Light Meson Decays at KLOE/KLOE-2

S. Giovannella
(INFN Frascati)

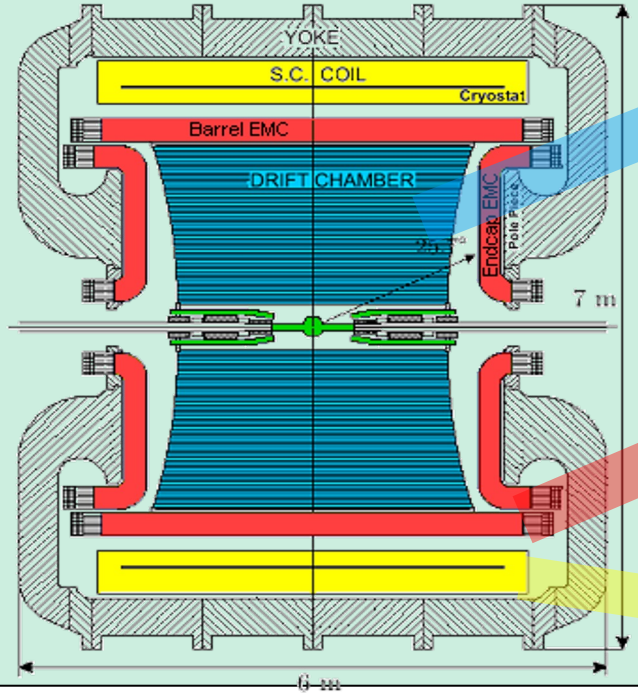
on behalf of the KLOE-2 Collaboration

Precision Tests of Fundamental Physics with Light Mesons
Trento, 12 – 16 June 2023

Outline

- KLOE and KLOE-2
- The $\eta \to \pi^0\gamma\gamma$ decay
- Search for $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$
- $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$ cross section
- Search for leptophobic B boson
- $\gamma^*\gamma^* \to \pi^0$
- Conclusions

The KLOE experiment



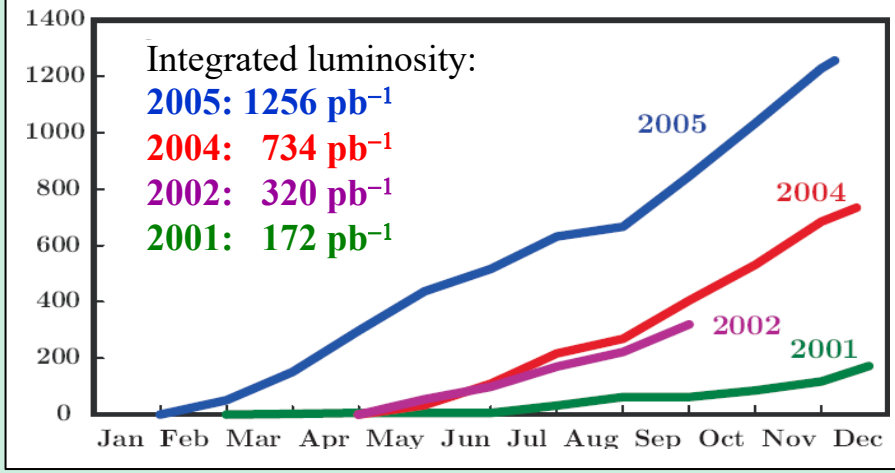
Drift chamber

- Gas mixture: **90% He + 10% C_4H_{10}**
- **dp_t / p_t < 0.4% (θ>45°)**
- **$\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm**

Electromagnetic calorimeter

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

Magnetic field: 0.52 T

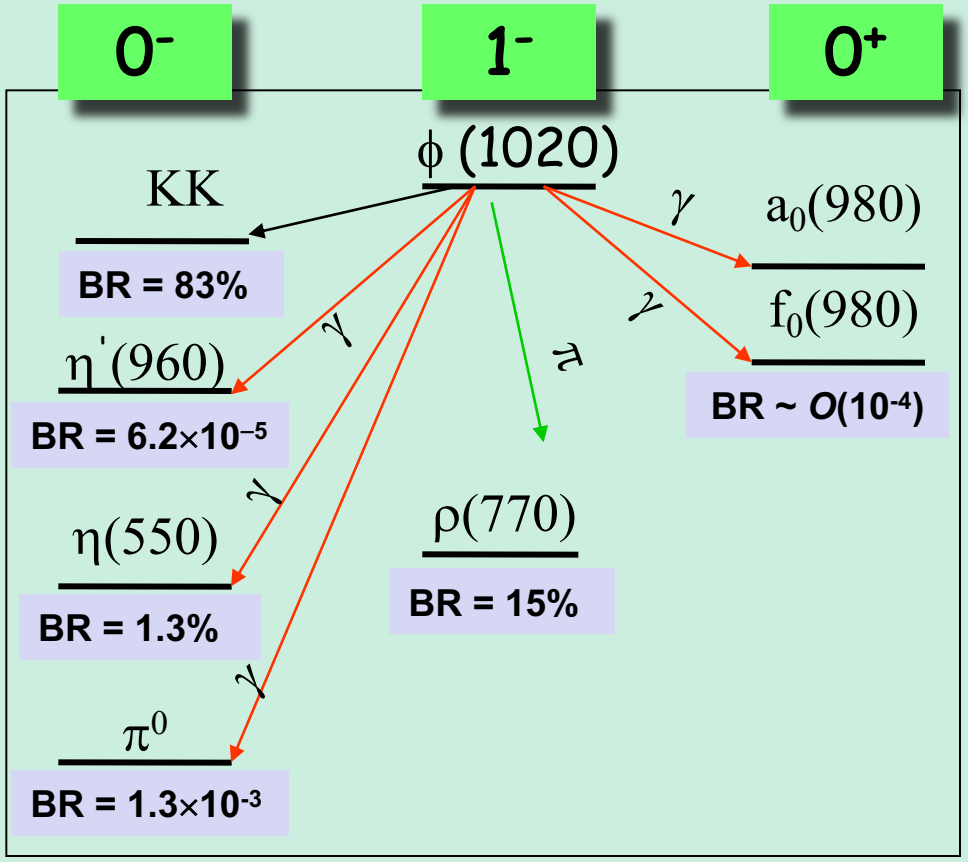


Data taking ended on March 2006

- **2.5 fb^{-1} on tape @ $\sqrt{s} = M_\Phi$ (8×10^9 ϕ)**
- **10 pb^{-1} @ $\sqrt{s}$ = 1010, 1018, 1023, 1030 MeV**
- **250 pb^{-1} @ $\sqrt{s}$ = 1000 MeV**

Physics @ a ϕ-factory

- Kaon Physics
- ϕ radiative decays: pseudoscalar and scalar mesons
- Hadron production in γγ collisions
- Hadronic cross section via ISR, ππ channel: hadronic corrections to $(g-2)_\mu$

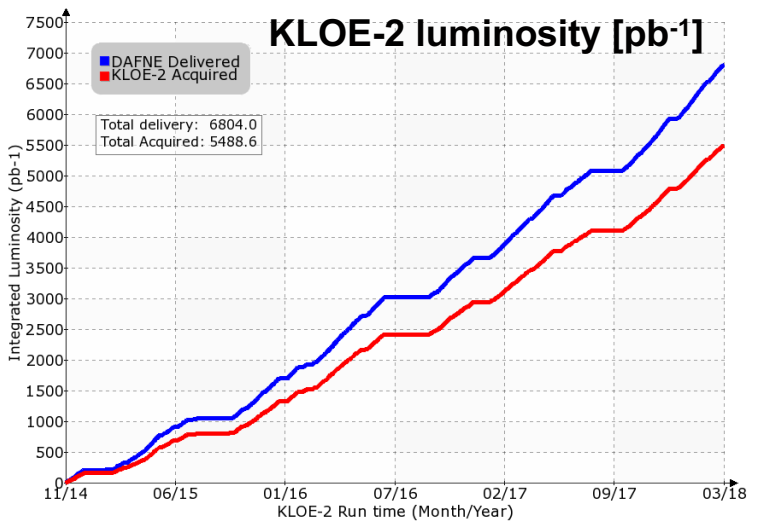


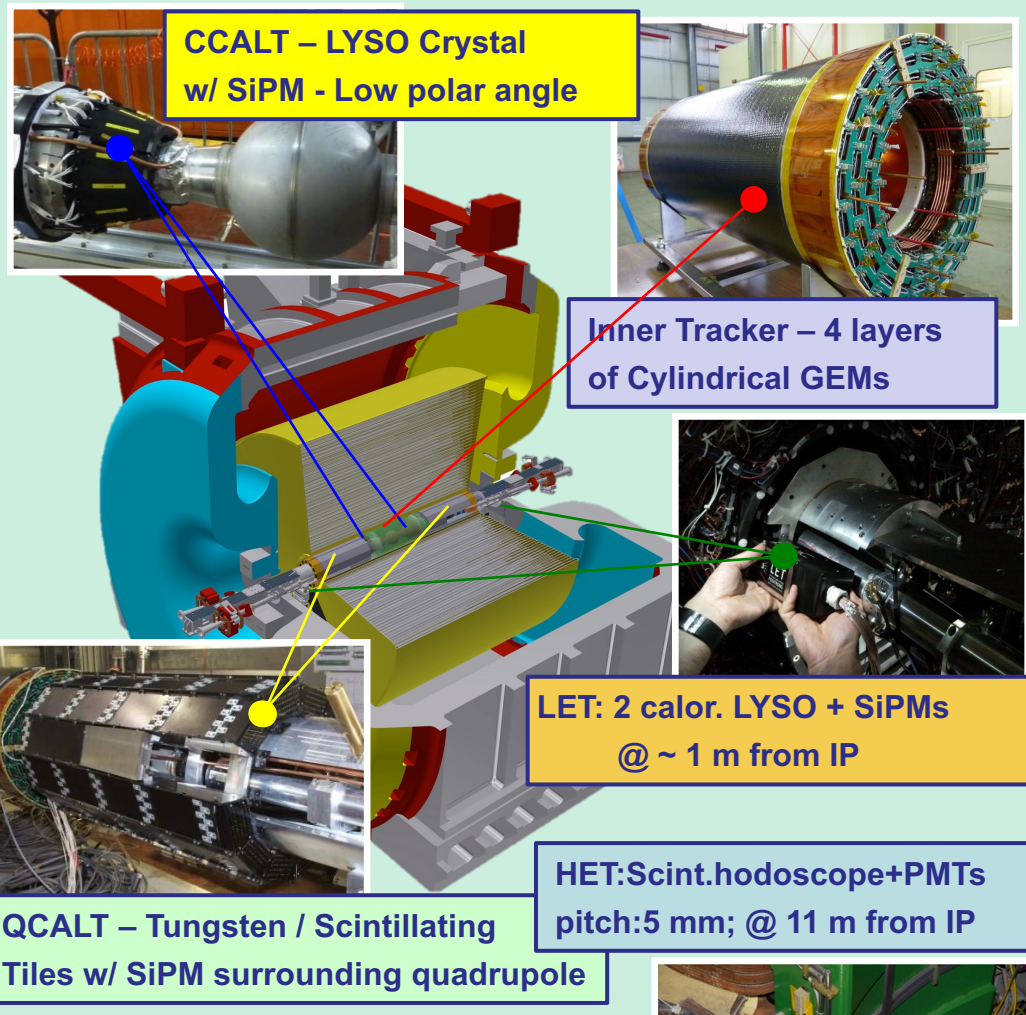
ϕ decay	Produced ev/fb^{-1}
K^+K^-	1.5×10^9
K_LK_S	1.0×10^9
η	5×10^7
η′	2×10^5

η/η′ tagged with recoil monochromatic photon (363 and 60 MeV respectively)

KLOE-2 @ upgraded DAΦNE

- DAΦNE upgrade (2008)
  - new interaction scheme (crab-waist)
- Best performance:
  - $L_{peak} = 2.4 \times 10^{32}\ cm^{-2}\ s^{-1}$
  - $L_{int} = 14\ pb^{-1}$ / day
- Data taking: 2014-2018
  - 5.5 fb^{-1} collected @ $\sqrt{s} = M_\phi$





KLOE + KLOE-2 data sample: ~ **8 fb^{-1}** ⇒ **2.4 × 10^{10} φ**'s produced
⇒ **largest sample ever collected at a φ-factory**

KLOE-2 physics program on light mesons

Extension of the KLOE physics program [Eur. Phys. J. C 68 (2010), 619]

- **Light meson physics**
  - η decays, ω decays
  - Transition form factor
  - C/P/CP violation: $\eta \to \gamma\gamma\gamma/\pi\pi/\pi\pi\gamma$
  - $\eta \to \pi^+\pi^- e^+e^-$
  - ChPT test: $\eta \to \pi^0\gamma\gamma$
  - Light scalar mesons: $f_0(500)$ in $\phi \to K_S K_L \gamma$
  - $\gamma\gamma$ physics: $\gamma\gamma \to \pi^0$ and π^0 TFF
  - $e^+e^- \to \pi^0\gamma\gamma_{ISR}$ (π^0 TFF)
- **Searches for dark forces**
  - Improve limits on dark photon & Higgsstrahlung searches
  - Leptophobic B boson search
  - Search for axion-like particles
- **Hadronic cross section**
  - ISR studies: $\pi\pi$ $\pi\pi\pi$ $\pi\pi\pi\pi$ final states
  - F_π with increased statistics
- **Kaon physics**
  - CPT and QM tests w/ interferometry
  - Direct T and CPT tests w/ entanglement
  - CPviol CPT test: $K_S \to \pi^0\pi^0\pi^0$ and $\Im(\varepsilon'/\varepsilon)$
  - CKM V_{US} and rare K_S decays

The $\eta \to \pi^0\gamma\gamma$ decay: motivations

ChPT "golden mode": p^2 null, p^4 suppressed, p^6 dominates | **BR & $d\Gamma/dM_{\gamma\gamma}$**

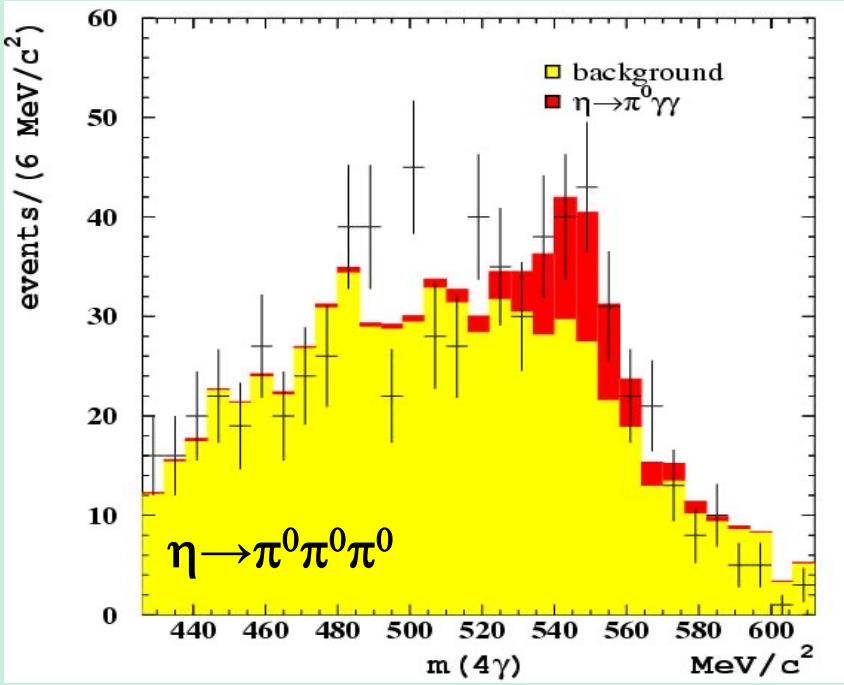
KLOE prel. 2006, 450 pb^{-1} : 70 signal events, 3σ signal

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

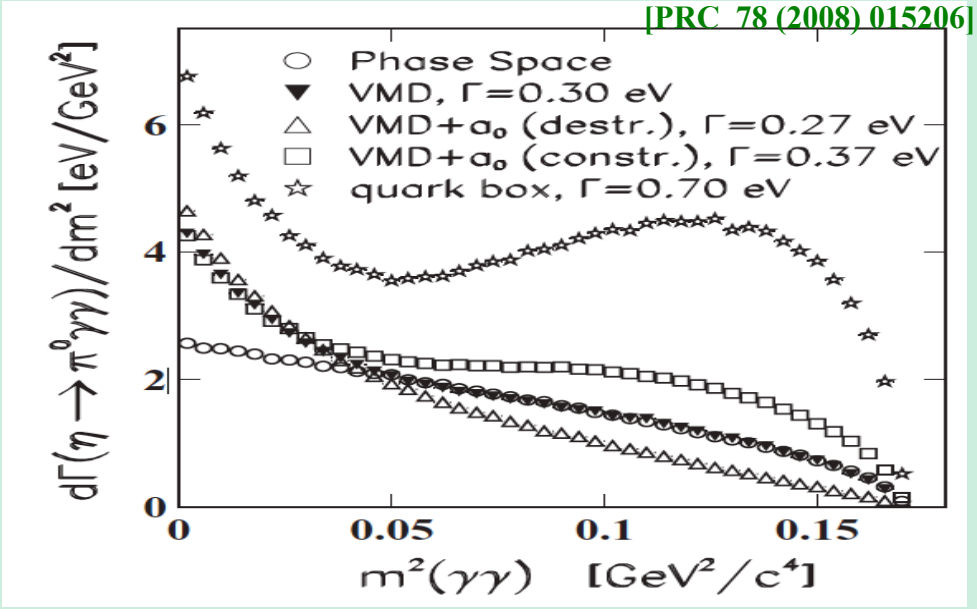
CB@AGS: $BR = (22.1 \pm 2.4 \pm 4.7) \times 10^{-5}$
CB@MAMI: $BR = (25.2 \pm 2.5) \times 10^{-5}$

PRC 78 (2008) 015206, ~500 signal events

PRC 90 (2014) 025206, ~1200 signal events



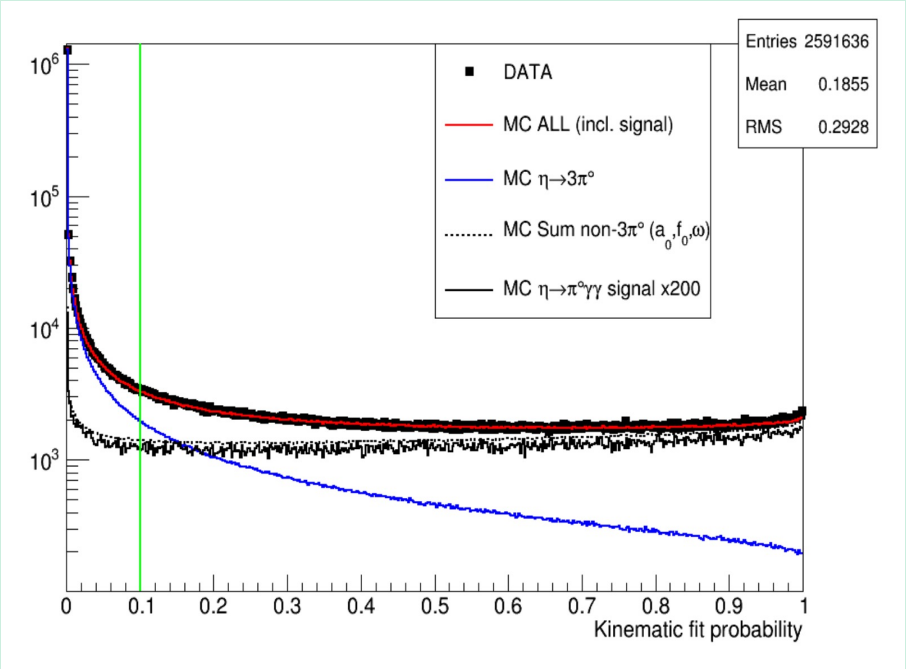
[PRC 78 (2008) 015206]

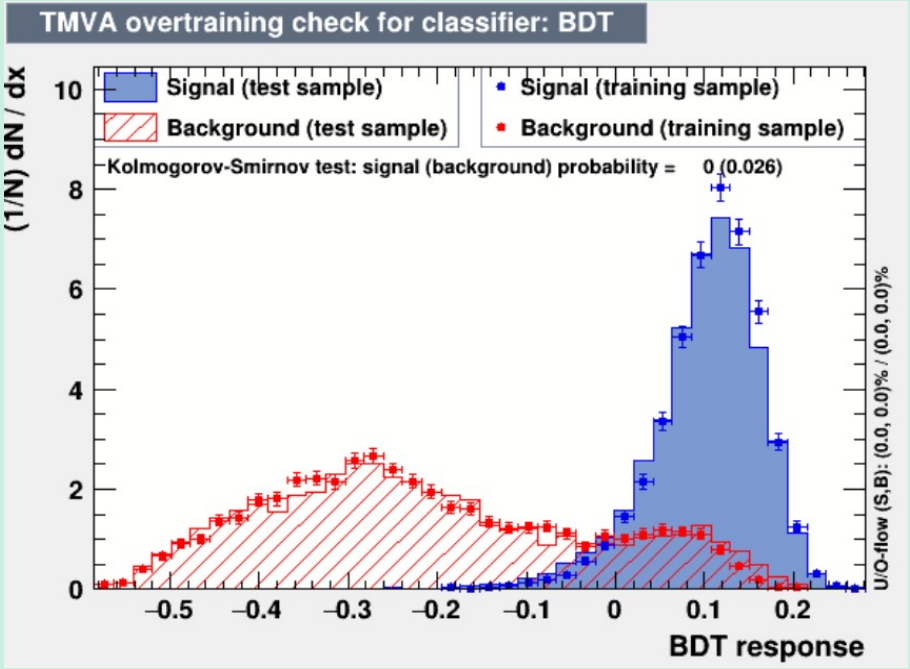


Invariant mass of non-π^0 photons can be used to test theoretical models

$\eta \to \pi^0\gamma\gamma$: new KLOE-2 analysis

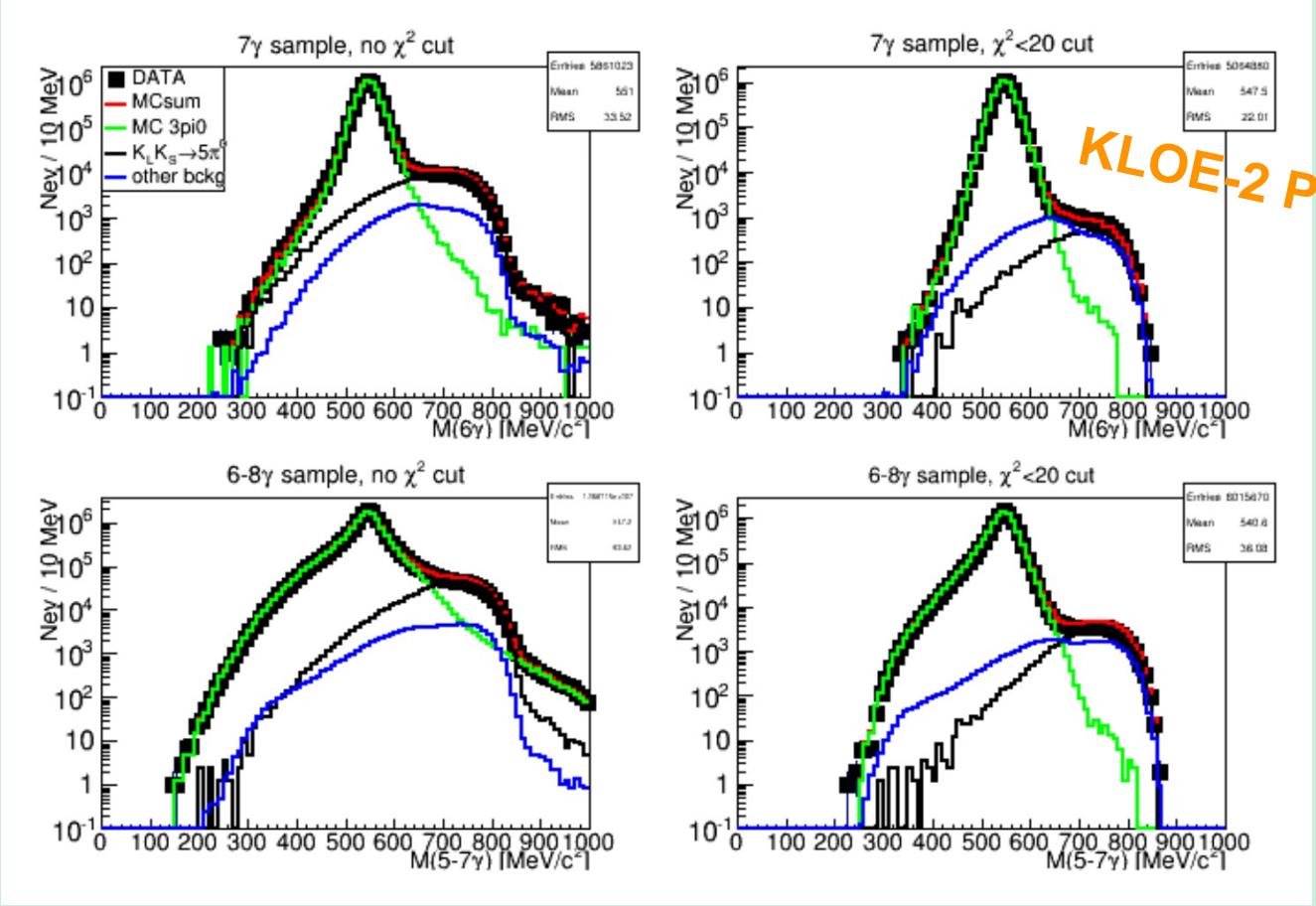
- L_{int} = 1.7 fb^{-1}
- Selected sample: 5 neutral prompt clusters
- Main background: $\phi \to \eta\gamma$, $\eta \to 3\pi^0$ with lost or merged photons
- Background reduction through kinematic fit and MVA-BDT on cluster shape





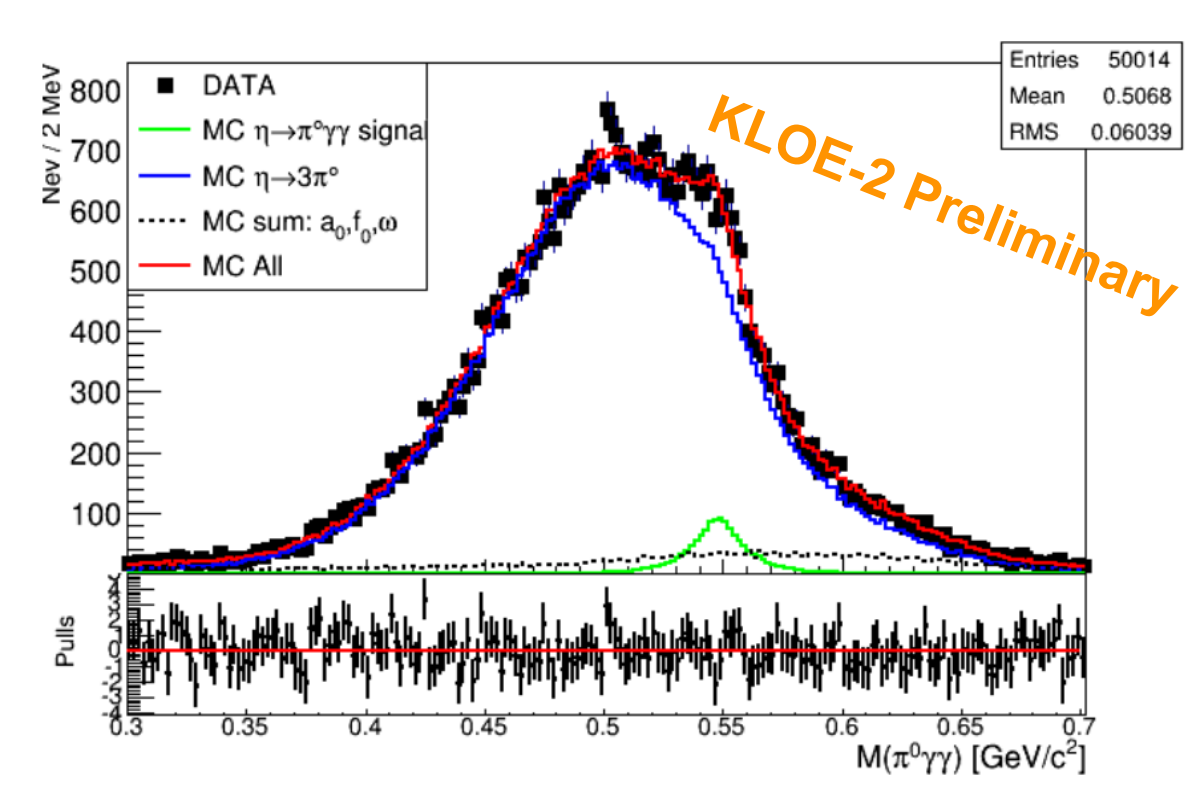
$\eta \to \pi^0\gamma\gamma$: normalization sample

- Same data of signal events
- Nη extracted from $\phi \to \eta\gamma$, $\eta \to 3\pi^0$: 7 prompt neutral clusters, very clean, low bckg
- Nη evaluated with both 7γ's and 6-8 γ's final states: differences taken as systematics



$\eta \to \pi^0\gamma\gamma$: BR measurement

- Cluster with energy closest to 363 MeV identified as recoil photon
- Unbinned 3-component maximum likelihood fit using signal and bckg MC shapes
- Fit results: η^2/ndf = 215/200 (p-value of 22%)



~ 1200 signal events

same statistics as Crystal Ball

$Br(\eta\to\pi^0\gamma\gamma) = (0.99 \pm 0.11_{stat} \pm 0.24_{syst}) \times 10^{-4}$

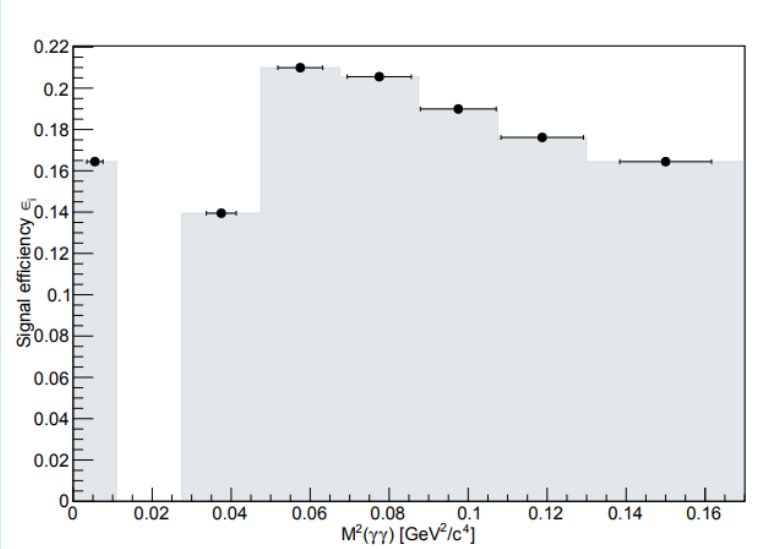
Confirmed:

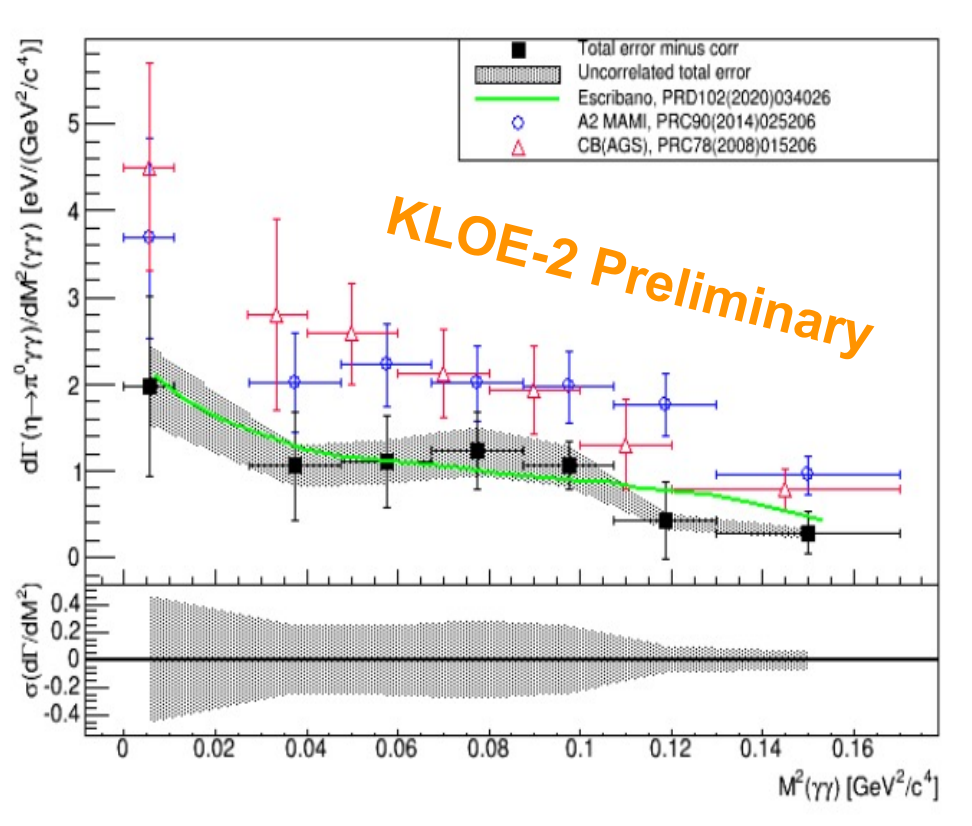
- **KLOE prel. central value**
- **4 σ's difference with CB**

$\eta \to \pi^0\gamma\gamma$: $d\Gamma / dM^2_{\gamma\gamma}$

- Separate $M_{\pi\gamma\gamma}$ fits in bins of $M^2_{\gamma\gamma}$
- Second bin missing due to the veto for $\pi^0\pi^0$ events ($\phi \to f_0\gamma$, $e^+e^- \to \omega\pi^0$)

Efficiency vs $M^2_{\gamma\gamma}$





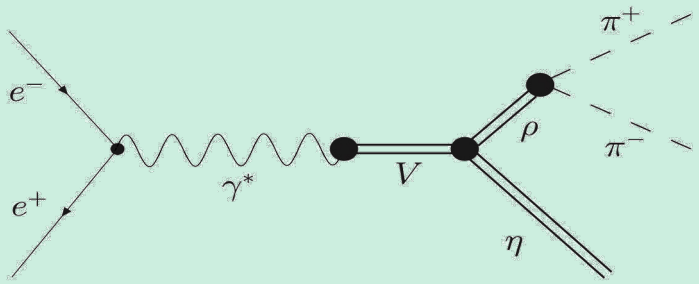
Compared to a recent prediction from R. Escribano based on LσM + VMD

PRD 102 (2020) 034026

$\phi \to \eta\pi^+\pi^-$ / $\eta\mu^+\mu^-$: motivations

- In VMD models $e^+e^- \to \eta\pi^+\pi^-$ occurs through the $\rho\eta$ intermediate state
- $\phi \to \eta\pi^+\pi^-$ violates the OZI rule and G-parity
  - BR ($\phi \to \eta\pi^+\pi^-$) < 1.8 × 10^{-5} @ 90% C.L.

[CMD-2, PLB491(2000)81]



- The same sample can be used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$
  - BR ($\phi \to \eta\mu^+\mu^-$) < 1.8 × 10^{-5} @ 90% C.L.

[CMD-2, PLB501(2001)191]

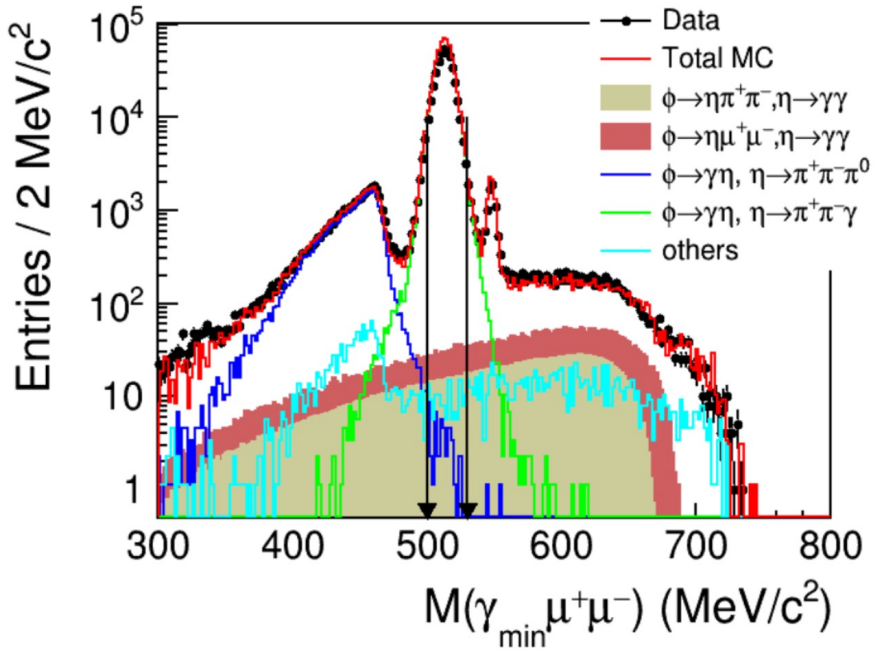
- L_{int} = 1.6 fb^{-1} analyzed
- Focus on $\phi \to \eta\mu^+\mu^-$, exploiting both $\eta \to \gamma\gamma$ and $\eta \to \pi^0\pi^0\pi^0$
- Goal: BR measurement and extraction of the Transition Form Factor

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

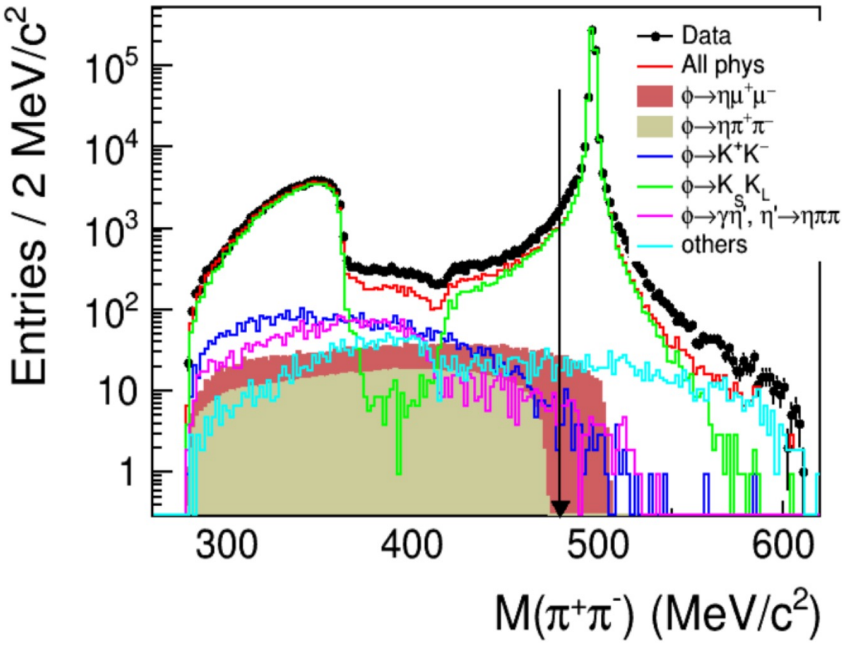
$\phi \to \eta\mu^+\mu^-$: selection

- 2 charged tracks + 2/6 prompt neutral clusters, depending on the $\eta \to \gamma\gamma/\pi^0\pi^0\pi^0$ final state
- $380 < M(\gamma\gamma/\pi^0\pi^0\pi^0) < 750$ MeV/c^2
- Kinematic fit with 4-momentum and time conservation
- Kinematical cuts, depending on the final state

$\eta \to \gamma\gamma$ channel



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

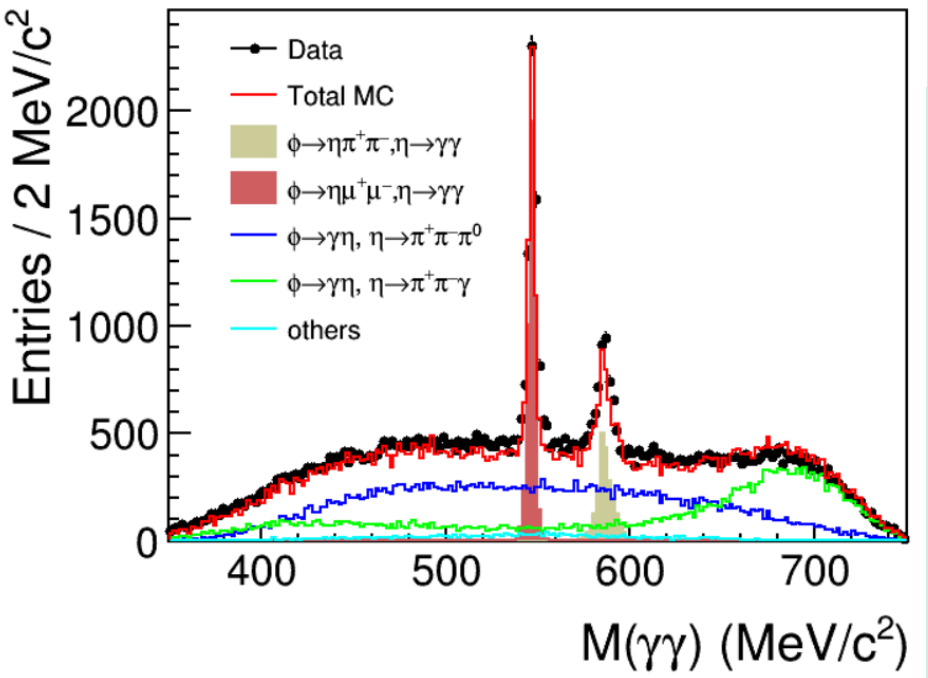


$\phi \to \eta\mu^+\mu^-$: final sample

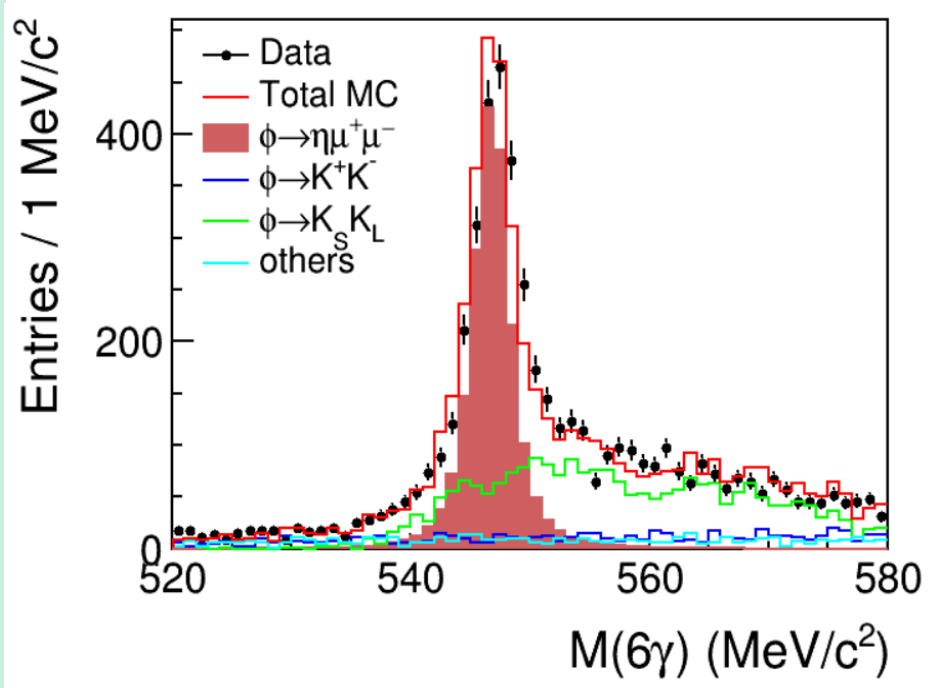
Clean $\phi \to \eta\pi^+\pi^-$ and $\phi \to \eta\mu^+\mu^-$ signals observed after all analysis cuts

KLOE-2 Preliminary

$\eta \to \gamma\gamma$ channel



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

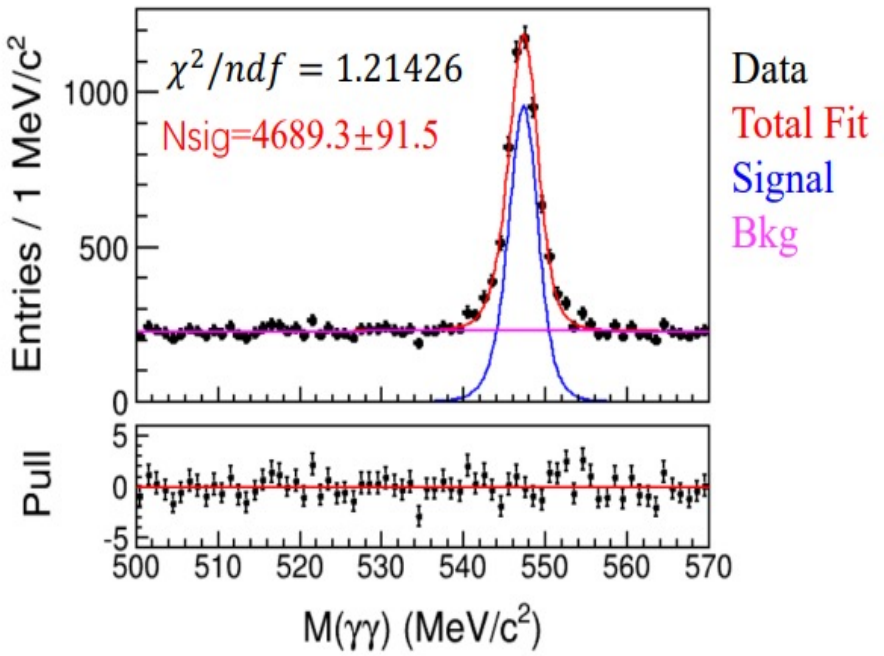


$\phi \to \eta\mu^+\mu^-$: BR results

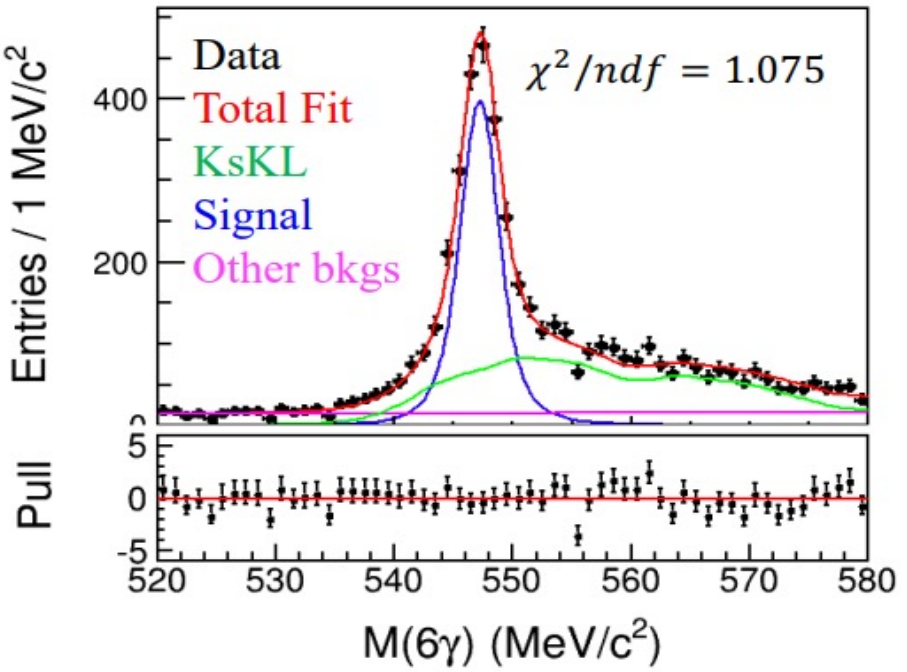
Fit with MC shape convoluted with a Gaussian (+ KK bckg) + 3rd order polynomial

KLOE-2 Preliminary

$\eta \to \gamma\gamma$ channel



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



Br($\phi \to \eta\mu^+\mu^-$) = (5.65 ± 0.11$_{stat}$) × 10^{-6}

Br($\phi \to \eta\mu^+\mu^-$) = (5.76 ± 0.19$_{stat}$) × 10^{-6}

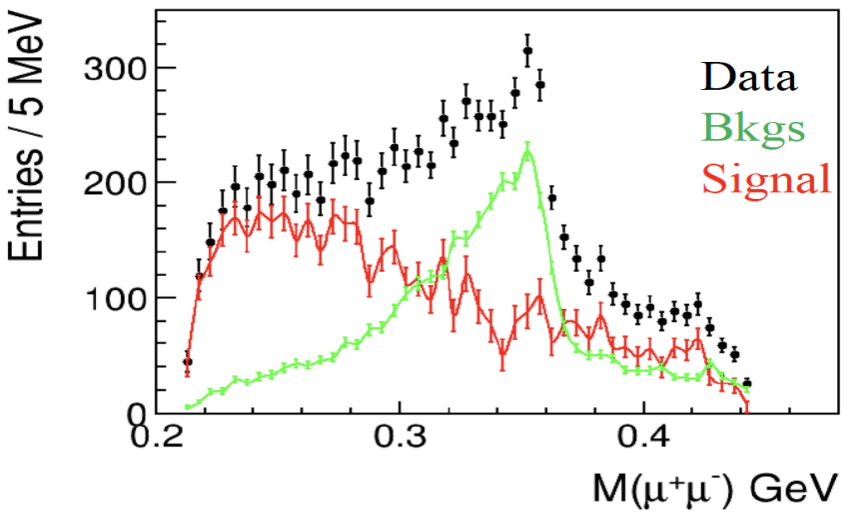
Systematics uncertainty is being evaluated

$\phi \to \eta\mu^+\mu^-$: TFF results

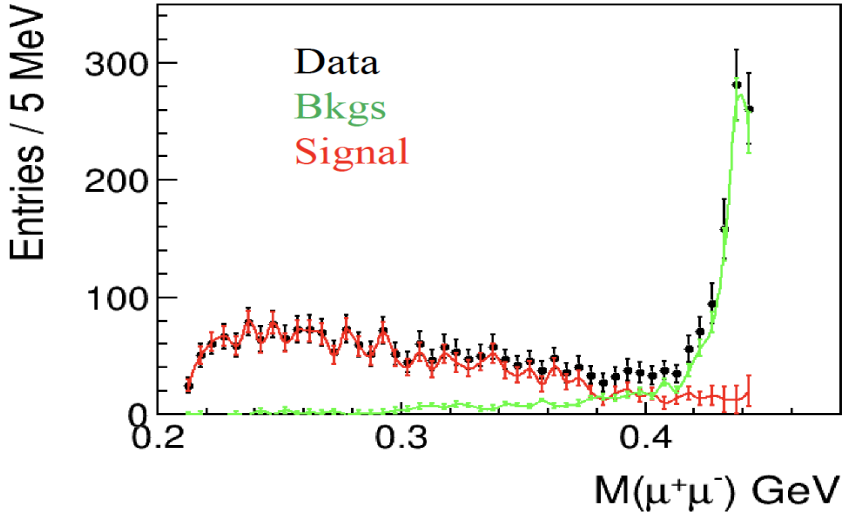
- Unbinned likelihood fit to M_η distribution are performed in different $M(\mu^+\mu^-)$ range
- Transition Form Factor extracted from $M(\mu^+\mu^-)$ shape

KLOE-2 Preliminary

$\eta \to \gamma\gamma$ channel



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



In VMD model, $F_{\phi\eta}(q^2) = \dfrac{1}{1 - q^2/\Lambda^2_{\phi\eta}}$

$$b_{\phi\eta} \equiv \frac{dF}{dq^2}\Big|_{q^2=0} \approx \Lambda^{-2}_{\phi\eta}$$

$b_{\phi\eta}(\eta\to\gamma\gamma) = (\ 3.011 \pm 0.104_{stat}\ )\ \text{GeV}^{-2}$

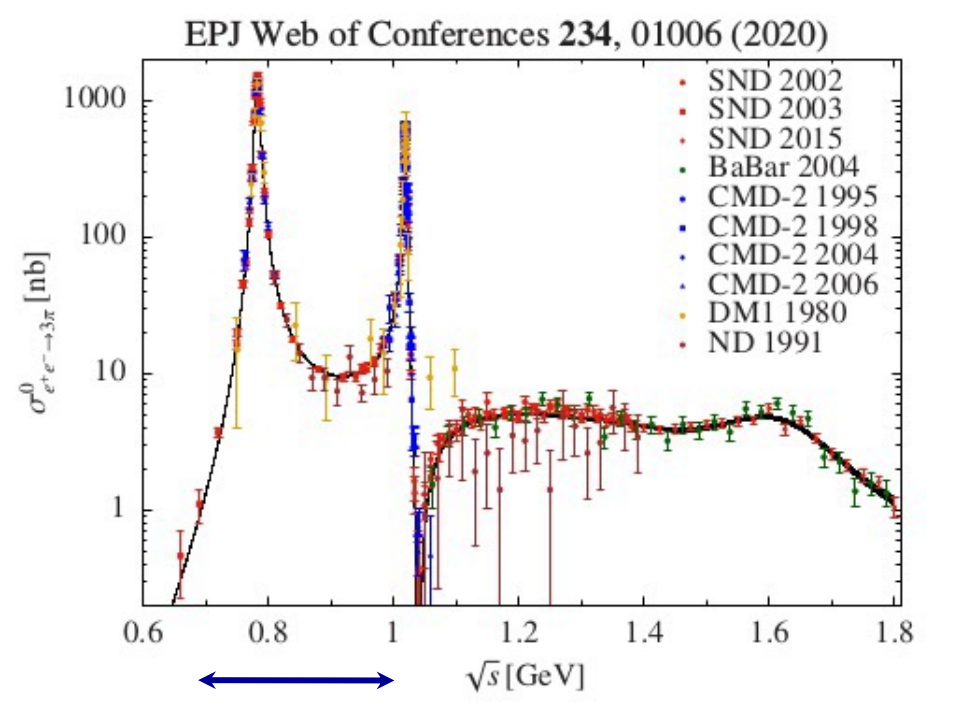
$b_{\phi\eta}(\eta\to\pi\pi\pi) = (\ 2.903 \pm 0.198_{stat}\ )\ \text{GeV}^{-2}$

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

- Second largest contribution to the calculation of the Hadronic Vacuum Polarization for $(g-2)_\mu$ and to its uncertainty
- Initial State Radiation (ISR) measurement at KLOE is complementary to energy scan in the range $\sqrt{s} < M_\phi$ (SND and CMD-2)

Current measurements:

- CMD-2 and SND through energy scan
- BESIII and BaBar through ISR



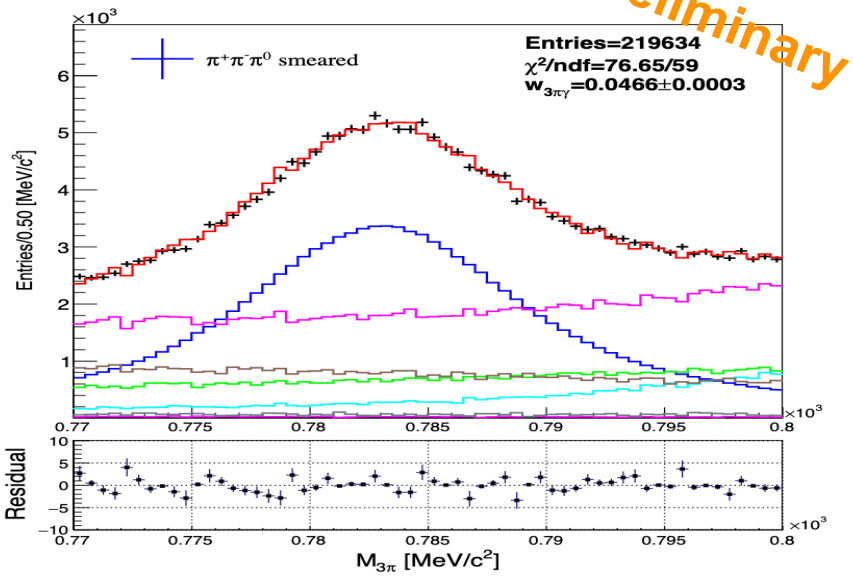
Goals:

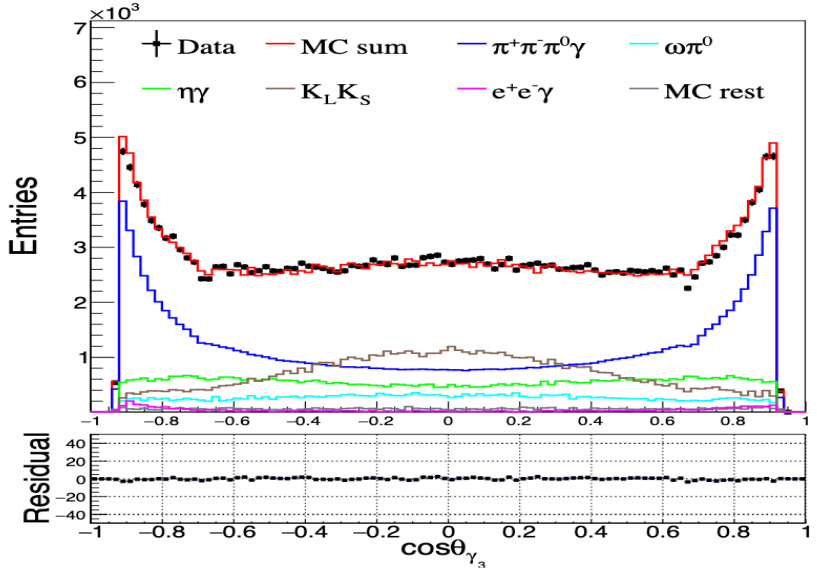
- Cross section measurement in the $\omega(782)$ region
- Evaluation of BR($\omega \to e^+e^-$) × BR($\omega \to \pi^+\pi^-\pi^0$)

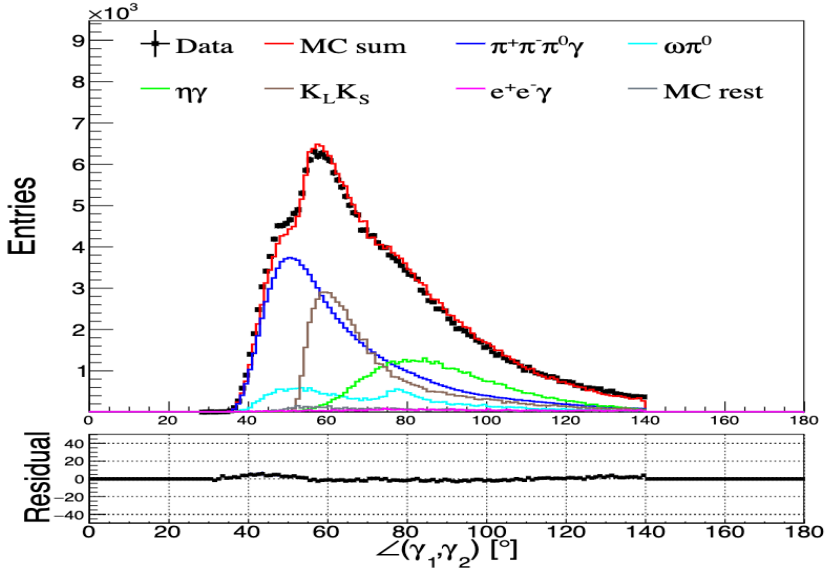
$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$: analysis

KLOE-2 Preliminary

- L_{int} = 1.7 fb^{-1} @ ϕ peak
- At least 2 tracks with opposite curvature
- 3 prompt neutral clusters
- Kinematic fit
- Fit to data: signal and bckg MC shapes
- Excellent data-MC comparison



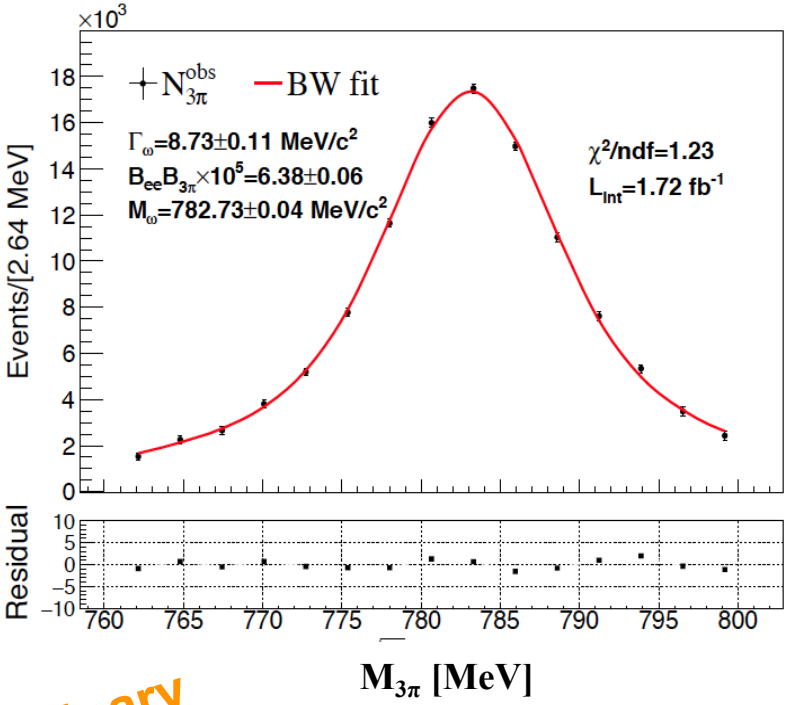


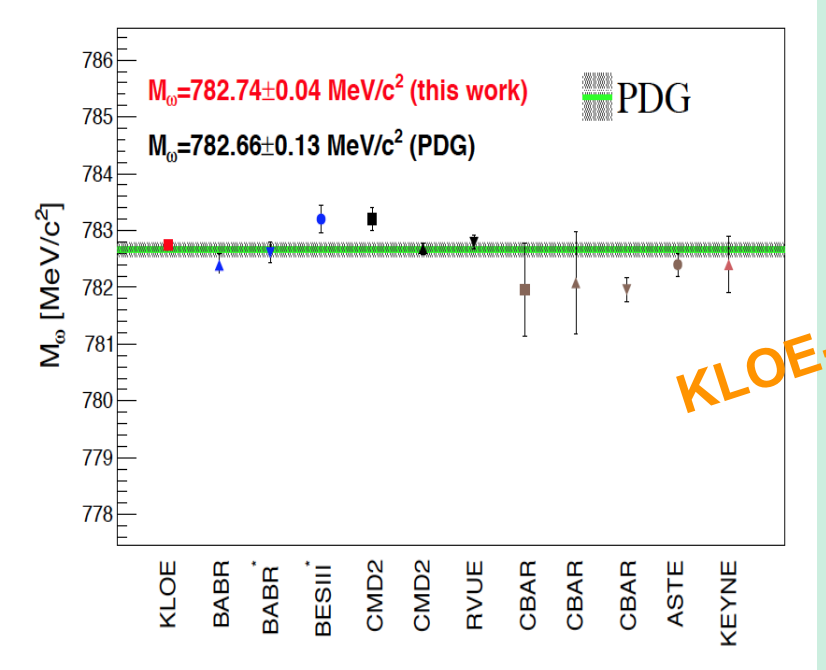


$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$: results

Signal extraction:

- Fit with Breit-Wigner convoluted with smearing matrix
- ISR correction factor taken into account





KLOE-2 Preliminary

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

*** Stat. uncertainty only**

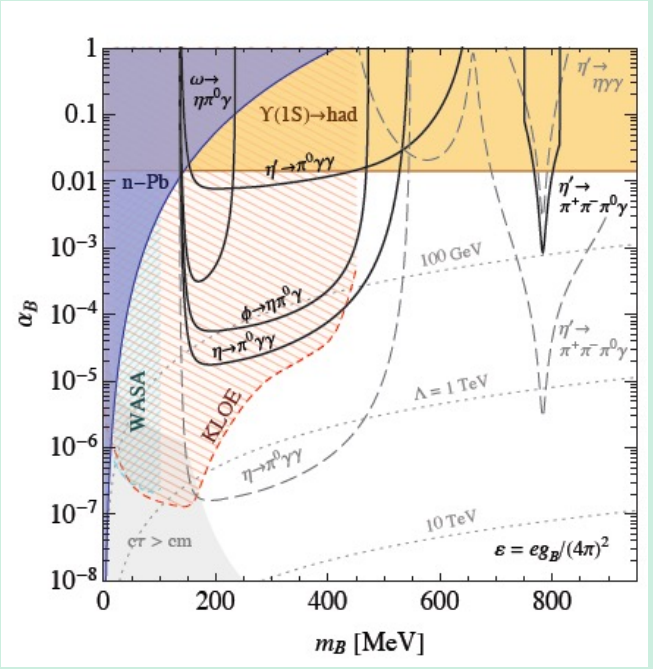
Leptophobic B boson

- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the $\omega(782) \Rightarrow I^G = 0^-$
- Can have an impact in (g-2) muon anomaly

[S.Tulin, PRD89(2014)114008]

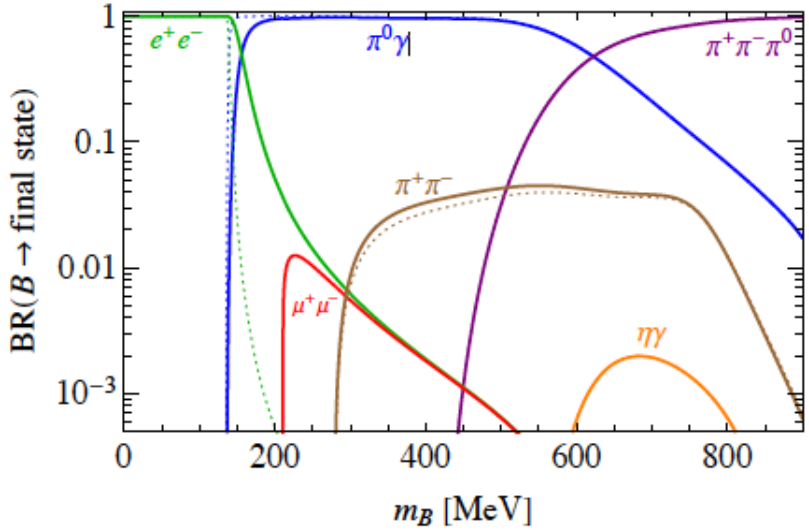
$$\mathcal{L} = \frac{1}{3} g_B \bar{q} \gamma^\mu q B_\mu$$

$$\alpha_B = \frac{g_B^2}{4\pi} \lesssim 10^{-5} \times (m_B/100\text{MeV})$$



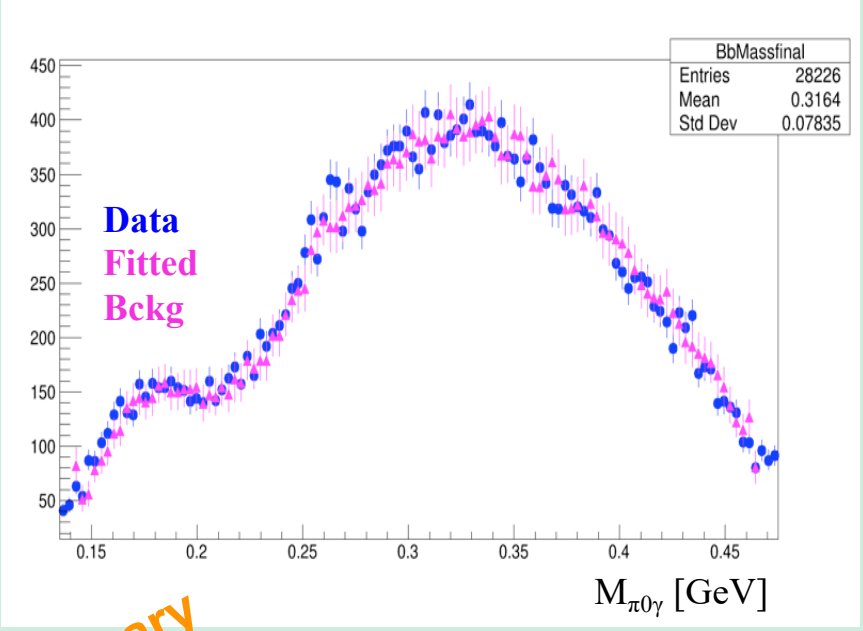
- Dominant decay channel for $M_B < 600$ MeV: $B \to \pi^0\gamma$
- Possible searches @ KLOE:
  - $\phi \to \eta B \ , \eta \to \gamma\gamma$
  - $\phi \to \eta\gamma \ , \eta \to B\gamma$
  - $e^+e^- \to B\gamma_{ISR}$

} 5 prompt γ's final state

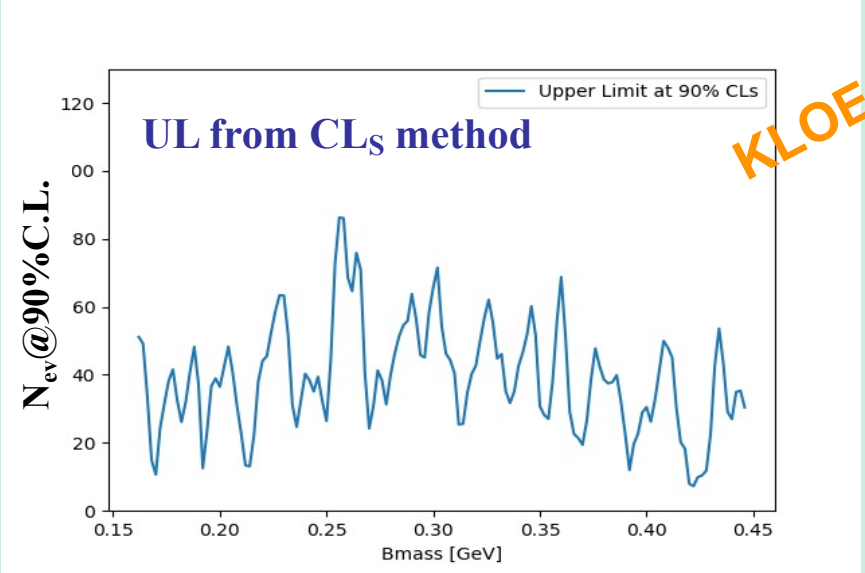


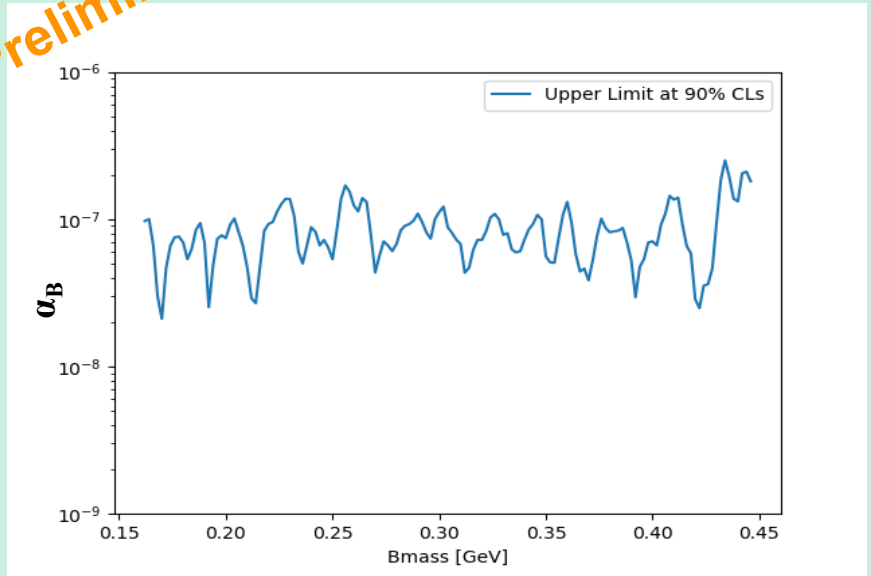
Leptophobic B boson

- L_{int} = 1.7 fb^{-1} analyzed
- Selection of 5 prompt neutral clusters
- Kinematic fit to improve energy resolution
- Main bckg from $\phi \rightarrow a_0(980)\,\gamma \rightarrow \eta\pi^0\gamma$ and $\phi \rightarrow \eta\gamma \rightarrow \pi^0\pi^0\pi^0\gamma$ with lost/merged photons
- Background evaluation from sidebands



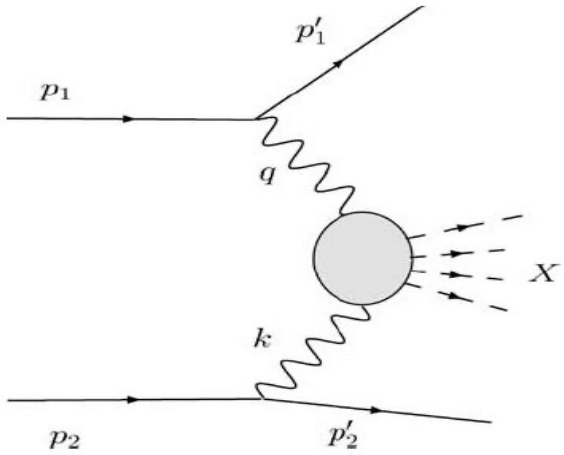
KLOE-2 Preliminary





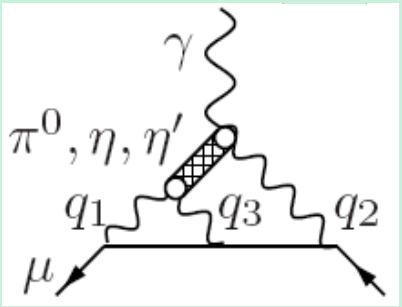
Upper limit on the coupling constant α is set to ≈ O(10^{-7}) at 90% CLs

$\gamma^{(*)}\gamma^{(*)}$ interactions



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

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



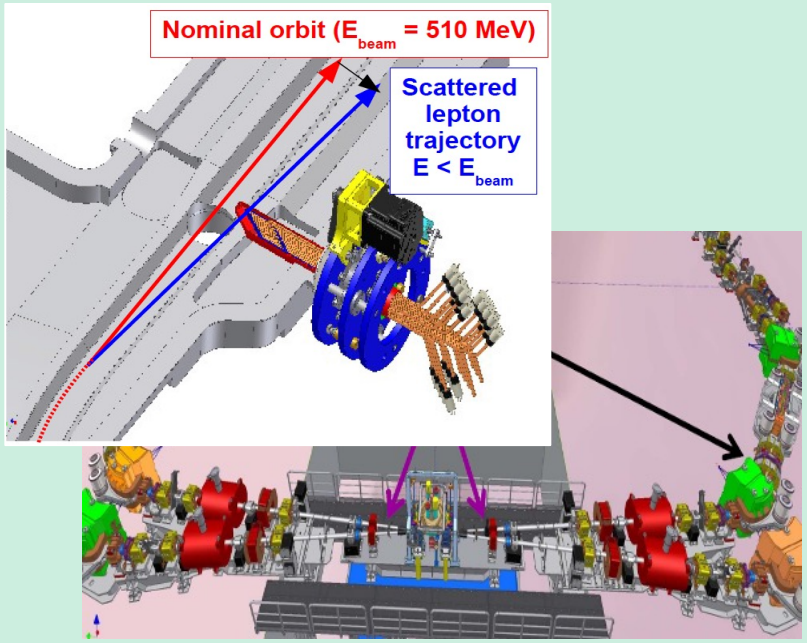
$\gamma\gamma$ physics @ KLOE/KLOE-2:

KLOE: no $e^{\pm}$ tagging

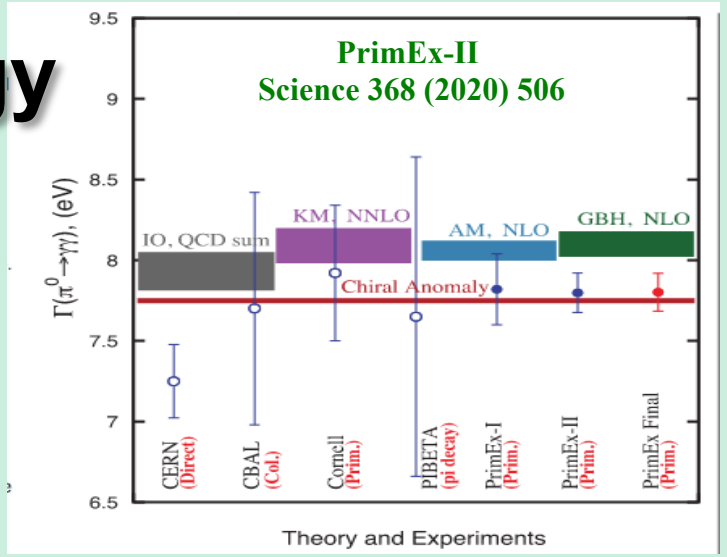
⇒ $\sqrt{s}$ = 1 GeV

KLOE-2: tagger to reduce background from ϕ and to close kinematics

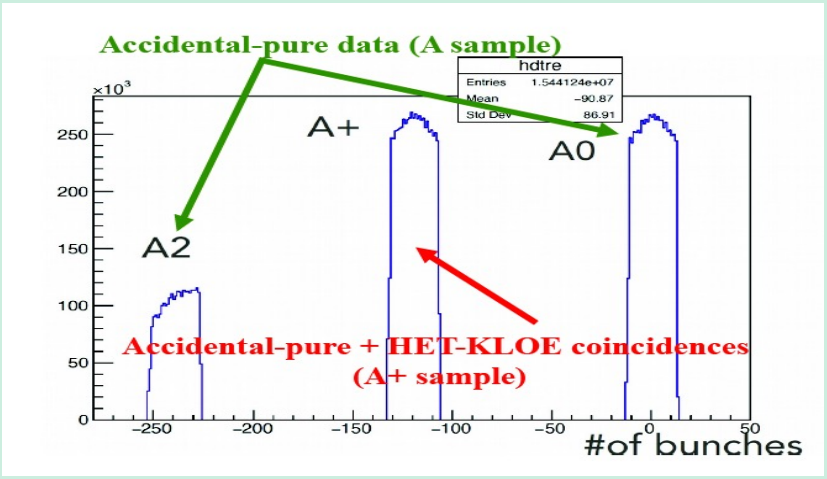
⇒ $\sqrt{s} = M_\phi$

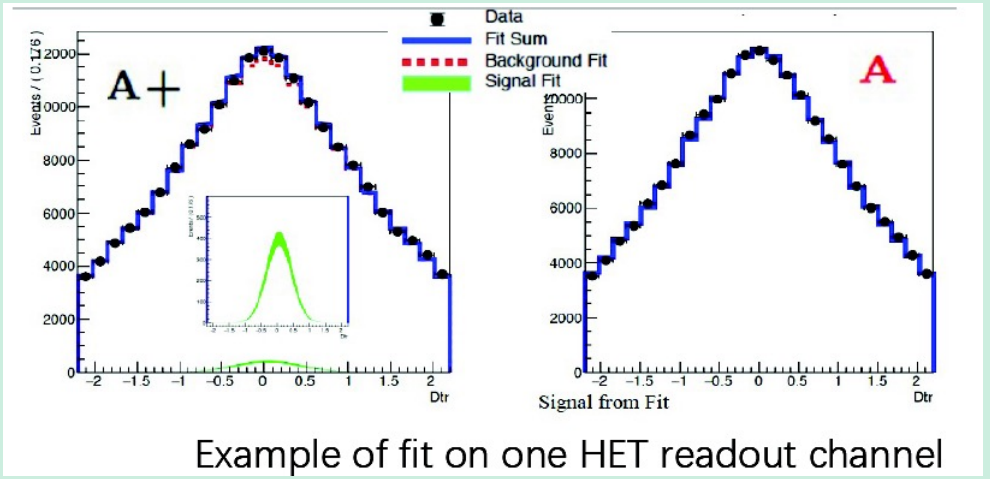


$\gamma^{(*)}\gamma^{(*)} \rightarrow \pi^0$: analysis strategy



- Goal: measurement of $\Gamma(\pi^0\rightarrow\gamma\gamma)$ @ few % level
- Single arm selection:
  - KLOE: 2 neutral prompt clusters in barrel emc
  - HET signal in a 40 ns time window around the KLOE trigger
- Analysis strategy:
  - HET acquisition time 2.5 times larger than KLOE
  - Simultaneous fit to A+ and A samples
    - **A sample**: outside overlapping time window → HET-only (**bckg only**)
    - **A+ sample**: overlapping KLOE-HET time window (**signal + bckg**)





Example of fit on one HET readout channel

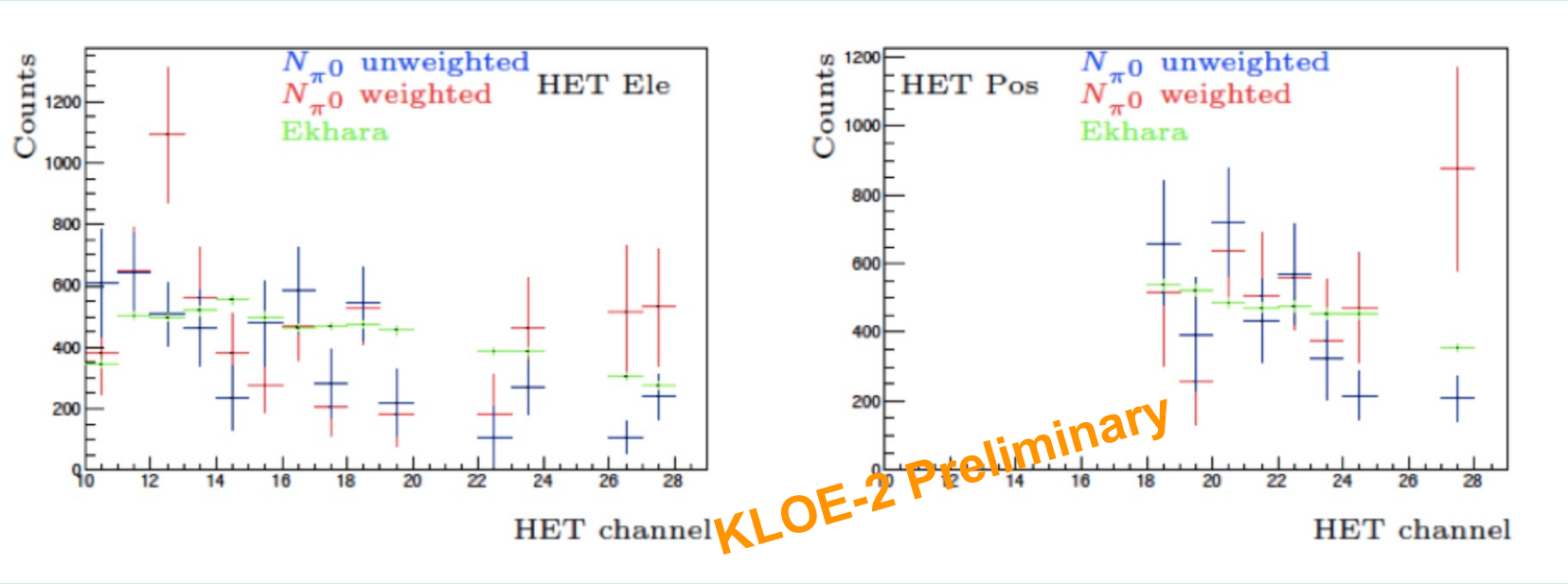
$\gamma^{(*)}\gamma^{(*)} \rightarrow \pi^0$: results

- L_{int} = 3 fb^{-1}
- Counting of π^0 candidates: final checks on weights ongoing
- Normalization to radiative Bhabha's at very small angle
  - Bhabha x-sec measured @ few % level
  - Luminosity measurement from KLOE online + cross check with $e^+e^- \rightarrow \gamma\gamma$
- Analysis efficiency evaluation completed
- $A_{Bha}/A_{\pi 0}$: full simulation of signal from BBBREM/Ekhara generators + BDSIM for lepton transport → evaluation of systematics in progress

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

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

Number of tagged π^0's



Conclusion

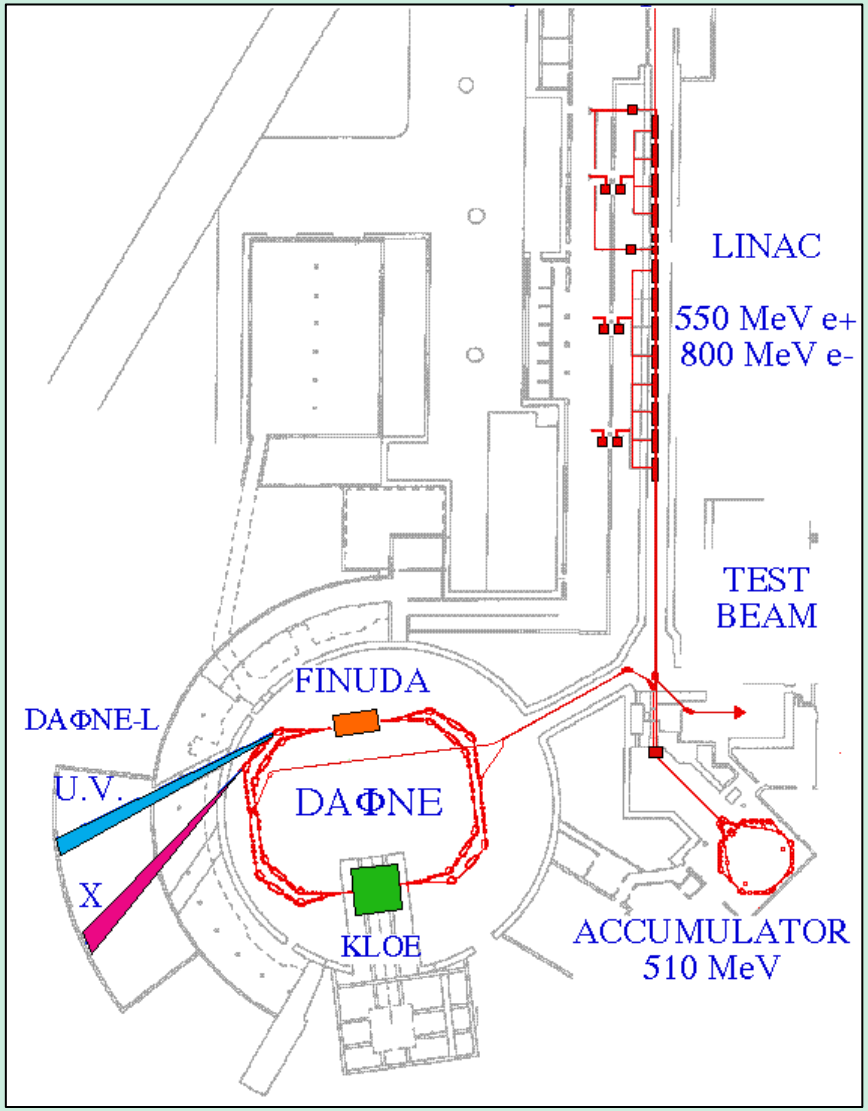
- KLOE-2 data taking successfully completed on March 2018
  - 20 years after the first events collected @ KLOE

- KLOE + KLOE-2 sample: 8 fb^{-1} 2018
  - 2.4 $\times 10^{10}$ ϕ's produced ⇨ unique sample worldwide

- KLOE data sample provided important results on decay dynamics of light mesons, Transition Form Factors, discrete symmetries of the nature, and also on searches for New Physics in the Dark Sector

- 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

DAΦNE: the Frascati Φ-factory



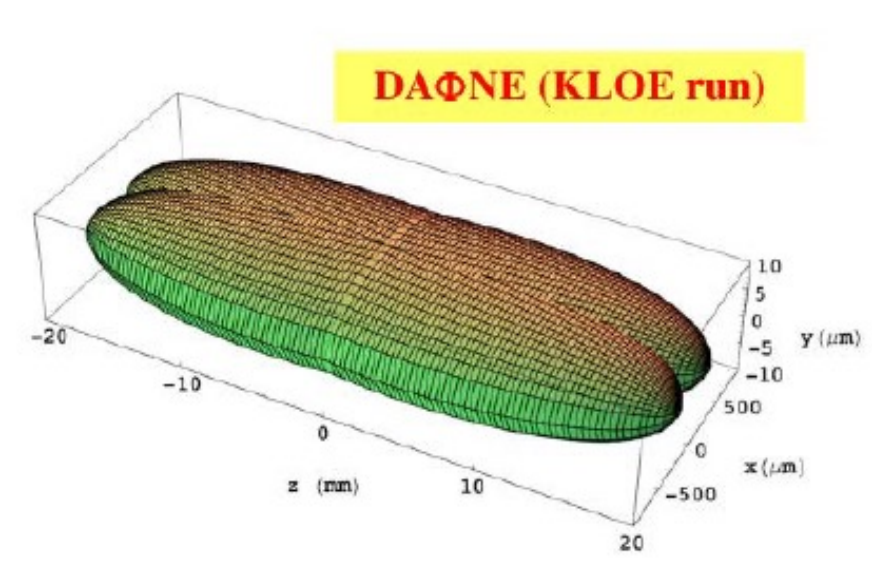
- e^+e^- collider @ $\sqrt{s} = M_\Phi = 1019.4$ MeV
- 2 interaction regions
- Separate e^+e^- rings
- 105+105 bunches, 2.7 ns bunch spacing
- $I^-_{peak} \sim 2.4$ A $I^+_{peak} \sim 1.5$ A
- Injection during data taking
- Crossing angle: 2×12.5 mrad

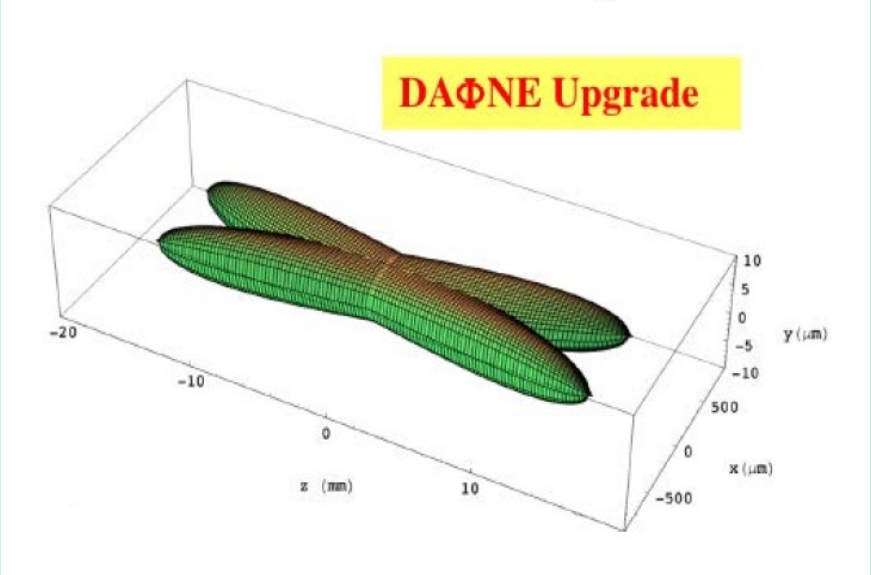
- Running period: 2001-2006
- Best performances:
  - $L_{peak} = 1.5 \times 10^{32}$ cm^{-2} s^{-1}
  - $L_{int} = 8.5$ pb^{-1} / day

DAΦNE and KLOE upgrade

DAΦNE: new interaction scheme

- Large angle beam crossing
- Crabbed waist sextupoles



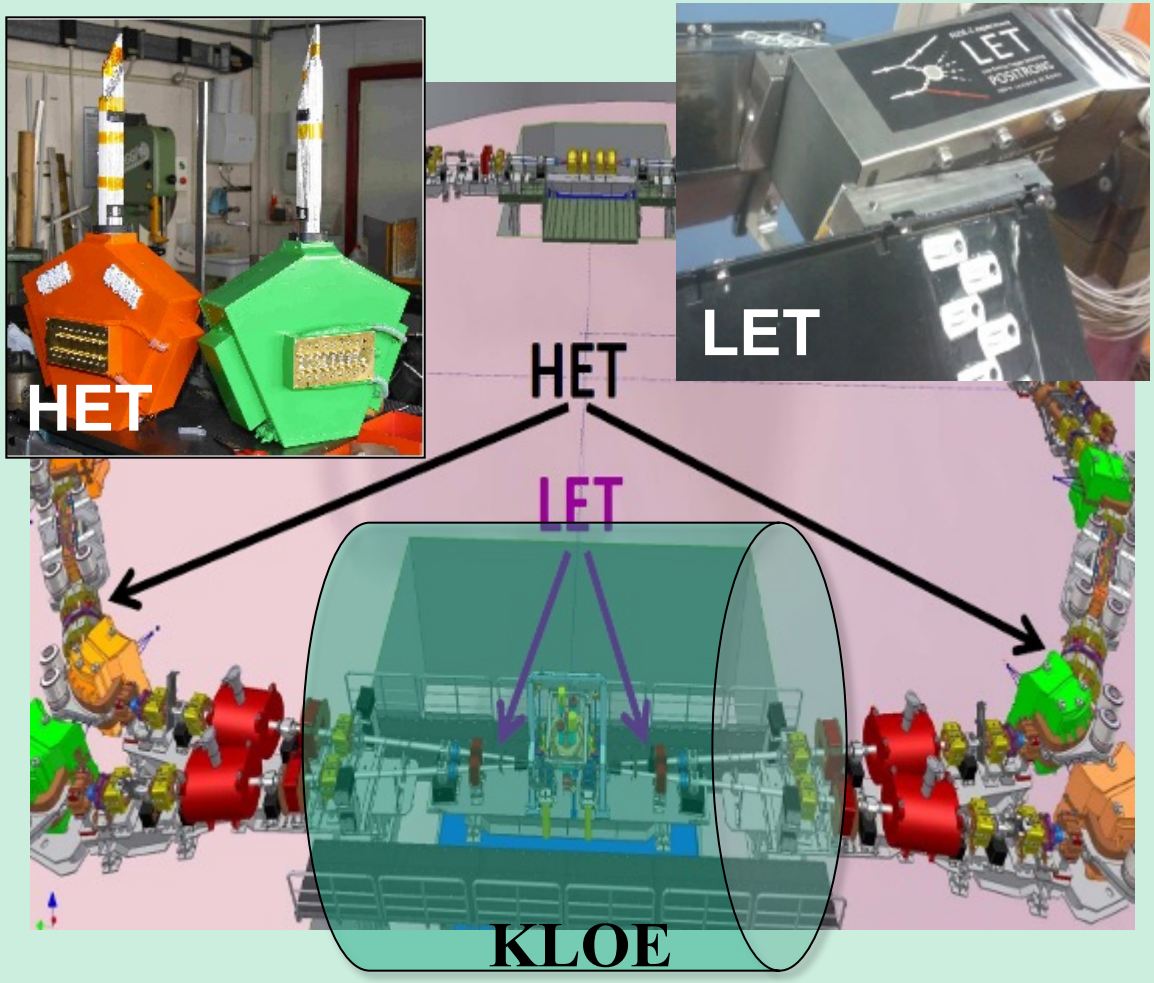


KLOE-2:

- Detector upgrade ($\gamma\gamma$ taggers + GEM inner tracker + low-θ EMCs)
- Extension of the KLOE physics program [Eur. Phys. J. C 68 (2010), 619]

The KLOE-2 upgrade: γγ taggers

2+2 γγ taggers installed inside/outside the detector
Measurement of lepton momenta in $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$



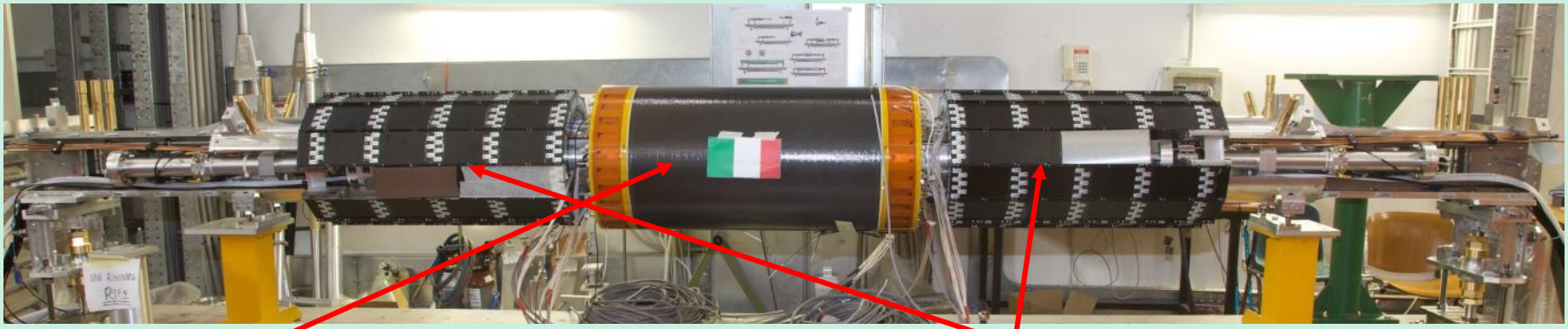
LET : E=160-230 MeV

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

HET : E > 400 MeV

- 11 m from IP
- Scintillator hodoscopes
- $\sigma_E \sim 2.5$ MeV
- $\sigma_T \sim 200$ ps

The KLOE-2 upgrade: IR region



INNER TRACKER

- 4 layers of cylindrical triple GEM
- Better vertex reconstruction near IP
- Larger acceptance for low p_t tracks

QCALT

- W + scintillator tiles + WLS/SiPM
- QUADS coverage for K_L decays

CCALT

- LYSO + SiPM
- Increase acceptance for γ's from IP ($21^o \rightarrow 10^o$)