Two-photon physics at KLOE-2

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on behalf of the KLOE-2 $\mathcal{C}$ollaboration

The 16th International Workshop on Tau Lepton Physics

Outline

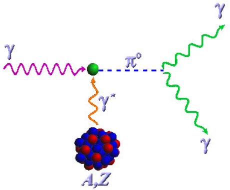
The $\pi^\circ \to \gamma\gamma$ width

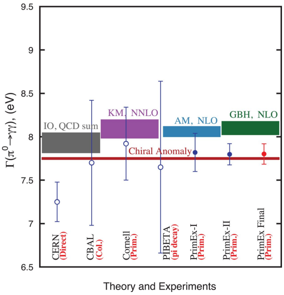
- The QCD Green's function $\langle VVA \rangle$ exhibits the axial anomaly of Adler, Bell and Jackiw (non-conservation of the axial vector current), which is responsible for the decay $\pi^0 \to \gamma\gamma$.
- The anomaly is a pure one-loop effect (triangle diagram).
- Link between the strong dynamics at low energies (pions) with the perturbative description in terms of quarks and gluons at high energies.
- The ChPT@NNLO prediction for the decay width $\Gamma_{\pi^0\to\gamma\gamma}$ is know with a 1.4% accuracy:

$$\Gamma^{\rm theor}_{\pi^0\to\gamma\gamma} = 8.09 \pm 0.11 \text{ eV}.$$

Experimental data available

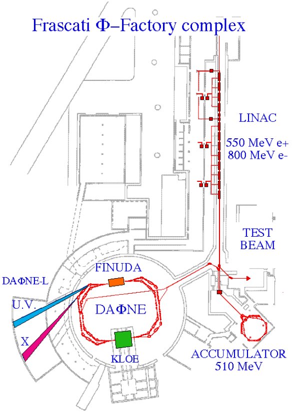
The more precise experimental information on this decay comes from the photo-production of pions on a nuclear target via the Primakoff effect.





- PrimExII: $\Gamma_{\pi^0 \to \gamma\gamma} = 7.802 \pm 0.052(\text{stat.}) \pm 0.105(\text{syst.})$ eV: 1.50 % from *Science* **368** (2020) 506:
- Data from $\gamma\gamma$: $\Gamma_{\pi^0 \to \gamma\gamma} = 7.7 \pm 0.5(\text{stat.}) \pm 0.5(\text{syst.})$ eV: 9.18 %, from *Phys. Rev. D***38** (1988) 1365

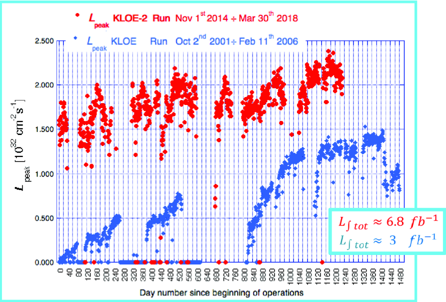
DAΦNE: the ϕ factory



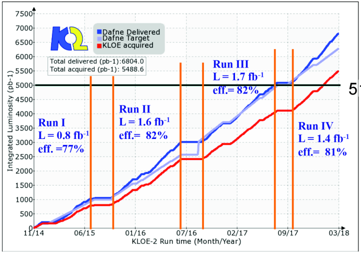
New interaction region:

- Large beam crossing angle: 2×12.5 mrad.
- Sextupoles for crabbed waist optics: 59% increase in terms of peak luminosity.

- e^+e^- collider @ $\sqrt{s} = M_\Phi$ =1019.4 MeV
- 2 interaction regions and 2 separate rings
- 105 + 105 bunches, $T_{RF} = 2.7$ ns
- Best Performance (1999–2006): $\mathcal{L}_{\rm peak} = 1.5 \times 10^{32}$ cm^{-2} s^{-1}
- Best Performance (2014–2018): $\mathcal{L}_{\rm peak} = 2.4 \times 10^{32}$ cm^{-2} s^{-1}



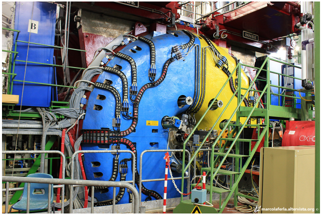
KLOE-2



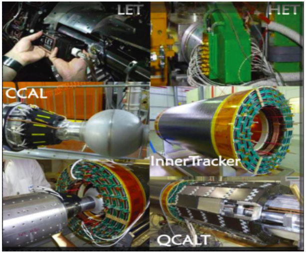
KLOE-2 experiment ended on March 30$^{\text{th}}$ 2018:

- $\mathcal{L}_{\text{delivered}} = 6.8\ \text{fb}^{-1}$
- $\mathcal{L}_{\text{acquired}} = 5.5\ \text{fb}^{-1}$
- KLOE + KLOE-2 data sample: $\mathcal{L}_{int} = 8\ \text{fb}^{-1}$ corresponding to 2.4×10^{10} ϕ mesons produced, the largest sample ever collected at the $\phi(1020)$ peak in collider experiments

The KLOE detector has been rolled out from the IR after almost 20 years of operation

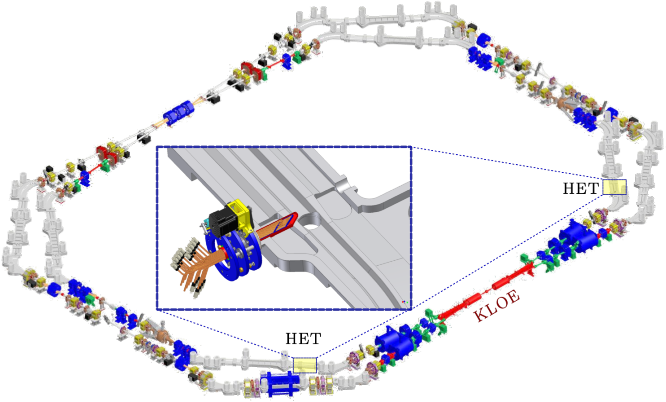


The KLOE-2 sub-detectors

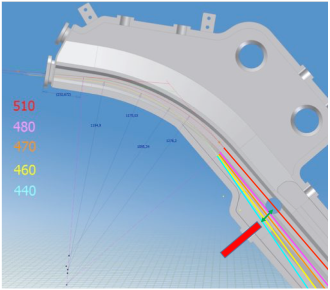


HET Detector Idea

- $e^+_{in} e^-_{in} \to e^+_{fin} e^-_{fin} \gamma\gamma \to e^+_{fin} e^-_{fin} X$;
- $e^+_{fin} e^-_{fin}$ detected by HETs;
- $X = (\pi^\circ, \cdots)$ detected by KLOE.



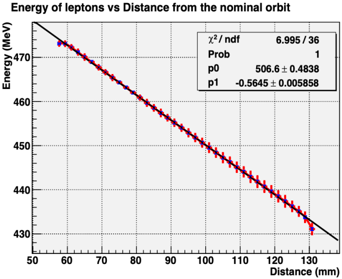
Tracking of the final leptons



Simulation is based on a GEANT4 toolkit: `BDSIM` (*Comput. Phys. Commun.* **252** (2020) 107200)

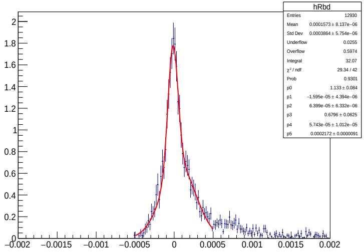
- HET tagged energy covers:
  - 430 up 480 MeV for scattered leptons;
  - 60 MeV up 160 MeV for two photons, which overlap with the π° at rest.
- The energy resolution is of the order of 0.5 MeV/mm.

- The HET detector cover very forward angle $\vartheta \leq 20$ mrad since is located at 11 m from IP.
- Time resolution should be less than 2.7 ns (DAFΦNE interbunch separation) in order to distinguish two consecutive bunch-cross.
- 28 plastic scintillators of 5 mm pitch is the optimal solution.



Simulation of $\gamma\gamma \to \pi^\circ$ with $\mathcal{L}_{int} = 5\ \text{fb}^{-1}$

- Our Simulation is based on Ekhara V2.1 and BDSIM: *Comput. Phys. Commun.* **182** (2011) 1338
- Physics goals:
  1. $\Gamma_{\pi^0 \to \gamma\gamma}$ at few % level.
  2. First measurement of the $\mathcal{F}_{\pi^0 \to \gamma^*\gamma}(Q^2)$ at $Q^2 < 0.1\ \text{GeV}^2$.
- $\Longrightarrow$ **Have impact on $a_\mu^{\mathrm{HLbL};\pi^0}$ (red numbers).**

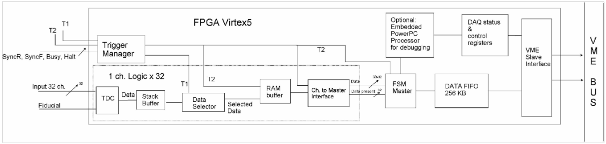


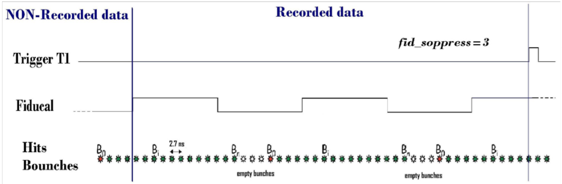
Q^2 [GeV^2] resolution after kinematical fit

Model	Data	$\chi^2/d.o.f.$	$a_\mu^{\mathrm{LbyL};\pi} \times 10^{11}$
VMD	A0	6.6/19	$(57.2 \pm 4.0)_{JN}$
VMD	A1	6.6/19	$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$(57.3 \pm 1.1)_{JN}$
LMD+V, $h_1 = 0$	A0	6.5/19	$(72.3 \pm 3.5)_{JN}$ * $(79.8 \pm 4.2)_{MV}$
LMD+V, $h_1 = 0$	A1	6.6/19	$(73.0 \pm 1.7)_{JN}$ * $(80.5 \pm 2.0)_{MV}$
LMD+V, $h_1 = 0$	A2	7.5/27	$(72.5 \pm 0.8)_{JN}$ * $(80.0 \pm 0.8)_{MV}$
LMD+V, $h_1 \neq 0$	A0	6.5/18	$(72.4 \pm 3.8)_{JN}$ *
LMD+V, $h_1 \neq 0$	A1	6.5/18	$(72.9 \pm 2.1)_{JN}$ *
LMD+V, $h_1 \neq 0$	A2	7.5/26	$(72.4 \pm 1.5)_{JN}$ *
LMD+V, $h_1 \neq 0$	B0	18/35	$(71.9 \pm 3.4)_{JN}$ *
LMD+V, $h_1 \neq 0$	B1	18/35	$(72.4 \pm 1.6)_{JN}$ *
LMD+V, $h_1 \neq 0$	B2	19/43	$(71.8 \pm 0.7)_{JN}$ *

TDCV5: a TDC based on a Virtex5 FPGA

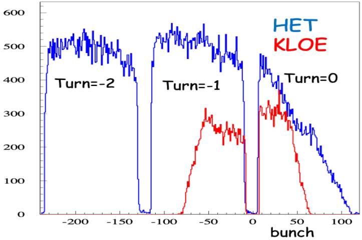
- Usually DAΦNE is filled with 105 bunches over 120: an hole is needed for stability reason.
- We use the Fiducial, a signal in phase with the first bunch circulating in DAΦNE, as TDCV5 common start.
- The TDCV5 time resolution is 625 ps.
- The TDCV5 could stores information corresponding to $N = 1, \cdots, 8$ turns of DAΦNE then is send to KLOE DAQ when KLOE provides the triggers (T_1 and T_2): we choose $N = 3$.
- The two DAQ systems (HET and KLOE) are asynchronous, we synchronize them acquiring the T_1 in a channel of the TDCV5. In the KLOE DAQ T_1 provide the TDC common start.





Data Analysis Strategy

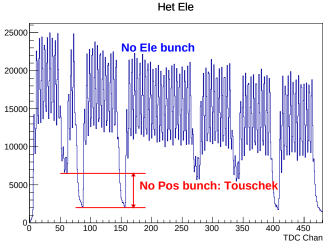
- $\mathcal{A}+$ events: the events in the KLOE and HET overlapping window.
- $\mathcal{A}$ events: the events outside the KLOE and HET overlapping window.

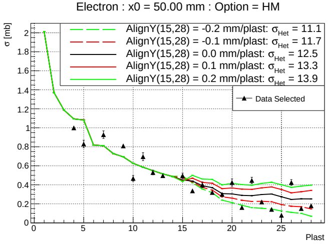


- The $\mathcal{A}$ events are **background** events: radiative Bhabha $\oplus$ Touschek.
- The $\mathcal{A}+$ events are **background** $\oplus$ $\gamma\gamma \to \pi^{\circ}$ events.
- $\mathcal{A}+ \ominus \mathcal{A}$ give us the $\gamma\gamma \to \pi^{\circ}$ events.
- $\mathcal{A}+$ and $\mathcal{A}$ events are evaluated at the same moment.

HET Counting Rate: $\mathcal{A}$ events

$$N_{\mathcal{A}} \propto \sigma^{HET}_{\mathrm{Bhabha}} \varepsilon_{\mathrm{HET}} \mathcal{L}_{\mathrm{Kloe}} + \alpha I^{\beta}{}_{\mathrm{DA\Phi NE}}$$



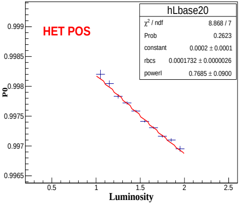


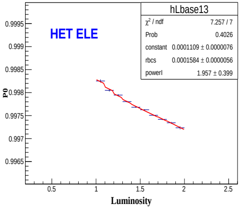
The $\sigma^{HET}_{Bhabha} = \sigma_{Bhabha} A^{HET}_{cc}$ is computed using the BBBREM code (*Comput. Phys. Commun.* **81** (1984) 372) and BDSIM.

Low-angle radiative $A_{cc}^{HET} \varepsilon_{HET} \sigma_{\rm Bhabha}$

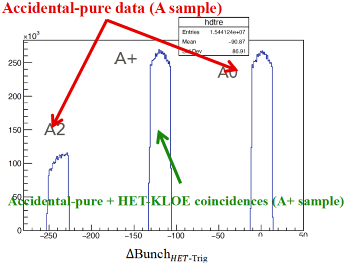
Reference period: Oct17-Dec17

- P_0: probability to have no signal in the HET
- $P_0 = (1 - P_b)^N$
- P_b is the probability per bunch-crossing to register at least one radiative Bhabha event with the HET: linearly increasing with luminosity ($\mathcal{L}$ $[10^{32}\,{\rm cm}^{-2}{\rm s}^{-1}]$)
- N: number of bunches considered in the measurement (N=22)
- Data analyzed per bin of circulating DAΦNE currents ($\rm I_{e,p}$ [A]) and per HET channel
- Measured probability $P = P_b \times (T_{bunch}/10\,{\rm ns})$
- $A_{cc}^{HET} \sigma_{\rm Bhabha}$ estimated by a fit to P_0 as a function of $\mathcal{L}$ measured by KLOE with large-angle Bhabha
- **Fit function: $(1 - \mathbf{P})^{\mathbf{N}}$ where:**
- $\mathbf{P} = \alpha \mathbf{I}_{\rm e,p}^{\beta} + \mathbf{A}_{\mathbf{cc}}^{\mathbf{HET}} \varepsilon_{\mathbf{HET}} \sigma_{\rm Bhabha} \mathcal{L}_{\mathbf{Kloe}}$





$\gamma\gamma \to \pi^0$ analysis



- **The reconstruction of 3 fb^{-1} of good-quality data has been completed: 2015-16-17-18 data-taking periods.**

Single-arm selection:

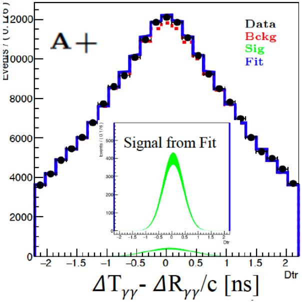
- Sample of 2 clusters associated with the same bunch-crossing in the KLOE barrel calorimeter.
- Selected bunch-crossing, and, independently selected HET signal, are in a time window of 40 ns around the KLOE trigger.

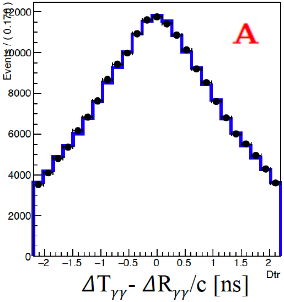
Analysis Strategy:

- The variables studied is: $M_{\gamma\gamma}$, $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$, $P_z^{\pi^\circ}$ vs plastic position correlation and $\cos(\theta_{\gamma\gamma})$.
- Simultaneous fits of $\mathcal{A}$ccidental+Signal and $\mathcal{A}$ccidental-pure events.
- Fit to $\mathcal{A}$ samples used to constrain the number of accidentals in $\mathcal{A}+$.
- $M_{\gamma\gamma}$ and $\cos(\theta_{\gamma\gamma})$ with a signal-enriching cut ($\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c < 0.3$ ns) separately fitted.

Signal Counting-Simultaneous Fits: $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$

Preliminary:

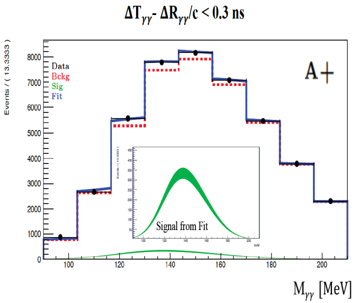


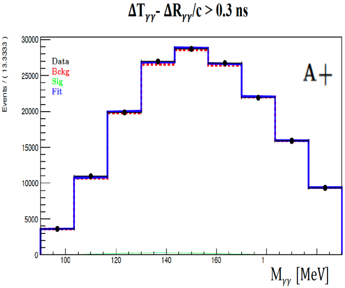


2017-18 data sample, $\mathcal{A}+$ and $\mathcal{A}$: $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$ fits
HET-KLOE coincidence window: 4×2.7 ns

Signal Counting-Simultaneous Fits: $M_{\gamma\gamma}$

Preliminary:





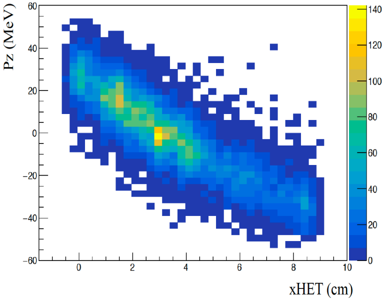
2017-18 data sample, $\mathcal{A}+$ and $\mathcal{A}$: $M_{\gamma\gamma}$ fits
HET-KLOE coincidence window : 4×2.7 ns

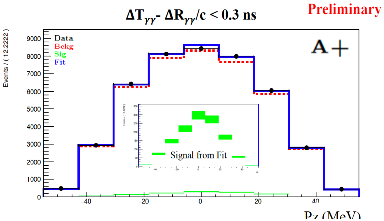
Signal Counting-Simultaneous Fits: $P_z^{\pi^\circ}$ vs xHET

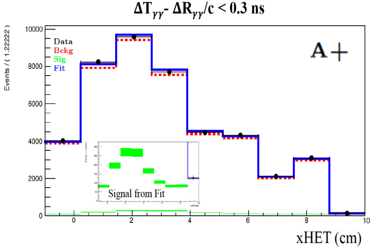
Simultaneous fit of bidimensional Pz-plastic positions (xHET) distribution

Acceptance per channel measured with low-angle radiative Bhabha in the HET

Expected Pz-xHET signal correlation



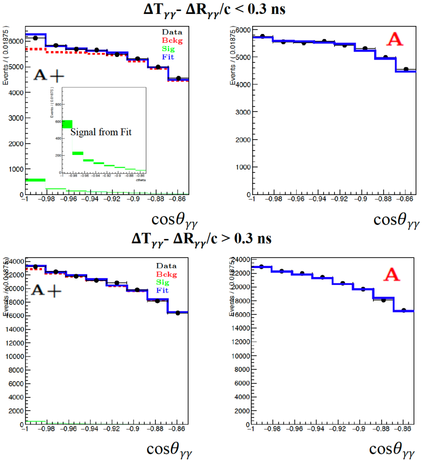




Signal Counting-Simultaneous Fits: $\cos(\theta_{\gamma\gamma})$

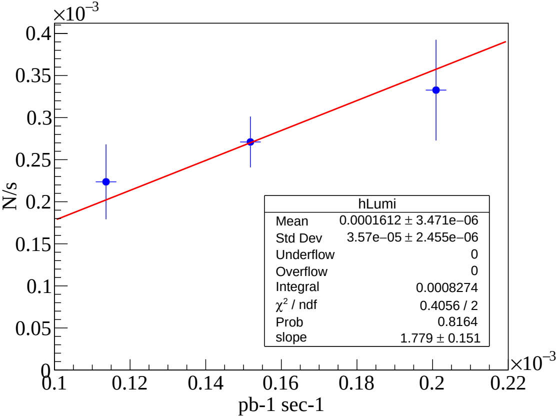
Preliminary Results:

- 8% precision on signal with about 1.5 fb^{-1} 2017-2018 data
- HET e^{-} station with most stable plastics (from 11 to 28)
- HET-KLOE coincidence window: 4×2.7 ns



π^0 events vs Instantaneous Luminosity

We analyzed the behavior with $\mathcal{L}$ of signal events extracted from the fits for a sub sample of 2017-18 data, the trend is the expected one



Conclusions

1. The HET detector has been designed to study $\gamma\gamma$ physics at KLOE-2;
2. Measurements of the low-angle radiative Bhabha cross section obtained for both HET stations for the whole reconstructed data set (2015-16-17-18);
3. Present status of the analysis:
   - $\Gamma_{\pi^0\to\gamma\gamma}$ analysis in advanced level: 8% precision is achieved with e^- HET data acquired between 2017 and 2018 (1.5 fb^{-1}) looking only at plastics from 11÷28;
   - $\mathcal{F}_{\pi^0\to\gamma^*\gamma}(Q^2)$ at $Q^2 < 0.1\ \mathrm{GeV}^2$ under study: kinematical fit permits to reach a resolution on Q^2 of the order of 65 MeV^2/c^2.