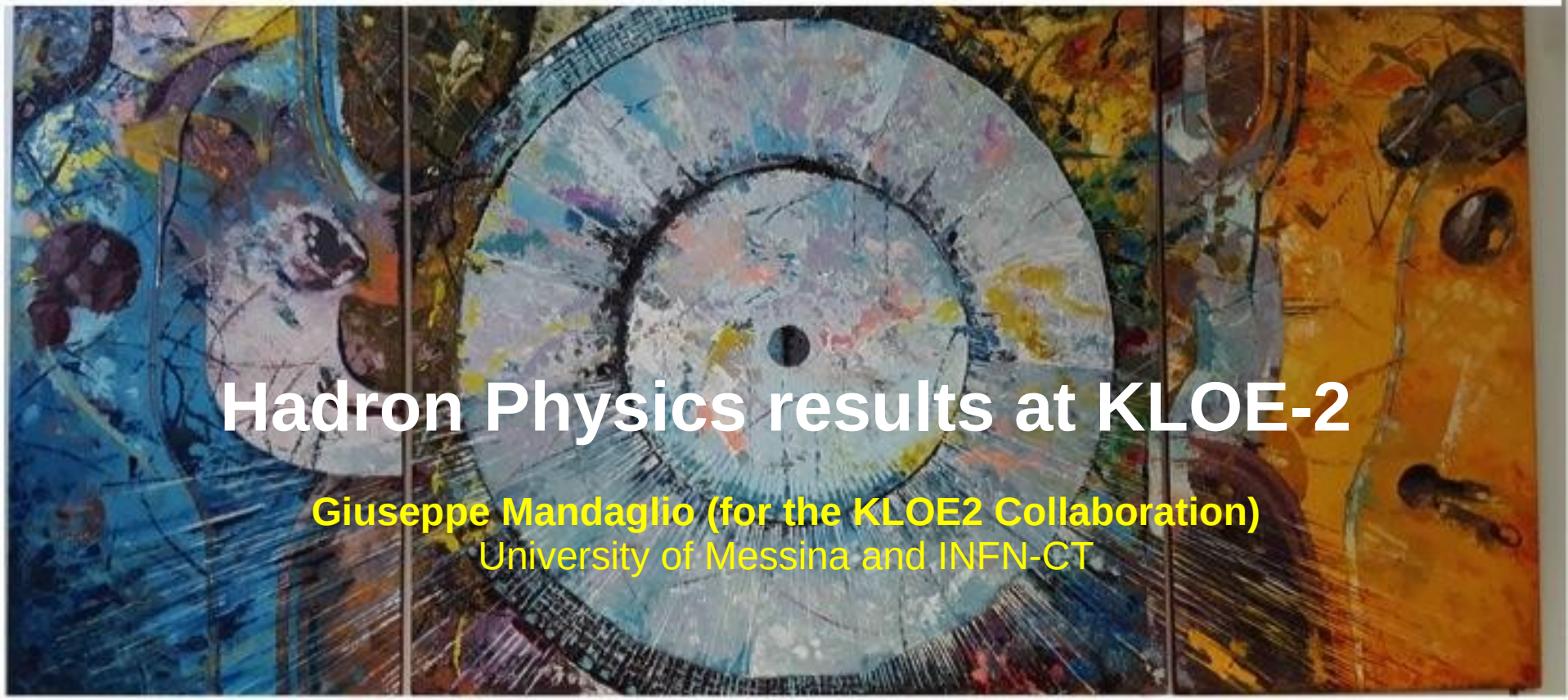


Hadron Physics results at KLOE-2

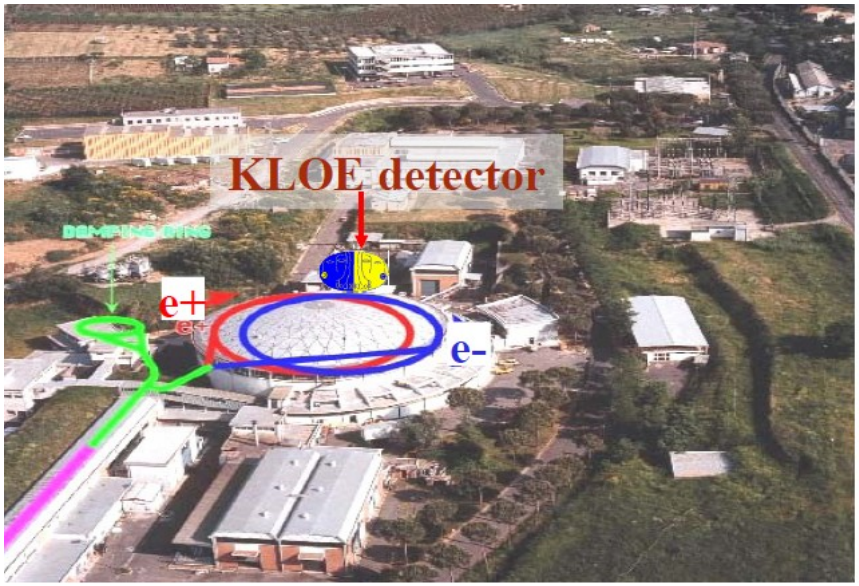
Giuseppe Mandaglio (for the KLOE2 Collaboration)
University of Messina and INFN-CT

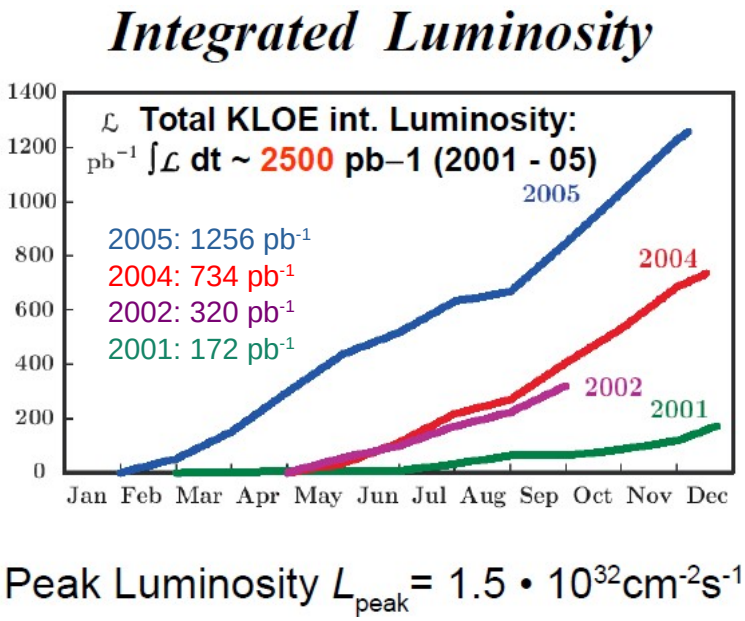
Excited QCD 2022 – Giardini Naxos (Italy) 27 ottobre 2022

Outline

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

KLOE @ DAΦNE





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

- **DAΦNE: Frascati φ-factory, e^+e^- collider**
  @ $\sqrt{s} \approx 1020$ MeV $\approx M_\varphi$; $\sigma_{peak} \approx 3.1$ μb

- **Best performance in KLOE run (2005):**
  $L_{peak} = 1.5 \times 10^{32} cm^{-2} s^{-1}$ $\int Ldt = 8.5$ pb^{-1}/day

- **2001 – 2006: KLOE data-taking**
  ⇒ 2.5 fb^{-1}@$\sqrt{s}=M_\varphi$
  + 250 pb^{-1} off-peak @ $\sqrt{s}$=1000 MeV

KLOE Detector

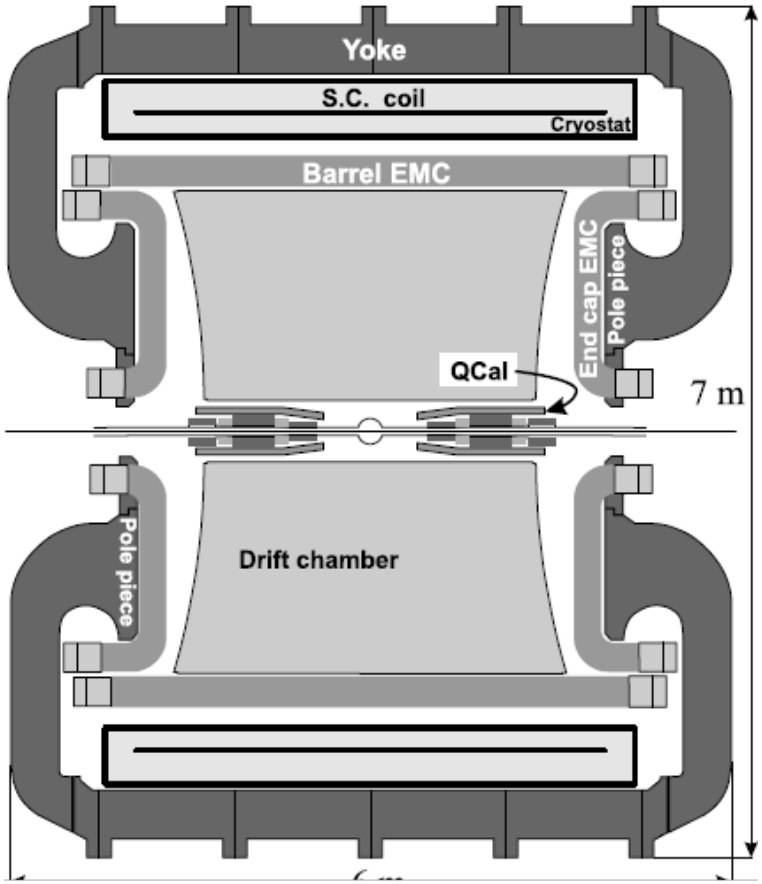
Magnetic field: 0.52 T

Drift chamber: 90% He-10% iC_4H_{10}

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

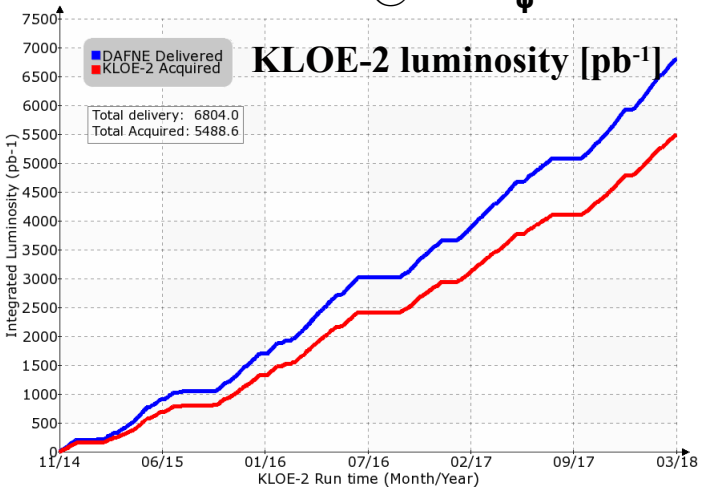
Calorimeter (Pb-Sci.Fi.): 98% of 4π

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

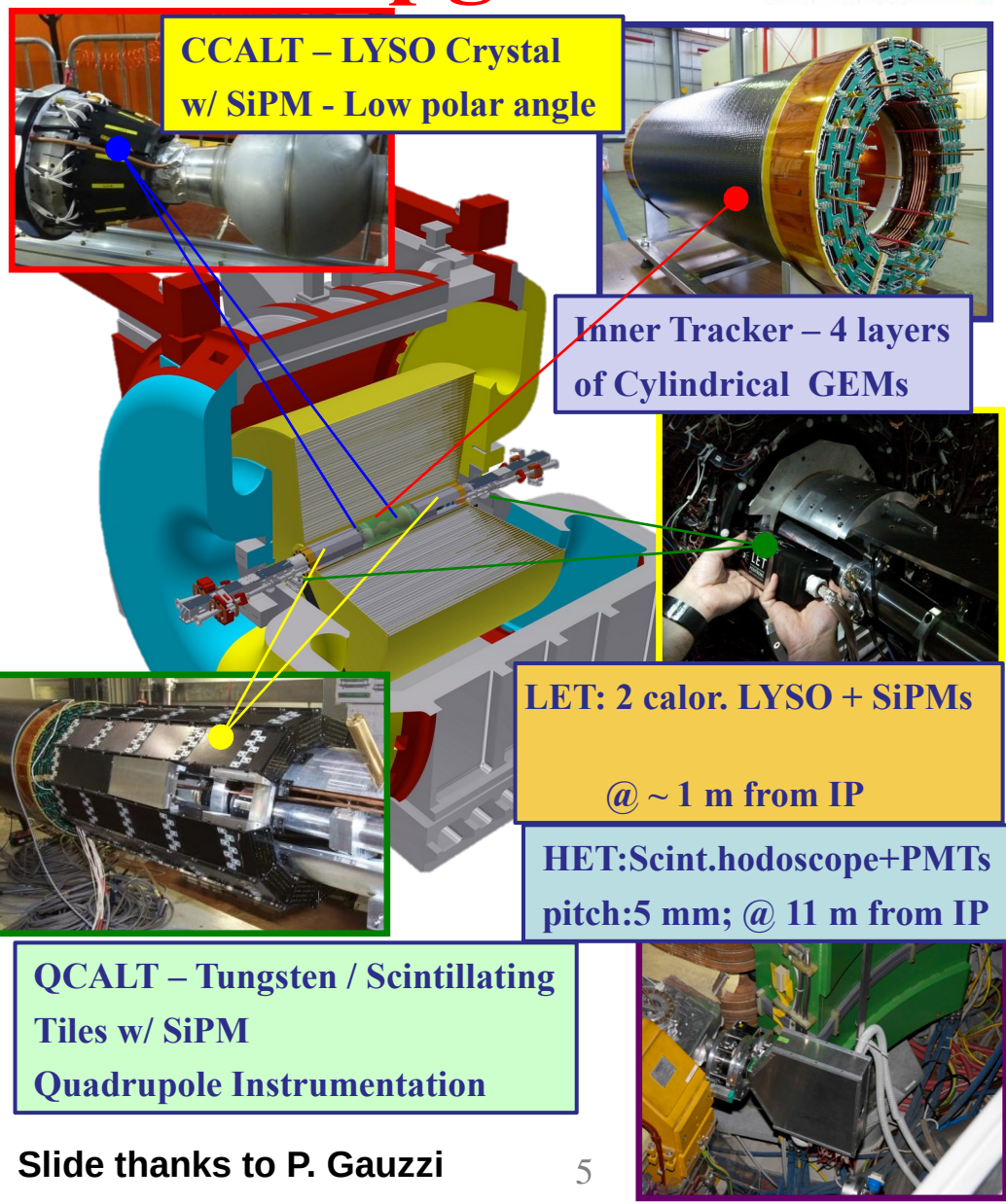


KLOE-2 @ DAΦNE upgraded

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



KLOE + KLOE-2 data sample:
~ 8 fb^{-1} ⇒ 2.4×10^{10} ϕ's produced
⇒ 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**
  $\eta \to \gamma\gamma\gamma$, $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\pi^0\gamma$
- **$\eta \to \pi^+\pi^- e^+e^-$**
- **ChPT : $\eta \to \pi^0\gamma\gamma$**
- **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)**

Hadronic cross section:

- **ISR studies: 2π, 3π, 4π final states**
- **F_π with increased statistics**

In red discussed in this talk

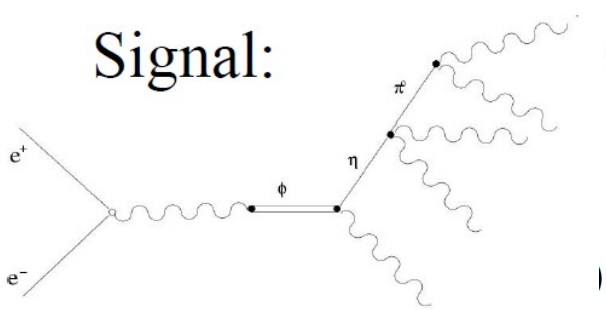
Dark force searches:

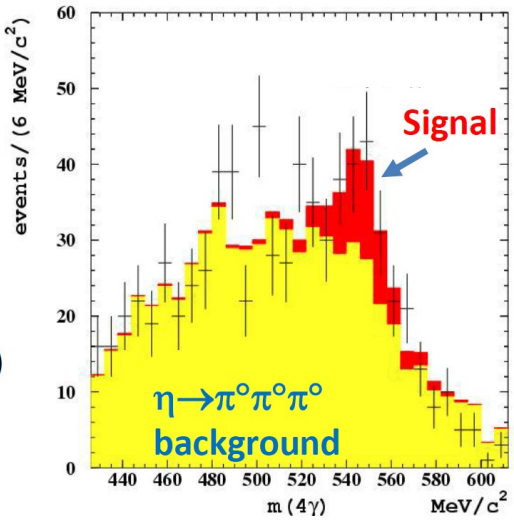
- **Improve limits on**
  - **Uγ associate production**
    $e^+e^- \to U\gamma \to \pi\pi\gamma$, $\mu\mu\gamma$
  - **Higgsstrahlung:**
    $e^+e^- \to Uh' \to \mu^+\mu^-$ + miss. energy
- **Leptophobic B boson search:**
  $\phi \to \eta B$, $B \to \pi^0\gamma$, $\eta \to \gamma\gamma$
  $\eta \to B\gamma$, $B \to \pi^0\gamma$,
- **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:**
  $K_S \to 3\pi^0$
  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**

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



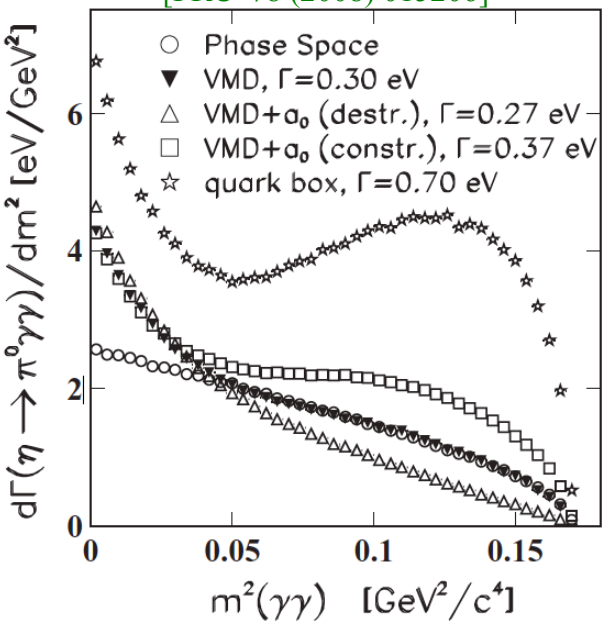


$\eta \to \pi^0\gamma\gamma$ (from $\phi \to \eta\gamma$): ChPT golden mode, $O(p^2)$ null, $O(p^4)$ suppressed ⇒ sensitive to $O(p^6)$

Br = $(22.1 \pm 2.4 \pm 4.7)\times10^{-5}$ CB@AGS(2008)
[PRC 78 (2008) 015206]
Br = $(25.2\pm2.5)\times10^{-5}$ CB@MAMI (2014) A2
[PRC 90 (2014) 025206]

Old KLOE preliminary: $(8.4\pm2.7\pm1.4)\times10^{-5}$
(L = 450 pb^{-1} ~ 70 signal events)

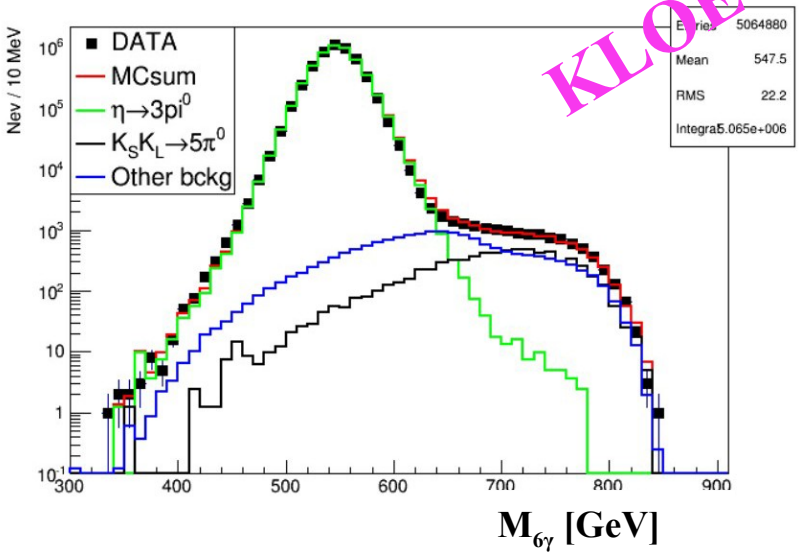
[PRC 78 (2008) 015206]

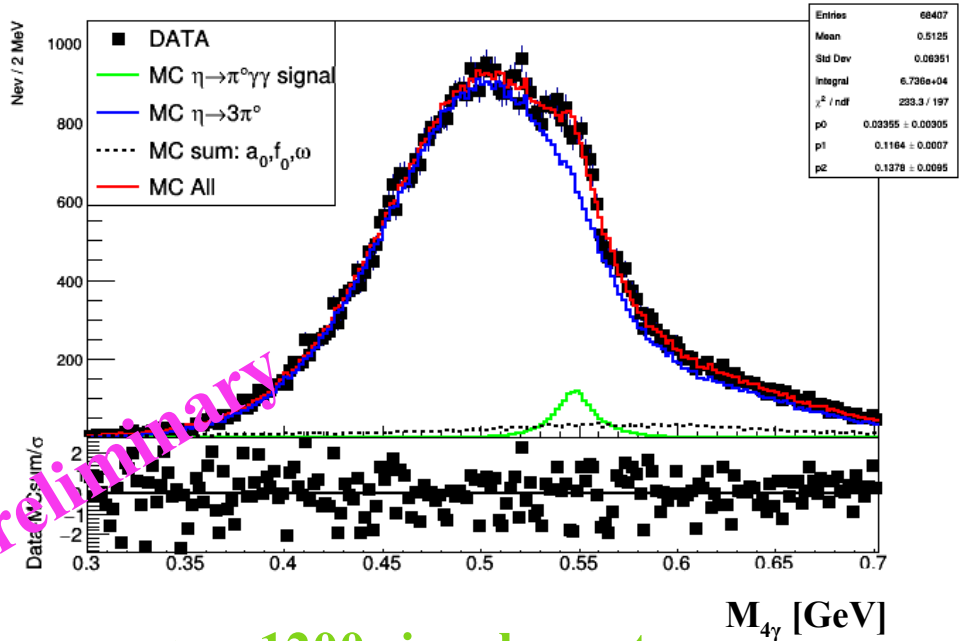


Invariant mass of non-π^0 photons can be used to test theoretical models

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

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





KLOE-2 preliminary

⇒ ~ 1200 signal events

$Br(\eta \to \pi^0\gamma\gamma) = (1.21 \pm 0.13_{stat}) \times 10^{-4}$

Recent prediction based on LσM + VMD

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

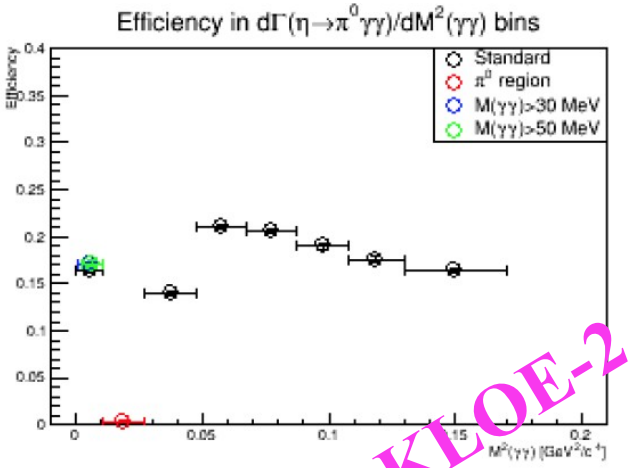
[R.Escribano et al., PRD 102 (2020) 034026]

linear sigma model and vector meson dominance frameworks

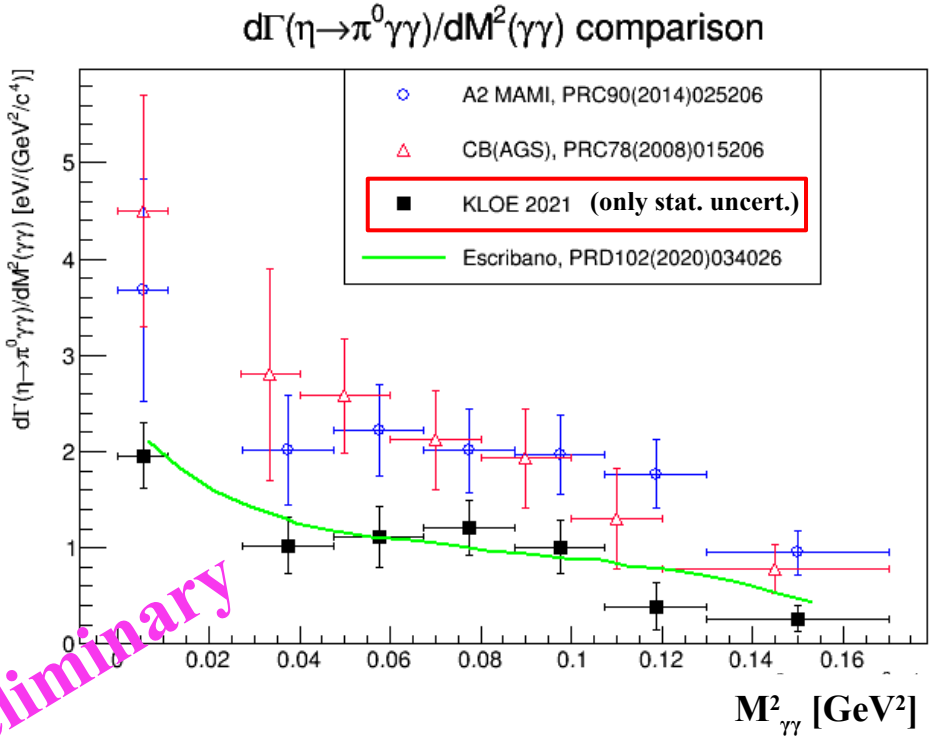
Last checks on systematics ongoing

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

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



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

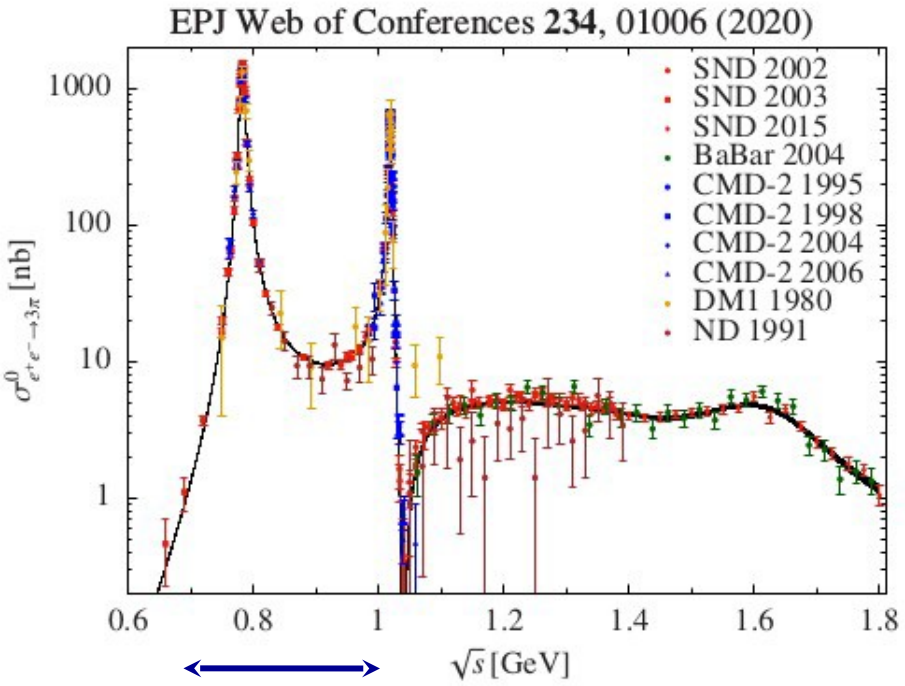


KLOE-2 preliminary

A factor of about 2 less than previous measurements

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

- $e^+e^- \to \pi^+\pi^-\pi^0$ 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 ω(782) region**
- **Evaluate the product $Br(\omega \to e^+e^-) \times Br(\omega \to \pi^+\pi^-\pi^0)$**

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

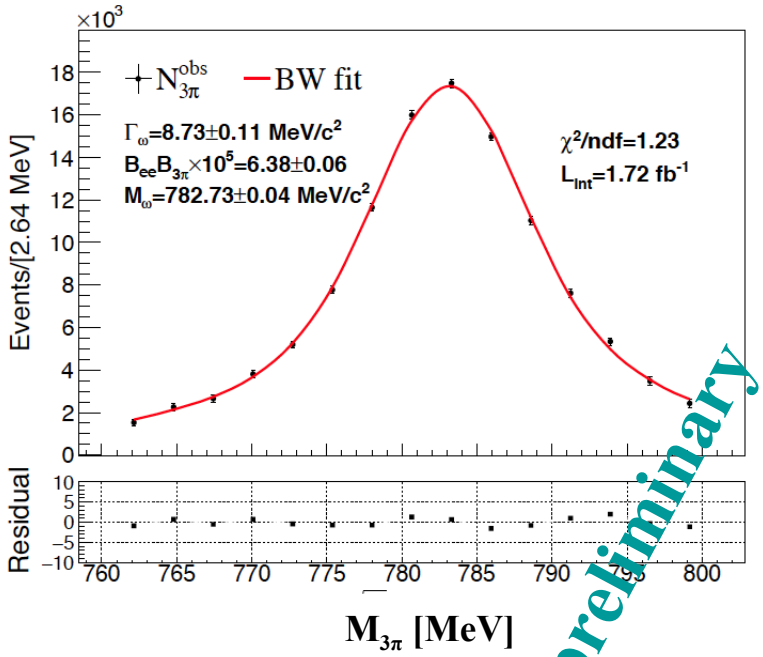
- L = 1.7 fb^{-1} at ϕ peak

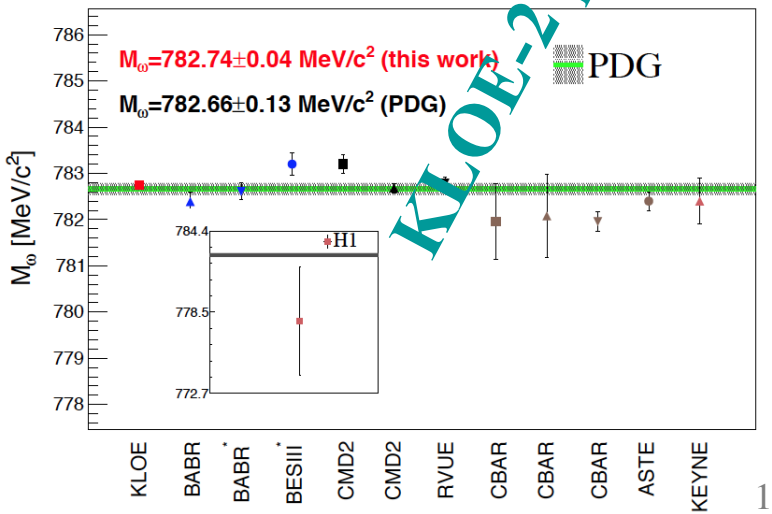
Selection:

- 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



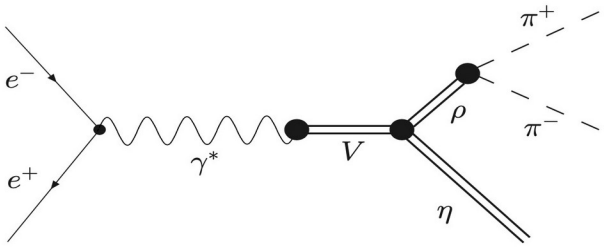


KLOE results* compared with PDG

	M_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**

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



- 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
  $\Rightarrow$ $Br(\phi \to \eta\pi^+\pi^-) < 1.8 \times 10^{-5}$ @ 90% C.L. [CMD-2, PLB491(2000)81]

- The same sample can be used to search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$
  $\Rightarrow$ $Br(\phi \to \eta\mu^+\mu^-) < 9.4 \times 10^{-6}$ @90% C.L. [CMD-2, PLB501(2001)191]

- L = 1.6 fb^{-1} analyzed

- Focus on $\phi \to \eta\mu^+\mu^-$ process, exploiting both $\eta \to \gamma\gamma$ and $\eta \to 3\pi^0$ decays

- Goal: measure the Branching fraction, and extract the Transition Form Factor

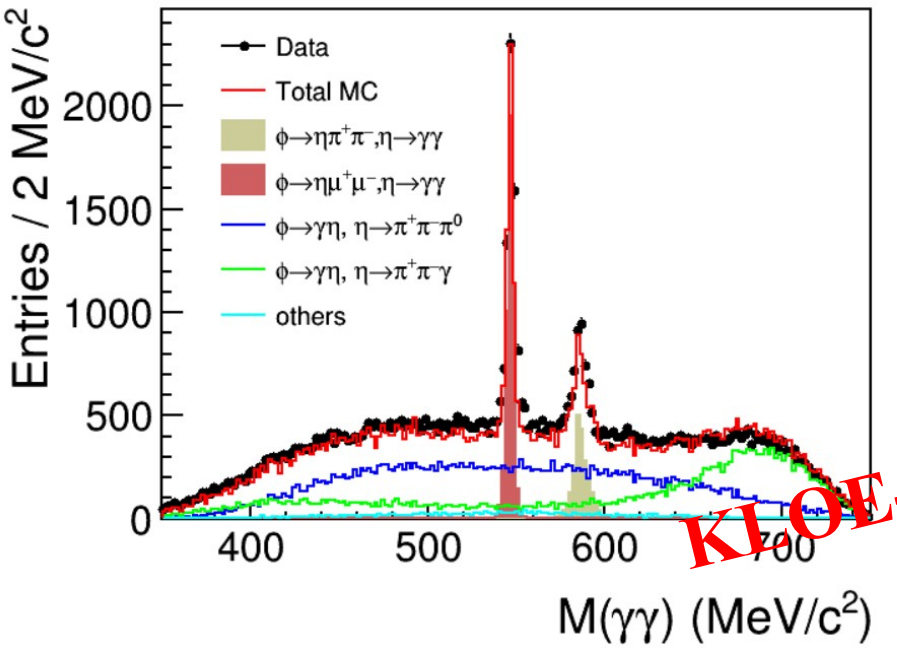
$$\frac{1}{\Gamma(\phi \to \gamma\eta)}\frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = |F_{\phi\eta}(q^2)|^2 \times \frac{\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4M_\mu^2}{q^2}}\left(1+\frac{2M_\mu^2}{q^2}\right) \times \left[\left(1+\frac{q^2}{M_\phi^2-M_\eta^2}\right)^2 - \frac{4M_\phi^2 q^2}{(M_\phi^2-M_\eta^2)^2}\right]^{3/2}$$

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

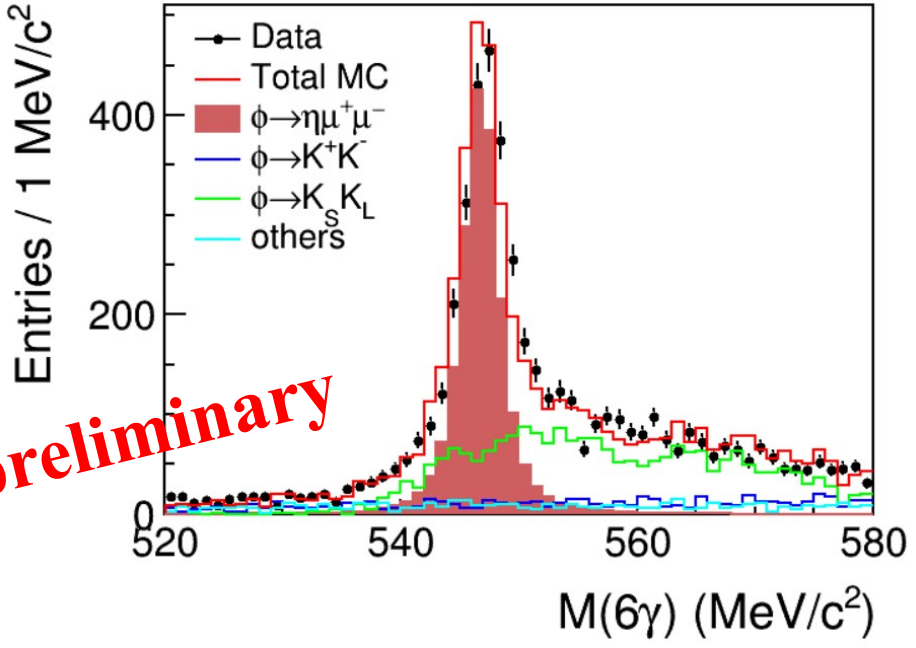
Selection:

- 2 charged tracks + 2 ($\eta\to\gamma\gamma$) or 6 ($\eta\to 3\pi^0$) prompt γ
- $M(\pi^+\pi^-) < 480$ MeV (tracks are considered pions to reject K_SK_L events)
- Kinematic fit with 6 or 10 constraints
- Cut on $M(\gamma\mu^+\mu^-)$ to veto $\phi\to\gamma\eta$, $\eta\to\gamma\pi^+\pi^-$

$\eta\to\gamma\gamma$ channel



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



KLOE-2 preliminary

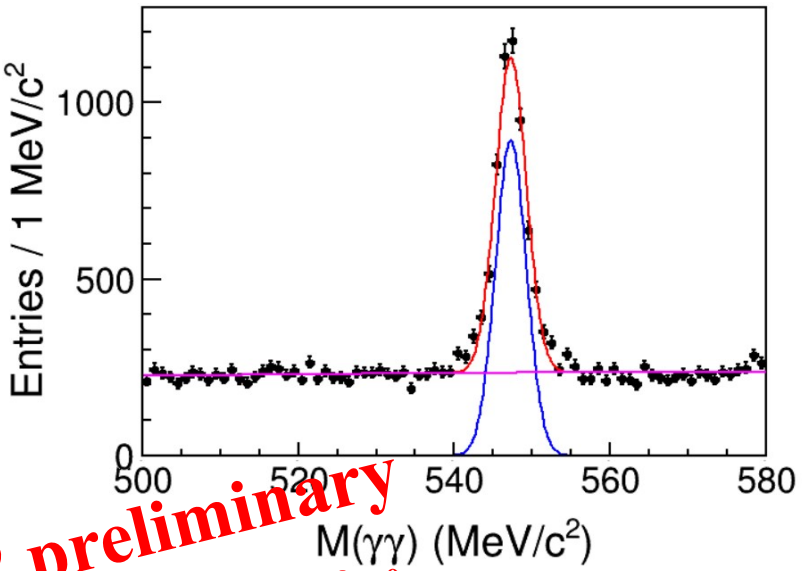
Continuum backgrounds from
$\phi\to\eta\gamma$, $\eta\to\pi^+\pi^-\pi^0$, $\pi^+\pi^-\gamma$

Main background:
$\phi\to K_SK_L\to\pi^+\pi^-\pi^0\pi^0\pi^0$

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

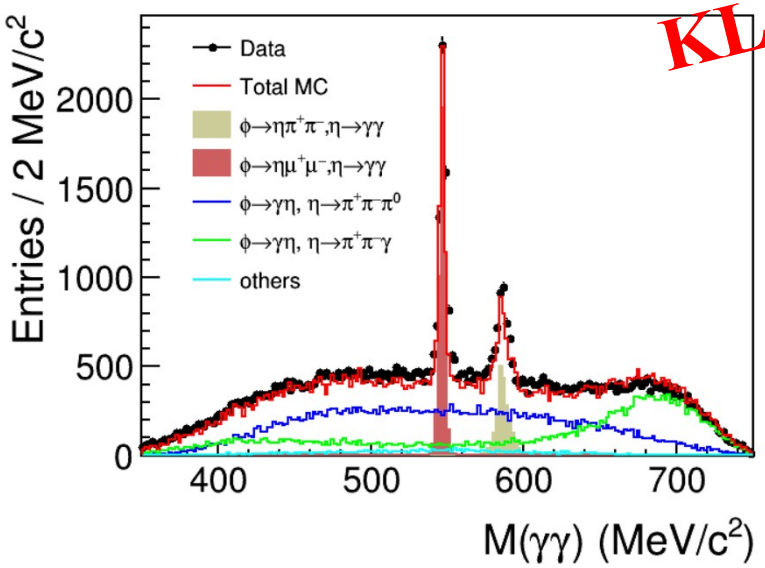
>Clear $\phi \rightarrow \eta \pi^+ \pi^-$ and $\eta \mu^+ \mu^-$ signals are observed

>The analysis is on going!

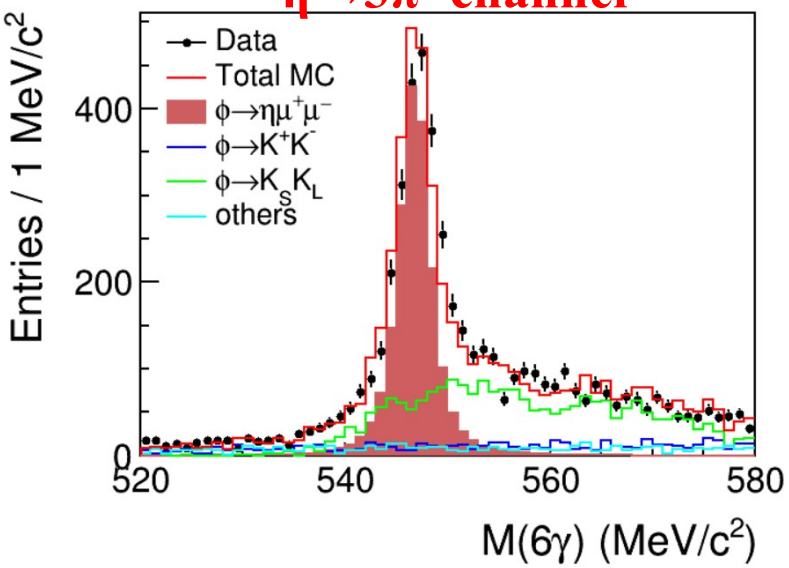


KLOE-2 preliminary

$\eta \rightarrow \gamma\gamma$ channel



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



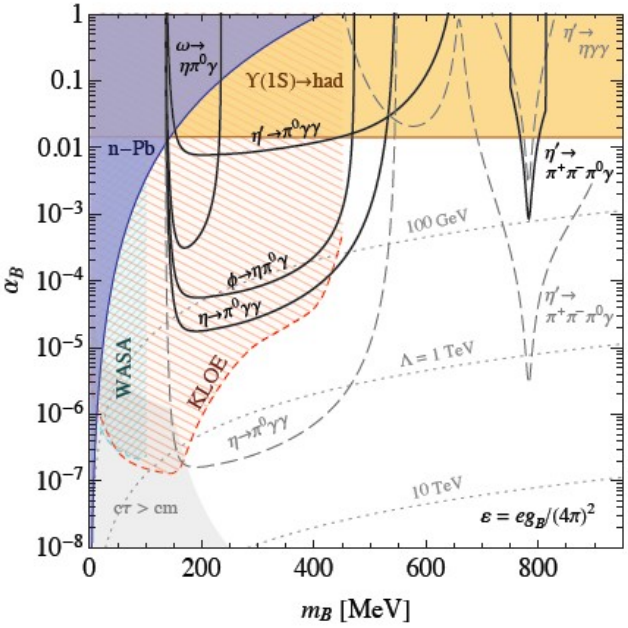
Leptophobic B-boson

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

- **Can have an impact in (g-2) muon anomaly**

[S.Tulin, PRD89(2014)114008]

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



- **Dominant decay channel (m_B < 600 MeV):**

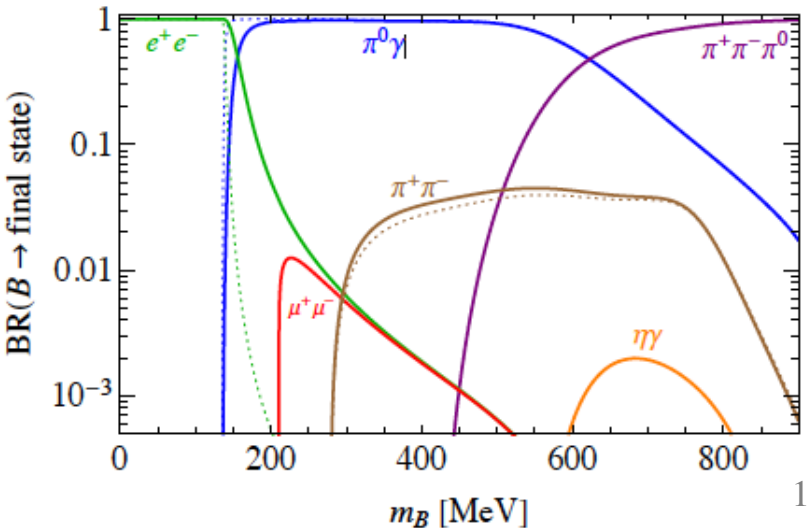
  $B \to \pi^0\gamma$

- **Can be searched for in:**

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

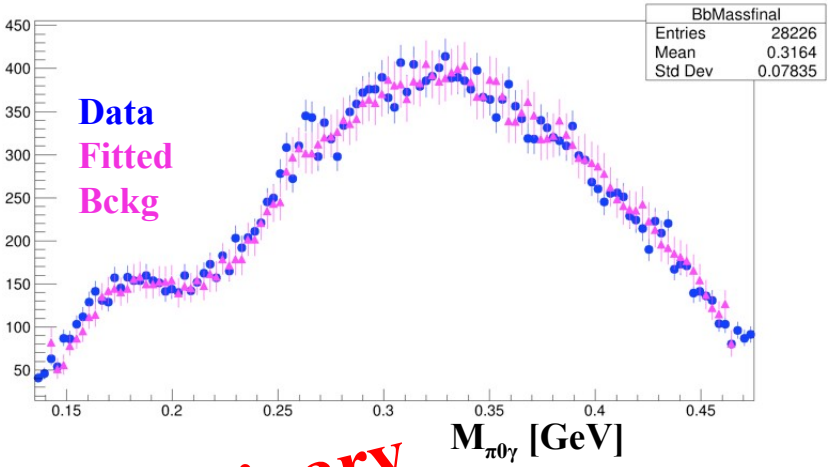
  $\phi \to \eta\gamma$, with $\eta \to B\gamma \Rightarrow (\eta \to \pi^0\gamma\gamma)$

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

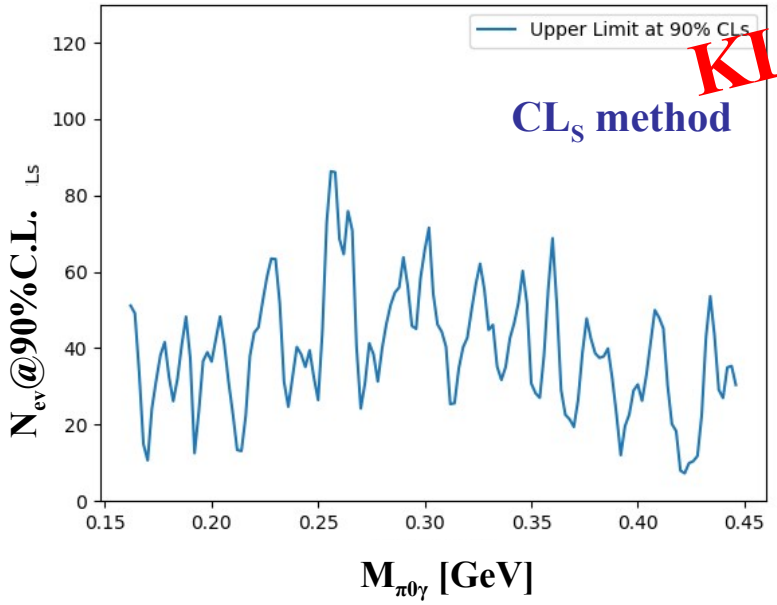


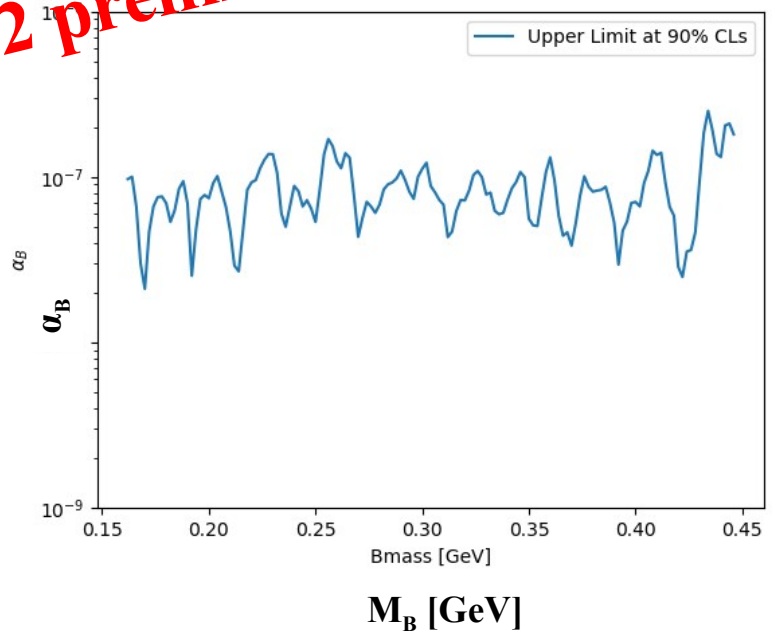
Leptophobic B-boson

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



KLOE-2 preliminary

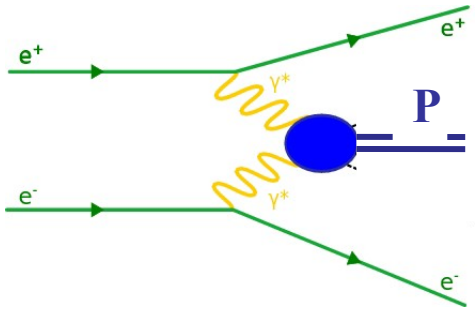




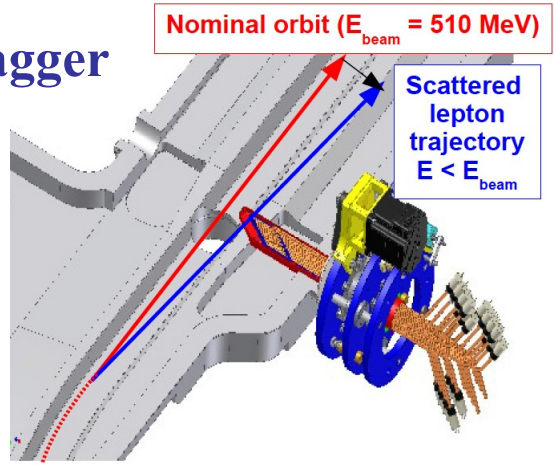
Upper limit on the coupling constant α are set around O(10^{-7}) at 90% CLs

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

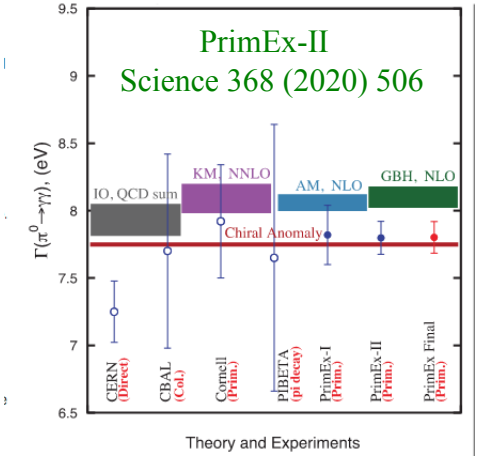
$e^+e^- \rightarrow e^+e^-\gamma^\star\gamma^\star \rightarrow e^+e^-\mathrm{P} \quad [\mathrm{C(P)} = +1]$



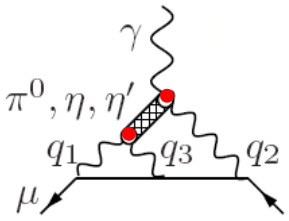
HET: e^+/e^- tagger



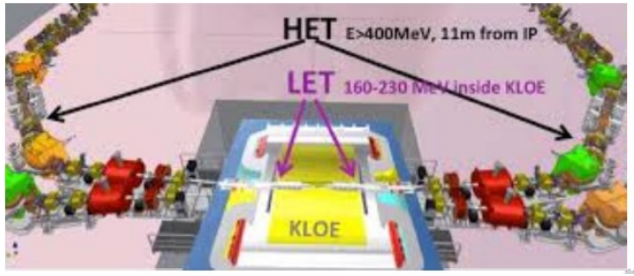
Goal: measurement of $\Gamma(\pi^0 \rightarrow \gamma\gamma)$ @ few % level

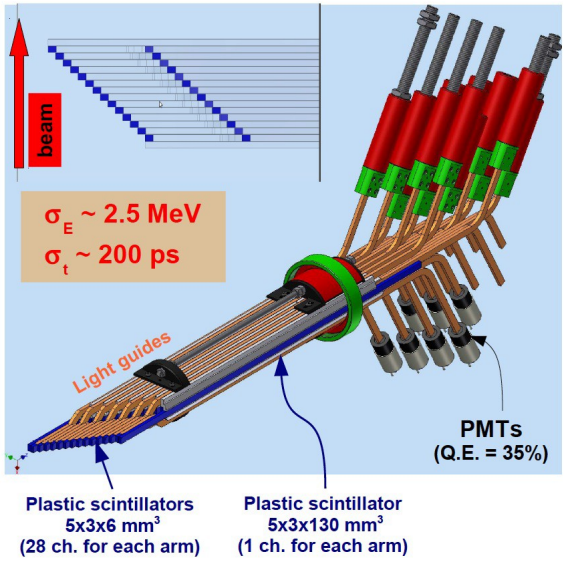


- **Transition Form Factor $F_{\pi\gamma\gamma^*}(q^2,0)$ at space-like q^2 ($|q^2| < 0.1\ \mathrm{GeV}^2$), relevant for the Light-by-Light scattering contribution to $(g-2)_\mu$**



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

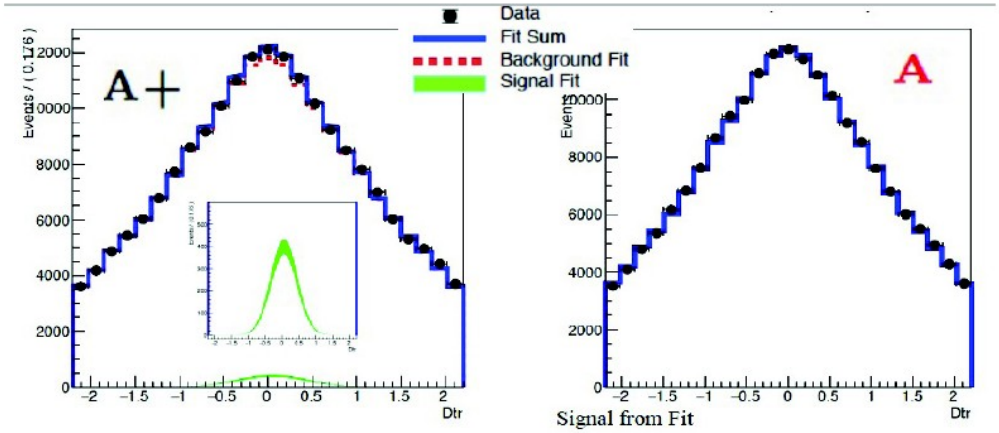




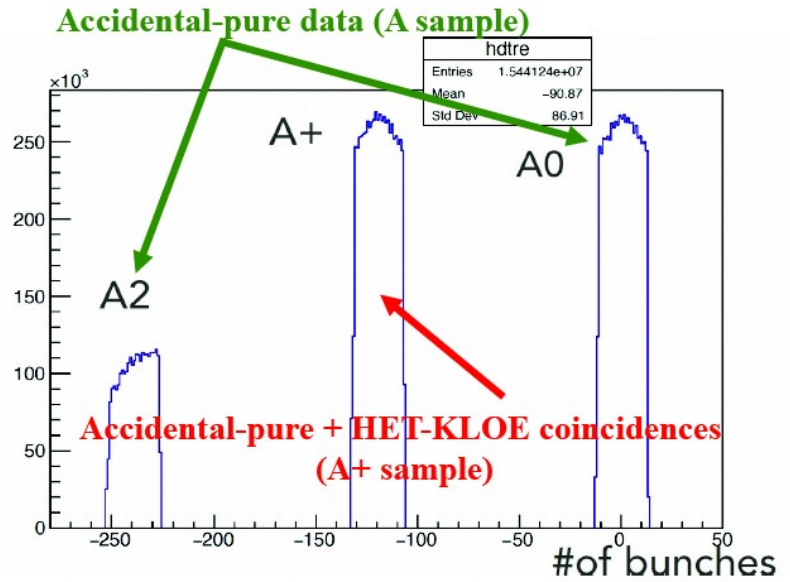
$\gamma^*\gamma^* \rightarrow \pi^0$

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

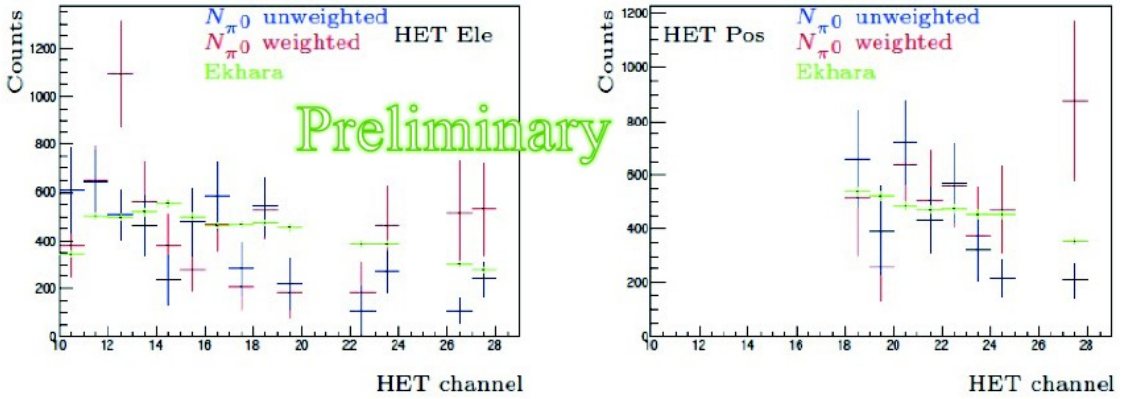


$\gamma^*\gamma^* \rightarrow \pi^0$

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

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

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



- ✓ **$N_{\pi 0}$ counting: final checks on weights ongoing**
- ✓ Normalize to Radiative Bhabha at very small angle
- ✓ $\sigma_{\mathrm{Bha}}^{\mathrm{meas}}$ 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
- ✓ $A_{bha}/A_{\pi 0}$: 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 succesfully completed on March 30, 2018
~ 20 years after the first events collected in KLOE

KLOE + KLOE-2 sample ⇒ ~ 8 fb^{-1} – unique sample worldwide
⇒ ~ 2.4 × 10^{10} ϕ'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...