

Latest hadron Physics results at KLOE-2

Giuseppe Mandaglio (for the KLOE2 Collaboration)
University of Messina and INFN-CT



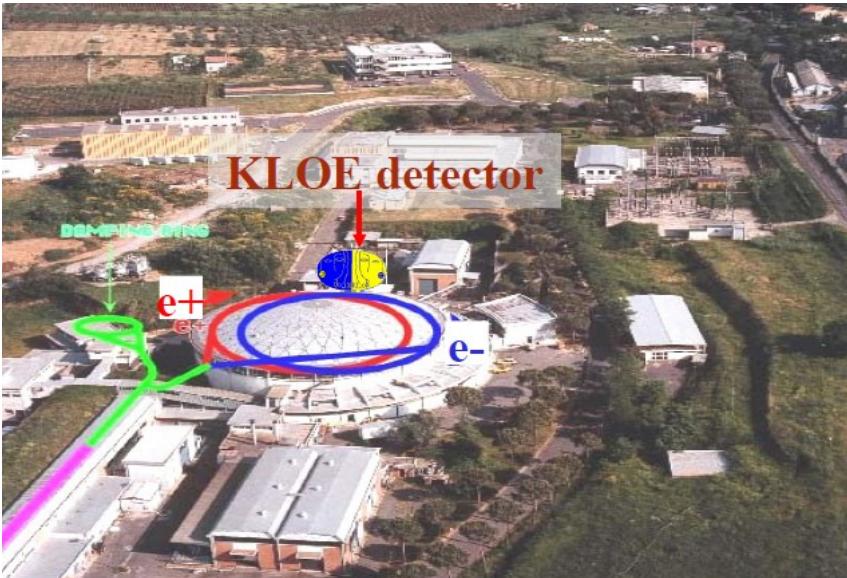
Hadron23 – 6 June – Genoa (Italy)

INFN
Catania
Istituto Nazionale di Fisica Nucleare

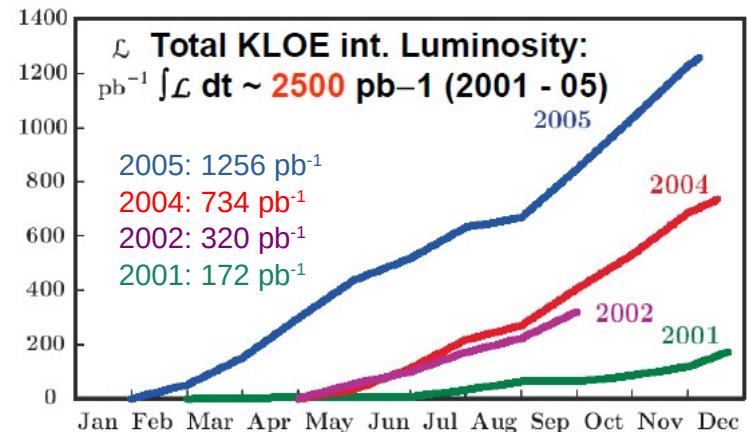
Outline

- KLOE & KLOE-2 experiment at DAΦNE
- The $\eta \rightarrow \pi^0\gamma\gamma$ decay
- $e^+e^- \rightarrow \pi^+\pi^-\pi^0\gamma_{ISR}$ cross section measurement
- Search for $\phi \rightarrow \eta\pi^+\pi^-$ and $\phi \rightarrow \eta\mu^+\mu^-$ decays
- Leptophobic B boson search
- $\gamma^*\gamma^* \rightarrow \pi^0$
- Summary

KLOE @ DAΦNE



Integrated Luminosity



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

- DAΦNE: Frascati ϕ -factory, e^+e^- collider
 $\text{@ } \sqrt{s} \approx 1020 \text{ MeV} \approx M_\phi ; \sigma_{\text{peak}} \approx 3.1 \mu\text{b}$
- Best performance in KLOE run (2005):
 $L_{\text{peak}} = 1.5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \int L dt = 8.5 \text{ pb}^{-1}/\text{day}$
- 2001 – 2006: KLOE data-taking
 $\Rightarrow 2.5 \text{ fb}^{-1}$ @ $\sqrt{s} = M_\phi$
+ 250 pb⁻¹ off-peak @ $\sqrt{s} = 1000 \text{ MeV}$

KLOE Detector

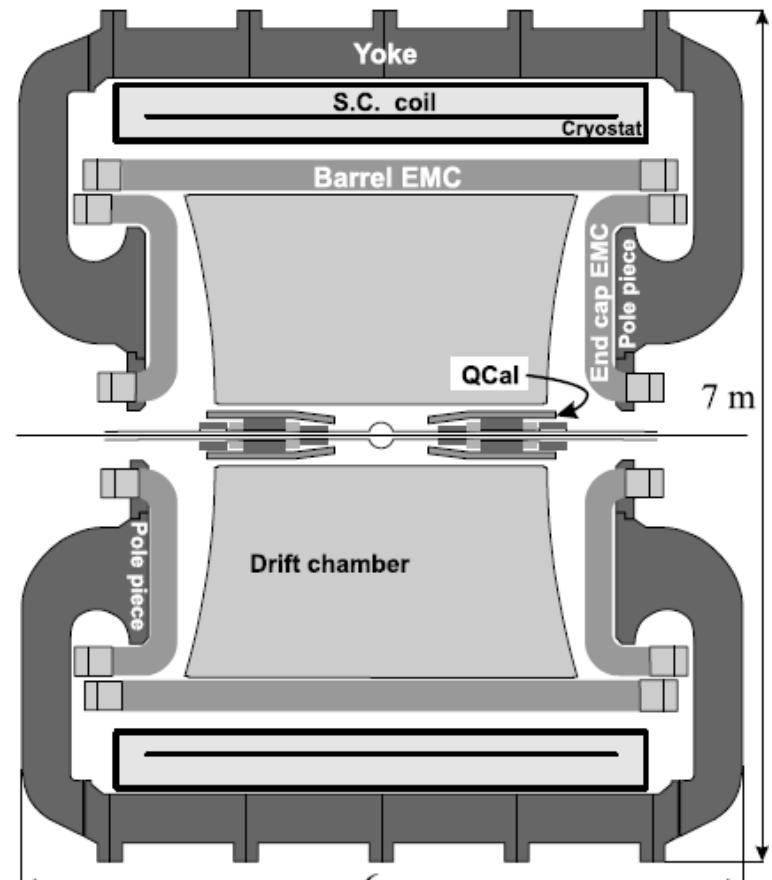
Drift chamber: 90% He-10% $i\text{C}_4\text{H}_{10}$

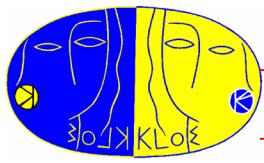
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150 \mu\text{m}$; $\sigma_z \approx 2 \text{ mm}$; $\sigma_{\text{vertex}} \approx 3 \text{ mm}$

Calorimeter (Pb-Sci.Fi.): 98% of 4π

- $\sigma_E/E = 5.7\% / \sqrt{E(\text{GeV})}$
- $\sigma_t = 54 \text{ ps}/\sqrt{E(\text{GeV})} \oplus 100 \text{ ps}$

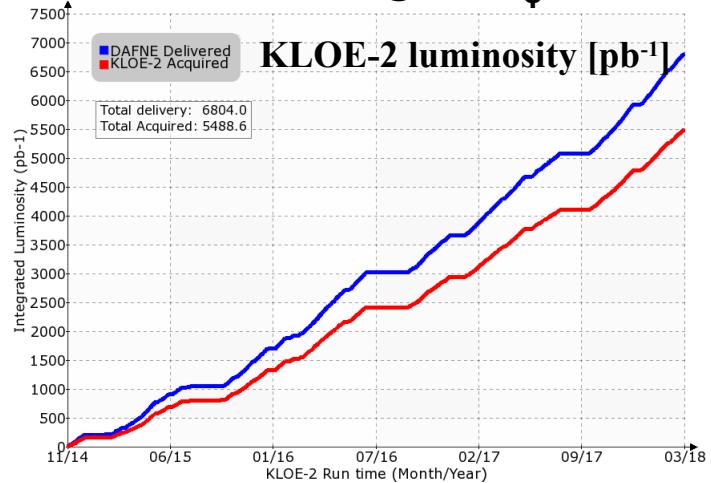
Magnetic field: 0.52 T



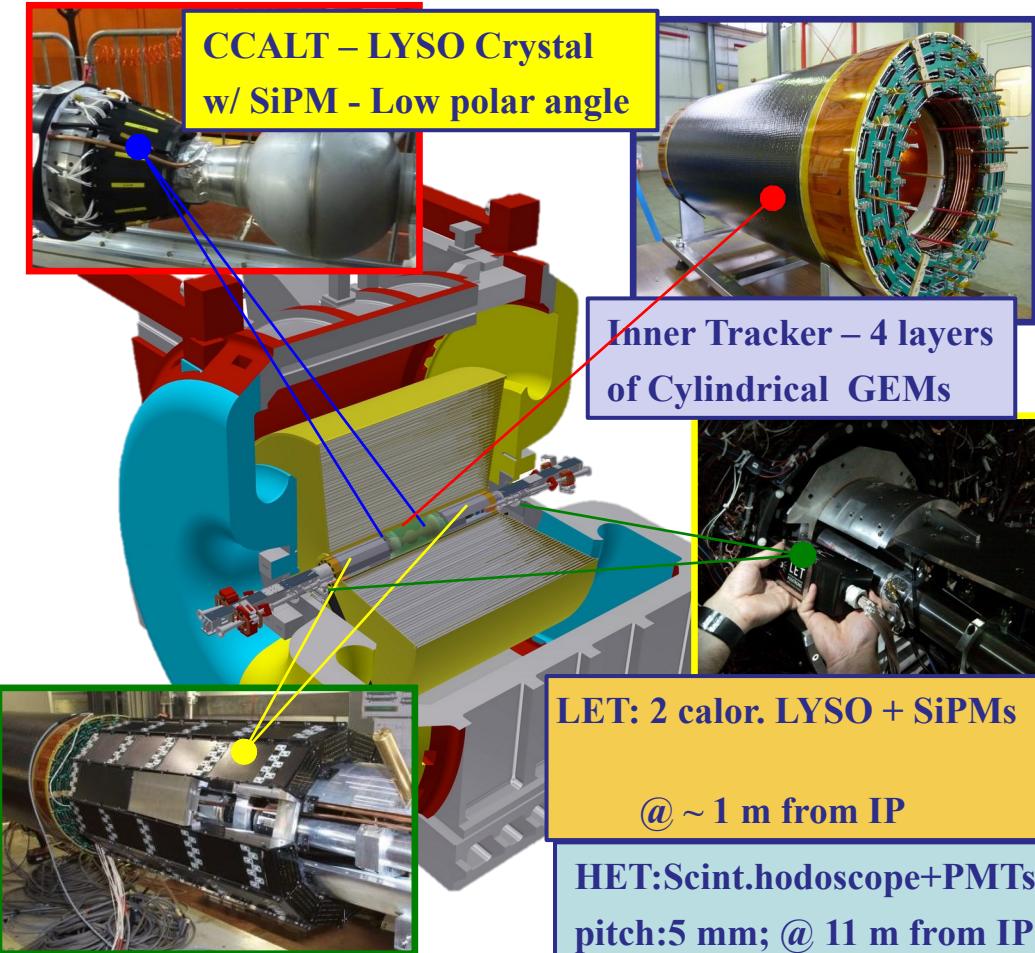


KLOE-2 @ DAΦNE upgraded K2

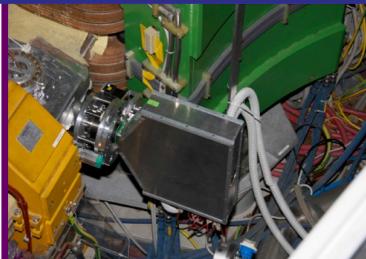
- DAΦNE upgrade (2008), new interaction scheme: large beam crossing angle + crabbed waist sextupoles
- Best performance in KLOE-2 run:
 $L_{\text{peak}} = 2.4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ ∫ Ldt = **14 pb⁻¹/day**
- 2014 – 2018: KLOE-2 data-taking
 $\Rightarrow 5.5 \text{ fb}^{-1}$ collected @ $\sqrt{s} = M_\phi$



KLOE + KLOE-2 data sample:
 $\sim 8 \text{ fb}^{-1} \Rightarrow 2.4 \times 10^{10} \phi$'s produced
 \Rightarrow the largest sample ever collected at a ϕ -factory



Slide thanks to P. Gauzzi



KLOE2 Physics

Light meson Physics:

- η decays, ω decays
- Transition Form Factors
- C,P,CP violation: improve limits on
 $\eta \rightarrow \gamma\gamma\gamma, \pi^+\pi^-, \pi^0\pi^0, \pi^0\pi^0\gamma$
- $\eta \rightarrow \pi^+\pi^-e^+e^-$
- ChPT : $\eta \rightarrow \pi^0\gamma\gamma$
- Light scalar mesons: $f_0(500)$ in $\phi \rightarrow K_s K_s \gamma$
- $\gamma\gamma$ Physics: $\gamma\gamma \rightarrow \pi^0$ and π^0 TFF
- $e^+e^- \rightarrow \pi^0\gamma\gamma_{\text{ISR}}$ (π^0 TFF)

Hadronic cross section:

- ISR studies: $2\pi, 3\pi, 4\pi$ final states
- F_π with increased statistics

In red discussed in this talk

Dark force searches:

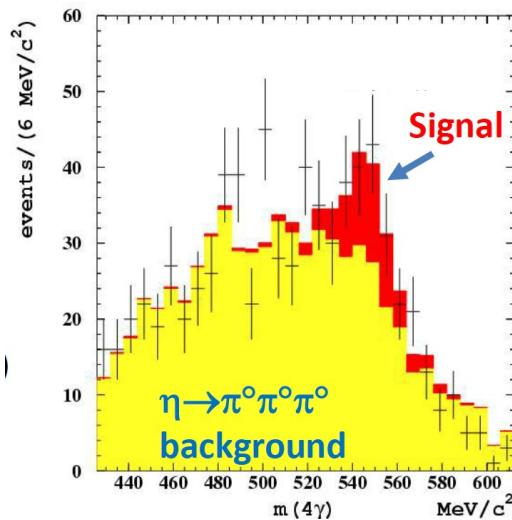
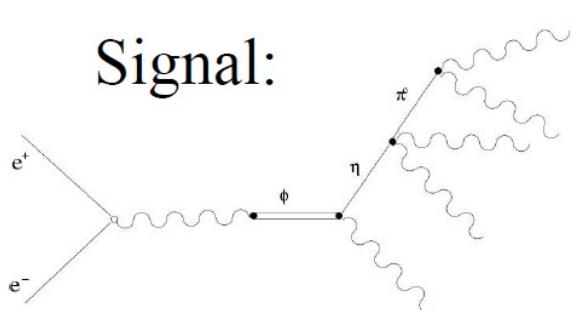
- Improve limits on
 - $U\gamma$ associate production
 $e^+e^- \rightarrow U\gamma \rightarrow \pi\pi\gamma, \mu\mu\gamma$
 - Higgsstrahlung:
 $e^+e^- \rightarrow Uh' \rightarrow \mu^+\mu^- + \text{miss. energy}$
- Leptophobic B boson search:
 $\phi \rightarrow \eta B, B \rightarrow \pi^0\gamma, \eta \rightarrow \gamma\gamma$
 $\eta \rightarrow B\gamma, B \rightarrow \pi^0\gamma,$
- Search for axion-like particles

Kaon Physics:

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

$\eta \rightarrow \pi^0 \gamma\gamma$ ($\phi \rightarrow \eta\gamma$)

Signal:



$\eta \rightarrow \pi^0 \gamma\gamma$ (from $\phi \rightarrow \eta\gamma$): ChPT golden mode, $O(p^2)$ null, $O(p^4)$ suppressed \Rightarrow sensitive to $O(p^6)$

$$\text{Br} = (22.1 \pm 2.4 \pm 4.7) \times 10^{-5} \text{ CB@AGS(2008)}$$

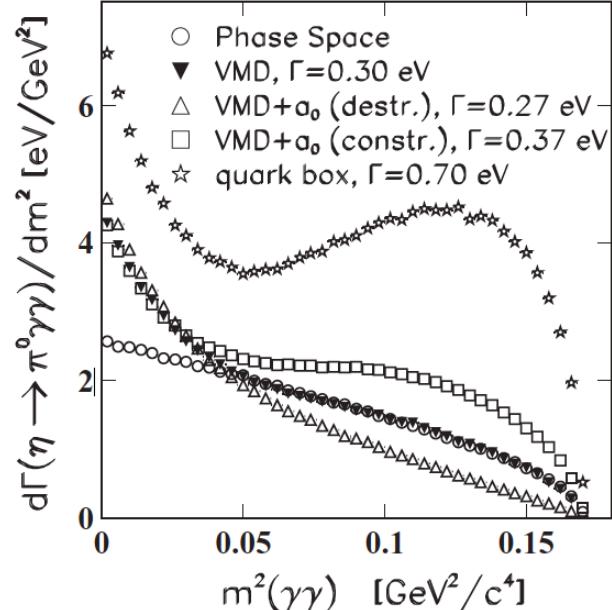
[PRC 78 (2008) 015206]

$$\text{Br} = (25.2 \pm 2.5) \times 10^{-5} \text{ CB@MAMI (2014) A2}$$

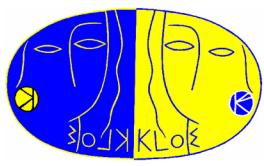
[PRC 90 (2014) 025206]

Old KLOE preliminary: $(8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$
($L = 450 \text{ pb}^{-1} \sim 70$ signal events)

[PRC 78 (2008) 015206]



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

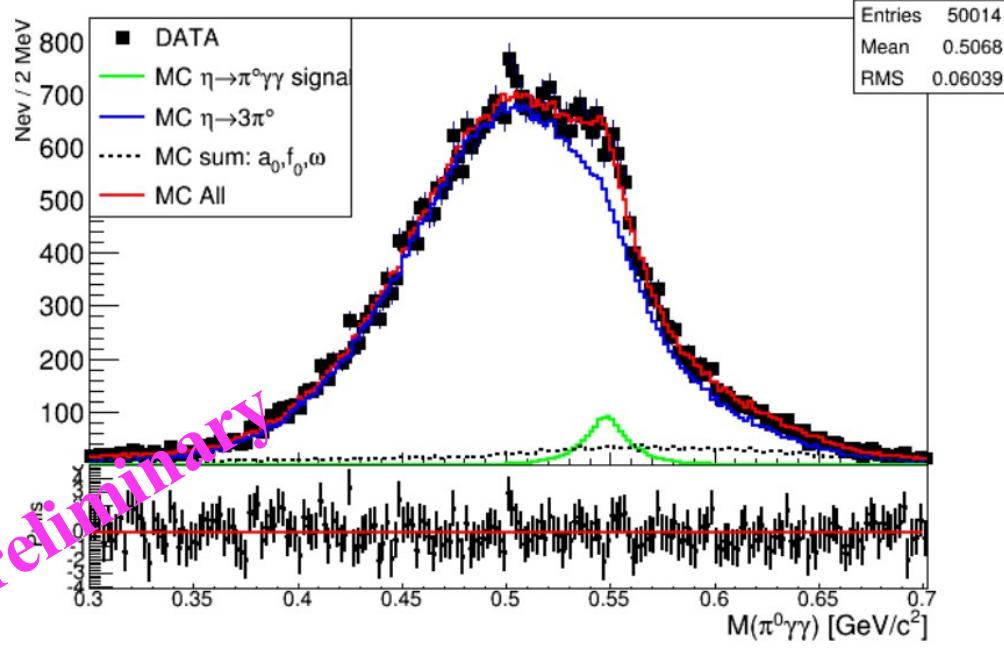
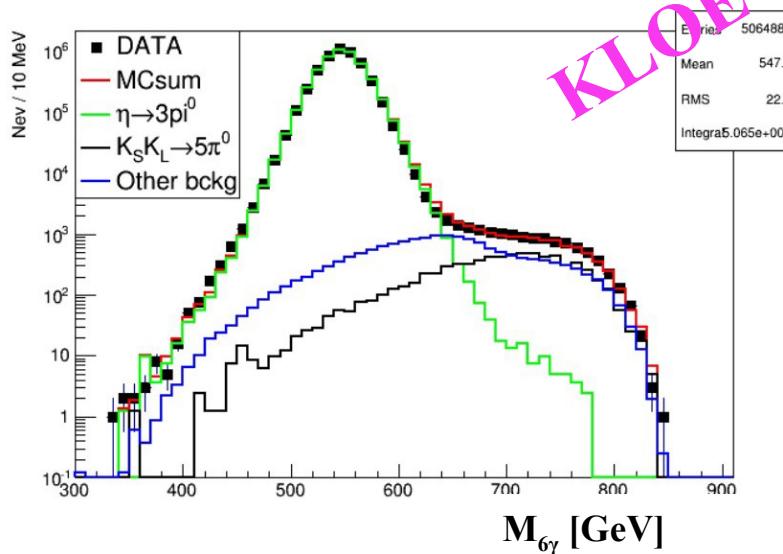


$\eta \rightarrow \pi^0 \gamma \gamma$ ($\phi \rightarrow \eta \gamma$)



- $L = 1.7 \text{ fb}^{-1}$ – 5 prompt γ sample selected
- Main bckg: $\phi \rightarrow \eta \gamma$, $\eta \rightarrow 3\pi^0$ with lost or merged photons
- Normalization to $\phi \rightarrow \eta \gamma$, $\eta \rightarrow 3\pi^0$ (7 prompt clusters, very clean channel, low background)

KLOE-2 preliminary



$\Rightarrow \sim 1200$ signal events

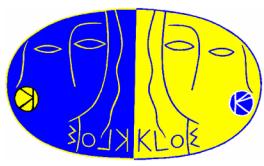
$$\text{Br}(\eta \rightarrow \pi^0 \gamma \gamma) = (0.99 \pm 0.11_{\text{stat}} \pm 0.24_{\text{sys}}) \times 10^{-4}$$

Recent prediction based on L σ M + VMD

$$\text{Br}(\eta \rightarrow \pi^0 \gamma \gamma) = (1.30 \pm 0.08) \times 10^{-4}$$

[R.Escribano et al., PRD 102 (2020) 034026]

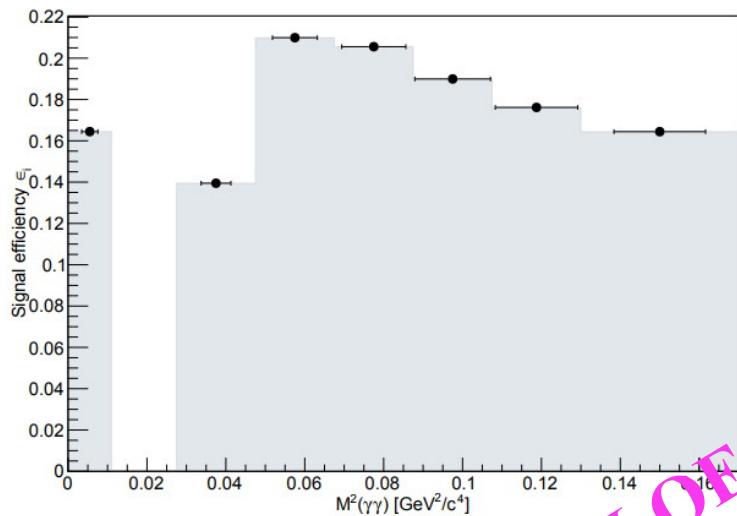
linear sigma model and vector meson dominance frameworks



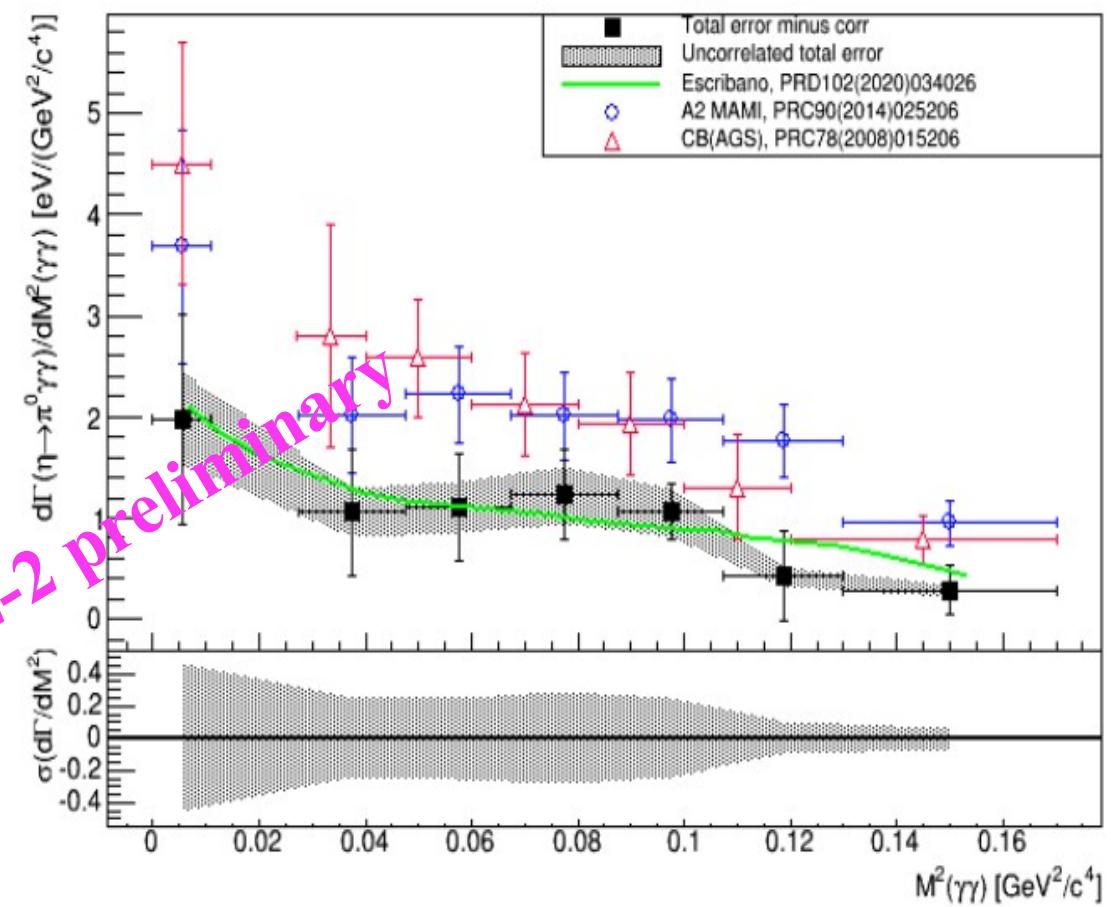
$d\Gamma(\eta \rightarrow \pi^0 \gamma \gamma) / dM^2_{\gamma \gamma}$



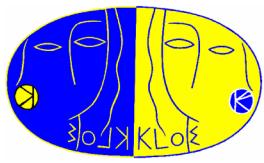
- Separate fits in bins of $M^2(\gamma\gamma)$
- Second bin missing due to the veto for $\pi^0\pi^0$ events (from $\phi \rightarrow f_0(980)\gamma$ and $e^+e^- \rightarrow \omega\pi^0$ with $\omega \rightarrow \pi^0\gamma$)



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



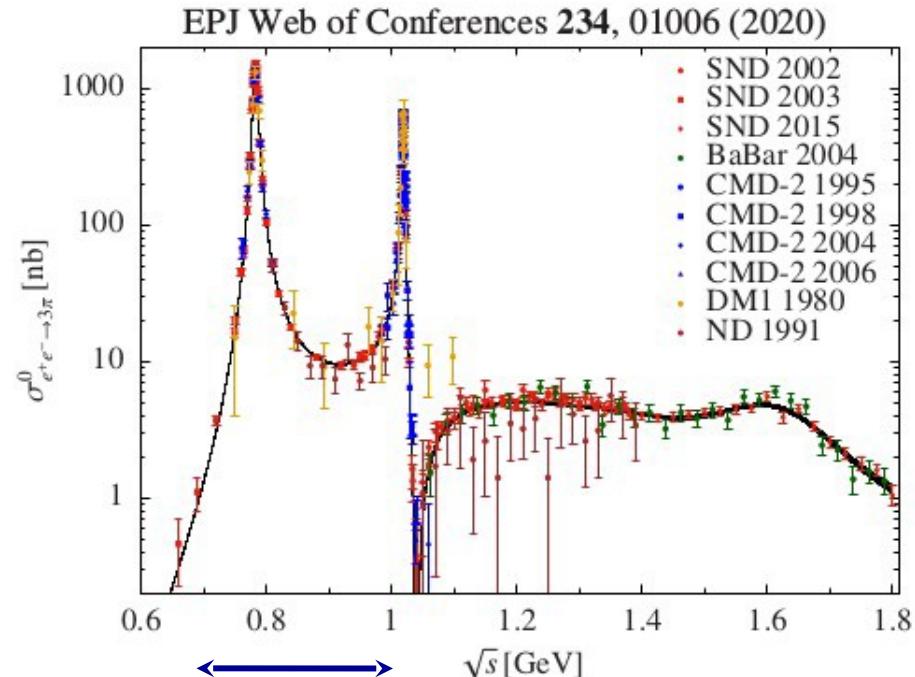
MODEL: [R.Escribano et al., PRD 102 (2020) 034026]



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



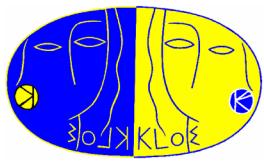
- $e^+ e^- \rightarrow \pi^+ \pi^- \pi^0$ is the **second largest contribution** to the **calculation of the Hadronic Vacuum Polarization for $(g-2)_\mu$** and to its uncertainty
- Initial State Radiation (**ISR**) measurement at KLOE is **complementary to energy scan** in the range $\sqrt{s} < M_\phi$ (**SND and CMD-2**)



Current measurement by
CMD-2/SND via energy scan
BES3/BaBar via ISR

Goals:

- Measure the cross section in the $\omega(782)$ region
- Evaluate the product $\text{Br}(\omega \rightarrow e^+ e^-) \times \text{Br}(\omega \rightarrow \pi^+ \pi^- \pi^0)$



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



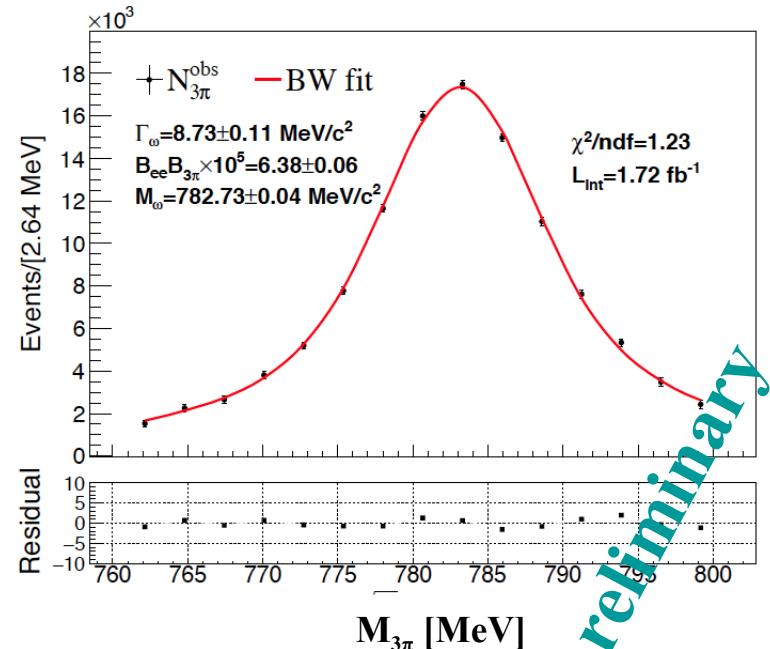
- $L = 1.7 \text{ fb}^{-1}$ at ϕ peak

Selection:

- At least **2 tracks with opposite curvature**
- 3 neutral clusters**
- Kinematic fit

Signal extraction:

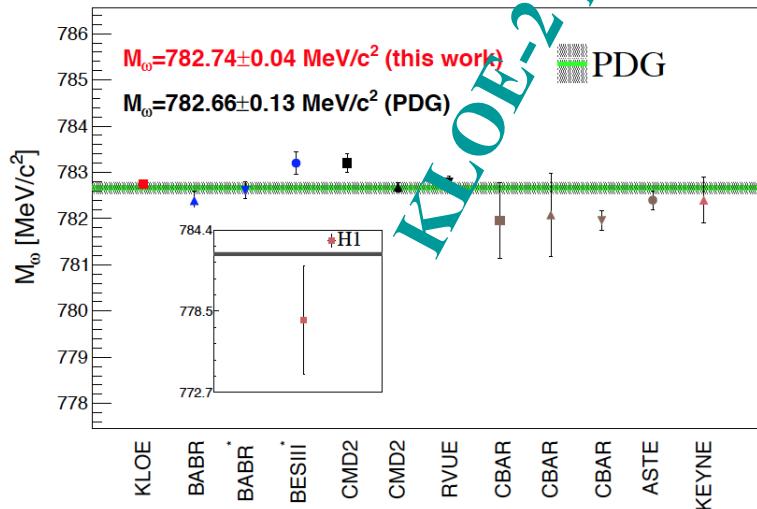
- Fit with **Breit-Wigner convoluted with smearing matrix**
- ISR correction factor taken into account**

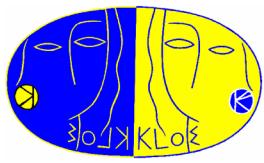


KLOE results* compared with PDG

	$M_\omega [\text{MeV}/c^2]$	$\Gamma_\omega [\text{MeV}]$	$\mathcal{B}_{ee} \times \mathcal{B}_{3\pi} [10^{-5}]$
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

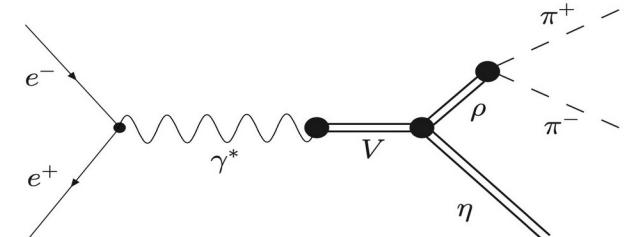




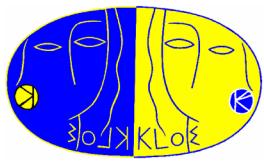
$\phi \rightarrow \eta\pi^+\pi^-$, $\eta\mu^+\mu^-$



- In VMD models $e^+e^- \rightarrow \eta\pi^+\pi^-$ occurs through the $\rho\eta$ intermediate state
- $\phi \rightarrow \eta\pi^+\pi^-$ violates the OZI rule and G-parity
 $\Rightarrow \text{Br}(\phi \rightarrow \eta\pi^+\pi^-) < 1.8 \times 10^{-5}$ @ 90% C.L. [CMD-2, PLB491(2000)81]
- The same sample can be used to search for the Dalitz decay $\phi \rightarrow \eta\mu^+\mu^-$
 $\Rightarrow \text{Br}(\phi \rightarrow \eta\mu^+\mu^-) < 9.4 \times 10^{-6}$ @ 90% C.L. [CMD-2, PLB501(2001)191]
- $L = 1.6 \text{ fb}^{-1}$ analyzed
- Focus on $\phi \rightarrow \eta\mu^+\mu^-$ process, exploiting both $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow 3\pi^0$ decays
- Goal: measure the Branching fraction, and extract the Transition Form Factor



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

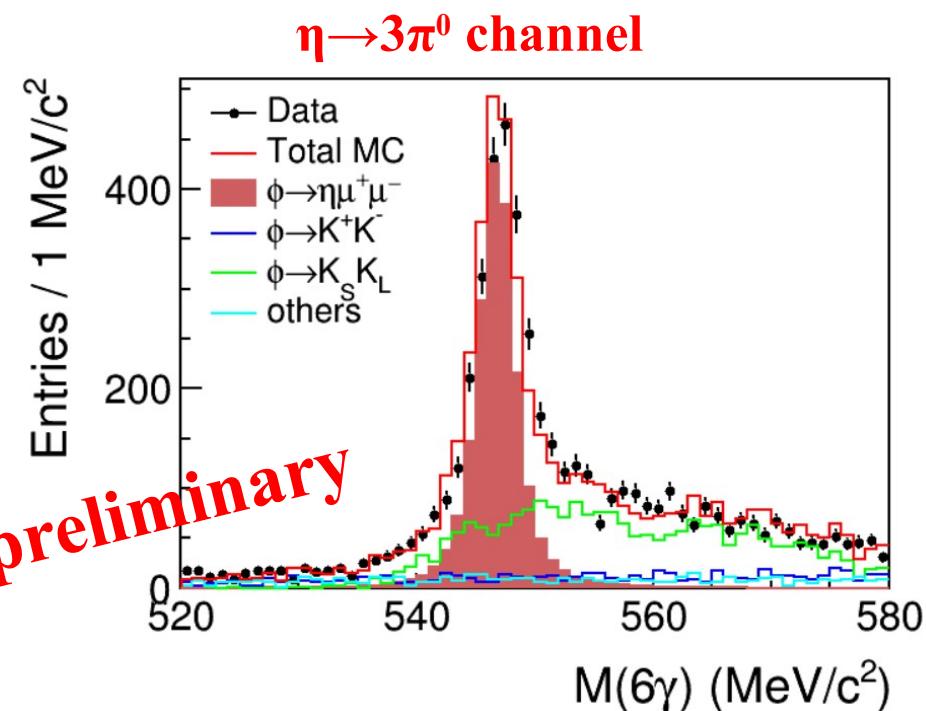
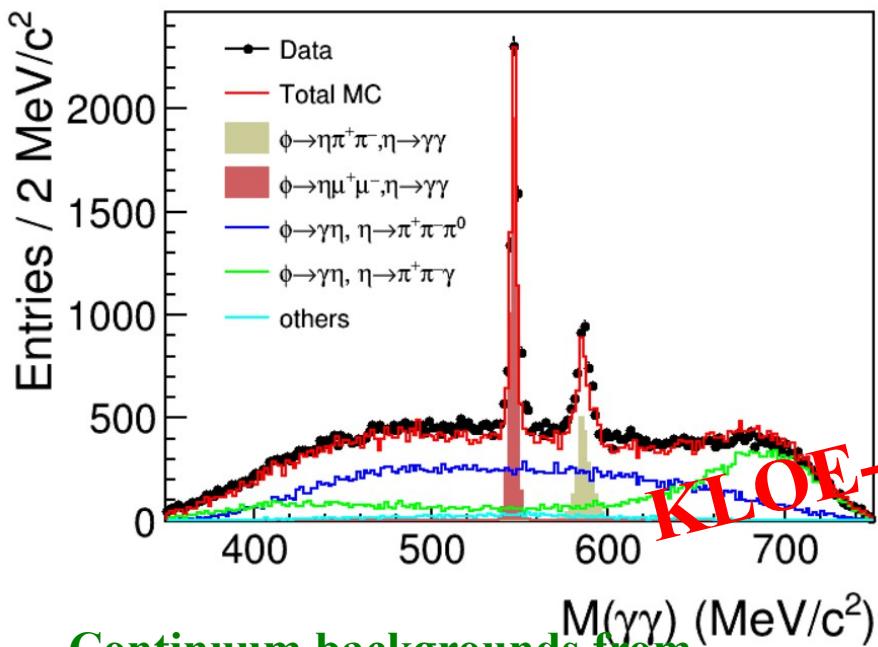


$\phi \rightarrow \eta \mu^+ \mu^-$

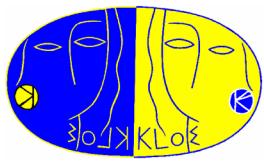


Selection:

- 2 charged tracks + 2 ($\eta \rightarrow \gamma\gamma$) or 6 ($\eta \rightarrow 3\pi^0$) prompt γ
- $M(\pi^+\pi^-) < 480$ MeV (tracks are considered pions to reject $K_S K_L$ events)
- $380 < M(\gamma\gamma) < 750$ MeV/c²
- Kinematic fit with 6 or 10 constraints
- Cut on $M(\gamma\mu^+\mu^-)$ to veto $\Phi \rightarrow \gamma\eta$, $\eta \rightarrow \gamma\pi^+\pi^-$
 $\eta \rightarrow \gamma\gamma$ channel



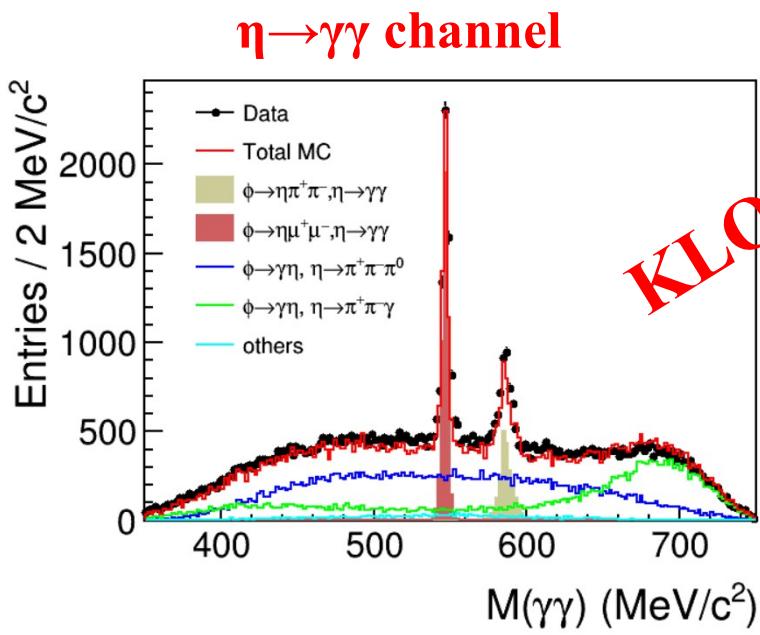
Main background:
 $\phi \rightarrow K_S K_L \rightarrow \pi^+\pi^-\pi^0\pi^0\pi^0$



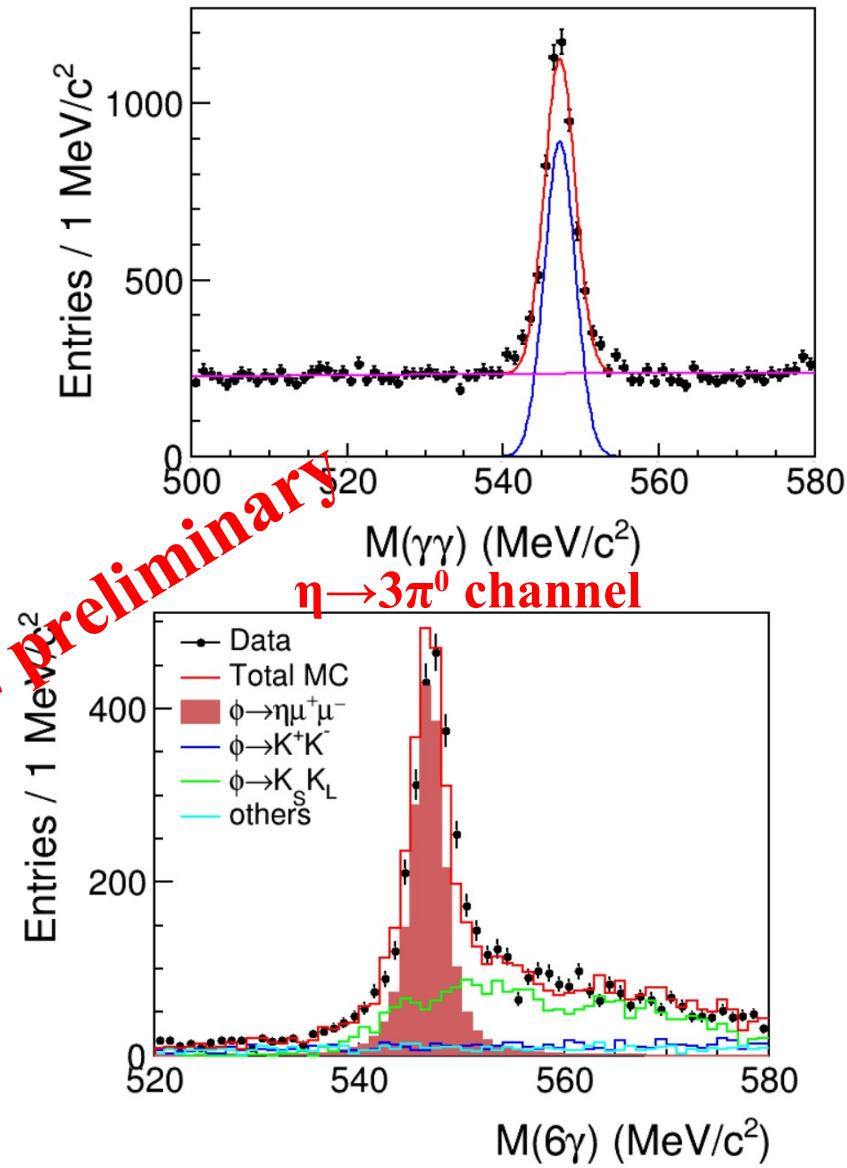
$$\phi \rightarrow \eta \mu^+ \mu^-$$

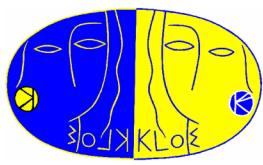


>Clear $\phi \rightarrow \eta \pi^+ \pi^-$ and $\eta \mu^+ \mu^-$ signals are observed



KLOE-2 preliminary

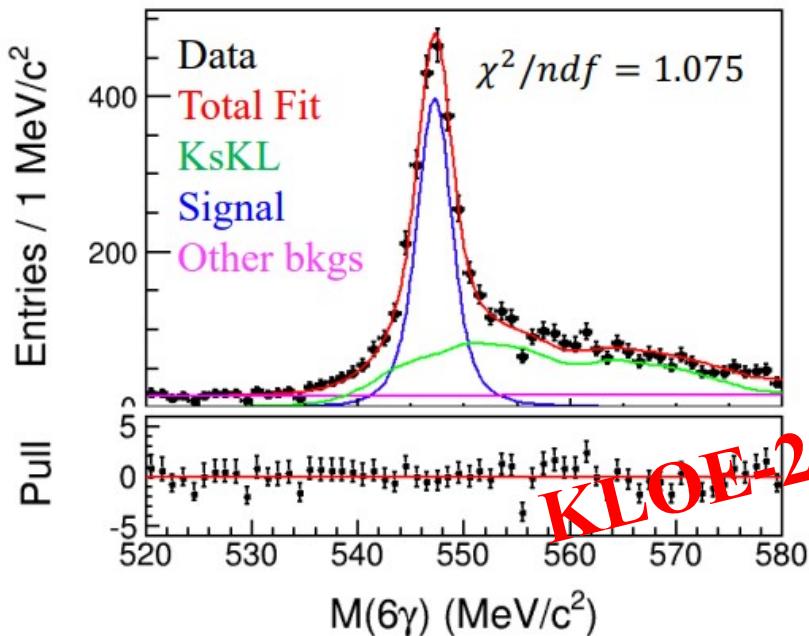




$\phi \rightarrow \eta \mu^+ \mu^-$ - preliminary results

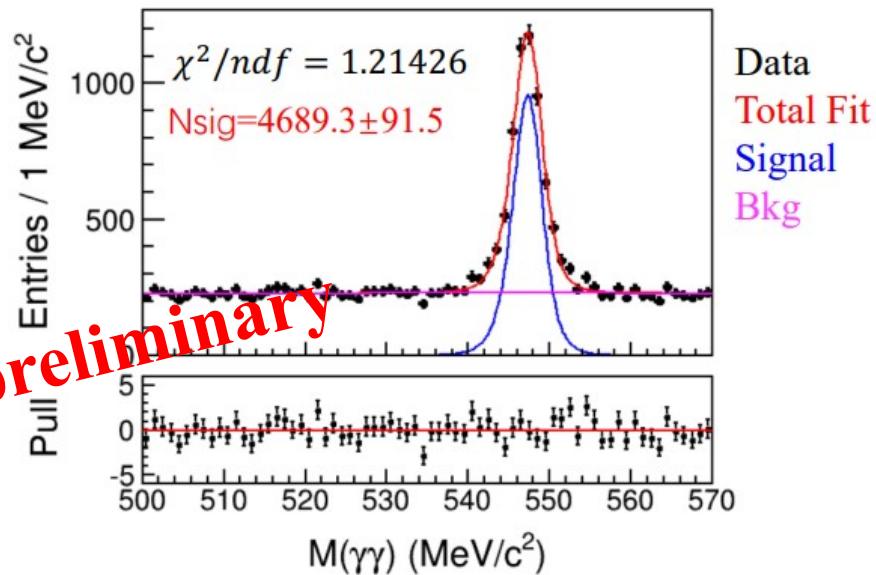


$\eta \rightarrow 3\pi^0$ channel



$\eta \rightarrow \gamma\gamma$ channel

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



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

Systematics under investigation!

$$F_{\phi\eta}(q^2) = \frac{1}{1 - q^2/\Lambda_{\phi\eta}^2}$$

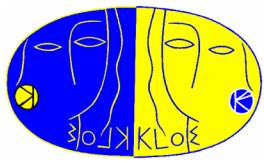
$$Br(\phi \rightarrow \mu^+ \mu^- \eta) = \frac{N(\phi \rightarrow \mu^+ \mu^- \eta)}{\mathcal{L}_{int} \sigma(e^+ e^- \rightarrow \phi) \mathcal{B}(\eta \rightarrow \gamma\gamma) \varepsilon} = (5.65 \pm 0.11) \times 10^{-6}$$

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

$$b_{\phi\eta(\rightarrow 3\pi^0)} = (2.903 \pm 0.198) \text{ GeV}^{-2}$$

$$\Lambda_{\phi\eta(\rightarrow\gamma\gamma)} = (0.576 \pm 0.010) \text{ GeV}$$

$$\Lambda_{\phi\eta(\rightarrow 3\pi^0)} = (0.587 \pm 0.020) \text{ GeV}$$



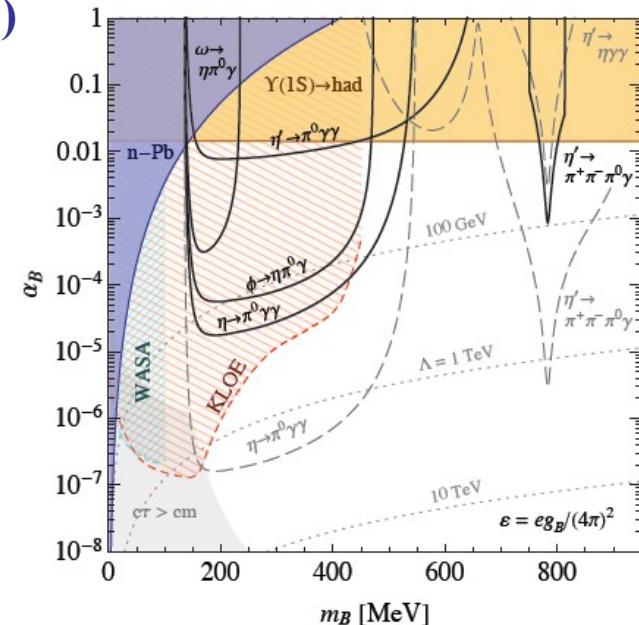
Leptophobic B-boson



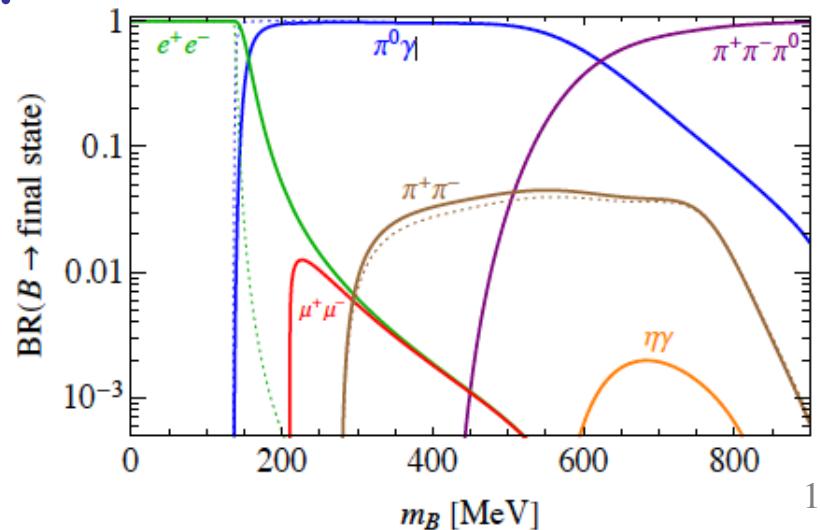
- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the $\omega(782)$ $\Rightarrow I^G=0^-$
- Can have an impact in (g-2) muon anomaly

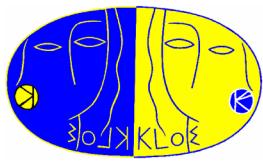
[S.Tulin, PRD89(2014)114008]

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



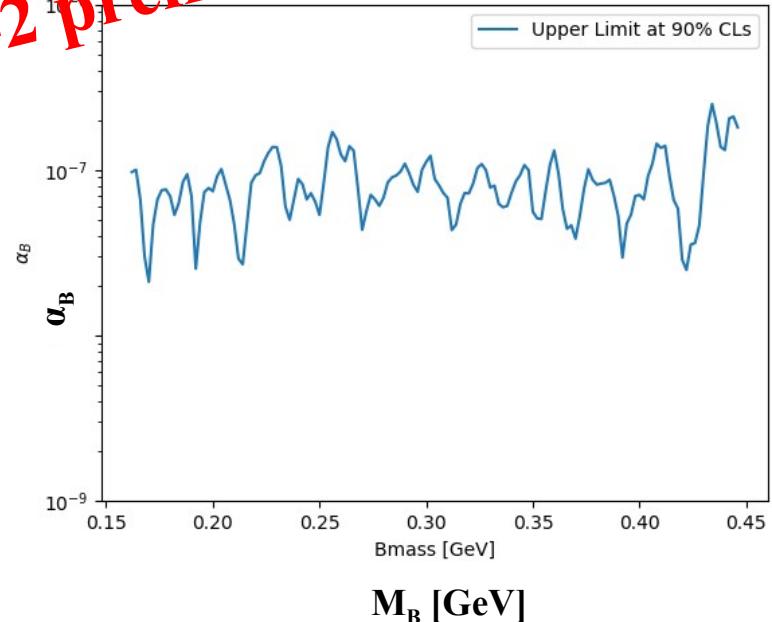
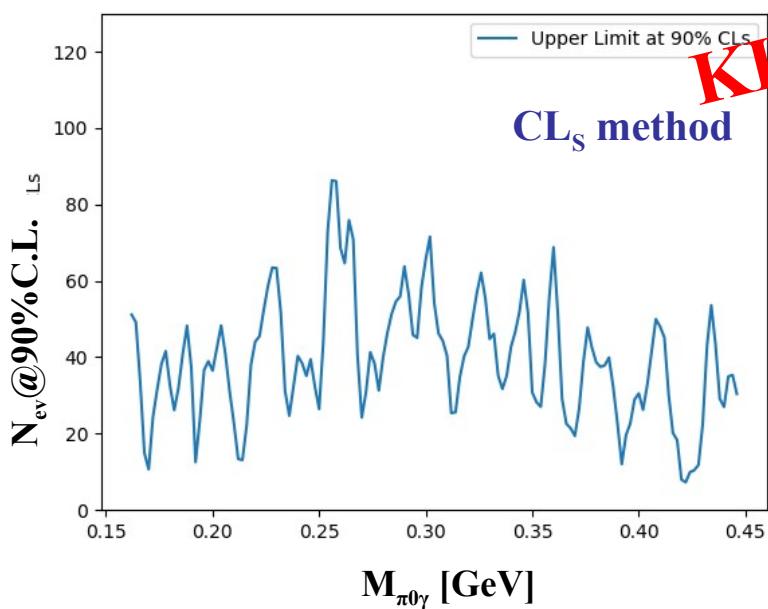
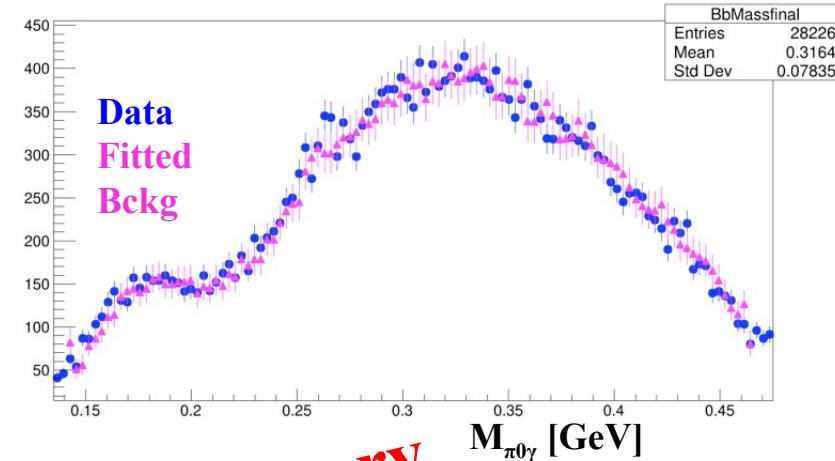
- Dominant decay channel ($m_B < 600$ MeV):
 $B \rightarrow \pi^0 \gamma$
- Can be searched for in:
 $\phi \rightarrow \eta B \Rightarrow \eta \pi^0 \gamma \Rightarrow 5$ prompt γ final state
 $\phi \rightarrow \eta \gamma$, with $\eta \rightarrow B \gamma \Rightarrow (\eta \rightarrow \pi^0 \gamma \gamma)$
 $e^+ e^- \rightarrow B \gamma_{\text{ISR}} \rightarrow \pi^0 \gamma \gamma_{\text{ISR}}$



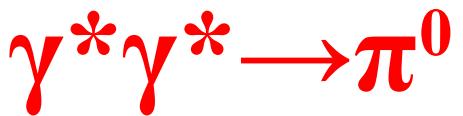
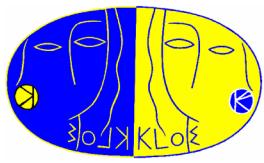


Leptophobic B-boson

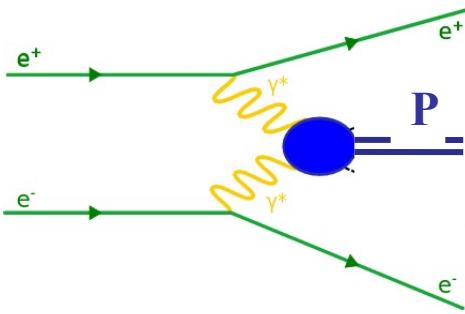
- $L = 1.7 \text{ fb}^{-1}$ analyzed
- Selection of 5 prompt photon events
- Kinematic fit to improve energy resolution
- Main background from $\phi \rightarrow a_0(980)\gamma \rightarrow \eta\pi^0\gamma$ and $\phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$ with lost/merged photons
- Background evaluation from sidebands
(fit region 5σ with 1σ exclusion region, $\sigma \sim 2 \text{ MeV}$)



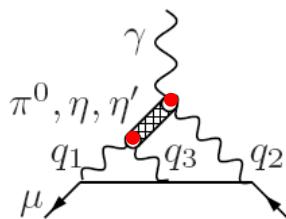
Upper limit on the coupling constant α are set around $O(10^{-7})$ at 90% CLs



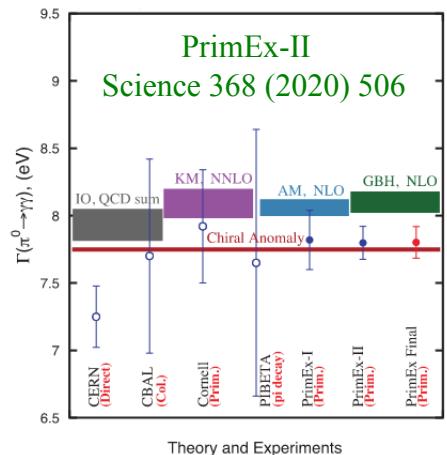
$$e^+ e^- \rightarrow e^+ e^- \gamma^* \gamma^* \rightarrow e^+ e^- P \quad [C(P) = +1]$$



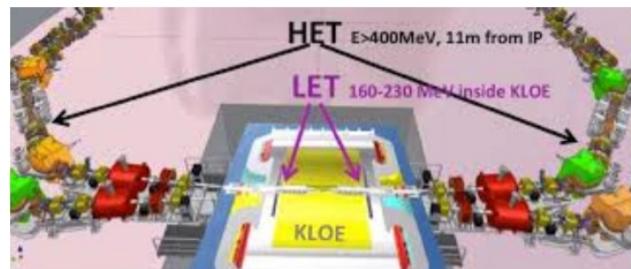
- Transition Form Factor $F_{\pi\gamma\gamma^*}(q^2, 0)$ at space-like q^2 ($|q^2| < 0.1 \text{ GeV}^2$), relevant for the Light-by-Light scattering contribution to $(g-2)_\mu$



Goal: measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ few % level

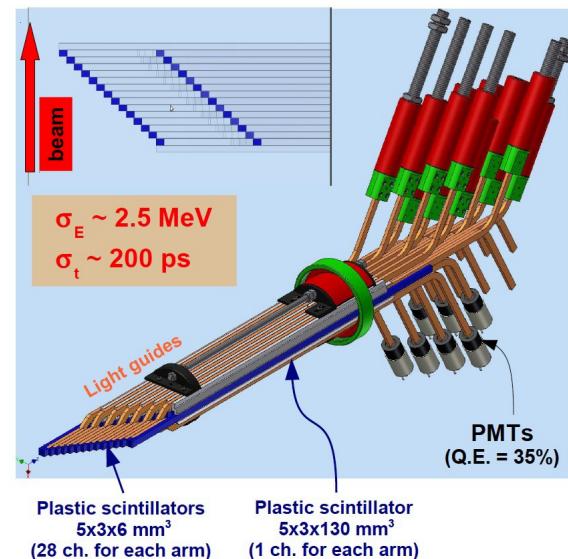
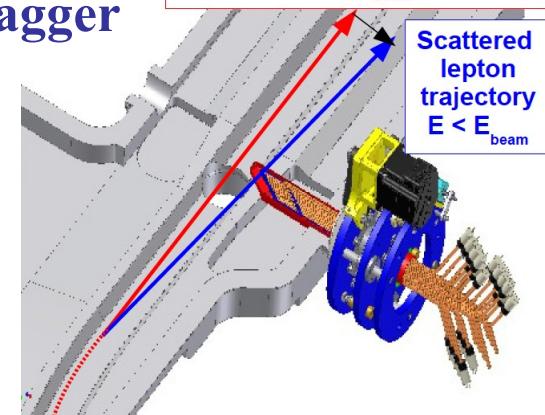


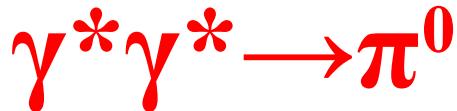
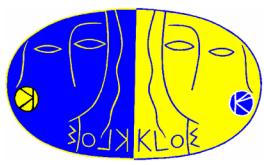
High energy tagger (HET) located 11 m away the IP after the bending dipoles acting like spectrometer for scattered e^+/e^- ($420 < E < 495 \text{ MeV}$)



HET: e^+/e^- tagger

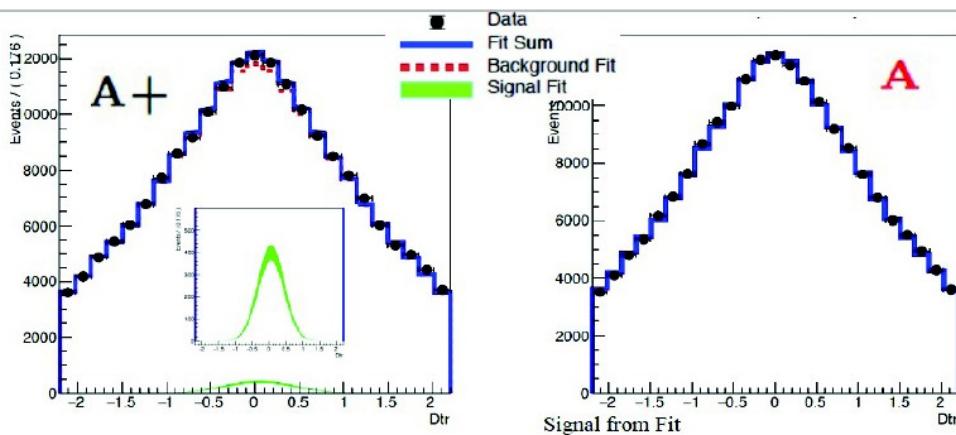
Nominal orbit ($E_{beam} = 510 \text{ MeV}$)



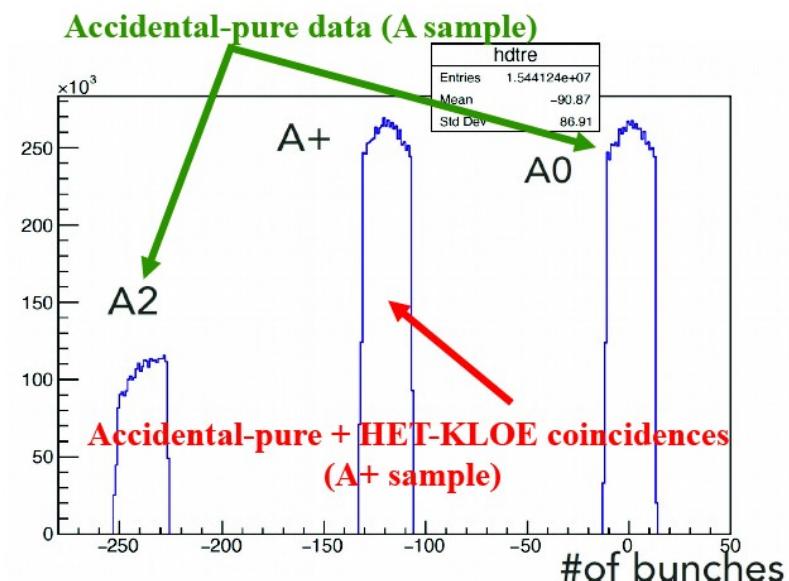


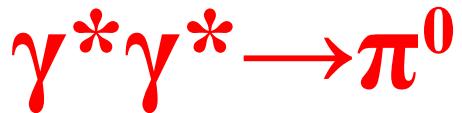
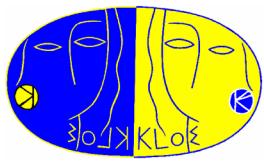
Analysis strategy

- ✓ Hits in HET station and at least one bunch in KLOE associated with only 2 clusters in EMC
- ✓ HET acquisition time 2.5 times larger than KLOE →
 - **A sample:** outside overlapping time window HET-only
 - **A+ sample:** overlapping KLOE-HET time window
- ✓ Simultaneous fits of A+ and A samples



Example of fit on one HET readout channel

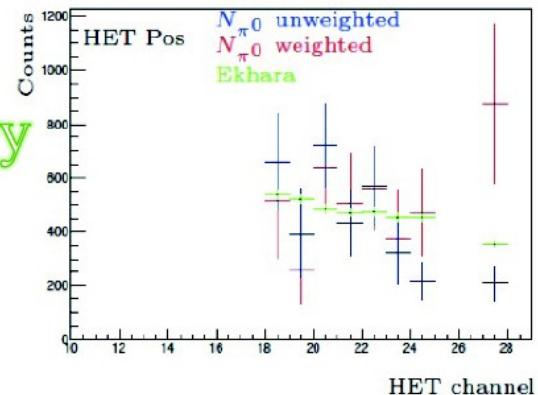
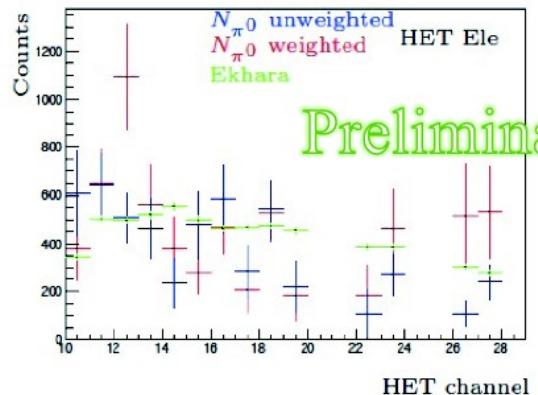




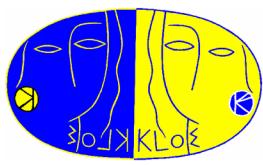
The number of tagged π^0 with 3 fb^{-1} data

$$\frac{\sigma_{\pi^0}}{\sigma_{\text{Bha}}} = \frac{N_{\pi^0}^{\text{meas}}}{\epsilon_{\text{ana}} N_{\text{Bha}}^{\text{meas}}} \frac{A_{\text{Bha}}}{A_{\pi^0}}$$

$$N_{\text{Bha}}^{\text{meas}} = \sigma_{\text{Bha}}^{\text{meas}} \int L dt$$



- ✓ N_{π^0} counting: final checks on weights ongoing
- ✓ Normalize to Radiative Bhabha at very small angle
- ✓ $\sigma_{\text{Bha}}^{\text{meas}}$ 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_{bha}/A_{π^0} : Full simulation of signal and control sample, evaluated from Ekhara/BBBREM generator + BDSIM for lepton transport, **evaluation of systematics in progress**



Summary

KLOE-2 data-taking successfully completed on March 30, 2018
~ 20 years after the first events collected in KLOE

KLOE + KLOE-2 sample $\Rightarrow \sim 8 \text{ fb}^{-1}$ – unique sample worldwide
 $\Rightarrow \sim 2.4 \times 10^{10} \phi$'s produced

The data sample collected by KLOE 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

High precision investigation on light hadron physics and on fundamental symmetries with KLOE/KLOE-2 data are in progress...