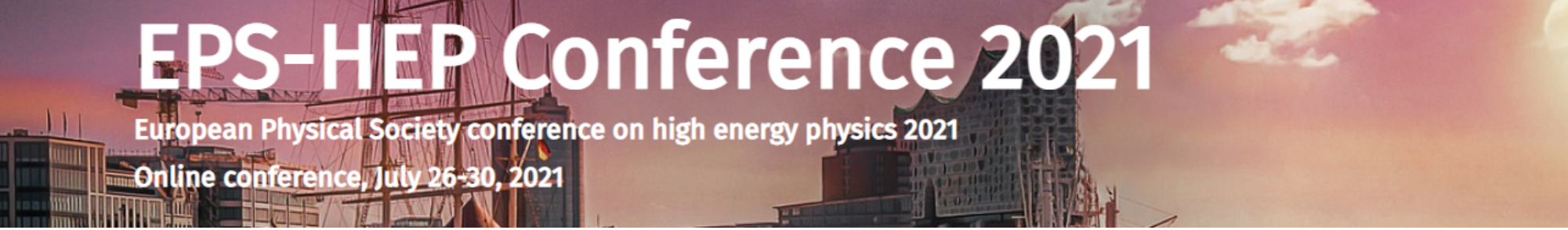


Hadron Physics at KLOE/KLOE-2

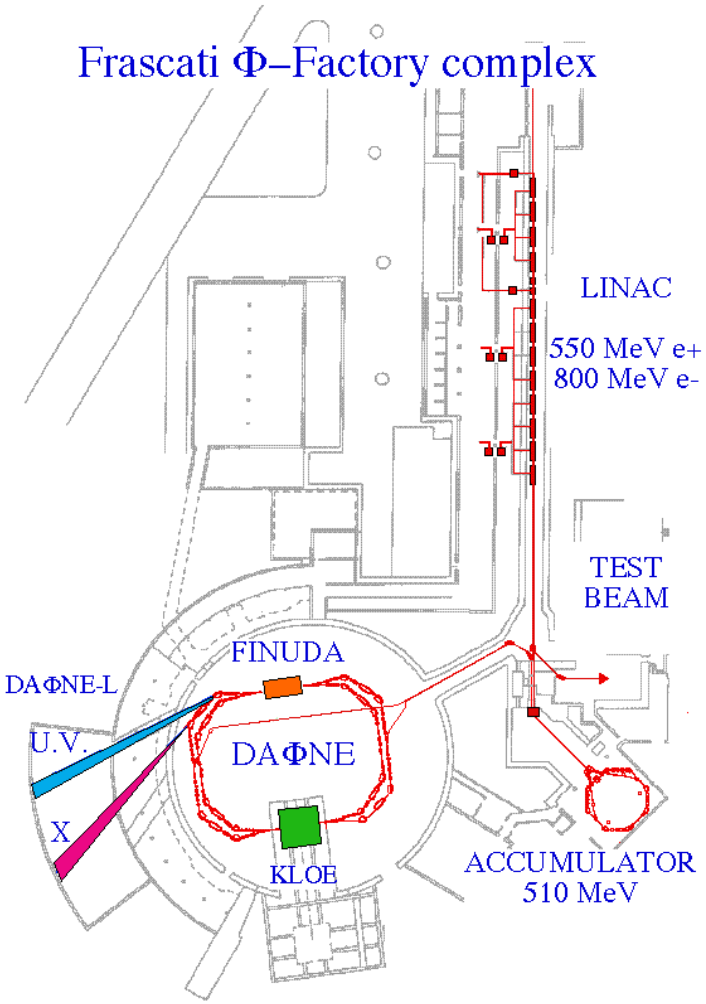
Bo Cao

On behalf of the KLOE-2 Collaboration

July 28, 2021

Outline

DAΦNE Collider



$\sqrt{s} \sim 1.02$ GeV

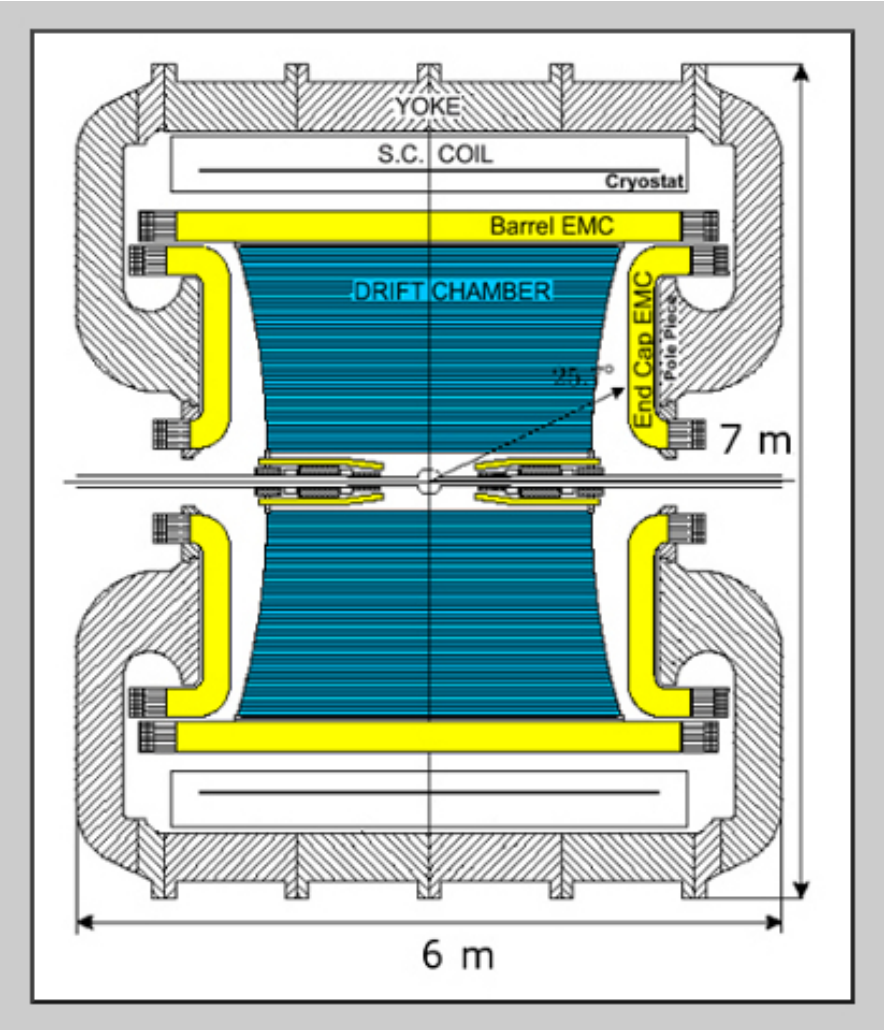
Phase-I (1999-2006)

- $\mathcal{L}_{\text{peak}} = 1.4 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$
- $\int \mathcal{L}\ \text{dt}\ > 2.5\ \text{fb}^{-1}$
- $\theta_{\text{cross}} = 2 \cdot 12.5$ mrad

Phase-II Upgrade

- Crab waist collision scheme
- Large angle beam crossing; reduced horizontal beam size
- $\theta_{\text{cross}} = 2 \cdot 25$ mrad
- $\mathcal{L}_{\text{peak}} = 2.0 \cdot 10^{32}\ \text{cm}^{-2}\text{s}^{-1}$

KLOE Detector



Superconducting coil, ~ 0.52 T

Drift Chamber

- Gas mixture: 90% He, 10% C4H10 (isobutane)
- sense/field wire
- $\sigma_{xy} \sim 150\ \mu$m; $\sigma_z \sim 2$ mm, $\frac{\sigma_{p_t}}{p_t} < 0.4\%$ $(45° < \theta < 135°)$

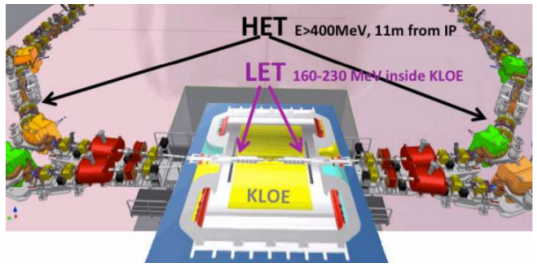
Electromagnetic Calorimeter

- lead/scintillating fibers
- covers 98% of 4π solid angle
- $\frac{\sigma_E}{E} = \frac{5.7\%}{\sqrt{E(\text{GeV})}}$,
  $\sigma_T = \frac{57\ \text{ps}}{\sqrt{E(\text{GeV})}} \oplus 140\ \text{ps}$

KLOE-2 Upgrade

Taggers

- Low/High Energy Tagger (LET/HET)
  LET: LYSO with SiPM read out/HET:
  Scintillator + PMT



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  LET: LYSO with SiPM read out/HET:
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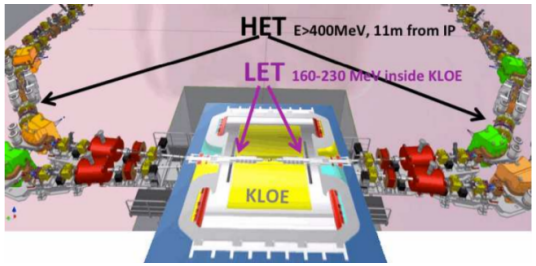
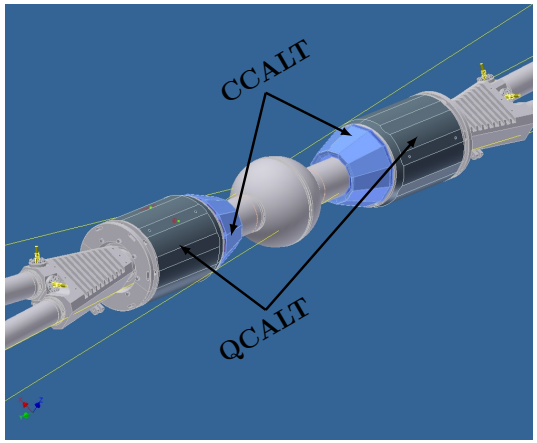
Calorimeters

- Quadrupole Calorimeter with Tiles (QCALT), SiPM read-out: Increase the acceptance of K_L decays
- Crystal Calorimeter with Timing (CCALT), LYSO-cristals: Increase the acceptance for low-angle photons from IP.





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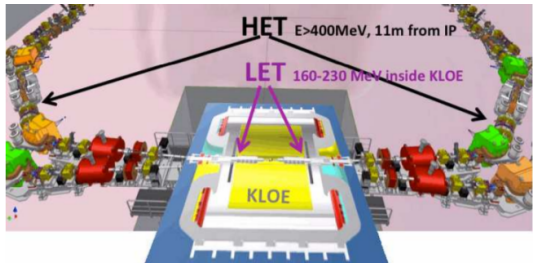
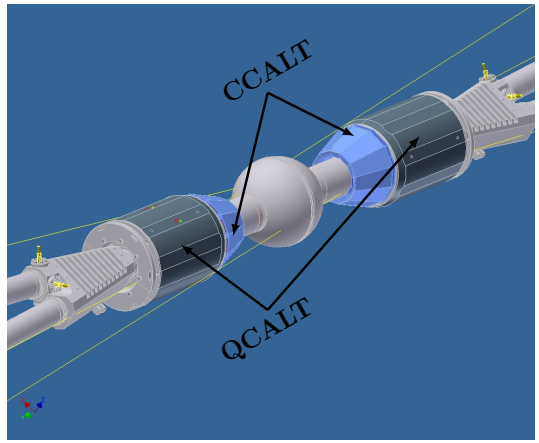
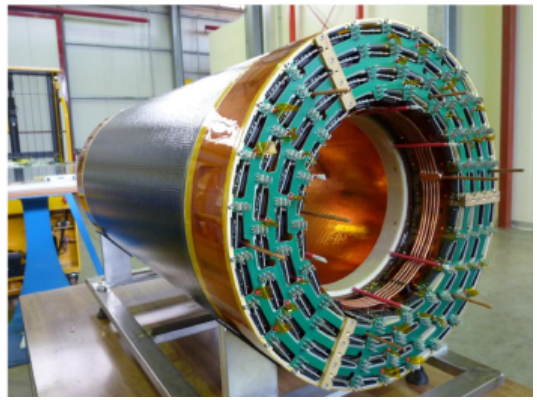
- Crystal Calorimeter with Timing (CCALT), LYSO-cristals: Increase the acceptance for low-angle photons from IP.

Inner Tracker (IT)

- Gas Electron Multiplier (GEM), first cylindrical GEM ever built.
- Larger acceptance for low p_t tracks to improve vertex resolution at IP.

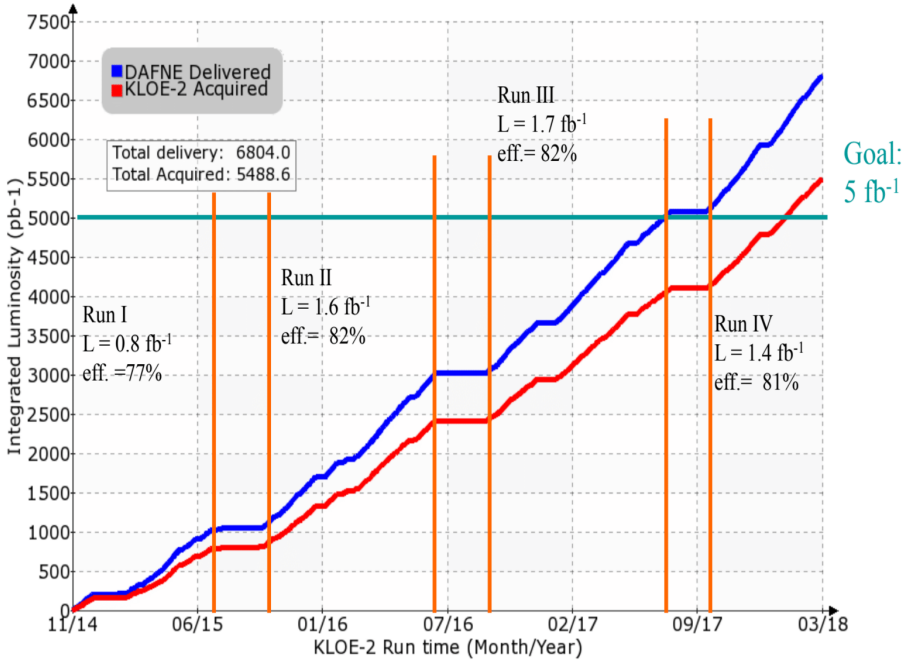






KLOE-2

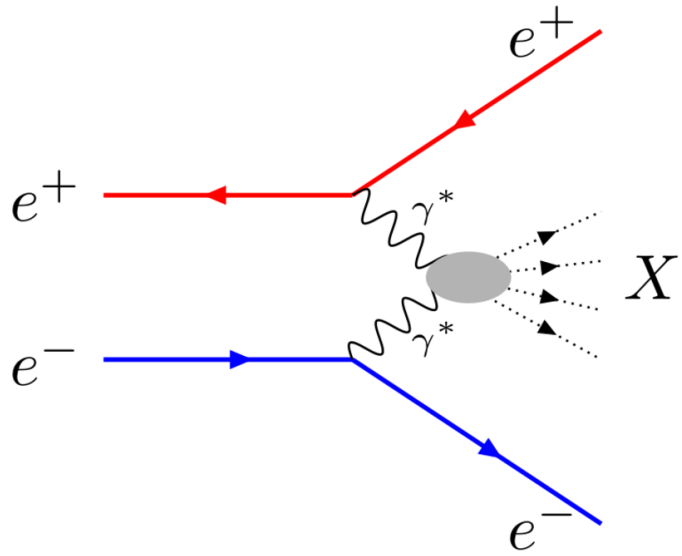
- Data taking period (2014-18) from RunI-III, collected $\mathcal{L}_{\rm int} > 5$ fb^{-1}.
- Reconstruction ~ 3 fb^{-1} of good-quality completed. MC generation in a good shape.
- Several on-going "new"-data driven analyses, high precision measurements.



$\gamma\gamma$ Physics

Motivation

- $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$, $C(X) = +1$, $X = \pi^0, \eta, \pi\pi$.
  Test low-energy QCD.



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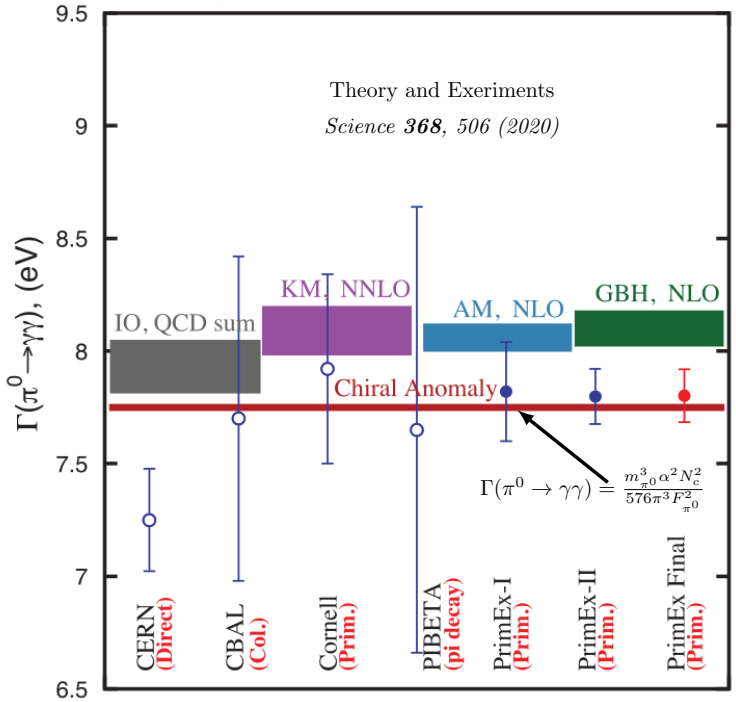
- $e^+e^- \to e^+e^-\gamma^*\gamma^* \to e^+e^-X$, $C(X) = +1$, $X = \pi^0, \eta, \pi\pi$. Test low-energy QCD.
- High precision measurement of the π^0 width $\sim 1\%$ accuracy. Collider approach (alternative PrimEx).



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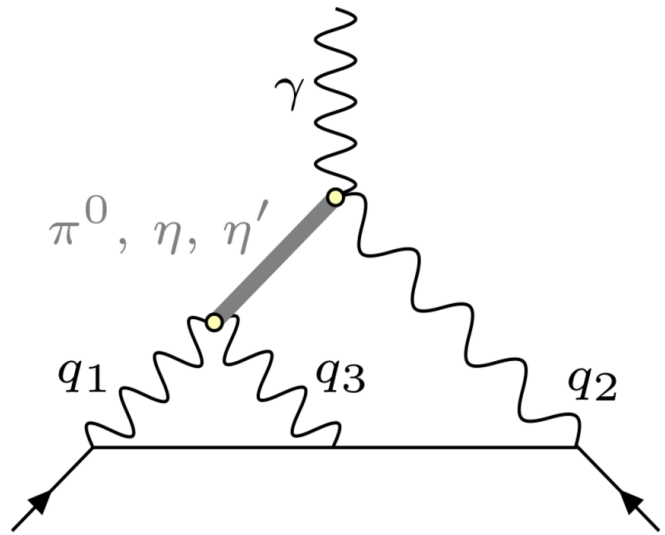
- High precision measurement of the π^0 width $\sim 1\%$ accuracy. Collider approach (alternative PrimEx).
- Improve SM prediction on $(g-2)_\mu$, TFF impact on $a_\mu^{\mathrm{LbyL};\pi^0}$.



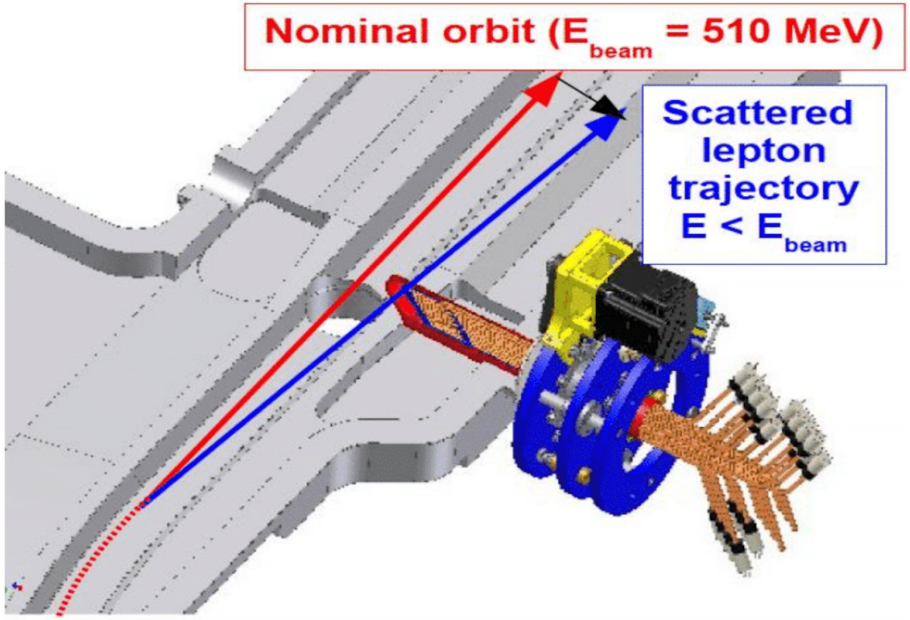
$\gamma\gamma$ Physics

Data Status

- ~ 1.5 fb^{-1} data sample collected during RunIII-IV (2017-18).

Set up and Signal Selection

- HET Tagging, synchronized acquisition, time window $\sim 2.5\sigma_t$ (DAΦNE).
- Single-arm selection. Bunch crossing selection, 2 photon sample associated to the same bunch crossing. Time window 40 ns (KLOE trigger).



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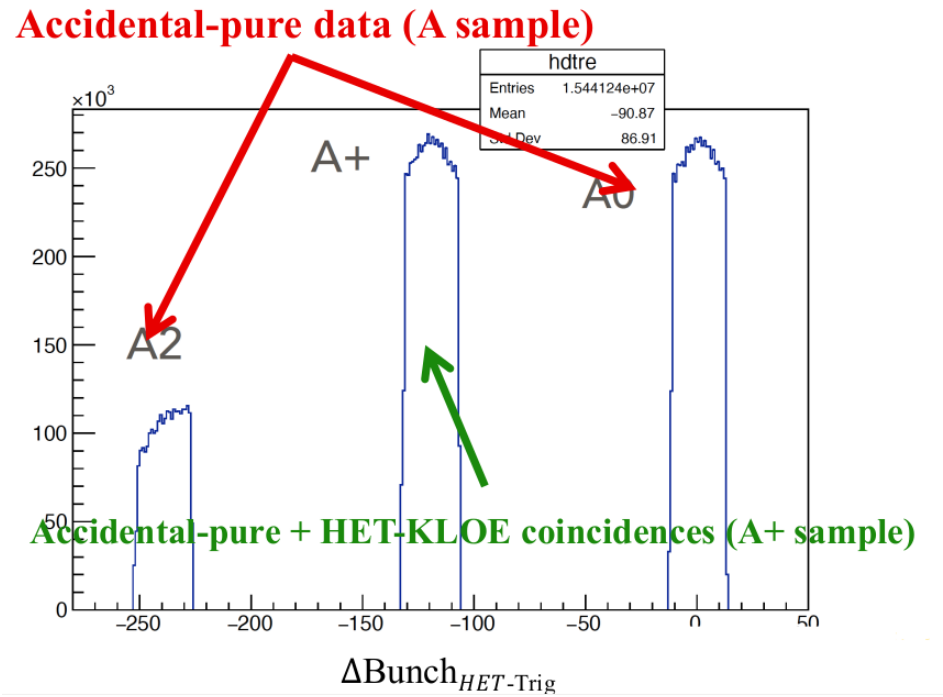
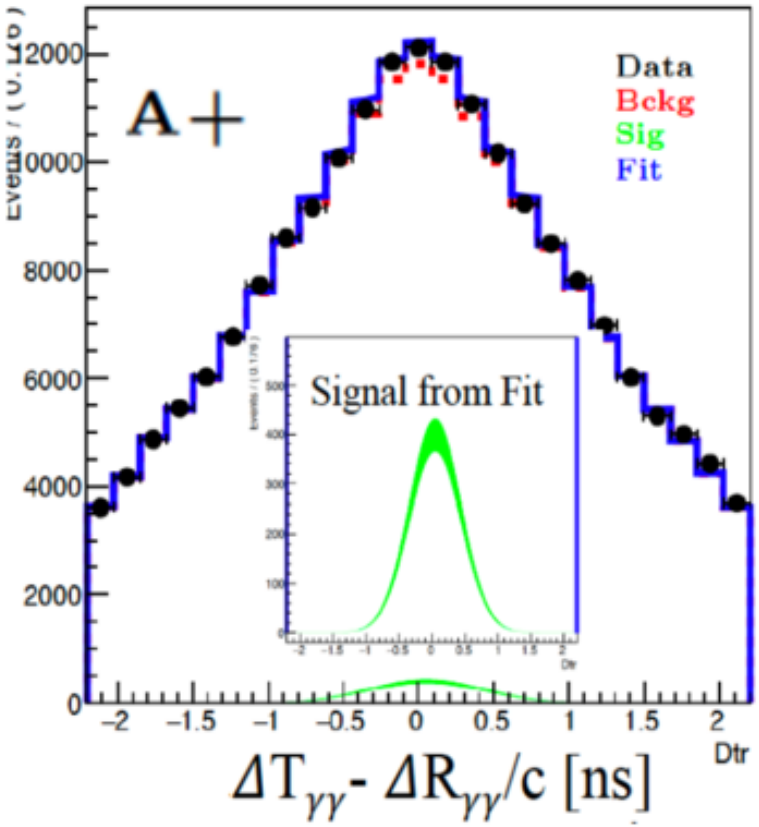
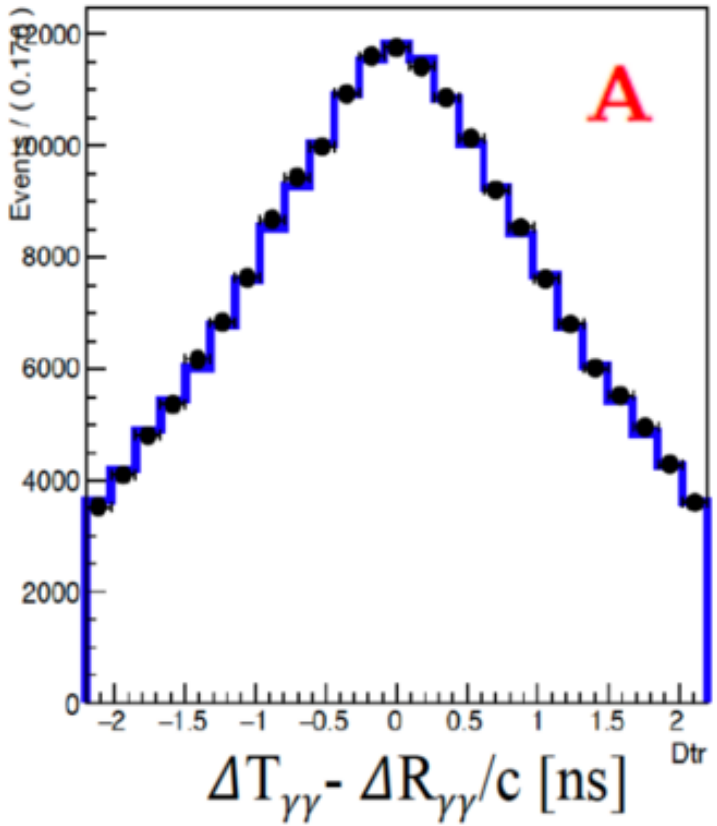
- Single-arm selection. Bunch crossing selection, 2 photon sample associated to the same bunch crossing. Time window 40 ns (KLOE trigger).
- Signal(HET*KLOE coincidences), accidental pure (A0/A2 sample) w.r.t the accident+signal (A+ sample).



Analysis Strategy

- Simultaneous fits of A+/A samples in $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$. Constrain # of accidentals in A+. HET-KLOE coincidence window: 4×2.7 ns.

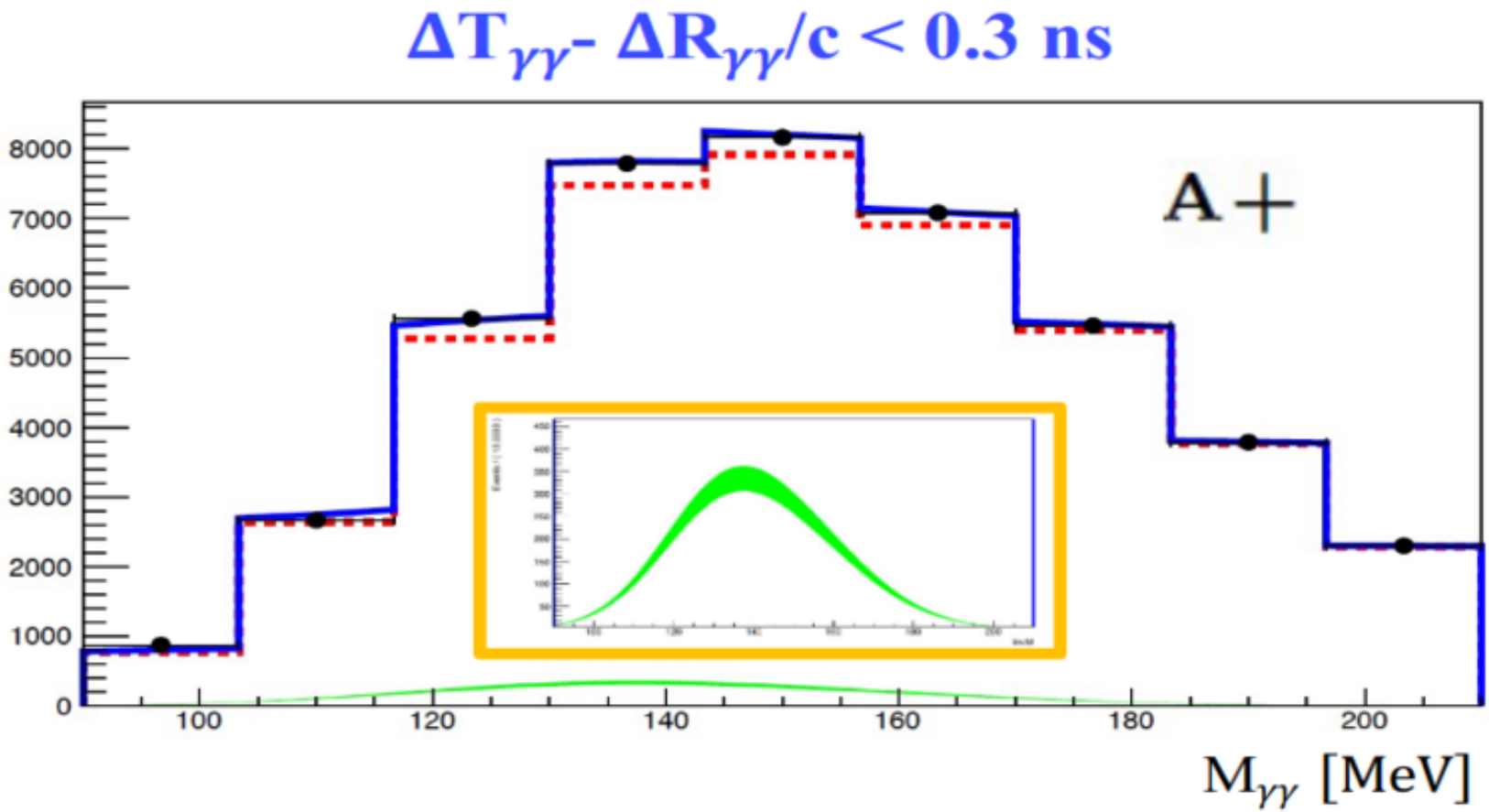




$\gamma\gamma$ Physics

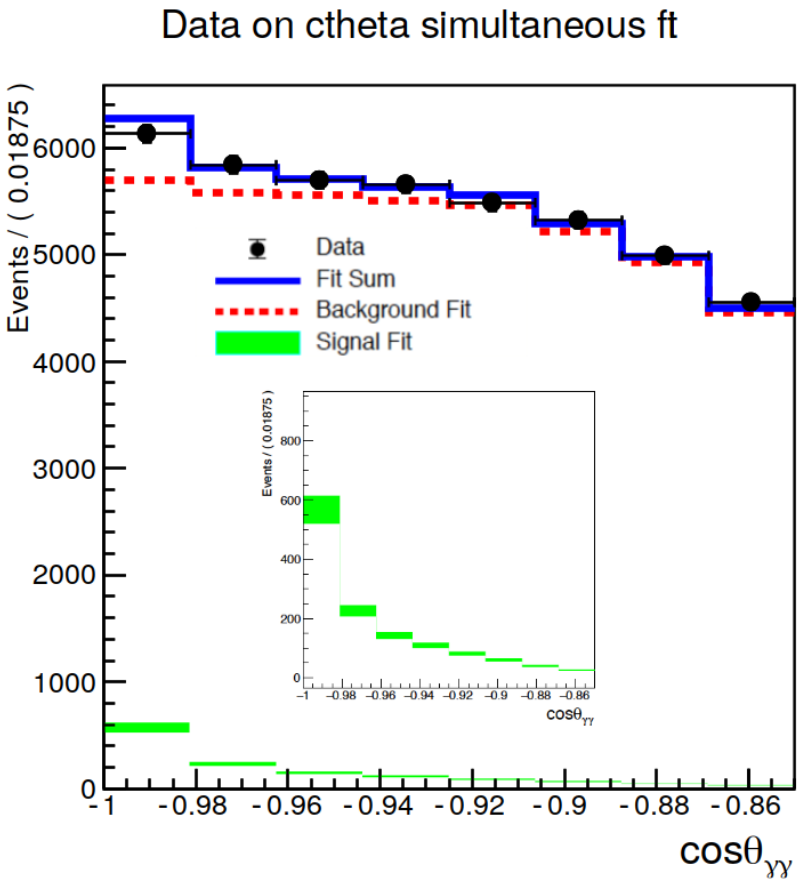
Analysis Strategy

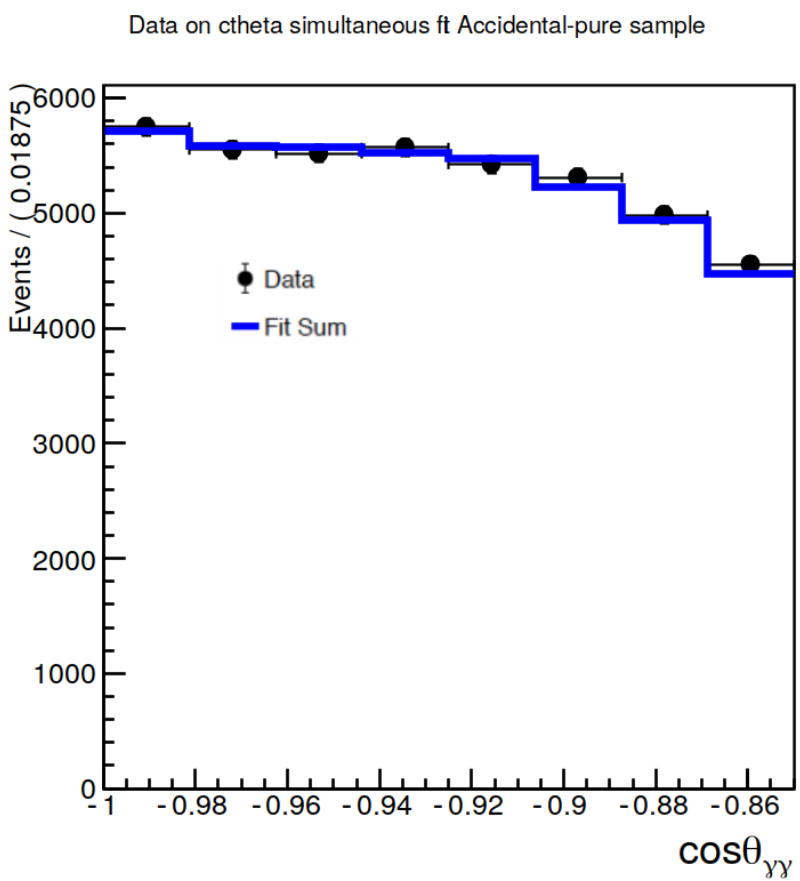
- Simultaneous fits of A+/A samples in $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c$. Constrain # of accidentals in A+. HET-KLOE coincidence window: 4×2.7 ns.
- Signal simulation, Ekhara event generator. Single enriched cut: $\Delta T_{\gamma\gamma} - \Delta R_{\gamma\gamma}/c < 0.3$ ns



$\gamma\gamma$ Physics

- 8% statistical uncertainty on signal reached with ~ 1.5 fb^{-1} (2017-18).
- On-going calibration of more data samples, checks of simulated signal and fit results. Investigating effect of kinematic fit on reconstructed variables.





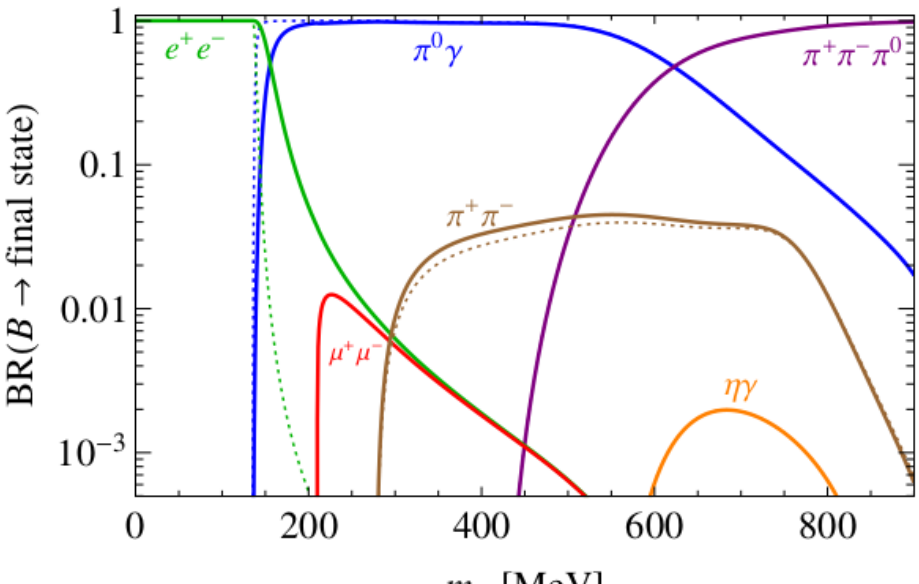
B-Boson Search

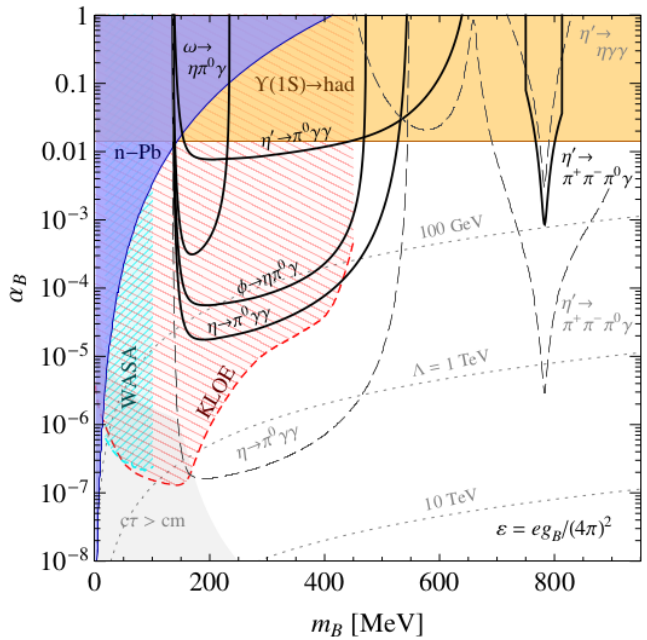
- Similar to dark photon, A'-coupling $\propto \varepsilon Q_f e$. In quark sector, baryonic force is considered

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

Signatures (5-photon final state)

- Dominant decay channel ($m_B < 600$ MeV): $B \to \pi^0\gamma$.
- $\phi \to \eta\gamma \to B\gamma\gamma \to \pi^0\gamma\gamma\gamma$ with π^0 intermediate state.
- $\phi \to \eta B \to \eta\pi^0\gamma$ with η/π^0 intermediate states.





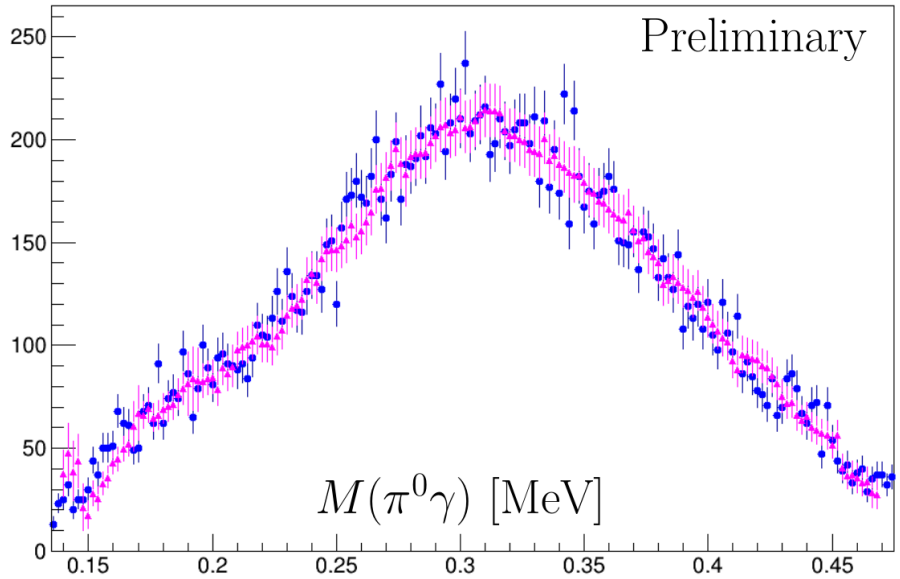
- Current constraints from decay $\phi \to a_0\gamma$ KLOE measurement with ~ 400 pb^{-1}.
- +KLOE A' dark photon search exclusion using BR($B \to e^+e^-$) as a function of mixing parameter.

Decay → / Production ↓	$B \to e^+e^-$ $m_B \sim 1-140$ MeV	$B \to \pi^0\gamma$ 140–620 MeV	$B \to \pi^+\pi^-\pi^0$ 620–1000 MeV	$B \to \eta\gamma$
$\pi^0 \to B\gamma$	$\pi^0 \to e^+e^-\gamma$	...	...	...
$\eta \to B\gamma$	$\eta \to e^+e^-\gamma$	$\eta \to \pi^0\gamma\gamma$	...	...
$\eta' \to B\gamma$	$\eta' \to e^+e^-\gamma$	$\eta' \to \pi^0\gamma\gamma$	$\eta' \to \pi^+\pi^-\pi^0\gamma$	$\eta' \to \eta\gamma\gamma$
$\omega \to \eta B$	$\omega \to \eta e^+e^-$	$\omega \to \eta\pi^0\gamma$	...	...
$\phi \to \eta B$	$\phi \to \eta e^+e^-$	$\phi \to \eta\pi^0\gamma$	...	

B-Boson Search

Analysis strategy

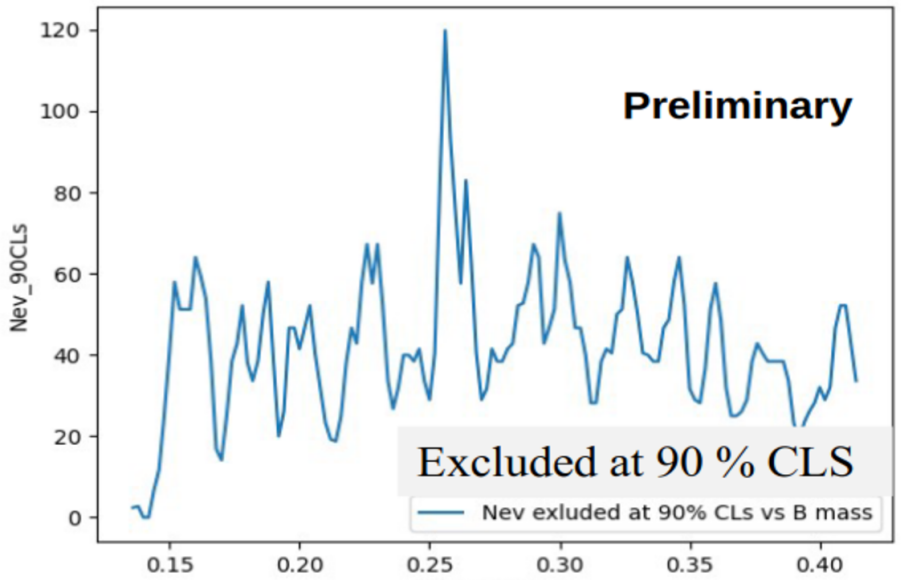
- Study on ~ 1.7 fb^{-1} full data sample 2004/2005 KLOE data
- Kinematic fit used to improve energy resolution, all photon final state. Remove $2\pi^0$ background events using the combinatorial distribution.
- Main backgrounds
  $\phi \to a_0\gamma \to \eta\pi^0\gamma$
  $\phi \to \eta\gamma \to 3\pi^0\gamma$ (7-photon final state with 2 lost or merged photons).
- B-Boson signal signature appears as a peak on $M(\pi^0\gamma)$ distribution.



B-Boson Search

Upper limit evaluation

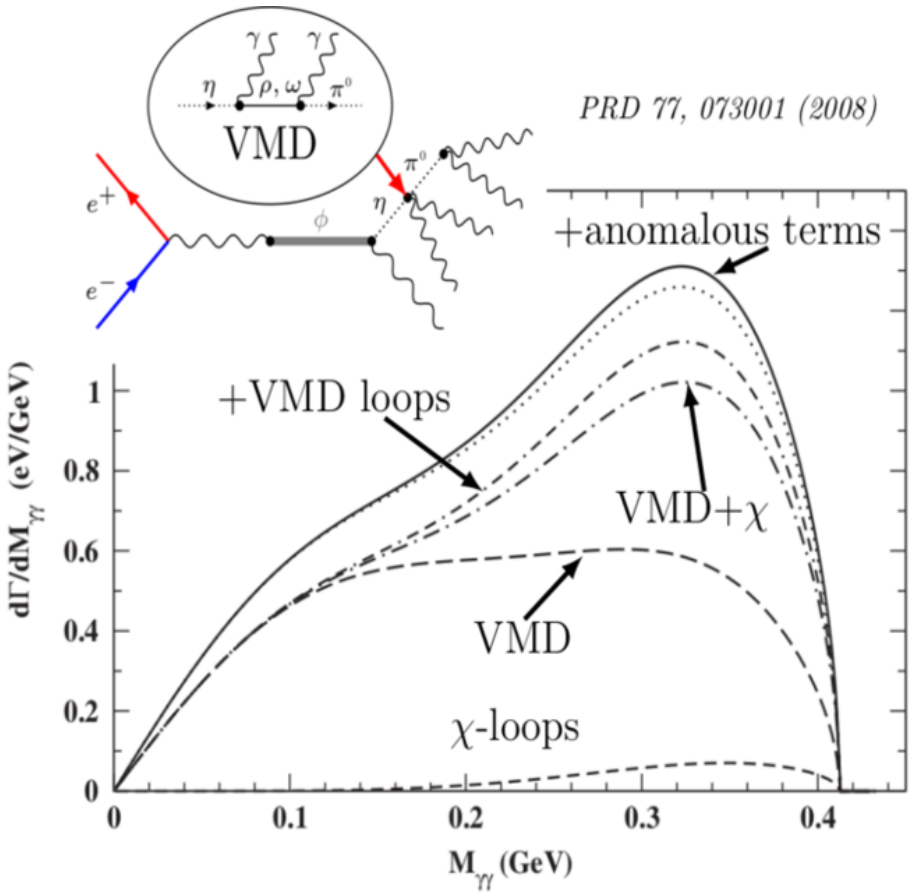
- Background is estimated from fitting to the side-bands excluding the signal region.
- Calculation based on CLs technique.
- On-going correction for reconstruction efficiency and luminosity to set a limit on BR.
- Expect to vastly improved existing limits on α_B.



$\phi \to \eta\gamma,\ \eta \to \pi^0\gamma\gamma$

Motivation

- χPT "golden mode": $\mathcal{O}(p^2)$ null, $\mathcal{O}(p^4) = 0$ on the tree level and suppressed on 1-loop by G-parity and large kaon mass, therefore $\mathcal{O}(p^6)$ are dominating.
  [Ll. Ametller et al. PLB 276(1) (1984)]
- $M(\gamma\gamma)$ that are not coming from π^0 gives insight of theoretical models.



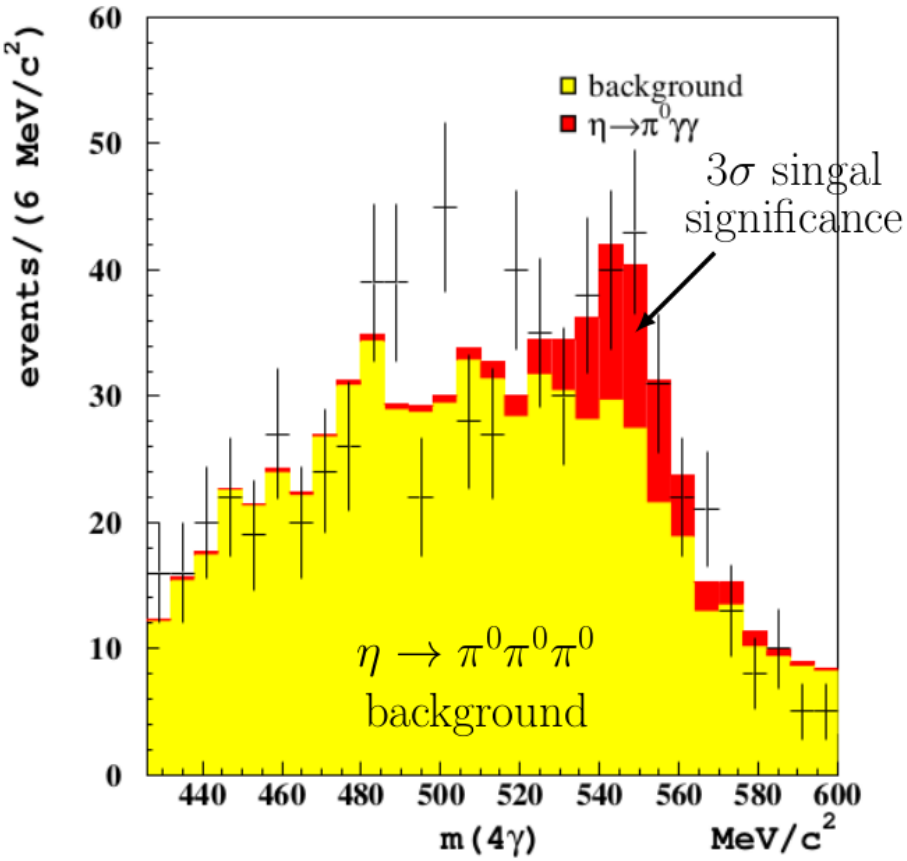
$\phi \to \eta\gamma,\ \eta \to \pi^0\gamma\gamma$

Branching Ratio Measurement

- $(22.1 \pm 2.4 \pm 4.7) \times 10^{-5}$ [CB@AGS (2008)].
  $(25.2 \pm 2.5) \times 10^{-5}$ [CB@MAMI (2014)].
- $(8.4 \pm 2.7 \pm 1.4) \times 10^{-5}$ [KLOE (2006)].

Prediction

- $(13.5 \pm 0.8) \times 10^{-5}$ [PRD 102 (2020) 034026].

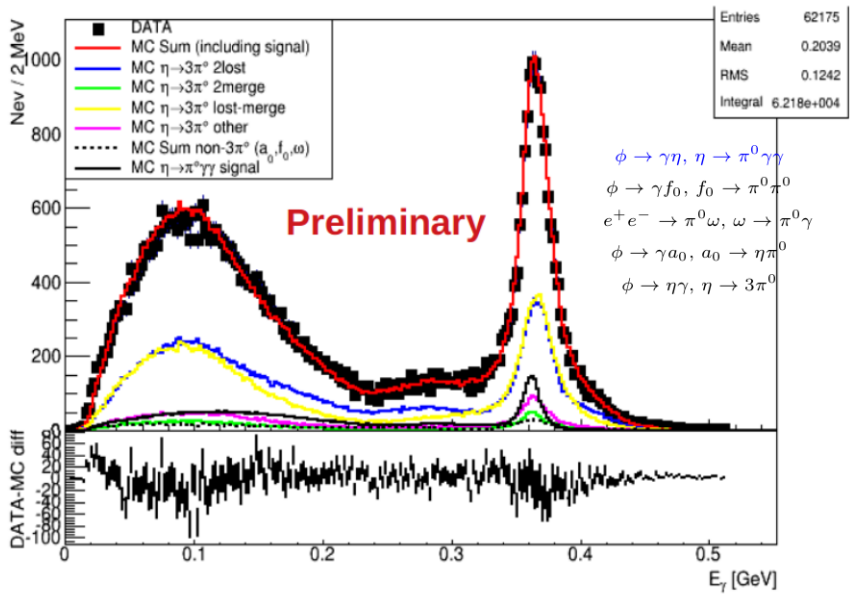


$\phi \to \eta\gamma,\ \eta \to \pi^0\gamma\gamma$

- Data sample $\mathcal{L}_{\rm int} \sim 1.72$ fb^{-1} (2004/05), fourfold larger than previous KLOE analysis.

Background rejection

- Five-photon final state.
- Large backgrounds. Use kinematic fit to improve resolution, constraints of η/π^0 mass to reject $2\pi^0$ in $\omega\&f_0$, a_0 and $\eta \to 3\pi^0$ (2 lost photons).
- TMVA-BDT (ROOT) training rejects $\eta \to 3\pi^0$ (merged clusters) using cluster parameters as input (remove up to 50%).
- Pseudo-chi2 effectively rejects $2\pi^0$ in non-$3\pi^0$ background ($\sim 90\%$ reduction of remaining $\omega\&f_0$).



- Good MC-Data agreement (sig+all backgrounds). Reasonable pull distribution.

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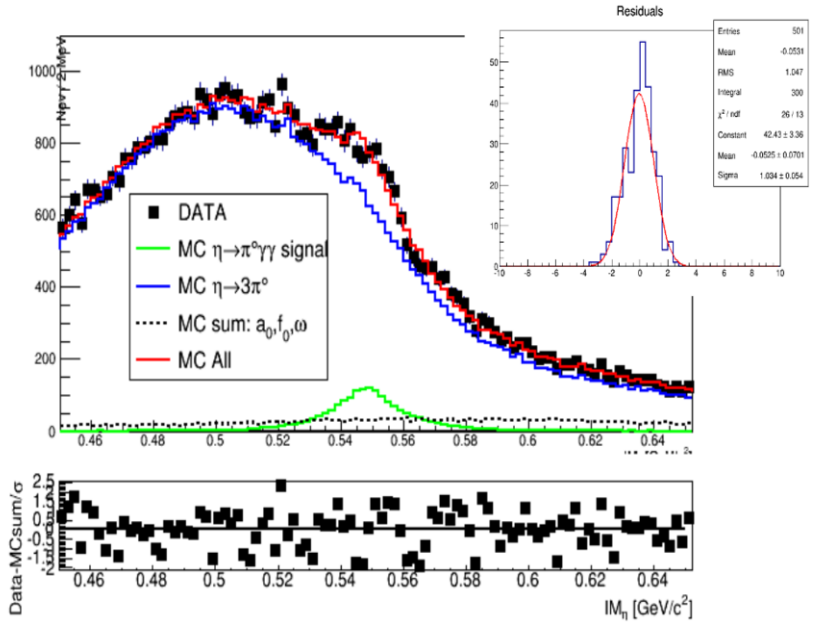


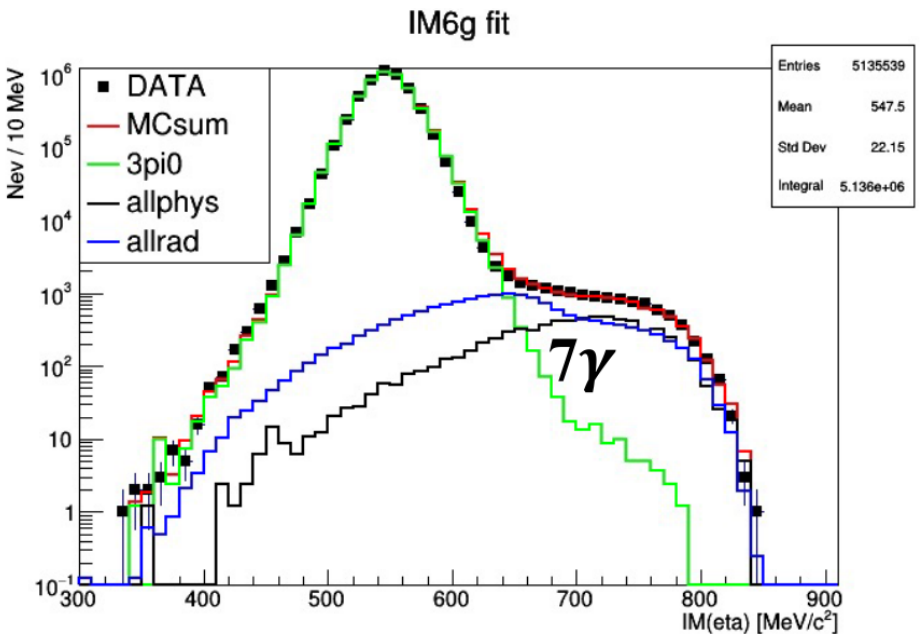
- Good MC-Data agreement (sig+all backgrounds). Reasonable pull distribution.
- Clear signal evidence (S/B$\sim$ 0.1), $\sim 20\%$ efficiency.

$\phi \to \eta\gamma,\ \eta \to \pi^0\gamma\gamma$

Preliminaly Result

$$\frac{\mathrm{BR}(\eta \to \pi^0\gamma\gamma)}{\mathrm{BR}(\eta \to 3\pi^0)} = \frac{N_S/\varepsilon_S}{N_{3\pi^0}/\varepsilon_{3\pi^0}}, \quad \mathbf{BR} = (\mathbf{1.23 \pm 0.14_{stat}}) \times \mathbf{10^{-4}}$$

- Stable $3\pi^0$ normalization based on 7 photons events counting, a few percent variation on the stability if integrating 6-8 photon events.



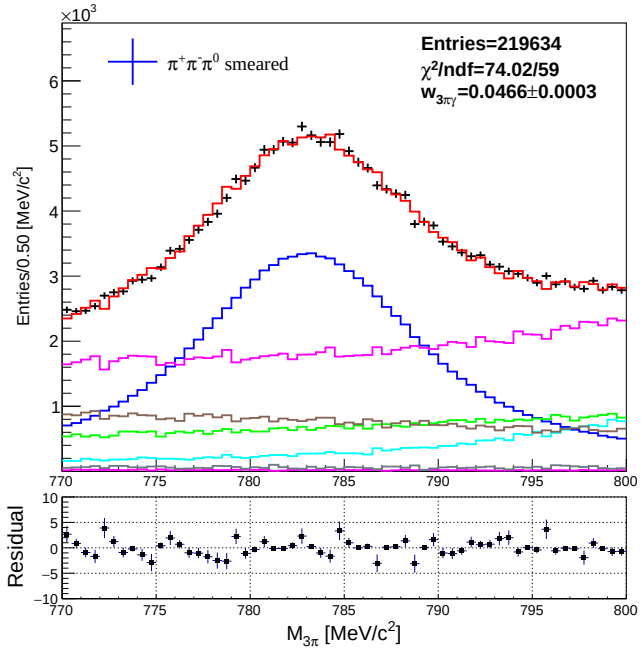
- In agreement with latest prediction. $\mathrm{BR}^{\mathrm{theo}}_{\eta\to\pi^0\gamma\gamma} = 1.365(8) \times 10^{-4}$. Compatible with KLOE(2006) with $\sim 10\%$ stat. error (3 times better), larger signal efficiency. $\mathrm{BR}^{\mathrm{pdg}}_{\eta\to\pi^0\gamma\gamma} = (2.56 \pm 0.22) \times 10^{-4}$.
- On-going systematics analysis, $M(\gamma\gamma)$ spectrum.

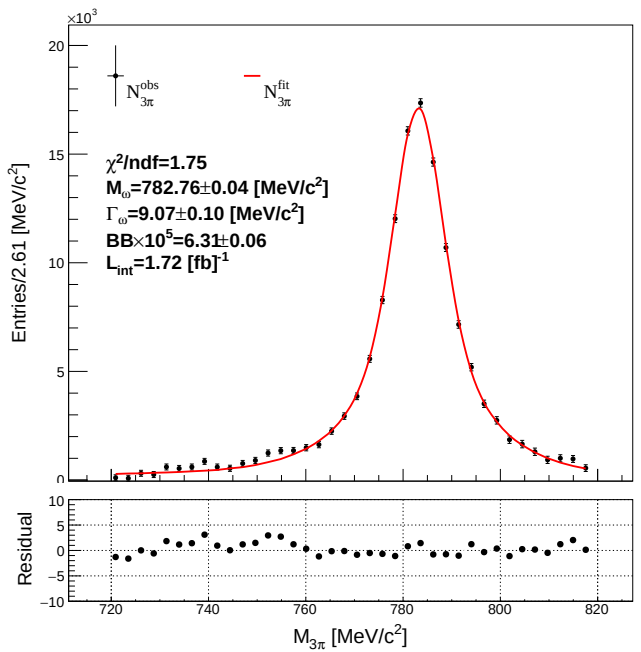
	KLOE (2006)	This work
$\mathcal{L}_{\mathrm{int}}$ [fb^{-1}]	~ 0.45	~ 1.7
# η	1.6×10^6	7.1×10^7
# signal	68 ± 23	1250 ± 130
$\varepsilon_{\mathrm{sig}}$	$\sim 4.6\%$	$\sim 20\%$
BR $\times 10^4$	$0.84 \pm 0.27_{\mathrm{stat}} \pm 0.27_{\mathrm{stat}}$	$\mathbf{1.23 \pm 0.14_{stat}}$

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

- 3π channel counts for the second largest contribution on $a_\mu^{\mathrm{HVP,LO}}$, both in absolute values and uncertainties.
- Current cross section measurement of comes from CMD-2/SND measurement with energy scan and by Babar/BESIII with ISR technique.
- For $\sqrt{s} < m_\phi$, this measurement is feasible using ISR technique in KLOE/KLOE-2.
- Improve lack of ISR data samples in low energy region, complementary results to direct energy scans.

- Data fit with a single BW convoluted with the ISR radiator and a mass resolution smearing function
- Large improvement on fit quality with better mass resolution description (2 gaussians).
- Analysis of systematics on analysis cuts, background subraction still on-going.
- Errors on fit parameters are excellent. (10-50 keV on Γ and mass and % on $B_{ee} \times B_{3\pi}$.)
- Theory fit model being refined.





Summary

Hadron KLOE/KLOE-2

- Sample of 5-photon final state:
  • Provide the best limit on the B-Boson search using decay $B \to \pi^0\gamma$, in a good progress and highly anticipated.
  • Study the golden χPT process $\eta \to \pi^0\gamma\gamma$. Preliminary KLOE BR shows great improvement and in agreement with the most recent prediction.
- $\gamma\gamma$-physics, Using π^0 produced with $\gamma\gamma$ fusion and tagged with KLOE-2 low angle tagging system to determine the braching ratio. Very promising result of reaching 8% statistical error on the first 1.5 fb^{-1}.
- $e^+e^- \to \pi^+\pi^-\pi^0$ (ISR method), extract cross section $\sigma_{3\pi}$ in omega region, reduce uncertainties on $a_\mu^{\text{HVP, LO}}$.
- $\phi \to \eta\pi^+\pi^-$ (G-parity and OZI rule violated), test VMD model, measuring the line shape around ϕ.
  Search for the Dalitz decay $\phi \to \eta\mu^+\mu^-$. On-going MC studies, clear evidence for $\phi \to \eta\pi^+\pi^-/\eta\mu^+\mu^-$ signals.

Thank You!