Hadron physics results at KLOE-2

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The 13th International workshop on e+e- collisions from Phi to Psi

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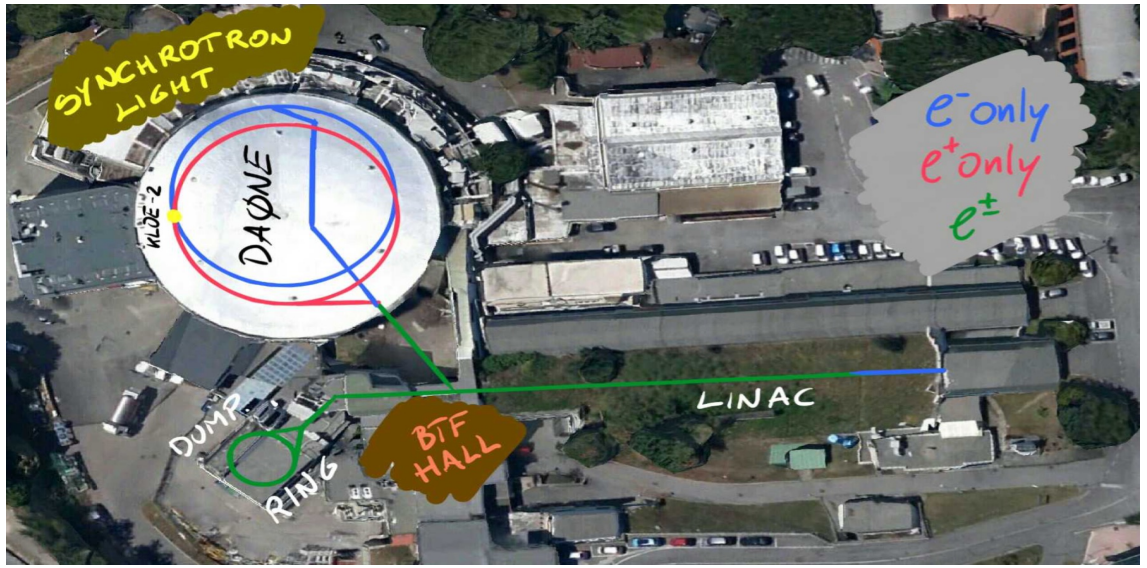
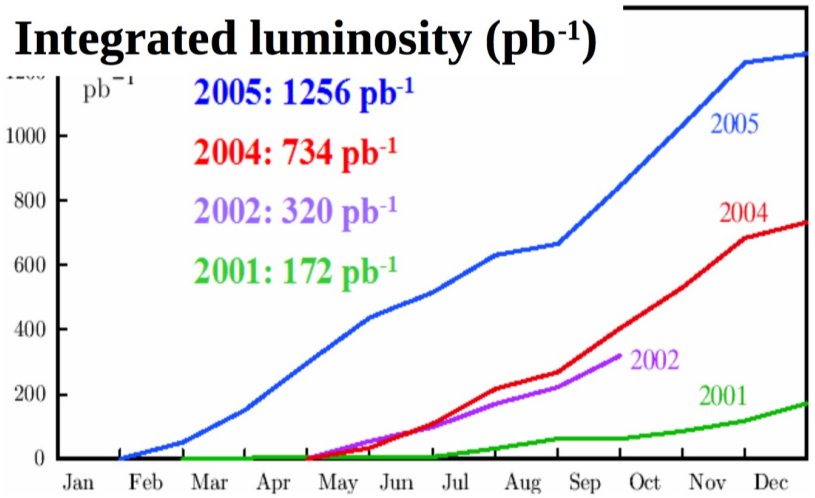
Outline

- KLOE and KLOE-2
- Recent research activities on hadron physics
  - ✓ Study of $\eta \to \gamma\gamma\pi^0$ decay
  - ✓ Leptophobic B boson in the $\phi \to \eta B \to \eta\pi^0\gamma$
  - ✓ Cross-section measurement of $e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$ in ω region
  - ✓ Search for $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$
  - ✓ Investigation of π^0 production via $e^+e^- \to \gamma^{(*)}\gamma^{(*)}e^+e^- \to \pi^0e^+e^-$
- Conclusions

KLOE @ DAΦNE

- DAΦNE: Double rings e^+e^- collider @ $\sqrt{s}=M_\phi=1019.4$ MeV; $\sigma_{peak}\approx 3.1$ μb
- Best performance in KLOE run: $\mathcal{L}_{peak}=1.5\times10^{32}cm^{-1}s^{-1}$
- 2001-2005 KLOE collected ~2.5 fb^{-1} @ φ peak and 250 pb^{-1} off-peak @ $\sqrt{s}=1000$ MeV





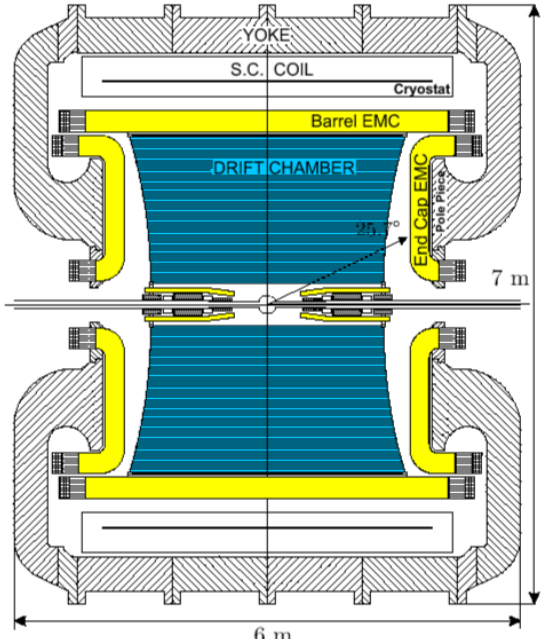
Drift Chamber:

- **90% He-10% isobutane**
- **$\delta p_T/p_T < 0.4\%$ ($\theta>45^0$)**
- **$\sigma_{xy}\approx 150$ mm, $\sigma_z\approx 2$ mm**
- **$\sigma_{vtx}\approx 3$ mm**

SC Magnet: B = 0.52 T

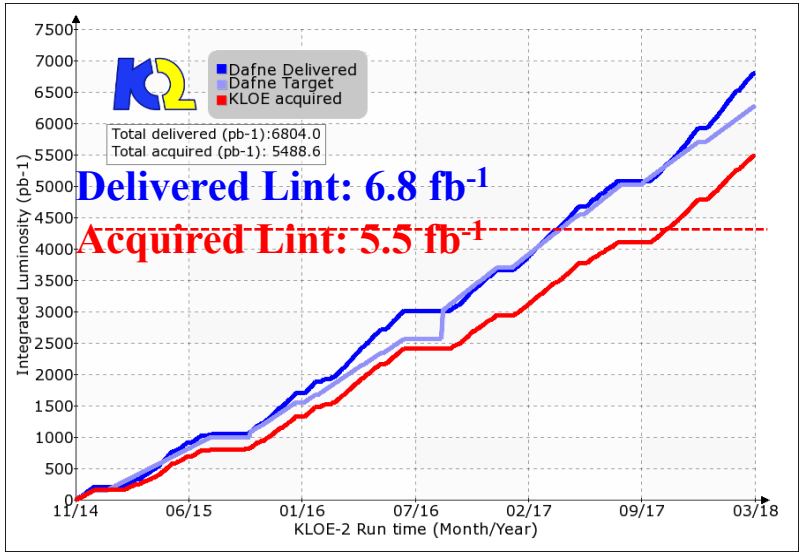
Calorimeter: 98% of 4π

- **$\sigma_E/E = 5.7\%/\sqrt{E(GeV)}$**
- **$\sigma_t = 54$ ps$/\sqrt{E(GeV)} \oplus 140$ ps**



KLOE-2 @ DAΦNE Updated

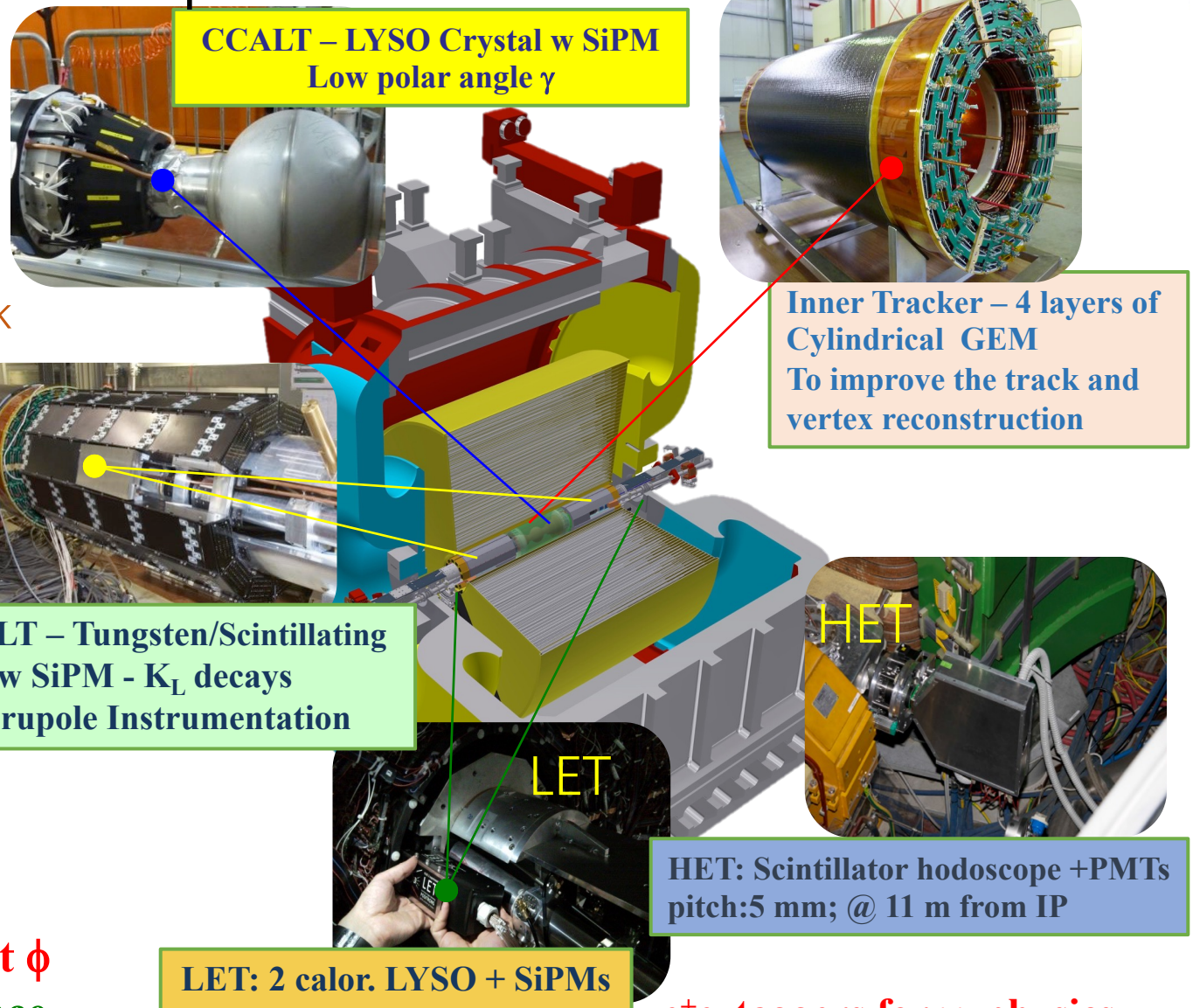
- Updated DAΦNE (2008), crabbed waist interaction scheme + large beam crossing
- Best performance: $\mathcal{L}_{peak}=2.4\times10^{32}cm^{-1}s^{-1}$
- 2014-2018 KLOE-2 collected ~5.5 fb^{-1} @ ϕ peak



KLOE+KLOE-2 data sample: ~ 8 fb^{-1}

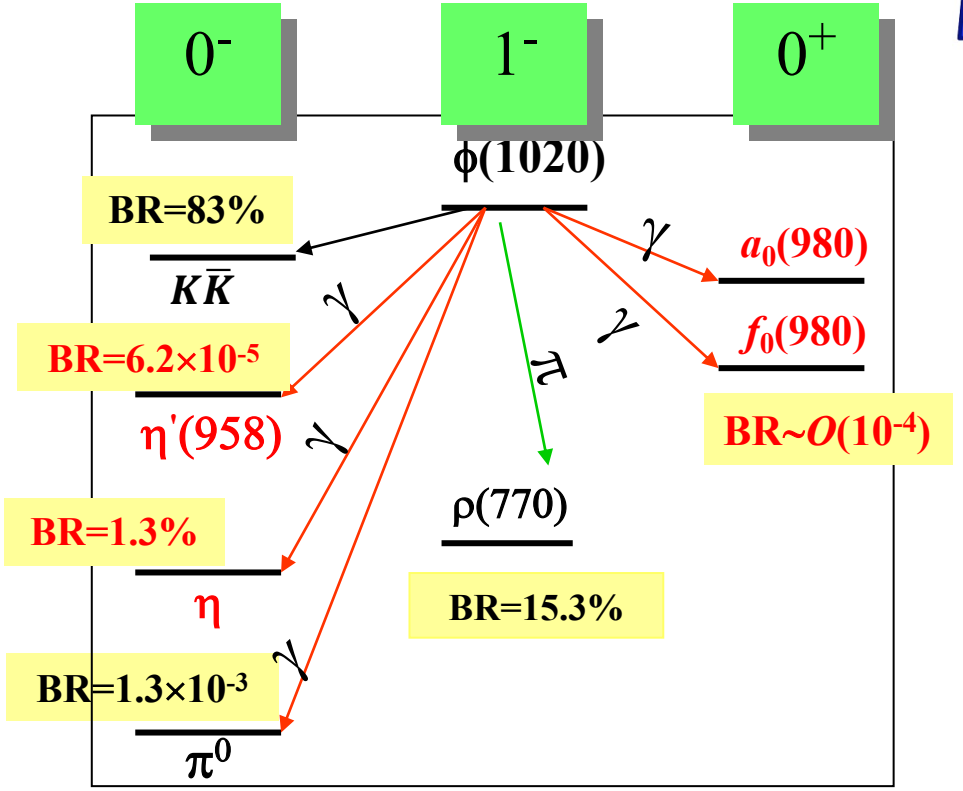
~2.4×10^10 ϕ mesons, the largest sample collected at ϕ

Unique sample for typology and statistical relevance



Physics @ KLOE-2

- **Kaon physics: 8.2×10^9 Ks and K_L events**
  - CKM unitarity test, CPT and QM tests with kaon interferometry, Direct tests of T and CPT using entanglement, Ks rare decays…
- **Light hadronic physics**
  - 3.1×10^8 η events
  - 1.5×10^8 η' events
- **γγ physics: $e^+e^-\to e^+e^-\gamma^*\gamma^*\to e^+e^-X$**
  - $X=\pi^0/\eta \Rightarrow \Gamma(\pi^0\to\gamma\gamma)$, space-like TFF

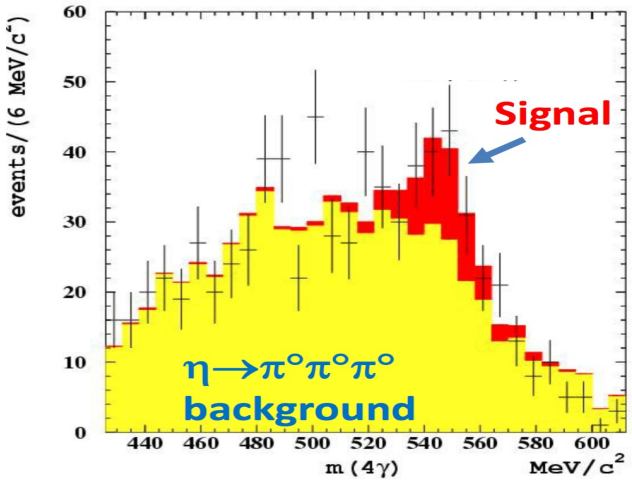


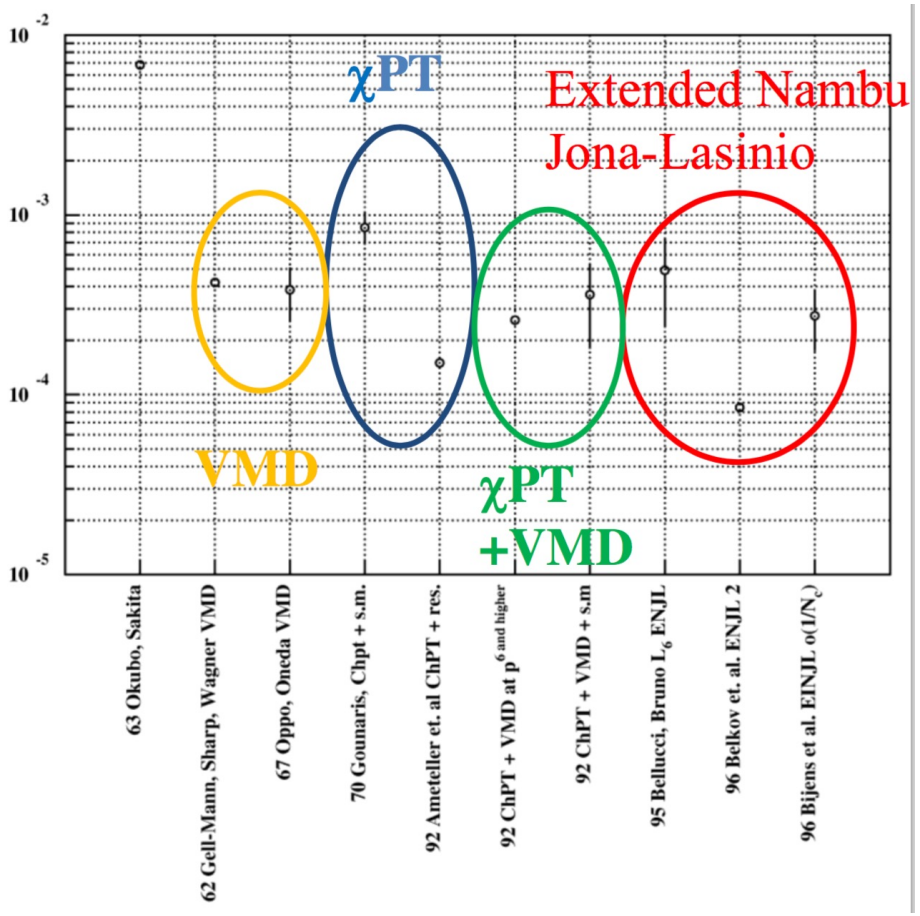
- **Hadronic cross section via ISR [$e^+e^-\to\gamma(2\pi, 3\pi, 4\pi)$]: hadronic corrections to $(g-2)_\mu$**
- **Dark force searches:**
  - $e^+e^- \to U\gamma \to \pi\pi\gamma$, $\mu\mu\gamma$
  - Leptophobic B boson search: $\phi\to\eta B$ ($B\to\pi^0\gamma$), $\eta\to B\gamma$ ($B\to\pi^0\gamma$)
  - Higgsstrahlung: $e^+e^-\to Uh'\to\mu^+\mu^-$ + miss. Energy

KLOE-2 Coll., EPJC68(2010)619, EPJ WoC 166 (2018)

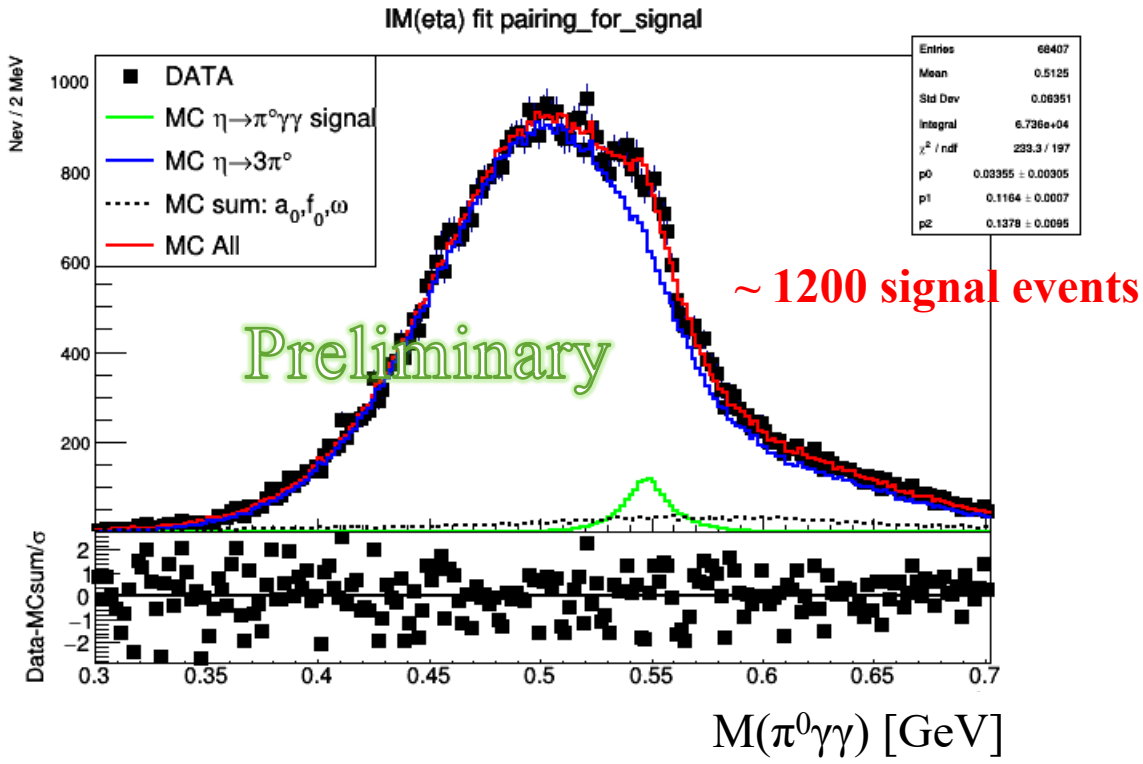
Doubly radiative decay $\eta \to \gamma\gamma\pi^0$

- ChPT "golden mode" : $O(p^2)$ null, $O(p^4)$ suppressed, $O(p^6)$ dominates [PLB 276(1) (1984) 185]
- Discrepancy between experimental and theoretical results
  - Br = $(2.21 \pm 0.24 \pm 0.47) \times 10^{-4}$ CB@AGS (2008)
  - Br = $(2.52 \pm 0.25) \times 10^{-4}$ CB@MAMI (2014)
  - Br = $(0.84 \pm 0.27 \pm 0.14) \times 10^{-4}$ from old KLOE preliminary result based on 450 pb^{-1} data (~70 signal events)





- L = 1.7 fb^{-1} data are analyzed and $\phi \rightarrow \eta\gamma$, $\eta \rightarrow \gamma\gamma\pi^0$ candidates are selected
- Main backgrounds: $\phi \rightarrow \eta\gamma$, $\eta \rightarrow 3\pi^0$ with lost or merged photons



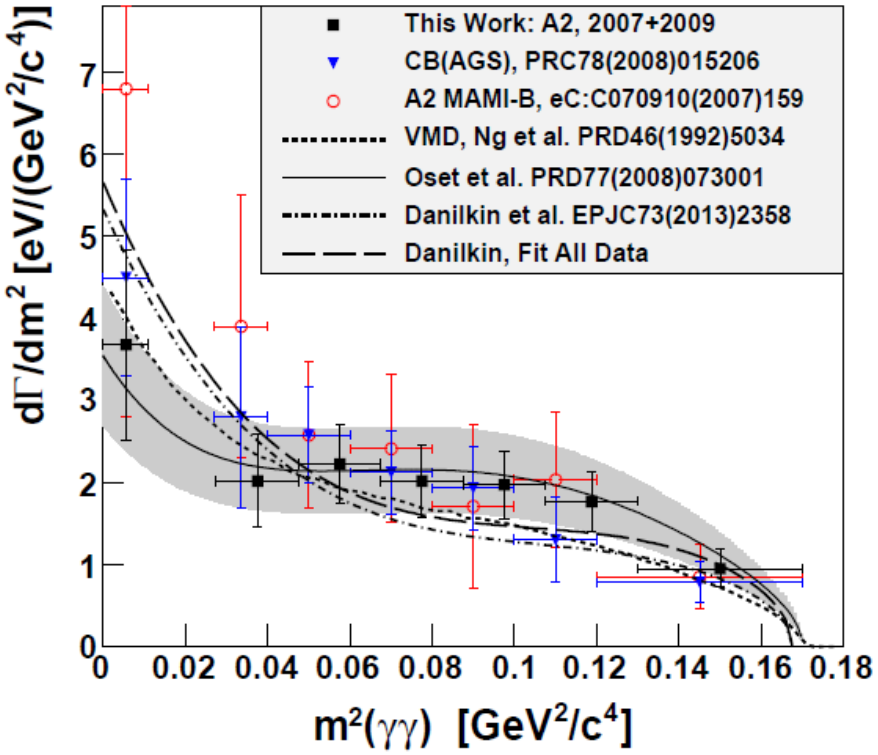
$Br(\eta \rightarrow \pi^0\gamma\gamma) = (1.21 \pm 0.13_{stat} \pm 0.25_{syst}) \times 10^{-4}$

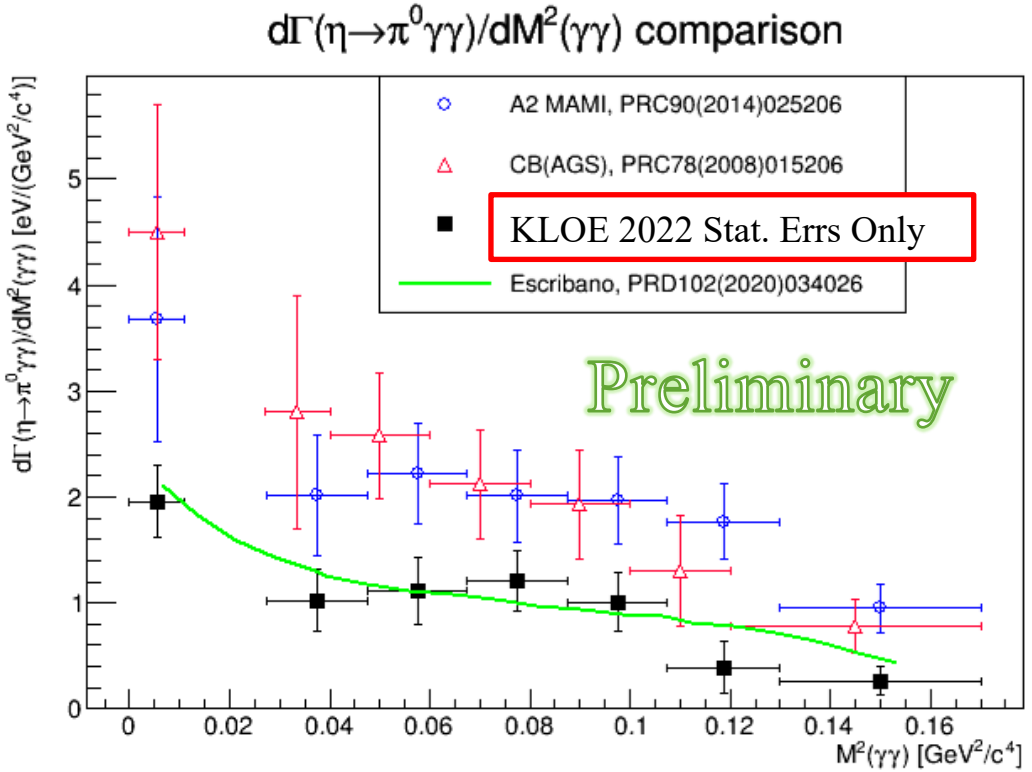
Last checks on systematics ongoing

Consistent well with the recent theoretical prediction based on LσM + VMD:[R.Escribano et al., PRD 102 (2020) 034026]

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

- Invariant mass of non-π^0 photons can be used to test theoretical models
- Separate fits to $M(\pi^0\gamma\gamma)$ in bins of $M^2(\gamma\gamma)$
- Second bin missing due to the veto of $\pi^0\pi^0$ events ($\phi \to f_0(980)\gamma \to \pi^0\pi^0\gamma$ and $e^+e^- \to \omega\pi^0 \to \pi^0\pi^0\gamma$)



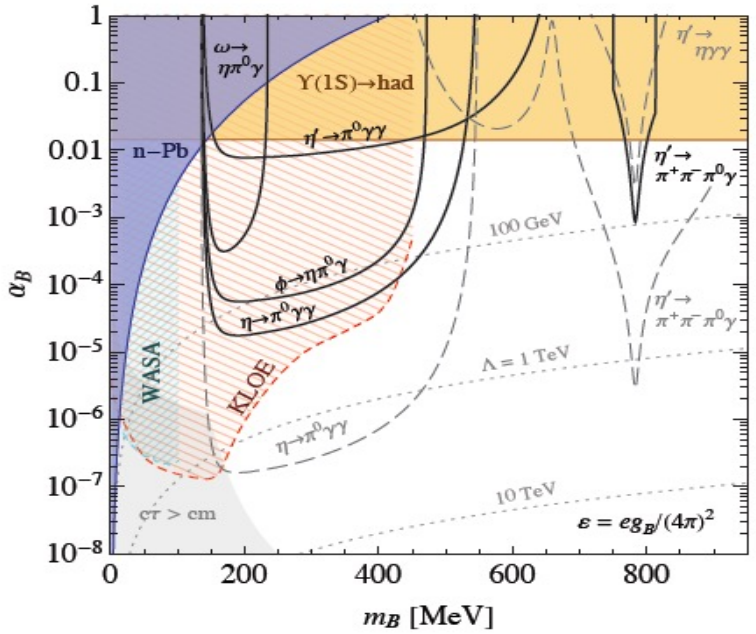


A factor of about 2 less than previous measurements

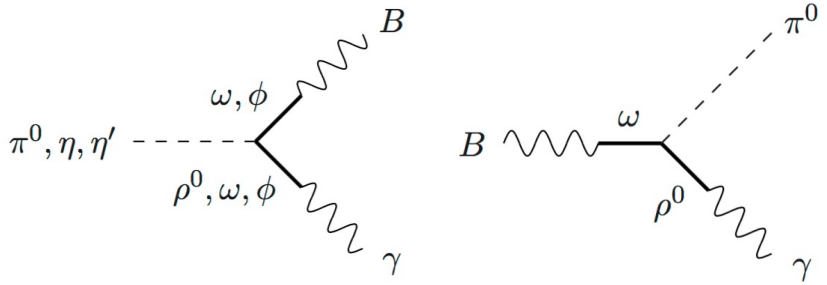
Search for Leptophobic B-boson

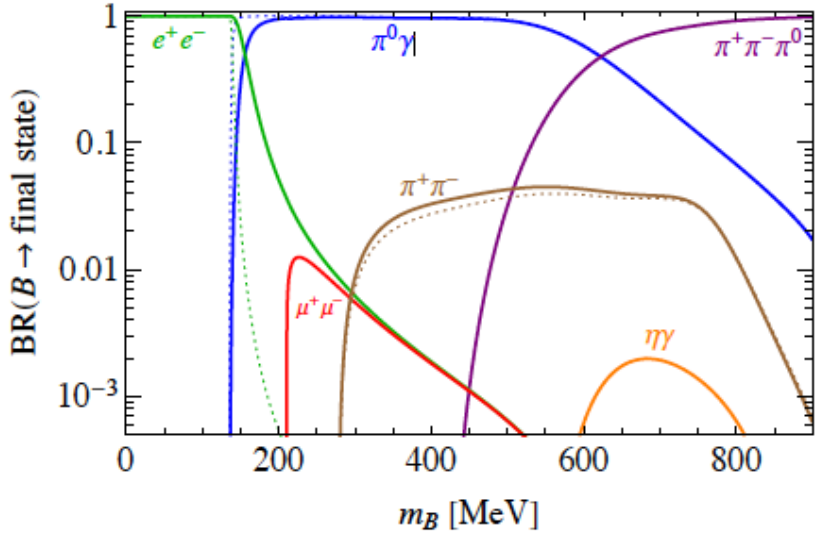
- Dark Force mediator coupled to baryon number (B-boson) with the same quantum numbers of the ω(782) ⇒ $I^G=0^-$ [S. Tulin, PRD 89 (2014) 14008]
- Couples mostly to quarks and have impact on $(g-2)_\mu$ anomaly

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

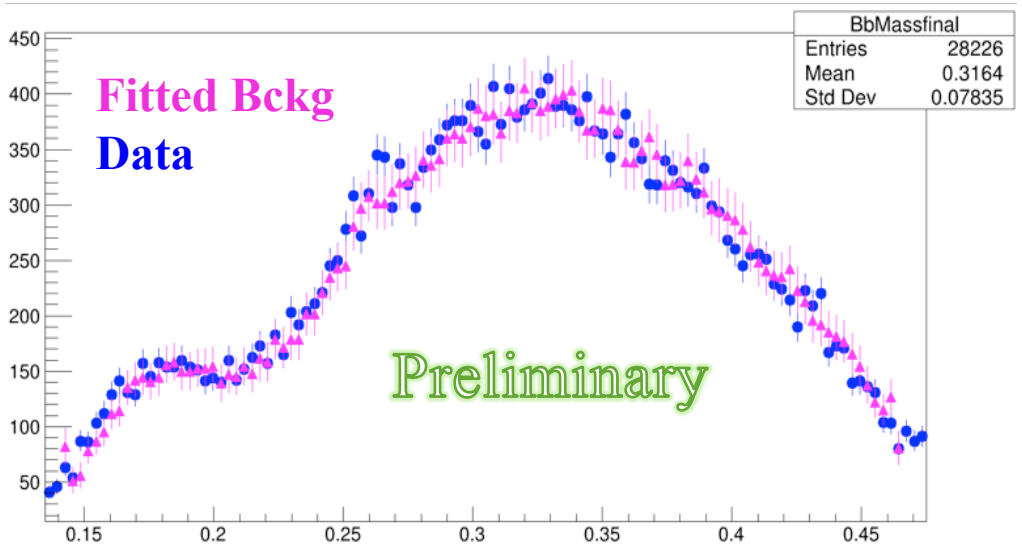


- Dominant decay channel (m_B < 600 MeV): $B \to \pi^0\gamma$
- Can be searched for in:
  - $\phi \to \eta B \to \eta\pi^0\gamma$
  - $\phi \to \eta\gamma$ with $\eta \to B\gamma \to \pi^0\gamma\gamma$
  - $e^+e^- \to B\gamma_{ISR} \to \pi^0\gamma\gamma_{ISR}$

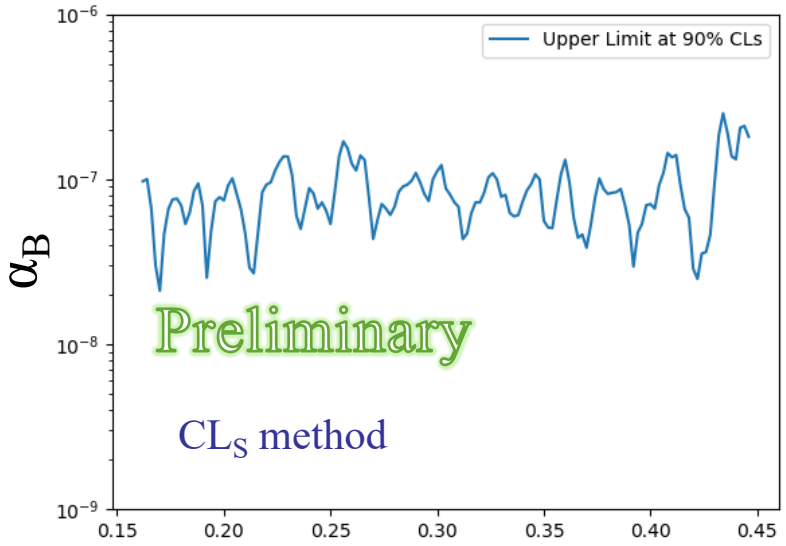




- L = 1.7 fb^{-1} data analyzed and selection of $\phi \rightarrow \eta B \rightarrow \eta\pi^0\gamma$ candidates with $\eta/\pi^0 \rightarrow \gamma\gamma$
- No obvious peaks are observed
- Main background from $\phi \rightarrow a_0(980)\gamma \rightarrow \eta\pi^0\gamma$ and $\phi \rightarrow \eta\gamma \rightarrow 3\pi^0\gamma$ with lost/merged photons
- Background evaluation from sidebands (fit region 5σ with 1σ exclusion region, σ ~ 2 MeV)
- Upper limit on the coupling constant α are set around O(10^{-7}) at 90% CLs

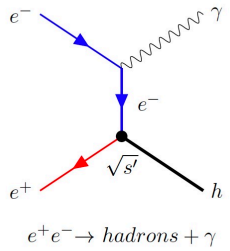


$M(\pi^0\gamma)$ [GeV]

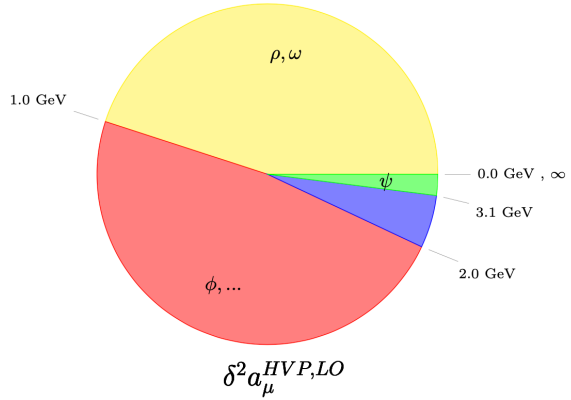


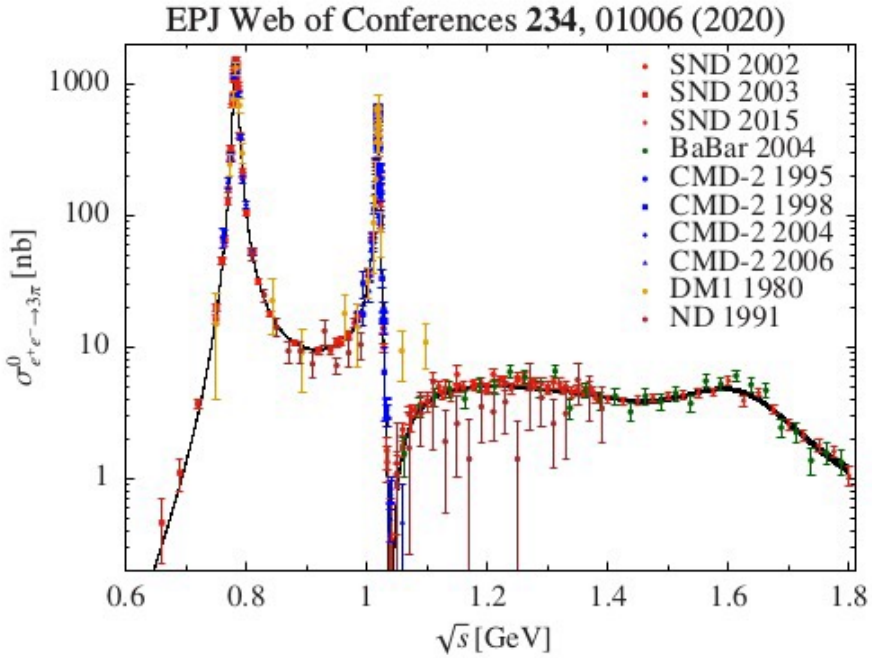
M_B [GeV]

ISR process $e^+e^- \to \pi^+\pi^-\pi^0\gamma$

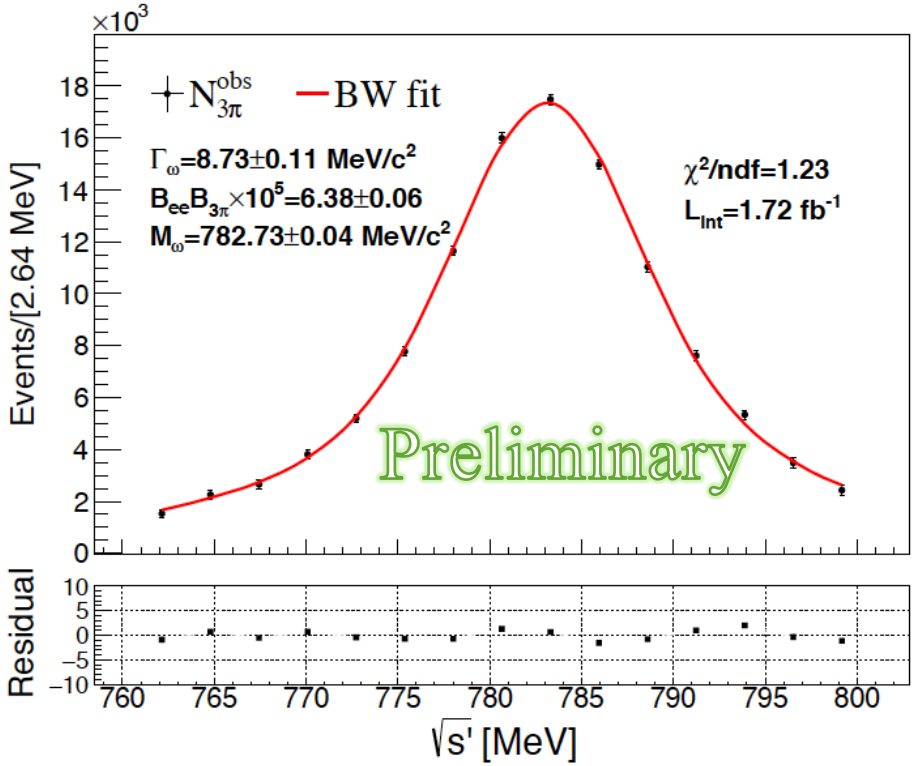


- $e^+e^- \to 3\pi$ is the second largest contribution on a_μ^{HVP} at the leading order, both in absolute values and uncertainties
- Current cross section measurement of $e^+e^- \to 3\pi$ comes from CMD-2/SND measurement with energy scan and by Babar/BES? with ISR technique
- ISR measurement at KLOE/KLOE-2 is complementary to energy scan in the range $\sqrt{s} < M\varphi$ (SND and CMD-2)



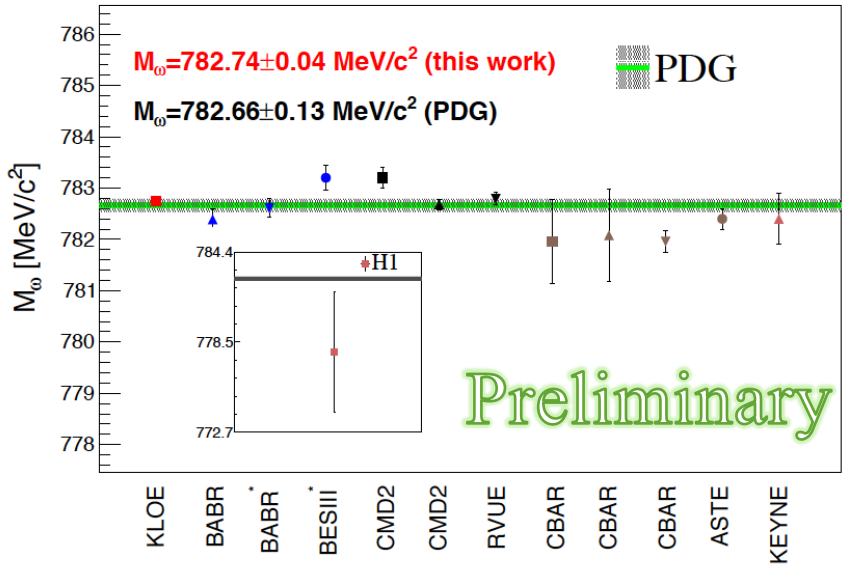


- Analysis on ~1.7 fb-1 on-peak and ~246 pb-1 off-peak data samples
- To select $\pi^+\pi^-\pi^0\gamma$ candidates, 2 tracks with opposite curvature + 3 neutral clusters are required
- After considering the radiation correction, a simple BW is used to fit the background-free $M(\pi^+\pi^-\pi^0)$ distribution

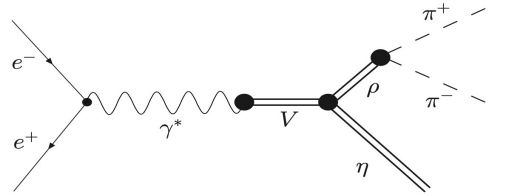


KLOE results (Only stat. uncertainty) compared with PDG

	M_ω [MeV/c²]	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

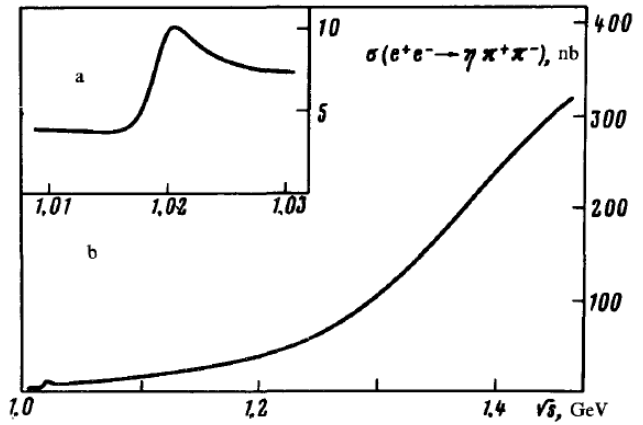


Study of $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$



ρ(770)
ρ(1450)
...

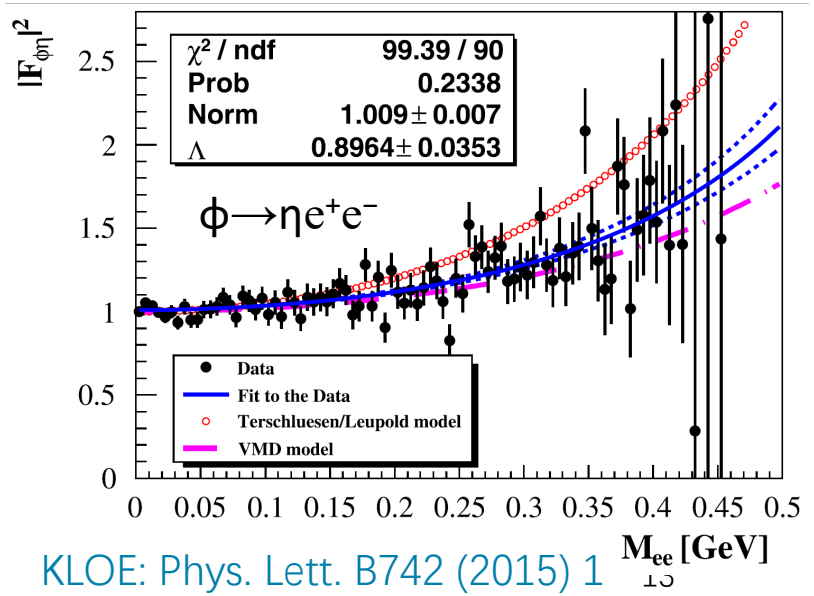
- In VMD model, $e^+e^- \to \eta\pi^+\pi^-$ proceeds via ρ resonances, mainly via ρη intermediate state, KLOE/KLOE-2 allow to measure the line shape around ϕ



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

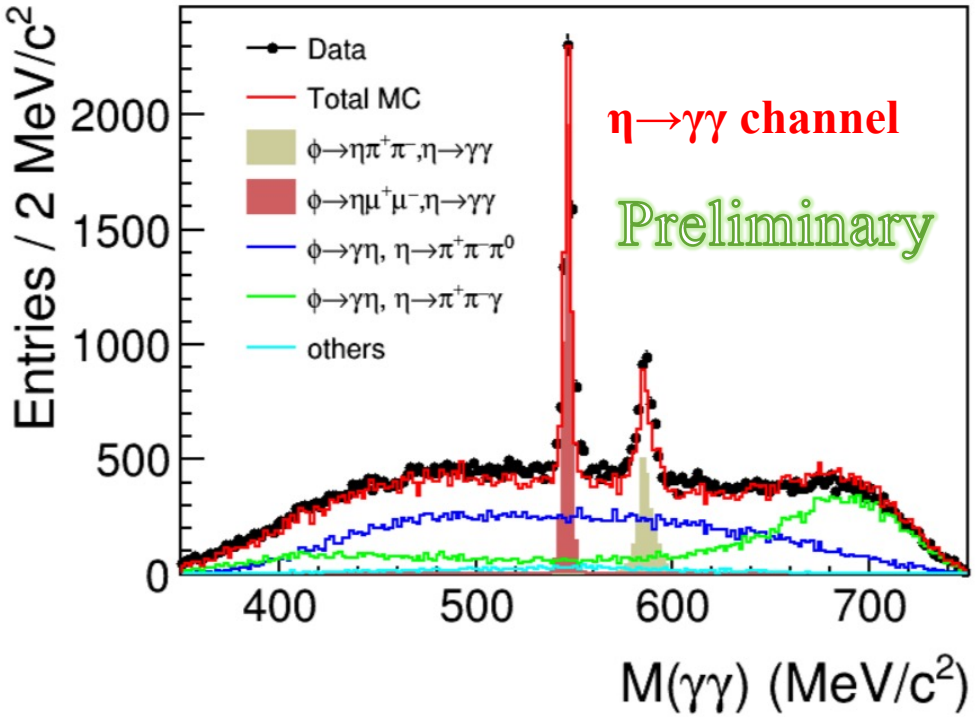
- The same data sample can be used to search for $\phi \to \eta\mu^+\mu^-$
  - ✓ Br($\phi \to \eta\mu^+\mu^-$)<9.4×10^{-6} @90% C.L. [CMD-2, PLB501(2001)191]
  - ✓ Investigate the transition form factor

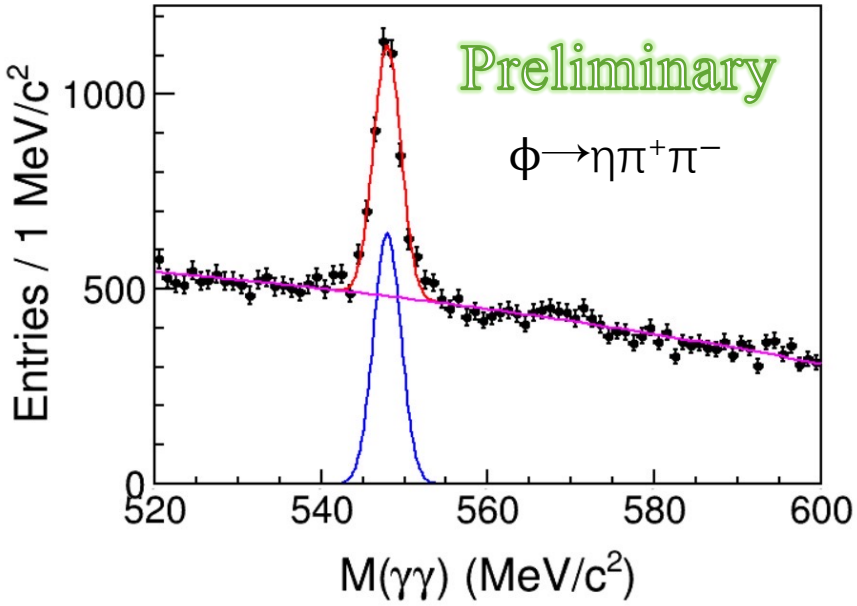
$$\frac{1}{\Gamma(\phi \to \gamma\eta)}\frac{d\Gamma(\phi \to \eta\mu^+\mu^-)}{dq^2} = |F_{\phi\eta}(q^2)|^2 \times \frac{\alpha}{3\pi}\frac{1}{q^2}\sqrt{1-\frac{4M_\mu^2}{q^2}}\left(1+\frac{2M_\mu^2}{q^2}\right)\times\left[\left(1+\frac{q^2}{M_\phi^2-M_\eta^2}\right)^2-\frac{4M_\phi^2 q^2}{(M_\phi^2-M_\eta^2)^2}\right]^{3/2}$$

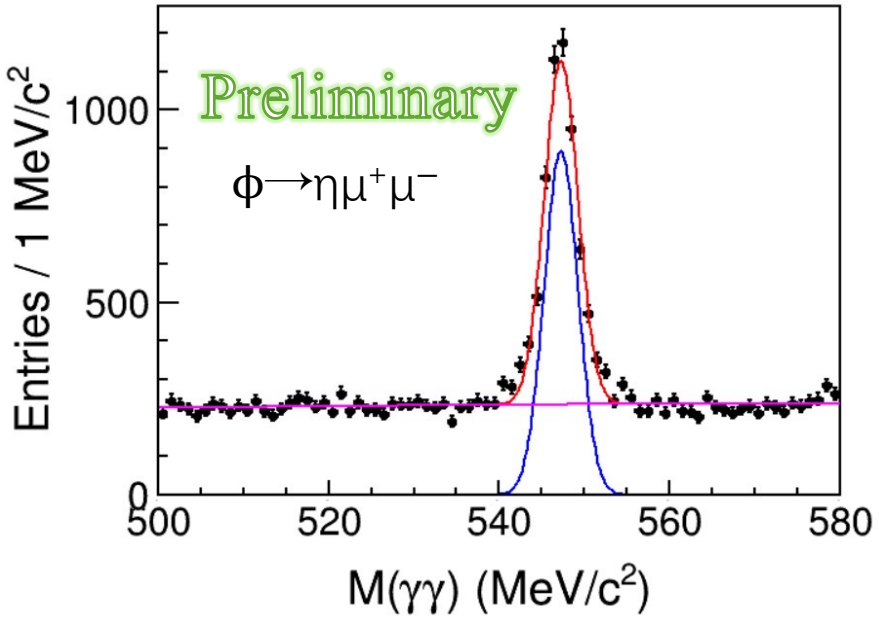


KLOE: Phys. Lett. B742 (2015) 1

- 1.7 fb^{-1} data analyzed
- Clear $\phi \to \eta\pi^+\pi^-$ and $\eta\mu^+\mu^-$ signals are observed
- The analysis is on going







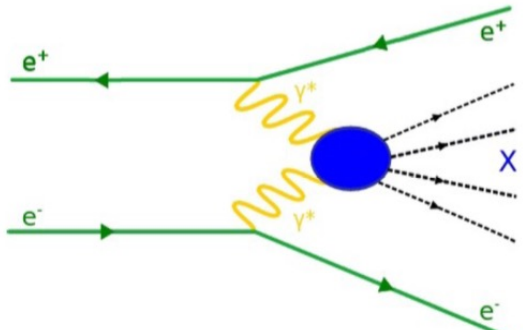
$\gamma^*\gamma^* \rightarrow \pi^0$ analysis

$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$$

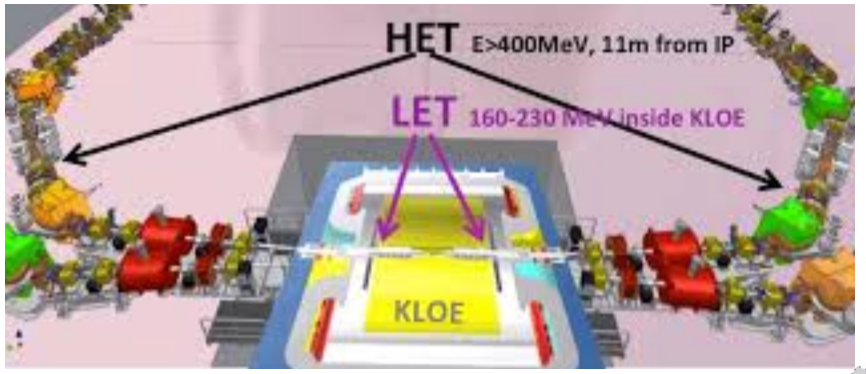
Reach HET

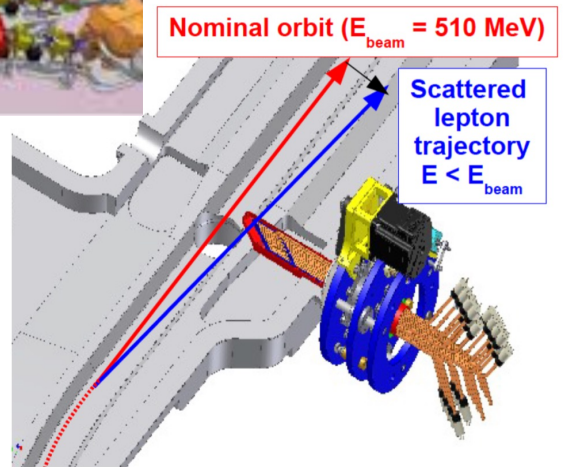
In KLOE detector

for quasi-real photons $J^{PC}(X) = \{0^{\pm,+}, 2^{\pm,+}\}$
$\rightarrow X = \{\pi^0, \pi\pi, \eta\}$



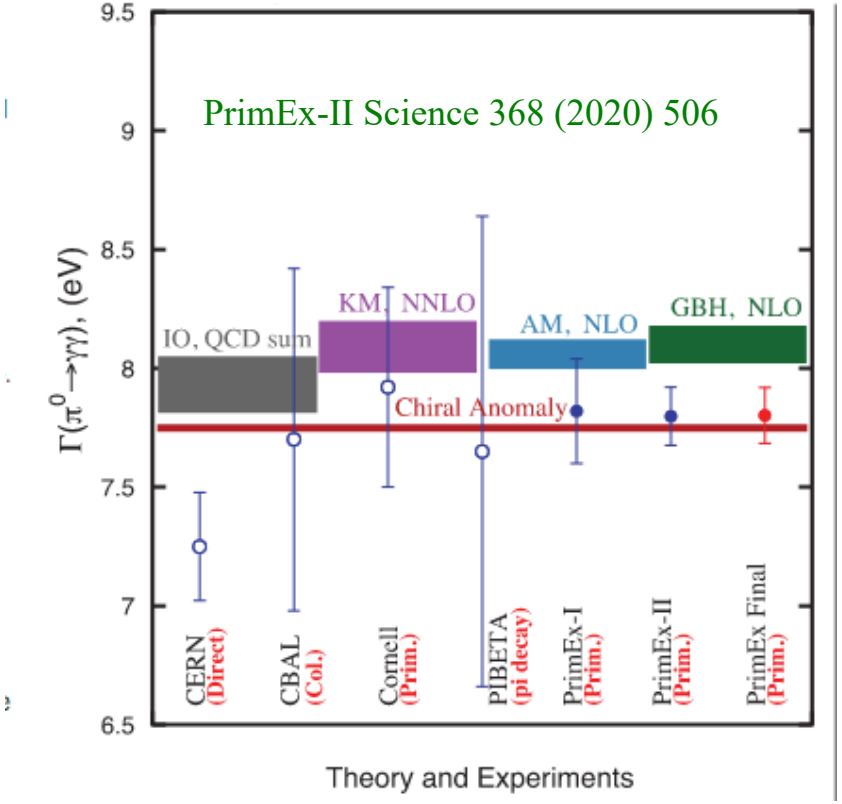
- High energy tagger (HET) located 11 m away the IP after the bending dipoles acting like spectrometer for scattered e^+/e^- (420<E<495 MeV)
- Asynchronous DAQ systems for HET and KLOE

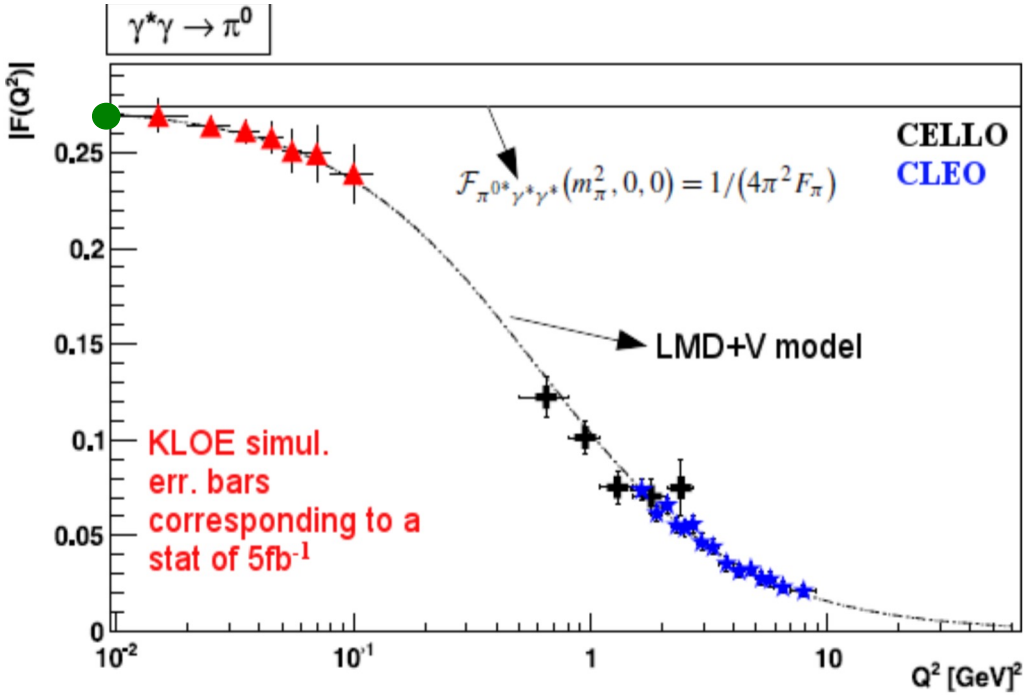




Physic goal:

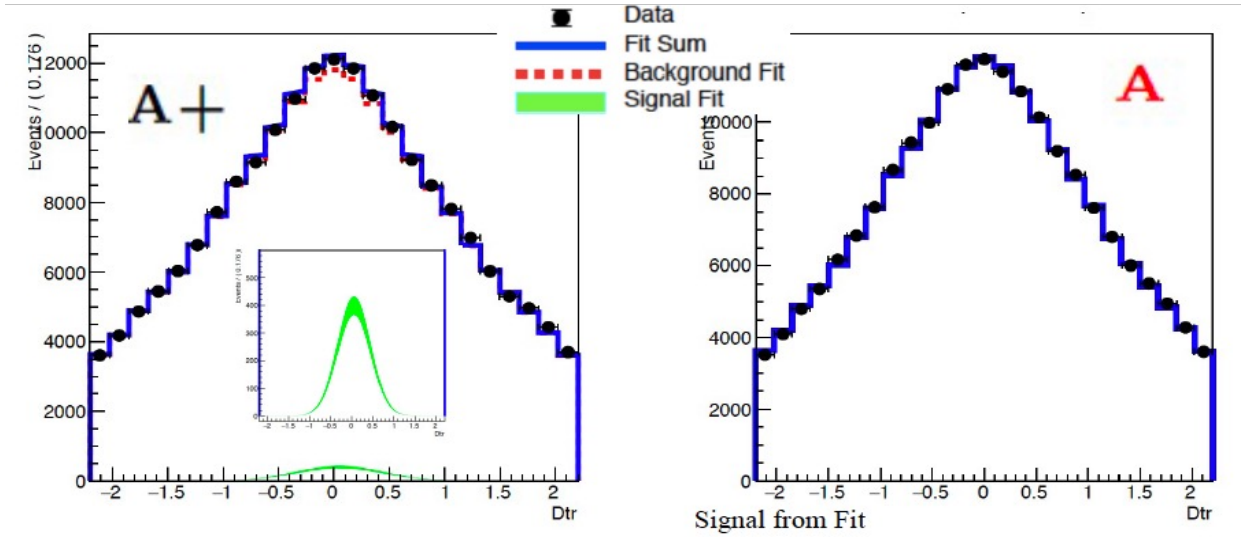
- $\Gamma_{\pi 0 \to \gamma\gamma}$ at few % level (green point)
- First measurement of the $F_{\pi 0 \gamma^* \gamma}(q^2)$ at $q_{\gamma^*}{}^2 \leqslant 0.1$ GeV^2 (red points) ⇒ crucial for HLBL $(g-2)_\mu$



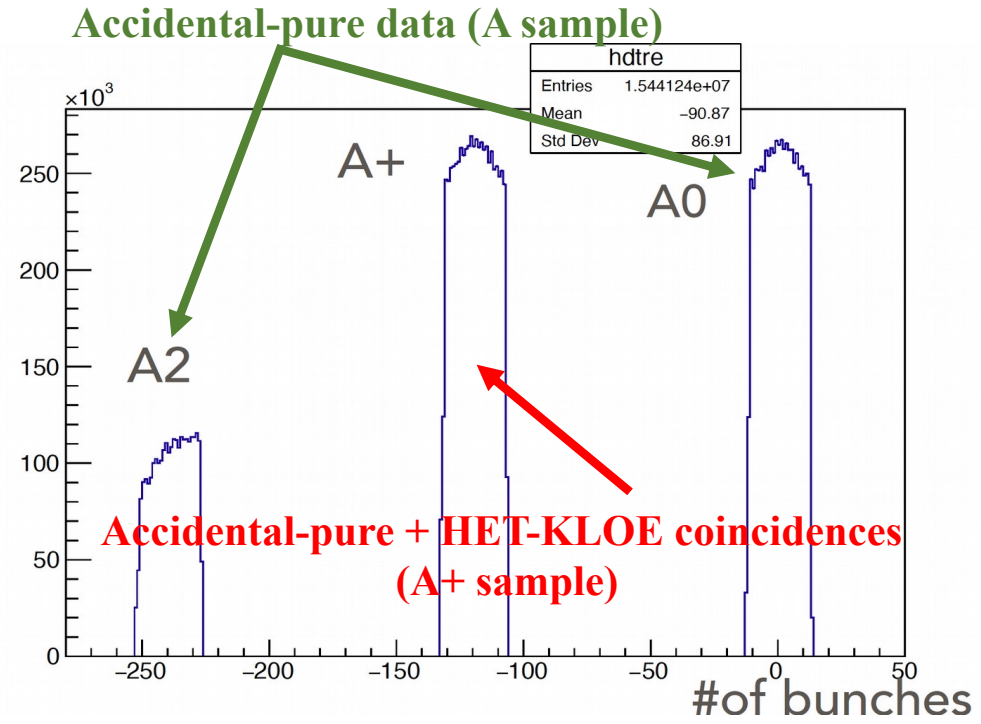


Analysis strategy

- ✓ 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



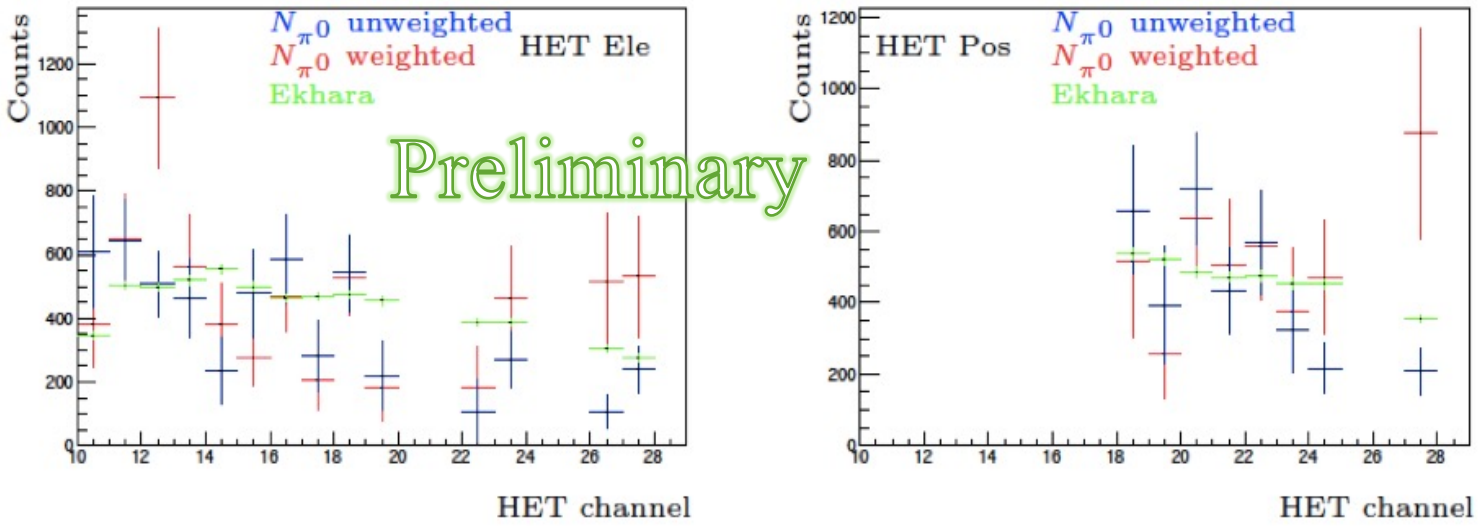
Example of fit on one HET readout channel



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

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

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



- ✓ **$N_{\pi 0}$ counting: final checks on weights ongoing**
- ✓ Normalize to Radiative Bhabha at very small angle
- ✓ $\sigma^{\rm meas}_{\rm Bha}$ is measured at few % level
- ✓ Luminosity measurement from KLOE online and cross-checks with $e^+e^- \to \gamma\gamma$
- ✓ 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**

Conclusions

- KLOE + KLOE-2 sample ⇒ ~8 fb^{-1} – unique sample worldwide

  ⇒ ~ 2.4 × 10^{10} ϕ sample produced

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

- With KLOE+KLOE-2 data, more interesting results on light hadron physics and fundamental symmetries are foreseen with high precision

Thanks for your attention!!!