



# Precision Measurement of the Two-Pion Contribution to the Hadronic Vacuum Polarization with KLOE

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# The anomalous magnetic moment of the muon

- Charged particles with spin possess a magnetic moment:

$$\vec{\mu} = g \frac{e}{2m} \vec{S}$$

- For a spin- $\frac{1}{2}$  particle, the Dirac theory predicts  $g = 2$
- Quantum loop corrections modify this value:

$$a_{\mu} = \frac{g - 2}{2} \neq 0$$

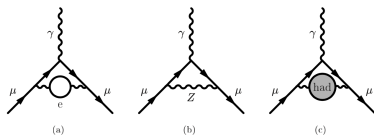
- Precision measurements of  $a_{\mu}$  provide a stringent test of the Standard Model and sensitivity to new physics
- The muon is of particular interest due to the increased sensitivity to new physics because of the larger mass compared to the electron

# Standard Model prediction of $a_\mu$

The Standard Model prediction can be decomposed into distinct contributions:

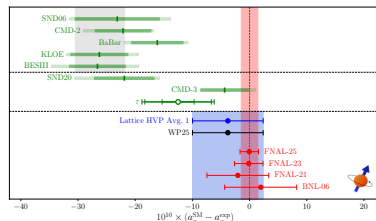
$$a_\mu^{\text{SM}} = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{had}}$$

- **QED:** Dominant contribution, calculated to very high precision
- **Electroweak:** Smaller contribution from  $W$ ,  $Z$ , and Higgs bosons
- **Hadronic:** Contributions from strong interactions
  - Cannot be calculated perturbatively
  - Dominates the theoretical uncertainty



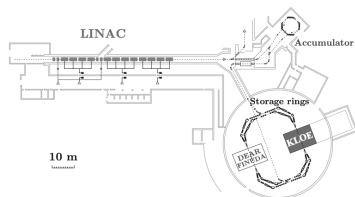
# The current situation

- Precision measurements such as from  $g - 2$  at Fermilab show a persistent discrepancy with the Standard Model prediction
- The main source of uncertainty lies in the hadronic contribution:
  - **Dispersive approach:** Uses  $e^+e^- \rightarrow$  hadrons data
  - **Lattice QCD:** First-principles numerical calculation
- Recent lattice results reduce the tension, but are in tension with dispersive results
- Future inputs such as from MUonE will help to further clarify the picture

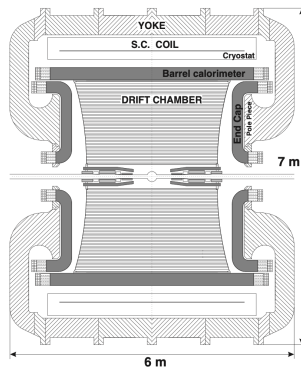


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# DAΦNE and KLOE



The DAΦNE (*Double Annular Φ-factory for Nice Experiments*) is an  $e^+e^-$  collider located in Frascati near Rome, Italy, running at the  $\phi$  peak at  $\sqrt{s} = 1020 \text{ MeV}$



KLOE (K Long Experiment) detector consisting of an inner drift chamber surrounded by an electromagnetic calorimeter

# Measuring $a_\mu^{\text{HLO}}$ at KLOE

- The leading-order hadronic contribution,  $a_\mu^{\text{HLO}}$ , cannot be computed perturbatively and must be determined from data
- It is obtained via a dispersion relation connecting  $a_\mu^{\text{HLO}}$  to the hadronic cross section:

$$a_\mu^{\text{HLO}} = \frac{\alpha^2}{3\pi^2} \int_{m_\pi^2}^{\infty} ds \frac{K(s)}{s} \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

- $a_\mu^{\text{HLO}} \propto \frac{1}{s}$  means low-energy contributions are weighted more strongly
- KLOE measures the dominant contribution,  $a_\mu^{\pi\pi}$ , by:

$$e^+e^- \rightarrow \pi^+\pi^-\gamma$$

- Using initial-state radiation (ISR), the effective centre-of-mass energy is reduced, enabling a scan over a range of energy

# Previous KLOE analyses

KLOE has published three  $a_\mu^{HLO}$  results in the past: KLOE08, KLOE10 and KLOE12.

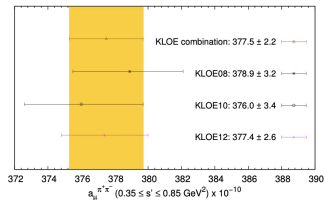
- KLOE08 and KLOE10 measured  $\sigma(\pi\pi(\gamma))$  by normalizing to the integrated luminosity (**absolute approach**):

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

- KLOE12 measured  $\sigma(\pi\pi(\gamma))$  by normalizing the  $\pi\pi\gamma$  sample to the  $\mu\mu\gamma$  sample (**ratio approach**):

$$\sigma_{\pi\pi(\gamma)} = \sigma_{\mu\mu(\gamma)} \frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}$$

With this approach, the luminosity and several systematics cancel, however, an additional analysis of muon events is required



Combination of results gives a value of

$$a_\mu^{\pi\pi}(0.10 < s' < 0.95 \text{ GeV}^2) = (489.8 \pm 5.1) \times 10^{-10}.$$

# The current KLOE analysis: KLOE-NXT

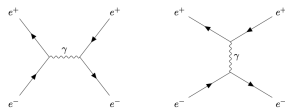
- The ongoing KLOE-NXT analysis uses  $1.7 \text{ pb}^{-1}$  of data collected in 2004–2005, corresponding to  $\sim 25$  million previously unanalysed  $\pi\pi\gamma$  events
- Follows a procedure similar to KLOE12 to minimise systematic uncertainties
- First blinded KLOE analysis, reducing potential bias via random event removal that shifts the extracted  $a_\mu$
- Key improvements: significantly higher statistics, improved Monte Carlo generators, improved Data/Monte Carlo tuning, potential ML methods for background subtraction
- Target total uncertainty of 0.4%:

$$0.1\% \text{ (stat)} \oplus 0.2\% \text{ (th)} \oplus 0.3\% \text{ (sys)}$$

- The ratio method requires a highly precise analysis of  $\mu\mu\gamma$  events, demanding accurate knowledge of the integrated luminosity and associated systematic uncertainties
- Luminosity is measured with the KLOE detector using very large angle Bhabha (VLAB) events,  $e^+e^- \rightarrow e^+e^-$

$$\int \mathcal{L} dt = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\sigma_{\text{eff}}}, \text{ where } \sigma_{\text{eff}} \text{ is taken from Monte Carlo simulation}$$

- Advantages of Bhabha events:
  - 1 Very high statistics ( $\sigma \sim 430 \text{ nb}$ ) for  $55^\circ < \theta_{\text{clu}} < 125^\circ$
  - 2 Excellent theoretical precision of the process
  - 3 Clean and well-defined event topology



# Luminosity study: Systematics and goals

- Previous luminosity measurement (from 2006, based on 2001 data) established the baseline methodology
- Dominant systematics arise from Data/Monte Carlo differences, which must be carefully evaluated and corrected
- This analysis will:
  - Analyse 2002, 2004, and 2005 datasets individually
  - Use the updated BABAYAGA@NLO generator (C.M. Carloni Calame et al., Nucl. Phys. Proc. Suppl. 131 (2004) 48)
  - Perform an independent cross-check using  $e^+e^- \rightarrow \gamma\gamma$  events

	correction (%)	systematic error (%)
acceptance	$\delta_{\text{accept}} = +0.25$	$\Delta_{\text{accept}} = 0.25$
tracking	-	$\Delta_{\text{track}} = 0.06$
clustering	$\delta_{\text{split}} = +0.14$	$\Delta_{\text{cluster}} = 0.11$
background	$\delta_{\text{bkg}} = -0.55$	$\Delta_{\text{bkg}} = 0.08$
cosmic veto	$\delta_{\text{cosmic}} = +0.40$	-
dependence on $\sqrt{s}$	$\delta_{\sqrt{s}} = +0.10$	$\Delta_{\sqrt{s}} = 0.10$
$E_{\text{clu}}$ drifts	-	$\Delta_{E_{\text{clu}}} = 0.10$
Total experimental	$\delta_{\text{tot}} = +0.34$	$\Delta_{\text{tot}} = 0.32$

Systematics from 2006 luminosity study

Eur.Phys.J.C 47 (2006) 589–596

- **Pre-selection:** at least two energy clusters with  $800 \text{ MeV} > E_{\text{clu}} > 240 \text{ MeV}$ , within 4 ns, and separated by  $d > 200 \text{ cm}$
- **LAB selection (calorimeter only):** two clusters with  $800 \text{ MeV} > E_{\text{clu}} > 300 \text{ MeV}$  in the barrel region. The pair minimising the acollinearity

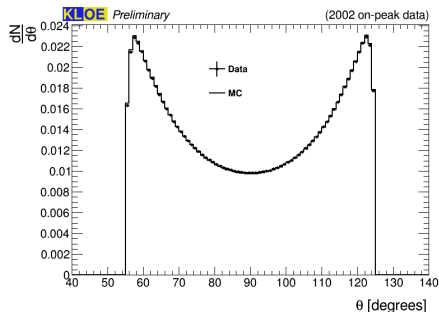
$$\zeta = |\theta_{\text{clu}_1} + \theta_{\text{clu}_2} - 180^\circ|$$

is selected, with  $\zeta < 10^\circ$

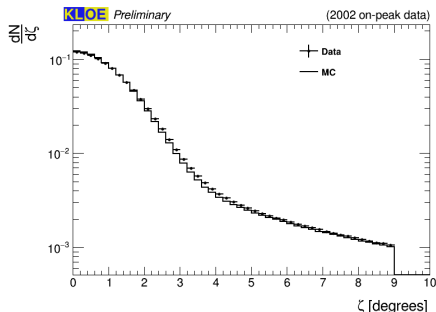
- **Final VLAB selection:** inclusion of drift chamber information to improve selection and suppress background. Two oppositely charged tracks are required with  $|p| > 400 \text{ MeV}$ , satisfying track quality cuts, as well as tighter angular requirements on the clusters

# Preliminary luminosity results

Initial work studying 2002 dataset evaluating Data/Monte Carlo differences. Resolution differences were found in cluster variables and smearing applied to Monte Carlo in order to match resolution of data, by fitting the difference of the reconstructed cluster positions, to the extrapolated cluster positions from the tracks to the calorimeter

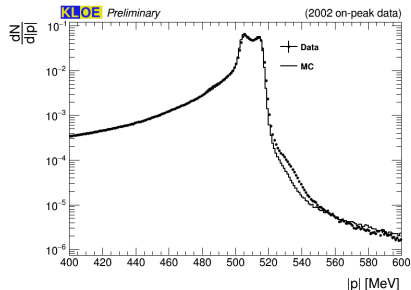


Polar angle of VLAB clusters after Monte Carlo smearing

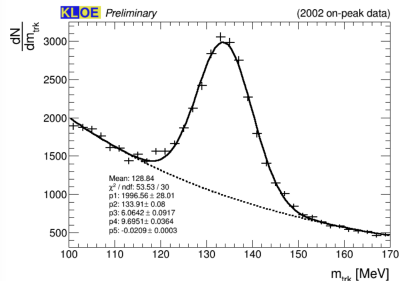


Acollinearity of VLAB clusters after Monte Carlo smearing

# Preliminary luminosity results



Track momentum of selected VLAB events



Background subtraction based on Gaussian fit of trackmass ( $m_{trk}$ ) distribution of data with background due to collinear  $\pi^+\pi^-$  events.

$m_{trk}$  is evaluated from

$$(\sqrt{s} - \sqrt{|\mathbf{p}_+|^2 + M_{trk}^2} - \sqrt{|\mathbf{p}_-|^2 + M_{trk}^2})^2 - (\mathbf{p}_+ + \mathbf{p}_-)^2 = 0$$

- The current tension in  $a_\mu$ , particularly between dispersive and lattice approaches, remains an open question
- Reducing uncertainties in the hadronic contribution is essential to clarify this picture
- The ongoing KLOE analysis provides precise input to the dispersive approach
- The new luminosity study is a key component of the KLOE-NXT analysis, aiming to improve the overall precision, with work currently in progress to evaluate all of the relevant associated systematic uncertainties

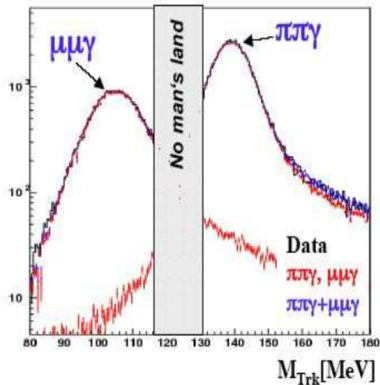
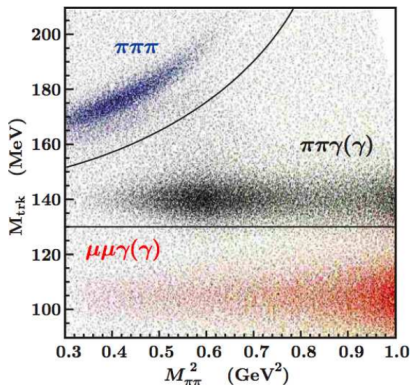


Thank you!



# Backup

# Pion/Muon separation



$$\left( \sqrt{s} - \sqrt{|\mathbf{p}_+|^2 + M_{\text{trk}}^2} - \sqrt{|\mathbf{p}_-|^2 + M_{\text{trk}}^2} \right)^2 - (\mathbf{p}_+ + \mathbf{p}_-)^2 = 0$$

# Resolution smearing

