

# Prospects for $\gamma\gamma \rightarrow \pi^0$ with KLOE-2

(D. Babusci et al., arXiv:1109.2461)

Sergiy IVASHYN

Akhiezer Institute for Theoretical Physics  
NSC "KIPT", Kharkiv

September 23, 2011



# Credits

This is a brief summary of a joint venture

Poland H.Czyż

India A.Nyffeler

Italy D.Babusci, M.Mascolo, D.Moricciani, G.Venanzoni  
F.Gonnella, R.Messi

Ukraine S.Ivashyn

*D. Babusci et al., arXiv:1109.2461*

# Definitions

One defines the  $\pi^0 \gamma^* \gamma^*$  form factor  $\mathcal{F}_{\pi^0 \gamma^* \gamma^*}(q_1^2, q_2^2)$  via the QCD Green's function  $\langle VVA \rangle$  with the on-shell pion

$$\begin{aligned} i \int d^4x e^{iq_1 \cdot x} \langle 0 | T\{j_\mu(x) j_\nu(0)\} | \pi^0(q_1 + q_2) \rangle \\ = \varepsilon_{\mu\nu\rho\sigma} q_1^\rho q_2^\sigma \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(q_1^2, q_2^2) \end{aligned}$$

$j_\mu$  is the electromagnetic current of the light quarks ( $u, d, s$ ),

$\varepsilon_{\mu\nu\rho\sigma}$  is the Levi-Civita symbol

$q_1$  and  $q_2$  are the 4-momenta of the off-shell photons

For real photons it is related to the  $\pi^0 \rightarrow \gamma\gamma$  decay width:

$$\mathcal{F}_{\pi^0 \gamma^* \gamma^*}^2(q_1^2 = 0, q_2^2 = 0) = \frac{4}{\pi \alpha^2 m_\pi^3} \Gamma_{\pi^0 \rightarrow \gamma\gamma}$$

One defines the pion-photon transition form factor  $F(Q^2)$  with one on-shell and one off-shell photon

$$F(Q^2) \equiv \mathcal{F}_{\pi^0 \gamma^* \gamma^*}(-Q^2, q_2^2 = 0), \quad Q^2 \equiv -q^2$$

# Objectives

- ➊ demonstrate that a per cent level of precision can be achieved in the measurement of  $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$  by the KLOE-2 experiment at Frascati
- ➋ show that the KLOE-2 experiment can perform the first measurement of  $F(Q^2)$  in the space-like region in the vicinity of the origin:  $0.01 < Q^2 < 0.1 \text{ GeV}^2$
- ➌ estimate the impact of the proposed measurements on the evaluation of the Standard Model prediction for the anomalous magnetic moment of the muon,  $a_\mu$

# Experimental concept

- Detect both scattered leptons in  $e^+ e^- \rightarrow e^+ e^- \pi^0$
- Two Low Energy Taggers (**LET**) and two High Energy Taggers (**HET**) were specially designed for this experiment
  - ✓ detection of electrons and positrons scattered at very small polar angles ( $\theta < \theta_{max} \approx 1^\circ$ )
  - ✓ At the moment, only **HET** is considered  
(energy of the final leptons between 420 and 460 MeV)
- The first phase of data taking (step-0) is expected to have the integrated luminosity of  $5 \text{ fb}^{-1}$

[ Amelino-Camelia et al., Eur.Phys.J. C68,619 (2010) ]

# Simulation

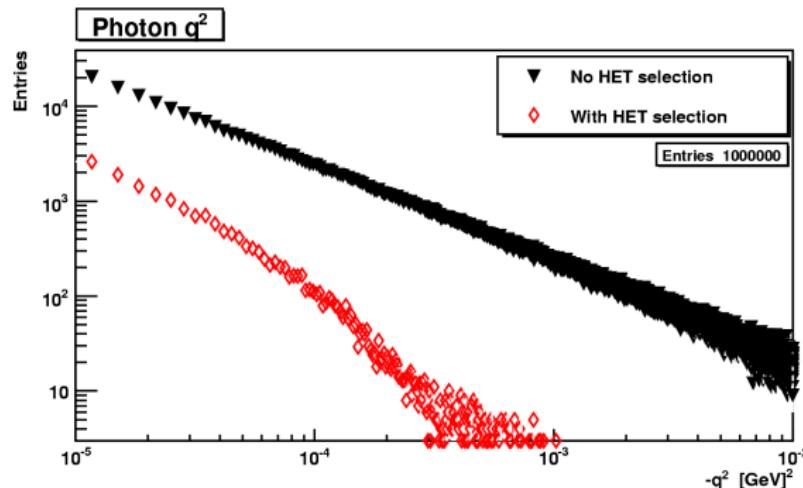
- The  $\pi^0$  production in  $e^+e^- \rightarrow e^+e^- \pi^0$  is simulated with **EKHARA 2.0**

[ H. Czyż, S. Ivashyn, Comp.Phys.Comm., 182, 1338 (2011) ]

- EKHARA has been interfaced with the **BDSIM** package
- ✓ trace the emitted electron (positron) through the magnetic elements of DAΦNE layout

# HET+HET coincidence $\Rightarrow \Gamma_{\pi^0 \rightarrow \gamma\gamma}$

The HET-HET coincidence leads to a significant restriction on the photon virtuality in  $\gamma^*\gamma^* \rightarrow \pi^0$ :  
for most of the events one has  $|q^2| < 10^{-4} \text{ GeV}^2$



Distribution of the photon virtuality in  $\gamma^*\gamma^* \rightarrow \pi^0$ . The lepton double tagging (HET-HET) selects the events (red diamonds) with small virtuality of the photons.

# HET+HET coincidence $\Rightarrow \Gamma_{\pi^0 \rightarrow \gamma\gamma}$

One can extract the value of the partial decay width from data, using the formula

$$\Gamma_{\pi^0 \rightarrow \gamma\gamma} = \frac{N_{\pi^0}}{\varepsilon \mathcal{L}} \frac{\tilde{\Gamma}_{\pi^0 \rightarrow \gamma\gamma}}{\tilde{\sigma}_{e^+ e^- \rightarrow e^+ e^- \pi^0}}$$

$N_{\pi^0}$  is the number of detected pions

$\varepsilon$  accounts for the detection acceptance and efficiency

$\mathcal{L}$  is the integrated luminosity

$\tilde{\Gamma}_{\pi^0 \rightarrow \gamma\gamma}$  is the model  $\pi^0$  width

$\tilde{\sigma}_{e^+ e^- \rightarrow e^+ e^- \pi^0}$  is the cross section obtained with a Monte Carlo simulation using the same model as for the  $\tilde{\Gamma}_{\pi^0 \rightarrow \gamma\gamma}$  calculation

# HET+KLOE $\Rightarrow F(Q^2)$

- ✓ one lepton inside the KLOE detector ( $20^\circ < \theta < 160^\circ$ , corresponding to  $0.01 < |q_1^2| < 0.1 \text{ GeV}^2$ )
- ✓ the other lepton in the HET detector (corresponding to  $|q_2^2| \lesssim 10^{-4} \text{ GeV}^2$  for most of the events)
- ✓ measure the differential cross section  $(d\sigma/dQ^2)_{data}$ , where  $Q^2 \equiv -q_1^2$

↓

The form factor  $|F(Q^2)|$  can be extracted from this cross section:

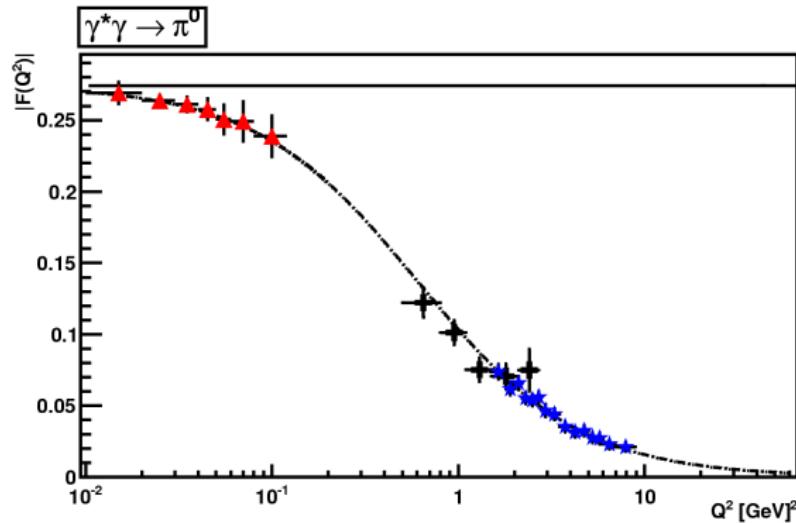
$$\frac{F^2(Q^2)}{F^2(Q^2)_{MC}} = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{data}}{\left(\frac{d\sigma}{dQ^2}\right)_{MC}}$$

$\left(\frac{d\sigma}{dQ^2}\right)_{data}$  is the experimental differential cross section

$\left(\frac{d\sigma}{dQ^2}\right)_{MC}$  is the Monte Carlo one obtained with the form factor  $F(Q^2)_{MC}$

# HET+KLOE $\Rightarrow F(Q^2)$

Expected experimental uncertainty on  $F(Q^2)$  achievable at KLOE-2 with an integrated luminosity of  $5 \text{ fb}^{-1}$ :



Simulation of KLOE-2 measurement of  $F(Q^2)$  (red triangles) with statistical errors for  $5 \text{ fb}^{-1}$ . The detection efficiency is estimated to be about 20%. Dashed line is the  $F(Q^2)$  form factor according to LMD+V model, solid line is  $F(0)$  given by Wess-Zumino-Witten term. CELLO (black crosses) and CLEO (blue stars) data at high  $Q^2$  are also shown for illustration.

# KLOE-2 impact on the accuracy of $a_{\mu}^{\text{LbyL};\pi}$

- Data sets used for fits:

A0 : CLEO, CELLO, PDG

A1 : CLEO, CELLO, PrimEx

A2 : CLEO, CELLO, PrimEx, KLOE-2

B0 : CLEO, CELLO, BaBar, PDG

B1 : CLEO, CELLO, BaBar, PrimEx

B2 : CLEO, CELLO, BaBar, PrimEx, KLOE-2

- Jegerlehner-Nyffeler (JN) and Melnikov-Vainshtein (MV) approaches are used for calculation of  $a_{\mu}^{\text{LbyL};\pi}$

# KLOE-2 simulation $\Rightarrow$ fitting the models

Model	Data	$\chi^2 / d.o.f.$	Parameters
VMD	A0	6.6/19	$M_V = 778(18)$ MeV $F_\pi = 0.0924(28)$ GeV
VMD	A1	6.6/19	$M_V = 776(13)$ MeV $F_\pi = 0.0919(13)$ GeV
VMD	A2	7.5/27	$M_V = 778(11)$ MeV $F_\pi = 0.0923(4)$ GeV
VMD	B0	77/36	$M_V = 829(16)$ MeV $F_\pi = 0.0958(29)$ GeV
VMD	B1	78/36	$M_V = 813(8)$ MeV $F_\pi = 0.0925(13)$ GeV
VMD	B2	79/44	$M_V = 813(5)$ MeV $F_\pi = 0.0925(4)$ GeV
LMD+V, $h_1 = 0$	A0	6.5/19	$\bar{h}_5 = 6.99(32)$ GeV $^4$ $\bar{h}_7 = -14.81(45)$ GeV $^6$
LMD+V, $h_1 = 0$	A1	6.6/19	$\bar{h}_5 = 6.96(29)$ GeV $^4$ $\bar{h}_7 = -14.90(21)$ GeV $^6$
LMD+V, $h_1 = 0$	A2	7.5/27	$\bar{h}_5 = 6.99(28)$ GeV $^4$ $\bar{h}_7 = -14.83(7)$ GeV $^6$
LMD+V, $h_1 = 0$	B0	65/36	$\bar{h}_5 = 7.94(13)$ GeV $^4$ $\bar{h}_7 = -13.95(42)$ GeV $^6$
LMD+V, $h_1 = 0$	B1	69/36	$\bar{h}_5 = 7.81(11)$ GeV $^4$ $\bar{h}_7 = -14.70(20)$ GeV $^6$
LMD+V, $h_1 = 0$	B2	70/44	$\bar{h}_5 = 7.79(10)$ GeV $^4$ $\bar{h}_7 = -14.81(7)$ GeV $^6$
LMD+V, $h_1 \neq 0$	A0	6.5/18	$\bar{h}_5 = 6.90(71)$ GeV $^4$ $\bar{h}_7 = -14.83(46)$ GeV $^6$ $h_1 = -0.03(18)$ GeV $^2$
LMD+V, $h_1 \neq 0$	A1	6.5/18	$\bar{h}_5 = 6.85(67)$ GeV $^4$ $\bar{h}_7 = -14.91(21)$ GeV $^6$ $h_1 = -0.03(17)$ GeV $^2$
LMD+V, $h_1 \neq 0$	A2	7.5/26	$\bar{h}_5 = 6.90(64)$ GeV $^4$ $\bar{h}_7 = -14.84(7)$ GeV $^6$ $h_1 = -0.02(17)$ GeV $^2$
LMD+V, $h_1 \neq 0$	B0	18/35	$\bar{h}_5 = 6.46(24)$ GeV $^4$ $\bar{h}_7 = -14.86(44)$ GeV $^6$ $h_1 = -0.17(2)$ GeV $^2$
LMD+V, $h_1 \neq 0$	B1	18/35	$\bar{h}_5 = 6.44(22)$ GeV $^4$ $\bar{h}_7 = -14.92(21)$ GeV $^6$ $h_1 = -0.17(2)$ GeV $^2$
LMD+V, $h_1 \neq 0$	B2	19/43	$\bar{h}_5 = 6.47(21)$ GeV $^4$ $\bar{h}_7 = -14.84(7)$ GeV $^6$ $h_1 = -0.17(2)$ GeV $^2$

- the main improvement is in the normalization parameter

# KLOE-2 simulation $\Rightarrow a_{\mu}^{\text{LbyL};\pi}$

- The errors of the fitted parameters are the MINOS (MINUIT from CERNLIB) parabolic errors
- Our estimate of the  $a_{\mu}^{\text{LbyL};\pi^0}$  uncertainty is given only by a propagation of these errors

therefore we may not reproduce the values of the  $a_{\mu}^{\text{LbyL};\pi^0}$  full uncertainty given in the original papers

# KLOE-2 simulation $\Rightarrow a_{\mu}^{\text{LbyL};\pi}$

Model	Data	$\chi^2/d.o.f.$	$a_{\mu}^{\text{LbyL};\pi} \times 10^{11}$
VMD	A0	6.6/19	$(57.2 \pm 4.0)_{JN}$
VMD	A1	6.6/19	$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$(57.3 \pm 1.1)_{JN}$
LMD+V, $h_1 = 0$	A0	6.5/19	$(72.3 \pm 3.5)_{JN}^*$ $(79.8 \pm 4.2)_{MV}$
LMD+V, $h_1 = 0$	A1	6.6/19	$(73.0 \pm 1.7)_{JN}^*$ $(80.5 \pm 2.0)_{MV}$
LMD+V, $h_1 = 0$	A2	7.5/27	$(72.5 \pm 0.8)_{JN}^*$ $(80.0 \pm 0.8)_{MV}$
LMD+V, $h_1 \neq 0$	A0	6.5/18	$(72.4 \pm 3.8)_{JN}^*$
LMD+V, $h_1 \neq 0$	A1	6.5/18	$(72.9 \pm 2.1)_{JN}^*$
LMD+V, $h_1 \neq 0$	A2	7.5/26	$(72.4 \pm 1.5)_{JN}^*$
LMD+V, $h_1 \neq 0$	B0	18/35	$(71.9 \pm 3.4)_{JN}^*$
LMD+V, $h_1 \neq 0$	B1	18/35	$(72.4 \pm 1.6)_{JN}^*$
LMD+V, $h_1 \neq 0$	B2	19/43	$(71.8 \pm 0.7)_{JN}^*$

- \* there is also an additional error coming from the “off-shellness” of the pion
- (part of) the error of  $a_{\mu}^{\text{LbyL};\pi}$  can be considerably reduced
- the improvement is similar regardless the way how  $a_{\mu}^{\text{LbyL};\pi}$  is calculated (MV vs. JN)

KLOE-2 data with luminosity of  $5 \text{ fb}^{-1}$  will give a reasonable improvement in the part of the  $a_\mu^{\text{LbyL};\pi^0}$  error associated with the parameters accessible via the  $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$  width and the  $\pi^0\gamma\gamma^*$  form factor  $F(Q^2)$ .

# Summary

- $\Gamma_{\pi^0 \rightarrow \gamma\gamma}$  can be measured with  $\sim 1\%$  statistical error by the KLOE-2 experiment
- ✓ better than the current experimental and theoretical average
- the  $\pi^0$  electromagnetic transition form factor  $F(Q^2)$  in the region  $0.01 < Q^2 < 0.1 \text{ GeV}^2$  can be measured



- can have impact on the value and precision of the contribution of a neutral pion exchange to the hadronic light-by-light scattering part of  $a_\mu$

# Spare slides



# $\mathcal{F}_{\pi^0 \gamma^* \gamma^*}$ in VMD model

Vector Meson Dominance

$$\mathcal{F}^{VMD}(q_1^2, q_2^2) = -\frac{N_C}{12\pi^2 F_\pi} \frac{M_V^2}{(q_1^2 - M_V^2)} \frac{M_V^2}{(q_2^2 - M_V^2)}$$

$$F^{VMD}(Q^2) = -\frac{N_C}{12\pi^2 F_\pi} \frac{M_V^2}{(M_V^2 + Q^2)}$$

# $\mathcal{F}_{\pi^0 \gamma^* \gamma^*}$ in LMD+V model

## Lowest Meson Dominance ansatz with two vector multiplets

based on large- $N_C$  QCD matched to short-distance constraints from the operator-product expansion

[ Knecht and Nyffeler, Eur. Phys. J., C21, 659 (2001) ]

$$\begin{aligned} & \mathcal{F}^{LMD+V}(q_1^2, q_2^2) \\ &= \frac{F_\pi}{3} \frac{q_1^2 q_2^2 (q_1^2 + q_2^2) + h_1 (q_1^2 + q_2^2)^2 + \bar{h}_2 q_1^2 q_2^2 + \bar{h}_5 (q_1^2 + q_2^2) + \bar{h}_7}{(q_1^2 - M_{V_1}^2)(q_1^2 - M_{V_2}^2)(q_2^2 - M_{V_1}^2)(q_2^2 - M_{V_2}^2)} \end{aligned}$$

$$F^{LMD+V}(Q^2) = \frac{F_\pi}{3} \frac{1}{M_{V_1}^2 M_{V_2}^2} \frac{h_1 Q^4 - \bar{h}_5 Q^2 + \bar{h}_7}{(Q^2 + M_{V_1}^2)(Q^2 + M_{V_2}^2)}$$

# There are two versions of LMD+V model

- with  $h_1 = 0$   
in contradiction with BaBar-2009
- $h_1$  — free parameter [ Nyffeler, PoS CD09, 080 (2009) ]
- ✓ can fit BaBar-2009 data  
but the form factor does not vanish at  $Q^2 \rightarrow \infty$

# JN and MV

The two approaches to calculate  $a_\mu^{\text{LbyL};\pi^0}$

- Jegerlehner-Nyffeler (JN) approach
  - ✓ off-shell pion form factor

[ Phys. Rept. 477, 1 (2009) ]

[ Phys. Rev. D79, 073012 (2009) ]

- Melnikov-Vainshtein (MV) approach
  - ✓ on-shell pion form factor in one vertex and the other vertex is constant (WZW)

[ Phys. Rev. D70, 113006 (2004) ]

$$(\text{HET vs. LET}) + \text{KLOE} \Rightarrow F(Q^2)$$

The effect of the LET detectors will be the subject of a forthcoming investigation

