Review on $\gamma\gamma$ physics at KLOE

Dario Moricciani
INFN Roma "Tor Vergata"

On behalf KLOE-2 Collaboration

Outline

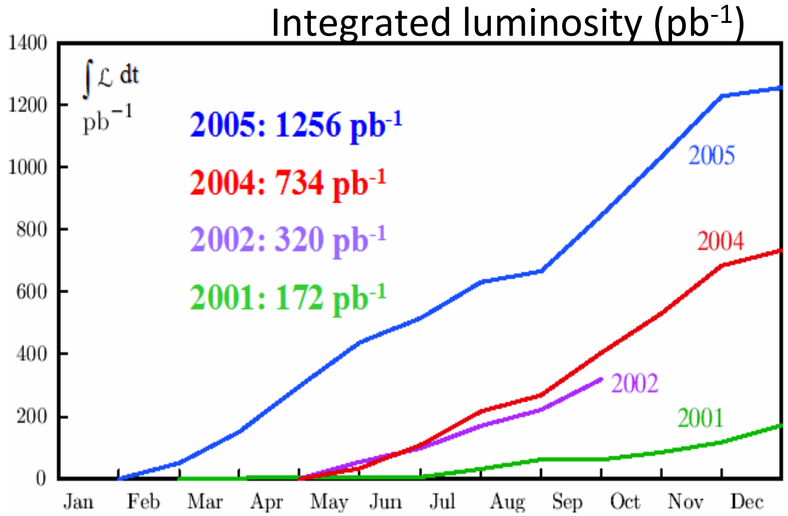
- KLOE-1 data f off peak
- KLOE-2 : new $\gamma\gamma$ tagger detectors LET and HET
- KLOE-2 : new dataset
- Conclusions

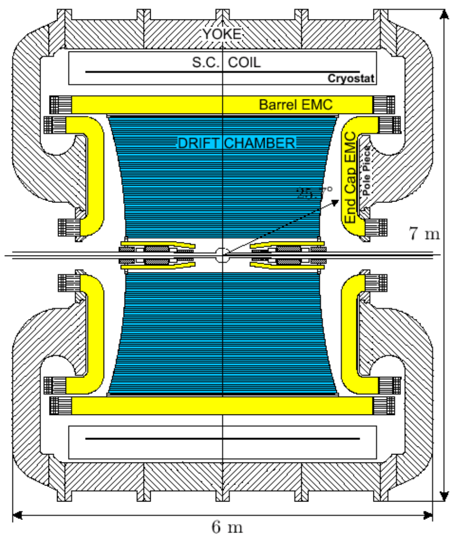
KLOE-1

- LNF ϕ-factory :
  e^+e^- collider @ $\sqrt{s} \approx 1020$ MeV $\approx M_\phi$;

- Best performances in 2005:
  - $L_{peak} = 1.4 \times 10^{32}\ cm^{-2}s^{-1}$
  - $\int L dt = 8.5\ pb^{-1}/day$

- KLOE: 2.5 fb^{-1} @ $\sqrt{s} = M_\phi$ and
  + 250 pb^{-1} off-peak @ $\sqrt{s} = 1$ GeV





Drift chamber:

- gas: 90% He-10% C_4H_{10}
- $\delta p_T/p_T = 0.4\%$
- $\sigma_{xy} \approx 150\ \mu m$; $\sigma_z \approx 2$ mm
- $\sigma_{vertex} \approx 1$ mm

Calorimeter (Pb-Sci.Fi.):

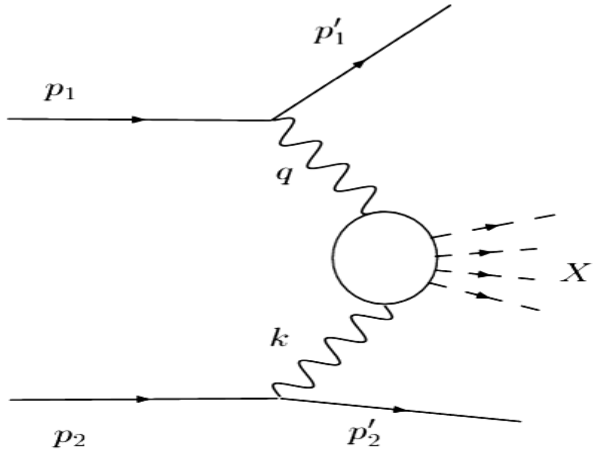
- $\sigma_E/E = 5.7\% / \sqrt{E(GeV)}$
- $\sigma_t = 55\ ps/\sqrt{E(GeV)} \oplus 100\ ps$
- 98% of 4π

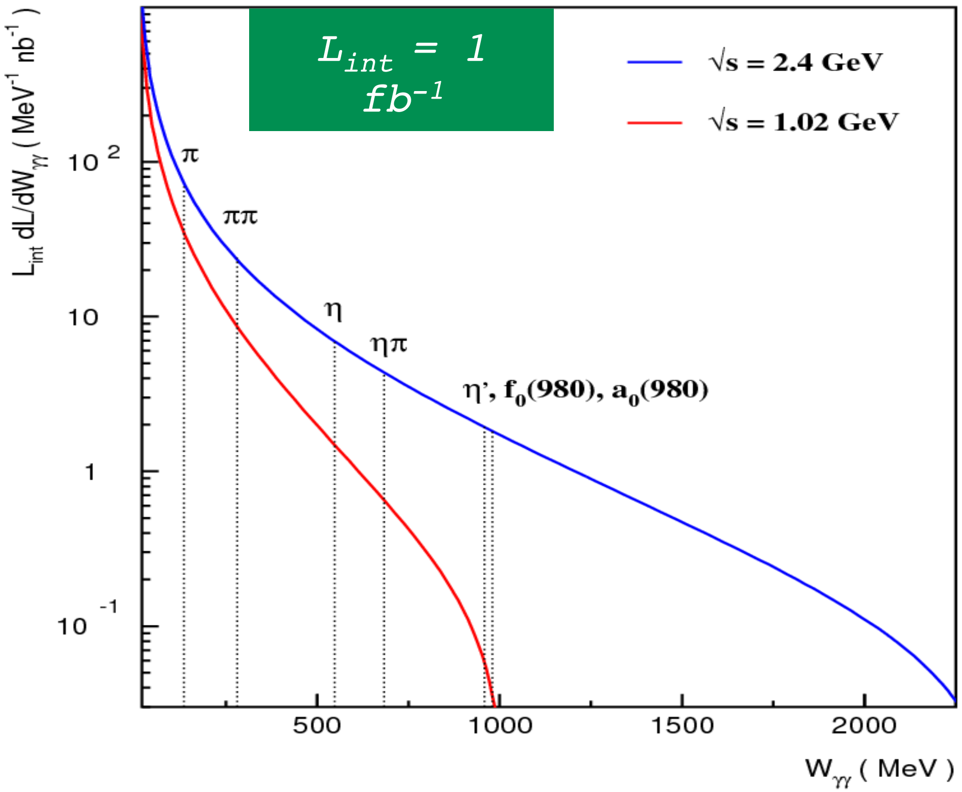
Data from off-peak data set are used essentially to study the channels : $\gamma\gamma \rightarrow \eta$ and $\gamma\gamma \rightarrow \pi^o\pi^o$

$\gamma\gamma$ - physics

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

$$\frac{dN_X}{dW_{\gamma\gamma}} = L_{int} \frac{dL}{dW_{\gamma\gamma}} \sigma(\gamma\gamma \to X)$$





$X \equiv \pi\pi$ ⟹ σ meson, ChPT tests

$X \equiv \pi^0, \eta$ ⟹ 2-photon widths, transition FFs @ low q^2

$(W_{\gamma\gamma} = M_X)$

Off-peak or tagger

$\gamma\gamma$ physics can be done at a φ–factory, on the φ peak: gives access to many interesting final states through photon emission from both colliding electron and positron

TRUE, BUT...

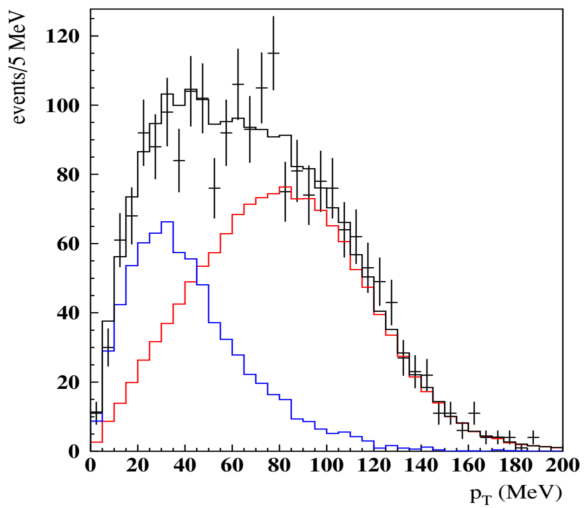
$\gamma\gamma$ events acquired at the φ peak would suffer from φ decays as background

$\gamma\gamma$ channel	(L = 10 fb^{-1})
$e^+ e^- \to e^+ e^- \pi^0$	4×10^6
$e^+ e^- \to e^+ e^- \eta$	1×10^6
$e^+ e^- \to e^+ e^- \pi^+\pi^-$	2×10^6
$e^+ e^- \to e^+ e^- \pi^0\pi^0$	2×10^4

ϕ decays	Missing particle	Events ($\mathcal{L}$ = 10 fb^{-1})	Background for :
$K_S(\pi^0\pi^0)\ K_L$	K_L	$\sim 10^9$	$\pi^0\pi^0$
$K_S(\pi^+\pi^-)\ K_L$	K_L	$\sim 2\times10^9$	$\pi^+\pi^-$
$\pi^+\pi^-\pi^0$	π^0	$\sim 10^9$	
$\eta(\gamma\gamma)\ \gamma$	γ	$\sim 10^8$	η
$\pi^0(\gamma\gamma)\ \gamma$	γ	$\sim 5\times10^8$	π^0

Tagging $\gamma\gamma$ events by detecting e^+e^- in the final state is mandatory to reduce backgrounds, otherwise we have to run off-peak from the ϕ events

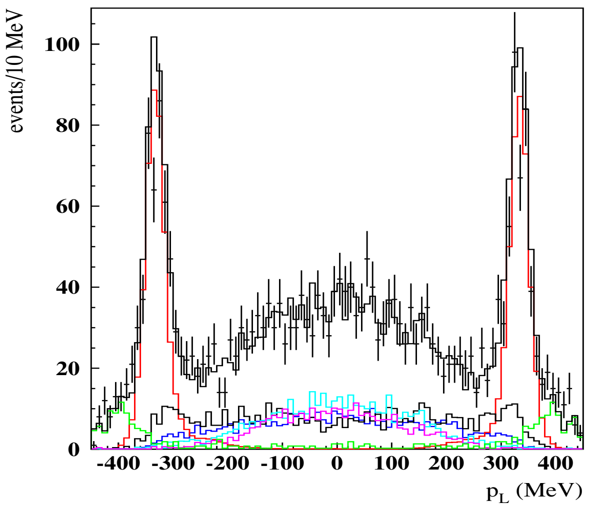
KLOE-1 off-peak : $\gamma\gamma \to \eta$



$\eta \to \pi^o\pi^o\pi^o$

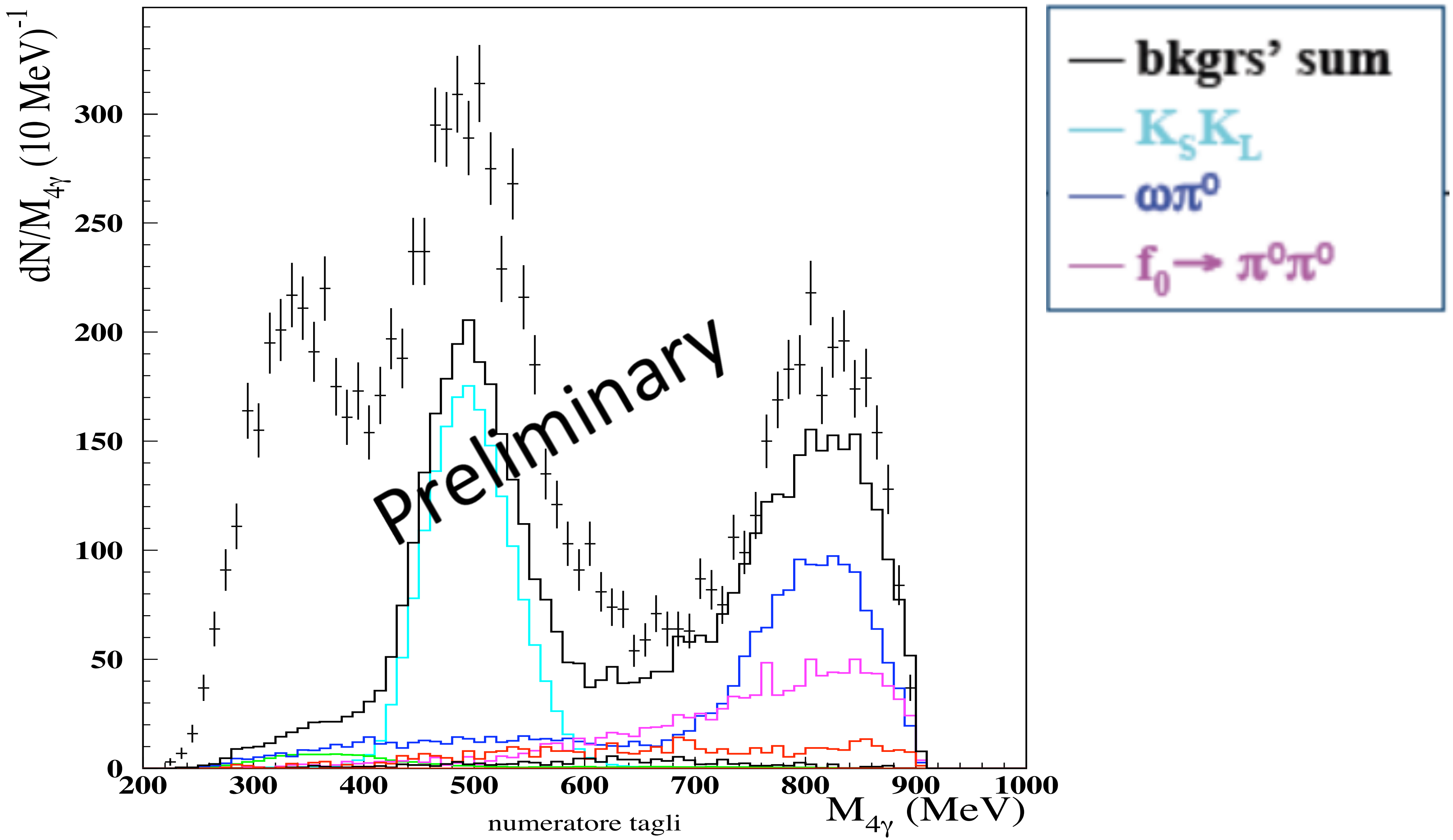
$$\sigma(e^+e^- \to e^+e^-\eta) = (32.7 \pm 1.3_{\rm stat} \pm 0.7_{\rm syst})\ {\rm pb}\,.$$

$$\Gamma(\eta \to \gamma\gamma) = (520 \pm 20_{\rm stat} \pm 13_{\rm syst})\ {\rm eV}\,.$$



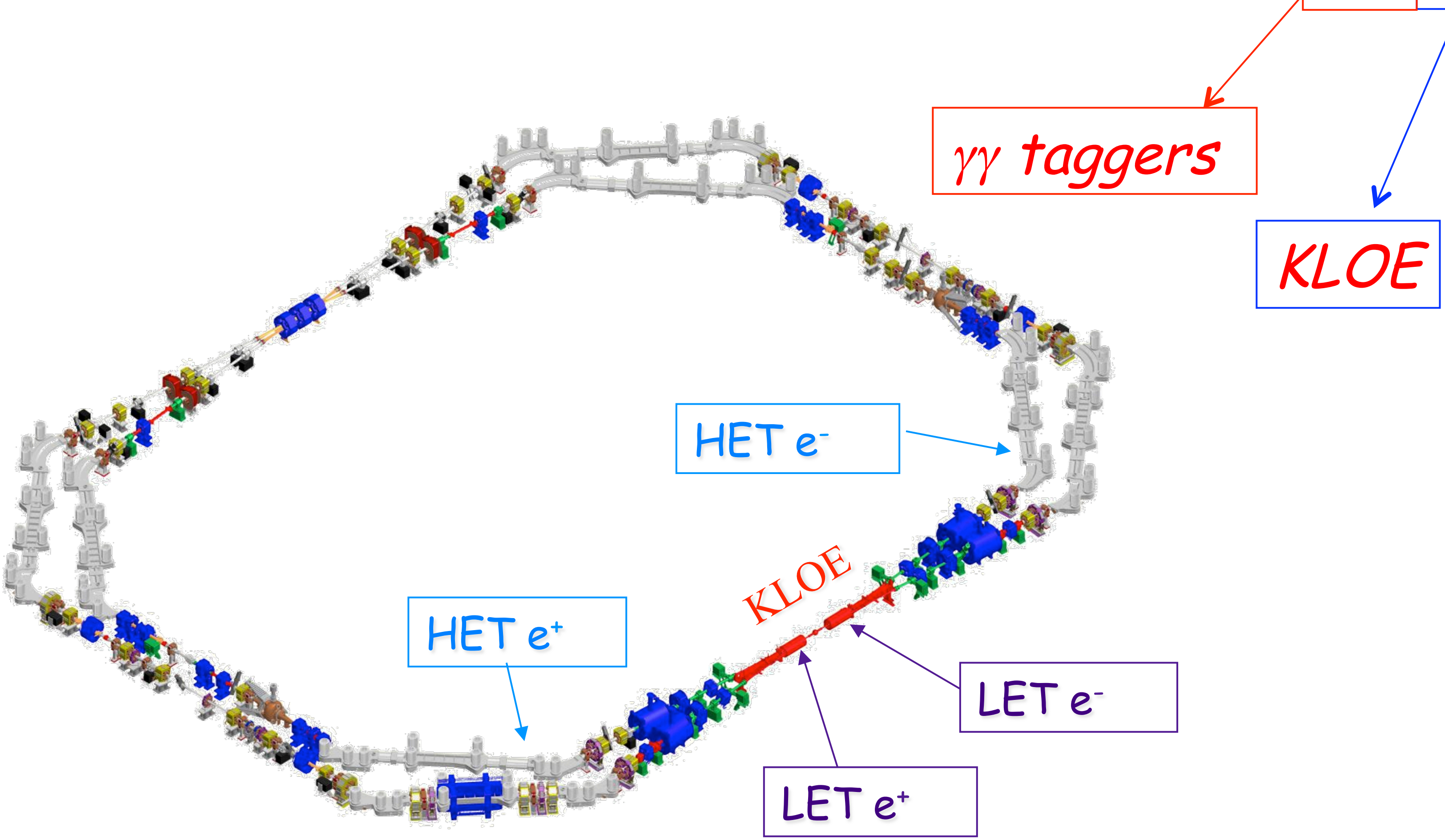
$\eta \to \pi^+\pi^-\pi^o$

KLOE-1 off-peak : $\gamma\gamma \to \pi^o\pi^o$

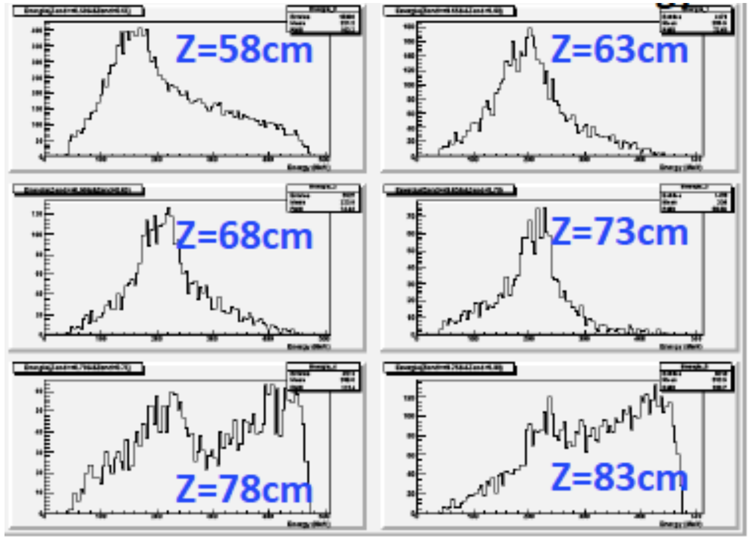


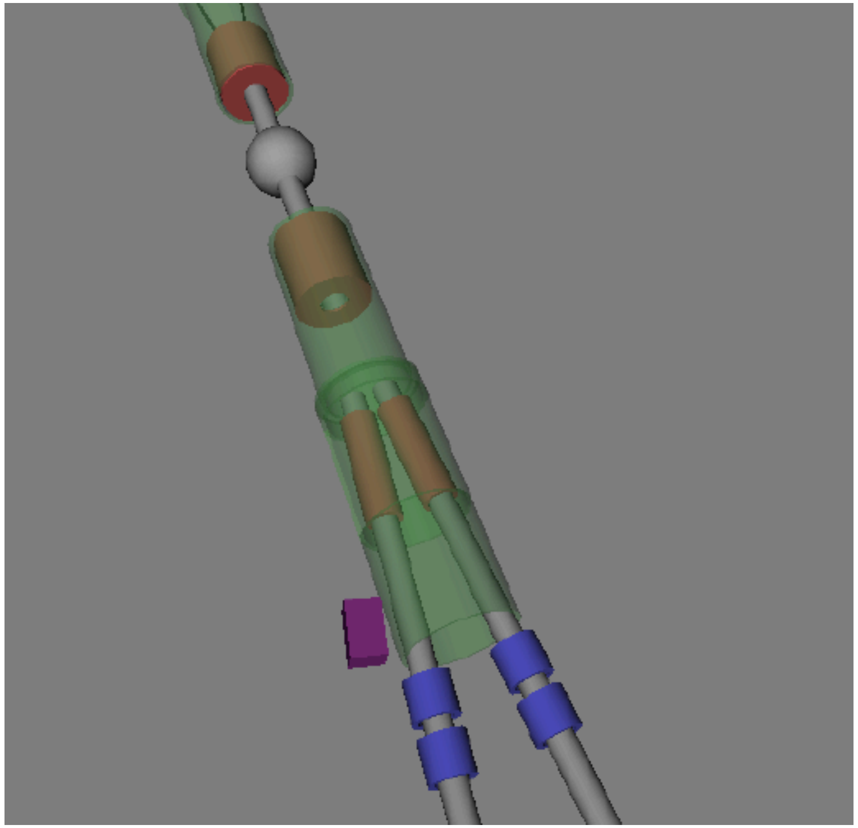
KLOE-2 : new γγ taggers

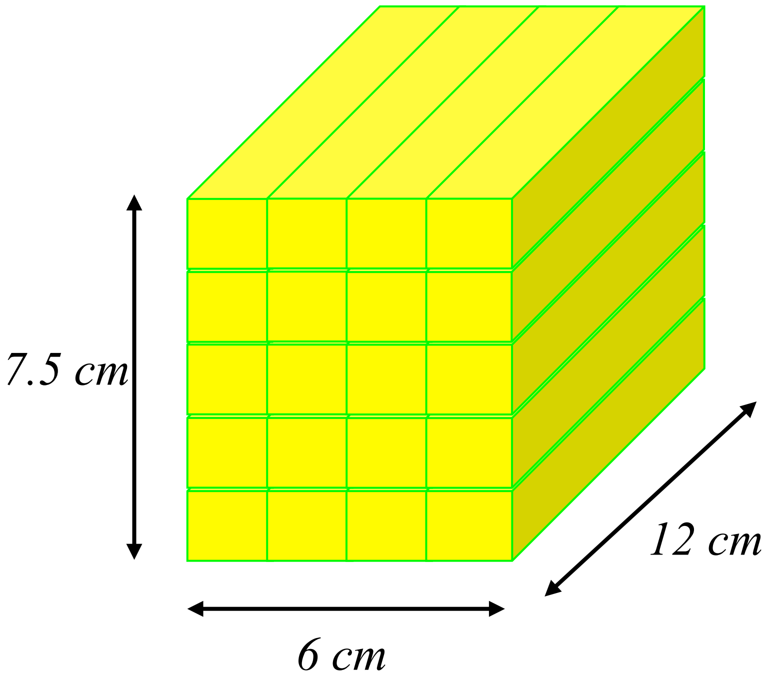
$$e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^- X$$



LET characteristics



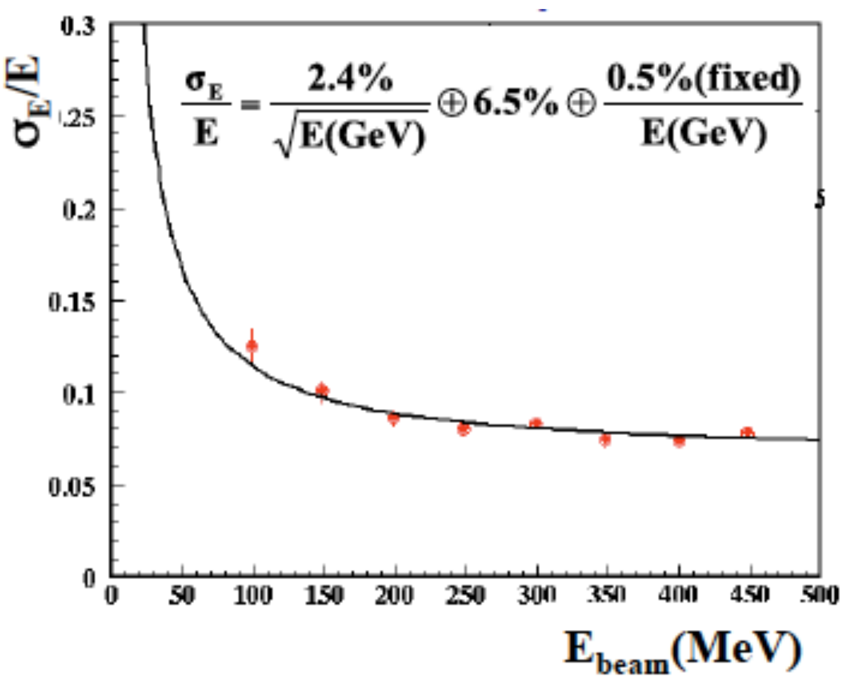


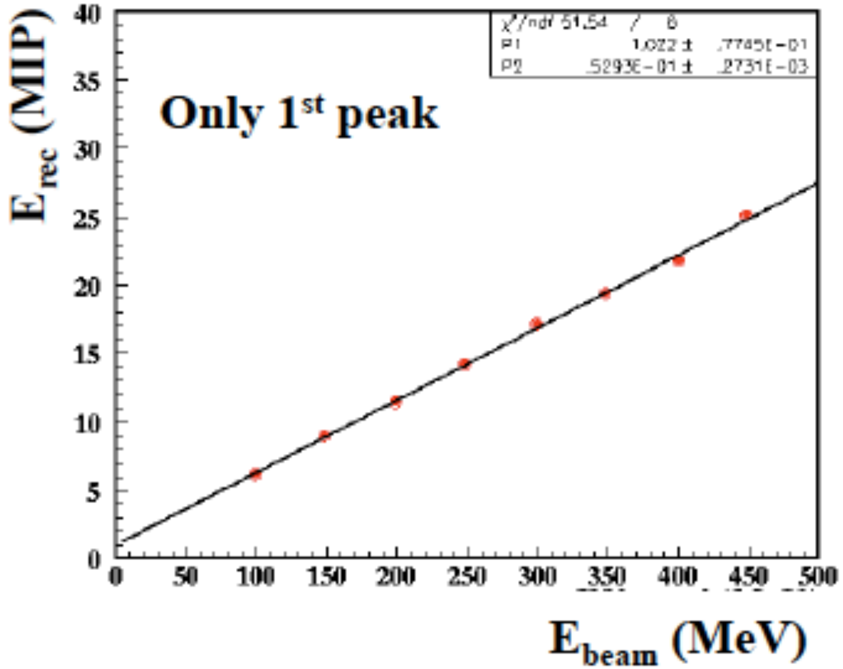


LET: Low Energy
Tagger(160-230 MeV)
lepton energy

Calorimeters, LYSO + SiPM

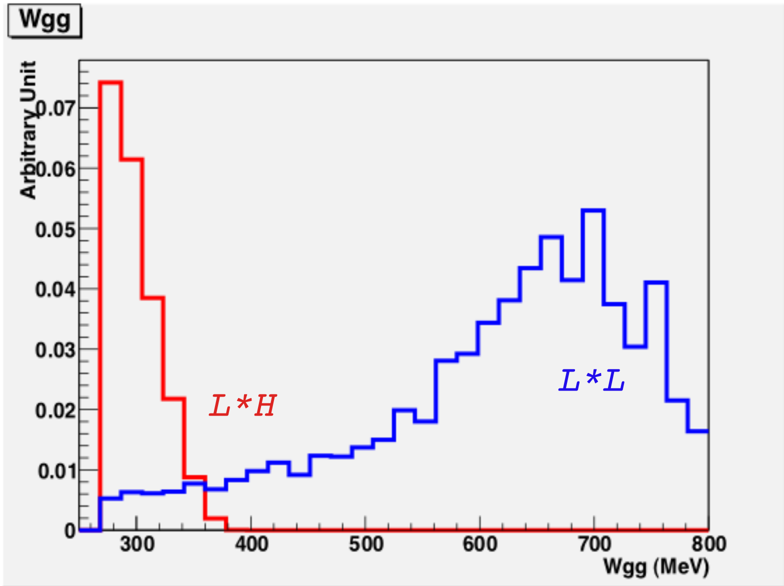
LET system and performance





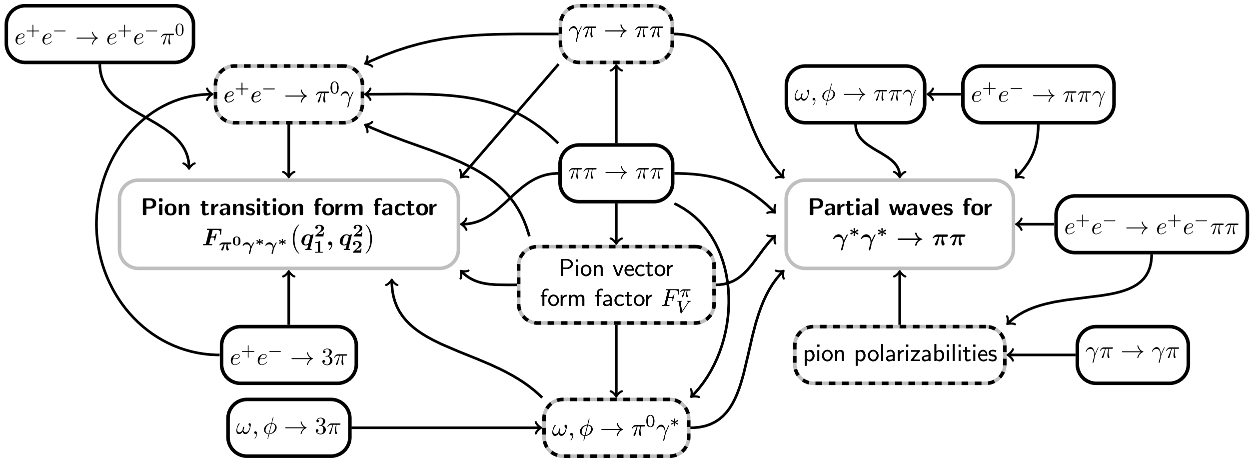
- 3rd term is fixed, since we have about 5 MeV noise
- Statistical term higher than expected (20 p.e./MeV → less than 1%/$E^{1/2}$(GeV))
- Contribution to constant term due to lateral leakage (matrix not fully readout)
- There is an unknown contribution from the beam
- Resolution is better than 10% for E > 150 MeV

LET acceptance



In this study we consider only the reaction $\gamma\gamma \to \pi^0\pi^0$

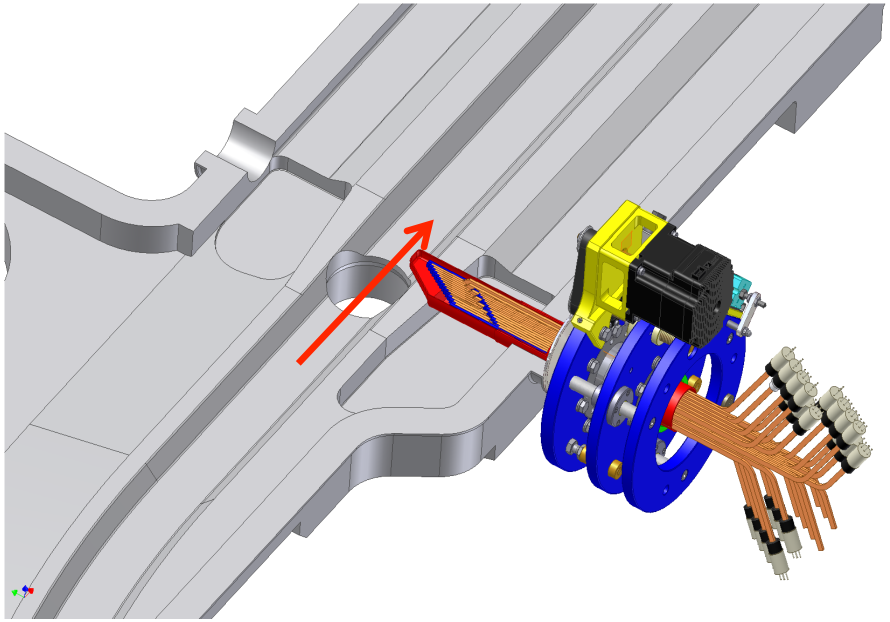
- Single arm acceptance: HET = 14%, LET = 17%
- Single Total acceptance (only 1 tagger fired) = 54%
- Double arm acceptance (H*H + 2*L*(H) + L*L) = 2+5+3 = 10%

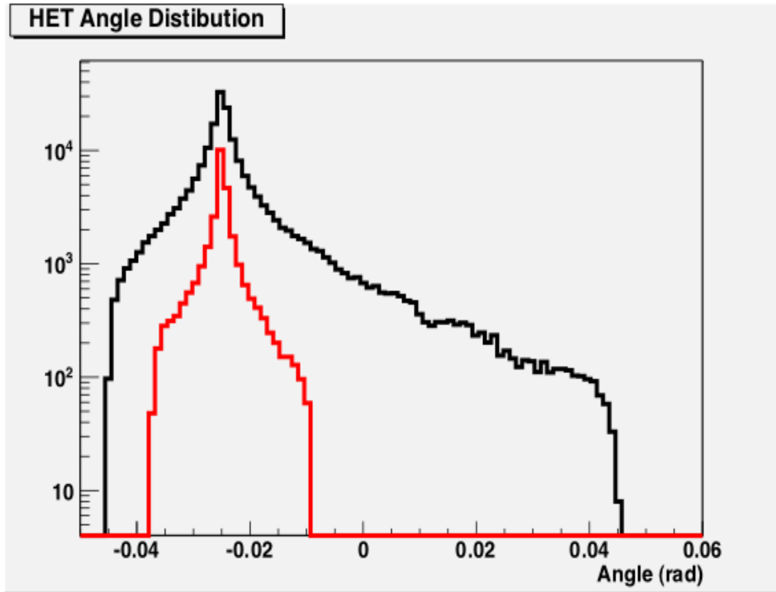


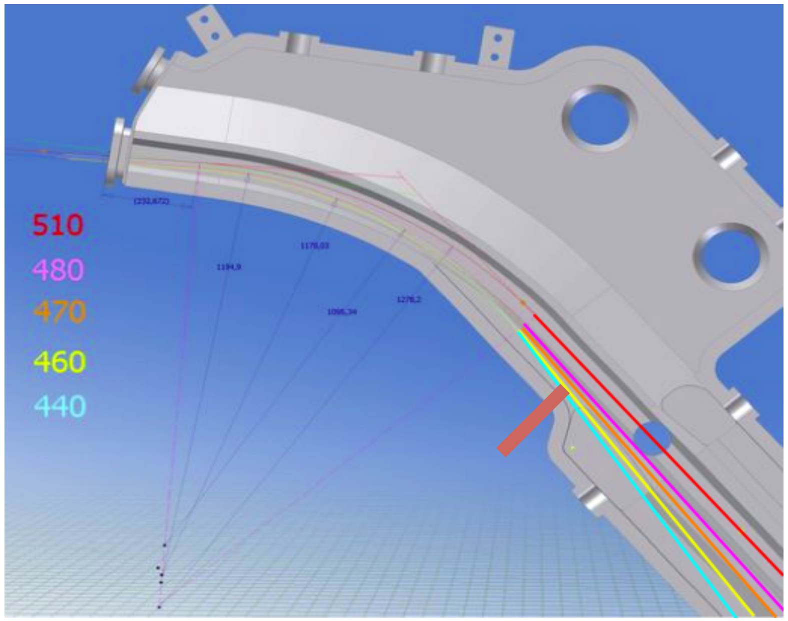
G. Colangelo et al. / Physics Letters B 738 (2014) 6–12

HET characteristics

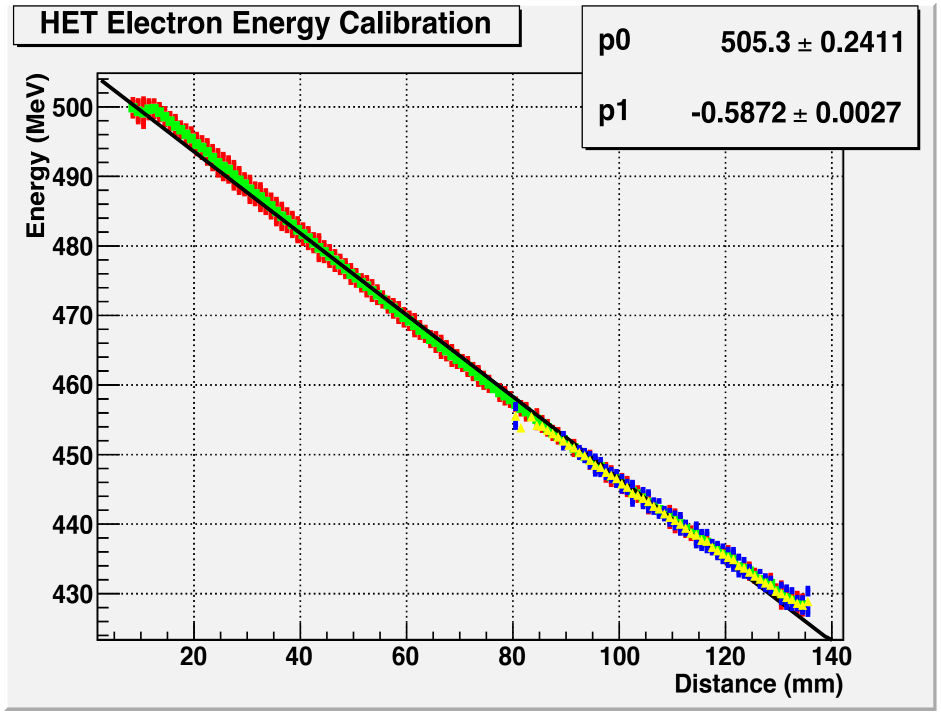
The HET detector will be located at 11 m from the IP behind a bending Magnet : Plastics + PMTs



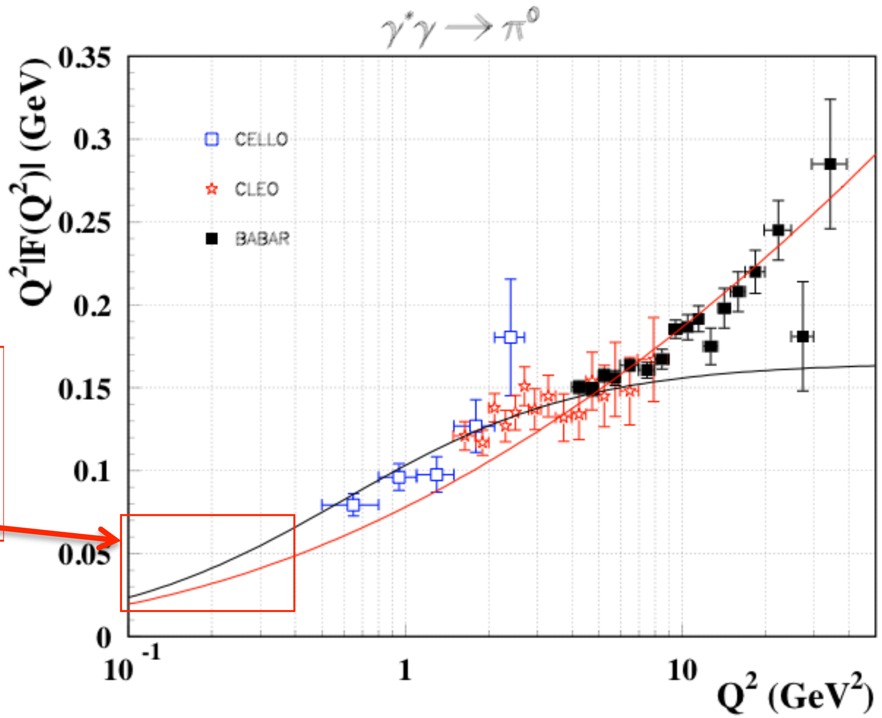




HET acceptance



HET detect leptons in energy range (20, 85) MeV.
2 HET (e^+e^-) coincidence cover the energy range (40, 170) MeV : $\gamma\gamma\rightarrow\pi^o$ could be measured from



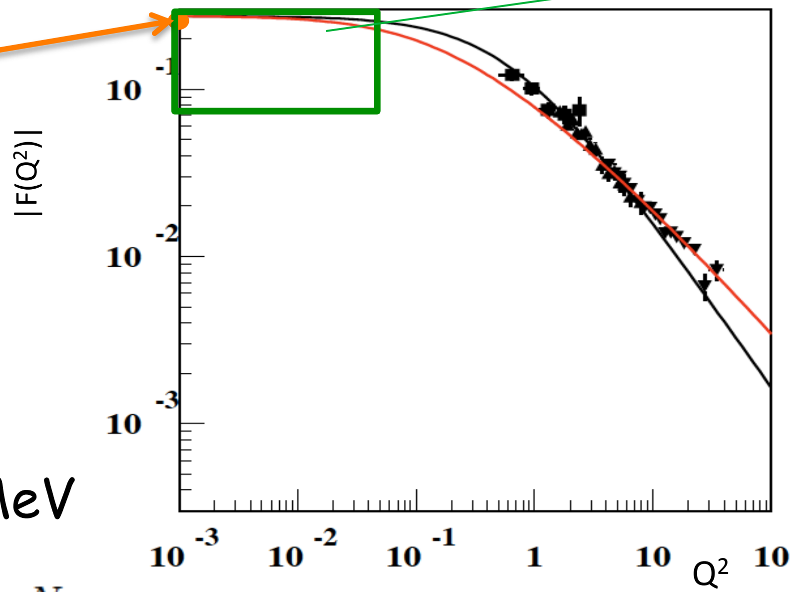
The π^o width could be measured
The low Q^2 of TFF for the reaction $\gamma^*\gamma\rightarrow\pi^o$ could be measured

$\pi^0 \rightarrow \gamma\gamma$ case

KLOE-2 data will fix the slope at $Q^2=0$

WZW term

$$\frac{1}{4\pi^2 F_\pi}$$



Where F_π come from $\pi \rightarrow \mu\nu(\gamma)$ decay :

$F_\pi = 92.2 \pm 0.14$ MeV

$$\mathcal{F}_{\pi^0\gamma\gamma}(m_\pi^2, 0, 0) = -\frac{N_C}{12\pi^2 F_\pi}$$

$$\mathcal{F}^2_{\pi^0\gamma\gamma}(m_{\pi^0}^2, 0, 0) = \frac{1}{(4\pi\alpha)^2}\frac{64\pi\Gamma(\pi^0 \rightarrow \gamma\gamma)}{M_{\pi^0}^3}$$

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

(1.4 %)

Phys.Rev.Lett.106:162303,2011

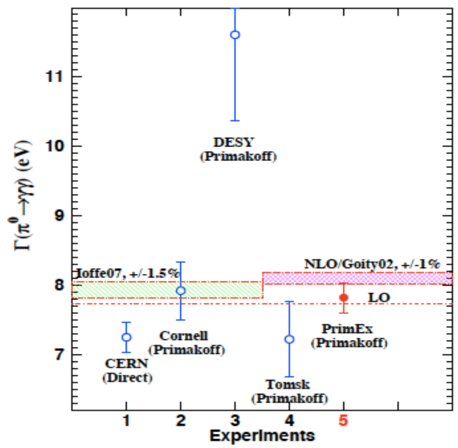
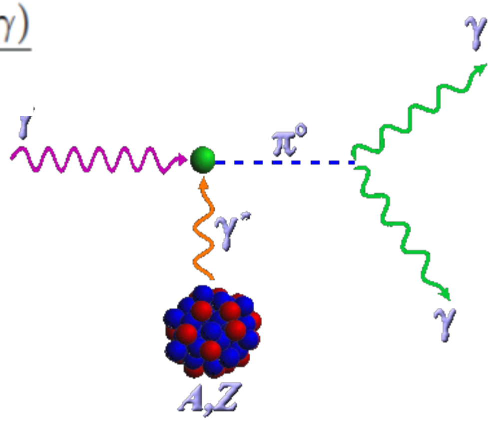


FIG. 1: $\pi^0 \rightarrow \gamma\gamma$ decay width in eV. The dashed horizontal line is the LO chiral anomaly prediction. NLO ChPT prediction [4] is shown as the shaded band on r.h.s. The l.h.s shaded band is the prediction from Ref. [7]. The experimental results, included in the PDG average, are for: (1) done with the direct method [12], (2, 3, 4) with the Primakoff method [9–11], and (5) is the current PrimEx result.



PRIMEX data

Target	$\Gamma(\pi^0 \rightarrow \gamma\gamma)$ [eV]	
^{12}C	7.79±0.18	2.3 %
^{208}Pb	7.85±0.23	2.9 %

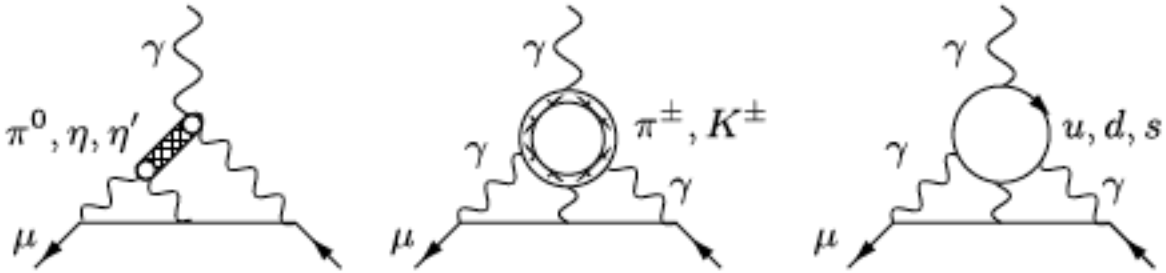
π^o TFFs

$e^+e^- \rightarrow e^+e^- \pi^o$

$\gamma^* \gamma \rightarrow \pi^o \quad \rightarrow$ *Amplitude* $\propto F(M^2_\pi, Q^2, 0)$

Slope near $Q^2 = 0$ crucial for hadronic LbL contribution to a_μ

F. Jegerlehner, A. Nyffeler / Physics Reports 477 (2009) 1–110



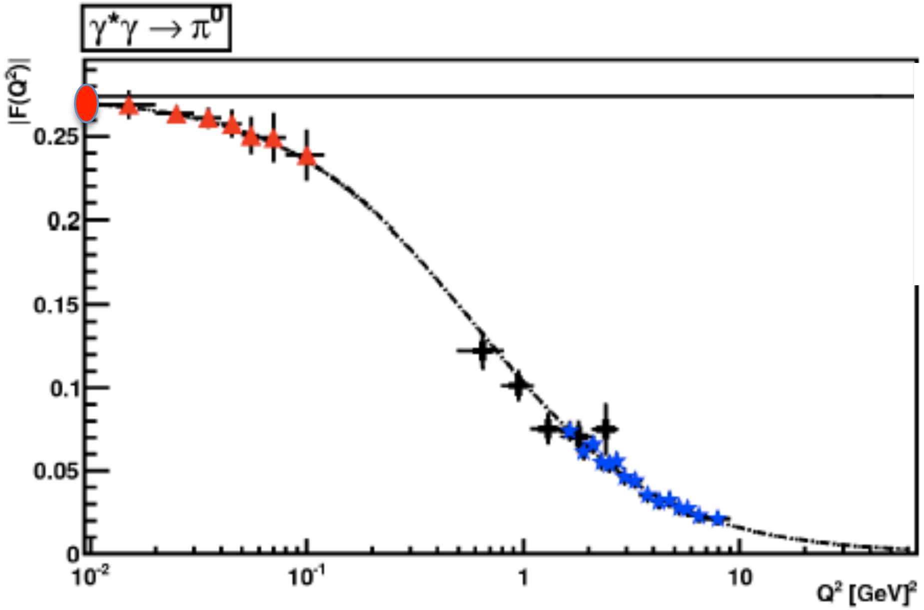
$$a_\mu^{\mathrm{LbL};\pi^0} = -e^6 \int \frac{d^4 q_1}{(2\pi)^4} \frac{d^4 q_2}{(2\pi)^4} \frac{1}{q_1^2 q_2^2 (q_1+q_2)^2 [(p+q_1)^2 - m_\mu^2][(p-q_2)^2 - m_\mu^2]}$$

$$\times \left[\frac{\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(q_2^2, q_1^2, q_3^2)\, \mathcal{F}_{\pi^{0*}\gamma^*\gamma}(q_2^2, q_2^2, 0)}{q_2^2 - m_\pi^2} T_1(q_1, q_2; p) \right.$$

$$\left. + \frac{\mathcal{F}_{\pi^{0*}\gamma^*\gamma^*}(q_3^2, q_1^2, q_2^2)\, \mathcal{F}_{\pi^{0*}\gamma^*\gamma}(q_3^2, q_3^2, 0)}{q_3^2 - m_\pi^2} T_2(q_1, q_2; p) \right],$$

Simulation in KLOE-2 case

Jegerlehner-Nyffeler (JN) and Melnikov-Vainshtein (MV) approaches are used for calculation of $a_\mu^{\mathrm{LbyL};\pi}$



$A0$: CLEO, CELLO, PDG
$A1$: CLEO, CELLO, PrimEx
$A2$: CLEO, CELLO, PrimEx, KLOE-2

$B0$: CLEO, CELLO, BaBar, PDG
$B1$: CLEO, CELLO, BaBar, PrimEx
$B2$: CLEO, CELLO, BaBar, PrimEx, KLOE-2

Simulation of KLOE-2 measurement of $F(Q^2)$ (red triangles) with statistical errors for 5 fb^{-1}. The detection efficiency is estimated to be about 20%. Dashed line is the $F(Q^2)$ form factor according to LMD+V model, solid line is $F(0)$ given by Wess-Zumino-Witten term. CELLO (black crosses) and CLEO (blue stars) data at high Q^2 are also shown for illustration.

D. Babusci et al., EPJC **72** (2012) 1917 : We aspect to collect ~ 10000 ev for $\mathcal{L}_{int}$ = 5fb^{-1}

Results on a_μ^{HLBL}

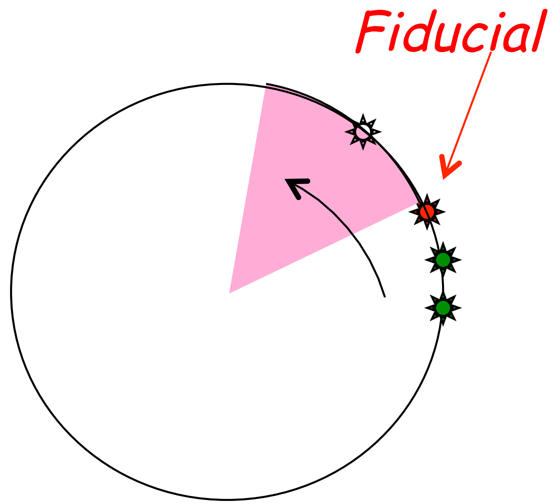
Model	Data	$\chi^2/d.o.f.$	$a_\mu^{\mathrm{LbyL};\pi} \times 10^{11}$
VMD	A0	6.6/19	$(57.2 \pm 4.0)_{JN}$
VMD	A1	6.6/19	$(57.7 \pm 2.1)_{JN}$
VMD	A2	7.5/27	$(57.3 \pm 1.1)_{JN}$
LMD+V, $h_1 = 0$	A0	6.5/19	$(72.3 \pm 3.5)_{JN}$ *
			$(79.8 \pm 4.2)_{MV}$
LMD+V, $h_1 = 0$	A1	6.6/19	$(73.0 \pm 1.7)_{JN}$ *
			$(80.5 \pm 2.0)_{MV}$
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	$(71.8 \pm 0.7)_{JN}$ *

- There is also an additional error coming from the "off-shellness" of the pion

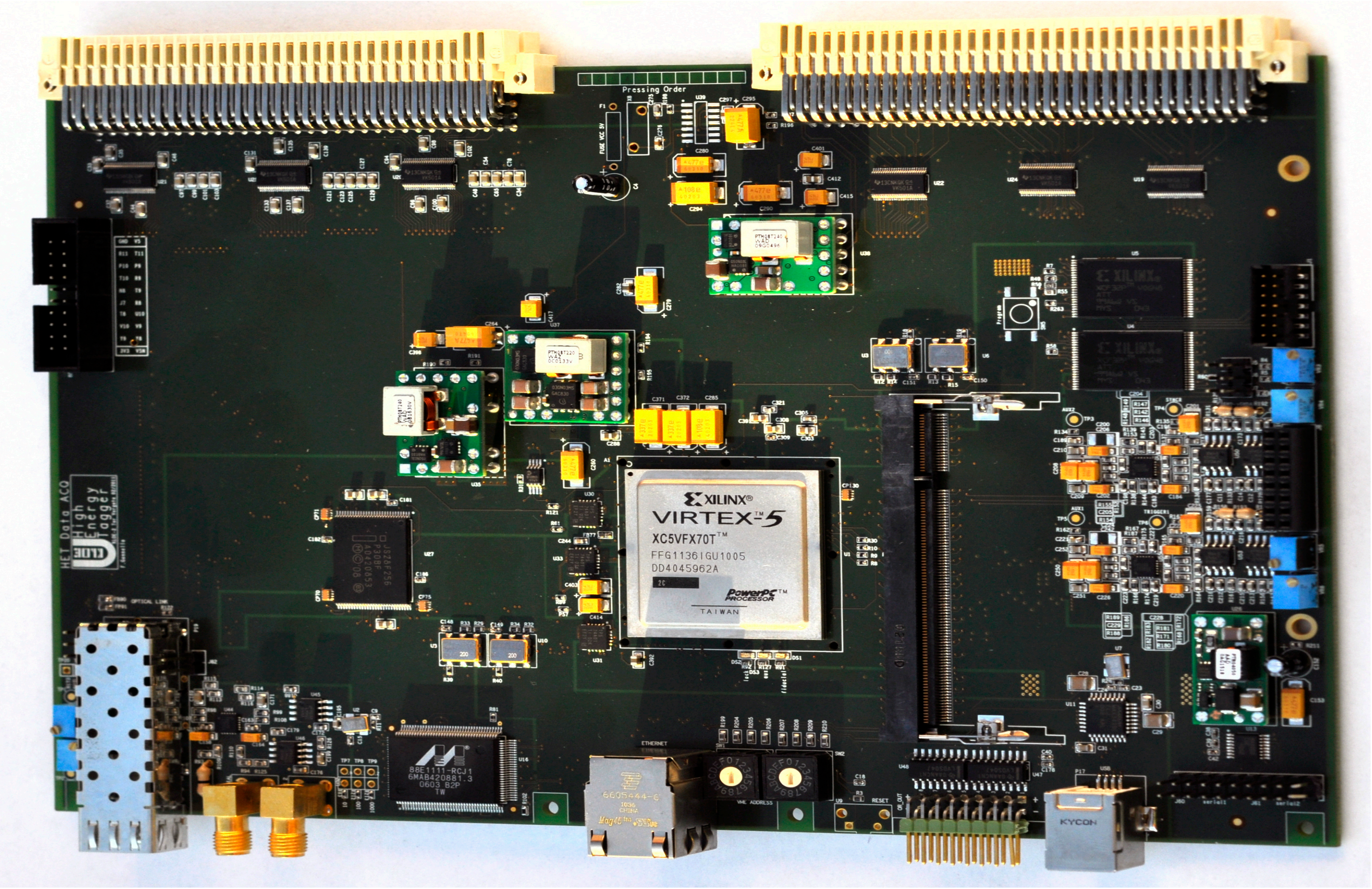
Experimental considerations

LET are located inside KLOE : we can use the KLOE DAQ without any problem of trigger synchronization.
HET if located 11 m far from KLOE : we have to take care about the trigger and the events synchronization.
The DAΦNE bunch structure could help us to manage this :

We have developed a custon TDC module based on a Xilinx Virtex 5 FPGA
It work in "Common Start", the "Fiducial" is the "start" while HET plastics provide the "stop". Conversion are made during the empty bunches "interval".
The LSB width is 625 ps in order to distinguish two consecutive bunches.
Three DAΦNE revolution is acquired for each KLOE trigger

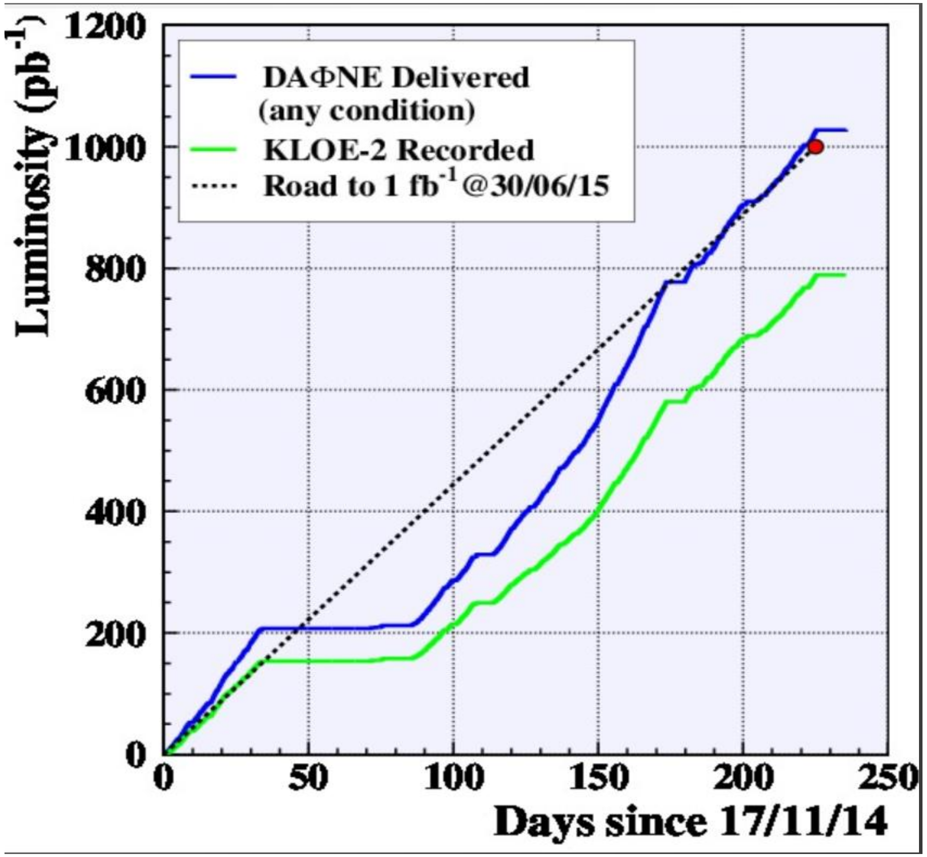


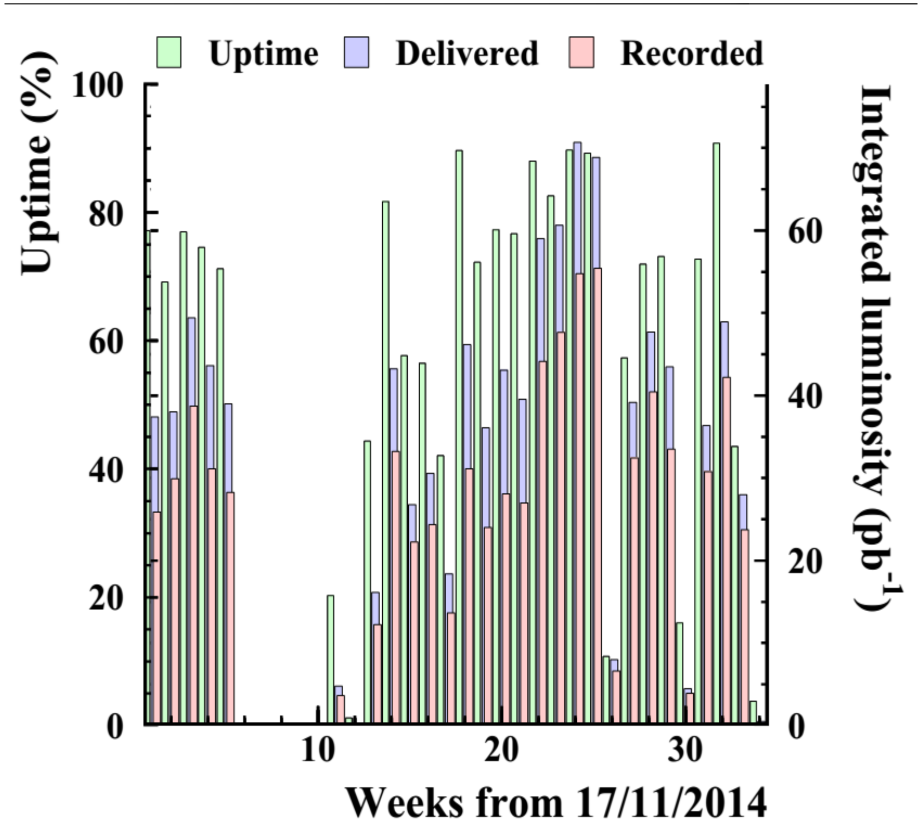
HET TDC_V5



NIM A 739 (2014) 75

KLOE-2 : data taking campaign



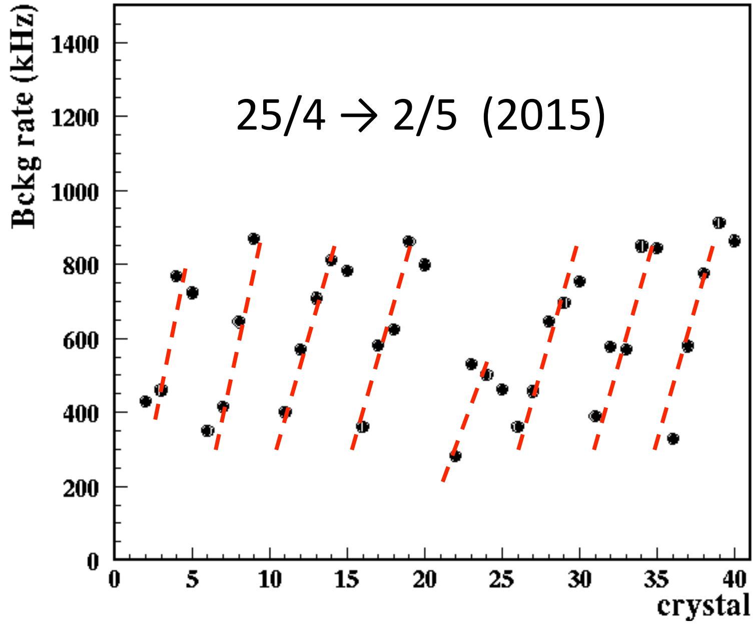


DAΦNE delivered 1030 pb^{-1}, and KLOE record 790 pb^{-1}.
Which correspond 77 % average efficiency

Low Energy Tagger

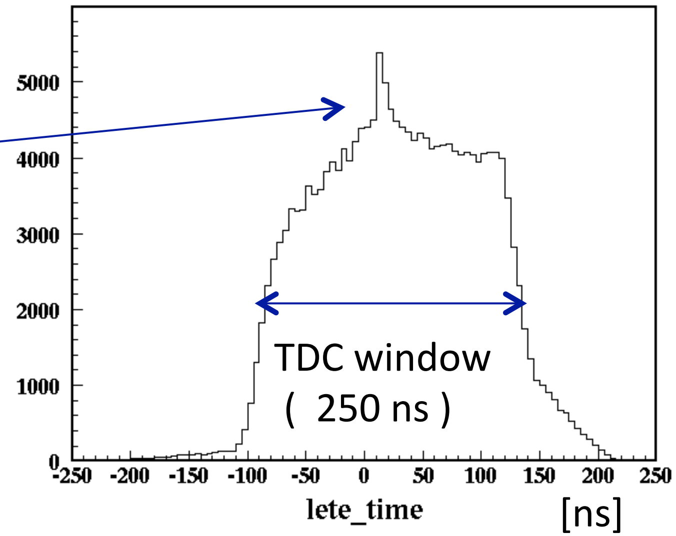
- LET calibration: equalization with MIPs, time alignment w.r.t. the EMC
- LET operation with circulating beams
  ⇒ high background environment

(bckg rate evaluated from out of time hits)

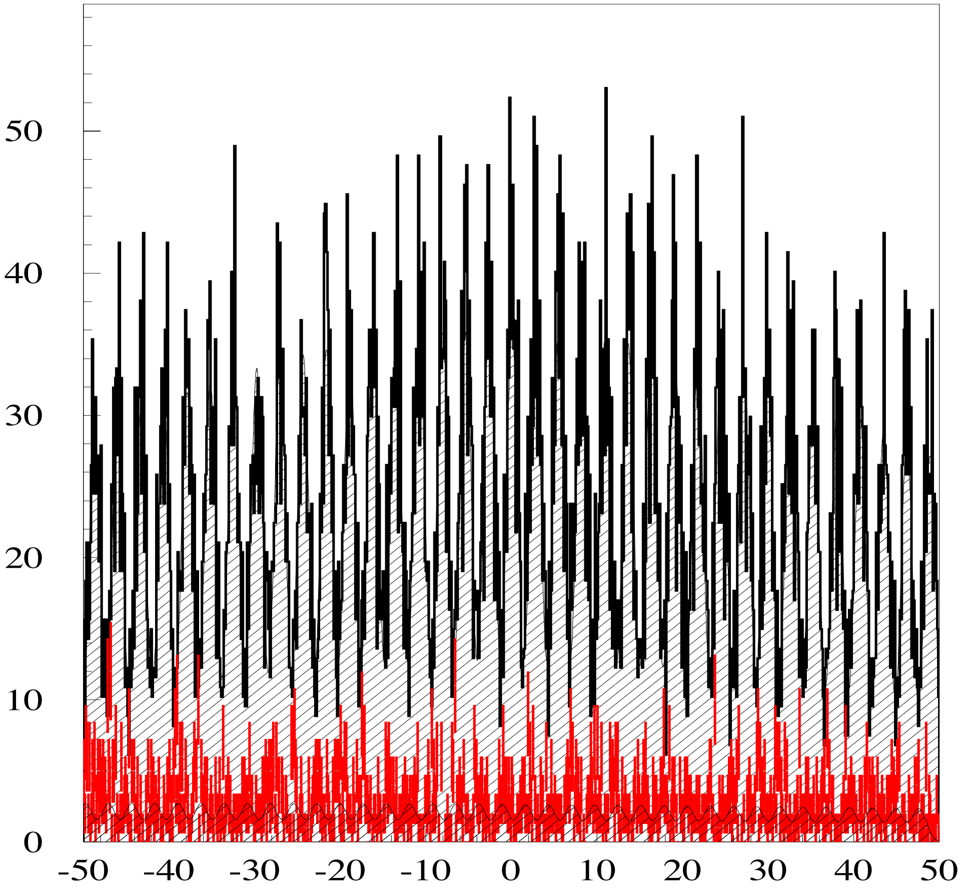


- Rough estimate of the radiative Bhabha expected
  rate with e^+ or e^- on LET (from Babayaga MC)
  ≈ 30 kHz on the whole LET (overestimated)

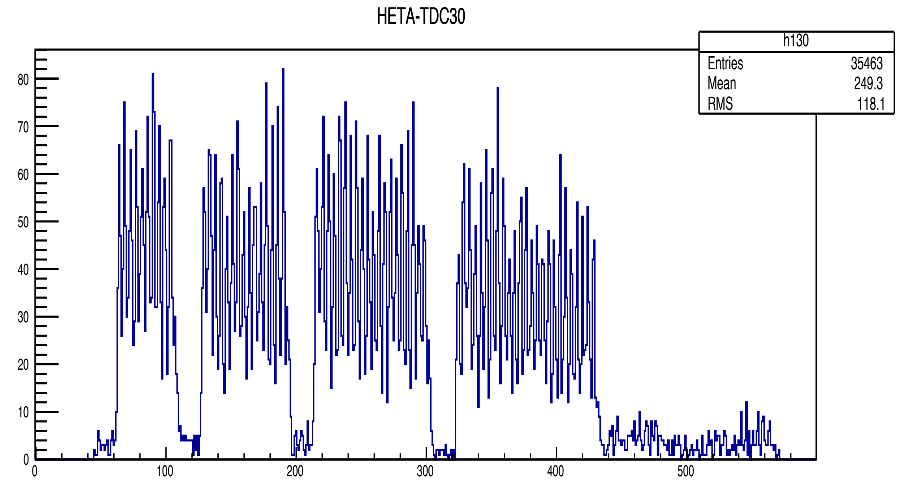
- Example of time distribution from data
  ⇒ peak over a large background
  Work in progress to understand
  these events with LET "in time" with the EMC

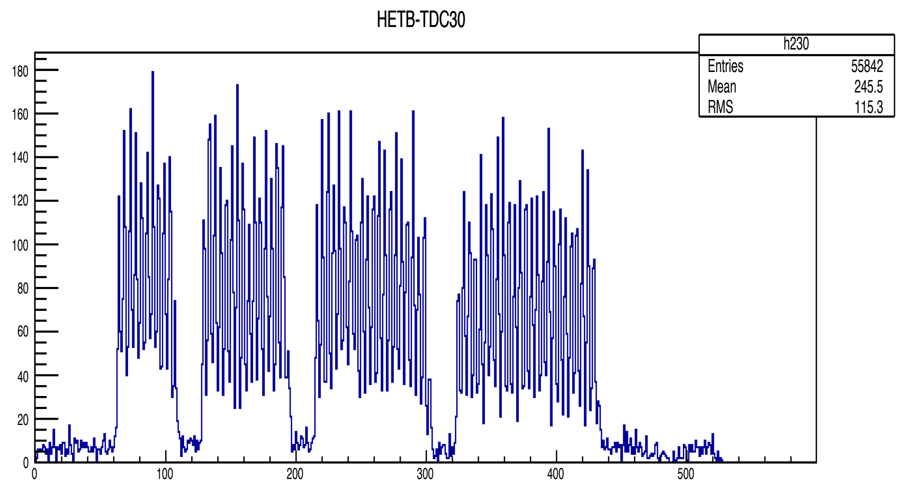


High Energy Tagger



DAΦNE no collision test : bck ≈ 11 %





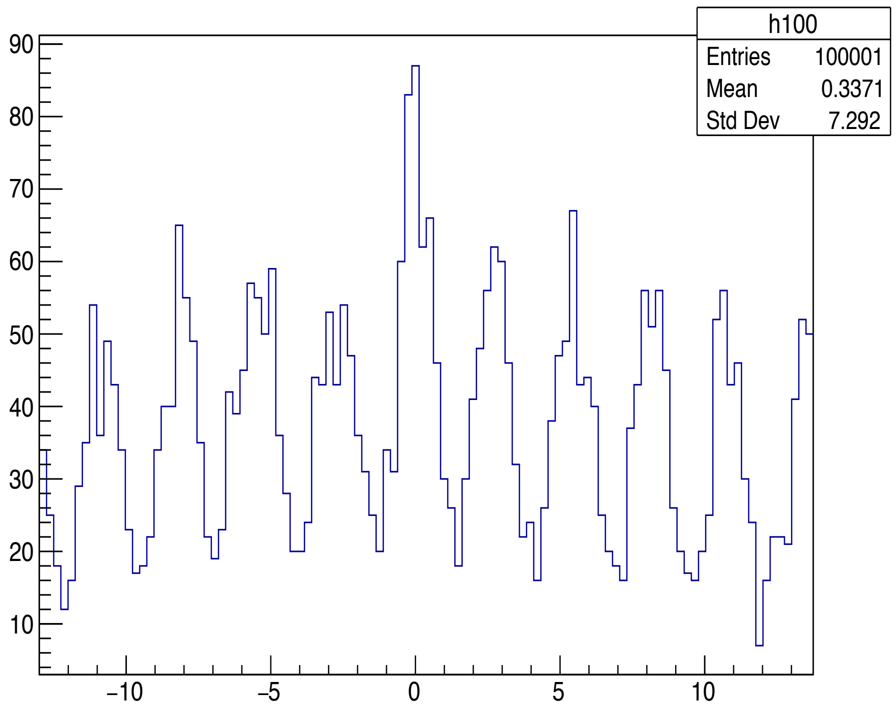
DAΦNE bunch : 5-10-5-15-5-20-5-25

HET Events

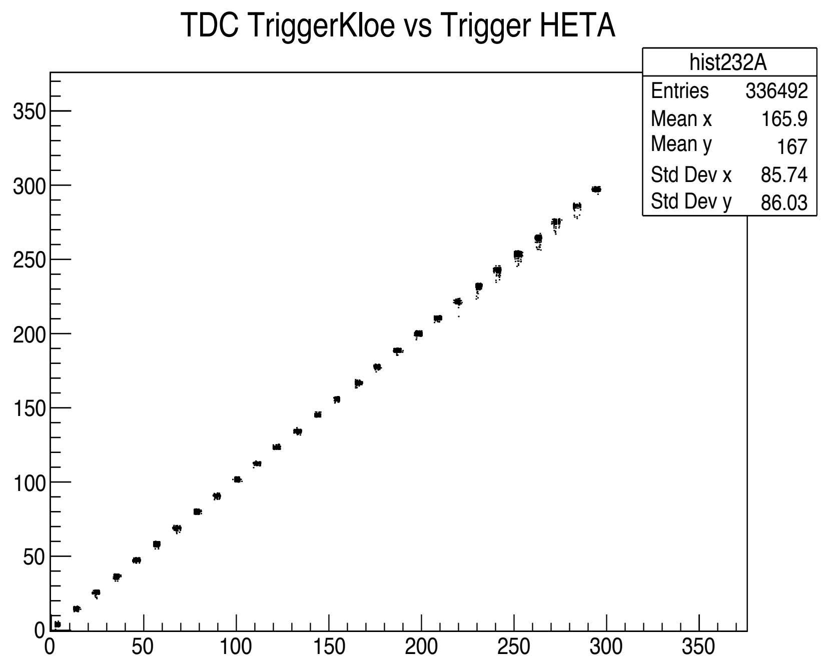
- Bhabhayaga : σ=11 mb ε_H=4.4 % ε_{HH}=1.9x10^{-5} (but radiative photons are not detected in KLOE). Visible σ_H=484μb and σ_{HH}=209nb
- Ekhara : $e^+e^- \rightarrow e^+e^-\pi^0$: σ=280 pb ε_H=7.7 % ε_{HH}=1.4 %. Visible σ_H=21.6nb and σ_{HH}=3.9nb

- S/B$_H$=44.6x10^{-6} S/B$_{HH}$=10.3 %

HET time structure



TDC(HETe⁻) – TDC(HETe⁺)



HET – KLOE Synchronization

Conclusion

- KLOE-1 $\gamma\gamma \rightarrow \pi^o\pi^o$ should published soon.
- KLOE-2 is running. Our goal is to collect ~ 5 fb^{-1} in the next two years.