Measurement of the $\pi^0 \rightarrow \gamma\gamma$ width and of the π^0 TFF at KLOE-2 and its impact on the muon (g-2)

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Università "Roma Tre" and INFN - Sezione "Roma Tre"

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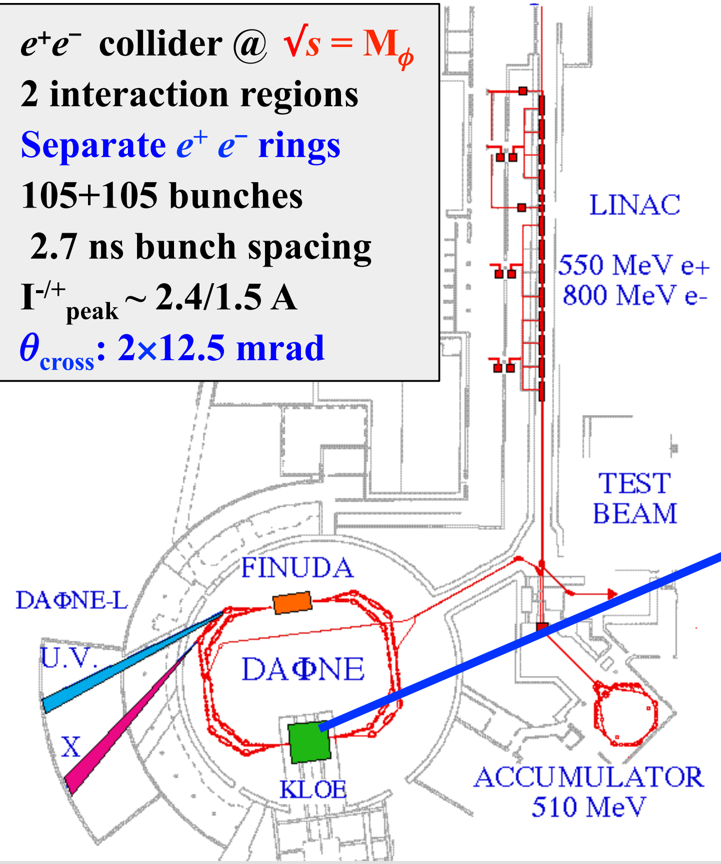
OUTLINE

- **DAϕNE and KLOE**
- **γγ physics at KLOE ($e^{\pm}$ untagged)**
- **Report on performed and on-going analyses on KLOE $\sqrt{s}$=1 GeV data**
- **KLOE-2: $e^{\pm}$ taggers**
- **Prospects: $e^+e^- \to e^+e^- \pi^0$ with KLOE-2**

DAΦNE & KLOE

- e^+e^- collider @ $\sqrt{s} = M_\phi$
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- θ_{cross}: 2×12.5 mrad

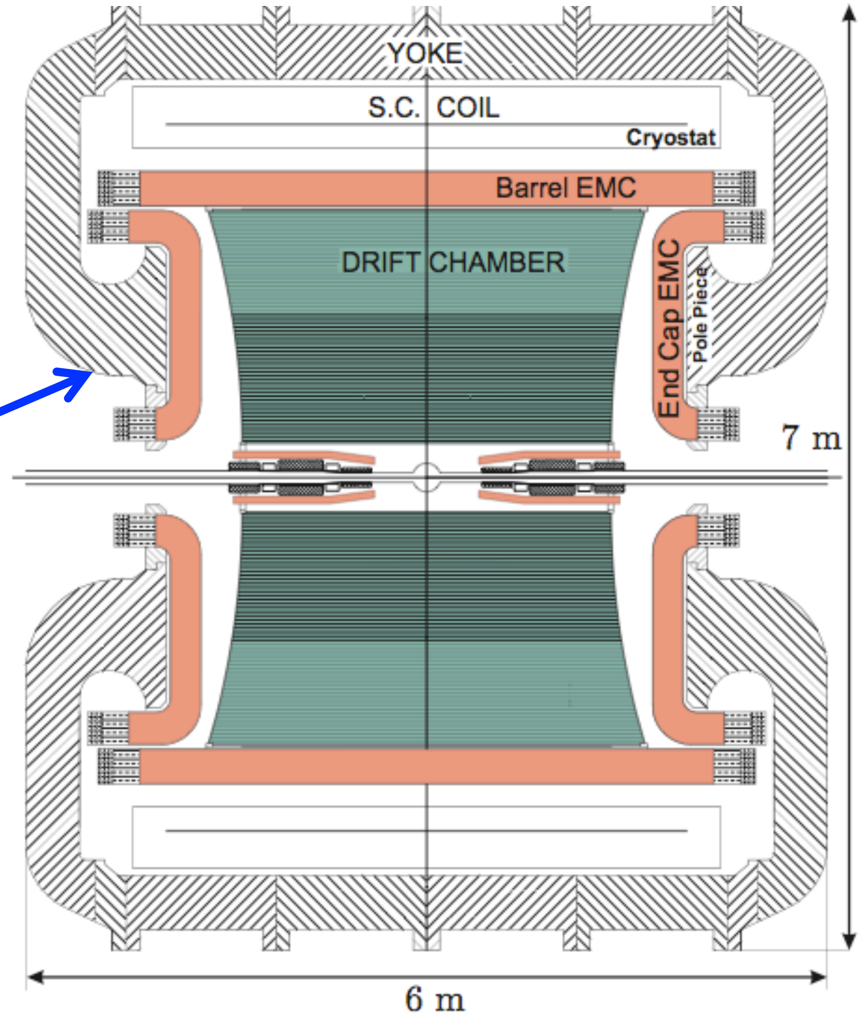


KLOE data taking: 2000-2006
Best performance:

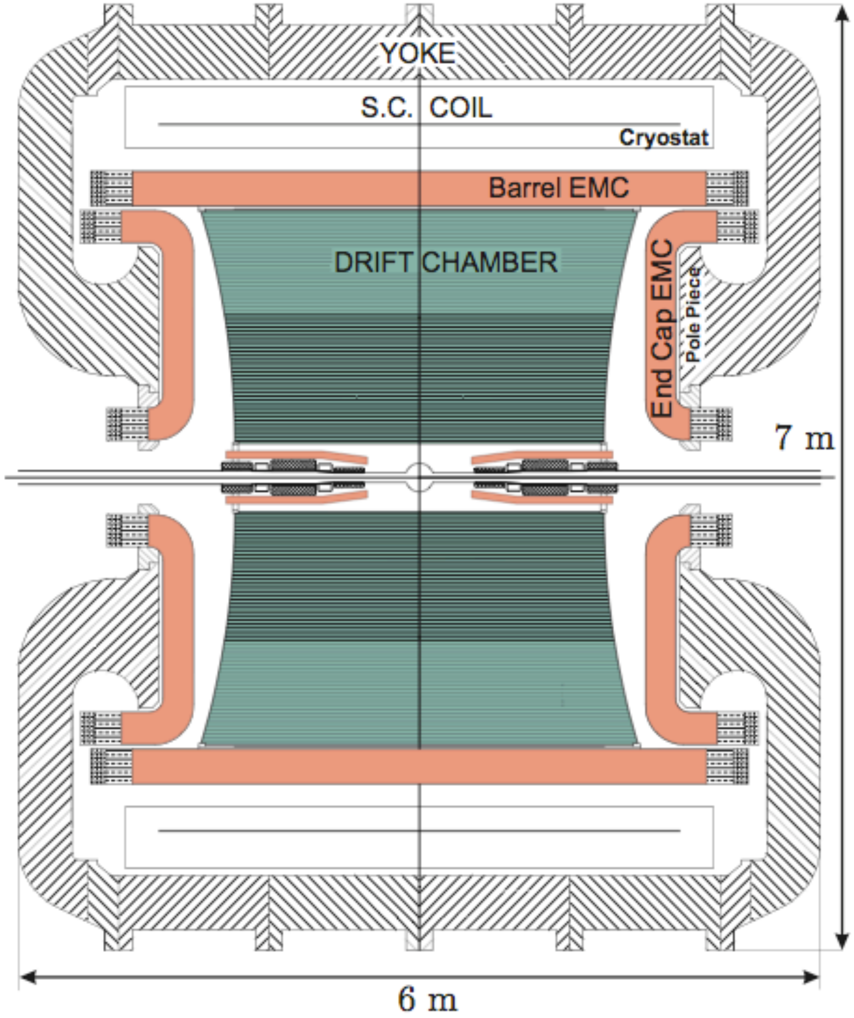
$$L_{peak} = 1.4 \times 10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\int L dt = 8.5\,\mathrm{pb}^{-1}/\mathrm{day}$$

KLOE DETECTOR



KLOE Detector



Electromagnetic calorimeter

- **lead/scintillating fibers**
- **98% solid angle coverage**
- **$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$**
- **$\sigma_t = 57\ ps/\sqrt{E(GeV)} + 100\ ps$**
- **PID capabilities**

Drift Chamber

- **Gas mixture 90% He + 10% C_4H_{10}**
- **$\delta p_T/p_T < 0.4\%$ ($45^0 < \vartheta < 135^0$)**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2\ mm$**

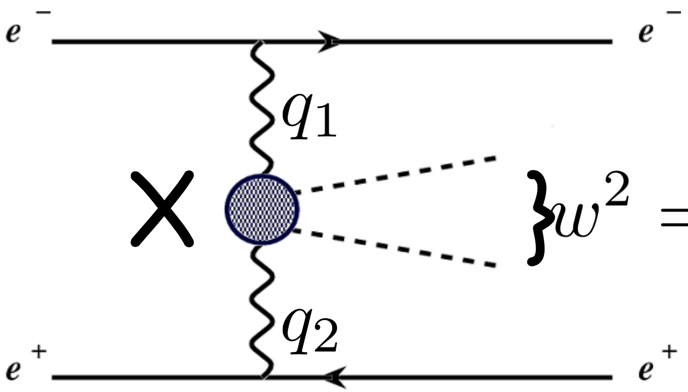
MAGNETIC FIELD 0.52 T

γγ physics @ KLOE

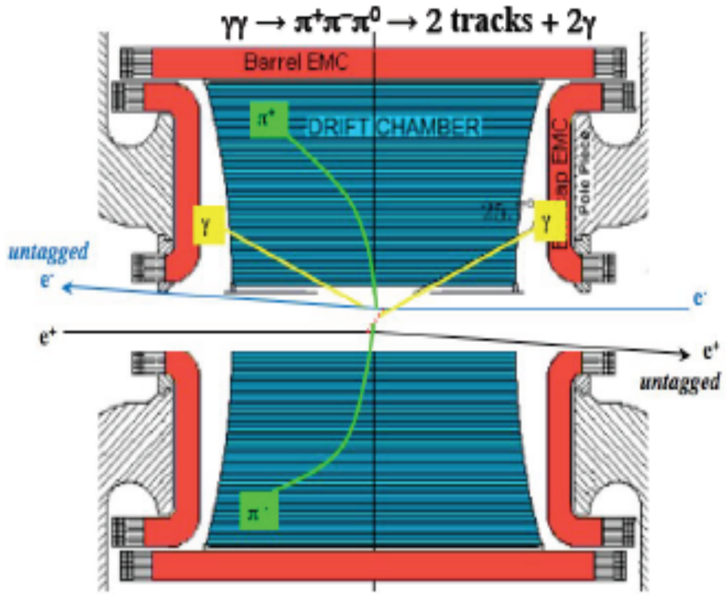
$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$$

X: $J^{PC} = 0^{\pm+}$

(π^0, η, η', σ(500))



$$w^2 = (q_1 + q_2)^2$$



Analyses on L=242.5 pb^{-1} off-peak data (collected at √s=1 GeV):

- **$e^+e^- \rightarrow e^+e^-\eta$**
- **$e^+e^- \rightarrow e^+e^-\pi^0\pi^0$**

$e^\pm$ tagging mandatory to study γγ processes at √s=1.02 GeV

γγ physics with KLOE data

Analyses on L=242.5 pb $^{-1}$ off-peak ($\sqrt{s}$=1 GeV) data:

- $e^+e^- \rightarrow e^+e^- \eta$, $\eta \rightarrow \pi^0\pi^0\pi^0$, $\eta \rightarrow \pi^+\pi^-\pi^0$
  [JHEP01(2013)119]

- $e^+e^- \rightarrow e^+e^- \pi^0\pi^0$ (work in progress)

$e^+e^- \to e^+e^- \eta$

Two channels:

$\eta \to \pi^0 \pi^0 \pi^0$

- 6γ only with E>15 MeV, $23^0 < \vartheta < 157^0$, $|t - r/c| < 3\sigma_t$
- no tracks in the drift chamber
- $\gamma\gamma$ pairing

$$\chi^2_{pair} = \sum_{\gamma\gamma\, pair}^{3} \left(\frac{M_{\gamma\gamma} - M_{\pi^0}}{\sigma(M_{\gamma\gamma})} \right)^2$$

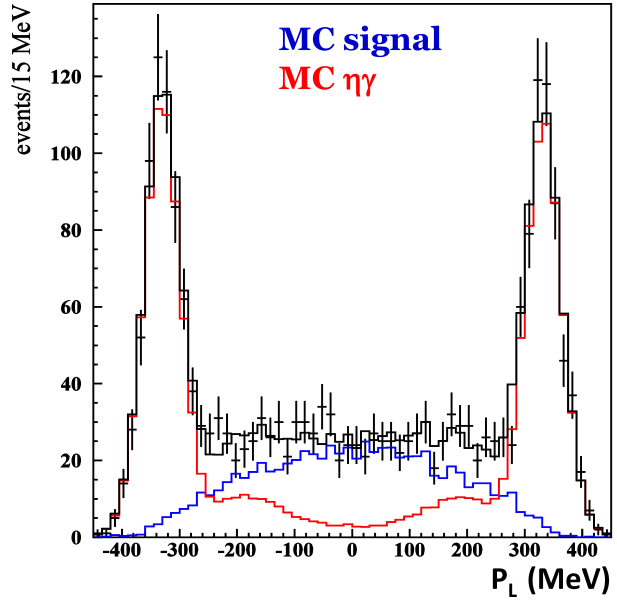
- kinematic fit requiring $M_{6\gamma} = m_\eta$

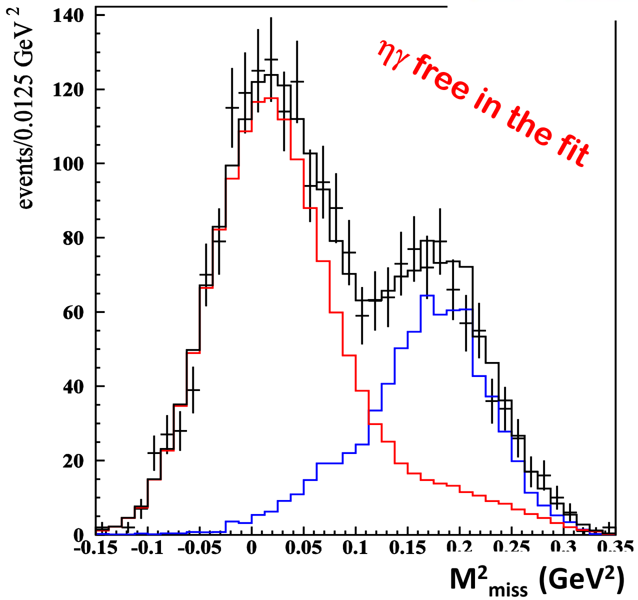
$\eta \to \pi^+ \pi^- \pi^0$

- 2γ only with E>15 MeV, $23^0 < \vartheta < 157^0$, $|t - r/c| < 3\sigma_t$
- 2 tracks with opposite charge from a cylinder $\rho_{PCA} < 8$ cm, $|z_{PCA}| < 8$ cm, $\rho_{first\text{-}hit} < 50$ cm
- $\gamma\gamma$ pairing to renconstruct π^0
- electron-pion likelihood cut
- kinematic fit requiring $M_{\pi\pi\gamma} = m_\eta$

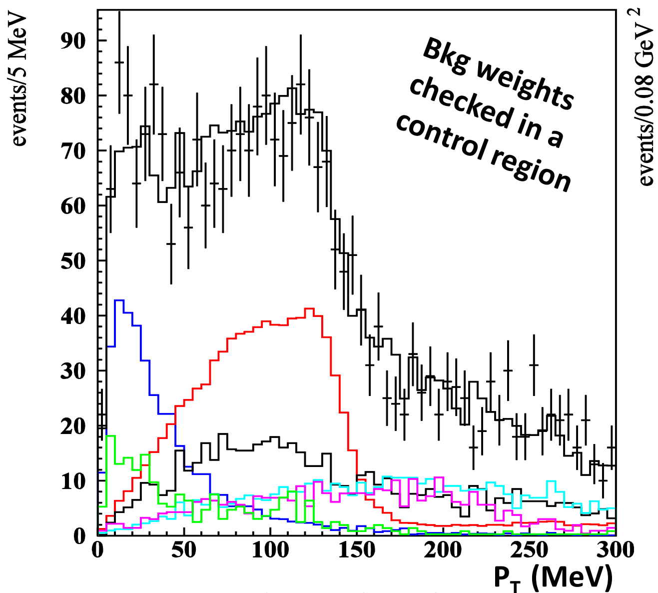
$e^+e^- \to e^+e^- \eta$: 2D fits

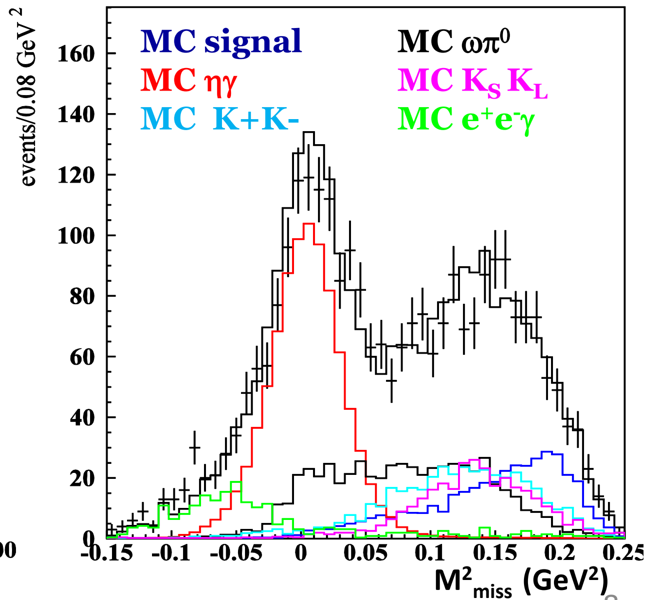
$\eta \to \pi^0 \pi^0 \pi^0$





$\eta \to \pi^+ \pi^- \pi^0$





$e^+e^- \to e^+e^-\eta$: results

Neutral channel, ≈ 720 signal events:

$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (32.0 \pm 1.5_{stat} \pm 0.9_{syst} \pm 0.2_{BR(\eta \to 3\pi)})$ pb

Charged channel, ≈ 390 signal events:

$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (34.5 \pm 2.5_{stat} \pm 1.0_{syst} \pm 0.7_{FF} \pm 0.4_{BR})$ pb

Combined

$\sigma(e^+e^- \to e^+e^-\eta, \sqrt{s} = 1\ \text{GeV}) = (32.7 \pm 1.3_{stat} \pm 0.7_{syst})$ pb

$\Gamma(\eta \to \gamma\gamma)$ extracted (see reference for details on luminosity function and FF parametrization):

$$\Gamma(\eta \to \gamma\gamma) = (520 \pm 20_{stat} \pm 13_{syst})\ \text{eV}$$

Most precise measurement,
In agreement with PDG value (510±26) eV

$e^+e^- \to e^+e^- \pi^0\pi^0$(work in progress)

(possible production of σ(500) as a resonant intermediate state)

Cut-based and multivariate analysis

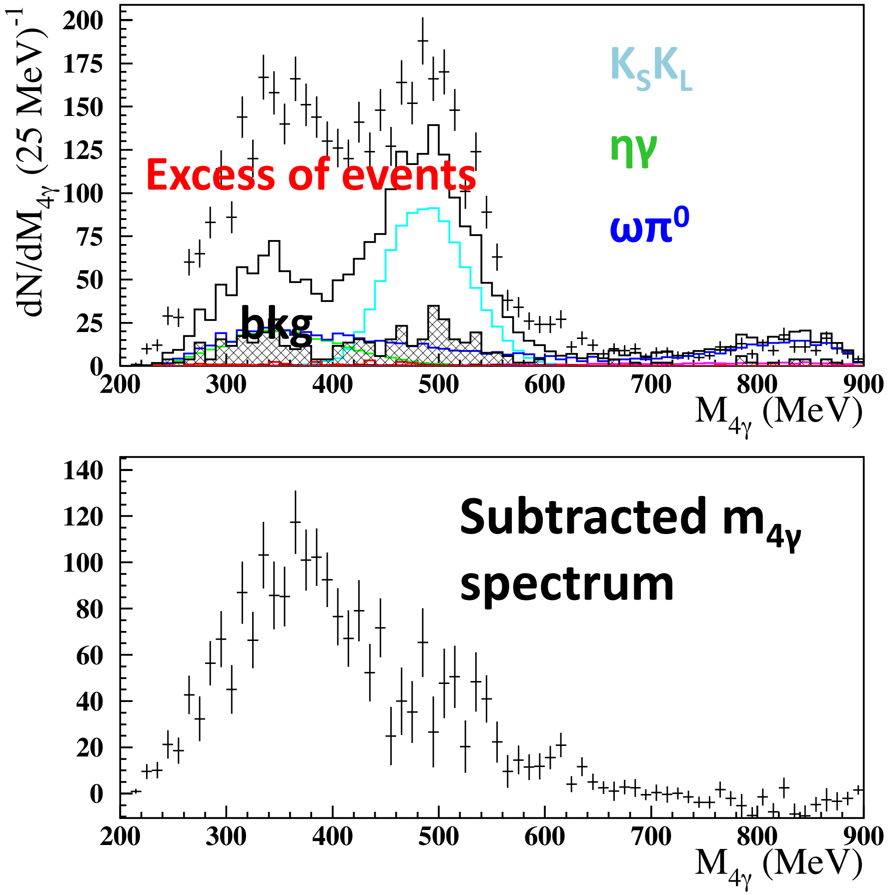
Analysis cuts

- 4γ only with E>15 MeV, $|t-r/c|<5\sigma_t$, in acceptance ($23^0<\vartheta<157^0$)
- no tracks
- no late clusters
- machine bkg selected from data by topological criteria

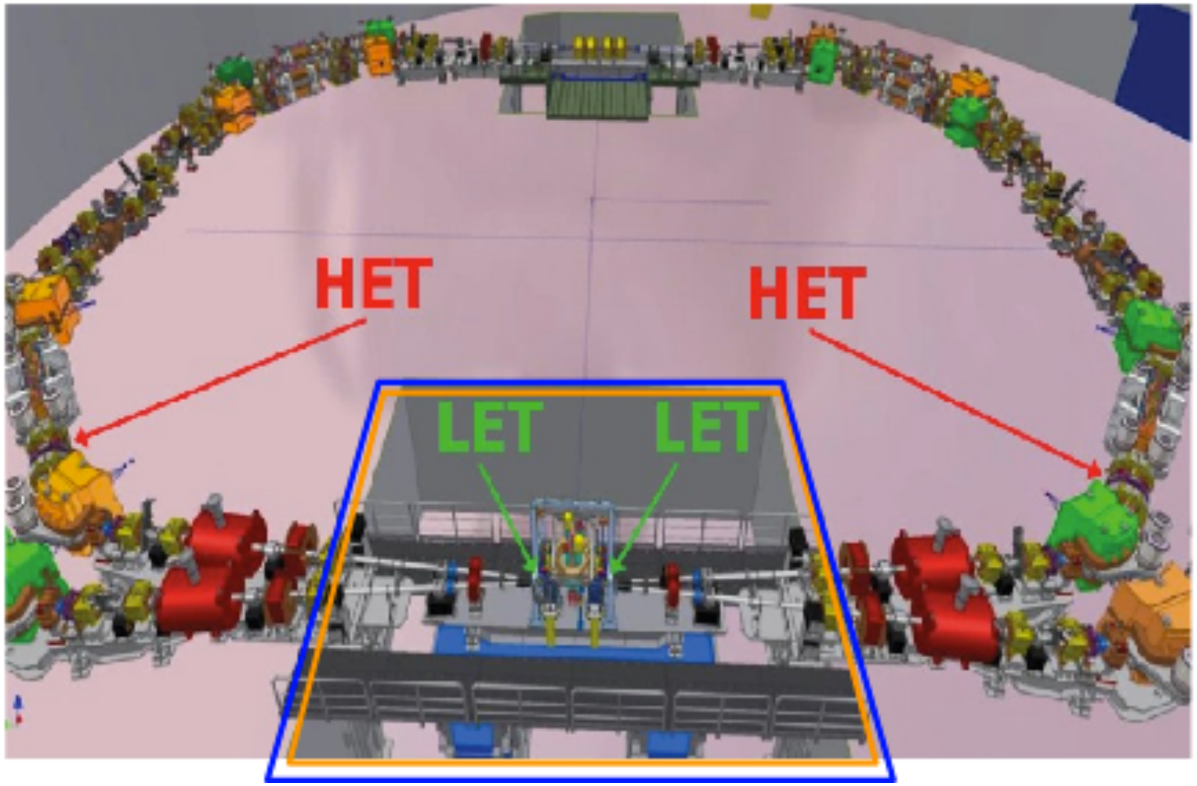
Multivariate analysis using TMVA package -> cut on the MVA output

$e^+ e^-$ annhiliation processes normalized according to Xsections

machine background estimation



γγ physics @ KLOE-2: e^+e^- taggers



$$e^+ e^- \to e^+ e^- \gamma^* \gamma^* \to \boxed{e^+ e^-}\ \boxed{X}$$

to taggers (HET or LET)

in KLOE

LET (Low Energy Tagger)
→ Inside KLOE detector (1m from IP)
→ energy acceptance (160-400) MeV

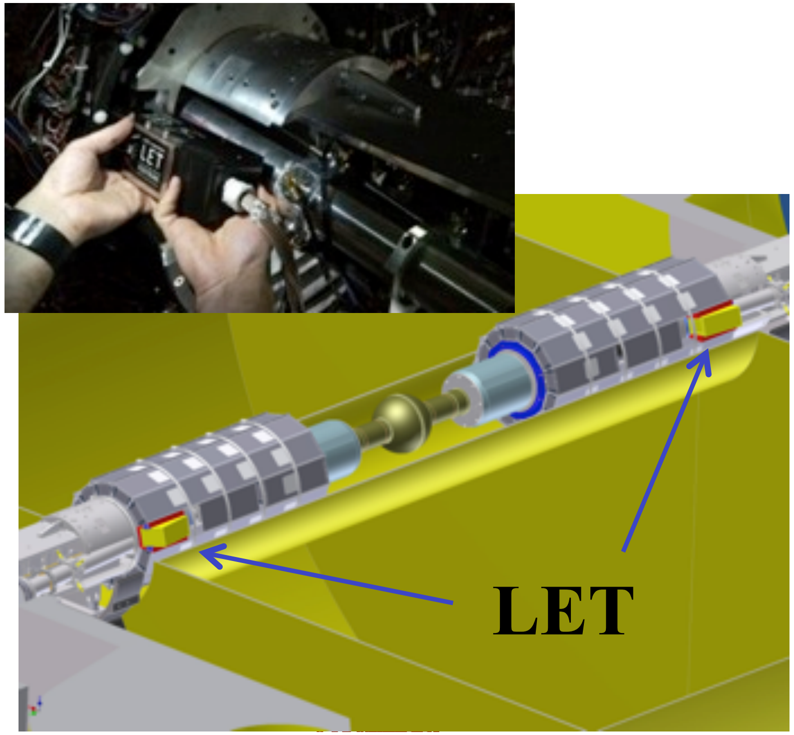
HET (High Energy Tagger)
→ After bending dipole (11m from IP)
→ energy acceptance (420-495) MeV

Outcoming $e^\pm$ tagging allow to close kinematics → rejection of ϕ decays background

γγ physics @ KLOE-2: e^+e^- taggers

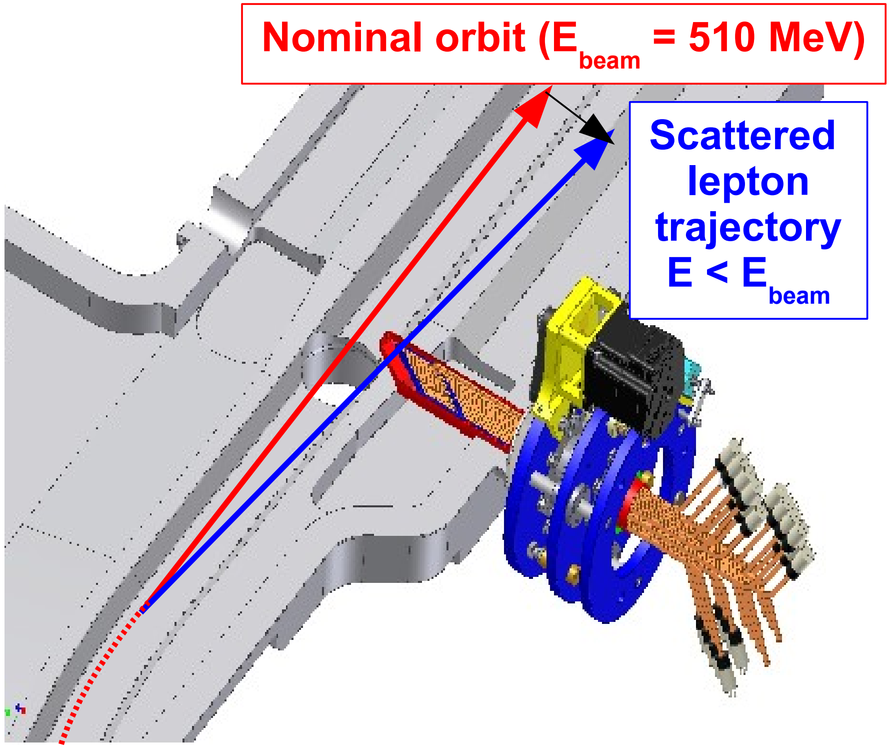
LET: 160-230 MeV

- ✓ Inside KLOE
- ✓ LYSO + SiPM calorimeters
- ✓ σ_E < 10% for E>150 MeV



HET: E > 400 MeV

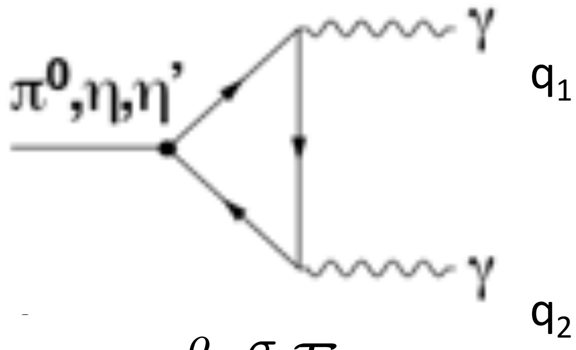
- ✓ 11 m from IP
- ✓ Scintillator hodoscopes
- ✓ $\sigma_E \approx 2.5$ MeV, $\sigma_T \approx 200$ ps



$e^+e^- \to e^+e^- \pi^0$ with KLOE-2

$e^+e^- \rightarrow e^+e^-\pi^0$ @ KLOE-2: Motivations

<VVA> QCD Green function with pion on-shell



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

Putting γs on-shell too one obtains the $\pi^0\rightarrow\gamma\gamma$ width:

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

$$\mathcal{F}_{\pi^0\gamma^*\gamma^*}(q_1^2,q_2^2)$$

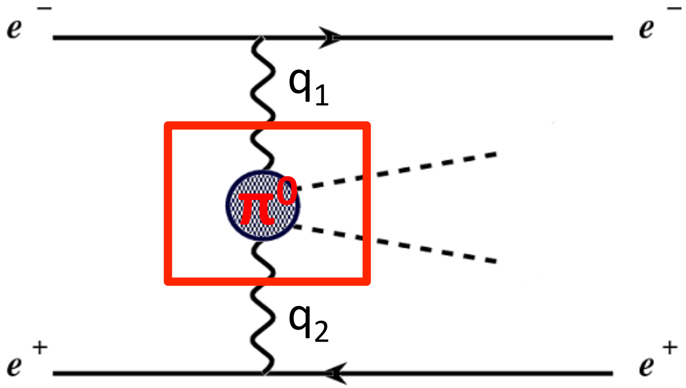
- Never studied experimentally **as a function of both photons virtualities** in the space-like region
- Studied with limited accuracy in the time-like region [Phys.Rev.Lett. 100 (2008) 182001]

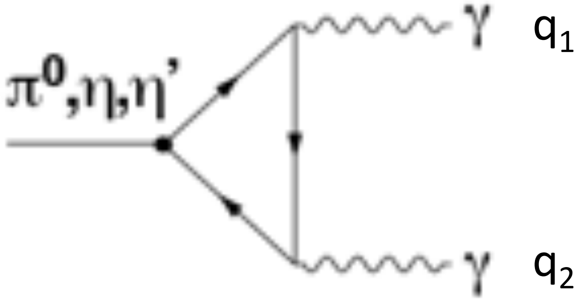
$$F(Q^2)\equiv\mathcal{F}_{\pi^0\gamma^*\gamma^*}(-Q_1^2,q_2^2=0), \qquad Q^2\equiv -q^2$$

TFF with one on-shell and one off-shell photon measured **at large space-like q^2** ($-q^2>0.5$ GeV) by

- CELLO [Z.Phys. C49 (1991) 401]
- CLEO [Phys.Rev. D57 (1998) 33]
- BaBar [Phys.Rev. D80 (2009) 052002]

$e^+e^- \rightarrow e^+e^- \pi^0$ with KLOE-2

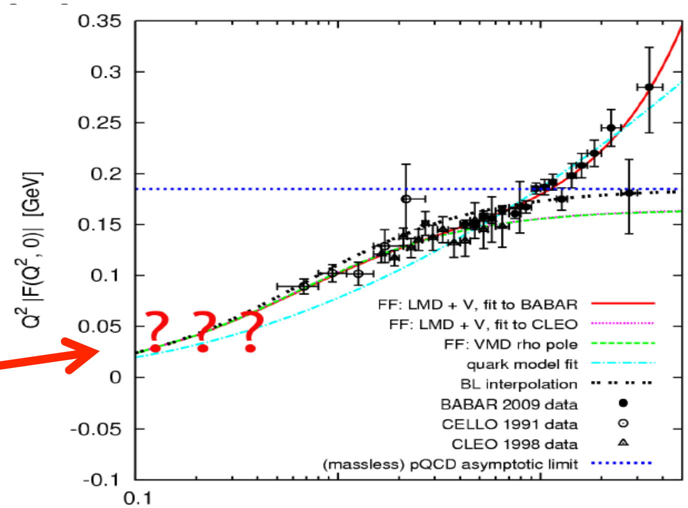




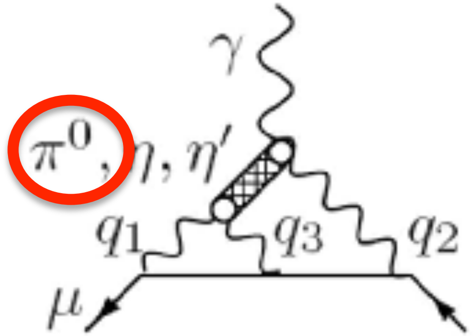
3 goals:

- **Measure $\Gamma(\pi^0 \rightarrow \gamma\gamma)$**

- **Extract $F(Q^2)$**
  (fill in the low Q^2 gap)

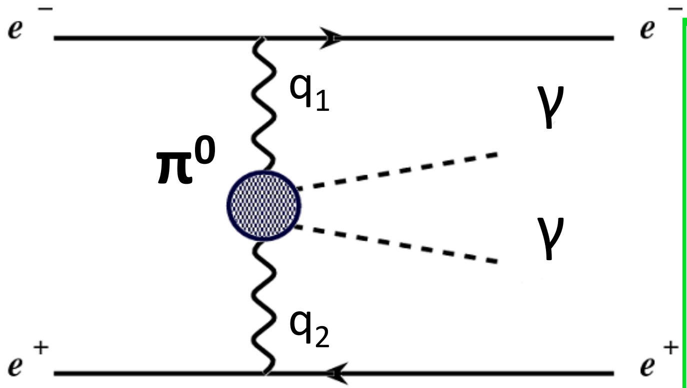


- **Hdronic light-by-light contribution to the muon g-2**



$e^+e^- \rightarrow e^+e^- \pi^0$ with KLOE-2

Events simulation performed with **EKHARA** MC generator
[Comp.Phys.Comm. 182, 6 (2011) 1338-1349]

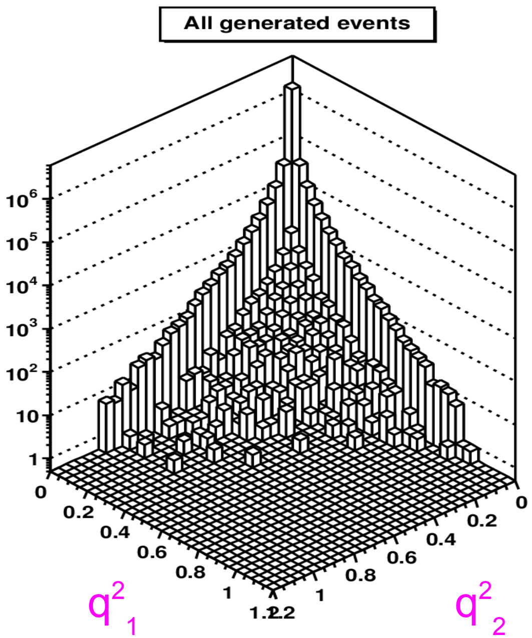


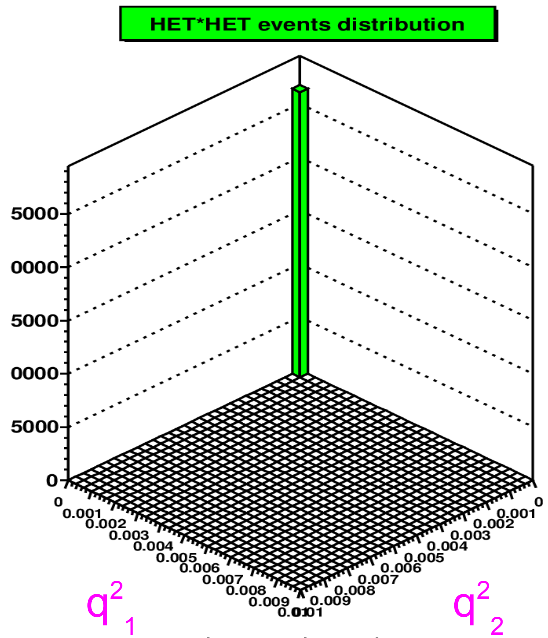
- **Both leptons tagged (HET-HET coincidence)**
- **$\pi^0 \rightarrow \gamma\gamma$ in KLOE**

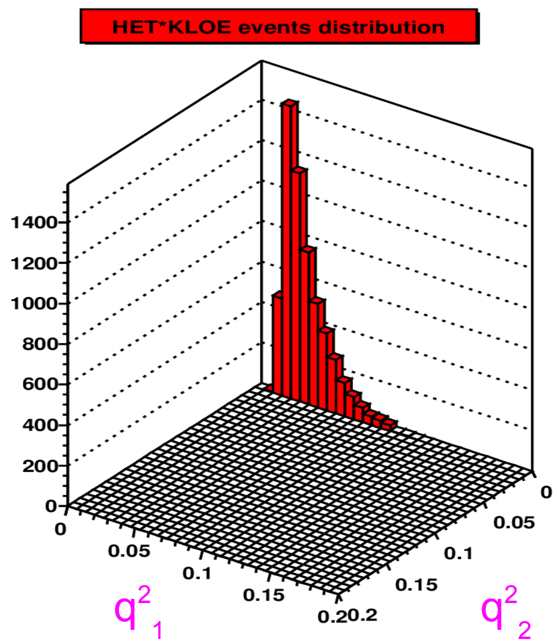
$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ measurement

- **one lepton in the HET, the other in KLOE**
- **$\pi^0 \rightarrow \gamma\gamma$ in KLOE**

$F(Q^2)$ measurement







$e^+e^- \to e^+e^-\pi^0$ with KLOE-2

$\pi^0 \to \gamma\gamma$ width

Theory (1.4% accuracy):

$$\Gamma^{theor}_{\pi^0\to\gamma\gamma} = 8.09 \pm 0.11\ \mathrm{eV}$$

Most precise measurement: PrimEx Coll
[PRL 106, 162303 (2011)] @ 2.8%

$$\Gamma_{\pi^0\to\gamma\gamma} = 7.82 \pm 0.14 \pm 0.17\ \mathrm{eV}$$

(using Primakoff effect-> huge model dependence in modelling the nuclear int.)

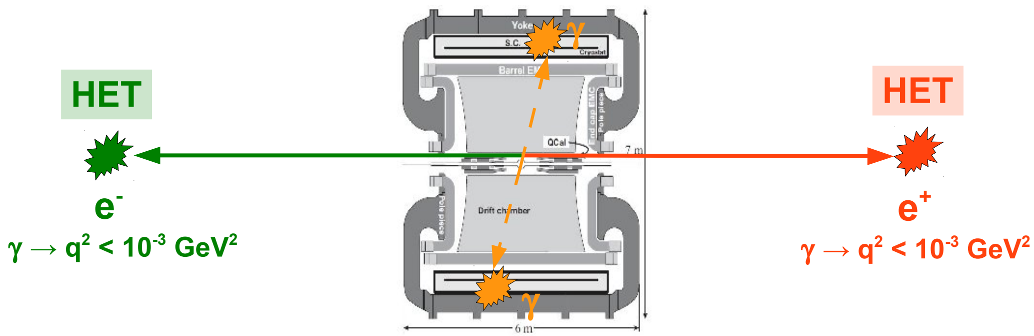
KLOE-2 PROSPECTS:

Feasible at 1% with 5-6 fb^{-1}
(lepton double-tagging)

Clean sample selected requiring both photons in the barrel of the EMC and HET-HET coincidence (small virtuality of the photons)

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

From MC simulation (modelling the π^0 width)



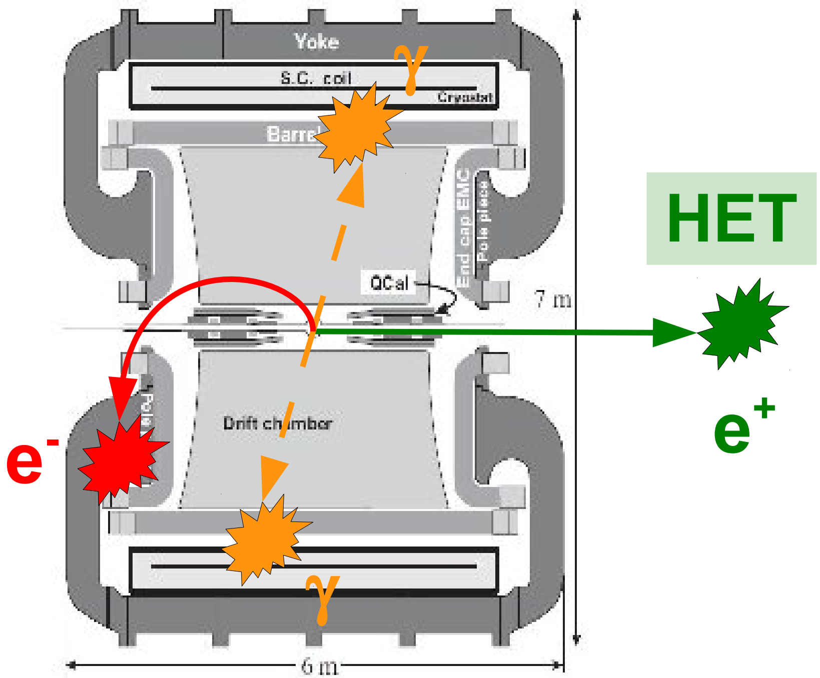
$e^+e^- \rightarrow e^+e^- \pi^0$ with KLOE-2

$\gamma^*\gamma\ \pi^0$ transition form factor

$e^- \rightarrow$ KLOE $\rightarrow 0.01 < |q^2| < 0.1\ \mathrm{GeV}^2$

$e^+ \rightarrow$ HET $\rightarrow |q^2| < 10^{-3}\ \mathrm{GeV}^2$

One can measure $(d\sigma/dQ^2)_{data}$ → Extract $F(Q^2)$ from



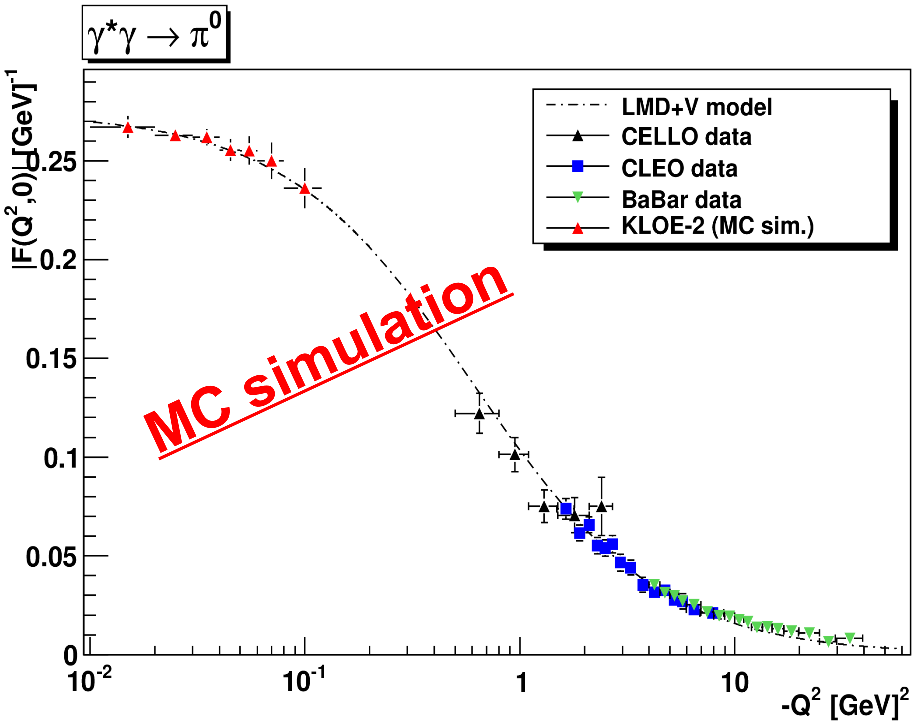
$$\frac{F^2(Q^2)}{F^2(Q^2)_{MC}} = \frac{\left(\frac{d\sigma}{dQ^2}\right)_{data}}{\left(\frac{d\sigma}{dQ^2}\right)_{MC}}$$

Lowest meson dominance with two vector multiplets assumed (LMD+V) for the FF

$e^+e^- \rightarrow e^+e^-\pi^0$ with KLOE-2

$\gamma^*\gamma\ \pi^0$ transition form factor

Filling the gap at Q^2<0.5 GeV^2



Uncertainty of 5-6% for every bin with 5 fb^{-1}

One can then evaluate the slope par. of the FF:

$$a \equiv m_\pi^2 \frac{1}{\mathcal{F}_{\pi^0\gamma^*\gamma^*}(0,0)} \left(\frac{d\mathcal{F}_{\pi^0\gamma^*\gamma^*}(q^2,0)}{dq^2} \right)_{q^2=0}$$

PDG average dominated by CELLO result:

LINEAR COEFFICIENT OF π^0 ELECTROMAGNETIC FORM FACTOR

VALUE	*EVTS*	*DOCUMENT ID*	*TECN*	*COMMENT*
0.032 ±0.004 OUR AVERAGE				
+0.026 ±0.024 ±0.048	7548	FARZANPAY 92	SPEC	$\pi^- p \rightarrow \pi^0 n$ at rest
+0.025 ±0.014 ±0.026	54k	MEIJERDREES 92B	SPEC	$\pi^- p \rightarrow \pi^0 n$ at rest
+0.0326 ±0.0026 ±0.0026	127	[20] BEHREND 91	CELL	$e^+e^- \rightarrow e^+e^-\pi^0$
−0.11 ±0.03 ±0.08	32k	FONVIEILLE 89	SPEC	Radiation corr.

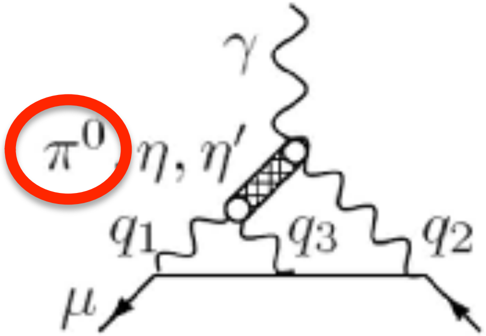
Data at low Q^2 can provide a validation for the FF parametrization (according to VMD) used by CELLO for fitting their data

$e^+e^- \rightarrow e^+e^-\pi^0$ with KLOE-2

Hadronic LbL term to the muon g-2

$a_\mu^{LbyL;\,\pi}$ evaluated using hadronics models → any experimental information on TFF important to constrain models

$$a_\mu^{\mathrm{LbL};\pi^0} = -e^6 \int \frac{d^4 q_1}{(2\pi)^4} \frac{d^4 q_2}{(2\pi)^4} \frac{1}{q_1^2 q_2^2 (q_1+q_2)^2 [(p+q_1)^2 - m^2][(p-q_2)^2 - m^2]} \times \left[\frac{\mathcal{F}_{\pi^*\gamma^*\gamma^*}(q_2^2, q_1^2, q_3^2)\, \mathcal{F}_{\pi^*\gamma^*\gamma}(q_2^2, q_2^2, 0)}{q_2^2 - m_\pi^2 + i\varepsilon} T_1(q_1, q_2; p) + \frac{\mathcal{F}_{\pi^*\gamma^*\gamma^*}(q_3^2, q_1^2, q_2^2)\, \mathcal{F}_{\pi^*\gamma^*\gamma}(q_3^2, q_3^2, 0)}{q_3^2 - m_\pi^2 + i\varepsilon} T_2(q_1, q_2; p) \right], \quad (48)$$



π^0 exchange contribution dominant

Theory:

[A. Nyffeler, 0912.1441]

[M. Knecht and A. Nyffeler, Phys. Rev. D65, 073034 (2002)]

[ibid.]

[A. E. Dorokhov, 0905.4577]

[G. P. Lepage and S. J. Brodsky, Phys. Rev. D 22, 2157 (1980)]

Full off-shell TFF needed $\mathcal{F}_{\pi^{0*},\gamma^*\gamma}(m_{\pi^0}^2, q_1^2, q_2^2)$

A measurement with KLOE-2 of $\mathcal{F}_{\pi^0,\gamma^*\gamma}(m_{\pi^0}^2, q_1^2, 0)$ **can be only sensitive to a subset of the model parameters**

Hadronic LbL term to the muon g-2: KLOE-2 impact on accuracy

Some models are very sensitive to the variation of the parameters related to the off-shellness of the pion:
e.g. off-shell LMD+V model

Other models do not have these sources of uncertainty:
e.g. VMD model

Phys. Rev. D79 (2009) 073012
Phys. Rev. D70 (2004) 113006

Estimate of KLOE-2 impact on the accuracy of $a_\mu^{LbyL;\pi}$: one uses EKHARA $e^+e^- \rightarrow e^+e^-\pi^0$ simulation as new "data" and consider the sets:

- **A1: CELLO, CLEO, PrimEx(PDG)**
- **A2: CELLO, CLEO, PrimEx, KLOE-2**
- **B1: CELLO, CLEO, BaBar, PrimEx(PDG)**
- **B2: CELLO, CLEO, BaBar, PrimEx, KLOE-2**

$a_\mu^{LbyL;\pi}$ evaluated fitting LMD+V and VMD models to these sets following 2 approaches: Jegerlehner-Nyffler (JN) and Melnikov-Vainshtein (MV)

Hadronic LbL term to the muon g-2

Table 1 Estimate of KLOE-2 impact on the accuracy of $a_\mu^{\mathrm{LbyL};\pi^0}$ in case of one year of data taking (5 fb^{-1}). For calculation we used the Jegerlehner-Nyffeler (JN) [19,20] and Melnikov-Vainshtein (MV) [17] approaches. The values marked with asterisk (*) do not contain additional uncertainties coming from the "off-shellness" of the pion (see the text). Data sets used for fits (A0, A1, A2, B0, B1, B2) — see the text, eq. (9).

PrimEx (PDG) -> KLOE: ≈ 2 reduction factor in the error

Model	Data	$\chi^2/d.o.f.$	Parameters			$a_\mu^{\mathrm{LbyL};\pi^0} \times 10^{11}$
VMD	A1	6.6/19	$M_V = 0.776(13)$ GeV	$F_\pi = 0.0919(13)$ GeV		$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$M_V = 0.778(11)$ GeV	$F_\pi = 0.0923(4)$ GeV		$(57.3 \pm 1.1)_{JN}$
VMD	B1	78/36	$M_V = 0.813(8)$ GeV	$F_\pi = 0.0925(13)$ GeV		—
VMD	B2	79/44	$M_V = 0.813(5)$ GeV	$F_\pi = 0.0925(4)$ GeV		—
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		$(79.8 \pm 4.2)_{MV}$ $(73.0 \pm 1.7)^*_{JN}$
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		$(80.5 \pm 2.0)_{MV}$ $(72.5 \pm 0.8)^*_{JN}$ $(80.0 \pm 0.8)_{MV}$
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, $h_1 \neq 0$	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	$(72.9 \pm 2.1)^*_{JN}$
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	$(72.4 \pm 1.5)^*_{JN}$
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	$(72.4 \pm 1.6)^*_{JN}$
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	$(71.8 \pm 0.7)^*_{JN}$

Eur. Phys. J. C72 (2012) 1917

SUMMARY

◆ KLOE@DAΦNE: good place to study γγ physics

Completed and ongoing analyses: $\gamma\gamma \rightarrow \eta$ (published), $\gamma\gamma \rightarrow \pi^0\pi^0$

◆ KLOE Upgrades:

- ✧ $e^{\pm}$ taggers (both LET nd HET) installed;
- ✧ Inner Tracker, QCALT and CCAL installation near to be completed
- ✧ Expect to collect O(10 fb^{-1}) in the next 3 years

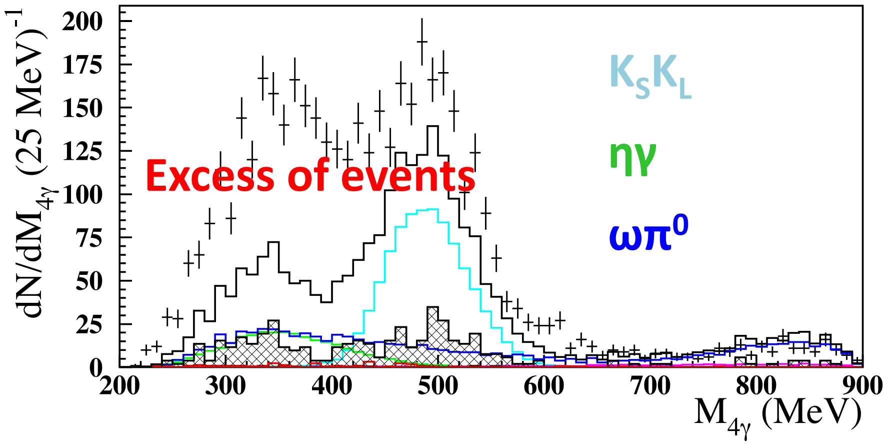
◆ Promising $e^+e^- \rightarrow e^+e^- \pi^0$ analysis with 5-6 fb^{-1} collected at KLOE-2:

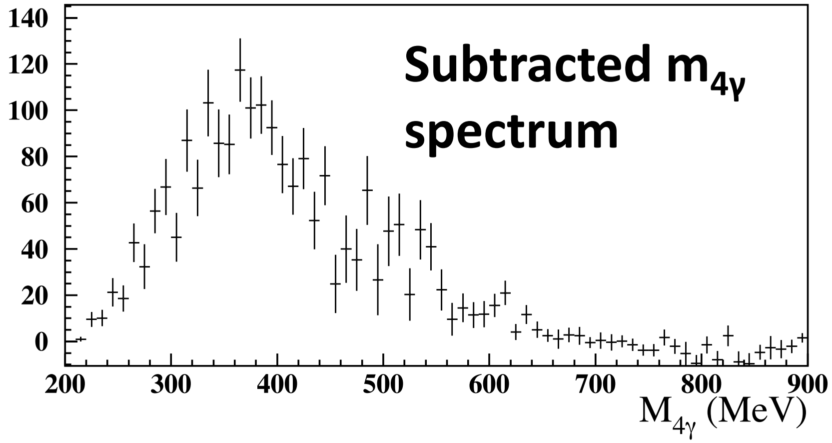
- ✧ $\pi^0\gamma\gamma$ width with statistical error of ≈1%
- ✧ Transition Form Factor in the space-like region at low Q^2 with statistical error of < 6% in each bin -> test consistency of the models fitted to CELLO, CLEO, BaBar data
- ✧ Pion-exchange contribution to the μ g-2: improvement of uncertainty, within several theoretical frames, thanks to KLOE-2 data

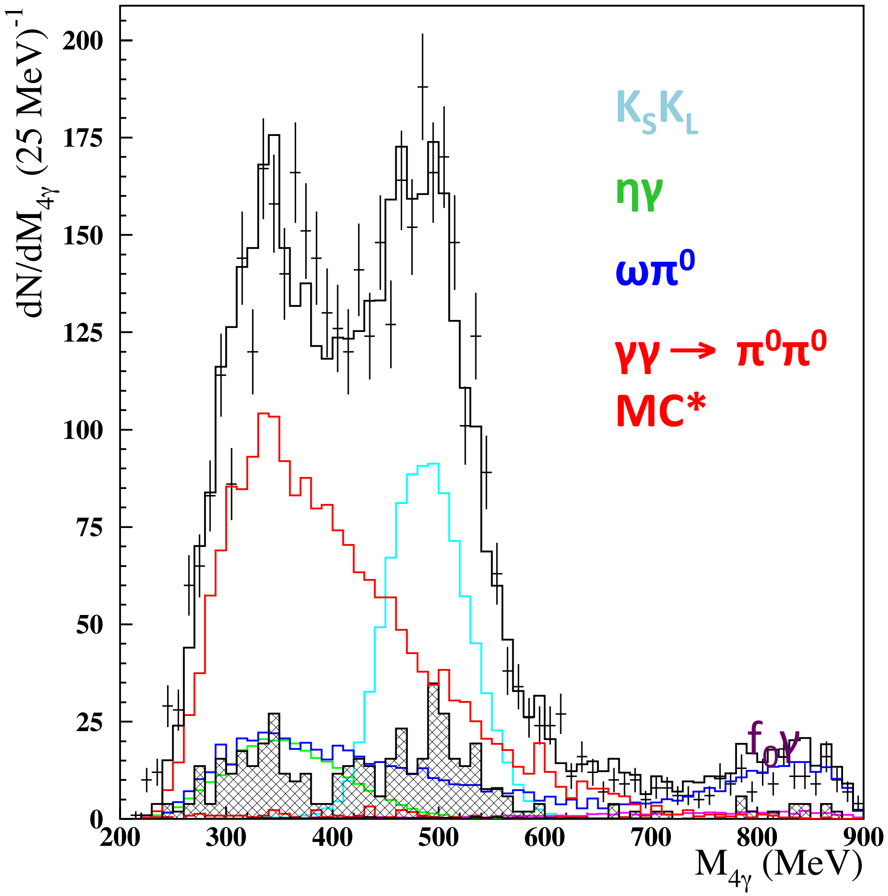
$e^+e^- \rightarrow e^+e^- \pi^0\pi^0$

(possible production of σ(500) as a resonant intermediate state)

Cut-based and multivariate analysis



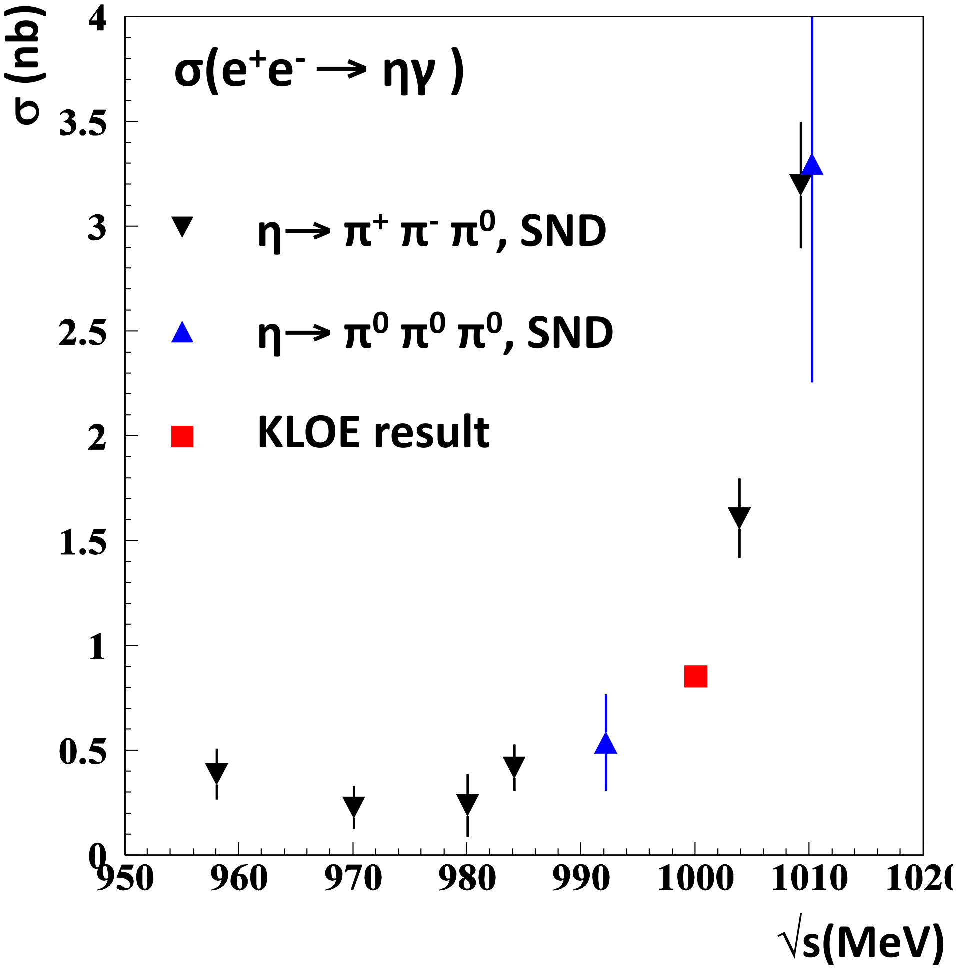




*Eur.Phys.J C47(65) 2006

As a by product: $e^+e^- \to \eta\gamma$

$\sigma(e^+e^- \to \eta\gamma, \sqrt{s}=1\ \text{GeV}) = (856 \pm 8_{stat} \pm 12_{syst} \pm 11_{BR})\ \text{pb}$

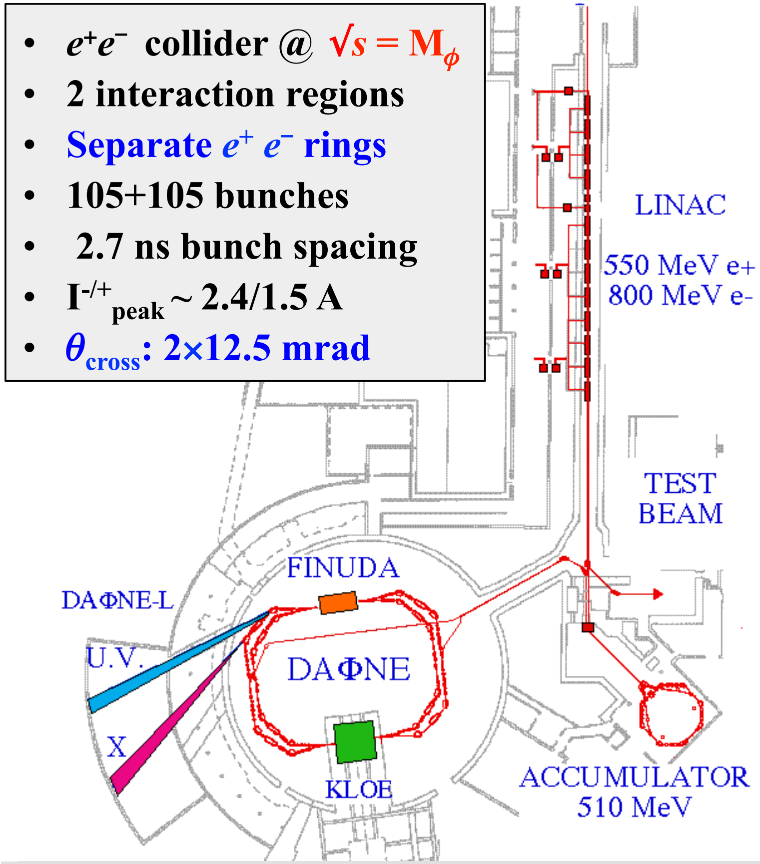


- Used as a constraint in the fit for $e^+e^- \to e^+e^-\eta \to e^+e^-\pi^+\pi^-\pi^0$

- $\sigma(e^+e^- \to \eta\gamma)$ can be independently derived as a by product of the main analysis in the case of $e^+e^- \to e^+e^-\eta \to e^+e^- 3\pi^0$, yielding $\sigma(e^+e^- \to \eta\gamma, \sqrt{s}=1\ \text{GeV}) = (853 \pm 25_{stat} \pm 5_{syst} \pm 6_{BR})\ \text{pb}$, in agreement with the value obtained in the dedicated analysis.

DAΦNE: the Frascati φ-factory

- e^+e^- collider @ $\sqrt{s} = M_\phi$
- 2 interaction regions
- Separate e^+ e^- rings
- 105+105 bunches
- 2.7 ns bunch spacing
- $I^{-/+}_{peak} \sim 2.4/1.5$ A
- θ_{cross}: 2×12.5 mrad



KLOE data taking: 2000-2006

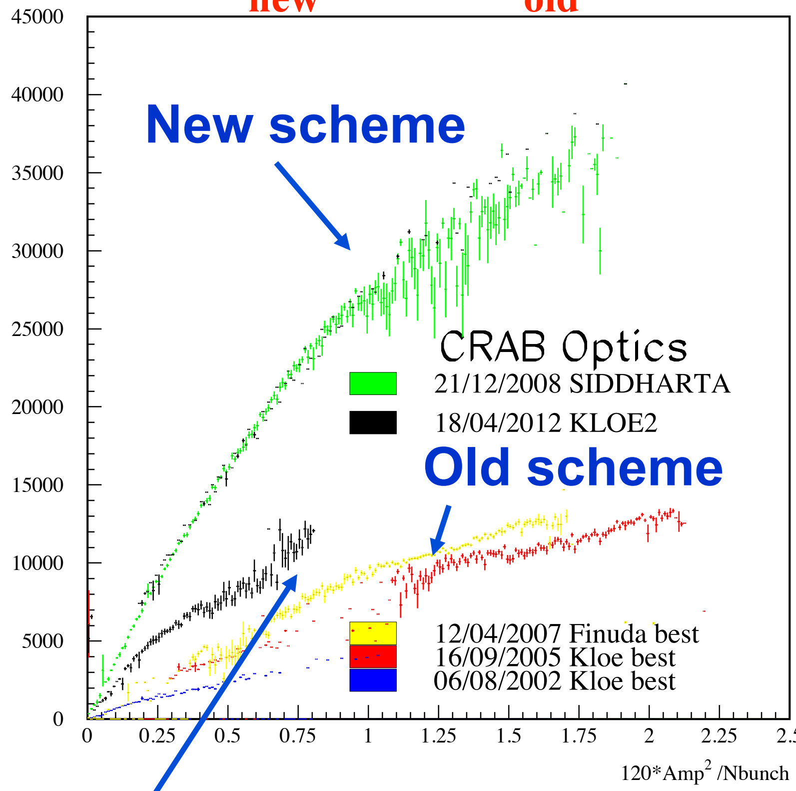
Best performance:

$$L_{peak} = 1.4 \times 10^{32}\,\mathrm{cm^{-2}s^{-1}}$$

$$\int L dt = 8.5\,\mathrm{pb^{-1}/day}$$

2008, new interaction scheme:

$L_{new} \sim 3 \times L_{old}$



Machine commissioning for KLOE-2 completed

KLOE Detector