Hadron Physics: the KLOE legacy

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Paolo Franzini and Juliet Lee-Franzini Memorial Symposium
19 April 2022 – Laboratori Nazionali di Frascati

90's life @ LNF

1992: The DAΦNE Physics Handbook

STUDYING the f_0 and η' at DAΦNE

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Abstract

At the end of 1995, the Frascati ϕ–factory will begin delivering of the order of 500 ϕ-mesons/sec. This provides a unique opportunity to study the $f_0(975)$ in ϕ radiative decays, even for branching ratios which in some estimates could be as low as 1×10^{-6}.

Hadron Physics @ KLOE

Key ingredients for precision Hadron Physics @ KLOE:

- Lots of light mesons! $\sim 4 \times 10^7\ \eta/\text{fb}^{-1}$
- η and η' produced from ϕ radiative decay: tagged by the monochromatic recoil photon
- State-of-the-art detector:
  - large acceptance
  - high precision momentum tracking
  - excellent calorimeter timing
- Kinematic fit constraint exploited to improve resolutions

My first steps in Hadron Physics

Kloe Memo 98-145

April 98

Detection of $f_0(975), a_0(980)$ with 5×10^8 ϕ decays

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INTRODUCTION

The decays $\phi \to f_0\gamma$, $\phi \to a_0\gamma$ have been studied with a full MonteCarlo simulation of the KLOE detector [1] [2], using the complete event reconstruction package [3], taking into account all possible sources of background, with the aim of evaluating the detector efficiency and the accuracy that can be reached on the BR.

For the decay $\phi \to f_0\gamma$ this study has been done both in the charged pion channel (BR($f_0 \to \pi^+\pi^-$)$\sim$ 52%) and in the neutral pion channel (BR($f_0 \to \pi^0\pi^0$)$\sim$ 26%). We especially emphasize the existence of an interesting interference pattern between $f_0\gamma \to \pi^+\pi^-\gamma$ and $e^+e^- \to \pi^+\pi^-\gamma$: the sign on the interference in unknown, it depends on the sign of the $\phi f_0\gamma$ coupling and therefore on the unknown nature of the f_0 [4]. For the decay $\phi \to a_0\gamma$ this study has been done in the neutral channel (BR($a_0 \to \eta\pi^0 \to \gamma\gamma\gamma\gamma$)$\sim$ 39%) [5].

The values 4.7×10^{-4} and 1.3×10^{-4}, recently measured by the SND collaboration [6], have been assumed respectively for the BR($\phi \to f_0\gamma$) and BR ($\phi \to a_0\gamma$). With these BR's, the following number of events are expected for 5×10^8 ϕ decays:

61000 events for $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$
160000 events for $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$ (positive interference)
41000 events for $\phi \to f_0\gamma \to \pi^+\pi^-\gamma$ (negative interference)
25500 events for $\phi \to a_0\gamma \to \eta\pi^0\gamma \to \gamma\gamma\gamma\gamma\gamma$

In order to see how well the f_0, a_0 signal can be isolated against other decay channels, the selection criteria for f_0, a_0 have been applied also to the following data sets from the "10^8 Events Project":

First KLOE data presented @ HADRON99

"Detection of Scalar and Pseudoscalar Mesons at DAΦNE with KLOE"
8th International Conference on Hadron Spectroscopy – HADRON99 – Beijing, 24–28 August 1999

A first glance to real data

KLOE data taking

- First collisions on 14th April 1999
- Short period of ϕ scan
- One month of parassitic running
- First period of continuos data taking: July 30th ÷ August 8th

Total integrated luminosity:

$\mathcal{L} \sim 200\,\mathrm{nb}^{-1}$

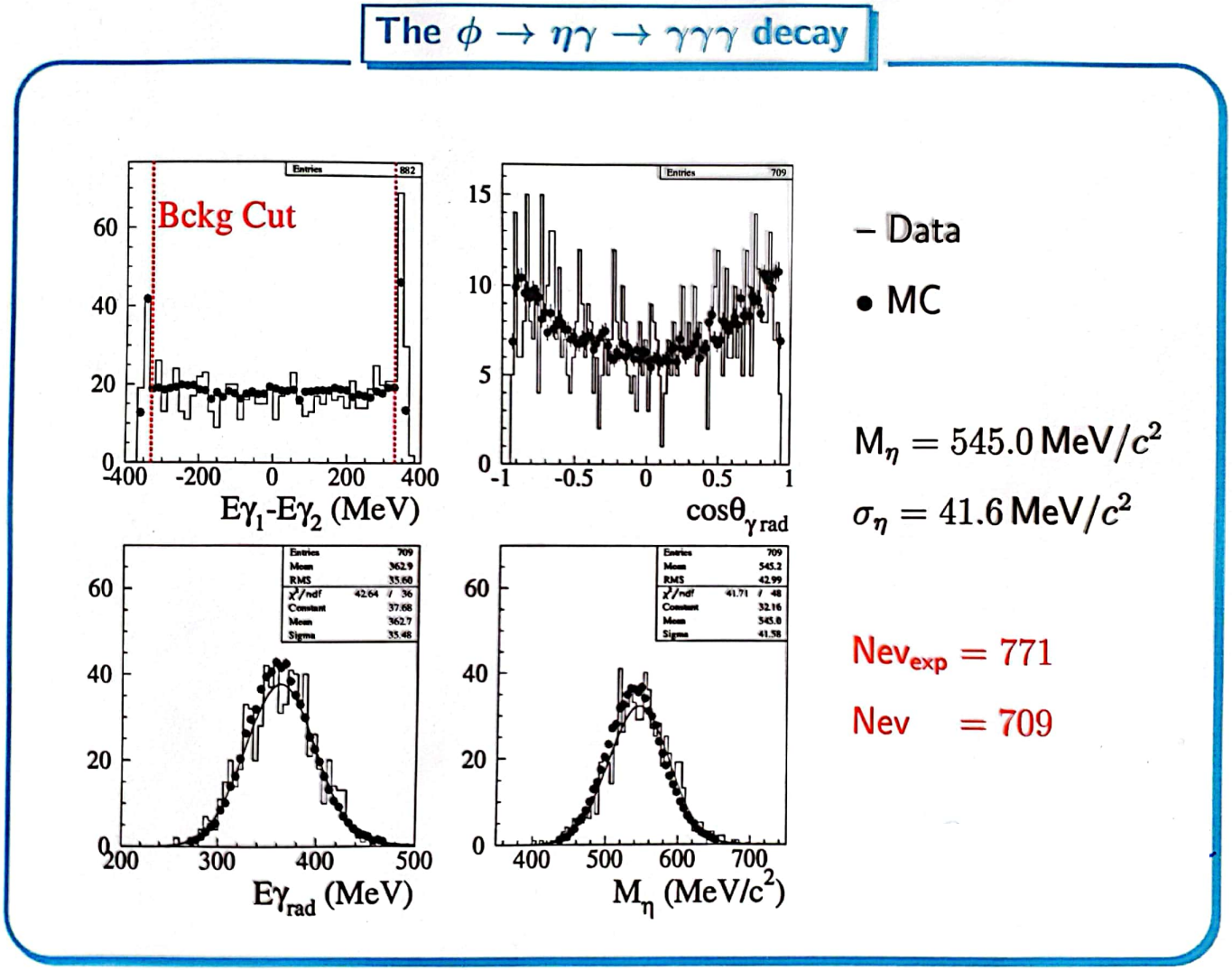
Radiative decays study

Analysis has been performed on first $89\,\mathrm{nb}^{-1}$ of data with similar trigger conditions out of the $150\,\mathrm{nb}^{-1}$ already reconstructed

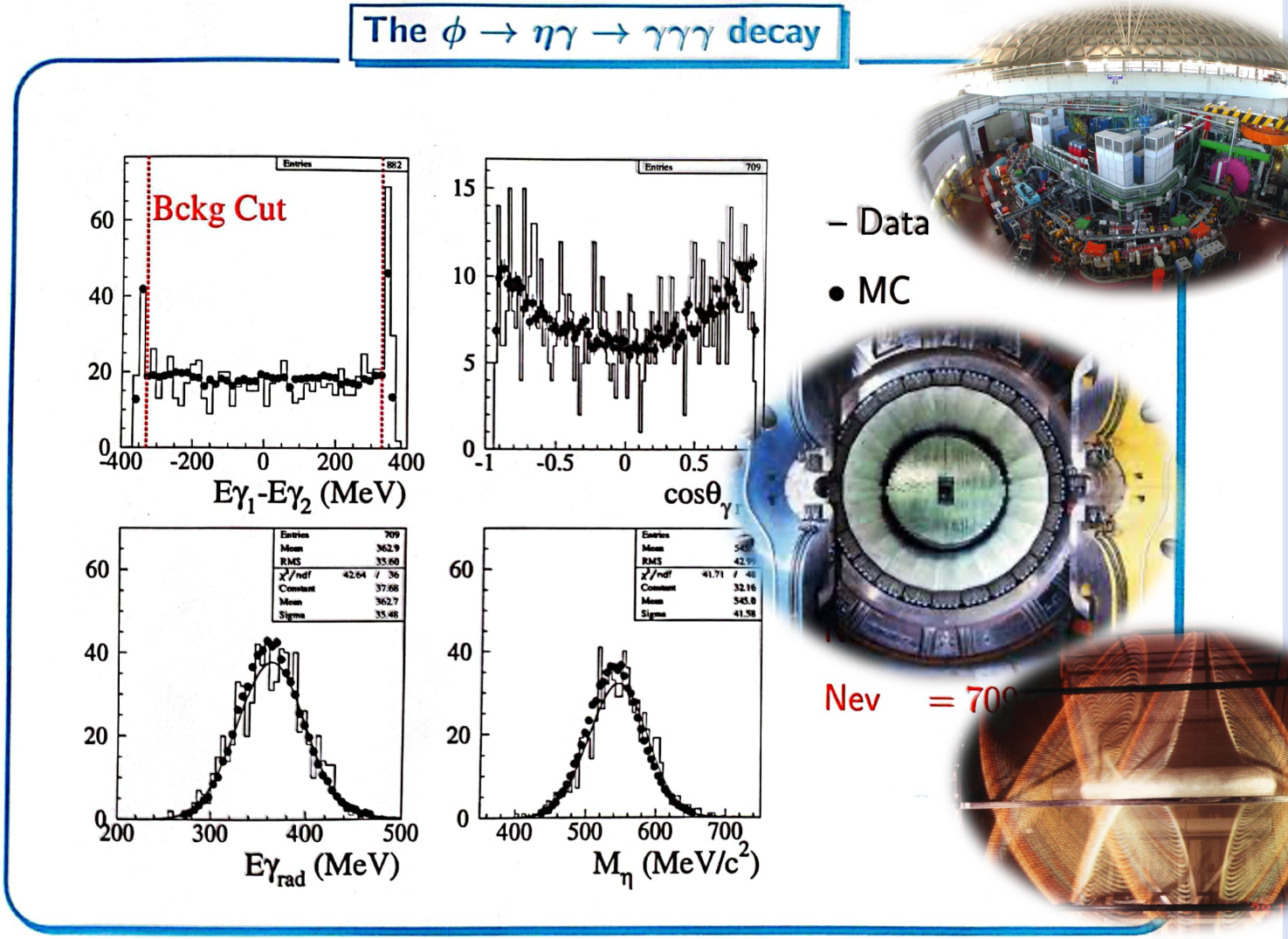
Sample obtained after background rejection with a fast calorimeter based filter and classification of radiative events

Preliminary studies performed on fully neutral decays of:
$\phi \to \eta\gamma, \pi^o\gamma, f_o\gamma$

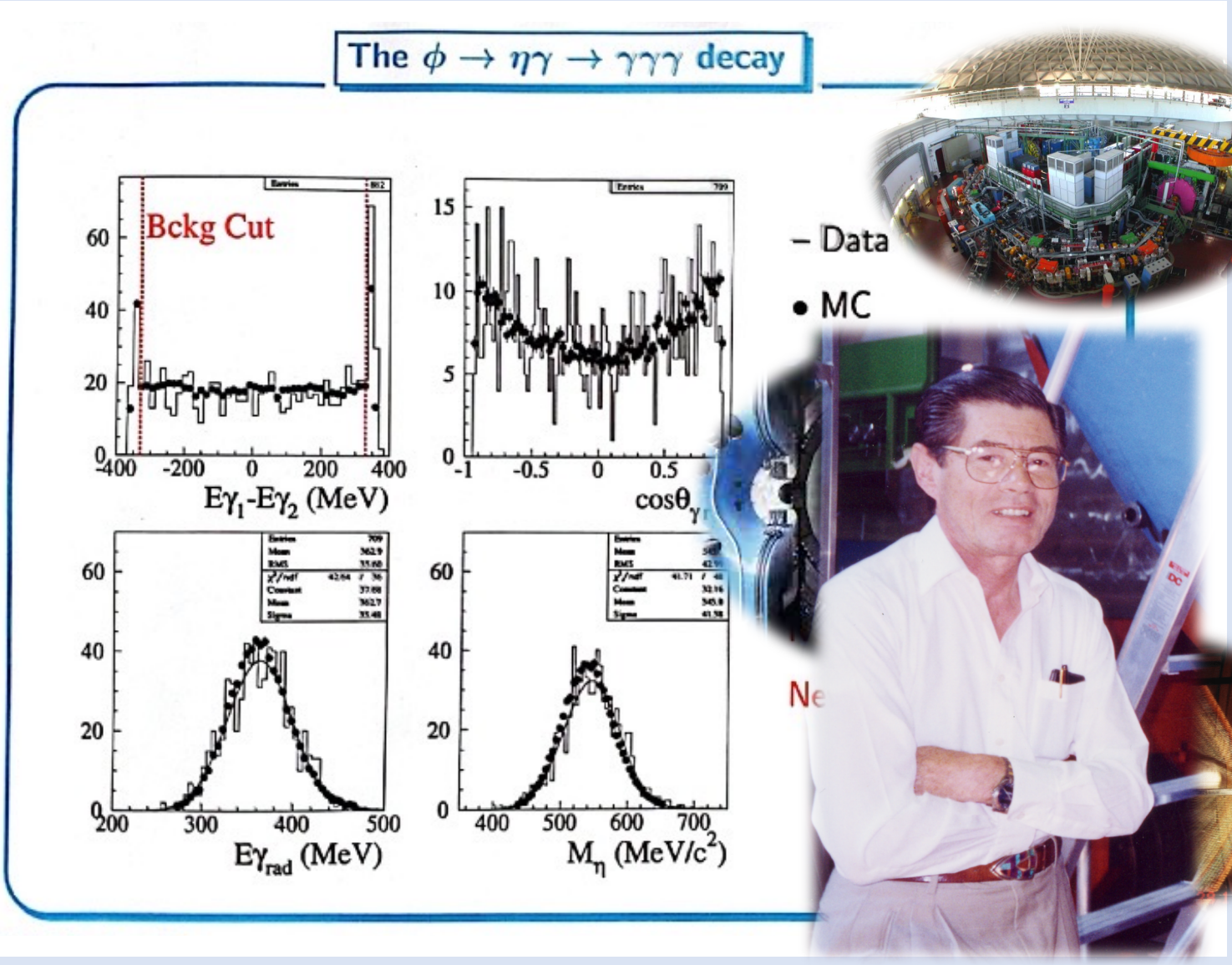
HADRON99: $\phi \to \eta\gamma \to \gamma\gamma\gamma$ events



HADRON99: $\phi \to \eta\gamma \to \gamma\gamma\gamma$ events

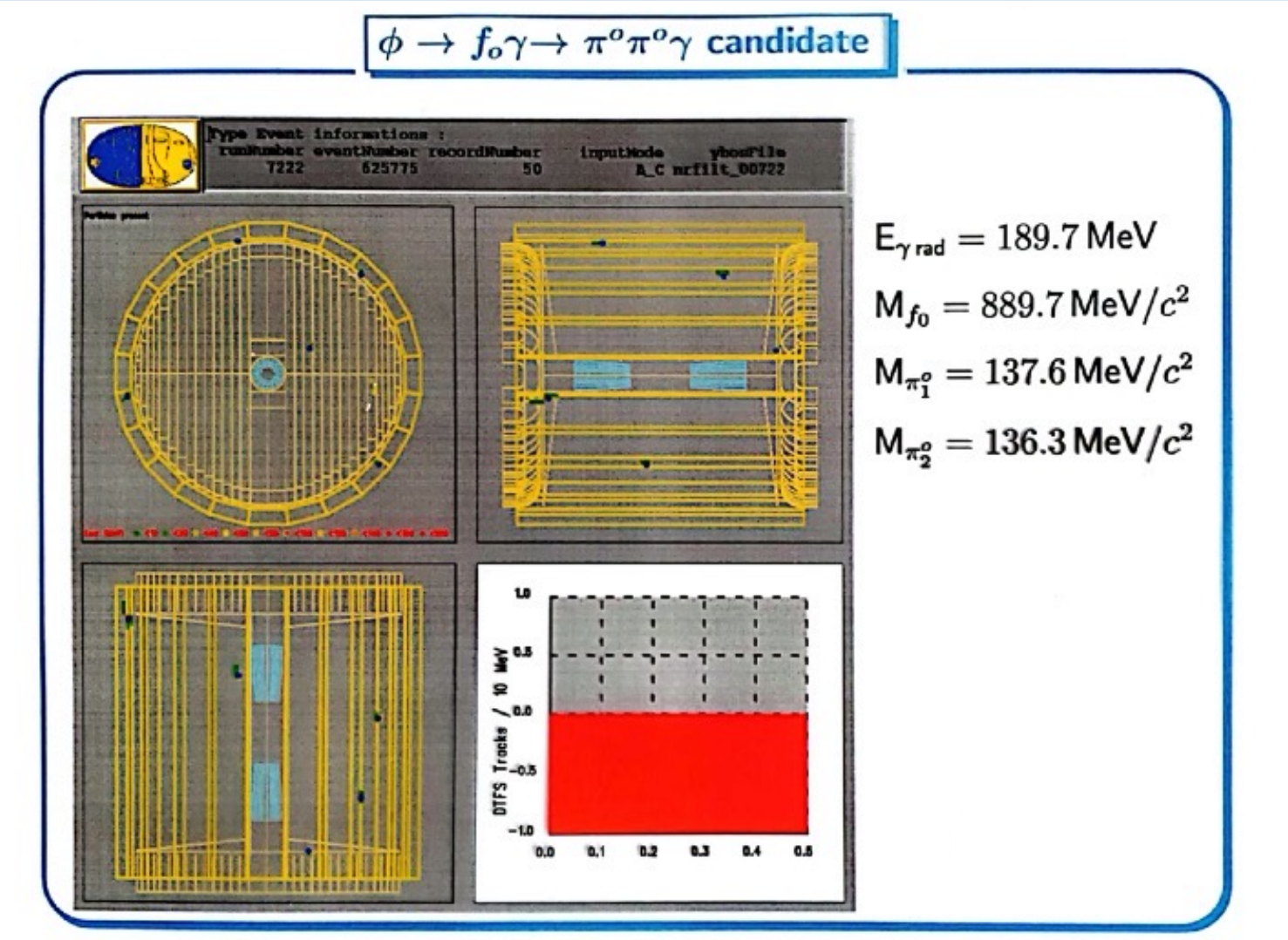


HADRON99: $\phi \to \eta\gamma \to \gamma\gamma\gamma$ events



HADRON99: $\phi \to f_0\gamma \to \pi^0\pi^0\gamma$ candidate

A dozen of f_0 candidates already available



2002: First papers on hadron physics

16 pb^{-1} from 2000 data

ELSEVIER

Physics Letters B 536 (2002) 209–216

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Study of the decay $\phi \to \eta\pi^0\gamma$ with the KLOE detector

KLOE Collaboration

ELSEVIER

Physics Letters B 537 (2002) 21–27

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Study of the decay $\phi \to \pi^0\pi^0\gamma$ with the KLOE detector

KLOE Collaboration

ELSEVIER

Physics Letters B 541 (2002) 45–51

PHYSICS LETTERS B

www.elsevier.com/locate/npe

Measurement of $\Gamma(\phi \to \eta'\gamma)/\Gamma(\phi \to \eta\gamma)$ and the pseudoscalar mixing angle

KLOE Collaboration

Papers based on KLOE data (I)

Channel	Topic	Statistics	Reference
$\phi \to \eta\pi^0\gamma$	$a_0(980)$	16 pb^{-1}	PLB 536 (2002) 209
$\phi \to \pi^0\pi^0\gamma$	$f_0(980)$	16 pb^{-1}	PLB 537 (2002) 21
$\Gamma(\phi\to\eta'\gamma)/\Gamma(\phi\to\eta\gamma)$	BR, η-η' mixing	16 pb^{-1}	PLB 541 (2002) 45
$\phi \to \pi^+\pi^-\pi^0$	DP, ρ params	16 pb^{-1}	PLB 561 (2003) 55
$\eta \to \gamma\gamma\gamma$	UL, C violation	410 pb^{-1}	PLB 591 (2004) 49
$\eta \to \pi^+\pi^-$	UL, P/CP violation	350 pb^{-1}	PLB 606 (2005) 276
$\phi \to \pi^+\pi^-\gamma$	$f_0(980)$	350 pb^{-1}	PLB 634 (2006) 148
$e^+e^- \to \pi^0\pi^0\gamma$	$f_0(980)$, $f_0(500)$	450 pb^{-1}	EPJC 49 (2007) 473
$\phi \to \eta\pi^0\gamma$	$a_0(980)$	400 pb^{-1}	PLB 681 (2009) 5
$\phi\to \eta\gamma$	η mass	410 pb^{-1}	JHEP 12 (2007) 073
$\Gamma(\phi\to\eta'\gamma)/\Gamma(\phi\to\eta\gamma)$	η-η' mixing, gluonium	427 pb^{-1}	PLB 648 (2007) 267
Global fit	η-η' mixing, gluonium		JHEP 07 (2009) 105
$\eta \to \pi^+\pi^-\pi^0$	DP params, C-inv.	450 pb^{-1}	JHEP 05 (2008) 006
$\eta \to \pi^0\pi^0\pi^0$	Slope parameter (α)	420 pb^{-1}	PLB 694 (2010) 16

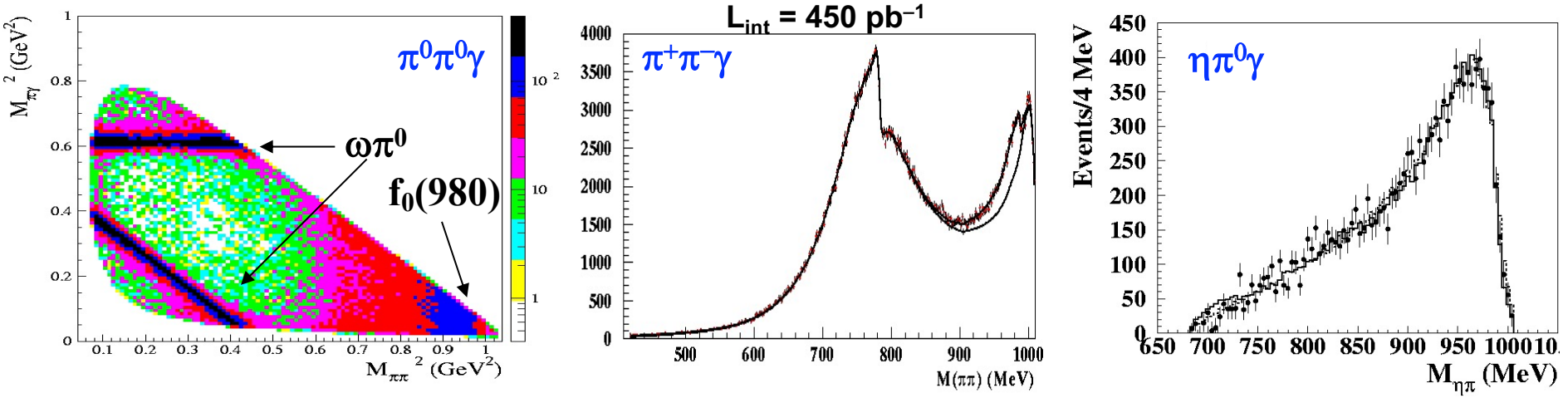
Papers based on KLOE data (II)

Channel	Topic	Statistics	Reference
$\phi \to K_S K_S \gamma$	UL, $a_0(980)$, $f_0(980)$	2.2 fb^{-1}	PLB 679 (2009) 10
$\eta \to \pi^+\pi^- e^+e^-$	BR, CP-viol asimm.	1.7 fb^{-1}	PLB 675 (2009) 283
$\eta \to e^+e^-e^+e^-$	First observation, BR	1.7 fb^{-1}	PLB 702 (2011) 324
$\eta \to \pi^+\pi^-\gamma$	BR, decay dynamic	558 pb^{-1}	PLB 718 (2013) 910
$\eta \to \pi^+\pi^-\pi^0$	DP params, C-inv.	1.6 fb^{-1}	JHEP 05 (2016) 019
$\phi \to \eta e^+e^-$	BR, TFF	1.7 fb^{-1}	PLB 742 (2015) 1
$\phi \to \pi^0 e^+e^-$	BR, TFF	1.7 fb^{-1}	PLB 757 (2016) 362
$\eta \to \pi^+\pi^-$	UL, P/CP violation	1.6 fb^{-1}	JHEP 10 (2020) 47
$\Gamma(\phi \to \ell^+\ell^-)$	$\Gamma_{\ell\ell}$, lepton univ.	17 pb^{-1} , 3 $\sqrt{s}$	PLB 608 (2005) 199
$e^+e^- \to \omega\pi^0$	ω BRs, BR($\phi \to \omega\pi^0$)	600 pb^{-1} 1000-1030 MeV	PLB 669 (2008) 223
$\gamma\gamma \to \eta$	$\Gamma(\eta \to \gamma\gamma)$, $\sigma(e^+e^- \to \eta\gamma)$	240 pb^{-1}, 1 GeV	JHEP 01 (2013) 119

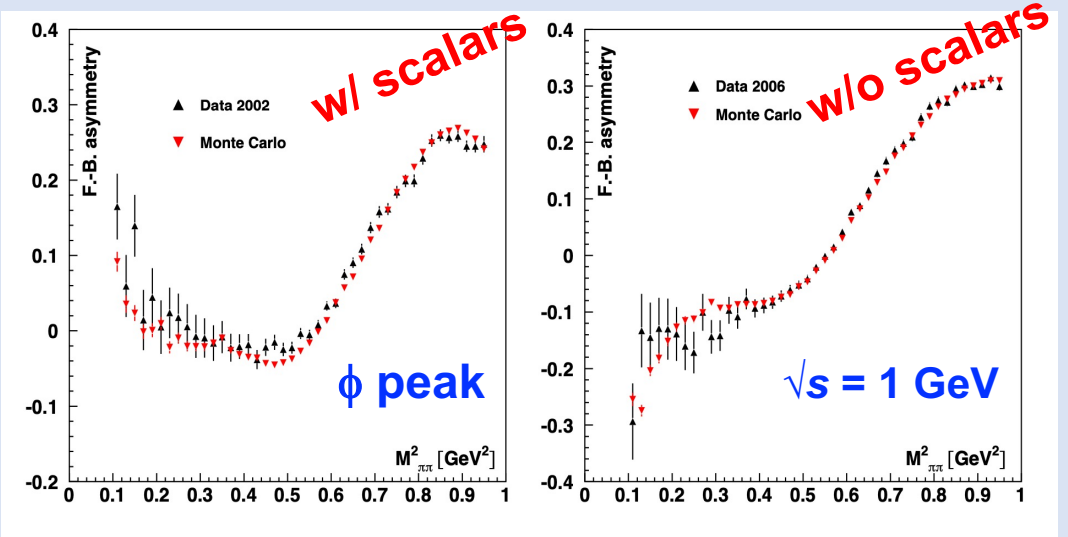
- 25 papers in 20 years
- Properties of light scalar, pseudoscalar and vector mesons deeply investigated
- Several state-of-the-art measurements

Scalar mesons @ KLOE

- **BR($\phi \to f_0(980)\gamma$ / $a_0(980)\gamma$) and mass spectra sensitive to scalar structure**
- Mass/Dalitz distributions fitted with Kaon Loop model, interference with irr. bckg



- **BR values and large couplings to kaons point to a 4–quark structure**
- $f_0(500)$ needed in $\pi^0\pi^0\gamma$
- PHOKHARA MC with scalar + VMD contribution extracted from $\pi^0\pi^0\gamma$ well reproduce $\pi^+\pi^-\gamma$ FB asymmetry

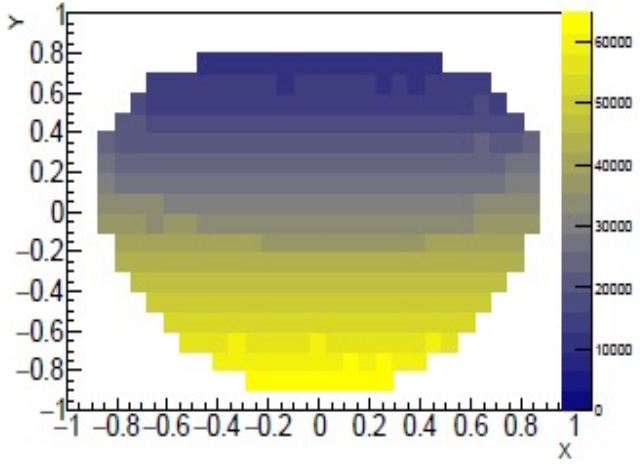


Light quark masses: $\eta \to \pi^+\pi^-\pi^0$

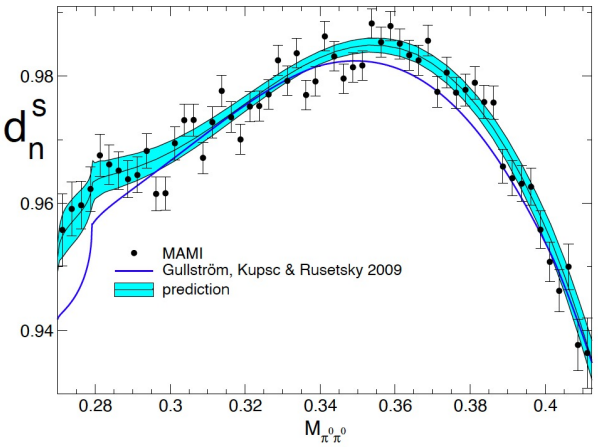
- Isospin violating decay, sensitive to light quark mass difference
- A precision measurement of the Dalitz plot density allows an accurate determination of the light quark mass ratio through dispersive techniques
- Precise KLOE analysis of $\eta \to \pi^+\pi^-\pi^0$ Dalitz plot density, based on **4.7×10^6 η events**
- Dispersive analyses of $\eta \to 3\pi$ based on fits to unfolded KLOE data

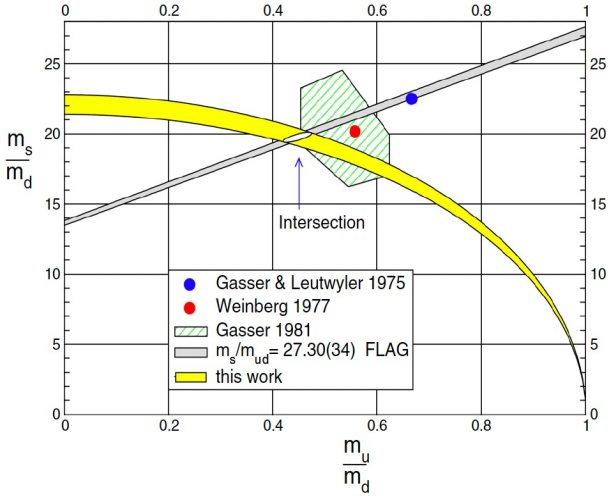
[Colangelo, Lanz, Leutwyler, Passemar, EPJC 78 (2018) 947]

Unfolded KLOE data



Prediction for $\eta \to \pi^0\pi^0\pi^0$





$$Q = \frac{m_s^2 - \hat{m}^2}{m_d^2 - m_u^2} = 22.1 \pm 0.7$$

$$\frac{m_u}{m_d} = 0.45 \pm 0.03$$

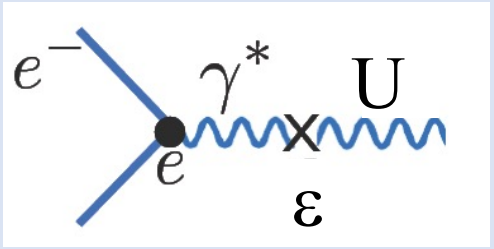
2006: End of KLOE data taking

Low energy dark forces

[Arkani-Hamed et al. PRD79 015014 (2009)]
[Essig et al., PRD80 015003 (2009)]

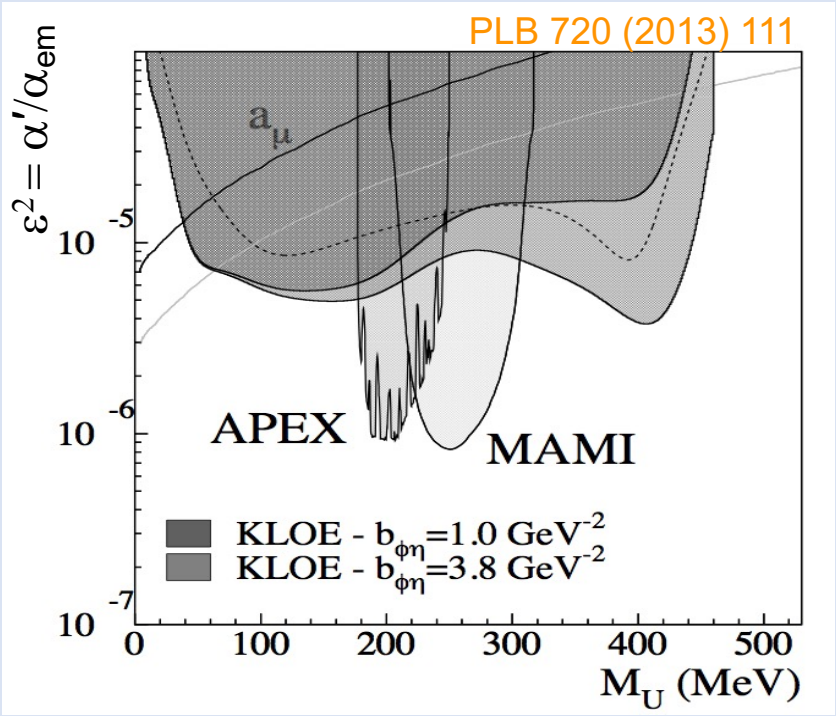
Hidden gauge sector weakly coupled with SM through a mixing mechanism:

- U mass range: **1 MeV – few GeV**
- Coupling constant of electric charge to U: **$\varepsilon \leq 10^{-3}$**
- Observable at low energy colliders
- Possible source of a_μ discrepancy

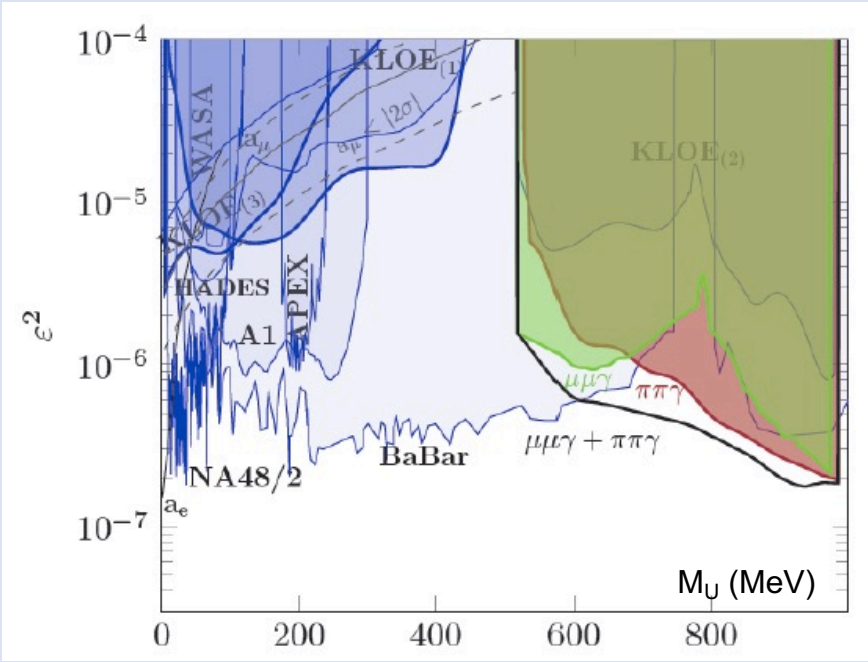


First KLOE search: $\phi \rightarrow \eta U (e^+e^-)$

PLB 720 (2013) 111

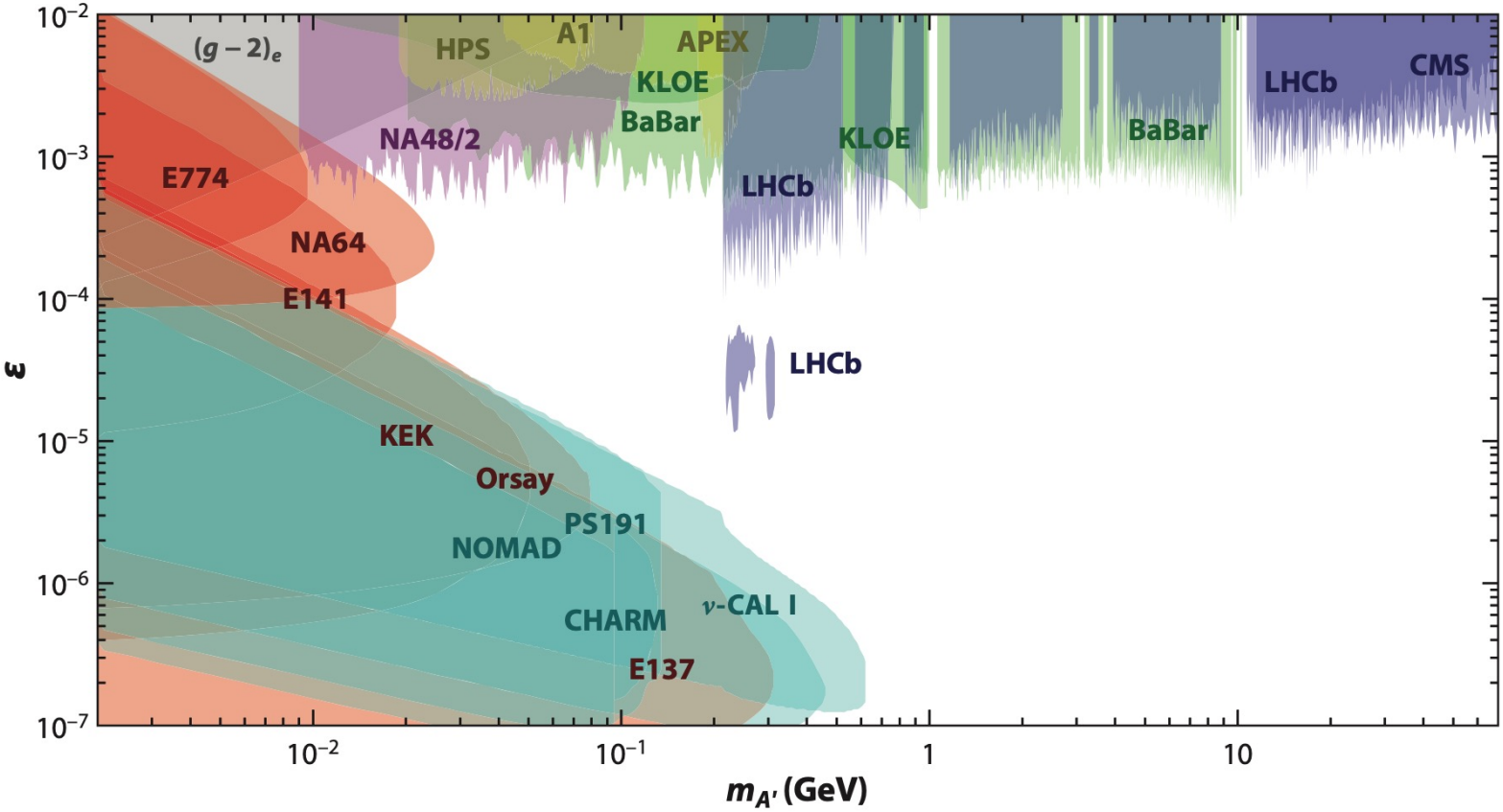


U boson searches in continuum events



$e^+e^- \rightarrow \mu^+\mu^-\gamma$: PLB 736 (2014) 459 $e^+e^- \rightarrow \pi^+\pi^-\gamma$: PLB 757 (2016) 356
$e^+e^- \rightarrow e^+e^-\gamma$: PLB 750 (2015) 633 $\mu^+\mu^-\gamma/\pi^+\pi^-\gamma$: PLB 784 (2018) 336

Recent status of U boson searches



Annu. Rev. Nucl. Part. Sci. 2021. 71

KLOE data are still alive

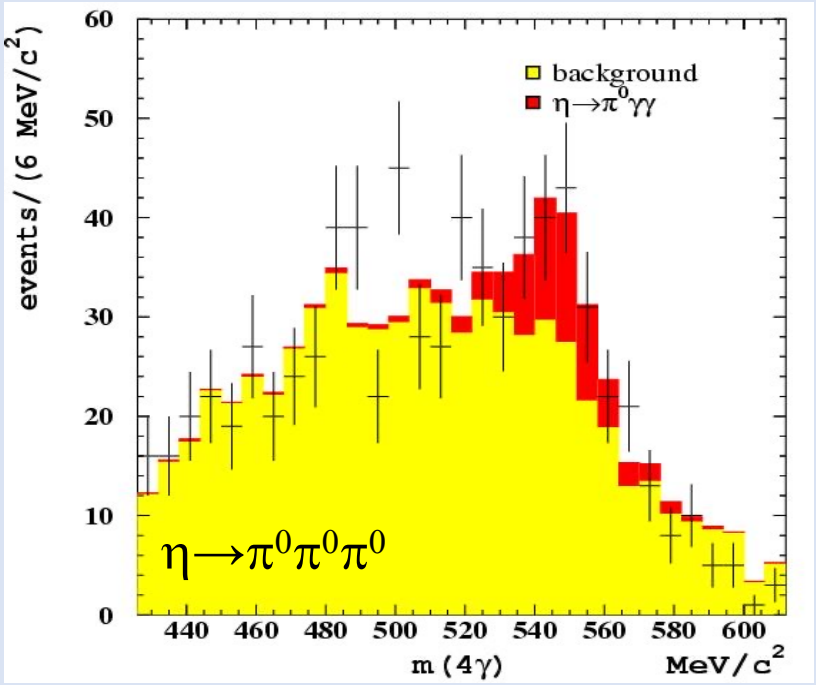
KLOE and KLOE-2 data still providing competitive results in the hadron physics sector:

- Largest existing **η meson sample** from **3×10^8** $\phi \to \eta\gamma$ events produced
- Searches for new physics: leptophobic dark force mediator, ALPs
- **2.4×10^{10} ϕ** mesons to complete and extend the study of TFF from Dalitz decays of vector mesons
- **4×10^6 ω** mesons produced through $e^+e^- \to \omega\, \gamma_{ISR}$
- **$\gamma\gamma$ physics** using High Energy Taggers to detect scattered electrons and positrons

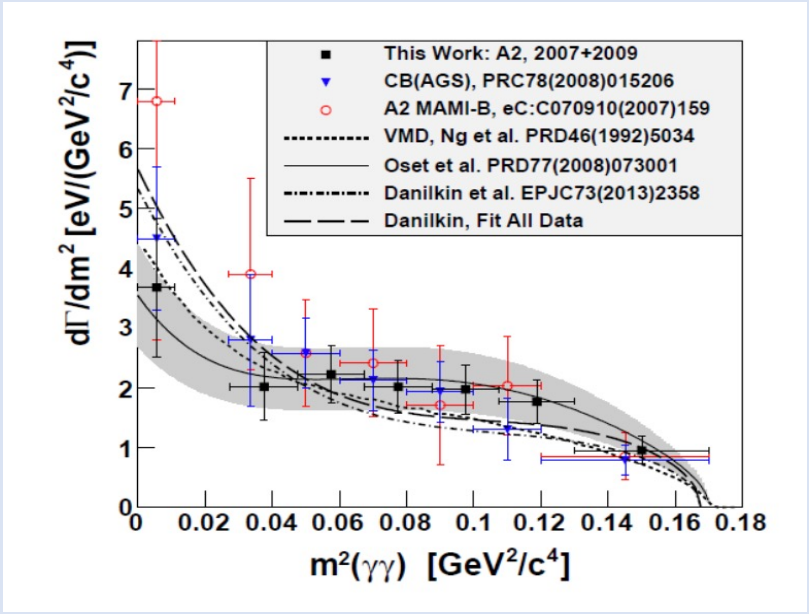
KLOE-2 analyses in progress in all of these sectors

A long-standing debate: $\eta \to \pi^0\gamma\gamma$

- ChPT "golden mode": p^2 null, p^4 suppressed, p^6 dominates
- Measured value decreased by 3 order of magnitude since the '60s
- KLOE prel. 2006, 450 pb^{-1} : 70 signal events, 3σ significance



Mass of non-π^0 photons can be used as a test of theoretical models



$BR(\eta\to\pi^0\gamma\gamma) = (8.4 \pm 2.7_{stat} \pm 1.4_{syst}) \times 10^{-5}$

CB@AGS: BR = ($22.1 \pm 2.4 \pm 4.7$) $\times 10^{-5}$
PRC 78 (2008) 015206, ~500 signal events

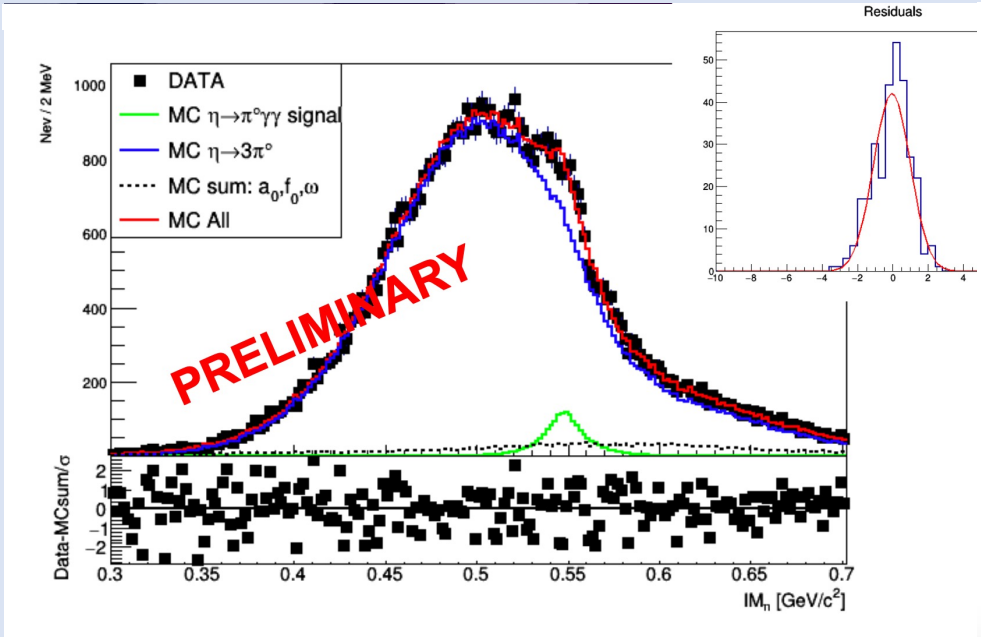
CB@MAMI: BR = (25.2 ± 2.5) $\times 10^{-5}$
PRC 90 (2014) 025206, ~1200 signal events

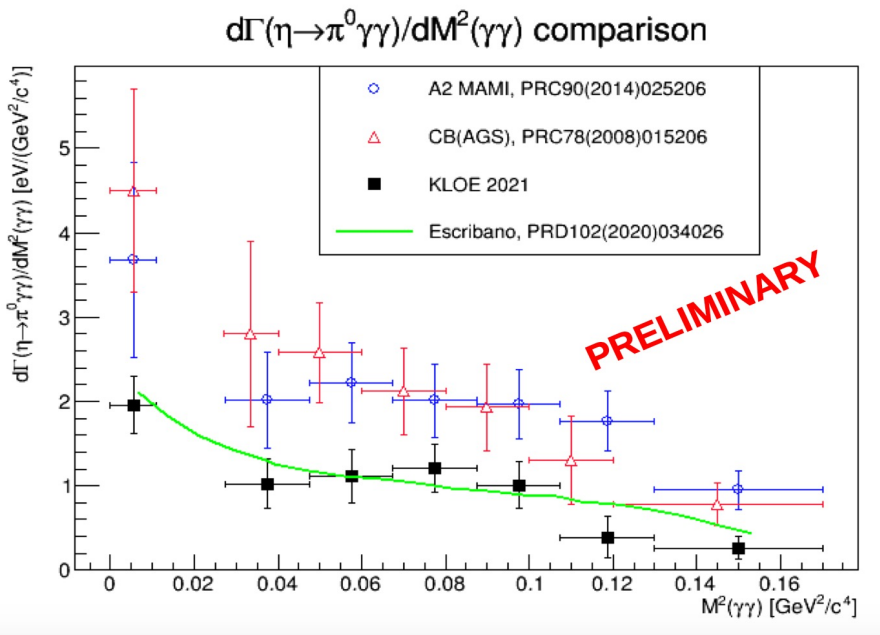
Recent theoretical evaluation:
- BR = $1.35(8) \times 10^{-4}$
- Several predictions differ by a factor ~ 2

R. Escribano etal, PRD 90 (2020) 034026

New $\eta \to \pi^0\gamma\gamma$ KLOE measurement

- New analysis using 4x larger data sample, 1.7 fb^{-1}
- Kinematic fit with signal and background hypotheses
- Main background $\eta \to \pi^0\pi^0\pi^0$ suppressed using MVA-BDT method





- Signal, $\eta \to 3\pi^0$ + other bckg fitted to data
- BR normalization to $\eta \to 3\pi^0$ channel

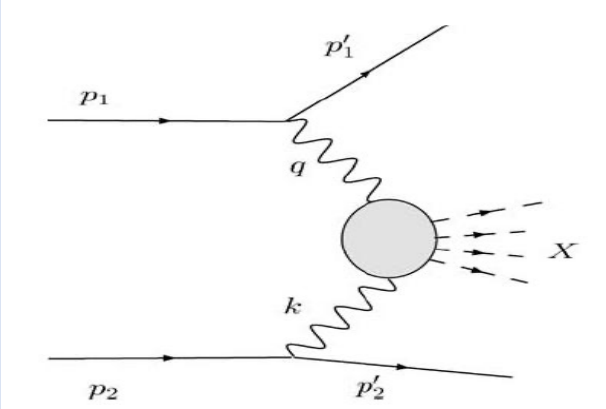
- Separate fit to each $M_{\gamma\gamma}$ slice
- BR interpolating $d\Gamma/dM$

$$BR(\eta\to\pi^0\gamma\gamma) = (1.2 \pm 0.13_{stat}) \times 10^{-4}$$

$$BR(\eta\to\pi^0\gamma\gamma) = (1.3 \pm 0.13_{stat}) \times 10^{-4}$$

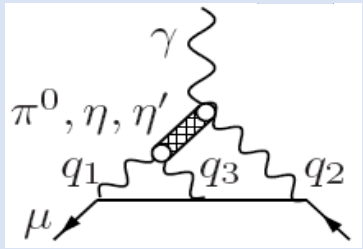
In agreement (1.2σ) with KLOE 2006 preliminary measurement

$\gamma\gamma$ physics @ KLOE-2

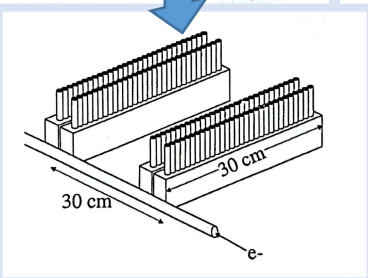


$$\sigma_{\gamma\gamma\to R}(q_1,q_2) \propto \Gamma_{R\to\gamma\gamma}\frac{8\pi^2}{M_R}\delta((q_1+q_2)^2-M_R^2)\left|F(q_1^2,q_2^2)\right|^2$$

- Transition form factors crucial for hadronic light-by-light contributions to muon g-2
- $\Gamma_{\gamma\gamma}$ should be known precisely



Feasibility studies already in the 90s: DAΦNE Physics Handbooks



Tagging system for small angle scattered e^+/e^-

$\gamma\gamma$ physics @ KLOE-2: $\gamma\gamma \rightarrow \pi^0$

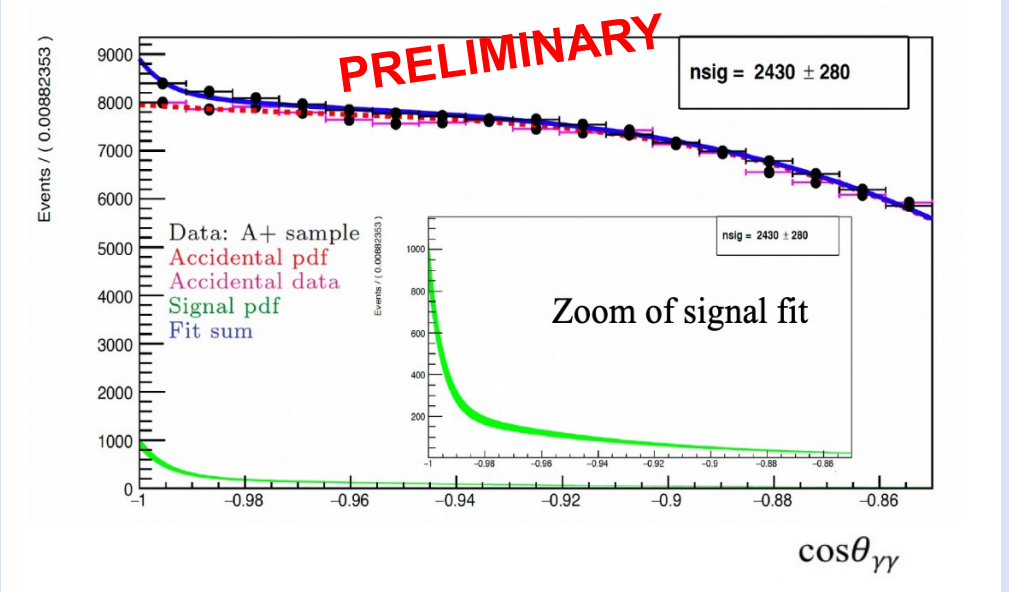
- HET data synchronized with DAΦNE (each 325 ns) and KLOE trigger
- HET acquisition window: 2.5 DAΦNE revolutions, enabled by KLOE trigger
- Single arm selection: HET signal within ±40 ns w.r.t. KLOE $\gamma\gamma$ event

Two data samples used:

- **pure accidentals** (A) for bckg modelling (shape & number)
- **HET-KLOE coincidence** (A+), signal + accidentals
- Maximum Likelihood fit to A and A+
  - → constraints on accidentals in A+
  - → background pdf from A sample

Signal pdf : EKHARA MC, control samples and BDSIM transport of the leptons through the beamline

HET electrons – 2 fb^{-1}



Signal-enriching cut applied:
$|\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c| < 0.5$ ns
Cut efficiency 80% from control sample studies

Light hadron physics perspectives

- Light mesons still offer a unique opportunity:
  - Test of chiral dynamics at low energy
  - Fundamental parameters of the Standard Model (e.g. light quark mass)
  - Investigation of exotic particles
  - Study of fundamental symmetries
  - Search for physics beyond Standard Model

- KLOE have provided (and it is still providing) fundamental results on light meson properties, decay dynamics and transition form factor, together with limits on new physics… still the largest η dataset by far

- Hadron Physics investigation is continuing with current experiments:
  - @ e^+e^- and hadron colliders: BES-III, Belle-II, LHCb…
  - @ scattering experiments: GlueX, COMPASS

- More to come with JEF and REDTOP experiments

Paolo & Juliet legacy

- Deep interest and passion for physics, and for all the steps of the experiment, from technical aspects to physics outcome
  - In particular Paolo, in addition to his ample physics knowledge, enlightened us with his competences in detectors, electronics, statistics
- The importance of creating a stimulating, exciting and familiar working environment to create a good synergy inside the collaboration
- Push young collaborators to stand out, contribute and take leading responsibilities, thus shaping a generation of brilliant and enthusiast researchers
- The rigorous attention of the English, avoiding slang and jargon

It was a privilege to take part of the amazing adventure of KLOE. Our scientific community and the lab experienced a period of great excellence!

Thank you!