Hadron physics results at KLOE-2

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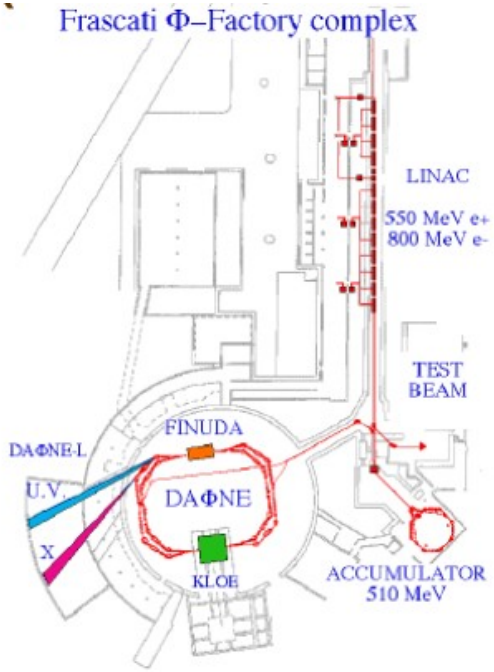
22nd - 27th June 2023, Krakow, Poland

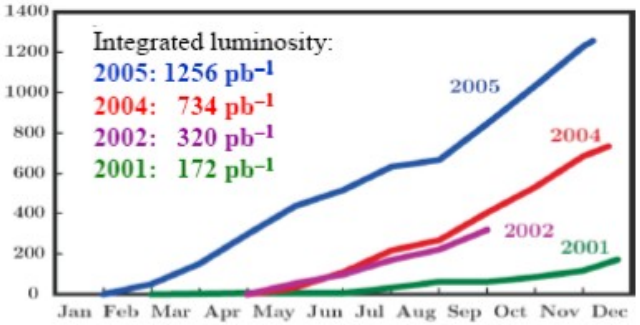
Outline

- KLOE-2 at DAΦNE
  - KLOE-2 Physics Program
- Hadron Physics results of the KLOE-2 collaboration
  - The $\eta \to \pi^0\gamma\gamma$ decay
  - Dark Matter searches
    - Leptophobic B boson
  - Measurement of $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$ decays
  - $\gamma\gamma \to \pi^0$ measurement
  - ω cross section measurement in the $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$
- Summary

KLOE @ DAΦNE



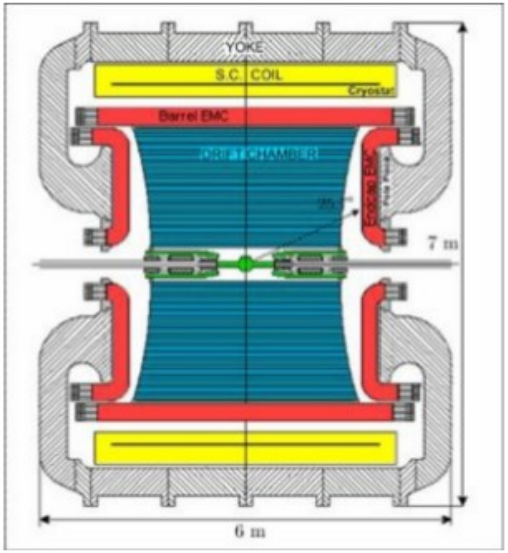
- $e^+ e^-$ collider $\sqrt{s} = M_\Phi = 1019.4$ MeV
  - 2 interaction regions
  - $e^+ e^-$ separated rings
  - 105 + 105 bunches spaced by 2.7 ns



- **Drift Chamber**
- Low-mass gas mixture 90% Helium + 10% isobutane
- $\delta p_\perp / p_\perp < 0.4\%$ ($\theta > 45°$)
- $\sigma_{xy} = 150\ \mu m$; $\sigma_z = 2$ mm
- 12582 cells
- Stereo geometry
- 4m diameter, 3.3m long

- **Calorimeter**
- 98% coverage full solid angle
- $\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_T = 54$ ps $/ \sqrt{E(GeV)} \oplus 100$ ps
- Barrel + 2 end-caps:
  - Pb/scintillating fiber read out by 4880 PMTs

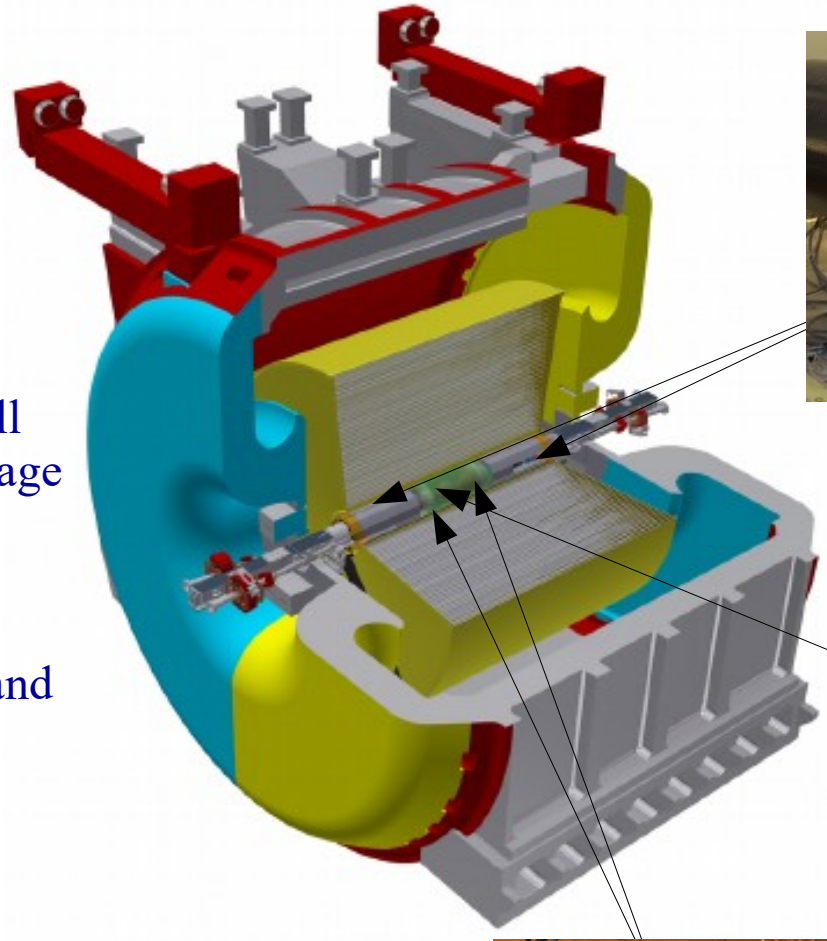
Magnetic field B = 0.52 T

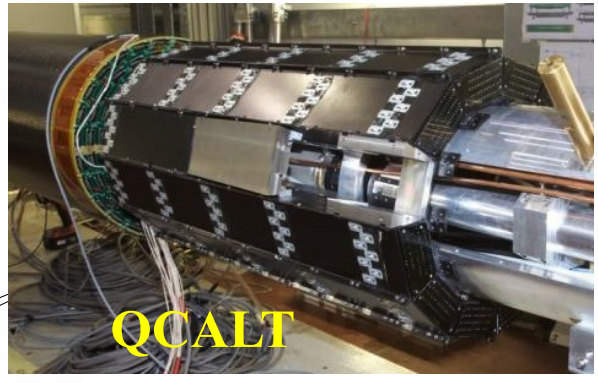


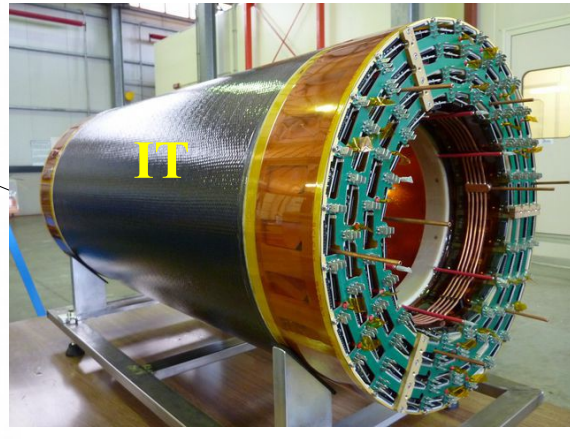
KLOE-2

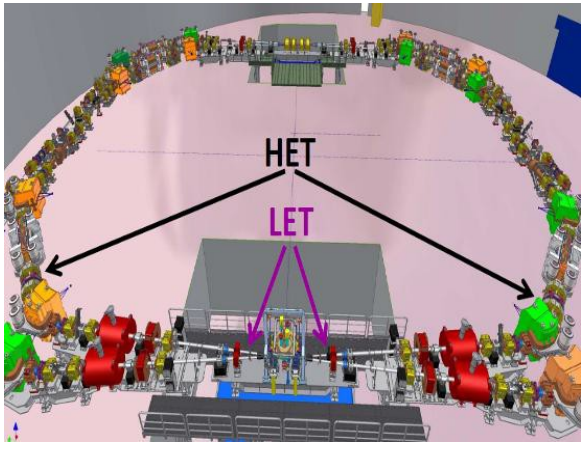
- LET (Low Energy Tagger) & HET (High Energy Tagger)
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters (for small angle γs & quadrupole coverage from K_L decays)
- IT (Inner Tracker)
  - 4 layers of Cylindrical-GEM
  - better vertex reconstruction and

Track parameters





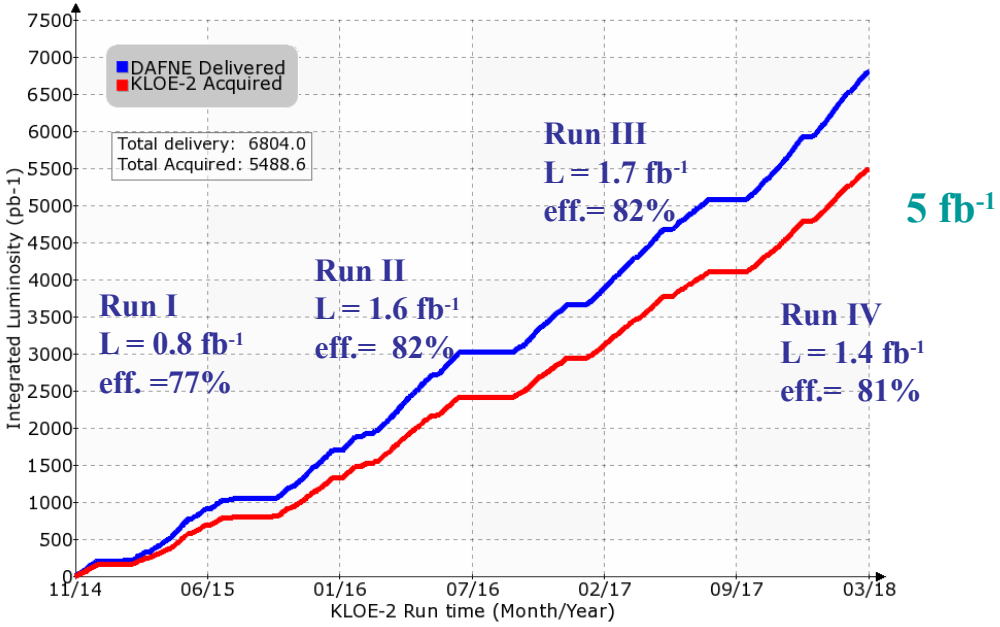




KLOE/KLOE-2 Experiment

- 1999: KLOE experiment starts
- 2000 – 2006: KLOE data-taking campaign
  - 2.5 fb^{-1}@$\sqrt{s}=M_\phi$
  - + 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV

- 2008: DAΦNE upgrade: new interaction scheme
- Dec.2012-July 2013: installation of the new detectors
- 2014-2018: KLOE-2 data-taking campaign



5 fb^{-1}

5.5 fb^{-1} collected @$\sqrt{s}=M_\phi$

KLOE + KLOE-2 data sample
~ 8 fb^{-1} represents the largest sample collected at a Φ-factory

About 2.4 x 10^{10} ϕ-mesons

KLOE-2 Physics Program

Light meson Physics:

- η decays, ω decays

Transition Form Factors

- C,P,CP violation: improve limits on
  $\eta \to \gamma\gamma\gamma$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0\gamma$
- improve $\eta \to \pi^+\pi^- e^+e^-$
- χpT : $\eta \to \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \to K_S K_S \gamma$
- γγ Physics: $\gamma\gamma \to \pi^0$ and π^0 TFF

$e^+e^- \to \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)

- search for axion-like particles

Dark force searches:

- Improve limits on

Uγ associate production

$e^+e^- \to U\gamma \to \pi\pi\gamma$, $\mu\mu\gamma$

Higgsstrahlung:

$e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy

- Leptophobic B boson search:
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$, $\eta \to \pi^0\gamma\gamma$
- Search for U invisible decays

Kaon Physics:

- CPT and QM tests with kaon interferometry
- Direct T and CPT tests using entanglement
- CP violation and CPT test:
  $K_S \to 3\pi^0$
  direct measurement of $\mathrm{Im}(\varepsilon'/\varepsilon)$
- CKM V_{us}:
  K_S semileptonic decays and A_S
  (CP and CPT test)
  $K_{\mu 3}$ form factors, K_{l3} radiative corrections
- χpT : $K_S \to \gamma\gamma$
- Search for rare K_S decays

Hadronic cross section:

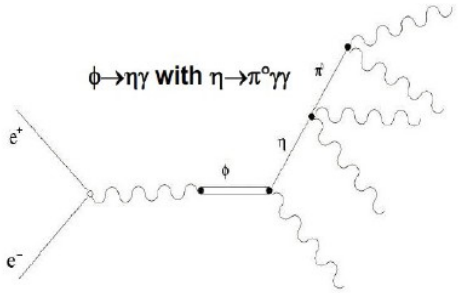
- ISR studies with 3π, 4π final states
- F_π with increased statistics

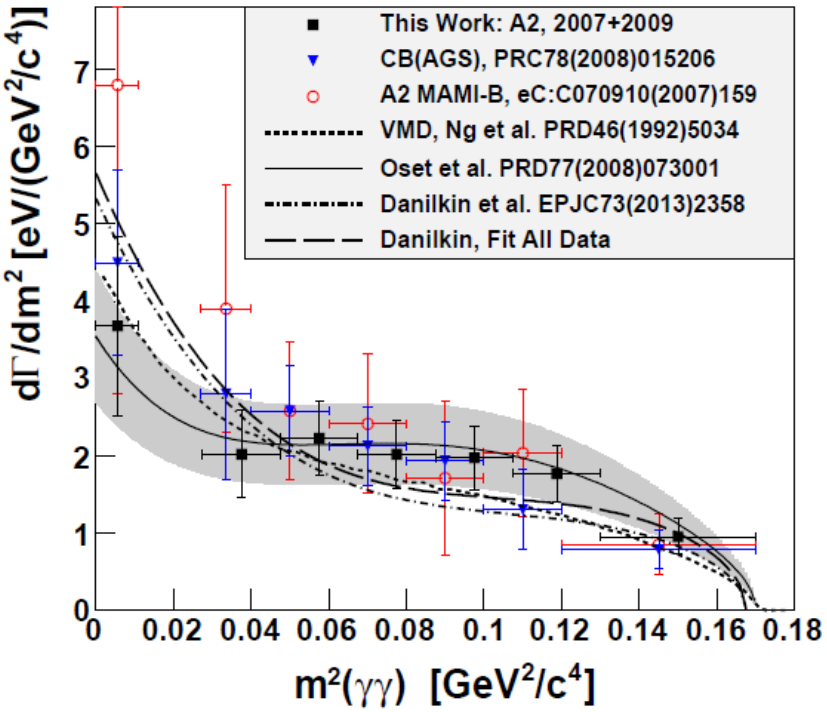
Measurement of a_μ^{HLO} in the space-like region using Bhabha process

KLOE-2 Coll., EPJC68(2010)619
http:// agenda.infn.it/event/kloe2ws Proceedings: EPJ WoC 166 (2018)

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

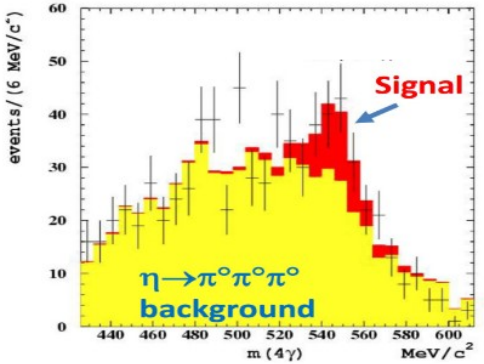
- $\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): χPT golden mode,
  - $O(p^2)$ null, $O(p^4)$ suppressed ⇒ sensitive to $O(p^6)$
- Mass of non-π^0 photons can be used as a test of theoretical models





Previous measurements:

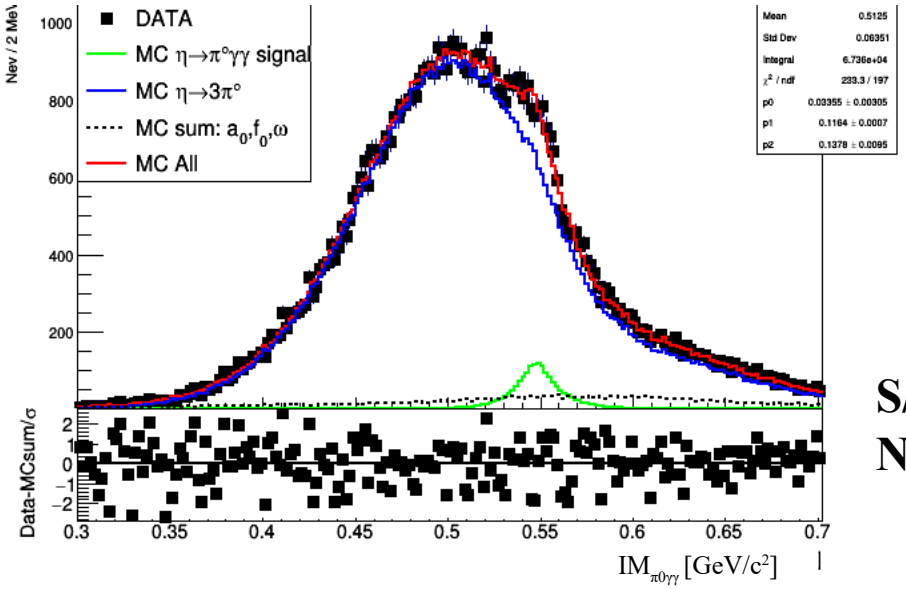
- **BR = (22.1 ± 2.4 ± 4.7) x 10^{-5} CB@AGS (2008)** ***[PRC 78 (2008) 015206]***
- **BR = (25.6 ± 2.4) x 10^{-5} CB@MAMI (2014) A2 MAMI** ***[PRC 90 (2014) 025206]***
  - **Sample of ~$6 \cdot 10^7$ η's**
  - **~1200 $\eta \to \pi^0\gamma\gamma$ events found**
- **Old KLOE preliminary: (8.4 ± 2.7 ±1.4) x 10^{-5}**
  - **(L = 450 pb^{-1} ~ 70 signal events) [*B. Di Micco et al, Acta Phys. Slov. 56, 403 (2006)]***



[B. Di Micco et al, Acta Phys. Slov. 56, 403 (2006)]

- Latest theoretical studies by Escribano et al. *PRD 90 (2020) 034026*:
  - Calculated BR = $1.30(8) \cdot 10^{-4}$
- Many previous predictions differ by a factor ~2

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



S/B ~ 2%
N_s ~ 1200

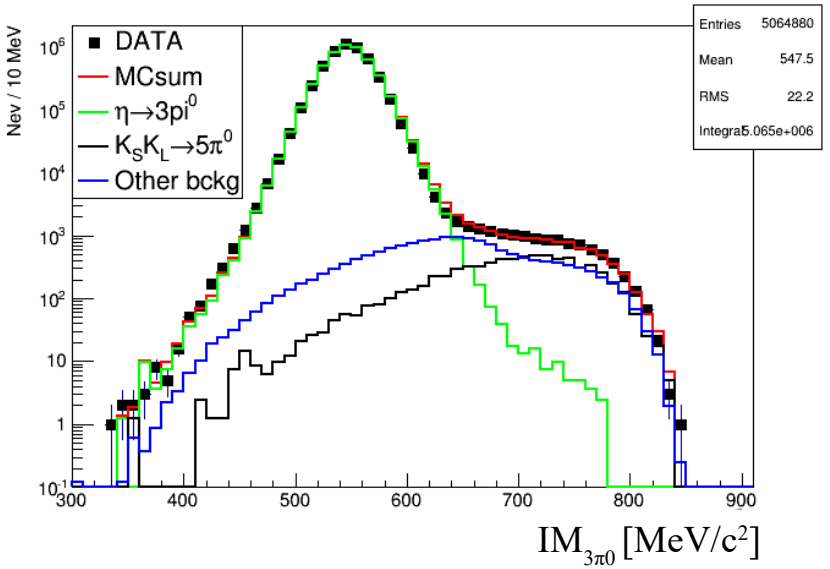
PRELIMINARY

- **Integrated luminosity of 1730 pb^{-1}, around $(8.13 \pm 0.34)\cdot 10^7$ η's**
- **$\eta \to 3\pi^0$, $\eta \to \pi^0\gamma\gamma$ signal and $\sum$ of non-3pi0 MC's fitted to data**
- **Fit χ^2/(ndf=98)=1.223 (fit_prob=22%)**

BR normalization to $3\pi^0$

Similar analysis as for $\eta \to \pi^0\gamma\gamma$ channel, but this time $\phi \to \eta(\to 3\pi^\circ)\gamma \to 7\gamma$ in the final state (BR~33%)

- Very pure channel, backgrounds well bellow 1%
- When used, can reduce part of systematic effects

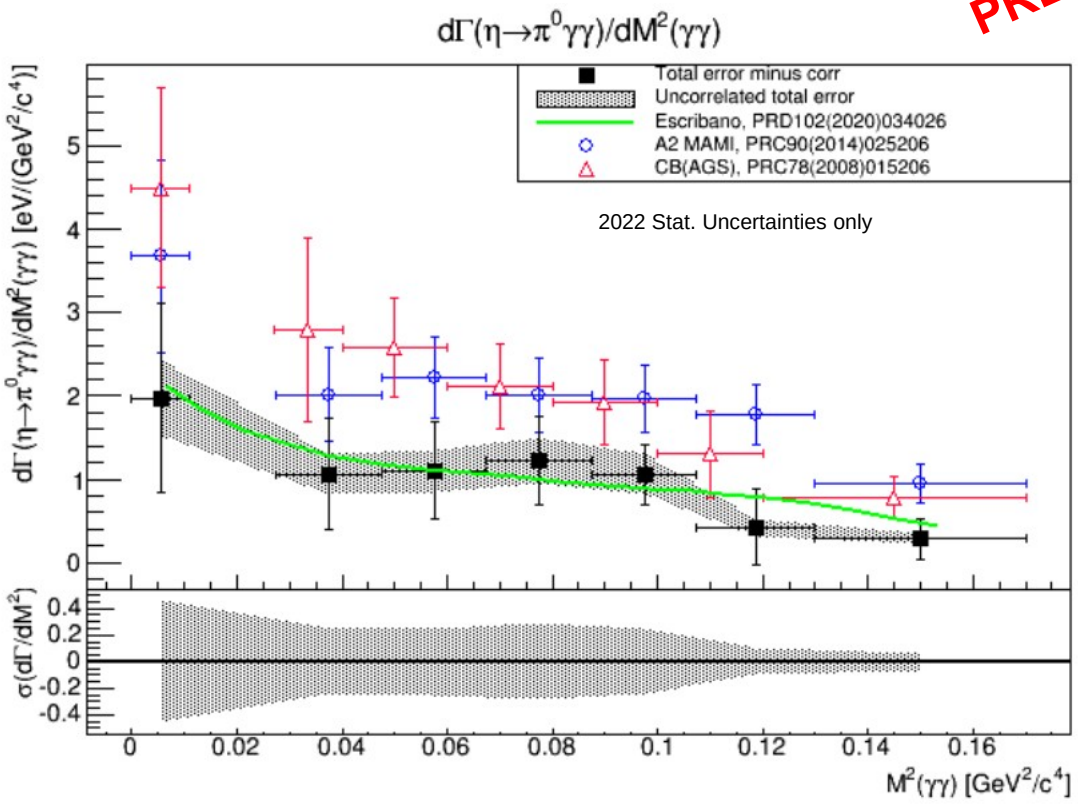


$$\frac{BR(\eta \to \pi^\circ\gamma\gamma)}{BR(\eta \to 3\pi^\circ)} = \frac{N_S/\varepsilon_S}{N_{3\pi^\circ}/\varepsilon_{3\pi^\circ}}$$

$$BR = (0.99 \pm 0.11_{stat} \pm 0.24_{syst}) \cdot 10^{-4}$$

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

PRELIMINARY



- Separate fits to $M^2(\gamma\gamma)$ slices
- Bin 0.011-0.0275 GeV^2/c^4 missing due to $\pi^\circ\pi^\circ$ veto
- about 1/2 compared with other experiments and confirms old KLOE preliminary result
- Latest theoretical prediction by Escribano et al. From 2020 ($BR=1.30(8)\cdot10^{-4}$) reproduce our data [PRD 102 (2020) 034026]

Leptophobic B-boson

- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the ω(782) ⇒ $I^G=0^-$

$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu \qquad \alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\text{MeV})$$

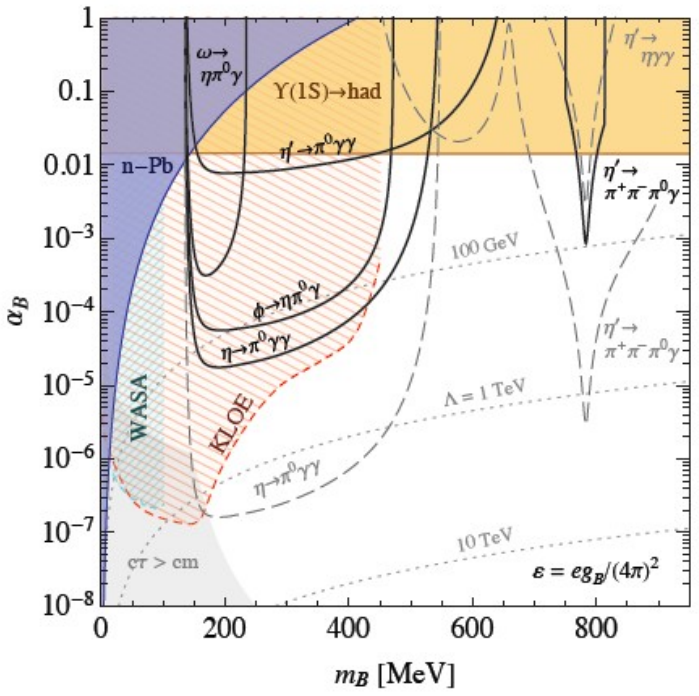
- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be studied in:

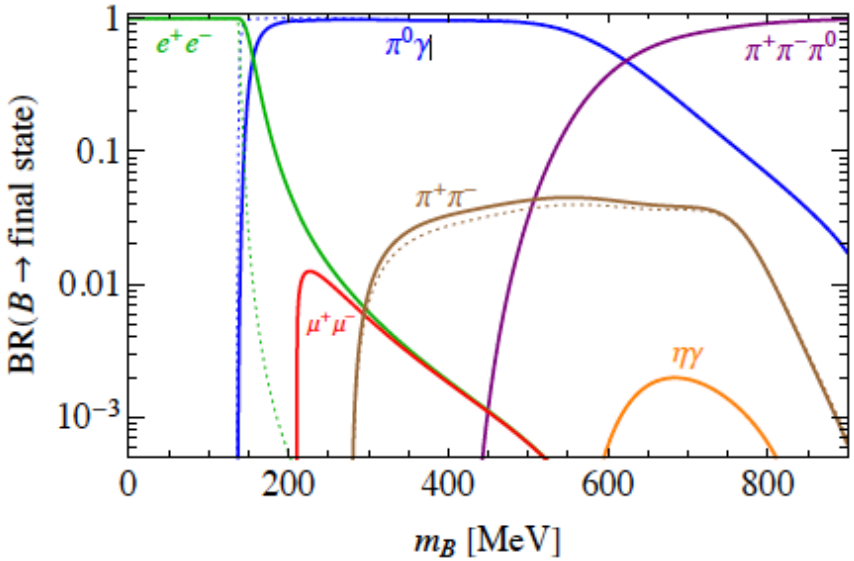
  $\phi \to \eta B \Rightarrow \eta\pi^0\gamma \Rightarrow$ 5 prompt γ final state

  $\eta \to B\gamma \Rightarrow \pi^0\gamma\gamma$ " "

  $e^+e^- \to \pi^0\gamma\ \gamma_{ISR}$

[Tulin, PRD89(2014)114008]

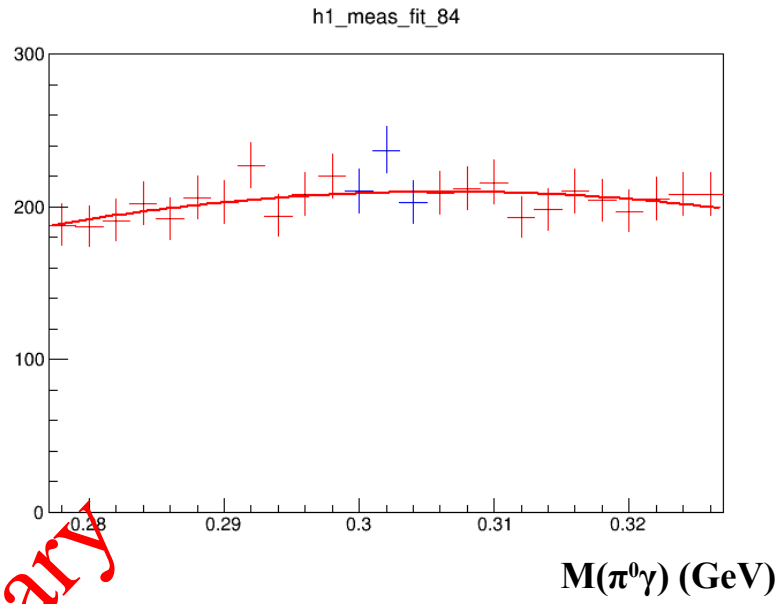




Decay → / Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\eta$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

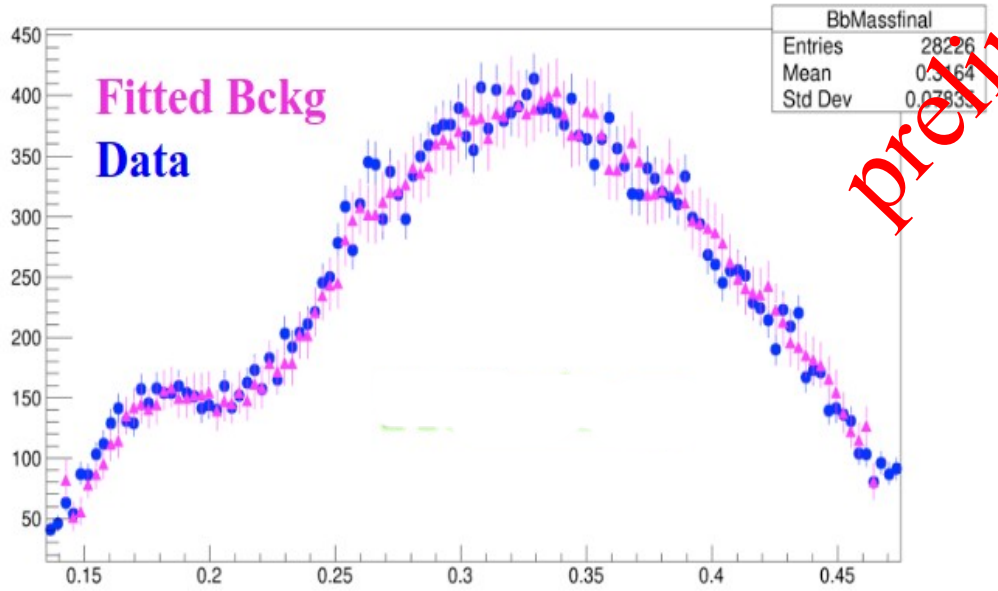
Leptophobic B-boson

- Study on ~1.7 fb^{-1} KLOE data sample
- Background evaluation from sidebands
- Selection of 5 prompt γ's
- Kinematic fit to improve energy resolution
- Main residual background
  from $\phi \rightarrow a0\gamma \rightarrow \eta\pi^0\gamma$ and $\phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$ with lost or merged photons.
- No signal is observed
  - Upper limit calculation
  - Upper limit in number of events at 90% CLs sets limits on the coupling constant α_B at O(10^{-7})

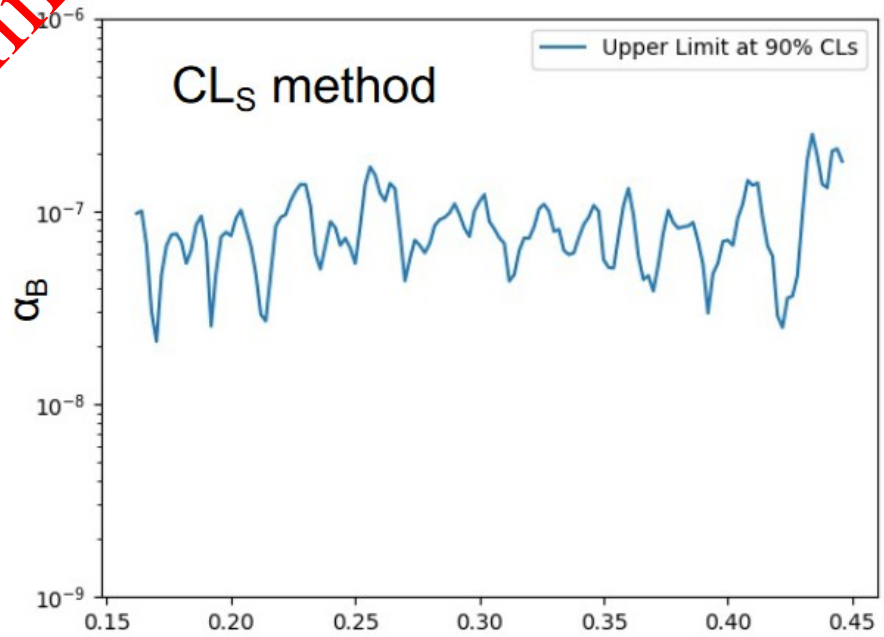


M($\pi^0\gamma$) (GeV)

preliminary



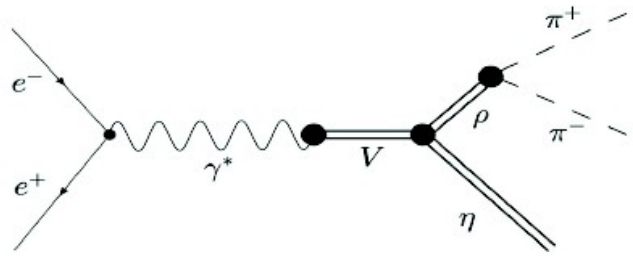
M($\pi^0\gamma$) (GeV)



M($\pi^0\gamma$) (GeV)

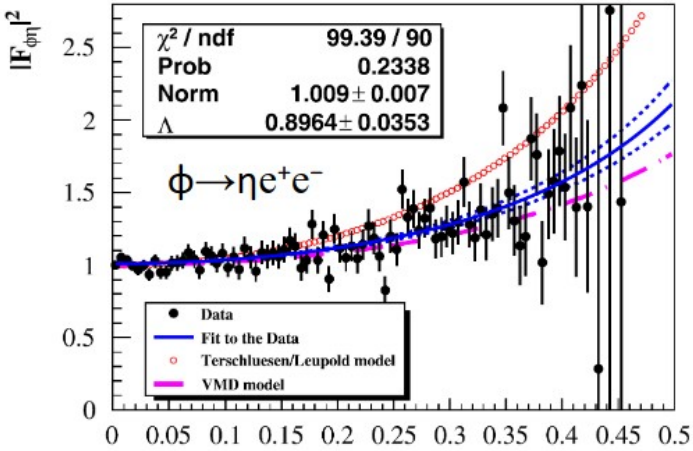
$\Phi \to \eta\pi^+\pi^-$ and $\Phi \to \eta\mu^+\mu^-$

- In VMD model, $e^+e^- \to \eta\pi^+\pi^-$ proceeds via ρ resonances, mainly via ρη intermediate state. KLOE/KLOE-2 data allow to measure the line shape around ϕ



- $\phi \to \eta\pi^+\pi^-$ violates the OZI rule and G-parity
  - VMD predicts the Br~ 0.35×10^{-6}.
  - Br<1.8×10^{-5} @ 90% CL @ CMD-2 *PLB491(2000)81*

- The same sample can be used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$
  - Br<0.94×10^{-5} @ 90% CL @ CMD-2 *PLB501(2001)191*
  - Investigate the transition form factor

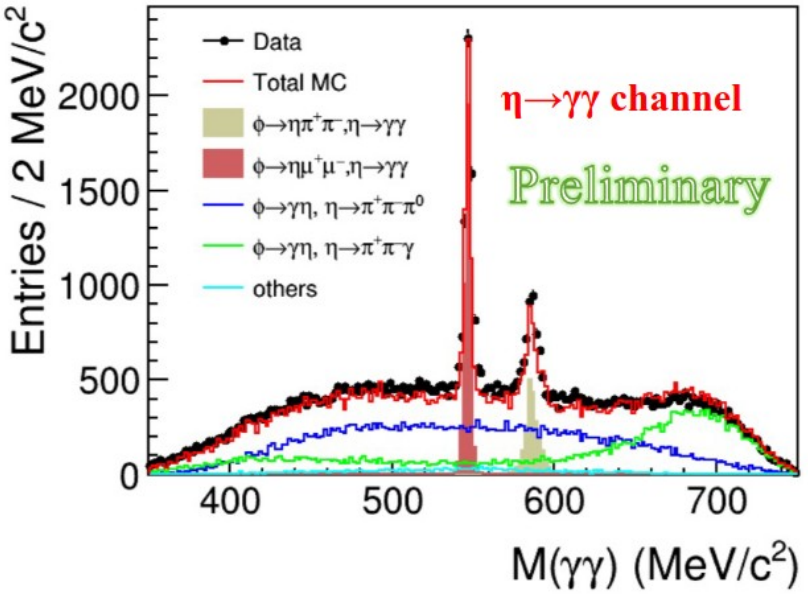


KLOE: Phys. Lett. B742 (2015) 1

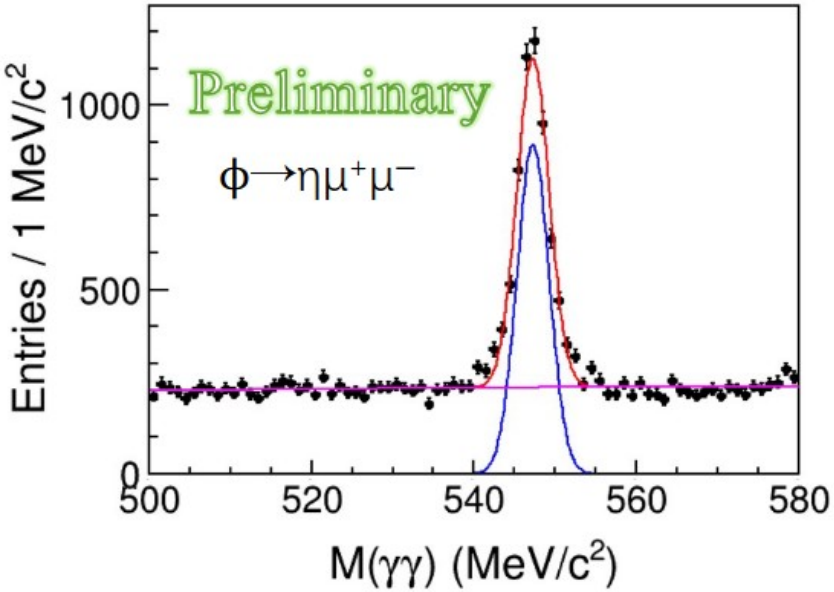
$$\frac{1}{\Gamma(\phi \to \gamma\eta)}\frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = |F_{\phi\eta}(q^2)|^2 \times \frac{\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4M_\mu^2}{q^2}}\left(1+\frac{2M_\mu^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{M_\phi^2-M_\eta^2}\right)^2-\frac{4M_\phi^2 q^2}{(M_\phi^2-M_\eta^2)^2}\right]^{3/2}$$

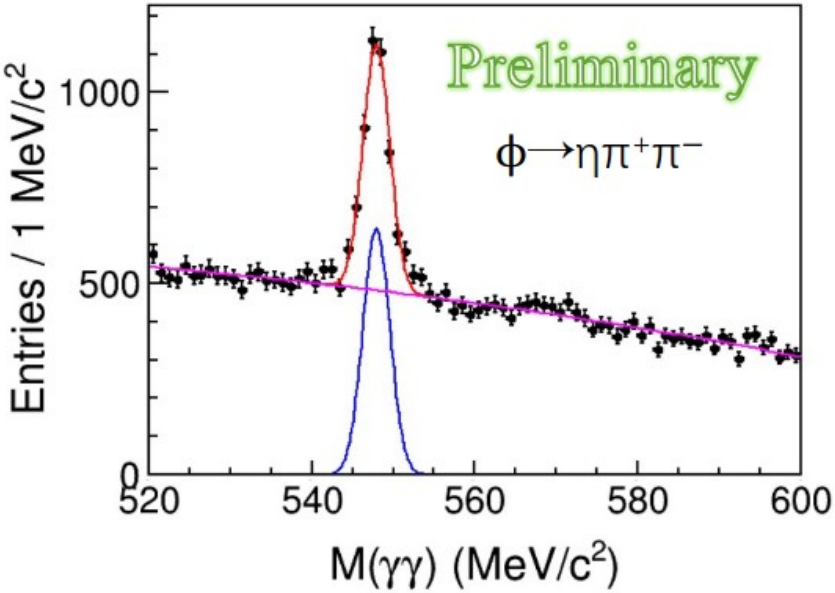
$\Phi \to \eta\pi^+\pi^-$ and $\Phi \to \eta\mu^+\mu^-$

- **1.635 fb^{-1} data analyzed**
- **Clear signals for both $e^+e^- \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$**
- **Ongoing analysis**



clear $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ signals

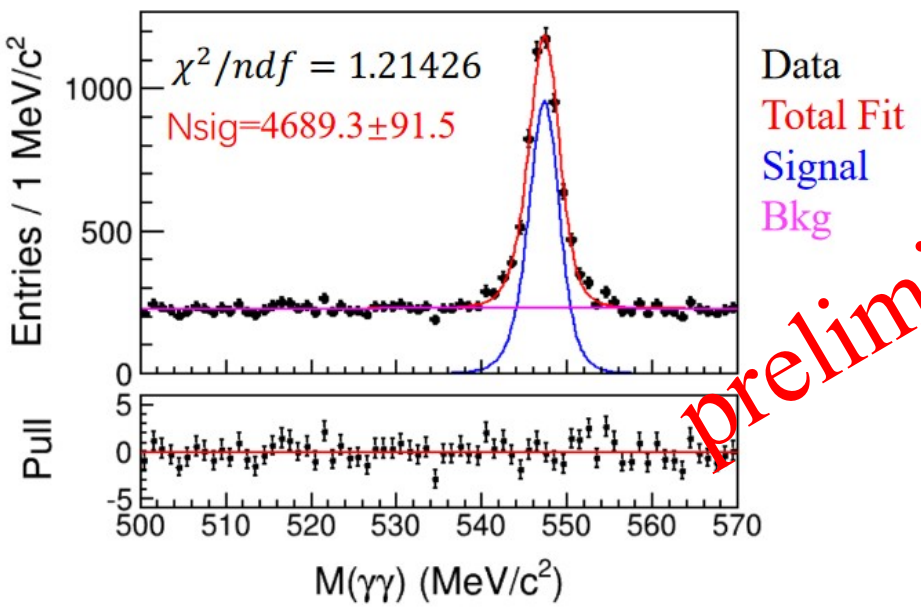




$\Phi \rightarrow \eta\mu^+\mu^-$

$\eta \rightarrow \gamma\gamma$

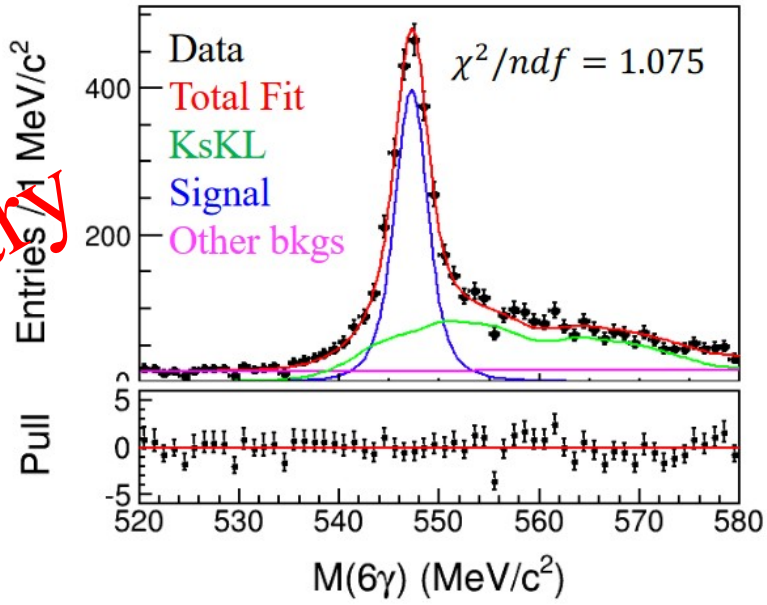
Fit with MC shape convoluted with Gaussian + 3-rd poly



$$Br(\phi \rightarrow \mu^+\mu^-\eta) = \frac{N(\phi \rightarrow \mu^+\mu^-\eta)}{\mathcal{L}_{int}\sigma(e^+e^- \rightarrow \phi)\mathcal{B}(\eta \rightarrow \gamma\gamma)\varepsilon}$$

$$= (5.65 \pm 0.11)\times 10^{-6}$$

$\eta \rightarrow 3\pi^0$



$$Br(\phi \rightarrow \mu^+\mu^-\eta) = (5.76 \pm 0.19)\times 10^{-6}$$

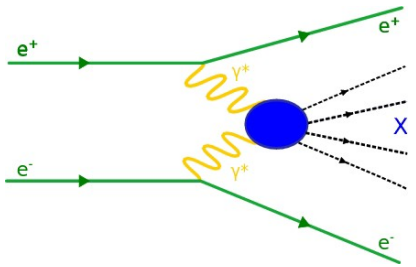
Ongoing check on systematic uncertainties

$\gamma^*\gamma^* \to \pi^0$ Analysis (High Energy Tagger - HET)

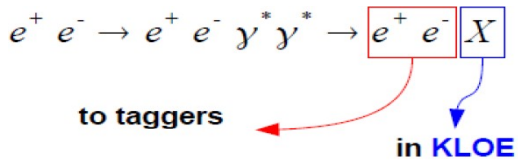
$$e^+e^- \to e^+e^-\gamma^\star\gamma^\star \to e^+e^-X$$

$$[C(X) = +1]$$

$$X = \pi^0, \pi\pi, \eta$$

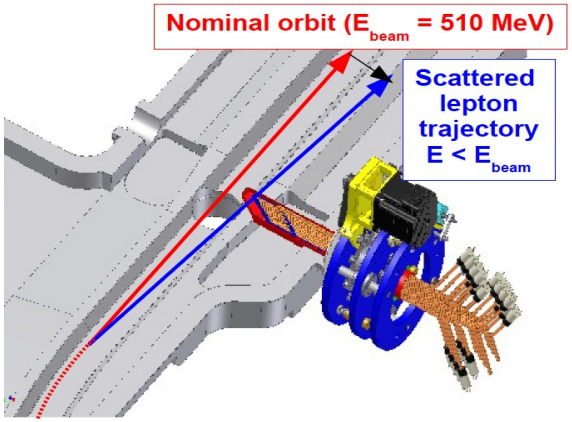


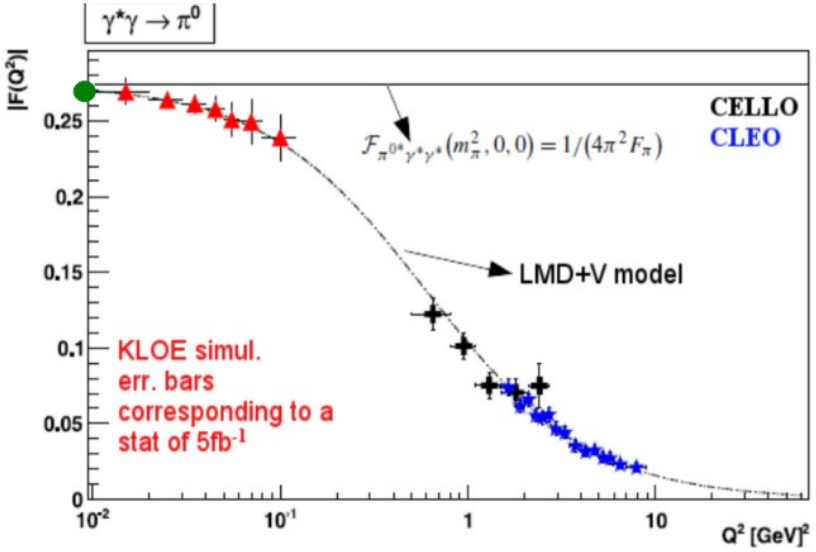
Bernstein & Holstein, Rev. Mod. Phys., 85 (2013) 49



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

- Precision measurement of $\Gamma(\pi^0 \to \gamma\gamma)$
- Transition form factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2| < 0.1$ GeV^2), impact on value and precision of $a_\mu^{LbyL;\pi 0}$





First bending dipoles of DAΦNE act as spectrometers for scattered leptons (420 < E < 495 MeV)

Scintillator hodoscope + PMTs, inserted in Roman pots pitch: 5 mm, ~ 11 m from IP (σ_E~2.5 MeV σ_t~500 ps)

HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5 - FPGA),synchronization with the "Fiducial» signal from DAΦNE (each 325 ns)and the KLOE trigger

HET acquisition window corresponds to about 2.5 DAΦNE revolutions, data are recorded only when a KLOE trigger is asserted

The analysis is based on the HET-KLOE coincidences and the accidental-pure samples used for background modelling (shape and number)

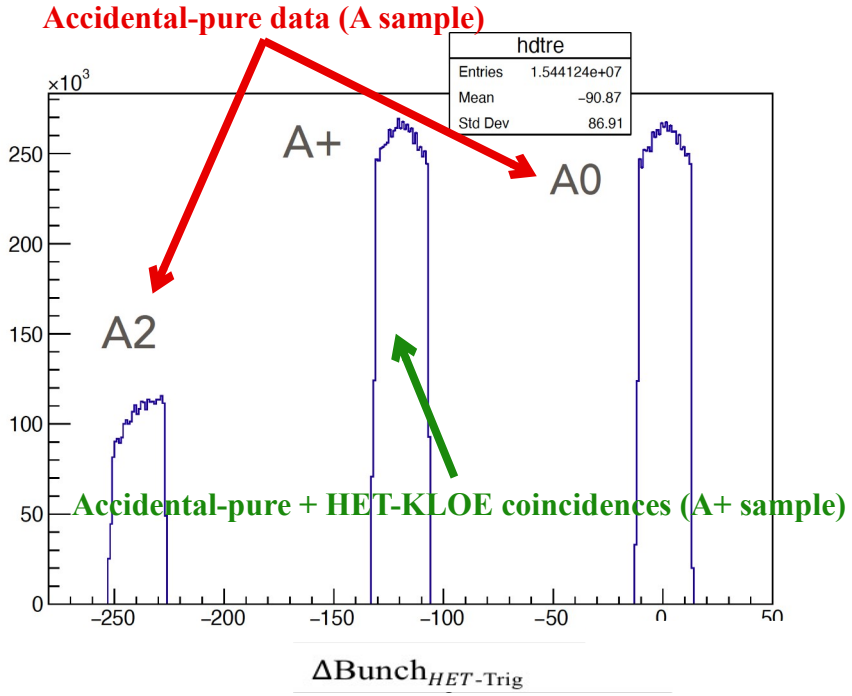
$\gamma^*\gamma^* \to \pi^0$ Analysis

Single-arm selection:
-Sample of 2 clusters associated with the same bunch crossing in the KLOE barrel calorimeter
-Selected bunch crossing, and, independently selected HET signal, are in a time window of 40 ns around the KLOE trigger

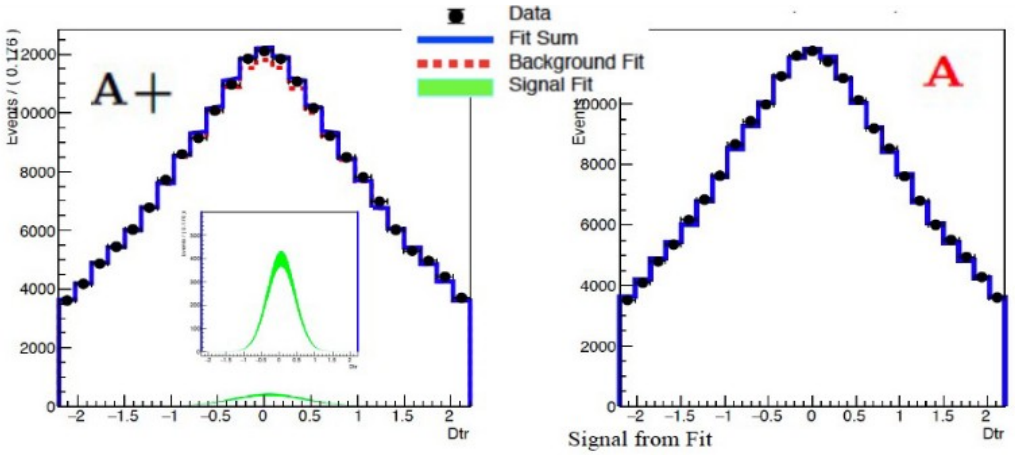
Analysis Strategy:
-ML fits of A+/A samples.
-Fit to accidental−pure samples used to constrain the number of accidentals in A+
-Time coincidence window : 4 ÷ 5 bunch crossings depending on the period

-Accidental pure sample (A) used to model background pdf

-Signal pdfs by Ekhara simulation, control samples and BDSIM transport of the leptons through the beam line



Simultaneous fit of A+ signal rich and A samples



Example of fit on one HET readout channel

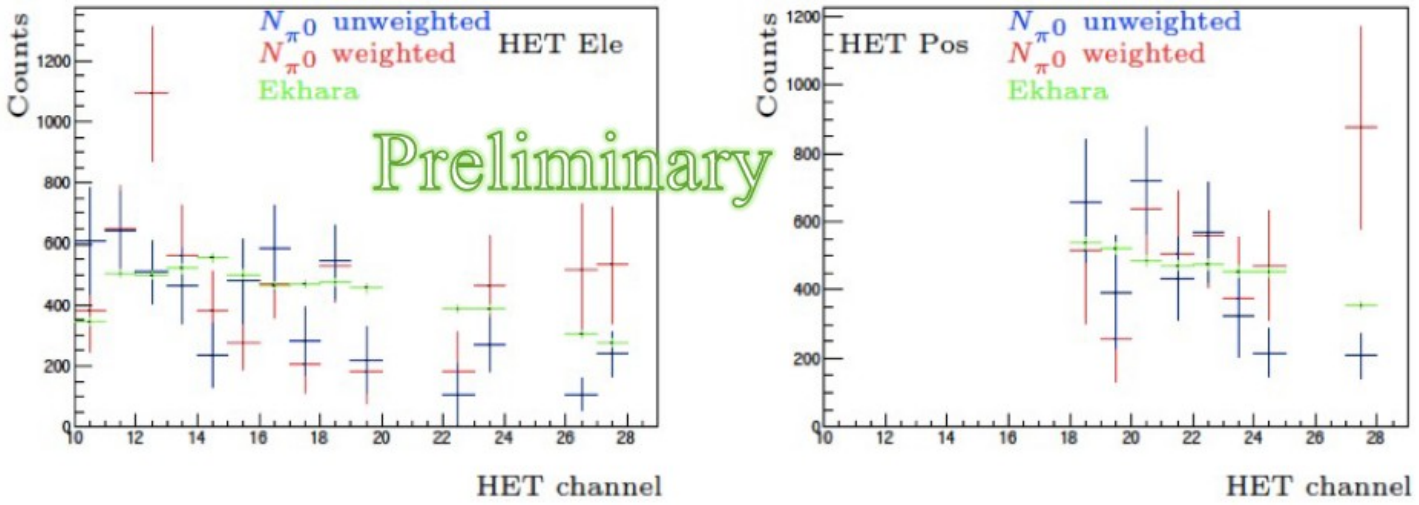
$\gamma^*\gamma^* \rightarrow \pi^0$ Analysis

$$\frac{\sigma_{\pi^0}}{\sigma_{\mathrm{Bha}}} = \frac{N^{\mathrm{meas}}_{\pi^0}}{\epsilon_{\mathrm{ana}}\, N^{\mathrm{meas}}_{\mathrm{Bha}}} \frac{A_{\mathrm{Bha}}}{A_{\pi^0}}$$

- **Number of π^0 candidates counting**: final checks on weights ongoing
  - Normalize to Radiative Bhabha at very small angle
  - $\sigma^{\mathrm{meas}}_{\mathrm{Bha}}$ is measured at few % level
  - Luminosity measurement from KLOE online and cross-checks with $e^+e^- \rightarrow \gamma\gamma$
  - ϵ_{ana}: Analysis efficiency evaluation completed
  - $A_{\mathrm{Bha}}/A_{\pi 0}$: Full simulation of signal and control sample, evaluated from Ekhara/BBBREM generator + BDSIM for lepton transport, evaluation of systematic uncertainties in progress

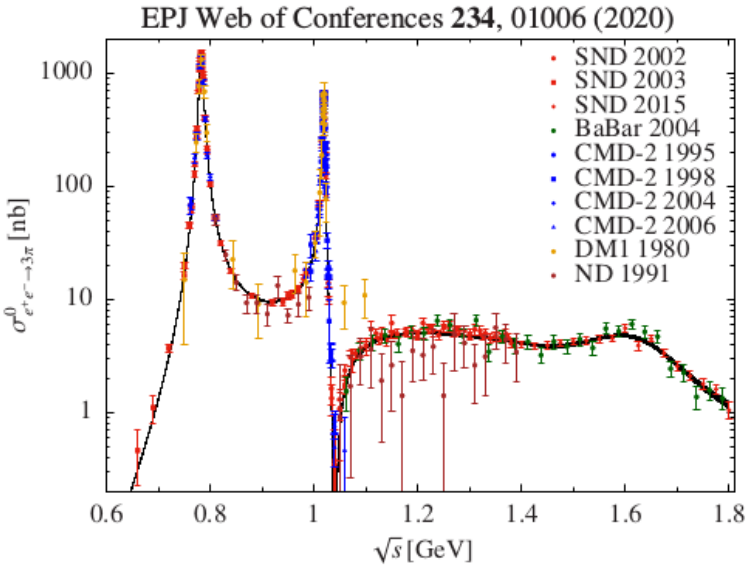
$$N^{\mathrm{meas}}_{\mathrm{Bha}} = \sigma^{\mathrm{meas}}_{\mathrm{Bha}} \int \mathbf{Ldt}$$

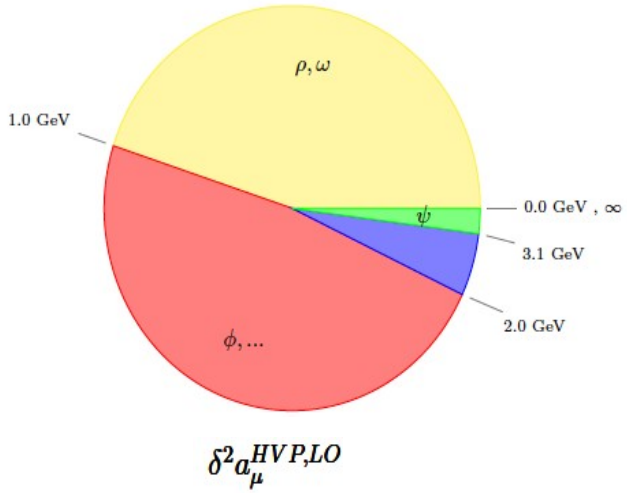
Tagged π^0 in 3 fb^{-1} of data



$e^+e^- \to \pi^0\pi^+\pi^-\gamma_{ISR}$

- $e^+e^- \to 3\pi$ is the second largest contribution on a_μ^{HVP} at the leading order, both in absolute values and uncertainties.
- Current cross section measurement of $e+e- \to 3\pi$ comes from CMD-2/SND measurement with energy scan and by Babar/BES with ISR technique.
- For $\sqrt{s} < M\phi$ this measurement is feasible using ISR technique in KLOE/KLOE-2
- ISR KLOE measurement in low energy region, complementary to direct energy scans.

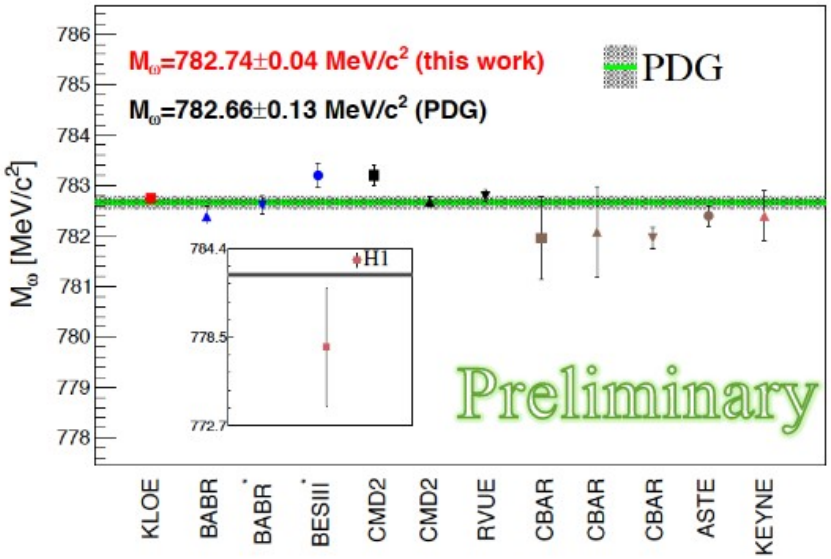




Further physics goals:
- to extract the peak cross section of the process $e^+e^- \to V \to 3\pi$, involving vector resonances V = φ, ω
- to measure cross section of non-resonant process $e^+e^- \to \gamma^* \to 3\pi$.
- to measure product of branching fractions $B(\omega \to e^+e^-) \times B(\omega \to 3\pi)$

$e^+e^- \to \pi^0\pi^+\pi^-\gamma_{ISR}$

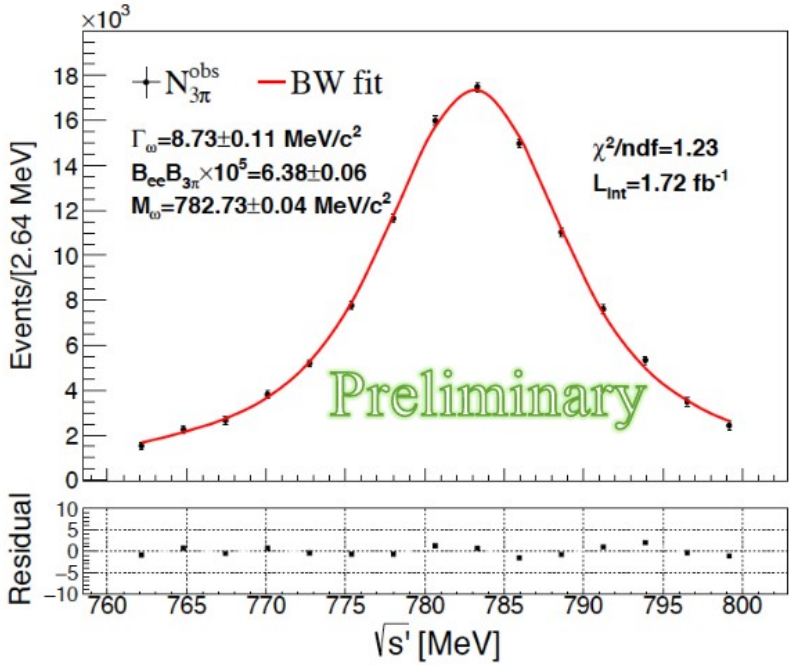
- Analysis on ~1.7 fb^{-1} on-peak and ~246 pb^{-1} off-peak data samples.
- Selection based in at least 2 tracks with opposite curvature + 3 neutral clusters
- Kinematic fit to improve resolution



KLOE results* compared with PDG

	M_ω [MeV/c^2]	Γ_ω [MeV]	$\mathcal{B}_{ee}\times\mathcal{B}_{3\pi}$ [10^{-5}]
KLOE	782.73 ± 0.04	8.73 ± 0.11	6.38 ± 0.06
PDG	782.66 ± 0.13	8.68 ± 0.13	6.60 ± 0.16

* Only stat. uncertainty



- After considering the radiation correction, a simple BW is used to fit the background-free M($\pi^+\pi^-\pi^0$) distribution
- Systematics evaluation ongoing
- Recent result from BaBar [*PRD104(2021)112003*]
  B_{ee} x $BR_{3\pi}$ = (6.56 ± 0.10) · 10^{-5}

Summary

- KLOE and KLOE-2 experiments have collected **~ 8 fb^{-1} , which represents the largest sample collected at a ϕ-factory.**
  - Rich KLOE-2 program for Kaon and Hadron Physics.

- We are **studying the golden χ-PT** process $\phi \rightarrow \eta\gamma$, $\eta \rightarrow \pi^0\gamma\gamma$

- We are studying 5 photon final state to set the first limit on the leptophobic B-Boson searching for the decay chain $\phi \rightarrow \eta B$, $B \rightarrow \pi^0\gamma$.

- We have observed for the first time, clean signals for $\phi \rightarrow \eta\pi^+\pi^-$ and $\phi \rightarrow \eta\mu^+\mu^-$ decays.

- We are using π^0's produced with $\gamma^*\gamma^*$-fusion and tagged with our small angle tagging system (HET) to determine the $\Gamma(\pi^0 \rightarrow \gamma\gamma)$.

- A clean signal of 3π final state in the ω region through ISR method is established.

- **The program of high precision investigation on light hadron physics and on fundamental symmetries is being continued with the analysis of KLOE/KLOE-2 data.**

Backup

γγ cross section measurement, concept and status

Measurement concept:

$$\frac{\sigma_{\pi^0}}{\sigma_{\mathrm{Bha}}} = \frac{N_{\pi^0}}{\epsilon_{\mathrm{ana}}\,\sigma_{\mathrm{Bha}}^{\mathrm{meas}} \int Ldt}\,\frac{A_{\mathrm{Bha}}}{A_{\pi^0}}$$

Status of the measurement:

N_{π^0} → Number of π^0 tagged events. Preliminary results on the whole reconstructed data sample (electron station) obtained, 10% precision level.

ϵ_{ana} → Analysis efficiency evaluation completed, only small refinement needed.

$\frac{A_{\mathrm{Bha}}}{A_{\pi^0}}$ → Full simulation of signal ($\gamma\gamma \to \pi^0$ triggering KLOE DAQ and one lepton in the HET) and normalization channel (low angle $e^+e^-\gamma$ with one lepton reaching HET) events, obtained with EKHARA/BBBREM generators + BDSIM for lepton transport, completed.

$\sigma_{\mathrm{Bha}}^{\mathrm{meas}} \int \mathrm{Ldt}$ → Obtained from the KLOE online luminosity measurement. Product independent from luminometer scale, scaling behavior checked along data-taking periods.