Hadron physics results at KLOE-2 experiment

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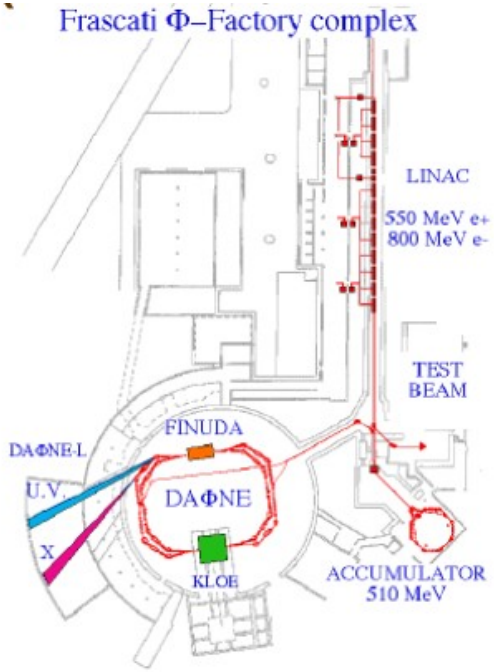
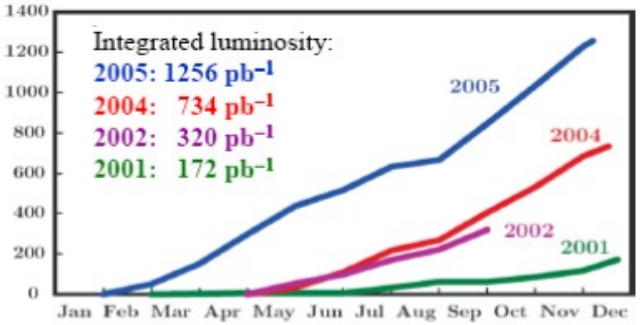
Outline

- 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
  - $\eta \to \pi^+\pi^-$ analysis results
  - Search for $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$ decays
  - $\gamma\gamma \to \pi^0$ search
  - ω cross section measurement in the $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$
- Summary

KLOE @ DAΦNE



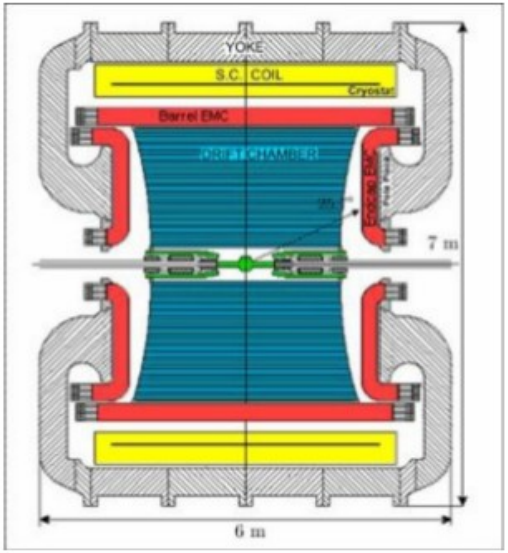
- $e^+ e^-$ collider $\sqrt{s} = M_\Phi = 1019.4$ MeV
  - 2 interaction regions
  - $e^+ e^-$ separated rings
  - 105 + 105 bunches spaced by 2.7 ns



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

- **Calorimeter**
- 98% coverage full solid angle
- $\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_T = 57$ ps $/ \sqrt{E(\text{GeV})} \oplus 140$ ps
- Barrel + 2 end-caps:
  - Pb/scintillating fiber read out by 4880 PMTs

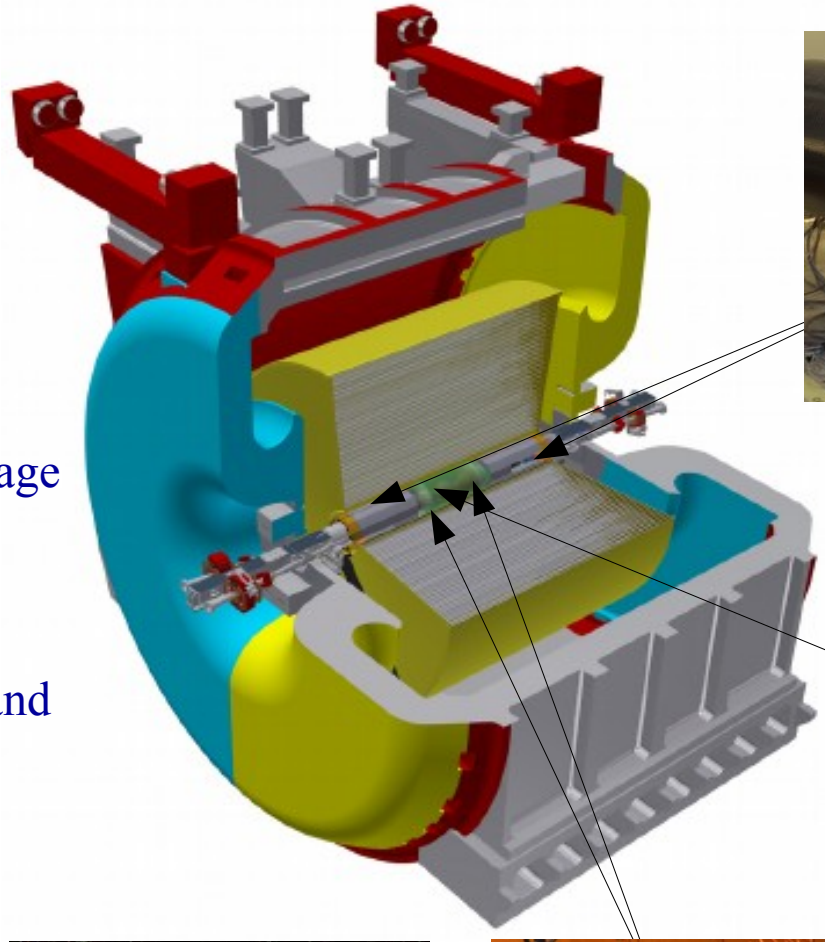
Magnetic field B = 0.52 T

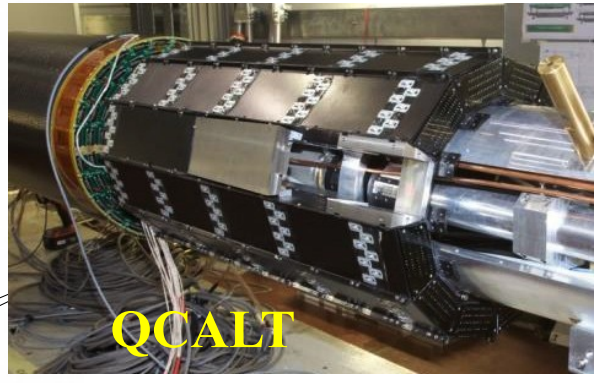


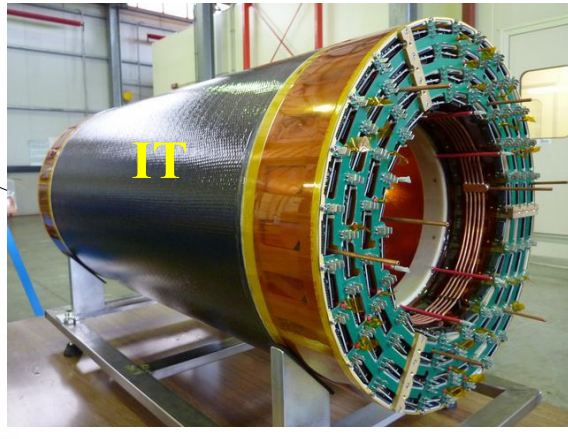
KLOE-2

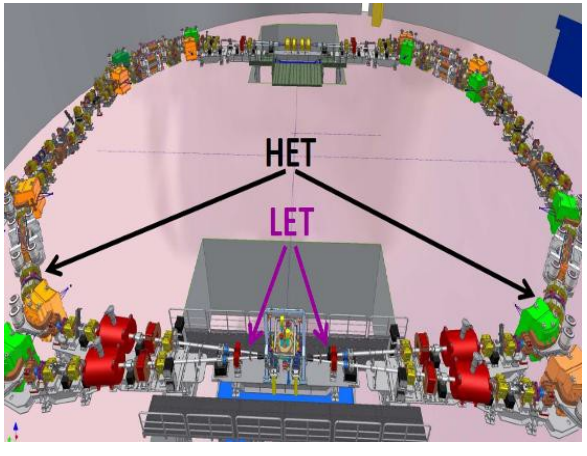
- LET (Low Energy Tagger) & HET (High Energy Tagger)
  - e+e--taggers for γγ-physics
- CCALT & QCALT
  - 2 new calorimeters (for low angle γs & quadrupole coverage from K_L decays)
- IT (Inner Tracker)
  - 4 layers of C-GEM
  - better vertex reconstruction and

Track parameters





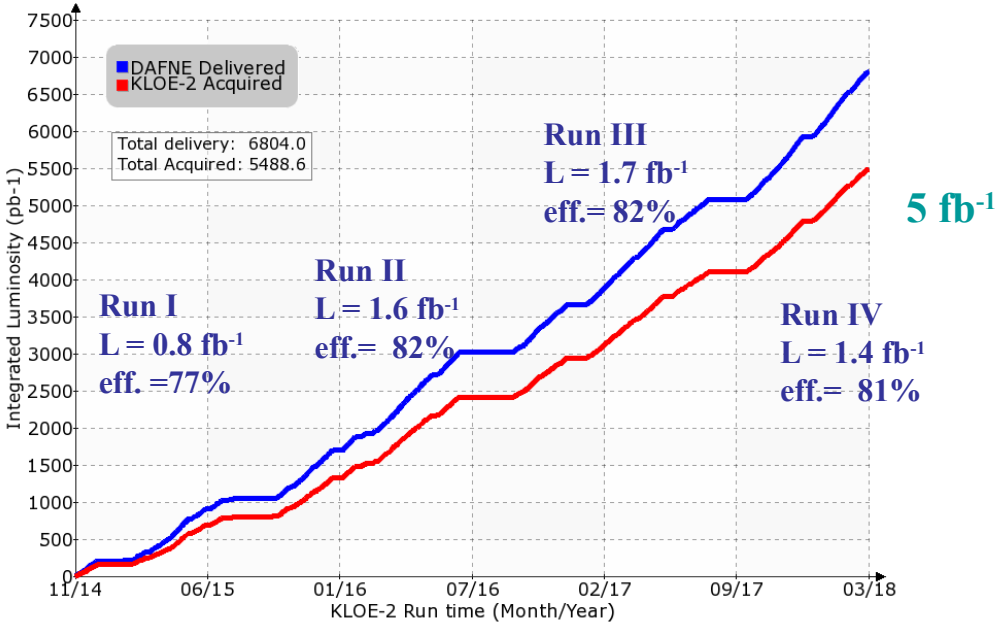




KLOE/KLOE-2 Experiment

- 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



5.5 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 $\phi \to K_S K_S \gamma$
- $\gamma\gamma$ 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 Im(ε'/ε)
- 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:

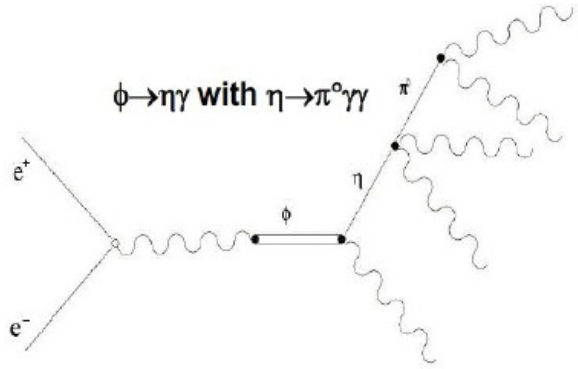
- ISR studies with 3π, 4π final states
- F_π with increased statistics

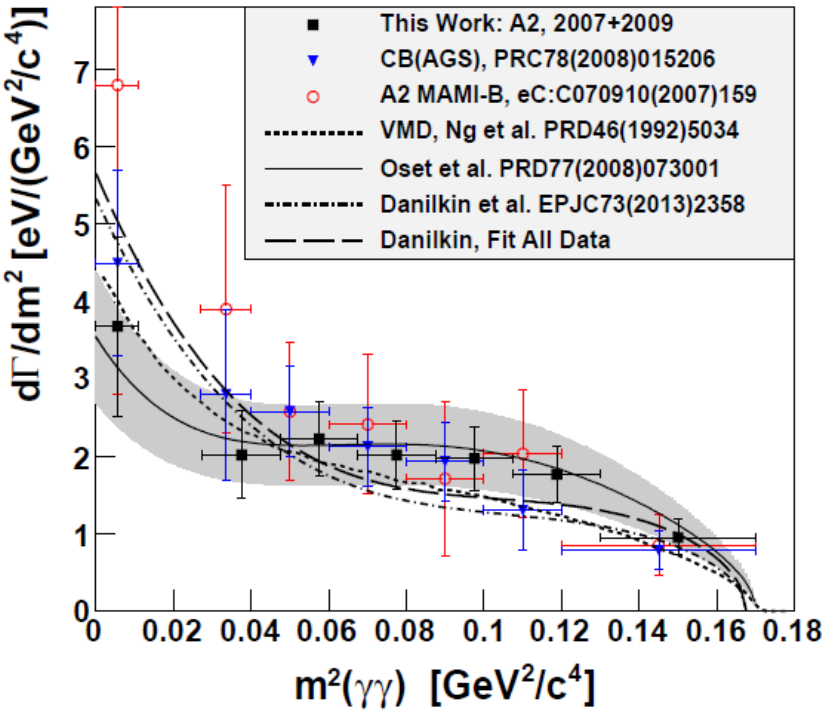
Measurement of a_μ^{HLO} in the space-like region using Bhabha process

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(p2) null, O(p4) suppressed ⇒ sensitive to O(p6)
- Mass of non-π^0 photons can be used as a test of theoretical model



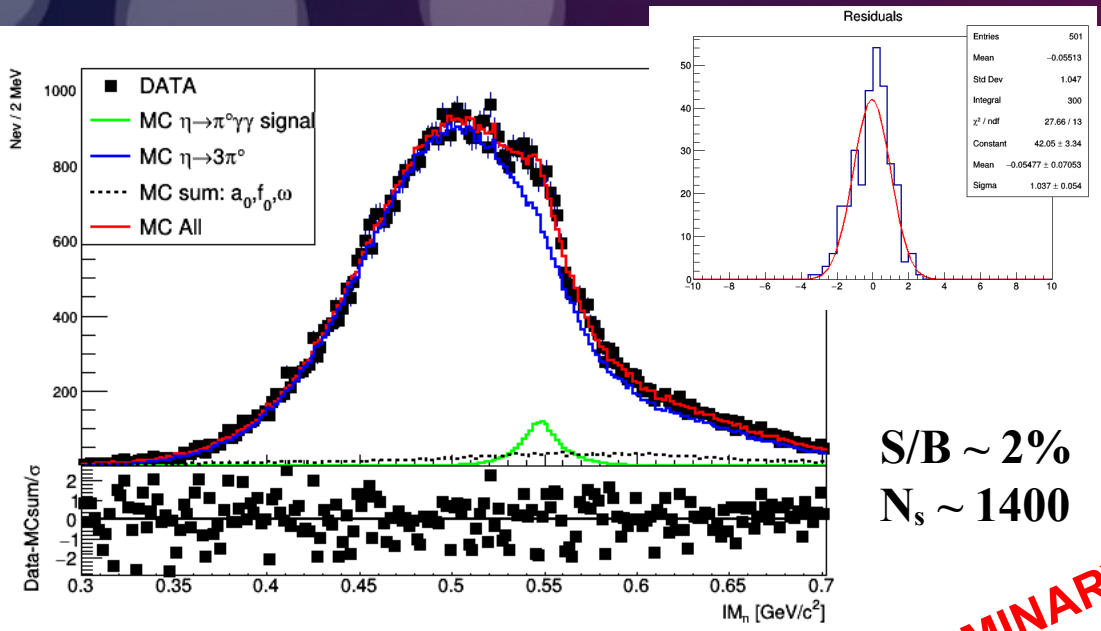


Previous measurements:

- **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)**

- Latest theoretical studies by Escribano et al. *PRD 90 (2020) 034026*:
  - Calculated BR = $1.35(8) \cdot 10^{-4}$
- Many previous predictions differ by a factor ~2

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



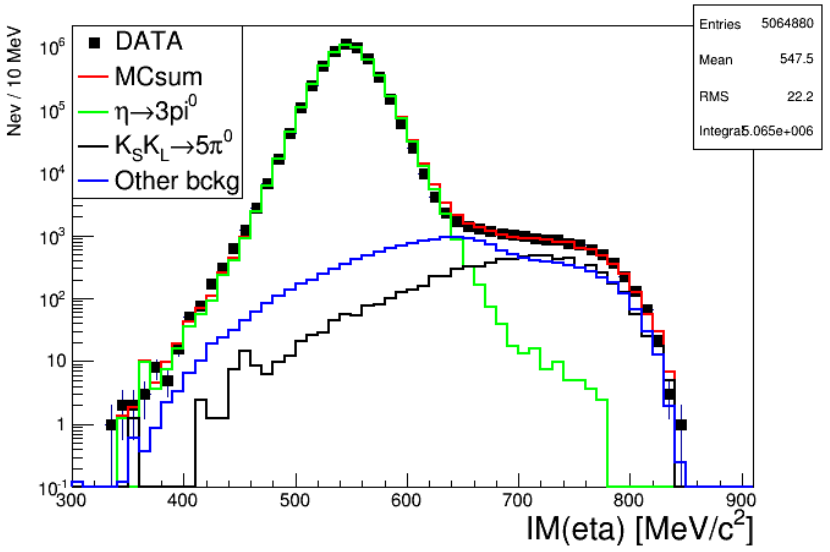
S/B ~ 2%
N_s ~ 1400

PRELIMINARY

- **Integrated luminosity of 1730 pb^{-1}, around 7·10^7 η's**
- **$\eta \to 3\pi^0$, $\eta \to \pi^0\gamma\gamma$ signal and ∑ of non-3pi0 MC's fitted to data**
- **Fit χ^2/(ndf=98)=1.033 (fit_prob=39%)**
- **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

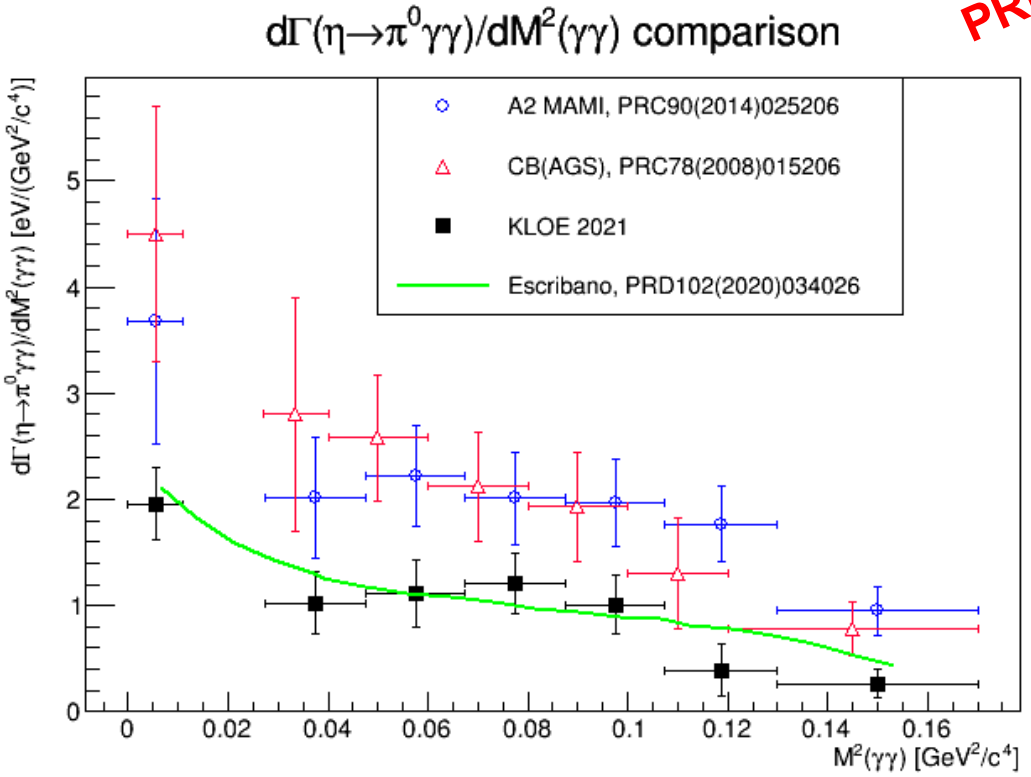


$$\frac{BR(\eta \to \pi^\circ\gamma\gamma)}{BR(\eta \to 3\pi^\circ)} = \frac{N_S/\varepsilon_S}{N_{3\pi^\circ}/\varepsilon_{3\pi^\circ}}$$

$BR = (1.21 \pm 0.13_{stat}) \cdot 10^{-4}$

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

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
- Half of contribution compared with previous experiments
- Good agreement with the latest theoretical predictions by Escribano et al. From 2020 ($BR=1.35(8)\cdot10^{-4}$)

From integration of $d\Gamma/dM^2$ (missing bin linearly interpolated) one can calculate KLOE preliminary:

$$\mathbf{BR=(1.30 \pm 0.13_{stat})\cdot10^{-4}}$$

Leptophobic B-boson

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

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

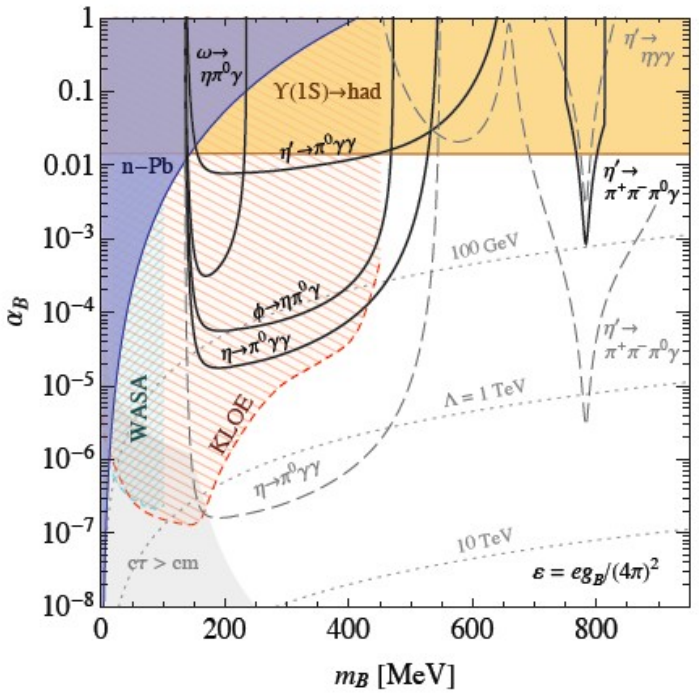
- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be studied in:

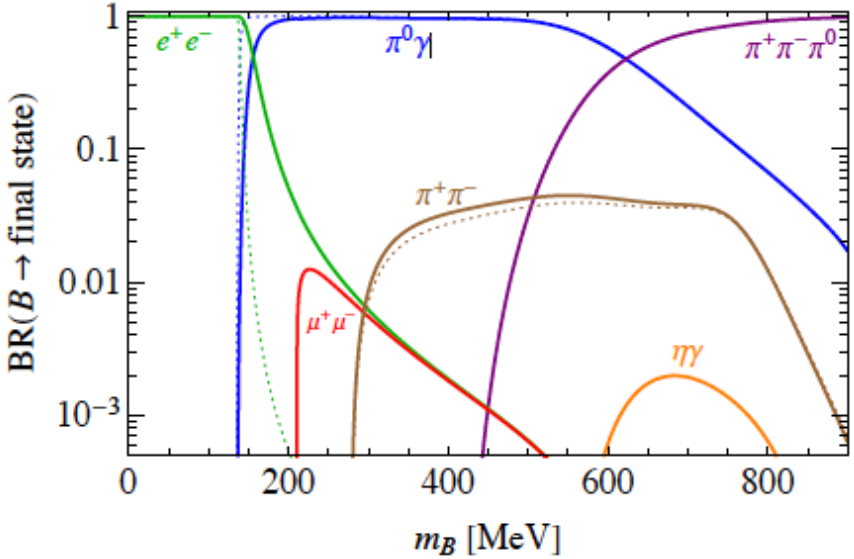
  $\phi \to \eta B \Rightarrow \eta\pi^0\gamma \Rightarrow$ 5 prompt γ final state

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

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

[Tulin, PRD89(2014)114008]

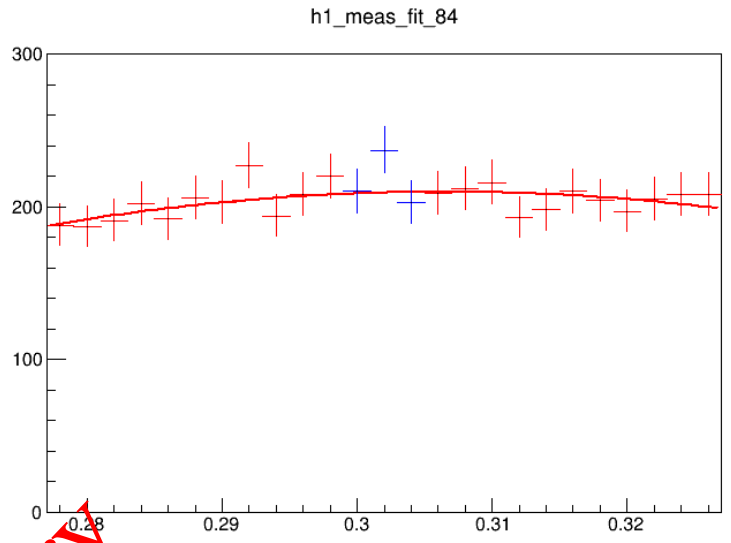




Decay → / Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\eta$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	…	…	…
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	…	…
$\eta' \to B\gamma$	$\eta' \to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

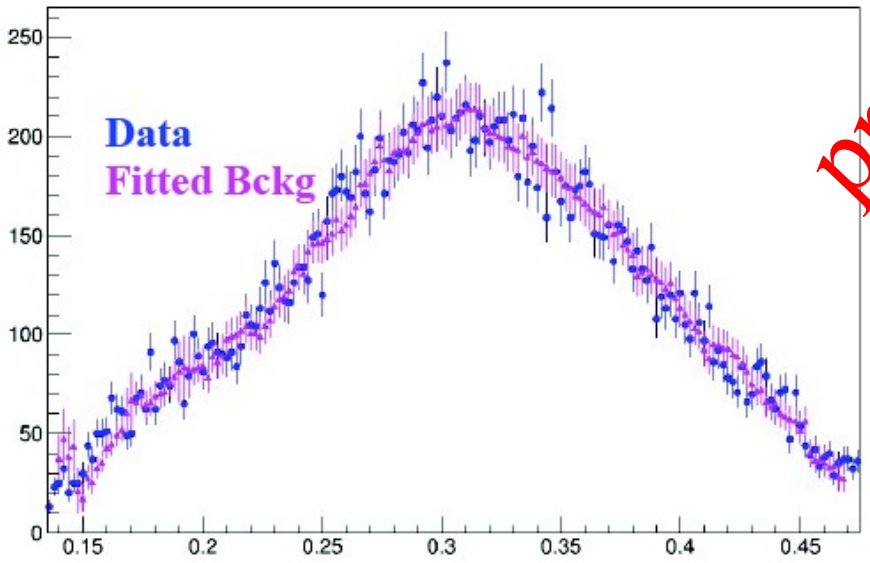
Leptophobic B-boson

- 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 $O(10^{-7})$

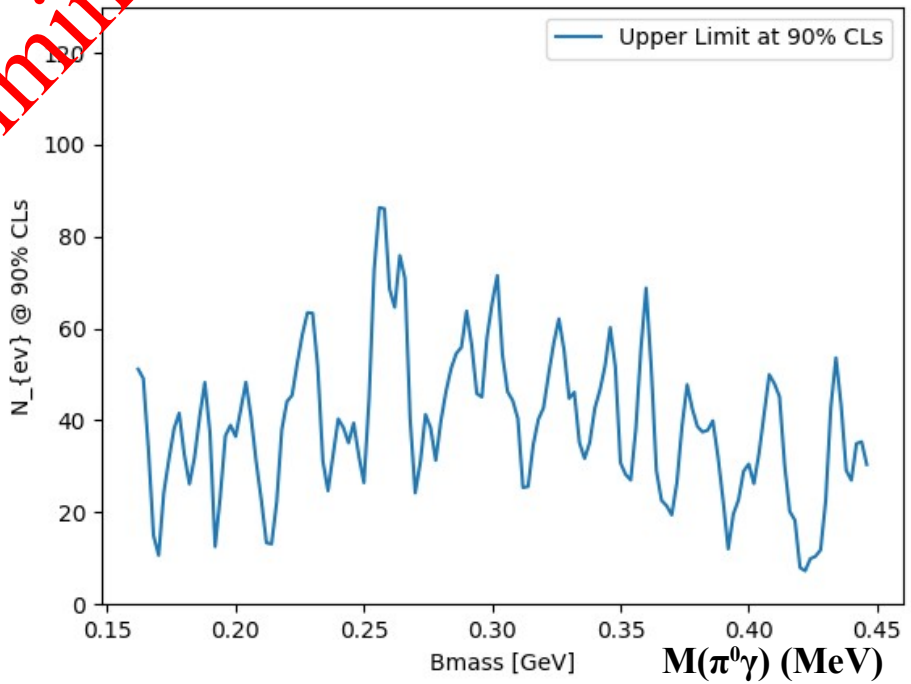


$M(\pi^0\gamma)$ (MeV)

preliminary



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



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

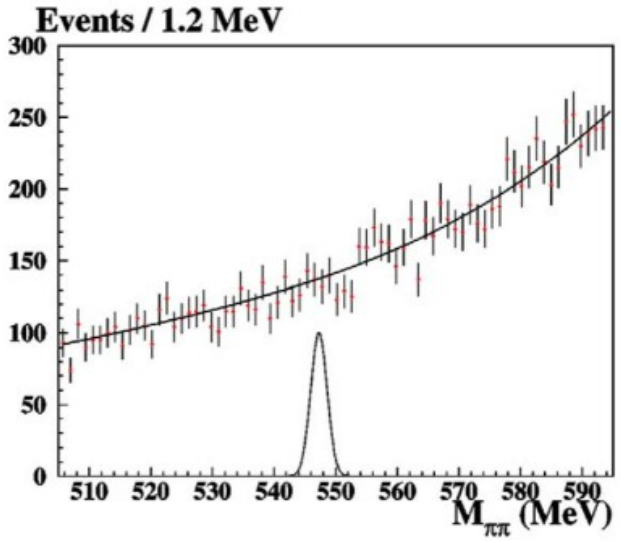
Search for $\Phi \rightarrow \eta\gamma$, with $\eta \rightarrow \pi^+\pi^-$

- $\eta \rightarrow \pi + \pi -$ is P and CP violating process

- The BR prediction in SM [Phys. Scripta T99, 23 (2002)]
  - proceeds only via the CP-violating in weak interaction $\rightarrow 10^{-27}$
  - introducing a CP violating term in QCD $\rightarrow$ to 10^{-17}
  - allowing CP violation in the extended Higgs sector $\rightarrow 10^{-15}$

Any observation of larger branching ratio would indicate a new source of CP violation in the strong interaction

- The previous limit **Br($\eta \rightarrow \pi + \pi -$) <1.3×10^{-5}** @ 90% C.L. by **KLOE** with $L_{int} \sim 350\ pb^{-1}$
- LHCb limit BR($\eta \rightarrow \pi + \pi -$)<1.6×10^{-5} @ 90% C.L. with Lint~3.3 fb^{-1}

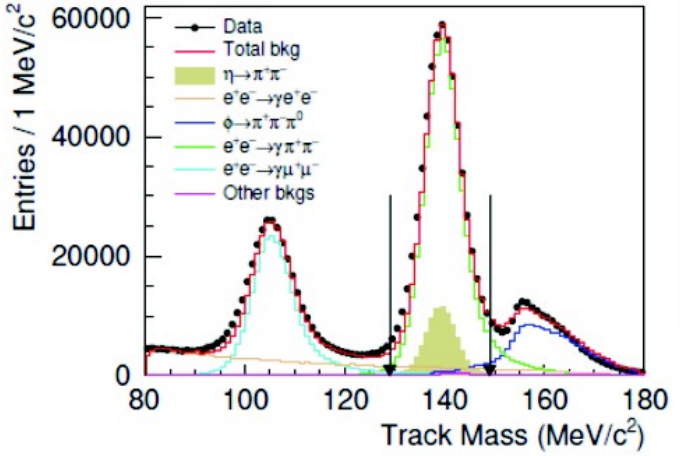


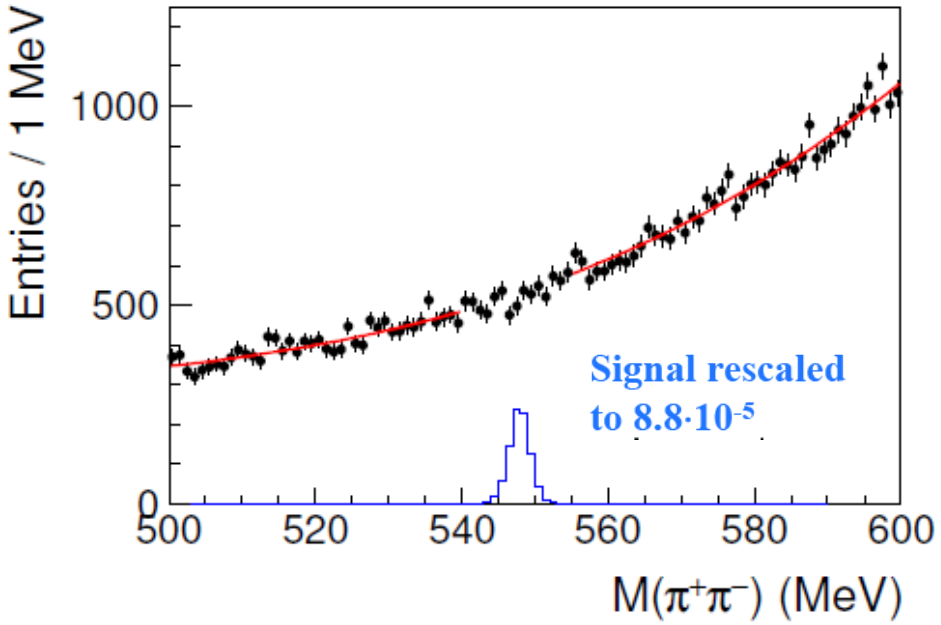
Search for $\Phi \rightarrow \eta\gamma$, with $\eta \rightarrow \pi^+\pi^-$

- New analysis using independent 1.6 fb^{-1} of KLOE data
- No event excess in the η region, limit extracted using CLs technique

Track mass 80 < M_{trk} < 180 MeV to reject $\mu^+\mu^-\gamma$ and $\pi^+\pi^-\pi^0$ backgrounds

$$|\vec{p}_\phi - \vec{p}_1 - \vec{p}_2| = E_\phi - \sqrt{|\vec{p}_1|^2 + M_{trk}^2} - \sqrt{|\vec{p}_2|^2 + M_{trk}^2}$$





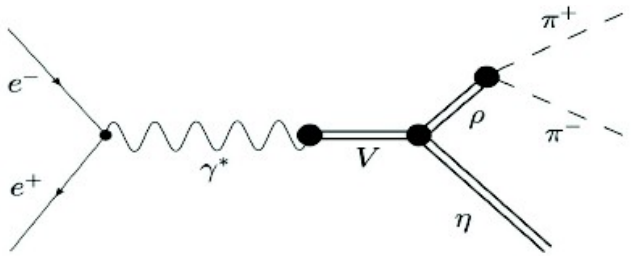
Br(η→π + π −) <4.9×10⁻⁶ @ 90% C.L.

- Combined with previous KLOE result (~ 0.4 fb^{-1})
  - **BR(η→π + π −)<4.4×10⁻⁶ @ 90% C.L.**

Published in JHEP10 (2020) 047

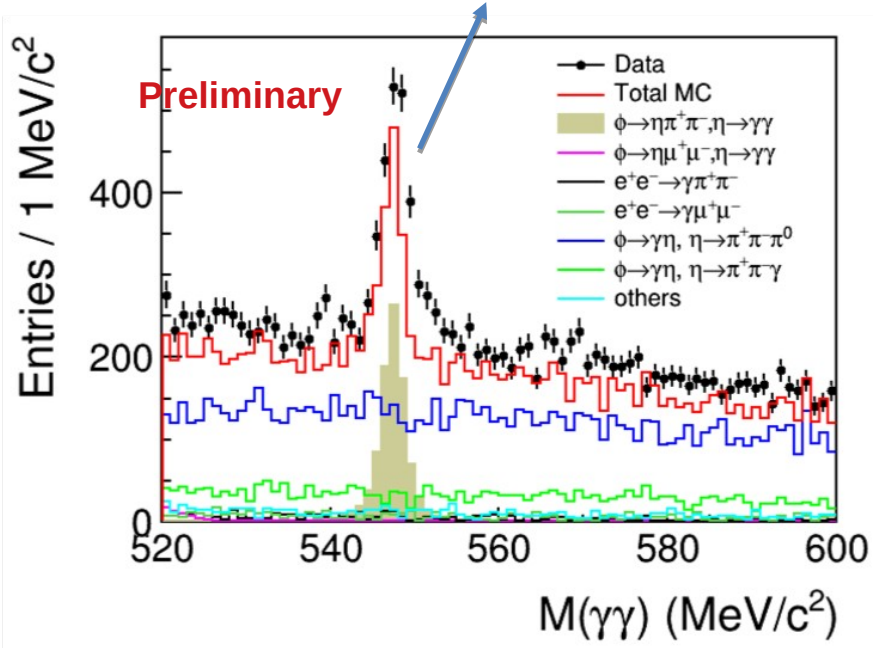
$\Phi \to \eta\pi^+\pi^-$ and $\Phi \to \eta\mu^+\mu^-$

- 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 also used to search for the Dalitz decay $\Phi \to \eta\mu^+\mu^-$, Br<0.94×10^{-5} @ 90% CL @ CMD-2 *PLB501(2001)191*

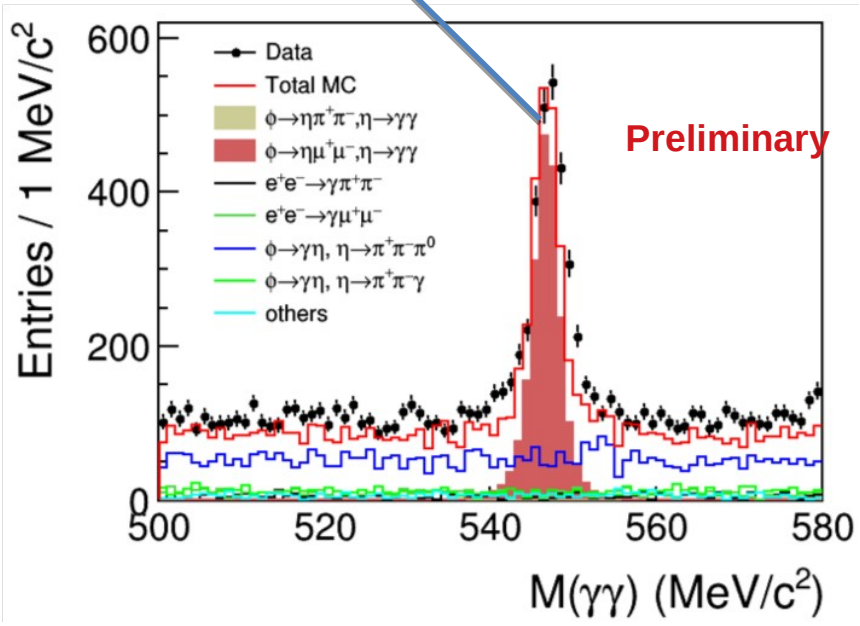


clear $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ signals

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



$\phi \to \eta\mu^+\mu^-$

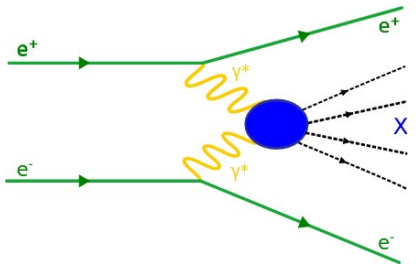


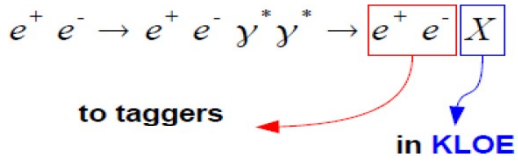
$\gamma\gamma$ physics with High Energy Tagger (HET)

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

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

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

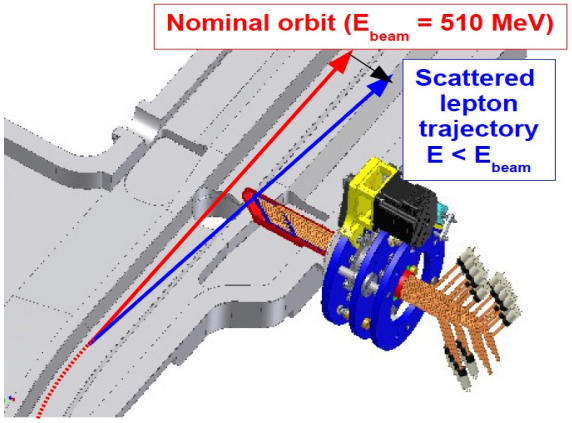




Measurement concept:
Eur. Phys. J. C 72 (2012) 1917

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

- 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 $a_\mu^{LbyL;\pi 0}$



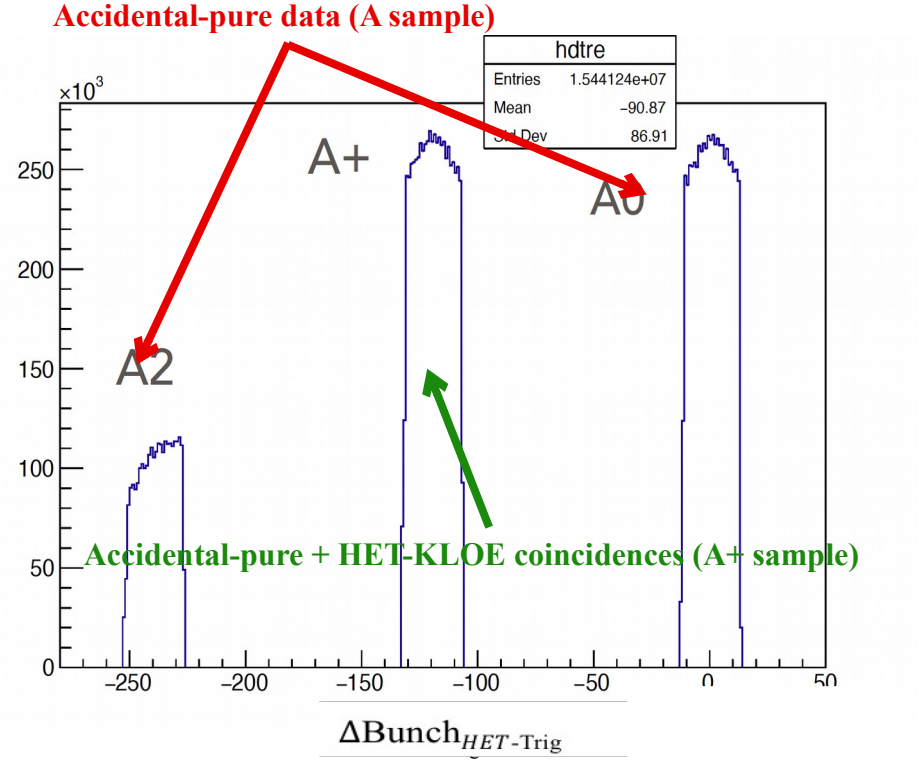
First bending dipoles of DAΦNE act as spectrometers for scattered leptons (420 < E < 495 MeV)

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)



Status of $\gamma\gamma$ 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

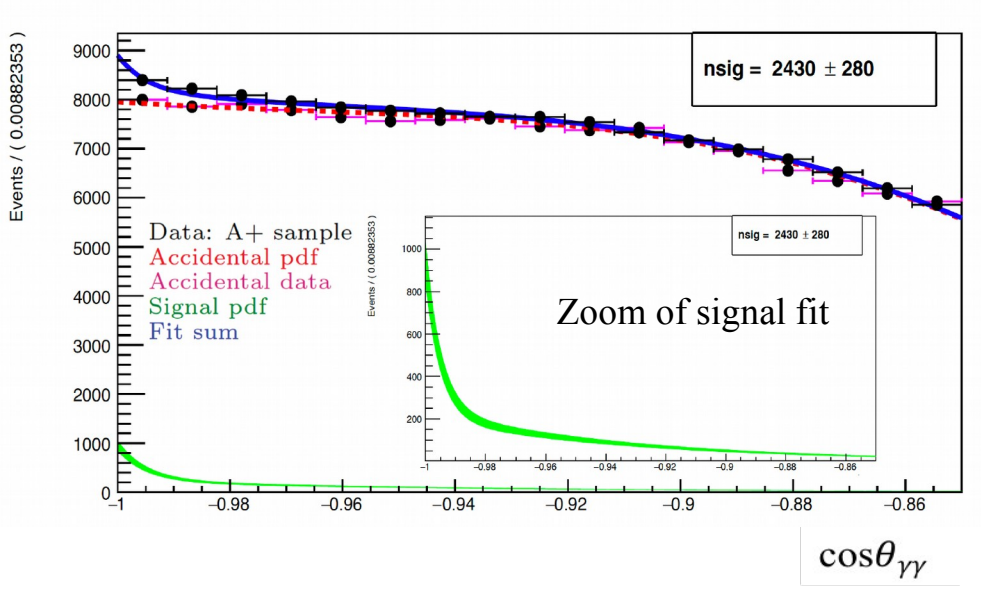
Analysis Strategy:
-ML fits of A+/A samples.
-Fit to accidental−pure samples used to constrain the number of accidentals in A+
-Time coincidence window : 4 ÷ 5 bunch crossings depending on the period

-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

Example of ML fit, statistics: $2fb^{-1}$, HET electron data from October '16 to March '18

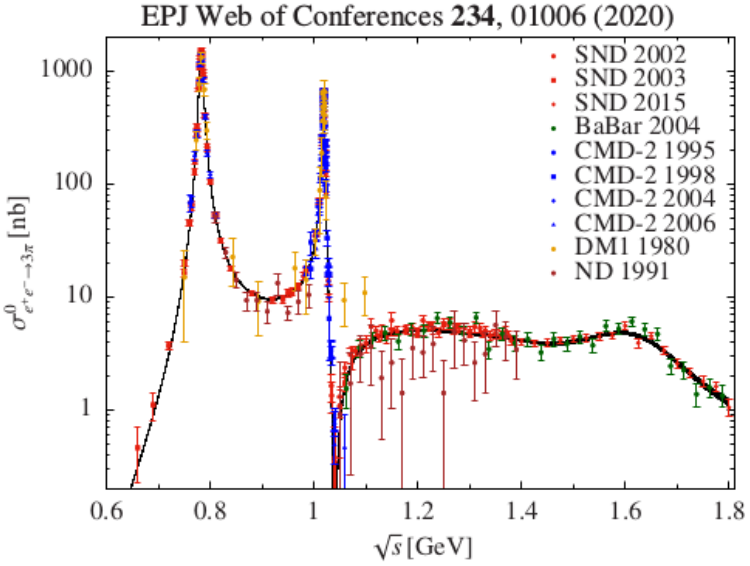
Signal-enriching cut applied: $|T-R/c| < 0.5$ ns, cut efficiency 80% from control sample studies

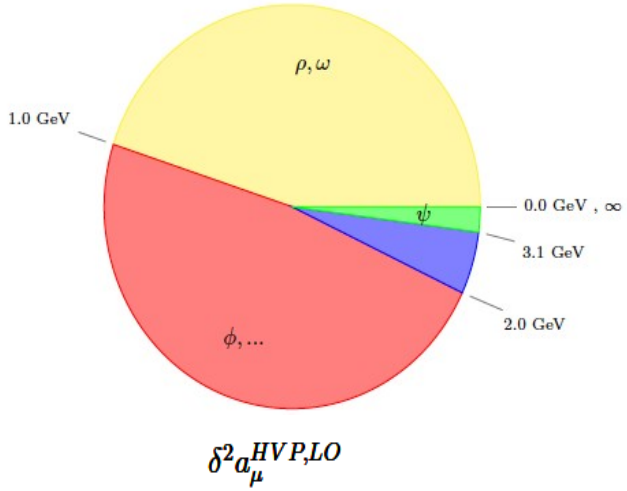


10% precision level on signal reached.
Some improvements still possible.

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

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

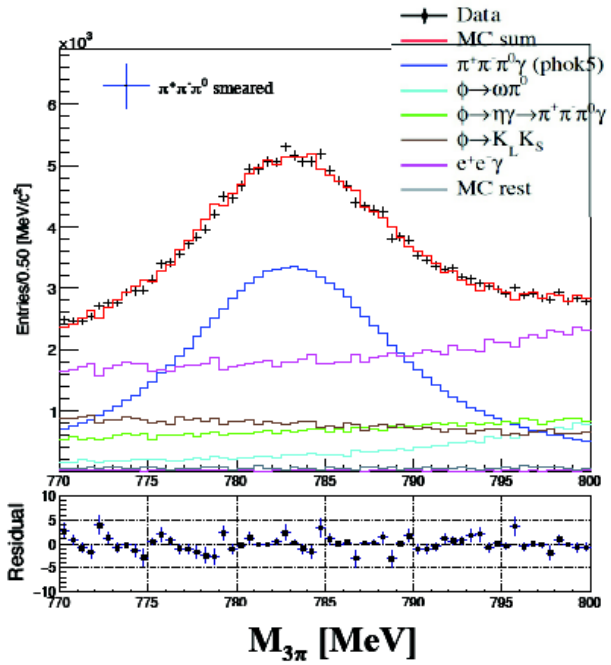




Further physics goals:
- to extract the peak cross section of the process $e^+e^- \to V \to 3\pi$, involving vector resonances V = φ, ω
- to measure cross section of non-resonant process $e^+e^- \to \gamma^* \to 3\pi$.
- to measure product of branching fractions $B(\omega \to e^+e^-) \times B(\omega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

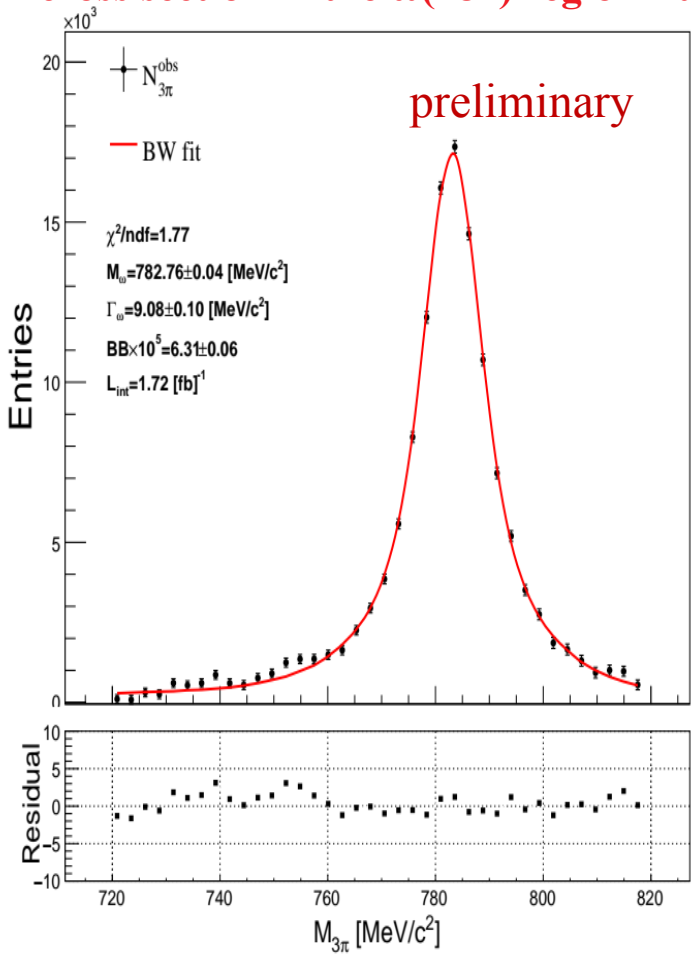
$e^+e^- \to \pi^0\pi^+\pi^-\gamma_{ISR}$

- 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



- Fit with a single Breit-Wigner convoluted with the ISR radiator and mass resolution smearing function
- Systematics evaluation ongoing
- Theoretical model for fit is being refined

cross section in the ω(782) region fit



in agreement with PDG value

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 **$\Phi \to \eta\gamma$, $\eta \to \pi^0\gamma\gamma$**
  - Preliminary BR is ~1/2 of previous best measurements and in agreement with the most recent theory calculation.

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

- We have published **the world best limit on $\eta \to \pi^+\pi^-$** using the KLOE data sample reaching a **Br($\eta \to \pi^+\pi^-$) <4.9×10^{-6} @ 90% C.L.** , 3 times better than previous one. Limit has already been included in the PDG.

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

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

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

γγ cross section measurement, concept and status

Measurement concept:

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

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.

$\epsilon_{\rm ana}$ → Analysis efficiency evaluation completed, only small refinement needed.

$\frac{A_{\rm Bha}}{A_{\pi^0}}$ → 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.

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