Results and prospects on hadronic cross section and γγ physics at KLOE/KLOE-2

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Outline

KLOE measurements of $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ via ISR :

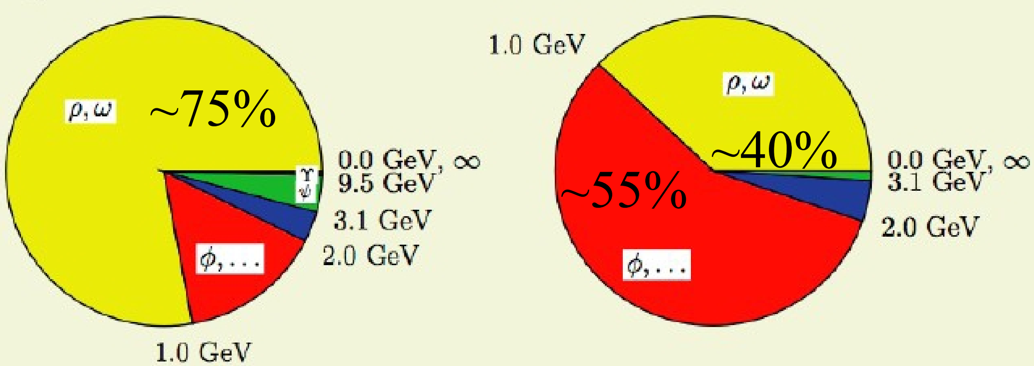
- Small (photon) angle measurements: KLOE08 and KLOE12
- Large (photon) angle measurements: KLOE10
- Evaluation of $a_\mu^{\pi\pi}$ and comparison with CMD-2/SND/BaBar
- Preliminary combination of KLOE08, KLOE10, KLOE12 for $a_\mu^{\pi\pi}$
- $\gamma\gamma$ physics at KLOE
  - $\gamma\gamma \to \eta$
  - $\gamma\gamma \to \pi^0\pi^0$

- $\gamma\gamma$ Physics program at KLOE-2

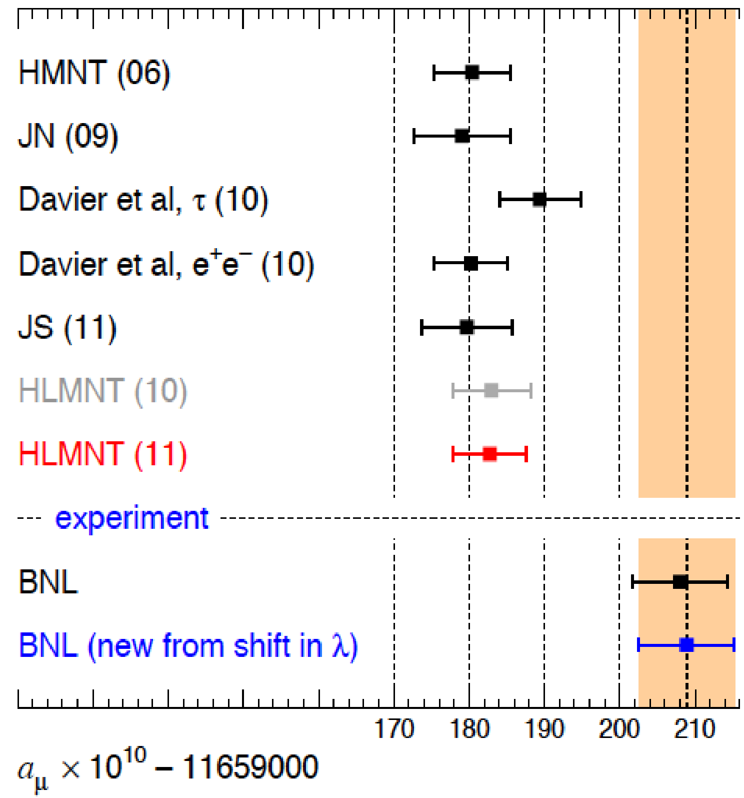
Motivation

$a_\mu^{Exp} - a_\mu^{Theo} = (27.6 \pm 8.7) \times 10^{-10} \sim 3.4\,\sigma$

F. Jegerlehner, Talk at PHIPSI08



contributions error



Hagiwara et al. arxiv:1105.3149

M. Davier at al. Eur.Phys.J. C71 (2011) 1515

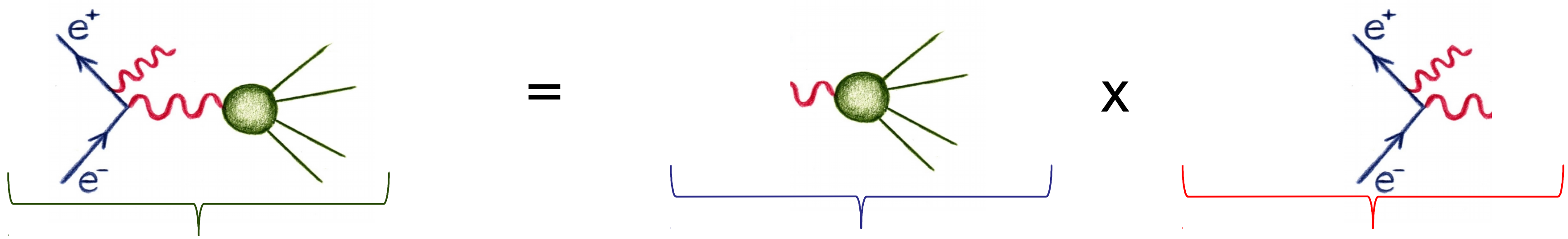
Channel	$a_\mu^{\mathrm{had,LO}}$ $[10^{-10}]$
$\pi^0\gamma$	$4.42 \pm 0.08 \pm 0.13 \pm 0.12$
$\eta\gamma$	$0.64 \pm 0.02 \pm 0.01 \pm 0.01$
$\pi^+\pi^-$	$507.80 \boxed{\pm 1.22 \pm 2.50 \pm 0.56}$
$\pi^+\pi^-\pi^0$	$46.00 \pm 0.42 \pm 1.03 \pm 0.98$

2.8×10^{-10} $(\delta a_\mu^{Theor.} \sim 5 \times 10^{-10})$

ISR: Initial State Radiation

Neglecting final state radiation (FSR):

$$\frac{d\sigma(e^+e^- \to hadrons + \gamma)}{dM^2_{hadr}} = \frac{\sigma(e^+e^- \to hadrons, M^2_{hadr})}{s} H(s, M^2_{hadr})$$



measured cross section | resulting cross section | radiator function

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

→ **EVA + PHOKHARA MC Generator**

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

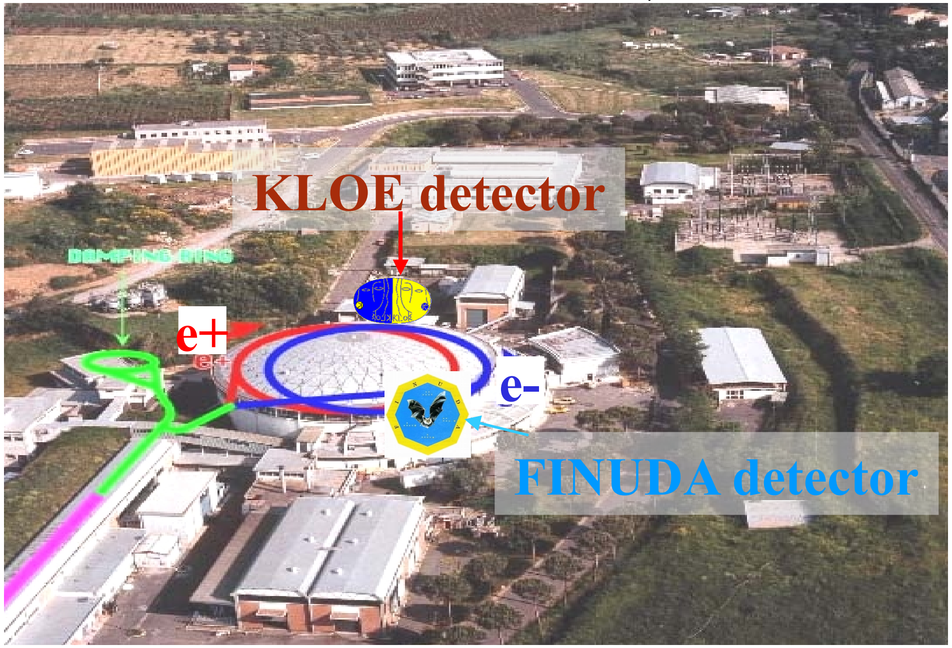
H. Czyż, A. Grzelińska, J.H. Kühn, G. Rodrigo, Eur. Phys. J. C 27, 2003

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

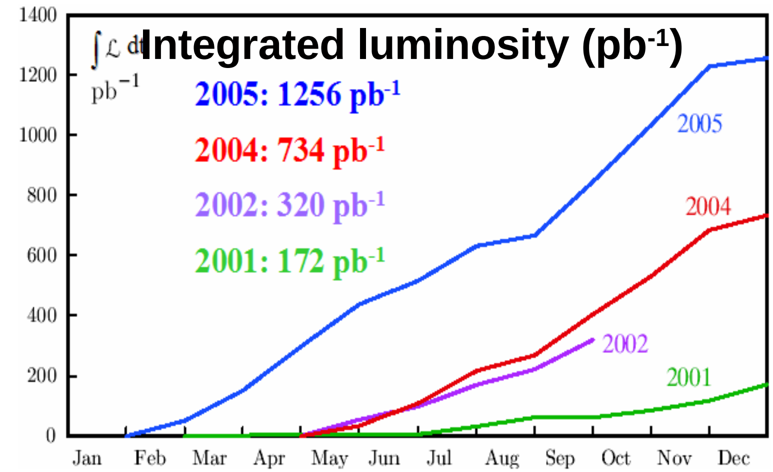
IN 2005 KLOE has published the first precision measurement of $\sigma(e^+e^- \to \pi^+\pi^-)$ with ISR using 2001 data (140pb^{-1}) PLB606(2005)12 ⇒ ~3σ discrepancy btw a_μ^{SM} and a_μ^{exp}

DAΦNE: A ϕ-Factory in Frascati (near Rome)

e^+e^- collider with $\sqrt{s} = m_\phi \approx 1.0195$ GeV



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



KLOE: 2.5 fb^{-1} @ $\sqrt{s}=M_\phi$
+ 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV

KLOE05 measurement
(PLB606(2005)12)
based on 140pb^{-1} of 2001 data
(Superseded by KLOE08)

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

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

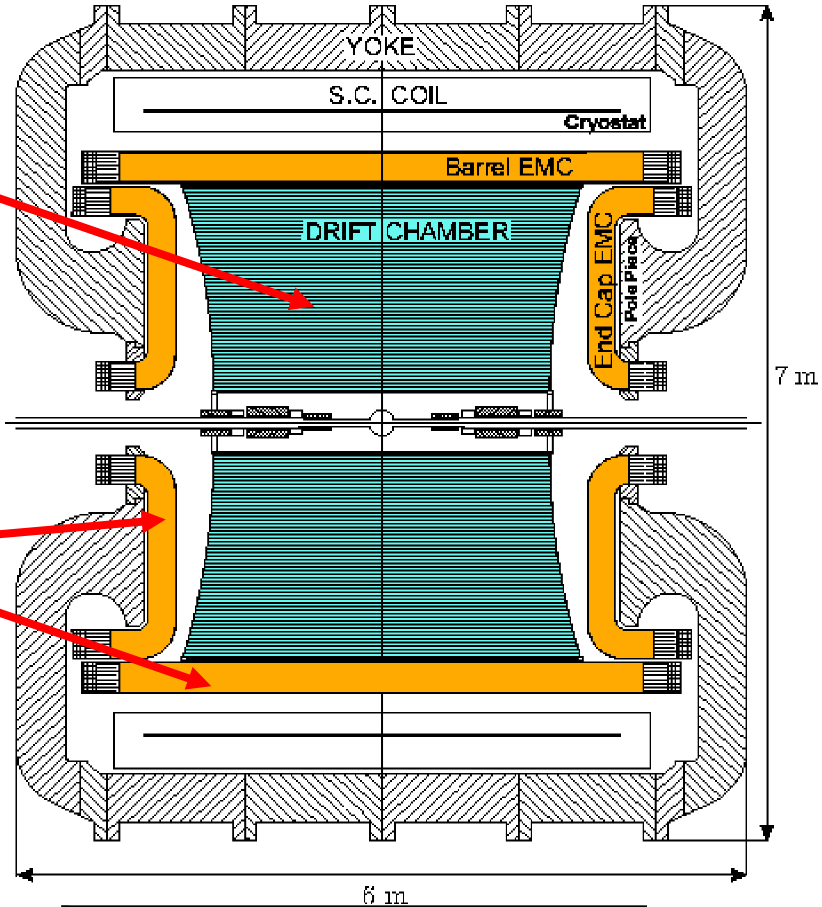
KLOE12 measurement (PLB720(2013)336)
based on 240 pb^{-1} of 2002 data
(from $\pi\pi\gamma/\mu\mu\gamma$ ratio)

KLOE Detector

Drift chamber:
- gas: 90% He-10% iC_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 1$ mm

Excellent momentum resolution

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



Calorimeter (Pb-Sci.Fi.):
- $\sigma_E/E = 5.7\% / \sqrt{(E(GeV))}$
- $\sigma_t = 55\ ps/\sqrt{(E(GeV))} \oplus 100\ ps$
- 98% of 4π

Excellent timing resolution

Magnetic field: 0.52 T

KLOE08: Small Angle ($\sqrt{s}$= 1020 MeV)

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

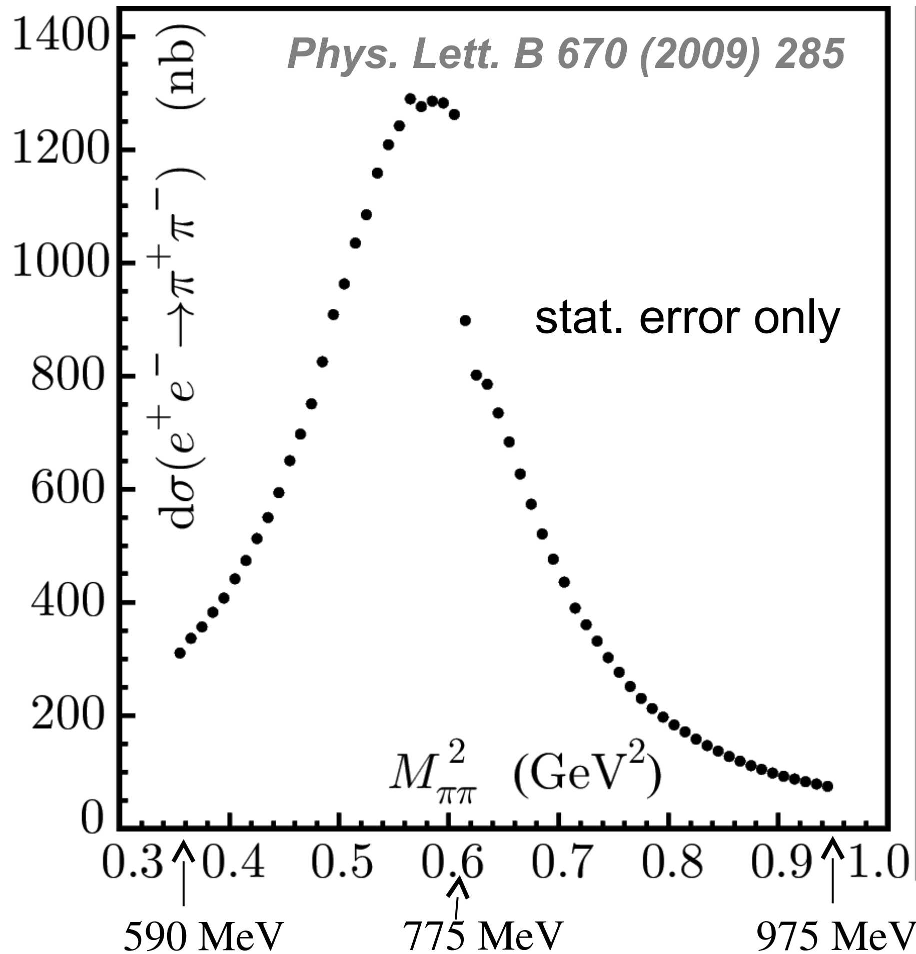
Reconstruction Filter	negligible
Background	0.3%
Trackmass/Miss. Mass	0.2%
p/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.1%
Acceptance ($\theta_{\pi\pi}$)	0.2%
Acceptance (θ_π)	negligible
Unfolding	negligible
Software Trigger	0.1%
$\sqrt{s}$ dep. Of H	0.2%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%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

experimental fractional error on a_μ = 0.6 %

FSR treatment	0.3%
Radiator H	0.5%
Vacuum polarization	0.1%

theoretical fractional error on a_μ = 0.6 %

$\sigma_{\pi\pi}$, undressed from VP, inclusive of FSR as function of $(M^0_{\pi\pi})^2$



$$a_\mu^{\pi\pi} = \int_{x1}^{x2} \sigma_{ee\to\pi\pi}(s)K(s)ds$$

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

KLOE10: Large Angle ($\sqrt{s}$= 1000 MeV)

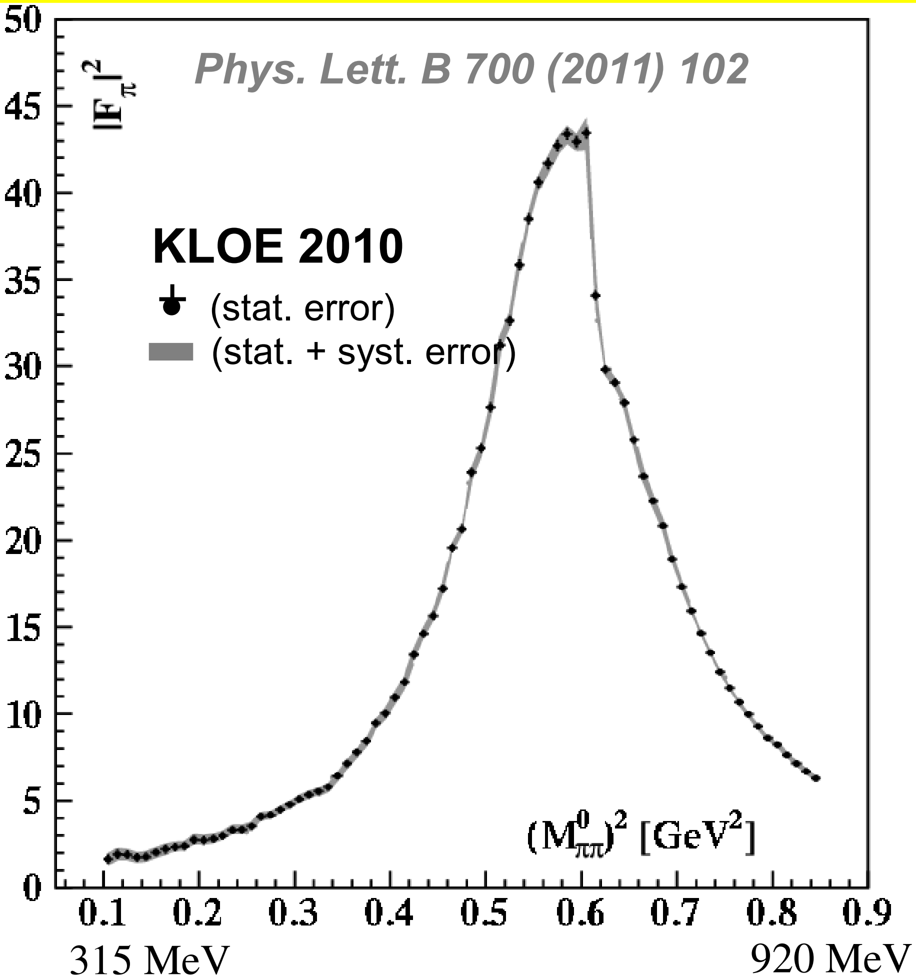


Table of systematic errors on $a_\mu^{\pi\pi}$

Reconstruction Filter	negligible
Background	0.5%
f0+ρπ	0.4%
Ω cut	0.2%
Trackmass	0.5%
p/e-ID and TCA	negligible
Tracking	0.3%
Trigger	0.2%
Acceptance	0.5%
Unfolding	negligible
Software Trigger	0.1%
Luminosity($0.1_{th} \oplus 0.3_{exp}$)%	0.3%

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

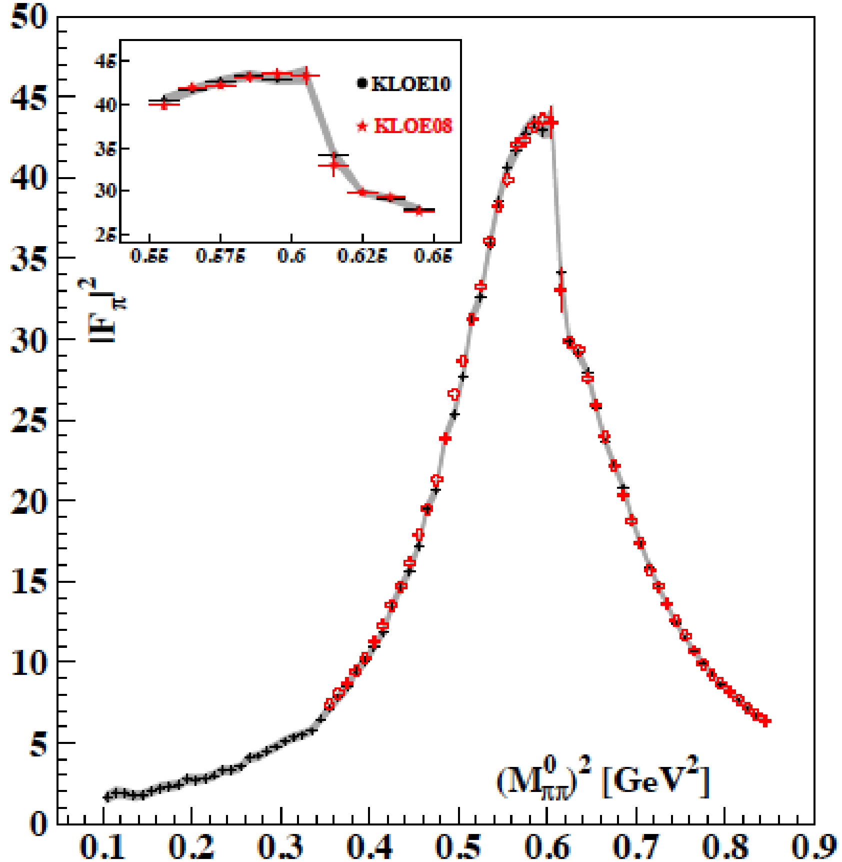
experimental fractional error on a_μ = 1.0 %

theoretical fractional error on a_μ = 0.9 %

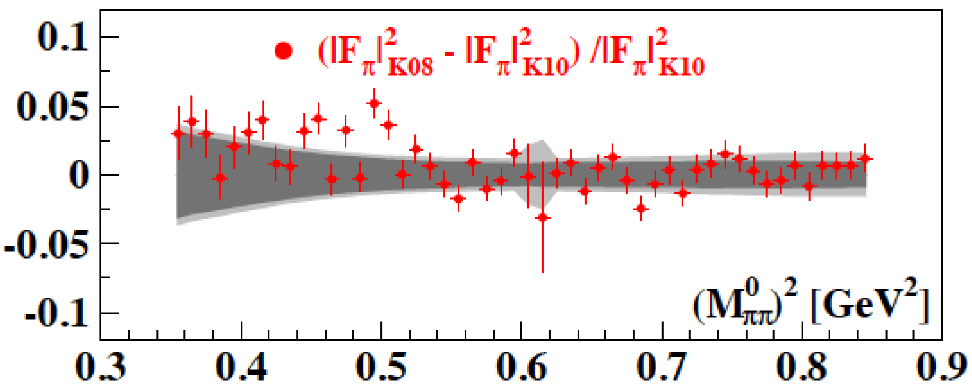
$a_\mu^{\pi\pi}$(0.1-0.85 GeV^2) = $(478.5 \pm 2.0_{stat} \pm 5.0_{syst} \pm 4.5_{theo}) \cdot 10^{-10}$

Comparison of results: KLOE10 vs KLOE08

KLOE08 result compared to KLOE10:



Fractional difference:



Good agreement with KLOE08, especially above 0.5 GeV²

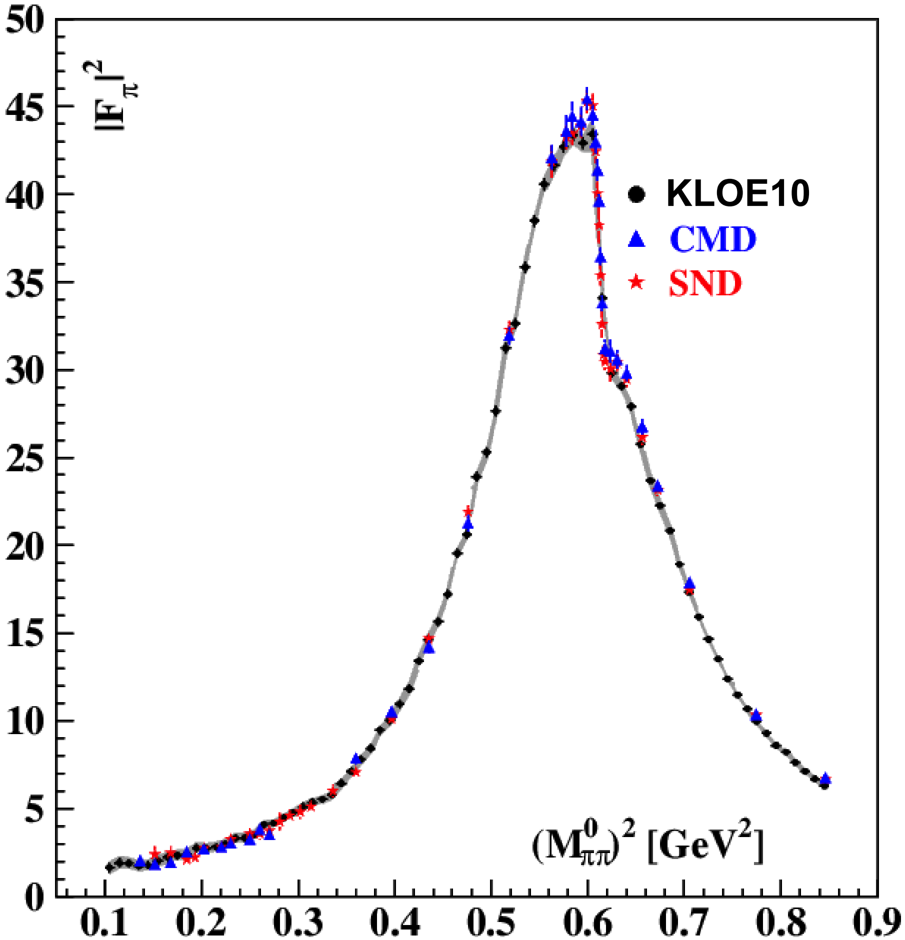
Combination of KLOE08 and KLOE10:

$a_\mu^{\pi\pi}$(0.1-0.95 GeV²) = (488.6±6.0) · 10^{-10}

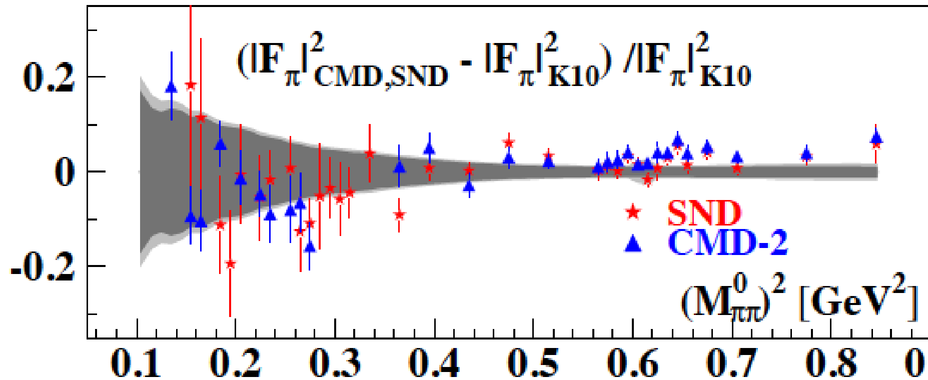
KLOE covers ~70% of total a_μ^{HLO} with a fractional total error of 1.2%

Comparison of results: KLOE10 vs CMD-2/SND

CMD and SND results compared to KLOE10: Fractional difference



SND: M.N. Achasov et al., J. Exp. Theor. Phys. 103, 480 (2006)
CMD-2: R.R. Akhmetshin et al., PLB648, 28 (2007)

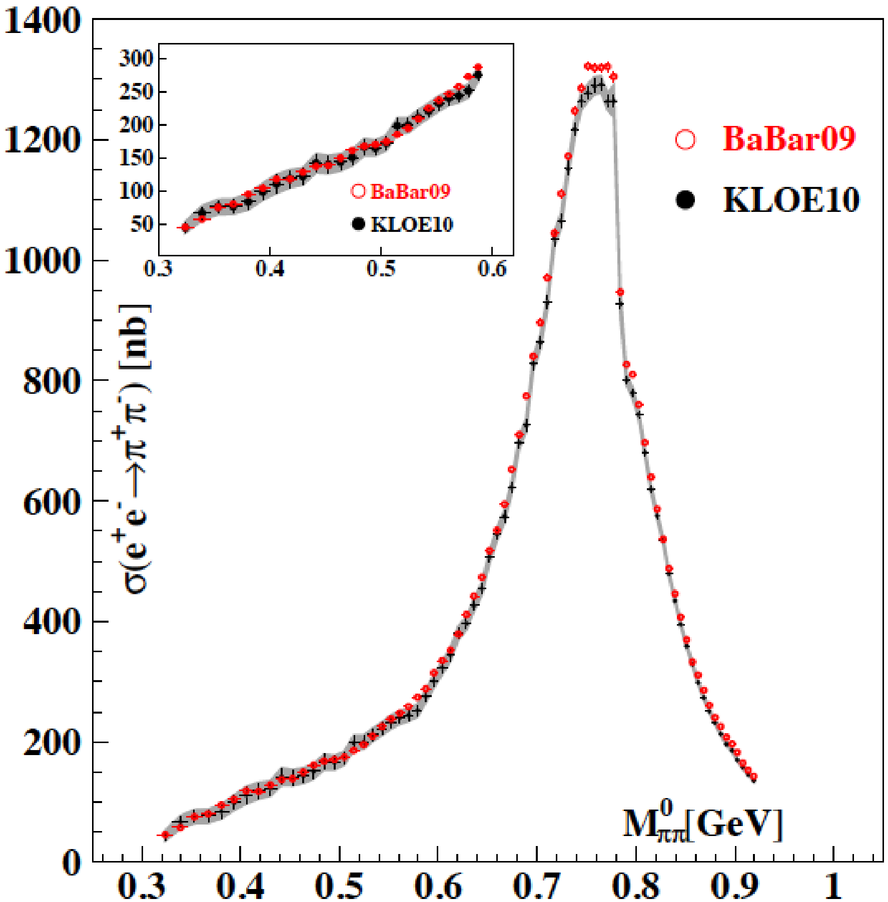


band: KLOE10 error

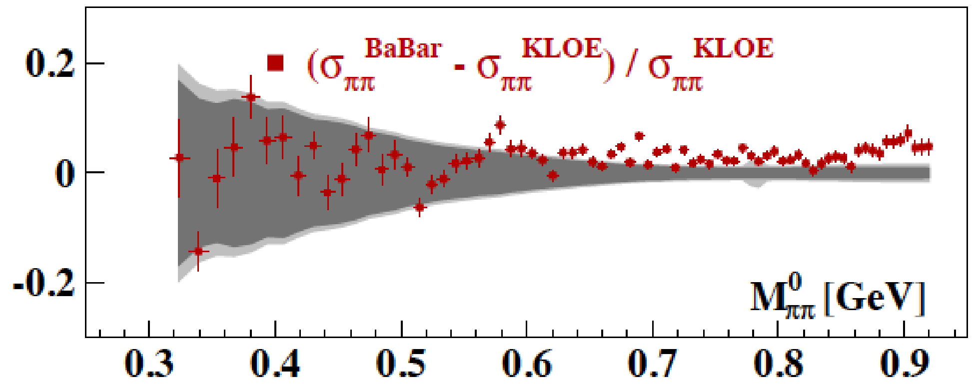
Below the ρ peak good agreement with CMD-2/SND.
Above the ρ peak KLOE10 slightly lower

Comparison of results: KLOE10 vs BaBar

BaBar results compared to KLOE10: Fractional difference



BaBar: B. Aubert et al., Phys. Rev. Lett. 103, 231801 (2009)



band: KLOE10 error

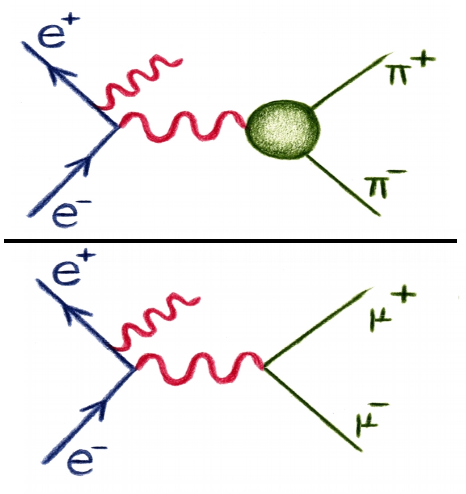
Agreement within errors below 0.6 GeV; BaBar higher by 2-3% above 0.6 GeV

KLOE12: $\sigma_{\pi\pi}$ measurement from $\pi\pi\gamma/\mu\mu\gamma$

Phys. Lett. B 720 (2013) 336–343

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).

$$\boxed{|F_\pi(s')|^2 \approx \underbrace{\frac{4\left(1+2m_\mu^2/s'\right)\beta_\mu}{\beta_\pi^3}}_{\substack{\text{kinematical factor}\\ (s_{\mu\mu}^{\text{Born}}\,/\,s_{\pi\pi}^{\text{Born}})}} \underbrace{\frac{d\sigma_{\pi\pi\gamma}/ds'}{d\sigma_{\mu\mu\gamma}/ds'}}_{\substack{\text{meas.}\\ \text{quantities}}}}$$



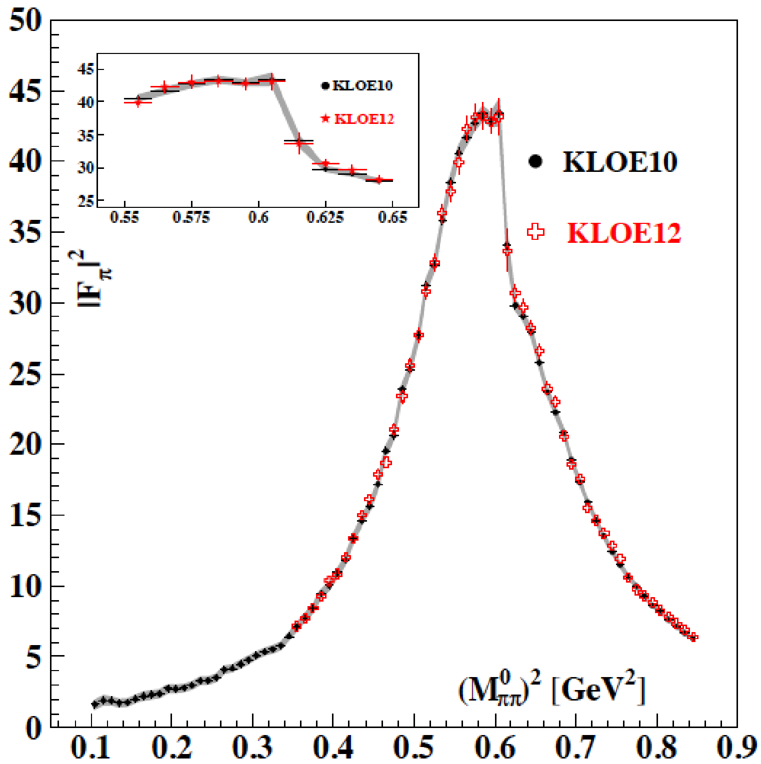
Many systematic effects drop out:

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

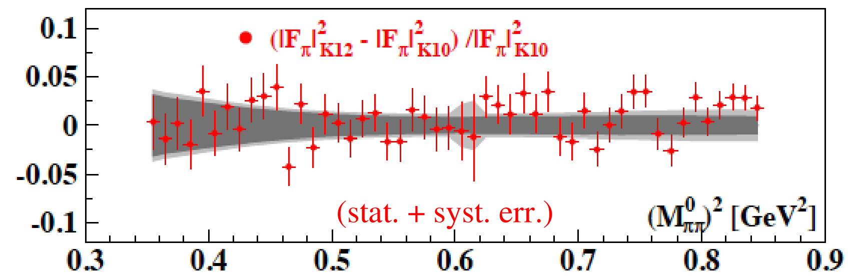
Data Sample:

- 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

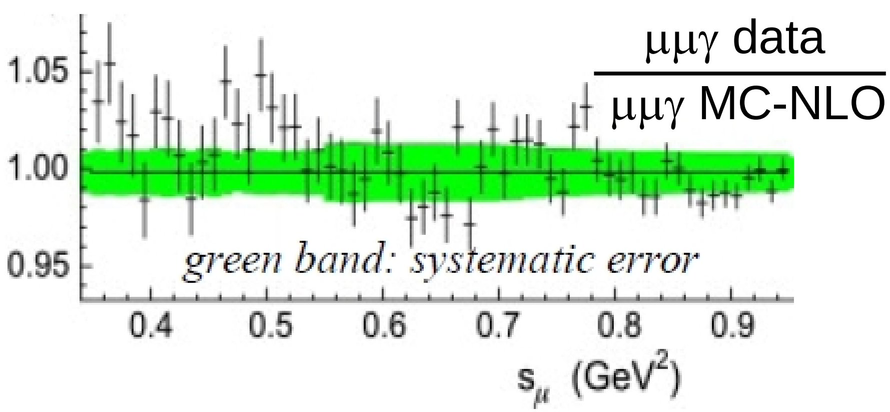
Comparison of results: KLOE12 vs KLOE10



Fractional difference:



band: KLOE10 error

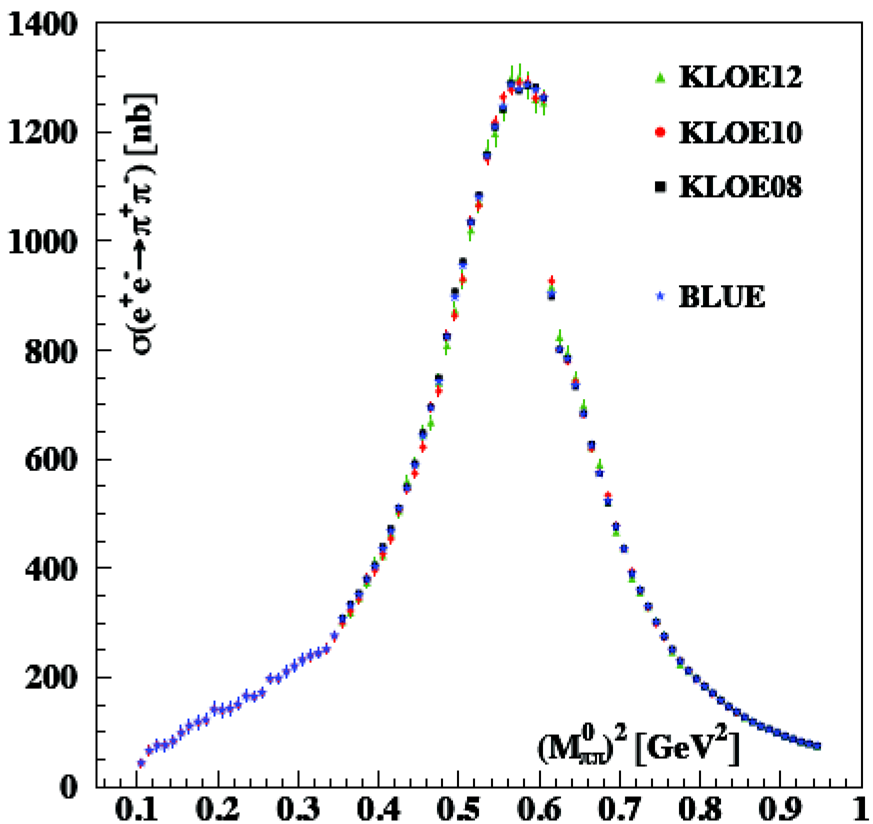


Excellent agreement between these two independent measurements!

Analysis	$a_\mu^{\pi\pi}(0.35 - 0.85\ \text{GeV}^2) \times 10^{10}$
KLOE12	$377.4 \pm 1.1_{\text{stat}} \pm 2.7_{\text{sys+theo}}$
KLOE10	$376.6 \pm 0.9_{\text{stat}} \pm 3.3_{\text{sys+theo}}$

Preliminary combination of KLOE08,10,12

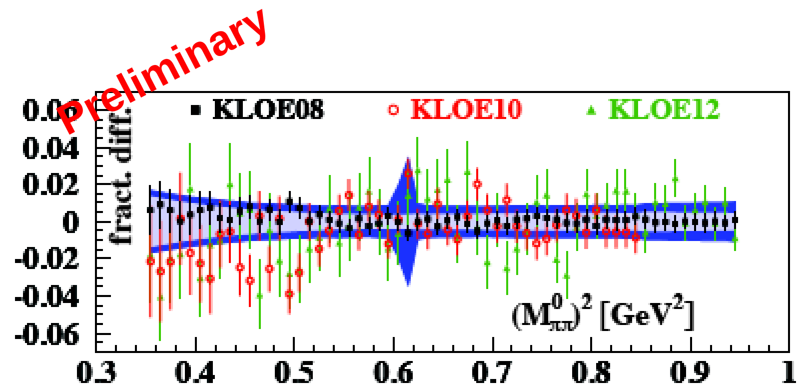
by Stefan E. Müller



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



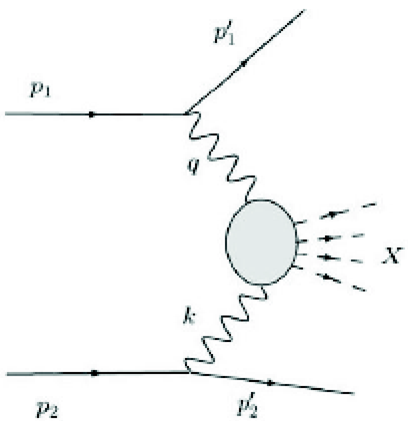
$$\frac{|F_{\mathrm{KLOEXX}}|^2 - |F_{\mathrm{BLUE}}|^2}{|F_{\mathrm{BLUE}}|^2}$$

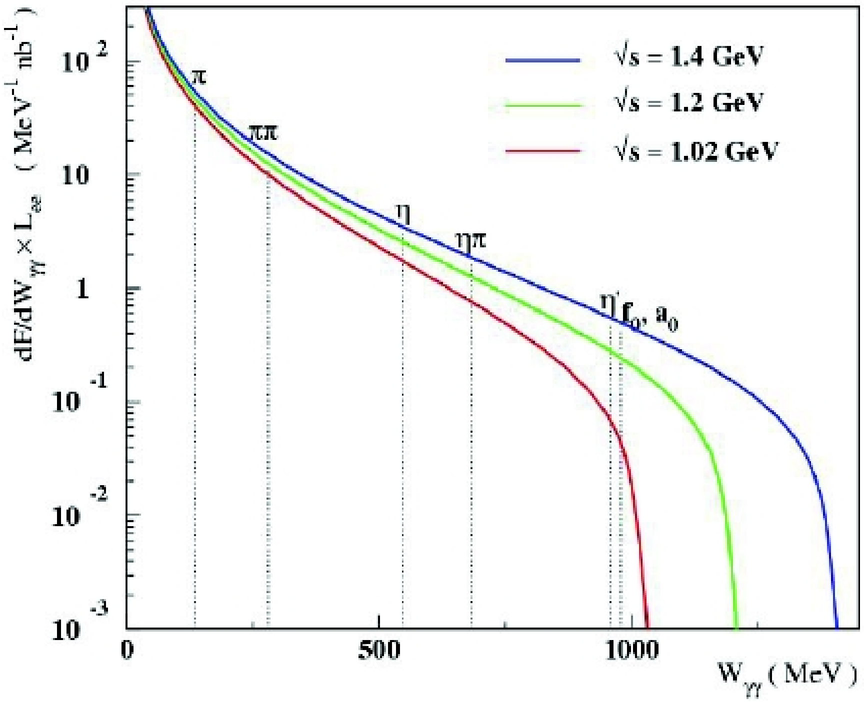
Grey band: Stat. errors

Blue band: Stat. + Syst. errors

$a_\mu^{\pi\pi}(0.1\text{-}0.95\ \mathrm{GeV}^2) = (487.8 \pm 5.7) \cdot 10^{-10}$

γγ physics





- $X = \pi\pi \Rightarrow$ search for $\sigma(600)$
- $X = \pi^0, \eta, (\eta') \Rightarrow \Gamma(X \to \gamma\gamma)$;
- Transition form factors $F_{X\gamma^*\gamma^*}(q_1^2, q_2^2)$

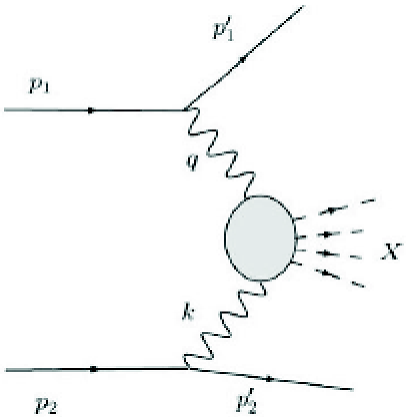
Tagger is essential to reduce the background from the ϕ and to close the kinematics--> KLOE2

In KLOE we didn't have the taggers-->off-peak data

$\Gamma(\eta\to\gamma\gamma)$ measurement in $\gamma\gamma$ interaction at KLOE

JHEP01(2013)119

KLOE published in 2013 the $\Gamma(\eta\to\gamma\gamma)$ measurement based on an integrated luminosity of 242.5 pb^{-1} collected at e+e- energy of 1 GeV.



Final state leptons were undetected (high probability out of detector acceptance)

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

$$\sigma(e^+e^-\to e^+e^-\eta) = (34.5 \pm 2.5_{\rm stat} \pm 1.0_{\rm syst} \pm 0.7_{\rm FF} \pm 0.4_{\rm BR})\ {\rm pb}\,.$$

$\eta\to3\pi^0$

$$\sigma(e^+e^-\to e^+e^-\eta) = (32.0 \pm 1.5_{\rm stat} \pm 0.9_{\rm syst} \pm 0.2_{\rm FF} \pm 0.2_{\rm BR})\ {\rm pb}$$

$$\boxed{\sigma(e^+e^-\to e^+e^-\eta) = (32.7 \pm 1.3_{\rm stat} \pm 0.7_{\rm syst})\ {\rm pb}\,.}$$

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

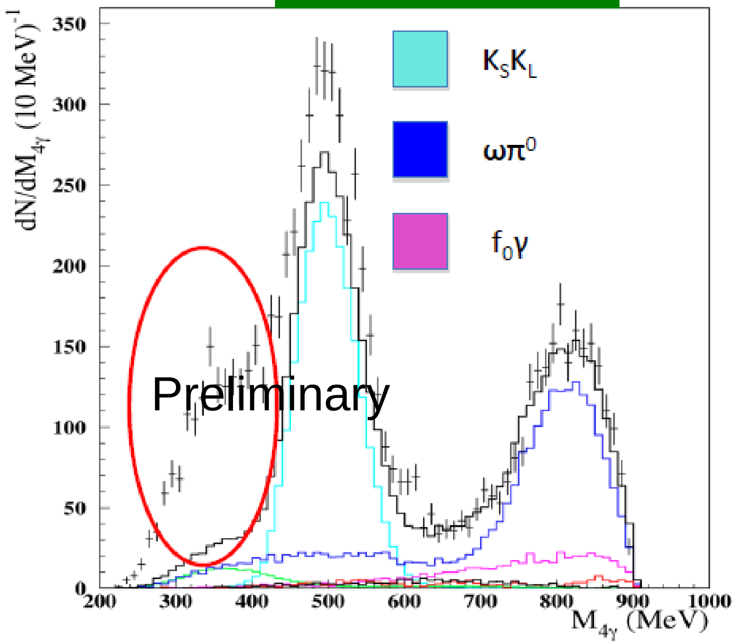
Best single measurement result driving the new world average.

$\gamma\gamma\rightarrow\pi^0\pi^0$

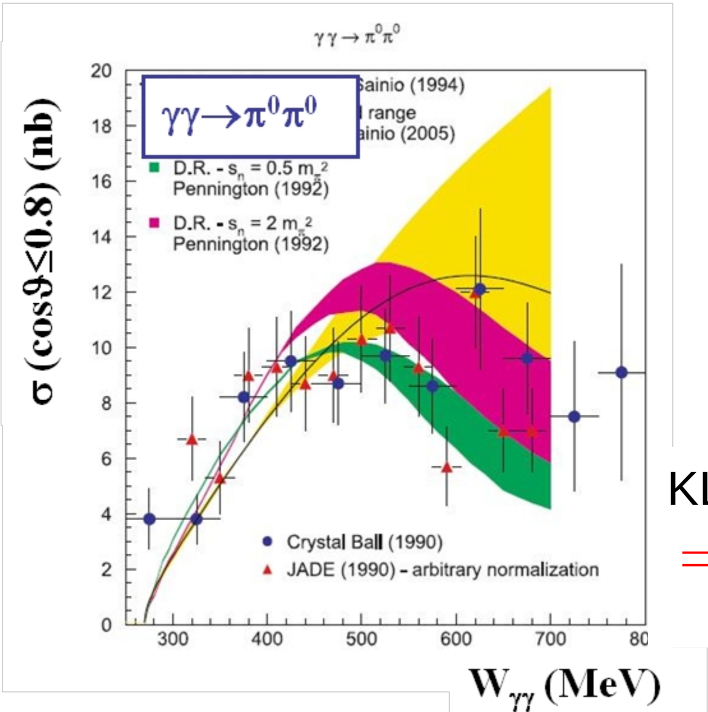
- $e^+e^- \rightarrow e^+e^- \pi^0\pi^0$
- 240 pb^{-1} off-peak ($\sqrt{s}$ = 1 GeV)
- Selected sample: 4 prompt photons
- Excess of events with respect to background in the low mass region

∀ $\gamma\gamma\rightarrow\pi^0\pi^0$ cross-section evaluation in progress

8090 events after selections



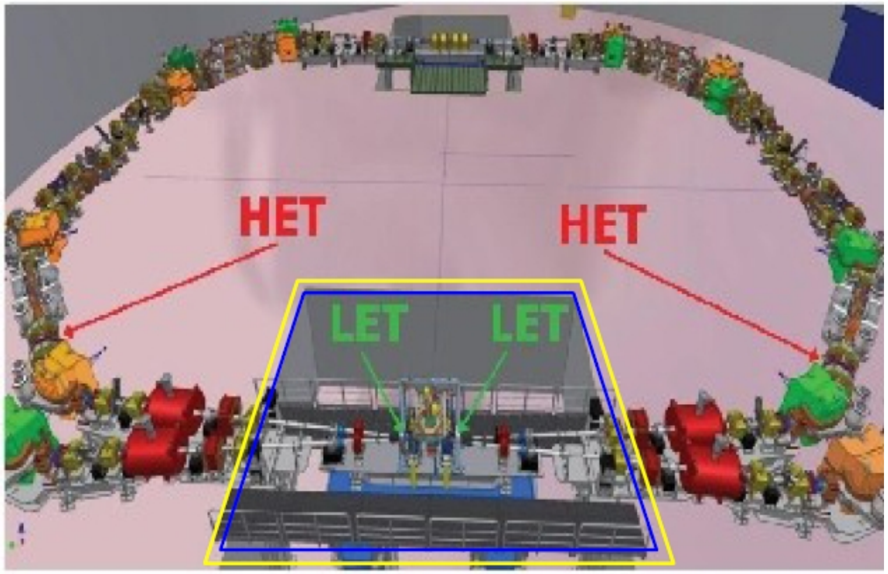
4γ invariant mass distribution



KLOE-2: *O*(10 fb^{-1})at $\sqrt{s}$ = M_ϕ with $e^\pm$ tagging

⇒ 2% statistical accuracy using the same energy bin as Crystal Ball (~20% error)

$\gamma\gamma$ physics at KLOE2

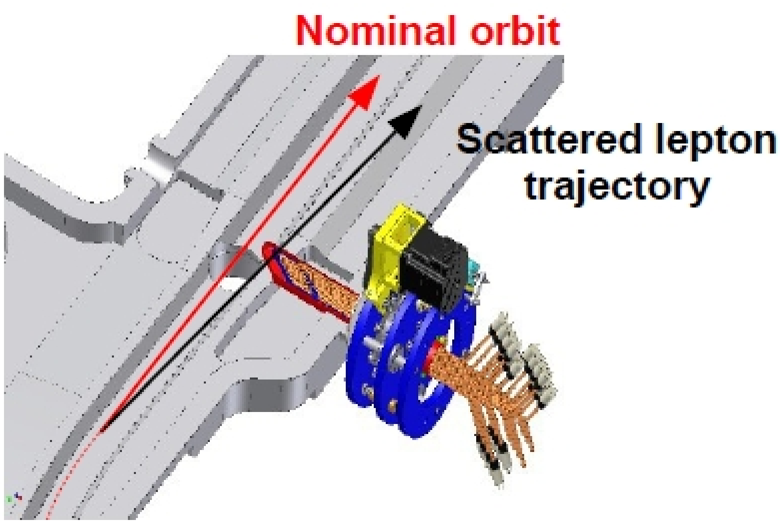


$$e^+ e^- \to e^+ e^- \gamma^* \gamma^* \to \boxed{e^+ e^-}\ \boxed{X}$$

to taggers
(HET or LET)

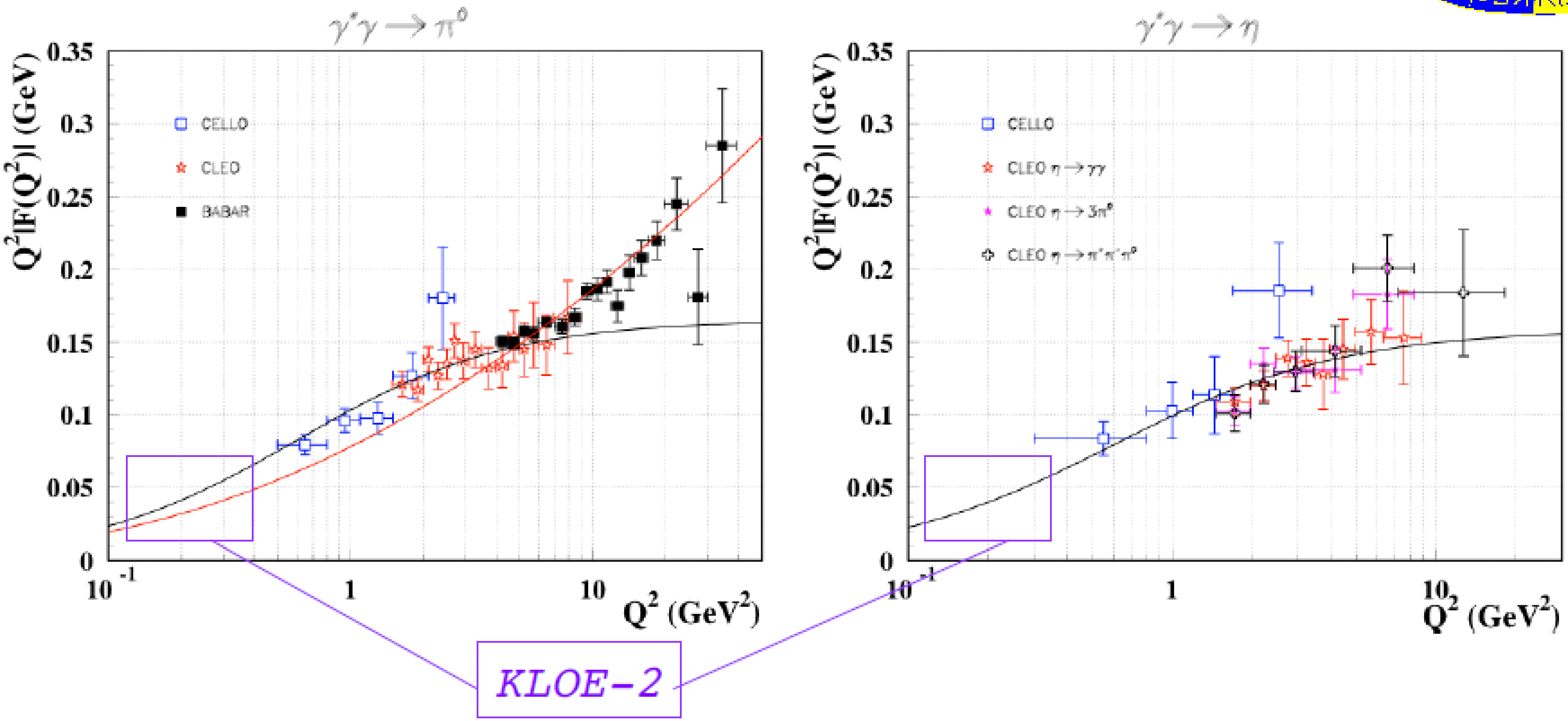
in KLOE

LET (Low Energy Tagger)
calorimeters, LYSO + SiPM
Inside KLOE det. (1m from IP)
Energy acceptance 160-400 MeV.

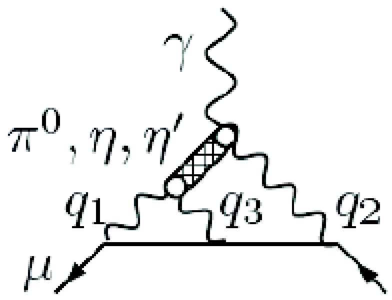


HET (High Energy Tagger)
position sensitive detectors
(strong energy-position correlation
$\Rightarrow$ use the DAΦNE magnets as $e^{\pm}$ spectrometer)
After bending dipole (11m from IP)
Energy acceptance 420-495 MeV.

KLOE-2 contribution to a_μ^{LbL}

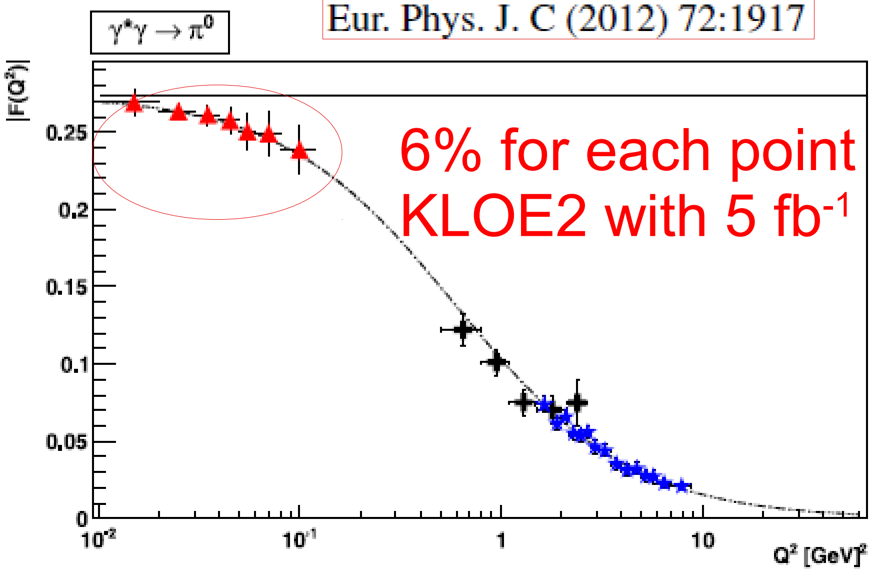


- **Measurement of $\Gamma(P\rightarrow\gamma\gamma)$**
- **Transition form factors $F_{P\gamma^*\gamma^*}(q_1^2,q_2^2)$:**
  - **input for the calculation of the Light-by-Light contribution to g-2 of the muon**



Feasibility of the $\gamma^*\gamma\pi^0$ transition form factor measurement

Eur. Phys. J. C (2012) 72:1917



$0.01<Q^2<0.1$ GeV^2

By including KLOE-2→a reduction of a factor 2 in the error of $a_\mu^{\pi 0}$!

In addition the measurement of $\Gamma(\pi^0\to\gamma\gamma)$ will constrain $F_{\pi 0}(q^2=0)$ (which is now obtained by WZW model $1/(4\pi^2 f_\pi)$ w/o error). **~1% st. accuracy** with 5 fb^{-1} int. lum..

A0 : CELLO, CLEO, PDG;

A1 : CELLO, CLEO, PrimEx;

A2 : CELLO, CLEO, PrimEx, KLOE-2;

B1 : CELLO, CLEO, BaBar, PrimEx;

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

Estimate of KLOE-2 impact on the accuracy of $a_\mu^{\mathrm{LbyL};\pi^0}$

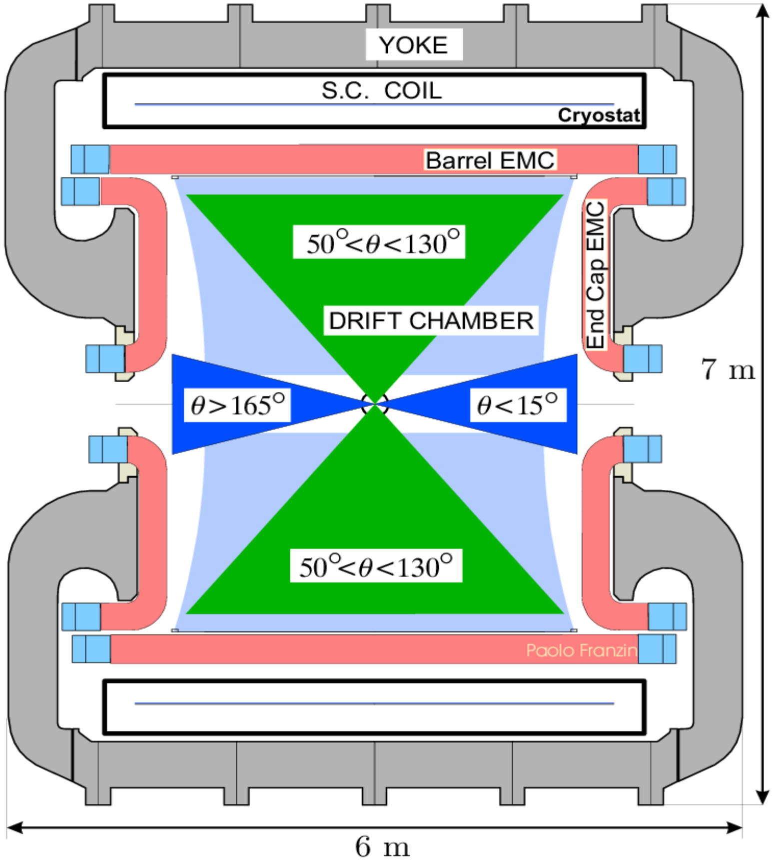
Model	Data	χ^2/d.o.f.	Parameters			$a_\mu^{\mathrm{LbyL};\pi^0} \times 10^{11}$
VMD	A0	6.6/19	$M_V = 0.778(18)$ GeV	$F_\pi = 0.0924(28)$ GeV		$(57.2 \pm 4.0)_{JN}$
VMD	A1	6.6/19	$M_V = 0.776(13)$ GeV	$F_\pi = 0.0919(13)$ GeV		$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$M_V = 0.778(11)$ GeV	$F_\pi = 0.0923(4)$ GeV		$(57.3 \pm 1.1)_{JN}$
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	$(71.8 \pm 0.7)^*_{JN}$

Conclusion

- KLOE has performed a series of precision measurements with ISR KLOE08, and KLOE10, normalized to Bhabha events, and KLOE12 normalized to muons allowing to measure $a_\mu^{\pi\pi}$ in the region below 1 GeV with **~1%** total error. $|F_\pi|^2$ KLOE12 measurement (**0.7%** systematic error), it doesn't rely on specific theoretical input allowing a stringent cross check of the published measurements with comparable systematic error .

KLOE published $\Gamma(\eta\to\gamma\gamma)$ usign $\gamma\gamma$ events off-peak; measurement of $\gamma\gamma\to\pi^0\pi^0$ cross section in progress.

- KLOE2 can give an important contribution to $\gamma\gamma$ physics. using $\gamma\gamma$ taggers for example:
  - $\Gamma(\pi_0\to\gamma\gamma)$ at 1%
- - $F_{\pi 0}(Q^2)$ in the region Q^2<0.1 GeV^2 with 6% stat. uncertainty for each point.
- KLOE2 data taking is currently running and data analysis of new data are in progress . It is expected to take 5-10 fb^{-1} in the next 3 years.



SPARE SLIDES

Luminosity:

KLOE measures L with Bhabha scattering

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

Eur.Phys.J.C47:589-596,2006

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

Generator used for σ_{eff}: **BABAYAGA** (Pavia)

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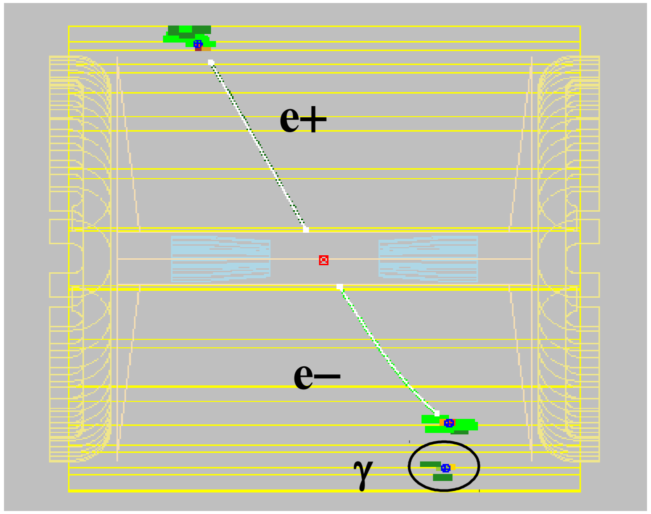
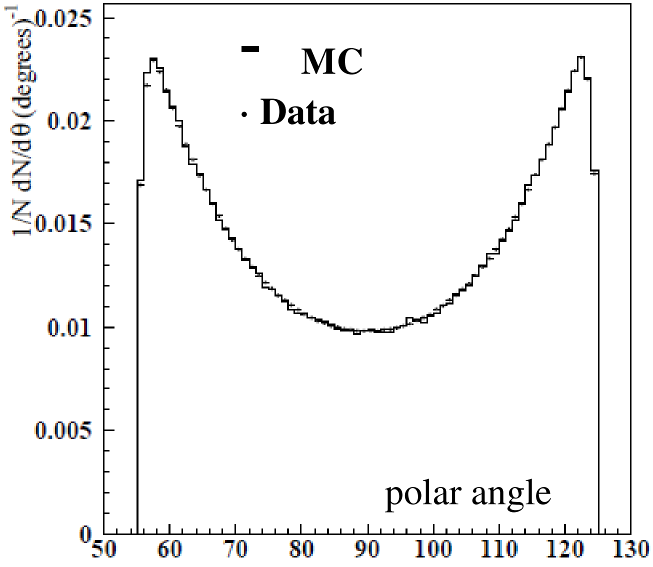
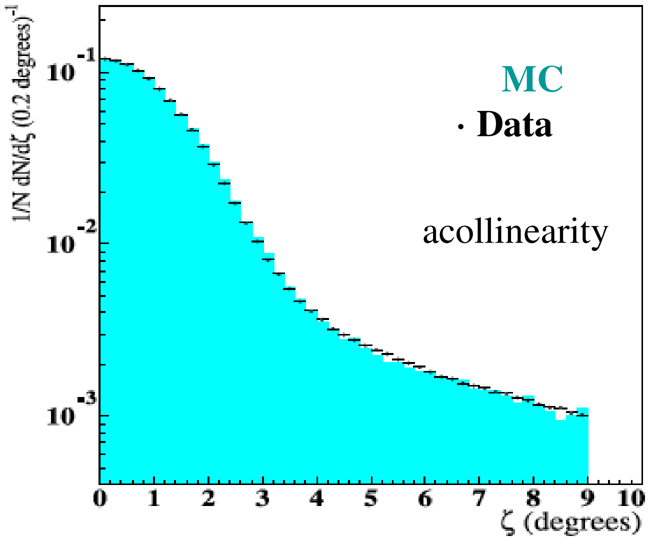
New version (**BABAYAGA@NLO**) gives 0.7% decrease in cros. sect., and better accuracy:0.1%

Systematics on Luminosity:

TOTAL 0.1 % th $\oplus$ 0.3% exp = 0.3%







Luminosity:

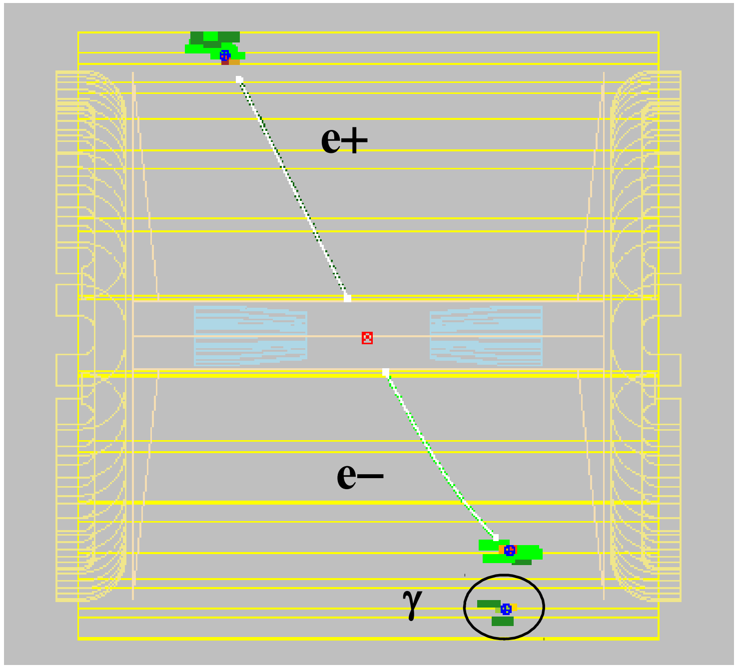
KLOE measures $\mathcal{L}$ with Bhabha scattering

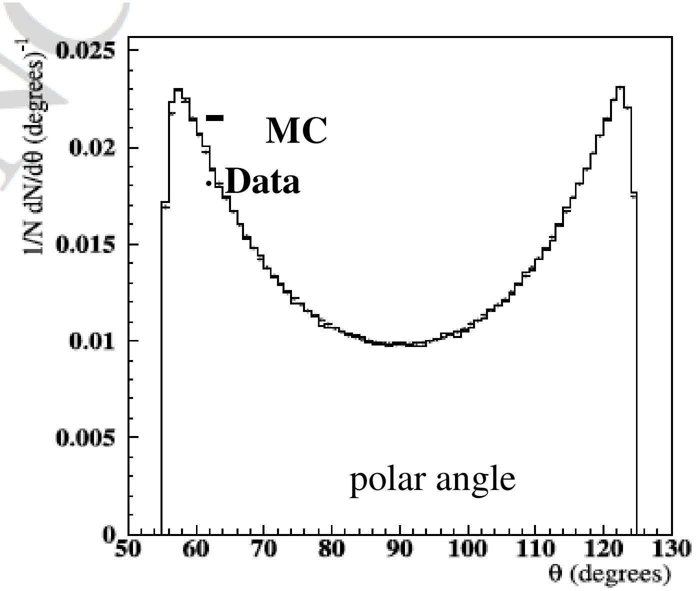
$55° < \theta < 125°$

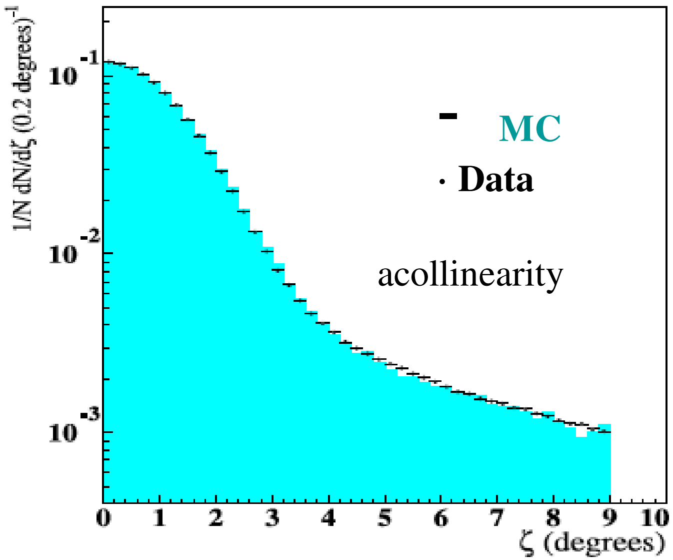
acollinearity $< 9°$

p $\geq$ 400 MeV

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







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)
  >> δMππ2~2 10-3 GeV2

⇒ Unfolding only relevant at low Mππ2 (up to 4%) and at ρ−ω cusp,

- Negligible contribution of LO FSR, and <2% contribution of NLO FSR(1γISR+1γFSR) only at low Mππ2
- Normalize to **Luminosity** (=Bhabha), but also to **μμγ** (K12)
- Use **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

⇒ Larger effects on the unfolding

- Negligible contribution of LO FSR, % contribution of NLO FSR(1γISR+1γFSR)
- Normalize to **μμγ**
- Interplay btw **Phokhara** and **AfkQED** to estimate additional-photon effects

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