi\pi}/\sigma_{\mu\mu} \sim 10$

- Obtained $\sim 1\%$ uncertainty in the muon selection
- $\pi/\mu$ separation cross-checked with three different methods ($M_{\text{Track}}$ fit, Kinematic fit, cut on $\sigma_{M\text{Track}}$)

$\mu\mu\gamma$ (and $\pi\pi\gamma$) efficiencies (Tracking, Triggering, PID) done on measurement data

Excellent measurement/simulation agreement for many kinematic variables: $M_{\text{Track}}$, tracks, and $\gamma$ polar angle, etc...

\[
(\sqrt{s} - \sqrt{|p_+|^2 + M_{\text{Track}}^2} - \sqrt{|p_-|^2 + M_{\text{Track}}^2})^2 - (p_+ + p_-)^2 = M_\gamma^2 = 0
\]

Separation btw $\pi\pi\gamma$ and $\mu\mu\gamma$ using $M_{\text{Track}}$

- **muons**: $M_{\text{Track}} < 115$ MeV
- **pions**: $M_{\text{Track}} > 130$ MeV
\( \mu\mu\gamma \) cross section: meas/simu comparison

\[
\frac{d\sigma^{obs}_{\mu\mu(\gamma)}}{dM_{\mu\mu}^2} = \frac{\Delta N_{\text{Obs}} - \Delta N_{\text{Bkg}}}{\Delta M_{\mu\mu}^2} \cdot \frac{1}{\epsilon_{\text{Sel}}} \cdot \frac{1}{\int L dt}
\]

\[
\frac{d\sigma^{DATA}_{\mu\mu(\gamma)}}{d\sigma^{MC}_{\mu\mu(\gamma)}} = 0.998 \pm 0.001_{\text{stat}} \pm 0.011_{\text{syst}}
\]

- 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…
### KLOE12 result: $|F_\pi|^2$ and comp. with KLOE08

#### Good agreement btwn the two measurements, especially in the $\rho$ region.
#### Improved syst. error in KLOE12.
#### Theoretical error strongly reduced
#### These two measurements are not independent ($\pi\pi\gamma$ sample is the same)

<table>
<thead>
<tr>
<th>Source</th>
<th>Syst. errors (%)</th>
<th>$\Delta \pi\pi a_\mu$ abs</th>
<th>$\Delta \pi\pi a_\mu$ ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recons. Filter</td>
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<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Background subtraction</td>
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<td>0.6</td>
<td></td>
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<tr>
<td>Trackmass</td>
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<td></td>
</tr>
<tr>
<td>Particle ID</td>
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<td></td>
</tr>
<tr>
<td>Tracking</td>
<td>0.3</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Trigger</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Unfolding</td>
<td>negligible</td>
<td>negligible</td>
<td></td>
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<tr>
<td>Acceptance ($\theta_{\pi\pi}$)</td>
<td>0.2</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Acceptance ($\theta_\pi$)</td>
<td>negligible</td>
<td>negligible</td>
<td></td>
</tr>
<tr>
<td>Software Trigger (L3)</td>
<td>0.1</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.3 ($0.1_{th} \oplus 0.3_{exp}$)</td>
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<td></td>
</tr>
<tr>
<td>$\sqrt{s}$ dep. of $H$</td>
<td>0.2</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total exp systematics</td>
<td>0.6</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>Vacuum Polarization</td>
<td>0.1</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>FSR treatment</td>
<td>0.3</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Rad. function $H$</td>
<td>0.5</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>Total theory systematics</td>
<td>0.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Total systematic error</td>
<td>0.9</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$a_{\mu\pi\pi} (0.35 - 0.95 \text{ GeV}^2) \times 10^{10}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLOE12</td>
<td>385.1 $\pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}$</td>
</tr>
<tr>
<td>KLOE08</td>
<td>387.2 $\pm 0.5_{\text{stat}} \pm 3.3_{\text{sys+theo}}$</td>
</tr>
</tbody>
</table>
Comparison of results: KLOE12 vs KLOE10

KLOE12 result compared to KLOE10:

Excellent agreement between these two independent measurements!
Preliminary combination of KLOE08,10,12

Combination of KLOE08, KLOE10, and KLOE12 using the Best Linear Unbiased Estimate (BLUE) based on:
A. Valassi, NIM A500 (2003) 391
G. D'Agostini, NIM A346 (1994) 306

\[
\begin{align*}
\alpha_{\pi\pi}(0.1-0.95 \text{ GeV}^2) &= (487.8 \pm 5.7) \cdot 10^{-10} \\
\alpha_{\pi\pi}(0.1-0.85 \text{ GeV}^2) &= (378.1 \pm 2.8) \cdot 10^{-10}
\end{align*}
\]

Grey band: Stat. errors
Blue band: Stat. + Syst. errors
\[ a_\mu = (g_\mu - 2)/2: \]

Theoretical predictions compared to the BNL result

- Discrepancy between \( a_{\mu}^{SM} \) and \( a_{\mu}^{EXP} \) at the 3.5\( \sigma \) level is confirmed by the KLOE measurement of the ratio of cross sections \( \pi\pi\gamma/\mu\mu\gamma \)

- KLOE12 is in agreement with previous KLOE measurements and confirms this discrepancy.

- Previous tension between \( e^+e^- \) and \( \tau \) data is reduced by 1\( \sigma \) [F. Jegerlehner et al., Eur.Phys.J. C71 (2011) 1632, \( \rho-\gamma \) treatment]

Results from new g-2 experiments (at FNAL and JPARC) will be very interesting!

* Our extrapolation based on DHMYZ10
Conclusion

- During the last 10 years KLOE has performed a series of precision measurements with ISR which confirmed a $3\sigma$ discrepancy between $a_{\mu}^{SM}$ and the value measured at BNL.

- The published measurements (KLOE05, KLOE08, KLOE10), normalized to Bhabha events, have allowed us to measure $a_{\mu}$ in the region below 1 GeV with $\sim 1\%$ total error.

- A new measurement (KLOE12) of $|F_{\pi}|^2$ from the $\pi\pi\gamma/\mu\mu\gamma$ ratio (based on 240 pb$^{-1}$) with 0.7% systematic error has been published ([PLB720 (2013) 336–343]).

- It doesn’t rely on specific theoretical input (like luminosity and radiator function) and allows a stringent cross check of the published measurements with comparable systematic error.

- Good agreement for $\mu\mu\gamma$ cross section with NLO QED calculation (PHOKHARA MC) and for $|F_{\pi}|^2$ with previous KLOE measurements (confirming $3\sigma$ discrepancy on $a_{\mu}$).
Outlook

- Still more than 1.5 fb$^{-1}$ of KLOE data on tape. This would represent a factor ~4 improvement in statistics.

- A new round of data taking with KLOE-2 upgraded detector is expected to begin Fall 2013.
SPARE SLIDES
A careful work has been done to achieve a control of ~1% in the muon selection, especially ~0.6 GeV2 (ρ peak) where π/μ ~10.

- ππγ % background to μμγ signal (MTRK<115 MeV) is ~15% at ρ peak

ππγ MTRK tail in the μμγ region must be well under control.

- ππγ MTRK tail tuned using φ→π+π−π0 control sample.

- Excellent agreement on MTRK (ππγ and μμγ) distributions.
A careful work has been done to achieve a control of ~1% in the muon selection, especially ~0.6 GeV² (ρ peak) where $\pi/\mu \sim 10$.

$\pi\pi\gamma$ % background to $\mu\mu\gamma$ signal (MTRK<115 MeV) is ~15% at ρ peak. $\pi\pi\gamma$ MTRK tail in the $\mu\mu\gamma$ region must be well under control.

$\pi\pi\gamma$ MTRK tail tuned using $\phi \rightarrow \pi^+\pi^-\pi^0$ control sample.

Excellent agreement on MTRK ($\pi\pi\gamma$ and $\mu\mu\gamma$) distributions

DATA/MC = 1.000 ± 0.007
Background:

Main backgrounds estimated from MC shapes fitted to data distribution in MTrk ($\pi\pi\gamma/\mu\mu\gamma$, $\pi\pi\pi$, $ee\gamma$)

0.60 < $M_{\pi\pi2}$ < 0.62 GeV$^2$, $\chi^2$/ndof = 158/180

0.84 < $M_{\pi\pi2}$ < 0.86 GeV$^2$, $\chi^2$/ndof = 179/258

- Systematic error on $\mu\mu\gamma$ due to background 1% in the $\rho$ peak
Cross check of $\pi/\mu$ separation

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

A. Palladino – International workshop on e+e- collisions from phi to psi - 9 September 2013
Results of $\sigma$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 is the systematic error of the kinematic fit method.

- Black dots are the differences of $\mu\mu\gamma$ yields obtained with std and $\sigma$MTRK methods; Red line is the total systematic error of the difference.
The efficiencies of $\mu\mu\gamma$ (and $\pi\pi\gamma$) for trigger, tracking, and PID have been carefully studied with data, using the single particle method and taking into account the kinematics by MC. Differently from $\pi\pi\gamma$, where the 3$\pi$ sample was used to get the data/MC corrections, for $\mu\mu\gamma$ there is no a direct control sample and we had used mmg itself with lose selection criteria.

All the efficiencies has been found to be above 96% with ~1% data/MC correction as maximum.
Extracting $\sigma_{\pi\pi}$ and $|F_{\pi}|^2$ from

a) Via absolute Normalisation to Bhabha events (KLOE05,08,10):

1) \[ \frac{d\sigma^{obs}_{\pi\pi(\gamma)}}{dM^2_{\pi\pi}} = \frac{\Delta N_{\text{Obs}} - \Delta N_{\text{Bkg}}}{\Delta M^2_{\pi\pi}} \cdot \frac{1}{\varepsilon_{\text{Sel}}} \cdot \frac{1}{\int L dt} \]

\[ d\sigma_{\pi\pi}\gamma(\gamma)/dM^2 \] is obtained by subtracting background from observed event spectrum, divide by selection efficiencies, and \textit{int. luminosity}:

2) \[ \sigma_{\pi\pi}(s) \approx s \frac{d\sigma^{obs}_{\pi\pi(\gamma)}}{dM^2_{\pi\pi}} \times \frac{1}{H(s)} \]

Obtain $\sigma_{\pi\pi}$ from (ISR) - radiative cross section
\[ ds_{\pi\pi}\gamma(\gamma)/dM^2 \] via theoretical radiator function $H(s)$:

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

Relation between $|F_{\pi}|^2$ and the cross section $\sigma(e^+e^- \rightarrow \pi^0 + \pi^-)$

b) Via bin-by-bin Normalization to rad. Muon events (New measurement!)
Radiative Corrections

Radiator-Function $H(s,sp)$ (ISR):
- ISR-Process calculated at NLO-level
  **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 Polarization $d(s)=(a(s)/a(0))^2$
   from F. Jegerlehner

ii) **FSR**
   Cross section $spp$ must be incl. for FSR
   for use in the dispersion integral of amplitude

$$s \times \frac{d\sigma_{\pi\pi\gamma}}{ds\pi} = \sigma_{\pi\pi}(s_{\pi}) \times H(s,s\pi)$$

FSR corrections have to be taken into account in the efficiency eval. (Acceptance, MTrk) and in the mapping $s\pi \rightarrow s\gamma^*$

LA Event Selection (KLOE10)

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

Photons at large angles
50° < θγ < 130°

- independent complementary analysis
- threshold region (2mπ)² accessible
- γISR photon detected
  (4-momentum constraints)
- 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)

At least 1 photon with 50° < θγ < 130°
and Eg > ≈ 0 MeV ≈ photon detected

Threshold region non-trivial
due to irreducible FSR-effects, which
have to be estimated from MC using
phenomenological models
(interference effects unknown)
2 pion tracks at large angles
$50^\circ < \theta_p < 130^\circ$

Photons at large angles
$50^\circ < \theta_\gamma < 130^\circ$

- independent complementary analysis
- threshold region $(2m_\pi)^2$ accessible
- $\gamma$ISR photon detected (4-momentum constraints)
- lower signal statistics
- larger contribution from FSR events
- larger $\phi \rightarrow \pi^+\pi^-\pi^0$ background contamination
- irreducible background from $\phi$ decays ($\phi \rightarrow f_0 \gamma \rightarrow \pi\pi\gamma$)

At least 1 photon with $50^\circ < \theta_\gamma < 130^\circ$ and $E_\gamma > 0$ MeV detected

Use data sample taken at $\sqrt{s} \approx 1000$ MeV, 20 MeV below the f-peak

statistics: 233pb-1 of 2006 data
600 kEvents
Event selection

- Experimental challenge: Fight background from
  - $e^+e^- \rightarrow \mu^+\mu^- \gamma$
  - $e^+e^- \rightarrow e^+e^- \gamma$
  - $\phi \rightarrow \pi^+\pi^-\pi^0$

  separated by means of kinematical cuts in trackmass $M_{Trk}$ and the angle $\Omega$ between the photon and the missing momentum

$$p_{\text{miss}} = -(p_+ + p_-)$$

To further clean the samples from radiative Bhabha events, a particle ID estimator for each charged track based on Calorimeter Information and Time-of-Flight is used.
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 $M_{Trk}$ - $M_{\pi\pi}$ plane

$M_{Trk}$: defined by 4-momentum conservation assuming 2 charged particle (of same mass) and one $\gamma$ in the final state

$$\left( \sqrt{s} - \sqrt{p_1^2 + M_{Trk}^2} - \sqrt{p_2^2 + M_{Trk}^2} \right)^2 - (p_1 + p_2)^2 = 0$$

To further clean the samples from radiative Bhabha events, we use a particle ID estimator (PID) for each charged track based on Calorimeter Information and Time-of-Flight.
μ Tracking efficiency

Since for muons we don’t have an control sample (like 3π for pions), we have refiltered MMISS all 2002 data set (240 pb-1) according to:

1) a “good” tagging track extrapolating back to the IP, which satisfies the trigger associated to a cluster with LogrL>0, 1 and MLP>0.7
2) 1 neutral prompt clusters not associated to the tagging track with E>50 MeV. A constraint on the photon energy and time to further clean the sample, and improve missing momentum and energy
3) The tagging track must have p > 450 MeV (to reject π+π−π0 events), the candidate track must have mass (built from 4 momentum conservation) 50 <Mmiss < 130 MeV
Example of data/MC comparison for $\mu\mu\gamma$ and $\pi\pi\gamma$: momentum components of $\mu$ and $\pi$
ISR: KLOE vs BaBar 2π

KLOE:
• The photon is “soft” (detected or not)
• No Kinematic fit
• Bin of 0.01 GeV² (~8 MeV at ρ peak)
  \[ \delta M_{\pi\pi}^2 \approx 10^{-3} \text{ GeV}^2 \]
  \( \Rightarrow \) Unfolding only relevant at low \( M_{\pi\pi} \) (up to 4%) and at \( \rho-\omega \) cusp,
• Negligible contribution of LO FSR, and <2% contribution of NLO FSR(1γISR+1γFSR) only at low \( M_{\pi\pi} \)
• Normalize to \textbf{Luminosity} (=Bhabha), but also to \( \mu\mu\gamma \) (K12)
• Use \textbf{Phokhara} for acceptance, radiator and additional-photon effects

BaBar:
• The photon is “hard” and detected
• Kinematic fit to improve resolution
• Bin of 2 MeV in the region 0.5-1 GeV
  \( \Rightarrow \) Larger effects on the unfolding
• Negligible contribution of LO FSR, % contribution of NLO FSR(1γISR+1γFSR)
• Normalize to \( \mu\mu\gamma \)
• Interplay btw \textbf{Phokhara} and \textbf{AfkQED} to estimate additional-photon effects

Different selections and use of theoretical ingredients (R.C., Luminosity, Radiator).
Additional cross checks are possible (and needed)

A. Palladino – International workshop on e+e- collisions from phi to psi - 9 September 2013