Status report on the $\gamma\gamma \to \pi^0$ and the $\omega \to \pi^+\pi^-\pi^0$ analyses by the KLOE-2 collaboration

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on behalf of the KLOE-2 Collaboration

Workshop of the Muon $g-2$ Theory Initiative
June 29^{th} 2021

DAΦNE and KLOE-2

The KLOE-2 High Energy Taggers

Low angle radiative $A' \times \sigma_{\mathrm{Bha}}$ measurements

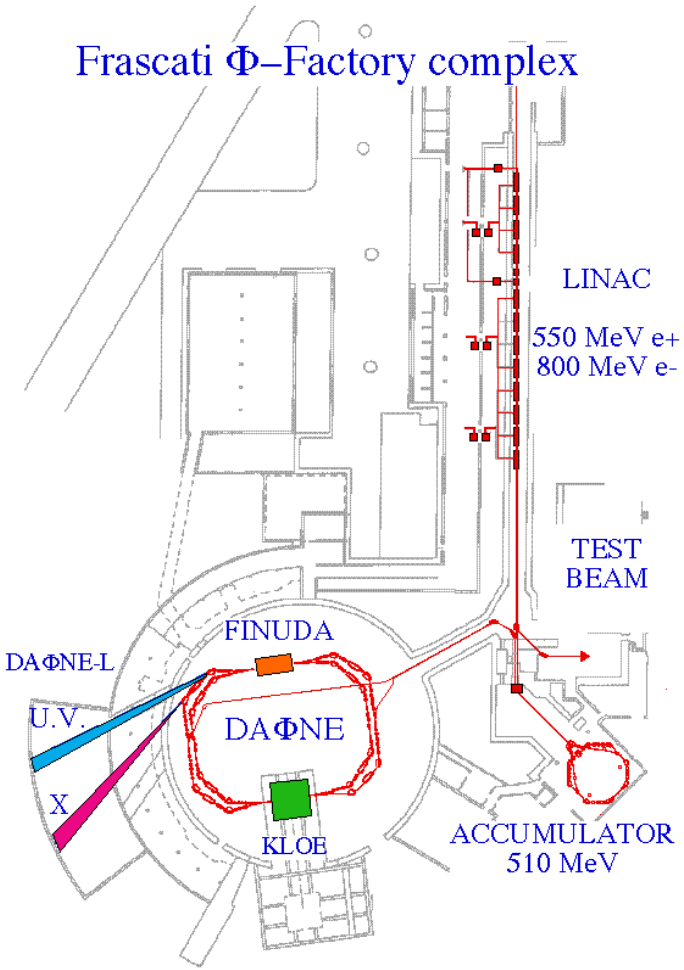
HET Acceptance Studies

$\gamma\gamma \to \pi^0$ Analysis

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

Conclusions

DAΦNE: THE Φ-FACTORY



e^+e^- collider @ $\sqrt{s} = M_\Phi = 1.0194$ GeV

2 interaction regions

2 separate rings

105 +105 bunches, $T_{RF} = 2.7$ ns

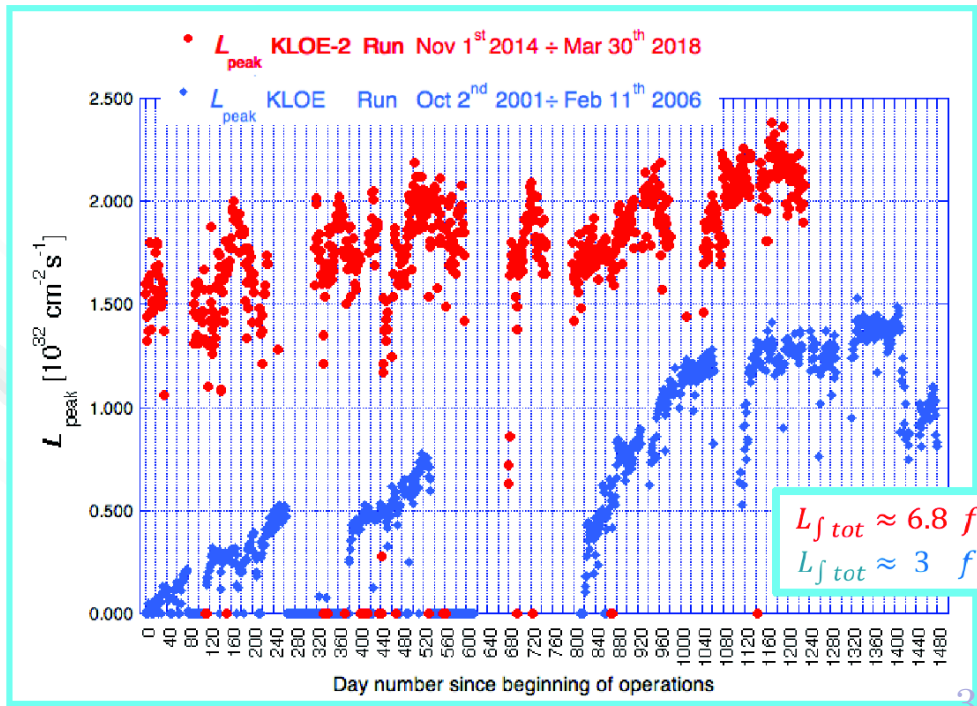
Injection during data taking

Crossing angle: 2×12.5 mrad

Best Performance (1999–2006):
$L_{\text{peak}} = 1.5 \times 10^{32}$ cm^{-2} s^{-1}

Best Performance (2014–2018):

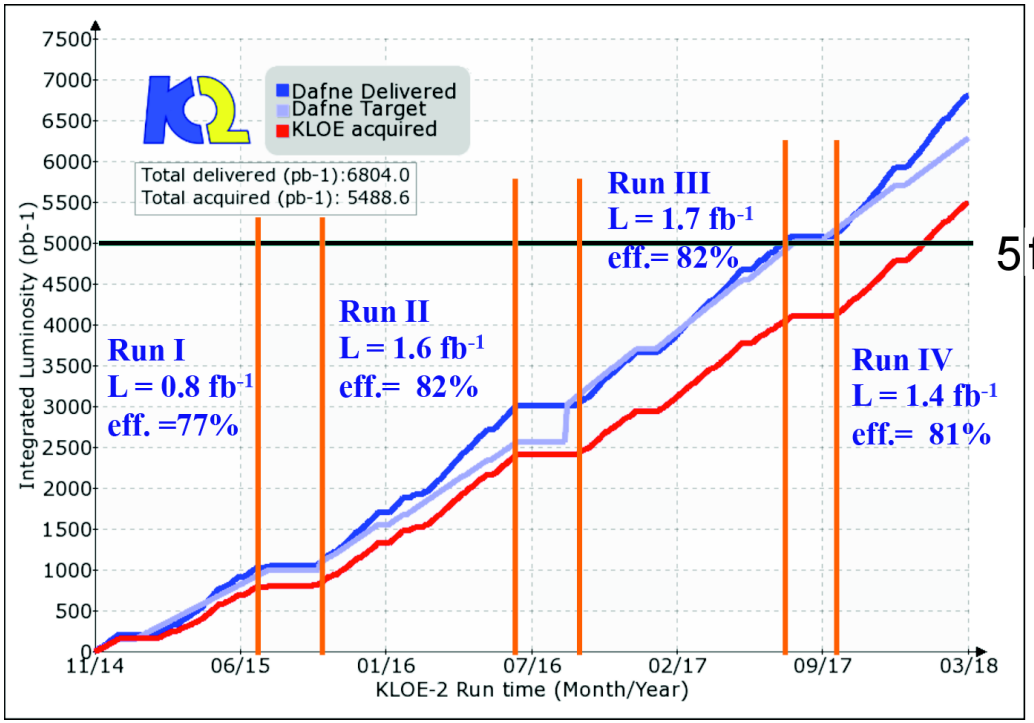
$L_{\text{peak}} = 2.4 \times 10^{32}$ cm^{-2} s^{-1}



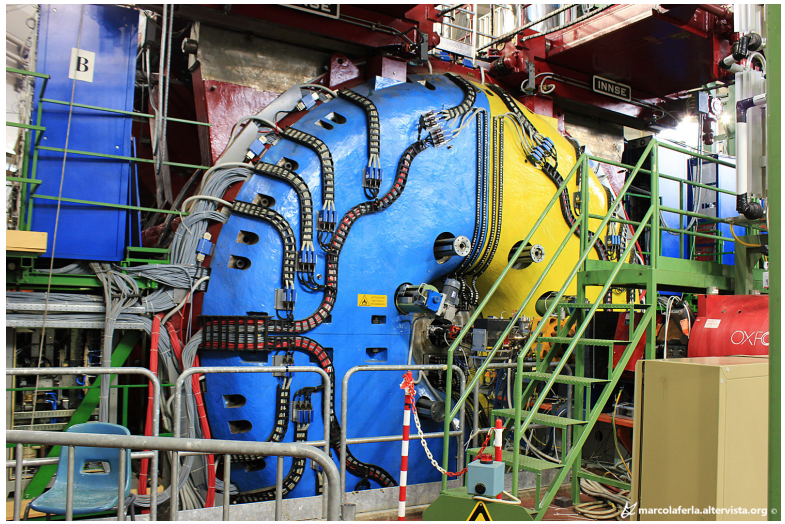
DAΦNE UPGRADES

New interaction region: large beam crossing angle + sextupoles for crabbed waist optics → 59% increase in terms of peak luminosity

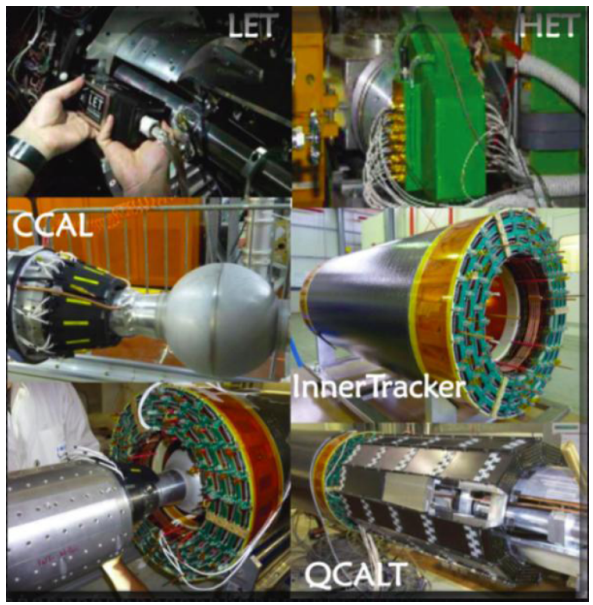
The KLOE-2 Experiment



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



The KLOE-2 sub-detectors



KLOE-2 run:

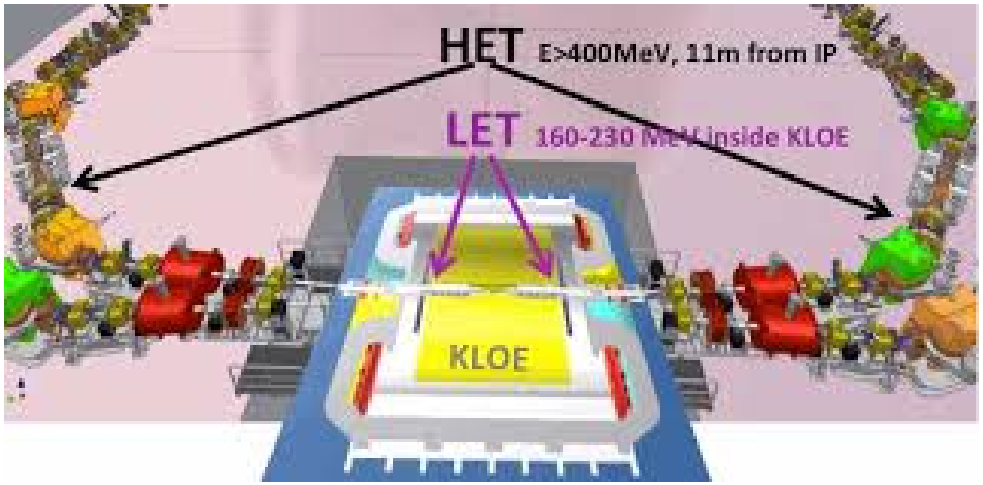
$$\int L_{\text{delivered}} = 6.8 \text{ fb}^{-1}$$

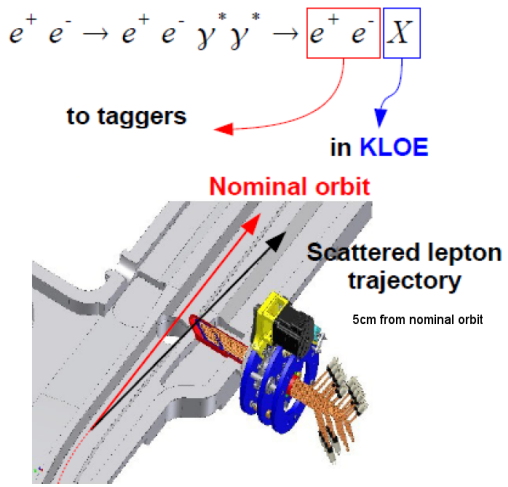
$$\int L_{\text{acquired}} = 5.5 \text{ fb}^{-1}$$

KLOE + KLOE-2 data sample:
$8 \text{ fb}^{-1} \rightarrow 2.4 \times 10^{10}$ ϕ mesons produced, the largest sample ever collected at the $\phi(1020)$ peak

The HET Detector

The HET stations are located 11m away the IP after the bending dipoles

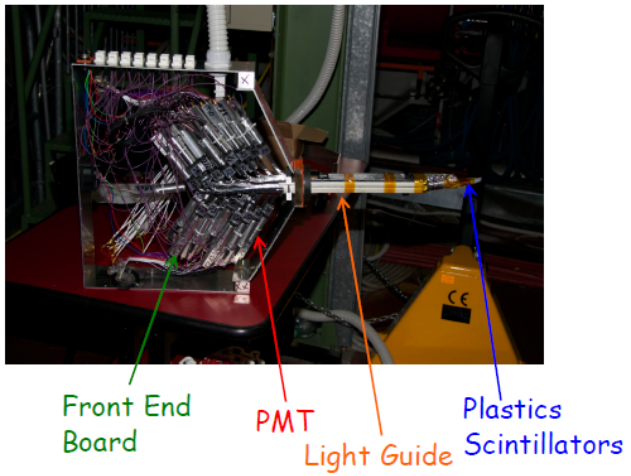




MC generators: BBBrem for low angle radiative Bhabha's, Ekhara for $\gamma\gamma \to \pi^0$ events
Leptons tracking along machine optics: BDSIM package (GEANT4 toolkit)

Scintillator hodoscope: 28 plastic scintillators (5x6x3 mm^3) inserted in roman pots at about 5 cm from the beam. 1 Long Plastic for coincidence

$\sigma_\theta \sim 2,5$mrad, $\sigma_r \sim 5$mm, $\sigma_t \sim 500(1)$ps



First bending dipoles of DAΦNE act as spectrometers for scattered leptons (420 < E < 495 MeV)

HET is acquired asynchronously w.r.t. the KLOE-2 DAQ (Xilinx Virtex 5-FPGA), synchronization with the "Fiducial" signal from DAΦNE (each 325 ns) and the KLOE trigger

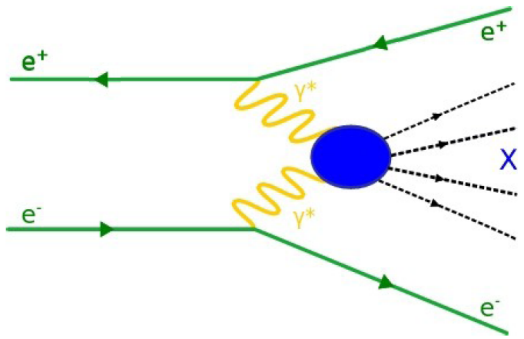
HET acquisition window corresponds to about 2.5 DAΦNE revolutions, data are recorded only when a KLOE trigger is asserted

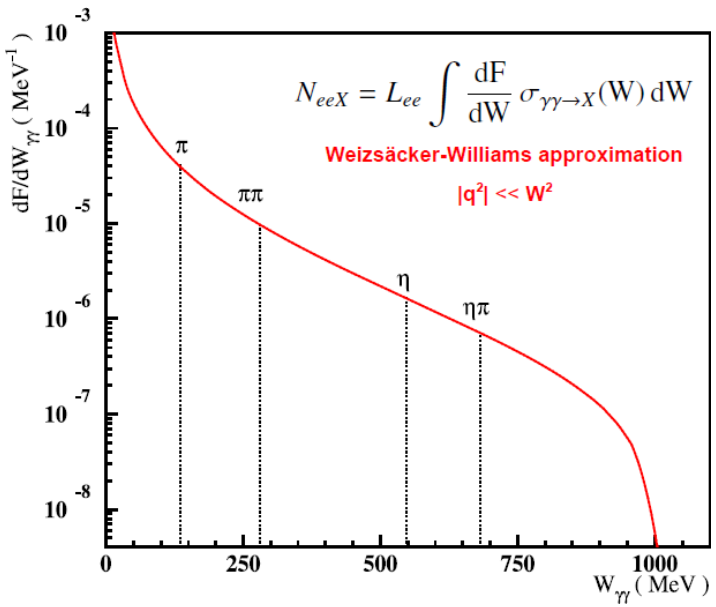
The analysis is based on the HET-KLOE coincidences and on the accidental-pure samples used for background modeling (shape and number)

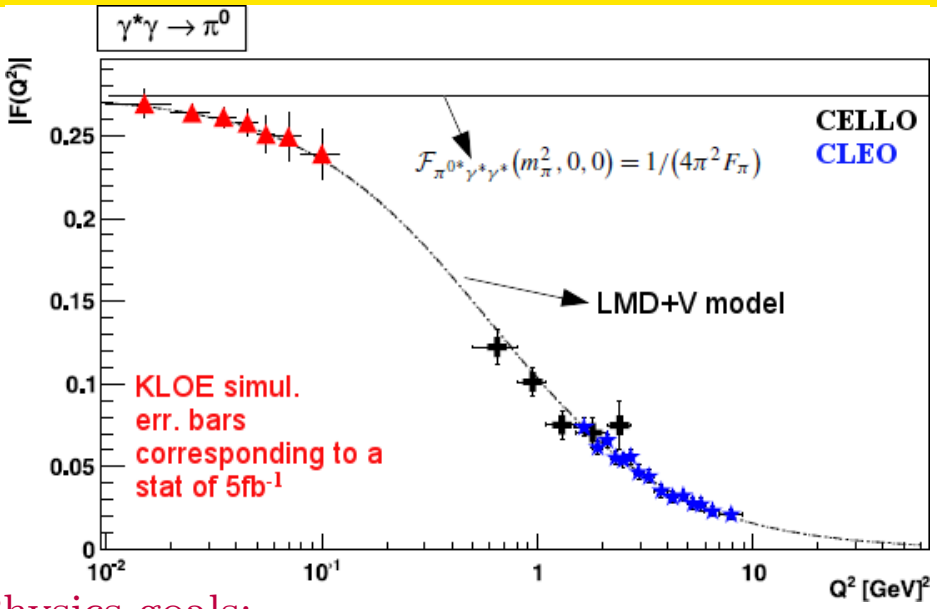
$\gamma\gamma$ Physics at KLOE-2 : Motivations

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

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

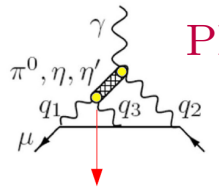






Physics goals:

- Precision measurement (1%) of the $\Gamma_{\pi^0\to\gamma\gamma}$
  $\Gamma^{\text{Th.}}_{\pi^0\to\gamma\gamma} = 8.09 \pm 0.11\text{eV}$ (1.4% precision)
- First measurements of the $F_{\pi^0\gamma^\star\gamma}(q^2, 0)$ in the space-like region for $q^2 < 0.1\,\text{GeV}^2$



$F_{PS^*\gamma^*\gamma^*}$
Phenomenological
Estimation

Physics motivation:
impact on the value and
precision of the $a_\mu^{\text{LbyL};\pi^0}$

Low angle radiative $A' \times \sigma_{\mathrm{Bha}}$

Reference period: Oct17-Dec17

Motivation: infer HET $A' = A \times \varepsilon$ with high precision

$P_0 = (1 - p_b)^N$

P_0: probability to have no signal in the HET

p_b: probability per bunch crossing to register one radiative Bhabha with the HET, linearly increasing with luminosity (L $[10^{32}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}]$)

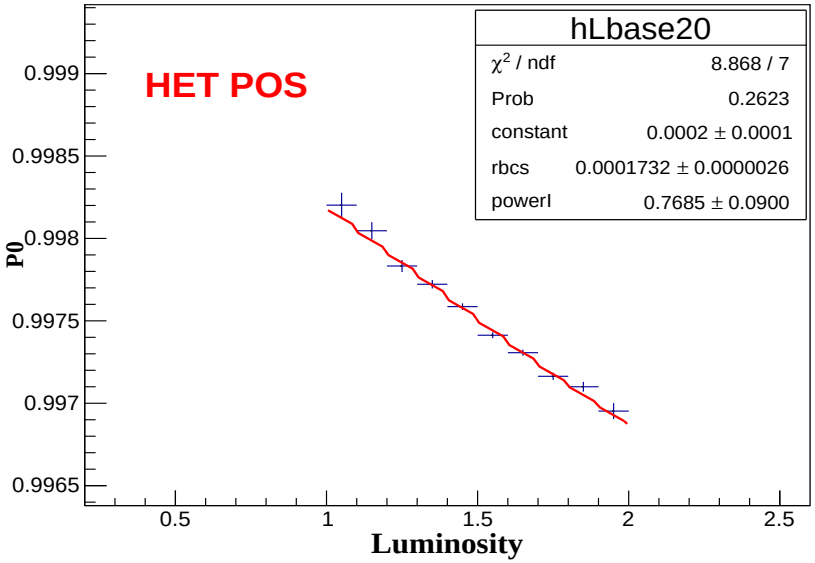
N: number of bunches considered in the measurement (N=22)

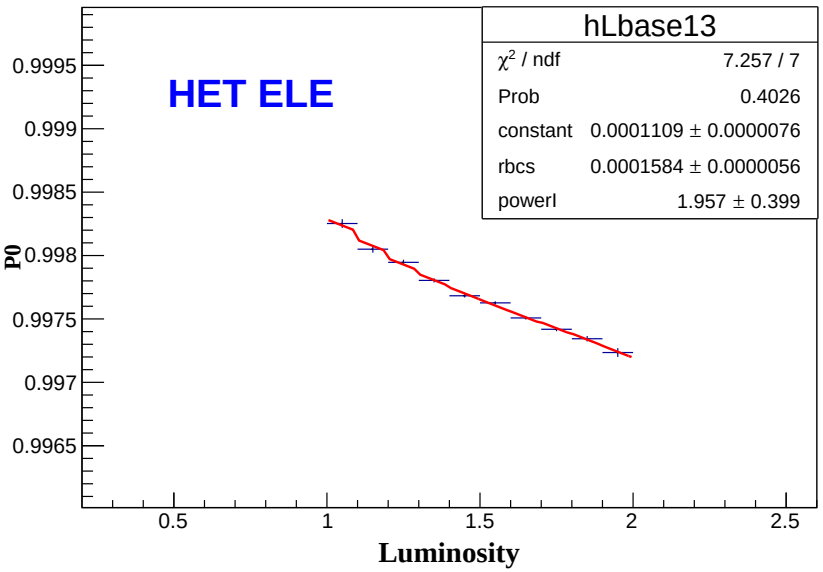
Data analyzed per bin of circulating DAFNE currents ($\mathrm{I_{e,p}}$ [A]) and per HET channel

Measured probability $\mathrm{p} = \mathrm{p_b} \times (\mathrm{T_{bunch}}/10\,\mathrm{ns})$

$A' \times \sigma_{\mathrm{Bha}}$ estimated by a fit to P_0 as a function of L measured by KLOE with Large Angle Bhabha

Fit function: $\mathbf{(1-p)^N}$,
$\mathbf{p = K + A' \times \sigma_{Bha} \times L}$, $\mathbf{K = \alpha \times I_{e,p}^{\beta}}$





Low angle radiative $A' \times \sigma_{\text{Bha}}$ Vs Bbbrem

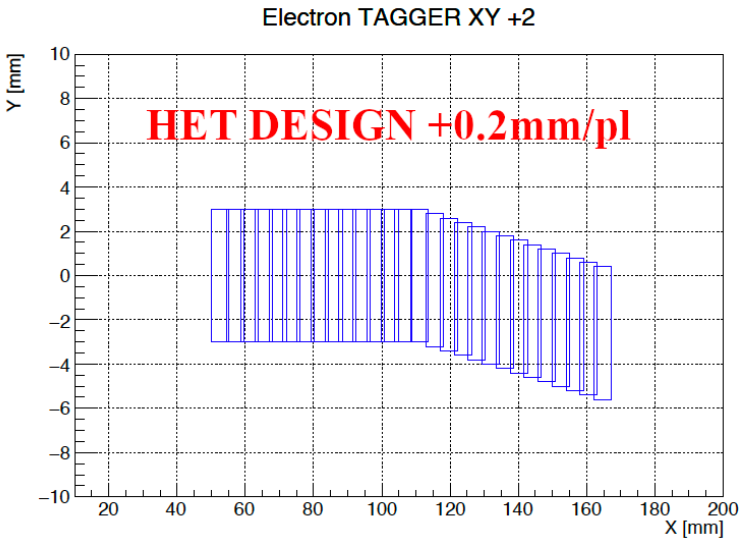
HET design:

Scintillators 1-14 are on the horizontal plane

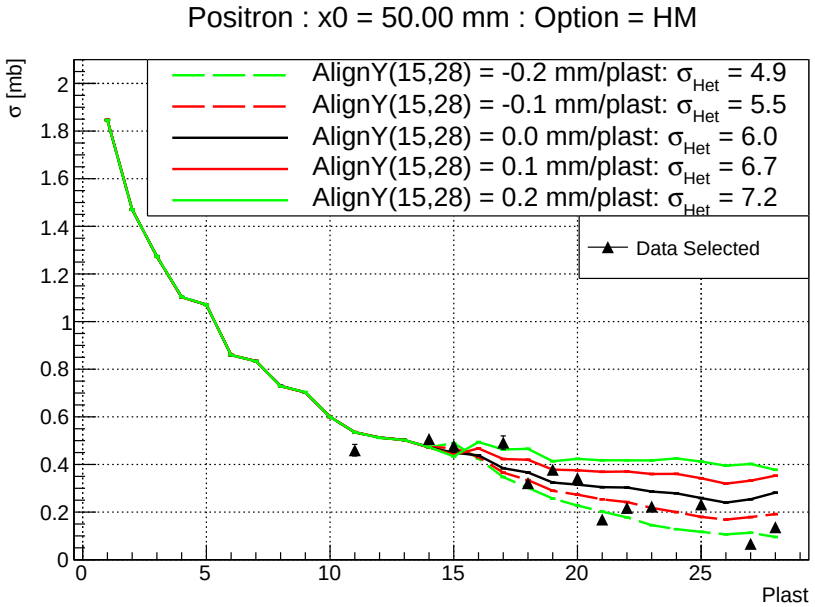
Scintillators 15-28 are displaced by a maximum of 2.8mm, in step of 0.2mm

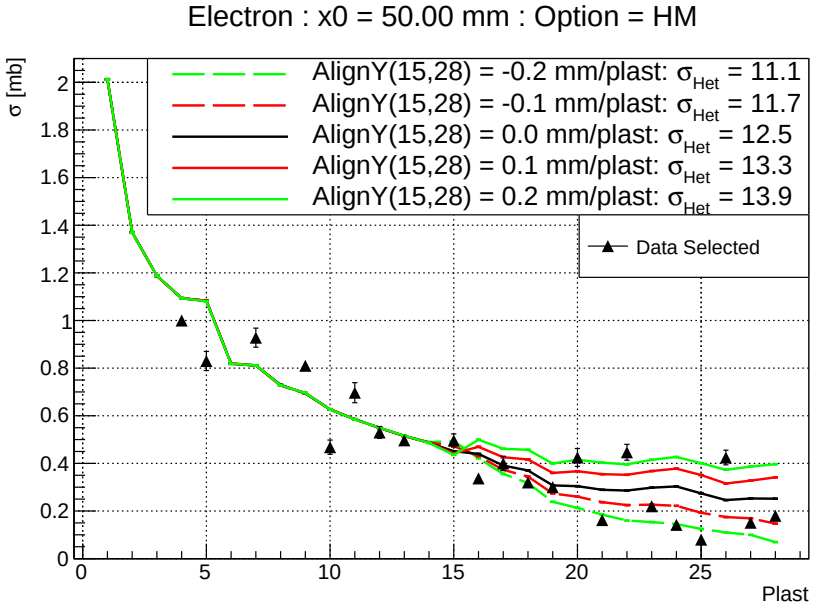
Different Y displacements correspond to different energy acceptances for the HET plastics

HET Acceptance can be derived through the "tuning" of the Y displacement in the simulation in order to reproduce the observed σ_{Bha} per scintillator spectrum



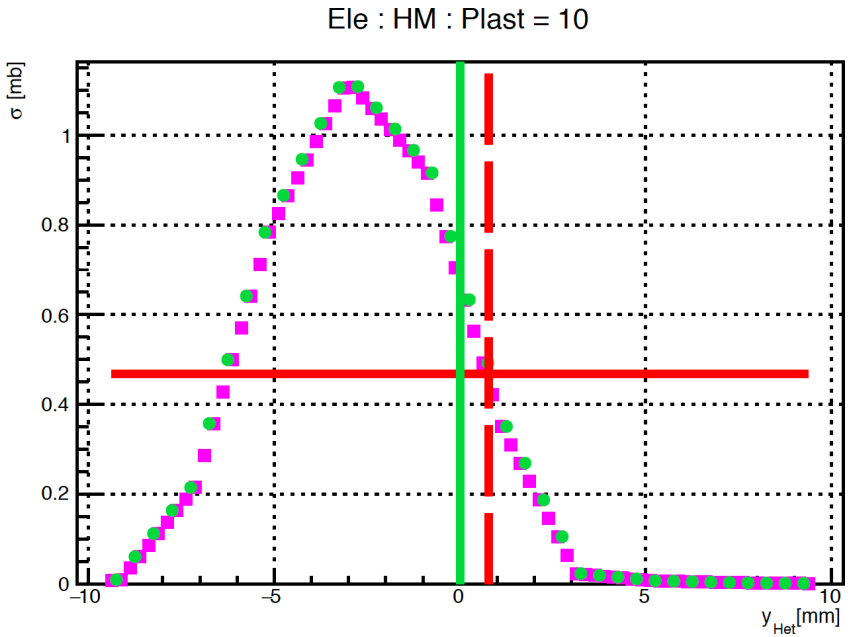
σ_{Bha} from Bbbrem compared with measurements

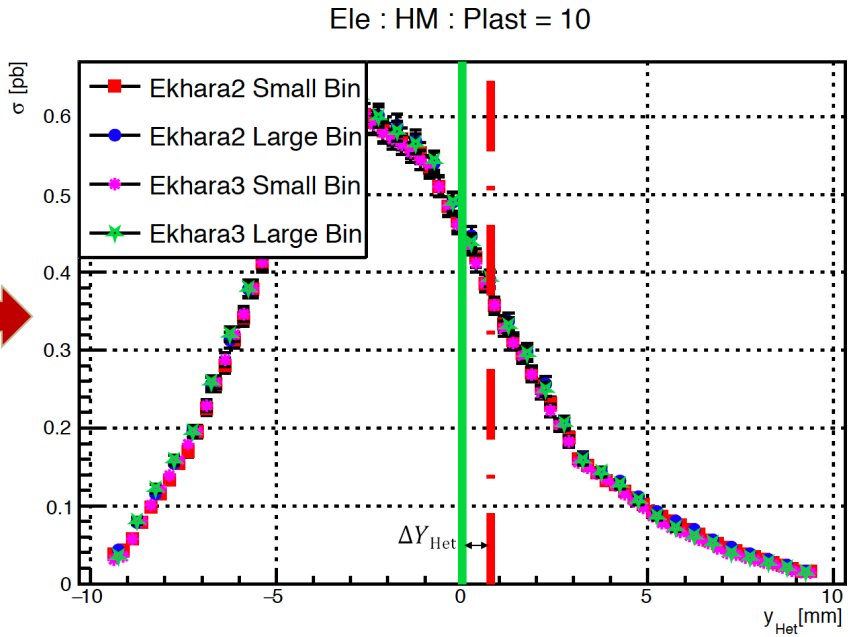




Data Selected: Data corrected for efficiency

BBBREM AND EKHARA $\sigma(Y_{Het})$ FOR A GIVEN X_{Het} (HET PLASTIC)





Magenta squares: BBBrem $\sigma(Y_{Het})$ (small binning)

Green circles: BBBrem $\sigma(Y_{Het})$ (large binning)

Vertical green line: Plastic design position

Horizontal red line: $A' \times \sigma_{Bha}$ measurement

Vertical dashed red line: Plastic position from $A' \times \sigma_{Bha}$ measurement

Vertical green line: Plastic design position

Vertical dashed red line: Plastic position from $A' \times \sigma_{Bha}$ measurement

Plastic position shifts, ΔY_{Het}, are derived for each data-taking period and then included in the $\gamma\gamma \to \pi^0$ signal simulation

$\gamma\gamma \to \pi^0$ 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:

-Simultaneous fits of Accidental+Signal/Accidental-pure (A+/A) samples in $M_{\gamma\gamma}$, $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$, $cos\theta_{\gamma\gamma}$

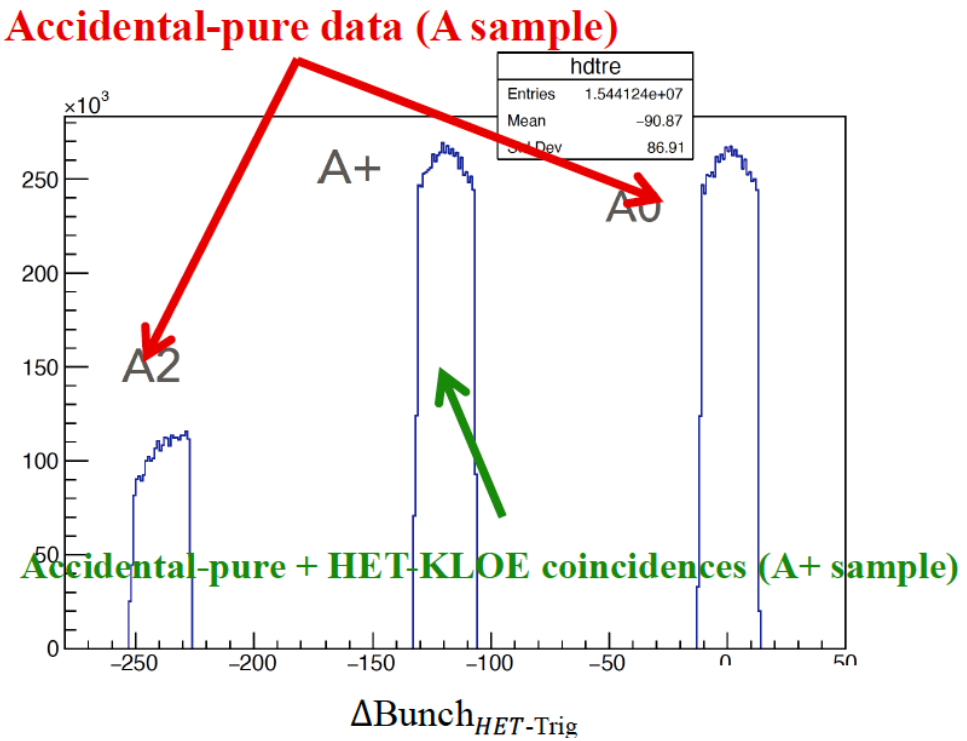
-Fit to A samples used to constrain the number of accidentals in A+

-Accidental pure sample (A) used to model background pdf

-Signal pdfs by Ekhara simulation, control samples and BDSIM transport of the leptons through the beam line

-$M_{\gamma\gamma}$ 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 fraction (0.55) fixed from Ekhara signal

Expected Pz Vs plastic position correlation included in the fits

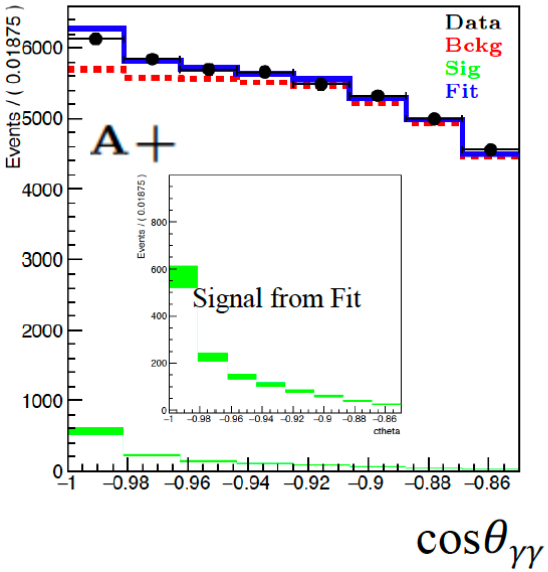


Signal Counting-Simultaneous Fits

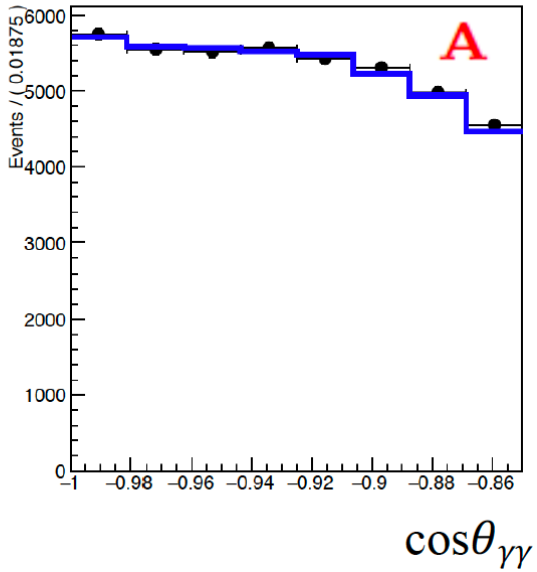
Premiminary Results :

8% precision on signal reached with about 1.5 fb^{-1} (17-18 data) and HET ele station most stable plastics (from 11 to 28)

$\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c < 0.3$ ns



$\cos\theta_{\gamma\gamma}$



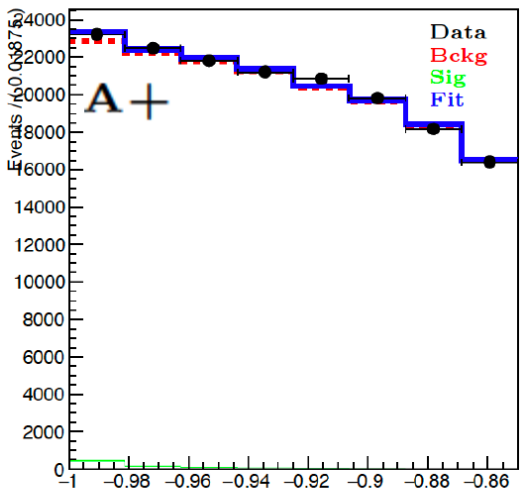
$\cos\theta_{\gamma\gamma}$

A+ $cos\theta_{\gamma\gamma}$ fits with signal/background-enriching cuts

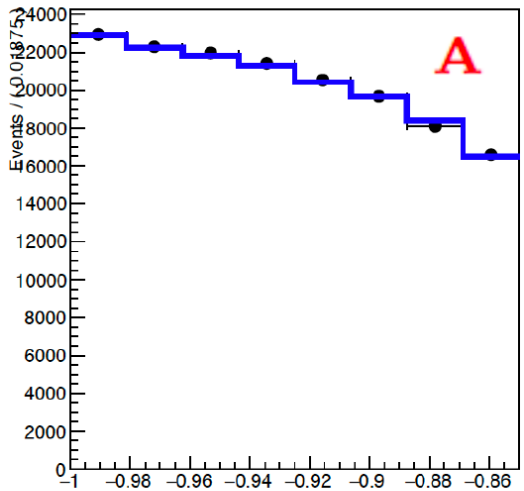
2017-18 data sample

HET-KLOE coincidence window: 4 × 2.7 ns

$\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c > 0.3$ ns



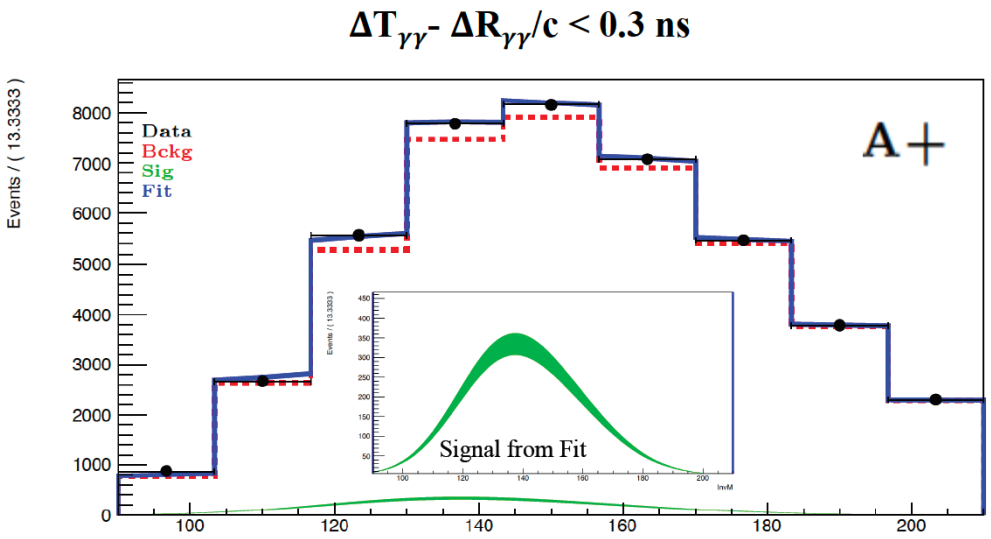
$\cos\theta_{\gamma\gamma}$



$\cos\theta_{\gamma\gamma}$

Signal Counting-Simultaneous Fits

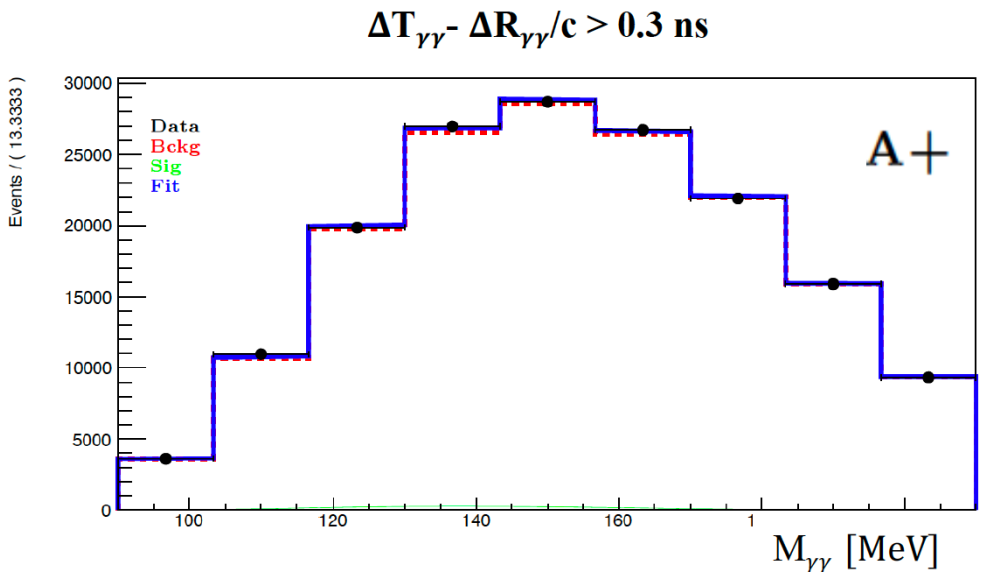
Preliminary



A+ InvM fits with signal/background-enriching cuts

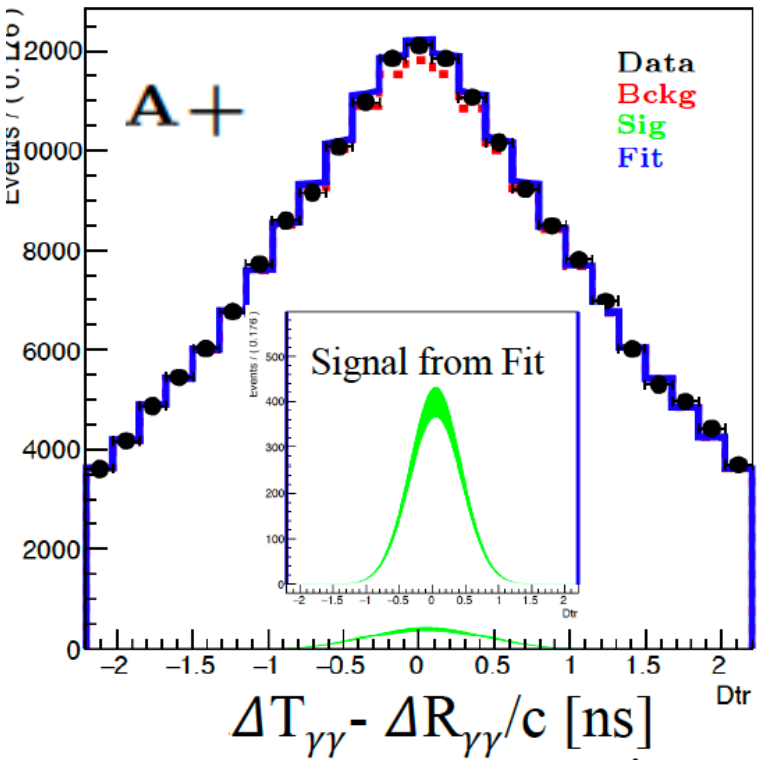
2017-18 data sample

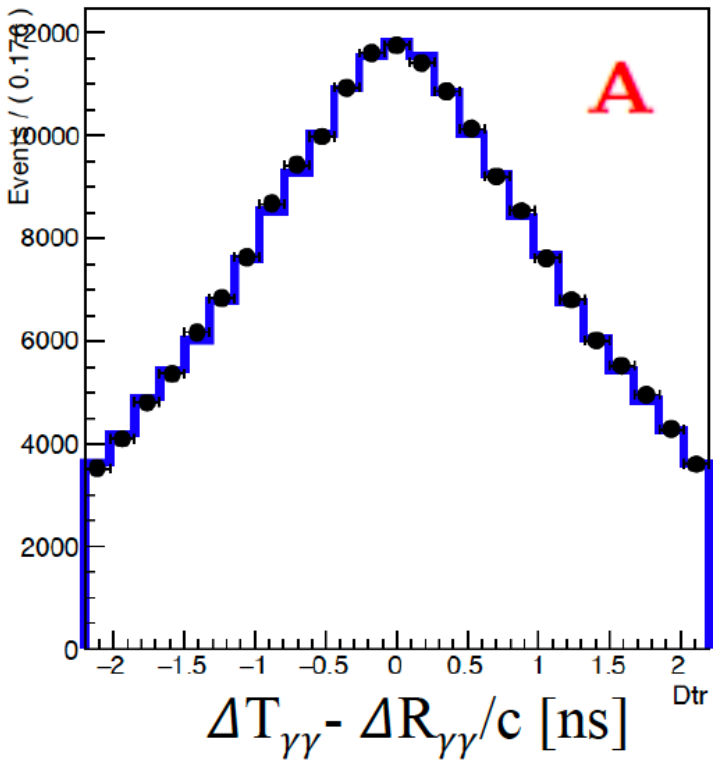
HET-KLOE coincidence window: 4×2.7 ns



Signal Counting-Simultaneous Fits

Preliminary



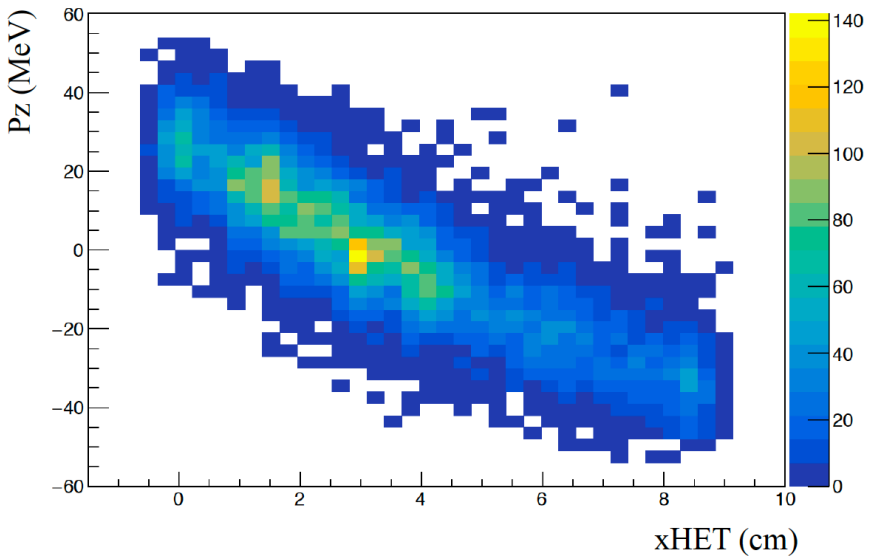


2017-18 data sample, A+ and A $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$ fits
HET-KLOE coincidence window : 4×2.7 ns

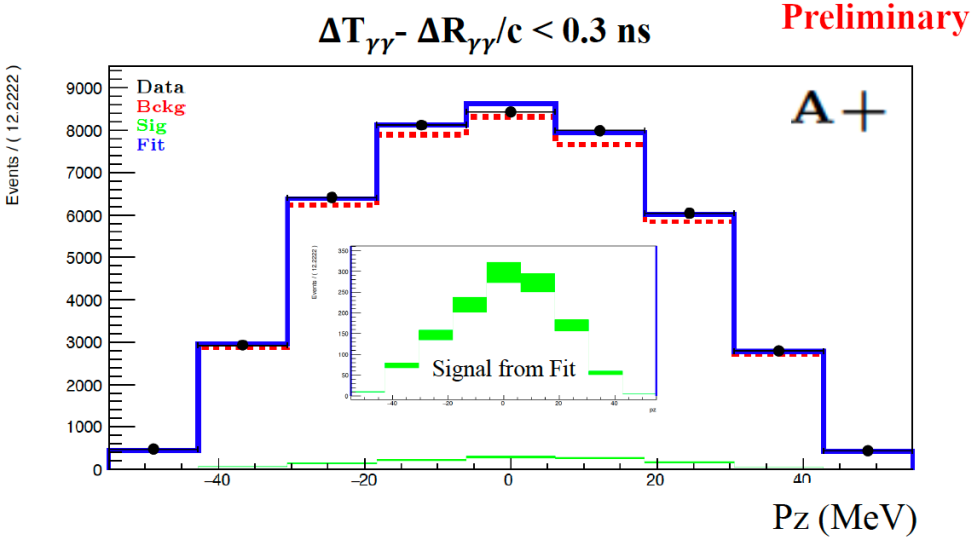
Signal Counting-Simultaneous Fits

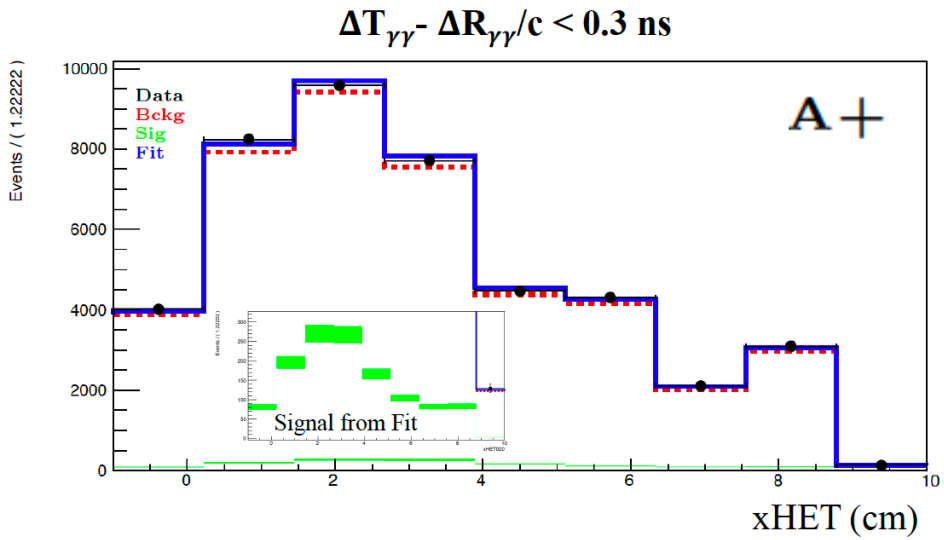
Simultaneous fit of bidimensional Pz-plastic positions (xHET) distribution
Acceptance per channel measured with low angle radiative Bhabha in the HET

Expected Pz-xHET signal correlation derived from acceptance studies



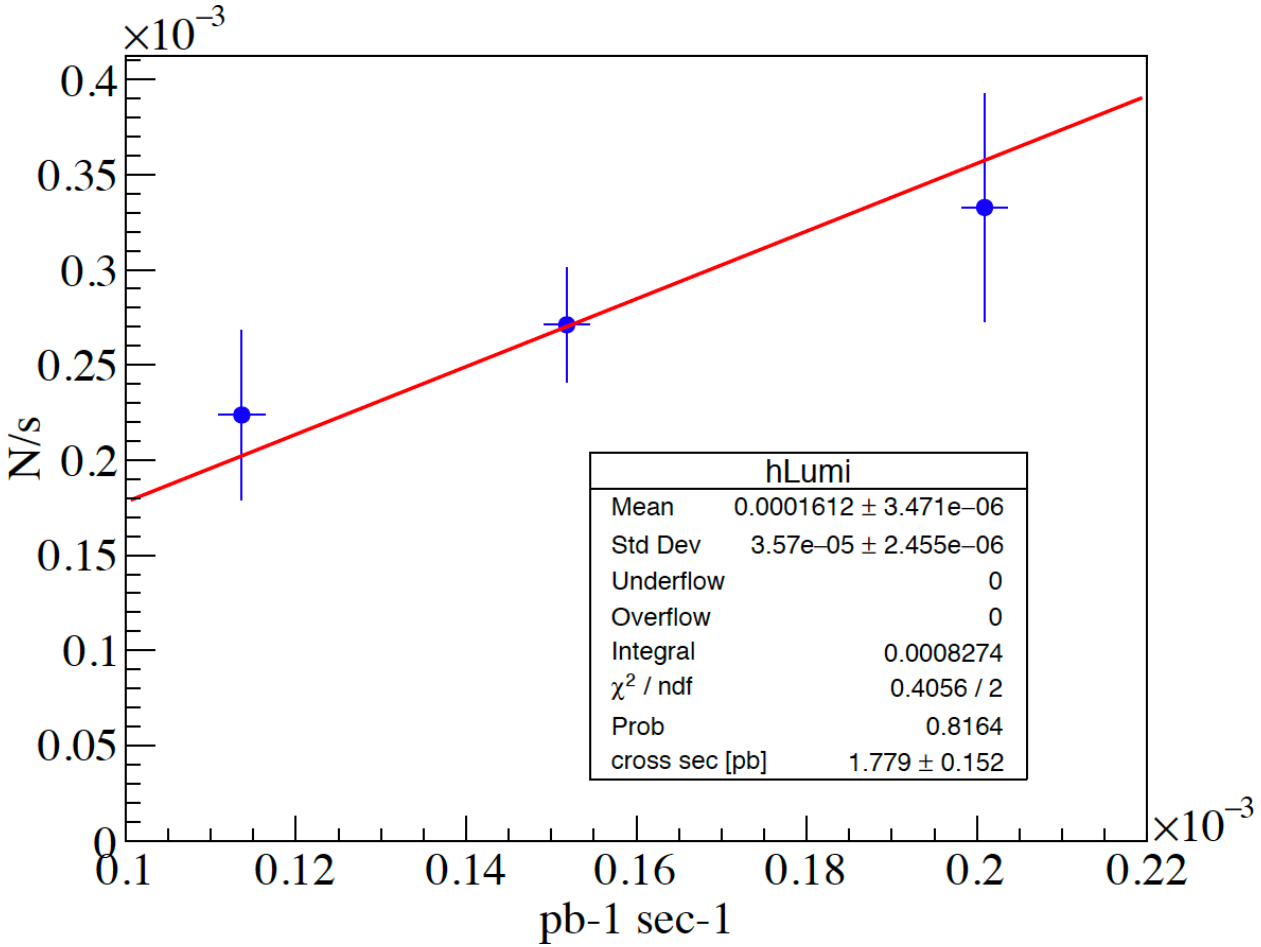
Preliminary





π^0 events vs Instantaneous Luminosity

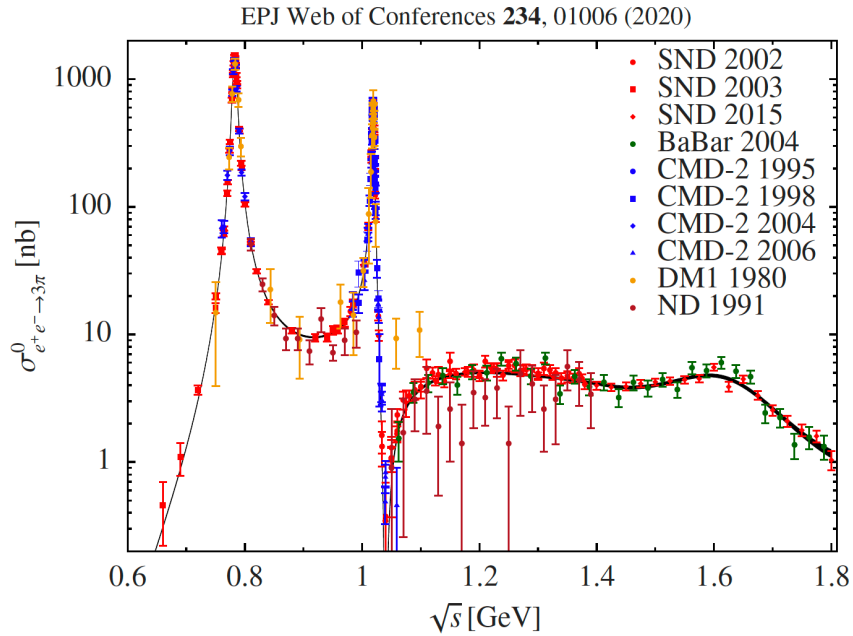
We analyzed the behavior with L of signal events extracted from the fits for a sub sample of 2017-18 data, the trend is the expected one

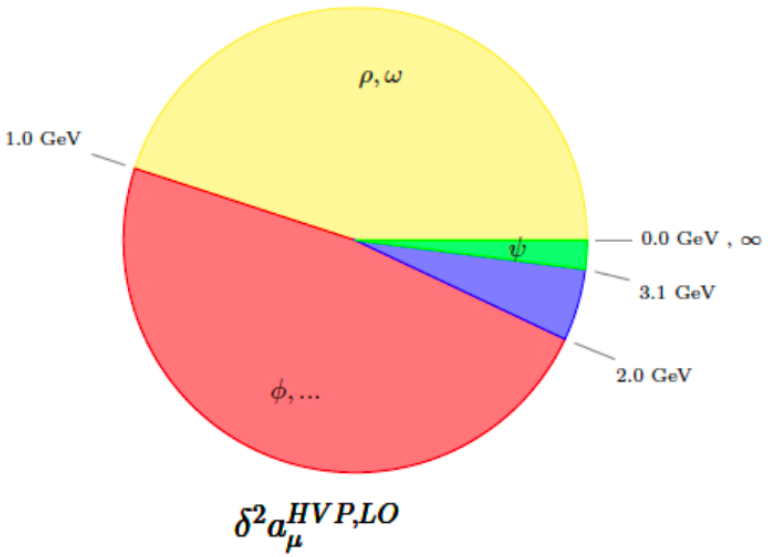


Preliminary measurement of the $\gamma\gamma \to \pi^0$ cross section within October

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

- 3π channel encounters the second largest contribution on $a_\mu^{\rm HVP}$ at the leading order both in absolute values and uncertainties.
- Cross section measurement of $e^+e^- \to 3\pi$ is feasible using ISR technique with fewer energy points at KLOE
- Improve lack of ISR data samples in low energy region, complementary results to direct energy scans
- Analysis ongoing on 1.72 fb^{-1} on-peak and $\sim$ 246 pb^{-1} off-peak data samples





Physics goals:

- to extract the peak cross section of the process $e^+e^- \to V \to 3\pi$, involving vector resonances V $= \phi, \omega$
- to measure cross section of non-resonant process $e^+e^- \to \gamma^* \to 3\pi$
- to measure product of branching fractions B$(\omega \to e^+e^-) \times$ B$(\omega \to 3\pi)$

ANALYSIS SELECTION

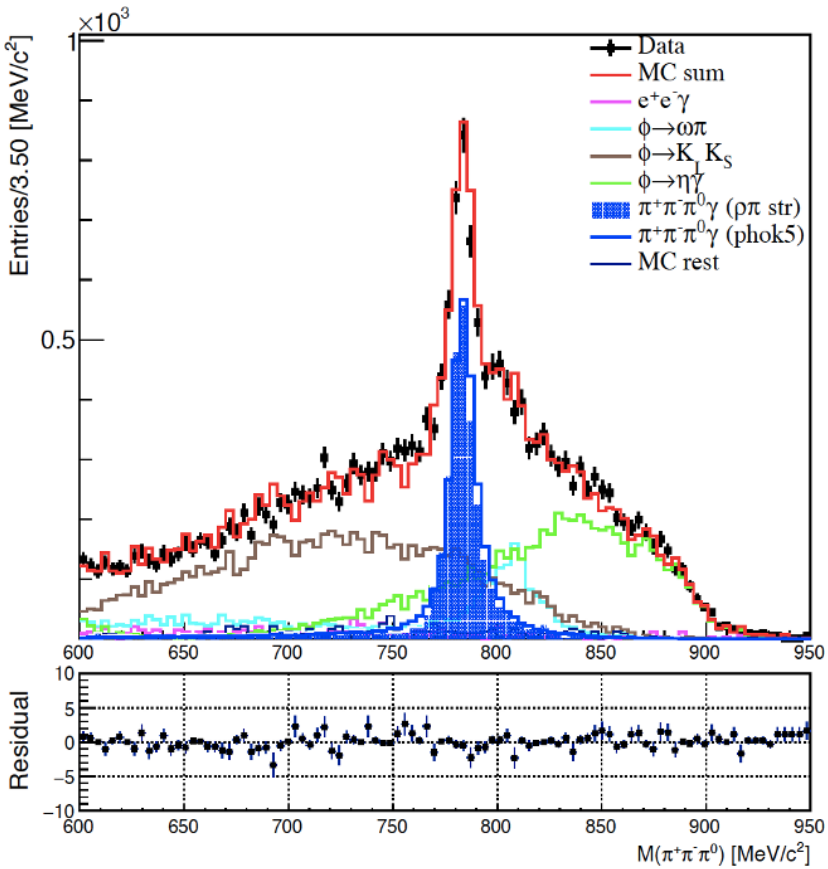
Sample statistics: about 1.7 fb^{-1}

Event selection:

- KSKL stream
- at least two tracks with opposite curvature
- three neutral clusters with $|cos\theta| < 0.92$, Eclu > 15 MeV,
- Tclu-Rclu/c <min $(2,5\sigma_t)$ ns
- Two tracks with opposite curvature extrapolated inside a cylinder with $\sqrt{x^2+y^2} < 4\,\text{cm}$ and $|Z| < 10\,\text{cm}$

Additional selections:

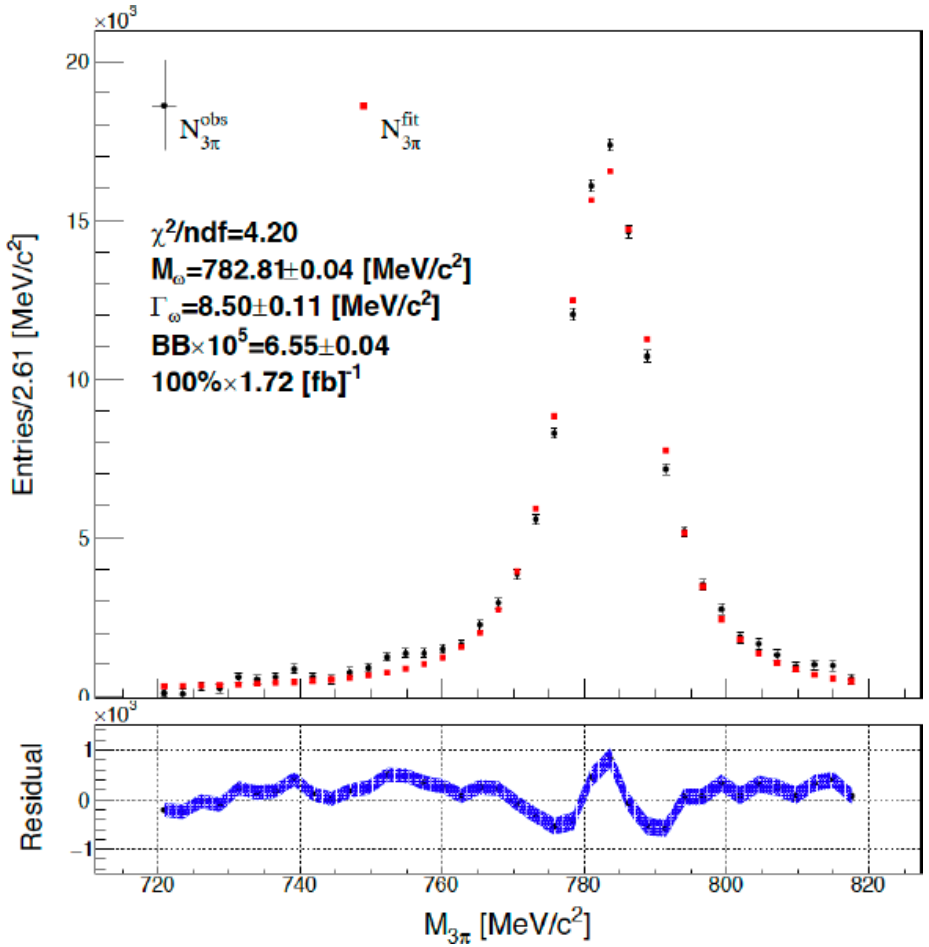
- Kinematic fit with seven constraints χ^2_{7C}C < 26 rejects Kaons
- $\theta_{\gamma\gamma} < 140^\circ$ to reject Bhabha events
- M > 300 MeV to reject $\rho\pi$ events with M from $\sqrt{s} - \sqrt{M^2+p_+^2} - \sqrt{M^2+p_-^2} - |\vec{p_\phi} - \vec{p_+} - \vec{p_-}| = 0$
- $\beta_\pi < f_\beta(M_{2\pi})$ to reject further backgrounds, with : $f_\beta(M_{2\pi}) = 1.98 + \frac{1}{1-\exp(\frac{M_{2\pi}-0.8}{0.11})}$



Good Data-MC agreement

Preliminary results

Cross section extraction in the ω region in progress:



Preliminary fit obtained with a simple BW line shape convoluted with smearing matrix
Integrated luminosity and ISR correction factors taken into account
Refinement of the fit model in progress

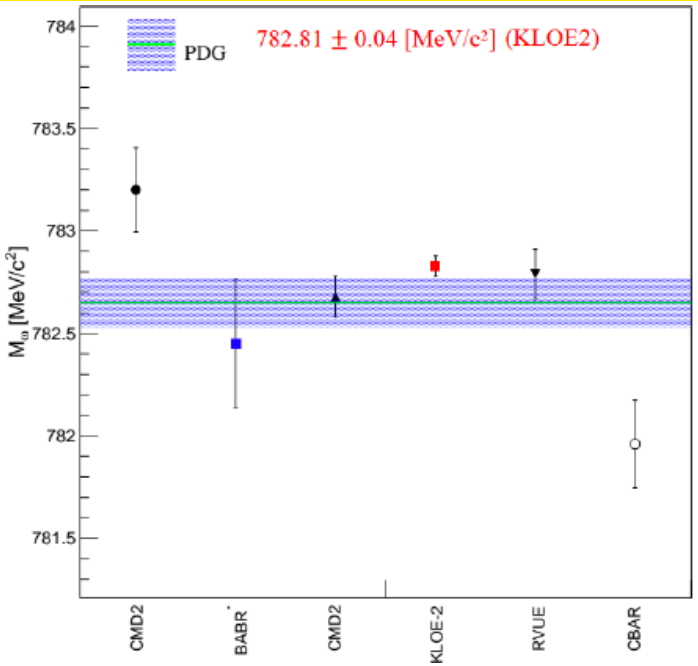
Preliminary results

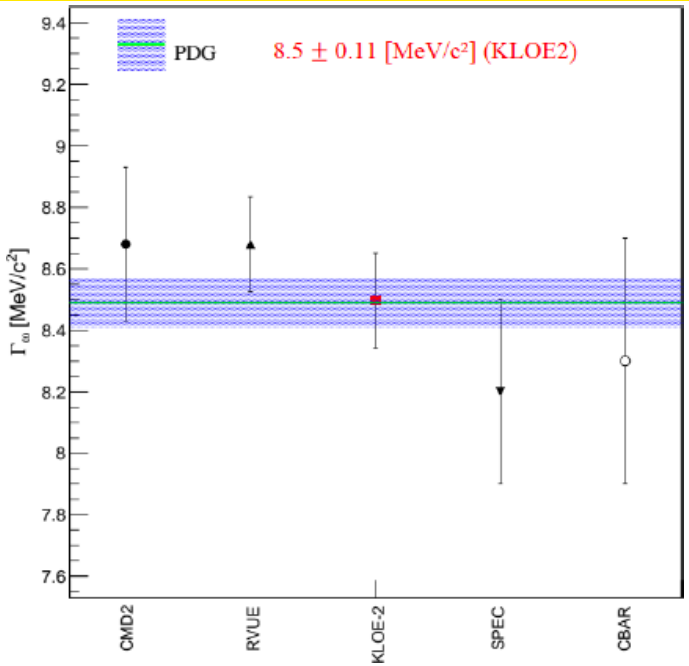
KLOE-2 preliminary results:

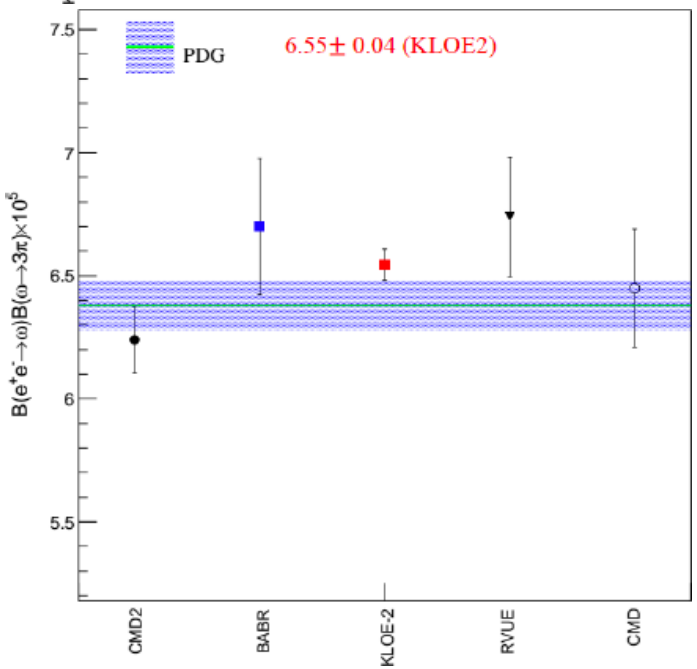
Luminosity $[\text{fb}]^{-1}$	M_ω $[\text{MeV}/c^2]$	Γ_ω $[\text{MeV}/c^2]$	$\mathscr{B}_{ee}\mathscr{B}_{3\pi} \times 10^5$ [-]
1.7	782.81 ± 0.04	8.50 ± 0.11	6.55 ± 0.04
PDG	782.65 ± 0.12	8.49 ± 0.08	6.38 ± 0.10

Sources of systematic errors identified
Systematic error evaluation ongoing

Preliminary results







Conclusions

$\gamma\gamma \to \pi^0$ cross section measurement:

- Measurements of the raw low angle radiative Bhabha cross section obtained for both stations for the whole reconstructed data set (2015-16-17-18).
- HET Acceptance evaluation, for both low angle radiative Bhabha's and $\gamma\gamma \to \pi^0$ events, in advanced state.
- 8% precision on signal counting achieved with HET ele data acquired between 2017 and 2018 (1.5 fb^{-1}), with plastics from 11 to 28 in a KLOE-HET coincidence window of 4 bunches and, taking into account Pz Vs xHET correlation.
- Preliminary cross section measurement within October.

$e^+e^- \to \pi^+\pi^-\pi^0\gamma_{ISR}$ cross section measurement:

- $\sigma_{3\pi}$ cross section measurement, using the ISR method and KLOE data corresponding to 1.7 fb^{-1}, in progress.
- Preliminary results, obtained by fitting data with a simple BW model convoluted with the smearing matrix, are promising.
- Refinement of the fit model in progress.
- Results are expected to improve PDG world average.

Thank You!